Comparing Simulated Size Distributions of Precipitation Systems at Different Model Resolution

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Abstract

Size distributions of tropical convective systems in regional numerical atmospheric models are analyzed over a 2.5 × 10⁵ km² domain using different model grid spacing and parameterization schemes. The 5- and 20-km-resolution experiments are configured with a cumulus parameterization scheme, whereas the 2- and 4-km-resolution experiments are not. Precipitation systems are defined by either synthetic satellite infrared images, surface rain rates, or vertical winds at 600 hPa. The size distributions of systems defined by shallower clouds, lower rain rates, and weaker updrafts follow power laws, whereas those defined by deep clouds, higher rain rates, and stronger updrafts show lognormality. The cloud size distribution of the 5-km-resolution experiment is most similar to that of the real geostationary satellite observations. Generally, the largest system size becomes larger in the 5- and 20-km-resolution experiments, implying that the cumulus parameterization may have an impact on that scale. Exceptionally, all the model-simulated size distributions of heavy rain areas agree well at the largest scale. Lower-resolution experiments tend to underestimate the number of small-scale systems when compared with higher-resolution experiments. The size distributions also capture a temporal modulation of precipitation during the 2007 Jakarta flood event; small-scale intense precipitation systems increase at the largest scale. Lower-resolution experiments tend to underestimate the number of small-scale systems when compared with higher-resolution experiments. The size distributions also capture a temporal modulation of precipitation during the 2007 Jakarta flood event; small-scale intense precipitation systems increase during the period.

(Citation: Otsuka, S., N. J. Trilaksono, and S. Yoden, 2017: Comparing simulated size distributions of precipitation systems at different model resolution. SOLA, 13, 130–134, doi:10.2151/sola.2017-024.)

1. Introduction

Accurate numerical simulations of convective precipitation are of great interest in terms of scientific understanding and weather forecasting. However, predictability of cumulus convection is limited by the chaotic nature of the atmosphere, insufficient observations, and imperfect numerical models (e.g., Melhauser and Zhang 2012). It becomes more complicated to evaluate reproducibility in convection-permitting or convection-resolving numerical simulations because finding the same convective systems between observations and simulations or between different simulations becomes difficult.

Probabilistic representations are therefore important to evaluate numerical simulations. Our previous studies (Trilaksono et al. 2011, 2012) employed ensemble simulations to construct cumulative distribution functions of precipitation rate to investigate the dependency of the reproducibility of a heavy rain event on the model resolution and cumulus parameterizations. Temporal changes of the statistics associated with the time evolution of atmospheric circulations were also investigated.

Size distributions of cumulus convections is directly observable with various instruments such as satellites, airborne radars, and ground-based radars. Previous studies revealed that lognormal distributions were frequently observed (López 1977; Houze and Cheng 1977; Mapes and Houze 1993; Mesnard and Sauvageot 2003; Cetrone and Houze 2006; Holder et al. 2008). Other functional forms such as a power law (Machado and Rossow 1993), a double power law (Benner and Curry 1998), and an exponential form (Mesnard and Sauvageot, 2003) were also reported.

Therefore, size distributions of cumulus convections can be used to verify numerical simulations. Inoue et al. (2008) compared simulated and observed cloud size distributions using a global convection-permitting model NICAM (Nonhydrostatic ICosahedral Atmospheric Model) and the Multi-functional Transport Satellite (MTSAT)-1R geostationary meteorological satellite, and concluded that both the observation and simulation showed similar lognormals. Wood and Field (2011) analyzed near-global satellite data, aircraft observations, and a global numerical simulation, and concluded that the size distribution can be expressed using a single power law.

This paper aims to show how size distributions of convective systems is usable for analyzing numerical simulation data with different model resolution and choice of parameterizations. The model horizontal grid spacing (Δ) will be a key factor. For example, convective updrafts in NICAM are represented by only a single horizontal grid point if Δ ≥ 3.5 km (Miyamoto et al. 2013; Kajikawa et al. 2016).

Cumulus convection includes different processes such as conditional instability, cloud microphysics, and advection. Thus, a comprehensive approach will help understand physics behind the size distributions and their numerical model representations with different horizontal resolution. This paper analyzes the size distributions of precipitation systems defined by different variables, i.e., synthetic satellite infrared images, surface rain rates, and updrafts, by taking advantage of the full meteorological field in the model. In addition, different time periods are compared to see if the size distribution can illustrate temporal modulations of atmospheric circulations.

The paper is organized as follows; Section 2 describes data and methodology, Section 3 shows the results, and Section 4 draws conclusions.

2. Data and methodology

2.1 Data

The outputs of numerical experiments described in Trilaksono et al. (2011, 2012) are analyzed. The numerical model is the Japan Meteorological Agency Nonhydrostatic model (JMA-NHM; Saito et al. 2007). The model is configured with two nested computational domains; Δ = 20 km for the outer domain, whereas Δ = 5, 4, or 2 km for the inner domain. Experiments on these domains are referred to as EXP20km, EXP5km, EXP4km, and EXP2km, respectively. EXP20km and EXP5km use a modified Kain-Fritsch cumulus parameterization, whereas EXP4km and EXP2km do not use any cumulus parameterizations. EXP2km, EXP4km, and EXP5km use the same microphysics parameters that are tuned by JMA for operational precipitation forecasting over Japan at the 5-km resolution. A nonlinear damping coefficient is tuned to suppress excessive upper-air clouds in the tropics. The experimental
period of EXP20km is from 0000 UTC 1 January to 2300 UTC 1 March, 2007, whereas that of EXP5km, EXP4km, and EXP2km is from 0000 UTC 31 January to 2300 UTC 4 February. Time-lagged ensemble simulations were performed to produce nine members at each output time, and all ensemble members are used in the following analyses. The analysis domain covers the western part of Java Island, Indonesia, and the experimental period includes a flooding event occurred in Jakarta in February 2007 (Wu et al. 2007).

The following model outputs are analyzed: hourly black body temperatures equivalent to the MTSAT-1R infrared channel 1 ($T_{\text{BB}}$), 30-minute accumulated precipitation every 30 minutes ($R_{\text{30min}}$), and hourly vertical winds at 600 hPa ($W_{\text{600hPa}}$). Here, 600 hPa is chosen because the overlap between the updraft cores and surface precipitation areas maximizes at this altitude. Hourly MTSAT-1R $T_{\text{BB}}$ observations with horizontal resolution of 0.05° × 0.05° (hereafter, MTSAT) are used for verification. All the data are analyzed within a 500 km × 500 km domain as shown in Fig. 1, which is the computational domain of EXP2km.

2.2 Methodology
An area of a precipitation system is computed from the gridded data at their original resolution. If a grid cell and each of its four adjacent cells exceed a threshold, these cells constitute a part of the same system. Figure 1 shows examples of convective systems in the EXP2km forecasts valid for 2000 UTC 31 January initialized at 1800 UTC 29 January (cf., Fig. 1b of Trilaksono et al. 2011). The current method will be affected by the finite size of analysis domain. Although there are discussions on how to reconstruct the true distribution (e.g., Wood and Field 2011), no special treatment is applied in this study, so that the frequency of precipitation systems close to the domain size needs to be interpreted with caution. Note that the lateral boundaries do not seem to produce fake signals in the current experiments.

3. Results
3.1 Cloud size
First, observed or simulated hourly $T_{\text{BB}}$ are used to define a continuous cloud area. Figures 2a and 2b show the histograms of cloud shield size for MTSAT (bold black), EXP2km (black), EXP4km (red), EXP5km (blue), and EXP20km (green). Cloud systems are defined by $T_{\text{BB}} < 270$ (both high and low clouds) or 220 K (a), $R_{\text{30min}} > 20$ mm h$^{-1}$ (b), $W_{\text{600hPa}} > 1$ m s$^{-1}$ (c). Each system is filled with different color. Same data as Fig. 1b in Trilaksono et al. (2011).

The histograms for 220 K (Fig. 2a) are mostly linear on the double logarithmic chart except left and right tails, indicating power laws. The histograms agree well at around 10$^{-10}$ km$^2$ except EXP20km. The smallest scales corresponding to Δ show lower frequencies compared to the higher resolution counterparts. The largest scale decreases as Δ decreases. The right tails seem to be affected by the domain size, 2.5 × 10$^4$ km$^2$.

The histograms for 270 K (Fig. 2b) generally look parabolic on the double logarithmic chart; lognormality will be examined later in Section 3.4. The histograms for different datasets agree well at around 10$^{-3}$ km$^2$ except EXP20km. The slope of EXP5km agrees well with that of MTSAT observation, and the absolute value is slightly overestimated. EXP2km and EXP4km underestimate the frequency of cloud systems greater than 10$^4$ km$^2$, and EXP20km overestimates that of the systems greater than 10$^6$ km$^2$. Histograms for 210 K are similar (not shown).

3.2 Size of precipitation area
Next, $R_{\text{30min}}$ is analyzed in the same way as in Section 3.1. The size distributions for $R_{\text{30min}} > 1$ mm h$^{-1}$ (Fig. 2c) are mostly linear on the double logarithmic chart except the tails, indicating power laws. This is consistent with satellite observations (Teo et al. 2017). The leftmost parts deviate from the power law toward lower frequencies. The right tails vary between the experiments; EXP20km is the largest, EXP5km is the next, and EXP4km and EXP2km are almost the same. Generally, the histograms are similar to those of cloud shield size in Fig. 2a. However, the largest scale is smaller than that in Fig. 2a, probably due to non-precipitating clouds such as low-level clouds and cirrus clouds.

The size distributions for $R_{\text{30min}} > 20$ mm h$^{-1}$ (Fig. 2d) are similar to the curves in Fig. 2b, but steeper. All the experiments agree well at the largest scale around 1–5 × 10$^5$ km$^2$. The largest scale is smaller than that in Fig. 2b. The leftmost parts suddenly bend toward lower frequency. EXP4km shows slightly higher frequencies than EXP2km and EXP5km around 10$^{-9}$ km$^2$.
Sizes smaller than four grid points are also excluded from the model data.

Table 1. Fitting parameters for the histograms in Fig. 2a. The data are fit to the lognormal distribution.

| Dataset     | $\alpha$ | $\beta$ |
|-------------|----------|---------|
| MTSAT       | 97.16    | -1.602  |
| EXP2km      | 202.8    | -1.673  |
| EXP4km      | 190.9    | -1.635  |
| EXP5km      | 120.2    | -1.613  |
| EXP20km     | 6.096    | -1.293  |

3.3 Updraft core size

Finally, $W_{\text{updraft}}$ is analyzed in the same way to investigate the relationship with the model dynamics. In the histograms for $W_{\text{updraft}} > 0.1 \text{ m s}^{-1}$ (Fig. 2e), EXP2km and EXP4km show similar curves bending toward smaller frequency as the size increases, whereas EXP5km and EXP20km lie on the same straight line, indicating a power law. The large difference between the two groups could be attributed to the use of cumulus parameterization.

The histograms for $W_{\text{updraft}} > 1 \text{ m s}^{-1}$ (Fig. 2f) look similar to those in Figs. 2b and 2d. The clearest difference from Figs. 2b and 2d is that the entire size distributions move toward the smaller side as $\Delta$ decreases. The difference between EXP4km and EXP5km is not prominent among others; this indicates that the size of strong updraft core depends on $\Delta$, not the cumulus parameterization, in the current experiments.

It is also clear in Fig. 2f that the maximum updraft core size does not converge between different $\Delta$. However, the right tails in the rain area size distributions in Fig. 2d are almost the same in all the experiments, meaning that the population of updrafts in the largest-scale precipitation areas are different even though the maximum precipitation areas are similarly reproduced.

3.4 Lognormality of the size distributions

As shown in Figs. 2b, 2d, and 2f, the size distributions for high clouds, heavy rain, and strong updrafts do not follow simple power laws. Figure 3 examines lognormality of these distributions with the log-probability format (e.g., López 1977), in which a lognormal distribution becomes a straight line. The empirical cumulative distributions (solid curves) are mostly linear with deviations at the left and right tails, implying that the distributions are truncated lognormals (López 1977). The truncation may occur due to the finite computational domain, intrinsic upper limit of cumulus convection, and the finite $\Delta$.

For $T_{\text{th}} < 220 \text{ K}$ (Fig. 3a), MTSAT deviates the most from the fitted lognormal. EXP5km deviates the most from the fitted lognormal among the models, and EXP5km is the closest to MTSAT. In contrast, EXP2km and EXP4km show lognormality. For $R_{\text{mean}} > 20 \text{ mm h}^{-1}$ (Fig. 3b), EXP2km deviates from the fitted lognormal between $2 \times 10^4$ and $2 \times 10^5 \text{ km}^2$. EXP4km also deviates at around the same scales, but less prominent. EXP5km and EXP20km are more lognormal. The $W_{\text{updraft}}$ core size distributions fit well with the lognormals in all the four experiments (Fig. 3c).

Table 2 shows the fitting parameters for the lognormal, $y = (\alpha/\gamma)\exp(-(\ln x - \mu)^2/(2\sigma^2))$, where $x$ is the system size and $y$ is the probability density. The parameters $\mu$ and $\sigma$ are computed by the sample means and standard deviations of $\ln x$, and $\gamma$ is a normalization factor. The parameter $\mu$ for 220 K becomes about 5 in EXP4km and EXP5km, which is similar to that of MTSAT. The parameter $\sigma$ of EXP5km is 1.65, which is the closest to that of MTSAT observations, 1.63. A visual inspection of Figs. 2b and 3a also indicates that EXP5km is the closest to MTSAT.

The parameter $\mu$ increases as $\Delta$ increases regardless of the variable used. This means that $\Delta > 2 \text{ km}$ is not sufficiently small to represent a population of cumulus convections. On the other hand, the parameter $\sigma$ is similar to each other except EXP20km. EXP20km always show smaller $\sigma$; this is probably because the horizontal resolution is too coarse. The parameters for EXP20km do not change much even if the analysis domain is enlarged.

3.5 Temporal variability of the size distributions

It is of our interest if the size distribution of precipitation systems can capture temporal changes in the atmospheric circulations. Here we compare the five days from 31 January to 4 February with a longer period from 1 January to 1 March. Note that the two-month experiment is conducted only with EXP20km due to the limited computer resources. Despite its coarser resolution, EXP20km can capture the temporal modulation of precipitation associated with cold surges (Trilaksono et al. 2012).

Figure 4 shows the size distributions for (a) $T_{\text{th}} < 270$, 220 K, and (b) $R_{\text{mean}} > 1.5$, 10, 20, 30, 40, and 50 mm h$^{-1}$ for the five days (solid) and two months (dashed). Here, the five-day period has the following differences from the two-month period. In
the size distributions for 270 K and 1 mm h\(^{-1}\) (Figs. 4a and 4b), precipitation systems greater than \(3 \times 10^4 \text{ km}^2\) increase during the flood event. This is consistent with the formation of a rain band along the northern coast of Java Island. For 5, 10, and 20 mm h\(^{-1}\) (Fig. 4b), the number of systems increases at all scales. For 30 and 40 mm h\(^{-1}\) (Fig. 4b), small-scale systems increase, and large-scale systems slightly decrease. For 220 K (Fig. 4a), the number of systems decreases at all scales, and the maximum size decreases significantly. These are common between MTSAT and EXP20km. These characteristics do not change much even if the analysis domain is extended to the entire computational domain of EXP20km.

4. Concluding remarks

Size distributions of precipitation systems in regional numerical simulations and observations were investigated. The 5- and 20-km-resolution experiments adopted a cumulus parameterization scheme, whereas the 2- and 4-km-resolution experiments did not. Precipitation systems were defined by either black body temperature, surface precipitation, or vertical winds. A temporal change of the size distributions was also investigated. The target region was the western part of Java Island, and the experimental period included a flooding event in Jakarta, Indonesia in 2007.

The size distributions become power laws for shallower clouds, lower rain rates, and weaker updrafts, whereas they become lognormals for deeper clouds, higher rain rates, and stronger updrafts for all the experiments (Fig. 2 and Fig. 3). This is the first description, as far as we know, of the transition from the power laws to the lognormals by changing the thresholds for the convective feature detection.

The cloud size distribution of the 5-km-resolution experiment decreases significantly. These are common between MTSAT and EXP20km. These characteristics do not change much even if the analysis domain is extended to the entire computational domain of EXP20km.
is most similar to that of MTSAT observations (Figs. 2a and 2b), implying that the model parameters of cloud microphysics are optimized for the 5-km resolution. The 5- and 20-km-resolution experiments have more large-scale structures in clouds, weak precipitation, and updrafts, compared to the 2- and 4-km-resolution experiments. This might be due to the use of Kain-Fritsch scheme in the 5- and 20-km-resolution experiments; well-organized convective lines tend to appear. Light precipitation may increase when a cumulus parameterization is used (e.g., Holloway et al. 2012). In contrast, large-scale structures in the strong precipitation areas are almost the same in all the experiments (Fig. 2d).

In the size distributions (Fig. 2), the first three points from the left (i.e., objects represented by three grid points or fewer) are clearly underestimated except MTSAT. Note that an effective model resolution is usually several times coarser than the model grid spacing (e.g., Skamarock 2004). The size distributions of strong updraft cores move to the smaller side as the model resolution increases. In the 20-km-resolution experiment, the precipitation area size distributions revealed that small-scale intense precipitation systems increased during the Jakarta flood event period compared to normal conditions (Fig. 4).

To the knowledge of the authors, size distributions of clouds, rain areas, and updraft cores have not been considered simultaneously in the previous studies. Because of the page limitation, only the above three variables were examined, and similarities and differences were discussed. However, these and other model variables may have interesting characteristics to deepen understand the model representation of moist convective systems.

Although this paper uses only the satellite infrared images as the observation dataset, the current analysis procedure can be easily applied to various data such as radar images. Comparing the model-simulated size distributions with the observation-based distributions will become a guide to improve numerical models.

Acknowledgments

The authors thank Dr. Tomoe Nasuno and the two anonymous reviewers. This work was supported by the MEXT Global Center of Excellence programme, “Sustainability/Survivability Science for a Resilient Society Adaptable to Extreme Weather Conditions” (GCOE-ARS; programme leader: Prof. Kaoru Takara), Kyoto University. This work was also partly supported by JSPS KAKENHI Grant Number JP16K17807 and JP17H01159, and the JSPS Core-to-Core Program: Asia-Africa Science Platforms. The figures were produced by the GFD-DENNOU Library.

Edited by: T. Nasuno

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Manuscript received 26 April 2017, accepted 20 June 2017

SOLA: https://www.jstage.jst.go.jp/browse/sola/