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Resolution dependencies of tropical convection in a global cloud/cloud-system resolving model

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Abstract

The properties of tropical convection are evaluated using one-month long simulation datasets produced by the non-hydrostatic icosahedral atmospheric model (NICAM) using 3.5-, 7-, and 14-km horizontal meshes with identical cloud-microphysics configurations. The simulations are targeted on the 2nd Madden-Julian oscillation (MJO) event observed in the CINDY2011/DYNAMO field campaign. An increase of high cloud fraction at 200 hPa level and a reduction of surface precipitation occur as the horizontal resolution increases, corresponding to the reduction of precipitation efficiency due to the shorter residence time inside stronger updrafts that occur at the higher resolution. The increase of high cloud fraction is followed by the warming of the troposphere, which results in an increase in the column water vapor and an elevation of the freezing level. The total water condensation is decreased at higher resolutions, which is likely due to a balance with the decreased outgoing longwave radiation (OLR). The reproduced MJOs, which accounted for a large portion of the tropical convections, were similar in the 3.5-km and 14-km simulations in terms of eastward propagation speeds and structures, including the characteristic westward tilt of the moisture anomaly with height. However, the amplitude of the anomalous MJO circulation was considerably smaller in the 3.5-km simulation. The robust resolution dependence and the interpretations presented in this study underline the necessity for a resolution-aware cloud-microphysics optimization method that will have value in the coming era of global cloud-resolving simulations.
Keywords resolution dependency, cloud-resolving model, tropical convection
1. Introduction

Aided by the continuous improvement of computational power, global simulations using sub 4-km horizontal meshes, which are often referred to as global cloud-resolving (or convection-permitting) simulations, are becoming increasingly affordable. The length of such simulations was limited to about 10 days in the 00’s even when top-tier supercomputers were used to perform the simulations (Tomita et al. 2005, Miura et al. 2007). Year-long simulations and month-long ensemble simulations at 3.5-km mesh are now considered as costly but available options for the non-hydrostatic icosahedral atmospheric model (NICAM, Tomita and Satoh 2004, Satoh et al. 2014) when it is executed on the K computer (Hasegawa et al. 2011), a 10-petaflops scale supercomputer used for the simulations in this study. The finest horizontal mesh used for NICAM is in the sub-kilometer range (870 m, Miyamoto et al. 2013, Kajikawa et al. 2016), although it is only practical for short simulations of several days. An increase in the horizontal resolution is reportedly capable of largely improving the representation of detailed convective features.

Sato et al. (2009) found that the diurnal cycles that are too strong and too late in a 14-km mesh global cloud-system resolving model can be significantly improved by applying a 3.5-km mesh. Weisman et al. (2008) reported that an explicit convective model executed with a 4-km mesh reproduces fine details in convective systems such as squall lines, bow echoes, and mesoscale convective vortices in 36-hour real-time forecast simulations. An advantage of treating clouds explicitly in lieu of parameterizing them in simulations using
O(10)-km meshes, in the so-called “cloud-system resolving” resolution range, is that the simulation with the former converges to a cloud resolving simulation as the resolution improves. However, the models’ physics components contain uncertainties in parameters for various processes, and to optimize or “tune” these parameters is a necessary procedure to elicit high-performance, even for the cloud resolving models. This tuning is often performed largely with a trial-and-error approach, and the necessary computational resources drastically increase with increases in resolution. Complications arise in the case of global cloud resolving simulations because the required resources become so large that a sufficiently large amount of trial-and-error becomes unaffordable. In practice, NICAM is usually tuned using the cloud-system resolving simulations (mostly 14-km, occasionally 7-km or 28-km). Cloud resolving simulations of 3.5-km mesh or finer either apply the same set of physics scheme parameters with the cloud-system resolving simulation to maintain consistency, or apply a modified set based on a relatively shorter and smaller set of simulations to improve fine-scale convective features or other aspects of the model assessable in a short time window. Thus, the parameters are not optimized to maximize the performance of the high-resolution model; there is no guarantee that the convergence of the model towards higher resolution leads to improved performance, especially in terms of longer time scale phenomena and model climatology. Such issues have been raised and discussed in Jung and Arakawa (2004) using 2-dimensional non-hydrostatic models at multiple resolutions ranging from 2-km to 32-km, by which they demonstrated that the
results are sensitive to time scales of cloud-microphysics. Additionally to the issues discussed using regional models, resolution sensitivity in global models contain a complication that the altered convection can also modulate the large-scale environments by affecting the large-scale balance of radiation and convection. Tomita et al. (2005) compared a 10-day long aqua-planet simulation using NICAM with 3.5-, 7-, and 14-km meshes, using a simple cloud-microphysics scheme that include ice phase effects (Grabowski 1998) and indicated that the precipitation rates near the equator decrease as the resolution increases.

In this study we analyze the simulation dataset used in Miyakawa and Kikuchi (2018), hereafter referred to as MK18, which compared features of a Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) event produced by NICAM with three different meshes, namely, 3.5-km, 7-km, and 14 km, using an upgraded cloud-microphysics scheme with common parameter values. The simulated MJO event was the later of the two MJO events captured in a major international observation campaign called the Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011/Dynamics of the MJO (CINDY2011/DYNAMO; Yoneyama et al., 2013). The MJO was successfully produced with 3.5-km and 14-km meshes in terms of propagation speed, while the propagation was slow, and the convective envelope was distorted in the 7-km mesh, likely due to an overestimation of the latent heat flux associated with a prolonged existence of eddy disturbances near the equator. Interestingly, the mean cloud and precipitation
features appeared to have a considerable resolution dependency, but it was not investigated in detail in MK18, which focused on wavelet powers of disturbances embedded in the MJO convective envelope.

We aim to clarify the impact of resolution change on basic cloud features in the tropics and the MJO, and also gain insight into what features need to be maintained for a good representation of the MJO among multiple resolutions.

2. Data and methods

2.1 Model description and configuration

The simulation datasets analyzed in this paper were the outputs of 30-day global 3.5-, 7-, and 14-km CINDY2011/DYNAMO experiments initialized at 00 UTC on Nov. 17, 2011 used in MK18. The 14-km output was part of the MJO simulation series in Miyakawa et al. (2014), performed by the 2012 version of NICAM (NICAM.12). The 3.5-km and 7-km data were produced by the early 2014 version (NICAM.14.1), which included minor upgrades to NICAM.12. The model configurations of the 3.5-km, 7-km and 14-km mesh simulations were identical in all other senses. The governing equations are fully compressible and non-hydrostatic. The finite volume method was used for spatial discretization. An icosahedral grid system, modified using spring dynamic smoothing, was applied for horizontal grids (Tomita et al., 2001; Tomita et al., 2002). A terrain-following grid system with 38 vertical layers was also employed. The model top height was set to
approximately 38 km. The layer thickness was configured to increase gradually with altitude, starting from 80.8 m for the bottom-most layer. Applied physics schemes included: the NICAM Single-Moment Water 6 cloud-microphysics scheme (Tomita, 2008), which considers six categories of hydrometeors as prognostic variables; a modified version of the Mellor–Yamada turbulence scheme (Noda et al. 2010; Mellor and Yamada 1982; Nakanishi and Niino 2004); two-stream radiative transfer with a correlated k-distribution scheme (MSTRNX; Sekiguchi and Nakajima 2008); an improved version of the Louis scheme for land surface fluxes (Louis 1979; Uno et al. 1995); and the MATSIRO land surface model (Takata et al. 2003). The model was executed without any cumulus parameterization scheme. A mixed-layer ocean (Maloney and Sobel 2004) model was used herein, in which the surface heat flux affected both the sea surface temperature (SST) and the atmosphere. The depth of the ocean mixed-layer was set to 15 m, and its temperature was relaxed to an externally provided time-varying SST by using an e-folding time of seven days. Initial conditions of the atmosphere and the ocean were derived by linear interpolation of the European Centre for Medium-Range Weather Forecasts Reanalysis Interim (ERA-Interim, Dee et al., 2011) without any additional initialization process. Initial shock occurs, but mostly settles in about 2-days. The external SST was defined as the sum of the time-varying mean annual cycle (calculated for 1989-2011) and constant anomalous component. The difference from the mean annual cycle was averaged over the week before the initial date to derive the constant anomalous component.
2.2 Other datasets

The NOAA interpolated outgoing longwave radiation (OLR) product (NOAA-OLR; Liebmann and Smith 1996), the 0.1-degree daily precipitation reanalysis product of the Global Satellite Mapping of Precipitation (GSMaP; Okamoto et al. 2005, Kubota et al. 2007), and horizontal winds of the ERA-interim dataset were used as observational references.

3. Results

3.1 Mean features of the tropics

Largely owing to the MJO event, convection was active from the tropical Indian Ocean to the western Pacific during Nov 17 to Dec 16, 2011. Most of the observed precipitation was confined within 10° from the equator, whereas the cloudy area with a 1-month mean OLR lower than 240 W/m² covered about 15° from the equator (Fig. 1a).

Bottom panels in Fig. 1 indicate that the overall amount of tropical precipitation in the simulations was mostly in a similar range with the observation, near 4-6 mm/day. The total amount of precipitation was the largest in the 14-km simulation, especially to the east of 130°E. Precipitation in the 7-km simulation was overestimated in the western Indian Ocean, which was consistent with the lingering MJO convective envelope described in MK18. The total amount of precipitation in the 3.5-km mesh was the smallest and closest to the observation. The change in resolution had a significant impact on the OLR. The OLR in the tropics decreased significantly as the resolution increased from 14-km mesh to 7-km and
3.5-km meshes, indicating an increase in cloud coverage and/or cloud-top heights. Column water vapor increased with resolution in the tropics, as indicated in Fig. 2 by red contours. The SST was warmer in the higher resolution simulations in most of the tropics, although it was at its lowest in the 7-km simulation in the western Indian Ocean, which reflects decrease of insolation and increase of latent heat flux form the ocean surface due to prolonged organized convective activity associated with twin-cyclonic-eddies that enhanced wind-induced evaporation by equatorial westerlies, as described in MK18.

Tropical mean vertical profiles of hydrometeors (Fig. 3) showed that as the resolution increased, cloud ice particles and frozen precipitation increased in the upper troposphere, confirming that the decrease in the OLR was due to increased area-coverage by high-clouds. A large decrease of frozen precipitation near the 550 hPa level in higher resolution simulations accompanied with an increase in the cloud liquid water and rain indicated that the freezing level was higher in the higher resolution simulations. The tropical troposphere was warmer in the higher resolution simulations below 200 hPa, and more so in the upper troposphere (not shown). The warming was consistent with the increase of higher clouds considering the cloud-radiative feedback. The increase of column water vapor in the tropics in the higher resolutions (Fig. 2) was mostly attributed to an increase of water vapor throughout the troposphere. The increase of water vapor was consistent with the warmer troposphere, which can contain a larger amount of moisture following the Clausius–Clapeyron equation. On the other hand, the total amount of condensed water
decreased in higher resolution simulations. This is consistent with decreased OLR due to increased high clouds reducing the condensation heating required to counter radiative cooling.

The remaining key to understanding the resolution dependency of the mean structures of the tropical troposphere is understanding why the high clouds increased in the upper troposphere in higher resolution simulations. The resolution dependency of convective updrafts appears to provide an explanation. In a snapshot of vertical velocity in the tropical Indian Ocean (Fig. 4), the horizontal scale of updrafts is strongly influenced by the mesh size in these resolutions. The monthly and tropical (20°S - 20°N) mean vertical velocities for 14-, 7-, and 3.5-km were $1.10 \times 10^{-3}$ [m/s], $1.17 \times 10^{-3}$ [m/s], and $1.23 \times 10^{-3}$ [m/s], respectively. The monthly conditional means for positive vertical velocities in the same region for 14-, 7-, and 3.5-km were $3.46 \times 10^{-2}$ [m/s], $3.87 \times 10^{-2}$ [m/s], and $4.63 \times 10^{-2}$ [m/s], respectively. These suggest that the upward branch of the Hadley circulation (e.g., Nguyen et al., 2013), which are similar or slightly stronger in higher resolutions, are realized as stronger and narrower updrafts in the higher resolution simulations. The residence time of an air parcel within an updraft tends to be shorter in higher resolution simulations. The shortened residence time leads to decreased transformation from cloud ice and small frozen precipitation (snowflakes) to larger frozen precipitating particles (e.g., graupels), and larger amounts of the former are supplied to the upper troposphere as high clouds. The consistency of the explanation above is further confirmed in the next
subsection.

3.2 Time evolution of the mean features of the tropics

We now investigate the time evolution of the mean features of the tropics. The tropical mean vertical velocity did not display a clear distinction between different resolutions (Fig. 5a). This is likely because the tropical mean vertical velocity is bounded by large-scale energy balance associated with the general circulation, and is insensitive to the details of tropical convective features. The mean updraft (vertical velocity > 0) velocities have robust differences (Fig. 5b), confirming that the upward branch of the Hadley circulation is realized by stronger and narrower updrafts in higher resolution simulations. The difference between 3.5-km and 7-km simulations is larger than that between 7-km and 14-km, which may be reflecting that the ratio of the area-size of the smallest grids is 1:4:16 for 3.5-, 7-, and 14-km meshes. Mean precipitation also displayed distinct differences (Fig. 5c), confirming that total precipitation values were systematically larger in the lower-resolution simulations. The amounts of cloud ice and frozen precipitation at 200 hPa (Fig. 5d-e) appeared to equilibrate within the first 5 days, settling at larger amounts for higher resolution simulations as depicted in Fig. 3. As indicated by the mean updraft velocity (Fig. 5b), the difference between 3.5-km and 7-km simulation was larger than that between 7-km and 14-km, which is consistent with the view that the amount of high-clouds are closely related with updraft velocities. The OLR difference quickly developed (Fig. 5f) by the increase in high clouds. A decrease in the frozen precipitation at 550hPa and an
increase in column water vapor in higher resolution simulations were evident, as shown in Fig. 5g-h. Unlike the hydrometeors related to high clouds, these features required longer than 20 days to equilibrate. This reflects the time required for the atmosphere to warm up and reach a quasi-equilibrium state after the OLR difference quickly developed. This was confirmed by the gradual increase of temperature difference, which was clearly visible at 300 hPa (Fig. 5i). The slower adjustment is likely part of the adjustment of the general circulation pointed out in Miyakawa et al. (2018) that investigated the model sensitivity of NICAM to installation of convective parameterization schemes.

3.3 MJO relative features

The considerable resolution dependencies of tropical convection described above pose a question regarding the structural difference of MJOs that were successfully produced in the 3.5-km and 14-km simulations in terms of the eastward speed and associated precipitation in MK18, which account for a significant portion of the tropical convections. The eastward propagation is visualized in the two-daily series of precipitation over the tropical Indian to western Pacific Oceans (Fig. 6a-b). Dashed lines indicate the eastward propagation of the convective envelope from Nov 23 to Dec 7 when the envelope was compact and well-defined. The eastward speed was about 5° per day in the 14-km simulation and observation (Fig. 1a of MK18), and was about 4° per day in the 3.5-km simulation. OLR and SST anomalies relative to the MJO (the dashed lines in Fig. 6a-b) composited for the term from Nov 23 to Dec 7 (Fig. 6c-d) show that the horizontal structures
were qualitatively similar between 3.5-km and 14-km simulations. However, the negative OLR anomaly associated with the convective envelope of the MJO was smaller in the higher-resolution simulation, unlike the mean OLR. The amplitude of the SST anomalies was also larger in the 14-km simulation, although the spatial structures were similar in that the positive anomalies led the convective envelope and negative anomalies exist to the west. Zonal-vertical composites (Fig. 6e-f) also show that the humidity structures are qualitatively similar, including westward tilts of moist anomalies with height, a feature known to be associated with the MJO in observations but often not captured in numerical model simulations. The amplitude of the humidity anomaly was larger in the 14-km simulation and was associated with a much stronger circulation despite having a similar overall structure and eastward propagating speed. The center of the zonal circulation was higher near 400-500 hPa in the 14-km simulation compared to near 550-600 hPa in the 3.5-km simulation. Consistent with OLR anomalies in Fig. 6c-d, the amplitude and spatial extent of positive cloud ice anomalies were larger in the 14-km simulation.

4. Summary and discussion

Comparing vertical velocity, hydrometeors, and related features between outputs of 3.5-, 7-, and 14-km mesh simulations that apply identical cloud-microphysics configurations revealed that the tropical mean vertical motions were of similar magnitude among different resolutions while they tended to be realized by narrower and more intense updrafts at
higher resolutions, which likely give less time for hydrometeors in ascending air parcels to transform to larger ice particles, resulting in a higher production of small ice particles at the top of the troposphere, i.e., high cirrus clouds. Additionally, it is possible that the more intense updrafts at higher resolutions prevented light hydrometeors from falling out, further supporting production of high cirrus clouds. The increased high cirrus clouds warm the troposphere beneath by absorbing the upward long-wave radiation and then radiating a significant portion of the absorbed energy back downwards. Due to the increased temperature of the troposphere, the melting layer was elevated and column water vapor was increased in higher resolution simulations. Likely in concert with the decreased OLR, the countering condensation heating and thus the precipitation both decreased. Anomalies of moisture, OLR, and circulation associated with the MJO event were larger in the 14-km compared to the 3.5-km mesh simulation, despite having a similar structure and eastward propagation speed.

The essence of the resolution dependency presented in this study is that the difference of the updraft velocities affected the cloud-microphysics processes. This occurred because the model resolutions were not fine enough for the convection to select its horizontal scale purely in terms of the principles of its own nature. Considering that the minimum horizontal scale of the updraft cores were only marginally freed from the nonphysical constraints of the mesh sizes even at 870 m mesh (Miyamoto et al. 2013), it will continue to be an issue of concern in global cloud resolving simulations in the coming
decades, as the mainstream resolution approaches the sub-kilometer scale. This study suggests the necessity for a resolution-aware optimization method for cloud-microphysics schemes.

The tropical mean OLR decreased about 15 W/m$^2$ each time the resolution was doubled. However, it is important to note that the consequence of the resolution dependence of updraft velocities may have been magnified in the simulations of the present study. Tropical mean OLR decreased only about 3 W/m$^2$ each time the resolution was doubled in the version of NICAM used in Kodama et al. (2015) for an AMIP-like simulation series (not shown), which applied a different set of cloud-microphysics parameters. The version of NICAM used in the present study tended to produce more snow near 200-250 hPa compared to the version used in Kodama et al. (2015), which likely magnified the resolution dependence of OLR. Although the issue is common among these different versions of NICAM, the sensitivity of OLR to model resolution was different, and it was affected by the difference in the detail of cloud-microphysics configurations. This may also explain why the large OLR sensitivity to resolution was not found in Tomita et al. (2005), which applied a different cloud-microphysics scheme.

The reason why the MJO was realized with a smaller amplitude in the 3.5-km mesh simulation compared to that of the 14-km mesh remains an open question. It may be attributed to a weaker radiative–convective feedback in the 3.5-km mesh simulation, due to the larger mean state cloud-cover by high cirrus clouds at higher resolutions. Reduced OLR
due to high cirrus clouds associated with the MJO is known to cause an anomalous net warming of the troposphere, which is balanced by increased upward motion. Andersen and Kuang (2012) showed in their numerical simulation that the MJO amplitude reduces when long-wave radiative cooling is homogenized horizontally. This radiative-convective feedback was likely less effective in the 3.5-km mesh simulation, because the amplitude of the anomalous OLR related with the MJO was limited by the larger mean state cloud-cover by high cirrus clouds. This may also be the reason why the center of the zonal circulation was lower in the 3.5-km mesh simulation, an indication of a less top-heavy anomalous condensation-heating profile. Although it is outside the scope of this paper, other interesting questions remain that may provide insights to the elusive dynamics of the MJO, such as why the propagation and structures of MJOs were overall similar despite a large difference in the amplitude of the anomalies, and whether or not the 1° per day difference of the eastward speed can be attributed to the different amplitudes. Analysis on a larger sample of MJOs produced in sensitivity experiments under a simplified situation would be useful for addressing these questions; aqua-planet simulations as in Takasuka et al. (2018) would be an ideal test-bed.

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Figure 1. Horizontal maps of OLR (gray shade and contour), precipitation (color), and 850 hPa horizontal winds (vector), averaged during Nov 17 – Dec 16, 2011. (a) Observations/reanalysis, (b) NICAM 14-km, (c) NICAM 7-km, and (d) NICAM 3.5-km. The OLR contours (30 [W/m²] interval) are overlaid on top of the precipitation colors. The bottom panels show the meridionally averaged (20ºS–20ºN) precipitation (black: observation, red: simulation). Observed OLR is from the NOAA-interpolated OLR.
(Liebmann and Smith 1996), precipitation is from the GSMaP (Okamoto et al. 2005, Kubota et al. 2007), and horizontal winds are from ERA-interim (Dee et al. 2011).
Mean SST, precipitable water

(a) NICAM 14 km

(b) NICAM 7 km

(c) NICAM 3.5 km

**Figure 2.** Horizontal maps of one-month-averaged SST (color) and column water vapor (contour). (a) NICAM 14-km, and (b, c) NICAM 7-km and 3.5-km, drawn as deviations from (a). Contour intervals are 10 [kg/m²] in (a), and 5 [kg/m²] in (b) and (c). Red/blue contours indicate positive/negative deviations.
Figure 3. Tropical mean (20°S–20°N) vertical profiles of hydrometeors. (a) NICAM 14-km, (b, c) NICAM 7-km and 3.5-km, plotted as deviations from (a). Red, blue, green, purple, and black plot represent cloud ice water, frozen precipitating water, cloud liquid water, rain water, and water vapor (divided by a factor of 1000), respectively.
Figure 4. Horizontal snapshots (00UTC Nov. 24, 2011) of vertical velocity at 700 hPa, (a) NICAM 14-km, (b) NICAM 7-km, and (c) NICAM 3.5-km.
Figure 5. Time series of tropical mean (20ºS–20ºN) variables; (a) mean vertical velocity at 700 hPa height, (b) mean updraft velocity defined as a conditional mean of positive vertical velocity at 700 hPa height, (c) surface precipitation rate, (d) cloud ice water at 200 hPa height, (e) frozen precipitating water at 200 hPa height, (f) OLR, (g) frozen precipitating water at 550 hPa height, (h) column water vapor, and (i) temperature at 300 hPa height. A three-day running mean is computed before plotting the time series. Blue, green and red plots represent 14-km, 7-km, and 3.5-km NICAM simulated values, respectively.
Figure 6. MJO related structures. Top panels show simulated two-daily (once per 2 days) series of precipitation over the tropical Indian to western Pacific ocean (adopted and edited Fig. 1b, 1d of Miyakawa et al. 2018). They consist of slices that show horizontal snapshots of the tropical Indian to the western Pacific oceans (10°S–10°N, 40°E–160°W). Dashed lines indicate the eastward propagation of the convective envelopes from November 23 to December 7. Middle panels show horizontal composite of MJO relative OLR (color) SST.
(contour), and 850 hPa wind (vector) anomalies during November 23 to December 7.

Bottom panels are as in the middle panels but longitude-height sections of specific humidity (color), cloud ice (contour), and wind (vector) anomalies, averaged over 15°S–15°N.

Left/right panels are for the 14-km/3.5-km NICAM. Contour intervals are 1 [K] in (c) and (d), and $6.25 \times 10^{-7}$ [kg/kg] in (e) and (f). Green/purple contours indicate positive/negative values.

Vertical component of winds are multiplied by a factor of 300 in the bottom panels.