Madden–Julian Oscillation prediction skill of a new-generation global model demonstrated using a supercomputer

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Global cloud/cloud system-resolving models are perceived to perform well in the prediction of the Madden–Julian Oscillation (MJO), a huge eastward -propagating atmospheric pulse that dominates intraseasonal variation of the tropics and affects the entire globe. However, owing to model complexity, detailed analysis is limited by computational power. Here we carry out a simulation series using a recently developed supercomputer, which enables the statistical evaluation of the MJO prediction skill of a costly new-generation model in a manner similar to operational forecast models. We estimate the current MJO predictability of the model as 27 days by conducting simulations including all winter MJO cases identified during 2003–2012. The simulated precipitation patterns associated with different MJO phases compare well with observations. An MJO case captured in a recent intensive observation is also well reproduced. Our results reveal that the global cloud-resolving approach is effective in understanding the MJO and in providing month-long tropical forecasts.

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the Madden–Julian Oscillation\(^1\,^2\) (MJO) is an eastward propagating atmospheric pulse with a typical lifespan of 30–60 days, most clearly visualized in the tropical Indian and Pacific Oceans as a massive envelope that consists of clouds of various horizontal scales. MJO events affect the tropics with heavy rainfall, produce conditions favourable for tropical cyclone developments\(^3\) and induce Rossby-wave trains that cause sustained anomalous conditions in the extra tropics\(^4\), for example, heat/cold waves. Owing to its elusive mechanism and uncertainty in behaviour of unresolved clouds represented by simplified approximation schemes called cumulus parameterization\(^5\) (CP), representation of the MJO remains problematic in many general circulation models (GCMs)\(^6\). While CP is regarded as a core issue in improving MJOs in conventional GCMs, the Nonhydrostatic Icosahedral Atmospheric Model\(^7\) (NICAM), a new-generation model developed under the concept of ‘explicitly resolving clouds’, has successfully reproduced an MJO convective envelope and its eastward migration\(^8\) avoiding the use of CP. However, the large amount of required computational resource has limited such experiments to a small number of case studies. The MJO prediction skill of the model has been perceived to be high but was unable to be assessed. The K computer\(^9\), a recently developed 10 peta-flops supercomputer broke the computational barrier. We conduct a series of 40-day MJO simulations on the K computer using NICAM to estimate its current MJO predictability. Details of the simulation members and the configuration of NICAM are outlined in Methods. The K computer won the first place on supercomputer ranking by TOP500 (http://www.top500.org/) in 2011. It has been widely accessible to researchers and companies for scientific and industrial use since September 2012, and is the most powerful computer currently available to the meteorological science community. The finest global mesh of NICAM achievable on the K computer is currently 870 m (ref. 10). Month-long global simulations at 3.5-km mesh are now available, compared with only a single 1-week simulation\(^9\) completed on the Earth simulator, which ranked highest in 2004.

In this study we use the enhanced computational power of the K computer to increase the number of simulations to enable statistical evaluation instead of applying high resolutions for small numbers of simulations. We apply a 14 km mesh that marginally resolves\(^11\) meso-beta-scale (20–200 km) convective clouds (hereafter referred to as cloud systems). Meshes of 12–14 km have produced eastward propagation of the MJO convective envelope successfully in previous studies by regional and global models without CP\(^12,\,^13\). We show from 54 simulations that NICAM has the potential to provide a valid prediction of MJO phase for 27 days, and that the precipitation anomaly structures associated with different MJO phases compare well with observation. We also show that NICAM well reproduces an MJO case that was captured in a recent intensive observation project. The high-quality observation and simulation provides together an opportunity for detailed mechanism studies. Our results reveal that the ‘global cloud-resolving’ approach is effective in understanding the MJO and providing month-long tropical forecasts.

Precipitation anomaly structures associated with MJO phases. Although COR is useful for evaluating prediction skills in terms of MJO phases, it disregards MJO structures. In particular, rainfall anomaly patterns that accompany MJO signals deserve validation, considering their large impact on human society. Figure 2 compares composites of observed\(^20\) and simulated precipitation anomalies for MJO phases 3, 5 and 7. Horizontal structures of the simulated precipitation anomalies well resemble the observations, even for phase 7, for which the average lead time is 28 days. An overestimation of signal in the Inter-Tropical Convergence Zone over the central Pacific found in phase 5 is a bias frequently caused by NICAM\(^12\). It is probably the result of under-resolved local vertical moisture transport, which could be a common problem for models that explicitly calculate cloud systems without CP at this resolution. More diagnostics are provided in Supplementary Figs 2–9 (composited RMM diagrams, lagged composites of phase probability distribution function, lagged composites and phase-composited vertical structures of MJO-related quantities).

**Results**

**MJO skill score.** Figure 1 shows the MJO skill score of NICAM plotted against the lead times from the initial dates, along with prediction limits of recent operational forecast GCMs\(^14\). The MJO skill score is defined by the bivariate correlation\(^15,\,^16\) (COR) between the observed and simulated real-time multivariate MJO (RMM) indices\(^17\). Details of RMM, COR and procedures for MJO case identification and initial date assignment are described in Methods. NICAM maintains COR higher than 0.6 for 26–28 days depending on the initial MJO phase, 27 days when all 54 cases are included. Phases 8, 1 and 2, respectively, correspond to when the centre of MJO convection is located over South America, Atlantic Ocean—Africa and the western Indian Ocean (Supplementary Fig. 1). GCMs that maintain COR higher than 0.5–0.6 for more than 2 weeks are typically the better models in terms of the MJO predictions\(^14,\,^18\). The Integrated Forecast System model developed by the European Centre for Medium-Range Weather Forecasts is arguably the current best performing GCM in terms of MJO prediction; the newest version maintaining COR higher than 0.6 for 26 days\(^19\). It is important to note that Fig. 1 is not a comparison between completely equivalent samples from NICAM and operational models due to data availability. The major differences are the following: (a) skill scores of operational models are calculated for simulations initialized at all days in winter, whereas the simulation series of NICAM only include limited initial dates that belong to phase 8, 1 or 2 of either already significant or developing MJOs, and (b) only the operational models apply ensemble forecasts\(^16\) (the sample differences are further described in Methods). However, the result reveals that the MJO prediction skill of the developing new-generation model is already competitive with that of the top performing, carefully adjusted operational GCMs.
8 km, which is consistent with the observation. Despite a lead
21 November. The simulated depth of the westerly wind is about
model captures the timing of westerly wind intrusion observed on
(Supplementary Fig. 10) for the MJO case shown in Fig. 3. The
and simulated zonal wind over Gan Island (73.2E, 0.7S;
(Supplementary Fig. 11).
contrast is reduced in a similar simulation applying a 7-km mesh
isolated sub-10 km scale clouds in the surrounding convectively
between the convective regions and the surrounding regions is
day, a speed similar with the observation. The contrast of OLR
Pacific, both in observation and simulation. The leading edge of
MJO25,26 selected the case for their next cross-institutional model
inter-comparison. The number of simulations of this particular
case in our series is too small for statistical skill evaluations.
 However, if simulations by NICAM are successful, which appears
to be the case as shown below, it will reinforce such activities by
providing useful information that enable detailed mechanism
studies. It will also provide the opportunity to compare a global
cloud system-resolving simulation with a major in situ
observation for the same MJO case for the first time.

Figure 3 shows two-daily snapshot series of outgoing longwave
radiation27 (OLR) and precipitation28 over the tropical Indian
to western Pacific Ocean (10N–10S, 40E–160W; Supplementary
Fig. 10), from 19 November to 19 December 2011. The
simulation is a single run initialized at 00 UTC 17 November
2011. A convectively active region of the MJO forms at 50E–90E
and migrates eastward from the Indian Ocean to the western
Pacific, both in observation and simulation. The leading edge of
the simulated convective envelope travels eastward at ~5° per
day, a speed similar with the observation. The contrast of OLR
between the convective regions and the surrounding regions is
larger in the simulation than the observation, possibly because
isolated sub-10 km scale clouds in the surrounding convectively
suppressed regions are not permitted in the 14-km mesh. Such
contrast is reduced in a similar simulation applying a 7-km mesh
(Supplementary Fig. 11).

Figure 4a,c shows time–height sections of observed and
simulated zonal wind over Gan Island (73.2E, 0.7S;
Supplementary Fig. 10) for the MJO case shown in Fig. 3. The
model captures the timing of westerly wind intrusion observed on
21 November. The simulated depth of the westerly wind is about
8 km, which is consistent with the observation. Despite a lead
time of nearly 4 weeks, the deepening of the westerly wind
accompanied by the evolution of the next MJO-like signal is also
captured near 15 December. Figure 4b,d shows similar sections
for relative humidity anomalies. Water vapour in the lower-
middle troposphere has strong control on the depth and
organization of tropical convections, and is presumed to be a
key factor for MJO evolution21. The model captures the transition
of moisture condition in the lower-middle troposphere (about
3–8 km), that is, the moistening that accompanies the first MJO,
the dry phase that follows and the re-moistening of the second
signal. While it is not surprising that the model misses the lower
tropospheric westerly wind around 9 December, considering the
3-week lead time, it is interesting that the model still develops the
second signal. It may be an indication that neither westerly
moisture advection nor local enhancement of wind-induced
surface evaporation around 9 December played vital roles in
setting up convectively favourable conditions for the second
signal.

Discussion
The physical reason why resolving cloud systems improve
the MJO simulations remains an open question. It is noteworthy
that the model performs well despite the lack of fine structures of
cloud systems in the initial data, which is a simple interpolation
from a lower-resolution data set. Thus, subtle details of individual
cloud systems are unlikely to be the sources of high predictability.
Statistical behaviours of feedbacks from cloud systems in realistic
relation with large-scale conditions are the key issues, improved
here by explicit calculation of the cloud systems. Finer
representation of generation/diffusion and redistribution of heat,
mass and momentum by the cloud systems are possible
contributors. A recent study29 based on an analysis of an MJO
case simulated by NICAM discusses that the convective
momentum transport, a crudely represented component in
current GCMs, may play a role in altering the eastward speed of
the MJO, and/or the tilt of its vertical structure, and in
enhancement of surface evaporation. Detailed cloud microphysics (for example, condensation/evaporation, freezing/melting, distinction of ice/snow/graupel, aggregation and so on) is also a possible contributor, which may lead to an improved representation of the balance between convective heating and cloud-radiative cooling of the MJO.

Achievement of high-quality global sub-kilometre simulations—which we may call global cloud-resolving simulations—is regarded as a key step needed for a quantum leap in the field, as emphasized by the leaders of climate and meteorological science in a 2008 summit. Computational powers have improved since then, with the top four supercomputers now sitting above the 10 peta-flops plateau. Our results show that the increase of computational power has efficiently pushed global cloud-resolving modelling activity forward, carrying it to a higher stage where simulations...
executed at resolutions that marginally resolve meso-beta-scale cloud systems can be statistically assessed, compared with operational forecasts, and be seriously considered for social use. More variations of global cloud/cloud system-resolving models are being developed, for example, MPAS32, ICON33. The high performance of NICAM is a promising indication that these models have the potential to take over as the new standard in the near future, thanks to the seemingly never-ending innovation of supercomputers. The increase of computational resource will open the scope for ensemble forecasts34 by these models, that are likely to further improve prediction skills, and provide additional information on uncertainties of the predictions. Conventional GCMs with CP remain important, however, especially for long-term future climate projections. Global cloud/cloud system-resolving simulations will contribute to improvements of CP by providing quantitative information on condensation/evaporation and on convective transport of mass, heat and momentum. Detailed comparisons with models that apply CP, such as in Project Athena34,35 that compared previous versions of NICAM and Integrated Forecast System, are essential in distinguishing the effects of cloud/cloud system features that need to be included in models for skillful MJO prediction. Hybrid models that substitute CP with two-dimensional cloud-resolving models called ‘super-parameterization’ also deserve detailed comparison3. The new paradigm of global cloud/cloud system-resolving models mark the arrival of a month-long MJO prediction era, play key roles in the improvement of climate simulations and promote mechanism studies of the MJO.

Methods

Model configuration. We use the 2012 summer version of NICAM (NICAM.12) modified for the K computer. Governing equations are fully compressible and non-hydrostatic. Finite volume method is applied for spatial discretization. Icosahedral grid system modified by spring dynamic smoothing is applied for horizontal grids36,37. The model has a terrain following grid system with 38 vertical layers. The model top height is 38 km, and layer thicknesses gradually increase with altitude. The model is run without CP. Applied physics schemes are the NICAM The model top height is 38 km, and layer thicknesses gradually increase with altitude. The model is run without CP. Applied physics schemes are the NICAM The model top height is 38 km, and layer thicknesses gradually increase with altitude. The model is run without CP. Applied physics schemes are the NICAM The model top height is 38 km, and layer thicknesses gradually increase with altitude. The model is run without CP. Applied physics schemes are the NICAM The model top height is 38 km, and layer thicknesses gradually increase with altitude. The model is run without CP. Applied physics schemes are the NICAM

Forecast skill evaluation. Forecast skills are assessed by COR between the reference and simulated RMMS indices, formulated as

\[ R(t) = \frac{\sum_{i=1}^{N} \{ a_i(t) b_i(t) \} - \sum_{i=1}^{N} \{ a_i(t) b_i(t) \}}{\sqrt{\sum_{i=1}^{N} \{ a_i(t)^2 \} \sum_{i=1}^{N} \{ b_i(t)^2 \}}} \]

where R, i, N, t, \(a\) and \(b\) are the COR score, labels for each simulation, total number of simulations, lead time from the initial date, RMSM indices of the reference data and RMSM indices of the model output, respectively. Climatologies are required on obtaining RMSM indices, which are unavailable for our model. We use climatologies of the ERA-Interim reanalysis data as substitutes. This may degrade the model skill if the climatologies of the model considerably differ from those of the reanalysis.

Sample differences between NICAM and operational GCMs. The operational model skills indicated in Fig. 1 are for late 2008-2012, and include simulations initiated nearly every day during November–March. The operational models apply ensemble forecasts, that is, the skills are calculated for an average of multiple simulations initiated at the same day with perturbed initial conditions. NICAM skills are those for the 54 initial dates that belong to phases assigned by the procedure described above. All of the initial dates belong to phase 8, 1 or 2, and are between October and March of 2003–2012. The mean initial amplitude of the MJO is 1.48. Ensemble forecast is not applied.

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