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Hiroaki Miura, *et al.*

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A Madden-Julian Oscillation Event Realistically Simulated by a Global Cloud-Resolving Model

Hiroaki Miura,[1]* Masaki Satoh,[1,2] Tomoe Nasuno,[1] Akira T. Noda,[1] Kazuyoshi Oouchi[1]

A Madden-Julian Oscillation (MJO) is a massive weather event consisting of deep convection coupled with atmospheric circulation, moving slowly eastward over the Indian and Pacific Oceans. Despite its enormous influence on many weather and climate systems worldwide, it has proven very difficult to simulate an MJO because of assumptions about cumulus clouds in global meteorological models. Using a model that allows direct coupling of the atmospheric circulation and clouds, we successfully simulated the slow eastward migration of an MJO event. Topography, the zonal sea surface temperature gradient, and interplay between eastward- and westward-propagating signals controlled the timing of the eastward transition of the convective center. Our results demonstrate the potential making of month-long MJO predictions when global cloud-resolving models with realistic initial conditions are used.

A Madden-Julian Oscillation (MJO) is an envelope of active convection thousands of kilometers wide that travels eastward at an average speed of 5 m/s over the Indian and Pacific Oceans (*1*). Given the large-scale (10^3 to 10^4 km horizontally) coupling between the atmospheric circulation and deep convection, an MJO influences not only the intraseasonal (30 to 90 days) variability of the tropics but also tropical cyclone genesis, the onset and break of the Asian-Australian monsoon, and the evolution of the El Niño–Southern Oscillation event (*2*, *3*). Despite its extensive effects on weather events and climate variability, weather prediction and climate models do not simulate the MJO well (*4*). Even recently, most of the coupled atmosphere-ocean general circulation models (GCMs) presented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change had difficulty simulating the variance and phase speed of the MJO (*5*). It is expected that weather forecasts beyond 10 days could be improved if the MJO representations in global weather prediction models were more realistic (*2*).

The major difficulty in simulating the MJO with GCMs involves cumulus parameterization used to estimate the vertical redistribution of heat and moisture by unresolved convective clouds in GCMs (*4*, *6*). Computational constraints have made it almost impossible to run global cloud-resolving models (GCRMs) that compute the effects of clouds explicitly and do not depend on cumulus parameterizations. However, recent increases in available computer power have begun to eliminate the models' artificial gap between cloud processes and the atmospheric circulation (*7*). Improved MJO simulations with GCMs substituting two-dimensional cloud-resolving models for cumulus parameterizations (*8*, *9*) suggest the importance of representing the variation in quasi-equilibrium states (*10*); that is, the statistical balance between stabilization by convection and destabilization by external forcing, which depends on large-scale atmospheric circulation. Therefore, GCRMs may allow realistic MJO simulations because convective activity can be linked directly to dynamic and thermodynamic atmospheric conditions of large-scale atmospheric circulation and convection. Here we report a numerical simulation of an MJO event that occurred between December 2006 and January 2007.

On the Earth Simulator, we ran a GCRM called the Nonhydrostatic Icosahedral Atmosphere Model (*11*), which has been upgraded as a result of aquaplanet experiments (*12*, *13*) and a realistic tropical cyclone experiment (*14*), with horizontal grids with mesh sizes about 3.5 and 7 km. These resolutions are almost fine enough to resolve the gross behavior of cumulus ensembles, including heating and moistening, as a response to large-scale atmospheric conditions. The 3.5-km grid run covered 1 week, whereas the 7-km grid run covered 30 days, which was long enough to reproduce the eastward migration of the convective center from the Indian to the Pacific Ocean. The initial atmospheric conditions were generated by linear interpolation from the National Centers for Environmental Prediction (NCEP) Global Tropospheric Analyses at 00:00 universal time coordinated (UTC) on 25 December 2006 for the 3.5-km grid run and at 00:00 UTC on 15 December 2006 for the 7-km grid run. We did not use any artificial techniques to nudge the model atmosphere to realistic atmospheric states during the numerical integrations (*15*).

The large-scale convectively active region of the MJO was reproduced approximately by the 3.5-km (Fig. 1) and 7-km (not shown in Fig. 1) grid runs. The convective center was near Borneo on 31 December 2006, and upper tropospheric clouds covered the islands of Southeast Asia and the surrounding seas. The typical multiscale structure of

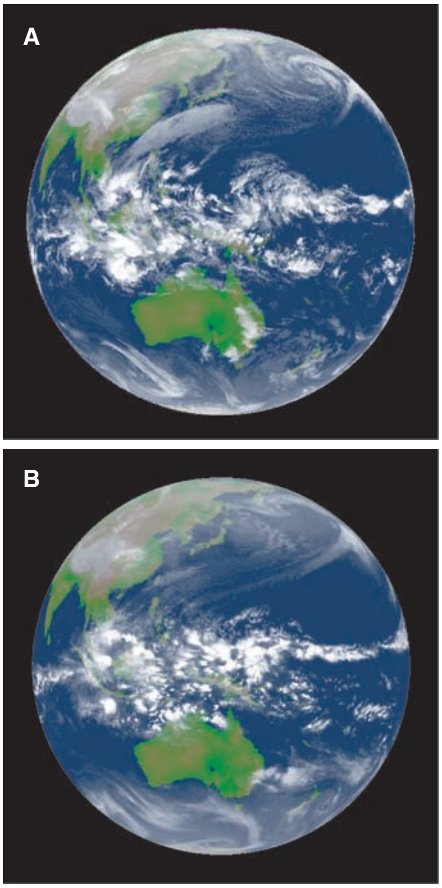

Fig. 1. (**A**) Infrared image from the Multi-Functional Transport Satellite (MTSAT-1R) at 00:30 UTC on 31 December 2006 and (**B**) outgoing long-wave radiation from the 3.5-km run averaged from 00:00 UTC to 01:30 UTC on 31 December 2006.

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[1] Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showamachi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan. [2] Center for Climate System Research, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8568, Japan.

*To whom correspondence should be addressed. E-mail: miurah@jamstec.go.jp

convective systems (*16*, *17*) existed within the convectively active region. The active convective envelope consisted of cloud clusters covering hundreds of kilometers horizontally.

The 7-km grid run simulated the temporal evolution of the large-scale atmospheric circulation realistically during the 30-day integration (Fig. 2 and fig. S1). Before the intense convective activity began, an easterly wind dominated over the Indian and Pacific Oceans on 23 December 2006 (Fig. 2, A and B). Strong westerly and easterly winds near the north end of Madagascar were related to a developing tropical cyclone. As the active convective envelope passed eastward over the Indian Ocean and maritime continents (100° to 150°E), a low-level westerly wind was induced as a response to the latent heating of cloud systems (*18*). On 6 January 2007, the low-level westerly region was about 60° in width (90° to 150°E) at the equator, and strong westerly winds blew around the leading edge of the eastward-moving system (Fig. 2, C and D). The 7-km grid run resolved a strong westerly region northeast of New Guinea that consisted of several archlike structures.

The 7-km grid run computed the slow eastward movement of the convective center at a speed of about 5 m/s (Fig. 3, A and B). Heavy rainfall occurred over the Indian Ocean before 28 December 2006, over the maritime continents from 29 December 2006 to 6 January 2007, and over the Pacific Ocean after 7 January 2007. The slow-moving active convective envelope included internal structures propagating eastward at speeds exceeding 10 m/s, which is in the range of the propagation speeds of convectively coupled Kelvin waves (*19*, *20*). The Indian and Pacific Oceans were connected by a complex of higher-frequency, smaller-scale, eastward-propagating signals (*16*, *17*). The rapidly propagating signals conveyed low-level cool air maintained by consecutive rain evaporation to the east (fig. S2), and the moisture convergence zone shifted eastward following the leading edges of the signals (fig. S3). Over the maritime continents, rapidly propagating signals were generated every 1-day period, suggesting enhancement of the diurnal variation of convection under a moist environment.

The fast eastward-propagating signals faded away at around 150°E before 6 January 2007 (Fig. 3, A and B). The disappearance of the signals appeared to result from interference from topography and a zonal gradient of the sea surface temperature (SST). For example, on 2 January 2007, there was a large amount of moisture over an area between Australia and New Guinea (Fig. 4A), and a large-scale rainband system located at 140°E led the active convective envelope of the MJO (Fig. 4B). Subsequently, the northern part of this rainband system collided with the mountains of New Guinea and weakened rapidly, and the southern part decayed when it encountered drier air over the Coral Sea, where the SST was cooler. As a result, this rainband system did not reach the

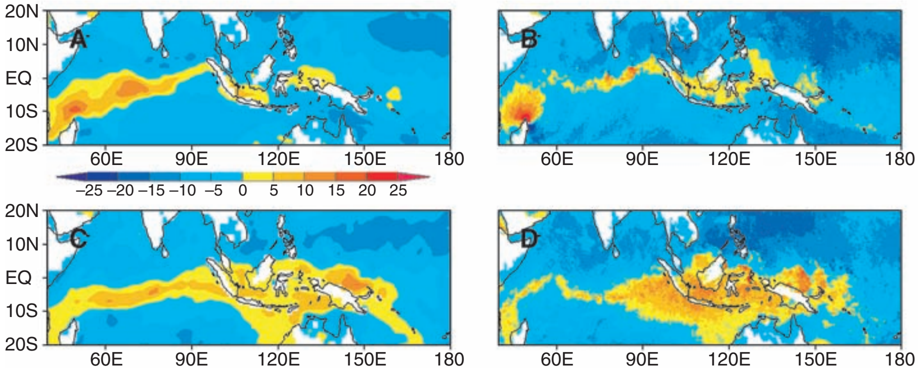

Fig. 2. Spatial distribution of the zonal wind velocity (in meters per second) at the 975-hPa level from (**A** and **C**) the NCEP analyses data and (**B** and **D**) the 7-km grid run at 00:00 UTC on 23 December 2006 [(A) and (B)] and 00:00 UTC on 6 January 2007 [(C) and (D)].

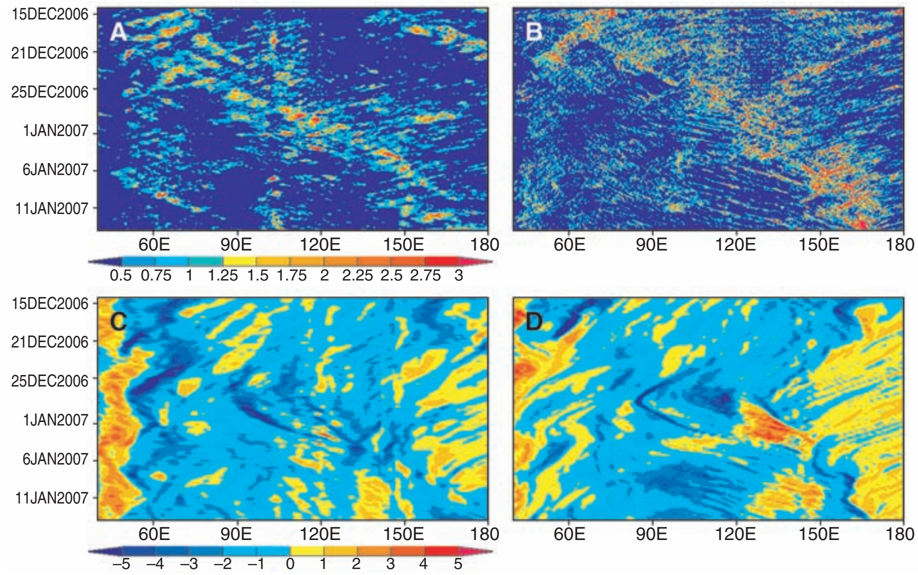

Fig. 3. Time/longitude (Hovmöller) sections. Surface precipitation (in millimeters per hour) averaged between 10°S and 5°N from (**A**) the TRMM 3B42 data and (**B**) the 7-km grid run. The vorticity (10^{-5} per second) at the 850-hPa level averaged between 10°S and 5°S from (**C**) the NCEP analyses and (**D**) the 7-km grid run.

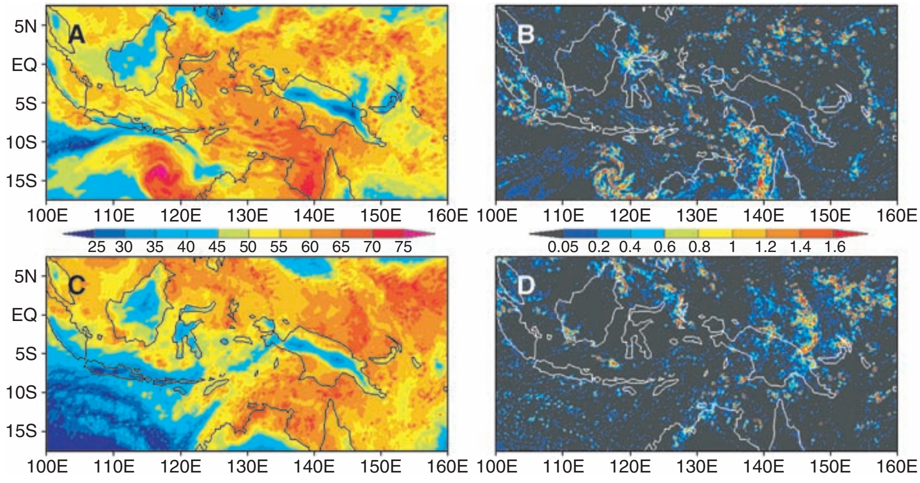

Fig. 4. Longitude/latitude sections of (**A** and **C**) precipitable water (in kilograms per square meter) and (**B** and **D**) column-integrated cloud water (in kilograms per square meter) from the 7-km run at 00:00 UTC on 2 January 2007 [(A) and (B)] and 00:00 UTC on 6 January 2007 [(C) and (D)].

Pacific Ocean. Behind the leading edge, counterclockwise and clockwise vortices were generated at the equator and at 15°S, respectively, at around 120°E. The clockwise vortex northwest of Australia corresponded well with a real tropical cyclone named Isobel. The 7-km grid run successfully predicted this tropical cyclone at the proper location and time, even after the integration continued for more than 2 weeks.

On 2 January 2007, a smaller cloud system was simulated at around 105°E in association with a clockwise vortex (Fig. 4B). This clockwise vortex near the south end of Sumatra originated from a tropical depression–type (TD-type) disturbance (*21*), which changed its direction from westward to eastward west of 90°E around 29 December 2006 (Fig. 3, C and D). As the negative-vorticity region proceeded eastward, a rainband system began to grow around 130°E, traveled to the northwest of New Guinea, and developed into a mature system at around 148°E on 6 January 2007 (Fig. 4D). Around 6 January 2007, a large amount of moisture northeast of New Guinea provided suitable atmospheric conditions for the growth of cloud systems (Fig. 4C). Moisture was transported mainly from the central Pacific, where the SST was as warm as in the western Pacific because of an El Niño event (fig. S3). The eastward-propagating rainband system brought low-level cool air into the South Pacific Convergence Zone (fig. S2), and the convective center of the MJO shifted from the maritime continents to the Pacific Ocean. Rainband systems northeast of New Guinea were also observed in the other MJO events during TOGA-COARE IOP (Tropical Ocean Global Atmosphere–Coupled Ocean Atmosphere Response Experiment, Intensive Observation Period) from November 1992 to February 1993 (*22*, *23*).

Overall, the 7-km grid run realistically reproduced the slow eastward migration of the MJO from the Indian to the Pacific Ocean. However, some features could have caused errors in the movement speed of the MJO. The 7-km grid run failed to simulate individual clouds correctly during the month-long integration. The zonal wind velocity tended to be overestimated over the tropics, and the effect of the overvalued surface precipitation might result in inaccuracy in the estimated amount of latent heat release. Despite these imperfections, the leading edge of the active convective envelope was positioned almost identically to that of observational data sets after the integration of more than 3 weeks on 6 January 2007. A possible explanation for the good correspondence between the 7-km grid run and observations is that the temporal evolution of the MJO is dominated by large-scale systems that the 7-km grid can resolve sufficiently. As inferred from the results of resolution-sensitivity studies using cloud-resolving models in limited domains (*24*, *25*), GCRMs probably have the ability to respond to a given large-scale forcing and restore statistical equilibrium states in a realistic time scale, even if a coarse horizontal resolution is used.

Our results demonstrate the potential ability of GCRMs to make month-long MJO predictions when they run with realistic initial conditions. The principal factors governing the realistic eastward migration of the MJO were the interference of preceding rainband systems from New Guinea and drier air over an area with a relatively cool SST, an eastward-propagating signal that originated from a TD-type disturbance, and abundant moisture supply from the east, probably in association with a westward-propagating disturbance. These results support the hypothesis derived from analyses of the TRMM (Tropical Rainfall Measuring Mission) data, which showed that a group of eastward-propagating Kelvin waves and their interaction with westward-propagating equatorial Rossby waves play a crucial role in MJOs (*26*); and they emphasize the influence of topography and the zonal SST gradient on the MJO.

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Deep Ocean Impact of a Madden-Julian Oscillation Observed by Argo Floats

Adrian J. Matthews,[1,2]* Patama Singhruck,[1] Karen J. Heywood[1]

Using the new Argo array of profiling floats that gives unprecedented space-time coverage of the upper 2000 meters of the global ocean, we present definitive evidence of a deep tropical ocean component of the Madden-Julian Oscillation (MJO). The surface wind stress anomalies associated with the MJO force eastward-propagating oceanic equatorial Kelvin waves that extend downward to 1500 meters. The amplitude of the deep ocean anomalies is up to six times the amplitude of the observed annual cycle. This deep ocean sink of energy input from the wind is potentially important for understanding phenomena such as El Niño–Southern Oscillation and for interpreting deep ocean measurements made from ships.

The Madden-Julian Oscillation (MJO) (*1*–*3*) is characterized by large-scale (1000 km across) precipitation anomalies that propagate slowly eastward from the Indian Ocean to the western Pacific. The lifetime of an individual MJO event is between 30 and 60 days. Dynamically, the MJO can be interpreted as a moist atmospheric Kelvin-Rossby wave in the tropics (*4*) and a modified Rossby wave response propagating on the climatological basic state in the extratropics (*5*). The MJO is thermodynamically coupled with the upper layers of the tropical

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[1] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK. [2] School of Mathematics, University of East Anglia, Norwich NR4 7TJ, UK.

*To whom correspondence should be addressed. E-mail: a.j.matthews@uea.ac.uk