



Global cloud-system-resolving model NICAM successfully simulated the lifecycles of two real tropical cyclones

Hironori Fudeyasu,¹ Yuqing Wang,¹ Masaki Satoh,^{2,3} Tomoe Nasuno,³ Hiroaki Miura,³ and Wataru Yanase²

Received 12 September 2008; revised 8 October 2008; accepted 17 October 2008; published 25 November 2008.

[1] The increasing capability of high-end computers allows numerical simulations with horizontal resolutions high enough to resolve cloud systems in a global model. In this paper, initial results from the global Nonhydrostatic ICosahedral Atmospheric Model (NICAM) are highlighted to demonstrate the beginning of a potentially new era for weather and climate predictions with global cloud-system-resolving models. The NICAM simulation with a horizontal resolution of about 7 km successfully reproduced the lifecycles of two real tropical cyclones that formed in Indian Ocean in the austral summer 2006. Initialized with the atmospheric conditions 1–2 weeks before the cyclones genesis, the model captured reasonably not only the timing of the observed cyclone geneses but also their motions and mesoscale structures. The model provides a high temporal/spatial resolution dataset for detailed studies of mesoscale aspects of tropical cyclone genesis. These promising results suggest the predictability of tropical cyclones by high-resolution global cloud-system-resolving models. **Citation:** Fudeyasu, H., Y. Wang, M. Satoh, T. Nasuno, H. Miura, and W. Yanase (2008), Global cloud-system-resolving model NICAM successfully simulated the lifecycles of two real tropical cyclones, *Geophys. Res. Lett.*, 35, L22808, doi:10.1029/2008GL036003.

1. Introduction

[2] For several decades, cloud-resolving models have greatly contributed to our understanding of cloud and mesoscale atmospheric processes. These models have been run so far in limited areas because of their excessive computational needs. In realistic simulations, the large-scale control of the cloud and mesoscale processes is either through lateral boundary conditions or spectral nudging of the large-scale component in the limited-area model domain [Wang *et al.*, 2004]. One caveat of problem with this approach is the implicit assumption that the processes in the limited-area cloud-resolving model domain do not significantly affect the large-scale circulation that drives the cloud-resolving model. Although two-way nesting can reduce this discrepancy, the best way to avoid the problem completely is to run cloud-resolving models globally. This

is now being made possible by the ever-increasing capability of powerful computers.

[3] The first global cloud-system-resolving model, namely, the Nonhydrostatic ICosahedral Atmospheric Model, or in brief NICAM, has been developed at the Frontier Research Center for Global Change (FRCGC) on the Japan's powerful supercomputer, the Earth Simulator [Tomita and Satoh, 2004; Satoh *et al.*, 2008a]. With a horizontal grid-size of only a few kilometers, the global NICAM simultaneously models cloud clusters, organized mesoscale convective systems, and the associated large-scale circulations, such as the Madden-Julian Oscillation (MJO). Integrating NICAM once at a horizontal resolution of about 3.5 km and once at 7 km, Miura *et al.* [2007] reported the realistic simulation of an MJO event in the austral summer 2006. The model reproduced not only the large-scale organized cloud systems in the MJO, but also the lifecycles of multiscale cloud clusters in the convective phase in the MJO.

[4] The study we present here reports on additional analyses of the 7-km NICAM run used by Miura *et al.* [2007]. Our analyses reveal the first successful simulation of the lifecycles of two real tropical cyclones (TCs) over the Indian Ocean. We will show that, initialized with the atmospheric conditions 1–2 weeks before the cyclones genesis, NICAM reproduced not only the timing of the observed TC geneses and their subsequent intensification but also their motions and mesoscale structures

2. Model, Experimental Design, and Observational Data

[5] NICAM is a global cloud-system-resolving model, which was documented in detail by Tomita and Satoh [2004] and Satoh *et al.* [2008a]. The model was run twice, once with a horizontal grid spacing of about 3.5 km and once with 7 km; there are 40 unevenly distributed vertical levels with the model top at about 38 km in a terrain-following height coordinate [Miura *et al.*, 2007]. The explicit cloud-microphysics scheme of Grabowski [1998] was used for moist processes without subgrid-scale convective parameterization. The model run at 7-km resolution was integrated for 32 days, starting at 0000UTC 15 December 2006 and with initial conditions of atmospheric variables and soil moisture given by the National Centers for Environmental Prediction (NCEP) analysis, which has a horizontal resolution of 1.0° latitude by 1.0° longitude. The sea surface temperature (SST) was spatially and temporally interpolated from the weekly Reynolds SST. Miura *et al.* [2007] indicated that the structure and propagation of the MJO event were well represented in both 3.5-km and 7-km

¹International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa, Honolulu, Hawaii, USA.

²Center for Climate System Research, University of Tokyo, Kashiwa, Japan.

³Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan.

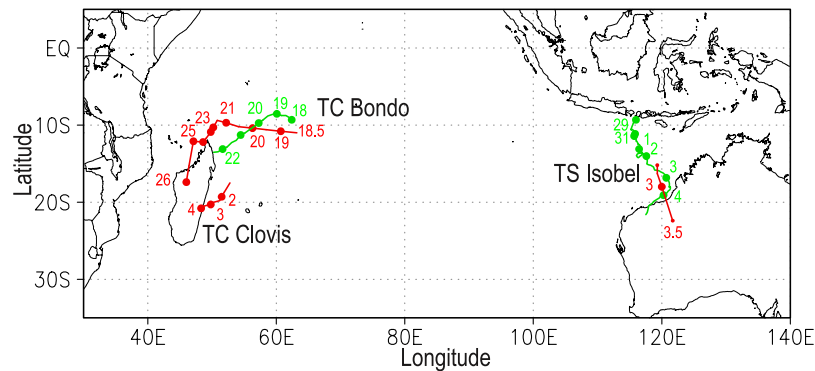


Figure 1. Tracks and locations at 0000UTC (green lines and closed circle) from simulated tropical cyclones, compared with these (red lines and closed circle) from JTWC best track data. Numbers mean the dates of the month.

mesh experiments, though the integration time of the 3.5-km mesh experiment was only for a week. We thus focus on the 7-km mesh experiment, in which TCs were generated along the passage of the MJO propagation as described below.

[6] Satellite observations were used to verify the spatial structure of the simulated TCs. The mesoscale precipitation pattern and the convective activity associated with the TCs were derived from the 2A12 product of the Tropical Rainfall Measuring Mission Microwave Imager (TRMM-TMI). The TRMM-TMI data consist of instantaneous precipitation retrievals and profiles of hydrometeors with a horizontal resolution of approximately 5.1 km. To evaluate the large-scale organized cloud pattern, the global (60°N–60°S) black body temperature (T_{BB}) merged from 11 infrared (IR) channels aboard 5 geostationary satellites of the Climate Prediction Center (CPC-IR) were also used. These satellite data have a horizontal resolution of approximately 4 km.

[7] The tracks of the observed TCs were obtained from the Joint Typhoon Warning Center (JTWC). The JTWC best track dataset includes locations and maximum wind speeds of TCs, generally recorded at 6-h intervals. Estimates of the hourly positions of the storm centers were obtained by linear interpolation in this study.

3. Results

[8] During the NICAM simulation period from 15 December 2006 to 16 January 2007, three TCs that had maximum 10-m wind speeds greater than 34 knots were observed in the JTWC best track data. TCs Bondo and Clovis occurred in the western Indian Ocean and Tropical Storm Isobel in the eastern Indian Ocean (Figure 1). The NICAM simulation reproduced Bondo and Isobel (Figure 1).

3.1. TC Bondo

[9] TC Bondo was first observed as a tropical storm at 1200 UTC 18 December 2006 in the central Indian Ocean (Figure 1). It moved westward and intensified to a category-4 storm. In the NICAM simulation, a low pressure system became identifiable at 0000 UTC 18 December, i.e., after 3 days of the model integration. The storm system, resembling the observed Bondo, had closed isobars and a minimum sea level pressure (SLP) less than 1000 hPa near its center (not shown). The simulated track, determined on the basis of the central position of minimum SLP, is in good agreement with the observed track taken by TC Bondo (Figure 1).

[10] Figure 2 compares the cloud features of the simulated storm and of the observed TC Bondo. The simulated clouds first organized in the Intertropical Convergence Zone (ITCZ) in the central and eastern Indian Ocean (Figure 2b). The storm's cyclonic vorticity originated also in the ITCZ in the central Indian Ocean (not shown). The distribution of the simulated cloud pattern is roughly similar to that depicted in the T_{BB} image of the CPC-IR (Figure 2a). Although the comparison of T_{BB} with the model outgoing longwave radiation (OLR) is not straightforward, they both reflect the cloud-top features of cloud systems in tropics. The simulated storm reached a minimum SLP of 960 hPa and a maximum azimuthal mean 10-m wind speed of about 100 knots, which is comparable to the observed maximum 10-m wind speeds of 90–120 knots during TC Bondo's mature phase given in the JTWC best track data. [Note that a direct comparison of winds is not straightforward since the sustained 10-m wind in the best track data was not from direct measurements but was estimated based on the Dvorak technique, while the model winds are the instantaneous values at a given time step and represent an area mean in a given individual grid boxes].

[11] As can be seen from the surface rain rate from TRMM-TMI products (Figure 2c), Bondo developed an eyewall with a ring of heavy precipitation, a clear eye with little rain near the storm center, and several spiral rainbands with embedded deep convective cells outside the eyewall. The simulated Bondo also developed a typical eyewall structure and spiral rainbands (Figure 2d) that are comparable to the observed. The storm, however, developed these features (shown in Figure 2d) about 24 h later and its center was about 350 km to the west of the real storm center. The vertical structure of the simulated cloud systems was also comparable to the observed except that the simulated hydrometers were higher (Figures 2e and 2f). This is partly due to the use of the relatively coarse model resolution of 7 km and the peculiar features of the cloud microphysics scheme of Grabowski [1998], as reported by Satoh *et al.* [2008b]. Nevertheless, despite some discrepancies, these results strongly suggest that NICAM, given the atmospheric and SST conditions existing 4–7 days before TC Bondo occurred could successfully reproduce not only the development but also the mesoscale structure of Bondo.

[12] In addition, it is interesting to note that a cloud cluster with cyclonic circulation appeared in the northwestern Indian

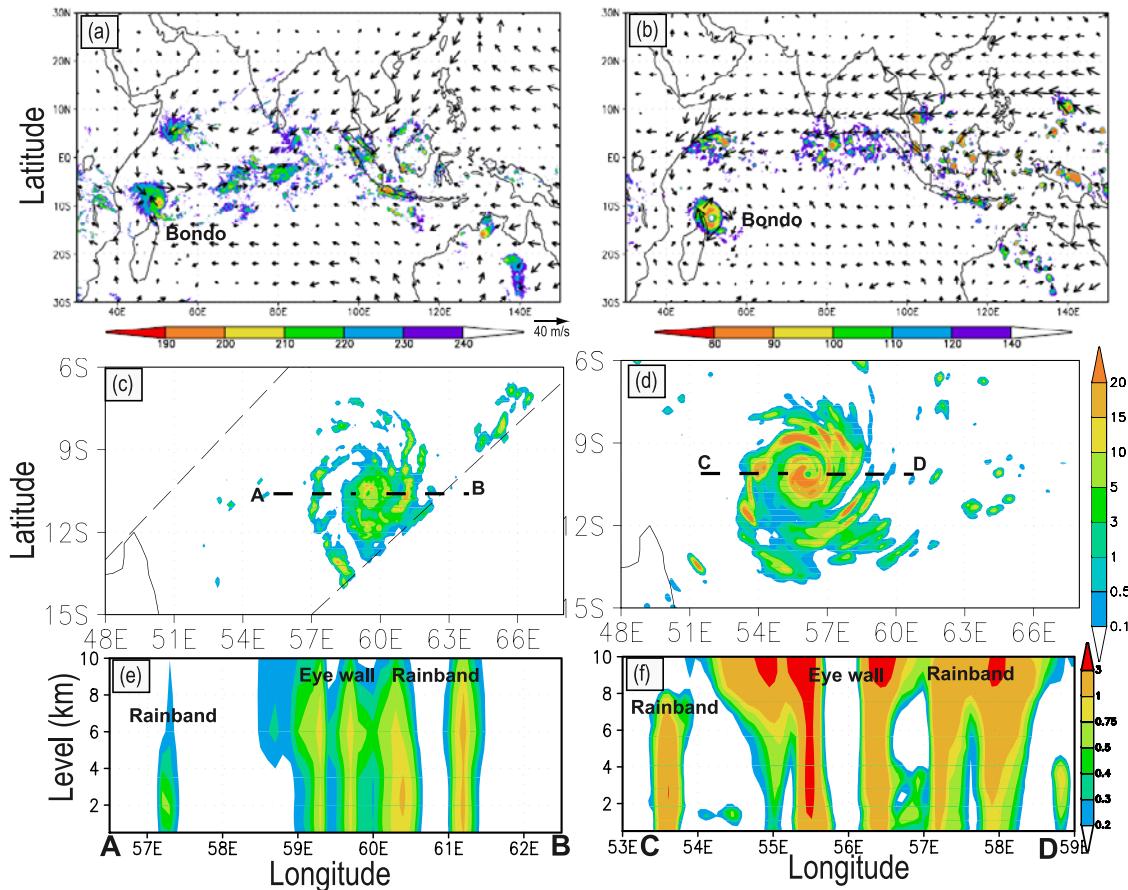


Figure 2. (a) Equivalent black body temperature (T_{BB} , K) from CPC-IR and 850-hPa winds from NCEP analysis and (b) outgoing longwave radiation flux (OLR, $W m^{-2}$) and 850-hPa winds from NICAM simulation at 1200 UTC 21 December 2006. Surface rain rate ($mm hour^{-1}$) derived from (c) TRMM-TMI at 0537 UTC 19 and (d) NICAM simulation at 0600 UTC 20. Cross-section of the mixing ratio of total hydrometeors (cloud water, precipitation water, cloud ice, and precipitation ice; $g kg^{-1}$) derived from (e) TRMM-TMI at 0537 UTC 19 and (f) NICAM simulation at 0600 UTC 20. Locations of cross-sections are marked as the lines AB and CD in Figures 2c and 2d, respectively.

Ocean in both observation and simulation (Figures 2a and 2b). The cyclonic gyre north of the equator and TC Bondo displayed the typical twin cyclone structure with two cyclones straddling the equator, indicating the important role of equatorial Rossby waves in the genesis of Bondo, consistent with previous findings [e.g., Frank and Roundy, 2006].

3.2. Tropical Storm Isobel

[13] Tropical Storm Isobel was first observed over the eastern Indian Ocean at 0600 UTC 2 January 2007 (Figure 1). It moved southward and finally made landfall on the northwest coast of Australia at 0300 UTC 3 January. In the NICAM simulation, a storm was detected after 14-day model integration in the SLP field over the sea south of Java at 0000 UTC 29 December 2006. The model storm intensified as it moved southeastward over the eastern Indian Ocean and reached its peak intensity with a minimum SLP of 965 hPa and a maximum 10-m wind speed of around 60 knots. The JTWC data for Tropical Storm Isobel showed a maximum 10-m wind speed of 40 knots, indicating that the simulated storm was stronger than the real one. Although the simulated Isobel made landfall on the north-

west coast of Australia about 1 day later than the real storm, it is promising that NICAM, given the atmospheric conditions more than 2 weeks beforehand and the observed SST, simulated the overall lifecycle of Tropical Storm Isobel.

[14] NICAM reproduced well the large-scale environmental conditions around the Maritime Continent region characterized by the onset of the MJO [Miura *et al.*, 2007] and the penetration of the northeast monsoonal surge into the Southern Hemisphere in a longitudinal band between $100^{\circ} E$ and $120^{\circ} E$ (Figures 3a and 3b). Accompanying the MJO onset on 28–29 December 2006 in the eastern Indian Ocean and its eastward propagation were loosely organized convective activities over the Maritime Continent region and an equatorial westerly wind burst (WWB) (Figures 3a and 3b). As indicated by observational study of Wu *et al.* [2007], the northerly cross-equatorial flow originated from the cold surge over the South China Sea intensified in late December 2006. It seems that the cross-equatorial flow and the MJO provided the favorable large-scale conditions for the genesis of Isobel in both observations and the NICAM simulation.

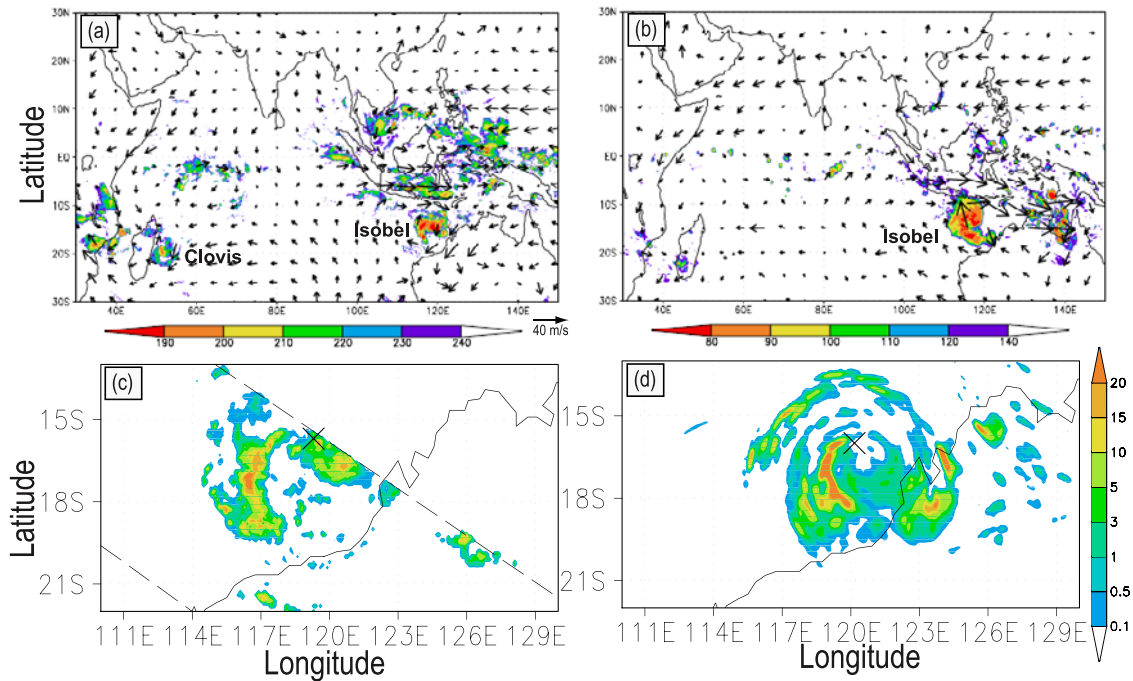


Figure 3. Same as Figure 2 except for cross sections. The time is (a) and (b) 0000 UTC, (c) 0920 UTC, and (d) 2230 UTC 2 January 2007. Crosses represent the position of the storm center.

[15] Tropical Storm Isobel did not develop a typical eyewall as Bondo did, but a large, broken one with little convection in its southeastern section on 2 January 2007 (Figure 3c). The NICAM simulation reproduced the broken eyewall structure, especially the stronger convection in western than in the eastern section of the eyewall (Figure 3d). Remarkable is that this took place after about 18 days of model integration, indicating the possible use of high-resolution cloud-system-resolving global models in predicting not only the large-scale flow patterns, such as the MJO, but also the organized convective systems, such as TCs.

[16] Furthermore, the NICAM simulation provides a high temporal and spatial resolution dataset for detailed studies of the mesoscale processes responsible for TC genesis and the associated interactions with the large-scale environmental flow. An example of such a multi-scale interaction associated with the genesis of Isobel is given in Figure 4. It is clear that the large-scale cyclonic shear closely related to the WWB in the MJO provided a favorable condition for deep convection, as evidenced by the organized convective precipitation over the sea north of Java (Figure 4a). The deep convection was accompanied by small-scale high low-level cyclonic potential vorticity with diameters less than 40 km (Figure 4b), very similar to the so-called vortical hot towers discussed by *Simpson et al.* [1998], *Hendricks et al.* [2004], and *Montgomery et al.* [2006]. Isobel thus formed as a result of the following events: increased cyclonic shear due to the WWB, collective heating from the vortical hot towers, the merging and strengthening of low-level potential vorticity of the hot towers (Figures 4c, 4d, and 4e), and eventually the axisymmetrization of mesoscale features by the storm-scale low-level cyclonic circulation (Figures 4e and 4f) over the sea south of Java. A detailed process study

on the genesis of Isobel is under way, and the results will be reported elsewhere.

4. Concluding Remarks

[17] This paper highlights a successful simulation of the lifecycles of two real TCs over the Indian Ocean by the global, nonhydrostatic, cloud-system-resolving model NICAM at about 7-km horizontal resolution. The model had been initialized with the observed synoptic scale atmospheric conditions on 15 December 2006 and then let run freely until 16 January 2007 with the observed SST. The successful simulations are due to the realistic simulations of not only the large-scale circulation, such as the MJO and the cross-equatorial flow, but also the embedded mesoscale convective systems, such as vortical hot towers and their subsequent organization and axisymmetrization.

[18] NICAM also reproduced the twin cyclones straddling the equator in the Indian Ocean. However, it failed to reproduce the development of the third storm seen in observations, TC Clovis. We noted that NICAM did capture the cloud features near Madagascar (Figures 3a and 3b), indicating that the failure could be due to a mismatch between the convective cloud systems in the simulation and in the observations either with regard to time or location or both.

[19] The present NICAM simulation also provides a dataset of high temporal and spatial resolution for detailed studies of TC genesis. The formation mechanism and the size of the two simulated TCs were quite different. This might be due to the different large-scale environmental conditions and the internal dynamics associated with the organization of the convective and mesoscale cloud features. These will be the topic for a future study. Therefore,

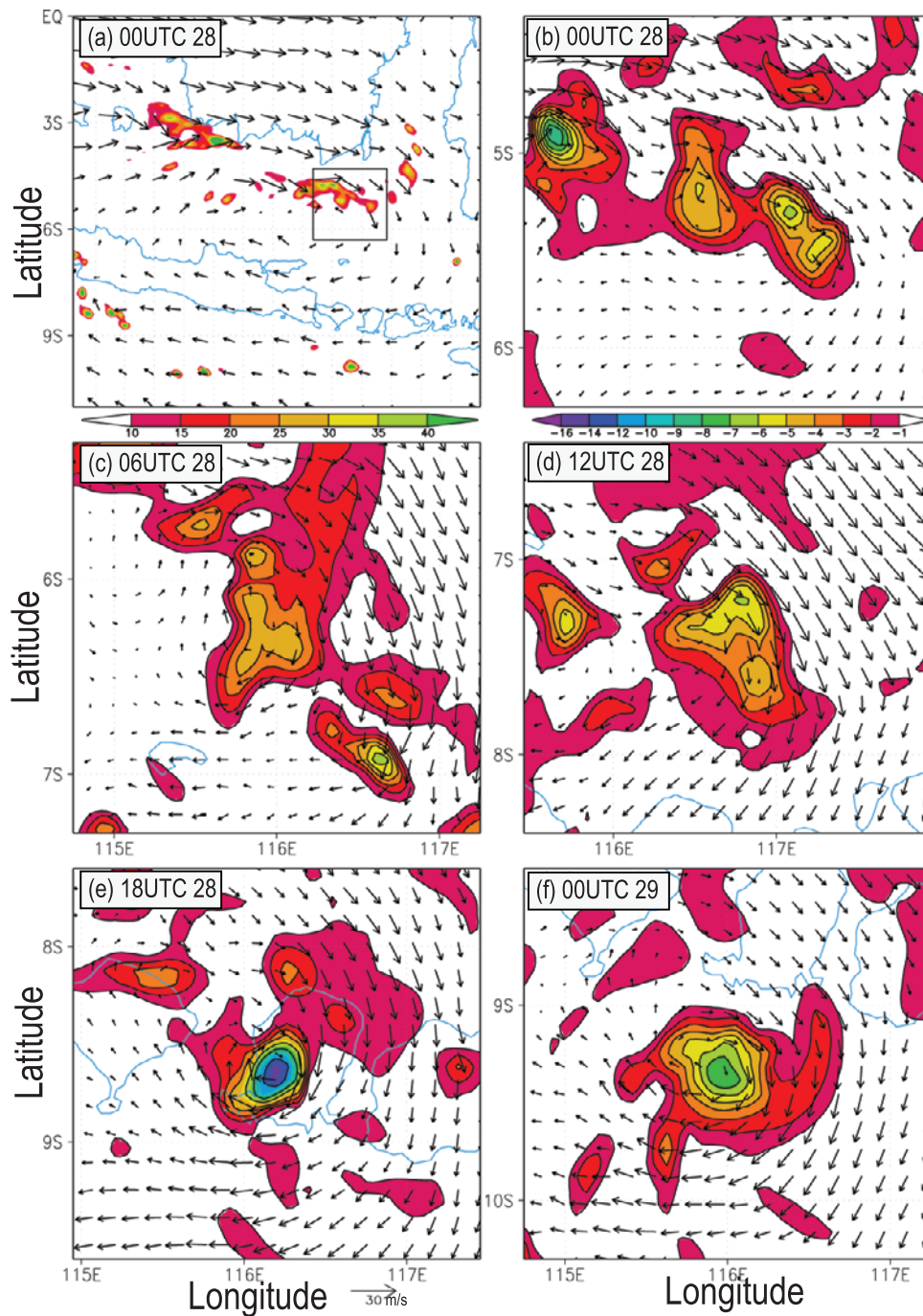


Figure 4. (a) Precipitation rate (shading, mm h^{-1}) and horizontal winds at 310-K level at 0000 UTC 28 December 2006 showing the WWB associated with the MJO. The evolution of cyclonic potential vorticity (shading and contour, PVU) and horizontal winds at 310-K level in a $2.5^\circ \times 2.0^\circ$ box are shown at (b) 0000 UTC, (c) 0600 UTC, (d) 1200 UTC, (e) 1800 UTC 28, and (f) 0000 UTC 29 December 2006. Rectangle in Figure 4a represents the domain in Figure 4b.

this paper not only demonstrates that global cloud-system-resolving models may be able to predict tropical cyclone formation and evolution but the data set created also marks an unprecedented opportunity for advancing our understanding of multiscale interactions related to TC genesis, intensification, and evolution in a global context.

[20] Two long-term simulations at both 7-km and 14-km resolutions have recently been completed. One is a one-month perpetual July-equilibrium run and the other is a five-

month run of the boreal summer 2004. Our preliminary analyses are encouraging. These runs also allow us to study the statistics of the model TCs in different ocean basins, which is a key test of a model to be used for the study of TC climate. Again, in these runs, the model reproduced many important scenarios of TC genesis, including the large-scale circulation features (such as equatorial waves, easterly waves, the MJO, and the monsoon circulation) and the

mesoscale cloud system organizations. The results from these new simulations will be reported separately.

[21] Promisingly, the model captured some mesoscale structures of the real TCs about 1–2 weeks after initialization. As the capability of supercomputers increases, NICAM will be run at 3.5-km resolution for monthly-to-seasonal simulations. With such a fine resolution, cloud systems can be resolved much better. We thus look forward to a new era for weather and climate predictions with global cloud-system-resolving models.

[22] **Acknowledgments.** The authors are grateful to Gisela Speidel for her careful reading and editing of the manuscript. This study has been supported in part by NSF grants ATM-0427128 and ATM-0754039 and ONR grant 00014-06-10303 and in part by the JAMSTEC, NASA, and NOAA through their sponsorships of the International Pacific Research Center (IPRC) in the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawaii. The Earth Simulator is used for the NICAM simulations. This is the SOEST publication 7578 and IPRC publication 557.

References

- Frank, W. M., and P. E. Roundy (2006), The role of tropical waves in tropical cyclogenesis, *Mon. Weather Rev.*, *134*, 2397–2417.
- Grabowski, W. W. (1998), Toward cloud resolving modeling of large-scale tropical circulations: A simple cloud microphysics parameterization, *J. Atmos. Sci.*, *55*, 3283–3298.
- Hendricks, E. A., M. T. Montgomery, and C. A. Davis (2004), The role of “vortical” hot towers in the formation of tropical cyclone Diana (1984), *J. Atmos. Sci.*, *61*, 1209–1232.
- Miura, H., M. Satoh, T. Nasuno, A. T. Noda, and K. Oouchi (2007), A Madden-Julian Oscillation event realistically simulated by a global cloud-resolving model, *Science*, *318*, 1763–1765.
- Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. B. Saunders (2006), A vortical hot tower route to tropical cyclogenesis, *J. Atmos. Sci.*, *63*, 355–386.
- Satoh, M., T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S. Iga (2008a), Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulations, *J. Comput. Phys.*, *227*, 3486–3514, doi:10.1016/j.jcp.2007.02.
- Satoh, M., T. Nasuno, H. Miura, H. Tomita, S. Iga, and Y. Takayabu (2008b), Precipitation statistics comparison between global cloud resolving simulation with NICAM and TRMM PR data, in *High Resolution Numerical Modelling of the Atmosphere and Ocean*, edited by W. Ohfuchi and K. Hamilton, chap. 6, pp. 99–112, Springer, New York.
- Simpson, J., J. B. Halverson, B. S. Ferrier, W. A. Petersen, R. H. Simpson, R. Blakeslee, and S. L. Durden (1998), On the role of “hot towers” in tropical cyclone formation, *Meteorol. Atmos. Phys.*, *67*, 15–35.
- Tomita, H., and M. Satoh (2004), A new dynamical framework of nonhydrostatic global model using the icosahedral grid, *Fluid Dyn. Res.*, *34*, 357–400.
- Wang, Y. Q., L. R. Leung, J. L. McGregor, D. K. Lee, W. C. Wang, Y. H. Ding, and F. Kimura (2004), Regional climate modeling: Progress, challenges, and prospects, *J. Meteorol. Soc. Jpn.*, *82*, 1599–1628.
- Wu, P., M. Hara, H. Fudeyasu, M. D. Yamanaka, J. Matsumoto, S. Fadli, S. Reni, and D. S. Yusuf (2007), The impact of trans-equatorial monsoon flow on the formation of repeated torrential rains over Java Island, *Sci. Online Lett. Atmos.*, *3*, 93–96.

M. Satoh and W. Yanase, Center for Climate System Research, University of Tokyo, Kashiwa 277-8568, Japan.

H. Miura and T. Nasuno, Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama 236-0001, Japan.

H. Fudeyasu and Y. Wang, IPRC/SOEST, University of Hawai'i at Manoa, 1680 East-West Road, Honolulu, HI 96822, USA. (fudeyasu@hawaii.edu)