



Asian summer monsoon simulated by a global cloud-system-resolving model: Diurnal to intra-seasonal variability

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[1] Interaction of convection and circulation is key to the Asian summer monsoon, but difficult to represent in global models. Here we report results from simulations for the summer of 2004 by a global cloud-system-resolving model, NICAM. At both 14- and 7-km horizontal resolution, NICAM simulates the observed monsoon circulation patterns, and the northward propagation of precipitation. The 7-km run simulates summer-mean precipitation maxima in narrow bands along the western Ghats, Himalayan foothills, the Arakan Yoma highlands, and the Annamite range. Precipitation 1) is modulated by orography, 2) is affected by synoptic-scale systems, and 3) displays a pronounced diurnal cycle, especially over Indo-China, with its strong/weak signal propagating westward/eastward in the wet/dry phase of the intraseasonal oscillation. This set of simulations captures these intraseasonal changes of the Indian monsoon with high fidelity from June to early July. NICAM exhibits a positive bias in precipitation over the Indian Ocean, common to atmospheric models with prescribed sea surface temperature. This calls for the inclusion of ocean-atmosphere coupling process to improve monsoon simulation skills. **Citation:** Oouchi, K., A. T. Noda, M. Satoh, B. Wang, S.-P. Xie, H. G. Takahashi, and T. Yasunari (2009), Asian summer monsoon simulated by a global cloud-system-resolving model: Diurnal to intra-seasonal variability, *Geophys. Res. Lett.*, 36, L11815, doi:10.1029/2009GL038271.

1. Introduction

[2] The Asian summer monsoon is among key targets for weather/climate research and prediction. Monsoon convection is highly organized in space and time, on diurnal, intraseasonal and seasonal time scales [Krishnamurthy and Shukla, 2007]. Its modeling remains a major challenge. Here we take a new approach of using a global cloud-system-resolving model (GCRM) that represents cloud clusters explicitly.

[3] The GCRM used is NICAM (Nonhydrostatic ICosahedral Atmospheric Model) [Satoh *et al.*, 2008; Tomita and Satoh, 2004] that showed great promise in its

successful simulation of a boreal winter Madden-Julian Oscillation (MJO) event [Miura *et al.*, 2007] in terms of its eastward propagation and associated cloud features, compared quite consistently with observations [Masunaga *et al.*, 2008; Inoue *et al.*, 2008; Nasuno *et al.*, 2009; H. Taniguchi *et al.*, Diagnostic evaluation of a global cloud-resolving model simulation of a Madden-Julian Oscillation event, submitted to *Monthly Weather Review*, 2009]. Although the time integration was limited to one month due to highly demanding computational resource, NICAM is successful in reproducing the diurnal cycle of precipitation [Sato *et al.*, 2008] and tropical extreme events including tropical cyclones [Fudeyasu *et al.*, 2008]. We have since completed a seasonal-long, boreal summer (June–August, 2004) simulations using NICAM with 14- and 7-km grid spacing. This letter presents highlights of some results from these first seasonal-long NICAM simulations, focusing on precipitation features spanning various time scales.

[4] Boreal summer is a challenging season for climate and weather forecasts. The insight obtained from the present study will help improve the simulation and prediction of tropical phenomena, and explore GCRM's potential for climate studies as high-end computing continues to improve performance [Satoh *et al.*, 2008; Heffernan, 2008].

2. Experimental Design

[5] The NICAM experiments are performed using the grid spacing at 7- and 14-km, which resolve gross features of mesoscale convection, and cloud clusters. The experimental setup is explained by Oouchi *et al.* [2009], including the use of an improved turbulent boundary layer scheme [Noda *et al.*, 2009] of the Mellor-Yamada scheme modified by [Nakanishi and Niino, 2004].

[6] The time integration is performed from 1 June to 31 August/10 November 2004 for 7-/14-km mesh run, and represents the mature phase of monsoon. The initial atmospheric conditions are interpolated from the National Centers for Environmental Prediction (NCEP) Global Tropospheric Analyses at 00 UTC on 1 June, 2004. The experiment is conducted using the sea surface temperature (SST) dataset from a weekly interpolated National Oceanic and Atmospheric Administration (NOAA)-Optimum Interpolated (OI) SST dataset. No nudging is applied; clouds are fully interactive with atmospheric disturbances.

[7] Ocean-atmosphere coupling processes are important for oceanic precipitation [Wang *et al.*, 2004] and prediction of monsoon intraseasonal oscillation [Fu *et al.*, 2007]. The NICAM experiments with the prescribed SST can provide insights into the problem, and help clarify the relative importance between ocean-atmosphere coupling process

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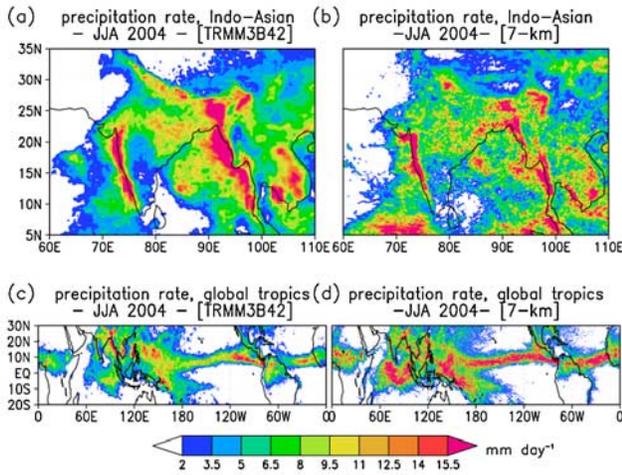


Figure 1. (a and c) Observed and (b and d) simulated precipitation rate over the Indo-China monsoon region (Figures 1a and 1b) and global tropics (Figures 1c and 1d) as June–July–August average (in units of mm day^{-1}). The observed precipitation is from TRMM_3B42, and the simulation is for 7km-mesh run.

and cloud-resolving framework for modeling monsoon precipitation. The seasonal integrations include a few MJO cycles and associated tropical cyclogenesis [Oouchi *et al.*, 2009], and demonstrate an improvement in low-level/boundary layer clouds [Noda *et al.*, 2009]. This paper presents a case study based on one single realization with NICAM at 7 or 14 km resolution. Ensemble experiments are underway for a more rigorous assessment of NICAM’s skills in simulating monsoon variability.

3. Results

[8] The Asian monsoon affects local weather in the Indian-subcontinent, and Southeast Asian regions. The GCRM allows investigation into complex regional features by representing explicitly convection systems and their interactions with synoptic- and meso-scale disturbances, and topography. Such a potential of GCRM is partly confirmed in Figure 1, which compares the precipitation rate averaged for June–August period between TRMM observations (Figure 1a) and the 7-km grid run (Figure 1b). The 7-km model simulates successfully most of the local maxima of summer precipitation organized in narrow strips on the west slope of the western Ghats range, Himalayan foothills, the Arakan Yoma highlands, and the Annamite range. These orography-induced precipitation features significantly regulate the wet and dry phases of local monsoon [Takahashi and Yasunari, 2006; Xie *et al.*, 2006]—features poorly reproduced in large-scale atmospheric models [Xie *et al.*, 2006]. The result is encouraging, and suggests a high potential of GCRM in process and regional climate studies.

[9] To understand association of these local precipitation maxima with the orography, and temporal variations embodied in them, Hovmöller diagrams of the precipitation are plotted for the latitudinal band of 14° – 16°N in Figure 2 (top), superimposed on zonal velocity at 850 hPa in con-

tours (the westerly exceeding 6 m s^{-1}). The time average of precipitation is displayed in Figure 2 (bottom), along with the orography. Strikingly, precipitation displays conspicuous diurnal cycle both in TRMM observations and NICAM simulation. The diurnal cycle is the most evident over the land area of the Indo-China peninsula (98° – 108°E), and to a lesser degree, in regions west of the coastal mountains (70° – 75°E and 95° – 100°E). The observed increase in westerly winds over the Bay of Bengal (Figure 2) persists from 16 June to 5 July, but rainfall is concentrated on three synoptic “events” around 16 June, 26 June, and 2 July, indicative of the importance of synoptic-scale systems. Orographic lift can be a factor enhancing the synoptic system-induced rainfall. The simulation also captures such synoptic-scale precipitation systems. Sensitivity of synoptic systems and intraseasonal behavior to initial conditions is an important area for future work [Goswami, 1998; Krishnan *et al.*, 2009]. On the windward side of narrow mountain ranges, the impinging westerlies intensify precipitation by orographic lift, as suggested in an observational study [Xie *et al.*, 2006]. The simulation overestimates the precipitation maxima by a factor of 1.5–2 times compared to the observations, as revealed in a precipitation analysis of the boreal-winter NICAM simulation [Sato *et al.*, 2009]. The result nonetheless suggests the importance of the interaction among the synoptic-scale systems, mesoscale orography and diurnal precipitation for the monsoon season.

[10] Figure 2 also demonstrates that the intraseasonal oscillation (ISO) modulates the diurnal cycle over the Indo-china region; it controls not only its amplitude but its propagation direction. The observed diurnal cycle is strong, and propagates westward during the first part of

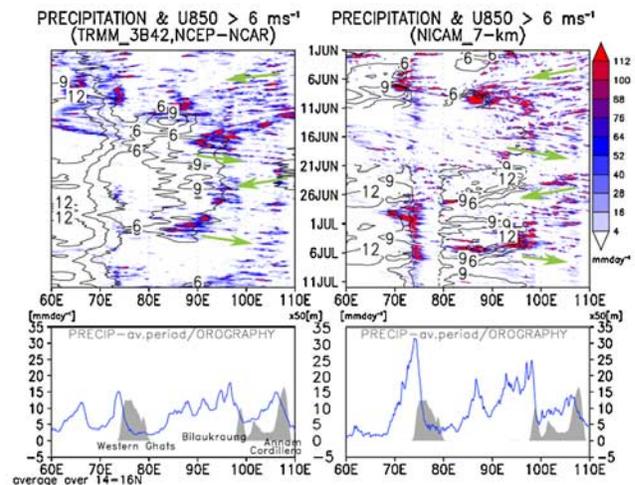


Figure 2. (top) Hovmöller representation of precipitation rate (mm day^{-1} , shaded) and zonal velocity (contoured for 6, 9 and 12 m s^{-1}) for the average over 14° – 16°N , for TRMM_3B42 (precipitation) and NCEP/NCAR Reanalysis (zonal velocity), and 7km-mesh run. The plot period spans from 1 June to 11 July. (bottom) Precipitation amount averaged over the period (blue lines), and the orography (elevation $\times 50 \text{ m}$; grey) that is constructed by the spatial smoothing of the global digital elevation model GTOPO30 from the U.S. Geological Survey.

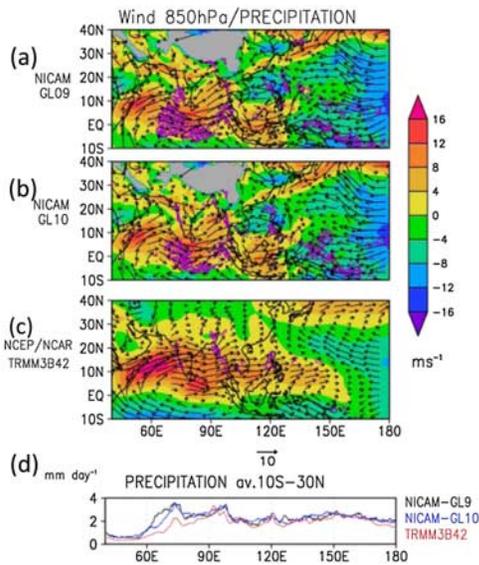


Figure 3. (a) 14 km run, (b) 7 km run and (c) observed 850-hPa horizontal wind (arrows), its zonal component (shade) and precipitation region (purple, exceeding 14 mm day^{-1}). The observed wind and precipitation is from NCEP_NCAR Reanalysis dataset and TRMM_3B42, respectively. (d) precipitation rate in meridional average ($10\text{--}30^\circ\text{N}$) for both runs, and observation.

June (wet phase of ISO), but it weakens and propagates eastward during the second part of June (dry phase of ISO). The westward/eastward propagation is apparently initiated from Annam Cordillera/Bilaukraung. The model simulates these two features of ISO modulation quite well. The simulated westward/eastward propagations seem to be embedded in the low-level (700 hPa) easterly/westerly regions (not shown). The relationship between monsoon flows and precipitation systems is discussed by H. G. Takahashi et al. (High-resolution modelling of the potential impact of land-surface conditions on regional climate over Indochina associated with the diurnal precipitation cycle, submitted to *International Journal of Climatology*, 2009). The interpretation of these findings is an interesting future research topic.

[11] The relationship between precipitation and velocity fields are shown in Figure 3 displaying the June–August mean 850 hPa zonal velocity (vector), its zonal component (color shade) and precipitation (purple) for the NICAM runs and observation. The simulated precipitation patterns are generally in consistent with observations, except for the excessive precipitation in the Indian Ocean and east of the maritime continent; the bias is somewhat improved in the 7-km mesh run in the $60^\circ\text{--}70^\circ\text{E}$ area (Figure 3d). The simulated 850 hPa zonal velocity captures general features of observations, including the Somali jet. Following biases are identified: the simulated winds over the Indian longitudes are too strong over the equator while they are too weak over the Indian landmass compared to observation. The simulated westerlies north of the equator do not extend east of 115°E whereas they extend up to 150°E . Likewise the easterly trades over the tropical Pacific are too strong in the model.

[12] Monsoon is also characterized by the northward migration of precipitation ISO [Fu and Wang, 2004; Rajendran and Kitoh, 2006]. Figure 4 (top) illustrates this phenomenon in time-meridional sections of precipitation and 850 hPa velocity (vector) and its zonal component (shade). The 7-km mesh run predicts the strength of the Indian monsoon trough quite well up to 40 days (1 June to 10 July), although more ensemble members are necessary to conclude robustness of the result. The observed northward migration of the precipitation area is simulated in early June to mid-July, but becomes unclear thereafter in the simulations.

[13] To investigate the monsoon evolution, the time series of two monsoon circulation indices (Indian Monsoon Index; IMI and Western North Pacific Monsoon Index; WNPMI) as defined by Wang et al. [2004] are compared with observations in Figure 4 (bottom). The indices provide measures to track dynamical features of the regional monsoon subsystems. Remarkably, IMI is high (enhanced monsoon trough) during the first part of June and low

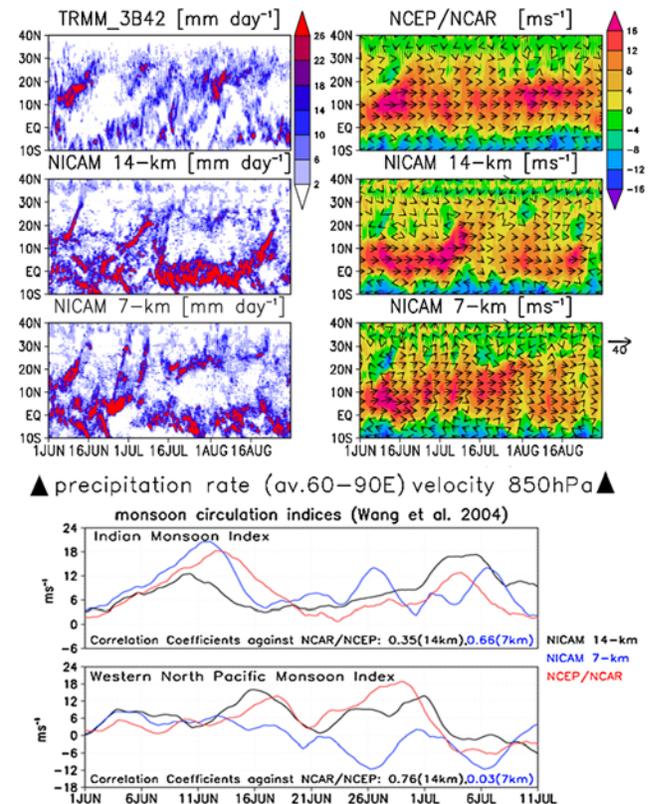


Figure 4. (top) Time-meridional plots of (left) precipitation rate in mm day^{-1} and (right) 850-hPa horizontal wind (arrows) and its zonal component in m s^{-1} (shade), as average over the Indo-monsoon region ($60\text{--}90^\circ\text{E}$) during June, July and August 2004. (bottom) Time series (1 June to 10 July) of monsoon circulation indices for Indian Monsoon and Western North Pacific sectors defined by Wang et al. [2004]. They are smoothed with the 2-day running mean. The numbers in the bottom panels denote the correlation coefficients between the simulation (14 km-mesh, black; 7 km-mesh, blue) and NCEP_NCAP Reanalysis.

(weakened monsoon trough) in the second half of June. The model thus captures both the wet and dry spells well, although its sensitivity to initial conditions remains to be seen.

4. Concluding Remarks

[14] The advantage of NICAM over conventional GCMs in simulating tropical clouds and convection was demonstrated by *Miura et al.* [2007] for a boreal winter MJO event. This paper discusses the results from the first boreal summer (2004) seasonal-long GCRM simulations, in an attempt to simulate complex multi-scale interaction among the monsoon-related precipitation and circulation. Our study identifies a number of strengths and weaknesses of NICAM.

[15] NICAM exhibits an encouraging simulation results of intraseasonal variability of the Indian monsoon up to 40-days (June to early July), and the representation of local precipitation features, especially those anchored by mountain ranges over the Indian Subcontinents, and Indo-China Peninsula—features poorly reproduced in conventional GCMs [*Xie et al.*, 2006]. Some precipitation features tend to be organized into synoptic systems as speculated by an observational study [*Yokoi and Satomura*, 2008], and modulated by orographic effects in the West Ghats, and at the foothills of Himalayas; both features are clearly simulated in the 7-km. Precipitation there involves a unique diurnal cycle, especially over Indo-China. These relationships merit further investigation, along with the attracting multiscale features of oceanic convection [*Zuidema*, 2003]. The good performance of NICAM in simulating monsoon convection should come from improved representation of interaction among moisture, circulation and topography in GCRM.

[16] A weakness of the model is the over-prediction of precipitation over the Indian Ocean, a common problem for state-of-the-art conventional atmospheric GCMs [*Wang et al.*, 2004]. The problem can have the same root as in conventional atmospheric GCMs from the prescription of SST as the bottom boundary condition. By design, the prescribed SST method does not capture the observed negative correlation between SST and rainfall over warm oceans with weak SST gradients [*Wang et al.*, 2004; *Krishna Kumar et al.*, 2005]. The lack of oceanic feedback may be a source of precipitation bias, which in turn affects ISO and seasonal variations of monsoon [*Goswami*, 1998; *Krishnan et al.*, 2006]. We are working to include ocean-atmosphere interaction in NICAM.

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