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Rainfall Diurnal Variation over the Indonesian Maritime Continent Simulated by 20 km-mesh GCM

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Abstract

Rainfall diurnal variation over the Indonesian Maritime Continent simulated by a super high resolution atmospheric general circulation model (GCM–TL959) is examined. GCM–TL959 is successful in representing spatio-temporal characteristics of observed rainfall diurnal cycle over the region. The model also seems to simulate local circulations such as land-sea breeze. The speed of rainfall migration over land and coastal sea in GCM–TL959 is consistent with that of a gravity current.

1. Introduction

Tropical convective activities are among the engines that drive atmospheric circulations through the uptake and release of a significant amount of latent heat of vaporization. Because of no synoptic scale baroclinic disturbances that cause rainfall in the extratropics, the diurnal cycle of convections and its regional variations are important in the tropics. The Indonesian Maritime Continent, in particular, has a unique environment where convective activities respond to forcing on various timescales and space scales whose net effect is able to influence climate on a global scale (Ramage 1968). It is therefore important for an atmospheric general circulation model (GCM) to simulate well the observed climate over the region, not only in terms of the mean climate and its spatial distribution but also by means of various time-scale variations. Many GCMs, though, whose horizontal resolution are more than 100 km in general, have not been so successful in representing the climate over the region. For example, Neale and Slingo (2003) showed that their model, whose horizontal resolution is about 300 km, had diurnal variations with the phase precedent by several hours compared to the observation over the Indonesian Maritime Continent even with a threefold increase in horizontal resolution.

A global climate model with the horizontal grid size of about 20 km has been developed by the Meteorological Research Institute (MRI)/Japan Meteorological Agency (JMA) (Mizuta et al. 2005). Due to the very high horizontal resolution, the model has more realistic representation of both land-sea distribution and topography with elevated orography than those GCMs have ever had, so it is expected to have an ability to simulate more adequately the diurnal cycle of convections over the Indonesian Maritime Continent.

The aim of this paper is to demonstrate how well the model simulates rainfall diurnal variation over the Indonesian Maritime Continent.

2. Model and data

The model used is a prototype of the next generation global numerical weather forecasting model of JMA (Mizuta et al. 2005). We analyze the present-day climate simulation performed at a triangular truncation 959 with linear Gaussian grid (TL959) in the horizontal, in which the transform grid uses 1920 960 grid cells, corresponding to the grid size of about 20 km. The model has 60 layers in the vertical with the model top at 0.1 hPa. For the cumulus parameterization, the Arakawa-Schubert scheme with prognostic closure similar to that of Randall and Pan (1993) is used. Hereafter we refer to the model as “GCM–TL959”. The simulation is performed with the monthly mean climatological sea surface temperature (SST) and sea ice concentration as lower boundary conditions. Time integration over 10 years is carried out after a spin-up for 5.5 years. The present-day climate simulated by GCM–TL959 agrees well with the observation except for some errors such as an overestimation of global precipitation (Mizuta et al. 2005).

Due to limitation of our storage capacity, we stored only an hourly precipitation, and some 6-hourly surface and atmospheric variables such as winds, temperature, specific humidity and vertical pressure velocity in lower troposphere for analyses of diurnal variation. We utilize an hourly precipitation and 6-hourly surface winds to analyze the diurnal variation of rainfall over the Indonesian Maritime Continent in this study.

For model evaluation, we use the Tropical Rainfall Measuring Mission (TRMM) 3G68 V5 product distributed by the National Aeronautics and Space Administration (NASA), Goddard Distributed Active Archive Center (DAAC) as the observed precipitation data. The 3G68 product includes an hourly gridded dataset derived from TRMM instruments, for example, the precipitation radar (PR) and TRMM Microwave Imager (TMI), which estimate near-surface rain rate. The horizontal resolution of the dataset is 0.5° × 0.5° over the region equatorward of 36.5°. A six-year (1998–2003) time average of near-surface rain rate is made based only on the PR sensor. Each hourly grid rainfall data is smoothed over a 4-hour running mean to minimize the sampling errors of the rainfall diurnal cycle after the analysis of Negri et al. (2002).

Now we refer to an hourly precipitation at a given time as a value accumulated by an hour until the given time. For example, an hourly precipitation at 01LT (local time) is the value accumulated between 00:00LT and 01:00LT.

3. Results

In order to show climatological characteristics of rainfall diurnal variation over the Indonesian Maritime Continent, we analyze 10-year averaged annual mean rainfall diurnal cycle.

Figure 1 shows spatial distribution of a ratio of annual mean rainfall accumulated between 12 : 00LT and 24 : 00LT (hereafter referred to as evening rain) to annual mean daily precipitation over the Indonesian Maritime Continent in the observation (TRMM) and GCM–TL959. Hereafter, we refer to rainfall accumulated between 00 : 00LT and 12 : 00LT as morning rain. In the observation (Fig. 1a), as already shown by Mori et al.

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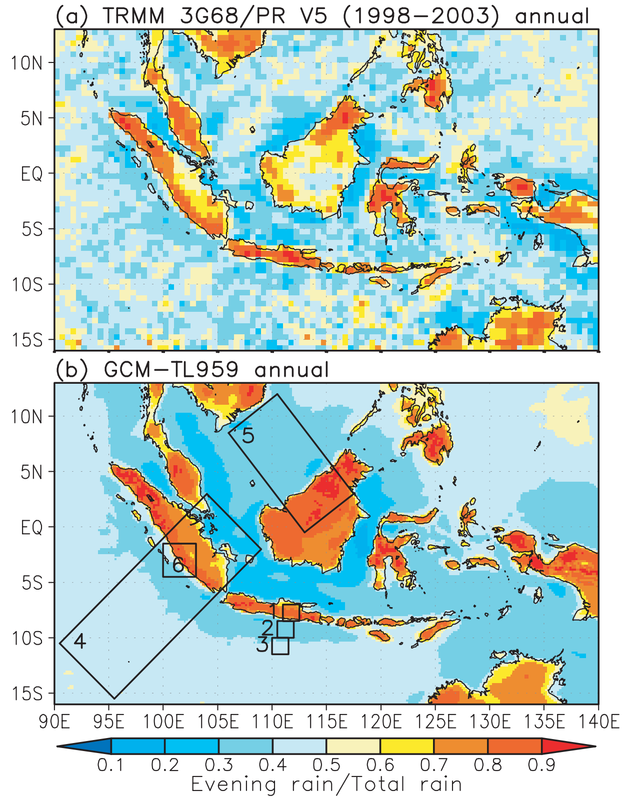

Fig. 1. Spatial distribution of a ratio of annual mean evening rain (12:00LT-24:00LT) to annual mean daily precipitation over the Indonesian Maritime Continent, for (a) the observation (TRMM) and (b) GCM–TL959. In (b), small rectangles around Java Island indicate the following regions: 1) land region (region 1), 2) coastal sea region (region 2), and 3) offshore region (region 3). Large rectangles around Sumatra Island (region 4) and Borneo Island (region 5) are domains of calculation for regional variation of diurnal cycle in hourly precipitation shown in Fig. 3 and Fig. 4. A small rectangle around southwestern Sumatra Island (region 6) is the area over which annual mean composites of an hourly precipitation and diurnal component of 6-hourly surface winds are shown in Fig. 5.

(2004), there is more rainfall in the evening than in the morning over land. GCM–TL959 simulates well the observed characteristics of both evening and morning rain except for a tendency to overestimate evening rain over land (Fig. 1b). It also reproduces the observed characteristics of the morning rain over coastal sea region stronger than that over offshore region as well as the land-ocean contrast between evening and morning rain.

In order to reveal the reproducibility of the land-sea contrast in the observed rainfall diurnal variation in GCM–TL959, let us refer to Fig. 2 which shows annual mean rainfall diurnal cycle over contiguous three regions shown in Fig. 1b (region 1, land region; region 2, coastal sea region; region 3, offshore region) in both the observation and GCM–TL959, as an example. Over region 1 (land region), GCM–TL959 simulates well the observed diurnal cycle, with an exception of precedence by an hour compared to the observation. For region 2 and 3, GCM–TL959 simulates well the peaktime of both the maximum and the minimum in the observed diurnal cycle, but not the multi-modal variation in the observation.

Hereafter regional variation of the annual mean diurnal cycle simulated by GCM–TL959 is examined. Figure 3 shows regional variation of annual mean rainfall diurnal cycle averaged over the rectangular area normal to the southwestern coastline of Sumatra Island (region 4 in Fig. 1b) in GCM–TL959. The abscissa corresponds with the number of grids from the coastline, and positive (negative) area stretches toward the Indian Ocean (Sumatra Island or South China Sea). In this figure, one grid corresponds to about 28 km. It clearly shows migrating rainfall peaks over both land and ocean areas as shown in Mori et al. (2004).

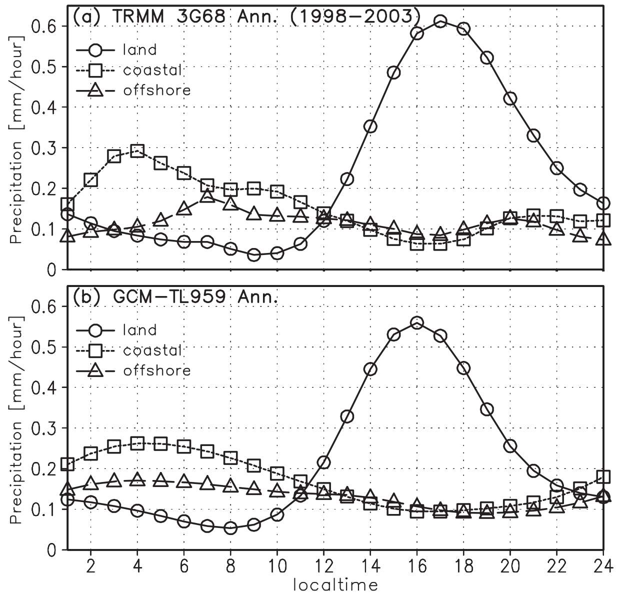

Fig. 2. (a) Annual mean precipitation diurnal variations averaged over the three boxes shown in Fig. 1b for the observation (TRMM). Solid line with circle, dashed line with square and long dashed line with triangle indicate region 1 (land region), region 2 (coastal sea region) and region 3 (offshore region) in Fig. 1b, respectively. (b) Same as (a) except for GCM–TL959.

A rainfall peak over land area travels 5 grids (about 150 km) in 5 hours toward inland area from the southwestern coastline of Sumatra Island.

The maximum rainfall appears around 14–15LT near the mountain range that is located near and along the southwestern coastline of Sumatra Island. The average speed of the migration is about 8 m/s. After the rainfall peak travels a few hours to the northeast over land, weaker rainfall peak shifts from the northeastern coastline toward the inland area with nearly the same speed. Migrating rainfall peaks from both coastlines meet over the central area of Sumatra Island at late afternoon, when rainfall over the southwestern coastal land area and the mountains is in decaying phase. The rainfall peak migration over land in GCM–TL959 is very similar to that in the observation (Mori et al. 2004) except for a few hours earlier peaktime. Rainfall over the ocean starts from the grid adjacent to the coastline at 19LT, when rainfall over the coastal land area and the mountains is in decaying phase, and travels offshore to the area about 100 km away from the coastline. The migration speed is about 8 m/s within the area. After 22LT, rainfall area quickly expands offshore and the maximum appears around 02–03LT, which is also a few hours earlier than that of the observation. Consequently, GCM–TL959 simulates well the rainfall peak migration over the ocean except for the peaktime appearing a few hours earlier than that of the observation.

Figure 4 shows regional variation of annual mean rainfall diurnal cycle averaged over the rectangular area normal to the northwestern coastline of Borneo Island (region 5 in Fig. 1b) in GCM–TL959. There exist the rainfall peak migrations over both land and the

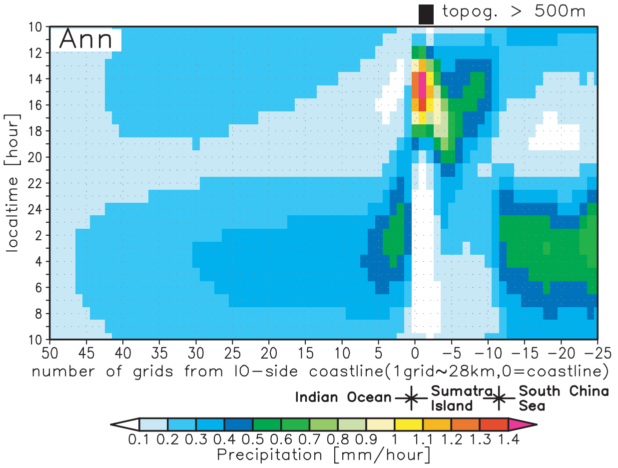

Fig. 3. Regional variation of annual mean rainfall diurnal cycle over the rectangular area shown in Fig. 1b (region 4) in GCM−TL959. The abscissa indicates the number of grids away from the southwestern coastline of Sumatra Island. Positive (negative) area stretches toward the Indian Ocean (Sumatra Island or the South China Sea). A black rectangle is the area with mean topography higher than 500 m in GCM−TL959.

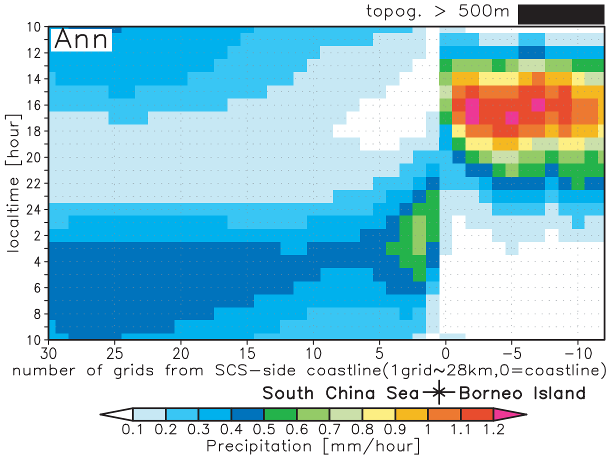

Fig. 4. The same as Fig. 3 except for northwestern Borneo Island (region 5). Positive (negative) area stretches toward the South China Sea (Borneo Island).

ocean similar to those in Fig. 3. Rainfall over land has the maximum around 16–17LT and seems to travels inland from the coastline with the migration speed around 8 m/s. Rainfall over the ocean starts from the coastal sea in the evening and expands offshore with the speed of about 8 m/s. The maximum appears at 02–03LT. It is a peculiarity common to that over Sumatra Island that rainfall travels offshore to the area about 100 km away from the coast with the speed of about 8 m/s and that rainfall area quickly expands offshore from the area. In comparison with the observation (Ohsawa et al. 2001), GCM−TL959 simulates observed regional variation of rainfall diurnal cycle over northwestern Borneo Island except for the peaktime appearing a few hours earlier than that of the observation. However, it is known that the peaktime of convective activity based on an equivalent black body temperature (TBB) tends to follow that of rainfall (Houze et al. 1981).

Figure 5 shows spatial distributions of annual mean composites of an hourly precipitation and diurnal component of 6-hourly surface winds over the area shown in Fig. 1b (region 6) at 00Z (07LT), 06Z (13LT), 12Z (19LT) and 18Z (01LT), respectively. Daily means are removed in surface winds in order to obtain diurnal component. It is clearly revealed that there exists spatially-varying diurnal cycle of surface winds consistent with that of rainfall. In the early afternoon (13LT), it rains over land and there is strong rainfall over the mountains that are along western coastline of Sumatra Island. Surface winds blow toward and converge over the mountains. The maximum wind speed of about 3 m/s appears over the mountains and coastal sea area. In the evening (19LT), strong rainfall moves east of the mountains and it also rains along the coastline. There exists surface wind divergence over the mountains and convergence over coastal sea area. In the middle of the night (01LT), rainfall decays over the land and develops over the ocean. Surface winds diverge over the mountains and blow toward both sides of the mountains. In the morning (07LT), there is little rain over land and rainfall over the ocean is in decaying phase. Surface winds diverge over the mountains and blow offshore over the ocean as in the middle of the night. In association with surface wind diurnal variations, threre are diurnal variations of horizontal winds in lower troposphere (not shown). In the early afternoon, horizontal winds around 850 hPa diverge over the mountains and blow offshore, while they blow toward and converge over the mountains in the middle of the night. GCM−TL959 seems to simulate land-sea breeze circulations. To investigate the structure of local winds in the model, however, is a problem to be solved in future study.

4. Discussion and summary

The aim of this study is to show how well the super high resolution (about 20 km grid size) GCM (GCM−TL959) simulates observed rainfall diurnal variation over the Indonesian Maritime Continent. We analyzed long-term means of the simulation performed with the observed monthly mean climatology of SST and sea ice. It is shown that GCM−TL959 has the ability to represent observed diurnal variations with high accuracy over the region.

Over Sumatra and Borneo Island, GCM − TL959 succeeds in representing observed regional variation of rainfall diurnal cycle except for a few hours before peaktime. The speed of rainfall migration over both land and coastal sea is nearly constant over both islands regardless of background horizontal winds. The speed of surface wind diurnal component is an order of 2–3 m/s as shown in Fig. 5. This implies that the rainfall migration does not result from horizontal advection and that there exists a mechanism common to that over both islands. This also supports the implication mentioned above. Gille et al. (2005) used rain-free surface winds derived from satellites to analyze diurnal wind variations, and showed that rain-free land breeze front propagated with the average speed of about 9 m/s and that the propagation rate is roughly an order of magnitude greater than the speed of land breeze. They concluded that diurnal wind variations propagated offshore progressively like a gravity current. A comparable rainfall migration speed of about 8 m/s in GCM−TL959 indicates the possibility that the GCM-simulated rainfall migration over land and coastal sea is associated with a gravity current. More analysis for the mechanism of the rainfall migration in GCM−TL959, though, is a future study.

There have been limited studies on diurnal variations in GCMs. GCMs with horizontal resolution of about 300 km have had a tendency to simulate rainfall diurnal variations with the phase precedent by several

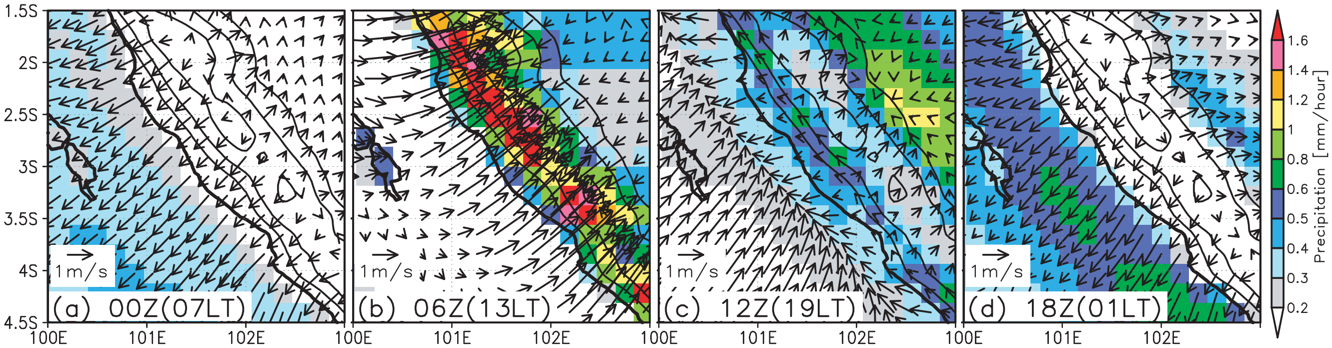

Fig. 5. Spatial distribution of annual mean composites of an hourly precipitation (shade) and diurnal component of 6-hourly surface winds (vector) around southwestern Sumatra Island area (100°E–103°E, 4.5°S–1.5°S). Contours indicate topography in GCM–TL959 and those of 200 m, 500 m and 1000 m are drawn. Thick black line is the coastline of Sumatra Island and other small islands.

hours compared to the observation (Neale and Slingo 2003; Dai and Trenberth 2004; Collier and Bowman 2004). GCMs, in general, have had the horizontal resolution of about 200–300 km, some of which have less than 100 km grid size, and those horizontal resolution are too coarse to represent properly the land-sea distribution of the real world in the Indonesian Maritime Continent. The Indonesian Maritime Continent, over which convection is a dominant heat source for atmospheric circulations, consists of a complex distribution of several large islands with elevated orography and is surrounded by the warmest ocean in the world. In order to represent properly not only the land-sea distribution but also the complex distribution of topography in the region, GCMs need to have higher horizontal resolution than they have ever had.

More precise representation of land-sea distribution and topography with elevated orography may result in a better description of energy and hydrological cycles in the Indonesian Maritime Continent. According to Neale and Slingo (2003), the diurnal cycle over the islands and the complex circulation patterns generated by land-sea contrasts are crucial for describing the energy and hydrological cycles and for determining the mean climate of the Indonesian Maritime Continent. They also showed that incorrect climate over the region would result in poor climate over other regions such as the western Indian Ocean, over which GCMs overestimate precipitation in general. It is expected, therefore, that the GCM with a very high horizontal resolution like GCM–TL959 would have a chance of reproducing realistic atmosphere-land interactions. More realistic diurnal variations over the region would result in a better simulation of the global climate in GCMs. Successful representation of realistic tropical rainfall diurnal variation in GCM–TL959 encourages us to put in efforts in order to improve the representation of diurnal cycle in GCMs.

All the present-day GCMs use the hydrostatic equilibrium approximation. Of course, the GCM that does not use the approximation, i.e., the cloud-resolving GCM, is more sophisticated than present GCMs. For several more years, limitations such as computational burden, though, would hinder us from developing a cloud-resolving GCM available for long-term simulations. It is, therefore, important to improve the present-day GCMs with the hydrostatic equilibrium approximation in order to have better representation of diurnal variations.

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Comments and supplements

An animation of annual mean rainfall diurnal cycle in GCM–TL959 is shown in the Supplement.

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