Reduction in tropical rainfall diurnal variation by global warming simulated by a 20-km mesh climate model

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Received 27 April 2005; revised 3 August 2005; accepted 19 August 2005; published 24 September 2005.

[1] A time-slice global warming experiment was performed with a very high-resolution (20-km mesh) atmospheric general circulation model. Due to increased horizontal resolution, land-sea distribution over the Indonesian Maritime Continent is well represented. A clear contrast in precipitation change at the end of the twenty-first century is found over Borneo Island and the Java Sea; over the ocean the morning precipitation decreases and evening precipitation increases, while over the island morning precipitation increases, resulting in reduced amplitude of rainfall diurnal variation over both land and ocean. Weakened land-sea breeze circulation by global warming due to larger nighttime temperature increases over land than during the day contributes to this decreased rainfall diurnal variation. Citation: Kitoh, A., and O. Arakawa (2005), Reduction in tropical rainfall diurnal variation by global warming simulated by a 20-km mesh climate model, Geophys. Res. Lett., 32, L18709, doi:10.1029/2005GL023350.

1. Introduction

[2] The diurnal cycle is the most dominant signal among various time-scale variations in the climate system. Energy and water exchanges between the atmosphere and underlying surface are largely regulated by the diurnal cycle [e.g., Dai, 2001]. Thus precise phase or timing of these phenomena is a necessity for modeling, not only for the short-time integration but also for long-term climate simulations. Thus rainfall diurnal cycle in general circulation models (GCMs) are investigated [e.g., Collier and Bowman, 2004; Dai and Trenberth, 2004]. In particular, the Indonesian Maritime Continent is a region with many islands surrounded by the warmest ocean in the world, and thus is known as a heat engine of world climate. However, most of atmospheric GCMs, whose horizontal resolution is more than 100 km in general, have not had the ability to represent well the land-sea contrast over the region [Neale and Slingo, 2003]. Recently, a global climate model with the horizontal grid size of about 20 km has been developed in collaboration between Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI) (R. Mizuta et al., 20 km-mesh global climate simulations using JMA-GSM model, submitted to Journal of the Meteorological Society of Japan, 2005, hereinafter referred to as Mizuta et al., submitted manuscript, 2005). With the very high horizontal resolution, it is expected that the model would be able to simulate well the land-sea contrast in the tropics.

[3] Anthropogenic forcing may alter the diurnal cycle. Because models cannot simulate the present-day diurnal cycle well [e.g., Trenberth et al., 2003; Dai and Trenberth, 2004], there are very few studies on possible changes of rainfall diurnal variation by anthropogenic climate change or global warming experiments. Arakawa and Kitoh [2005] examined rainfall diurnal variation over the Maritime Continent simulated by this 20-km-mesh atmospheric GCM. More realistic representation of land-sea distribution and topography due to the very high horizontal resolution enables the GCM to simulate observed rainfall diurnal variation characteristics. The GCM also simulates realistic lower tropospheric circulations like land-sea breezes. In this paper, we use this 20-km-mesh GCM to investigate possible changes of rainfall diurnal variation over the Maritime Continent in the context of global warming scenarios.

2. Model and Experiment

[4] The atmospheric GCM used is a prototype of the next generation numerical weather prediction model of JMA. The simulations were 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 a grid size of about 20 km. The model has 60 layers in the vertical with the model top at 0.1 hPa. Detailed description of the model is given by Mizuta et al. (submitted manuscript, 2005).

[5] We have performed two “time-slice” 10-year simulations. One (AJ run) is a present-day climate simulation using the observed climatological (1982–1993 average) sea surface temperature (SST) as boundary conditions. Concentrations of greenhouse gases in AJ run are set to the same values as those of the Atmospheric Model Intercomparison Project (AMIP) II. Time integration over 10 years is carried out after a spin-up for 5.5 years. The other (AK run) is a global warming simulation forced by climatological SST plus anomalies. The SST anomalies are the difference between the last 20 years of the twenty-first century in the SRES A1B scenario simulation and the last 20 years of the twentieth century in the 20C3M (20th Century Climate in Coupled Models project) simulation (S. Yukimoto et al., Climate change of the twentieth through twenty-first centuries simulated by the MRI-CGCM2.3, submitted to Papers in Meteorology and Geophysics, 2005). Concentrations of greenhouse gases are assumed as those for the year 2090 prescribed by the A1B scenario.

[6] Model’s performance in the present-day simulation is described by Mizuta et al. (submitted manuscript, 2005). The simulated precipitation agrees well with the observations in terms of spatial patterns, such as the Intertropical
Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), and Asian summer monsoon rainy area, but its amount is under-estimated in the western Pacific region and over-estimated around Bay of Bengal and also the eastern Pacific in the JJA season. Model’s high horizontal resolution enables us to simulate orographic rainfall such as a maximum to the west of the Western Ghats in southern India and a southern periphery of the Himalaya range.

In addition to monthly mean fields, we stored hourly precipitation and some selected variables at 6-hourly intervals. These variables are used to analyze the diurnal variation of precipitation in this study. Here 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 01 LT (local solar time) is the value accumulated between 00:00 LT and 01:00 LT.

3. Results

Figure 1 shows the 10-year mean change in annual mean precipitation, AK–AJ. Due to global warming, the precipitation generally increases in the tropics as well as mid- and high-latitudes and decreases in some part of the subtropics. The model also shows a mean El Niño-like tropical climate response with the equatorial eastern Pacific SST increases more than the western Pacific (not shown). Associated with this El Niño-like change, major precipitation area shifts eastward with positive precipitation anomalies over the central tropical Pacific and negative anomalies over the western tropical Pacific. While the results in this paper may be sensitive to the El Niño-like nature of the SST response pattern used to force the model, such a response pattern is a common feature across climate models.

A large contrast is noted between land and the ocean in the Maritime Continent where precipitation change is positive over land while there are some areas where precipitation decreased over the ocean, in particular, significant over coastal sea region. Spatial distributions of the land-sea contrast of annual mean precipitation difference between AJ and AK are similar to those of the land-sea contrast between evening (13 LT-24 LT) and morning (01 LT-12 LT) rain difference shown by Arakawa and Kitoh [2005] for AJ and Mori et al. [2004] for the observation over the Indonesian Maritime Continent. This implies a modulation of diurnal rainfall amplitude due to global warming. Next we examine how diurnal rainfall variation has changed due to global warming.

Figure 2 shows the annual mean diurnal variation of hourly precipitation over Borneo Island (110°E–116°E, 2°S–0°S) and over the Java Sea (110°E–116°E, 6°S–4°S) for AJ and AK (upper panel) and the difference AK-AJ (lower panel). The present-day simulation (solid lines) has afternoon maximum (16–17 LT) and morning minimum (8 LT) over Borneo Island, while there is morning maximum (4 LT) and afternoon minimum (18 LT) over the Java Sea. As shown by Arakawa and Kitoh [2005], this land-sea contrast is in general agreement with the observation based on the convective activity derived from satellite infrared channel data [Ohsawa et al., 2001] and the Tropical Rainfall Measuring Mission (TRMM) 3G68 V5 product [Mori et al., 2004]. However, these simulated peak times are a few hours earlier than the observation, in particular, the maximum over inland region of Borneo Island appearing several hours earlier than that of the TRMM-based observation [Hirose and Nakamura, 2005].
At the end of the twenty-first century, the model projects significant changes in the morning precipitation over both land and ocean (lower panel of Figure 2). Morning precipitation increases over Borneo, while it decreases over the Java Sea. Daytime precipitation changes are rather small. An increased precipitation over the Java Sea during 17–22 LT is, though, statistically significant. They result in a weakened contrast of day and night precipitations over both regions.

The diurnal variation in precipitation is closely related to the land-sea breeze circulation. Figure 3 shows composite diagrams of six-hourly surface air temperature, surface winds and precipitation distributions of the present-day simulation (AJ) and the future change (AK-AJ). To obtain diurnal component, daily mean values are removed in these composites. We first see the composites of the present-day simulation (AJ). The diurnal range in surface air temperature over land is larger than that over the ocean. At 14 LT, surface air temperature over land is warmer than that over the ocean, and vice versa at 02 LT. Diurnal components of surface winds clearly show sea breeze circulation at 14 LT with positive precipitation anomalies (relative to daily mean) over land and negative precipitation anomalies over the ocean (Figure 3j). The situation is similar at 20 LT (Figure 3k). At 02 LT, precipitation over the ocean along the coastline of Borneo Island reaches its daily maximum as land breeze circulation becomes dominant (Figure 3l). At 08 LT, precipitation over the ocean is
still above the daily average, while land precipitation reaches its daily minimum (Figure 3i).

[13] The composite changes (AK-AJ) reveal the modulation of diurnal variations due to global warming. Surface air temperature rises in the future climate, but its magnitude is different during day and night, and also over land and the ocean. Large warming relative to daily mean in night is evident over land at 02 LT (Figure 3h), contrasted against relative cooling (less warming) in daytime (14 LT; Figure 3f). This decreasing trend in diurnal temperature range is observed over the continent [Karl et al., 1993] and is considered to be due to increases in clouds moderated by changes in soil moisture [Dai et al., 1999; Stone and Weaver, 2003]. The use of atmospheric GCM prohibits large change in diurnal variation of maritime temperature, but qualitative conclusion may not change with a coupled model because of large contrast of heat capacity between land and the ocean. This point, however, should be pursued in future using coupled GCMs.

[14] We can see changes in land–sea breeze circulations where anomalous land breeze circulation with negative rainfall anomaly over land and positive rainfall anomaly over the ocean is found at 14 LT (Figure 3n) when diurnal component of temperature change over land is negative (Figure 3f), i.e., change in land surface temperature is less than change in daily average between the future and the present. Conversely, at 02 LT when diurnal component of land surface temperature rise is positive (Figure 3h), there are sea-breeze circulation anomalies (Figure 3p). Larger warming in nighttime temperature but smaller in daytime over land resulted in a weakening of diurnal component in land–sea breeze circulations, and thus less diurnal range in precipitation. As a whole, morning precipitation increase over land and decrease over the ocean dominates daily average precipitation changes in this region (Figure 2), and resulted in land–sea precipitation contrast in the annual mean changes (Figure 1).

4. Conclusions

[15] Rainfall diurnal variation is an important ingredient of tropical climate system, but its potential change by global warming has not been studied so far, mainly because previous GCMs had coarse horizontal resolution and their performance in reproducing diurnal variations is poor. Here a first attempt of time-slice global warming experiments with a high-resolution GCM (about 20 km grid size) enables us to attack this problem. Although the model used in this study still uses cumulus parameterization and hydrostatic approximation, its performance in simulating tropical rainfall diurnal variation is reasonable [Arakawa and Kitoh, 2005]. We found that diurnal variations of precipitation change in opposite way between land and ocean in the Maritime Continent: over the ocean morning precipitation decreases and evening precipitation increases, while over land morning precipitation increases, resulting in smaller amplitude of rainfall diurnal cycle both over land and over ocean. Larger warming at night than during the day weakens the local land–sea breeze circulation, resulting in smaller diurnal variations of rainfall over the Maritime Continent. These different characteristics in precipitation change between the ocean and land may lead to changes in air–sea heat flux and moisture exchanges and thus regional circulation changes by global warming. The results reported here may be affected by neglecting SST diurnal variations, but this effect is unlikely to change the results qualitatively.

[16] Acknowledgments. OA was supported by the Cooperative Systems for Supporting Priority Research, Japan Science and Technology Agency. This work is based on the results of experiments performed by global warming group under the framework of the “Kyosei Project 4: Development of Super High Resolution Global and Regional Climate Model” supported by the Ministry of Education, Sports, Culture, Science and Technology of Japan (MEXT). The 20-km mesh model calculations were made on the Earth Simulator.

References


