Numerical Examination of the Diurnal Variation of Summer Precipitation over Southern China

Masaki Satoh¹, ², and Yushi Kitao¹

¹Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Japan
²Research Institute for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

Abstract

Diurnal variation of precipitation is frequently observed over southern China in summer. We investigate it using the regional version of the nonhydrostatic icosahedral atmospheric model (NICAM), with particular focus on the interactions among land, cloud, and radiation processes. The NICAM almost exactly reproduces the diurnal variation of precipitation but slightly overestimates its amplitude. The simulated spatial distribution of precipitation is similar to that observed by the Tropical Rainfall Measuring Mission 3B42 product. Precipitating region propagates inland from the coast during 14–20 LT.

We perform sensitivity experiments to study the effects of surface conditions, cloud, and radiation interactions, and the results are as follows. 1) When volumetric soil moisture is reduced, surface temperature increases and surface evaporation decreases. Water vapor inflow increases owing to enhanced land–sea contrast; however, the decrease in surface evaporation counteracts this increase, thus decreasing precipitation. 2) When cloud amount is reduced, net downward radiation and surface temperature increase. Precipitation does not appear to vary with cloud conditions.

The zone of the horizontal convergence of water vapor flux propagates inland in the afternoon, although local evaporation has a greater impact than water vapor inflow on the diurnal variation of precipitation.

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1. Introduction

It is well known that a distinct diurnal variation of clouds is observed over southern China from June to August (see Supplemental Fig. S1). Moreover, precipitation in the region exhibits a large-amplitude diurnal variation, with a peak time around 15–18 LT. Because this precipitation falls over a large continental mass, its diurnal variation exhibits characteristics typical of precipitation over land: deep convection is triggered by the instability of the planetary boundary layer caused by the warming of the ground surface by daytime insolation, resulting in a late afternoon peak in precipitation. In fact, it has been analyzed (see Fig. 2c of Yu et al. 2007) that the precipitation peak in southern China (23°N–26°N, 110°E–117°E) occurs at 17 LT. However, despite the presence of these characteristics of deep convective precipitation over land, it has also been argued that water vapor inflow associated with the sea breeze due to the land–sea contrast causes the diurnal variation of precipitation in this region (Zhou et al. 2005, 2008; Huang et al. 2010).

In general, the diurnal change of precipitation over land is affected by interactions between many processes related to cloud cover, solar insolation, and ground surface conditions (e.g., May et al. 2012). Such cloud–radiation–ground interactions are complex, and it remains unclear how these processes affect the characteristic feature of diurnal variations. From the modeling perspective, mesoscale-resolving models with horizontal mesh sizes of less than around 10 km are generally able to simulate diurnal variations of deep convection. However, it has proven difficult to accurately reproduce the amplitude of diurnal cycles of precipitation, because many processes contribute to the above-mentioned cloud–radiation–ground interactions. Sensitivity studies using numerical models have been performed to isolate some of the key processes (Koo and Hong 2010; Hong et al. 2012). High-resolution global non-hydrostatic models with mesh sizes of around 5 km have recently become available (Satoh et al. 2008) and are able to simulate the diurnal variation of precipitation relatively well at the global scale (Sato et al. 2009; Kinter et al. 2013). However, it would be premature to conclude that the cloud–radiation–ground interactions are simulated entirely appropriately by these high-resolution models.

As described above, two mechanisms have been proposed to explain the diurnal variation of summer precipitation over southern China: the sea breeze due to the land–sea contrast and convective precipitation due to heating of the ground by daytime insolation. This study investigates which mechanism explains the diurnal variation through sensitivity experiments using a numerical model. We use the stretch version of the nonhydrostatic icosahedral atmospheric model (stretched-NICAM; Tomita 2008a; Satoh et al. 2010) to reproduce the precipitation over southern China. In particular, we design the sensitivity experiments from the viewpoint of the radiation–cloud–ground interactions. Section 2 describes the numerical model and the simulation design, and Section 3 describes the results of the control experiment. In Section 4, we discuss the mechanism underlying the diurnal variation based on sensitivity experiments in which we vary the soil moisture and cloud fraction.

2. Model and experimental design

Here, we used the stretched-NICAM (Satoh et al. 2008; Tomita 2008a; Satoh et al. 2010), which has a variable horizontal mesh interval over the globe; this mesh interval is the finest at the center of the target region and becomes gradually coarser with increasing distance from the center. We set the center of the target region to 25°N, 115°E to focus on southern China (23°N–26°N, 110°E–117°E); this corresponds to the region defined by Yu et al. (2007). Two grid resolutions are tested: NICAM-5.6km has a grid interval of 5.6–12 km in the target region, and NICAM-11.2km which has a grid interval two times that of NICAM-5.6km. We adopted the NICAM single moment water 6 (NSW6) cloud microphysics scheme, which predicts six water categories (vapor, cloud water, rain, cloud ice, snow, and graupel; Lin et al. 1983; Tomita 2008b) and switched off cumulus parameterization. We also adopted level 2 of the Mellor–Yamada–Nakanishi–Niino model (MYNN2.0; Mellor and Yamada 1974; Nakanishi and Niino 2009) as the planetary boundary scheme, the surface flux scheme of Louis (1979), and the radiation scheme based on the two-stream k-distribution method (MSTRNX; Sekiguchi and Nakajima 2008), and use the minimal advanced treatments of surface interaction and runoff (MATSITO; Takata et al. 2003) as the land surface model.
We performed a sequence of 4-day integrations by providing initial data from August 14 to 28, 2009, i.e., we performed 15 simulations to obtain a general example of the diurnal variation behavior. To choose the simulation period, we excluded tropical cyclone cases and the Meiyu periods to obtain typical cases of diurnal variation of summer precipitation. For each simulation, we used the last three days for analysis, and discard the first day of simulation for spin-up. We analyzed the domain enclosed by the latitudinal range 23°N–26°N and the longitudes 110°E–117°E, following Yu et al. (2007) and Zhou et al. (2008). The initial atmospheric conditions and the surface boundary conditions are interpolated from the National Centers for Environmental Prediction (NCEP) analyses.

For evaluation of simulated precipitation, we use the observational dataset from the Tropical Rainfall Measurement Mission (TRMM) product (hereafter, TRMM-3B42). We used the version 6 of TRMM-3B42 with 3 hourly temporal resolution (Huffman et al., 2007). Note that the use of infrared geostationary satellite data for the TRMM-3B42 product might cause delay of phase of diurnal variation (Kikuchi and Wang 2008; Sato et al. 2008).

3. Results

First, we present the results from the control experiment. Figure 1 compares the geographical distribution of time-mean precipitation of the observational dataset from TRMM-3B42 with those of NICAM-5.6km and NICAM-11.2km. Both simulations reproduce the geographical distribution of the rainfall well, agreeing closely with the observations along the southeast coast of China between 110°E and 120°E. Figure 2 illustrates composite curves of the diurnal variation of precipitation for TRMM-3B42, NICAM-5.6km, and NICAM-11.2km. All of these results exhibit a clear diurnal cycle with a peak in the evening (17–19 LT). However, the simulated amplitudes are stronger than the observed ones (i.e., in TRMM-3B42). The precipitation peak occurs at around 17 LT in NICAM-5.6km, which is similar to the time of the peak in TRMM-3B42; conversely, the precipitation peak of NICAM-11.2km lags these peaks by about 2 h. Such resolution dependency agrees with that found by Sato et al. (2009).

Figure 3 illustrates the temporal evolution of vertical profiles of moist static energy (MSE) for the two simulations, which shows the deviation from the diurnal average. The positive depth indicates the convective layer. The positive MSE deviation grows in the morning with the amplitude peak occurring at around 14 LT below an altitude of 2 km, and it rapidly deepens between 14–17 LT. As the resolution becomes finer, the peak of MSE occurs earlier, and the amplitude of MSE deviation below 2 km becomes stronger. This profile is typical of the diurnal variation of deep convection simulated over land by numerical models (Guichard
As demonstrated by Figs. 1 and 2, the characteristics of diurnal variations of precipitation are reproduced well by the simulations. Next, we examine the propagation of the precipitation system. Figure 4 presents composite maps of the low-level horizontal divergence of water vapor flux at an altitude of 835 m and the associated precipitation. In particular, these maps indicate northwestward propagation from the coastal region at 23°N, 118°E to the inland area at 27°N, 114°E for two cycles of the diurnal variation. The low-level divergence clearly indicates propagation toward the inland area from the initiation near the coastal line at around 23.5°N, 117.5°E. The precipitation also shows propagation, although this propagation occurs slightly later than convergence. Moreover, the propagation length of precipitation is shorter than that of convergence: precipitation region whose strength larger than 1 mm h$^{-1}$ ends at about 116°E, whereas convergence propagates beyond 115.5°E. Supplemental Fig. S2 includes an animation of the low-level horizontal divergence fields of water vapor flux. A strong convergence zone emerges at about 11−12 LT along the coastal line and propagates inland. Interestingly, a divergence zone simultaneously emerges, located just off the coastal line and aligned parallel to the convergence zone between 12 and 18 LT.

The water vapor budget in the target domain is shown in Table 1. For the control experiment shown here (NICAM-11.2km), the average precipitation is $2.07 \times 10^7$ kg s$^{-1}$ and the inflow (convergence) is $0.78 \times 10^7$ kg s$^{-1}$; that is, water vapor convergence is much smaller than precipitation. Yasunari et al. (2000) described the relative magnitudes of precipitation, evaporation, and convergence in eastern Asia for a larger domain than that investigated in this study (i.e., enclosed by 25°N−35°N and 105°E−120°E). Yasunari et al. (2000) shows that, the contribution of water vapor convergence to precipitation decreases from June to August, with water vapor convergence constituting less than approximately one third of total precipitation at its maximum contribution in June. Our result is consistent with that of Yasunari et al. (2000). Moreover, although Figs. 3 and S2 suggest that the propagation of the precipitation system is primarily caused by the land−sea contrast, the water budget shown in Table 1 suggests that the local recycling of water is more important. Note also that it is thought that the contribution of inflow generally becomes larger in mountainous regions. For the period examined in this study, because the precipitation is stronger in the mountainous region (24°E−29°E and 116°E−120°E; Fig. 1), the contribution of inflow would be larger if the target domain is shifted northeastward.

### 4. Sensitivity experiments

We perform sensitivity experiments to assess the relative importance of inflow from the ocean and the local recycling of water for the precipitation in southern China by varying land surface conditions and cloud properties. We compare these results
with that of NICAM-11.2 km (the control experiment). In general, the hydrological cycle over land is caused by interactions between many processes such as solar insolation, land conditions, and cloud cover. Evaporation and precipitation tend to be enhanced over wetter land, and both solar insolation and temperature tend to be lower in regions with more extensive cloud cover. Moreover, daytime convection will be enhanced where ground temperatures are increased, assuming all other factors remain constant. However, all of the above interactions can be modified if the land–sea contrast affects the diurnal variation.

We perform the following additional experiments wherein the horizontal resolution of all simulations matches that of NICAM-11.2 km. First, we either halve or double the soil moisture of the initial conditions of the land surface; we refer to these experiments as CLDMNS (referred to CLDPLS). For the control experiment, WGH Alf and WGD DBLE are about 0.36, 0.18, and 0.42 m³ m⁻³, respectively. Note that the soil wetness of WGDDBLE approaches the saturated value. The control value is taken from the NCEP analysis and is comparable to the values of 0.29 m³ m⁻³ obtained by the European Centre for Medium-Range Weather Forecasts Interim reanalysis (ERA-Interim), thus we can assume the uncertainty of soil wetness to be in the range between 0.3–0.4 m³ m⁻³.

For our next sensitivity experiments, we replicate the experiments designed by Kodama et al. (2012) by varying cloud conditions. Specifically, we conduct an experiment in which we assign a fall velocity to cloud ice (referred to CLDMNS) using the formula presented by Heymsfield and Donner (1990) and an experiment in which we increase the threshold value of autoconversion from cloud ice to snow to qicr = 0.1 g kg⁻¹ (referred to CLDPLS). For the control experiment, cloud ice has no fall velocity and qicr = 0.005 g kg⁻¹.

Table 1 summarizes the sensitivity of the water budget, whereas Table 2 details the sensitivity of the energy budget at the surface. The results show that temperature increases and precipitation decreases as the soil moisture is decreased (from WGDDBLE to WGH Alf). The water inflow increases, likely owing to increases in the temperature of the land surface and enhancement of the land–sea contrast as soil moisture is reduced. However, because the reduction of evaporation is greater than the increase of the inflow of water, precipitation decreases. Moreover, cloud amount decreases as soil moisture is decreased, which is consistent with a reduction in precipitation. Such a decrease in the cloud amount leads to an increase in the net downward shortwave radiation, which can exert a positive feedback on surface temperature.

For the experiments in which cloud cover is varied (from CLDPLS to CLDMNS), the simulated cloud amounts are 40.6%, 13.7%, and 97.2% for the control experiment, CLDMSN, and CLDPLS, respectively. That is, almost all of the sky is covered by clouds for CLDPLS. In this case, the solar insolation decreases at the surface and the temperature becomes cooler than that of the control experiment as shown by Table 2. On the other hand, when the cloud amount is reduced (CLDMSN), the solar insolation increases, and the surface temperature increases slightly. Evaporation also increases, although precipitation does not change systematically and the water vapor inflow decreases despite the enhanced land–sea contrast as cloud cover decreases.

The above results suggest that the diurnal variation of precipitation in southern China is driven primarily by local forcing over land, rather than by the sea breeze induced by the land–sea contrast. Such precipitation characteristics are typical of those seen over land, although propagation toward the inland area is observed.

Although the daily mean surface temperature of the control experiment is similar to that of the observations, the maximum surface temperature exhibits a warm bias; it is about 306 K for the observations (ERA-interim) but about 313 K for the control experiment. This bias cannot be reduced if the soil moisture is increased; the reduction of the maximum temperature is as small as 0.5 K for WGDDBLE, and it still has a warmer bias. Even if we control the cloud amount, the maximum temperature change is about 1 K (for CLDPLS). The warm bias of the maximum temperature is robust and is not easily reconciled. It may be one of the reasons underlying the overestimation of precipitation compared to the observations (Fig. 2). Although the warmer bias tends to enhance the evaporation in general, it can be shown that the evaporation is still larger than the inflow even when reduction of the warmer bias is taken into account by using a bulk formula (reduction of the warmer bias of 7 K would lead to 38% reduction of the evaporation).

5. Summary and concluding remarks

The diurnal variation of summer precipitation in southern China is studied by a numerical model (stretched-NICAM). In general, convection and precipitation systems over land are governed by many processes, such as land characteristics, surface fluxes, cloud microphysics, and radiation. Therefore, the realistic simulation of the diurnal variation of precipitation over land is a challenging issue. It is thought that mesoscale-resolving models with horizontal mesh sizes of less than 10 km can reproduce the diurnal variation of precipitation, although the amplitude and phase lag of such variation depend on various factors such as model resolution. This study demonstrates that stretched-NICAM can reproduce the characteristics of the diurnal variation of summer precipitation in southern China, at least in terms of geographic location and phase. The simulated amplitude is greater than that observed by TRMM as is the case with many other numerical models. The model data show the inland propagation of the low-level convergence of water vapor and precipitation. However, the water budget shows that local evaporation contributes more than the land–sea contrast to the precipitation in southern China.

The sensitivity experiments described here help in determining the dominant mechanism forcing the diurnal variation of precipitation. Surface evaporation and precipitation decrease with reductions in soil moisture, although surface temperature and then the land–sea contrast increase. Moreover, surface temperature increases with reductions in the upper cloud cover owing to enhanced solar insolation. However, water vapor inflow decreases, compensating for the increase of surface evaporation, thus, only small changes in precipitation occur. The above results suggest that the primary mechanism driving the diurnal variation of precipitation in southern China is local forcing over land and not the sea breeze induced by the land–sea contrast. Such characteristics are typical of precipitation over land, although propagation toward inland areas is also observed.

### Table 2. Sensitivity of average energy budget at the surface in the target domain (23°N−26°N, 110°E−117°E). Direction of radiative flux is downward.

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<tr>
<td>CTL</td>
<td>301.7</td>
<td>195.7</td>
<td>246.5</td>
<td>−50.8</td>
<td>40.6</td>
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<tr>
<td>WGH Alf</td>
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<td>251.1</td>
<td>−62.6</td>
<td>35.7</td>
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<tr>
<td>WGD DBLE</td>
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<td>246.0</td>
<td>−49.1</td>
<td>42.3</td>
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<tr>
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<td>202.9</td>
<td>255.9</td>
<td>−53.0</td>
<td>13.7</td>
</tr>
<tr>
<td>CLD PL S</td>
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<td>163.8</td>
<td>208.5</td>
<td>−44.7</td>
<td>97.2</td>
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Supplement

S1. Animation of the diurnal variation of upper clouds in southern China for August 14–31, 2009. Data are plotted using the global half-hourly pixel-resolution infrared dataset (Janowiak et al. 2001).

S2. Animation showing the propagation of low-level water vapor divergence at 835 m.

References


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SOLA: http://www.jstage.jst.go.jp/browse/sola/