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An equilibrium cloud-resolving modeling study of diurnal variation of tropical rainfall

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ABSTRACT

The diurnal variation of tropical rainfall is examined through the analysis of an equilibrium cloud-resolving model experiment. Model domain mean rain rate is defined as a product of rain intensity and fractional rainfall coverage. The diurnal variation of the mean rain rate is associated with that of fractional rainfall coverage because the diurnal variation of rain intensity is significantly weakened through the decrease in rainfall in early morning hours. The decrease in rainfall corresponds to the reduction in secondary circulations through the barotropic conversion from the perturbation kinetic energy to the mean kinetic energy under the imposed negative vertical gradient of westerly winds. The fractional rainfall coverage shows the diurnal signal with the maximum in the early morning hours primarily due to nocturnal infrared radiative cooling.

1. Introduction

The diurnal variation of tropical rainfall is one of the important temporal variations in the tropics and has fundamental impacts on variability at synoptic and climate time scales. The dominant diurnal signal is the nocturnal rainfall peak that occurs in the early morning. The diurnal variation of tropical rainfall has been intensively studied in observational analysis and numerical modeling for decades (e.g., Sui et al., 1997; Yang and Smith, 2008), in which the diurnal rainfall variation may be associated with the diurnal variation of radiation (e.g., Kraus, 1963; Randall et al., 1991; Tao et al., 1996; Sui et al., 1998) or radiational differences between cloudy regions and clear-sky regions (Gray and Jacobson, 1977), or diurnal variation of large-scale circulation (e.g., Petch and Gray, 2001). The diurnal variation of rainfall is also affected by diurnal variation of sea surface temperature (Cui and Li, 2009) and radiative and microphysical effects of ice clouds (Ping and Luo, 2009).

Gray and Jacobson (1977) argued that radiational differences between cloudy regions and clear-sky regions enhance the nocturnal rainfall through the strengthening of secondary circulation. Randall et al. (1991) carried out sensitivity experiments using a general circulation model and showed that the phase of simulated diurnal rainfall variation is not sensitive to cloud radiative effects but the amplitude is much weakened by the exclusion of cloud radiative effects. Tao et al. (1996) showed that modeling nocturnal surface precipitation is enhanced by infrared cooling through the increase in relative humidity. Sui et al. (1997, 1998) revealed that nocturnal rainfall peak is associated with the strengthening of net condensation through the decrease in saturation mixing ratio caused by nocturnal radiative cooling in their observational and numerical studies. Liu and Moncrieff (1998) found that the diurnal variation of rainfall simulated by a cloud-resolving model is primarily associated with the direct interaction between radiation and convection and the mechanism proposed by Gray and Jacobson (1977) is

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a secondary factor. Petch and Gray (2001) showed that the simulated diurnal rainfall variation of the tropical west Pacific is determined by large-scale forcing. Gao et al. (2009) performed a series of sensitivity cloud resolving model experiments during the 21 days of the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) and revealed that diurnal variations of radiation and large-scale forcing can produce a nocturnal rainfall through infrared and advective cooling, respectively. Gao and Li (2010) analyzed diurnal variations of surface rainfall budgets and revealed that the diurnal variations of water vapor convergence and heat divergence associated with diurnally varying imposed large-scale upward motions play a primary role in the development of rainfall peaks in both afternoon and nighttime while the diurnal variation of radiation is secondary in the formation of nocturnal rainfall peak. The diurnal variation of radiation associated with diurnally varying solar zenith angle determines the diurnal variations of tropical oceanic rainfall when the diurnal variation of large-scale circulation is absent.

The area-averaged rain rates have been analyzed in previous studies because the rain rates are averaged over a whole rainfall system in which narrow upward motions are sandwiched by broad downward motions. The diurnal variation of radiation is responsible for the diurnal variation of rainfall, but radiation is negligibly small in the thermal budget over rainfall area (e.g., Zhou and Li, 2011). If the rain intensity is defined as the rain rate averaged over rainfall area, does the rain intensity show a diurnal variation? The area-averaged rain rate can be a product of rain intensity (RI) and fractional rainfall coverage (FRC), where the fractional rainfall coverage is defined as the ratio of rainfall area to whole area over which rain rate is averaged. Do the fractional rainfall coverage and rain intensity have diurnal variations?

Vertical wind shear affects surface rain rate through the change in perturbation kinetic energy associated with secondary circulations. The change in kinetic energy corresponds to the barotropic conversion between the mean and perturbation kinetic energy in the presence of vertical wind shear. Vertical wind shear contributes to rainfall asymmetries associated with tropical cyclones (e.g., Chen et al., 2006). Wang et al. (2009) conducted sensitivity experiments of severe tropical storm Bilis using a two-dimensional (2D) cloud-resolving model and found that the inclusion of negative vertical gradient of westerly winds produces well-organized convection and strong convective rainfall because it causes kinetic energy transfer from large-scale forcing to perturbation circulations. Shen et al. (2011) showed that the exclusion of positive vertical gradient of westerly winds increases the mean pre-summer rain rate through the slowdown in the decrease of perturbation kinetic energy. Since rainfall is usually associated with large-scale circulations, does the vertical wind shear affect diurnal variations of RI and FRC?

In this study, a 2D equilibrium cloud-resolving model experiment data are analyzed to investigate the effects of vertical wind shear on diurnal variations of rain intensity and fractional rainfall coverage. In the next section, the cloud model and experiment are briefly described. The results are presented in Section 3. The summary is given in Section 4.

2. Model and experiment

In this study, a 2D Goddard Cumulus Ensemble Model developed by Soong and Ogura (1980), Soong and Tao (1980), and Tao and Simpson (1993) and modified by Sui et al., 1994, 1998) and Li et al. (1999, 2002b) are used. The model has prognostic equations for potential temperature, specific humidity, mixing ratios of five cloud species, and perturbation zonal wind and vertical velocity. The model also includes cloud microphysical (Rutledge and Hobbs, 1983, 1984; Lin et al., 1983; Tao et al., 1989; Krueger et al., 1995; also see Table 1) and solar (Chou et al., 1998) and thermal infrared (Chou et al., 1991; Chou and Suarez, 1994) radiation parameterization schemes. The model uses cyclic lateral boundaries. The basic model parameters include a horizontal domain of 768 km (512 horizontal grid points), 33 vertical levels, a horizontal grid resolution of 1.5 km, and a time step of 12 s. The detailed descriptions of model setup can be found in Gao and Li (2008a). The 2D cloud-resolving model simulation has been validated with observations in terms of atmospheric thermodynamic profiles, surface fluxes, and surface rain rate in the tropics during Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) (Li et al., 1999) and the simulation data are analyzed for process studies (Li et al., 2002a,c; Gao et al., 2004, 2005, 2006, 2007, 2009; Sui et al., 2005; Cui and Li, 2006; Gao and Li, 2008b; Ping et al., 2008; Shen et al., 2010).

In the equilibrium experiment, the model is imposed by time-invariant large-scale forcing. The forcing is constructed by averaging the data from 0400 LST 18 December 1992 to 1000 LST 9 January 1993 during TOGA COARE (Li et al., 2002a). The 21-day mean vertical velocity generally shows upward motions throughout the troposphere with a maximum of 1.5 cm s^{-1} around 8 km (Fig. 1a). The time-mean westerly winds prevail throughout the troposphere with a maximum of 10 m s^{-1} around 3 km (Fig. 1b). The profile of zonal wind shows a negative vertical gradient of westerly winds from 3 km to 12 km. The zonally-uniform vertical velocity and zonal wind are observed and derived from 6-hourly TOGA COARE observations within the Intensive Flux Array (IFA) region provided by the research group of Prof. M. Zhang at the State University of New York at Stony brook. The SST averaged from hourly data at the Improved Meteorological (IMET) surface mooring buoy (1.75°S, 156°E) from Weller and Anderson (1996) is 29 °C. The experiment is integrated for 40 days and equilibrium state is reached after day 20. Thus, the data from the last 20 days are used to construct diurnal composites in the following discussions.

3. Results

The diurnal composite of model domain mean rain rate shows a rainfall maximum during nighttime and a rainfall minimum during daytime (Fig. 2a). The nocturnal rainfall peak is associated with the nocturnal infrared radiative cooling through the increase in relative humidity (the decrease in saturation mixing ratio) (e.g., Gao and Li, 2010). The maximum