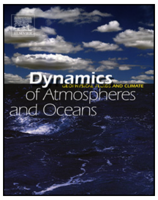
Dynamics of Atmospheres and Oceans 82 (2018) 54–63

Contents lists available at ScienceDirect

Dynamics of Atmospheres and Oceans

journal homepage: www.elsevier.com/locate/dynatmoce



Impacts of raindrop evaporative cooling on tropical cyclone secondary eyewall formation

Xuyang Ge[a],[*], Liang Guan[b], Ziyu Yan[a]

[a] *Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory of Meteorological Disaster, Nanjing University of Information Science & Technology, Nanjing 210044, China*
[b] *Shanghai Meteorological Science and Technology Service Center, Shanghai 200030, China*

ARTICLE INFO

Article history:
Received 18 November 2017
Received in revised form 7 March 2018
Accepted 8 March 2018
Available online 9 March 2018

Keyword:
Raindrop evaporation
Tropical cyclone
Secondary eyewall formation

ABSTRACT

The impacts of raindrop evaporative cooling on secondary eyewall formation (SEF) of simulated tropical cyclones are investigated using idealized numerical experiments. The results suggest that the raindrop evaporative cooling effect is beneficial to the development of secondary eyewall through the planetary boundary layer (PBL) cold pool process. The evaporative cooling-driven downdrafts bring about the surface cold pool beneath a precipitation cloud. This cold pool dynamics act as a lifting mechanism to trigger the outer convection. The radially outward propagation of spiral rainbands broadens the TC size, by which modifies the surface heat fluxes and thus outer convection. Furthermore, the unbalanced PBL process contributes to the SEF. The radially outward surface outflows forces convection at outer region and thus favors a larger TC size. A larger TC implies an enhanced inertial stability at the outer region, which favors a higher conversion efficiency of diabatic heating to kinetic energy.

1. Introduction

The intensity and structure changes of tropical cyclones (TCs) are among the most challenging issues in the operational forecasting. A secondary eyewall (SE) may form when the surface maximum wind speed of a TC reaches 60 m s^{-1} (Willoughby et al., 1982; Kuo et al., 2009). A tropical cyclone with two or more closed concentric eyewalls collocated with responded maximum wind speed is defined as a TC with a SE. An eyewall replacement cycle (ERC) contains a series of processes including the outer eyewall formation, contraction and the inner eyewall vanishing (Willoughby et al., 1982). During the ERC, the TC's intensity and structure experience dramatic fluctuations (Black and Willoughby, 1992; Sitkowski et al., 2011; Zhou and Wang, 2013; Kossin and Sitkowski, 2012; Yang et al., 2013, 2014; Ge, 2015), leading to a great uncertainty in TC forecasting. Hence, it is important to examine the possible underlying processes leading to a SEF.

Previous studies have focused on the SEF (Willoughby et al., 1984; Kuo et al., 2004, 2008; Nong and Emanuel, 2003; Houze et al., 2007; Zhou and Wang, 2011; Huang et al., 2012; Rozoff et al., 2012; Qiu et al., 2010; Wu et al., 2012; Abarca and Montgomery, 2013; Wang et al., 2013; Wang et al., 2016; Ge et al., 2016; Guan and Ge, 2018). To summarize, both inner dynamics and external environmental forcing contribute to the SEF. Nong and Emanuel (2003) pointed out that an external forcing can generate a SE through the wind-induced surface heat fluxes exchanges (WISHE). Montgomery and Kallenbach (1997) emphasized the role of the vortex Rossby wave on the SEF. Terwey and Montgomery (2008) proposed a concept of so-

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[*] Corresponding author at: Pacific Typhoon Research Center, NUIST, China.
E-mail address: xuyang@nuist.edu.cn (X. Ge).

https://doi.org/10.1016/j.dynatmoce.2018.03.001
0377-0265/

Table 1
Experiment description.

Experiment	Description
CTL	Control run with rainwater evaporation cooling
EVP0.5	As in CTL, but rainwater evaporation cooling is reduced by half
EVP0.25	As in CTL, but rainwater evaporation cooling is multiplied by 0.25

called beta-skirt axisymmetrization. More recently, Wu et al. (2012) and Huang et al. (2012) suggested that the unbalanced dynamics in the boundary layer plays an important role on the SEF. That is, the broadening of the tangential winds, with enhanced PBL supergradient winds, force convection outside of the primary eyewall, and lead to a SEF eventually.

Numerous studies suggested crucial roles of outer rainbands in governing the TC structure. Zhu and Zhu (2014) proposed that the outer rainband convection must reach a critical strength relative to the eyewall before the SEF. Qiu and Tan (2013) pointed out that the unbalanced boundary layer responses to asymmetric inflow forcing induced by outer rainbands, triggering the sustained convection outside the primary eyewall during the early phase of the SEF. It has been well realized that the spiral rainbands are important components of TCs, since the associated diabatic heating is a key driver of the secondary circulation and affects the transport of absolute angular momentum (Fudeyasu and Wang, 2011). Previous literatures suggested an important role of cold pool dynamics in the development of the TC outer spiral rainbands (Ushijima, 1958; Barnes et al., 1983; Powell, 1990b; Zhou et al., 2016). Specifically, Yamasaki, (1983) found that evaporative cooling forms the cold pools in the PBL, which is essential for the origins and outward propagation of rainbands. The SEF is highly sensitive to the cloud microphysical process (Willoughby et al., 1984; Zhou and Wang, 2011). These studies found that the cloud microphysics (i.e., ice-phase) are beneficial to the SEF. In the lower troposphere, the behavior of cold pools is largely determined by the raindrop evaporative cooling. On one hand, the downdrafts induced by the evaporative cooling bring cold and dry air from the middle troposphere to the PBL and weaken the TC intensity, which are unfavorable for the SEF. On the other hand, the downdrafts form surface cold pools beneath precipitation clouds, resulting in an outward spreading at the surface and formation of a convergent region around the cold pool front, which trigger convection and outer spiral rainbands (Yamasaki, 1983; Sawada and Iwasaki, 2010). The prolific outer convection favors a larger TC size. A larger TC is apt to establish a SEF (Ge et al., 2016). As such, the spiral rainbands likely impact TC size and thus modulate the SEF. Hence, the main purpose of this study is to clarify the possible roles of the raindrop evaporative cooling in the SEF using cloud-resolving simulations under an idealized environment.

The paper is organized as follows. In Section 2, the model and experimental designs are introduced. Section 3 compares the evolution characteristics of the simulated SEFs. Section 4 presents possible physical explanations. Conclusions and discussion are given in Section 5.

2. Model and experiment designs

In this study, the WRF-ARW model (version 3.7.1) is utilized. There are four nested domains, with the mesh sizes of 121 × 121, 121 × 121, 181 × 181, and 241 × 241 grid points. The horizontal resolutions are 54, 18, 6, and 2 km, respectively. In the control experiment (CTL), the model configurations are identical to Ge et al. (2016). Namely, an initial TC-like vortex with the maximum wind speed of 25 m s^{-1} at the radius of 50 km.

The model strategy follows Sawada and Iwasaki (2010). The cloud microphysics scheme is from Lin et al. (1983). The changes are made in this scheme by modifying the simulated rainwater evaporative cooling rate. In CTL, the simulation is performed by using the default setting. Two additional sensitive experiments (i.e., Table 1) are designed to investigate the impacts of raindrop evaporation on the SEF. That is, in EVP0.5, the raindrop evaporative cooling is reduced by a half. In EVP0.25, the cooling effect is further reduced by multiplying 0.25. Nevertheless, we allow the conversion from rainwater into water vapors in each time step. By comparing these experiments, the impacts of evaporative cooling on the SEF are investigated. All the experiments are integrated with a 10-day period on an *f*-plane.

3. Simulated results

Fig. 1 compares the time evolution of tangential wind fields near the surface. Generally, as the vortex develops, the tangential wind velocity increases and the outer size broadens with time in all experiments. Notice that a distinct outer maximum tangential wind appears at the outer region (i.e., at the radius of 100–150 km) emanates in both CTL and EVP0.5. The results indicate that a SEF occurs in both CTL and EVP0.5, whereas no SEF appears in EVP0.25 during the period of interest. Once the outer eyewall forms, the intensification of the storm is halted, or even becomes weakening. The inner eyewall demises gradually and is eventually replaced by the outer one. As such, the simulations capture the major features of the canonical eyewall replacement cycle (Willoughby et al., 1982). Notice that a difference in the onset timing of SEF between CTL and EVP0.5. Namely, The SEF emanates about t = 192 h in CTL, which is 6 h earlier than that in EVP0.5. To summarize, when the evaporative cooling is reduced, a SEF in a TC is delayed or even disappears. The results indicate that the raindrop evaporation has a great impact on the SEF.