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Simulated sensitivity of tropical cyclone track to the moisture in an idealized monsoon gyre

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ABSTRACT

In this study, the sensitivity of tropical cyclone (TC) track to the moisture condition in a nearby monsoon gyre (MG) is investigated. Numerical simulations reveal that TC track is highly sensitive to the spatial distribution of relative humidity (RH). In an experiment conducted with higher (lower) RH in the eastern (western) semicircle of an MG, the TC experiences a sharp northward turning. In contrast, when the RH pattern is reversed, the simulated TC does not show a sharp northward turning. The RH distribution modulates the intensity and structure of both the TC and MG, so that when the TC is initially embedded in a moister environment, convection is enhanced in the outer core, which favors an expansion of the outer core size. A TC with a larger outer size has greater beta-effect propagation, favoring a faster westward translational speed. Meanwhile, higher RH enhances the vorticity gradient within the MG and promotes a quicker attraction between the TC and MG centers through vorticity segregation process. These cumulative effects cause the TC to collocate with the MG center. Once the coalescence process takes place, the energy dispersion associated with the TC and MG is enhanced, which rapidly strengthens southwesterly flows on the eastern flanks. The resulting steering flow leads the TC to take a sharp northward track.

1. Introduction

A tropical cyclone can experience a sudden track change interacting with a large-scale and low-frequency monsoon gyre (Carr and Elsberry, 1995; Liang et al., 2011; Bi et al., 2015; Liang and Wu, 2015). The monsoon gyre (MG) is identified as a low-frequency circular cyclonic circulation with a diameter of about 2500 km (Lander, 1994; Harr et al., 1996; Molinari and Vollaro, 2017) over the western North Pacific (WNP) basin. Using a barotropic model, Carr and Elsberry (1995) investigated the interaction between a TC and MG, and found that a sudden northward track change appears when a TC enters the eastern semicircle of an MG. It was proposed that during the coalescence of these two systems, Rossby wave energy dispersion enhances the southwesterly flows to the southeast quadrant. As such, this enhanced southwesterly flow acts as a steering flow and leads to a sharp northward turning.

Wu et al. (2013) compared 15 TCs with sharp north-turning tracks and 14 cases with west-turning tracks during an 11-yr period (2000–2010) in the WNP. The composited peak intensity and outer size between these two groups are compared based on the best track data of JTWC (Table 1). The mean center minimum sea level pressure (CMSLP) and radius of 34-kt

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Table 1
Comparisons between TCs with sharp north-turning and westward propagation.

	Sharp northward-turning	Westward-propagation
Peak intensity (hPa)	933	952
Outer size (R34; km)	240	220

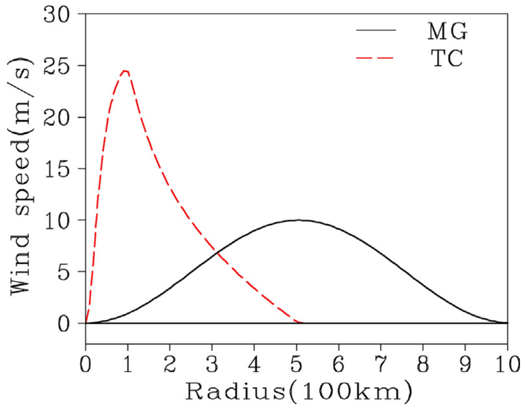

Fig. 1. Initial radial profiles of tangential wind speed (m s^{-1}) near the surface for MG (solid) and the TC (dashed).

wind (R34) is 935 (952) hPa and 240 (220) km, respectively, in the northward-turning (west-turning) group. The results indicate that a TC with a sharp northward turning track is generally accompanied with a stronger intensity and a relatively larger outer size compared to a west-turning TC. Numerous studies (Hill and Lackmann, 2009; Ge, 2015; Stovern and Ritchie, 2016) revealed that the ambient atmospheric conditions (i.e., temperature and moisture profiles) significantly modulate TC size and intensity. Hence, this stimulates us to examine the possible impacts of the ambient conditions on TC track.

The paper is organized as follows. The model and experimental design are briefly introduced in Section 2. The overall comparisons and analyses are presented in Section 3. Finally, a short summary and discussion are given in the last section.

2. Model and experiment designs

The WRF-ARW (version 3.3.1) is utilized to examine the interaction between a TC and MG. The model is configured with four two-way interactive domains with the horizontal resolutions of 54, 18, 6, and 2 km, respectively. The outer domain centered on 15° N, includes an area of about 6000 km × 6000 km, which is adequately large to permit the interaction between two systems. The model is initialized with a larger but weaker MG-like vortex embedded with a relatively smaller but stronger TC on a β-plane over an open ocean with a constant sea surface temperature (SST) of 28 °C. The model includes a Purdue Lin microphysics scheme (Lin et al., 1983), Kain–Fritch convective scheme (Kain, 2004), Dudhia scheme (Dudhia, 1989) for shortwave radiation processes, and Rapid Radiation Transfer Model (RRTM) for longwave radiation processes (Mlawer et al., 1997).

Fig. 1 displays the initial radial profiles of tangential wind near the surface for both the MG and TC. Initially, the TC and MG are axisymmetric vortices but with different radial distributions of tangential velocity. Specifically, the TC has an initial maximum tangential wind speed of 25 m s^{-1} at a radius of 100 km. The strength of tangential wind decreases with the height and vanishes at 100 hPa. For the MG, its initial radial profile of near-surface tangential wind follows Carr and Elsberry (1995), which has an initial maximum tangential wind speed of 10 m s^{-1} at a radius of 500 km. The diameter of the MG is about 3000 km. This idealized MG has a baroclinic structure with lower (upper) level cyclonic (anticyclonic) circulation, and the transition level is set to 300 hPa. The vertical profiles of environmental temperature and moisture are based on the summer season mean tropical sounding (Jordan, 1958). In each experiment, the TC is initially located 400 km to the east of the MG center. The model integrations last for 3 days.

In previous studies (Liang and Wu, 2015), the initial environmental field is simply specified to be horizontally uniform. In this study, the major purpose is to examine the impact of its heterogeneity on TC track. To this end, a set of idealized numerical simulations are specified. Specifically, a zonal gradient in the initial RH field is specified as follows:

$$\text{In EXP1}: \ \text{RH}(x,z) = \text{RH}_o(z) \times \left(1 + \frac{x - 3400}{6000}\right) \times 40\% \quad (1)$$

$$\text{In EXP2}: \ \text{RH}(x,z) = \text{RH}_o(z) \times \left(1 - \frac{x - 3400}{6000}\right) \times 40\% \quad (2)$$

where $\text{RH}_0(z)$ is the mean environmental RH, which is only a function of height, and x is the distance away from the western boundary. As shown in Fig. 2, the RH field increases with longitude in EXP1. In detail, the value of RH in the lower troposphere