Sensitivity of Tropical Cyclone Track to the Vertical Structure of a Nearby Monsoon Gyre

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ABSTRACT

The impact of different vertical structures of a nearby monsoon gyre (MG) on a tropical cyclone (TC) track is investigated using idealized numerical simulations. In the experiment with a relatively deeper MG, the TC experiences a sharp northward turn at a critical point when its zonal westward-moving speed slows down to zero. At the same time, the total vorticity tendency for the TC wavenumber-1 component nearly vanishes as the vorticity advection by the MG cancels the vorticity advection by the TC. At this point, the TC motion is dominated by the beta effect, as in a no-mean-flow environment, and takes a sharp northward turn. In contrast, the TC does not exhibit a sharp northward turn with a shallower MG nearby. In the case with a deeper MG, a greater relative vorticity gradient of the MG promotes a quicker attraction between the TC and MG through the vorticity segregation process. In addition, a larger outer size of the TC also favors a faster westward propagation from its initial position, thus having more potential to collocate with the MG. Once the coalescence is in place, the Rossby wave energy dispersion associated with the TC and MG together is enhanced and rapidly strengthens the southwesterly flow on the eastern flank of both systems. The steering flow from both the beta gyre and the Rossby wave dispersion leads the TC to take a sharp northward track when the total vorticity tendency is at its minimum. This study indicates the importance of good representations of the TC structure and its nearby environmental flows in order to accurately predict TC motions.

1. Introduction

Tropical cyclones (TCs) may experience sudden track changes through interactions with a large-scale 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 cyclonic circulation with a diameter of about 2500 km in the western North Pacific (WNP) basin (Lander 1994; Harr et al. 1996; Molinari and Vonnegut 2017). Using a barotropic model, Carr and Elsberry (1995) demonstrated that a sudden northward track change appears when TC enters the eastern semicircle of an MG. It was proposed that, during the coalescence of TC and MG, Rossby wave energy dispersion enhances the southwesterly winds in the southeast quadrant. This enhanced southwesterly flow acts as a steering flow for the sharp northward turn. Recently, Liang and Wu (2015) showed that TC track changes are sensitive to the size and intensity of both the MG and TC. Using a full-physics model, they identified...
three types of TC tracks when a TC is initially located in the eastern semicircle of an MG: a westward propagation, a sudden northward turn from a westward propagation, and a northward propagation without a sharp turn. The sudden northward track changes can be generally accounted for by the changes in the steering flow.

Wu et al. (2013a) compared 15 TCs with sharp northward turns and 14 cases with westward turns during an 11-yr period (2000–10) in the WNP. Their study indicates that these two types of track are closely associated with interactions between TCs and their surrounding low-frequency and synoptic flows. In Bi et al. (2015), it was demonstrated that the reason behind the failure of the ECMWF global prediction system in predicting the sharp northward turn of Typhoon Megi (2010) was the weak structure of Megi in their initial conditions. This hypothesis was tested using the WRF Model. When the ECMWF original analysis was used as the initial condition, WRF produced the same track for Megi as in the EC-EARTH model without a northward turn. When the TC structure was enhanced in the ECMWF analysis and used as the initial condition in WRF, the latter successfully predicted the northward turn of Megi. Their study indicated the importance of good representations of both the TC and MG to allow correct interactions between them and thus accurate predictions of the track.

Velden and Leslie (1991) demonstrated that the environmental steering flow corresponds better with the TC motion when the depth of the steering layer is constructed as intensity dependent. With this regard, when a TC is under the influence of MGs with different vertical structures, it is expected that the MG-related steering flows and vertical shears would impact both the TC motion and intensity. Meanwhile, the southwesterly flow induced by the Rossby wave energy dispersion is sensitive to the MG vortex strength (Carr and Elsberry 1995) and the environmental flow (Ge et al. 2007). The Rossby wave energy dispersion also depends on the three-dimensional structure of a tropical cyclone (Ge et al. 2008). Specifically, the energy-dispersion-induced Rossby wave train associated with a baroclinic vortex has an alternating cyclonic–anticyclonic–cyclonic–anticyclonic circulation in the lower (upper) troposphere. This will modulate the environmental flow and thus the TC motion. While prior works have demonstrated that TC motion is influenced by MG, we will study the sensitivity of TC motions to different vertical structures of MG and the mechanisms involved.

As a background understanding, we first examine whether there are differences in the intensity and size between groups of TCs that have experienced a sharp northward turn and those without. We examine the two groups identified by Wu et al. (2013a). We examine the statistical difference of the size and intensity between these two groups using the skewness following An and Jin (2004). The skewness is defined as

$$\text{Skewness} = m_3 / (m_2)^{3/2},$$

where $m_k$ is the $k$th moment,

$$m_k = \frac{\sum_{i=1}^{N} (x_i - \bar{x})^k}{N},$$

and $x_i$ is the $i$th pressure or size of TC observation ($i$ is each sample), $\bar{x}$ is the sample mean, and $N$ (=15 or 14) is the number of sample observation. Figure 1 compares the statistical skewness evolution of the intensity [represented by the central minimum sea level pressure (CMSLP)] and the size [represented by the radius of 34-kt (1 kt = 0.51 m s$^{-1}$) wind speed (R34)] of the two groups. The data were obtained from the Joint Typhoon Warning Center best-track archive (Chu et al. 2002). Two days prior to the peak intensity, TCs with a sharp northward turn generally have a stronger intensity and a larger outer size compared with their counterparts without a sudden northward turn. The differences exceed the 95% confidence level.

The remainder of this paper is organized as follows. In section 2, the model and experimental designs are described. Results and analyses using vorticity budget analysis, relative positions between the TC and
monsoon gyre, and Rossby wave energy dispersion are presented in section 3. The summary and discussion are given in the last section.

2. Model and experiment designs

The WRF-ARW Model, version 3.3.1 (Davis et al. 2008), is used to study the interaction between TC and MG in an idealized framework. The model is configured with three two-way-interactive nested domains with the horizontal resolutions of 27, 9, and 3 km. The outer domain is centered at 15°N, covering an area of about 6000 km × 6000 km, which is large enough to allow proper interactions between the TC and MG. The model is initialized with a large and weak MG-like cyclonic circulation and a small but strong TC-like vortex on the β plane over an open ocean with a constant sea surface temperature (SST) of 28°C. The model physics includes the microphysics scheme by Lin et al. (1983) and the Kain–Fritch convective scheme (Kain and Fritch 1993) in the two outer domains. For the radiation process, the Dudhia shortwave radiation and RRTM longwave radiation parameterizations are used. More details of the model are discussed in Davis et al. (2008).

Figure 2 displays the initial radial profiles of the tangential wind near the surface for the TC and MG. The TC vortex has an initial maximum tangential wind of 25 m s⁻¹ at a radius of 100 km. Its strength decreases with height and vanishes at 100 hPa. The MG has an initial maximum tangential wind of 15 m s⁻¹ at a radius of 500 km near the surface, following Carr and Elsberry (1995). The diameter of the MG is about 2000 km. This idealized MG has a baroclinic structure with a lower-level cyclonic circulation and an upper-level anticyclonic circulation. The transition level in between determines the depth of the cyclonic MG. The vertical profiles of the environmental temperature and moisture are based on the mean tropical sounding (Jordan 1958). The TC is initially located 400 km to the east of the MG center. The model integration lasts for 3 days.

The main purpose of this study is to examine the sensitivity of TC track to the vertical structure of a nearby MG. The experiments are designed by specifying different transition levels for the MG in changing its structure from a lower-level cyclonic flow to an upper-level anticyclonic flow. Based on observations, Wu et al. (2013b) showed that the average transition level of MG is around 300 hPa. In our first experiment (SG04), the transition level is set to be σ = 0.4 (~400 hPa), whereas it is at σ = 0.5 (~500 hPa) in the second experiment (SG05). Figure 3 displays the vertical profiles of the tangential wind associated with MGs in these two experiments. The MG has a deeper layer of the cyclonic flow in SG04, but a deeper and stronger upper-level anticyclonic circulation in SG05. We will examine how TC tracks are influenced by these different vertical structures of the MGs.

3. Results and analyses

a. Track and intensity

The intensities and tracks in the two experiments are shown in Fig. 4. There are marked differences between them. In SG04 (with a deeper MG cyclonic circulation), the simulated TC has a larger intensity and experiences a sharp northward turn at around \( t = 36 \) h. In contrast, the simulated TC intensity is weaker, and it takes a nearly constant northwestward track without a northward turn in SG05 (with a shallower MG cyclonic circulation). These results indicate that TC tracks are sensitive to the vertical structure of a nearby MG and not all TCs would experience a sharp northward turn around the MG.
To further demonstrate the difference between SG04 and SG05, Fig. 5 depicts time evolution of the zonal and meridional components of the TC motion, computed from the 3-h position differences of the TC center. In SG04, prior to the sharp turn, the zonal speed of the TC movement changes from $-3 \, \text{m s}^{-1}$ at $t = 24 \, \text{h}$ to near zero before the turning point at around $t = 36 \, \text{h}$ and then increases to $1.5 \, \text{m s}^{-1}$ within a short period (i.e., by $t = 42 \, \text{h}$). Meanwhile, a gradual increase occurs in the meridional component during the same time frame (Fig. 5b). In summary, the TC in SG04 experiences a change from a westward to an eastward movement, and an increase of the northward movement with the sharp turn occurred almost exactly at the time when its zonal movement decreased to zero. In contrast, the TC in SG05 keeps a rather uniform zonal and meridional moving speed and its track does not exhibit a sharp turn. To reinforce our result, an additional experiment was conducted to further increase the height of the MG transition level to $s = 0.2$ (~200 hPa), representing an even deeper MG cyclonic circulation. The TC in that experiment also experiences a sharp northward turn at around $t = 39 \, \text{h}$, similar to SG04 (figure not shown).

**b. Vorticity budget analysis**

In general, a TC moves toward the direction of maximum vorticity or potential vorticity tendency (Holland 1983; Wu and Wang 2000; Chan et al. 2002; Bi et al. 2015). To understand the underlying processes
accounting for the distinct track difference in the two experiments, we conduct a vorticity budget analysis. Figure 6 depicts snapshots of the simulated TC direction of movement and relative vorticity tendency for the wavenumber-1 component at \( z = 1.5 \text{ km} \). The time examined was before (at 12 h) and after (at 42 h) the sharp turn in SG04. The maximum wavenumber-1 vorticity tendency corresponds reasonably well with the TC movement in both experiments. In SG04, the pattern of maximum vorticity tendency points to the northwest prior to the sudden turn and to the northeast after the turn. This differs from SG05, in which the maximum vorticity tendency always points to the northwest and the TC did not experience a northward turn.

Changes in the wavenumber-1 vorticity tendency tend to reflect the track changes, so we use it to explore the specific mechanism. For a similar TC–MG environment, Bi et al. (2015) conducted the vorticity budget and indicated that the major contribution to the total vorticity tendency is from the horizontal advection. The total horizontal advection of the vorticity (HAD) is decomposed into three components as follows:

\[
- u \frac{\partial \xi}{\partial x} - v \frac{\partial \xi}{\partial y} = - \bar{u} \frac{\partial (\xi')}{\partial x} - \bar{v} \frac{\partial (\xi')}{\partial y} - u' \frac{\partial (\xi')}{\partial x} - v' \frac{\partial (\xi')}{\partial y}
\]

\[
- u \frac{\partial (\xi)}{\partial x} - v \frac{\partial (\xi)}{\partial y} ,
\]

where the overbar represents the mean state (the MG), and the prime denotes the perturbation (the TC). The first term on the right-hand side is the mean-flow advection (MAD), the second one is the perturbation advection (PAD), and the third one is the whole-flow advection of the mean vorticity gradient (HAM), which is small and thus is ignored. A spatial filtering technique following Hendricks et al. (2011) is used to separate the MG and TC circulations. That is, the circulation with a wavelength greater than 500 km is considered as the mean state (the MG flow), and the remaining component with a wavelength shorter than 500 km represents the perturbation (the TC circulation). The value of 500 km chosen as the separation between the basic state and the TC length scale is based on the scale of the MG shown in Fig. 2. The results presented in the following are not very sensitive to the choice of the separation wavelength between 400 and 600 km.

Figures 7–9 compare these advection terms in SG04 and SG05 during three time periods: before, during, and after the sudden turn observed in SG04. Prior to the sharp turn (i.e., \( t = 12 \text{ h} \)), the wavenumber-1 tendencies of the MAD and PAD term show a similar pattern in both experiments (Fig. 7). Both the MAD and PAD are oriented in the northwest–southeast direction with the maximum of the vorticity tendency located to the northwest of the TC center. This indicates a northwestward movement for the TC. Note that MAD dominates in both experiments. Near the TC northward turning point at \( t = 36 \text{ h} \), the pattern of PAD in SG04 has rotated nearly 180° with its positive maximum center now pointing southeast while the MAD remains pointing to the northwest. The magnitude of MAD is considerably smaller now, and the sum of the two terms leads to a very weak total vorticity advection (Fig. 8a).

The fact that the PAD term rotated 180° at the critical time indicates that the cyclonic circulation of the MG acts as the mean flow to rotate the TC, leading to the opposite pattern of PAD in SG04 (Fig. 8c). After the sudden northward turn (i.e., \( t = 42 \text{ h} \)), the pattern of the MAD and PAD in SG04 line up again, and the maximum tendency is situated to the northeast of the TC center (Fig. 9). With the MAD and PAD having a similar orientation, the combination of them leads to a sharp northward turn. Note that the PAD now has a slightly larger contribution than MAD to the total advection.

When the HAD patterns in SG04 are examined more frequently (Fig. 10), we observe that the magnitude of the total vorticity tendency decreases as time approaches the sharp turning point. At \( t = 36 \text{ h} \), the total vorticity tendency almost vanished when the MAD nearly cancels with the PAD (Figs. 8a–c, 10b). This can be viewed as a stagnant point corresponding to the near-zero movement of the TC in both the zonal and meridional directions (Fig. 5). Beyond this point, the HAD pattern rotates by 90° as shown at \( t = 39 \text{ h} \) (Fig. 10c), marking the start of the sharp northward turn.

In contrast, the wavenumber-1 component of MAD dominates in SG05 and is oriented roughly in the same northwest–southeast direction throughout the period. Meanwhile, the PAD is small and is oriented in the northeast–southwest direction (about a 90° rotation counterclockwise). Therefore, the TC track in SG05 is primarily controlled by MAD. An important question remains as to why the TC suddenly made a northward turn in SG04 when the total vorticity advection is nearly zero at \( t = 36 \text{ h} \). We will come back to answer this question later.

c. Relative position between TC and monsoon gyre

Previous studies on this topic (Carr and Elsberry 1995; Liang and Wu 2015; Bi et al. 2015) demonstrated the
importance of relative positions between the TC and the MG center. It has been identified that the sudden northward turn will happen when the two centers move close enough to each other. Figure 11 compares the evolution of the TC center relative to the MG center. The centers of the TC and MG are defined as the positions of the maximum relative vorticity in their filtered fields, respectively. During the early stage in SG04, the TC exhibits a counterclockwise rotation steered by the cyclonic flow associated with the MG. By $t = 42$ h,

![Figure 11](image1.png)

**Figure 11.** The evolution of the TC center relative to the MG center. The centers of the TC and MG are defined as the positions of the maximum relative vorticity in their filtered fields, respectively. During the early stage in SG04, the TC exhibits a counterclockwise rotation steered by the cyclonic flow associated with the MG. By $t = 42$ h,
the two centers have approached each other and almost collocated with each other. In SG05, the two systems show a similar rotation characteristic as in SG04 initially. However, at the later stage, the two systems do not collocate as in SG04. To further demonstrate the difference in the two experiments, the radial profiles of the azimuthally averaged relative vorticity and radial vorticity gradient for the MG at \( t = 12 \) and 42 h are compared (Fig. 12). The radial vorticity gradient of the MG is larger in SG04, especially within 800 km. It is likely that the TC motion is modulated by the radial gradient of relative vorticity associated with the MG through the segregation process (Schecter and Dubin 1999; Ge et al. 2015). This possibility will be discussed later. In addition, the relative vorticity gradient for the MG also

![Fig. 9](image-url)

**Fig. 9.** As in Fig. 7, but at \( t = 42 \) h, which is after the northward turn in SG04 (shaded; \( 1 \times 10^{-9} \) s\(^{-2}\)).

![Fig. 10](image-url)

**Fig. 10.** Snapshots of the wavenumber-1 total vorticity tendency fields (shaded; \( 1 \times 10^{-9} \) s\(^{-2}\)) for SG04.

![Fig. 11](image-url)

**Fig. 11.** Filtered relative vorticity of MG (contours; \( 1 \times 10^{-5} \) s\(^{-1}\)) and TC locations (shaded; \( 1 \times 10^{-9} \) s\(^{-2}\)) in (a),(b) SG04 and (c),(d) SG05 at (a),(c) 12 and (b),(d) 42 h at \( z = 1.5 \) km.
shows an increase from before the turn to the turning point in SG04 while it is decreased during the same period in SG05 (figure not shown).

The distinctively different results from the two experiments are further demonstrated by plotting the relative trajectories of TC and MG (Fig. 13). Following Lander (1994) and Bi et al. (2015), the origin (0, 0) in the reference frame is defined as the midpoint between the centers of the two entities, illustrating the relative motion between them. In the beginning, the centers of the MG and TC are separated from each other, with the TC situated on the eastern flank of the MG. In SG04, TC moves cyclonically and approaches the MG center. These two centers attract gradually and are nearly collocated by \( t = 42 \text{ h} \). Note that the two systems do not merge together to become one but instead drift apart after 48 h (Fig. 4). In SG05, these two systems rotate around each other and remain separated, even at the time with only a short distance in between. More discussion is given in Bi et al. (2015) on this Fujiwara-type effect between two cyclonic circulations with different spatial scales.

A question remains as to why there are attractions between the TC and MG in some situations, but not in others. Recall that the TC in SG04 shows a relatively fast westward propagation prior to the sudden turn (Fig. 5). As it moves westward quickly, it has a potential to catch up with the MG center while both are moving north-westward under the beta effect. The TC is generally steered by the large-scale environmental flows and beta drift effect (Holland 1983; Chan and Williams 1987; Fiorino and Elsberry 1989; Wang and Holland 1995; Wu and Wang 2000). In general, a TC with a larger outer size has faster beta-effect propagation (BEP).

Two mechanisms are postulated to account for the discrepancies in the transition speed. First, the TC propagation speed is associated with the BEP: the larger the outer size, the greater the westward deflection of track. To this end, the azimuthal-mean tangential wind profiles of TCs in the lower part are compared at \( t = 36 \text{ h} \) (Fig. 14). As anticipated, the outer size of the TC in SG04 is larger than its counterpart in SG05. This is due to a stronger interaction between the TC and MG in SG04 than in SG05. As a result, the TC in SG04 has the potential to have a faster BEP, resulting in a quick westward movement to catch up with the center of MG. In addition, a higher transition level of the MG structure allows a smaller vertical shear for the environment of the TC and thus favors more
intensification. With a larger and more intense TC in SG04, the TC motion responds to a deeper layer of the steering flow, reflecting a larger influence from the environment (in this case, a deeper MG). This is consistent with the concept of layer-dependent steering flow linked to the TC intensity by Velden and Leslie (1991).

The second mechanism is likely attributed to the so-called vorticity segregation (Schecter and Dubin 1999; Ge et al. 2015). Specifically, a cyclonic (anticyclonic) vorticity entity will move up (down) the ambient vorticity gradient. In the current environment, this segregation process is proportional to the vorticity gradient of the MG and moves the TC toward the MG center. As shown in Fig. 12, the low-level averaged relative vorticity of MG is about the same in SG04 and SG05 at \( t = 12 \) h, but it is larger in SG04 than in SG05 at \( t = 42 \) h. Consequently, a larger vorticity gradient reflects a quicker segregation process, leading to a rapid attraction between TC and MG center in SG04 at the later stage.

To validate this concept, a pair of additional experiments is conducted by using a barotropic model on the \( \beta \) plane with different radial gradients of the relative vorticity for the MG (Fig. 15a). In the first experiment, identified as RK, the MG is constructed with a Rankine-type radial profile with constant relative vorticity within the radius of maximum wind (RMW). In the second experiment, identified as NRK (non-Rankine profile), there is a pronounced radial gradient of the relative vorticity within the RMW for the MG. Both MGs have the same RMW of 500 km and the same outer size of 1500 km. Simulations of these experiments show distinctive TC tracks (Fig. 15b). The TC in NRK experiences a sharp northward turn as in SG04, whereas the one in RK moves northwestward smoothly without a northward turn. Figure 16 displays the evolution of the relative positions between the TC and MG in these two cases. Consistent with the results in the baroclinic model, the TC and MG are attracted to each other in NRK and are nearly collocated by \( t = 60 \) h. In contrast, the two entities do not experience such a merging process and remain separated in RK. The simple barotropic dynamics further confirms the important role of the radial vorticity gradient of MG in modulating the TC motion. It is interesting to note that the relative trajectories of the MG and TC in the barotropic model (Fig. 16) are very similar to those in the baroclinic model (Fig. 13).

d. Rossby wave energy dispersion

As diagnosed in previous sections, the positions of the TC and MG play a critical role in their interactions...
and affect their tracks. In SG04, there is an initial cyclonic orbiting between them at far separation, and then these two systems attract to each other sufficiently to be considered as collocated. Once the two systems move closer and collocate, the coalescence results in a superposition of the beta drift effect (Bi et al. 2015). Because of the Rossby wave energy dispersion, the combined two systems will induce more enhanced alternative anticyclonic and cyclonic circulations in the wake than the TC would have without the MG. A negative relative vorticity rapidly strengthens on the right side and thus enhances the southerly flow between the cyclonic and the first anticyclonic circulation. The resulting steering flow may bring about a northward turn. To confirm this hypothesis, the simulated streamfunction for the large-scale MG circulation is compared (Fig. 17). As expected, the streamfunction pattern shows a northwest–southeast orientation and consists of an anticyclone to its wake, similar to the one behind the TC. This agrees with Carr and Elsberry (1995). Note that the strength of the MG and the associated Rossby waves in SG04 are larger than that in SG05. While the collocation of the TC and MG in SG04 helps enhance the Rossby wave energy dispersion, the circulations of the two cyclonic systems may cancel part of them when they are nearby but not collated and weaken the dispersion.

Why is there a more pronounced Rossby wave energy dispersion in the SG04? The Rossby wave energy dispersion is sensitive to the vortex strength (Carr and Elsberry 1995) and environmental flows (Ge et al. 2007). As suggested by Bi et al. (2015), the combination of the TC and MG likely enhances the strength and size of the total cyclonic system when they are collocated and thus enhances the Rossby wave energy dispersion. The enhanced southwesterly flow in the southeast quadrant strengthens the environmental steering flow. Furthermore, TC energy dispersion is possibly modulated by the vertical shear induced by the large-scale MG circulation. Because of its baroclinic structure, the large-scale MG imposes vertical wind shear (VWS) on the TC’s neighboring environment. To this end, we examine the vertical profiles of the filtered MG circulation around the TC center (Fig. 18). The VWS is computed as the wind difference between 1.5 and 12 km in the vertical, averaged over an area within a radius of 500 km from the TC center.
Initially, SG05 has a stronger westerly VWS than SG04 (i.e., $t = 12$ h). With time, marked differences in the magnitude and orientation of VWSs developed. Specifically, after the turning point ($t = 60$ h), there is a north-easterly VWS in SG04, whereas there is a south-westerly VWS in SG05. The orientation of the vertical shear depends on the relative position of the TC with respect to the MG.

Ge et al. (2007) pointed out that the TC energy dispersion is highly sensitive to the orientation of VWS. A significant asymmetry occurs in the development of wave train under easterly and westerly VWS, respectively. On the one hand, the development of Rossby wave train is modulated by the mean flow through a “Doppler shift effect” and modified by the barotropic–baroclinic mode coupling (Wang and Xie 1996; Ge et al. 2007). The combination of these two effects leads to an easterly (westerly) shear, confining the maximum amplitude of the wave train primarily to lower (upper) levels. In this study, an initial weaker westerly shear in SG04 indeed shows a greater TC energy dispersion at lower levels than in SG05. As a result, a stronger peripheral anticyclone is rapidly established that strengthens the south-westerly flows.

In summary, the reason for the sudden northward turn of the TC and MG in some situations is a combined mechanism of the vorticity tendency and the beta effect. As the TC is being rotated by the cyclonic flow of the MG, there is a critical point when the total vorticity advection nearly vanished by the cancellation between the vorticity advection by the MG and the vorticity advection by the TC. When this occurs in a small window of time, the TC movement is not controlled by the maximum vorticity tendency but mainly by the beta effect, almost like in an environment without a mean flow (Chan and Williams 1987; Fiorino and Elsberry 1989). In addition, when the center of the TC and MG nearly collocate, the beta effect and the ventilation flow are enhanced to push both systems northward. Therefore, the sudden northward turn occurred at the time when a delicate balance exists in the vorticity advection that depends on the structure of the TC and MG, the orientation of the TC, and their relative positions.

4. Summary and discussion

In this study, the impact of different vertical structures of a nearby MG on the TC motion is investigated using idealized numerical simulations. The vertical structure of the MG is baroclinic with cyclonic circulation at lower levels, transitioning into anticyclonic circulation at upper levels. A parameter that controls this transition level for the MG is set differently in the two major experiments conducted. The first experiment has its transition level at around 400 hPa (a deeper MG) while it is at around 500 hPa (a shallower MG) in the second experiment. When a TC is initially placed on the eastern side of a deeper MG, the simulated TC experiences a sharp northward turn. By contrast, the TC does not exhibit a sharp northward turn with a shallower MG. The sharp turn in the deeper MG experiment occurs at a point where the east–west component of the TC motion slows down to zero from a westward movement. At this critical point, the total vorticity tendency of the TC’s wavenumber-1 component nearly vanishes by a canceling between the vorticity advection of the MG and vorticity advection by the TC. At this point, the TC acts as if it is in an environment with no mean flow and the beta drift takes control, which leads to a northward turn. The centers of the TC and MG remain collocated for a short period without actually merging together (Bi et al. 2015).

After the turn, the total vorticity tendency takes on a $90^\circ$ rotation with its maximum located to the northeast of the TC.

In the case with a deeper MG, a greater relative vorticity gradient promotes a quicker attraction between the TC and MG through vorticity segregation process. Meanwhile, the TC near a deeper MG also develops faster and thus has a greater outer size than with a shallower MG. Once the coalescence process...
takes place, the Rossby wave energy dispersion associated with the TC and MG together is enhanced and the southwesterly flow on the eastern flank is strengthened. The resulting steering flow contributes to the northward motion when the vorticity tendency is at its minimum.

The results indicate the importance of good representations for both the TC structure and nearby environmental flows in order to accurately predict TC motions.

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