Simulated Impacts of a Mesoscale Convective System on the Track of Typhoon Robyn during TCM-93

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ABSTRACT

The contribution that a mesoscale convective vortex that developed within the circulation of Typhoon Robyn (1993) may have had to a significant tropical cyclone track change is simulated with a mesoscale model using initial conditions that approximate the circulations measured by aircraft during the Tropical Cyclone Motion (TCM-93) field experiment. A dry version of the PSU–NCAR Mesoscale Model is used to first investigate the dynamic aspects of the interaction. A deceleration of about 2 m s$^{-1}$ and then more northward movement, similar to that observed for Typhoon Robyn, could have been produced by an interaction with the mesoscale convective vortex of the type modeled in the control run. Sensitivity of the simulated track change is tested for various aspects of the mesoscale vortex and tropical cyclone. It is found that track deflections between 67 and 130 km in 18–24 h could be produced under a variety of realistic scenarios.

As the mesoscale vortex is advected around the tropical cyclone by the cyclonic winds, it is also being filamented by the horizontal shear of the tropical cyclone outer winds. Whereas the rate at which the vortex is advected about the tropical cyclone is critical to the amount of curvature of the tropical cyclone track deflection, the timescale of the filamentation of the mesoscale vortex is critical to the longevity of the track deflection, and thus maintenance of the vortex is a crucial factor. For the same tropical cyclone and separation distance, the track deflections are greater for a larger, deeper, and more intense mesoscale vortex. For the same mesoscale vortex, a variety of track deflections is possible, depending on the outer wind structure of the tropical cyclone due to both the advective effect and to the change in the gradient of vorticity. For a large tropical cyclone, positive vorticity extends farther from the core region, and the curvature of the track deflection is greater than for a smaller tropical cyclone where the vorticity becomes anticyclonic at smaller radii. Although a large initial effect on the tropical cyclone path occurs for small separation distances, the mesoscale vortex is rapidly filamented so that effects on the tropical cyclone track are negligible by 12 h. For larger separation distances, the mesoscale vortex does not filament as rapidly, and a smaller but longer lasting track deflection is simulated.

When the control simulation is extended to a β plane, it is found that the primary contribution to the tropical cyclone track change is still due to the interaction with the mesoscale convective vortex. However, a secondary effect due to a nonlinear interaction between the β gyres and the mesoscale convective vortex adds a small component of propagation to the tropical cyclone that becomes significant after about 15 h of simulation.

1. Introduction

It has been recently established that mesoscale convective systems in the Tropics develop midlevel vortices similar to those that develop in the midlatitudes (e.g., McKinley 1992; Harr et al. 1996; Simpson et al. 1997; Ritchie and Holland 1997). Simpson et al. (1997) investigated the interaction between two such mesoscale convective systems during the development of Tropical Cyclone Oliver in the Australian region. Data collected within the mesoscale convective systems using two airborne platforms clearly identified and mapped a vortex structure associated with each system. In addition, both vortices were tracked continuously using Geostationary Meteorological Satellite (GMS) and C-band radar imagery. A centroid-relative diagram of the tracks indicated a cyclonic rotation and approach, which was suggestive of a vortex interaction and merger. Simpson et al. (1997) proposed that the “merger” of the weaker vortex into the stronger vortex contributed to the subsequent development of Tropical Cyclone Oliver.

The possibility that significant track changes or medium-scale meanders on the order of tens to hundreds of kilometers over several days may result from an interaction between a tropical cyclone and a persistent mesoscale convective system has been hypothesized by Holland and Lander (1993). They proposed that an interaction between a tropical cyclone and a (hypothesized) midlevel vortex associated with a mesoscale convective system in close proximity may have been responsible for some of the observed track changes. They
showed an example of two mesoscale convective systems that developed outside the core region of Tropical Storm Sarah in 1989 that may have contributed to the observed unusual track of Sarah. Using a barotropic model, they simulated two separate vortex–vortex interactions between the tropical cyclone and a mesoscale vortex assumed to be associated with the mesoscale convective system, and the track was successfully reproduced. If this hypothesis is valid, then mesoscale convective systems can be identified in satellite imagery, and short-term track changes may be more reliably forecast.

The interaction and merger of vortices as it relates to tropical cyclone motion change has been studied both observational (e.g., Dong and Neumann 1983; Lander and Holland 1993) and numerically (e.g., Smith et al. 1990; Ritchie and Holland 1993; Holland and Dietachmayer 1993; Wang and Holland 1994). The majority of observational studies emphasize interaction between two tropical cyclones that are approximately equal in mass. Less than half of these systems merge during interaction (Lander and Holland 1993). Indeed, Carr et al. (1997) found the merger of two tropical cyclones rarely occurred (less than one event per two years) in the western North Pacific, which has the largest frequency of simultaneous multiple cyclones. It is more common for the two tropical cyclones to undergo a mutual rotation that terminates rapidly, generally due to external synoptic influences. Pronounced track deflections of the order of one hundred to a few hundred kilometers are common during the orbit phase.

Numerical simulations have been used to explore a range of unequal vortex–vortex interactions and their impact on motion that may have more relevance to the track deflection hypothesis proposed by Holland and Lander (1993). For example, Smith et al. (1990) used a barotropic model to show that an interaction between one vortex five times the intensity of the other produced a rapid rotation and dispersion of the weaker vortex, with only a short-term change in the track of the stronger vortex. Ritchie and Holland (1993) used a two-dimensional, contour dynamics model (Zabusky et al. 1979) to study a range of motion changes that might be expected when two vortices of different sizes and intensities, such as a tropical cyclone and a vortex generated by a mesoscale convective system, interact (see their Fig. 7). The large vortex had a radius of maximum winds that was three times that of the small vortex and the ratio of the intensities of the two systems \( I_1/I_2 \) was varied over a range from three (i.e., large vortex intensity three times that of the small vortex) to one-third (i.e., large vortex intensity one-third of the small vortex). They found that the center of the large vortex undergoes small-scale oscillations during the interaction that increase in amplitude and period as the ratio of the intensity decreases. When the small vortex is weaker than the large vortex, it is rapidly sheared into a filament that wraps around the large vortex, similar to the Smith et al. (1990) simulation, except that the track of the large vortex continues to oscillate until the end of the simulation.

These results suggest that several scales of tropical cyclone meanders may be induced owing to interaction between vortices of different sizes and intensities. Varying the initial separation distance between the two vortices also affects the induced track meander. As the separation distance increases, both the advective component and the horizontal shear imposed over each vortex by the adjacent vortex’s outer circulation decrease, which results in slower motion, and less distortion of each vortex, and the period of the imposed track meander increases. This indicates that a mesoscale convective system that forms in the outer circulation of a tropical cyclone may exist longer (i.e., not be stretched into a filament so quickly because of the weaker horizontal shear in that region) and affect the tropical cyclone track for a longer period, but with a smaller track deflection.

Although these numerical simulations give insight into the range of possible vortex interactions and their effects on motion, considerable limitations prevent direct application to atmospheric vortices. For example, the simulations have usually had the same tangential wind profile for both vortices, but this is unlikely to be true for a tropical cyclone and a midlevel vortex associated with a mesoscale convective system. In fact, tropical cyclones in the western North Pacific occur in a large variety of sizes, from midgets with a rapid decrease in tangential wind with radius to monsoon depressions with a circulation that extends beyond a thousand kilometers (Lander 1994). It is also likely that the vertical structures of the vortices will affect the resulting interaction; that is, a midlevel vortex associated with a mesoscale convective system may not interact strongly with either the near-surface or upper-level circulation of the tropical cyclone. Some recent simulations that investigate the first-order effects of convection on the development of tropical cyclones using vortices as proxies have illustrated this differential effect (Montgomery and Enagonio 1998; Ritchie and Holland 1997). In addition, the depth and elevation of the mesoscale convective vortex will determine the magnitude of vertical shear imposed by the tropical cyclone circulation and, thus, the amount of strain on the midlevel vortex structure. The vertical structure of the midlevel vortex will also impose a vertical shear on the tropical cyclone structure, albeit in a limited horizontal and vertical area. It is not obvious how these imposed vertical shears will affect the motion of the two vortices, or the extent to which disruptions of the vortex structure will persist. Convec-
tive heat release and momentum transport processes that are not represented in the above two-dimensional model simulations are also likely to change the timescales on which the vortices, particularly that associated with the mesoscale convective system, exist as coherent systems (e.g., Fritsch et al. 1994). Recent studies demonstrate that a vortex in which latent heat release and transfer of convective momentum are present remains unaffected by stronger environmental vertical wind shear for longer periods than a vortex in a dry model (e.g., Flatau et al. 1994; Wang and Holland 1996; Frank and Ritchie 1999). Thus, it seems likely that a vortex in which transfer of convective momentum is present will resist the horizontal and vertical shears imposed by the tropical cyclone circulation and affect the track for a longer period.

To describe vortex–vortex interaction between a tropical cyclone and a midlevel vortex, a high-resolution dataset is needed that adequately resolves the evolution of the horizontal and vertical structure of both the tropical cyclone and the mesoscale vortex before, during, and after a possible interaction. To the authors’ knowledge, such a dataset has never been collected. However, the Tropical Cyclone Motion (TCM-93) field experiment in the western North Pacific during 1993 provided two high-resolution datasets during a period when a mesoscale convective system developed in close proximity to the core of Typhoon Robyn (Fig. 1). A particularly intriguing feature of this case is that during a 36-h period that included the life cycle of the mesoscale convective system, the westward-moving typhoon slowed, turned to the north, then accelerated northward (Fig. 2). Harr and Elsberry (1996) suggest two processes may have possibly influenced the track of Robyn at the time of the deceleration and northward turn. First, an interaction between the tropical cyclone and a potential vorticity anomaly associated with the mesoscale convective system may have produced the observed track change, as has been proposed by Holland and Lander (1993) for Tropical Storm Sarah. However, Harr and Elsberry (1996) could not validate the vortex–vortex interaction mechanism. Difficulties included a spatial resolution of both the in situ observations and the final reanalyzed grids that did not resolve the wind structure of both vortices clearly enough to test this hypothesis. Another obstacle was an uncertainty as to how to separate the symmetric wind structure of both the storm and the mesoscale convective vortex from the environmental flow.

The second track alteration mechanism proposed by Harr and Elsberry (1996) was that the large-scale environment in which Robyn was embedded may have changed in a manner consistent with the observed motion of Robyn. They concluded this was the more likely mechanism as the storm was moving from a trade easterly environment into the eastern region of the monsoon trough. Radial averages of the environmental winds at various steering levels provide some support for this mechanism (Harr and Elsberry 1996). However, they did conclude that changes in the environmental steering vector calculated from the reanalysis data gave a better indication of the future motion of Typhoon Robyn than the original analyses. These data included a better representation of both the environment and the mesoscale convective vortex through the special TCM-93 dataset. In addition, it is notable that the data used to calculate the environmental steering vector include the mesoscale convective vortex. This suggests that an interaction between Typhoon Robyn and the mesoscale convective system may have added to the environmental flow changes to produce the observed track deflection of Typhoon Robyn.

The objective of this paper is to investigate more thoroughly conditions in which the hypothesized interaction between Typhoon Robyn and this impressive mesoscale convective system (Fig. 1b) may contribute significantly to a tropical cyclone track change. The approach here is to use the information provided by the special TCM-93 dataset and other conventional data sources to produce balanced vortices that realistically represent both Typhoon Robyn and the mesoscale convective system. A dry version of the Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model is then initialized with these idealized fields and integrated to simulate a variety of interactions between a tropical cyclone and a mesoscale convective system and the resulting effects on the track of the tropical cyclone. The range of tropical cyclone–mesoscale convective system configurations will be based on the dataset of the Typhoon Robyn interaction and observational studies of tropical and midlatitude mesoscale convective systems (e.g., Menard and Fritsch 1989; Bartels and Maddox 1991; Fritsch et al. 1994; Simpson et al. 1997; Bartels et al. 1997).

An analysis of the mesoscale convective system and Typhoon Robyn interaction is given in section 2. Characteristics of the model and experimental design are described in section 3. The model results and their relation to the actual track change in Typhoon Robyn are presented in section 4. A summary and conclusions are provided in section 5.

2. The interaction between Typhoon Robyn and the mesoscale convective system

Typhoon Robyn developed from a tropical disturbance at a very low latitude (7°N) in late July 1993 and was upgraded to a tropical storm (17 m s$^{-1}$) at 0600 UTC 2 August. Based on aircraft reconnaissance associated with the TCM-93 field experiment, the storm was upgraded to typhoon strength (33 m s$^{-1}$) at 0000 UTC 4 August. During the development period (1–3 August), Robyn propagated toward the west-northwest at a speed that varied between 5 and 7.5 m s$^{-1}$ (Fig. 2). The organization of convection improved throughout this period, and a discrete central dense overcast associated with the core of Robyn was evident in satellite
Fig. 1. Enhanced infrared satellite sequence of Typhoon Robyn. The black region in the center of the typhoon near 10°N, 142°E defines temperatures below -80°C, and the adjacent dark gray, gray, and then black regions represent temperature increases in 5°C intervals. A standard grayscale is used for temperatures between -65°C and -30°C, and temperatures warmer than -30°C are set to black: (a) 0930 UTC 3 Aug 1993, (b) 1530 UTC 3 Aug 1993. The mesoscale convective system is located at 13°N, 141°E, and the center of Robyn is at 10°N, 142.5°E: (c) 2030 UTC 3 Aug 1993. Regions 1 and 2 are the convective and stratiform regions of the mesoscale convective system and region 3 is centered on Typhoon Robyn. Line A–B is the line that the cross section in Fig. 3 is taken along: (d) 0930 UTC 4 Aug 1993 (adapted from Harr and Elsberry 1996).
the northwest (Fig. 2). The storm translation subsequently increased to about 6 m s$^{-1}$.

The development of the mesoscale convective system is discussed in some detail in Harr and Elsberry (1996). Of particular interest is the movement of the convective and stratiform regions of the mesoscale convective system and the implications for a possible interaction between an associated mesoscale convective vortex and the tropical cyclone. Based on the satellite imagery, the mesoscale convective system is divided into two regions (Fig. 1c). The convective region, which is forced by surface convergence, is centered near 14$^\circ$N, 138$^\circ$E in Fig. 1c and has the lowest cloud-top temperatures. A second region, which is immediately south of the convective region in Fig. 1c, is labeled the stratiform region based on dropwindsonde observations with near-saturated mid- to upper levels, and low-level drier regions commonly associated with stratiform anvils (e.g., Zipser 1977). In general, the stratiform region will develop downstream of the convective region depending on the mid- to upper-level advective flow. Whereas Robyn remained nearly stationary during the period 1500 UTC 3 August to 0100 UTC 4 August, the convective region of the mesoscale convective system moved westward at a speed near 14 m s$^{-1}$ due to a combination of the strong easterly flow to the north of Robyn and the Robyn circulation. However, the stratiform region of the mesoscale convective system was advected cyclonically by the tropical cyclone circulation. By 2000 UTC 3 August the stratiform region was located near 11$^\circ$N, 137.5$^\circ$E (Fig. 1c), whereas the convection was located at 14$^\circ$N, 138$^\circ$E after having moved directly west from its initial location (Fig. 1b).

Theoretical studies have demonstrated that the stratiform anvil is crucial for the development of a mesoscale convective vortex (e.g., Raymond and Jiang 1990; Chen and Frank 1993). Chen and Frank (1993) hypothesize that the Rossby radius of deformation reduces in scale in the saturated conditions of the anvil region since the moist static stability is reduced. Vertical stretching between the upward vertical motion in the stratiform cloud and mesoscale subsidence below the stratiform cloud induces a localized rotational response by the wind field.

A mesoscale convective vortex did develop in association with the stratiform region (labeled 2 in Fig. 1c) of the mesoscale convective system. A vertical cross section of the analyzed fields shows a potential vorticity anomaly between 400 and 750 mb centered near 10.5$^\circ$N, 138$^\circ$E (Fig. 3), which would be expected if the mesoscale convective system had developed a vortex that continued to move with the stratiform clouds.

The period from 2030 UTC August 3 to 0930 UTC August 4 was characterized by little movement of either the convective or stratiform regions of the mesoscale convective system (Fig. 1d). Although the impressive organization that was observed in the initial stages of the system never redeveloped, the system did remain intact through this period. The potential vorticity anomaly was still detectable in the reanalyzed fields in the stratiform region (Fig. 4). However, the anomaly was both weaker and more shallow, which indicates the horizontal and vertical shear associated with the strengthening typhoon was probably causing the mesoscale convective vortex to disperse gradually.

The orbiting-type motion of the mesoscale convective system during the period 1230–2030 UTC is similar to that observed during vortex–vortex interactions (e.g., Ritchie and Holland 1993). However, it is possible that a similar track would be followed by a passive particle embedded in the cyclonic flow. For a vortex–vortex interaction to have occurred, the tropical cyclone should also be affected. Since Harr and Elsberry (1996) were
The ability to simulate accurately mesoscale convective system formation and maintenance in numerical weather prediction models is in early stages of evaluation, and the details of moist process representations are likely to lead to variations in the simulations. As the primary purpose of this study is to evaluate the underlying vortex dynamics of the (hypothesized) interaction between the tropical cyclone and the mesoscale convective system, it is not necessary to represent the convective processes that result in mesoscale convective system development. Thus, these model simulations are dry. In addition, surface friction and fluxes of heat and moisture are neglected to avoid an unrealistic spindown of the tropical cyclone when convective processes are not included. Because momentum transport by convective processes is not included, the mesoscale convective system will be dispersed more rapidly in the model simulations than may be observed in the atmosphere. Thus, the analysis of the simulations is restricted to the first 24 h.

b. Experimental design

1) LARGE-SCALE CONDITIONS AND BALANCE CONDITIONS

The balanced vortices in these simulations are configured on an $f$ plane centered at 10°N in an environment at rest. The environmental temperature sounding is from a composite analysis of a western North Pacific prestorm tropical depression by McBride and Zehr (1981). The environment has a uniform surface pressure of 1008.7 mb. The radial and vertical variations in the tangential wind field of each vortex are analytically specified and the mass field is then determined by solving for gradient wind and hydrostatic balance on a cylindrical grid. The equations are solved at 1-km resolution and interpolated to the 15- and 45-km resolution Cartesian grids. For convenience, the size of the tropical cyclone is defined as the radius of gale force (17 m s$^{-1}$) winds. The size of the mesoscale convective vortex is defined as the radius where the wind speed drops to less than 5 m s$^{-1}$.

2) TROPICAL CYCLONE VORTEX STRUCTURE

The horizontal structure of the tropical cyclone in the control simulation is based on both the structure of Typhoon Robyn as determined from the 50-km analysis (Harr and Elsberry 1996) and on the original wind data (Fig. 5a). The horizontal profile follows the DeMaria (1987) expression with a maximum wind of 30 m s$^{-1}$ at a radius of 90 km, and the profile shape constant $b$ is set such that the radius of gale-force winds is 340 km. This profile reproduces the observed tangential winds in Robyn within reasonable limits (Fig. 5a). The corresponding vorticity profile becomes anticyclonic at a radius of approximately 350 km, with the gradient in vorticity becoming cyclonic (i.e., increasingly cyclonic with radius) at 530 km (Fig. 5b).
Despite the rigor of the method used by Harr and Elsberry (1996), some uncertainty was involved in extracting the symmetric structure of Typhoon Robyn from the environment. Thus, additional profiles were generated using variations of the control profile (Fig. 5a) by varying the parameter $b$, which lead to radii of gale-force winds from 530 to 250 km, respectively. The corresponding vorticity profiles are also shown in Fig. 5b. The vertical variation of the cyclonic winds is specified so that maximum wind shear is above 500 mb. A weak, symmetric, upper-level anticyclone with a maximum tangential wind speed of $-5 \text{ m s}^{-1}$ at 1100-km radius and 200 mb is added to the wind field. The anticyclone does not affect the results. The balanced vortex has a warm-core structure with maximum $T$ deviation of $5.5^\circ\text{C}$ at 500 mb.

3) STRUCTURE OF A CONVECTIVELY GENERATED VORTEX

As documented by Harr and Elsberry (1996), a distinct, midlevel potential vorticity anomaly developed in the stratiform region of the mesoscale convective system and extended from about 750 mb to 350 mb (Fig. 3). Careful examination of the data suggests that the vortex could not have contained winds of more than 10 m s$^{-1}$ or less than 7 m s$^{-1}$. By imposing gradient and hydrostatic balance conditions, a vortex with maximum winds of 10 m s$^{-1}$ at a radius of 180 km resulted in a horizontal potential vorticity structure similar to that observed (Fig. 6a). The vertical structure of the control potential vorticity anomaly is represented with a Gaussian function with maximum amplitude near 550 mb. Specification of shallow or deep vortices is controlled by the spread in the Gaussian distribution (Fig. 6b). The horizontal structure also follows the DeMaria (1987) expression giving a radius of outer winds of about 390 km (Fig. 6c). Because Fritsch et al. (1994) observed that the upper-level anticyclone induced during the mesoscale convective vortex formation is inertially unstable and rapidly dissipates, only the cyclonic part of the flow is specified.

The spatial resolution (50 km) of the analyzed fields used by Harr and Elsberry (1996) to calculate the potential vorticity cross section in Fig. 3 may have resulted in a weaker, more diffuse signature than actually existed in the mesoscale convective system. Thus, other documented cases of the midlevel vortices that develop within mesoscale convective systems were studied for bounds on the possible size and strength of the mesoscale convective vortex (e.g., Menard and Fritsch 1989; Bartels and Maddox 1991; Fritsch et al. 1994; Ritchie 1995; Harr et al. 1996; Bartels et al. 1997). Considerable variability is found from case to case and there is no uniform measure of size. The horizontal diameter of the midlevel vortex circulation may range from 200 to 1000 km with a radius of maximum winds from 50 to 250 km, respectively. The vertical extent of the circulation has generally been observed to be between 400 and 700 mb with a maximum near 550 mb but can extend over a greater depth if the mesoscale convective system exists for longer periods.

According to these studies, the diameter of the mesoscale circulation is generally about twice the size of the cold cloud shield (221–240-K contour) of the mesoscale convective system at its maximum extent. In addition, the circulation extent (diameter) is about four times the radius of maximum winds if observed, or twice the extent of the analyzed cyclonic potential vorticity anomaly. The cold cloud shield (208-K contour) of the mesoscale convective system that developed within the circulation of Typhoon Robyn had a maximum extent of approximately 530 km by 400 km. The cross section of potential vorticity in Fig. 3 has a dimension of approximately 4° latitude (444 km), which is reasonable given the cloud shield dimensions. Based on the above studies, this would indicate a circulation diameter of 900 km with a radius of maximum wind of about 225 km.

Although the calculated maximum potential vorticity value of 1.1 PVUs (potential vorticity units) is small...
compared with other observations [e.g., 6 PVUs in Fritsch et al. (1994) and 6.3 PVUs in Bartels et al. (1997)], this may be due to several factors. Most importantly, the 50-km resolution of the analyzed fields in Harr and Elsberry (1996) will lead to an underestimate of the maximum value of potential vorticity. In addition, the presence of horizontal and vertical shear due to Typhoon Robyn’s circulation is the likely cause of dispersion of the vortex even as it develops, despite the apparent longevity of the mesoscale convective system (>15 h). In other studies, only very weak vertical shear was generally observed. A smaller Coriolis parameter in this tropical case may also be a factor as the main vorticity generation mechanism is believed to be convergence acting on the Coriolis parameter (Bartels and Maddox 1991). Mesoscale convective systems with midlatitude vortices between 30° and 41°N have a Coriolis parameter three times that of the latitude of interest here. Thus, a vortex generated in a comparable mesoscale convective system at 13°N is probably weaker.

Based on the above considerations, a “large” and a “small” horizontal profile was generated with a radius of outer winds of 435 and 345 km respectively (Fig. 6c). The relative vorticity profiles associated with these mesoscale convective vortices differ from that of the control mesoscale convective vortex. Two other mesoscale vortex profiles were also developed based on the horizontal profile of the control vortex, but with a shallower (420–700 mb) and a deeper (300–875 mb) potential vorticity signature to test the sensitivity of the simulated track deflections to the depth of the mesoscale vortex (Fig. 6b).
4. Results

The model is initialized with several configurations of the primary vortex and mesoscale convective vortex. The control simulation is designed to approximate the conditions observed between Typhoon Robyn and the mesoscale convective system as closely as can be determined from the data. The other simulations are designed to explore differences due to reasonable changes in the initial conditions. Both satellite imagery (Fig. 1) and aircraft observations (Fig. 3) suggest the center of the mesoscale convective system (and associated vortex location) is at a distance of approximately 400 km (3.6° latitude) north of the center of Typhoon Robyn. Although the initial orientation of the mesoscale convective system is approximately north-northwest of the tropical cyclone center, the initial configuration is north–south in the model for simplicity and to ensure that both vortices are located on a grid point. The control simulation will be described in some detail next. All sensitivity simulations are analyzed in terms of significant differences from the control run.

a. Simulated interaction between a mesoscale convective vortex and Typhoon Robyn

In the control case, the simulated mesoscale convective vortex with maximum intensity at 550 mb is initially located 400 km north of the tropical cyclone center, which corresponds to the approximate location relative to TY Robyn of the mesoscale convective system at its maximum cold cloud shield extent. Two major factors are expected to affect the mesoscale vortex during the simulation, which may in turn impact the tropical cyclone motion. The first is the strength of the mean advecting current due to the tropical cyclone circulation, which will affect the rate at which the mesoscale convective vortex advects around the tropical cyclone. This is important as the location of the mesoscale convective vortex relative to the tropical cyclone center prescribes the direction of the advective flow over the tropical cyclone. The faster the rotation of the mesoscale vortex, the larger the changes of the tropical cyclone motion direction. The second is the horizontal shear across the mesoscale vortex due to the radial change in the tropical cyclone circulation, which is expected to affect the rate of filamentation of the mesoscale vortex. As the mesoscale vortex becomes more distorted from a circular shape, the strength of the advective flow across the tropical cyclone is expected to weaken.

During the control simulation, a mutual rotation occurs and the separation between the vortices decreases (Fig. 7a) similar to that simulated with unequal, barotropic vortices (Smith et al. 1990; Ritchie and Holland 1993). The relative motion of each vortex is primarily due to the mutual advective flow imposed across it by the outer circulation of the other vortex. Thus, the weaker mesoscale convective vortex, which is initially em-bedded in a mean (over a radius of 400 km) 550-mb flow of 12.3 m s⁻¹ and horizontal shear of $3.3 \times 10^{-5}$ s⁻¹, is advected farther by the stronger tropical cyclone circulation. Given the mean advective flow of 12.3 m s⁻¹ the mesoscale vortex should be advected ~270 km in the first 6 h of the simulation. A calculation of the actual mesoscale vortex motion shows that it moves 280 km.

Because the shear flow in the simulated tropical cyclone is sufficiently strong, the mesoscale convective vortex is rapidly sheared into a filament and incorporated into the circulation of the stronger vortex (Figs. 7b–f). The center of the mesoscale convective vortex may be considered a coherent region of stronger potential vorticity that persists about 12 h. After 12 h, the
mesoscale convective vortex has become difficult to discern as a coherent vortex. Rather, it exists as an asymmetry (or perturbation) in the midlevel winds of the tropical cyclone. This asymmetry is gradually damped over time by the swirling winds of the tropical cyclone as the vorticity filament wraps around the tropical cyclone center, which is commonly known as axisymmetrization (Melander et al. 1988). In an environment without shear, a similar barotropic stabilization process (Carr and Williams 1989) will damp small perturbations or asymmetries in the mesoscale vortex circulation and maintain its initial circular flow. As the horizontal shear of the cyclone circulation is imposed over the mesoscale vortex, it is deformed from axisymmetry, and this barotropic stabilization is the only restoring mechanism in the dry simulation by which circular flow may be re-established. Filamentation occurs because the shearing flow of the cyclone vortex over the mesoscale convective vortex is stronger than the restoring force of the mesoscale vortex circulation. In general, a region of strong winds will be associated with the filament and thus a radial cross section through the filament will have some qualitative similarities to secondary wind maxima observed by Willoughby et al. (1982) during eyewall replacement cycles.

In contrast to the barotropic simulations (e.g., Smith et al. 1990; Ritchie and Holland 1993), the present baroclinic simulations include realistic cyclone and mesoscale vortex vertical structures so that some variations at different heights may be expected. Although the mesoscale convective vortex is most intense at middle levels, the tropical cyclone circulation is much stronger, and the vortex is sheared into a filament as illustrated in Figs. 7b–f. The tropical cyclone is more intense at lower levels and the mesoscale convective vortex is weaker than at middle levels, so the mesoscale vortex is sheared into a filament slightly more rapidly although it is not easy to see (cf. Fig. 7d and Fig. 8a). A comparison of the eccentricity of the mesoscale vortex provides a measure of the filamentation. A value of one indicates a circular vortex, whereas a value near zero indicates a filament. At 12 h, the eccentricity of the mesoscale vortex at 550 mb (750 mb) is 0.08 (0.07). Thus, the mesoscale vortex is slightly more filamented at lower than at middle levels. In addition, the mesoscale convective vortex has rotated slightly farther around the tropical cyclone by the stronger tropical cyclone circulation at lower levels. At 850 mb and lower, no mesoscale convective vortex filament is detected. At higher tropospheric levels, both the tropical cyclone and the mesoscale convective vortex are weaker and the interaction differs from the lower levels (Fig. 8b). By 12 h, the mesoscale convective vortex has not rotated as far around the tropical cyclone and the filament is not elongated as much (eccentricity = 0.21). It is difficult to discern the mesoscale convective vortex at levels above 300 mb. Although the mesoscale vortex also initially imposes a limited vertical shear over the tropical cyclone circulation, the tropical cyclone remains vertically coherent throughout the 24-h simulation.

Asymmetric components of the wind fields (Fig. 9) at the three pressure levels corresponding to Figs. 7d, 8a, and 8b are calculated by subtracting from the total wind field a symmetric component of the wind calculated relative to the minimum 550-mb wind speed center of the cyclone. The effects of varying vertical structures are apparent by tracking the maximum in the asymmetric component of the relative vorticity field, which is almost entirely associated with the mesoscale convective vortex. The mesoscale convective vortex has been advected farther at lower levels and middle levels than at upper levels (Fig. 9), similar to that shown in Fig. 8. The average asymmetric flow within a 350-km
radius of the tropical cyclone center (Fig. 9d) is strongest from about 450 through 750 mb. The rotation of the average steering vector with height is another indication of the changing rate of rotation of the mesoscale vortex with height where the vortex has rotated less at higher levels and more at lower levels. In addition, the advective flow across the tropical cyclone at higher and lower levels is weak and, thus, is expected to have less effect on the tropical cyclone displacement.

In response to the changes in the mesoscale convective vortex circulation, the tropical cyclone initially moves east, then northeast, and then north, and finally northwest during the 24-h period (Fig. 7a) covering a total distance of about 109 km. Because the environment is uniform, there is no propagation of the tropical cyclone due to the environment. Thus, the location of the mesoscale vortex relative to the tropical cyclone center determines the direction of motion of the tropical cyclone and the cyclonic rotation of the mesoscale vortex results in a rapidly changing directional component of advection over the tropical cyclone. Furthermore, the impact of the mesoscale vortex on the tropical cyclone motion diminishes as the mesoscale convective vortex is stretched into a filament (Figs. 7b–f). A deep-layer (950–200 mb) mean steering vector averaged within 350-km radius of the tropical cyclone center is calcu-
lated every 3 h and compared to the actual 3-h tropical cyclone motion at sea level (Fig. 10a). The speed and direction of motion of the tropical cyclone are closely associated with the advective flow from the mesoscale convective vortex. Although the initial deflection of the tropical cyclone is about 2 m s\(^{-1}\) to the east and then northeast (Fig. 10a), the mesoscale vortex effect on the tropical cyclone track rapidly weakens as the mesoscale vortex filaments. After 12 h, the mesoscale filament is west of the tropical cyclone center, and it imposes a north-northwestward advective flow of about 1.0 m s\(^{-1}\) over the tropical cyclone (Fig. 9d) whereas the actual tropical cyclone motion is 1.5 m s\(^{-1}\) to the north-northwest. By 15 h into the simulation, the tropical cyclone motion is 1.1 m s\(^{-1}\) to the northwest, whereas the advective flow due to the mesoscale vortex is 0.8 m s\(^{-1}\) to the northwest, and by 24 h the tropical cyclone has almost stalled (Fig. 10a). *This simulation suggests that an initial westward motion of 5 m s\(^{-1}\) of Robyn (Fig. 2) might have been modified by an interaction with the mesoscale convective system of the type simulated here. That is, as much as a 2 m s\(^{-1}\) deceleration in Robyn’s westward motion might have resulted in the first 6–9 h of interaction, and then a more northward track deflection, which is similar to that observed.*

This simulation suggests that the effect on the storm track by such an interaction may only occur for a limited time. In this dry simulation, the effects on the storm track due to the interaction have become small after about 15 h (Fig. 10a). This result differs from that of Ritchie and Holland (1993) based on contour dynamics model results, as they showed that a track perturbation imposed on a tropical cyclone–like vortex patch by a smaller nearby vortex patch could last long after the patch had sheared into a filament that is unresolvable by normal model resolutions or observing systems. The
results differ because of the stronger diffusion in grid-point models such as the one used here. Because the continuation of the tropical cyclone track deflection depends on the timescale of the filamentation of the mesoscale convective vortex (Figs. 7b–f), the maintenance of the mesoscale convective vortex circulation against the shear deformation effects of the tropical cyclone circulation becomes a critical factor. If the mesoscale convective vortex can be sustained longer as a perturbation on the tropical cyclone circulation, then the track deflection effect will persist longer. In the case of Typhoon Robyn, the mesoscale convective vortex was still observable as a discrete potential vorticity anomaly at least 18 h after the mesoscale convective system first developed, albeit shallower and weaker. This indicates that although the horizontal and vertical shear environment of the typhoon circulation may be acting to disperse the observed vortex similar to the simulated vortex, the continued development of a stratiform anvil over the vortex probably results in continued development of the vortex, partially counteracting the dispersive effects. Thus, the simulated track deflection might be expected to persist longer in a simulation where momentum transport processes are accurately represented.

The 950–200-mb deep-layer mean averaged flow provides a reasonable estimate of the tropical cyclone motion, particularly after about 9 h of simulation. However, the simulated asymmetric circulations in Fig. 9 suggest caution is required in choosing an appropriate layer mean because the bulk of the advective flow may be constrained to the middle levels of the atmosphere, particularly in the early stages of the simulation. In fact, the deep-layer mean flow in the first 12 h of the simulation is dominated by midlevel (450–750 mb) flow. However, the deep-layer mean flow by 18 h is less dominated by the midlevel flow, and low-level asymmetries become more important. In addition, the vertical variation in the advective flow over the tropical cyclone described earlier may be affected when moist processes are included. Although the basic dynamics of the vortex–vortex interaction leading to the cyclone track deflections are believed to be represented in these dry simulations, moist simulations that depend on an accurate representation of the generation of vorticity within the mesoscale convective system will be required to fully test this premise.

b. Sensitivity of the track deflections to the tropical cyclone outer wind structure

Whereas the simulated tropical cyclone has been constructed to be a proxy of Typhoon Robyn, the outer wind structure can vary considerably from storm to storm. Thus, sensitivity tests are used to examine how the interaction, and the resulting track of the tropical cyclone, would be affected if the storm were larger or smaller than in the control (Fig. 5). Although the same mesoscale convective vortex is placed at the same distance from the tropical cyclone, three factors will be changed. First, the advecting current will be greater (less) for the larger (smaller) tropical cyclone. Second, the horizontal wind shear across the mesoscale convective vortex imposed by the tropical circulation is less (greater) for the larger (smaller) tropical cyclone. Third, the vorticity in which the mesoscale convective vortex is embedded will be cyclonic (anticyclonic) for the large (small) tropical cyclone.

A similar filamentation of the mesoscale convective vortex as in Fig. 7 occurs for both the larger and smaller tropical cyclone (Fig. 11). The spread in the final 24-h positions of the large and small tropical cyclones is approximately 125 km.
The tropical cyclone with stronger outer winds moves in a tighter circle over a larger distance (136 km) than the control tropical cyclone (Fig. 12), because the mesoscale convective vortex is embedded in a stronger (mean = 16.6 m s\(^{-1}\)) cyclonic flow compared with the control case and is advected more rapidly around the tropical cyclone. This relatively larger rotation results in a more rapidly changing directional component of advection over the tropical cyclone (Fig. 10b, filled arrows). Although the initial tropical cyclone motion is eastward, it rapidly changes direction through northward, westward, and finally southwestward (Fig. 10b, open arrows). Similar to the control case, the tropical cyclone translation speed decreases considerably after 15 h, as the mesoscale vortex becomes filamented (Fig. 11a). However, the translation speed of the larger tropical cyclone is faster than the control cyclone at all times after 3 h (Fig. 10b). Although the mesoscale convective vortex is advected around the large tropical cyclone more rapidly than the control case, the filamentation is slightly slower because it is embedded in weaker shear (initially 2.3 \(\times\) 10\(^{-5}\) s\(^{-1}\)). The eccentricity of the mesoscale vortex at 12 h is 0.1 compared with 0.08 for the control. Thus, the advective component over the tropical cyclone due to the mesoscale convective vortex remains slightly stronger for a longer period and a greater distance has been covered than for the control simulation. The asymmetric 550-mb wind field (Fig. 13a) indicates an average (within 350-km radius) steering vector of \(-2.3\) m s\(^{-1}\) toward the north-northwest at the midlevels of the tropical cyclone. The average deep-layer mean steering vector within 350 km of the tropical cyclone center is 1.0 m s\(^{-1}\) toward the northwest, which is similar to the surface motion vector at 12 h (Fig. 10b).

For the smaller tropical cyclone, significantly less rotation of the cyclone path is predicted (Fig. 12). The tropical cyclone initially moves toward the east-northeast through northeast, then maintains a north-northeast path until the end of the simulation. This smaller directional change of the small tropical cyclone occurs because the mesoscale convective vortex is embedded in weaker advective flow (mean = 7.3 m s\(^{-1}\)) compared with the other two simulations. Thus, the mesoscale vortex is advected much more slowly around the small tropical cyclone (Fig. 11b), resulting in a much smaller change in the directional component of the advection over the small tropical cyclone (Fig. 10c, solid arrows). Although the translation speed again continues to decrease during the simulation, a smaller speed reduction...
occurs for the small tropical, which moves a total distance of 118 km in the 24 h of simulation.

The 550-mb asymmetric wind field (Fig. 13b) at 12 h indicates an average (within 350-km radius) steering vector of 2.9 m s$^{-1}$ to the northeast, and the deep-layer mean flow is 1.0 m s$^{-1}$ to the northeast similar to the tropical cyclone motion (Fig. 10c). In addition, the mesoscale vortex has not filamented as much as for the large tropical cyclone in spite of being initially embedded in stronger horizontal shear ($-3.9 \times 10^{-5}$ s$^{-1}$), because the small tropical cyclone has an outer region of anticyclonic relative vorticity (Fig. 5b) at the radius of the mesoscale convective vortex. Since the core of the mesoscale convective vortex is located in a region of positive vorticity gradient (i.e., increasingly cyclonic with radius from the tropical cyclone center; Fig. 5b), the two vortices move apart (DeMaria and Chan 1984) rather than closer together as in the other two cases, and the mesoscale convective vortex moves into a region of weaker shear. Thus, the mesoscale vortex becomes filamented considerably more slowly than the control (eccentricity at 12 h = 0.18), and the effect on the smaller tropical cyclone track persists longer (Fig. 12).

c. Sensitivity of the track deflections to initial separation distance between the vortices

The mesoscale convective vortex in Fig. 3 was located approximately 400 km from the center of Typhoon Robyn. Since this separation distance may vary greatly from case to case, it was varied in simulations from a smaller (225 km) to a larger (600 km) distance. Since the advective effect of one vortex depends on the outer circulation of the other vortex, a smaller separation distance causes a larger rotation about some intermediate point. Given the nonlinear wind speed increase in the tropical cyclone (e.g., Fig. 6a) or the mesoscale convective vortex (Fig. 6c) toward the center, the increase in rotation rate will be nonlinear as the separation distance decreases. Unlike previous barotropic studies (e.g., Zabusky et al. 1979; Ritchie and Holland 1993) that used Rankine vortices, an upper limit will exist on the interaction distance for vortices with outer wind speeds that tend to zero at finite radii. This is particularly true in a more realistic environment as nearby synoptic circulations are also likely to affect the tropical cyclone motion (e.g., Holland and Dietachmayer 1993; Carr and Elsberry 1994). Two physical processes change as the separation distance is varied. First, the mesoscale convective vortex will be embedded in anticyclonic (cyclonic) vorticity (Fig. 5b) for the larger (smaller) separation distance. Second, the horizontal wind shear (Fig. 5a) across the mesoscale convective vortex will be weaker (stronger) for the larger (smaller) separation distance.

More rapid filamentation of the mesoscale convective vortex compared with Fig. 7 occurs for the smaller separation distance because of the very strong horizontal shear ($4.7 \times 10^{-5}$ s$^{-1}$) associated with the tropical cyclone core (Fig. 14a). By 12 h, the mesoscale convective vortex is indistinguishable from the axisymmetric tropical cyclone circulation. In contrast, the larger separation distance results in an elongation of the mesoscale convective vortex, which is a much slower filamentation (Fig. 14b) because it is initially in relatively weak shear ($1.9 \times 10^{-5}$ s$^{-1}$). The mesoscale convective vortex is also in a cyclonic vorticity gradient (Fig. 5b), which causes the vortex to move away from the tropical cyclone into a region of even weaker horizontal shear.

These separation distance variations result in a 72-km difference in the 24-h positions of the tropical cyclone center (Fig. 15). The smaller separation distance
results in a rapid acceleration of the tropical cyclone in the first 3–6 h because of the strong initial advective flow (mean = 18.1 m s$^{-1}$) associated with the mesoscale convective vortex (Fig. 10d). The direction of motion also changes more rapidly than in any previous case, because the mesoscale vortex is quickly advected around the tropical cyclone by the strong core winds. As the mesoscale vortex is filamented and wrapped into the tropical cyclone core (Fig. 14a), this advective flow rapidly decreases after 6 h (Fig. 10d), and the final weak west-southwestward motion is maintained until the end of the simulation. Although the tropical cyclone moves a total distance of 100 km, this simulation suggests that a mesoscale convective vortex that developed very close to the core of a tropical cyclone would not persist long enough to have a large effect on the tropical cyclone track.

The larger separation distance results in an eastward then northward tropical cyclone motion (Fig. 15) and a total track length of 92 km. Because the mesoscale convective vortex is embedded in weak advective flow (mean = 7.2 m s$^{-1}$), it is advected slowly around the tropical cyclone, which causes an eastward, through northeastward, and finally northward motion (Fig. 10e). In addition, the mesoscale vortex is embedded in weak horizontal shear, which becomes weaker as the separation distance from the tropical cyclone increases. Thus, the mesoscale vortex filament slowly, and the resulting advective flow over the tropical cyclone due to the mesoscale vortex weakens very slowly through the simulation (Fig. 10e and Fig. 15). This result supports the hypothesis that a mesoscale convective vortex that develops in the outer, low horizontal shear region of a tropical cyclone will filament slower and, so, affect the tropical cyclone track for a longer period.

d. Sensitivity of the track to the vertical structure of the midlevel vortex

It is difficult to estimate the possible depth of the mesoscale convective vortex from satellite imagery alone. Fritsch et al. (1994) speculate that the depth of the vortex is related to the length of time the mesoscale convective system exists. Thus, it is useful to examine how the interaction, and the resulting track of the tropical cyclone, would be affected if the vertical structure of the mesoscale convective vortex were deeper or shallower than the control. The vertical structures of the “deep” and “shallow” mesoscale convective vortices in Fig. 6b are within the limits in observational studies of mesoscale convective vortices (e.g., Menard and Fritsch 1989; Fritsch et al. 1994). Although the profiles do not look very different, the one major factor that has changed from the control is that the integrated circulation associated with the deep (shallow) mesoscale convective vortex that will advect the tropical cyclone has increased (decreased).

Very little change in the filamentation occurs at any level compared with the control, and the 550-mb vorticity patterns for the deep and shallow mesoscale vortex after 12 h of simulation are indistinguishable from the control (Fig. 8). However, the vorticity is stronger (weaker) at these levels for the deeper (shallower) mesoscale vortex (not shown).

These vertical variations in the mesoscale vortex structure result in a small (37 km) difference in the 24-h positions of the tropical cyclone center (Fig. 16). The deeper mesoscale vortex forces a stronger advective flow over the tropical cyclone center over a greater depth of the atmosphere (not shown) compared with the control, which results in a faster motion (Fig. 10f), larger oscillation, and greater length (136 km) in the tropical cyclone track compared to the control vortex (Fig. 10a).
Although the shallower mesoscale convective vortex forces an advective flow at 550 mb of similar magnitude over the tropical cyclone center, the advective flow at higher and lower levels is much weaker (not shown). This results in a weaker deep-layer mean advective flow over the tropical cyclone center (Fig. 10g), and a total track length that is about half that for the deep mesoscale vortex (Fig. 16). Overall, the resulting tropical cyclone positions for the deep and shallow mesoscale vortex are at about a 2:1 distance ratio, which corresponds to the approximately 2:1 ratio in the initial amount of circulation of each mesoscale vortex.

e. Sensitivity of the track deflections to the horizontal wind structure of the midlevel vortex

In the case of the mesoscale convective system associated with Typhoon Robyn, aircraft and dropwindsonde observations are available to describe the structure. However, such observations are not generally available and uncertainty is inherent in using satellite imagery to estimate the size of the mesoscale convective system. Thus, it is useful to examine the sensitivity of the interaction, and the resulting track of the tropical cyclone, if the horizontal structure of the mesoscale convective vortex is varied within reasonable limits. The tangential wind structure of a large and a small mesoscale convective vortex is varied (Fig. 6c) such that the observed potential vorticity structure of the mesoscale convective vortex (Fig. 3) is approximately maintained. Although the mesoscale vortex will be located at the same horizontal distance from the tropical cyclone center as in the control, two physical factors will have changed. First, the tropical cyclone will be located within the cyclonic (anticyclonic) gradient in vorticity of the smaller (larger) mesoscale convective system. Second, the initial mean advective speed over the tropical cyclone will be weaker (stronger) for the smaller (larger) mesoscale convective system.

As in the previous section, the filamentation of the large and small mesoscale vortices is very similar to that for the control, because the mesoscale vortex is located in the same initial mean flow and horizontal shear. The larger mesoscale vortex, which initially had a stronger vorticity core than the smaller vortex, remains slightly stronger throughout the simulation.

The variation in the mesoscale vortex sizes again results in a small (34 km) difference in the simulated 24-h tropical cyclone positions (not shown). As expected, the stronger outer winds of the larger mesoscale vortex initially produce a slightly faster advection of the tropical cyclone (Fig. 10h) compared with the smaller mesoscale vortex (Fig. 10i). Because the initial radial vorticity gradients associated with the mesoscale vortices are quickly distorted as the mesoscale vortices become filamented, there does not seem to be any effect caused by the location of the tropical cyclone within the cyclonic (anticyclonic) vorticity gradient of the smaller (larger) mesoscale vortex.

f. Simulated interaction between a mesoscale convective vortex and Typhoon Robyn on a β plane

The simulations on an f plane in section 4a suggest that an interaction between Typhoon Robyn and a mesoscale convective vortex could have contributed to a slowing of an initially westward motion and a subsequent more northerly path similar to that observed. Whereas the vortex dynamics are easier to interpret on an f plane, it is possible that the track modifications may differ on a β plane. Thus, the tropical cyclone was first integrated on a β plane for 24 h to allow development of the β gyres. After the mesoscale vortex was inserted similar to the control f-plane simulation, the simulation was integrated for a further 24 h on a β plane.

Similar advection and filamentation of the mesoscale vortex occurs as in the control f-plane simulation (not shown). Because the filamentation occurs within about 15–18 h on relatively small spatial scales, the direct interaction between the mesoscale vortex and the tropical cyclone is not changed on a β plane. However, the tropical cyclone motion induced by the interaction with the mesoscale vortex is slightly stronger than in the f-plane simulations (Fig. 17). Although the direction of motion after 24 h of the β-plane simulation with the mesoscale vortex is almost identical as in the tropical cyclone–only simulation, a net poleward deflection has occurred. In addition, the vector difference (Fig. 18d) relative to the β-plane control (Fig. 18b) is slightly (0.2–
Fig. 18. Three-hourly tropical cyclone motion vectors (solid arrows) and 950–200-mb deep-layer mean averaged within 350-km radius of the tropical cyclone center (open arrows). The 3-h tropical cyclone motion speeds (m s$^{-1}$) are printed below each vector: (a) $f$-plane control simulation, (b) tropical cyclone only on a $b$ plane, (c) tropical cyclone and mesoscale vortex on a $b$ plane, and (d) difference between (c) and (b).

0.3 m s$^{-1}$) faster in the simulation with the mesoscale vortex than in the $f$-plane simulation (Fig. 18a). This larger propagation speed is due to a nonlinear interaction between the tropical cyclone and earth vorticity gradient that results in an energy loss from the tropical cyclone vortex via Rossby wave dispersion. Fiorino and Elsberry (1989) demonstrated that the outer wind strength of the tropical cyclone is important in determining the strength, and orientation, of the $\beta$ gyres. Insertion of the mesoscale convective vortex increases (decreases) the outer (inner) winds in the tropical cyclone (Fig. 19).

Thus, the $\beta$ gyres would be expected to be proportionally stronger and provide a faster propagation speed than for the $b$-plane control simulation. In the case of the tropical cyclone with an embedded mesoscale vortex, the short-term effect of the interaction between the two vortices is to produce a decrease in the westward motion of the storm as demonstrated in both the $f$- and $b$-plane simulations. Whereas this interaction is limited to the timescale of the filamentation of the mesoscale vortex, a longer-term effect may be produced because the $\beta$ gyres are enhanced while the mesoscale vortex is contributing to a stronger outer cyclone circulation. In this simulation, a slightly different orientation and enhanced strength of the $\beta$ gyres produced a faster tropical cyclone motion that persisted through the end of the simulation, that is, beyond when filamentation has eliminated the mesoscale vortex.

5. Summary and conclusions

These dry numerical simulations illustrate possible contributions to track deflections of a tropical cyclone (e.g., Typhoon Robyn) because of an interaction with a mesoscale convective system that develops in proximity to the cyclone core. A special dataset collected during the TCM-93 field experiment in the western North Pacific is used to develop idealized representations of the structure of the tropical cyclone and the potential vorticity anomaly that was associated with the mesoscale convective system. These idealized vortices are then used to examine the sensitivity of the simulated tropical cyclone motion over a range of tropical cyclone–mesoscale vortex interactions.

The control simulation suggests that as much as a 2
m s$^{-1}$ deceleration in Robyn’s westward motion might have resulted in the first 6–9 h, and then a more northward track deflection, due to an interaction with a mesoscale convective system of the type simulated here. The control simulation also suggests that the direct effects on the storm track due to the mesoscale vortex become small as the mesoscale vortex is stretched into a filament, which occurs in about 15 h in this dry simulation. An additional small, but long term, cyclone translation occurs when the interaction is simulated on a $\beta$ plane rather than an $f$ plane because the mesoscale vortex increases the outer wind strength and results in subtle changes in the strength and orientation of the $\beta$ gyres. An implication of the $\beta$-plane simulation is that the first-order, direct tropical cyclone–mesoscale vortex interactions may be examined on an $f$ plane. Even though the mesoscale convective vortex induced changes in the tropical cyclone motion have longer timescales on the $\beta$ plane, the track changes are small because the modification of the large-scale steering environment are limited to the time scales of the filamentation of the mesoscale vortex.

Because the continuation of the tropical cyclone track deflection depends on the timescale of the filamentation of the mesoscale vortex, the maintenance of the mesoscale vortex circulation against the shear deformation effects of the tropical cyclone circulation becomes a critical factor. If the mesoscale convective vortex can be sustained longer as a perturbation on the tropical cyclone circulation, then the track deflection effect will persist longer. This sensitivity was illustrated by changing the initial separation distance of the tropical cyclone and mesoscale vortex. For small separation distances, there is an initially very large effect on the tropical cyclone path due to the mesoscale vortex. However, the mesoscale vortex is rapidly filamented so that effects on the tropical cyclone track are negligible by 12 h. For larger separation distances, the mesoscale vortex does not filament and the storm track is affected throughout the simulation. In these simulations, the rate of filamentation of the mesoscale vortex is due to the strength of the horizontal shear of the tropical cyclone circulation. Another factor that will affect the longevity of the mesoscale vortex that is not represented in these dry simulations is the development and maintenance of the parent mesoscale convective system. The persistence or redevelopment of the mesoscale convective system will probably result in maintenance of the mesoscale vortex against filamentation and dispersion, which would result in a larger track deflection than in these simulations.

These simulations also suggest that variations of the mesoscale vortex structure are not very important for the resulting track deflections. When all other aspects are the same, a mesoscale vortex with a greater circulation, whether horizontal or vertical, produces a slightly larger tropical cyclone track deflection than a mesoscale vortex with less total circulation. Since the timescale of the filamentation process does not change, the timescale of the track deflections also varies only slightly.

The outer wind structure of the tropical cyclone is of importance in determining the amount and direction of the tropical cyclone track deflection. For the types of wind profiles tested here, a larger tropical cyclone exerts less horizontal shear across the mesoscale vortex, so it filaments more slowly. However, the mean advective flow is stronger so the mesoscale vortex is advected around the tropical cyclone faster, which results in a rapidly changing directional component of advective flow over the tropical cyclone center. The resulting track deflection of the larger tropical cyclone is larger than the control. For a smaller tropical cyclone, the mesoscale vortex is initially embedded in stronger horizontal shear. Because the vortex is also embedded in the outer anticyclonic part of the tropical cyclone, it is advected away from the tropical cyclone into a region of weaker shear. Thus, the rate of filamentation decreases and the effect on the storm track deflection persists until the end of the simulation.

The control and sensitivity simulations with this dry model suggest that tropical cyclone track deflections of up to 130 km over 18–24 h could be produced by an interaction with a mesoscale convective vortex that is embedded close to the core of the storm, or far away, and for a large or small tropical cyclone. Because the continuation of the track deflection depends on how quickly the mesoscale vortex filaments, these dry simulations probably underestimate the persistence of the track deflections owing to the rapid filamentation. Although this needs to be simulated with a moist model with convective heat release and momentum transports, it is expected that real mesoscale vortices would resist the horizontal shear deformation by the tropical cyclone circulation for longer periods and result in larger track deflections. It is left for future work to determine if existing moist models can also simulate the development and structure of the mesoscale vortex, rather than simply inserting the vortex as done here. The curvature of the track deflection depends on how rapidly the mesoscale vortex is advected around the tropical cyclone, which is primarily determined by the initial separation distance and the tropical cyclone wind profile. Whether such track deflections are a significant contribution to the overall track depends on the strength and direction of the environmental flow in which the tropical cyclone is embedded. For the mesoscale vortex and cyclone structures tested here, it appears plausible that the mesoscale convective system about 400 km north of Typhoon Robyn contributed to a deceleration and poleward deflection of Typhoon Robyn through a combination of direct interaction and modification of the large-scale steering.

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