Statistical characteristics of meso-scale vortex effects on the track of a tropical cyclone*

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This paper examines initial meso-scale vortex effects on the motion of a tropical cyclone (TC) in a system where coexisting two components of TC and meso-scale vortices with a barotropic vorticity equation model. The initial meso-scale vortices are generated stochastically by employing Reinaud's method. The 62 simulations are performed and analysed in order to understand the statistical characteristics of the effects. Results show that the deflection of the TC track at $t = 24$ h induced by the initial meso-scale vortices ranges from 2 km to 37 km with the mean value of 13.4 km. A more significant deflection of the TC track can be reduced when several initial meso-scale vortices simultaneously appear in a smaller TC circulation area. It ranges from 22 km to 37 km with the mean value of 28 km, this fact implies that the initial meso-scale vortices-induced deflection may not be neglected sometimes.

Keywords: meso-scale vortex, tropical cyclone, statistical characteristics

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1. Introduction

Meso-scale convective systems (MCSs) or meso-scale vortices have been identified over many regions of the globe (see, e.g., Refs. [1]–[16]). The MCS or meso-scale vortex effects on the track of a tropical cyclone (TC) have been investigated extensively. Willoughby[17] indicated that the MCS near a TC centre could cause track meanders on shorter timescales of 4 h–12 h. Holland and Lander[5] have suggested that MCSs may have a significant role in causing meanders in TC tracks with amplitudes of about 100 km and periods of 1–2 days. They show a case of Typhoon Sarah (No. 8921) that had a long-lasting MCS with a cloud dimension similar to Sarah, for the tracks of the two systems, a binary cyclonic orbit appears around a centroid, which was assumed to be the midpoint between Sarah and the MCS. Lander and Holland[18] assumed that the MCS had a substantial meso-scale vortex and used a barotropic model to demonstrate that such a combined MCS-TC system might have caused deflections in Sarah's track. Harr and Elsberry[6] have investigated another MCS embedded in the circulation of Typhoon Robyn (No. 9309) by two aircraft missions during the TC motion (TCM-93) mini field experiment. Coincident with the occurrence of the MCS, the motion of the Robyn changed from west-northwestward to a slow drift to the north. The structure of the MCS is investigated to examine whether the changes in motion of the Robyn could be related to a mid-tropospheric vortex circulation in the MCS. Their results showed that the MCS circulation is judged to be too weak, too shallow, and separated too far from the Robyn to be responsible for the observed track changes. Chen and Luo[19] indicated that a TC would turn leftwards with prominent oscillation when a small vortex appears in the northeast quadrant of the TC circulation. Luo and Liu[20] have demonstrated the complexity of a major vortex motion in

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a system where four sub-systems with different scales are coexisting (a subtropical high ridge, a major vortex, meso- and small-scale vortices), and three kinds of the major vortex tracks have been observed.

Previous studies on TC motion related to meso-scale vortex processes often involve one or two case analyses and generalization of the results is difficult. Here we are attempting to explore the problems including the statistics associated with the effects based on large sample analyses. The paper is arranged as follows. The brief description of the methodology is given in the next section. The case study results on effects of meso-scale vortices on a TC track are presented in Section 3. In Section 4 the statistics are discussed. Summary will be given in Section 5.

2. Methodology

2.1. Model

Vortex dynamics in two dimensions can be described by the following equation governing the evolution of the relative vorticity:

$$\frac{\partial}{\partial t}\nabla^2\psi + J(\psi, \nabla^2\psi) + \beta\frac{\partial\psi}{\partial x} = -\nu\nabla^4\psi, \qquad (1)$$

where ψ is geostrophic stream function, $\xi = \nabla^2\psi$ is relative vorticity, J Jacobian operator, $\beta = 2\Omega\sin\varphi$ with Ω being the angular velocity of the Earth rotation and φ being the latitude; ν is the hyper-viscosity coefficient, which compresses the dissipation range into a smaller range of scales[21] and $\nu = 1.0\times10^{-7}$ m$^4\cdot$s^{-1},[22] ∇^2 is the Laplacian in x and y.

The computational domain is a square of 1200 km $\times$ 1200 km with a resolution of $\Delta x = \Delta y =$ 3 km and total of 401×401 grid points. The time step is taken as $\Delta t = 30$ s for integration. The time-filter central difference scheme[23] is employed at every time step to suppress nonlinear instability.

2.2. Boundary and initial conditions

Periodic conditions are assumed at the east and west borders of the domain while $\partial\psi/\partial t = 0$ is set at the north and south borders. At $t = 0$, we set

$$\xi(x, y, 0) = \xi_{\rm d}(x, y, 0) + \xi_{\rm s}(x, y, 0), \qquad (2)$$

where $\xi_{\rm d}(x, y, 0)$ denotes a deterministic vorticity field, which is described by the following formula[24]

$$\xi_{\rm d}(x, y, 0) = (2V_{\rm m}/R_{\rm m}) \times (1 - 0.5(r/R_{\rm m})) \times {\rm EXP}(1 - (r/R_{\rm m})), \qquad (3)$$

where $V_{\rm m}$ is the maximum wind speed, $R_{\rm m}$ is the radius of maximum wind, r is the radius, $V_{\rm m} =$ 20 m$\cdot$s^{-1}, $R_{\rm m} = 81$ km. The initial vorticity field and the tangential wind profile are shown in Figs. 1 and 2, respectively.

The $\xi_{\rm s}(x, y, 0)$ denotes a meso-scale vorticity field, which is generated stochastically. The generation steps of the meso-scale vorticity field are as follows.[25] First, the centre coordinates of seven small vortices are positioned in the computational domain using a random number table. Second, it is assumed that the starting conditions consists of uniform vorticity vortices, with an equal number having $\xi_{\rm s0} = 1.2\times10^{-4}$ s^{-1} and with an equal radius being 27 km. Third, the examination for the vortices is made to ensure that they are not overlapped one another. The 62 initial stochastic vorticity fields are generated, named by RP$_1$, RP$_2$, ..., RP$_{62}$, respectively. The RP$_1$, RP$_2$, and RP$_3$ are shown in Figs. 3(a), 4(a), and 5(a), respectively.

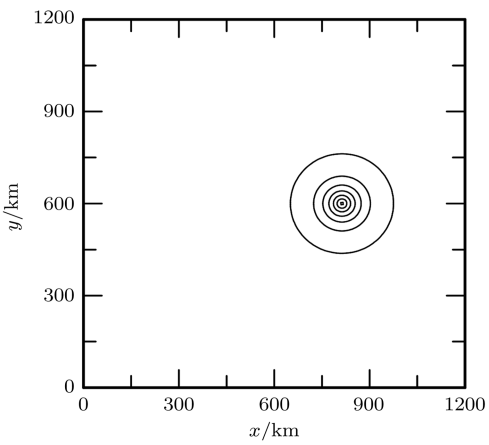


Fig. 1. Vorticity of the TC in the control experiment without any initial meso-scale vortices at $t = 0$ h, contour interval is 2.0×10^{-4} s^{-1}.

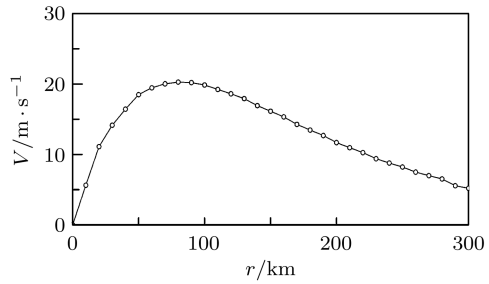


Fig. 2. Tangential wind profile of the TC.

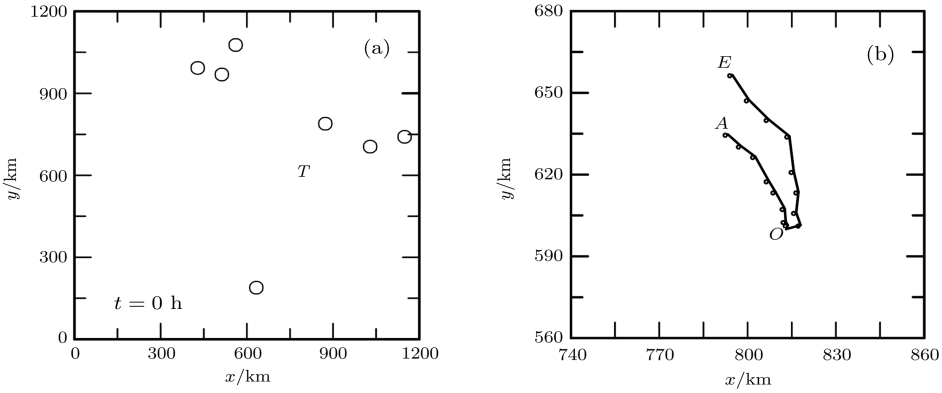


Fig. 3. Vorticity of the initial meso-scale vortex in EXA_1 contour interval is 2×10^4 s^{-1}, T denotes the position of the centre of the TC (a), the track OA for (0–24) h in the control experiment, and OE in EXA_1.

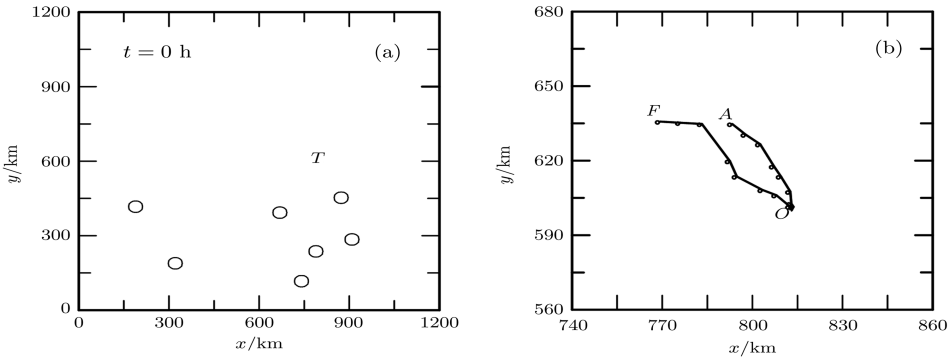


Fig. 4. Same as in Fig. 3 except for EXA_2 and and OF in EXA_2.

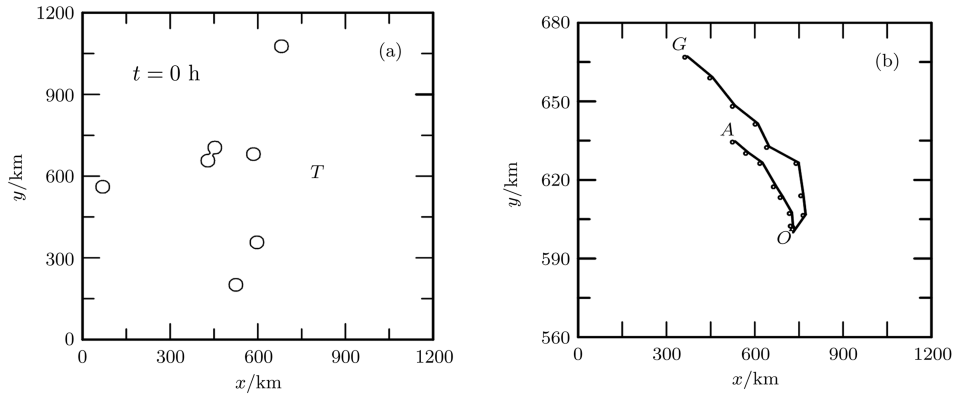


Fig. 5. Same as in Fig. 3, except for EXA_3, and OG in EXA_3.

2.3. Experimental design

There are two categories of experiments performed: category A and category B. In category A, EXA_i $(i = 1, \ldots, 62)$ include a TC and a stochastic vorticity field RP_i $(i = 1, \ldots, 62)$. In category B, EXB_{1j}, EXB_{2j}, and EXB_{3j} $(j = 1, \ldots, 8)$ are conducted with different maximum TC wind speed V_m, $V_m = 5, 10, 15, 20, 25, 30, 35$, and 40 $m \cdot s^{-1}$, respectively. In EXB_{1j}, EXB_{2j}, and EXB_{3j} stochastic vorticity fields RP_1, RP_2, and RP_3 are chosen, respectively.

3. Preliminary results

3.1. Meso-scale vortex effects on the track of a TC-case study

Comparison of the TC tracks from EXA_i $(i = 1, 2,$ and 3) (OE in Fig. 3, OF in Fig. 4, and OG in Fig. 5) and that from the control experiment without any initial meso-scale vortices (OA in Figs. 3, 4 and 5) in-

dicates that the deflections occur, which range from 22 km to 37 km with the mean value of 28 km, this fact implies that the deflections of the TC tracks caused by the stochastically positioned initial meso-scale vortices have the same order of magnitude and are close each other.

Three initial meso-scale vortices appear in the north-western (NW) quadrant of the TC in EXA_1, the TC turns to the north for 0–15 h (Fig. 3) while five initial meso-vortices emerge in the south-western (SW) quadrant in EXA2, it turns to the west (Fig. 4). Four meso-scale vortices lie in the NW quadrant in EXA3, the TC also turns to the north during 0–9 h (Fig. 5). The results are similar to the observational facts.[26,27]

There are other small vortices in the initial fields of EXA_1, EXA_2, and EXA_3 (Figs. 3–5), except the ones described above. Three small vortices among them lie in the NE quadrant in EXA_1 (Fig. 3(a)). As indicated by Chen and Luo,[19] the interaction between a TC and a small vortex in the NE quadrant of the TC would result in a track deflection to the north. It implies that the track deflection to the north in Fig. 3(b) would cause from the common effect of all small vortices in the NW and north-eastern (NE) quadrant in Fig. 3(a). Similarly, also seen on Fig. 4(a) or Fig. 5(a) are: the other small vortices lie in the south-eastern (SE) or SW quadrant, which would lead to the fact that the TC motion direction has a north or a west deviation, respectively.[19] Therefore, the track deflection in Fig. 4(b) or in Fig. 5(b) would be attributed to the common effect of the small vortices in the SW and the SE quadrants (Fig. 4(a)) or in the NW and the SW quadrants (Fig. 5(a)).

3.2. Meso-scale vortex effects on the track of a TC-statistics

In order to understand the statistical characteristics about the effects of meso-scale vortices on the TC track excluding the three initial stochastically vorticity fields which have been used in EXA_i ($i = 1, 2,$ and 3), other 59 initial stochastically vorticity fields are generated and they are used for further 59 experiments.

Figure 6 derived from simulations of the 62 cases indicates that there are many scattered points, which represent the TC centre positions at $t = 24$ h. The distance between one of the scattered points and point A, which denotes the TC centre coordinates at $t = 24$ h in the control experiment without any initial meso-scale vortices, ranges from 2 km to 35 km with the mean value of 13.4 km.

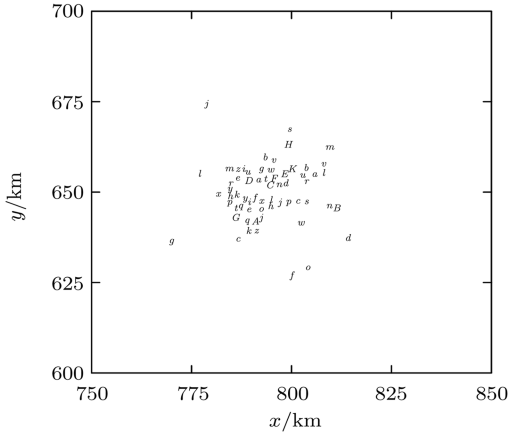


Fig. 6. Positions of the TC centre derived from 62 simulations with various initial stochastic vorticity fields in EXA_i ($i = 1, \ldots, 62$) at $t = 24$ h. A denotes the position of TC centre at $t = 24$ h in the control experiment without any initial meso-scale vortices.

3.3. Sensitivity to the design of the initial maximum TC wind speed

Figure 7 derived from 24 simulations in EXB_{1j}, EXB_{2j} and EXB_{3j} ($j = 1, \ldots, 8$) with various initial maximum wind speed V_m for each of three initial stochastic vorticity fields, RP_1, RP_2, and RP_3, shows that the deflection of the TC track depends closely on the change of both V_m and the initial stochastic vorticity field. There is a trend that the larger V_m is, i.e., the stronger TC is, the track deflection is smaller for the three curves in Fig. 7. Meanwhile, note that there are two small vortices from the west to point T (T denotes the initial position of TC centre) (Fig. 5(a)), they are close each other and undergo a mergence process afterwards. The merged vortex is stronger than the vortex before mergence. The interaction between the TC and the more strong meso-scale vortex would make a larger track deflection (see curve RP_3 in Fig. 7).

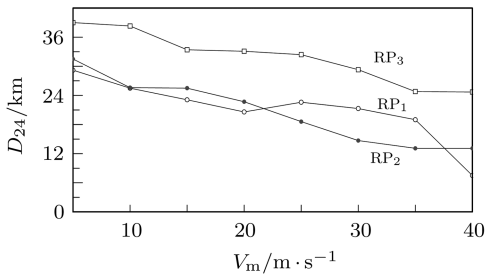


Fig. 7. Evolutions of the deflection of the TC track with maximum wind speed V_m for EXB_{1j} (curve RP_1), for EXB_{2j} (curve RP_2), for EXB_{3j} (curve RP_3) ($j = 1, \ldots, 8$). The D_{24} denotes the deflection of the track of the TC caused by initial meso-scale vortices at $t = 24$ h.

4. Summary

Several important theories associated with the motion of a TC such as the uniform flow theory[28,29] as well as the potential vorticity tendency theory[30,31] have been successfully proposed and applied. The multi-scale components have not been involved, however, in previous theories. More than 40 years ago, Feynman,[32] Nobelist in physics, gave a well-known lecture named "there is plenty of room at the bottom", which influenced not only physics but also the other natural sciences including chemistry, biology, and geophysics, etc. For example, it has formed the theoretical basis of the "Bottom–Up" nano-scale self-assembly process. We wish to combine the lecture with TC motion in this work. The key point of the lecture is that the microscopic change of properties at small scales may control the macroscopic properties at large scales. We preliminarily consider that the TC track may be viewed as a macroscopic behaviour of a complicated system where two components of TC and meso-scale vortices are coexisting in the initial vorticity field and that the meso-scale vortices could be viewed as a microscopic change. The problem is that whether the microscopic change can lead to a modification of the macroscopic behaviour.

The 62 simulations are performed and analysed by using a barotropic vorticity equation model. The deflection of the TC track induced by the initial meso-scale vortices at $t = 24$ h ranges from 2 km to 37 km. A more significant deflection of the TC track can be reduced when several initial meso-scale vortices simultaneously appear in a smaller TC circulation region, as it is shown in the EXA_i ($i = 1, 2$, and 3) where the deflection ranges from 22 km to 37 km with the mean value of 28 km. Davidson[33] pointed out that the 24-h mean forecast track error is 128 km for the NW Pacific TC for consensus of 8 models, including NOGAPS, UKMO, JMA, NCEP, MM5, GFDL, and so on. Results here imply that the initial meso-scale vortices-induced deflection might not be neglected sometimes.

The initial stochastic vorticity fields and the model used in this study are all idealized. Understanding the sensitivity of the design of initial conditions remains limited, such as the intensity of meso-scale vortices, as well as of computational parameters, such as the size of the computation domain. Further investigations that include these effects may be needed to produce the results closer to the circumstances in the real atmosphere. New analytical methods[34,35] should also be introduced into studies of TC track.

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