Reply to Dr. C.-C. Wu (reviewer 1)

Thanks very much for your editorial efforts and valuable suggestion. We have revised the manuscript and the point-to-point responses to your comments are as follows:

1. The author chose Matsa as a case to investigate the role of steering. However, In Fig.2, Matsa appears as a highly asymmetric typhoon after 24 hr of simulation. Since other processes such as VA and DH can cancel each other due to the coherent structure of the TC, it is confusing that VA and DH term of Matsa can also cancel each other because the structure is highly asymmetric. Please clarify this issue.

Although the terms VA and DH are closely associated with the asymmetric components of the tropical cyclone circulation, the contributions of the VA and DH terms cancel each other due to the coherent structure of the tropical cyclone circulation.

As shown in the attached figure (Fig. 10 in the revised manuscript), this figure shows the wavenumber-one components of the 500-hPa vertical motion, 700-hPa winds relative to tropical cyclone motion, and 500-hPa heating rate after 18 hours of integration. The upward (downward) motion generally occurs in the entrance (exit) region of the 700-hPa winds. Bender (1997) found that vorticity stretching and compression is closely associated with the vorticity advection due to the relative flow (difference between the wavenumber-one flow and the TC motion). The vorticity stretching leads to upward vertical motion and convective heating in the entrance region (Fig. 10). Thus the contribution of the HA term is negatively correlated with those of the VA and DH terms. Please refer the text in the section of contributions of diabatic heating and vertical advection.

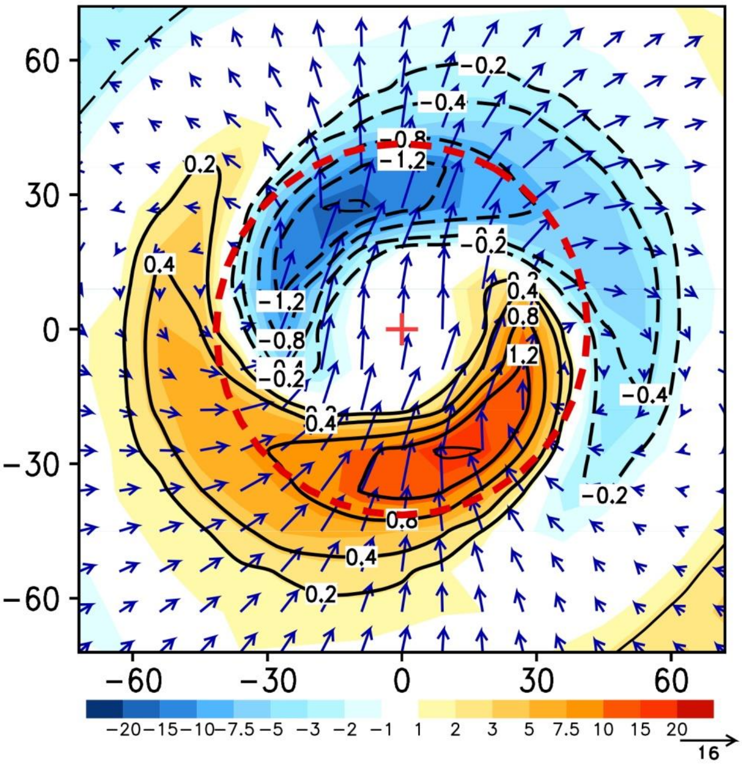

Figure 1 The wavenumber-one components of the 500-hPa vertical motion (contours, m s^{-1}), 700-hPa winds relative to the tropical cyclone motion (vectors, m s^{-1}), and 500-hPa heating rate (shaded, 10^{-4} K s^{-1}) after 18 hours of integration. The dashed circle indicates the radius of maximum wind.

2. This paper did not provide the track and intensity, and structural changes of the simulated TC. Meanwhile, since the TC structure is highly asymmetric, and the TC center is defined as the geometric center of the circle. How different the center would be when using other methods to define the center, such as sea level pressure center, PV weighted center, or streamline center? The definition of the center is very crucial because it will affect the results related to trochoidal motion.

1. **The track and intensity, and structural changes of the simulated tropical cyclone**: The figures have been provided in Figures 1-3. It should be mentioned that the track, intensity and structural changes are different from those of Typhoon Matsa because we used only the low-frequency environment of the case in this numerical experiment. We designed the numerical experiment to make the simulated tropical cyclone move in a realistic environment, typically over the western North Pacific.

2. **Different definitions of the tropical cyclone center**: We examined the TC

center defined in different ways, including minimum SLP center, minimum geopotential height center and the pressure centroid method, as discussed in Nguyen et al (2014). The results are shown in the attached figure (Fig. 2). We can see that the resulting speeds and fluctuations are generally similar. In particular, the results from the pressure centroid method is very close to those from the method in this study. We conclude that the trochoidal motion discussed in this study does not depend on the definition of the tropical cyclone center.

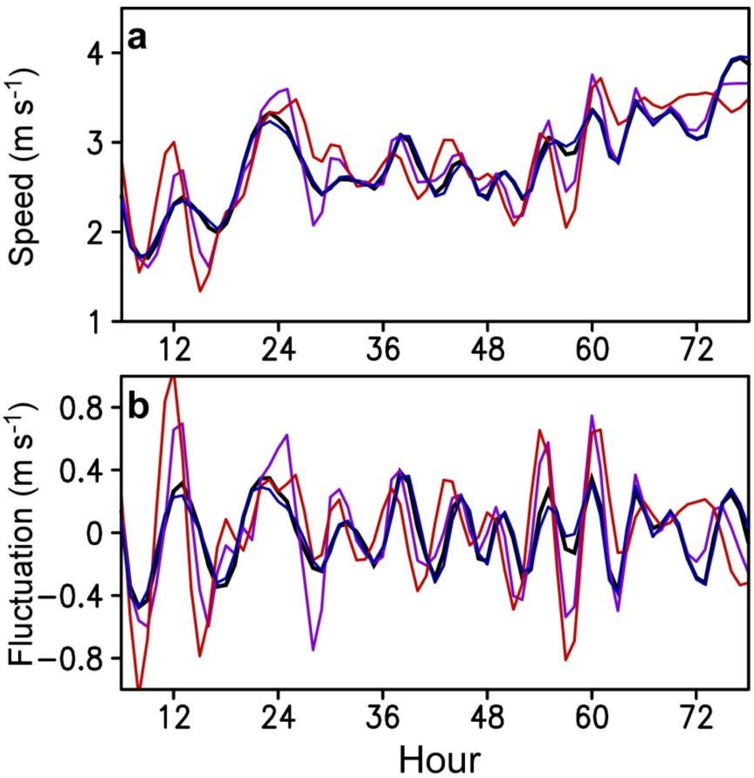

Figure 2 The TC speed calculated by different TC center definition (Black: the method used in this study; Red: the minimum SLP center; Purple: the minimum geopotential center on each level; Blue: the pressure centroid center defined by Nguyen et. al. 2014): (a) translation speed (m s^{-1}), and (b) fluctuation of translation speed (m s^{-1})

3. The change of RMSEs of the speed and direction decrease with time. It's not intuitive to have larger error in the initial time while the error decreases later. What is the possible cause of such a result?

Figure 6 in the revised version shows the RMSEs of speed and direction between tropical cyclone motion and conventional steering. It is indicated that the RMSEs decrease with increasing average time periods. That is, the conventional steering cannot represent the short-term fluctuations of TC motion. We have corrected the figure and caption in the revised manuscript.

4. The concept of steering flow is very confusing, since there so many words like conventional steering flow (line 43 and line 243-246), steering effect (line 242), the steering effect of HA1 (line 248). Please rephrase all these to make it clear. Also, the reviewer cannot figure out the relationship between HA1, HA2, and steering flow. Please clarify.

In this manuscript, the conventional steering flow, which have been widely used in previous studies, is obtained by averaging the winds within the radius of 270 km from the tropical cyclone center over a layer of 300-850 hPa.

The HA term in the PVT equation can be approximately written as: $-\mathbf{V}_1 \cdot \nabla \mathbf{P}_s - \mathbf{V}_s \cdot \nabla \mathbf{P}_1$, where $\mathbf{V}_s$ is the symmetric component of the tangential wind and $\mathbf{V}_1$ is the wavenumber-one component of the asymmetric wind. The first term (HA1) represents the advection of the symmetric potential vorticity component by the asymmetric flow. The second term is the advection of the wavenumber-one potential vorticity component by the symmetric flow (HA2). The contribution of the HA1 term is literally the steering effect, which is determined by the distribution of asymmetric flows. **The contribution of the HA1 term is not the conventional steering**.

The contribution of HA2 is part of the horizontal advection. In fact, the contributions of the HA1 and HA2 terms are highly anticorrelated. The correlations for the zonal and meridional components are -0.82 and -0.80, respectively. The negative correlations suggest the cancellation between the contributions of the HA1 and HA2 terms. As a result, the combined effect of the HA1 and HA2 terms can actually account for the effect of the conventional steering except the short-time fluctuations, as shown in Fig. 8.

5. Correct me if I'm wrong. HA=HA1+HA2 If this is right, in Fig.7, HA1+HA2 would not be HA.

In Figure 7, the contribution of conventional steering flow has been removed from the contribution of the HA1 term. We have mentioned it in the figure caption.

6. Line 272 In Fig.8, the maximum (minimum) HA1 is in the entrance (exit) of the flow, but the statement in line 272 is the opposite. What is wrong?

Sorry for the mistake. We have corrected the figure in the revised manuscript.

7. Line 285-286 What does it mean "the individual contributions can cancel each other due to the coherent structure of the TC." Is the structure coherent?

The sentence has been rewritten as "it is suggested that the contributions of individual terms can cancel each other due to the coherent structure of the tropical cyclone". We discuss the coherent structure in the following text.

8. Since the relationship among the terms of HA, VA and DH are nonlinear, is it fair to calculate the correlation of these terms and make interpretations?

Although the terms of HA, VA and DH are nonlinear, the contributions of the terms to tropical cyclone motion estimated with the PVT approach are linear. That is, the total contribution to tropical cyclone motion are the sum of the contributions of individual terms. Therefore, it is reasonable to calculate the correlation between the contribution of two terms.

9. Line 297-299 The reviewer cannot get the point of this explanation. Please provide further details. Regarding the statement, "The contribution of the HA term is negatively correlated with those of the VA and DH term", please provide more supporting evidences.

The correlations between HA and VA (DH) for the zonal and meridional components are -0.26 (-0.44) and -0.54 (-0.02), respectively. This is added to the revised manuscript. Please see No. 1 for understanding the negative correlations.

10. The author did not provide specific answer to the question when steering plays a *dominant role, and when TC motion deviates from the steering. The reviewer can only tell that the small-amplitude trochoidal motion results from asymmetric dynamics of the TC inner core. This answers "why" TC motion deviate from the steering, but not "when" TC motion deviate from the steering.*

The dominant role of the conventional steering: The conventional steering contains the contribution of the advection of the symmetric potential vorticity component associated with a tropical cyclone by the asymmetric flow and the contribution from the advection of the wavenumber-one potential vorticity component by the symmetric flow. The contributions from other processes are largely cancelled due to the coherent structure of tropical cyclone circulation and thus the conventional steering plays a dominant role.

Deviation from the conventional steering: The trochoidal motion around the mean tropical cyclone track with amplitudes smaller than the eye radius and periods of several hours cannot be accounted for by the effect of the conventional steering. Thus the instantaneous tropical cyclone motion can considerably derivate from the conventional steering.

11. Line 38, "paradigm" is not a suitable word here. Please change "potential vorticity tendency (PVT) paradigm" to "potential vorticity tendency (PVT) diagnostics".

It has been changed.

12. Line 207 : : :: : : speed of -1.02 (-1.01) m/s: : :.. What does it mean to mention -1.01?

The speed (-1.01 m/s) is estimated with the PVT approach. The sentence has been rewritten.

13. Line 201 What is secondary steering flow?

Secondary steering, which differs from large-scale environmental steering, is also called beta drift. The sentence has been rewritten.

Reply to Reviewer 2

Thank you very much for your suggestions and comments. Our manuscript has been revised based on the reviewers' suggestions and comments. Our point-to-point responses to your comments are as follows:

Title: The study refers only to one case simulation. Therefore, it should become apparent from the title that this is a case study. Maybe the title "Revisiting the Steering Principal of Tropical Cyclone Motion: A case study of Typhoon Matsa (2005)" could be more appropriate.

In Section 2, we mentioned that in this numerical experiment we only adopted the large-scale environment from Typhoon Matsa (2005). The low-frequency background was obtained with a 20-day low-pass filter. We designed this numerical experiment to make the simulated tropical cyclone move in a realistic environment. For this reason, we changed the title into "Revisiting the Steering Principal of Tropical Cyclone Motion in a Numerical Experiment".

1. Equation 1: It would be good for the reader to find more explanations. The equation is used to determine the migration velocity C but it is not clear to me how the tendencies $\left(\frac{\partial P_1}{\partial t}\right)_f$ and $\left(\frac{\partial P_1}{\partial t}\right)_m$ are determined. It would also be good to see the formulas for the various contributions (HA, VA, DH and FR).

In the revised manuscript, we add the potential vorticity tendency equation as Eq. 2, which can make the reader better understand the contributions of individual terms to tropical cyclone motion. We also mentioned how to calculate the PV tendencies in the revised version of the manuscript.

The PV tendency in the moving reference frame can be calculated with the two-hour change of the wavenumber one component in the frame that moves with the tropical cyclone center. The PV tendency in the fixed reference frame can be calculated with the PV tendency equation, which has been included in the revised manuscript. The tendencies $\left(\frac{\partial P_1}{\partial t}\right)_f$ *and* $\left(\frac{\partial P_1}{\partial t}\right)_m$ can be further obtained by transforming the resulting PV tendencies to the cylindrical coordinates originating at on the tropical cyclone centers and then obtaining the wavenumber one components.

2. Page 11, line 232: I can see only in Fig. 6b that DH and VA are anticorrelated. Is there any explanation why these two terms should cancel each other out?

As shown in the attached figure (Fig. 10 in the revised manuscript), this figure shows the wavenumber-one components of the 500-hPa vertical motion, 700-hPa winds relative to tropical cyclone motion, and 500-hPa heating rate after 18 hours of integration. The upward (downward) motion generally occurs in the entrance (exit) region of the 700-hPa winds. Thus the contribution of the HA term is negatively correlated with those of the VA and DH terms.

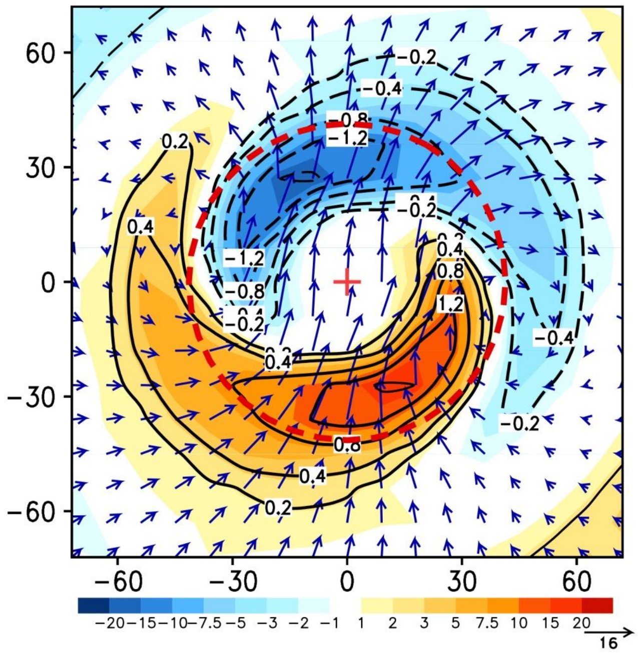

Figure 1 The wavenumber-one components of the 500-hPa vertical motion (contours, m s^{-1}), 700-hPa winds relative to the tropical cyclone motion (vectors, m s^{-1}), and 500-hPa heating rate (shaded, 10^{-4} K s^{-1}) after 18 hours of integration. The dashed circle indicates the radius of maximum wind.

3. Figure 8: To understand the figure better, the authors should show arrows of wavenumber 1 flow, V1 and contours of symmetric PV, Ps in Fig. 8a while Fig. 8b should display the symmetric flow Vs and the wavenumber one PV field, P1. This would facilitate the understanding why HA1 and HA2 exhibit the displayed pattern. It *is impossible for me to follow the explanation in the text. When the flow is northward HA1 should be positive (negative) north (south) of the cyclone given that the symmetric PV is positive. However, Fig. 8 shows the opposite result.*

Thank you for your suggestion. Based on your suggestion, the figure (Fig. 9 in the revised manuscript) was modified.

4. Caption Figure 2: Please indicate the pressure level for the wind vectors. I assume that the radar reflectivity results from a vertical integral. How is vertical wind shear defined? Is it just the difference wind vector between 200 and 850hPa? Is it the bold vector shown in the center? What is the scale of this vector?

Sorry for the confusion. The caption for this figure has been revised. The wind vectors and radar reflectivity are at 700 hPa. The vertical wind shear is calculated as the difference between 200 and 850 hPa winds, which is the bold vector in the tropical cyclone center. As shown in the figure, two scale vectors are located at the right lower corner. The upper one is for the wind vectors at 700 hPa and the lower one is for the vertical wind shear.

5. Fig. 5: The y axis should start at 0. In the figure caption please write "red boxes" and "black dots" instead of "right" and "left", respectively.

We have revised the y-axis and the figure caption in the manuscript.

6. Page 11, line 237: It would improve the readibility to use bold letters for vectors. Therefore, replace V1 and Vs by V1 and Vs, respectively.

Done

7. Page 12, line 254: The authors should use a notation like HA1' to denote that the contribution to conventional steering is removed.

It has been used.

8. Page 12, line 258: It should read "highly anticorrelated".

It has been corrected.

9. Page 13, line 288-291: The denotations VA1 and VA2 should be interchanged to have it consistent with HA1 and HA2.

We have revised the denotation of VA1 and VA2 terms.

10. Page 14, line 303: Replace q_s by $\boldsymbol{q}_s$.

Revised

11. Page 15, line 318: "Cyclone speed" does not relate to a direction. Use "cyclone motion" instead.

Replaced

12. Caption of Fig. 10: Replace "daiabtic" by "diabatic".

Corrected

13. Page 16, line 343: I would write this sentence as follows: "In general, the tropical cyclone center rotates cyclonically relative to the mean track position".

Revised

14. Caption of Fig. 12: Please indicate the level of the displayed PV fields. Fig. 13a: Does this figure show anomalies of 9 hour running mean? If so, this should be indicated in the figure caption.

The 700-hPa PV fields are demonstrated in Fig. 12. We have revised the figure captions of Fig. 12 and Fig. 13a have been revised.