A Diagnostic Method for Computing the Typhoon Steering Flow

Guo-Ji Jian[1] and Cheng-Shang Lee[2]
[1] Central Weather Bureau
[2] Department of Atmospheric Sciences, National Taiwan University

Abstract

A kinematic method is proposed to quantitatively diagnose the environmental steering flow surrounding an intense typhoon using an asymmetric geopotential field, which is determined by eliminating the symmetric portion of the total field based upon the model simulated data. The diagnosed steering vector of a typhoon is then defined as the average asymmetric flow in a ring within the radius of the larger Rossby number, up to a radius of 700 km. Diagnostic results of four intense typhoons, Haitang (2005), Longwang (2005), Shanshan (2006), and Sepat (2007), indicate that the "flow deflection" occurred as the diagnosed steering flow moves across the inner core region, suggesting that the vortex is inertially stable (with a larger Rossby number) near the center region. The inner core of the intense typhoon acts as an obstacle to prevent the steering flow from reaching the vortex center. The diagnosed steering flow, the major contributor to the vortex motion, is relatively uniform in the outer region of the typhoon. Analyzed results also show that the diagnosed steering vector is generally consistent with the observed storm motion except that the translation speed is underestimated for a faster-moving storm, such as the Longwang typhoon. The proposed method provides a starting point for resolving a more reasonable distribution of the steering flow surrounding an intense typhoon.

Key word: typhoon, steering flow

1. Introduction

Most of the earlier observational studies used a composite approach to examine the relationship between tropical cyclone movement and the environmental flow. George and Gray (1976) found that 500 hPa rawinsonde data at 1-7° radial belt (cyclone circulation removed) appeared to be appropriate in predicting cyclone motion over the western North Pacific area. Their results further indicated that 700 hPa wind fields could be used as a good indication of cyclone movement speed. Chan and Gray (1982) also found that the mean wind at 5-7° radius over the layer between 700 and 500 hPa was more appropriate for steering cyclones. Results of numerical studies (e.g., Smith et al., 1990) further showed that the cyclone motion generally agreed well with the flow averaged over a very small domain around the cyclone center, suggesting that azimuthal average winds near the cyclone center can effectively represent the steering flow.

Although significant research efforts have been directed toward applying the steering concept to predict tropical cyclone motion, the relationships between the distribution of steering flow and cyclone movement still remains unclear. Fundamental research problems include the ambiguous definition of the steering flow and the different schemes used to calculate the steering field. Other factors such as cyclone intensity, size, and track also seem to affect the determination of the best level in defining the steering flow. In addition, the interaction between a tropical cyclone and the steering flow may play an important role in generating the cyclone track. Our study, using a kinematic approach, develops a modified scheme for calculating the steering flow surrounding a typhoon. The advanced version of the Weather Research and Forecasting (WRF-ARW) model is used to simulate the motion of Supertyphoon Haitang (2005) with full physics for examining the validity of the proposed method. The steering flows associated with the three intense typhoons in this study, Longwang (2005), Shanshan (2006), and Sepat (2007), are also diagnosed using the data from operational Nonhydrostatic Forecast System at the Central Weather Bureau (CWB-NFS) for further evaluation of the performance of the method.

2. Basic framework and methodology

If friction can be neglected and a tropical cyclone reaches a steady state, the horizontal momentum equations in cylindrical coordinates can be written as

$$fv_\theta + \frac{v_\theta^2}{r} = \frac{\partial\Phi}{\partial r} \qquad (1)$$

$$fv_r + \frac{v_r v_\theta}{r} = -\frac{1}{r}\frac{\partial\Phi}{\partial\lambda} \qquad (2)$$

where v_r and v_θ are the radial (r) and azimuthal (λ) wind components, and Φ is the geopotential. Note that the above relations should be satisfied for a mature typhoon in the middle troposphere, where the friction is much smaller than in the boundary and outflow layers.

Applying a non-dimensional scaling parameter, the Rossby number ($R_o = \frac{v_\theta}{fr}$; the ratio of the centrifugal to Coriolis accelerations), and decomposing the variables into the symmetric and the asymmetric portions, equations (1) and (2) may be rewritten as

$$f\left(\overline{v_\theta} + v'_\theta\right)\cdot\left(1 + R_o\right) = \frac{\partial\left(\overline{\Phi} + \Phi'\right)}{\partial r} \quad (3)$$

$$f\left(\overline{v_r} + v'_r\right)\cdot\left(1 + R_o\right) = -\frac{1}{r}\frac{\partial\left(\overline{\Phi} + \Phi'\right)}{\partial \lambda} \quad (4)$$

Hence, the asymmetric winds are obtained by removing the symmetric portion and solving (3) and (4) for (v'_θ, v'_r) to yield

$$v'_\theta = \frac{\partial\Phi'/\partial r}{f\left(1 + R_o\right)} \quad (5)$$

$$v'_r = -\frac{\partial\Phi'/\partial\lambda}{rf\left(1 + R_o\right)} \quad (6)$$

As indicated in (5) and (6), the derived asymmetric winds give scientifically meaningful representations of the steering flow. The asymmetric winds are much weaker at the region near the vortex center (where the Rossby number is larger) than in the outer regions of the cyclone. This implies that penetration of the flow through the inner core region of a typhoon is negligible, due to the high inertia there. In other words, the environmental steering flow of a typhoon is highly sensitive to the vortex structure. The inner core region of a typhoon makes a relatively insignificant contribution to the asymmetric winds, due to its high inertial stability (close to a solid body rotation). Therefore, in this study, the diagnosed environmental steering flow is defined as the average asymmetric winds in a ring with a radius of the higher inertial region (larger values of R_o ; say greater than 5) out to 700 km in radius.

3. Diagnostic results of intense typhoons

To investigate the possibility of operational use by the CWB, the proposed method is applied to Longwang, Shanshan, and Sepat using the data from the operational CWB-NFS model, which are available every 12 h on a 15 km x 15 km grid. The time period specified for testing is at the most developed stage of each storm, when it was moving on the sea east of Taiwan. During this stage (i.e., between 1800 UTC 30 September and 1800 UTC 1 October 2005), Longwang moved rapidly westward toward the island at about 7.6 m s^{-1}, with an estimated maximum sustained wind of 51 m s^{-1} (10-min-averaged wind) and a minimum mean sea level pressure (MSLP) of 925 hPa. Inspection of the 700 hPa winds (figure not shown) indicates that a subtropical ridge axis extended from the sea south of Japan into southeastern China. Supertyphoon Longwang was south of the subtropical ridge axis. The asymmetric geopotential field, the diagnosed asymmetric winds, and the diagnosed steering vector ($\boldsymbol{C}_{Ro=5}$) for Longwang at 500 hPa and 700 hPa (bold arrow) are shown in Figs. 1a and 1b. Comparing this result to the motion of Longwang (open arrow) reveals that the diagnosed moving direction agrees fairly well with that of the actual storm. However, the magnitude of $\boldsymbol{C}_{Ro=5}$ (4.69 m s^{-1} at 500 hPa and 4.68 m s^{-1} at 700 hPa) is smaller than the translation speed of Longwang (7.6 m s^{-1}). Note that the results of diagnosed $\boldsymbol{C}_{Ro=2}$(4.81 m s^{-1} at 500 hPa and 4.88 m s^{-1} at 700 hPa; not shown) are very similar to the $\boldsymbol{C}_{Ro=5}$, suggesting that the diagnosed easterly flow in the northern and southern quadrants of the outer region plays a major role in steering the storm westward. In addition, the characteristic structure of flow deflection is also found near the vortex center, since the environmental flow can penetrate the inner core region only with great difficulty.

Typhoon Shanshan was a category 4 typhoon based on the Saffir–Simpson scale at its most developed stage (i.e., between 1200 UTC 15 and 1200 UTC 16 September 2006). During this time period, it moved northward and then turned toward the northeast at about 5.8 m s^{-1} in the sea east of Taiwan, with estimated maximum winds of 48 m s^{-1} and a minimum MSLP of 940 hPa. The 12 h forecast (valid at 0000 UTC 16 September 2006) for the winds and geopotential height at 700 hPa indicates that Shanshan was west of the subtropical ridge with a synoptic-scale trough to the northwest. The trough was oriented approximately northeast–southwest along the southeastern coast of China (figure not shown). The results of the diagnosed steering current in Figs. 1c and 1d show that Typhoon Shanshan was embedded in a southwesterly flow of around 20-25 kts in the northwestern and southeastern portions of the outer region. The diagnosed steering vector is pointing to the northeast and generally in good agreement with the observed movement, except that the actual storm moved to the left of the diagnostic results. The magnitude of the 500 hPa diagnosed steering flow (5.43 m s^{-1} for $\boldsymbol{C}_{Ro=5}$ and 5.54 m s^{-1} for $\boldsymbol{C}_{Ro=2}$; Fig. 1c) is also close to the translation speed of Shanshan (5.8 m s^{-1}). At 700 hPa (Fig. 1d), the diagnostic scheme underestimates the storm's speed of movement by about 4.61 m s^{-1} for $\boldsymbol{C}_{Ro=5}$ and 4.71 m s^{-1} for $\boldsymbol{C}_{Ro=2}$.

Supertyphoon Sepat reached its peak intensity of 53 m s^{-1} just before approaching the southeastern coast of Taiwan (i.e., between 0600 UTC 16 and 1200 UTC 17 August 2007). During its most intense stage, Sepat moved northwestward at a forward speed of about 5.4 m

s^{-1} around the southwestern periphery of the subtropical high centered over Japan. Results of the diagnosed asymmetric winds (Figs 1e and 1f) suggest that the kinematic method proposed in this study provides a useful tool for deriving the environmental flow surrounding the storm. The diagnosed steering vector yields a fairly good estimate of the storm motion in this case study (4.76 m s^{-1} for $C_{Ro=5}$ and 4.84 m s^{-1} for $C_{Ro=2}$ at 500 hPa). The distribution of diagnosed asymmetric winds demonstrates again that the inner core of a supertyphoon acts as an obstacle to the steering current, which prevents the environmental flow from reaching the core.

4. Discussion and conclusions

Although "steering" has been the dominant concept in predicting the tropical cyclone motion, the relationship between the tropical cyclone motion and the mean steering flow still remains unclear. In the present study, a kinematic method is proposed and applied to calculate the asymmetric winds through the asymmetric geopotential field, which is determined by eliminating the symmetric component from the total field based upon the model simulated data. The diagnosed steering vector of the storm is then defined as the average asymmetric winds in a ring with a radius of the larger Rossby number, to a 700 km radius.

Results indicate that the Rossby number (or the inertial stability) greatly increases as the surrounding flow is moving toward the vortex center, creating a "flow deflection" around the inner core region of the vortex. Such a result is quite different from the traditional expectation of the steering concept, in which the tropical cyclone is regarded as a point vortex being advected by the mean surrounding flow at its center.

This kinematic method is also applied to calculate the steering flow associated with three intense typhoons [Longwang (2005), Shanshan (2006), and Sepat (2007)] using the data from operational CWB-NFS model for further evaluation of the diagnostic performance. Analyzed results reveal that the diagnosed steering vector is generally consistent with the observed movement, except that the translation speed is underestimated for the faster-moving storm in the Longwang case study. By comparing the motion of Shanshan with the diagnosed results, this method helps understand the northeastward turn of Shanshan, as well as providing a useful tool to determine the distribution of the environmental steering current. The characteristic structure of flow deflection is also found in these intense typhoons, which demonstrates again that the inner core of the intense typhoon acts as an obstacle to prevent the environmental flow from reaching the core.

Although only few cases were investigated in this study, it provides a starting point for resolving a more reasonable distribution of the steering current. However, more cases need to be examined in detail to address the generality of this proposed method.

REFERENCES

Chan, J. C. L., and W. M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. *Mon. Wea. Rev.*, **110**, 1354-1374.

George, J. E., and W. M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. *J. Appl. Meteor.*, **15**, 1252-1264.

Smith, R. K., W. Ulrich and G. Dietachmayer, 1990: A numerical study of tropical cyclone motion using a barotropic model. Part I. The role of vortex asymmetries. Quart. J. Roy. Meteor. Soc., 116, 337-362.

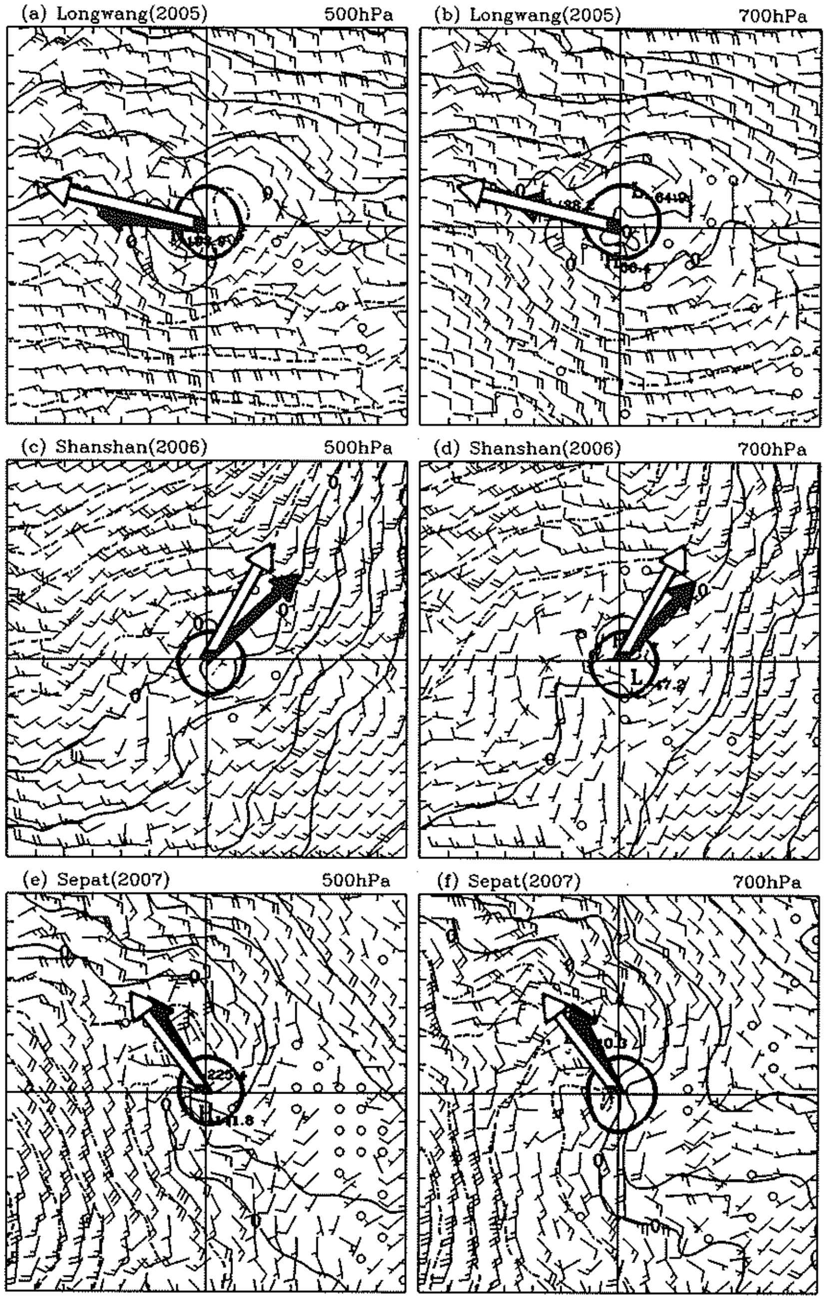

Fig. 1. Diagnostic asymmetric wind vectors (one full wind barb = 5 m s^{-1}) and asymmetric geopotential field (contour interval of 100 $m^2 s^{-2}$) at (a) 500 hPa for Longwang, (b) 700 hPa for Longwang, (c) 500 hPa for Shanshan, (d) 700 hPa for Shanshan, (e) 500 hPa for Sepat, and (d) 700 hPa for Sepat from CWB-NFS 12-h forecast. The open arrows indicate the simulated storm motion vector. The boldface arrows in each panel show the diagnostic steering flow defined as the average of diagnostic asymmetric winds in a ring with a radius of *Ro*=5 (heavy solid contour) to 700-km radius. The domain in each panel is 1400 km × 1400 km.