# A STUDY ON TYPHOON MOVEMENT PART Ⅱ: DYNAMICAL ROLE OF SMALL TOPOGRAPHY AND THE PLANETARY BOUNDARY LAYER①

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**ABSTRACT**

The dynamic effects of small topography (in the sense of the characteristic height of the topography as compared with the vertical thickness of the system of motion) and the Ekman pumping caused by the frictional convergence in the bounary layer on the motion of a typhoon have been qualitatively discussed in this part based on the governing equation of typhoon motion derived in part Ⅰ of this paper. The results show that a topographical ridge tends to attract the typhoon approaching it and this explains at least partially the phenomenon that the typhoon over the western Pacific tends to accelerate just before their making landfall over the coastal areas. It is also shown that the Ekman pumping at the top of the boundary layer favors the typhoon acceleration along the local steering current.

**Key words**: typhoon movement, topographical forcing, Ekman steering current

## Ⅰ. INTRODUCTION

As an extension of part Ⅰ our attention will be focused on the lifting effect of small topography, of which the characteristic height is much smaller than the vertical thickness of a typhoon system and the effect of the Ekman pumping caused by the frictional convergence in the planetary boundary layer (PBL) on the motion of a typhoon. It has been shown by observational and laboratory studies (Chen and Ding, 1979, Brand and Belelloch, 1973, 1974, Dong and Li, 1980 and Zhang, Wei and He, 1975) that typhoons over the west Pacific and the South China Sea tend to accelerate just before their making landfall over the coastal areas. The purpose of this part is to show qualitatively that the phenomenon above and the so-called Fujiwhara effect (Qi, 1980, Qi and Guan, 1980, Tang and Zhu, 1983) are at least partially related to topographical lifting effect and the effect of Ekman pumping at the top of the PBL, respectively.

## Ⅱ. THE GOVERNING EQUATION FOR THE EFFECTS OF TOPOGRAPHY AND THE PBL

The basic equation governing the motion of a typhoon center [ see Eq. (9) in part Ⅰ ] can be rewritten as

$$M\frac{d\vec{V}_0}{dt} = \sigma\,\overline{(\rho w\vec{V})_b} + \vec{R}, \tag{1}$$

where

$$M \equiv \int_\tau \rho d\tau, \quad \vec{R} \equiv \int_\tau \vec{R} d\tau, \quad \overline{(\quad)} \equiv \frac{1}{\sigma}\int_\tau (\quad) d\sigma$$

① This paper summarizes the work of a specialized research coded 85-906-07-02.

$$\begin{aligned} \overset{\Delta}{R} \equiv & - \nabla p - \rho f \vec{k} \wedge \vec{V} - \rho \vec{V} \frac{\partial \ln p}{\partial t} - \rho \frac{\partial \vec{V}_R}{\partial t} - \nabla \cdot (\rho \vec{V} \vec{V}) \\ & + \left[ \frac{Q}{C_p} - \vec{V} \cdot \nabla T - w(r_d - r) \right] \rho \vec{V} + \rho \vec{F}, \end{aligned} \tag{2}$$

$p$, $\rho$, $T$, $\vec{V}$ and $w$ are respectively the pressure, density, temperature, horizontal and vertical velocities of air, $\vec{V}_0$ the velocity of a typhoon center, $\vec{V}_R$ the relative velocity of air with respect to the typhoon center, $\sigma$ and $\tau$ the horizontal area and volume of the typhoon system respectively, and the subscript "$b$" denotes the values at the bottom ($z = z_b$, on the top of the PBL) of the typhoon system. Readers are referred to part I for the meaning of other symbols.

For small topography with characteristic height smaller than the vertical thickness of a system of motion, the boundary condition at the top of the tilted Ekman layer (i. e. on the lower boundary of the inner region) can be approximately given (see Pedlosky, 1979) as

$$w = (\vec{V} \cdot \nabla h + n^2 \zeta)_b, \qquad at\ z = z_b \tag{3}$$

where $h = h(x,y)$ represents terrain height, $\nabla$ the horizontal gradient operator, $\zeta$ the vertical component of the vorticity of flow field and $n^2 \equiv \left(\frac{A_v}{2f}\right)^{1/2}$ is a parameter determined by the vertical turbulent viscous coefficient ($A_v$) and the Coriolis parameter ($f$). The first term on the r. h. s. of (3) is the vertical velocity caused by topographical lifting with order of $O(UH/L)$. Here $L$ and $U$ are respectively the horizontal characteristic length and velocity scales of motion and $H$ is the characteristic scale of the terrain height variation over $L$. The second term on the r. h. s. of (3) is the Ekman pumping velocity due to turbulent viscous in the PBL, which is of the order of $O(U\delta_E/L)$. $\delta_E \equiv \left(\frac{2A_v}{f}\right)^{1/2}$ is the characteristic thickness of the Ekman layer. The ratio of the topographically forced velocity to the Ekman pumping velocity is therefore $O(H/\delta_E)$. The topographical forcing dominates over the Ekman pumping when $H > \delta_E$. On the contrary, the Ekman pumping dominates over the topographical forcing when $H < \delta_E$.

Using (3) and (1), the partial acceleration of a typhoon center forced by topographical lifting and Ekman pumping can be expressed as

$$\frac{d\vec{V}_0}{dt} = \frac{\sigma}{M} \overline{(\rho w \vec{V})_b} = C^2 [\overline{\vec{V} (\vec{V} \cdot \nabla h)} + \overline{n^2 \zeta \vec{V}}]_b, \tag{4}$$

where

$$C^2 \equiv \frac{\sigma \bar{\rho}_b}{M}. \tag{5}$$

The forcing terms included in $\overset{\Delta}{R}$ in Eq. (1) will not be discussed in this part of the paper. Some of them have been treated in part I and some others will be analysed and discussed in part III of this paper.

## III. THE EFFECTS OF TOPOGRAPHY ON THE MOVEMENT OF A TYPHOON

The partial acceleration of a typhoon forced by topography in Eq. (4) can be expressed as

$$\frac{d\vec{V}_0}{dt} = C^2[\overline{\vec{V}(\vec{V} \cdot \nabla h)}]_b. \quad (6)$$

A natural coordinate system, of which the $s$-axis is set to be along the direction of $\vec{V}_0$, the $n$-axis is perpendicular to and directed to the left of the $s$-axis, $\vec{s}$ and $\vec{n}$ are respectively the unit vectors along the $s$-axis and $n$-axis, will be used in the following discussion. $\vec{V}_0$ and $\vec{V}$ can then be written as

$$\vec{V}_0 = V_0\vec{s}, \quad (7)$$
$$\vec{V}_0 = V_s\vec{s} + V_n\vec{n}. \quad (8)$$

For simplicity, an idealized case of topography with a constant slope will be employed to explain qualitatively the effects of topographical forcing on the movememt of a typhoon. Equation (6) can be divided into its tangential and normal components:

$$\frac{dV_0}{dt} = C^2\left(\overline{V_s^2}\frac{\partial h}{\partial s} + \overline{V_s V_n}\frac{\partial h}{\partial n}\right)_b, \quad (9)$$

$$K_T = C^2 V_0^{-2}\left(\overline{V_n^2}\frac{\partial h}{\partial n} + \overline{V_s V_n}\frac{\partial h}{\partial s}\right)_b, \quad (10)$$

where $K_T$ is the curvature of a typhoon path which is positive ( $K_T > 0$ ) for left-turning path and negative ( $K_T < 0$ ) for right-turning path. Equations (9) and (10) express the effects of topography on the change rate in speed and in direction of a typhoon respectively.

The first term on the r. h. s. of (9) depends on the tangential gradient of topography ( $\frac{\partial h}{\partial s} \neq 0$ ). We would have $\frac{dV_0}{dt} > 0$ when the terrain hight increases along the moving direction of the typhoon i. e. $\frac{\partial h}{\partial s} > 0$ and the typhoon would tend to accelerate. On the contrary, we have $\frac{dV_0}{dt} < 0$ when $\frac{\partial h}{\partial s} < 0$ and the typhoon would tend to decelerate. In short, the typhoon would tend to accelerate when it moves uphill and decelerate when it goes downhill. Physically speaking, there would be horizontal momentum in $s$-direction transported upward through the top of the PBL ( $\overline{\rho w V_s} > 0$ ) contributing to the increase of the total $s$-momentum of the typhoon system and to its acceleration in the same direction when the typhoon moves uphill. On the contrary, the typhoon would lose horizontal $s$-momentum and decelerate when it moves downhill.

The second term on the r. h. s. of Eq. (9) depends on both the normal gradient of topography and the correlation between $V_s$ and $V_n$. For convenience, we consider an especially simple case of $\frac{\partial h}{\partial n}$ = constant $< 0$ and $\frac{\partial h}{\partial s} = 0$. In this case, higher topography is located to the right side of typhoon (Fig. 1). In Fig. 1, the gradient of the topography is directed to the north and the typhoon to the south slope is heading westward. A dashed line across the typhoon center divides the system into a front and a rear semi-part. We usually have $(V_sV_n)_b > 0$ in the right-front affecting area (denoted by RF) and $(V_sV_n)_b < 0$ in the left rear affecting area (denoted by RR). If we have, on the average, $(V_sV_n)_b < 0$ (e. g. stronger wind speed appears in the region RR) the typhoon will speed up west-

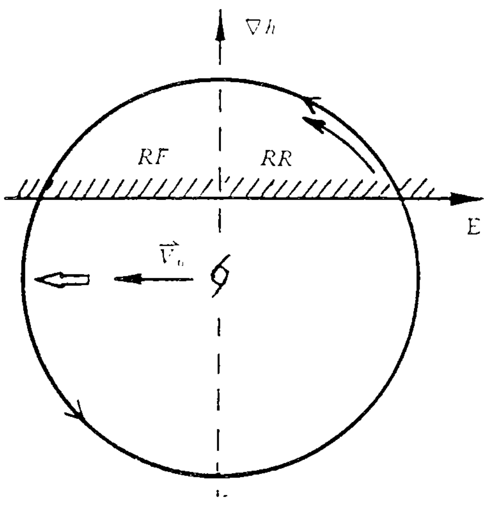


Fig. 1. Schematic of typhoon acceleration due the topographical slope normal to the typhoon track.

ward ( $\frac{dV_0}{dt} > 0$ , shown by the hollow arrow). On the contrary, in the case of $(V_sV_n)_b > 0$ (e. g. stronger wind speed appears in the region RF) the typhoon will decelerate ( $\frac{dV_0}{dt} < 0$). It is not difficult to show that we would have $(V_sV_n)_b = 0$ ,if the flow field is axially symmetric with respect to the typhoon center. That is to say, the role of this term substantially depends on the axial asymmetry of the flow field in the affecting area. Over the South China Sea the accelerating phenomenon of a typhoon heading westwards along the coast of South China is often observed (Chen et al, 1979). The analysis above showed clearly that a proper couple of a south slope of topography and a typhoon circulation can cause a partial westward acceleration of the typhoon.

The role of the two terms on the r. h. s. of Equation (10) can be referred to as the deflecting effect of topography on the movement of a typhoon. The first term depends on the normal gradient of topography. When higher topography is located to the left of an advancing typhoon (Fig. 2a), $\frac{\partial h}{\partial n} > 0$ and $K_T > 0$ hold, i. e. the typhoon will tend to be deflected to the left. When higher topography is located to the right of an advancing typhoon (Fig. 2b), we have $\frac{\partial h}{\partial n} < 0$ and $K_T < 0$ , i. e. the typhoon will be deflected to the right. The deflecting direction of the typhoon due to the effect of topography is indicated by the dashed arrows in Fig. 2. It is obvious from Fig. 2 that a typhoon always turns uphill due to the deflecting effect of topography no matter which side, left or right, the higher topography is located on. We see clearly an interesting phenomenon from the

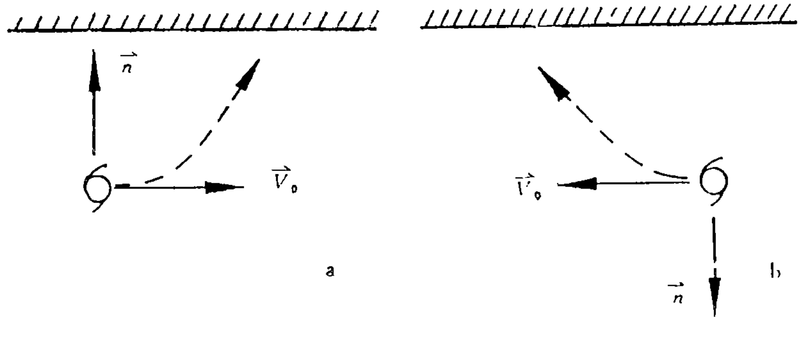


Fig. 2. Schematic of the typhoon track deflection by the topographical slope normal to the track.

a. $\frac{h}{n} > 0$; b. $\frac{h}{n} < 0$

preceding discussion on the deflecting and the accelerating [revealed by the first term on the r. h. s. of Eq. (9)] effects that a higher topograhy seems to have an "attracting effect" to a moving typhoon rather than to push it away.

The second term on the r. h. s. of Eq. (10) is determined by the tangential gradient of topography and the correlation between $V_s$ and $V_n$. We consider a special case of $\frac{\partial h}{\partial s}$ = constant $> 0$ and $\frac{\partial h}{\partial s} = 0$. Without losing generality, we particularly examine the case shown in Fig. 3, in which a typhoon to the east slope of the topography is moving westward. The typhoon will turn to the right when the axial-asymmetry of the flow field in the affecting area is such that $(\overline{V_s V_n})_0 < 0$ (e. g. greater wind speed is observed in the left-front section of the system) and $K_T < 0$ hold (Fig. 3a). And it will turn to the left when the axial-asymmetry of the flow field in the affecting area is such that $(\overline{V_s V_n})_0 > 0$ and $K_T > 0$ hold (Fig. 3b).

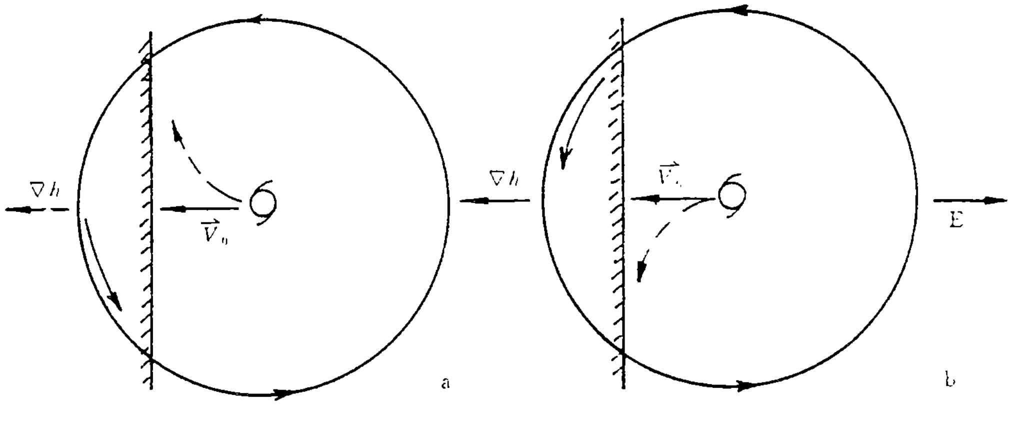


Fig. 3. Schematic of typhoon deflection caused by topographical slope along the typhoon track.

The effects of topography on the movement of a typhoon can be summarized as its attracting and deflecting effects. Reviewing what we have discussed in Part I, it can easily be realized that the role of a region of higher topography in the movement of a typhoon is equivalent to that of a region of lower temperature.

Quite a few observational studies of the effect of topography on the movement of a typhoon appeared in the literature of meteorology. The statistical results by Chen et al. (1979) showed that over the coastal areas of the western Pacific, accelerating phenomenon of a typhoon was often observed before its landfall. Quite often a sudden acceleration of a typhoon near the coast appeared 6～12 hours before making a landfall and the maximum acceleration can reach a value of 1. 2 km/hr$^2$. Brand et al. (1974) examined 30 cases of typhoons landed over the Philippine Islands and 20 others landed over Taiwan Island. The results showed that the average speed of the typhoons before landfall appeared to be increasing. The moving speed increased continuously for typhoons of weaker intensity and decreased for those of stronger intensity during their crossing over Taiwan Island. Zhang et al. (1975) observed in annulus experiments the phenomenon of accelerating of the land-falling vortexes over the southeast coast of China.

## IV. THE EFFECT FOR EKMAN PUMPING

The partial acceleration of a typhyoon produced by the Ekman pumping due to turbulent viscosity in PBL can be expressed [see Eq. (4)] as

$$\frac{d\vec{V}_0}{dt} = C^2 \overline{(n^2 \zeta \vec{V})_b}. \tag{11}$$

Neglecting the horizontal non-uniformity of the turbulent viscous coefficient $A_v$ and taking $n$ as a constant, Eq. (11) can then be written as

$$\frac{d\vec{V}_0}{dt} = C^2 n^2 \overline{(\zeta \vec{V})_b}. \tag{12}$$

According to the definition of flow-field steering and local steering currents presented in Part I, $\vec{V}_b$ is simply the local steering velocity at the top of PBL. $(\zeta\vec{V})_b$ can be referred to as Ekman steering velocity, a weighted steering velocity with $\zeta$ as the weighting function, which coincides with the local flow-field steering velocity when $\zeta>0$ as we usually observed in the lower layer of a typhoon system. It can be seen from Eq. (12) that the Ekman pumping effect is determined by the axial-asymmetry of the Ekman steering velocity, otherwise, $\overline{(\zeta\vec{V})_b} = 0$ and there would be no net contribution of friction in PBL to the movement of a typhoon.

It is observed that when two typhoons (twin typhoons) appear simultaneously and get close enough to each other (e. g. within 12 Lats., as estimated by Tang et al., 1983) the two centers usually rotate anticlockwisely around a point somewhere in between. This is the so-called Fujiwhara effect. What we want to explain is that the Ekman effect described above supports the Fujiwhara effect. Suppose the two centers of twin typhoons are initially at the same latitude and the associated flow fields and the Ekman steering velocity fields are axially symmetric, the flow field in between would become relatively weaker because the canceling out of the reverse winds and the initial axial symmetry of the flow field would be destroyed when the two centers get close enough to each other (Fig. 4). In the resultant flow field, strong southerly and northerly would

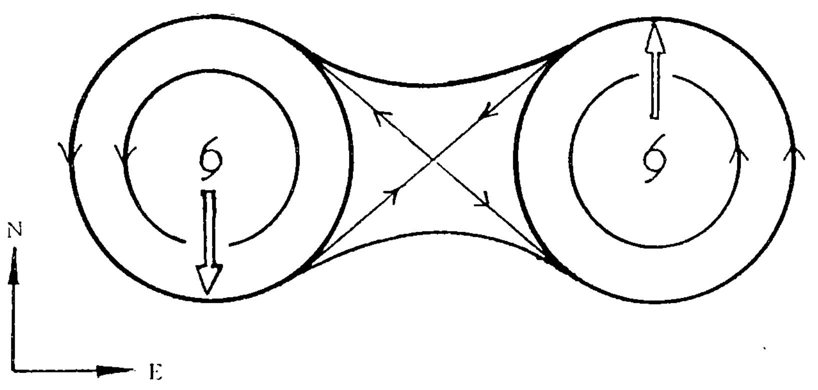


Fig. 4. Schematic of the Ekman steering current and the Fujiwhara effect.

appear respectively in the eastern part and the western part of the twin typhoons. The right gyre is steered by a net northward Ekman steering and obtained a northward partial acceleration (shown by hollow arrow); the left gyre steered by a net southward Ekman steering. Therefore the Ekman steering associated with the Ekman pumping at the top of the PBL supports or enhances the so-called Fujiwhara effect.

## V. SUMMARY AND DISCUSSIONS

a. The effect of topography on the movement of a typhoon can be summarized as its attracting effect and deflecting effect. The role of a region of higher topography in the movement of a typhoon is equivalent to that of a region of lower temperature. The effect of topography is physically the result of the vertical (downward or upward) transportation of horizontal momentum through the bottom of a typhoon by the vertical motion forced by the topography. A typhoon under the effect of Ekman steering at the top the PBL tends to accelerate ( $\zeta_b > 0$ ) or decelerate ( $\zeta_b < 0$ ) along the flow field steering current.

b. Ekman pumping and the heating of cumulus convection discussed in Part I are two key factors of the well-known CISK mechanism which is regarded as the main mechanism for the development of tropical cyclones. It seems from the analysis above that the CISK mechanism determines not only the development but also the movement of a tropical cyclone. The moving and the developing of a tropical cyclone are therefore closely related.

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