A STUDY ON TYPHOON MOVEMENT PART III: EFFECT OF THE HORIZONTAL MOMENTUM EXCHANGE BETWEEN TYPHOONS AND ENVIRONMENT

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ABSTRACT

Two semi-asymmetric flow patterns of typhoons are chosen to qualitatively determine the effect of exchange of horizontal momentum between inflow and outflow layers and the environment on the motion of typhoons. The results show that only the asymmetric flow component (residual after azimuthal mean flow has been removed) could cause a net momentum input into or output from a typhoon and therefore contribute to the changes in speed and direction of the typhoon movement. A typhoon with major inflow and/or outflow channels on its right (left) side would tend to accelerate and turn left (decelerate and turn right); On the other hand, a typhoon with major inflow and/or outflow channels in the rear (front) semicircle would tend to accelerate and turn right (decelerate and turn left).

Key words: typhoon movement, horizontal momentum exchange, semi-asymmetric typhoon

I. INTRODUCTION

We have learned from the documentation (He, 1995, He and Yang, 1996) that the effect of diabatic heating distribution, temperature distribution, topographic features and friction at the planetary boundary layer on the movement of a typhoon is at least partially related with the asymmetry of the typhoon flow field. With ignorance of the inhomogeneity in the distribution of air density, the exchange of horizontal momentum between the typhoon system and the environment can then be proved to depend entirely on the non-axisymmetry of the flow field in the domain of typhoon. A large amount of results from observational analyses (Chen and Ding, 1979, Russell Elsberry and Frank, et al., 1987) have shown that in reality the flow field of a tropical cyclone is always highly axially asymmetric about the height, which causes the exchange of horizontal momentum between the typhoon and the environment that is not negligible in the development and movement of typhoon.

In spite of multiple and complicated forms of asymmetric flow field where the typhoon activates, two representative patterns of semi-asymmetric typhoon can roughly be induced from. They are left- or front-rear asymmetric patterns, to sum up generally. Analyses will be done of the two models of typhoon in terms of the abstracted, idealized semi-asymmetry to illustrate the qualitative characteristics of the influence of exchange of horizontal momentum between the inflow and outflow layers upon the speed at and direction in which the typhoon moves.

II. RELATIONSHIP BETWEEN THE ASYMMETRIC FLOW FIELD AND THE ACCELERATION OF TYPHOON

Pertaining the contribution of the exchange of horizontal momentum between the typhoon regime and the outer field to the storm's acceleration, let's first justify that it depends on that (1) the normal (or radial) velocity transversing the lateral side of typhoon must not be zero everywhere, or, there will be no such things as the exchange of horizontal momentum; and (2) the flow field must be non-axisymmetric, otherwise, there will be no net exchange of the horizontal momentum.

Following basic equations [See Eq. (9) in He, 1995] for the movement of typhoon center and ignoring other possible factors, the partial acceleration of typhoon forced by the exchange of horizontal momentum between the typhoon system and the environment can be expressed by

$$M\frac{\mathrm{d}\vec{V}_0}{\mathrm{d}t}\equiv-\int_\tau \nabla\cdot(\rho\vec{V}\vec{V})\mathrm{d}\tau \tag{1}$$

where

$$M\equiv\int_\tau \rho\mathrm{d}\tau$$

is the total mass of the typhoon system, τ its volume, ρ the density of air; $\vec{V}$ and ∇ the horizontal velocity and the operative symbol of horizontal gradient; $\vec{V}_0$ the velocity at which the center of the typhoon moves.

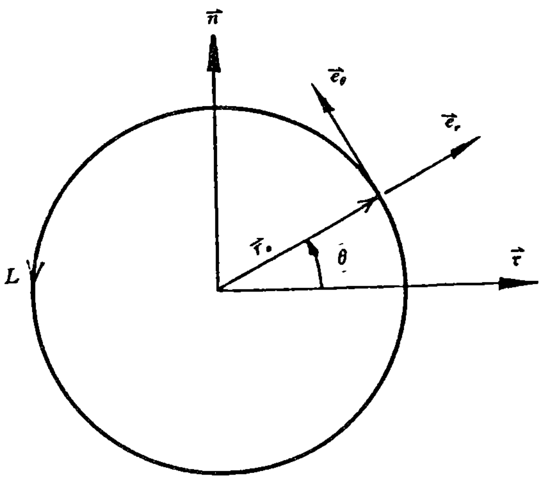

Fig. 1. Natural-cylindrical coordinates with origin at a typhoon center.

The typhoon is now idealized as a cylindrical system with a vertical thickness of H, a base radius of r_0 and a lateral area of S. To illustrate the effect of the non-asymmetry of flow field on the typhoon movement, it is more convenient to use the natural-columnar coordinates as shown in Fig. 1. $\vec{\tau}$ is the unit vector in the moving direction of typhoon at a given time, $\vec{n}$ the unit vector that is normal to $\vec{\tau}$ and pointing to the left. $\vec{e}_r$ and $\vec{e}_\theta$ are the radial and azimuthal vectors of the cylindrical coordinates, respectively, where the angle of θ is increasing clockwisely relative to the direction of $\vec{\tau}$ ($\theta=0$). The horizontal velocity of the air can be expressed by

$$\vec{V}=v_r\vec{e}_r+v_\theta\vec{e}_\theta \tag{2}$$

where $v_r\equiv \mathrm{d}r/\mathrm{d}t$ and $v_\theta\equiv r\mathrm{d}\theta/\mathrm{d}t$ are radial and tangential components of wind velocity.

Applying the Guassian theorem, Eq. (1) can be rewritten as

$$\begin{aligned} M\frac{\mathrm{d}\vec{V}_0}{\mathrm{d}t} &= -\iint_S (\rho v_r\vec{V})\mathrm{d}S \\ &= -\int_0^H \oint_L (\rho v_r\vec{V})\mathrm{d}l\mathrm{d}z \\ &\simeq -2\pi r_0\bar{\rho}\int_0^H \overline{(v_r\vec{V})}\mathrm{d}z \end{aligned} \tag{3}$$

where

$$\overline{(\quad)}\equiv\frac{1}{2\pi r_0}\oint_L(\quad)\mathrm{d}l \tag{4}$$

stands for the mean value along the periphery L (of the horizontal surface), and $dl = r_0 d\theta$ is the element of the integral line. The asymmetry of density is omitted in Eq. (3) and ρ is approximately replaced by $\bar{\rho}$. From Eq. (3), it is known that the question of computing the exchange of horizontal momentum can be summed up by derivation of $\overline{(v_r\vec{V})}$ at individual heights. It is noted that ($\vec{e}_r$, $\vec{e}_\theta$) and ($\vec{\tau}$, $\vec{n}$) are inter-related as

$$\vec{e}_r = \cos\theta\vec{\tau} + \sin\theta\vec{n}$$
$$\vec{e}_\theta = -\sin\theta\vec{\tau} + \cos\theta\vec{n}$$

$\vec{V}$ can be expressed by

$$\vec{V} = (v_r\cos\theta - v_\theta\sin\theta)\vec{\tau} + (v_r\sin\theta + v_\theta\cos\theta)\vec{n} \tag{5}$$

then

$$\overline{(v_r\vec{V})} = \frac{1}{2\pi r_0}\oint_L (v_r\vec{V})dl$$
$$= \frac{1}{2\pi}\int_0^{2\pi} [(v_r^2\cos\theta - v_r v_\theta\sin\theta)\vec{\tau} + (v_r^2\sin\theta + v_r v_\theta\cos\theta)\vec{n}]d\theta. \tag{6}$$

Obviously, if $v_r \equiv 0$ (the normal velocity is zero) or $\partial v_r/\partial\theta = \partial v_\theta/\partial\theta = 0$ (the flow field is symmetric about the axis) on the periphery L of the typhoon then $\overline{(v_r\vec{V})} = 0$, or, given no net exchange of horizontal momentum between the typhoon and the outer field, the typhoon will not change its moving velocity or direction. Apparently, $\overline{(v_r\vec{V})}_\tau$ and $\overline{(v_r\vec{V})}_n$ can be taken as the forcing factors to change the velocity and direction the typhoon takes.

Ⅲ. SIMPLIFIED MODELS OF ASYMMETRIC TYPHOON

In general, a typhoon regime can be divided into inflow and middle layers, in the lower troposphere, and an outflow layer in the upper troposphere. In the middle layer between the inflow and outflow layers, the azimuthal circulation is predominant and the radial movement is little or zero in approximation (Chen et al., 1979). Observational analyses have shown that both of the azimuthal and radial wind fields are well non-axisymmetric in the two layers and can be quite complicated, especially for the outflow layer. Some common characteristics, however, can still be found in the horizontal distributions of the flow field. Fig. 2 gives the 750 hPa horizontal distributions of azimuthal (c) and

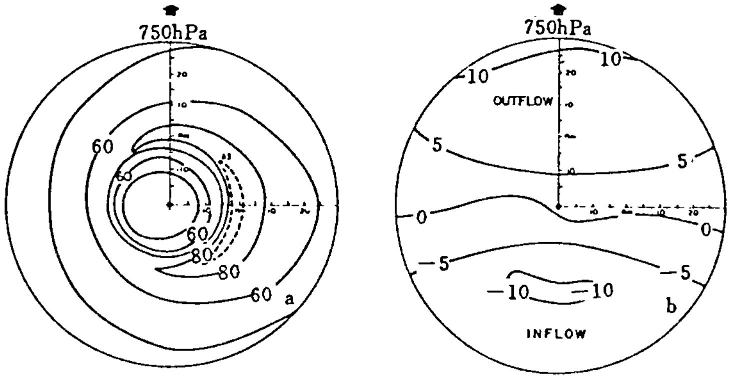

Fig. 2. Plan views of the composite azimuthal wind (a) and radial wind (b) at 750 hPa.

radial (b) velocities composited by Shea and Gray (1973) for the core regions of northern Atlantic hurricanes in respect to the radius of maximum winds (RMW). The velocity is in unit of 0.515 m/s, the unit of distance from the radius of maximum winds (RM) is 1609 m. The arrow points to the direction in which the storm is moving. The figure reveals that the crescent-shaped maximum azimuthal winds is basically located in the semicircle to the right of the direction in which the storm moves, so that the asymmetry is mainly about the right-left line. Things are different for the case of the radial wind field. There is outflow in the front semicircle of the storm and significant inflow in the rear one, showing in general asymmetry about the front-rear line. Analyses show that for areas outside the core the distributional characteristics in the lower tropospheric wind field are averagely similar to the situation described above. In other words, in the Northern Hemisphere, the maximum azimuthal winds are to the right of the storm, accompanied by radial inflow at the left-rear quadrant and radial outflow at the right-front quadrant. Fig. 3 plots the streamlines and isotaches of the asymmetric part (Subtracting what is left in the mean azimuthal flow) of the mean upper tropospheric outflow composited by Merrill (1985). The composition is completed in respect to the maximum outflow channel and the center of movement; N denotes a due north direction; the composited direction of the storm movement is to the northwest by north. (It is shown in the figure that the outflow is mainly located to the right of the storm and the inflow to the left of it.) Asymmetric outflow is mainly a structure of wavenumber one.

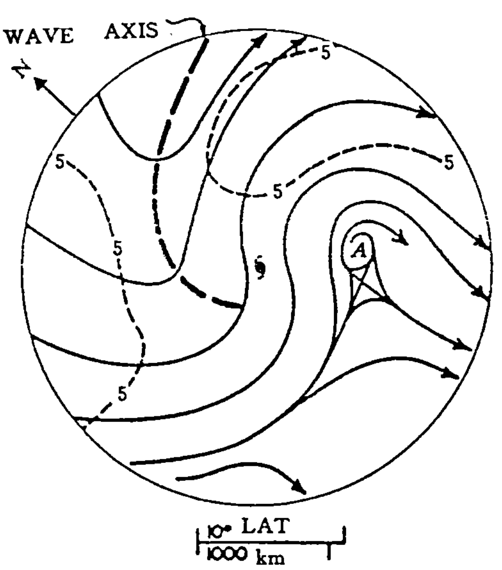

Fig. 3. Streamlines and isoteches (Merrill, 1985) of the asymmetric part at the composited outflow layer.

Based on the observational characteristics of the typhoon flow field, two semi-asymmetric (or, semi-symmetric) typhoon models are abstracted to become ideally left-right (L-R) or front-rear (F-R) asymmetric patterns. Before detailed mathematic description of the models, it is necessary to clarify the definition of the front, rear, left and right semicircles of the typhoon. For an observer who is standing at the center and facing the direction ($\theta = 0$) in which it moves ($\vec{\tau}$), the typhoon is divided into semicircles in the front ($0 < \theta \leqslant \pi/2$ and $3\pi/2 < \theta \leqslant 2\pi$) and the rear ($\pi/2 < \theta \leqslant 3\pi/2$) or in the left ($0 < \theta \leqslant \pi$) and the right ($\pi < \theta \leqslant 2\pi$) . Therefore, the two models above can be mathmetically expressed as

$$\begin{cases} (v_r)_{right} = \bar{v}_r + v_r' & \text{when } \pi < \theta \leqslant 2\pi \quad r = r_0 \\ (v_r)_{left} = \bar{v}_r - v_r' & \text{when } 0 < \theta \leqslant \pi \quad r = r_0 \end{cases} \tag{7}$$

$$\begin{cases} (v_\theta)_{right} = \bar{v}_\theta + v_\theta' & \text{when } \pi < \theta \leqslant 2\pi \quad r = r_0 \\ (v_\theta)_{left} = \bar{v}_\theta - v_\theta' & \text{when } 0 < \theta \leqslant \pi \quad r = r_0 \end{cases} \tag{8}$$

for the L-R pattern, with

$$\frac{\partial v_\theta'}{\partial \theta} = \frac{\partial v_r'}{\partial \theta} = 0 \tag{9}$$

where $\bar{v}_r$ and $\bar{v}_\theta$ are mean radial and azimuthal velocities and the quantities with "'" belong to the asymmetric part of the flow field; and

$$\begin{cases} (v_r)_F = \bar{v}_r + v_r' & \text{when } o < \theta \leqslant \pi/2 \quad 3\pi/2 < \theta \leqslant 2\pi \quad r = r_0 \\ (v_r)_R = \bar{v}_r - v_r' & \text{when } \pi/2 < \theta \leqslant 3\pi/2 \quad r = r_0 \end{cases} \tag{10}$$

$$\begin{cases} (v_\theta)_F = \bar{v}_\theta + v_\theta' & \text{when } o < \theta \leqslant \pi/2 \quad 3\pi/2 < \theta \leqslant 2\pi \quad r = r_0 \\ (v_\theta)_R = \bar{v}_\theta - v_\theta' & \text{when } \pi/2 < \theta \leqslant 3\pi/2 \quad r = r_0 \end{cases} \tag{11}$$

for the F-R pattern. v_r' and v_θ' all satisfy (9) too. For the L-R pattern, the asymmetric part of the flow field is featured by left-right anti-symmetry (of equal magnitude but opposite signs); in the same left or right semicircle, however, both azimuthal and radial velocities are independent of θ. For the F-R pattern, the asymmetric part of the flow field is characteristic of front-rear anti-symmetry; but the velocity is independent of θ on the front or rear semicircle. For these simplified models, the integration to the right of (6) is easily and accurately derived by

$$\begin{cases} \overline{(v_r\vec{V})}_\tau = \frac{2}{\pi}(\bar{v}_r v_\theta' + \bar{v}_\theta v_r') & (12) \\ \overline{(v_r\vec{V})}_n = -\frac{4}{\pi}\bar{v}_r v_r' & (13) \end{cases}$$

for the L-R pattern; and by

$$\begin{cases} \overline{(v_r\vec{V})}_\tau = \frac{4}{\pi}\bar{v}_r v_r' & (14) \\ \overline{(v_r\vec{V})}_n = \frac{2}{\pi}(\bar{v}_r v_\theta' + \bar{v}_\theta v_r') & (15) \end{cases}$$

for the F-R pattern. Following Eqs. (13) and (14), it is seen that any changes in the moving direction of the L-R or moving speed of F-R patterns are all independent of azimuthal asymmetric velocity v_θ', but rather resulted entirely from the radial asymmetric velocity v_r'.

It is indicated previously in this paper that the exchange of horizontal momentum between the typhoon and environment mainly takes place in the inflow and outflow layers. The focus now is only on the discussion of the effect of the horizontal exchange arizen from the asymmetry of the layers on the movement of typhoons. The layers of inflow and outflow are defined as the ones in which ($\bar{v}_\theta<0$) and ($\bar{v}_\theta>0$) without any well-cut restraints on $\bar{v}_\theta$. In reality, however, the inflow layer is usually convergent with cyclonic circulation ($\bar{v}_\theta>0$)and divergent with anti-cyclonic circulation, a most likely situation for the Northern Hemisphere, for such combination conforms with the general case of cyclones and anticyclones in the hemisphere. For a definite discussion, it is assumed that $\bar{v}_r<0$ and $\bar{v}_\theta>0$ in the inflow layer and $\bar{v}_r>0$ and $\bar{v}_\theta<0$ in the outflow layer. Of course, pure theory allows for definition of the inflow (outflow) layers with $\bar{v}_\theta>0$ ($\bar{v}_\theta>0$), or, to be anti-cyclonically (cyclonically) structured, though there is no significant use in practice.

Ⅳ. INFLOW LAYER

In view of the purpose of qualitative illustration of the characteristics of horizontal momentum exchange resulted from the asymmetry of flow field on the movement of typhoon, any vertical difference of the inner flow field in the inflow layer (with a thickness of h) will be ignored for simplicity. The lower mark "IL" stands for the inflow layer. Following (3) then, the partial acceleration of typhoon produced by the inflow layer can be decomposed into

$$\left(\frac{\mathrm{d}V_0}{\mathrm{d}t}\right)_{\mathrm{IL}}=-\frac{2\pi r_0}{M}\left[\bar{\rho}h\ \overline{(v_r\vec{V})_\tau}\right]_{\mathrm{IL}} \tag{16}$$

$$(K_T)_{\mathrm{IL}}=-\frac{2\pi r_0}{MV_0^2}\left[\bar{\rho}h\ \overline{(v_r\vec{V})_n}\right]_{\mathrm{IL}} \tag{17}$$

where K_T is the locus curvature of typhoon movement defined by

$$\frac{1}{V_0}\frac{\mathrm{d}\vec{\tau}}{\mathrm{d}t}=K_T\vec{n}. \tag{18}$$

Symbolically, when $K_T>0$, the typhoon tends to turn left; when $K_T<0$, it tends to turn right.

(1) L-R pattern

Substituting (12) and and (13) into (16) and (17), respectively, we have

$$\left(\frac{\mathrm{d}V_0}{\mathrm{d}t}\right)_{\mathrm{IL}}=-\frac{4r_0}{M}\left[\bar{\rho}h\left(\bar{v}_r v_\theta'+\bar{v}_\theta v_r'\right)\right]_{\mathrm{IL}} \tag{19}$$

and

$$(K_T)_{\mathrm{IL}}=\frac{8r_0}{MV_0^2}\left[\bar{\rho}h\bar{v}_r v_r'\right]_{\mathrm{IL}}. \tag{20}$$

They are the governing equations of the L-R pattern typhoon for which the net inflow or outflow of horizontal momentum in the inflow layer influences variations in the velocity and direction of the storm. Fig. 4 schematically plots two typical distributions of the flow field for the L-R pattern of asymmetric inflow layer. Specifically, for the case shown in Fig. 4a, the flow velocity (indicated by the horrow arrow) on the right semicircle is relatively large and the asymmetric part of the flow field is characterized by $v_r'\equiv[(v_r)_{right}-(v_r)_{left}]/2<0$, and $v_\theta'\equiv[(v_\theta)_{right}-(v_\theta)_{left}]/2>0$. Then, for Eq. (19), $\bar{v}_\theta v_r'<0$, and $\bar{v}_r v_\theta'<0$ so that $(\mathrm{d}V_0/\mathrm{d}t)_{\mathrm{IL}}>0$, or, the typhoon will accelerate. For (20), on the other hand, $\bar{v}_r v_r'>0$ and $(K_T)_{\mathrm{IL}}>0$, that is to say, the typhoon will recurve to the left.

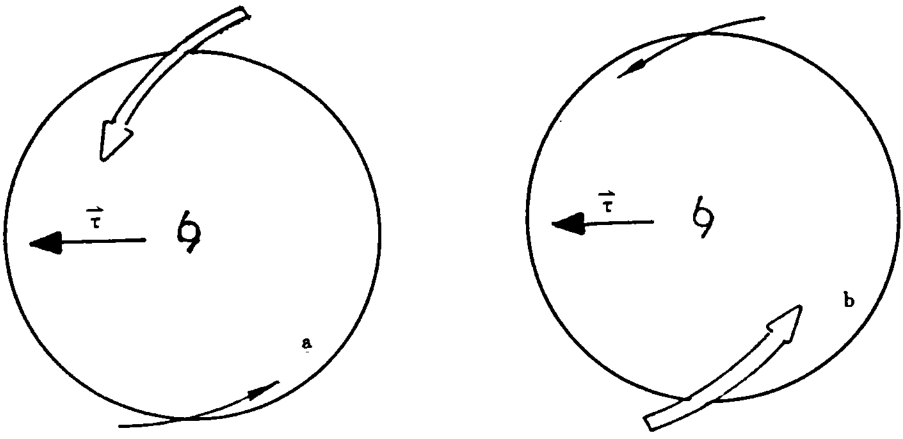

Fig. 4. L-R type asymmetric inflow layer.

The acceleration and recurvature, as they turn out to be, are the consequence of net momentum input in the direction of $\vec{\tau}$ (in which the typhoon moves) and $\vec{n}$ (pointing to the left of the direction of typhoon movement) caused by the asymmetric flow field. This is the pattern that is most representative of all asymmetric patterns for the Northern Hemisphere. Realistic cases for this pattern can be found in Chen et al., (1979) who described that typhoons travelling westward south of a continental cold high or moving in front of a trough of the easterly wave would accelerate such movement or recurve to the left or even follow a track of a parabola due to the invasion of an east by north airstream to the right. For the case shown in Fig. 4b, there is a large velocity of flow on the left semicircle of the typhoon and the asymmetric part of the stream field is featured by $v_r' > 0$ and $v_\theta' < 0$. As a result, one should find that $(dV_0/dt)_{IL} < 0$ and $(K_T)_{IL} < 0$, or the typhoon will decelerate and recurve to the right. For this pattern, the typhoon would decelerate and recurve to the north due to the intrusion of a southerly flow to the left, when it moves west towards where there is a trough of the southwesterly or just enters a converging line joining the southwesterly and southeasterly monsoons (Chen et al., 1979).

(2) F-R pattern

Substituting (14) and (15) into (16) and (17), respectively, we have

$$\left(\frac{dV_0}{dt}\right)_{IL} = -\frac{8r_0}{M}[\bar{\rho}h\bar{v}_r v_r']_{IL} \tag{21}$$

and

$$(K_T)_{IL} = -\frac{4r_0}{MV_0^2}[\bar{\rho}h(\bar{v}_r v_\theta' + \bar{v}_\theta v_r')]_{IL}. \tag{22}$$

Fig. 5a is the case in which the flow velocity is relatively large on the rear semicircle. The asymmetric part of the flow field is characterized by $v_r' \equiv [(v_r)_F - (v_r)_R]/2 > 0$, $v_\theta' \equiv [(v_\theta)_F - (v_\theta)_R]/2 < 0$. Then, $(dV_0/dt)_{IL} > 0$ and $(K_T)_{IL} < 0$, meaning that the typhoon will accelerate and make a rightward recurvature. The acceleration is resulted from a strong radial inflow from the rear part of the typhoon and the rightward recurvature is the consequences of the gain of net rightward momentum by the typhoon because of the strong radial inflow in the rear and high tangential velocity. Fig. 5b illustrates the situation in which a large velocity of flow exists on the front semicircle when $v_r' < 0$ and $v_\theta' > 0$, so that $(dV_0/dt)_{IL} < 0$ and $(K_T)_{IL} > 0$, suggesting a tendency of deceleration and leftward recurvature of the typhoon.

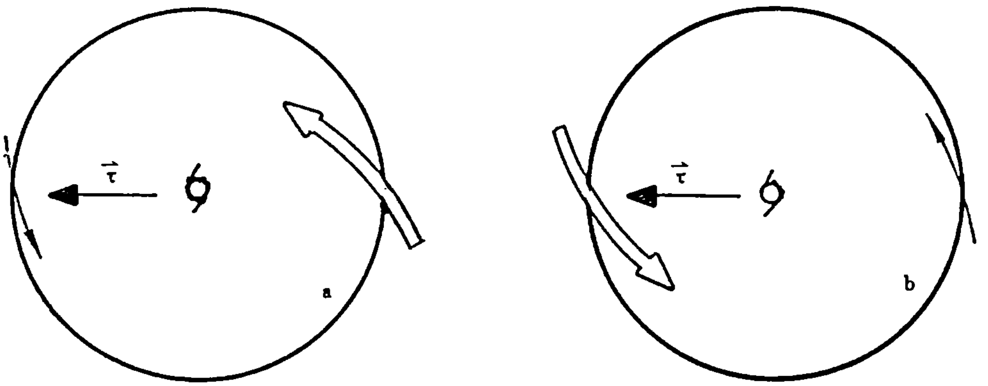

Fig. 5. F-R pattern of asymmetric inflow layer shown as accelerating and recurving to the right (a) or decelerating and recurving to the left (b).

V. OUTFLOW LAYER

In a manner entirely similar to the above section, the partial acceleration of the typhoon produced by the asymmetry of the outflow field can be expressed as

$$\left(\frac{dV_0}{dt}\right)_{OL} = -\frac{2\pi r_0}{M}[\bar{\rho}h\,\overline{(v_r\vec{V})_\tau}]_{OL} \tag{23}$$

and

$$(K_T)_{OL} = -\frac{2\pi r_0}{MV_0^2}[\bar{\rho}h\,\overline{(v_r\vec{V})_n}]_{OL} \tag{24}$$

where the subscript "OL" stands for the outflow layer and h the thickness of the outflow layer. Using Eqs. (12) ~ (15) for both L-R and F-R patterns of outflow, the equations governing the partial acceleration of the typhoon are respectively expressed by

$$\left(\frac{dV_0}{dt}\right)_{OL} = -\frac{4r_0}{M}[\bar{\rho}h(\bar{v}_r v_\theta' + \bar{v}_\theta v_r')]_{OL} \tag{25}$$

$$(K_T)_{OL} = \frac{8r_0}{MV_0^2}[\bar{\rho}h(\bar{v}_r v_r']_{OL} \tag{26}$$

for the L-R pattern and

$$\left(\frac{dV_0}{dt}\right)_{OL} = -\frac{8r_0}{M}[\bar{\rho}h(\bar{v}_r v_r')]_{OL} \tag{27}$$

$$(K_T)_{OL} = -\frac{4r_0}{MV_0^2}[\bar{\rho}h(\bar{v}_r v_\theta' + \bar{v}_\theta v_r')]_{OL} \tag{28}$$

for the F-R pattern.

(1) L-R pattern

Fig. 6a shows a case of large velocity of flow on the right semicircle, which should be marked by $v_r' > 0$ and $v_\theta' < 0$. It is noted that $\bar{v}_r > 0$ and $\bar{v}_\theta < 0$ in the outflow layer, then, from (25) and (26) we have $(dV_0/dt)_{OL} > 0$ and $(K_T)_{OL} > 0$. The asymmetric outflow enables the typhoon to accelerate and turn left when there is net momentum out-

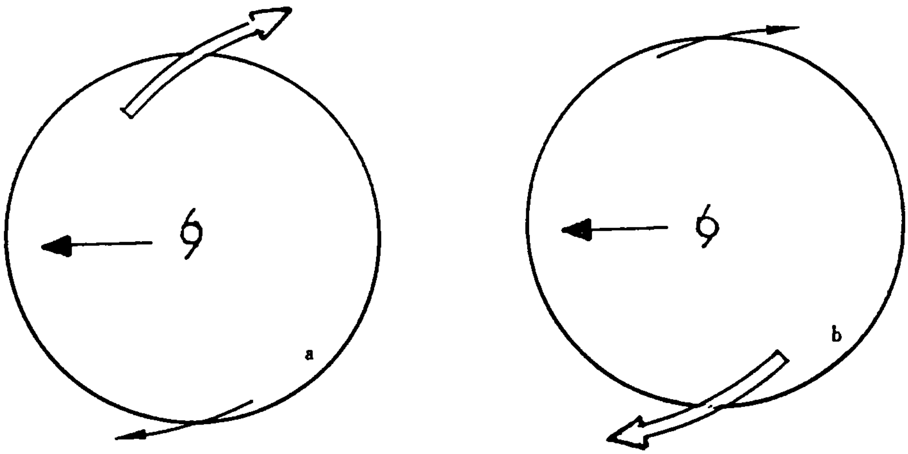

Fig. 6. L-R pattern of asymmetric outflow layer shown as accelerating and turning to the left (a) and decelerating and turning to the right (b).

flow in the negative directions of $\vec{\tau}$ and $\vec{n}$, or equivalently, the typhoon accelerates and turns left after obtaining momentum in the positive directions of $\vec{\tau}$ and $\vec{n}$. The composite asymmetric flow pattern given in Fig. 3 falls roughly in the group. Fig. 6b is the case in which the major outflow channel lies to the left of the typhoon. As $v_r' < 0$ and $v_\theta' > 0$ are the features of the asymmetric flow field, we have $(dV_0/dt)_{OL} < 0$ and $(K_T)_{OL} < 0$, implying the appearence of a decelerating and right-turning typhoon.

(2)F-R pattern

Fig. 7a tells that the major outflow channel is located on the front semicircle of the typhoon in which $v_r' > 0$ and $v_\theta' < 0$. Following (27) and (28), we have $(dV_0/dt)_{OL} < 0$ and $(K_T)_{OL} > 0$, or, that the typhoon is going to decelerate and turn to the left. For Fig. 7b, the main outflow channel is on the rear semicircle of the typhoon when $v_r' < 0$ and $v_\theta' > 0$ are the features of the asymmetric flow field. As a result, $(dV_0/dt)_{OL} > 0$ and $(K_T)_{OL} < 0$, the typhoon is going to accelerate and turn to the right.

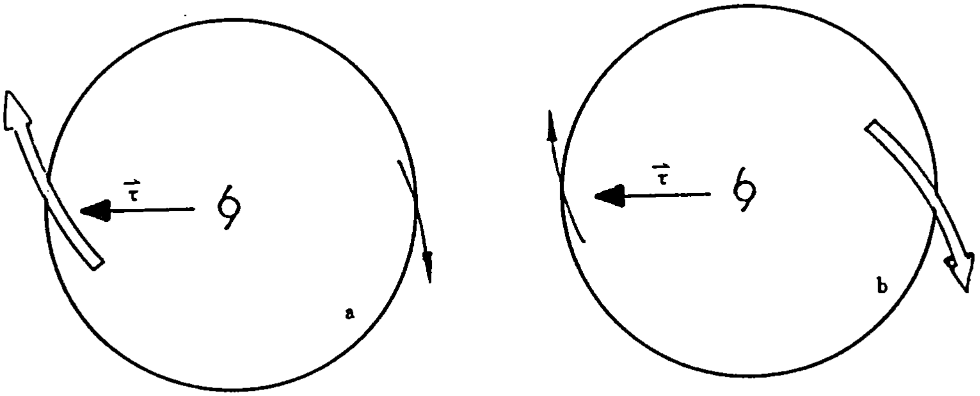

Fig. 7. F-R pattern of asymmetric outflow layer shown as accelerating and turning to the left (a) and decelerating and turning to the right (b).

Ⅵ. CONCLUSIONS AND DISCUSSIONS

a. Any net exchange of horizontal momentum between a typhoon system and the environment (defined as net momentum into or out of the system) depends on the asymmetry of the flow field of the typhoon region. Therefore, the effect of horizontal momentum exchange on the movement of typhoon is actually equivalent to the effect of the asymmetry of flow field.

b. For a typhoon mainly displaying a pattern of left-right asymmetric flow field (L-R pattern), the acceleration and leftward recurvature are favoured when the major inflow (outflow) channel is located on the right of the typhoon; on the contrary, the deceleration and rightward recurvature are favoured when the major inflow (outflow) channel is located on the left of the typhoon.

c. For a typhoon mainly displaying a pattern of front-rear asymmetric flow field (F-R pattern), the acceleration and rightward recurvature are favoured when major inflow (outflow) channel is situated in the rear of the typhoon; on the other hand, the deceleration and leftward recurvature are favoured when the major inflow (outflow) channel is situated in the front part of the typhoon.

d. By the way, in accordance with the viewpoint of local steering put forward by He (1995), the local momentum flux $\bar{\rho} v_r \vec{V}$ on the right hand side of Eq. (3) can be taken as a local steering velocity with a weight of $\bar{\rho} v_r$. The typhoon acceleration produced by the transfer of local horizontal momentum is directionally opposite to the local steering velocity $\bar{\rho} v_r \vec{V}$. As a result, in the inflow layer ($v_r < 0$), the direction of typhoon acceleration generally agrees with that of the airstream on the main inflow channel while it generally disagrees with the direction ($v_r > 0$) of the main outflow channel. It can be used as a qualitative rule for determining the tendency with which the typhoon moves based on the line-up of orientation of major inflow and outflow channels.

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