ON DIAGNOSTIC ANALYSIS OF ENERGY FIELDS OF EXPLOSIVE ENHANCEMENT OF TYPHOON OFFSHORE①

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ABSTRACT

The energetics process of offshore typhoon in three kinds of explosive enhancement (T_{EE}) are analyzed using ECMWF data. The results are as follows: (a) During the explosive development process, the enhancement of the rotational kinetic energy (K_ψ) is mainly in the lower troposphere while that of the potential energy (PE) is in the upper troposphere. The magnitude of rotational kinetic energy is largely bigger than that of divergent energy (K_χ). (b) The environmental energy advected into the typhoon was about 30% of the internal increment of typhoon energy. The magnitude of energy was an order larger than increment of typhoon energy. (c) Among those three kinds of explosively developed typhoon, the energy transformation mechanisms are different. (d) The influence of environment fields on abrupt intensification of typhoons couldn't be overestimated.

Key words: explosive enhancement, rotational kinetic energy, coefficient of conversion

I. INTRODUCTION

Much difficulty is brought forth for operational forecast if a typhoon, especially one that activates offshore, intensifies abruptly. Investigation into the mechanism behind, therefore, is one of the important subjects that is both theoretically and practically significant. The authors (1995) have studied the characteristics of temporal and spatial distribution and upper/lower layers of environmental fields for the type of typhoon, which is divided into those groups based on the way it intensifies. Difference in the field of physical quantities between typhoons that intensify and those that do not is statistically analysed②. A schematic picture is outlined through the above work of the low generally observed with the typhoon that intensifies abruptly. For mechanism illustrating the phenomenum, Ding et al. (1985) analysed the budget for internal kinetic energy during the process. It is aimed at in this paper that the three groups of typhoon are discussed from the veiwpoints of change and transformation of the energy for the intensification.

II. DATA AND COMPUTATIONAL METHOD

In conformity with the standards of classification in documentation (1995), three typhoons, Amy, Sarah and Polly, are selected as cases representing each of the three abrupt intensification. Amy represents Group 1 in which the pressure drops simultaneously with the enhancement of wind around the center. Sarah represents Group 2 in which the central pressure falls before any other elements. Polly represents Group 3 in which the central pressure rises before any other elements. With grid data from the European Center

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② Rong Guangxun and Liu Chunxia, Statistic characteristics of abruptly-intensified typhoon offshore. (In press) for Medium-range Forecast, divergent and rotational kinetic energy (K_χ) and (K_Ψ), total potential energy ($P+I$) and exchange cofficients among them C ($P+I$, K_χ), C (K_χ, K_Ψ), for periods before and after the abrupt intensification, are computed for standard pressure levels of 1000, 850, 750, 700, 500, 300, 200 and 100 hPa, by a set of expressions as in

$$K_\Psi = \frac{1}{2}\left|\vec{K} \wedge \nabla\Psi\right|^2 = \frac{1}{2}\left[\left(\frac{\partial\Psi}{\partial x}\right)^2 + \left(\frac{\partial\Psi}{\partial y}\right)^2\right] \tag{1}$$

$$K_\chi = \frac{1}{2}\left|-\nabla\chi\right|^2 = \frac{1}{2}\left[\left(\frac{\partial\chi}{\partial x}\right)^2 + \left(\frac{\partial\chi}{\partial y}\right)^2\right] \tag{2}$$

$$P + I = C,T \tag{3}$$

$$C(K_\chi, K_\Psi) = f\nabla\chi\nabla\Psi + \zeta\nabla\chi\nabla\Psi + \omega J\left(\Psi \cdot \frac{\partial\chi}{\partial p}\right) + \frac{\left|\nabla\Psi\right|^2}{2}\nabla^2\chi \tag{4}$$

$$C(P + I, K_\chi) = -\frac{R}{p}\omega T + \nabla\cdot(\chi\nabla\Phi) - \nabla\cdot(\Phi\nabla\chi). \tag{5}$$

Here Ψ and χ are streamfunction and velocity potential, respectively and derived by $\nabla^2\Psi = \zeta$ and $\nabla^2\chi = D$; f is the Earth vorticity, ω the vertical velocity, p the pressure, T the temperature, Φ the geopotential, P the geopotential energy, and I the internal energy. For (5), if the typhoon is taken as a closed system, then $C(P + I, K_\chi) = -\frac{R}{p}\omega T$ and R is a constant.

Ⅲ. CHANGES IN KINETIC ENERGY OF ROTATIONAL AND DIVERGENT WINDS IN T_{EE}

Table 1 gives the percentage in the entire air column by increments of the kinetic energy of rotational and divergent winds (ΔK_Ψ and ΔK_χ, respectively) the total potential energy $\Delta(P+I)$ and the low-level energy, around the time before or after the intensification of typhoons. Ted and Brendan intensified just short of the criteria for adrupt change.

Table 1. The increment of rotational kinetic energy, divergent kinetic energy and total potential energy before and after the development.

Typhoon	ΔK_Ψ 1000/700hPa	ΔK_Ψ 500/100hPa	$\frac{\Delta K_\Psi\ (1000-700)}{\Delta K_\Psi}$	ΔK_χ 1000/700hPa	ΔK_χ 500/100hPa	$\frac{\Delta K_\chi\ (1000-700)}{\Delta K_\chi}$%	$\Delta(P+I)\times10^3$ 1000/700hPa	$\Delta(P+I)\times10^3$ 500/100hPa	$\frac{\Delta(P+I)\ (500-100)}{\Delta(P+I)}$%
Amy	897.4	493.3	65	183.5	75.6	71	7.5	7.4	50
Sarah	383.1	−56.3	117	47.9	30.7	61	−0.8	0.5	−167
Polly	472.2	−53.4	108	64.9	44.8	60	−1.7	3.9	325
Ted *	608.3	929.9	67	82.3	33.1	71	1.2	−0.8	−200
Brendan *	−240.2	54.7	−128	−27.9	−15.9	64	2.8	2.1	43

* denotes typhoons enhanced to sub-standard level.

It is clear from Table 1 that the increment in the kinetic energy of rotational and divergent winds is larger at the lower layer than at the upper one, taking up over 60 % of the entire column, and the energy increment for the former wind is much greater (even by a whole order of magnitude) than the latter. For the total potential energy, the increment is an order of magnitude higher at the upper level than the kinetic energy of rotational wind while the variation at lower level of total potential energy differs with the typhoon group, showing a decreasing tendency in the process of intensification for Groups 2 and 3.

It is concluded, therefore, that a T_{EE} is featured by the principal increase of K_ψ and K_χ at the lower level, especially that of the latter and the accompanying increase of PE at the upper level. Computation vary with the difference of group for the typhoon that does not enhance explosively. Brendan, falling within Group 1, tends to decrease in K_ψ. For Ted which is in Group 2, the increase of K_ψ is large versus decrease in PE at the upper level. Being different from the characteristics of T_{EE}, they are unfavourable for explosive enhancement of typhoon.

Ⅳ. EXPLOSIVELY ENHANCED TYPHOON IN ENVIRONMENTAL FIELD

In order to estimate the role the environmental field plays, the ratio of the transfer into a typhoon of K_χ and K_ψ, which are advected from the boundary of square boxes with origins at the eye and sides each measured in 5 latitudes, to the increment of its internal energy, is computed.

Table 2. Comparison of the increment of K_χ and K_ψ with the energy advected across boundaries during explosively enhancing development.

Classification		Internal increment (J)		Input via boundary		Ratio of increment to input
		ΔK_χ	ΔK_ψ	ΔK_χ	ΔK_ψ	
Group 1	Amy	259.1	1390.7	31.1	181.9	13%
	Brendan *	−43.8	−185.5	−0.4	−50.5	36.0%
Group 2	Sarah	109.7	326.7	45.3	82.7	29.3%
	Ted *	115.4	901.2	3.6	−160.5	−15.0%
Group 3	Polly	78.6	438.6	−6.5	−77.7	−16.0%

It is known from Table 2 that K_ψ, K_χ and PE are increasing as far as the typhoon is concerned during the explosive intensification. For the input amount through the boundary concrete values are different with the group of typhoon. The input, accounting for about 30 % of the increment, is positive for Groups 1 and 2 (Amy and Sarah) so that the internal K_ψ and K_χ increase for development. It is negative for Group 3 (Polly) so that K_ψ and K_χ decrease within the typhoon against development. It cannot be overestimated for the role of advection through the boundary in the process of explosive intensity change.

For Brendan and Ted that do not intensify abruptly, the boundary advection acts negatively to pose an immediate check for any explosive develpment.

V. INTERNAL ENERGY CONVERSION AND ITS MECHANISM IN T_{EE}

1. *Internal energy conversion*

1) CONVERSION BETWEEN K_χ AND K_ψ

Based on Eq. (4), the value of coefficients $C(K_\chi, K_\psi)$ for conversion are determined between the divergent and the rotational kinetic energy at all levels with T_{EE}. Fig. 1 gives the vertical distribution of $C(K_\chi, K_\psi)$ for the three groups of typhoon. The figure indicates positive values of C (K_χ, K_ψ) at lower level for all groups, i. e., divergent kinetic energy is converted to rotational kinetic energy so that the latter is increased at the lower level to support the strengthening of vortex circulation. At the upper level, however, C (K_χ, K_ψ) is negative to make it possible for the rotational kinetic energy to convert to the divergent kinetic energy so that divergence is favoured for strengthening at the level.

The conversion coefficient for Group 1 typhoon (Amy) falls between Groups 2 and 3 and divides into positive and negative layers at 400 hPa, and K_χ is converted to K_ψ below it while the reverse is true above it. For the lower level in this group, the increment is just 8.97×10^2J/m^2 (Table 1) and the input from the boundary is also a small portion (taking up 13 % of the increment) while the conversion from K_χ to K_ψ amounts up to 83 $\times10^2$J/m^2, which is suggestive that the main source for the increment of lower-level vortex momentum is the conversion from the divergent kinetic energy (K_χ).

Group 2 has the largest positive area of lower-level C (K_χ, K_ψ) that extends upward to 250 hPa, or, layers below 250 hPa are marked by conversion from K_χ to K_ψ by a value as high as 97.8×10^2J/m^2, the largest of all groups of typhoon. Additionally, the lower-level increment reaches 3.83×10^2J/m^2 for K_ψ, with 36 % of which being accountable by boundary input, revealing that the increase of K_ψ at lower levels comes from the conversion of energy within the typhoon.

That upper-level negative area is larger than lower-level positive area is shown in the conversion coefficient of Group 3. Having the smallest positive area of all groups, Group 3 is marked by minimum conversion from K_χ to K_ψ at lower level by a value of 67.6×10^2J/m^2 and greater negative area than the other two groups. During the explosive development, the increment for K_ψ is 4.72×10^2J/m^2 with negative input through the boundary, suggesting a similar source from typhoon internal energy for its increment.

Fig. 2 is the vertical distribution of C (K_χ, K_ψ) for two groups of typhoon. It is understood in comparison with that of similar typhoons in Fig. 1 that sharp difference exists between typhoons that intensify abruptly and those that do not.

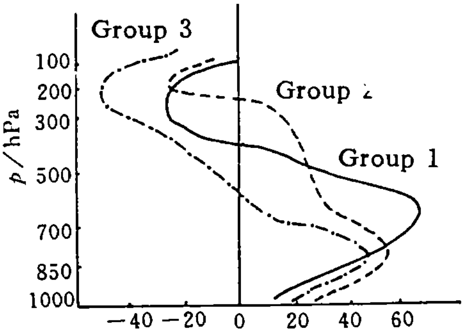

Fig. 1. The vertical distribution of $C(K_\chi, K_\psi)$ of three kinds of explosively enhancing typhoon during development in unit of 10^{-3}w/m^2.

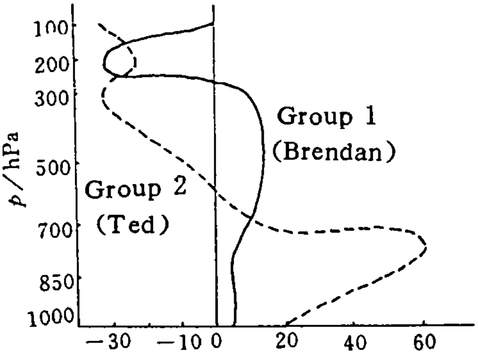

Fig. 2. The same as Fig. 1 but for non-explosively enhancing typhoon.

To summerize, there is marked difference in the conversion coefficient C (K_χ, K_ψ) among all groups of typhoon. It is the largest in Group 2, followed by Group 1 and further by Group 3, the smallest. The common feature of the three is a positive value for

$C(K_\chi, K_\psi)$) at lower level, a small percentage of boundary input in the whole increment and major role of energy conversion inside the typhoon in the increase of its rotational kinetic energy. It is, therefore, known that the environmental field plays a partial, rather than overwhelming, role in the explosive development of typhoon.

2) CONVERSION BETWEEN TOTAL POTENTIAL ENERGY ANE DIVERGENT KINETIC ENERGY INSIDE T_{EE}

Fig. 3 gives the vertical distribution of the conversion coefficient $C(P+I, K_\chi)$ at the stage of explosive development for all groups of typhoon.

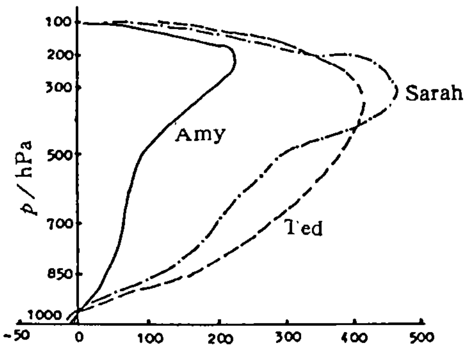

Fig. 3. The vertical distribution of $C(P+I, K_\chi)$ of three kinds of explosive development during typhoon growth.

It is known from Fig. 3 that the coefficient is all positive at the mid- and upper-levels, i.e. the total potential energy $(P+I)$ is converted to the divergent kinetic energy which is increased to be favourable for the growth of vertical motion as indicated by the expression $C(P+I, K_\chi)$. At about 1000 hPa, however, $C(P+I, K_\chi)$ becomes negative, i. e. the divergent kinetic energy is converted to the total potential energy. The maximum of the conversion coefficient is observed above 300 hPa, a common feature for all the groups. Compared with $C(K_\chi, K_\psi)$, $C(P+I, K_\chi)$ is much larger. But sharp difference in it still remains among the three groups. The coefficient is the smallest for Group 1 (Amy), followed in order by Group 2 (Sarah) and Group 3 (Polly), the largest of all (see Table 3 in the next section).

By combining the vertical distribution of conversion coefficients $C(K_\chi, K_\psi)$ and $C(P+I, K_\chi)$ as displayed in Figs. 1 and 3, one knows that the magnitude of energy conversion in each group depends on the way in which the typhoon intensifies. For Group 1 which shows $C(P+I, K_\chi) > 0$, the total potential energy is converted to divergent kinetic energy, especially so at the upper level, so that the enhanced upper-level divergence helps the vertical motion to increase; $C(K_\chi, K_\psi) > 0$ at the lower level and K_χ is changed into K_ψ, resulting in stronger vortex circulation at lower level and increased typhoon within a relatively short time. For Group 2, which is also marked with a conversion of total potential energy towards K_χ throughout the depth of the whole air column, and a $C(K_\chi, K_\psi)$ greater than zero from lower level to 250 hPa that converts K_χ to K_ψ with an extent largest in all groups, the typhoon vortex circulation increases rapidly. It is just because of it that the conversion of total potential energy into K_χ is larger than that in Group 1. For Group 3, it is energetically typical of strong vortex circulation at lower level with $C(K_\chi, K_\psi)$ the smallest (in the conversion from K_χ to K_ψ) in all the groups. Following the computations of $C(P+I. K_\chi)$, it is inferred that part of the conversion from total potential energy to K_χ in Group 3, which is the largest of all, is consumed to increase K_ψ and the majority to increase K_χ at upper level so that the previously weak divergence gets stronger, the pumping becomes more active and the vertical motion turns more violent, and finally a T_{EE} is resulted.

2. *Mechanism of K_Ψ increase in all groups of typhoon*

Table 3 gives principal action terms of conversion coefficient $C(K_\chi, K_\Psi)$ for K_χ converting to K_Ψ in all typhoon groups. From comparisons in terms of energy conversion and boundary input, which are made above, one sees that the increase of K_Ψ at lower level mainly comes from the conversion of K_χ in the typhoon circulation, and which is why discussion now is shifted to the mechanism by which K_Ψ is increased.

Table 3. Values of conversion coefficient C $(P+I,\ K_\chi)$ over the whole layer and main terms of action.

Typhoon	$C(P+I, K_\chi)$(1000—100 hPa)	Terms of main action in $C(K_\chi, K_\Psi)$
Amy	631.4	C_1, C_2
Sarah	1527.9	C_2, C_4
Polly	1678.3	C_3

In Group 1, C_3 and C_1 are the terms of main action and the former, $C_3 = \omega J(\Psi, \frac{\partial \chi}{\partial p})$, is related with inhomogeneous distribution of vertical motion and divergent wind. In the explosive development of the typhoon, $C_3 < 0$ at upper level and acts negatively to intensify the vertical motion by converting the vortex kinetic energy, which is already relatively large, towards K_χ and increasing the effect of divergence and convergence; $C_1 = f\nabla\chi \cdot \nabla\Psi$ suggests an collocation between the thermodynamic field and flow field. Fig. 4 explains the collocation between the streamfunction and potential function for Group 1 (Amy). It is told in Fig. 4 that Ψ and χ fields are taking a generally the same direction in gradient so that $C_1 > 0$, i.e. making K_χ convert to K_Ψ at lower level and increasing the vortex circulation so that the typhoon is increased abruptly.

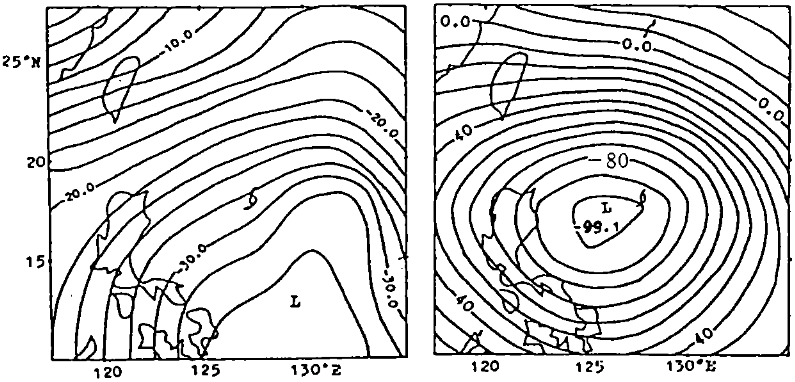

Fig. 4. χ and Ψ fields of the typhoon circulation.

In Group 2, C_2 and C_4 are the terms of main action. C_2 is identical to C_1; $C_2 > 0$ if the flow is well collocated with thermodynamic field so that the vortex kinetic energy is increased at lower level. $C_4 = \frac{|\nabla\Psi|^2}{2}\nabla^2\chi$, which is related to the circulation of typhoon. C_4 plays a dominant role in this group, i.e. the horizontal divergence and convergence of potential function is such that the conversion of K_χ to K_Ψ is favoured in the typhoon circulation and thus the vortex circulation strengthened.

In Group 3, C_3 is the term of main action and acts negatively in the group so that the upper-level K_χ is increased and divergence enhanced, and consequently stronger pumping effect intensifies the convection in the vertical to strengthen the typhoon explosively.

In summary, in Groups 1 and 3, the inhomogeneous vertical distribution of vertical motion and potential function is decisive for T_{EE}. It mainly contributes to the increase of divergent effect at upper level so that the internal vertical motion is further strengthened to the level of explosive development. In Group 2, the typhoon is intensified abruptly due to collocation between the horizontal divergence and convergence, thermodynamic field, and the flow field, which is favourable for the increasse of lower-level K_ψ.

Ⅵ. CONCLUSIONS

a. The increase of K_ψ during the explosive development of typhoons offshore mainly takes place in lower level while that of total potential energy in upper level. The main cause behind a T_{EE} is the increased lower-level K_ψ, which is much larger than K_χ in terms of increment.

b. The kinetic energy advected from the environment into a typhoon through the boundary takes up only about 30 % of the total increase of kinetic energy inside the typhoon circulation. The internal conversion is an order of magnitude higher than the increment. It is therefore illustrative that the kinetic energy inside the typhoon is increased mainly through the internal conversion from K_χ to K_ψ and the environmental field plays a minor role, which is obvious to some extent only when the circulation begins to intensify in the typhoon.

c. The mechanism by which energy is converted within the system is dependent on the way in which the offshore typhoon enhances abruptly. For Groups 1 and 3, a T_{EE} is benefited by the inhomogeneous vertical distribution of vertical motion and velocity potential. For Group 2, however, it is subject to strong divergence and convergence within the air column and the mutual collocation of potential function and flow field.

d. The conversion coefficient $C\ (K_\chi,\ K_\psi)$ appears positively in lower and negatively in upper levels, regardless of which group the typhoon belongs to. Another conversion coefficient, $C(P+I, K_\chi) > 0$, is almost positive throughout the column with the maximum at about 300 hPa. $C\ (K_\chi,\ K_\psi)$ is in the middle and $C\ (P+I,\ K_\chi)$ the smallest for Group 1; the former is the largest and the latter in the middle for Group 2; the former is the smallest and the latter the largest for Group 3.

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