A NUMERICAL STUDY ON THE FORMATION AND DEVELOPMENT OF ISLAND-INDUCED CYCLONE AND ITS IMPACT ON TYPHOON STRUCTURE CHANGE AND MOTION

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ABSTRACT

In this paper, the impact of the Taiwan Island topography on the structure change and motion of Typhoon Dot (9017) during its crossing the Taiwan Island is studied with a modified version of a JMA operational regional model (Japan spectral model, JSM). A series of sensitivity experiments are conducted to detect the forming and developing mechanism of an island-induced cyclone. Results show that lee side low pressure center plays a very important role in the formation of the induced-cyclone while a typhoon is approaching a large island with high mountains. The position and intensity of the induced cyclone is sensitive to the height and location of island mountain, intensity of TC and underlying surface topography distribution as well. A preliminary formation criterion of the island-induced cyclone is obtained.

Key words: lee side low pressure center, induced cyclone, formation, development, Taiwan Island, typhoon

I. INTRODUCTION

In recent years, impact of large island topography on typhoon motion has been drawing more attention of typhoon experts than ever before. Studies (Chen 1992; Luo and Chen 1993) show that island topography can cause a sudden turning of an approaching typhoon's track. Another significant effect of island topography on typhoons is the formation and development of induced cyclone. Observational studies (Chen and Ding 1979) show that the existence of induced cyclone and its interaction with typhoon's circulation can significantly influence typhoon's structure and motion while the typhoon is crossing the island and causes so-called "jumping" phenomenon of typhoon motion. Namely while a typhoon reaches a large island, the upper center will go ahead continuously, but the lower center will be blocked by island mountain. Then under certain conditions, an induced cyclone may occur at low level on

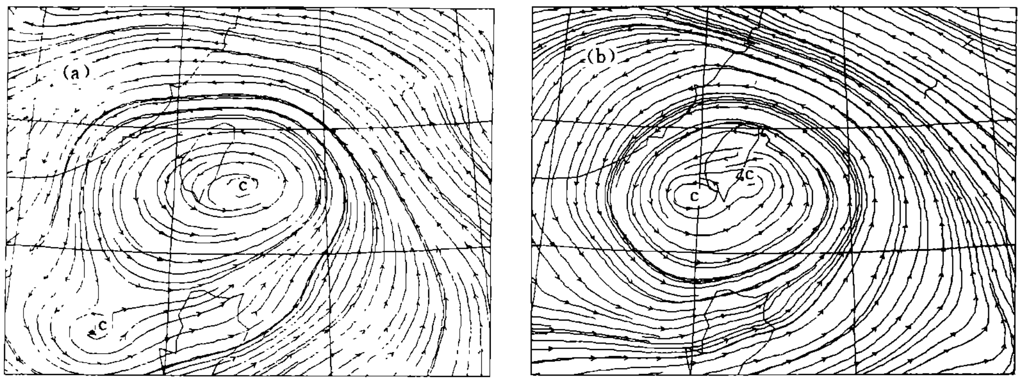

Fig. 1. Objective analysis data of TCM-90 for Typhoon Dot: (a) 500 hPa, 12 UTC, Sep. 7, 1990, (b) 850 hPa, 12 UTC, Sep. 7, 1990.

the other side of the island and wait there until the upper center moves over it. The original lower center will weaken and disappear gradually. The induced cyclone will eventually be coupled with the upper center and leave the island.

A statistical work (Meng 1994) shows that this kind of effect is most significant around the Taiwan Island among the five islands in western North Pacific, i. e. the Korea Peninsula, Taiwan, Japan, Luzon and Hainan Islands. Many experts paid a lot of attention to the impact of the Taiwan Island on the formation of induced cyclone (Elsberry 1989; Bender et al. 1987; Yang 1994). The previous studies simulated the induced cyclone under different conditions. But the formation mechanism is still unclear. During SPECTRUM-90, the Typhoon Dot (9017) showed a jumping phenomenon around the Taiwan Island. An induced cyclone formed to the southwest of Taiwan Island at lower level while Dot (9017) is approaching (see Fig. 1). The present paper is devoted to investigating the motion characteristics of Typhoon Dot with a limited area spectral model. The jumping process will be first vividly described, and the forming and developing mechanism of the induced cyclone will be summarized, which will be proved to be a valuable reference for operational forecast.

II. DATA SET AND MODEL DESCRIPTION

The data used in the present paper is regional objective analysis data made by Japan Meteorological Agency (JMA). The resolution of the data is 150 km at 60°N on the polar-stereographic projection map. Actual resolution at low latitude (23°N) is around 112 km. The initial time in model integration is 00 UTC, Sep. 7, 1990 with Dot as the target typhoon.

The model employed in the present paper is the Japan spectral model (JSM) of JMA. In the original initialization process of JSM, there is not a plantation of a man-made typhoon. In the experiment in this paper, we plant a symmetric man-made typhoon into the JSM initialization process which makes it easy to change typhoon intensity. Another modification is that the integrated domain of JSM is shifted to the southwest with the Taiwan Island as its center.

The Japan spectral model was developed for operational use. The model has 23 levels in the vertical on the sigma coordinate. The spectral limited area model uses the transform method with double Fouries series as basic functions. It has a regular 129×129 transform grid in a square domain with a grid distance of 30 km at 60°N on a polar stereographic projection plane. The detailed specification of JSM is shown in Table 1.

Table 1. Specfication of JSM

Independent variables	x-y coordinate on a polar stereographic projection plane and σ-coordinate	Grid size	30 km at 60°N
Dependent variables	u, v, T_v, $\ln(p_s)$, q	vertical levels	23
Numerical technique	Euler semi-implicit time integration, double Fourier for horizontal representation and finite difference in the vertical	integration domain	129×129
Projection	polar stereographic projection	forecast phenomenon	meso-β
Initial	3-h cutoff analysis with 12-h GSM forecast at first guess	lateral boundary	0 — 24 h forecast by ASM*
Orography	10′×′10 (100 m) resolution orography data are smoothed and spectrally truncated (for Japan area in JSM). Envelope orography is adopted in JSM	horizontal diffusion	linear, second-order Laplacian
Moist processes	moist convective adjustment scheme + large-scale condensation with rain evaporation + shallow convection	radiation (shortwave) (longwave)	every hour every hour
PBL	Mellor-Yamada level-2 closure scheme and similarity theory for surface boundary layer	cloudiness	diagnosed from relative humidity maximum overlap
Surface state	observed SST (fixed during time integration) and sea ice distribution. b. snow cover, roughness length, albedo are climatological.	land surface	b (evaporability) depends on location and season

* ASM: Asian spectra model.

The model is formulated in terms of the primitive equations for momentum, mass, specific humidity, and virtual temperature using advection forms. They are expressed as follows:

Motion equations:

$$\frac{\partial u^*}{\partial t} = - m^2\left\{u^* \frac{\partial u^*}{\partial x} + v^* \frac{\partial u^*}{\partial y}\right\} - \frac{1}{2}u^*\left\{u^* \frac{\partial m^2}{\partial x} + v^* \frac{\partial m^2}{\partial y}\right\} - \dot{\sigma}\frac{\partial u^*}{\partial \sigma}$$
$$- \left\{\frac{\partial \Phi}{\partial x} + RT_v \frac{\partial \pi^*}{\partial x}\right\} + v^*\left\{f + \frac{1}{2}\left(u^* \frac{\partial m^2}{\partial y} - v^* \frac{\partial m^2}{\partial x}\right)\right\} + D_u - \frac{g}{mp_s}\frac{\partial \tau_x}{\partial \sigma},$$
$$\frac{\partial v^*}{\partial t} = - m^2\left\{u^* \frac{\partial v^*}{\partial x} + v^* \frac{\partial v^*}{\partial y}\right\} - \frac{1}{2}v^*\left\{u^* \frac{\partial m^2}{\partial x} + v^* \frac{\partial m^2}{\partial y}\right\} - \dot{\sigma}\frac{\partial v^*}{\partial \sigma}$$
$$- \left\{\frac{\partial \Phi}{\partial y} + RT_v \frac{\partial \pi^*}{\partial y}\right\} - u^*\left\{f + \frac{1}{2}\left(u^* \frac{\partial m^2}{\partial y} - v^* \frac{\partial m^2}{\partial x}\right)\right\} + D_v - \frac{g}{mp_s}\frac{\partial \tau_y}{\partial \sigma}.$$

Thermodynamic equation:

$$\frac{\partial T_v}{\partial t} = - m^2\left\{u^* \frac{\partial T_v}{\partial x} + v^* \frac{\partial T_v}{\partial y}\right\} - \sigma^\kappa \dot{\sigma}\frac{\partial}{\partial \sigma}(T_v \sigma^{-\kappa})$$
$$+ \kappa T_v\left\{\frac{\partial \pi^*}{\partial t} + m^2\left(u^* \frac{\partial \pi^*}{\partial x} + v^* \frac{\partial \pi^*}{\partial y}\right)\right\} + \frac{Q^*}{c_p} + \frac{g}{c_p p_s}\frac{\partial F_H}{\partial \sigma} + D_H.$$

Equation of water vapor:

$$\frac{\partial q}{\partial t} = - m^2\left\{u^* \frac{\partial q}{\partial x} + v^* \frac{\partial q}{\partial y}\right\} - \dot{\sigma}\frac{\partial q}{\partial \sigma} + M + \frac{g}{p_s}\frac{\partial F_q}{\partial \sigma} + D_q.$$

Tendency equation and continuity equation:

$$\frac{\partial \pi^*}{\partial t} = - \int_0^1 m^2\left\{\frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y}\right\}d\sigma - \int_0^1 m^2\left\{u^* \frac{\partial \pi}{\partial x} + v^* \frac{\partial \pi}{\partial y}\right\}d\sigma,$$
$$\dot{\sigma}_{\sigma+\triangle\sigma} = \dot{\sigma}_\sigma - m^2\int_\sigma^{\sigma+\triangle\sigma}\left\{\frac{\partial u^*}{\partial x} + \frac{\partial v^*}{\partial y} + u^* \frac{\partial \pi^*}{\partial x} + v^* \frac{\partial \pi^*}{\partial y}\right\}d\sigma - \triangle\sigma\frac{\partial \pi^*}{\partial t}.$$

Hydrostatic equation:

$$\frac{\partial \Phi}{\partial \sigma^\kappa} = - c_p T_v \sigma^{-\kappa}; \qquad \frac{\partial \Phi}{\partial \sigma} = - \frac{RT_v}{\sigma}.$$

III. TOPOGRAPHY CONSTRUCTION

As shown in Table 1. JSM adopts $10' \times 10'$ envelope orography. In order to detect factors affecting the formation of induced cyclone around the Taiwan Island, we prepared eight kinds of topography of the Taiwan Island as follows:

T1: Delete the mountains in the Taiwan Island in the original JSM orography, keep its land surface.

T2: Original JSM orography with the maximum height of 2515 m.

T3: Taiwan Island topography is elevated to 4/3 times higher than T2.

T4: Taiwan Island topography is elevated to 4.6/3 times higher than T2 and is closest to the real one.

T5: Taiwan island topography is elevated to 5/3 times higher than T2.

T6: Shift the Taiwan Island of T4 to northeast by 1.5 degrees.

T7: Shift the Taiwan Island of T4 to southwest by 1.5 degrees.

T8: Delete the Mainland China of T4 to enlarge the width of Taiwan Strait.

IV. THE FORMATION OF INDUCED CYCLONE

Experiment results show that the formation of induced cyclone is closely related to the topographical wave, especially the lee side low pressure center.

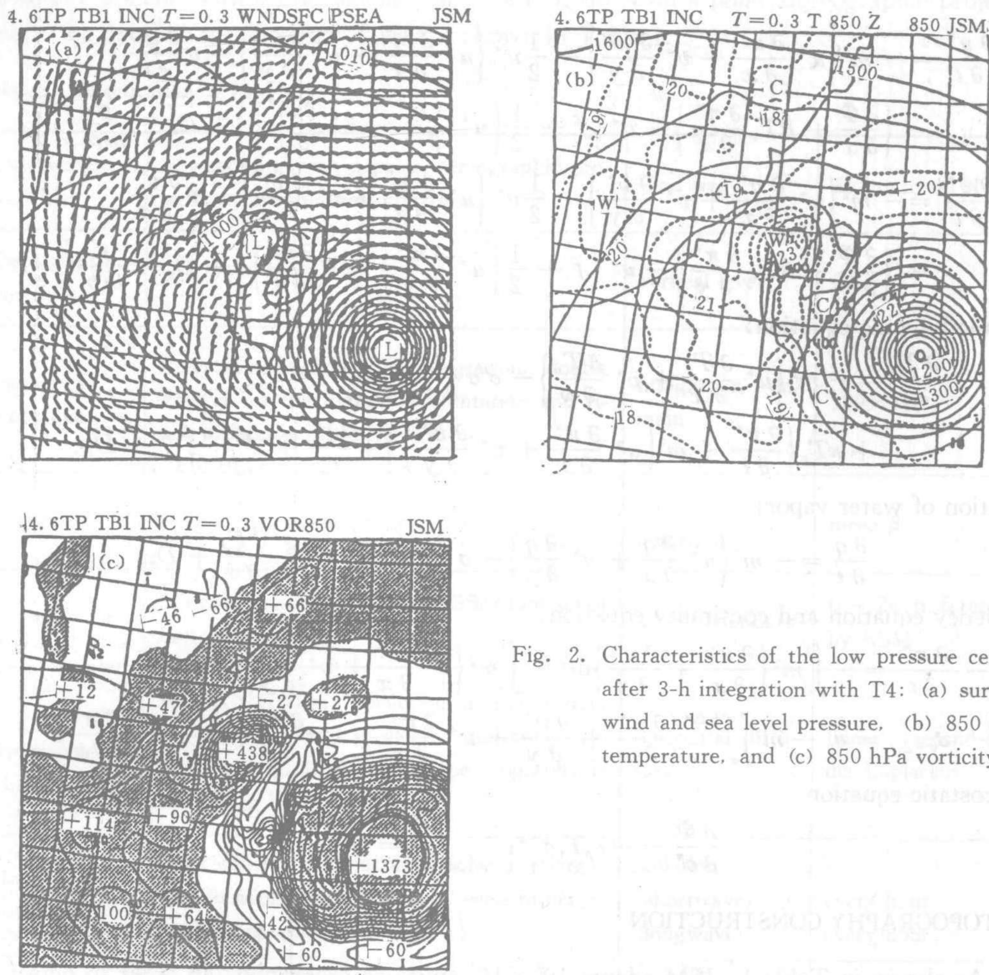

Fig. 2. Characteristics of the low pressure center after 3-h integration with T4: (a) surface wind and sea level pressure, (b) 850 hPa temperature, and (c) 850 hPa vorticity.

1. *Characteristics of Lee Side Low Pressure Center*

With T4, we conducted a 36-h integration as a control case. As shown in Fig. 2, after 3-h integration, a lee side low pressure center caused by the interaction between mountain range and typhoon circulation appears just off the northwestern coast of the Taiwan Island in sea-level pressure field. This low pressure center corresponds to a convergence center, a high temperature center and a high positive vorticity center in surface wind, 850 hPa temperature and 850 hPa vorticity fields respectively.

The radius of this low pressure center is about 100 km. And it reaches up to 700 hPa in geopotential height and vorticity field. But it is very shallow in wind field, and only appears in surface wind field.

2. *Impact of Low Pressure Center on the Formation of Induced Cyclone*

With the integration, the low pressure area gradually expands to the southwest of the original low pressure center. As shown in Fig. 3, a trough forms and extends to the southwest, corresponding to cyclonic vorticity in surface wind field. After 9-h integration, an induced

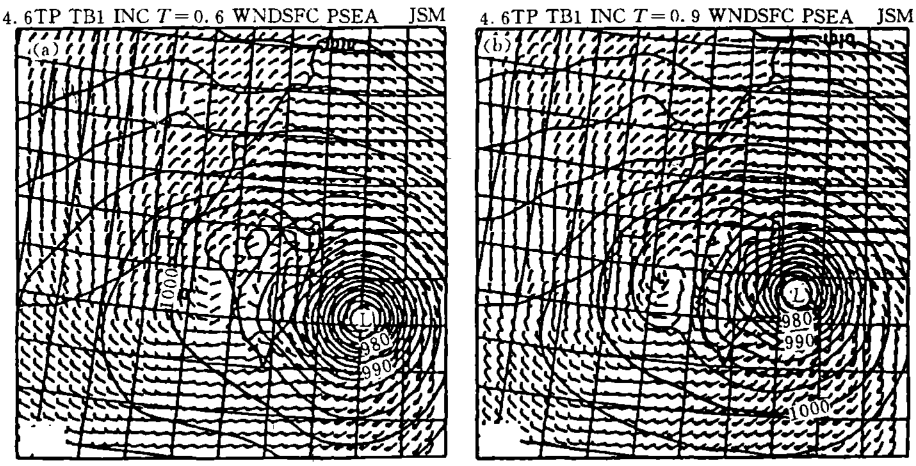

Fig. 3. A series of integration field of sea level pressure and surface wind field: (a) $t+6$h and (b) $t+9$h.

cyclone forms to the westsouthwest of the Taiwan Island.

It is considered that the formation of induced cyclone includes the following two aspects:

Firstly, as shown in Fig. 4, with the formation of induced cyclone, the 700 hPa high temperature center associated with the low pressure center weakens, in the meantime another higher temperature center forms on 700 hPa corresponding to the induced cyclone. This may suggest that there is some energy exchange among the low pressure center, the induced cyclone and the typhoon.

Secondly, from the vorticity cross section (Fig. 5), we can see that from $t+3$h to $t+9$h, the high vorticity center gradually expands to the southwest. In other words, during the period from $t+3$h to $t+9$h, a high vorticity center forms and develops which is higher than the low pressure center up to 500 hPa. Based on the above analyses, we may infer that the horizontal transportation of vorticity from the lee-side low pressure center is very important in the formation of the induced cyclone.

3. *Other Factors Affecting on the Formation of Induced Cyclone*

As we known from the above analyses, the lee side low pressure is a key factor in the formation of induced cyclone. Based on our sensitivity experiments, we can evaluate the affecting factors such as terrain height, intensity of typhoon, the width of Taiwan Strait, etc.

(1) *Terrain height*

Since the induced cyclone is closely related to the low pressure center which is caused by orographic wave, both the induced cyclone and the lee side low will have a close relationship with terrain height. Figures 6a—6d show the 3-h integration results with T2, T3, T4, T5, respectively. We can see that the higher the mountain is, the deeper the low pressure center will be. As a result, there occur large differences among their 9-h integration fields. On the sea-level pressure field, the low pressure area around where the induced cyclone should occur becomes larger with the increase of terrain height. From the surface wind field in Fig. 7, we

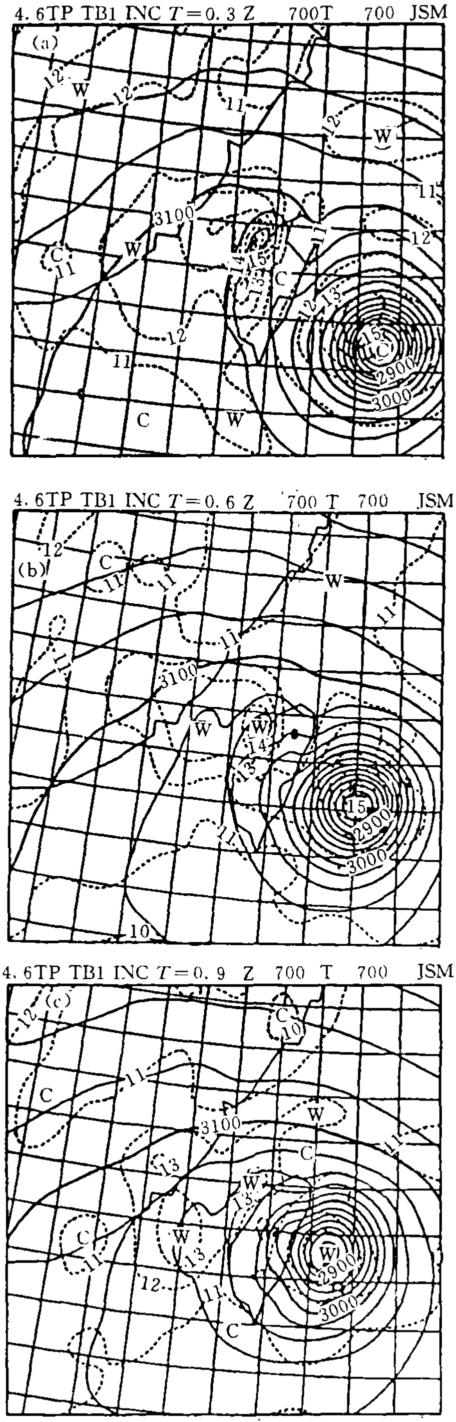

Fig. 4. Temperature variation during the formation of induced cyclone (a) $t+3$h, (b) $t+6$h, and (c) $t+9$h.

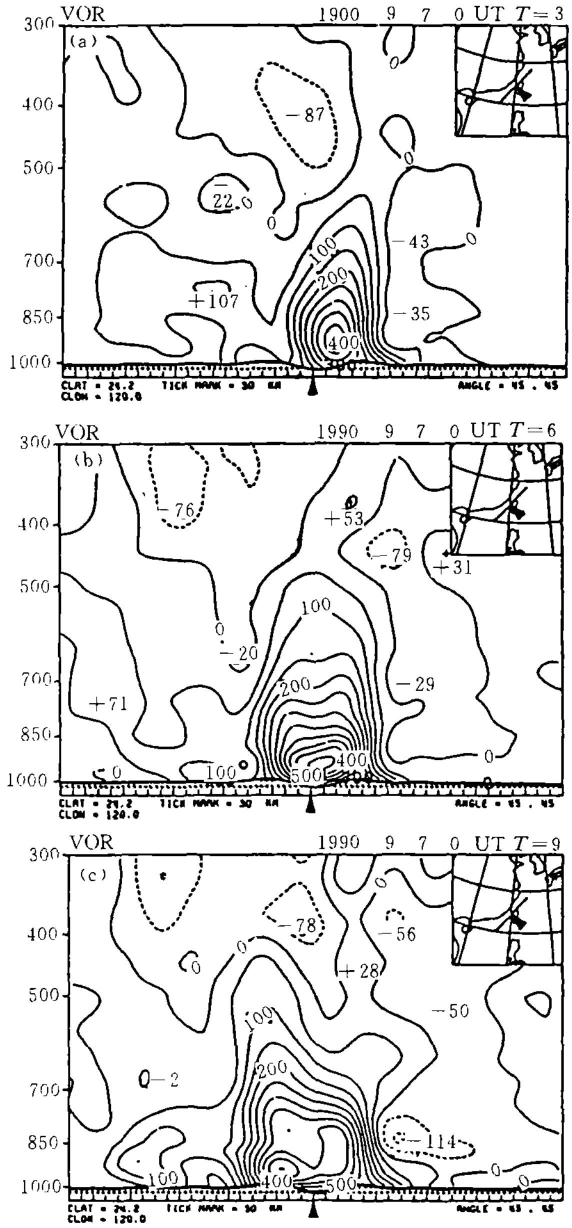

Fig. 5. As in Fig. 4. but for vorticity variation.

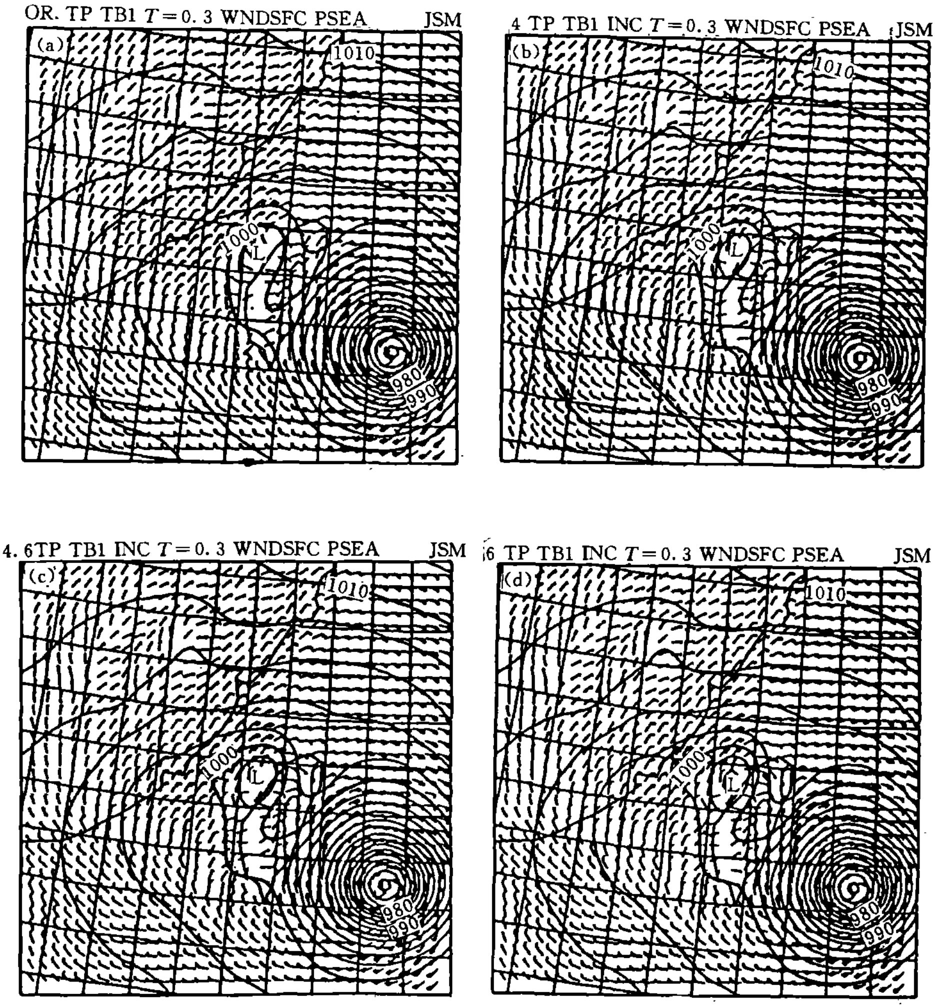

Fig. 6. Intensity of lee side low pressure center after 3 h integration with (a) T2. (b) T3. (c) T4. and (d) T5.

can see that there is no apparent cyclonic vorticity center under the condition of T2. When the terrain height approaches the real one. a cyclonic-vorticity center is induced. Results with T3, T4 and T5 demonstrate that the higher the mountain is. the stronger the induced cyclone will be.

These experiments show that induced cyclone may easily form around the island with high terrain under the given atmospheric conditions including typhoon intensity.

(2) *Intensity of typhoon*

Observational study shows that not all typhoons which approach Taiwan Island will cause an induced cyclone on the other side of the island. The characteristics of typhoon itself may affect the induced cyclone.

An experiment with an weakened Dot is conducted using the T4 topography. Comparison between the results with the original (central pressure 974 hPa) and the weakened Dot (central pressure 982 hPa) (see Fig. 8a) shows that no apparent induced cyclone occurs over

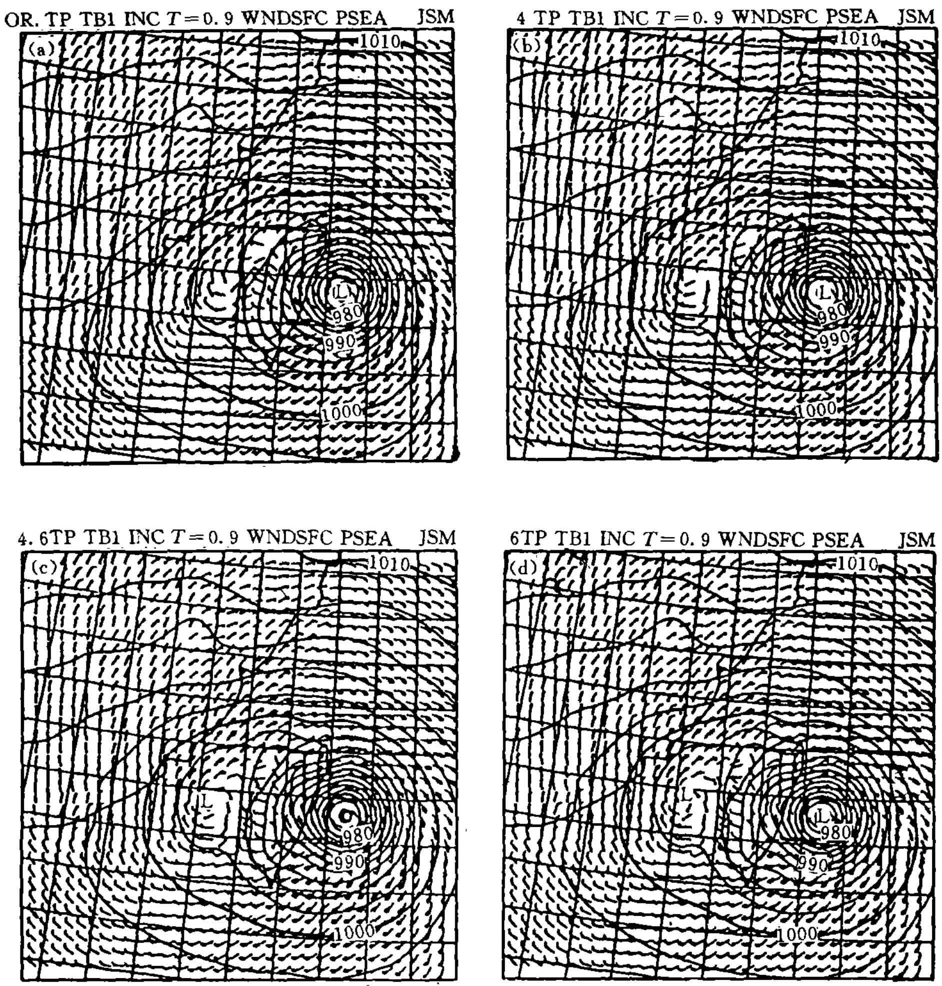

Fig. 7. Status of induced cyclone's formation after 9 h integration with (a) T2, (b) T3, (c) T4, and (d) T5.

Taiwan Strait with the weakened typhoon. This result demonstrates that a certain intensity is necessary for the formation of the induced cyclone.

Other experiments are carried out with the above weakened typhoon (central pressure 982 hPa), original typhoon (central pressure 974 hPa) and strengthened typhoon (central pressure 964 hPa) using the T2 topography. The 9-h integration (Figs. 8b—8d) shows that no induced cyclone forms in all the three cases. This result suggests that a certain terrain height may be necessary for the formation of the induced cyclone.

On the other hand, even though no apparent induced cyclone occurs in Figs. 8b—8d, there are large differences among the three surface wind fields. The largest possibility to form an induced cyclone is seen in the experiment with the original typhoon, which means there may exist some suitable combinations of typhoon intensity and terrain height for the formation of the induced cyclone. Further study is needed to investigate the mechanism of this phenomenon.

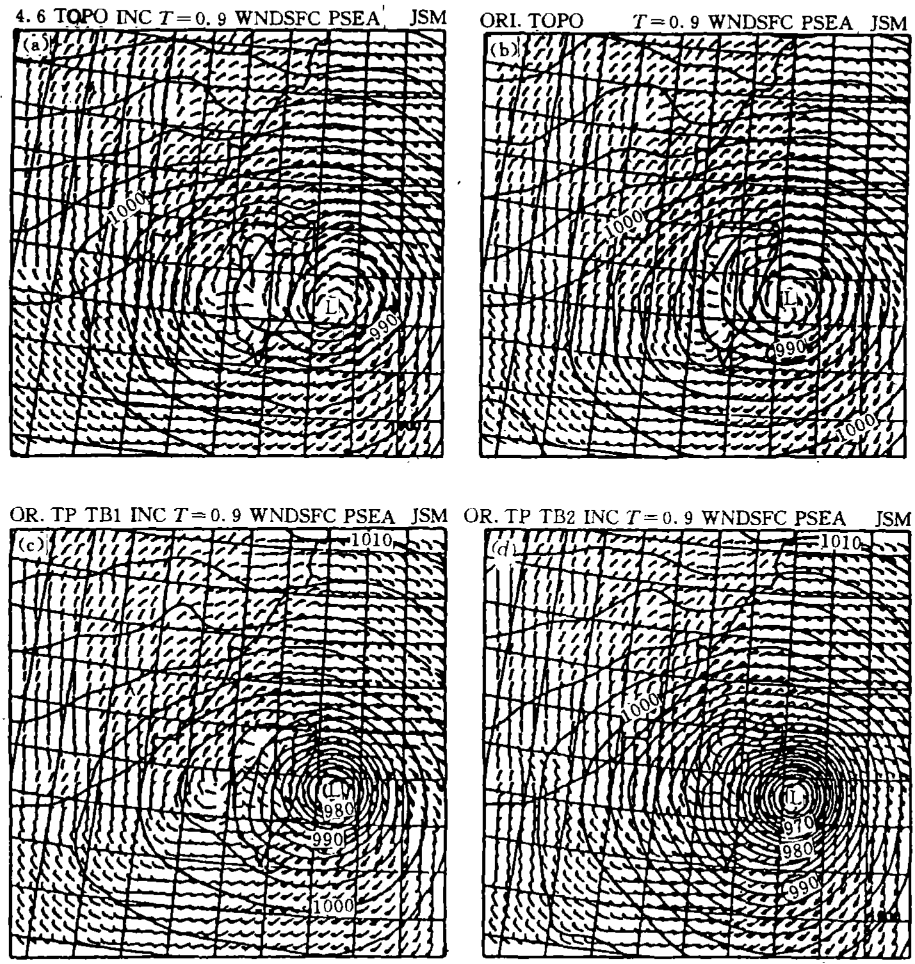

Fig. 8. Status of induced cyclone's formation with (a) T4 and weaker typhoon. (b) T2 and weaker typhoon. (c) T2 and original typhoon. and (d) T2 and stronger typhoon.

(3) *Width of the Taiwan Strait*

We expand the Taiwan Strait to an infinite width by deleting the Mainland China. Results show the low pressure area becomes much larger. corresponding to an apparent cyclonic circulation. than that of the original one. meaning that a wide strait is a beneficial factor for the formation of the induced cyclone (figure omitted).

V. THE DEVELOPMENT OF INDUCED CYCLONE AND ITS INTERACTION WITH TROPICAL CYCLONE CIRCULATION

When typhoon reaches the east coast of the Taiwan Island. typhoon circulation shows very different motion characteristics between at 500 hPa and surface. In Fig. 9. we can see that the surface center of Typhoon Dot is blocked by high mountain and disappears gradually on its windward slope. But the upper center of the typhoon continues to move across the Taiwan Island. Before it crosses the Taiwan Island. both the lower center and the higher center are corresponding to the original typhoon. But after it crosses the Taiwan Island. the higher

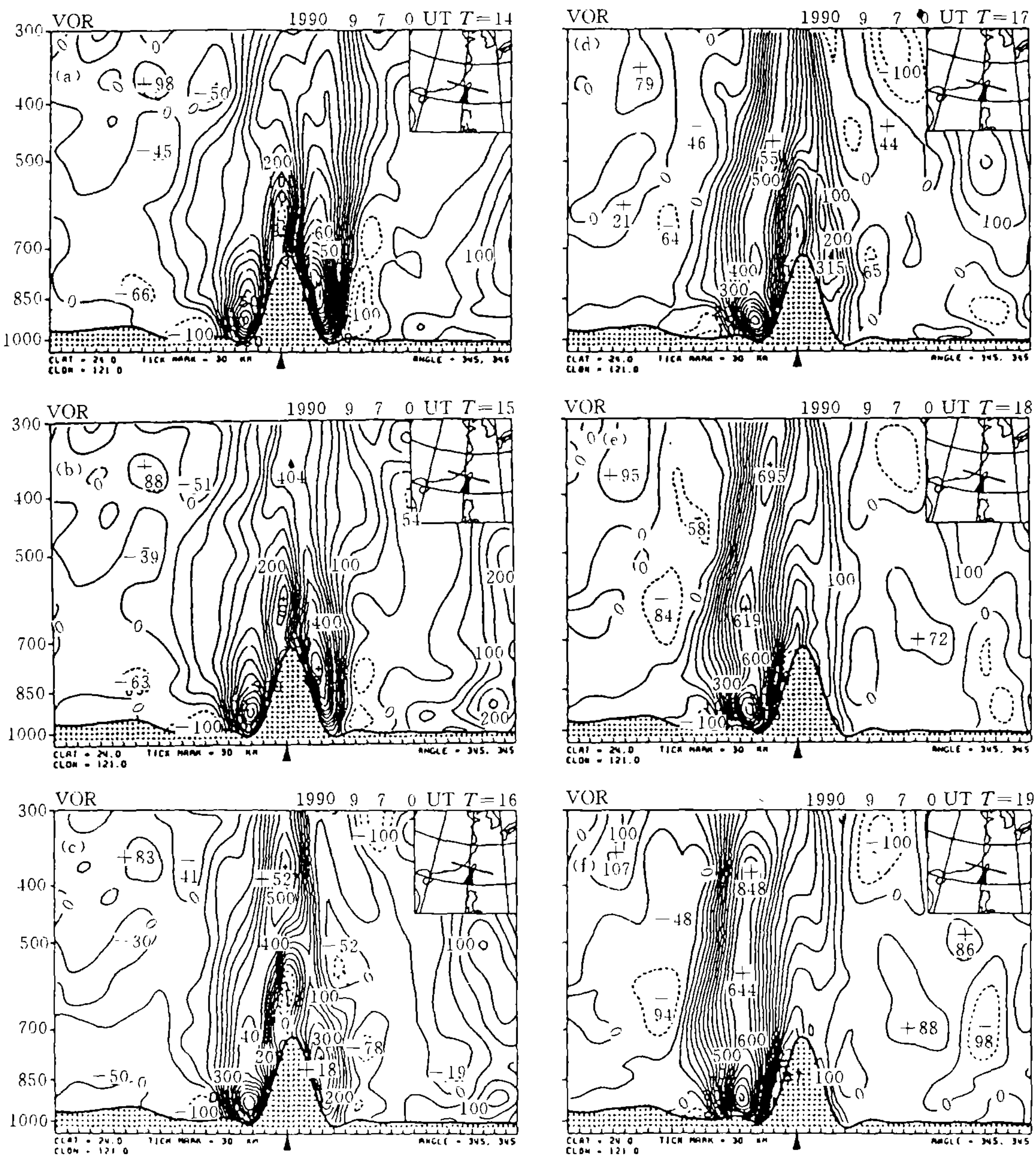

Fig. 9. Coupling process between Typhoon Dot and induced cyclone. (a) $t+14$h; (b) $t+15$h; (c) $t+16$h; (d) $t+17$h; (e) $t+18$h; (f) $t+19$h.

center becomes coupled with the induced cyclone. Through this coupling, the induced cyclone gets strengthened and resumes to move to the west, which vividly shows the interaction between induced cyclone and Typhoon Dot. This process in horizontal fields is shown in Fig. 10.

The coupling mechanism described above may be affected by other elements which influence the future development of the induced cyclone.

When we shift the Taiwan Island to southwest by 1.5°, as shown in Fig. 11, the induced

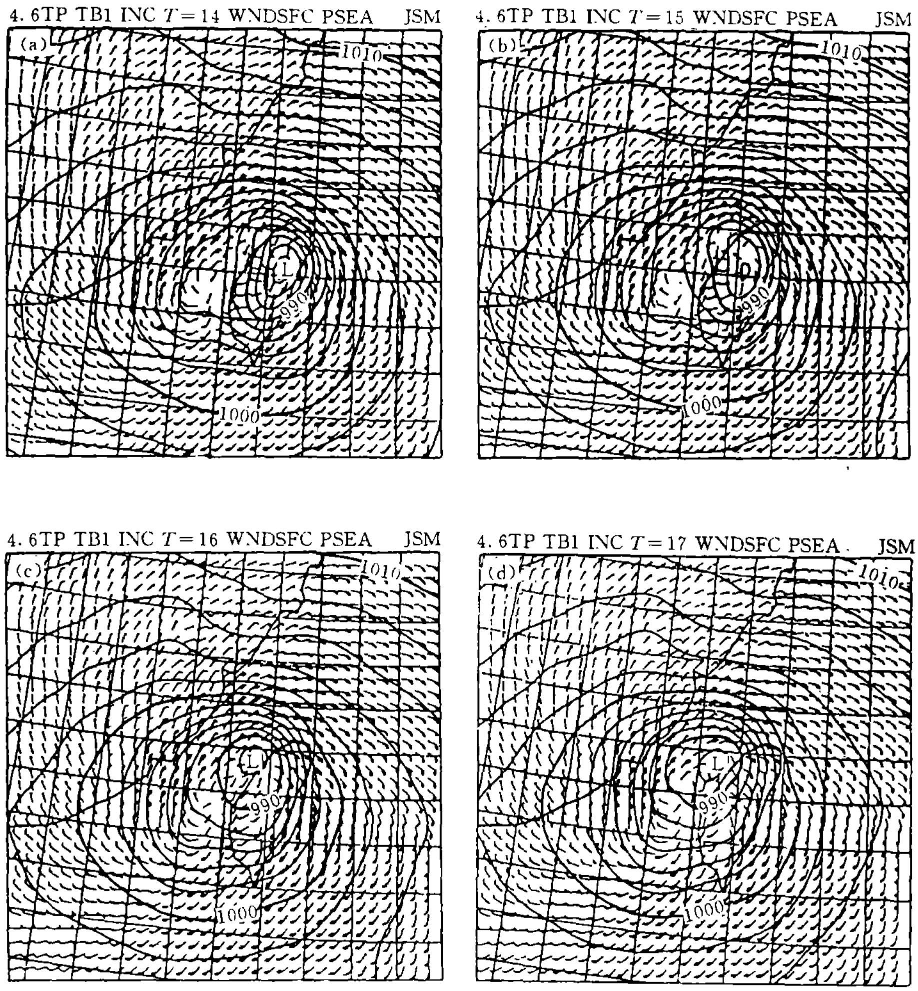

Fig. 10. Surface wind and sea-level pressure fields during coupling process. (a) $t+14$h; (b) $t+15$h; (c) $t+16$h; (d) $t+17$h.

cyclone occurs in the west of Taiwan Island but is far from the original typhoon center. Without coupling with the original center. the shallow induced cyclone disappears gradually.

Furthermore. in the experiment with a northeastward shifted island by 1. 5 degrees. it can be seen (figures omitted) that after 15—16 h the induced cyclone begins to couple with the upper level vorticity center at slightly northern position than the original case. It can be suggested that the landing point is also a very important factor for the development of induced cyclone. The further south the typhoon lands. the bigger the possibility of coupling between the induced cyclone and the typhoon will be.

Apart from the landing position. the large-scale steering flow is very important for the coupling possibility as well. In the present case. the strong steering flow due to subtropical high creates the coupling condition between the induced cyclone and westward moving upper-level vorticity center. If a typhoon locates just in front of a westerly trough while it is approaching the Taiwan Island. the induced cyclone may form. however the induced cyclone may weaken and disappear gradually without coupling with an upper level vorticity center.

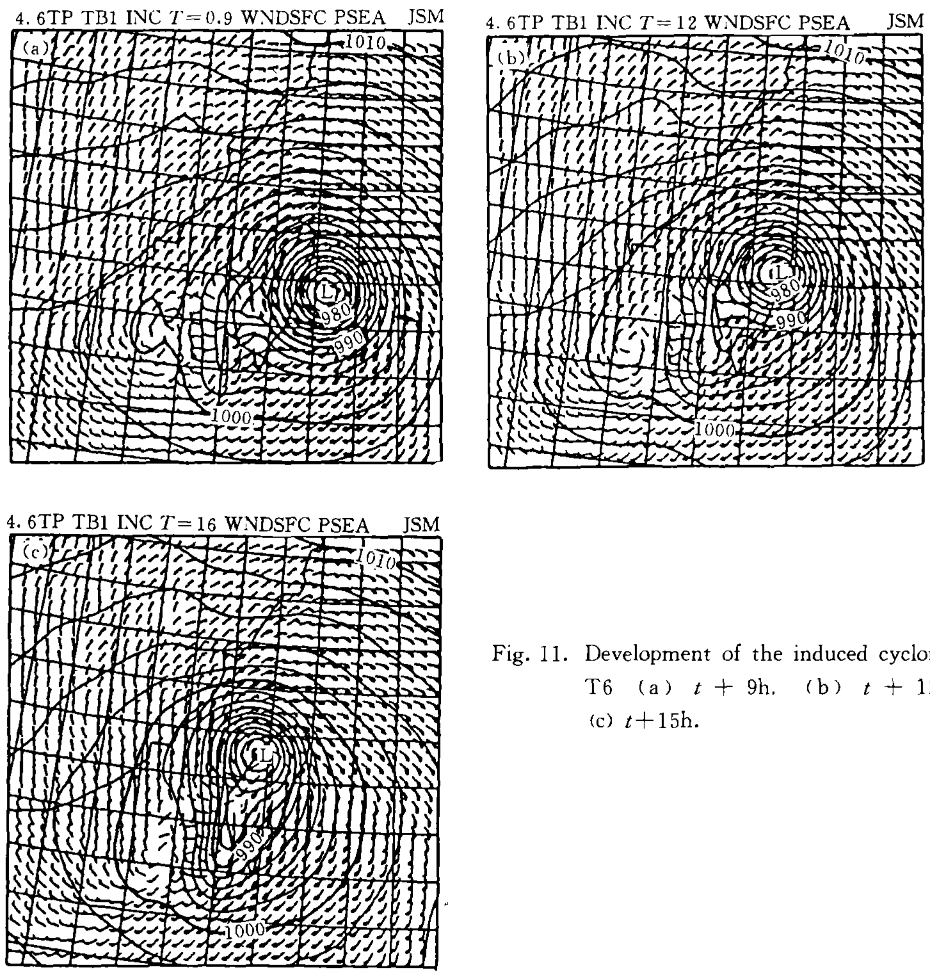

Fig. 11. Development of the induced cyclone with T6 (a) $t+9$h, (b) $t+12$h and (c) $t+15$h.

VI. CONCLUSIONS

Through the analyses of the results of control and sensitivity experiments, the following results are obtained:

(1) While a typhoon is approaching there always occurs a low pressure on the lee side of a mountain near the northern tip of the mountain range which is closely related to mountain wave. The higher the mountain is, the stronger the low pressure will be. This low pressure plays a very important role in the formation of an island-induced cyclone through providing a warm anomaly in temperature. The mountain also acts to create a positive anomaly in vorticity field.

(2) The terrain height, intensity of the typhoon and the width of the Taiwan Strait are also affecting factors for the formation of the induced cyclone. The higher the mountain is, the wider the strait is, the larger the formation possibility of the induced cyclone will be. The criterion height is around 3800 m. Furthermore, results also show that the role of typhoon intensity is not linear as the mountain height is, and very weak or very strong typhoons are not beneficial for the formation of the induced cyclone. The proper intensity of model typhoon is

around 960 hPa of minimum pressure.

(3) Under the situation where the original typhoon' s upper vorticity center moves towards the induced cyclone, a jumping phenomenon will happen: the low-level typhoon center is blocked by the mountain range, gets weakened and disappears gradually, the upper center keeps moving across the Taiwan Island and couples with the low-level induced cyclone and leaves the island. On the other hand, if the induced cyclone occurs far away from the future position of the approaching typhoon, it will get weakened and disappears gradually because of its shallow structure.

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