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PRELIMINARY STUDY ON RELATIONSHIP BETWEEN DOUBLE VORTICES SELF-ORGANIZATION AND TYPHOON FORMATION IN BAROCLINIC ENVIRONMENT

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Abstract: The relationship between the self-organization of double vortices (SODVs) and the formation of typhoons was discussed based on six numerical experiments with the Fifth-Generation National Center for Atmospheric Research/Penn State Mesoscale Model (MM5) and further discussion was made with a real typhoon case. The results showed that there is a critical distance d_c for SODVs in baroclinic atmosphere. When the distance between separated vortices is smaller than or equal to d_c, the double vortices self-organize into a typhoon-like vortex with two spiral bands. But the double vortices cannot have such organization if the distance between them is larger than d_c. The value of d_c is about 380 km in the context of ideal conditions in this paper, larger than that achieved in a barotropic model. A typical typhoon case in 2005 (Haitang) was selected to verify the above-mentioned conclusions. It was found that the SODV is one of the important and typical ways for the formation of typhoons.

Key words: baroclinic atmosphere; self-organization of double vortices; typhoon formation

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1 INTRODUCTION

The self-organization of a vortex is a process in which two or multiple vortices of smaller scale evolve into a larger vortex after a period of mutual interaction. There is no diabatic forcing and the boundary forcing is neglectable. The formation of the larger vortex is not due to any external forcing but pure internal nonlinear interaction (Zhou[1]). In recent years, there have been some published studies on the self-organization processes of double or multiple vortices using barotropic models. The vortex self-organization in a multiple scale system and the effects of the structure and scale of an initial vortex on the process have also been discussed (Shen[2], Zhou[3, 5], Luo[4]). However, further study on baroclinic atmosphere is necessary to understand better the relationship between the self-organization of double vortices and the formation of typhoons.

According to Chen and Yau[6], cloud clusters on satellite imagery correspond to vortices on vorticity fields. For instance, there are generally two spiral cloud bands in typhoons which represent spiral vorticity bands. Therefore, the relationship between self-organization of a vortex and the formation of typhoons can be studied by both voritcity fields and cloud images.

In studying the self-organization of vortices, the focus is on how two or more vortices self-organize into a larger vortex and the characteristics of the self-organized vortex. The merging of vortices is an important aspect of the study of self-organization, which emphasizes the conditions required for vortices to merge, with efforts especially on the judgment of critical distances for vortices merging.

The effect of self-organization of double vortices on typhoon formation is discussed in this paper based on idealized numerical experiments and a case study.

2 MODEL AND DESIGN OF EXPERIMENTS

Doubly nested experiments were conducted in ideal conditions without environmental flow, using the

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fifth-generation Pennsylvania State University/U. S. National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5). The spacing in the inner and outer areas is 20 and 60 km, respectively. The corresponding grid points are 253×253 and 101×101, and all of the results analyzed are given by the inner domain. The vertical coordinate has 17 σ-levels (1.00, 0.99, 0.98, 0.96, 0.94, 0.91, 0.88, 0.85, 0.82, 0.77, 0.66, 0.55, 0.44, 0.33, 0.22, 0.11, and 0.00). The model top is at 100 hPa. All experiments integrate for 120 hours and export results every 6 hours with a time step of 180 s. The Grell cumulus parameterization scheme and Blanckard planetary boundary level scheme are used. The vertical velocity is equal to 0.0 on the top and surface boundary, and the lateral boundary conditions are time-dependant.

When t=0, the velocity profile of mesoscale vortices is decided by Wang[7] as

$$V_M(r,\sigma)=\begin{cases} V_m(\frac{r}{r_m})\exp(1.0-(\frac{r}{r_m}))\times\sin(\frac{\pi}{2}\frac{\sigma+0.2}{1.2}) & r\le r_c, \\ 0 & r>r_c. \end{cases} \quad (1)$$

The corresponding vorticity structure is as follows:

$$\xi_M(r,\sigma)=\begin{cases} (\frac{2.0V_m}{r_m})(1.0-\frac{0.5r}{r_m})\exp(1.0-\frac{r}{r_m})\times\sin(\frac{\pi}{2}\frac{\sigma+0.2}{1.2}) & r\le r_c, \\ 0 & r>r_c. \end{cases} \quad (2)$$

where r is the distance to the vortex center, r_c is the scale parameter of a mesoscale vortex, V_m is maximum tangential wind velocity at surface, and r_m represents the distance where V_m appears.

$$\sigma=\frac{P-P_t}{P_s-P_t}. \quad (3)$$

where P is the reference-state pressure, P_t is a specified constant pressure at the top, and P_s is the reference-state surface pressure.

The values of parameters are: $V_m=32.0\ \mathrm{ms^{-1}}$, $r_m=100.0$ km, $r_c=500$ km, $P_s=1010$ hPa, $P_t=100$ hPa.

In ideal experiments without ambient flows, when t=0, the horizontal gradients of pressure and temperature are set to be zero (Zängl[8]). The sea surface temperature (SST), temperature on pressure levels and moist profiles are given in Duan et al.[9] The corresponding geopotential height field can be expressed by the hydrostatic equation. The stream function can be obtained by solving the Poisson equation with relative vorticity, and then the u and v components can be obtained by solving the streamline equation. The relative vorticity at t=0 is

$$\xi(x,y,\sigma)=\xi_{\mathrm{MW}}(x,y,\sigma)+\xi_{\mathrm{ME}}(x,y,\sigma) \quad (4)$$

where ξ is the total relative vorticity, ξ_{MW} is the relative vorticity of a mesoscale west vortex, ξ_{ME} is the relative vorticity of a mesoscale east vortex. ξ_{MW} and ξ_{ME} are the same except for position and decided by Eq. (2). The details of the initial fields for the ideal experiments of MM5 can be found in Chuang[10].

Six numerical experiments were conducted to examine the effect of different initial vortex parameters on the self-organization of double vortices and to obtain the critical distance at which two vortices self-organize into a larger-scale typhoon-like vortex with two distinct spiral bands (see Table 1).

Table 1. Setup of numerical experiments

Experiments	V_m/(ms^{-1})	d_{AB}/km	r_c/km
Exp.1	32.0	380.0	500.0
Exp.2	32.0	360.0	500.0
Exp.3	32.0	400.0	500.0
Exp.4	32.0	420.0	500.0
Exp.5	36.0	400.0	500.0
Exp.6	28.0	400.0	500.0

3 RESULTS

3.1 *Self-organization of double vortices and typhoon formation*

Figure 1 shows the temporal changes of the relative vorticity field at 700 hPa in Exp. 1 (d_{AB}=380 km). Vortices A and B co-rotate counter-clockwise with each other. The moving coordinate is applied to all experiments. The following features can be observed.

First, the initial axisymmetric double vortices move toward each other during their co-rotation. With the model integrated for 24 hours, the double vortices co-rotate 145 degrees and the contours in the outer part of each vortex begin to connect but there are still two independent vortex centers (Fig. 1b). The two mesoscale vortices have self-organized into a typical typhoon-like vortex with two clear spiral vorticity bands at the 48th hour of model integration, and there still maintain two vortex centers in the inner region of the typhoon-like vortex (Fig. 1c). After 72 hours of model integration, these two vortex centers begin to merge into one in the inner region of the typhoon-like vortex (Fig. 1d). And then, the typhoon-like vortex is formed through self-organization with an axisymmetric structure (Fig. 1e & 1f).

Second, there is distinct difference of moving velocity before and after the merging of double vortices. The double vortices move northwestward for about 300 km from the 0th to 48th hour due to the existence of interactions between them (Figs. 1a, 1b and 1c). After that, the typhoon-like vortex moves northwestward for about 500 km from the 48th to 96th hour, faster than the double vortices that do not merge.

Third, the negative vorticity zones also contribute to the self-organization of the typhoon-like vortex. At *t*=24 h, a region of negative vorticity surrounding the two vortices at initial time begins to separate into two parts, which stand on the east and west sides of the double vortices respectively (Fig. 1b). Afterwards, these two parts of the negative vorticity zone gradually stretch zonally during the co-rotating process of the double vortices (Fig. 1c), which evolves into a round negative band and surrounds the typhoon-like vortex closely.

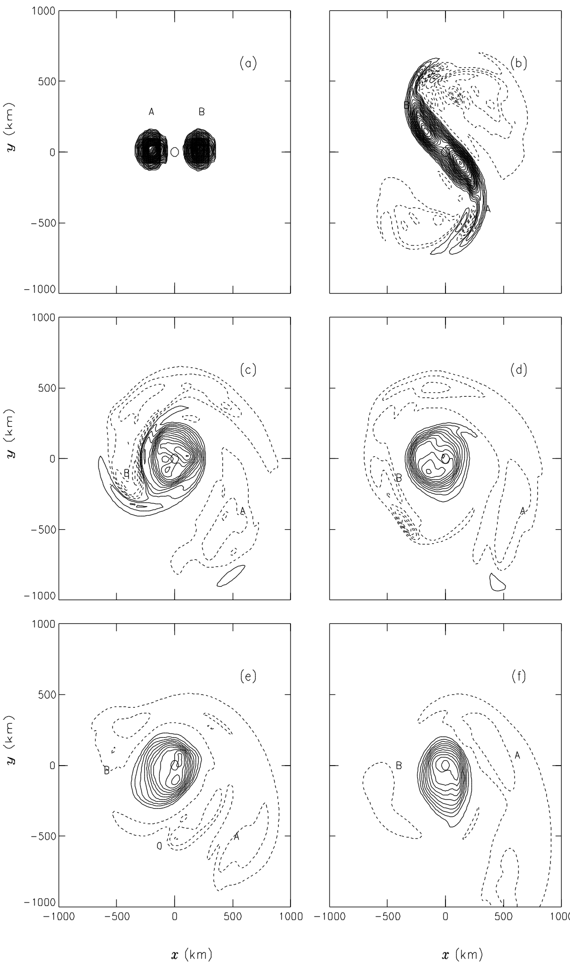


Fig. 1. Relative vorticity field evolving with time at 700 hPa in Exp. 1 (a. *t*=0 h; b. *t*=24 h; c. *t*=48 h; d. *t*=72 h; e. *t*=96 h; f. *t*=120 h; The solid line indicates the positive contour and the dash line the negative contour; The interval of contour is 0.2×10^{-4} s^{-1}. O is the center of the computed area.)

Figure 2 shows the zonal-vertical cross-section of the relative vorticity field at *t*=0 h and *t*=48 h respectively, which reveals the changes in vertical structure during the merging of double vortices. At *t*=0 h (Fig. 2a), the double vortices are axisymmetric and the intensity decreases with height from the lower-middle part of the model atmosphere. The vortices are weak at both the ground and upper levels of the troposphere with smaller size. Such a distribution of relative vorticity is consistent with the real typhoon vortex (Frank[11]). At *t*=48 h (Fig. 2b), a new typhoon vortex forms by self-organizing double mesoscale vortices below 400 hPa with a center on 500 to 600 hPa. Above 400 hPa, the western vortex intensifies and the eastern vortex weakens, which verifies the conclusion proposed by Wang et al.[12] for a barotropical environment: the interaction between double vortices is in fact a process with one vortex developing and the other weakening.

3.2 *Critical distance for typhoon vortex self-organization in a baroclinic atmosphere*

With the decrease of the distance between double vortices (Exp. 2, d_{AB}=360km, figures omitted), the self-organization completes earlier than in Exp. 1, and the phenomenon can be observed in the lower-middle, middle and upper-middle parts of the troposphere. In Exp. 3 (d_{AB}=400km, Fig. 3), the distance between double vortices is larger than in Exp. 1. The relative vorticity field is similar to that of Exp. 1 at *t*=24 h, but the co-rotating angle of double vortices is smaller. At *t*=48 h, the double vortices co-rotate for about 150 degrees (Fig. 3c). Afterwards, the double vortices stop co-rotating and both move westward with vortex B moving faster than vortex A. The distance between the two vortices enlarges and the double vortices separate finally.

When the double vortices are placed further away from each other, the co-rotating velocity and angle of the two vortices decrease further (Exp. 4, d_{AB}=420km, figures omitted). The two vortices also separate eventually.

From the above discussion, it can be determined that the initial axisymmetric double vortices can self-organize into a typhoon-like circulation when the distance between the two vortices (d_{AB}) are equal to or less than the critical distance (d_c=380 km), similar to that in a barotropic model. However, the critical distance is larger in the baroclinic atmosphere than in the barotropic model. On the other hand, the self-organization process evolves with the increase of vortex intensity in the barotropic model (Shen[2]) as a result of energy conservation. According to the experiments with MM5, the vortex intensity decreases with the self-organization process, showing that: (1) the energy of the vortex system does not conserve in a baroclinic model, (2) there are kinds of dissipating effect in the baroclinic model, and (3) the CISK mechanism (Charney[13]; Ooyama[14]) closely related to large-scale environmental flows is important for maintaining the intensity of a typhoon vortex formed by self-organization (Luo [15]).

Besides the distance between the double vortices, the initial intensity can also affect the self-organization process. As shown in Exps. 5 & 6 (Figures omitted), no self-organization phenomenon appears, indicating that the effect of vortex intensity is weaker than that of the distance between vortices. When the distance between double vortices is greater than 400 km, the increase or decrease of vortex intensity cannot cause the initially separated double vortices to self-organize into a typhoon-like vortex.

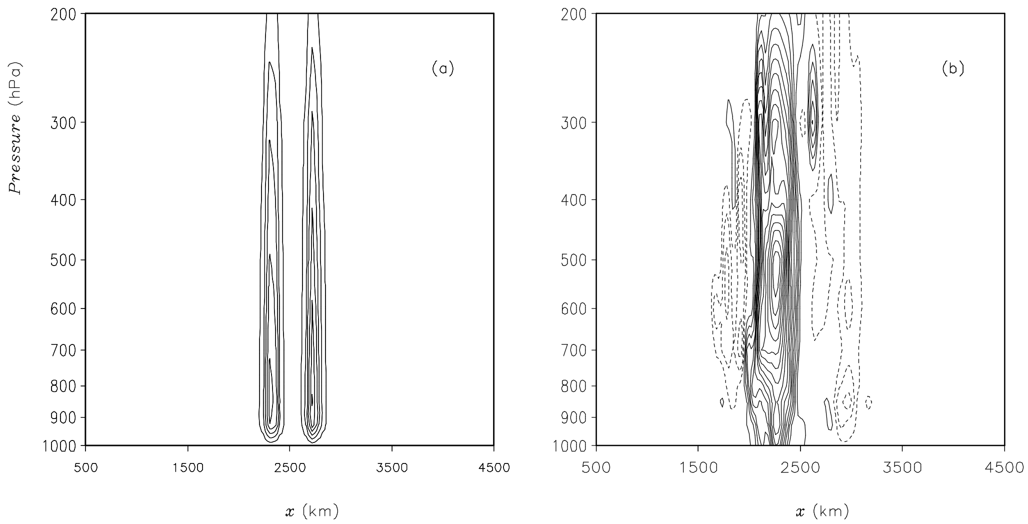


Fig. 2. Zonal-vertical cross-section of relative vorticity at t=0 h and t=48 h in Exp. 1 (a. t=0 h; b. t=48 h; The contour interval is 2.0×10^{-4} s^{-1} and 0.2×10^{-4} s^{-1} in a and b, respectively.)

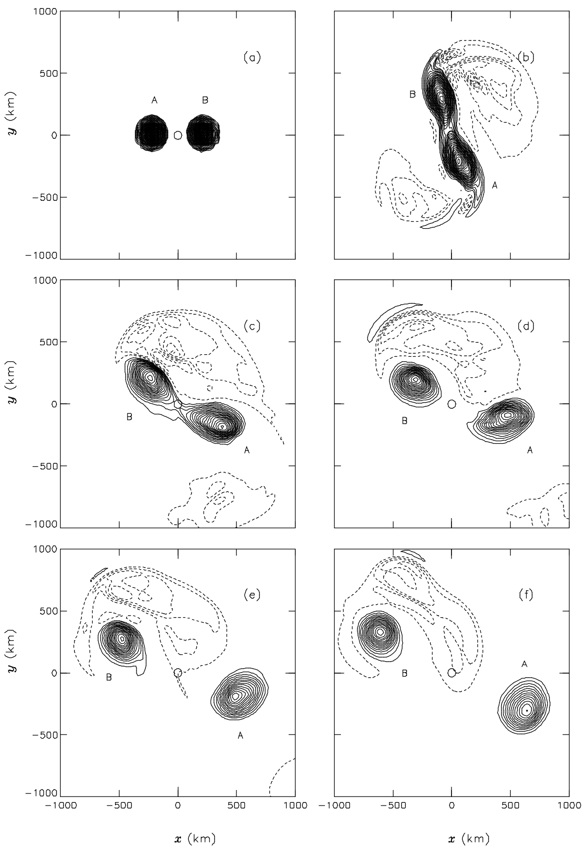


Fig. 3. Temporal changes of relative vorticity at 700 hPa in Exp. 3 (The same as in Fig. 1.)

4 CASE STUDY ON THE RELATIONSHIP BETWEEN SELF-ORGANIZATION OF DOUBLE VORTICES AND TYPHOON FORMATION

4.1 *Outline for data and the selected case*

The data used in this part include the global tropospheric grid data with a resolution of 1°×1° from the U.S. National Centers for Environmental Prediction (NCEP)/NCAR and the satellite cloud imagery data from FengYun-2C (FY-2C) of China. The 1°×1° grid data cover a wide range with multiple levels to disclose the 3-dimensional structure of typhoons. The time and space resolution is 1 hour and 0.5 degree respectively for the cloud imagery data from FY-2C, which can compensate to some extent the shortcoming of coarse resolution existent in grid data.

Typhoon Haitang (2005) was selected to study the role of the self-organization process during its formation. Formed 600 km to the northeast of Guam at 1200 (UTC, or Universal Coordinated Time, same below) on 12 July 2005, Haitang moved to southwest and intensified to be a typhoon at 1800 on 13 July. Haitang made landfall at the bay of Dong'ao, Yilan county, Taiwan province, at 0650 UTC on 18 July, and at Huangqi, Lianjiang county, Fujian province, at 0910 UTC on 19 July, respectively. It dissipated over inland China on 21 July.

4.2 *Double vortices self-organization and formation*

of typhoon Haitang

Figure 5 shows the temporal changes of relative vorticity at 850 hPa (Fig. 5A) and 500 hPa (Fig. 5B) for the 48 hours before being numbered by CMA. The double vortices were undergoing a clear self-organization process at 850 hPa during the formation of Haitang. Forty-eight hours before Haitang was numbered, a high-vorticity area corresponding to the double vortices laid in a northwest-southeast direction (Fig. 5A-a). Afterwards, the double vortices moved close to each other while co-rotating and their outer vorticity zones began to connect with each other. The co-rotating angle of the double vortices is about 45 degrees and a high-value area of vorticity extends in an ease-west direction, still with two vortex centers. The intensity of the eastern vortex center is greater than the western one (Fig. 5A-b). Six hours later (1800 UTC on 10 July 2005), the co-rotating angle decreased as the west vortex developed and extended. Simultaneously, the eastern vortex started to merge into the western one (Fig. 5A-c). Afterwards, the double vortices moved closer to each other and the eastern vortex completely merged into the western one at 1200 UTC on 11 July. Twelve hours before the typhoon was numbered (Fig. 5-f), the typhoon-like circulation intensified further and formed a typhoon vortex named Haitang at 0000 UTC on 12 July 2005.

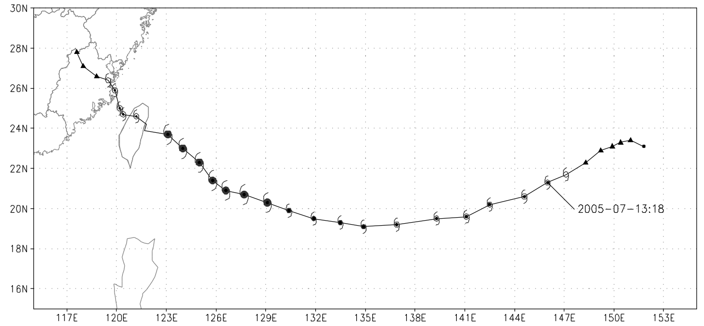
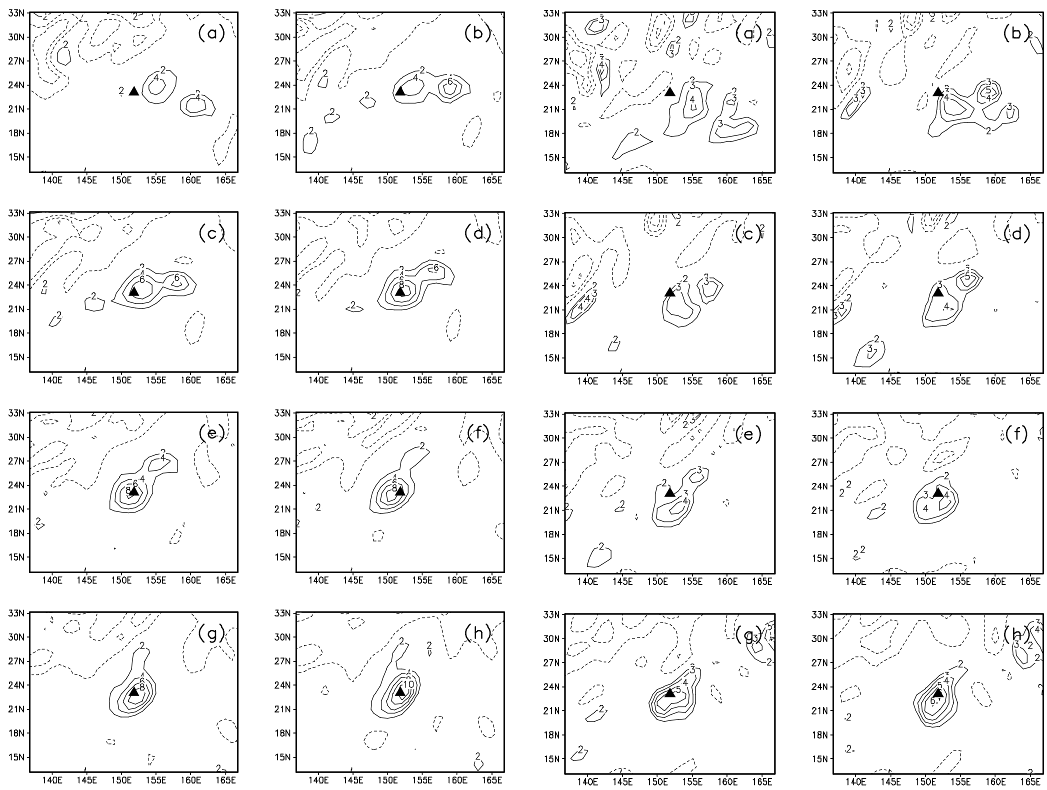


Fig. 4. Track of typhoon Haitang (2005-07-13:18 indicates 1800 UTC 13 July 2005.)



A B

Fig. 5. Temporal changes of the relative vorticity field on 850 (A) and 500 hPa (B) during the formation of Haitang (a. 0000 UTC on 10 July; b. 1200 UTC on 10 July; c. 1800 UTC on 10 July; d. 0000 UTC on 11 July; e. 0600 UTC on 11 July; f. 1200 UTC on 11 July; g. 1800 UTC on 11 July; h. 0000 UTC on 12 July; The interval of contour is $2\times 1e\text{-}05\ s^{-1}$ and $1e\text{-}05\ s^{-1}$ in A and B, respectively; ▲ is the position of typhoon's center at the time of numbering)

The self-organization process of the double vortices at 500 hPa is similar to that at 850 hPa (Fig. 5B), with three main differences though. (1) There are three vortices in the zonal direction, the western vortex, middle vortex and eastern vortex, 48 hours before Haitang was numbered (0000 UTC on 10 July, Fig. 5B-a). The middle vortex is the highest in intensity. Located at the southeast of the middle vortex, the eastern vortex takes the second place with two vortex centers in the north and south part respectively. The western vortex stands to the southwest of the middle vortex and the intensity is the weakest. (2) After 12 hours, the middle vortex intensifies as the western vortex merges into it. The outer vorticity contours of both the eastern and middle vortices begin to connect together, while the northern center of the eastern vortex develops significantly and its southern center decreases (Fig. 5B-b). (3) At 1800 on 10 July, the southern center of the eastern vortex began to dissipate, resulting in the northern center separating from the middle vortex (Fig. 5B-c). Till this time, the vorticity field at 500 hPa has been similar to that at 850 hPa. (4) At 0000 UTC on 11 July (Fig. 5B-d), the double vortices developed together during their interaction, and the vorticity distribution was in a northeast-southwest direction. The intensity of the northeastern vortex center is greater than the southwestern one. At 1200 UTC on 11 July, the double vortices moved closer to each other and finally self-organized into one typhoon-like vortex with asymmetric vorticity distribution which is dense in the east and loose in the west (Fig. 5B-e, 5B-f). (5) Six hours before Haitang was numbered (1800 UTC on 11 July, Fig. 5B-g), the outer vorticity field extended to the northeast and formed a vorticity tongue as a result of a negative vorticity area to the north 6 hours before. The inner relative vorticity value increases during the axisymmetrization process of typhoon Haitang. At the time when Haitang was numbered, the central intensity of the vortex further intensified (Fig. 5B-h).

At 300 hPa, the self-organization process of Haitang does not complete as a whole, but the phenomenon of vortex self-organization can be observed in some parts (Figures omitted) with the western vortex developing prior to the eastern one.

Thus, from the view of 3-dimensional structure changes of Haitang, the self-organization process appears at and below 500 hPa.

According to the TBB cloud images, forty-eight hours before the typhoon was numbered (0000 UTC on 10 July, Fig. 6a), there was a small scale cloud clump (labeled ‘a’) with a piece of continuous cloud region to its east. Six hours later, two small scale cloud clumps, labeled ‘b’ and ‘d’ respectively, appear in the north of cloud clump ‘a’, and cloud clumps ‘a’, ‘b’, and ‘d’ lie in a north-south distribution. At the same time, the continuous cloud region to the east of cloud clump ‘a’ merges into one cloud cluster (Fig. 6b). At 1100 UTC on 10 July, cloud clump ‘a’ develops with a bigger scale. Cloud clump ‘b’ develops too and begins to connect with cloud clump ‘a’. Cloud clump ‘c’ forms between cloud clumps ‘a’ and ‘b’ at this time (Fig. 6c). One hour later (1200 UTC on 10 July, Fig. 6d), cloud clumps ‘c’ and ‘d’ merge into cloud cluster ‘D’ with a bigger scale. Cloud cluster ‘D’ moves south to join cloud clump ‘b’, which results in the combination of cloud clumps ‘a’, ‘b’, and cloud cluster ‘D’ and the formation of a bigger cloud cluster ‘A’ (Fig. 6e). The formation of cloud cluster ‘A’ indicates that the first vortex self-organization process basically completes. Three hours later, cloud cluster ‘A’ experiences an axisymmetrization process (Fig. 6f). At 0000 UTC on 11 July, a small cloud clump ‘B’ forms and begins to intensify (Fig. 6g). The formation of cloud cluster ‘C’ results from the interaction between cloud clusters ‘A’ and ‘B’, which indicates the accomplishment of the second vortex self-organization process (Figs. 6h, 6i & 6j). Then cloud cluster ‘C’ begins to self-develop (Figs. 6d-6o) and intensify to become Typhoon Haitang (Fig. 6p).

It can be seen that the self-organization of double vortices resulting in the formation of Typhoon Haitang is completed in several different phases, which cannot be reflected by the grid data with resolution of $1°\times1°$. On the other hand, the vortex self-organization process of typhoon Haitang occurs at and below the middle level of the troposphere.

5 CONCLUSIONS AND DISCUSSIONS

The formation of Typhoon Haitang resulting from the self-organization of double vortices was analyzed based on idealized numerical experiments and a real case study. Several conclusions can be drawn as follows:

(1) The self-organization of double vortices is a typical way of typhoon formation.

(2) There is a critical distance (about 380 km) for the self-organization of double vortices in baroclinic atmosphere. This distance is farther than that in Luo[16] (about 340 km) in barotropic atmosphere.

(3) The formation of a typical typhoon case begins with the interaction of two or multiple vortices and ends with the self-organization of double vortices.

The abrupt changes related to a typhoon, including its formation over offshore waters, the abrupt changes of its intensity, and its structure and track, have been difficult issues in the prediction procedure and there has not been any valid method that can successfully predict these changes. Some research achievements have been proposed in the frame of vortex self-organization in a barotropic model (Zhou[1, 3], Shen[2], Luo[4, 15, 17-20]), which sets an appropriate direction of research for learning more about the abrupt changes of typhoons. Based on these achievements, the relationship between the self-organization of double vortices and the formation of typhoons was discussed further with six numerical experiments in a baroclinic model, and a typical typhoon case (Haitang) was studied in terms of its formation based on the results of numerical experiments in this paper. As this work is preliminary for this issue, more effort is needed to make progress in probing the abrupt changes of typhoons.

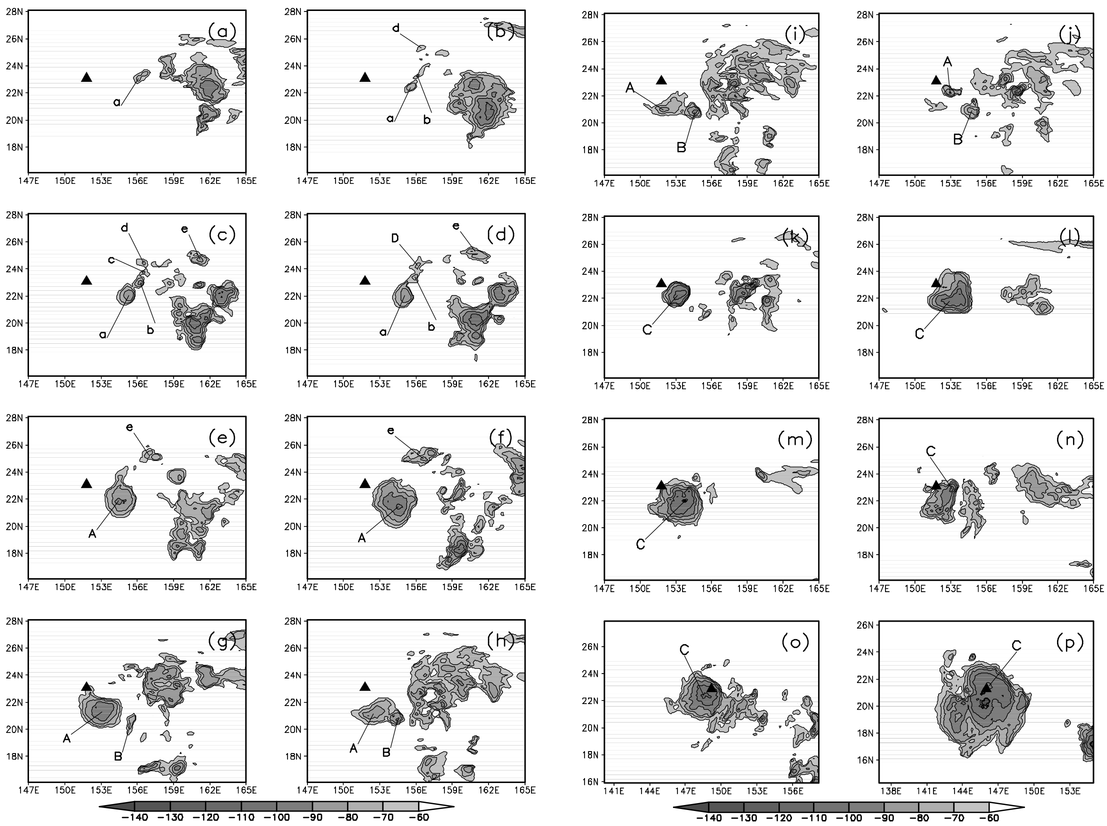


Fig. 6. Temporal evolution of TBB during typhoon Haitng's formation (a. 0000 UTC on 10 July 2005; b. 0600 UTC on 10 July; c. 1100 UTC on 10 July; d. 1200 UTC on 10 July; e. 1500 UTC on 10 July; f. 1800 UTC on 10 July; g. 0000 UTC on 11 July; h. 0300 UTC on 11 July; i. 0400 UTC on 11 UTC July; j. 0600 UTC on 11 July; k. 0800 UTC on 11 July; l. 1200 UTC on 11 July; m. 1800 UTC on 11 July; n. 0000 UTC on 12 July; o. 0000 UTC on 13 July; p. 1800 UTC on 13 July; the interval of contour is 10℃; ▲ is the position of typhoon center at the time of numbering.)

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