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THE APPLICATION OF CONDITIONAL NONLINEAR OPTIMAL PERTURBATION TO THE BINARY TYPHOONS INTERACTION —FENGSHEN AND FUNG-WONG

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Abstract: The interaction between the typhoons Fengshen and Fung-wong over the Western Pacific in 2002 is studied with the Conditional Nonlinear Optimal Perturbation (CNOP) method. The study discovered that the CNOP method reveals the process of one-way interaction between Fengshen and Fung-wong. Moreover, if the region of Fung-wong was selected for verification, the sensitivity area was mainly located in the region of Fengshen and presented a half-ring structure; if the region of Fengshen was selected for verification, most of the sensitivity areas were located in the region between the Fengshen and the subtropical high, far away from Fung-wong. This indicated that Fung-wong is mainly steered by Fengshen, but Fengshen is mainly affected by the subtropical high. The sensitivity experiment showed that the initial errors in the CNOP-identified sensitive areas have larger impacts on the verification-area prediction than those near the typhoon center and their developments take a large proportion in the whole domain. This suggests that the CNOP-identified sensitive areas do have large influence on the verification-area prediction.

Key words: Conditional Nonlinear Optimal Perturbation; binary typhoons; interaction; sensitivity area; prediction

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1 INTRODUCTION

In the typhoon season, two or more typhoons often emerge at the same time in the western Pacific. While the distance between two typhoons is small, interaction phenomena, such as the processes of mutual rotating, attracting and merging, escaping etc., often appear between them, and results in abnormal typhoon tracks. Thus, forecasts become difficult. For a long time, the issue of binary typhoons interaction has been addressed by meteorologists. In 1921, Fujiwhara[1] carried out theoretical analysis and experiments on the mutual effect between two eddies and it has been known as the *Fujiwhara effect*. With regard to the value of research on mutual effect between binary typhoons, Yang et al.[2] pointed out that it is not only a significant basic research for hydrodynamics, more importantly, it can also effectively improve the forecast accuracy of the mutual effect between binary typhoons.

In theory, to improve the numerical prediction accuracy of binary-typhoon mutual effect processes, we should not only know the forms of the mutual effect process, but also need to understand the cause of this phenomenon. In order to explore the impact of binary typhoon movements on the binary typhoon interactions, Zhu et al.[3] took a numerical experiment in 1989 for binary typhoons with a barotropic primitive equations model. The result showed that, in the conditions of no or weak environmental wind, the advection of typhoon tangential wind is the main factor that determines the rotating velocity of binary typhoons. In addition, Yan et al.[4] numerically studied the binary typhoons aligned in northwest-southeast direction with a barotropic non-divergence model, and discussed the application of the asymmetric theory to the mutual effect of binary typhoons. In addition, Chang[5] studied the mutual effect of two mesoscale vortexes with a 3-D baroclinic model and found that

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the mutual effect of two cyclonic vortexes with a barotropic non-divergence model is similar to the *Fujiwhara effect* acquired from observations, but the interaction processes have obvious difference. However, the fact that the 3-D baroclinic model can well simulate the *Fujiwara effect* of cyclonic vortex shows that the *Fujiwara effect* is not caused by the advection effect alone and more complex effects may still exist between them.

In this paper, we will study the interaction of binary typhoons with the Conditional Nonlinear Optimal Perturbation (CNOP) method. The CNOP method is the extension of the linear Singular Vector (SV) method into the nonlinear field; it can effectively reveal the nonlinear process. The method has been successfully applied to the research of many weather and climate events, such as ENSO, blocking, typhoons etc. (Mu and Duan[6], Duan and Mu[7], Mu and Jiang[8], Mu et al.[9, 10], Chen and Mu[11], Zhou and Mu[12], Qin[13]). Their nonlinear characteristics have been revealed due to the initial modes and nonlinear development. By studying the sensitive areas of individual typhoons from a binary-typhoon case (Fengshen and Fung-wong), we will search for the main factors which determine the typhoon track and examine them through a series of sensitivity experiments in order to learn more about the mutual interaction between binary typhoons.

In this paper, section 2 introduces the model, data and experimental framework, section 3 shows the analysis of experiment results, and the summary and discussion are presented in section 4.

2 MODEL, DATA AND EXPERIMENT DESIGN

2.1 Model and data introduction

Our study utilized the Fifth-Generation Pennsylvania State University and National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5) and its corresponding adjoint model. The parameterizations used in the nonlinear model are a simple ice explicit moisture scheme, Grell-cumulus parameterization and MRF PBL-scheme. The horizontal resolution is 60 km and the vertical range is divided into 23 sigma levels, with the top pressure at 100 hPa. The physical parameterizations in its adjoint model are identical with those in the nonlinear model except for a dry explicit moisture scheme. The center of the model is situated at (25.0°N, 137.5°E) and the model domain size is 75×85 (latitude×longitude).

The initial and boundary conditions are from the National Centers for Environment Prediction (NCEP) Global Forecasting Systems (GFS) global reanalysis (1°×1°) interpolated to the MM5 grids. In addition, the China Meteorological Administration-Shanghai Typhoon Institute (CMA-STI) Best Track Dataset for Tropical Cyclones in the Western North Pacific from Shanghai Typhoon Institute (STI) of the CMA was used as real data for comparison with the result of experiments.

2.2 *Description of cases*

The binary typhoons selected in this paper are Fengshen and Fung-wong. Occurring over the western Pacific in 2002, both of them showed obvious mutual effect between 00:00 July 23 and 00:00 July 25. Therefore, this period of time was set as the runtime of the model in this paper.

Fengshen, also known as Typhoon No.0209, was the strongest typhoon in 2002 over the northwestern Pacific. It was generated near the Marshall Islands in west Pacific, dissipated in Shandong Peninsula, and had the characteristics of long-life history and high intensity. On July 14 2002, Fengshen developed into a tropical depression at about 1000 km to the southeast by south of Wake Island (11.5°N, 170.7°E), rapidly intensified into a typhoon the next day and continued moving northwest in the next 10 days. Fengshen weakened gradually from July 22 but accelerated its movement to the northwest in the meantime. In the next day, the central dense overcast of Fengshen was separated from a southern cloud system, suppressing the water supply while the storm was moving to the north. On July 25, Fengshen was close to the Kyushu Island and weakened to a tropical storm at this point. During this period, however, it also caused serious damage to the local marine and air traffic and brought heavy rain to Beijing while landing on the southern side of Shandong Peninsula on 27 July. After that, Fengshen continued to move north and disappeared in the Bohai Sea.

Compared with Fengshen, the strength of typhoon Fung-wong (0211) was much weaker. Fung-wong formed at about 150 km to the southwest of Iwo Jima, moved west since the formation and strengthened to a typhoon on 23 July. At the same time, the mutual effect between Fengshen and Fung-wong was generated due to the *Fujiwara effect* and Fung-wong moved around Fengshen in the counterclockwise direction. On July 24, Fung-wong weakened to a tropical storm and moved northwest. Finally Fung-wong disappeared on July 27 over the ocean west of Kyushu.

In this experiment, the track error with a 48-h simulation with the MM5 model (the track indicated by the minimum of sea level pressure) is 240 km for Fengshen but 390 km for Fung-wong. Though slightly larger than that of Fengshen, the track error of Fung-wong is still acceptable. As a result, we will use the MM5 model in this experiment.

2.3 *Design of experiment*

(1) At first, the sensitive areas for each typhoon were identified by the CNOP method (refer to Zhou and Mu[12] for the details of the method).

a. Using the nonlinear model and the corresponding adjoint model of MM5, the CNOPs are calculated with dry energy and kinetic energy as objective functions.

b. The vertical integrals of dry and kinetic energies of CNOP are calculated following the integral formulas as follows:

$$E_{i,j}=\int_0^1[{u'_{i,j}}^2+{v'_{i,j}}^2+\frac{c_p}{T_r}{T'_{i,j}}^2+R_aT_r\left(\frac{p_{s_{i,j}}}{p_r}\right)^2]\mathrm{d}\sigma \quad (1)$$

$$K_{i,j}=\int_0^1({u'_{i,j}}^2+{v'_{i,j}}^2)\mathrm{d}\sigma \quad (2)$$

The i and j in the two formulas indicate horizontal grids and c_p and R_a are the specific heat at constant pressure and the gas constant of dry air, respectively (with numerical values of 1005.7 J/(kg·K) and 287.04 J/(kg·K)). The reference parameters are the following: T_r=270 K, p_r=1000 hPa. Here u', v', T' and p_s', which are components of the state vector, are the perturbed zonal and meridional wind components, temperature and surface pressure, respectively.

c. The big-value areas of the vertical integrals are taken as the sensitive areas with the dry or kinetic energy norm. In addition, according to Qin[13], the sensitive areas distinguished with the ETKF method are often located in the typhoon center and its surrounding, therefore these areas are selected and studied in this article.

(2) Sensitivity test for the sensitive areas

a. The CNOP type of initial errors is added in the whole model area and forecasts are made till the verification time;

$$J(\delta\mathbf{X}_0^*)=(PM(\mathbf{X}_0+\delta\mathbf{X}_0^*)-PM(\mathbf{X}_0))^{\mathrm{T}}\mathbf{C}(PM(\mathbf{X}_0+\delta\mathbf{X}_0^*)-PM(\mathbf{X}_0)) \quad (3)$$

b. The CNOP type of initial errors is only added in the sensitive areas identified with the dry energy norm, and forecasts are made till the verification time;

$$J(\delta\mathbf{X}_0^*)=(PM(\mathbf{X}_0+P_1\delta\mathbf{X}_0^*)-PM(\mathbf{X}_0))^{\mathrm{T}}\mathbf{C}(PM(\mathbf{X}_0+P_1\delta\mathbf{X}_0^*)-PM(\mathbf{X}_0)) \quad (4)$$

c. The CNOP type of initial errors is only added in the sensitive areas identified with the kinetic energy norm or in the area that surrounds the typhoon center, and forecasts are made till the verification time;

$$J(\delta\mathbf{X}_0^*)=(PM(\mathbf{X}_0+P_2\delta\mathbf{X}_0^*)-PM(\mathbf{X}_0))^{\mathrm{T}}\mathbf{C}(PM(\mathbf{X}_0+P_2\delta\mathbf{X}_0^*)-PM(\mathbf{X}_0)) \quad (5)$$

In these formulas, the value of P is 1 in the verification area but 0 in the other area. The value of P_1 is 1 in the sensitive areas but 0 outside them. The value of P_2 is given as follows: let $\sum_{i,j}E_{i,j}$ represent the sum of dry energy in the sensitive areas identified with the dry energy norm, let $\sum_{i,j}E_{Ki,j}$ represent the sum of dry energy in the sensitive areas identified with the kinetic energy norm (or areas surrounding the typhoon center), and then $P_2=\sum_{i,j}E_{i,j}\Big/\sum_{i,j}E_{Ki,j}$ in the sensitive areas, while $P_2=0$ outside the sensitive areas.

3 ANALYSIS OF THE RESULTS

Using the potential vorticity diagnosis method to study the tracks of Fengshen (2002) and Fung-wong (2002), Yang et al.[2] found that Fung-wong's track was steered by Fengshen and exhibited cyclonic looping since 23 July 2002. The Joint Typhoon Warning Center once classified this binary interaction as one-way interaction, that is, Fengshen affected Fung-wong's motion whereas Fung-wong had limited influence on Fengshen. However, study has shown that from 00:00 23 July to 00:00 25 July not only Fengshen influenced Fung-wong, but also Fung-wong impacted on Fengshen, although the impact was limited (Yang et al.[2]).

In 2007, Wu et al.[14] studied this interaction by the Adjoint-Derived Sensitivity Steering Vector (ADSSV) method and examined Fengshen and Fung-wong's sensitive areas. It was shown that the results obtained by using the ADSSV method are consistent with those by the potential vorticity diagnostic method. If the area around the Fengshen center at 00:00 25 July is taken as the verification area, the sensitive areas are mainly located in the north of Fengshen at 00:00 23 July, but little is located around Fung-wong. However, if the area around Fung-wong center at 00:00 25 July is taken as the verification area, the sensitive areas are mainly located around Fengshen and the maximum sensitivity is located between the two typhoons.

3.1 *Characteristics of the sensitive areas calculated by CNOP method*

In this section, the sensitive areas recognized by the CNOP method will be analyzed. First, we will analyze the characteristics of the sensitive areas obtained under the condition that the area of Fengshen center is taken as the verification area at 00:00 25 July with 48-hour simulation. Since the initial perturbations calculated by the CNOP method at each of the σ levels are not completely consistent with each other at the initial time, they are integrated in the vertical direction with energy norms in order to fully consider the distribution patterns at every layer. The patterns of dry energy and kinetic energy after the integration in the vertical direction are respectively shown in Fig. 1a and 1b. It can be seen from the figure that the areas of large kinetic energy are mainly surrounding Fengshen and the maximum value is located 1000 km northwest of the Fengshen center at the initial time. The areas of large dry energy are not surrounding Fengshen as clearly. They are mainly located northwest and northeast of Fengshen while just a small area is situated southeast of Fung-wong. Comparisons of the contours on 500 hPa in Fig.1 show that the large-value areas in the northeast of Fengshen are mainly located at the edge of the subtropical high, probably due to its impact on the Fengshen activity. It was also accurately defined by an experiment by Wu et al.[14] using the ADSSV method. Obviously, the typhoon during its motion is influenced not only by the subtropical high and large-scale circulation, but also by the nonlinear development process of the typhoon itself. The influence of the typhoon structure on the typhoon track cannot be ignored, especially when the intensity of the typhoon is strong. Fig. 1a shows that part of the sensitive areas identified by the CNOP method is located in the Fengshen center, probably resulting from the structural development of Fengshen, a super typhoon. However, as shown in Fig. 12d in Wu et al.[14], the ADSSV method does not indicate this region. Here, it should be pointed out that the ADSSV method is a kind of linear method and the premise of its application is that the linear approximation is tenable, while the CNOP method is a kind of nonlinear method, free of linear approximation restrictions. When using the CNOP method, it does not need to examine the efficiency of linear approximation. For the cases studied in this paper, Wu et al.[14] have demonstrated that their evolution can be taken as linear development, so it is no doubt that our results are consistent with those obtained by using linear methods. However, as far as those cases that cannot be taken as linear cases, the results achieved by using the CNOP method may be more reliable.

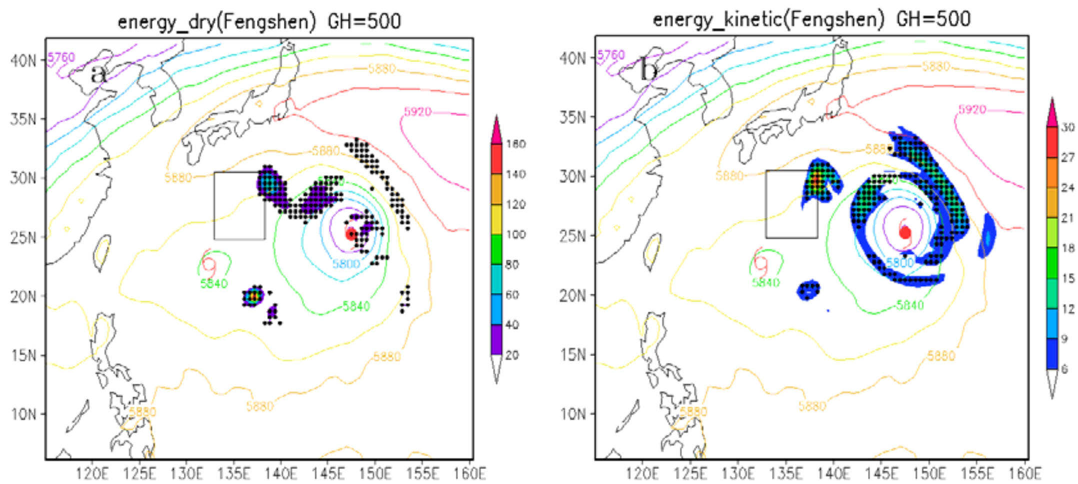

Figure 1. The vertically-integrated energy (a: dry energy; b: kinetic energy) of CNOP. The verification area is represented by a 600 km×600 km box centered at the MM5-simulated Fengshen center at the final forecast time. The black dots represent 200 grid points of large energy and the colorized contour lines indicate geopotential heights on 500 hPa at the initial time. The typhoon centers at the initial time are marked by typhoon symbols.

Next, we will analyze the characteristics of sensitive areas obtained under the condition that the area of Fung-wong center is taken as a verification area at 00:00 25 July with 48-hour simulation. Fig. 2a and 2b respectively show the areas of large dry and kinetic energy of CNOP after integration in the vertical direction. It can be seen from the figures that unlike Fengshen, both the areas of large dry and kinetic energy are beyond the surroundings of Fung-wong, but located about 1000 km to the southwest of Fengshen in a half-ring structure. The site of its maximum value is also located at the edge of the subtropical high, consistent with that of Fengshen, indicating that the subtropical high is also important for the track of Fung-wong. In addition, it can be seen that the sensitive areas obtained by the CNOP method are also located between Fengshen and Fung-wong, consistent with the sensitive areas calculated by the ADSSV method (Wu et al.[14]). This shows that both the CNOP and ADSSV method can identify the area between Fengshen and Fung-wong as the sensitive area, indicating that both methods can recognize the influence of Fengshen on Fung-wong. In this experiment, we can see that the position of Fung-wong center is not recognized as the sensitive area, unlike the experiment of Fengshen. The reason may be that the intensity of Fung-wong is so weak that the evolution of its structure cannot cause large effect on its track. By contrast, the intensity of Fengshen is strong and its nonlinear evolution can have important influence on its track.

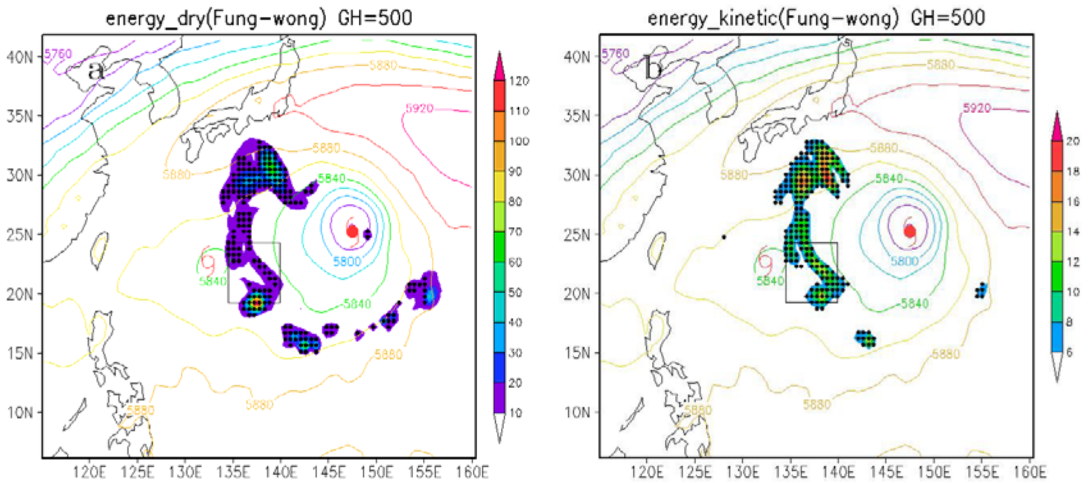

Figure 2. Same as Fig. 1 but with the verification area centered at the MM5-simulated Fung-wong center.

Through the study, we can find that although the areas identified by the CNOP method with dry- or kinetic- energy norms may have some differences, but in general, both patterns are similar. This indicates that the forecast error of the wind field takes up a large proportion in forecast errors (consistent with the result shown in Fig. 3), therefore the result obtained by considering overall forecast errors is consistent with the result obtained by only considering the forecast error of the wind field.

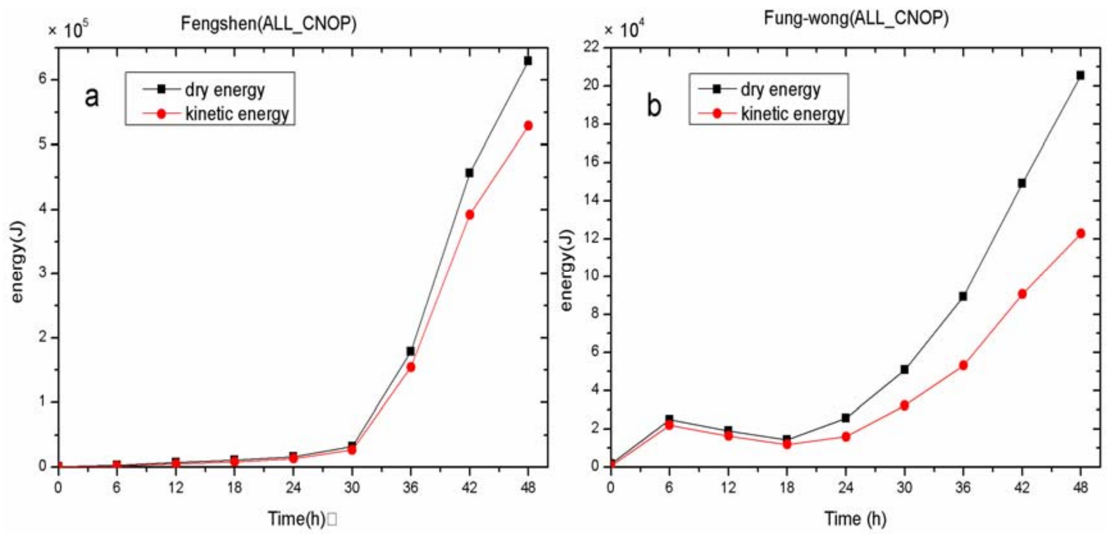

Figure 3. The influence of development of the CNOP-type initial errors on the energy of the forecast error within the verification area. (a): the verification area is centered at the MM5-simulated Fengshen center; (b): the verification area is centered at the MM5-simulated Fung-wong center.

3.2 Effectiveness of sensitive areas identified by CNOP method

In this part, we will respectively examined the impacts of the CNOP-type initial errors and the initial errors in sensitive areas on the forecasts in the verification area from the viewpoint of the evolution of the forecast errors' dry and kinetic energy.

3.2.1 The case of Fengshen

For the case of Fengshen, it can be seen from Fig. 3a that the nonlinear evolution of the CNOP-kind initial errors results in the increments of the total dry and kinetic energy of forecast errors within the verification area, especially after 30 hours, the error energy in the verification area increases dramatically. This indicates that the forecast errors increase dramatically in this area. The distributions of the vertically-integrated dry energy of the forecast errors at the final stage caused by the nonlinear evolution of CNOP-kind initial errors are also shown in Fig. 4a, and we can see that the error energy is mainly located in the verification area at the final stage and only small part is outside of it. This indicates that the CNOP-kind initial errors are important for the forecast of Fengshen at the final stage.

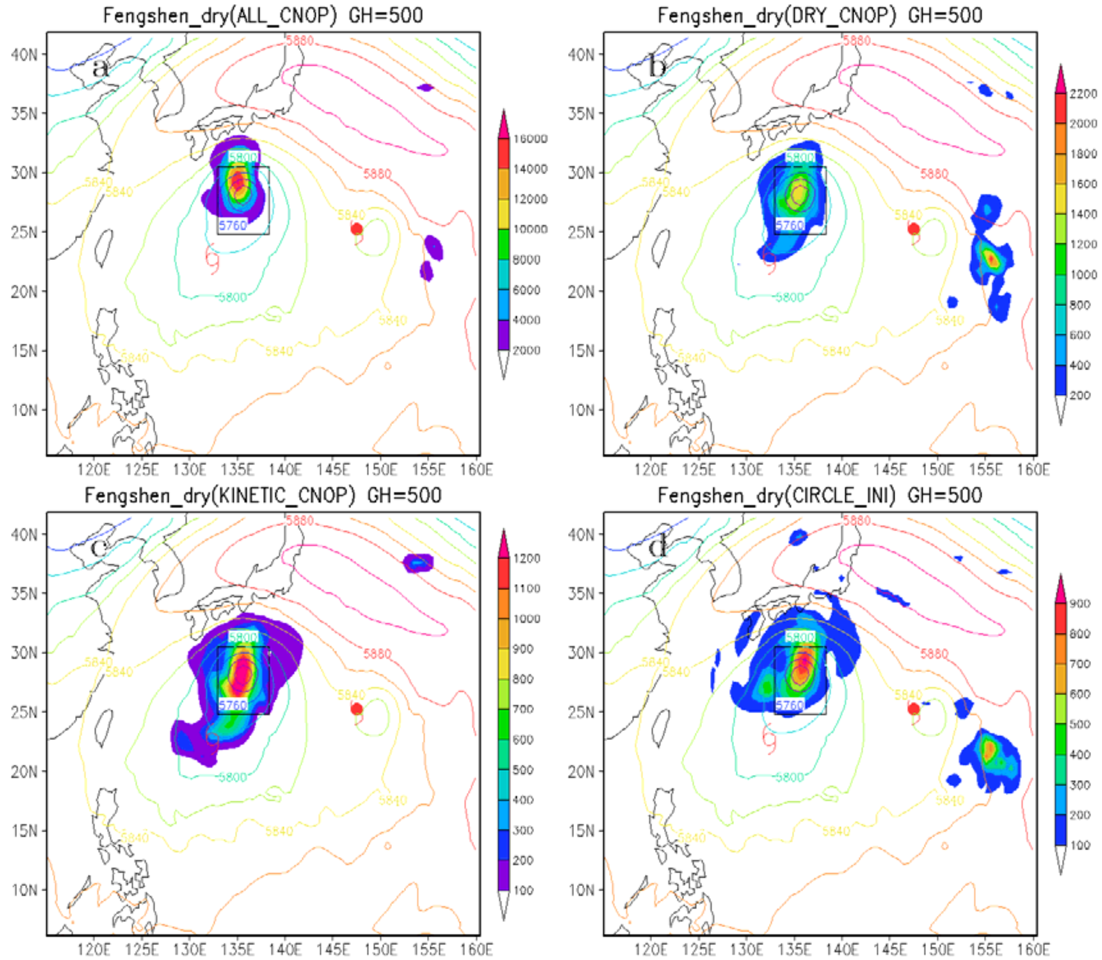

Figure 4. The horizontal distributions of the dry energy of forecast errors at the final stage. The forecast errors was caused by the CNOP kind of errors in (a) the whole model area, (b) sensitive areas with dry energy norm, (c) sensitive areas with kinetic energy norm, and (d) areas surrounding the initial-time Fengshen center, and in all the above cases the verification area is surrounding the final-stage Fengshen center. The black rectangular in the figures are the verification areas (Note: sensitive areas with dry and kinetic energy norms are respectively shown by the black dots in Fig. 1a and b).

In the section below, we will consider the evolution of initial errors within the sensitive areas. Fig. 5a shows the respective impacts of the initial errors in the sensitive areas identified with dry and kinetic energies and those in the areas surrounding the Fengshen center on the evolutions of the dry energy of the forecast errors in the verification area. It is shown that the evolutions of the errors in the three areas have caused the increment of error energy and that the increment has a large growth after 30 hours. However, the increment of the initial errors surrounding the Fengshen center is smaller than the increment of the initial errors in the CNOP sensitive areas regardless of whether the dry or kinetic energy norm is employed. This indicates that reducing the initial errors within the CNOP sensitive areas can improve forecast skills in the verification area.

The distributions of forecast-error dry energy caused by initial errors within these three areas have been respectively presented in Fig. 4b to 4d. It can be seen that forecast errors are mainly located in the verification area, and that the forecast errors are the largest if resulting from the initial errors within the sensitive areas identified with the dry energy norm. This demonstrates that the initial errors in these areas have important influence on the forecast quality within the verification area and the initial errors in the sensitive areas identified with the dry energy norm are the most important.

Figure 5b shows the influence of the evolution of initial errors on the kinetic energy of the forecast errors within the verification area. Similar to the influence on the dry energy of forecast errors, the evolution of initial errors surrounding the Fengshen center is weaker than that within the sensitive areas identified by the CNOP method. The difference between the patterns of dry energy and kinetic energy at the final stage is not obvious (figures not shown), with the kinetic energy slightly smaller than the dry energy.

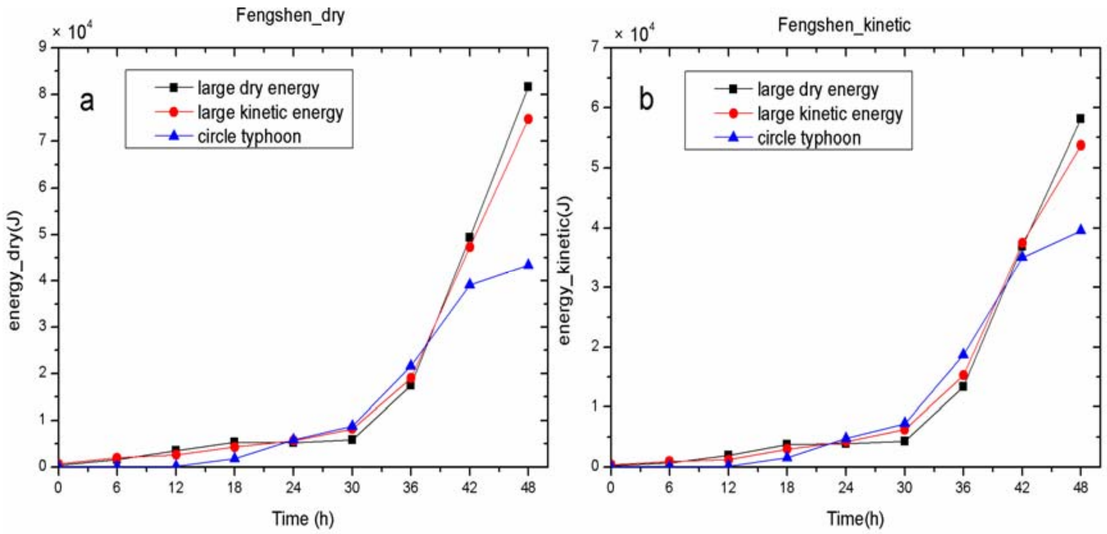

Figure 5, The (a) dry and (b) kinetic energy development of the forecast errors in the verification area due to the initial errors in the sensitive areas identified with the dry and kinetic energy norms and in the areas surrounding the initial position of the typhoon center. The verification area is centered at the MM5-simulated Fengshen center.

It can be seen that the initial errors in the sensitive areas identified with dry or kinetic energy norms have similar influences on the kinetic energy of forecast errors in the verification area. A little larger influence has been found for those in the sensitive areas identified with the dry energy norm.

This not only indicates that reducing the initial errors in the CNOP sensitive areas has more benefits on the forecasts of wind fields than reducing the initial errors in the areas surrounding the typhoon center, but also indicates that the CNOP kind of initial errors have more impacts on the kinetic energy than on the potential energy of the forecast variables.

3.2.2 THE CASE OF FUNG-WONG

In the previous part we have examined the effectiveness of the sensitive areas distinguished by the CNOP method when the verification area is located around the final-stage Fengshen center. In this part we will check the effectiveness of the sensitive areas when the verification area is located around the final-stage Fung-wong center.

First, we examined the impact of the nonlinear evolution of CNOP-kind initial errors on the dry energy of forecast errors. Fig. 3b presents the development of the dry and kinetic energy of the forecast errors in the verification area caused by the CNOP-kind initial errors. It can be seen from the figure that the dry and kinetic energy of forecast errors within the verification area slightly reduce from Hour 6 to 18, but then both of them grow quickly. This may be relative to the track of Fung-wong, because Fung-wong moved southwest and far away from the verification area during the time, so the dry and kinetic energy within the verification area have slight reduction. After that, Fung-wong began to turn to the southeast and then quickly turned to the east. This causes the energy to grow quickly during this time and then the energy achieves its maximum at the final stage. By comparing Fig. 6a with Fig. 3b, it is seen that the development of the initial errors in the CNOP sensitive areas is similar to that of the CNOP kind of initial errors in the whole domain, as both of them have large growth after 18 hours and attain their maximum at the final stage.

Figure 7 presents the final-stage patterns of dry energy of forecast errors developed from CNOP-kind initial errors and from the initial errors in the sensitive areas. We can see that the dry energy is mainly located in the verification area at the final stage and with a small part located east of the verification area at the edge of the subtropical high. These indicate that the CNOP-kind initial errors and the initial errors in the sensitive areas have important influence on the forecast of Fung-wong at the final stage. Besides, similar to the case of Fengshen, the perturbations in the sensitive areas have larger developments than those in the areas surrounding the initial-time typhoon center. It is different from Fengshen that the dry energy of forecast errors inside the verification area mainly developed from the initial errors in the sensitive areas identified with kinetic energy.

Similar to the case of Fengshen, the distributions of kinetic and dry energy of forecast errors have similar patterns no matter the forecast errors are caused by the CNOP kind of initial errors or by the initial errors in the sensitive areas. Besides, there are parts of kinetic energy located east of the verification area and at the edge of the subtropical high.

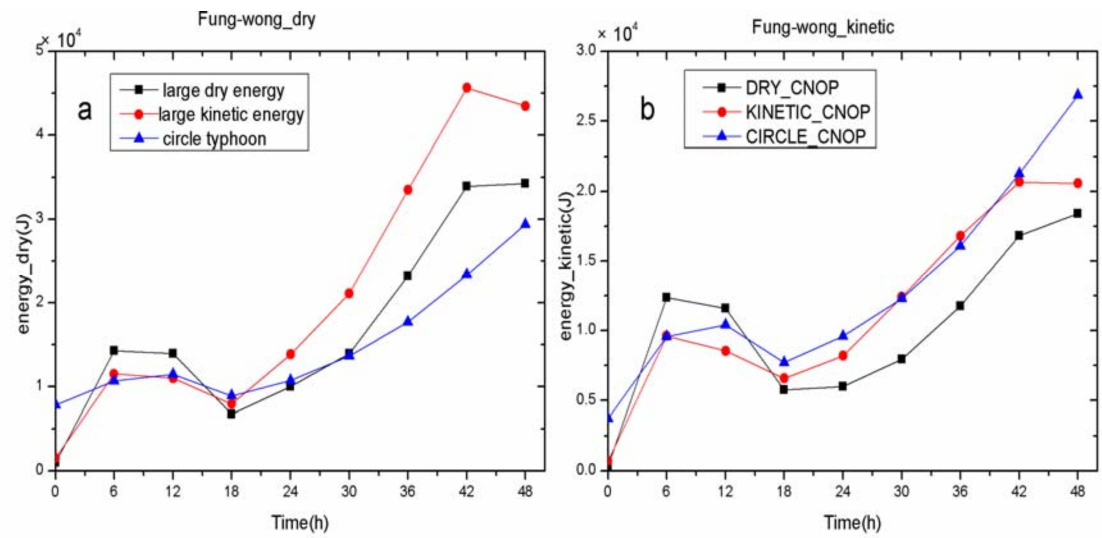

Figure 6. Same as Fig. 5 but for the verification area centered at the MM5-simulated Fung-wong center.

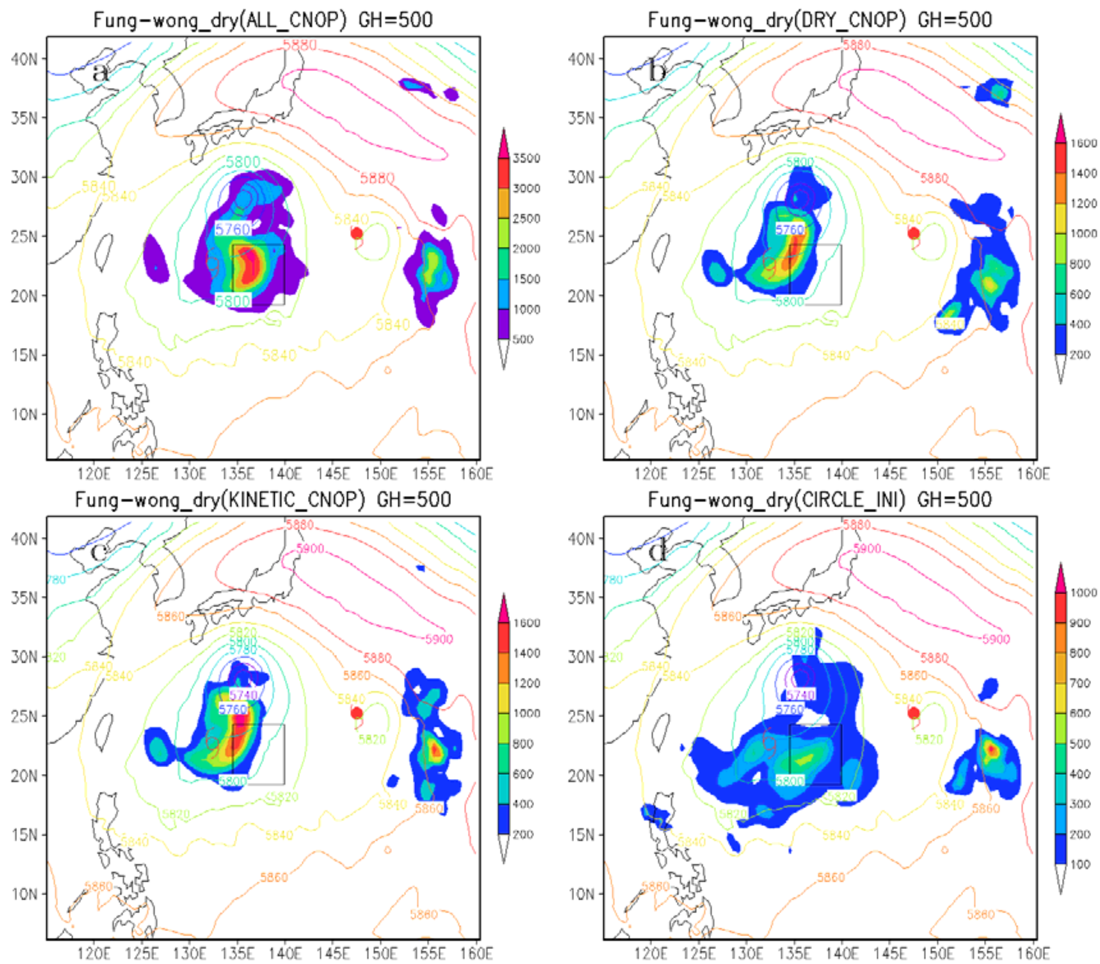

Figure 7. Same as Fig. 4 but for the verification area centered at the MM5-simulated Fung-wong center.

4 SUMMARY AND DISCUSSION

This paper used the typhoons Fengshen and Fung-wong that occurred in 2002 to discuss the application of the CNOP method in the mutual effect of binary typhoons.

Results showed that the sensitive areas of Fengshen and Fung-wong can be obtained by the CNOP method, and this helped us to reveal the interaction between the two typhoons. The nonlinearly integrated CNOP type of initial errors evolved into the verification areas at the final forecast time (verification time). In addition, by comparing the sensitive areas identified with the dry energy norm and kinetic energy norm with the areas surrounding the initial-time typhoon center, it was found that the developments of the initial errors in the CNOP sensitive areas (identified with the dry or kinetic energy norm) are larger than those in the areas surrounding the initial-time typhoon center.

This indicates that improving the accuracy of the initial states in the CNOP sensitive areas can effectively improve the forecast skills in the verification area at the verification time, and eventually improve the typhoon forecast.

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