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A DYNAMICAL INTERPRETATION OF THE WIND FIELD IN TROPICAL CYCLONES

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Abstract: Based on the primitive equations in polar coordinates and with the supposition that parcel velocity in tropical cyclones is in linear variation and that the distribution of surface pressure agrees with the Fujita formula, a set of equations are derived, which describe the impact of perturbations of central pressure, position of tropical cyclones, direction and velocity of movement of tropical cyclones on the wind field. It is proved that the second order approximation of the kinetic energy of tropical cyclones can be described by the equations under linear approximation. Typhoon Wipha (2007) is selected to verify the above interpretation method, and the results show that the interpretation method of the wind field could give very good results before the landfall of tropical cyclones, while making no apparent improvement after the landfall. The dynamical interpretation method in this paper is applicable to improving the forecasts of the wind field of tropical cyclones close to the coast.

Key words: tropical cyclones; strong wind; dynamical interpretation

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1 INTRODUCTION

Tropical cyclones are intense synoptic systems which occur over the tropical ocean. Since the conventional synoptic observations over the ocean are rare and unreliable, it is difficult to know the true structure of tropical cyclones and associated characteristics. Although there exist plenty of satellite observations, it is still difficult to get very good results due to some reasons, such as difficulties in assimilation technology. They are the most important reasons that lead to the difficulties of forecasts of tracks, intensities, wind and rainfall associated with tropical cyclones.

The disasters caused by tropical cyclones are mainly induced by strong wind and heavy rainfall. Torrential rainfall, especially typhoon-induced torrential rainfall, has been studied extensively by many scholars at home and abroad [1-8], but few studies have been carried out on strong wind of tropical cyclones. In order to improve numerical forecasts, a lot of efforts have been made to refine model capability, enhance initial fields, and so on. However, forecast errors are inevitable since the permanent existence of data errors and model errors. Then how to better interpret products of numerical forecasts and lessen the influence of the above mentioned errors becomes an important task.

Presently, methods for interpretation of products of numerical forecasts mainly include: statistical interpretation (such as MOS, PP and Kalman filter), synoptic interpretation, artificial intelligence interpretation, and so on. While no matter which method to select, the key factors influencing the errors must be grasped. According to the particularity of typhoons' structure, some reasonable typhoon models are set up by grasping the main factors which influence the wind and pressure field of tropical cyclones, such as Fujita formula, Myers formula and tangential wind velocity profile scheme by Williams in 1987, and

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applied to practical operations. Zou and Xiao [9] and Pu and Braun [10] constructed Bogus schemes by using typhoon models and assimilated them into initial fields, which improved forecasts. These simplified typhoon models could describe the main characteristics of typhoons since they grasp the key factors. While the wind fields of these typhoon models are mainly symmetric, which are different from those of actual typhoons with apparent asymmetric features. Lei and Chen [11] showed that the distributions of the physical fields associated with typhoons are often asymmetric due to the influences of moving speed, frictions and environmental synoptic systems. Many researches have focused on the asymmetric structures of typhoons at home and abroad. Zhang and his colleagues put forward a model of wind fields of typhoons by considering frictions in stable states in 1989 [12], and discussed it under ideal conditions. Hu et al. [13] and Huang et al. [14] further studied the model, verified it by using wind fields of real typhoon cases and pointed out that this model was applicable, which could describe the asymmetric distribution of wind fields of tropical cyclones.

In this paper, a dynamical interpretation method of wind fields in tropical cyclones is proposed by combining the method proposed by Zhang with operational forecasts and by analyzing the key factors influencing wind fields in tropical cyclones.

2 DYNAMICAL INTERPRETATION METHOD OF WIND FIELDS IN TROPICAL CYCLONES

2.1 *Correction equation of numerical forecasts of wind fields in tropical cyclones*

By setting the center of tropical cyclones as the origin of polar coordinates, the horizontal momentum equations of any air parcel in tropical cyclones [15] could be expressed as

$$\begin{cases} \dfrac{dv_r}{dt} - fv_\theta - \dfrac{v_\theta{}^2}{r} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial r} + F_r \\ \dfrac{dv_\theta}{dt} + \dfrac{v_r v_\theta}{r} + fv_r = -\dfrac{1}{r\rho}\dfrac{\partial p}{\partial \theta} + F_\theta \end{cases}, \quad (1)$$

in which F is the friction force and all other notations here are conventional in the meteorological context. The subscripts "θ" and "r" indicate the tangential and the radial directions, respectively. F could be further written as

$$F_\theta = kv\cos(\phi+\beta) = kv_\theta\cos\phi - kv_r\sin\phi$$

$$F_r = kv\sin(\phi+\beta) = kv_\theta\sin\phi + kv_r\cos\phi$$

where v is wind speed, k is frictional coefficient, β is inner deflection angle of wind direction, and ϕ denotes the angle between the friction force and the opposite direction of wind vectors.

Supposing that parcel velocity takes on linear variation in tropical cyclones, that is, $\dfrac{dv_r}{dt} = C_r$, $\dfrac{dv_\theta}{dt} = -C_\theta$ are constants, further supposing that the distribution of sea level pressure in tropical cyclones is circular, considering the influence of the speed of movement of tropical cyclones, v_s, on the cyclonic curvature radius r [16], and setting the counter-clockwise direction to be positive, Eq.(1) could be further written as

$$\begin{cases} \dfrac{v_\theta{}^2}{r} + \dfrac{v_\theta v_s\cos\alpha}{r} + fv_\theta \\ = \dfrac{1}{\rho}\dfrac{\partial p}{\partial r} - kv_\theta\sin\phi - kv_r\cos\phi + C_r, \\ \dfrac{v_r v_\theta}{r} + \dfrac{v_r v_s\cos\alpha}{r} + fv_r \\ = kv_\theta\cos\phi - kv_r\sin\phi + C_\theta \end{cases} \quad (2)$$

where α is the angle between the moving direction of tropical cyclones and tangential direction of parcels. Eq. (2) shows that v_θ and v_r could be expressed as functions of r, $\dfrac{1}{\rho}\dfrac{\partial p}{\partial r}$, v_s, α. ϕ is usually taken as constant, 38° [17]. In the operational application, wind fields in tropical cyclones are usually described as functions of central pressure P_0, distance from the center of tropical cyclones r, and the maximum wind speed radius r_m. Thus v_θ and v_r could be expressed as functions of r, P_0, r_m, v_s, α. By setting

$$A = \frac{1}{\rho}\frac{\partial p}{\partial r} \quad \text{and} \quad B = \frac{v_\theta + v_s\cos\alpha}{r} + f + k\sin\phi,$$

and differentiating Eq. (2) with respect to A, we obtain the influence of the change of pressure gradients on wind speed as follows:

$$\frac{\partial v_\theta}{\partial A} = \frac{rB}{(v_\theta + rB)B + k\cos\phi(rk\cos\phi - v_r)}, \quad (3)$$

$$\frac{\partial v_r}{\partial A} = \frac{(rk\cos\phi - v_r)}{(v_\theta + rB)B + k\cos\phi(rk\cos\phi - v_r)}. \quad (4)$$

By differentiating Eq. (2) with respect to v_s, we obtain the influence of the change of the moving speed of tropical cyclones on wind speed as follows:

$$\frac{\partial v_r}{\partial v_s} = -\frac{v_\theta\cos\alpha(rk\cos\phi - v_r) + (v_\theta + rB)v_r\cos\alpha}{(v_\theta + rB)rB + kr(rk\cos\phi - v_r)\cos\alpha}, \quad (5)$$

$$\frac{\partial v_\theta}{\partial v_s}=(\frac{\partial v_r}{\partial v_s}B+\frac{v_r\cos\alpha}{r})\frac{r}{rk\cos\phi-v_r}. \quad (6)$$

By differentiating Eq. (2) with respect to α, we obtain the influence of the change of the moving direction of tropical cyclones on the wind speed as follows:

$$\frac{\partial v_\theta}{\partial\alpha}=\frac{Bv_\theta v_s\sin\alpha-kv_r v_s\sin\alpha\cos\phi}{(v_\theta+rB)B+k(rk\cos\phi-v_r)\cos\phi}, \quad (7)$$

$$\frac{\partial v_r}{\partial\alpha}=\frac{1}{rB}[(rk\cos\phi-v_r)\frac{\partial v_\theta}{\partial\alpha}+v_r v_s\sin\alpha]. \quad (8)$$

By differentiating Eq. (2) with respect to r, we obtain the influence of the change of the distance between the observation points and the tropical cyclone center on the wind speed as follows:

$$\frac{\partial v_\theta}{\partial r}=\frac{(v_\theta B-v_r k\cos\phi)(v_\theta+v_s\cos\alpha)}{rB(rB+v_\theta)+rk\cos\phi(rk\cos\phi-v_r)}, \quad (9)$$

$$\frac{\partial v_r}{\partial r}=\frac{1}{rB}[k(v_\theta\cos\phi-v_r\sin\phi)+(rk\cos\phi-v_r)\frac{\partial v_\theta}{\partial r}-fv_r]. \quad (10)$$

It can be known that all the terms on the right hand sides of Eqs. (3 - 10) could be obtained from the forecasts of numerical models. Thus the correction equation of numerical forecasts of wind fields in tropical cyclones could be expressed as

$$dv_\theta=dA\frac{\partial v_\theta}{\partial A}+dr\frac{\partial v_\theta}{\partial r}+dv_s\frac{\partial v_\theta}{\partial v_s}+d\alpha\frac{\partial v_\theta}{\partial\alpha}, \quad (11)$$

$$dv_r=dA\frac{\partial v_r}{\partial A}+dr\frac{\partial v_r}{\partial r}+dv_s\frac{\partial v_r}{\partial v_s}+d\alpha\frac{\partial v_r}{\partial\alpha}, \quad (12)$$

where dA, dr, dv_s, $d\alpha$ represent the correction terms associated with pressure gradient errors, distance errors between the center and the observation point (determined by the position of tropical cyclones), the errors of moving speed and direction of tropical cyclones, respectively. Thus by grasping the errors of these four terms in operational applications, it is easy to correct the numerical forecasts of wind fields in tropical cyclones dynamically. In the above formulas, dr, dv_s, $d\alpha$ could be obtained by extrapolating the difference between model forecasts and observations of tropical cyclones, or by comparing the predictions of ensemble members. As dA could not be obtained directly, it needs to be estimated.

2.2 *Estimation of the correction term associated with pressure gradients*

Since the correction term associated with sea level pressure gradients could not be obtained directly, estimation is needed.

Supposing that the sea level pressure field of tropical cyclones is determined by the Fujita formula,

$$p=p_\infty-(p_\infty-p_0)/[1+2(r/r_m)^2]^{\frac{1}{2}},$$

where p_∞ is the pressure in the periphery of tropical cyclones, p_0 is the pressure in the center of tropical cyclones, and by introducing the equation of state, we obtain

$$A=\frac{2(p_\infty-p_0)RTr}{r_m^{\ 2}p}[1+2(r/r_m)^2]^{-\frac{3}{2}}, \quad (13)$$

where R is gas constant, T is sea surface temperature, and r_m is the function of p_0, which must be estimated. According to Eq. (2), and by applying $v_\theta=v\cos\beta$, $v_r=v\sin\beta$, the maximum wind speed radius r_m could be expressed as

$$r_m=\frac{A_m-v_m^2\cos^2\beta-v_m v_s\cos\alpha\cos\beta}{kv_{\mathrm{m}}\sin(\phi+\beta)+fv_m\cos\beta-C_r}, \quad (14)$$

where $A_m=\frac{2\cdot 3^{-3/2}RT_0(p_\infty-p_0)}{p_\infty-3^{-1/2}(p_\infty-p_0)}$, v_{m} is the maximum wind speed, T_0 is the sea surface temperature in the center of tropical cyclones. Supposing that β is known, by eliminating r in Eq. (2), we get the simple cubic equation of v_{m}. Due to the uncertainty of C_r and C_θ, the equation could not be solved directly. If v_{m} is replaced by the maximum wind speed of a stationary tropical cyclone, namely, C_r and C_θ are both zero, the equation reduces to quadratic equation as

$$v_m^2+v_{\mathrm{m}}v_s\frac{\cos\alpha}{\cos\beta}-A_m(1-tg\beta tg\phi-\frac{f}{k}\frac{tg\beta}{\cos\phi})=0, \quad (15)$$

where β is a complex function of P_0, v_{m}, v_s, α. According to the research of Zhang and Sui [12], in the maximum wind speed region of tropical cyclones, β <5°, namely 0.996< $\cos\beta$ <1, so $\cos\beta$ could be considered as constants. According to the discriminate conditions of quadratic equation, Eq. (15) has real root at the maximum wind speed radius. C_r in Eq. (14) is hard to confirm. In view of the fact that radial wind speed is far less than tangential wind and has little change in the maximum wind speed region, namely

C_r is close to zero, r_m could be solved.

From Eqs. (13 – 15), the correction term associated with pressure gradients could be

$$dA = A(p_0 + dp_0, T + dT, r + dr) - A(p_0, T, r) . \quad (16)$$

2.3 *Influence of assumption that wind speed presents linear variation on the calculation of kinetic energy of tropical cyclones*

The solutions of Eq. (2) are obtained under the assumption that $\frac{dv_r}{dt} = C_r$, $\frac{dv_\theta}{dt} = -C_\theta$ are all constants, namely the parcel velocity takes on linear variation in tropical cyclones. Then would this assumption largely affect the result of calculation? It will be discussed in this section.

Based on the above assumptions, the solutions of v_r and v_θ are

$$v_r(t) = C_r t + v_r(0) , \quad (17)$$

$$v_\theta(t) = -C_\theta t + v_\theta(0) . \quad (18)$$

Eqs. (17) and (18) could be regarded as the first order approximation of wind speed or the momentum of unit mass air parcel. Assuming that tropical cyclones consist of *N* unit mass air parcels, it could be proved that the average kinetic energy of unit mass air parcel is

$$\overline{E}_1(t) = \overline{E}(0) + [C_r \overline{v}_r(0) - C_\theta \overline{v}_\theta(0)]t + \frac{1}{2}(C_r{}^2 + C_\theta{}^2)t^2 . (19)$$

If the real solution of the above average kinetic energy is expressed as $\overline{E}(t)$, by applying Taylor expansion at t = 0, the second order approximation of $\overline{E}(t)$ is written as

$$\overline{E}(t) = \overline{E}(0) + \frac{\partial \overline{E}(0)}{\partial t} t + \frac{1}{2} \frac{\partial^2 \overline{E}(0)}{\partial^2 t} t^2 . \quad (20)$$

Comparing Eqs. (19) and (20), it shows that if C_r and C_θ could be confirmed, the solutions of Eq. (2) would be the second order approximation of kinetic energy of tropical cyclones. Thus assuming $\frac{dv_r}{dt} = C_r$, $\frac{dv_\theta}{dt} = -C_\theta$ as constants should be a better assumption. Since Eqs. (3 – 10) have nothing to do with C_r and C_θ, the correction of wind fields in tropical cyclones would not affect the characteristics of the solutions of Eq. (2).

3 REAL CASE VERIFICATION OF THE DYNAMICAL INTERPRETATION METHOD OF WIND FIELDS IN TROPICAL CYCLONES

3.1 *Model, data, and methodologies*

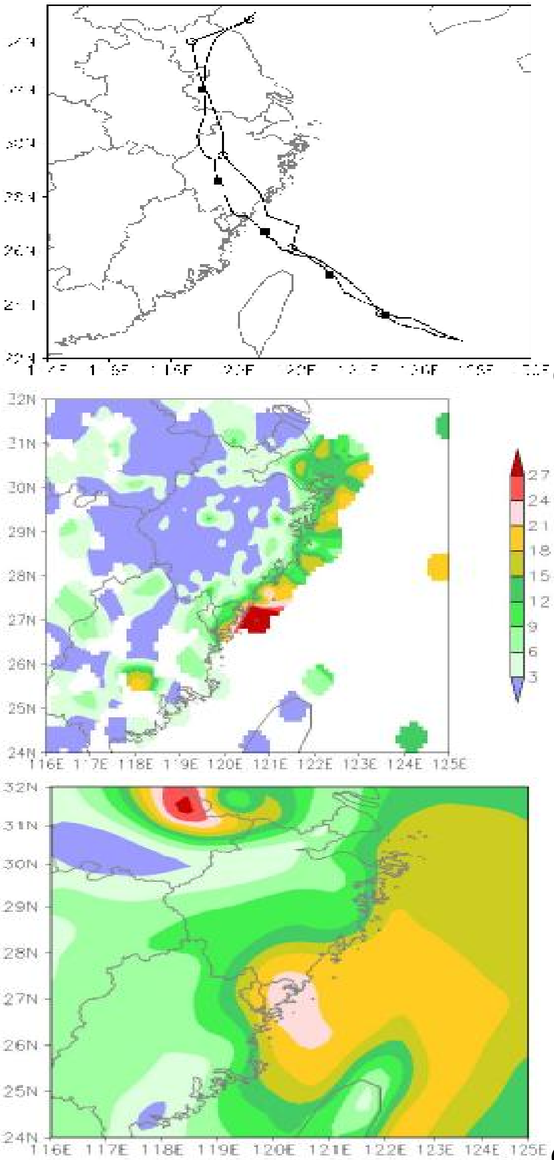
The numerical model used in this paper is WRFv2.2 with the horizontal resolution of 45 km and 41 layers in vertical direction. The top level of model is 50 hPa. The Betts-Miller-Janjic cumulus parameterization scheme and the YSU boundary layer scheme are used in the integration. The data are from 1°×1° GFS data of NCEP reanalysis data. The tropical cyclone Wipha, coded 0713 in China, is selected. The model is integrated from 0800 LST 17 September 2007 and the integration lasts for 72 h. Control experiment (Scheme 1) is direct forecast by the model, and Scheme 2 is the experiment of the dynamical interpretation method. dP_0, dr, dVs, $d\alpha$ are obtained from the observations and the forecasts of the control experiment, and the impact of the change of sea surface temperature is not considered. The inner deflection angle of wind direction at the maximum wind speed radius, β, is set to be 1°.

3.2 *Results*

Wipha occurred over the ocean to the northeast of the Philippines at 0800 LST 16 September and at 0200 LST 17 September it strengthened into a typhoon with a path towards the northwest. At 0230 LST 19 September, it made its landfall at Xiaguan town in Cangnan county of Zhejiang Province with a minimum central pressure of 950 hPa and a maximum wind speed of 45 m s^{-1}. It moved towards the northwest by west at a speed of about 20 km h^{-1}. Due to the influence of the typhoon, the wind of Yuliao in Cangnan reached 55.3 m s^{-1} (Level 16) at 0200 LST, and that of Xiaguan reached 39.1 m s^{-1} (Level 13). The wind generally reached Level 10-12 over the whole coastal sea surface.

Control experiment reproduced the track of the typhoon very well (Fig. 1a), which is basically consistent with the observed track to the east of 122°E. Deviations get a little bigger after that and the landfalling position is a little northward while the moving direction is basically the same as the observations after the landfall with a little eastward shift of track, and the average error of track is about 90 km.

Fig. 1b shows the observed wind speed at 0200 LST 19 September 2007. Fig. 1c and Fig. 1d are those from Scheme 2 and control experiment (Scheme 1), respectively. Obviously, control experiment fails in forecasting the wind speed near the landfalling position. Since the forecasted landfalling position of the control experiment is a little northward apart from the observation, the forecast of wind speeds in the control experiment is better than that of Scheme 2 in the coastal area of the northern Zhejiang Province. While Scheme 2 successfully forecasts the strong wind area of 18 – 21 m s^{-1} in the coastal area to the south of 29°N, and even successfully forecasts the strong wind area of 21 – 24 m s^{-1} in the coastal area near Cangnan, which is much consistent with the observations. The forecasted wind speed of Scheme 2 is obviously larger in the inland area, and especially there is a big false forecasted area near the boundary between Jiangsu and Anhui Provinces, which is possibly related with the neglecting of the influence of topography on the wind field of tropical cyclones.


(a) (b) (c)

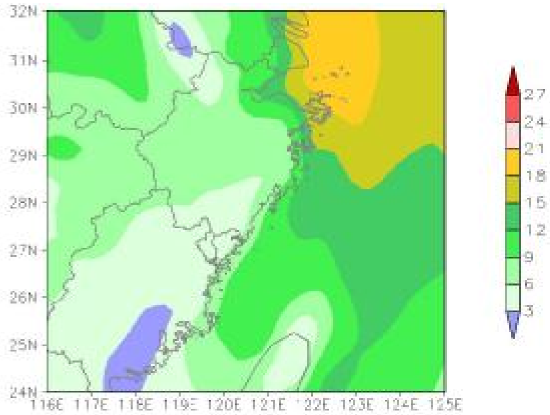
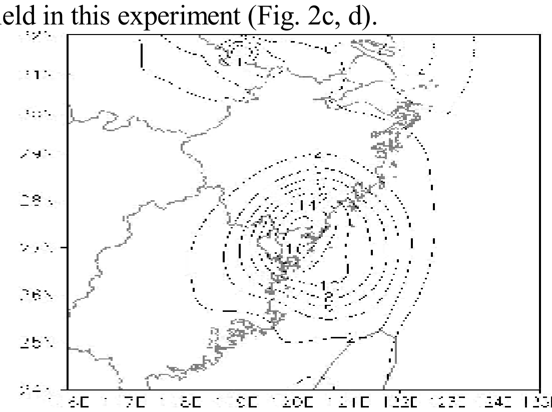
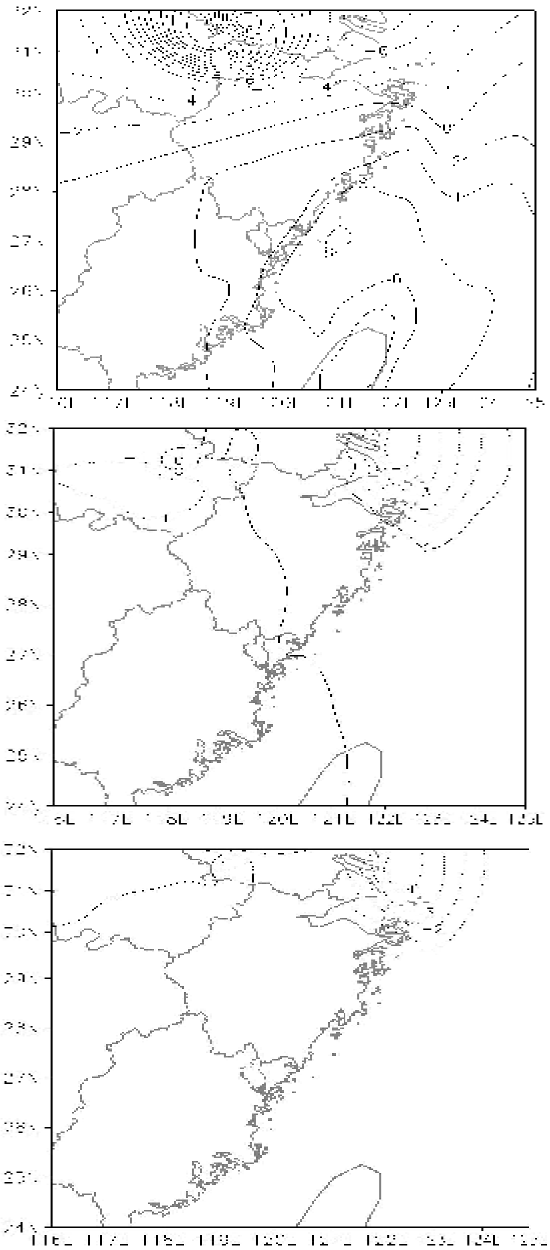

(d)

Fig.1 Observed and forecasted tracks of the typhoon(a), observed wind speed(b), forecasted wind speeds of Scheme 2(c) and control experiment(d) at 0200 LST 19 September 2007. "■" Observed, "○" Forecasted.

Fig. 2 gives the wind speeds corrections in Scheme 2 from the four correction terms associated with pressure gradients, tropical cyclone position, velocity and direction of movement on the right hand sides of Eqs. (11 – 12). From Fig. 2a, it is easy to note that the correction term associated with pressure gradients exerts the greatest influence on wind fields near the center of the tropical cyclone with a velocity increment of up to 16 m s^{-1} (From Eq. (16), we know that the correction term associated with pressure gradients has already contained the influence of the change of position of tropical cyclones). Fig. 2b shows the result of the correction term associated with tropical cyclone position. The influence area is larger than that of the pressure gradient correction term (Fig. 2a), and the influence on wind fields is also remarkable near the center of the tropical cyclone with an increment of up to 8 m s^{-1}. And the apparent error near the boundary between Jiangsu and Anhui Provinces in Fig. 1c is also caused by this term. In Fig. 2a – d, the corrections of wind speed at the coastal area of the northern Zhejiang province are all negative, and the contributions of the four correction terms are almost equal. The correction terms associated with velocity and direction of movement do not have too much influence on the wind field in this experiment (Fig. 2c, d).

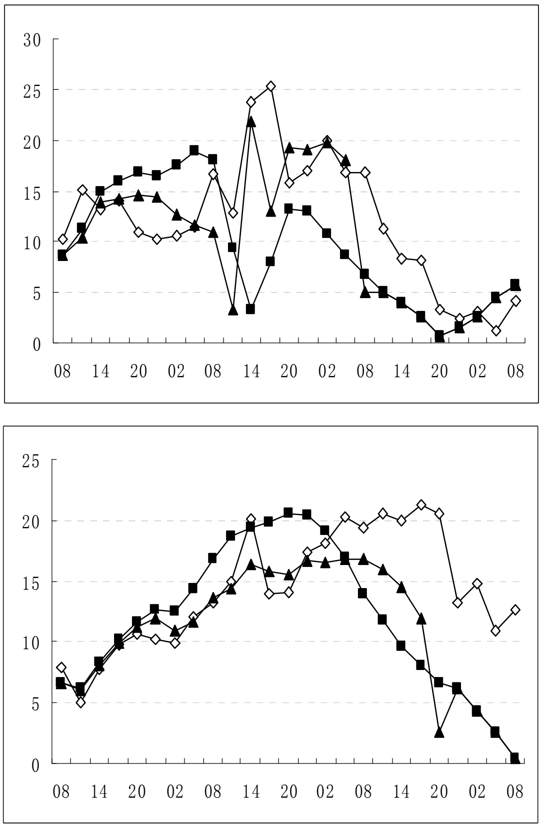

(a)



(b) (c) (d)

Fig.2 The wind speeds corrections in Scheme 2 from the four correction terms on the right hand sides of Eqs. (11-12) for pressure gradients(a), tropical cyclone position(b), velocity of movement(c), and direction of movement(d).

In order to further verify the correction effect of Scheme 2 in the whole forecast period of Wipha, Nanji station in the south of Zhejiang Province and Langgang station in the north of Zhejiang Province are chosen. Fig. 3 shows the time series of 72-h forecasts and observations of wind speed in the two stations. Nanji is an island station located to the east of Xiaguan town (the landfalling point). In Fig. 3a, control experiment and the observation are almost out-of-phase from 1400 LST 17 till 0200 LST 19 September, especially at 1400 LST 18 September when the error is the biggest. After dynamical interpretation, the forecast of wind speed is obviously closer to the observation, and the phase is more consistent with the observation. Especially from 0800 LST 18 to 0600 LST 19 September, during which the influence of Wipha is the strongest and the wind speed is the highest; the corrected average wind speed is about 20 m s^{-1}, which is almost the same as the observation. However, the effect of the dynamical interpretation gets remarkably weakened after the landfall, and the forecast of Scheme 2 is almost the same as the control experiment. Langgang is an island meteorological measuring wind station located at 30.4°N, 122.93°E. Fig. 3b shows that during the first 48 hours, the predicted wind speed of the control experiment is much stronger, while Scheme 2 is almost the same as the observation, the interpretation effect is very significant. Like Nanji station, the effect weakens quickly and considerably after the landfall, while it is a little better than that of Nanji station. From the above analysis, the effects of the dynamical interpretation at these two stations are not good after the landfall of the tropical cyclone, which may be directly associated with the neglecting of factors over the land such as topography in Eq. (2) and the fact that Fujita formula is not suitable on the land.



(a) (b)

Fig.3 Wind speed as a function of time from 0800 LST 17 September to 0800 LST 20 September 2007. (a): Nanji station, (b): Langgan station, "◇": Observed, "▲": Scheme 2, "■": control experiment .(Unit: m s^{-1})

4 CONCLUSIONS AND DISCUSSION

In this paper, based on the primitive equations in polar coordinates, a set of equations are derived, which describe the impact of perturbations of central pressure, positions of tropical cyclones, direction and velocity of movement of tropical cyclones on the wind field. A dynamical interpretation method of numerical forecasts of wind fields in tropical cyclones is proposed and discussed, and some conclusions are obtained.

(1) By considering the friction over the ocean, supposing that parcel velocity takes on linear variation in tropical cyclones and that the distribution of surface pressure accords with Fujita formula, an analytical expression of wind fields in tropical cyclones is obtained based on the primitive equations in polar coordinates. It is proved that under the condition of linear approximation, the solution can describe the second order approximation of the parcel's kinetic energy. Equations are derived, which describe the impact of perturbations of central pressure, position of tropical cyclones, direction and velocity of movement of tropical cyclones on the wind field.

(2) By using the above dynamical interpretation method of numerical forecasts of wind fields in tropical cyclones, the real case experimental study with Typhoon Wipha (0713) is performed. The results show that the correction terms associated with pressure gradients and positions of tropical cyclones have great influence on the wind field in the tropical cyclone, while the correction terms associated with moving speed and direction of tropical cyclones have relatively small influence. The wind speed is corrected significantly before the landfall of the tropical cyclone, but not good after the landfall. The improvement of wind speed forecasts at island stations is obvious, but the corrected wind speed in the inner land is relatively stronger than the observation. This may be directly associated with the neglecting of land factors such as topography. Another important reason may be that the Fujita formula is not suitable for the calculation of pressure over the land. This is a defect of the present method, and would be improved in our future work.

In routine weather forecast operations, based on the analysis of numerical forecasts in the first few periods, or based on the comparison among predications of ensemble members, it is easy to correct the numerical predications of wind fields in tropical cyclones dynamically only by grasping the four factors of central pressure, position, moving direction and velocity of tropical cyclones. The method presented in this paper is simple and applicable in routine operations.

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