EXPERIMENTAL STUDIES WITH AN OPERATIONAL NUMERICAL MODEL FOR PREDICTION OF TYPHOON TRACKS OVER THE SOUTH CHINA SEA REGION

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ABSTRACT

Experiments for short range forecasting of typhoon tracks over the South China Sea Region were carried out using limited- area numerical model recently developed by the authors. Due to the shortage of sounding data over the sea, typhoon circulations are usually obtained incompletely from objective analysis, or with significant deviation of the centre from reality. Therefore a set of schemes for typhoon initialization are proposed here to construct a bogus typhoon with the circulation being consistent with the physical processes included in the limited-area model. Based on the schemes bogus data over the model grids are created and analysed together with conventional observational data. Then the normal model initialization scheme is issued to further modulate the model typhoon with the numerical model. Some experiments of sensitivity in various aspects are conducted for further improvement of typhoon track predictions. The experimental results for a number of typhoon landing in southern China in 1993 and 1994 shows that the limited-area model is capable of predicting typhoon tracks in the southern China region.

Key words: tropical cyclone, prediction of typhoon track, sensitivity test

I. INTRODUCTION

Due to a pressing need for numerically predicting typhoon track, an operational numerical weather prediction system (noted as TL6) was developed in Guangzhou Institute of Tropical and Oceanic Meteorology during the mid-1980's. However, the TL6 has a low resolution and includes a package of relatively simple physical processes, as a result of limited computing resources at that time (Xue et al., 1988). With an increasing need of operational development and upgrade of computing facilities, a new generation of numerical weather prediction model was developed after successful exploration of new methods and study on current development in numerical weather prediction at home and abroad. Meanwhile a set of schemes to initialize typhoon circulation as model input are proposed. The principal idea is to construct a bogus typhoon, in which the structure is agreeable with basic characteristics of typhoon structure and the elements are consistent within the inner area and smoothly embedded into the environmental field, in terms of typhoon warning information such as the location of typhoon centre, minimum pressure of the centre, and the radius of gale wind (15 ms^{-1}), et al.

The accuracy of typhoon track prediction is to a large extent dependent on model resolution, complete packing of physical processes, and the rationality of the bogus typhoon circulation. In this article, we use the newly developed model and doubly embedded bogus typhoon to carry out some experiments against real cases to predict tracks for typhoons which landed in the southern China region during 1993 and 1994 so as to determine whether the model has a capability of predicting typhoon tracks in the South China Sea region.

Ⅰ. MODEL DESCRIPTION

The numerical model may be described by a set of primitive equations with a terrain-following coordinate, i.e., $\sigma = (p-p_r)/(p_s-p_r)$ in the vertical, where p denotes pressure, and p_s, p_r are the pressures at the surface and the top level of the model, respectively. The model equations and spatial difference scheme are similar to those of TL6 (Xue et al., 1988). An explicit economic scheme is used for the time integration (Xue et al., 1995).

A nested mesh structure (Fig. 1) is used in the numerical model system. The grid length of the coarse mesh is 333 km with 10 layers in the vertical, covering an area of 50°-170°E and 56.6°N-31.2°S while that of the fine mesh model is 111 km with 10 layers, covering an area of 89-150°E and 36.2°N-3°S. The model included a full package of physical processes which may be listed as follows:

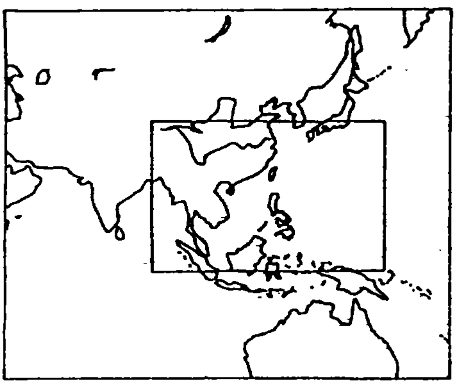

Fig. 1. Domains of coarse and fine meshes.

a) radiative energy transfer (including interaction between infrared radiation and cloud),
b) boundary layer process (based on Monin-Obukhov similarity theory),
c) deep convection (Betts's parameterization scheme),
d) shallow convection,
e) vertical diffusion, and
f) large scale condensation.

The fine mesh model domain covers almost all the typhoon tracks affecting the South China Sea region. Its boundary conditions for time integration are supplied by the coarse mesh model using one-way nesting. All the thermodynamic variables in the model are described by their deviation with respect to a static reference atmosphere such that an improvement to alleviate computational difficulties arisen from steep orography is made. The west boundary of the fine mesh model is located in 89°E which is close to the peak of the Tibetan Plateau. For model-length integrations, the radiative boundary condition is used for short-time steps while the tendentiously relaxed boundary is chosen for long-time steps. This technique of boundary treatment has an advantage of suppressing and absorbing perturbations initiated from the lateral boundary while enabling most waves to pass into the inner area during transformations between the coarse and fine mesh lattices. Therefore, in the whole process of integration, the transform between coarse and fine grids is well-coordinated and keeps stable computations.

Ⅱ. TYPHOON INITIALIZATION SCHEME

Due to the lack of sounding data over the tropical ocean, it is difficult to describe the initial typhoon circulation with objectively analysed results. It is necessary, therefore, to create a bogus typhoon following Fujita's formula, which satisfies dynamic and thermodynamic conditions and is convergent (divergent) in the lower (upper) layer and consistent with the model physics, based on typhoon warning information. The bogus typhoon is characteristic of fundamental typhoon structure, i.e. anti-cyclonic circulation in the upper layer and cyclonic circulation in the lower layer; the circulation intensity is closely related to pressure difference between the typhoon center and the environmental field; the non-divergence level is situated at a level with zero meridional component of wind speed; the maximum heating is centered around 250 hPa; and ascending movement dominates the whole column of the bogus typhoon so that it is asymmetric.

However, when a typhoon is formed over the oceans relevant data are from only a few or one observational station. It may result in inconsistence of position between the circulation center objectively analysed and the actual typhoon observed. Thus, when the bogus typhoon is superimposed on the objectively analysed field there may exist two centers of typhoon. Forecast results may be seriously affected. In order to solve this problem, a scheme of doubly embedding the bogus typhoon is designed. Firstly, artificial sounding stations are established on the model grids around the actual typhoon centre. The data are then in the objective analysis mixed with real sounding data to modify the false typhoon circulation previously existent, and correct the location of the typhoon centre analysed, completing the first embedment of the bogus typhoon into the environment. Then, a bogus typhoon is reconstructed against the backgroud of the objectively analysed field available through the first embedment, and superimposed onto it that is properly weighted. The second embedment is thus completed by this point. Because of the sparseness of sounding data over the oceans, there may appear unreasonable environmental temperatures in calculating environmental parameters. Generally, the stratification is unstable in the lower layer of the typhoon-affected area. When absolute stable temperatures of the background appear, they need to be modified till neutrally stratified. The initial field for model integration is formed when the doubly embedded field of objective analysis is initialized by normal modes to further coordinate betweeen the bogus typhoon and the numerical model. After experiments with dozens of real cases in 1990-1994, the technique of typhoon initialization has been improved and stabilized significantly that single and multiple typhoons in various intensity are automatically introduced into operational numerical predictions of the typhoon.

Fig. 2 shows comparisons at 850 hPa for Typhoon 9414 on 6 August 1994. Compar-

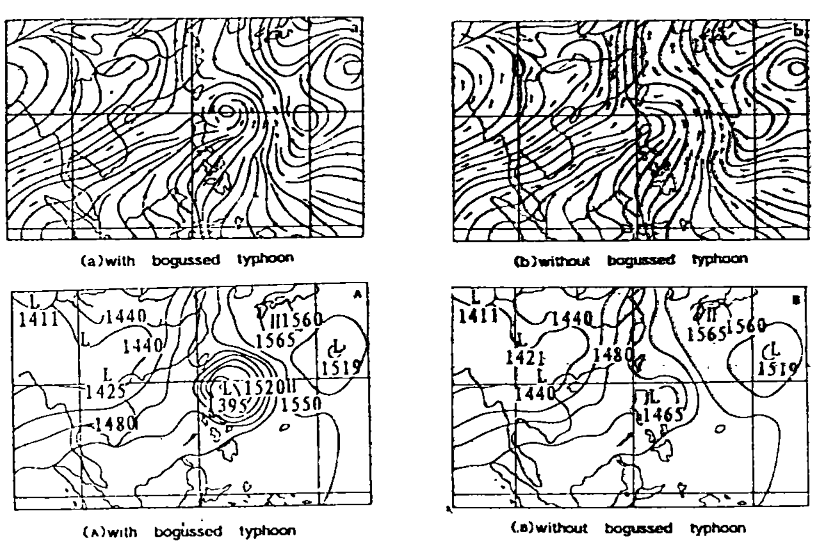

Fig. 2. Objective analyses of the 850 hPa field at 0400 GMT for 6 August 1994.

ing the objectively analysed fields with and without an embedded typhoon, it can be evidently seen that in the case of no inclusion of a bogus typhoon the circulation in the stream field analysis, the winds are smaller around the typhoon, the center is weaker geopotentially and shifted southward about 2 latitudes, and the high center of the moisture fields is not corresponding to the area of typhoon.

Ⅳ. MODEL SENSITIVITY EXPERIMENTS

This article describes real time predictions for each of the 13 typhoons and tropical cyclones that landed in southern China during 1993 and 1994. The data used were read from the archive base in the Guangzhou Regional Meteorological Center. The typhoon centres predicted are objectively located with the quadratic curvi-surface fitting based on the geopotential heights at 850 hPa. It has been verified that the mean errors of 24 hr and 48 hr forecasts for the above-described typhoon tracks are all less than 200 and 400 km respectively (Tables 1 and 2).

Table 1. Prediction errors of track at 1200 GMT by TL10 for typhoons making landfalls in southern China in 1993.

Typhoon codes	Date	Initial time		24 h				48 h				Errors (km)	
				Obervation		Prediction		Obervation		Prediction			
		Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	24 h	48 h
9302	25Jun.	16.3	124.0	19.0	118.6	18.6	119.2	21.3	112.8	21.0	116.7	94.7	405.2
	26Jun.	19.0	118.6	21.3	112.8	20.4	112.7	23.8	108.4	21.6	107.7	104.7	255.5
9303	9Jul.	15.9	117.1	18.3	110.7	18.7	113.5					293.0	
	10Jul.	18.3	110.7	19.0	106.8	19.9	108.2					179.1	
9309	18Aug.	19.8	118.9	19.7	114.9	20.6	118.0	21.0	112.7	21.4	116.3	342.2	373.7
	19Aug.	19.5	114.9	21.0	112.7	20.7	112.4	22.7	109.2	22.9	111.0	31.3	168.1
9315	11Sep.	20.8	122.0	21.3	119.2	22.4	119.9	22.3	117.6	23.2	117.9	138.5	102.6
	12Sep.	21.3	119.2	22.3	117.6	22.6	117.8					39.9	
9316	16Sep.	20.0	116.8	22.5	110.7	22.4	112.3					165.6	
9318	24Sep.	19.0	111.3	20.5	112.4	19.0	112.0	22.3	112.4	18.9	111.9	146.3	359.6
	25Sep.	20.5	112.4	22.3	112.4	21.4	112.3					100.6	
9323	1Nov.	16.2	121.0	17.2	117.2	17.8	116.0	18.7	114.2	18.6	112.9	138.8	137.8
	2Nov.	17.2	117.2	18.7	114.2	19.0	113.8	21.4	112.0	22.1	111.5	53.0	96.1
	3Nov.	18.7	114.2	21.4	112.0	20.5	110.5					184.3	

24 h mean errors: 144 km   48 h mean errors: 237 km

Table 2. Same as Table 1 except for 1994.

Typhoon codes	Date	Initial time		24 h Obervation		24 h Prediction		48 h Obervation		48 h Prediction		errors(km)	
		Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	24 h	48 h
9403	5Jun.	19.9	117.0	19.4	114.6	20.7	116.1	19.9	112.0	22.3	111.7	213.9	273.1
	6Jun.	19.4	114.6	19.9	112.0	20.7	111.8	21.7	110.1	22.8	108.1	89.6	236.6
	7Jun.	19.9	112.0	21.7	110.1	22.3	110.4	24.0	110.0	25.9	109.9	71.9	208.3
9304	23Jun.	16.3	118.4	19.7	112.6	19.4	114.2					168.7	
9405	2Jul.	18.5	118.7	20.2	112.9	20.1	114.4	21.7	111.3	21.8	112.1	162.2	86.2
	3Jul.	20.2	112.9	21.7	111.3	22.2	110.9					71.2	
9406	9Jul.	19.1	125.3	23.4	121.5	21.3	121.8	26.9	115.4	24.8	113.6	235.3	291.6
	10Jul.	23.4	121.5	26.9	115.4	25.7	115.4	32.8	115.7	32.1	112.3	135.9	326.2
9413	2Aug.	20.2	125.0	23.5	120.4	23.8	121.1	25.5	116.0	28.8	117.6	84.4	397.1
	3Aug.	23.5	120.4	25.5	116.0	26.6	116.2					125.5	
9419	25Aug.	18.0	118.4	19.6	114.0	20.2	114.1	20.4	110.7	21.6	111.7	65.4	169.1
	26Aug.	19.6	114.0	20.4	110.7	21.9	109.9	21.0	107.8	22.1	106.1	180.9	211.7
	27Aug.	20.4	110.7	21.0	107.8	21.3	106.9					104.2	
9424	10Sep.	18.8	120.8	20.3	116.6	20.0	117.8	19.0	111.1	20.6	110.3	128.0	195.6
	11Sep.	20.3	116.6	19.0	111.1	20.3	111.2	18.9	106.5	19.0	105.1	149.6	144.9
	12Sep.	19.0	111.1	18.9	106.5	18.9	108.1					167.0	

24 h mean errors: 135 km 48 h mean errors: 231 km

In order to understand effects of various model aspects on the prediction of typhoon tracks and to further improve the accuracy of relevant numerical predictions, the following sensitivity experiments are undertaken.

1. *Effects of model resolution on typhoon track prediction*

With permissible power of computing facilities, the increase of model resolution is one of the most effective ways to improve the accuracy of numerical prediction. A total of 14 runs of comparative forecasting experiments are done using TL6 (the current operational tropical limited area numerical weather prediction model) and the newly developed numerical model for 6 typhoons and 1 severe tropical storm that landed in southern China in 1993. The results may be described as below.

The resolution of the model system TL6 is 333 km with 6 layers in the vertical, and that of the nested fine mesh is 167 km with 6 layers in the vertical. The mean erors of predicting typhoon tracks for 24 hr and 48 hr are 196.8 km and 371.6 km respectively. (Table. 3)

The resolution of the new model system is 333 km with 10 layers in the vertical, and that of the nested fine mesh is 111 km with 10 layers in the vertical. The mean errors of predicting typhoon tracks for 24 hr and 48 hr are 143.7 km and 237.3 km respectively.

It is obvious to see the significant role of increased model resolution in reducing errors of the track prediction. It poses no problem on the aspect of computations for the model resolution to be increased to 55 km, only that it requires too much resource to

Table 3. TL6 prediction errors of tracks for typhoons landing in southern China in 1993.

Typhoon codes	Date	Initial time		24 h				48 h				errors (km)	
				Obervation		Prediction		Obervation		Prediction			
		Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	Lat.	Lon.	24 h	48 h
9302	25Jun.	16.3	124.0	19.0	118.6	18.0	120.2	21.3	112.8	21.4	119.0	202.0	642.1
	26Jun.	19.0	118.6	21.3	112.8	21.3	116.5	23.8	108.4	24.0	111.9	352.2	356.4
9303	9Jul.	15.9	117.1	18.3	110.7	18.3	113.8					327.8	
	10Jul.	18.3	110.7	19.0	106.8	19.0	108.0					126.1	
9309	18Aug.	19.8	118.9	19.7	114.9	21.0	117.2	21.0	112.7	22.3	117.0	279.8	467.3
	19Aug.	19.5	114.9	21.0	112.7	21.2	113.2	22.7	109.2	23.0	101.0	56.3	88.4
9315	11Sep.	20.8	122.0	21.3	119.2	21.5	120.4	22.3	117.6	24.0	117.5	126.1	189.3
9316	12Sep.	21.3	119.2	22.3	117.6	23.2	117.5					100.6	
	13Sep.	20.0	116.8	22.5	110.7	21.8	113.0					249.3	
9318	24Sep.	19.0	111.3	20.5	112.4	19.5	111.2	22.3	112.4	19.8	110.0	167.5	373.2
	25Sep.	20.5	112.4	22.3	112.4	21.8	111.8					83.0	
9323	1Nov.	16.2	121.0	17.2	117.2	18.5	120.0	18.7	114.2	20.0	119.0	329.7	523.8
	2Nov.	17.2	117.2	18.7	114.2	18.5	113.5	21.4	112.0	18.2	111.5	77.0	333.1
	3Nov.	18.7	114.2	21.4	112.0	19.0	111.2					279.6	

24 h mean errors: 196 km 48 h mean errors: 371 km

make it operational with the current conditions. Nevertheless, the new model system with 111 km resolution can be run on CD468 for a cost of only 1.7 hours for the 48 hr forecast. It is therefore realistic that the new model system can support real time operational forecasts.

2. *Effects of the fine mesh model domain on the typhoon track over South China Sea*

TL6 is self-nested. When there occur more than one typhoon, it only nests the one that is closest to the South China Sea. In fact, with the existence of multiple typhoons, interactions among individual circulation regimes will change the environmental fields that affect the movement of typhoon tracks. A number of tests were carried out for the case of multiple activity of typhoons. Typhoon 9009 forming around the end of July, 1990, for example, initially moved southward, then turned westward. It was stagnating during 28-29 July, and suddenly moving northward during 29-30 July. Analysis shows that the storm was closely correlated to Typhoon 9010 over the ocean east of the Phillipines, which was formed on 28 July 1990. It continually intensified and slowly moved northeastward until a significant increase in the lower-layer southerly from around Indonesia to the South China Sea suddenly made it recurve to the north and land in the eastern Pearl River Mouth (Xue et al., 1992). When the experiment was done with inclusion of only one typhoon (9009), the above-described phenomenon was not evident, and the typhoon moved westward and finally landed on the Leizhou Peninsula.

The domain of the fine mesh was determined in a number of case experiments for those typhoons which affected the southern China region, which took account of such aspects as the completeness of the prime part of the subtropical anticyclone, the effects of the southern branch of the westerly trough and cross-equatorial flow, and computing resources as well. If the domain is too large the computing time would increase exponentially. The effects of lateral boundary conditions should be minimized in a limited-area model. In the experiment with Typhoon 9302, for example, the western side of the boundary was shifted from 89°E to 100°E to cause adverse effects on the predictions such that the errors for typhoon tracks increase from 99.7 km to 259.5 km in the 24 hr prediction and from 330 km to 607.5 km in the 48 hr prediction. See Figs. 3 and 4.

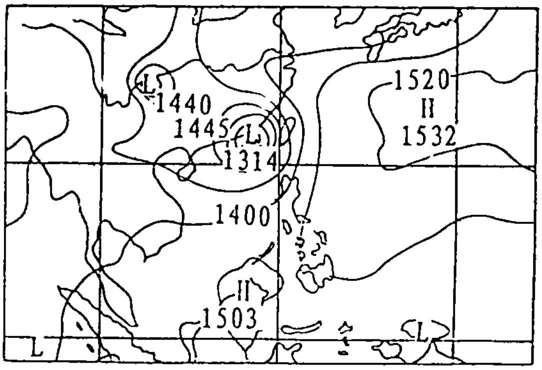

Fig. 3. Fine mesh model with the western boundary setting at 89°E.

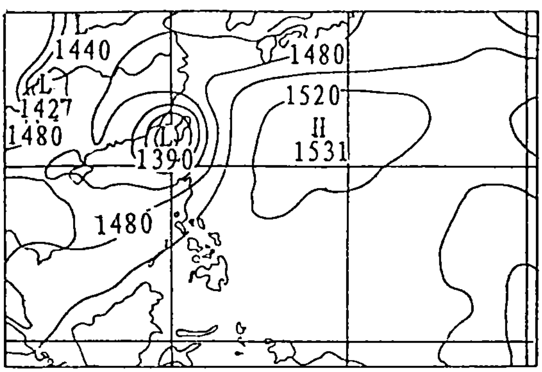

Fig. 4. Same as Fig. 3 except for 100°E.

3. *Effects of physical processes to the typhoon track prediction*

The effects of physical processes on the prediction of typhoon track are significant, among which the convective parameterization and the lower boundary conditions play an leading role in maintaining the typhoon circulation. In areas with the appearence of typhoons, there are always strong convective developments that transfer heat and moisture vertically and release the latent heat through condensation by lifting. The interactions between cumulus convection and radiation play an essential role in the development of typhoon and affect the boundary layer at the same time. The boundary layer parameterization in the new model is based on the Monin-Obukhov similarity theory. The prediction of ground temperature and water content of soil is done with the forced recovery techniques. The transfer coefficient of the near-surface turbulent flux is determined by the characteristics of the earth surface and the stability function in the near surface layer. When the ground temperatures increase, the near-surface layer becomes more instable, leading to the intensification of convective effects. As a result, the structure of the stratification dynamics and thermodynamics is changed. According to our tests, the convective adjustment scheme proposed by Betts is better than Kuo's scheme previously used in the parameterization of cumulus convection.

In the experiments that exclude convective parameterization and the effects of the boundary layer, i. e. , only the purely dynamic effect is retained, the forecast errors of typhoon track monotonically increase with time. Take Typhoon 9315 for example. The errors are 87. 2 (132. 4)km and 350. 0(469. 2)km with(without)convective parameterization and effects of the boundary layer. In addition, the intensity of typhoon circulation is also weakened with the exclusion (Figs. 5 and 6).

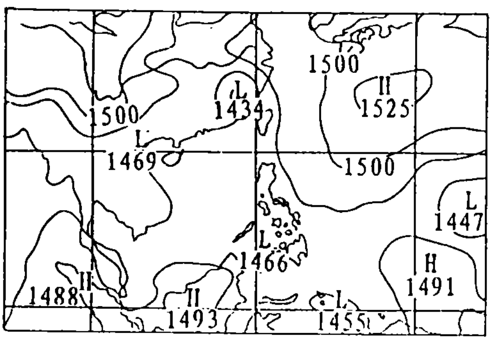

Fig. 5. The model that includes the boundary layer and convection parameterization.

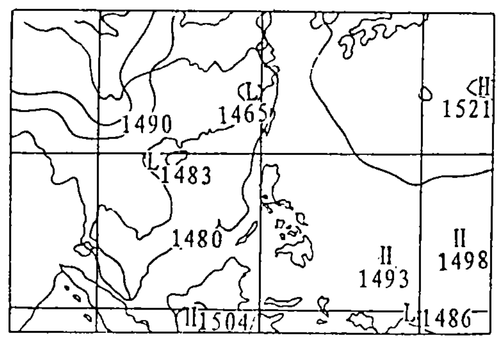

Fig. 6. Same as Fig. 5 except for no inclusion of the boundary layer and convection parameterization.

V. ANALYSIS AND ASSESSMENT OF PREDICTION RESULTS

The experiments for real cases of typhoons which landed in the southern China region during 1993 and 1994 show that the new model is capable of predicting typhoon tracks in the region. The strong tropical storm 9403, for example, which caused huge losses of property to the province of Guangdong, was correctly predicted 48 hours (especially 24 hours) prior to landfall. According to the prediction of the model, the tropical storm would first move westward, then direct towards the northeast to Hainan Island, and finally make landfall in the coastal areas of Xuwen County. After landing, the storm would turn northward, and cross over the areas of Zhanjiang, Suixi, and Lianjiang. The model prediction of the storm track is in general correspondence to the actual situation (Fig. 7). Another example is the

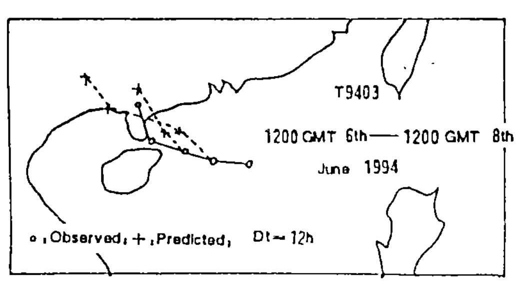

Fig. 7. Track of severe tropical storm 9403. Lines: solid for the observation and dashed for the prediction.

severe tropical storm 9405, which suddenly recurved rightwise 12 hours before landing, and then moved northward. The model result basically matched with the real case. The storm was formed over waters in the northeast of the South China Sea on 2 July 1994. During the life cycle, the upper-level subtropical anticyclone ridge was stably situated to the north of 30°N. A trough sitting in the west part of northern China was also stable. The tropical storm moved west-to-northwest at a speed of around 20 km per hour after its formation. At around 0000 GMT on 4 July 1994, the storm suddenly turned rightwise and moved northward before landing in the area of Yangxi County. Around the time of landfall it caused torrential rain in the Leizhou Peninsula and the west part of Guangdong. The whole procedure was successfully predicted by the model, especially for the sudden rightwise turning of the storm's track on 4 July and the torrential rain resulted.

Fig. 8 shows the actual tracks of the severe tropical storm 9405 against two model prediction results at 1200 GMT on 2 and 3 July 1994. It is understood from the observations that the sudden turning of the track occurred at 0000 GMT on 4 July 1994. In comparison with the real situation, the initial 12-hour result of 48 hr model forecast that was issued at 1200 GMT on 2 July 1994 was correct in the moving direction with a slower speed. For the rest 36 hours the model was largely right in both the direction and speed of the track. It is worth noting that the rightwise turning of the storm at the 36th model hour is evident, which is well corresponding to the real occurrence at 0000 GMT on 4 July 1994. The model prediction starting on 3 July 1994 is even better. The predicted storm track matches very well with the real case. In particular, the time of the rightwise turning was accurately predicted in two forecasts on 2 and 3 July 1994 respectively. The model also predicted the torrential rain in the northern part of Hainan Island and Leizhou Peninsula brought about by the tropical storm 24 hours after landfall, the northward movement of raining areas to the west part of Guangdong, and the ending of the torrential rain in the northern Hainan Island, all of which being in good agreement with the real case (Figure not shown).

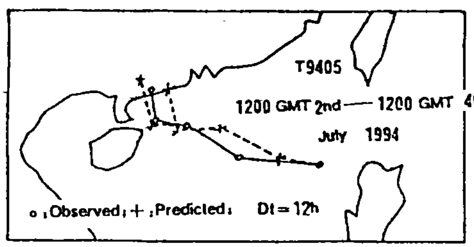

Fig. 8. Same as Fig. 7 except for STS 9405.

The sudden change of the track of the tropical storm 9405 may be analysed from the result of the numerical model integration starting from 1200 GMT on 2 July 1994. We calculated the mean wind direction and velocity at each level within the squares five grids away from the storm center in the east, west, north, and south directions in respect to the centre of the tropical cyclone. This treatment can generally indicate the direction of large scale flow with the cyclone filtered. The results listed in Tables 4 and 5 display the westward movement of the accompanying flow. In the upper layers the mean flow changes from the westerly to the easterly. The evident turning of wind direction occurs at the 36th hour of prediction with the increasing of the southerly component. This kind of phenomenon is more obvious in the lower layer. The above-described large scale fields of mean wind speed can be regarded as a guiding flow for the tropical storm moving generally along the guiding flow. It is worth mentioning that the computing domain is shifted with the movement of the cyclone. It may be concluded, based on the above analysis, that the tropical cyclone is generally along the direction of the guiding flow inside the stable large scale environmental field. The rightwise turning of the cyclone track falls in a categary of "turning before a trough" as stated by some experienced forecasters. The above example further proves that the model is capable of predicting changes in the tracks and erratic paths of typhoons.

Table 4. Average *u* variation on each level near storm center for initial time (1200 GMT, 2 July 1994) and 12, 24, 36, and 48 hr predictions.

h	200 hPa	500 hPa	700 hPa	850 hPa
0	−8.6	−6.4	−3.6	−1.6
12	−7.7	−4.1	−2.5	−0.9
24	−6.8	−4.3	−2.2	−0.8
36	−6.3	−3.3	0.0	3.4
48	−5.0	0.5	2.8	3.7

Table 5. Same as Table 4 except for *v*.

h	200 hPa	500 hPa	700 hPa	850 hPa
0	−6.1	3.7	3.2	2.7
12	−5.1	2.0	1.8	2.6
24	−0.5	0.7	0.5	2.7
36	0.4	1.1	2.1	4.3
48	0.9	2.6	6.9	4.9

Ⅵ. EXISTING PROBLEMS

There are two important problems which need to be solved in future. They are:

a. If the computing environment is permissible, the resolution of the fine mesh model can be increased to 55 km such that the forecasting accuracy can be improved further. For example, for Typhoon 9406 and the tropical storm 9407 which moved towards each other, the intensity of the former was much stronger than the latter which had a radius of only 80 km of the 15 ms^{-1} gale. As a result, the latter was sucked into the circulation of the former after 12 hours of integration. Therefore considerable errors were brought about in the prediction of the tracks of tropical storm 9407.

b. During the whole procedure of experiments, the quality of the analysed fields over the tropical ocean was a major bottleneck in numerical prediction of tropical cyclones in southern China. Due to the insufficiency of observational data over the oceans, the analysed circulation may be incorrect to lead to failures of model prediction. In addition, analysis of moisture fields is also very important. Moisture fields affect not only the prediction of precipitation but also the dynamics of tropical cyclones via the diabatic effects. Therefore, the moisture field analysis has a significant influence on the predicting of typhoon tracks, though it is still a difficult problem that needs urgent solution.

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