AN EFFECTIVE APPROACH TO SHORT- AND MEDIUM-RANGE PREDICTION OF TRACK AND INTENSITY OF TROPICAL CYCLONES

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ABSTRACT

An objective prediction approach to the 6 h- 144 h track and intensity of tropical cyclones over the northwestern Pacific is proposed. On the basis of both analog deviation technique and completed historical sample curve library, the track or intensity prediction for each forecast period are determined respectively through the optimum weighted superposition of displacement or intensity change of the cases, with different number and weighted coefficient corresponding to minimal analog deviation, from different tropical cyclone or different stage of the same cyclone, so that the prediction results for both forecast period and entire process are optimal. The verification suggests that the approach exhibits better forecast performance than other previous forecast methods by having remarkable decreasing forecast errors in short- and medium-range forecast of both track and intensity, and that the approach can also be used to predict effectively the decay process of tropical cyclone and is able to predict anomalous track and tropical depression.

Key words: track and intensity, prediction approach, tropical cyclone

I. INTRODUCTION

Being important components of tropical cyclone prediction, both track and intensity forecasts are still subjects of attention. A series of forecast methods such as CLIPER (Huang, Liao and Hu, 1994), regressive statistics method (Lin, 1982; Elsberry et al., 1975), statistical-dynamic scheme (Niu et al., 1987), numerical forecast model (Mathur, 1986; Yamasak, 1986), perfect prediction (PP) approach (Huang et al., 1996, 1997), etc. have been presented to deal with them. At present these methods involve some of their own merits and have performance in aspect such as short-range track forecast. However, most of them lack ensemble ability for short-range and medium-range forecasts of both track and intensity, especially in forecasts of more than 72 h. Again, on certain occasions such as ocean shipping, available data (e.g. initial fields in numerical model or numerical prediction products in PP approach) set limits to appropriate application of these methods. Thus for solution to these problems a new 6 h- 144 h prediction approach for both track and intensity of tropical cyclones is proposed in this study. It follows a principle in mathematics that analog deviation technique (Li, 1986) can be used to measure overall similarity between two sample curves, the track or intensity prediction for each forecast period are determined respectively through the optimum weighted superposition of corresponding displacement or intensity change of the cases, with different number and weighted coefficient, from different tropical cyclone or different stage of the same cyclone. Here a special implication is contained in the word "cases". Compared with other previous methods, the forecast performance and distinctive features are more remarkable in the newly proposed approach, hence deserving to be recommended as a valuable alternative approach in operation.

II. METHODOLOGY

Primary sets of methodologies are used in working at track and intensity forecasts, which include short-range (6 h – 72 h) forecast and medium-range (72 h – 144 h) forecast of location, center pressure and maximum wind speed.

1. *Analog deviation technique as mathematical tool*

In general, predicting the nature of a certain thing and its change by analogue method is that so long as the influencing factors in the homogeneous things are the same in combination, they share similar nature and change to some extent. Assuming that two different samples, i, j, involving M variables, can be regarded as two sample curves in the coordinate of the number of factor, K, as x axis whereas the value of factor, X, as y axis, analog deviation, C_{ij}, is defined as $C_{ij}=\frac{1}{2}(S_{ij}+D_{ij})$, where $S_{ij}=\frac{1}{M}\sum_{K=1}^{M}\left|X_{ijk}-E_{ij}\right|; D_{ij}=\frac{1}{M}\sum_{K=1}^{M}\left|X_{ijk}\right|; X_{ijk}=X_{ik}-X_{jk}; E_{ij}=\frac{1}{M}\sum_{K=1}^{M}X_{ijk}$.

Here, X_{ijk} represents the difference between kth variables, X_{ik} and X_{jk}, of samples i, j. D_{ij} is the mean absolute distance of M variables between two samples, i, j, and defined as "value coefficient" which reflects the discrepancy between total mean values of two samples, whereas S_{ij} is the mean absolute distance between differences of M variables and their mean values, and defined as "shape coefficient" which measures the shape similarity between two sample curves. If $X_{ij1}=X_{ij2}=\cdots=X_{ijM}=E_{ij}, S_{ij}=0$, i.e. when there is complete identity in shape for two sample curves, no equality is found with one another among $X_{ij1}, X_{ij2}, \cdots X_{ijM}$, $S_{ij}\neq 0$. In other words, two curves will digress toward different directions. The larger the differences are among different X_{ijk}, the larger S_{ij} will be. Thus analog deviation C_{ij} that is determined by both S_{ij} and D_{ij} measures overall similarity between two sample curves.

To remove the impact of numerical fields, the original variables are normalized by $X_k = \frac{X_k^0 - X_{km}^0}{X_{kM}^0 - X_{km}^0}$. Specifically, X_k^0 indicates the kth original variable and X_k indicates corresponding normalized variable. X_{kM}^0 and X_{km}^0 are the maximum and minimum of original variables in historical samples respectively. Hence it is easy to yield $0 \le C_{ij} \le 1$. Note that the smaller C_{ij} is, the more similar two sample curves will be. Fig.1 shows an example of two sample curves in real forecast. For the fixed real sample, i, there are different historical samples, j.

While both the value and shape are the most similar between j and i, C_{ij} reaches the minimum.

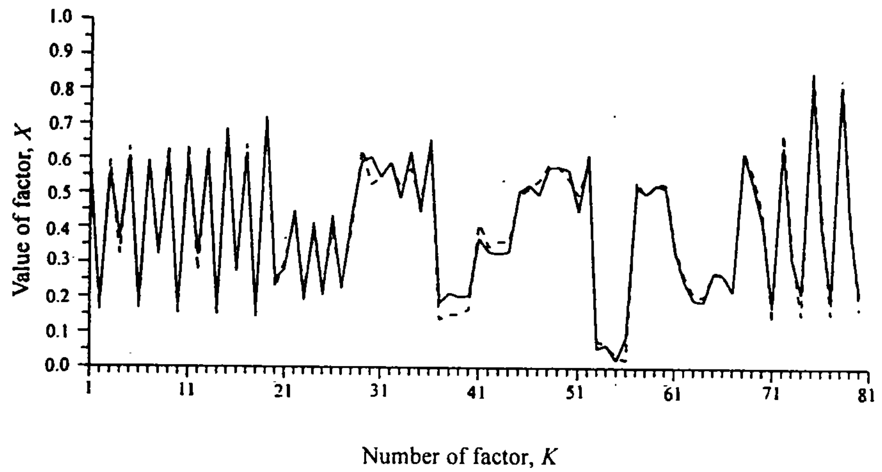

Fig.1. Real and historical sample curves, i (solid) and j (dashed), with minimal analog deviation C_{ij} =0.02478 for Typhoon Ketth (1997).

2. *Stepwise regression analysis used to determine physical factors*

Lots of candidate variables are derived from the tropical cyclone process data from 00 h to past 24 h. Through stepwise regression analysis in which displacements (intensity changes) are taken to be predictants, for a certain cutoff criterion F_a, a total of 80 (44) variables are selected as objective factors so as to compute analog deviation. Primary factors include: longitude, latitude, center pressure and maximum wind speed from 00 h to past 24 h at 6 h intervals; meridional, zonal and composed motion rate/acceleration; pressure difference and wind speed change; heading and its change; nonlinear combination factors; future location deduced from Newton's Second Law of Motion, etc.

The screened factors embody almost all information concerning a tropical cyclone at initial and past time, and have physical significance. As we know, the formation, movement and decay of tropical cyclone accompany climatologically certain peculiar locations. Again, previous track, intensity and their changes influence persistently future processes. Moreover, initial and previous motion rate, heading, intensity and their changes reflect indirectly the inner structure, change and dynamic-thermodynamic effects on tropical cyclones from circulation background and surface environment.

3. *Statistics procedure used to create historical curve library*

The basic data are taken from *Typhoon Yearly Book* for 1949–1996. A broad domain covers the northwestern Pacific Ocean of 105 °E–180° and 10–40°N. Thus a total of 1522 tropical cyclone processes are suitable. In historical data a few maximum wind speed records are absent. Considering that wind speed within the tropical cyclone results from large horizontal pressure gradient force and maximum wind correlates closely with center pressure, we derived, from a regression analysis for 35161 samples, the relationship between maximum wind speed, V, and center pressure, P, i.e. V=682.422485–0.665450×P, and then revised the default wind speed records.

By taking a 24-h period as a size, computing original variables one by one for each of the tropical cyclone processes, by solving their maximum and minimum, and normalizing, a great number of historical sample curves are yielded, of which each consists of 80 factors and is similar to the dashed line, j, in Fig.1. Notice that each of the tropical cyclone processes can construct many curves. However, if we define a future 6 h-144 h period after each 24 h period in an entire tropical cyclone process as a "case", each curve corresponds to only a case. The 6 h-144 h meridional and zonal displacements, pressure change and wind speed change of the case are recorded in correspondence to each of the curves. Here zonal displacement of 1° is converted into latitude distance according to $\Delta\lambda = \int_{\lambda_2}^{\lambda_1}\cos\varphi d\lambda = (\lambda_2 - \lambda_1)\frac{\sin\varphi_2 - \sin\varphi_1}{\varphi_2 - \varphi_1}$, where (φ_1, λ_1) and (φ_2, λ_2) are the sphere coordinates for two arbitrary locations.

A standard curve library involving 42158 historical sample curves and corresponding cases has been created.

4. *Computational aspects*

Based on longitude, latitude, center pressure and maximum wind speed of a tropical cyclone available at 6-h intervals from 00 h to past 24 h, each variable is computed and normalized for the real forecast time, thereby forming a real sample curve similar to the solid line, i, in Fig.1. We computed C_{ij} between this real curve and each of the historical curve in the library and queued them from small value to large one, and stored 6 h–144 h displacements, pressure and wind speed changes of each case corresponding to sequentially minimal C_{ij}.

Setting the 6 h–144 h location (or intensity) as predictants, the weighted superposition of displacement (or intensity change) is taken as the predicted 6 h–144 h displacement (or intensity change) for n cases that correspond to historical sample curves with the minimal analog deviations. Here, the weighted coefficient is $(1 - C_{ij})$. Hence the predicted location (or intensity) can be determined through the predicted displacement (or intensity change) and real initial location (or intensity).

For n cases there may be $m(m \leqslant n)$ cases with future life-span less than a particular period of forecast such as 96 h, it is natural that the forecasts at 96 h afterwards will be complementarily completed by the $(n - m)$ cases. Obviously, the corresponding weighted coefficient also changed due to different analog deviation. The same procedures go on for other forecast periods. Thus, the superposition forecast for each forecast period takes likely from different number of cases and different weighted coefficient. Additionally, the n cases are chosen from different tropical cyclones or different stages of the same cyclone. Therefore for each forecast period the superposed cases are nearly completely different.

Thereby two problems ensued. First, reliability for each forecast period can be measured in terms of analogue reference, $R = \frac{\sum_{l=1}^{n-m}(1 - C_{ijl})}{n - m}$, where C_{ijl} indicates the minimal analog deviation corresponding to the cases whose future life-span is less than a certain forecast period. Second, if n–m=0 or discontinuity of forecast occurs at a certain forecast period such as 72 h when n

reaches a sufficient size such as 150, it can be predicted that decay of a tropical cyclone or neutercane will occur within 72 h. This is very useful in forecast.

The miscellaneous forecast processes above were performed by programming.

5. *Least-square procedure used to control optimum forecast*

Since the prediction for each forecast period is based on minimal analog deviation and is optimal, the entire forecast will be optimal so long as the superposition number, n, is determined objectively. Least-square procedure is used to do it via solving the minimum root-mean-square errors (RMSE).

In order to determine n, 6 h–144 h track and intensity forecasts for a total of 88 tropical cyclone processes were made for 1994–1996 using the presented approach. Fig.2 shows the variation of RMSE for track and intensity forecast with n. It can be seen that while n increases gradually, RSME changes from the maximum, through fluctuant descending, to the minimum, before inclining to a steady state, followed by a slight ascent. Furthermore, a small value of n means a large fluctuation of RMSE. Although n corresponding to the minimal RMSE is different for respective forecast periods, nevertheless all RMSE for different periods approximate to the minimum when n is taken to be 21 for track forecast and n to be 41 for intensity forecast. Thus, the track (intensity) forecast for each forecast period will consist of the weighted superposition of displacement (or intensity change) of 21 (41) cases corresponding to historical sample curves with minimal analog deviations. Consequently, the entire predicted 6 h–144 h track (intensity) implies likely an optimal tropical cyclone motion (development) process.

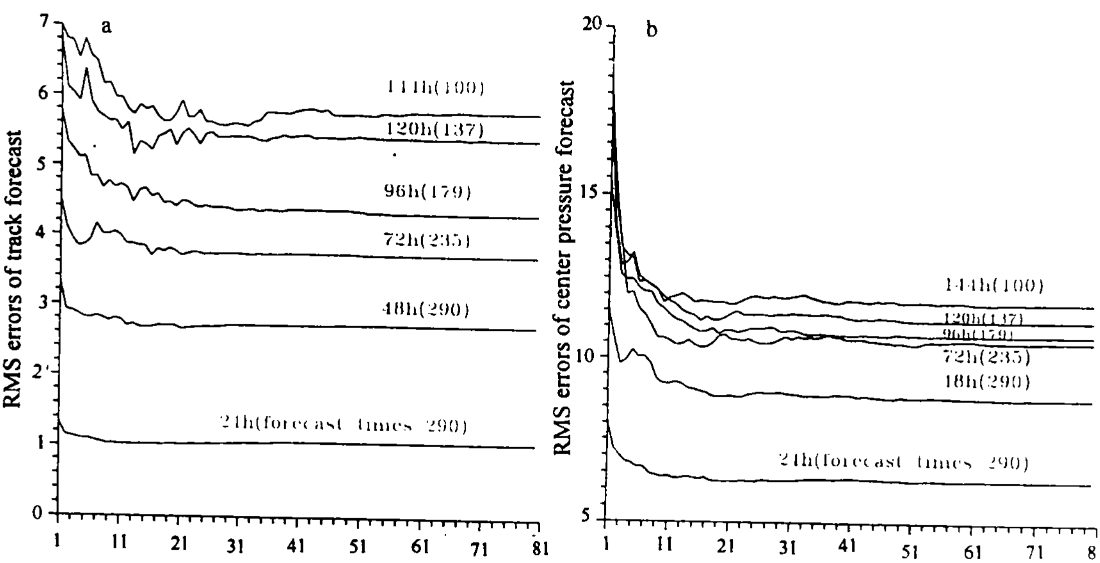

Fig.2. The variation of root-mean-square errors of track (a) and intensity (b) forecast with the number of weighted superposition cases, n, which is indicated on the abscissa.

III. THE VERIFICATION

All of the 29 tropical cyclones in 1997 were used to verify so as to test the performance of newly proposed approach. The forecast results of track and intensity are shown in Tables 1 and 2, respectively. In fact, the previous forecasts for 88 tropical cyclones during 1994–1996 can also be regarded as part of the verification.

Table 1. Short-and medium-range track forecast results for a total of 29 tropical cyclones including 4 tropical depressions in 1997 by the newly proposed approach; the results in bracket are forecast by the CLIPER '97 Model (not presented). (Unit: lat. dis.; lat. dis. =111.137 km)

Fcst period	6 h	12 h	18 h	24 h	30 h	36 h	42 h	48 h	54 h	60 h	66 h	72 h
Times	157	157	157	157	157	157	157	157	157	157	157	157
Mean	0.24	0.49	0.80	1.15	1.53	1.94	2.36	2.77	3.23	3.70	4.18	4.77
vec.err.	(0.26)	(0.57)	(1.13)	(1.36)	(1.79)	(2.32)	(2.79)	(3.25)	(3.90)	(4.45)	(5.23)	(5.78)
s. d	0.17	0.33	0.52	0.77	1.05	1.26	1.68	1.90	2.17	2.49	2.81	3.19
	(0.17)	(0.33)	(0.63)	(0.83)	(1.06)	(0.17)	(1.38)	(1.67)	(1.98)	(2.22)	(2.92)	(3.19)

Fcst Period	78 h	84 h	90 h	96 h	102 h	108 h	114 h	120 h	126 h	132 h	138 h	144 h
Times	112	112	112	112	73	73	73	73	45	45	45	45
Mean vec.err.	4.34	4.77	5.34	5.96	5.16	5.55	6.02	6.65	6.22	6.58	7.18	7.75
s. d	2.95	3.16	3.48	3.87	3.66	3.88	4.09	4.37	4.18	4.58	4.96	5.28

As seen in Table 1, both the mean vector errors and standard deviations for the short-range forecast within 72 h are distinctly less than those by the CLIPER method, suggesting that the newly proposed approach has better forecast skill. Although the results cannot be directly compared with those with other methods, the medium-range forecasts from 72 h to 144 h exhibit more remarkable decreases of error as indicated in both forecast experiences and PP results for the South China Sea typhoon (Huang, Hu and Chang, 1997). As far as the intensity forecast is concerned, the newly proposed approach not only offers a trend forecast in intensity change (intensifying, weakening, maintaining), but also provides quantitatively the predicted center pressure and max. wind speed, therefore perfect rate and mean absolute error or standard deviation can be used to measure the forecast performance of the intensity respectively. The results in Table 2 suggest that except for the medium-range intensity forecast that cannot be compared due to a lack in corresponding reference research, the short-range intensity forecast errors for each period are less than those in documented works (Lin, 1982; Elsberry et al., 1975; Niu et al., 1987; Steranka, Rodgers and Gentry, 1986; Xie and Li, 1981), especially for the max. wind speed forecast with maximum errors within 7 m/s. From the perfect rate, it is known that the measurement of the center pressure is nearly consistent with the one by the max. wind speed. Averaged perfect rate in the 6 h–72 h pressure trend prediction is 76.5% while the 72 h–144 h average is 85.5%, with the total average being 81%. It is greater than the results in the documented works (Steranka et al., 1986; Xie et al., 1981) in which the former is 67% whereas the latter is 70%, and also greater than the rate by the previous approach (71%) of Huang, Liao and Hu (1996).

Fig.3 shows the comparisons between the actual track (best track) and the forecasted for Typhoons Tina and Ketth (1997). A significant feature seen in Fig.3 is that both of the storms are very close to the 6-day track forecast and almost overlap the short-range forecast. Moreover, the predicted turning at 96 h for Typhoon Ketth coincides with the actual case. In addition, Fig.4 presents two 6-day sequent forecasts of intensity for the typhoon that is representative of strong development. It can be seen that the prediction is consistent with the observation not only in medium-range trend forecast, they are also identical in the magnitude and occurrence time of maximal deepening or extreme wind speed. Likewise, the accurate forecast also manifests in the decay forecast.

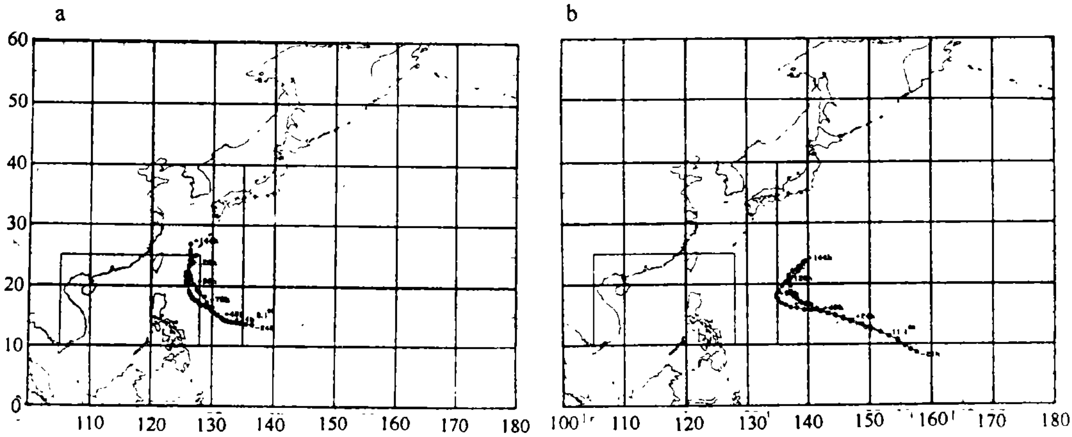

Fig.3. Comparisons between the actual (solid cycle) and the forecast (dashed cycle) track for Typhoon Tina (a) and Ketth (b), respectively.

Table 2. Tropical cyclone intensity forecast results by the newly proposed approach for 1997.

Forecast period (h)	Times	Perfect rate (%)	Absolute error (hPa/ms^{-1})	Standard deviation (hPa/ms^{-1})
6	157	44/45	3.02/1.70	2.45/1.35
12	157	64/64	4.53/2.62	3.90/1.98
18	157	73/71	5.40/3.18	4.98/2.62
24	157	76/73	7.14/4.04	5.97/3.34
30	157	77/77	8.07/4.54	6.83/3.59
36	157	80/78	9.48/5.32	8.00/4.07
42	157	80/79	9.82/5.45	8.40/4.39
48	157	82/82	10.70/5.80	9.11/4.83
54	157	85/84	11.14/6.06	9.50/5.21
60	157	86/83	12.00/6.58	10.11/ 5.50
66	157	86/82	12.52/6.82	10.41/ 5.81
72	157	85/81	12.31/6.95	11.27/ 6.19
78	112	85/83	12.05/6.50	11.48/ 5.77
84	112	85/82	11.92/6.41	11.76/ 5.91
90	112	86/84	12.00/6.69	11.21/ 5.75
96	112	84/80	12.33/6.68	11.15/ 6.09
102	73	82/82	11.20/6.07	10.38/ 5.33
108	73	82/81	11.39/6.18	10.38/ 5.61
114	73	82/82	11.76/6.50	9.96 / 5.65
120	73	82/82	11.26/6.23	9.66 / 5.70
126	45	90/92	11.68/6.58	10.24/5.49
132	45	90/86	10.98/6.10	9.36 / 5.21
138	45	90/86	10.82/6.26	9.66 / 5.21
144	45	88/92	9.60 / 5.30	8.60 / 5.08

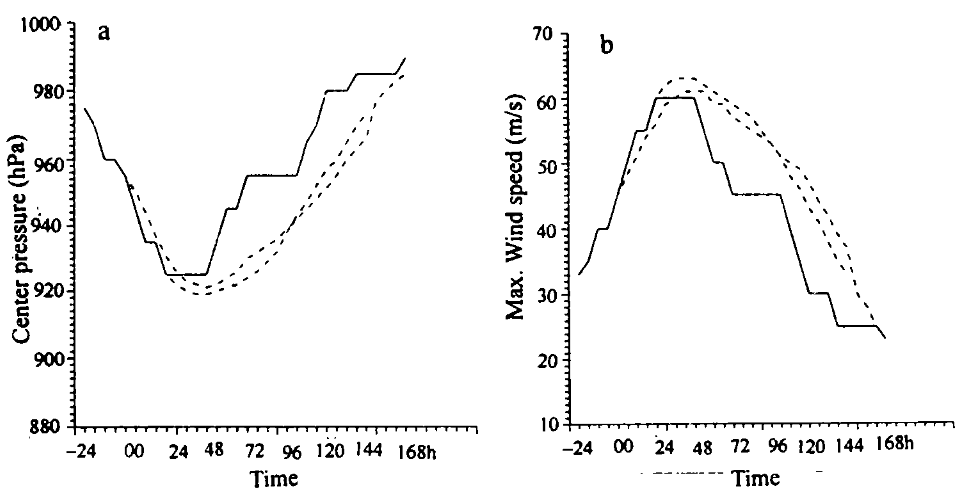

Fig.4. Comparisons between the actual (solid) and the forecast (dashed) intensity for Typhoon Ketth. (a) center pressure; (b) maximum wind speed.

Besides, Typhoon Victor (1997) forming over the South China Sea (not shown) was almost stationary within the incipient 24 h with an uncertain tendency of motion, suggesting unusual movement for the typhoon. Relevant forecasts indicate that it would move towards the north and then land on the coast of Guangdong in 78 h. The track and the landing point are verified by the observation and the actual decay occurred in 72 h. In addition, the forecast for a tropical depression over the northwestern Pacific at 1800 GMT 6 May 1997 (not shown) shows that the approach is also capable of predicting the tropical depression.

In the verification of short-range forecasts for all tropical cyclones in 1997 as well as 1994–1996, it is suggested that the newly proposed approach is indeed an effective objective way for short- and medium-range forecasts of both track and intensity.

IV. CONCLUSIONS

An objective prediction approach to 6 h–144 h track and intensity of tropical cyclones over northwestern Pacific has been proposed. On the basis of mathematics that analog deviation technique can be used to measure overall similarity between two sample curves, the track or intensity predictions for each forecast period were determined respectively through the optimum weighted superposition of displacement or intensity change of the cases, with different number and weighted coefficient corresponding to minimal analog deviation, from different tropical cyclone or different stage of the same cyclone in standard historical sample curve library, so that the prediction results for both individual forecast period and the entire process were optimal.

The forecast verification suggests that the approach presented in this study exhibits better ensemble forecast performance for either the track or intensity forecast and for either short-range or medium-range forecast. Its three predominant features are concluded as below: (1) The forecast accuracy is remarkably improved as compared to some other previous methods; (2) The prediction is made more effective for the medium-range track and intensity change trend and decay time of tropical cyclone process; (3) The prediction of anomalous track and tropical depression is also one of its capabilities. In addition, the approach, if used in operational forecast, is convenient and feasible since only the track and intensity data for the initial time and the past 24 h at 6 h intervals have to be inputted into a computer and then all of the forecast results can be promptly obtained. The effectiveness is relevant to the following elements: (1) Measuring overall similarity of two curves by both value and shape as merited by analog deviation itself; (2) Grasping all information of tropical cyclones at initial and past time; (3) Having longer historical data and extensive and enormous sample curve library; (4) Programming process and optimal control of forecast results.The presented approach has been adopted and embedded in the forecast module of "typhoon forecast-elusion and aid-decision system in ships", and are used to make further real ship experiments at present. Certainly, the approach is also qualified as a valuable alternative to the existing means for the short- and medium-range forecast of track and intensity for meteorological stations. It can be believed that the approach will exhibit even more vitality with the lapse of time and the expansion of historical sample data.

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