APPLICATION OF STATISTICAL INTERPRETATION TECHNIQUES WITH NWP PRODUCTS FOR OBJECTIVE FORECASTING OF TROPICAL CYCLONE MOTION

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ABSTRACT

Statistical study is first performed of the efficiency of the technique of statistical interpretation using the products of NWP. The result shows that the application of the technique has improved the predictability of predictors in objective forecasting of tropical cyclone motion, increased the forecasting skill of models and extended the valid period of forecast. Then a discussion is made of some technical problems in the application in the motion forecasting, suggesting: a large sample of data and perfect forecast method be employed in constructing objective forecast models for tropical cyclone motion, predictors be included that are so finely built that they reflect all synoptic features and physical quantity fields and NWP products be used and corrected that are available at multiple times. It is one of the effective ways to improve the skill and stability of the forecast by composite use of outcomes from various forecasting models.

Key words: tropical cyclone motion, objective forecast, statistical interpretation technique

Ⅰ. INTRODUCTION

For the objective forecast of tropical cyclone (TC) motion, a number of methods were developed abroad in the 1950's and 1960's, including the climatological persistence (CLIPER), analogue forecast (HURRAN) and statistical-synoptic approach. Due to inherent defects with themselves, they have been unable to increase in a sustainable way the forecasting accuracy and skill of TC motion. In 1973, a statistical-dynamical approach (a statistical interpretation of NWP products) was first incorporated in the motion forecast at the American National Hurricane Center (Neumann and Lawrence, 1975). Called NHC73, the procedure soon changes the situation in which progress has been stagnating and greatly upgrades the skill. It became one of the highest precision methods for TC motion forecasting in the United States in the 1970's and 1980's. Afterwards, a number of models have been developed there in succession , which include CUSM, NHC83, NHC90 and JTWC92 (JTWC, 1990; Charles, Neumann and Colion, 1991) and they become main guidance models in operational NHC forecast (Shapiro and Neumann, 1984).

Some methods appeared in the 1960's and 1970's in China that dealt with the statistic forecast. They were normally low in forecasting skill, virtually incapable of predicting TC motion for valid periods longer than 48 hours. Starting from the 1980's, home-made NWP models began phasing in operational use. Necessary conditions were thus maturer for development of the objective forecast by means of statistic interpretation.

In 1990 – 1995, a comprehensive and systematic study was made in an important scientific project (grant No.85-906-05) for developing statistic interpretation technique for NWP products of TC motion and some new models were constructed that result in objective forecast of multiple TC motion (Zhong, Jin and Wu, 1996; Zhong, 1996). Forecast skills are thus improved by a large margin and valid forecast periods are extended to 120 h from the original 60 h (Zhong and Li, 1996). It is about the technical points concerning the statistic interpretation of NWP products in the objective TC motion forecasts that the current work makes the investigation as follows.

II. EFFECTS OF STATISTIC INTERPRETATOIN TECHNIQUE ON OBJECTIVE TC MOTION FORECAST

It is on the statistic relationship between all initial predictor fields and the TC motion that previous methods are based. It is inevitable that a TC is subject to nonlinear changes in the internal forces and external environmental field over the course of motion. When input with predictors from the initial field, the forecast model fails to handle properly the nonlinear nature of the atmospheric variation, leading to substantial decrease in the predictability for long valid periods.

By introducing the products of NWP atmospheric models, objective forecasts of TC motion are much improved. The models are capable of describing the generation and decline of atmospheric disturbances and thus of expressing how energy is produced and dissipated in the atmosphere (ECMWF, 1987). They are being matured in forecasting the changes of large-scale, quasi-stationary weather patterns and thus recognized for operational value.

1. *Improvement of predictor predictability with statistic interpretation technique*

For the 500 hPa geopotential height field H over 20 – 55 °N, 60 – 180 °E and the predictor P derived from the surface pressure field over 22 – 55 °N, 105 – 140 °E representative of weather systems, with H_0, P_0 the predictors at the initial time and H_t, P_t the ones at a future time, a total of 450 samples are selected for statistic study of the maximal correlation coefficient r_{max} between the predictors and the TC motion and the total of predictors n with the correlative coefficient as high as $|r| \geq 0.35$ (see Table 1).

Table. 1 Correlation of initial and future predictors with tropical cyclone motion.

		φ_{24}	φ_{48}	φ_{72}	φ_{96}	φ_{120}	λ_{24}	λ_{48}	λ_{72}	λ_{96}	λ_{96}
r_{max}	H_0	-0.55	-0.55	-0.51	-0.47	-0.43	-0.43	-0.41	-0.39	-0.35	-0.30
	H_t	-0.55	-0.55	-0.55	-0.56	-0.52	-0.52	-0.54	-0.56	-0.51	-0.48
	P_0	0.48	0.48	0.45	0.40	0.34	0.36	0.40	0.40	0.35	0.30
	P_t	0.48	0.48	0.46	0.43	0.41	0.50	0.56	0.55	0.54	0.47
n	H_0	8	7	5	4	2	6	6	4	1	0
	H_t	9	9	9	11	9	7	12	14	14	12
	P_0	26	20	16	10	6	6	8	16	16	1
	P_t	35	28	25	13	17	11	28	32	26	21

When r_{max} is high or n is large, the predictor associated forecasts the TC motion better. As shown in Table 1, H_0, P_0, the environmental predictors, decrease significantly in the capability of forecasting TC motion with the increase of forecast valid time. It is caused a reduction of correlativity between the initial field and TC motion as a consequence of weakened initial inertia of TC motion with the increase of valid period of forecast. It is also a fundamental reason accounting for decreasing ability with statistic forecast models in the past.

2. *Improvement of forecast skill of objective TC motion models with statistic interpretation technique*

With a sample with the same length, two perfect prediction models, a statistic prediction model (ST) and a perfect prediction model (PP), are separately built using predictors and mathematical models of the same types (stepwise regression analysis). They take as the predictors the environmental field at the initial time and the future time, respectively. For the PP model, the complex correlation coefficient R and the residual root-mean-square deviation S are both better than those in the ST model (Table omitted). The longer the valid period lasts, the larger the significance. For $\lambda_{72}-\lambda_{120}$, for instance, R is up by 0.1 – 0.2 while S is down by 1.05 – 1.48.

A total of 272 forecasting experiments were done for 50 TCs in 1994 – 1997 using the preceding two models and the results are given in Table 2.

Table 2. Mean absolute error with the ST and PP models.

Prediction model	ST					PP				
Valid period (h)	24	48	72	96	120	24	48	72	96	120
Distance error (km)	192	404	645	898	102 2	152	331	536	738	826
Direction error (°)	15	18	23	22	19	12	15	20	18	16
Velocity error (km/h)	0.45	0.86	1.08	1.63	1.87	0.32	0.63	0.84	1.17	1.45

As shown in Table 2, all errors are much lower in the PP model than in the ST model and the validity is more significant with the increase of the forecast period. As the fitting agrees with the results of the experiments, it is suggested that the skill is much improved with the objective TC motion forecast model after the application of the statistical interpretation technique, and the result is much more remarkable when the valid period is long.

3. *Improvement of valid period of TC motion forecasting with statistic interpretation technique*

Generally, statistical models have a valid period of about 48 hours in the forecasting of TC motion. The forecast error increases dramatically if the period prolongs so that the results are of little use in practice. With the introduction of the statistical interpretation technique, the error is substantially reduced for valid periods lasting for 72 – 120 hours. Operational efficiency is good. In 1994 – 1997, twelve TCs posed severe influence on the coastal areas of China. Most of them are run with the prediction models above and the tendency is satisfactory for periods valid for 72 – 120 hours. The motion of typhoons Fred (1994), Kent (1995), Herb (1996) and Winnie (1997) is accurately predicted for the periods by using the statistical interpretation models. They all hitt mainland China on the front and caused destructive losses. For instance, at 1800 UTC August 14, 1997, Typhoon Winnie was about 2000 km away from the southeast coast of China at 20.6 °N, 140.2°E. As seen in Fig.1, Winnie is predicted to make landfall by the PP model on the Taizhou City, central Zhejiang Province in about 120 hours. The storm was observed to land on Rui'an, Taizhou, at 1330 UTC August 14. The landfall is close in both time and location and the valid period lasts for 116 hours. Running the CLIPER and ST models simultaneously, relevant predictions vary from a change in direction at the open sea to a rotation in the original place. It is obvious that the PP model employing the technique of statistical interpretation is much advantageous over the other two models as far as the 72-120 valid periods of forecast is concerned.

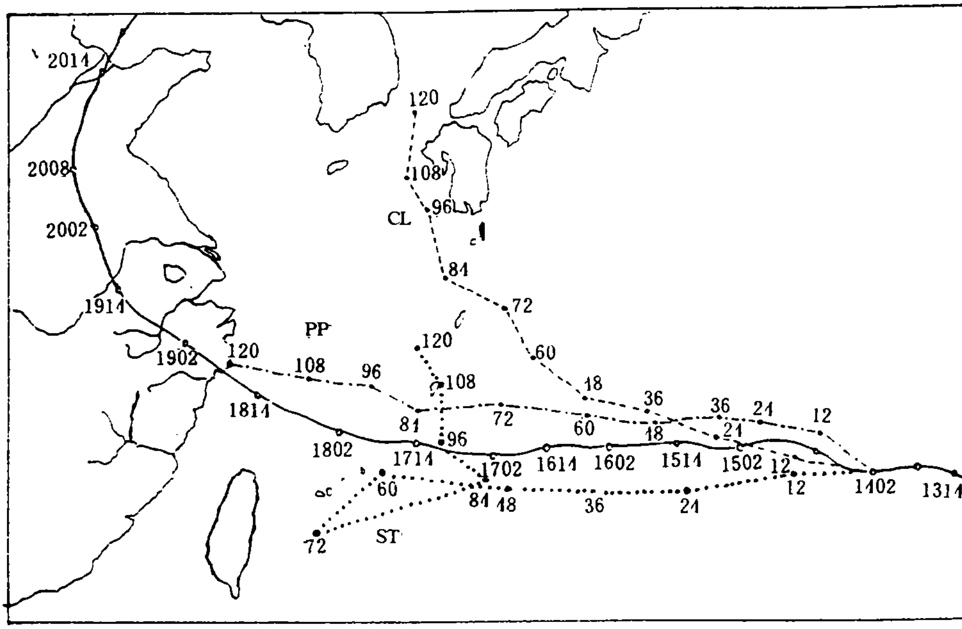

Fig. 1. Forecasts of Typhoon Winnie (1997) by different models. The solid line is the observed motion and the numerals near the hollow circles are the actual time. The dashed line is the forecast motion by the CLIPER model, the dotted line the one by the ST model and the dotted and dashed line the one by the PP model. The numerals near the full circles along the latter three lines are the forecast time.

III. DISCUSSIONS OF STATISTIC INTERPRETATOIN TECHNIQUES FOR OBJECTIVE TC MOTION FORECAST

As TC is a synoptic system that rotates and interacts with the environmental field as moves along, the forecasting has to be done with much difficulty. Efficient results can only be achieved only when a technique appropriate with the features of the motion of TC is used. It necessities from the difference in the application of the statistic interpretation technique between general weather forecasting and TC motion prediction.

1. *Selection of statistical interpretation models*

There are two models in the statistic interpretation of weather forecasting: the model output statistics (MOS) and the perfect prediction (PP).

As its advantages, the MOS method automatically removes the systematic error in forecasting and has direct access to various NWP products. On the other hand, it is much restrained by NWP models in the construction of TC motion models. The technique of NWP is updated continually. In China, the earlier differential (B) model has been improved to a spectral one, which also undertakes three major refinements of T_{42}, T_{63} and T_{106} in just a few years, leaving along numerous minor modifications. Discontinuity is then resulted in the specifications of NWP products. It is inevitable for a NWP model to have difference in systematic errors each time it is modified so that versions before and after the modification are to be used together. It is due to this reason that the MOS method is made a procedure with short record of data, small capacity of samples and thus causes unstable forecasting results. There is one more negative aspect about the use of NWP products. When a NWP model is renewed, the forecast model based on it by MOS will be out-of-date and has to be rebuilt if the forecast result is to be unaffected by inconsistency between the old model and the new data.

The PP method is capable of exploiting abundant historic data and large volumes of sample, producing stable outcome of forecast. One of its advantages is being free from any restraints of modifications with NWP models once the forecast model is set up. The independence of the PP-based model on NWP data is caused by the fact that the latter is not used unless in forecasting operation, because a statistic relationship is established in the PP procedure between the observed or objective analysis data and TC motion. On formulation, the PP-based forecast model need not to rebuild no matter how the NWP model is changed. With the improvement of the latter, its products are closer to the observation, increasing the accuracy of PP forecast models.

The PP method is recommended in view of the need for stable forecast of the TC motion models and high accuracy of quantitative forecasting and for avoidance of effects of frequent alterations of NWP models as much as possible.

2. *Selection of sample length*

Given that the historic record is sought for fitting, a forecast model for TC motion that is built with short historic samples is a little better than that with long ones, the opposite may be true in practice. Table 3 gives the comparison of averaged distance errors in 272 conducted forecasts of 50 TCs from 1994 to 1997 by forecast models of various length of samples. It is clear from the table that a forecast model gives large distance errors if the sample is small and a large-sample model produces better forecasts over longer periods of validity. The disagreement between the forecast result and the fitting may be contributed to the physical correlativity for statistic predictors that determine the efficiency of forecasting. For a forecast model built on smaller sample, the limited series of historic sample reflects incompletely the correlation among the statistic predictors, leading to relatively large errors due to a tendency of exceeding the value range of historic samples. With all possible situations considered in effect in constructing a large-sample model for better reflection of physical correlativity of the predictors, better forecasts are expected. It is then right to use a large sample to construct forecast models whenever possible.

Table 3. Mean absolute errors as they occur in forecast models with different lengths of sample in unit of km.

Size of sample	Valid period in hour					
	12	24	36	48	60	72
180	96	202	293	411	567	735
450	95	161	232	361	454	564
561	84	163	225	345	437	553
1427	85	152	221	331	415	536

3. *Construction of predictors*

In the application of the statistic interpretation, the choice of statistical model does not affect the overall result of forecasting if it is done with the same predictors. The most influential factor is the physical correlation between the predictor and the TC motion. Linking inherently with the

TC motion, good predictors are based to build a forecast model for satisfactory results.

1) ENVIRONMENTAL PREDICTORS DIRECTLY APPLYING NWP PRODUCTS

There are various products of NWP that are available for use, of which the geopotential field and the wind field are proven predictors that help produce good forecasting. The NWP geopotential height is the most up-dated product, which gives stable output and small errors and is valid for a week. The grid values, variables and derived predictors are directly used. The NWP wind field is not as accurate and stable as the geopotential height field. Though it is still all right to use both predictors in forecasts of shorter valid periods, it is save to have a second thought before using the wind product from NWP if the valid periods are long.

2) SYNOPTIC PREDICTORS

Constructed with NWP products, predictors such as location and intensity of weather systems, e.g. the trough, ridge, subtropical high, are of good reference in the forecasting of TC track. As the resolution is above $1°\times 1°$ for most of the NWP products, some of the synoptic predictors are not depicted unless the resolution is reduced to 0.5° or less. Generally, predictors sensitive to resolution, e.g. location of synoptic regimes, are to be replaced by those reflecting the intensity such as the area index of the subtropical high, intensity of vortex, index of zonal winds, etc. Predictors on the surface are preferred to those on the points or lines to keep them in a stable state.

3) PREDICTORS OF AMBIENT FLOW

The ambient flow is one of high correlation predictors for TC motion as it is steered by it. It has been proved in operation to do well in forecasting. A steering flow is by definition a mean over the entire layer, but a geostrophic current at a particular layer, e.g. 500 hPa or 700 hPa, usually takes the place due to limitation of data in practice. In computing the predictor, care should be taken that a moving mesh centered at the original point, when transformed from a fixed longitude-latitude mesh, is to be kept within the low-latitude boundary of the NWP product.

4) EOF PREDICTORS OF EMPIRICAL ORTHOGONAL EXPANSION IN GEOPOTENTIAL HEIGHT FIELD

Assuming some form of mesh distribution within a domain in the geopotential field, all samples are treated by the empirical orthogonal expansion. It is a procedure in which the geopotential field H is decomposed into a matrix product by a characteristic vector field X_i and a time weighting coefficient T_i:

$$H(t,x)=\sum_i T_i(t)X_i(x)$$

As the characteristic vector field $X_i(x)$ is specified by features of sample series of the geopotential field given, it reflects the nature and characteristics of a particular set of fields. Corresponding with the movement of TC, the time weighting coefficient $T_i(t)$ in some vector fields is highly correlated with TC motion and acts as a good predictor. If the time weighting coefficient T_p for a given characteristic vector X_p is made the predictor, the forecast values of T_p are estimated from the geopotential field and X_p before inputing into the model for outcome.

5) PREDICTORS IN TYPICAL FIELDS BY EXPANSION OF CHEBYSHEV POLYNOMIAL IN GEOPOTENTIAL HEIGHT FIELD

By defining a particular distribution of mesh for the TC motion or interactions synoptic systems between the middle and lower latitudes, the geopotential height field H is expanded by the

Chebyshev polynomial to a typical field $\psi_k(\lambda)\psi_s(\varphi)$ and the weighting coefficient A_{ks} :

$$H(\lambda,\varphi)=\sum_{k=0}^{k}\sum_{s=0}^{s}A_{ks}\psi_k(\lambda)\psi_s(\varphi)$$

$$A_{ks}=\frac{\sum_{\varphi,\lambda}H(\lambda,\varphi)\psi_k(\lambda)\psi_s(\varphi)}{\sum_{\lambda}\psi_k^2(\lambda)\sum_{\varphi}\psi_s^2(\varphi)}$$

The typical field $\psi_k(\lambda)\psi_s(\varphi)$ reflects all kinds of circulation background composed by geopotential height fields that have well-cut synoptic significance. The A_{ks} represents the weighting of the geopotential field composed by given typical fields. With some of the fields in high consistency with TC motion, the weighting coefficient A_{ks} can be made a predictor of strong capability as it is well correlated with TC motion. In the construction of the predictors, care should be taken to select the right domain and grid distribution for a typical field such that the latter is agreeable with the motion. It is achieved by expanding the truncated orders of K and S in a manner so as to adapt to the distribution of grids, which is 3 – 4 orders for all purposes.

6) PREDICTORS OF WAVE SPECTRA

The geopotential height H is expanded on the latitudinal circle following the Fourier series as below.

$$\begin{cases} H(\lambda,\varphi)=a_0(\varphi)+\sum_{n=1}^{\infty}\left[a_n(\varphi)\cos(n\lambda)+bn(\varphi)\sin(n\lambda)\right] \\ a_0(\varphi)=\frac{1}{2\pi}\int_0^{2\pi}H(\lambda,\varphi)\,d\lambda \\ a_n(\varphi)=\frac{1}{\pi}\int_0^{2\pi}H(\lambda,\varphi)\cos(n\lambda)\,d\lambda \\ b_n(\varphi)=\frac{1}{\pi}\int_0^{2\pi}H(\lambda,\varphi)\cos(n\lambda)\,d\lambda \end{cases}$$

The amplitude spectra and phase spectra for the wave 1–n and various spectra of derived physical quantities are obtained from the expanded Fourier coefficient spectrum $a_n(\varphi)$ and $b_n(\varphi)$.

As the predictor of the harmonic wave behaves on temporal and spatial scales identical with those in medium-term weather processes, it is efficient in forecasting the TC motion over long periods. The phase of the harmonic wave, especially the ultra-long and long waves are considered good indicators of the interactions between multiply-scaled systems and TC, predicting with high efficiency, as they agree well with the ultra-long and long waves in the real atmosphere.

The expansion of the harmonic wave can be done by taking 36 lines or 72 grids in geopotential height on the latitudinal circle, with 1 to 10 waves for computation of all predictors in the harmonic spectra.

4. *Application of NWP predictors at various times*

In the course of statistic interpretation, predictors in the environment over the entire period from the initial time to the time simultaneous with the TC motion can be regarded as information helpful for prediction. As shown in the analysis, the most capable predictor in the group at multiple times is not necessarily the one appear at the same time as TC motion — it changes with the period of validity and appears at different times (Zhong, 1997). It is, therefore, unnecessary to confine to predictors at the simultaneous time for the building of the forecast model. The NWP products appearing at various times of the course are potential predictors, thus increasing the extent of forecast information and recognizing as best predictors as possible.

5. *Correction of NWP products*

The inability of the statistic interpretation technique to remove the systematic error of NWP products has worsened the accuracy of forecasting the TC motion. Correction of the products seems one of ways to reduce the effect. There are mainly two approaches. The first is done by applying observed data and regression analysis and the second by means of earlier NWP products and statistic methods like the Kalmen filter. Comparing the forecasts with and without the correction of NWP products (Table omitted), one knows that the forecast accuracy is slightly increased by correcting products for valid periods 24 – 48 hours due to the high quality; the accuracy is much increased if the correction is done for periods of 72 – 120 hours, because of low quality of the NWP products. The reduction is 33 – 111 km for the mean distance error predicted.

6. *Composite of multiple model forecasts*

Due to the complexity of the TC motion and capabilities of models varying with TCs, none of the models is superior over any others at any time of forecast. A comprehensive forecast is the only way that enables us to use as much information as possible to obtain best possible forecasts. The former single model of statistic-synoptic forecasting was replaced in 1988 by a composite forecasting employing multiple model at NHC (Robert, 1990). A composite forecast (CF) is resulted by total regression with the outcome of four forecast models of climatological persistence (CL), statistic synotics (ST), perfect prediction (PP) and composite perfect prediction (CP). Table 4 lists the results of an experiment for 272 forecasts with 50 TCs by the five models. It is clear that the mean distance error is the less than all the four models and has the best result.

Table 4. Mean distance errors as they occur in five forecast models in unit of km.

Forecast models	Valid forecast period in hour				
	24	48	72	96	120
CL	151	361	589	756	921
ST	192	404	645	898	1022
PP	152	331	536	738	826
CP	150	325	545	731	835
CF	150	322	531	729	823

For a given TC, the forecast error varies with the forecast model. Positive errors are produced by some models with the forecast values larger than the actual TC motion by showing $\varphi_f - \varphi > 0$, $\lambda_f - \lambda > 0$ while negative errors by the other models by showing $\varphi_f - \varphi < 0$, $\lambda_f - \lambda < 0$. In the composition, positive and negative errors are compensated each other so that the error is reduced. On the other hand, much more information is combined in the composite forecast and favors the production of satisfactory forecasts. The result as achieved by the composite forecast is not found in any one of the forecast models even with all of the information input in it. It may be explained as follows. For the statistics with the single forecast model, only one or two optimum predictors are included. The composite model, on the contrary, has much more information by collecting optimum predictors from each of the single models so that it predicts better than the latter model does.

IV. CONCLUDING REMARKS

With the statistic interpretation technique for NWP products in the objective prediction of TC motion, the performance and skill of predictors are improved and the valid periods extended.

A large sample and the perfect prediction method are appropriate for constructing an objective forecast model for TC motion using the technique as stated above.

In selecting the NWP products, high accuracy and good stability are two features that receive primary attention in the building of predictors. Predictors are discarded if sensitive to the resolution of NWP products. Predictors on the surface are preferred to those on the points or lines. Well-defined synoptic significance and good forecasting capability for TC motion are found with the environmental steering flow, the EOF function in the geopotential field, the typical field as expanded by the Chebyshev polynomial and the harmonic wave spectra as expanded on the latitudinal circle. Predictors are constructed by careful selection of domain and distribution of grids.

NWP products at multiple times are used to increase the information and stability of the forecasting.

Corrections are made of the NWP products prior to the forecasting to remove effects of associated errors on the forecasting.

Composite use of output from various forecast models is an efficient way to improve the skill and stability of the objective prediction of TC motion.

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