FUZZY PROBABILITY PREDICTION METHOD FOR TROPICAL CYCLONE TRACK

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ABSTRACT

Based on forecasting criteria of tropical cyclone categories of left and right turning and stable track and fuzzy mathematical principles, a fuzzy probability prediction method is formulated for track changes. It is 48-h valid for forecasting sudden change or stable track as well as giving fuzzy probability of trajectory, for the use in decision-making. As shown in operational experiments, it is easy to operate, simple to illustrate, objective to quantify, definite to conclude, and satisfactory to actualize. It is dependable with high level of reference, especially when the fuzzy probability is greater than 70%, for errors in direction and 48-h mean distance errors are all lower than those at major forecasting centers at home or abroad.

Key words: tropical cyclone, track category, turning index, fuzzy probability

Ⅰ. INTRODUCTION

A number of diagnostic criteria and comprehensive recurvature indexes are drawn during 1991-1995 on basis of comparative study of causes for sudden change in tropical cyclone track in the region of the South China Sea (He, Hu and Zhang, 1995; Zhong, Chen and He, 1994). In the current work, a prediction method is set up using the fuzzy probability and important results in He et al. (1995) for the track of tropical cyclones with maximum winds ≥ Force 8 around the eye. The approach improves the creditability of decision-making in forecasting. It employs automatic use of 1.875 objective mesh-grids analyses from the T63 model on PCs networked with VAX 6440 or VAX 3400, featuring easy operation, direct illustration, objective and quantitative expression, definite conclusion and graphic output. It is useful for predicting the tropical cyclone track from the South China Sea to waters off the eastern coast of the Philippines and Taiwan.

Ⅱ. TRACK CATEGORIES AND RECURVATURE INDEXES

1. *Track Categories*

Based on statistics in the *Yearly Book of Typhoon* of China, three categories and eight subsidiary patterns are classified for the track of tropical typhoons in the area of the South China Sea and nearby areas.

(1) Category of left turn, to be subdivided into patterns of NE-turning and W-moving ($L_{NE\to WLY}$) and of NW-turning and W-moving ($L_{NW\to WLY}$);

(2) Category of right turn, to be subdivided into patterns of W-turning and N-moving ($R_{WLY\to NLY}$) and of NW-turning and NE-moving ($R_{NW\to NE}$);

(3) Category of stable motion, to be subdivided into patterns of stable W-moving (Q_{WLY}), stable NW-moving (Q_{NW}), stable N-moving (Q_{NLY}) and stable NE-moving (Q_{NE}).

A period of 24 h is set for all categories of track, totaling at 5 periods. The 3rd period is the one of sudden change in moving direction for the first two categories and of migration into the forecasting zone for the 3rd category. Mean direction and velocity of motion are statistically derived for each of the periods in each of the categories (Fig.1, omitting Pattern 4 in the 3rd category), revealing close relationship between the velocity and direction. A sudden decrease (increase) occurs before (after) the change in moving direction, the former case appearing most obviously at points after the turning for the northeast.

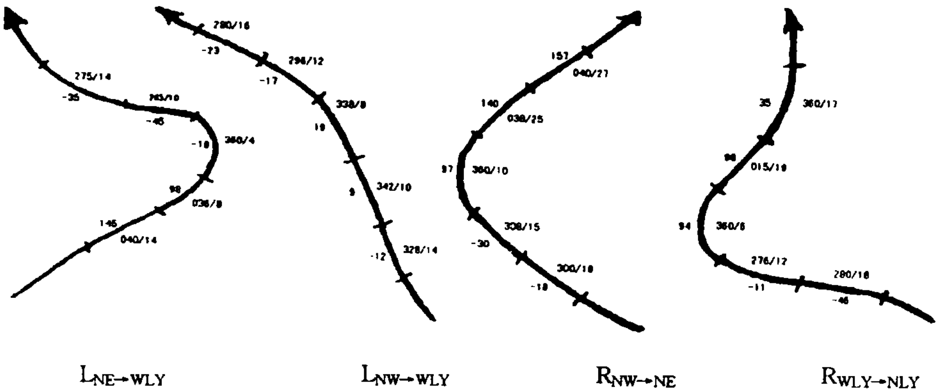

Fig.1. Mean tracks of tropical cyclones. The recurvature index is marked on the left of the moving direction and the moving direction (degree)/velocity (km/h) on the right.

2.*Main forecasting criteria and recurvature indexes (R)*

(1)As shown in a comparative study of the whole-column flow field at all azimuths in varying distances from the center of tropical cyclones, the most significant difference in flow field between the categories of left and right turning 24-36 h before the recurvature and the category of stable movement occurs in the mid- and high-flow field, which is from 5.0 to 7.5 latitudes away from the eye in the northern sector of circle. In other words, one finds the signs for left (right) turning track by isolating the appearance of obvious northeast (southwest) flow at the azimuths of N, NW and W, and obvious northwest (south to southeast) flow at the azimuth of NE, at the middle and upper levels.

(2)A close link is found between the track categories and the variations of upper zonal winds near the eye. The easterly keeps stable at the upper level near the eye for the patterns of Q_{WLY} and Q_{NW} and the westerly is with the patterns of Q_{NE} and Q_{NLY}. The track is most likely to turn left or right and the velocity to change from decelerating to accelerating correspondingly when the following conditions are met: the westerly (easterly) changes to the easterly (westerly) at the upper level near the eye for the categories of left (right) turning, i.e. when the dividing line for the upper easterly and westerly (U_0^{200}) west of the eye is higher (lower) than the part east of it in terms of latitude.

By combining the criteria above, the index of typhoon recurvature (R) is computed using the U and V values for 200 hPa and 500 hPa on the 7.5 and 5.0 latitudes of spacing to the north, northwest and west of the center of the tropical cyclone for each of the periods:

$$R=\sum_{i=1}^{3}\frac{(U_{7.5}+U_{5.0})_{200\mathrm{hPa}}}{2}+\sum_{i=1}^{3}\frac{(U_{7.5}+U_{5.0})_{500\mathrm{hPa}}}{2}+\sum_{j=1}^{2}\frac{(V_{7.5}+V_{5.0})_{200\mathrm{hPa}}}{2} \quad (1)$$

where i is the azimuth in the directions of north, northwest and west and j is the azimuth in the directions of north and northwest. The index of typhoon recurvature and its variations so derived well describe the variation categories of tropical cyclone track and their relationship with the flow fields at varied layers and zonal winds near the upper levels of the storm.

R is negative and varies narrowly in all periods of the Q_{WLY} and Q_{NW} patterns. It is positive in the Q_{NLY} and Q_{NE} patterns and the variability is decreasing and rapidly increasing, respectively. In the $L_{NE\to WLY}$ pattern, however, R rapidly drops from the a large positive value to a large negative value while shifting from a small negative value to a positive one before increasing in the negative domain further on in the $L_{NW\to WLY}$ pattern. R changes from negative to positive before the recurvature but reverses the change rapidly after the recurvature in the $R_{WLY\to NLY}$ pattern on the one hand, and it becomes positive rapidly from a small negative value before the recurvature and the positive value increases vigorously after it in the $R_{NW\to NE}$ pattern, on the other.

III. METHOD OF PREDICTION

1. *Setting up of standard mode fuzzy subsets*

Any of the tracks of tropical cyclones can be drawn into the three categories and eight patterns and their composition:

□Left-turning (L) in 2 patterns of $L_{NE\to WLY}$ and $L_{NW\to WLY}$;

□Right-turning (R) in 2 patterns of $R_{WLY\to NLY}$ and $R_{NW\to NE}$;

□Stable motion (Q) in 4 patterns of Q_{WLY}, Q_{NW}, Q_{NLY}, and Q_{NE}.

Each period in each of the patterns (covering 24 h) is described by three of the following characteristic quantities: Index of recurvature R, moving direction S and moving velocity C. Empirical statistics have shown that they contribute unevenly to the prediction of track turning. Different weight of n_1, n_2 and n_3 are assigned to them respectively. In this way, 8 fuzzy subsets of H_i (i=1, 2, ⋯8) in a standard mode are obtained.

$$H_i=\begin{bmatrix} R_{i1}, & R_{i2}, & \cdots & R_{in} \\ S_{i1}, & S_{i2}, & \cdots & S_{in} \\ C_{i1}, & C_{i2}, & \cdots & C_{in} \end{bmatrix} \qquad (i=1,2,\cdots,8) \quad (2)$$

2. *Fuzzy discrimination–Basic tuning of trajectory*

Given the early track of a tropical cyclone, a fuzzy subset of H_0 is determined for any of the corresponding initial time, which is derived by

$$H_0=\begin{bmatrix} R_{01}, & R_{02}, & \cdots & R_{0m} \\ S_{01}, & S_{02}, & \cdots & S_{0m} \\ C_{01}, & C_{02}, & \cdots & C_{0m} \end{bmatrix} \quad (3)$$

Introducing the concept of closeness in generalized distance

$$\Delta H_{0,i} = \left\| H_{0,k} - H_{i,(j+k)} \right\|$$

$$= \sqrt{n_1 \sum_{k=k_1}^{k_2} \left(R_{(0,k)} - R_{i,(j+k)}\right)^2 + n_2 \sum_{k=k_1}^{k_2} \left(S_{0,k} - S_{i,(j+k)}\right)^2 + n_3 \sum_{k=k_1}^{k_2} \left(C_{0,k} - C_{i,(j+k)}\right)^2} \tag{4}$$

where n is the number of standard mode periods, m is the number of periods at initial time and k is the number of periods.

When $m<n$, $k=1, 2, \cdots\cdots m; j=0, 1, \cdots\cdots n-k$, and

when $m \geq n$, $k=m-n, m-n+1, \cdots\cdots m; j=0$.

In other words, k is selected forward from the latest period and meets the condition of $n-k \geq 1$ to ensure its predictability. The rule governing the selection of closeness is that when the sample has the smallest closeness to a given standard mode, it is isolated to belong to it, i.e.

$$\Delta H_{0,p} = \min\left(\left\| H_{0,k} - H_{p,j+k} \right\|\right) \tag{5}$$

is taken. Then the present track is discriminated to fall into the $(k+j)^{th}$ period in the Pattern p. A basic tune has by now set up for the forecast trajectory.

3. *Fuzzy discrimination–Basic tuning of trajectory*

With the determination of the basic tune, the forecast trajectory is then fine-tuned with respect to the earlier track in terms of the deviation. The future moving direction and velocity are then known, by which the trajectory is computed.

$$\text{Moving direction: } \begin{cases} S_{24} = S_{p(k+j+1)} + m_1 \Delta S_{p(k+j)} \\ S_{48} = S_{p(K+j+2)} + m_1 \Delta S_{p(k+j)} \end{cases} \tag{6}$$

$$\text{Moving velocity: } \begin{cases} C_{24} = C_{p(k+j+1)} + m_2 \Delta C_{p(k+j)} \\ C_{48} = C_{p(K+j+2)} + m_2 \Delta C_{p(k+j)} \end{cases} \tag{7}$$

where m_1 and m_2 are correction coefficients, $\begin{cases} \Delta S_{p(k+j)} = S_{0(k+j)} - S_{p(k+j)} \\ \Delta C_{p(k+j)} = C_{0(k+j)} - C_{p(k+j)} \end{cases}$ (8)

4. *Fuzzy probability*

As the track itself is continuous, its fuzzy probability is computed stressing the continuity. Theoretically, as m gets larger, there are more periods taking part in the discrimination and greater extremes of fuzzy probability.

When $m \geq 3$, or when there are 3 or more periods in the fuzzy discrimination, the extreme becomes the largest, being set as μ_3; when $m=2$, the extreme is set as μ_2; when $m=1$, the extreme is the smallest, being set as μ_1, in which μ_1, μ_2, and μ_3 are statistic mean parameters. Then the whole fuzzy probability is derived for the maximum probable trajectory of motion by

$$F_{ii} = \mu_{R_i} n_1 \frac{(R_0, R_p)}{\|R_0\| \cdot \|R_p\|} + \mu_{S_i} n_2 \frac{(S_0, S_p)}{\|S_0\| \cdot \|S_p\|} + \mu_{C_i} n_3 \frac{(C_0, C_p)}{\|C_0\| \cdot \|C_p\|} \quad (i = 1, 2, 3) \tag{9}$$

where $\left(A_0, A_p\right) = \sum_{k=k_1}^{k_2} A_{0,k} \cdot A_{p,(j+k)}, \left\|A_0\right\| = \sqrt{\sum_{k=k_1}^{k_2} A_0^2, k}, \left\|A_p\right\| = \sqrt{\sum_{k=k_1}^{k_2} A_0^2, (j+k)}$.

Especially, the fuzzy probability is the largest as A_0=A_P, and the closeness is zero:

$$\min(F_u) = \mu_{Ri} n_1 + \mu_{Si} n_2 + \mu_{Ci} n_3 \qquad (i = 1,2,3) \tag{10}$$

When $F_u < 50\%$, the second smallest sample of closeness is selected for similar computation of forecast trajectory and fuzzy probability, adding one more track for reference.

IV. RESULTS OF EXPERIMENT AND DISCUSSIONS

The method in question was used in an operational forecasting experiment of tropical cyclones '96 headed by the Guangdong Meteorological Bureau (from June to October). The T_{63} data involved was available once a day and one experiment was conducted daily. There are 9 target typhoons in 18 times of experiment, in which 11 of them having fuzzy probability $F_u \geqslant$ 70%.

Table 1 shows a comparison between the current method in the experiment and those used by major centers at home and abroad in terms of mean error for the same period of time.

Table 1. Comparison of mean errors for 18 periods of valid forecast of tropical cyclones in 1996 between the current method and major centers at home and abroad.(Figures inside the brackets are number of forecast periods)

	Guangzhou			Beijing			Japan			Guam			Mao & He		
	24h	48h	az	24h	48h	az	24h	48h	az	24h	48h	az	24h	48h	az
Frankic(2)	190	345	17	92	184	16	156	302	20	146	268	24	77	118	9
Gloria(3)	85	215	15	110	147	7	112	179	11	85	189	15	118	252	4
Herb(2)	55	167	7	48	170	5	179	327	15	195	369	16	131	256	4
Niki(1)	60	78	4	50	225	8	106	186	1	79	138	2	78	154	2
Sally(2)	141	346	1	188	399	2	207	255	1	119	295	2	148	286	1
Violet(2)	144	436	44	142	474	52	161	408	48	95	247	24	134	260	34
Willie(1)	181	474	94	156	402	50	87	46	6	114	191	22	183	404	55
Zane(1)	113	330	17	165	342	21	49	304	27	95	261	11	75	254	19
Beth(4)	134	203	14	135	222	15	139	269	14	156	291	15	150	271	16
mean	122.6	288.7	23.7	120.7	285.0	19.6	132.9	252.9	15.9	120.4	249.9	14.6	121.6	250.6	16.0

It is clear in Table 1 that the method by Mao and He differs a little from the forecast centers as far as the 24-h mean error of distance while being superior over domestic ones and comparable to overseas ones in terms of the 48-h error for both distance and direction. The cause: it is capable of predicting any tendency of abrupt track change 24-48 h in advance.

Especially. when the fuzzy probability $F_u \geqslant 70\%$, the mean azimuthal error is 8.5 degrees in association with 110.2 km for 24 h and 216.2 km for 48 h in terms of mean distance error, which are less than the overall mean error (121.6, 250.6, and 16.0, respectively). The improvement is much larger for both errors in the period of 48-h.

Table 2 is a comparison of mean error between the current method and major forecast centers for 11 periods of forecasting when $F_u \geqslant 70\%$.

Table 2 A comparison chart of mean error between the current method and major centers when $F_t \geq 70\%$

	Guangzhou	Beijing	Japan	Guam	Mao & He
24-h error	108.8	107.5	129.4	112.8	110.2
48-h error	251.6	246.5	273.5	233.8	216.2
Azm. error	12.6	13.0	13.5	11.9	8.5

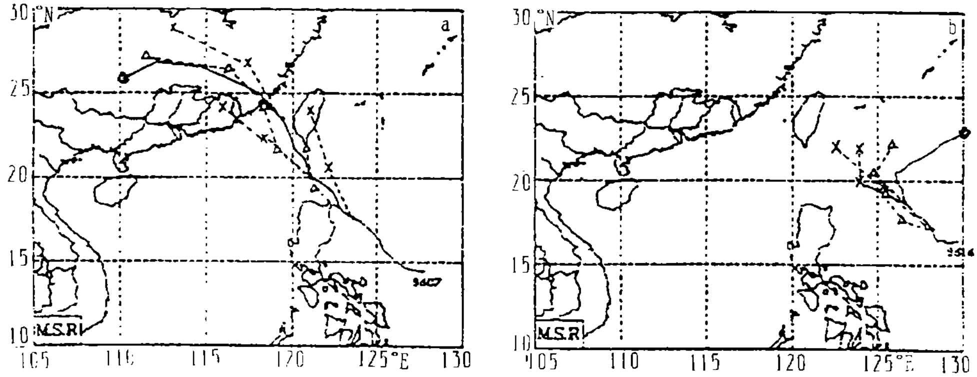

Fig.2. Comparison of track between Typhoons Gloria (a) and Violet (b) by observation and prediction. — observation; --- prediction; (Δ fuzzy probability; × national observatory (a) / Japan (b); • initial fcst point)

It is seen in Table 2 that there is much advantage over the centers listed in this method, which is also good for reference in practice.

Tests have shown that it gives good predictions of track tendency and well links error in both distance and direction with the fuzzy probability, the accuracy being considerably high when $F_t \geq 70\%$.

Fig2 (a, b) gives forecast and observed track of tropical cyclones Gloria and Violet (1996) for comparison. It shows once again how the current method forecasts more consistent track with the observation, being better than comprehensive forecasts.

V. CONCLUDING REMARKS

a. The current method is a good forecaster for the tendency of motion of tropical cyclones;

b. The fuzzy probability is well related to azimuthal (directional) error, especially when $F_t \geq 70\%$ both 48-h forecast accuracy and direction are much improved as compared with comprehensive forecasts, having high level of reference in practice.

On the other hand, however, the results presented above are only preliminary remarks as summed up in experiments with 9 tropical cyclones. Verification and optimization remain to be done in routine operation in the future to test whether it is generally applicable and stable.

One of the initial motives in developing the method is determining critical values of the relationship between the fuzzy probability and forecast error so as to increase the practical value of reference of objective forecast methods. It seems possible that the aim can turn into reality judging from the application.

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