Vol.11 No.4 Advances in Atmospheric Sciences November 1994

Seasonal Variation Features of Western North Pacific Tropical Cyclone Tracks with Their Predictability①

Peng Yongqing (彭永清) and *Yan Shaojin* (严绍瑾)
Nanjing Institute of Meteorology, Nanjing 210044, China

Received November 8, 1993; revised April 3, 1994

ABSTRACT

Analysis is done of monthly and seasonal variations as climatic features of the tracks from 1196 tropical cyclones originating in the western North Pacific over the period 1949 to 1980, followed by the investigation of 301 onland cyclone tracks over China mainland in terms of methodology for nonlinear system. Obtained by computing the accumulated distance distribution function of the tracks $C_m(l)$ is the characteristic chaos quantity for the related dynamic systems and then the fractual dimensionality $d = 4.86$ and Kolmogorov entropy approximation $K_2 = 0.0164$, thereby leading to the predictability time scale = 2.54 days. It is found that the reference path among the onland typhoon No.23 of 1971, or Bess in the international nomenclature. Our results could be of operational use as a kind of reference.

Key words: Tropical cyclone tracks, Seasonal variation, Predictability time scale

I. INTRODUCTION

The problem of typhoon path forecasting has been the subject of much concern, on which researchers, especially Chinese researchers, have made enormous efforts for the last five decades. Detailed case studies, for example, have been intensively undertaken of each of those ashore dangers that had done severe damages along its path, followed by development of a set of useful methods for the path prediction (see, for example, Zhong et al., 1986). These efforts are worthwhile and indispensable. While the tracks are so variable as to be determined, however, high accuracy is normally expected in forecasting. With this motivation in mind we made further exploration of the issue in an attempt to offer an enlightening aspect of the research.

It is known that factors responsible for tropical cyclone motion include: 1) steering of environmental flows; 2) beta effect; 3) their joint action; 4) Rossby poleward deflection; 5) surface friction; and 6) small–scale swing of the path. These contributing elements come from theoretical treatment based on the barotropic vorticity equation with the assumption that a tropical cyclone always moves where local cyclonic vorticity grows (Holland, 1985). This analysis concerns vorticity variation locally, meaning that the problem is handled merely from a local perspective. Such a treatment suffers from the lack of looking into the cyclone motion on a broader time scale and in its entirety. However, to these factors may be added the monthly and seasonal variation of the tracks recorded in the mainland station network. For this reason, an overall survey is carried out of the courses of 1949–1980 tropical cyclones of the

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①This work is funded by the National Natural Science Foundation of China.

western North Pacific origin, followed by an examination of the tracks of 301 typhoons landing on China through calculation of the tracks accumulated distance distribution function for the related characteristic chaotic quantity, wherewith the predictability time scale is estimated.

II. TRACKS OF WESTERN NORTH PACIFIC TROPICAL CYCLONE AND MONTHLY / SEASONAL VARIATION FEATURES OF ONLAND TYPHOONS IN CHINA

1. *Overview*

The data used coming from "1949–1980 Datasets of Typhoons Originating in the western North Pacific" compiled by Shanghai Institute of Typhoons (1984) show that 1196 tropical cyclones were generated during that period over the vast waters with the inclusion of the South China Sea, with 301 if they would land on the mianland. Table 1 illustrates the numbers of the typhoons on a monthly and seasonal basis.

Table 1. Monthly / Seasonal Numbers of the Tropical Cyclones and Onland Typoons in 1949–1980

type	seasonal and related months												1949–1980	
	spring			summer			autumn			winter			total	mean
	M	A	M	J	J	A	S	O	N	D	J	F		
GA*	18	49	43	87	174	267	218	151	96	54	25	14	1196	37.4
GB	0	0	10	28	71	88	74	19	10	1	0	0	301	9.4
B / A	0	0	0.23	0.32	0.40	0.33	0.34	0.13	0.10	0.02	0	0	0.25	0.25

* GA(GB) stands for Group *A*(*B*), denoting the systems of Pacific origin (landing on the mainland). B / A represents the ratio of the number in GB to that in GA.

It can be seen from the table the following facts of consequence: 1) the annual mean is 37–38, 1 / 4 of which invaded China as typhoons, a figure that deserves our serious attention, suggesting that 9 tempests, on average, hit the mainland each year; 2) the August's figure is maximum among all the months with these frequencies taking on a roughly normal distribution with respect to the particular month. Also, the ashore typhoons occurred chiefly from summer to fall, especially in July, August and September, for crop growth interval; 3) in general, the month with more cyclones generated is the period with more onland ones. Thus, May had the onland typhoons accounting for 1 / 4 of the total generation, with the number reaching > 1 / 3 of the respective total in June through September, followed by sharp reduction to 1 / 10 for October–December. None of the ashore cyclones for January to April were recorded because only a limited number was produced over the western North Pacific.

These points present us with a fundamental background for the cyclone activities on a temporal basis.

2. *Seasonal Variation of the Cyclone Tracks*

Here it is worthwhile to investigate the track seasonal variation features in the entirety.

For the sake of prediction some researchers morphologically classified the paths into two broad categories: the westward going ahead and the parabolic–form movements. In fact, their division into regular and anomalous kinds is more appropriate. For the westward going–ahead type can be viewed as a branch of its parabolic kind. The reason is that, if SE Asia were thought to be a vast stretch of ocean, then a typhoon would display its path as a parabola under the joint action of Coriolis force and Rossby deflection effect when travelling west a very long distance without being weakened by surface friction. As such, both the parabolic–form and the westward displacements can be grouped into one regular class in contrast to the anomalous type. In the latter can be included, for example, 1) the northward going–ahead directly from the central portion of the western North Pacific; 2) the snake–moving (zigzag) course in progression; 3) counterclockwise turning at sea due to interaction when two cyclones are getting close enough to tend to attract each other in their motion and 4) going north, followed by sudden turning west.

These phenomenological divisions, though acting to visualize our understanding, screen the seasonal variation as the important climatic features. Viewed on a monthly / seasonal basis, however, the 32–year dataset shows that, on the whole, the tropical cyclone tracks have experienced regular spatial evolution, which is given as follows.

1) The period January–March represents the lull phase of the cyclone activity, with the total of 57 only appearing in the dataset, averaging less than one each month (96 months). The genesis origin was mainly east of the Philippines and south of 10–12°N, with the track as a parabola, the turning point at 15°N, diminution and disintegration to the south of 25°N, a short displacement and usually, failure to reach the South China Sea during the stretching west. It follows that the cyclone effects are confined to low latitudes (see Fig.1a).

April is the phase of storm burgeoning marked by great increase of the genesis number, with the 32–year total of 47 for all April's. The turning north took place between 15 and 17°N and arrived at the South China Sea with a short displacement as well. The span January to April is obviously the typhoon–unaffected season for the mainland.

2) The period May to June is the phase of development at which still more cyclones are produced with the turning point happening poleward of 17°N, on average, at 20°N and moving west into the mainland. This is a time marking the incursion of typhoons into the country (Fig.1b).

3) The interval July to September is the active season for typhoons marching in succession into China. The paths are separated into a southern and a northern branch, the former (southern) denoting tracks running west through the South China Sea and landing at Guangdong and / or Guangxi provinces of China, and the latter (northern) showing the

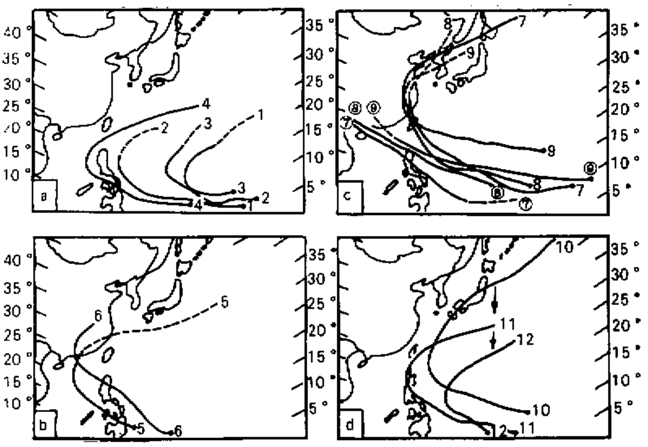

Fig. 1. Seasonal evolution of the tracks of western North Pacific tropical cyclones with the effects on China. a) January–March, April; b) May–June; c) July–September; d) October–December (For details see text). Figures with the lines denote months.

course into the mainland as a parabola. In the progress, the turning point occurs at 25–30°N, the journey long and the ending as far north as 50°N, both a time when typhoons are most active in this country and a season when low–latitude (the cyclone's origin) weather systems exert influence on extratropical circulations (Fig. 1c).

4) October is the month when the cyclones extend their courses into the northern North Pacific, characterized by a reduced (greatly increased) number of typhoons hitting China (Japan and the waters to the east), and a quite long course, reaching as far as the Aleutians north of 50°N in extreme cases. This is a still more important period during which heat and vapor are transported into the high from the low latitude atmosphere.

For November to December the cyclones retreat tracks as a whole southward to 20°N (15°N) in November (December). (see Fig.1d).

The foregoing analysis of the 32–year tracks on a seasonal basis will undoubtedly improve the understanding of the typhoon's courses as a whole on a space / time basis, thereby providing an approach to operational prediction.

3. *Estimate of Predictability Time Scale*

Although analysis of seasonal variation of the tracks yields fundamental spatial / temporal characteristics in the entirety, revealing some guiding results and thus providing some aid for prediction, the analysis does not supplant forecasting. After all, actual cyclone paths are highly complicated. Consequently, the ensuing problem is "To what degree the path is predictable". To answer it, a nonlinear dynamic technique (Fraedrich et al., 1989) is employed for investigating the multitude of the tracks by calculating their characteristic chaotic quantity, i.e., the fractal dimensionality in phase space, and then estimate is made of the predictability time scale in terms of Kolmogorov entropy from calculation.

The measure of dynamic system predictability is based on the time–dependent evolution of the system in relation to the growth rate of small initial error. The measure involved in our problem can be illustrated as follows: initially, two entities close to each other follow different paths through space and the error growth rate can be determined by the distance increasing versus time between the tracks. Accordingly, if a small initial error should grow beyond a given threshold in a limited span of time, then the interval would be the limit to the deterministic prediction from the dynamic system, or its predictability time scale.

(1) *Calculation of accumulated distance distribution function and fractal dimensionality*

In view of the fact that error growth is attributed mainly to the indeterminacy of initial conditions, all cyclone tracks should be examined when expressing the growth by means of the time–dependent distance between two paths. Thus, suppose that there are N independent paths, or cyclones, available and one of these cyclones, taken as a reference, is paired with each of the N−1 system by placing them onto the same starting point, resulting in N−1 pairs of cyclones. Note that the selection of the reference is carried out N−1 times from the sequence. In doing so, we can calculate the time variation of the cyclone–to–cyclone (path–to–path) distance for each pair.

Let a 2D space be expressed by $X = X(x,y)$ where $x(y)$ is latitude (longitude). For a tropical cyclone starting motion at initial time t_i, we take τ to be timestep and sample at m consecutive timesteps. Thus, we have

$$X_m(t_i) = \{x(t_i), y(t_i); x(t_i + \tau), y(t_i + \tau); \cdots\cdots, \\ x(t_i + (m-1)\tau, y(t_i + (m-1)\tau)\} \tag{1}$$

and then we express the distance for each of the pairs at k timestep by Euler norm

$$d_{ij}(k)=[(x(t_i+k\tau)-x(t_i+k\tau))^2+(y(t_i+k\tau)-y(t_j+k\tau))^2]^{\frac{1}{2}} \ , \tag{2}$$

we can therefrom find the number, $N_m(l)$, of pairs of the independent paths with the inter-distance less than the critical value l between $\tau=1$ and $\tau=m-1$, viz., $d_{ij}(k)<l$, with $k=0, 1, 2, \cdots m-1$, and computation is then performed of the following function

$$C_m(l)=N_m(l)/(n-1)^2 \ , \tag{3}$$

which represents the probability estimate of $d_{ij}(k)<l$ for $N_m(l)$ pairs. As a matter of fact, $C_m(l)$ yields a quantitative measure of temporal evolution of the dynamic system irregularity, commonly referred to as accumulated distance distribution function.

Theoretically, for $l\rightarrow 0$ and m getting big enough, a dynamic system exhibits its evolution over a low-dimensional attractor set in higher-dimensional phase space with the relation of the attractor's dimension D to $C_m(l)$ given by

$$C_m(l)\sim l^D \ , \tag{4}$$

so that D has the form

$$D=\lim_{\substack{l\to 0\\ m\to\infty}}\frac{|\ln C_m(l)|}{\ln l} \ . \tag{5}$$

Disregarding the cyclones disappearing far out at sea in the 1949—1980 sequence, focus is on 301 onland typhoons. With $l=0.5, 1.0, \cdots, 7.5, 8.0$ and $m=0, 1, 2, \cdots 7$, the distance $d_{ij}(k)$ between the paths are found from (2) and (3) for the 300 pairs (with one of the 301 typhoons as a reference) and then $C_m(l)$ obtained, with the results portrayed in Fig. 2. Based on this figure, $D=4.860$ is acquired by use of (5), suggesting that the construction of typhoon forecasts requires a dynamic system consisting of at least 5 variables.

(2) *Calculation of Kolmogorov entropy and predictability time scale*

Considering that the relative number of the pairs with $d_{ij}(k)<l$ decreases with increased time as the pairs advances. As the time elapses from $(m-1)\tau$ to $m\ \tau$, the related probability estimate is changed into $C_{m+1}(l)$ from $C_m(l)$. Then we define a physical quantity K_2, or the second-order entropy, which takes on the form

$$K_2=(\frac{1}{\tau})\ln C_m(l)/C_{m+1}(l) \ , \tag{6}$$

which serves as a measure of mean departure rate of the increased distance between the pair initially close to each other and as the lower limit of Kolmogorov entropy, of which the inverse represents predictability time scale, namely,

$$T=\frac{1}{k}\approx\frac{1}{K_2} \ . \tag{7}$$

Using the calculations of Fig. 2 and with $m=5$ and $l=3.0$, we get from (6)

$$K_2=0.016406 \ ,$$

such that the predictability time scale

$$T=60.95 \text{ hrs}\approx 2.54 \text{ days},$$

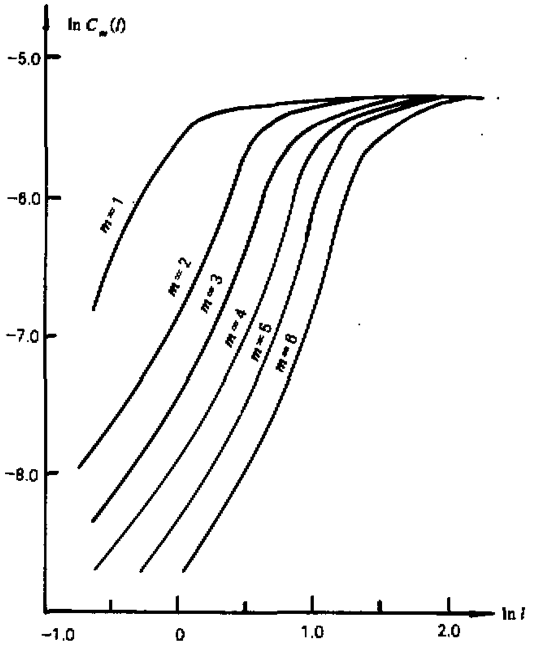

Fig. 2. The accumulated distance distribution function $C_m(l)$ of the independent path pairs of 301 onland typhoons for China with ordinate for $\ln C_m(l)$, abscissa for $\ln l$ and m being the consecutive samplings.

which will no doubt enhance our confidence in making deterministic prediction of typhoon paths.

(3) *Reference typoon track*

At present in the operational typhoon–forecasting system it is a more common practice to use the synoptic–dynamic statistical method, which consists of searching an analog in historical record, a task that is considerably painstaking. To alleviate the problem, we find out a reference typhoon path by use of the accumulated distance distribution values of $C_2^{301} = 301!/(301-2)!2! = 45150$ pairs from the 301 onland cyclones in the period 1949–1980. The reference track means its minimum accumulated distance among all the pairs. It is suggested that the reference course be employed in fitting for dynamic–statistical prediction. The reference typhoon is No.23 of 1971, or Bess in international nomenclature, which entered the scene as a strong tempest September 17–27 that year with its track shown in Fig. 3.

IV. SUMMARY

From the foregoing discussion, the following points are of note:

1) The western North Pacific, including the South China Sea, is the source of tropical storms evolving out of cloud cluster there, with 29 (53) cyclones generated in the least (most) active year, averaging 37–38 annually, and the corresponding figures are 6 (15) and 9,

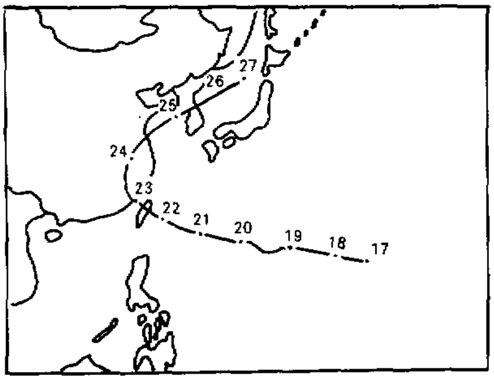

Fig. 3. The geometry of Typhoon No.23, or Bess, occurring September 17–27, 1971. Figures on the line denote days.

respectively, for the onland portion. The most important thing is the track seasonal variation, which can be separated roughly into such phases as lull, burgeoning, development, active, extension and retreat, divisions that contribute greatly to prediction. To illustrate this, we take for example Typhoon No.18 (September 1993) that did severe damage along its passage after landing on Guangdong but the subsequent three appeared in October without landing on the mainland (though reaching the warning line) but turning its way in the SE Taiwan Strait towards Japan. This seems related to nothing but the seasonal variation of the track.

Beyond considering the seasonal variation in typhoon prediction, the fractal dimensionality $D = 4.86$ is of help, indicating that any typhoon forecasting model has to be composed of at least 5 variables or a 5D dynamic system should be established for the purpose. Evidently, the combination of the 6 factors contributing to local vorticity change (Holland, 1985) meets the requirement, implying that the barotropic vorticity equation may serve as the basis for the theoretical treatment.

Moreover, the predictability time scale $T = 60.95$ hrs coming from the inverse of K_2 and the suggested path of Bess as the reference found are of noteworthy implication for operational prediction.

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