Analysis and Simulation of Typhoon Intensity Decay after Landfall over the Eurasia

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ABSTRACT: An intensity decay model of typhoon after landfall over the Eurasia is proposed. Based on the database of 267 typhoons from 1949 to 2010, the effectiveness of the model is analyzed and the filling rate (decay rate) is defined and calculated. It is found that the classical negative-exponent decay model can be used to describe the decay appropriately. The geographical distribution of the filling rate is explored, which indicates that the rate varies among regions and decreases with the increase of the latitude. In addition, the relationship associated with the filling rate and the intensity of the typhoon is constructed. A positive correlation between the filling rate and the initial difference of pressure is discovered. Particularly, there is an obvious linear relationship between these variables if the filling rate is calculated by 3 to 5 initial points after landfall or the typhoons with long track are eliminated. Based on this conclusion, two predictive methods are modeled. A simulative prediction was developed, indicating that the dynamic model performs better than the statics one on average with an advantage in predicting long-track typhoons.

KEY WORDS: Typhoon, Landfall, Decay, Prediction

1. Introduction

Tropical cyclones have demonstrated their destructive capabilities and brought huge damage to human activities. The Northwest Pacific is one of the major battle fields in human struggle against the cyclone disasters. The explicit assessment of cyclone hazard is urgent for the protection of lives and demands the modeling of cyclone decay after landfall. Cyclone intensity (central pressure) and maximum wind speed have great impact on the cyclone hazard and damage, which endows them priory considerations in the modeling.

Consequently, empirical methods have been applied to the simulation of post-landfall cyclone tracks. Kaplan has introduced an empirical simulation model to the prediction of cyclone wind speed in the US (Kaplan and DeMaria 1995 and 2001). At the same period, Vickery provides a filling model to describe the decay of cyclone intensity (central pressure) (Vickery and Twisdale 1995). Then Vickery updated the filling model and applied to cyclone tracks along the coast lines of United States (Vickery 2005). Both models, either wind speed or central pressure oriented, are classic exponential decay models for the US. Later, Bhowmik described wind speed prediction in the Indian Region with a limited sample size (Bhowmik et al. 2005). However the lack of the decay model for the Northwest Pacific remains.

Recently Wong examined the landfall along the South China coast with Hong Kong Observatory (HKO) best track data (Martin L. M. Wong et al. 2007). However, there is still increasing need to develop models to describe cyclones in the Northwest Pacific region, especially those landfall in China. Most existing efforts merely estimated single cyclone tracks and there is no overall analysis of the cyclone decay.

In this study, pre-existing models will be applied on Eurasian typhoons data. An overall geographical analysis will also be made. In addition, based on the decay rate, an existing prediction model will be examined and a new model will be proposed, after which a comparison is to be conducted. Attributes and remedy of data are introduced in chapter 2. Models, including decay model and prediction model as well as the test of models, are introduced in chapter 3. Conclusions are presented in Chapter 4.

2. Data

The Northwestern Pacific 6-hours best-track cyclone database is used in this paper, which provides latitude-longitude positions of the center at 0.1° resolution. A remedy process is primarily made before the calculation to add the information of landfall, including the position, time and pressure, are missed in the original database. First, the Eurasian land coastline has been approximated into 54 discrete coastal segments. In the case of landfall typhoon Wipha (Uniq_ID 200713), the landfall implies the fact that the track of the cyclone intersects with one of the coastal segment X_Y. The data points before and after the landfall, namely B and C, are marked and the cross point is naturally regarded as the landfall point. All of the data of the landfall point L, such as time, position, pressure, are linear interpolated based on the corresponding value of B and C on the weight of the length of BL and CL. The whole process is presented and illustrated in the Fig. 1.

In addition, except part of the cyclones from the year of 2001 to 2010, most of the cyclone misses the precise value of outer pressure, which is used in computing Δp. In the consideration of consistency, the uniform value 1010 mb is used in this paper. This method of simplification is consistent with most of the existing research of Ho (Ho et al.1987) and Vickery (Vickery and Twisdale 1995). However, a constant value of 1013 mb instead of 1010 mb is used in above researches. Yet the peripheral pressures of the Eurasian cyclones are generally lower than those in North America, which are usually replaced by the value of 1010 mb. Hence, the pressure difference in this paper is defined as $\Delta p = 1010\text{mb-}p$, where p is the inner pressure.

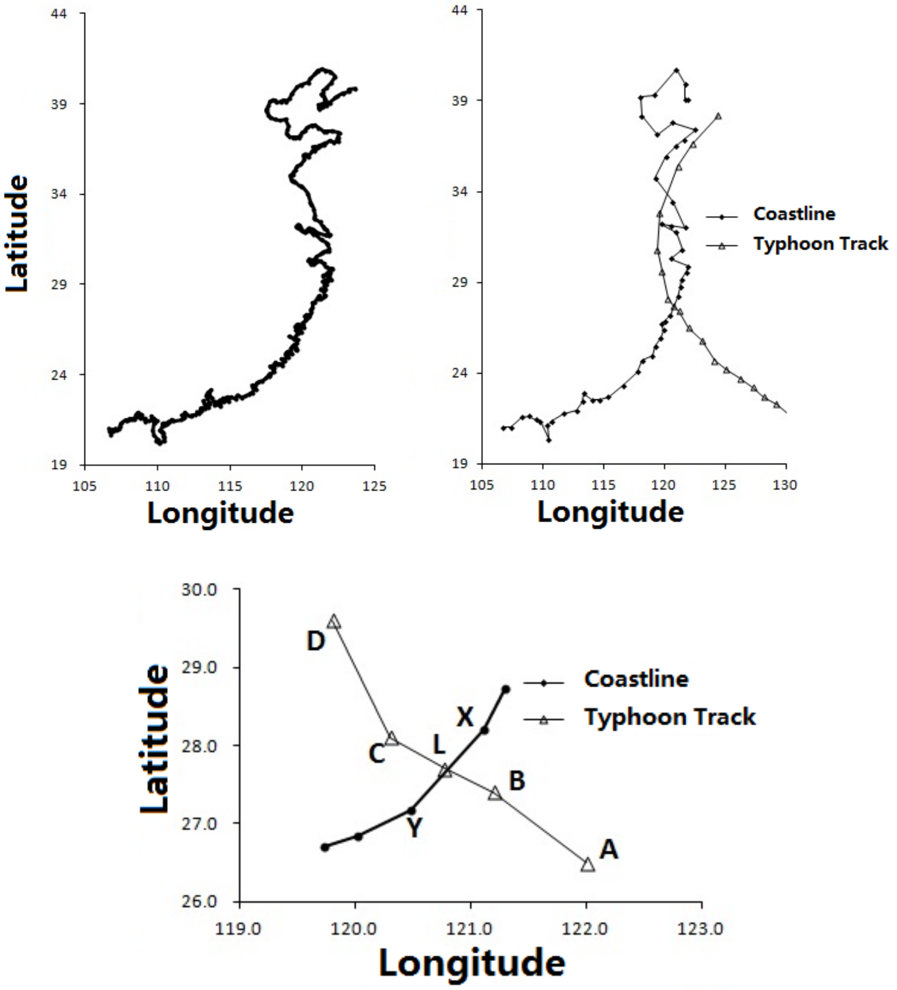


Fig. 1. Process of interpolation. Above is the process of discretization; below is interpolation.

On the bases of the Northwestern Pacific 6-hours best-track cyclone database between the year of 1949 and 2010, cyclones have made landfall on the Eurasia for 1010 times, most (743) of which, however, dies or advances into the ocean within 30 hours. To make the filling rate more meaningful, the landfalls whose duration on land is longer than 24 hours are selected into the sample set. That is, all of the samples in the sample set possess more than 4 land points. Consequently, the sample size in this paper is 267, which is much more than 19 in Bhowmik and 55 in Vickery.

3. Model and simulation

3.1 Decay model and decay rate

Decay models are aimed at constructing the relationship between the cyclone intensity and the time after landfall. Kaplan asserts that the decay rate of wind speed is proportional to the wind speed, thus propose the empirical wind speed decay model (Inland Wind Decay Model-IWDM), indicating that the wind speed generally decays as a negative exponential pattern, namely $V(t) = V_0 e^{-at}$ (Kaplan and DeMaria 1995). Since then, IWDM is widely used in the topic of typhoon intensity decay. For instance, Kaplan puts his own model in the computing of the cyclones in New England. He modifies his model into $V(t) = V_b + (RV_0 - V_b)e^{-at}$, where V_b=29.6kt， R=0.9， a=0.185h^{-1}(Kaplan and DeMaria 2001). Apart from wind speed, difference of pressure also can be an indicator of the intensity of cyclones. Thus, the model $\Delta p(t) = \Delta p_0 \exp(-at)$ is raised, where $\Delta p(t)$ and Δp_0 indicate the difference of pressure at the time of t and landfall respectively. The using of pressure instead of the land speed is on the consideration of the stability of the data for the reason that the pressure data is not easily influenced by the terrain and thus will lead to fewer errands in computing.By least square method, the model $\Delta p(t) = \Delta p_0 \exp(-at)$ is used in the 267 landfall typhoons in calculating the filling rate a of each one.

Kaplan discover a variance of the decay rate between north and south England, namely the decay rate of north cyclones are obviously faster than those in south England (Kaplan and DeMaria 2001). Vickery also believes the cyclone’s decay rate varies from different areas (Vickery and Twisdale 2005). Based on the above results of filling rate, 120 samples whose r^2 are greater than 85% have been selected into a new sample in testing the existence of regional variance. 120 samples are equally divided into 4 groups according to their landfall latitude. The latitude interval and the average decay rate of every group are presented in Table. 2. By using the technique of variance analysis, the significant difference between every group is found (P = 0.02).

Table. 1. Average decay rate in four latitude intervals.

Group	1	2	3	4
Interval of Latitude	11.08-20.77	20.9-22.74	22.77-25.44	25.54-48.17
Average Decay Rate	0.049	0.042	0.040	0.033

3.2 Prediction model

On the basis of decay model, some scientists develop a series of prediction model, which can be divided into three groups. First, some use the above negative-exponential model to make the prediction directly. For instance, Kaplan predicts the speed of wind by

$$V(t) = V_b + (RV_0 - V_b)e^{-at} - C,$$

in which he unifies the parameters thus lead to a errand around 7kt（1kt=0.5144m/s）. Second, some predict the change of intensity by the information of landfalling. Vickery, for example, points that there is a obvious relationship between the decay rate a and the landfalling pressure difference, which can be described as $a = a_0 + a_1 \Delta p_0$. a_0、a_1 can be regarded as two constants in a given district (Vickery and Twisdale 2005). Therefore, prediction of the pressure can be made when the initial pressure provided. After that, Vickery adds that two more predictors were found thus the model was modified as

$$a = a_0 + a_1(\Delta p_0 c / RMW).$$

That is, the decay rate not only presents a positive correlation between landfalling pressure difference, but a positive relationship with moving speed c and a negative relationship with radius of maximum wind. Third, some make the prediction iteratively by using the information after landfalling. In Bhowmik's study, he defined the decay factor e^{-at}, and made a regression analysis between the initial 6-hours decay factor $R_1 = \exp(-6a_1)$ and the later 6-hours decay factor $R_2 = \exp(-6a_2)$ (Bhowmik et al. 2005). He then develops an algorithm in predicting the variance of typhoon intensity. Bhowmik's uses 19 typhoons that landfalled on India to test the model. Compared to Kaplan's method, Bhowmik's algorithm performs better in the accuracy of prediction. Yet he disregards the prediction of the initial intensity just after landfalling.

Nevertheless, as shown in Fig.3, a unimodel distribution exits. Therefore, there is an obvious variance between the decay rates of typhoons that landfall on Eurasia. As a result, unification of the parameter will not lead to a scientific prediction case by case among typhoons. In terms of the second approach, Wong applies it into the data of Northwestern Pacific typhoons. Besides Δp_0, c and RMW, Wong collects nine possible predictors which may explain the difference of decay rate (Martin L. M. Wong et al. 2007). He uses three of them to construct a model of prediction and then finally made a convincing prediction. However, it is also a notable result that the goodness of fit is only 15% if no predictor other than Δp_0 is brought in. As the third method, few researches have been made on the Northwestern Pacific typhoons by using it.

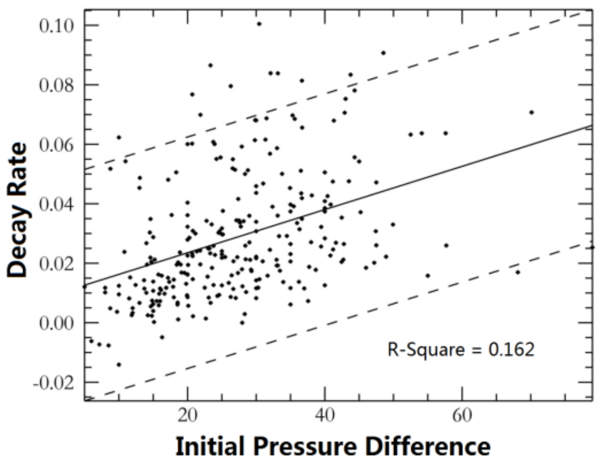


Fig. 2. Relationship between the initial pressure difference and decay rate.

Fig.4 presents the relationship between the 267 typhoons' decay rate and the initial pressure difference, whose correlation coefficient is 0.40. A least-square estimation leads to the result

$$a = x_0 + x_1 \cdot \Delta p_0 = 0.0089 + 0.00073 \cdot \Delta p_0.$$

The R-Square value is 0.162, which is close to 0.15 in Wong's study (Martin L. M. Wong et al. 2007).

However, if we ignore the typhoons whose duration on land are greater than 48 hours, new and better scatters can be shown in Fig. 5. The promotion of the goodness-of-fit is obvious and can be illustrated in the Table.4.

Table. 2. Relationship between the initial pressure difference and decay rate if long-track typhoons are eliminated. The correlation becomes more significant.

Points of the Sample	Sample Size	$a = x_0 + x_1 \cdot \Delta p_0$		r^2	σ_ε
		x_0	x_1		
Less than 6	75	0.0551	0.0013	0.3947	0.0191
Less than 7	125	0.0487	0.0012	0.3431	0.0191
Less than 8	167	0.0524	0.0011	0.3174	0.0188

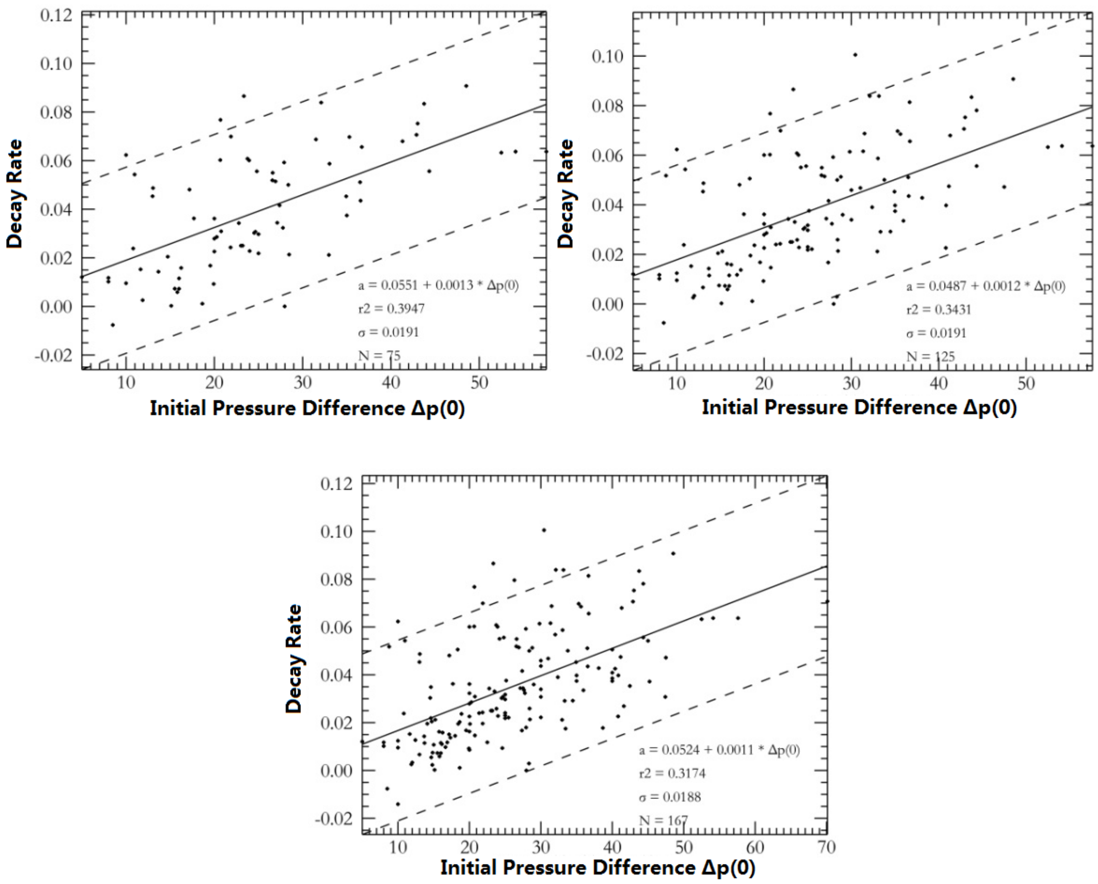


Fig. 3. Relationship between the initial pressure difference and decay rate if long-track typhoons are eliminated. Upper left, upper right and below are plots of typhoons whose track points are less than 6, 7, 8 respectively.

Similarly, in Tabel.5 and Fig. 6, an improvement of regression also emerges if the decay rate is calculated only by 3, 4, 5 initial points after landfall instead of all the points on lands.

Table. 3. Relationship between the initial pressure difference and decay rate if the decay rates are regressed by initial several points after landfall. The correlation becomes more significant too.

Number of Points Used in Calculating the Decay Rate	Sample Size	$a = x_0 + x_1 \cdot \Delta p_0$		r^2	σ_ε
		x_0	x_1		
3	267	0.0104	0.0012	0.2091	0.0290
4	267	0.0072	0.0012	0.2944	0.0219
5	267	0.0076	0.0010	0.2889	0.0191

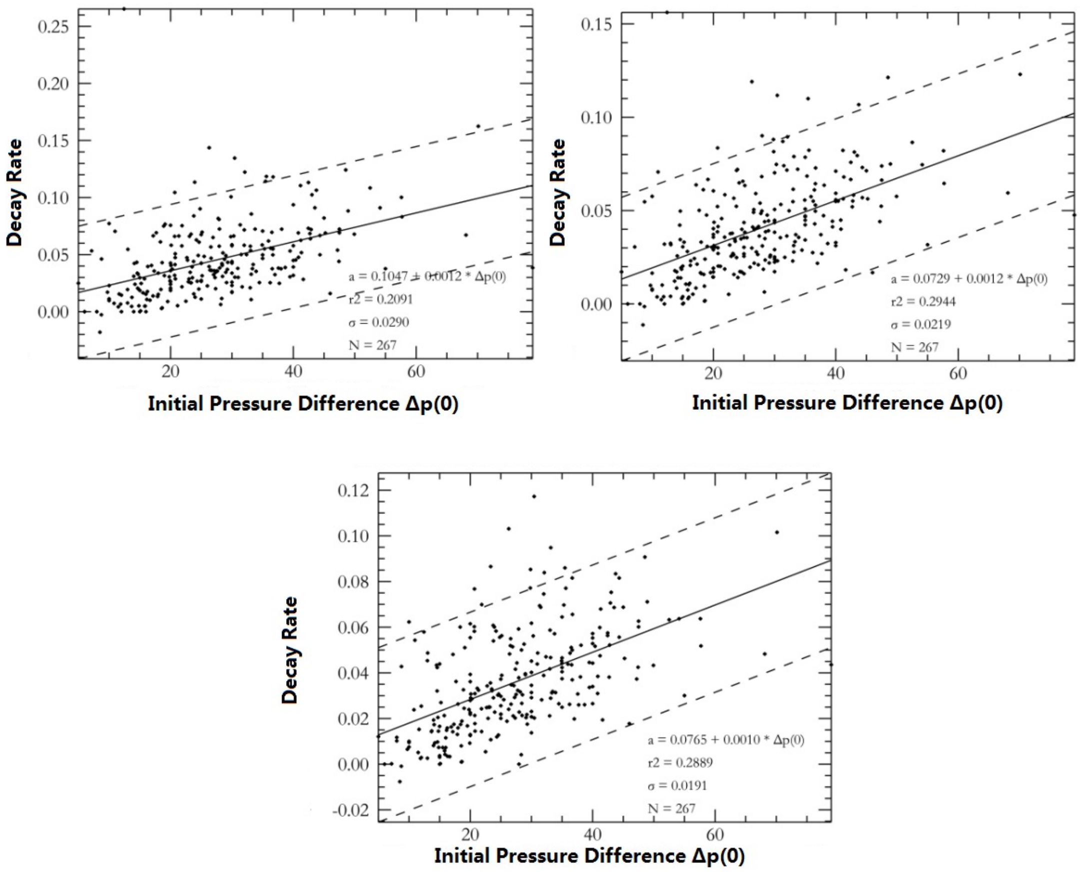


Fig. 4. Relationship between the initial pressure difference and decay rate if the decay rates are regressed by initial several points after landfall. Upper left, upper right and below are cases whose decay rates are regressed by initial 3, 4, 5 points respectively.

The difference between the Table.4 and Table.5 should be noticed. That is, the decay rates in Table.4 are calculated by all the points on land, but only short-track typhoon samples are selected in three new databases. On the contrary, all 267 typhoon samples are calculated in the Table.5 while the decay rate is calculated only by the 3, 4 or 5 initial points after landfall. The results indicate that the less information requested to be explained and predicted, the better of the relationship between decay rate and initial information, which is easy to be explained as: the original status will do better in predicting the intensity of initial several points than the tail points. This is also a proper explanation of the goodness in Vickery's paper. The duration after landfalling in Vickery's study – the longest time after landfalling in Vickery's paper is 36 hours. Thus the effect of prediction used only by the initial pressure difference is impressive. However, it is apparently rigorous to require the initial information to make a whole-track prediction on the typhoons whose durations are 100 hours or even more.

As discussed above, the landfalling information can be used in simulating the intensity changes of initial points, yet the tail points cannot be provided a precise forecast. Consequently, a model designed for predicting the change of intensities of long-track typhoons is to be described.

The model

$$a_{n+1} = f_n(a_n)$$

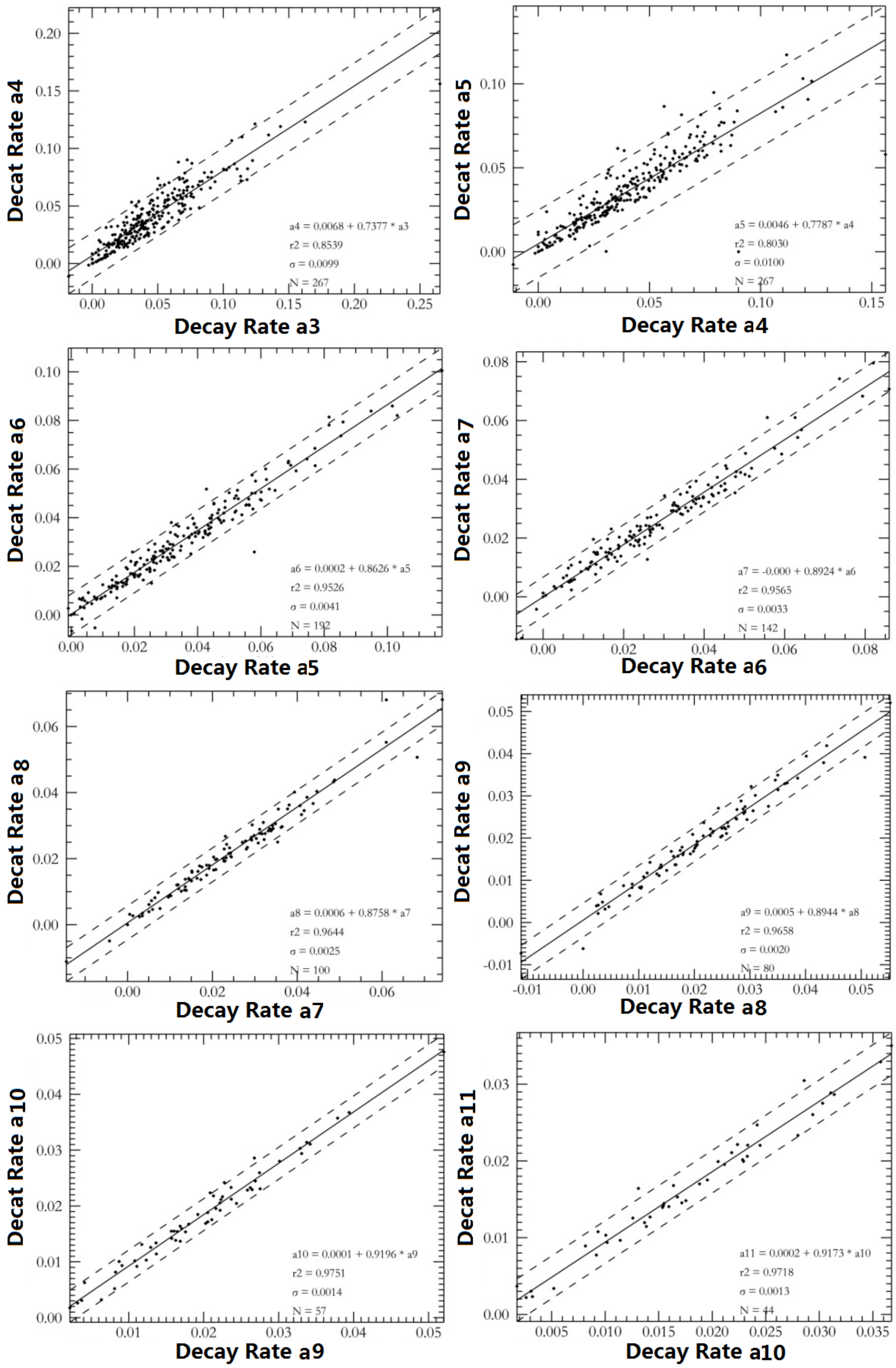
is aimed at predicting the information of first n+1 points (thus the n+1th point) by the information of first n points.

The scatters between a_n and a_{n+1} are shown in Fig.7 from n =3 to 14. It can be seen that a significant linear relation exists, yet the intercept and slope vary among each of them. So, a table to illustrate the detailed formulas is given in Table.6, which is regressed by least square method. Therefore, a prediction of the intensity of non-initial points can be made by this form iteratively.

Table. 4. Results of regression between an and an+1, where an is the decay rate calculated by initial n points.

Independent	Dependent	Sample Size	Intercept	Slope	r^2	σ_ε
a_3	a_4	267	0.0682	0.7377	0.8539	0.0099
a_4	a_5	267	0.0467	0.7787	0.8030	0.0100
a_5	a_6	192	0.0023	0.8626	0.9526	0.0041
a_6	a_7	142	0.0000	0.8924	0.9565	0.0033
a_7	a_8	100	0.0058	0.8758	0.9644	0.0025
a_8	a_9	80	0.0054	0.8944	0.9658	0.0020
a_9	a_{10}	57	0.0005	0.9196	0.9751	0.0014
a_{10}	a_{11}	44	0.0024	0.9173	0.9718	0.0013
a_{11}	a_{12}	37	-0.0020	0.9542	0.9737	0.0013
a_{12}	a_{13}	23	0.0039	0.9266	0.9648	0.0012
a_{13}	a_{14}	20	0.0006	0.9576	0.9728	0.0010

a_{14}	a_{15}	10	-0.0030	0.9894	0.9942	0.0005



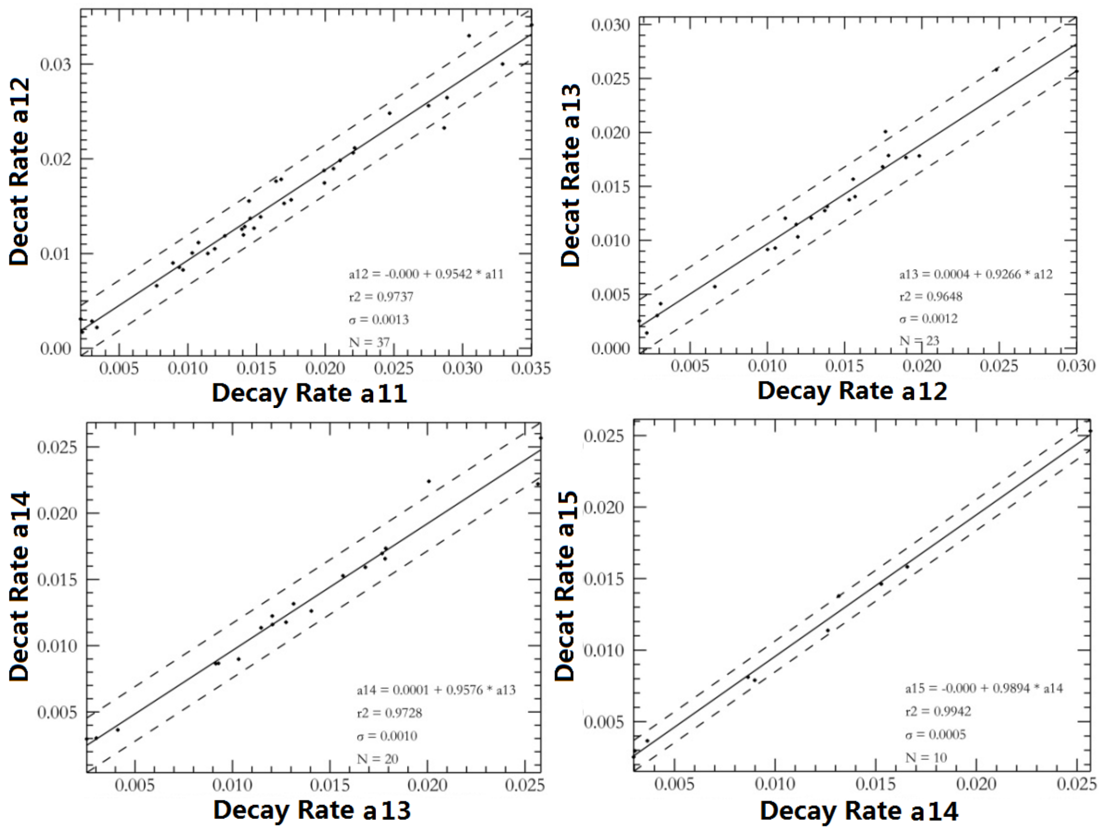


Fig. 5. Regressions between anand a n+1from n = 3 to 14.

3.3 Application of the Model

Researches of the decay models are partly aimed at predicting and thus simulating the development of the typhoons' intensity after landfalling. A series of prediction models, as mentioned above, have been utilized on this target. However, a model solely based on the initial information may fail to offer the change of the intensity after a long duration after landfalling. It is also no way, on the contrary, for a model just based on the after-landfall information to make a simulation on the initial changes, which is also of great importance to the human beings. Consequently, a modified algorithm emerges. Generally, we, in this algorithm, compute the intensity of initial points (3 points, namely less 18hours) by the pre-existing negative exponential model; and deal with the tail points by a newly raised iterative method. Detailed steps are presented as:

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Step1:  a[3] ← x0 + x1 * Δp(0) (by Table.5),
        p[1] = p(0) * exp{a[3] * 6},
        p[2] = p(0) * exp{a[3] * 12},
        p[3] = p(0) * exp{a[3] * 18}, n = 3
Step2: a[n + 1] = f[n] (by Table. 6),
Step3: p[n + 1] = p(0)/exp{-a[3] * 6(n + 1)}
Step4: If p[n + 1] > 1010, Then Stop; Else n ← n + 1, Goto Step2.
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In the following, the model solely based on the initial information will be named as Method 1 and the algorithm raised in this paper will be named as Method 2. The result of simulation shows that a error whose mean is 2.48hPa and standard variance is 1.89hPa exists by using Method 1, while 1.65hPa and 1.00hPa using Method 2 respectively. Several examples of simulation can be seen in the Fig. 8.

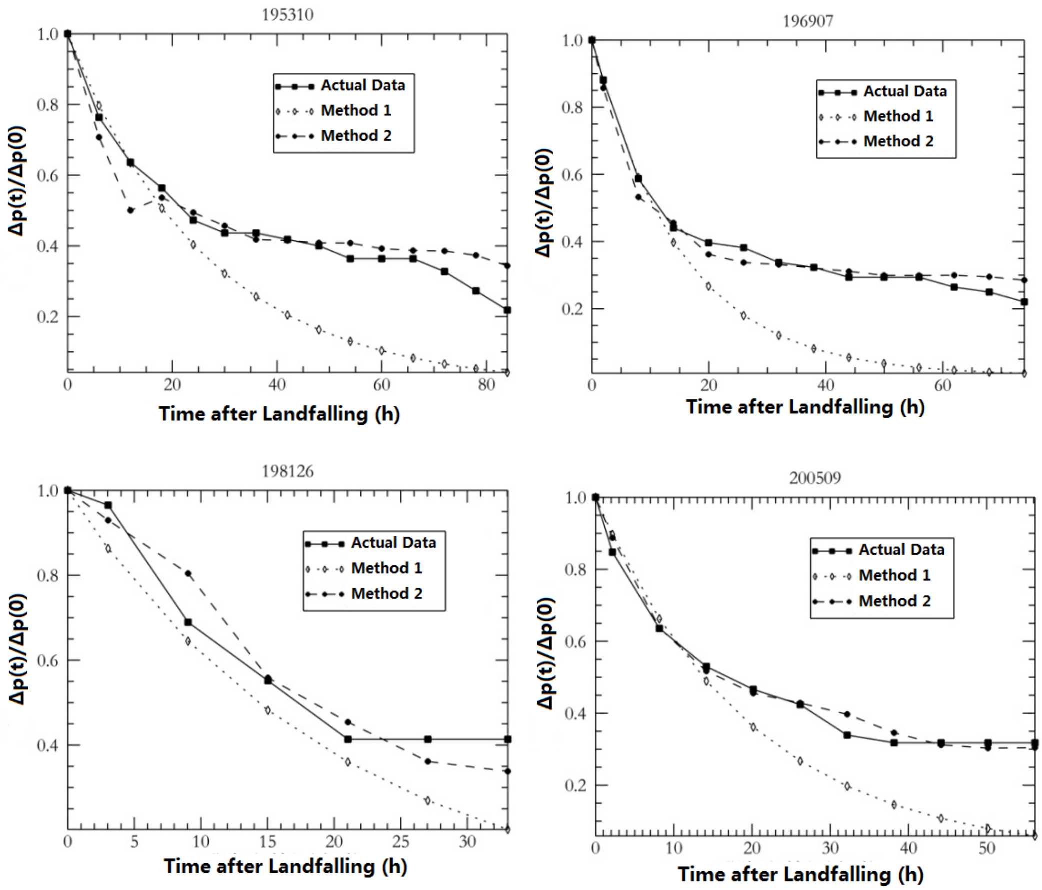

Fig. 6. Comparison between two simulation methods.

4. Summary and conclusion

Existing decay models are applied on the typhoons landfall on Eurasia in this study. Furthermore, the condition of using the pre-existing prediction model is explored and a new algorithm based on the model is developed. Several conclusions are summarized as:

(1) The existing decay model can be applied on the typhoons landfall on Eurasia properly as the median of the goodness-of-fit reach 82%;

(2) An evident difference of the decay rate can be found in the different area of Eurasia. The decay rate decreases as the increase of the latitude;

(3) Intensity of initial points can be predicted by the existing models only based on the initial pressure difference, while it fails to predict the tail points precisely;

(4) An algorithm is designed on the purpose of predicting the intensity change of long-track typhoons. A significant promotion of the efficiency can be found in a simulation test.

The model also can be modified. For example, a cluster analysis can be added before searching for the possible predictors. Namely, the relationship can be constructed according to a given district and a given time. Furthermore, more possible predictors are also needed to be explored, such as temperature and humidity.

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