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Statistics-based investigation on typhoon transition modeling

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ABSTRACT: The present study revisits the statistical modeling of typhoon transition. The objective of the study is to provide insights on plausible statistical typhoon transition models based on extensive statistical analysis. First, the correlation structures of the typhoon transition are estimated in terms of autocorrelation function (ACF) and partial autocorrelation function (PACF). This facilitates to specify a set of plausible models for further investigation. Then, the corrected Akaike Information Criterion (cAIC) is applied to investigate the relative goodness of fit of these models. The spatial inhomogeneity and the seasonality are taken into account by developing the models for different spatial grids and seasons separately. An appropriate size of spatial grids is investigated. The statistical characteristics of the random residual terms in the models are also examined. Finally, Monte Carlo simulations are performed to investigate the overall performance of the proposed model.

KEYWORDS: Typhoon transition, statistical analysis, spatial inhomogeneity, seasonality, non-normality, model selection.

1 INTRODUCTION

The methodology for probabilistic modeling of typhoon hazard and risks has experienced significant progress in the last few decades. Based on the methodology, probabilistic models have been developed. Presently, a spectrum of probabilistic models are available and widely utilized as a tool to quantify and manage typhoon risks in different contexts. Successful applications include the determination of design wind loads on structures and the pricing of re/insurance portfolio policies. More recently, the methodology and the probabilistic models have been applied beyond these classical applications: The methodology has been applied for quantifying the impact of the global climate change on wind risks due to typhoons, see e.g. Nishijima et al.[1]; a probabilistic model has been applied for real-time operational decision optimization in the face of an approaching typhoon, see Anders & Nishijima[2]. In these applications, among others, the modeling of typhoon transition plays the key role.

The modeling of typhoon transition from its genesis to dissipation, i.e. its whole life, has become the state-of-the-art in the modeling of the typhoon hazard and risks. This approach has several advantages over classical approaches. For example, a classical statistical approach for modeling the typhoon-induced wind hazard often encounters a lack of sufficient number of observations in reliably estimating the wind speeds of large return periods, whereas this approach alleviates the statistical problem by best utilizing the observations of historical typhoon tracks and by simulating sufficient number of typhoons by Monte Carlo techniques. It also facilitates to consider the spatial correlations of the hazard and risks, which are relevant for the estimation of the portfolio risks, while one of the classical approaches starts Monte Carlo simulations of typhoon events only at neighboring areas or at coastal lines of interest.

Vickery et al.[3] propose the first approach for modeling the transition of typhoon during its whole life, focusing on the Atlantic basin. They employ higher-order of Markov chains for modeling the changes of translation speed and angle as well as intensity of typhoons. Other modeling approaches are also proposed taking basis in different expressions for typhoon transition; see Powell et al.[4], James & Mason[5], Emanuel et al.[6], Rumpf et al.[7], Hall & Jewson[8], [9], Graf et al.[10], Yin et al.[11] and Yasuda et al.[12]. However, in spite of the proposals and their wide applications little attention has been paid on the relative performances of different transition models. Motivated by this and focusing on the Markov chain-based modeling, Graf & Nishijima[13] perform a systematic comparison of the performances of the different models; it is found that the performances are not too sensitive to the choices of the functional forms for the Markov chains and the way to deal with the spatial inhomogeneity (in terms of grid size) and seasonality, as long as the statistics on annual maximum wind speed is concerned. However, they do not investigate the plausibility of different models by extensive statistical analysis.

The present study aims at identifying plausible models by extensive statistical analysis; focusing on the translation speed and angle and the central pressure of typhoons, and restricting to the Markov-chain representation. First, by the statistical analysis, the order of Markov chains and the explanatory variables required in the modeling are investigated. Second, the appropriate size of the spatial grid in which the probabilistic characteristics of typhoons can be assumed to be stationary is examined. Third, the statistical characteristics of the residual terms in the Markov chain models are estimated. Thereby, a set of plausible typhoon transition models is identified. Selecting a proposed typhoon transition model, the performance of the model is compared to other competing models and the historical typhoons with respect to the statistics on the translation speed and angle and the central pressure of typhoons at several latitudes. For the statistical analysis and the modeling of the typhoon transition, the best track data provided by the Japan Meteorological Agency (JMA) in the period between 1951 and 2006 is utilized. In present paper, the term typhoon is employed for referring to tropical cyclones in general.

2 MODELING APPROACH

2.1 *Auto regression*

For the purpose to understand the basic statistical characteristics of the transition of historical typhoons, the successive translation speeds, successive translation angles and successive central pressures of the typhoons are plotted, see Figure 1. V_i, Γ_i and P_i represent the translation speed, translation angle, central pressure at time step i, respectively. These three variables are hereafter called the state variables of typhoons. Note the translation angle of a typhoon is 0° when traveling north and positive clockwise. It is found that there are linear relationships with moderate randomness between successive translation speeds and translation angles, respectively. This is consistent with the observation made in Emanuel et al.[6], where the historical typhoons in the north Atlantic basin are examined. The similar relationship is observed between the successive central pressures. Furthermore, by developing these scatter plots for different areas and seasons, it is observed that the statistical characteristics of the state variables are different; implying the existence of the spatial inhomogeneity and the seasonality.

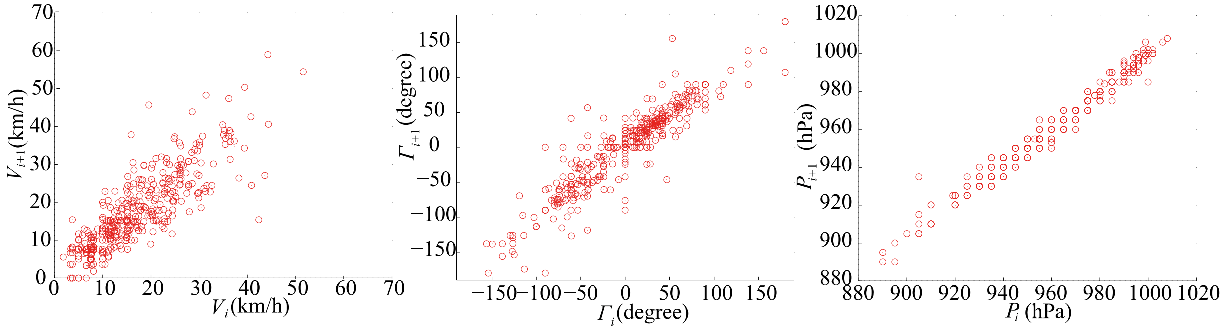

Figure 1. Scatter plots showing relationships between successive translation speeds, successive translation angles and successive central pressures. Track data utilized here to create the plots are on the typhoons travelling within the area bounded by the longitudes [124°E, 132°E] and the latitudes [24°N, 28°N] in September.

2.2 *Exploration of the regression form*

The relationships drawn in the scatter plots suggest that the autoregressive (AR) model can be appropriate to represent the transition of typhoons. Therefore, the autocorrelation coefficient function (ACF) and the partial autocorrelation coefficient function (PACF) are estimated in order to identify the necessary and sufficient orders of the AR models. Taking basis in the area bounded by the longitudes [124°E, 132°E] and the latitudes [24°N, 28°N] and the area bounded by the longitude [140°E, 148°E] and the latitude [28°N, 32°N] in September, and assuming the typhoon transition is stationary therein, ACF's and PACF's are estimated for the state variables as a function of the time lag, see Figure 2. Here, the unit of the time lag is 6 hours, at which interval the JMA best track data is available. Since the ACF's decay as a function of time lag and the PACF's show the cut off at around time lags of 2, it suggests the autoregressive models of the second orders, AR(2), can be plausible. Similar observations are made for other seasons and areas. Therefore, the first plausible transition models for the state variables are:

$$V_{i+1} = a_1 + a_2 V_i + a_3 V_{i-1} + \varepsilon_{V,i} \tag{1}$$

$$\Gamma_{i+1} = b_1 + b_2 \Gamma_i + b_3 \Gamma_{i-1} + \varepsilon_{\Gamma,i} \tag{2}$$

$$P_{i+1} = c_1 + c_2 P_i + c_3 P_{i-1} + \varepsilon_{P,i} \,. \tag{3}$$

Here, $\varepsilon_{V,i}$, $\varepsilon_{\Gamma,i}$ and $\varepsilon_{P,i}$ are the random residual terms for the state variables. Each of the residual term for different time steps is assumed to independently follow an identical distribution. For some seasons and areas the estimated PACF is significantly different from zero only at time lag of 1 for the translation speed and angle; hence, the autoregressive models of the first order, AR(1), are also plausible;

$$V_{i+1} = a_1 + a_2 V_i + \varepsilon_{V,i} \tag{4}$$

$$\Gamma_{i+1} = b_1 + b_2 \Gamma_i + \varepsilon_{\Gamma,i} \,. \tag{5}$$

As the third plausible models, regression models including the possible interrelations between the translation speed and the translation angle are assumed:

$$V_{i+1} = a_1 + a_2 V_i + a_3 V_{i-1} + a_4 \Gamma_i + \varepsilon_{V,i} \tag{6}$$

$$\Gamma_{i+1} = b_1 + b_2 \Gamma_i + b_3 \Gamma_{i-1} + b_4 V_i + \varepsilon_{\Gamma,i} \,. \tag{7}$$

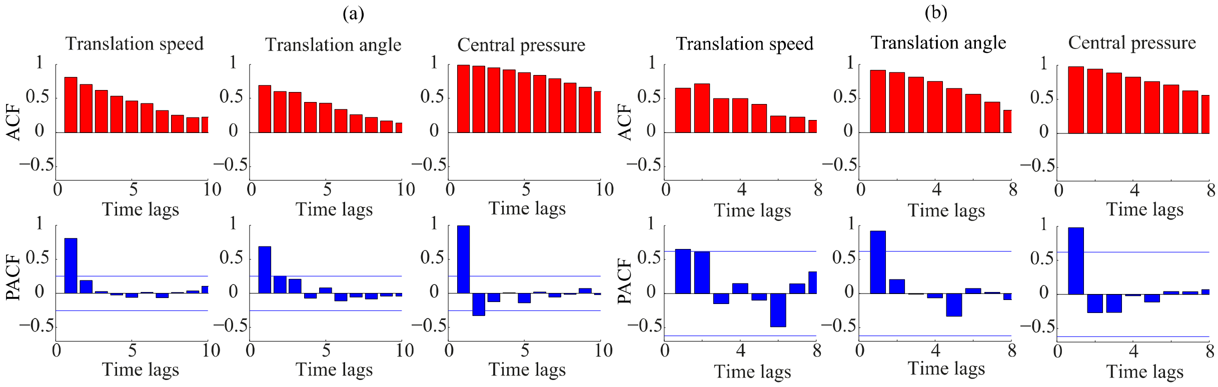

Figure 2. Illustration of the estimated ACF and PACF of the translation speed, the translation angle and central pressure as the function of lags. (a) is for the longitudes [124°E, 132°E] and the latitudes [24°N, 28°N] in September, and (b) is for the longitude [140°E,148°E] and the latitude [28°N,32°N] in September. The two lines in the figures of PACF's correspond to the 5%-significance level at which the PACF is considered to be different from zero.

Vickery et al.[3] indicate that the intensity of typhoon is subject to sea surface temperature (SST). Here, the following functional form is assumed as one of possible plausible models:

$$P_{i+1} = c_1 + c_2 P_i + c_3 P_{i-1} + c_4 T_i + \varepsilon_{P,i} \tag{8}$$

where T_i represents the SST at step i.

The goodness-of-fits of these plausible models is explored. The exploration is performed with respect to: AR(1) model vs. AR(2) model; whether or not the interrelation needs to be considered between the translation speed and the translation angle; whether the SST is necessarily included in the regression model. For this purpose, the corrected Akaike information criterion (cAIC) is employed. Note that the cAIC is capable of accounting for the non-normality of the residual terms, see e.g. Yanagihara[14]. It favors the model with a smaller value of cAIC. The cAIC is calculated for the model for each grid (latitude 4°× longitude 8°) for each month that contains at least 20 samples of the historical typhoon track record. Besides this, typhoons heading westward and eastward are separately treated in calculating the cAIC.

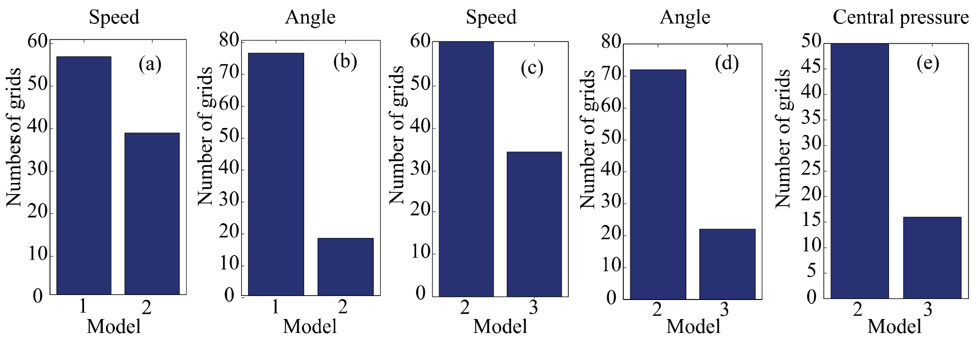

Figure 3. Histograms of the numbers of grids (and directions) with smaller cAIC values. The comparisons of these numbers are with respect to: (a) AR(1) vs. AR(2) for translation speed; (b) AR(1) vs. AR(2) for translation angle; (c) AR(2) for translation speed vs. interrelation model (Eq. (6)); (d) AR(2) for translation angle and interrelation model (Eq. (7)); (e) AR(2) for central pressure vs. model including SST (Eq. (8)). In the horizontal axis, AR(1) and AR(2) are indicated by 1 and 2, respectively, and 3 indicates the interrelation models for translation speed and translation angle and the model including SST for central pressure.

The numbers of the grids (and directions in case of the translation) with less cAIC are counted. In Figure 3, the histograms for these numbers are shown for the comparisons in those respects listed above, for September as an example. The results are: for all the months more grids favor AR(1) than AR(2), see (a) and (b) in the figure; more grids favor non-interrelation translation models, see (c) and (d) in the figure; more grids are in favor of not including SST in the model, see (e) in the figure.

2.3 *Estimation of the coefficients*

In order to reflect the spatial inhomogeneity and seasonality the regression models (Equations (1)-(8)) are developed separately for predefined spatial grids and time frames. The size of the grids must be determined by considering the balance between the numbers of samples available and the homogeneity of the characteristics of the samples in the grids. The average movements of the historical typhoons are approximately 0.4° in latitude and 0.8° in longitude in one time step (i.e. 6 hours). Considering that the set of the plausible models includes the second order of the (auto-) regression models, a grid size that can include two steps of typhoon transitions is required; hence, 0.8° in latitude and 1.6° in longitude at minimum. For the seasonality, it is postulated that the characteristics of typhoons do not significantly differ within one month period; hence, one month for the time frame. Furthermore, in order to taken into account the difference in the characteristics of the typhoon translation (speed and angle) eastward and westward, the models for the translation are developed separately for the two directions. These are the base line for estimating the coefficients of the regression models. However, in cases where sufficient number of samples is not available, the size of the spatial grid is expanded until the sufficient number of sample becomes available. The criteria for this are determined in accordance with the criteria on the validity of the regression analysis such as statistical power level and significance level, see Cohen[15], Cohen et al.[16].

2.4 *Modeling of residual terms*

Based on the functional forms of the plausible models, statistical characteristics of the residual terms are investigated. As shown in Figure 4, it is found that the residual terms for the state variables generally do not follow the normal distributions. This is consistent with the observation in Hall & Jewson[8]. In the figure, the normalized histograms of the frequencies of the residuals are shown together with the probability density functions of the two normal distributions that are fit to the histograms in two ways. One of the two normal distributions is obtained by considering all the data; the other normal distribution is obtained by neglecting both tails at quantiles larger than 1.5 times of the standard deviations. It either exaggerates the randomness if it is modeled by considering all the data (e.g. Graf et al.[10]) or underestimates the randomness if it is modeled by neglecting the tails (e.g. Emanuel et al.[6]).

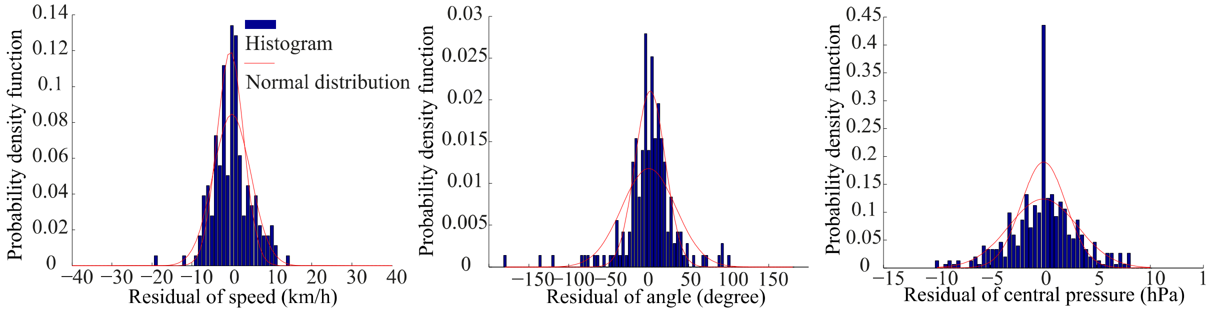

Figure 4. The normalized histograms of the frequencies of residuals for: (a) translation speed with model in Eq. (6); (b) translation angle with model in Eq. (7); (c) central pressure with model in Eq. (8). (a) and (b) are obtained by examining for typhoons in September travelling westward within the area bounded by the longitudes [124°E, 132°E] and the latitudes [24°N, 28°N].

The modeling of the residual terms becomes critical especially e.g. for the case when the typhoon transition model is utilized to predict the future transition of emerging typhoons. The consequences of the two ways of the approximations by the normal distributions on the simulated typhoon tracks are shown in the next section. It is not generally suggested to model the residual terms by the normal distributions; the empirical modeling of the residual terms, similar to the way by James & Mason[5], yet accounting for the spatial inhomogeneity and seasonality, or more flexible modeling such as mixture models are suggested.

3 PERFORMANCE OF MODELS

Based on the statistical investigation in the previous section, the following transition modeling is proposed: Eq. (6), (7) and (8) for modeling the state variables; the coefficients in the model are estimated by the method described in Section 2.3; the empirical distributions of the residual terms are employed. The performance of the proposed model is investigated by simulating typhoons by Monte Carlo techniques and then comparing several statistics of the typhoon transition with those of the historical typhoons. In the Monte Carlo simulation, the initial states of the typhoons are re-sampled from the initial states of the historical typhoons. Then, the transition of the typhoons is simulated using the transition model. Note that evolution of the typhoon intensity after landfall is simulated using a filling model, which takes basis in the modeling by Vickery et al.[17].

Figure 5a shows the tracks of the historical typhoons for the month September in the period between 1951 and 2006. Note that the other plots show the tracks of the simulated typhoons for September in the same period. Figure 5b illustrates the simulated typhoon tracks with the proposed model; Figure 5c with the modeling of the residual terms by the normal distribution considering all the data; Figure 5d with the modeling of the residual terms by the normal distribution considering the data only within the 1.5 times of the standard deviations. As can be clearly seen, two ways to model the residual terms by the normal distributions result in that the tracks are either overly fluctuated or overly smoothed. In contrast, it seems that the modeling of the residual terms by empirical distributions succeeds in reproducing the randomness in the historical typhoon tracks.

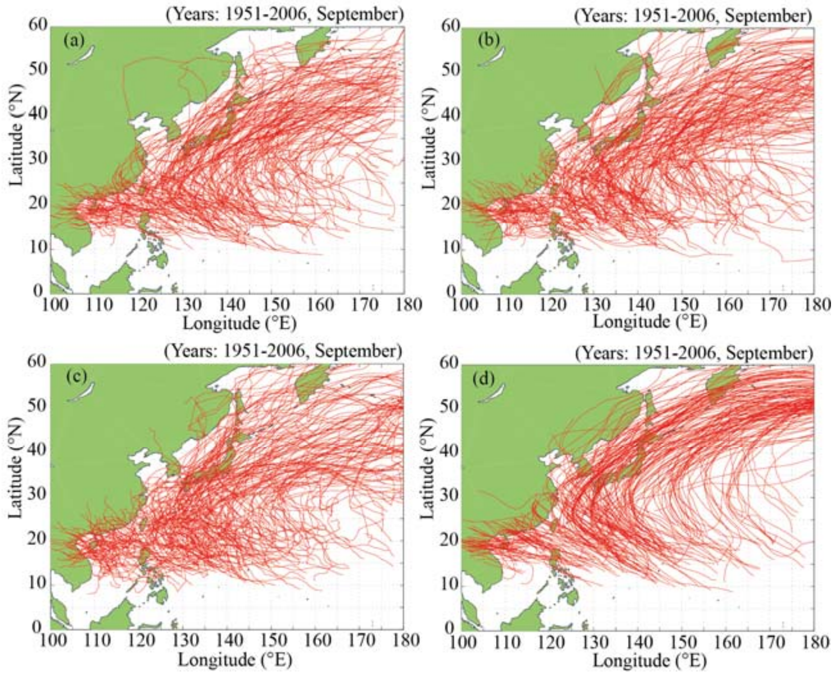

Figure 5. (a) Historical tracks occurred in September during 1951-2006; (b), (c) and (d) are the simulated tracks for the typhoon occurred in September over the same period. (b) is the result of proposed model; (c) is the result by modeling all the residual terms with normal distribution; (d) is the result by modeling the residual term with normal distribution disregarding both tails at quantiles larger than 1.5 times of standard deviation.

The statistics of the transitions of the typhoons simulated with the proposed model are calculated. These are compared to the statistics of the historical typhoons. Moreover, for comparison two competing (not recommended) models are developed and the statistics of the typhoons simulated by these models are also calculated. These competing models are, based on the proposed modeling, yet the ones whose coefficients of the regression models are estimated either by assuming the spatial homogeneity or by assuming no seasonality.

In Figure 6, cumulative annual average numbers (CAAN's) of typhoons are shown as the function of the translation speed, translation angle, and central pressure, respectively. These statistics are obtained by counting the typhoons traveling at the latitude 20°N or 35°N at the longitudes between 120°E and 160°E. CAAN's for translation angle and speed are the measures of the movements of the typhoons and CAAN's for central pressure is the measure of the intensity of the typhoons. The figure shows that the proposed model, as well as the second competing model (no seasonality), performs well in the sense that these agree with the statistics obtained by historical records at both latitudes. On the other hand, the simulations with the first competing model (spatial homogeneity) fail to generally reproduce the statistics obtained from the historical record.

In Figure 7, the statistics are shown for the month September only. It is seen that the simulated results from the proposed model fit the historical statistics for all three state variables at both latitudes. On the other hand, the first competing model fails to reproduce the statistics obtained from the historical record especially at 35°N, which may be accounted by the accumulation of errors in the simulations starting from lower latitudes. The second competing model also fails notably at 35°N, where the seasonality is more dominant.

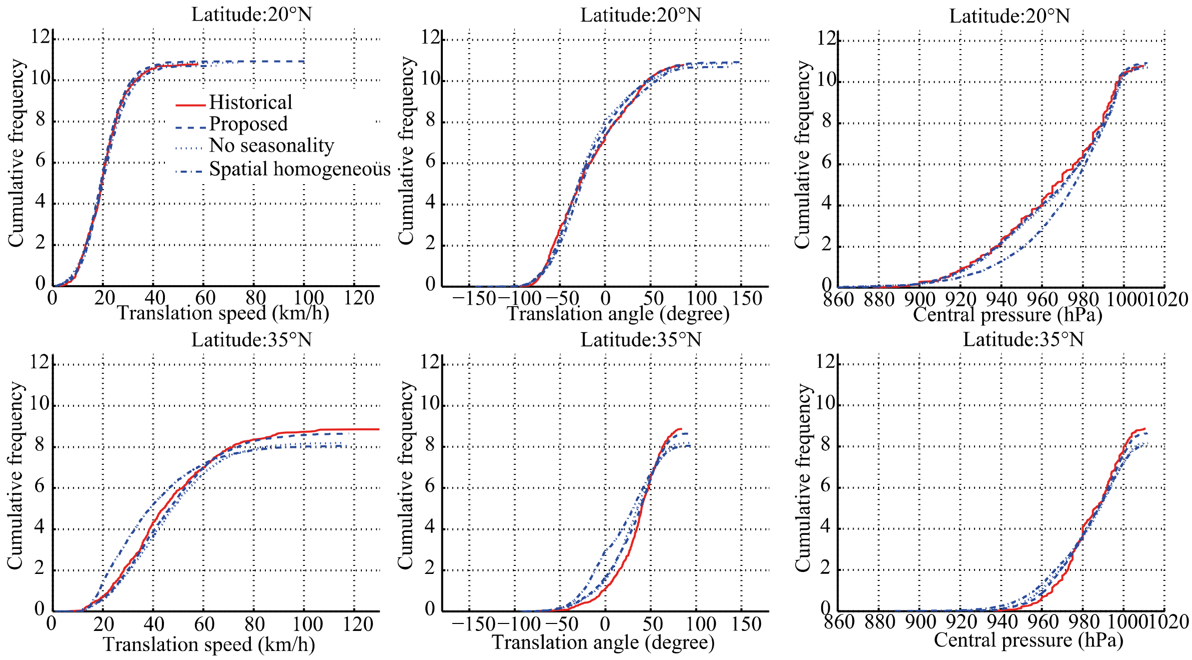

Figure 6. CAAN's calculated with the historical records and the Monte Carlo simulations as a function of the translation speed, translation angle and central pressure at latitudes 20°N and 35°N. By Monte Carlo techniques, 10000 times one- year typhoon events are simulated.

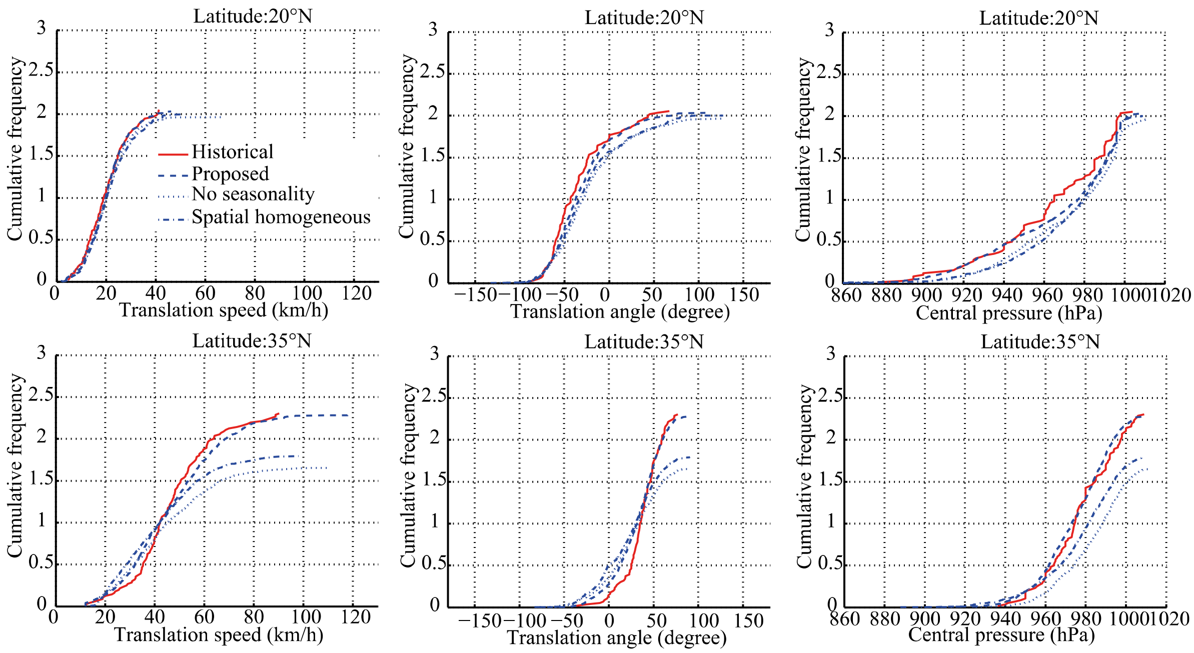

Figure 7. Cumulative average numbers of typhoons in September calculated with the historical records and the Monte Carlo simulations as a function of the translation speed, translation angle and central pressure at latitudes 20°N and 35°N. By Monte Carlo techniques, 10000 times one- year typhoon events are simulated.

4 DISCUSSIONS

The simulation results imply that the spatial inhomogeneity has to be appropriately taken into account in the modeling of the typhoon transition, reflecting the observation that the statistical characteristics show spatial inhomogeneity. The simulated results illustrated in Figure 6 and Figure 7 also show the importance of modeling of seasonality in the case that the typhoon transition of a specific season is of interest. However, the seasonality has not attracted sufficient attention in the statistical modeling of typhoon transition, except for the two of the models mentioned in Section 1; i.e. Emanuel et al.[6] and Graf et al.[10]. The consideration of the seasonality may become relevant for better understating and modeling of the typhoon transition under future climate change. Therefore, it is suggested to develop the transition models for different spatial grids and seasons separately where applicable; yet the optimal size of the grids is to be further investigated.

Although not illustrated in the present paper, it is found that the choice of the functional forms among the plausible models does not play significant roles in the statistical characteristics of the typhoon transition. Since the functional forms with less number of explanatory variables require less amounts of historical records to estimate the coefficients at same levels of confidence, it is suggested to employ simpler functional forms in the case where the numbers of the historical records are limited. On the other hand, if the forecasting of emerging typhoons is of interest, models with more numbers of explanatory variables have the advantage since they facilitate the use of more information.

5 CONCLUSIONS

The modeling of the typhoon transition is investigated by the extensive statistical analysis. First, the estimated ACF's and PACF's for the state variables of typhoon indicate that the second orders of the autoregressive models are sufficient. Second, by the cAIC, it is found that for many of the grids and months simpler functional forms for the modeling of the typhoon transition are in favor. Third, the choice of the functional forms is generally not relevant in the transition modeling; however, modeling of the residual terms has significant impact on the fluctuation of the simulated typhoon tracks. Fourth, the consideration of the spatial inhomogeneity is important in general and the consideration of the seasonality is also important in case the transition of the typhoon in a specific season is of interest. Based on these statistical analyses, the modeling of typhoon transition is proposed.

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