BASINWIDE TYPHOOON RISK MODELING AND SIMULATION FOR WESTERN NORTH PACIFIC BASIN

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ABSTRACT

This paper presents a novel basinwide typhoon risk modeling and simulation approach for the Western North Pacific (WNP) basin. It simulates synthetic typhoon tracks from genesis to lysis in the model domain bounded by 0° and 60°N latitude and 90° to 180°E longitude. The approach developed in this endeavor allows a typhoon to intensify when it travels on warm oceans, to weaken when it moves onshore and dwells on land, and to reintensify when it moves offshore again. Regression models for typhoon track motion and intensity are established at 5° by 5° grid resolution in the model domain. Typhoon genesis and lysis models are developed for the entire domain applying a two-dimensional Gaussian kernel smoother to historical typhoon genesis and lysis points, respectively. Optimal bandwidths for the smoothers are determined using Jackknife cross-validation technique. Typhoon best tracks (1951-2006) from Japanese Meteorological Agency (JMA) are used as the primary data supplemented by China Meteorological Administration (CMA) (1949-2006) and Hong Kong Observatory (HKO) (1961-2006) best tracks. Typhoon size is characterized by the radius of maximum winds and is modeled as a function of typhoon center latitude and intensity for typhoons over ocean and on land separately. Monte Carlo simulation techniques are employed to simulate synthetic typhoon tracks. Synthetic typhoons from this endeavor will ultimately be used to estimate property insurance losses and will take into account the correlation of losses from different countries/regions that are impacted by the same typhoon. Adequate quantification of loss correlation is critical in managing typhoon risks of globally-integrated corporations.

KEYWORDS: TYPHOOON, MONTE CARLO SIMULATION, KERNEL SMOOTHING, REGRESSION, CORRELATION, REINSURANCE/INSURANCE

Introduction

Tropical cyclones are among the most destructive and costly of all natural disasters, responsible for great losses of lives and extensive destruction of properties in many coastal areas in the world. Western North Pacific Ocean (WNP) is the most prolific basin for the tropical cyclone activity, accounting for roughly one third of all tropical cyclones globally. A tropical cyclone formed in the WNP is locally termed as “typhoon.” On average, China expects eight landfall typhoons annually [Wang and Ren (2008)]. Economic losses in the order of billions of US dollars have occurred to China during the past two decades [Guy Carpenter (2006)]. Property insurance losses in China are expected to escalate due to the rapid economic growth and accelerated insurance market penetration in the coastal region of China. Japan is also susceptible to typhoons. Typhoon Mireille of 1991 alone inflicted roughly ¥600 billion in insurance losses at the time of its occurrence [Fujii (1998)].
Typhoon risk has been of a great concern for the property insurance industry. The infrequent nature of catastrophic typhoons invalidates the standard actuarial loss estimation approaches. Computer models that are able to simulate tens, even hundreds, of thousands of synthetic typhoon tracks were developed in the past to compensate the scarcity of historical typhoon loss data and to achieve more stable typhoon loss estimates for regions where little to no historical data exist.

There have been two types of approaches in typhoon track modeling and simulation for property insurance loss estimation. One approach focuses on one country at a time by beginning typhoon track simulation at the moment of landfall or by simulating only the typhoon tracks that could cause damage to the country [Pawale et al. (2003) and Sousounis et al. (2008)]. Basinwide approaches, on the other hand, simulate typhoons from genesis to lysis and allow them to intensify, decay, and reintensify as they meander across multiple countries/regions. Among the noticeable basinwide models include those by [Rumpf et al. (2007)] for Western North Pacific typhoons, [James and Mason (2005)] for South Pacific tropical cyclones, and [Vickery et al. (2000), Emanuel et al. (2006), Hall and Jewson (2007), and Rumpf et al. (2009)] for North Atlantic hurricanes.

The WNP basinwide typhoon model developed by [Rumpf et al. (2007)] uses both JMA and Joint Typhoon Warning Center (JTWC) best tracks. The model divides the WNP basin into four zones and then splits the historical typhoon records into six classes according to the zones in which a typhoon track starts, passes, and dissipates. Complicated mathematical manipulations are devised to model and simulate typhoon frequency and track motion behaviors for each class. While splitting typhoons into classes may be more targeted in modeling and simulating typhoons of a particular class, additional uncertainty will be inevitably brought in simulation results as this approach dilutes the already scarce historical track information into six classes.

This paper presents a novel basinwide modeling and simulation approach for the WNP typhoons. The paper begins by discussing the typhoon best tracks used in this endeavor. The discussion then extends to the modeling of typhoon parameters that are crucial in estimating property insurance losses due to typhoons. Simulation of synthetic typhoon tracks using Monte Carlo techniques is also explained. The paper concludes its discussion by comparing the simulation results with historical observations and results from independent studies.

**Typhoon Best Track Data and Model Domain**

Four accredited institutions, CMA, HKO, JMA, and JWTC, have been collecting and maintaining their own 6-hourly best tracks for typhoons in WNP. These organizations have their own areas of responsibility and interests and hence have followed different standards and developed their own techniques to locate typhoons and to assess typhoon intensities. As a result, many substantial differences in typhoon location, intensity and wind distribution have been found among the best track datasets [Lander (2008) and Yu et al. (2007)]. JMA best tracks provide complete central pressures for typhoons with tropical storm intensity or greater since 1951. The typhoon central pressures were rigorously studied and validated using observations from land weather stations in Japan especially for the typhoons approaching and/or making landfall to Japan main islands [Fujii (1998), Fujii et al. (2002) and Mitsuta et al. (1979)]. Since the synthetic typhoon tracks simulated in this endeavor will ultimately be used to estimate property insurance losses, data quality for typhoons close to the countries/regions of concern is far more important than those far away in the ocean. JMA best tracks are hence selected as the primary data for typhoon modeling in this endeavor. CMA and HKO best tracks are used as supplementary data to model the typhoon filling in some countries/regions including China based on the same argument.
The model domain defined in this endeavor for typhoon modeling and simulation is bounded by 0° and 60°N latitude and 90° to 180°E longitude as shown in Figure 1. The model domain is further divided into 5° by 5° grids for modeling of typhoon track motion and intensity along the track. The 5° by 5° grid size chosen for typhoon track and intensity modeling is a tradeoff between the volume of JMA typhoon observations in the grids and the homogeneity of the observations within a grid. Selection of the grid size is encouraged by a successful modeling effort by [Vickery et al. (2000)] for North Atlantic hurricanes. The choice of smaller grids within the model domain also alleviates the problem of mixing high quality data observed for typhoons close to or over countries/regions of concern with the relatively low quality data for typhoons far out in the ocean.

![Figure 1: Model Domain and 5° by 5° Grids for Typhoon Modeling and Simulation](image)

**Typhoon Modeling Methodology**

The number of typhoons in a year is modeled by a Poisson distribution fitted to the JMA typhoon yearly counts between 1951 and 2006. Typhoon seasonality is defined by the starting date of a JMA typhoon record and is modeled by a Weibull distribution using JMA best tracks. The basinwide typhoon track modeling approach developed in this endeavor consists of typhoon genesis, intensity, motion, size and lysis models. Typhoon motion is characterized by the speed at which a typhoon moves (translation speed) and the direction in which a typhoon heads (heading direction). Typhoon filling models are developed for various countries/regions in the WNP rim to estimate typhoon intensity weakening after landfall.

Typhoon genesis and lysis models provide the likelihood that a future typhoon may form and dissipate in the model domain. Typhoon genesis and lysis probabilities for synthetic typhoons are achieved by smoothing the historical JMA typhoon genesis and lysis points, respectively. A two-dimensional Gaussian kernel smoother is used to smooth the first and last JMA track points observed in the model domain. The two dimensions are latitude and longitude. Optimal bandwidth, or standard deviation, for the Gaussian kernel smoother is defined as the bandwidth that achieves the maximum likelihood of the smoothed results fitting to the JMA observations. The optimal bandwidth is determined using the out-of-sample Jackknife cross-validation technique and the JMA first and last track points in the model domain are grouped by year. The optimal bandwidths are found in this endeavor to be 150 km and 140 km for typhoon genesis and lysis models, respectively. Shown in Figure 2 is the log-likelihood score for various bandwidths for JMA typhoon genesis points. The log-likelihood score reaches its maximum when the bandwidth is 150 km. Detailed explanation of kernel smoothing and Jackknife cross-validation technique can be found in [Hall and Jewson (2007)].

The regression models for typhoon motion and intensity are established using JMA 6-hourly best track observations for each of 5° by 5° grids shown in Figure 1. Typhoon intensity in this endeavor is measured by typhoon central pressure deficit, i.e., the difference between the peripheral pressure (1,013 hPa) and typhoon minimum sea level central pressure.
Regression models for typhoon intensity, heading direction, and translation speed are specified in this endeavor as below

\[
I_i = a_0 + a_1 \cdot I_{i-1} + a_2 \cdot I_{i-2} + a_3 \cdot \psi_i + a_4 \cdot \lambda_i + \varepsilon_I
\]  
\[
H_i = b_0 + b_1 \cdot H_{i-1} + b_2 \cdot H_{i-2} + b_3 \cdot \psi_i + b_4 \cdot \lambda_i + \varepsilon_H
\]  
\[
T_i = c_0 + c_1 \cdot T_{i-1} + c_2 \cdot H_i + c_3 \cdot \psi_i + c_4 \cdot \lambda_i + \varepsilon_T
\]

Where \(a_0, a_1, a_2, a_3\) and \(a_4\), \(b_0, b_1, b_2, b_3\) and \(b_4\), and \(c_0, c_1, c_2, c_3\) and \(c_4\) are regression constant sets for each 5° by 5° grid in the model domain and for typhoon intensity, heading direction, and translation speed, respectively; \(I_i, I_{i-1}\) and \(I_{i-2}\) are typhoon intensity in hPa at the current time, 6 and 12 hours earlier, respectively; \(H_i, H_{i-1}\) and \(H_{i-2}\) are typhoon heading direction at the current time, 6 and 12 hours earlier, respectively; \(T_i\) and \(T_{i-1}\) are typhoon translation speed at the current time and 6 hours earlier, respectively; \(\psi_i\) and \(\lambda_i\) are typhoon center latitude and longitude at the current time; and \(\varepsilon_I, \varepsilon_H\) and \(\varepsilon_T\) are random error terms for typhoon intensity, heading direction, and translation speed, respectively. The regression models are diagnosed carefully by examining the residuals of the regression models. Shown in Figure 3 are the regression residuals for typhoon intensity in a grid. There is no detectable trend in the residuals and the residuals can be approximated by a normal distribution with zero means.

Typhoon size in this endeavor is defined by the radius of maximum winds. It has been observed that WNP typhoons tend to be larger in size than its counterpart in North Atlantic. However, due to the lack of information in WNP, the radius of maximum winds models established using North Atlantic hurricane observations are used in this endeavor, instead. Typhoons on land tend to be smaller in size than those over ocean as they tend to contract more due to the high land surface friction. Therefore, two separate radius of maximum winds.
models developed by [Vickery and Wadhera (2008)] for North Atlantic hurricanes over ocean and on land are used in this endeavor.

\[
\ln( R_{\text{max, Ocean}} ) = 2.556 - 0.00005963 \cdot I^2 + 0.0458 \cdot \psi + \varepsilon_O \tag{4}
\]
\[
\ln( R_{\text{max, Land}} ) = 3.421 - 0.000046 \cdot I^2 + 0.00062 \cdot \psi^2 + \varepsilon_L \tag{5}
\]

Where \( R_{\text{max, Ocean}} \) and \( R_{\text{max, Land}} \) are radii of maximum winds in km for typhoons over ocean and on land, respectively; \( I \) is typhoon intensity in hPa; \( \psi \) is typhoon center latitude; \( \varepsilon_O (=0.456) \) and \( \varepsilon_L (=0.466) \) are random normal error terms for typhoons over ocean and on land, respectively. As implied by the above equations, the radii of maximum winds of intense typhoons at low latitudes tend to be smaller than those of weak typhoons at high latitudes.

Typhoons begin to weaken as they move onto land primarily because the amount of latent heat required to maintaining their intensity is being cutoff. Similar to the filling models used by [Fujii (1998) and Vickery (2005)], the typhoon filling model employed in this endeavor is a function of the typhoon intensity at landfall and the time elapsed after landfall.

\[
\Delta p(t) = \Delta p_0 \cdot e^{-\alpha t} \tag{6}
\]

Where \( \Delta p_0 \) and \( \Delta p(t) \) are typhoon central pressure deficits at landfall and at the time elapsed after landfall, \( t \), respectively; and \( \alpha \) is rate of typhoon weakening, or filling rate. Typhoon filling rate has been found to be variable and is influenced by the typhoon intensity and size at landfall [Vickery (2005)] and the environmental conditions such as land use/cover and topographic features like mountains [Wong et al. (2008)].

Separate filling rate regression models are established for the Korean peninsula, the Philippines, and Taiwan using JMA best tracks. Continental Asia is divided into three regions based on the topographic features in these three regions. HKO and CMA best tracks are used for those three regions. Japan is further divided into four areas as suggested by [Fujii (1998)]. Regression equation (7) is employed in this endeavor to model the filling rates for the typhoons made landfall in Areas A, B and C in Japan as shown in Figure 4 while Equation (8) is used to model the filling rate for typhoons in Area D in Japan and other countries/regions.

\[
\alpha = a_0 + a_1 \cdot (\Delta p_0 / R_{\text{max}}) + \varepsilon \tag{7}
\]
\[
\alpha = a_0 + a_1 \cdot \Delta p_0 + a_2 \cdot \psi + a_3 \cdot \lambda + \varepsilon \tag{8}
\]

Where \( a_0, a_1, a_2 \) and \( a_3 \) are regression constants; \( \Delta p_0 \) is typhoon central pressure deficit at landfall; \( R_{\text{max}} \) is typhoon radius of maximum winds at landfall in km; \( \psi \) and \( \lambda \) are typhoon center latitude and longitude, respectively; \( \varepsilon \) is random error term. Regression constants are achieved using historical observations for each area/country/region defined in this endeavor. Equation (7) introduces the radius of maximum winds in the regression as suggested by [Vickery (2005)] since \( R_{\text{max}} \) information is available in [Fujii (1998)] in the form of radius of maximum cyclostrophic winds. Introduction of \( R_{\text{max}} \) in the filling rate models improves the fit of the regression models to historical observations as shown in Figure 4 for Area B in Japan as an example.

![Figure 4: Area Definition for Japan and Regression Results for Area B](image-url)
Typhoon Simulation and Validation

Monte Carlo simulation techniques are employed for simulation of synthetic typhoons. Simulation starts with a simulation year. The number of the typhoons in a simulation year is drawn from a Poisson distribution fitted using the JMA yearly typhoon counts between 1951 and 2006. Typhoon seasonality is captured by simulating the date of a synthetic typhoon from Weibull distribution based on the JMA data. Figure 5 shows the comparison of Poisson distribution used in simulation with the JMA annual typhoon counts in 1951-2006. As shown in Figure 5, the Poisson distribution not only provides a reasonable fit to the JMA annual typhoon counts but also projects the annual typhoon counts that have not observed in the past.

![Figure 5: Poisson Distribution and JMA Annual Typhoon Counts in the Model Domain](image)

To simulate a synthetic typhoon track, a JMA typhoon track is first randomly selected. The latitudes and longitudes of the first (genesis) and second track points in the selected JMA track are perturbed together using the two-dimensional Gaussian kernel smoother with the optimal bandwidth derived in this endeavor for typhoon genesis. These perturbed locations are used as the first two points for the synthetic track. Intensities, heading directions and translation speeds of the first two points of the synthetic typhoon track are taken directly from the selected JMA track without alteration. The synthetic typhoon track is then propagated 6-hourly using the grid-based regression models discussed earlier in this paper for typhoon intensity, heading direction and translation speed. Variability in intensity, heading direction and translation speed is introduced for the synthetic typhoon by sampling the random error terms in the regression models. The random error terms are approximated by normal distributions with zero means. Typhoon filling models take place when a synthetic typhoon moves onshore and dwells on land for at least six hours. A synthetic typhoon is allowed to re-intensify when it moves offshore onto ocean again as do the typhoons in the real world. A synthetic typhoon terminates either through typhoon lysis model, or when the typhoon central pressure exceeds 1,013 hPa, or when it moves out of the model domain. Figure 6 shows the synthetic typhoon track pattern in comparison with the JMA best track for the same 56-year period. The synthetic typhoon tracks match in overall pattern with JMA 56-year best tracks.

![Figure 6: JMA Best Tracks and Synthetic Typhoon Tracks for a 56-Year Time Period](image)
The modeling and simulation approach developed in this endeavor is further validated by comparing the simulated landfall typhoon frequency with historical observations for the countries/regions of concern. It is a meaningful validation since this basinwide approach starts the simulation of a synthetic typhoon track at its genesis which tends to be far away from any country/region in the WNP rim. Synthetic typhoon tracks have to travel a long way before reaching any country/region. A reasonable match of the simulated landfall typhoon counts with historical observations can be achieved only when typhoon motions are properly modeled and simulated. Proper simulation of landfall typhoon frequency is critical for property loss estimation as the majority of property losses are caused by landfall typhoons. As an example, simulated annual landfall typhoon counts to Japan are compared with JMA observations. The comparison shown in Figure 7 is based on a 10,000-year simulation.

The importance of simulation of typhoon intensity at landfall can be manifested by the fact that intense hurricanes (Saffir-Simpson categories 3, 4, and 5) make up only about 21% of US landfall hurricanes but account for about 83% of US hurricane losses [Pielke and Landsea (1998)]. Simulated typhoon intensities at landfall are compared with JMA best tracks and other independent studies [Fujii (1998)] for the areas in Japan suggested by [Fujii (1998)]. The results for Areas A and B are shown in Figure 8 as an example. The definition of the areas in Japan can be found in Figure 4.

Concluding Remarks

The basinwide typhoon track modeling and simulation approach developed in this endeavor utilizes all available typhoon information to extend typhoon risk assessment to regions where little or no historical typhoon observations are available. The basinwide simulation model starts typhoon track simulation from genesis to lysis and allows typhoons to intensify, weaken, and re-intensify as do typhoons in the real world. Validation results show the approach developed in this endeavor is capable of simulating synthetic typhoon tracks that are in a reasonable match with JMA best tracks and other independent studies in terms of overall typhoon track pattern, landfall frequency and intensity for countries/regions of concern. Additional validation will be made to assure that the synthetic typhoon tracks
simulated in this endeavor will adequately reflect the correlation of landfall typhoon frequency and intensity between countries/regions observed by JMA/CMA/HKO/JTWC best tracks. This is an important feature especially for globally-integrated corporations since they are more likely to be exposed to typhoon hazard in multiple countries/regions.

References


