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# Improved Hypothetical Typhoon Generation Technique for Storm Surge Frequency Analyses on the Southwest Korean Coast

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## ABSTRACT

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In coastal disasters storm surges accelerate damages. To establish appropriate countermeasures, a probabilistic approach to storm surge prediction is required, particularly in case of the historical record of cyclone populations is slim. Among historical typhoons that affected the southwest coast of Korea, some arrived by passing through the Yellow Sea after landfall on southeast mainland China. This study aims to incorporate resurgence and the mid-latitude transition effect to generate more realistic synthetic storms. Synthetic typhoon simulations and surge analyses were performed by taking probability density function parameters from historical storm data, and the simulations were automated as batches using the Perl script. The results showed that the proposed synthetic generation scheme, which models the resurfacing effect, can produce realistic storm frequency results for the Korean coasts. This work can be applied in further vulnerability analyses of coastal zone management.

**ADDITIONAL INDEX WORDS:** *Resurgence, synthetic storm, filling effect, GEV, PDF.*

## INTRODUCTION

Global climate change has led to sea-level rise and associated increases of storm surge inundations over past years. Therefore, to prepare an appropriate coastal zone management (CZM) plan for the increasing probability of coastal disasters induced by storms, accurate predictions of storm surges are required that consider tidal hydrodynamics. One approach to this challenge is to determine the frequency of return periods in terms of surge elevation based on historical typhoons records. However, this approach may not be satisfactorily applicable when the historical record is insufficient. For example, there were only 99 typhoons that directly affected the Korean coast from 1950 to 2016, and therefore recurrence studies for 50- or 100-year return periods are not appropriate. Therefore, generating a well-designed statistical population of synthetic storms that represent historical typhoon characteristics is imperative to improve predictions.

However, according to previous research (Kim and Suh, 2016), storm surges based on synthetic typhoons generated using Topical Cyclone Risk Model (TCRM; Summons and Arthur, 2012) on the west coast of Korea (WCK) showed slightly different results compared to those predicted on the south coast of Korea (SCK). Of the storms synthesized based on the previous approach, none were predicted to cross the western boundary. Moreover, only 11.4% directly followed the Yellow Sea (YS). The TCRM-based generation of synthetic storms, which adopts decay parameters set

for the state of Florida using only nine storm data sets (Vickery and Twisdale, 1995), most of the generated typhoons were predicted to land on mainland southeast China (SEC), and showed a rapid decay tendency indicating they would not be expected to resurface. This rapid decay tendency follows known storm extinction patterns induced by the filling effect: any tropical storm that reaches land loses its storm potential as shown in the following exponential decay equation.

$$\Delta p(t) = \Delta p_0 \exp(-at) \quad (1)$$

where  $\Delta p(t)$  is the difference between the central pressure of the storm and the far field pressure;  $t$  hours after landfall;  $\Delta p_0$  (mb) is the difference between the central pressure of the storm and the far field pressure at the time the storm makes landfall; and  $a$  is the filling constant.

From this expression, the decay of the central pressure in the depression is very sensitive to the parameters in the equation. However, TCRM adopts a modified decay parameter following Vickery (2005), which includes the radius of maximum wind (RMW) of storms to represent realistic decay. Nevertheless, the expression insufficiently represents the generalized filling effects. Moreover, it may not be extended to other sites such as because of different geological effects, etc.

As shown in Figure 1, historical typhoons track the Korean coast on diverse paths. Most of the tracks crossed directly over the Ryukyu Islands. However, some of the tracks first hit the China coast or landed on SEC and then resurfaced over the YS and finally affected the WCK. These types of resurgence

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characteristics must be incorporated into synthetically generated typhoon tracks.

One reason for inaccurate track predictions may be the unrealistic logic of synthetic storm generation by TCRM, such as the biased parameters used to establish the rapid filling effect after landfall and/or failing to consider resurfacing cases. Historical tracks affecting the Korean Peninsula show the resurgence of tropical storms that previously hit SEC. According to previous tropical storm hazard researches on filling effects after landfall, *e.g.* Vickery and Twisdale (1995), Vickery (2005), Vickery *et al.* (2009), Xiao, *et al.* (2011), and Zhao *et al.* (2013), central pressure could lose some of its potential over the sea surface and then recover (fill) after landfall, depending on the travelling time and distance after landfall. Most researches on storm hazards consider maximum wind speed, the RMWs, and the central pressures in relation to their effects on inland facilities. From this perspective, there is no need to consider storm strength recovery as the storm redirects back to seaward. Regardless, insufficient research has been conducted on the resurgence of storm characteristics after landfall.

In the previous study, Kim and Suh (2016) proposed a modified approach to the generation of synthetic storms by TCRM by adjusting the maximum radii, wind speed, and central pressure of synthetic storms based on historical track data to represent the most appropriate probability. They generated a total of 177,244 synthesized storms by a fully automated procedure using a Perl script, which force as input to an ADvanced CIRCulation (ADCIRC) model that incorporates random tidal motion. By comparing the results of the hypothetical typhoon surges with observed data, they found that the synthetic storms based on historical tracks generally reproduced probabilistic surge elevations and showed similar characteristics to those actually observed. However, comparing the generated probabilities with the historical record, the WCK showed somewhat underestimated tendencies in relation to the SCK. That is, comparing the frequencies at which the typhoon tracks crossed the southern or western boundaries, fewer synthesized tracks were generated than historical record (Kim and Suh, 2016). Rapid decay after landfall on SEC was expected to be the reason for these results. In particular, the storm characteristics were lost very rapidly in relation to the exponential decay resulting from the time and travelling distance over land.

Approximately 30% of typhoons affect WCK after landing on SEC and recovering on the YS, and the relevant wind field characteristics show different patterns than those that appear in decayed storms on land. Therefore, synthetically generated resurgence storms that are representative of historical extratropical transition characteristics are sorely needed (Jones *et al.*, 2003). Toward this objective, this paper provides storm surge analyses that not only accounts for traditional storms travelling from the northwestern Pacific Ocean to the YS but also considers storms that land on SEC and then resurface to affect WCK and SCK. One purpose of this study is to enhance the filling function of TCRM by accounting for the resurfacing of typhoons over the YS based on historical typhoon track characteristics. In addition, transitioning effects arising in mid-latitude (Bruneau *et al.*, 2017; Jones *et al.*, 2003) have been introduced in the TCRM framework by assigning appropriate probability density functions (PDFs), which vary with latitude in the vicinity of 30° N.

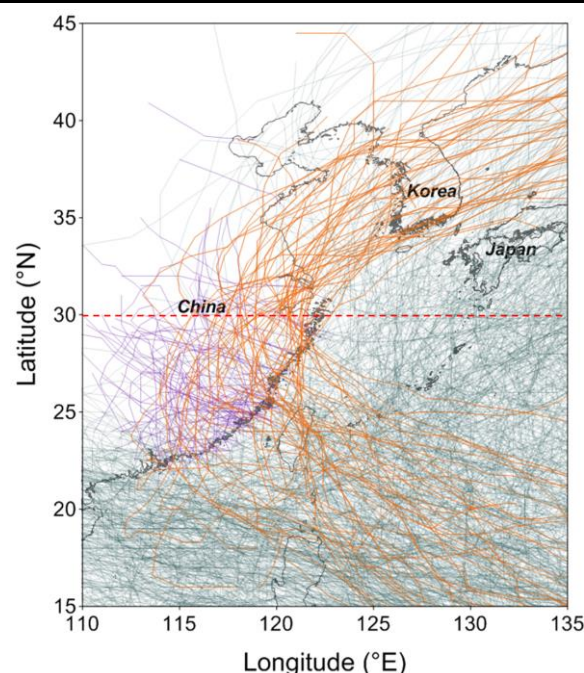


Figure 1. Historical typhoon tracks through SEC from 1951 to 2015: purple indicates decayed storms and brown indicates resurfaced storms that affected the Korean peninsula.

## METHODS

In this study, to determine the general probability of resurfaced typhoon occurrences, PDF analysis was performed on the 233 historical tracks that landed on SEC during 1951–2016, archived at Regional Specialized Meteorological Center (RSMC). Of these tracks, 114 typhoons decayed on SEC as they headed west, whereas 119 tracks turned east and resurfaced over the YS. To find and define appropriate probabilities for the tracks, generalized extreme value (GEV) analyses were performed using the R-package in extRemes (Gilleland and Kakz, 2016). Heading directions after landfall on SEC were defined as negative (positive) by comparing locations at every 6 h interval, *i.e.*, counter-clockwise (clockwise) with respect to north, because negative (positive) directions exhibited a decay (resurgence) tendency. As seen in Figure 2, the PDF for the decay and resurgence tracks followed the GEV and exhibited Gumbel and reverse Weibull distributions, respectively. Equation (2) represents the GEV distribution with the parameters,  $\xi$  (shape),  $\sigma$  (scale), and  $\mu$  (location). In addition, resurfaced typhoons strongly inflected in the vicinity of 30°N latitude because of the mid-latitude transition effect, as shown by the quite different PDFs in Figure 2, *i.e.*, the Gumbel and reverse Weibull distributions below and above 30°N, respectively. Detailed parameters for the decay (resurgence) PDFs are 0 (−0.61), −32.03 (35.77), and 59.60 (37.90) for  $\xi$ ,  $\sigma$ , and  $\mu$ , respectively.

$$f(x) = \begin{cases} \frac{1}{\sigma} \left[ 1 + \xi \left( \frac{x-\mu}{\sigma} \right) \right]^{-\frac{1}{\xi}} \exp \left[ - \left\{ 1 + \xi \left( \frac{x-\mu}{\sigma} \right) \right\}^{-\frac{1}{\xi}} \right] & \xi \neq 0 \\ \exp \left( -\frac{x-\mu}{\sigma} \right) \exp \left[ -\exp \left( -\frac{x-\mu}{\sigma} \right) \right] & \xi = 0 \end{cases} \quad (2)$$

When generating synthetic typhoons, a zonal adoption for the most appropriate PDF method was applied based on PDF parameters drawn from historical tracks. Thus, to generate resurgence typhoons, each 5° of latitude and longitude was represented by a single cell as shown in Figure 3 (b), and then a zonal PDF from the RSMC dataset was analyzed (Table 1). Moreover, two distinct categories were established by checking each track's landfall zone on SEC to generate realistic hypothetical storms that reproduce the decay or resurgence trends, incorporating the extratropical transition effect (Jones *et al.*, 2003) by assigning proper PDF parameters.

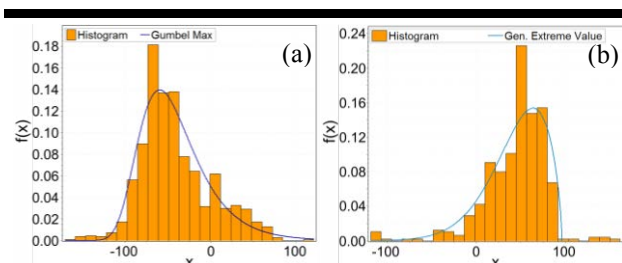


Figure 2. Fitted PDF of heading directions for typhoons that landed on SEC and: (a) decayed on land or (b) resurfaced over YS. (0°: north; negative: west; positive: east).

Table 1. PDF parameters of typhoon headings, in degrees, based on historical tracks shown in the SEC zones in Figure 3 (b).

Zone	Type	Shape	Scale	Location
1	GEV (Weibull)	-0.56	38.42	12.49
2		-0.66	36.03	25.36
3		-0.33	43.62	-24.07
4		-0.10	31.19	-34.62

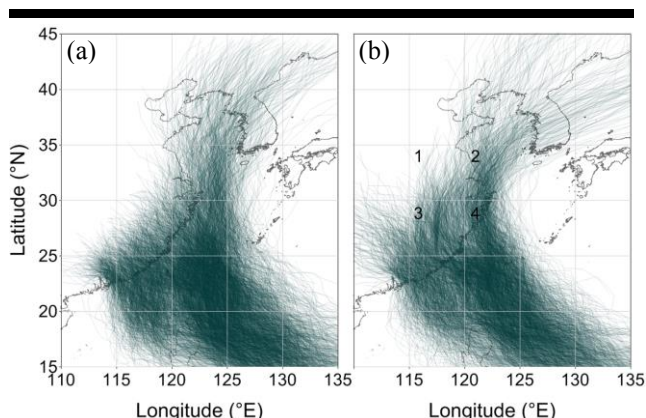


Figure 3. 25,000 synthesized typhoon tracks affecting Korean coasts after landing on SEC: (a) without and (b) with improvement.

After generating 174,689 synthetic storms, an ADCIRC+SWAN coupled model was automatically simulated based on the grid NWP-57k, which has 56,617 vertices and efficiently fitted the YS surge modelling (Suh *et al.*, 2015). Surge elevations could be determined based on synthesized storm generation using batch script files written with Perl, and frequency analyses for the major target stations on the WCK and SCK were then performed with the R package in extRemes.

In reproduction of surge heights by ADCIRC+SWAN model for each single synthesized track, 30 days of total simulation periods were considered, including an initial 15 days of ramp-up to remove instabilities owing to the cold start. Furthermore, randomly assigned tidal conditions were incorporated because nonlinear effects of tide and surge in macro-tidal environments such as WCK are major determinants of surge elevations.

## RESULTS

In the previous study (Kim and Suh, 2016) of historical typhoon tracks affecting the Korean peninsula, the results showed that 25.3% of total storms were passed through zones W1 and W2; 11.5% followed the Yellow Sea directly and the rest (13.8%) came across the YS after hitting mainland of China, turning to the northeast. However, storms synthesized by the existing TCRM, shown in Figure 3 (a), do not represent the actual physical characteristics of storm resurgence effect for the aforementioned reasons. Thus, 11.2% of total storms were predicted to pass through zones W1 and W2, affected the Korean coast after hitting SEC and turning northeast (Figure 4).

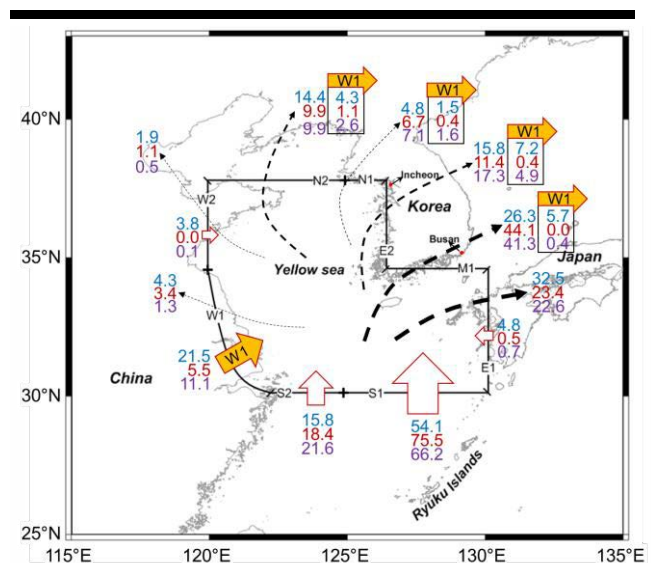


Figure 4. Typhoon headings affecting or predicted to affect the Korean peninsula: blue, brown, and purple indicate historical, synthetic tracks generated by the previous study, and synthetic tracks generated by this study, respectively. Storm tracks incoming via W1 (from SEC) diverge into four directions.



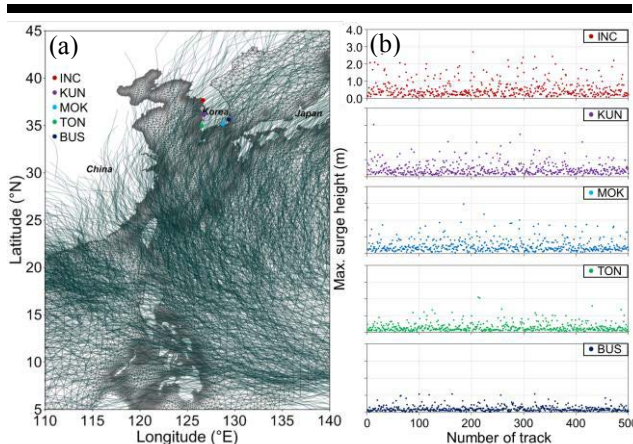


Figure 5. (a) Synthesized typhoon tracks and (b) occurrences of surge heights on the WCK and SCK for the 500 dataset.

Following the proposed typhoon track generation scheme, a total of 174,689 storms were generated and simulated to evaluate storm surge frequencies on the WCK and SCK (Figure 5). Because the observed dataset is confined to within approximately 55 years, the simulated dataset was also arbitrarily selected for a corresponding period, *i.e.*, 50 storm surges each station at Incheon, Kunsan, and Mokpo on the WCK and at Tongyeong and Busan on the SCK. The simulated frequency analysis results based on extreme values are summarized in Table 2 in comparison with the observed values. The table shows that the proposed method generated almost the same results as the recorded surge elevation when the dataset is confined to a similar population; however, when the population grows, the simulated surge for the 100-year return period grows higher than both the historical record and the simulated results based on the small population, which suggests even higher surges may occur in the future.

Table 2. 50- and 100-year of return period surge heights corresponding observed (in shading column), and 30 to 500 synthesized storms at selected stations.

Station / Obs. period (y)	50- (100-) year return period surge height (m)					
	Obs.	30	50	100	150	500
INC / 49 (Incheon)	1.22 (1.37)	1.12 (1.27)	1.22 (1.39)	1.26 (1.43)	1.40 (1.59)	1.47 (1.68)
KUN / 31 (Kunsan)	1.44 (1.82)	1.42 (1.80)	1.46 (1.82)	1.59 (2.05)	1.74 (2.31)	1.84 (2.49)
MOK / 54 (Mokpo)	0.81 (0.86)	1.02 (1.14)	1.04 (1.17)	1.02 (1.15)	1.17 (1.32)	1.24 (1.40)
TON / 35 (Tongyeong)	0.86 (0.96)	0.57 (0.64)	0.67 (0.76)	0.75 (0.85)	0.76 (0.96)	0.79 (0.89)
BUS / 55 (Busan)	0.62 (0.70)	0.57 (0.71)	0.63 (0.79)	0.77 (1.01)	0.84 (1.10)	0.80 (1.06)

## DISCUSSION

In the analyses of coastal vulnerability to storm surges, a probabilistic approach based on mathematical random generation is preferred because such a method can minimize numerical uncertainties and represent a more realistic situation with increasing numbers of synthesized tracks. Lin *et al.* (2010) suggested that return periods of storm surges could be used to evaluate hurricane-induced inundations of New York City, applying 7,555 synthesized storms. Kim and Suh (2016) applied 177,244 synthesized storms based on the approach of TCRM. Although several thousand tracks were used in the return period frequency analyses, the results showed different patterns with regard to WCK compared with the recorded historical tracks, primarily because the TCRM predicts a very rapid filling effect for landfall cases and neglected the resurgence effect.

Although some research papers (Powell *et al.*, 2005; Vickery, 2005) considered the filling rate in their analyses of storm hazards affecting land, none of these considered resurgence phenomena, which cannot be neglected in the analyses of certain coastal hazards, such as for the WCK. In addition, filling rate uncertainties arose because only a few populations were used in the analysis, representing a highly limited dataset from which it is difficult to generalize decay formulae. Moreover, diverse surface canopy conditions further hinder determinations of unified parameters for decay rates. For these reasons, Vickery and Twisdale (1995) distinguished three different zones: Florida, Gulf of Mexico, and Atlantic coast, each reflecting different zonal geological conditions. Vickery (2005) also included a radius maximum wind parameter and obtained improved results. Regardless, spatially different surface boundary layer conditions must be established to select decay parameters in further studies. In addition, to reflect the diverse effects of land conditions, local terrestrial altitudes and spatially varying canopy conditions should be incorporated in a newly enhanced tropical storm generation technique.

The recorded tracks of typhoons that resurfaced after landing on SEC showed an obvious inflection pattern around the latitude of 30°N due to the mid-latitude effect. The consideration of strongly inflected extra-tropical transition effects is one of the major challenges in generating synthetic storms and associated surge analyses. A similar issue is the transitioning of cyclones in a typical mid-latitude region because of extra-tropical characteristics (Bruneau *et al.*, 2017). They indicated that significant errors and bias can occur when assuming only tropical cyclone wind fields. To overcome such errors, the researchers incorporated the transitioning of a typhoon at mid-latitudes in their simulations of storm surge risks along the Japanese coasts.

However, when parametric representations of wind were adopted to generate large ensembles of storms, the simulated results do not fully encompass the randomness shown in the historical cyclone record. Moreover, because transitioning systems can exhibit damaging winds on the left side of the moving cyclone (Loridan *et al.* 2014), both the SCK and the WCK can be affected by resurfaced typhoons. Therefore, to overcome some limitations of existing cyclone generation tools, typical inflecting or transitioning schemes can be applied. In the present paper, PDF parameters drawn from archived typhoon tracks of RSMC were applied to the specified regions to account for the mid-latitude effect. Thus, the filling effect and

transitioning patterns were satisfactorily incorporated to synthesize resurgence typhoon tracks after landfall on SEC, and the resurfacing modeled by introducing improved parameters reflected historical track patterns.

The surge elevations simulated using the improved typhoon generation scheme considering resurgence and the mid-latitude effect show the possibility of high surges on the WCK. Such high surges did not occur during past recording periods; therefore, extreme value analysis based on limited observed data cannot be guaranteed to agree for 100 years or longer. However, the results of this study suggest that peak surge elevation can be higher than values based on the small population in the historical record. However, for the Busan and Tongyeong stations on the SCK, surge heights are almost the same regardless of population mass. Further study is required to figure out detailed responses on storm surge frequency for SCK.

### CONCLUSIONS

The ability to synthesize more storms yields an improved understanding and associated preparedness for storm hazards. To enhance confidence in synthetic storm results, seven sets of storm populations, each comprising approximately 25,000 random storms, were generated by modifying an existing automatic generation tool, TCRM. To represent realistic track patterns, some improvements were added to the TCRM Python code to represent moderate decay after landfall on SEC and to specify locally defined PDFs drawn from historical datasets to account for the mid-latitude effect and extra-tropical transitioning.

The results indicate that the proposed method improves predictions of the occurrence of storm heading frequencies, particularly those affecting the Korean peninsula after landfall on SEC, and the predicted results resemble historical paths. Because of the resurgence effect, storms showed higher incidences on the YS than previous predictions, especially the anticipated storm surge probability for the WCK. Simulated return periods of storm surges on the WCK and SCK showed reasonable values compared to surge elevations drawn from a small population of less than 100 years.

Frequency analysis of the surge heights of hypothetically generated storms showed the possibility of higher surges on the WCK. Surge elevations for corresponding return periods drawn recorded data are almost the same as the simulated surges. However, further work on the validity of surge height modeling and frequency analysis should be performed to confirm the findings of this study.

Thus, the proposed consideration of the resurgence effect could be satisfactorily applied not only to storm surge analysis but also to similar probability studies in other cases of regional CZM. However, more detailed studies on the connection between sea-level rise and return periods should be considered in further studies to prepare appropriate coastal disaster preventions.

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