A Multi-Hazard Assessment Framework for Tropical Cyclones in South Korea: Data Development and Joint Probability Analysis

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Abstract: Tropical cyclone (TC)-induced coastal hazards are inherently multi-hazard, typically involving strong winds, storm surge, and heavy rainfall. While a range of methods has been developed to assess individual and combined TC-induced coastal hazards along the North Atlantic coast of the United States, comparable multi-hazard assessment frameworks remain somewhat limited in other regions, such as the Northeast Asian coastal zone. This study aims to identify and evaluate the available data and methodologies for assessing compound TC-induced coastal hazards in South Korea. Our assessment reveals that limited data availability and the lack of predictive hazard models pose significant challenges to the direct application of North Atlantic–based hazard assessment approaches in this region. To address these challenges, extensive data processing was conducted to refine and augment historical TC and observational datasets. Local gauge records were matched to historical TC events and spatially and temporally interpolated to extract storm-specific peak values and occurrence times for storm wind, surge, and rainfall. Finally, a trivariate joint probability analysis was conducted to estimate the return periods of compound hazard events using multiple logical constructions (e.g., union and intersection of exceedances). The results highlight the importance of accounting for compound effects in TC hazard assessment and provide a foundation for developing region-specific multi-hazard frameworks for coastal risk analysis in South Korea.

1. INTRODUCTION

Infrastructure in South Korea near coastal regions can be exposed to typhoon (or, more generally, tropical cyclone (TC)) induced hazards. Recently, several studies have focused on predicting the behavior of TCs in the Western North Pacific (WNP) region and have projected an increasing frequency of high-intensity TCs [1-5].

TC-induced coastal hazards are inherently compound events, meaning TCs cause a combination of hazards, such as locally intense precipitation, storm surge, and river flow. This complexity has led to a growing need for comprehensive assessments of coastal hazards resulting from TC events in the South Korean region and throughout the world. This study aims to identify opportunities to adapt and extend existing probabilistic analysis methods for TC-induced hazards to the South Korean region, building on established methodologies in the North Atlantic region.

The Joint Probability Method (JPM) has been applied for TC-induced coastal hazards analysis for more than half a century, with substantial methodological advancements in recent decades (e.g., [6-8]). More recently, a series of studies [9-13] have leveraged a range of statistical and machine-learning techniques to advance the state of the art in this area, including extending the JPM framework to assess compound coastal hazards [14]. Because JPM-based frameworks typically require calibrated TC response models for hazard quantification, their application can be challenging in regions where such models are unavailable. In parallel, another group of studies has focused on assessing compound hazards by performing statistical analyses directly on coastal response quantities, such as ocean-side water levels (O-sWL) or precipitation depths [15, 16]. These analyses are typically based on extreme value analysis methods. Although such approaches do not explicitly account for the physical processes responsible for generating coastal hazards, they are generally much less computationally demanding to implement. Extensions of these methods for compound hazard assessment have commonly involved the use of multivariate distributions or copula-based approaches, sometimes augmented with heuristic modeling techniques [17-20].

This study explores opportunities to apply existing TC-induced compound coastal hazard assessment methods to the South Korean region. Considering the limitations of TC response simulation models and data availability in the study region, we focus on refining and processing the collected data and performing statistical analyses directly on the processed observational data.

1.1. Data Sources

Table 1 lists the data sources explored and collected in this study. It is noted that only recent records from the Korea Meteorological Administration (KMA), Korea Hydrographic and Oceanographic Agency (KHOA), and Water Management Information System (WAMIS) are publicly available. To obtain more complete datasets, requests can be sent directly to agencies for research purposes. In this study, selected requests were made to obtain additional data.

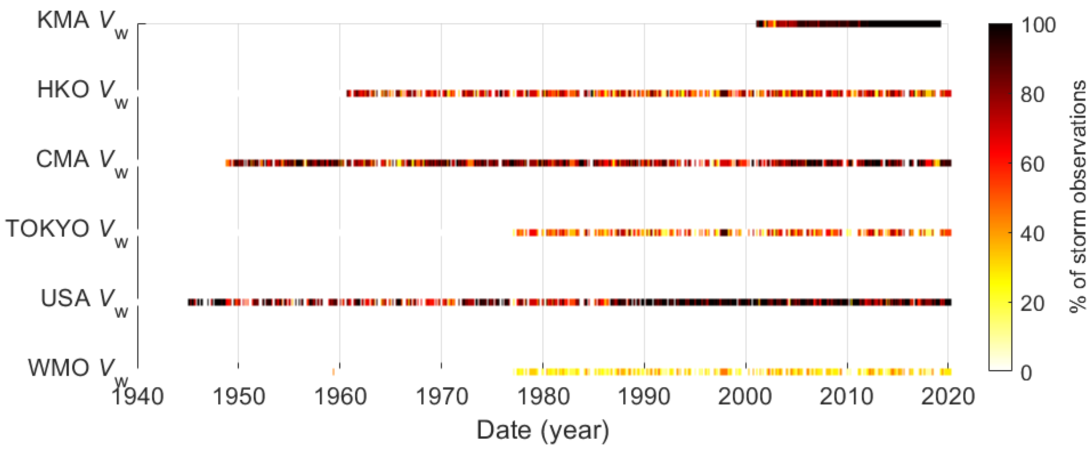
Table 1: Identified Data Resources

Category	Source	Accessible Format
Historical TC tracks	International Best Track Archive for Climate Stewardship (IBTrACS) https://www.ncei.noaa.gov/products/international-best-track-archive	CSV file
	KMA typhoon https://apihub.kma.go.kr/	API
O-sWL	KHOA http://www.khoa.go.kr/oceangrid/khoa/takepart/openapi/openApiObsSurveyDataInfo.do	API/TXT file
Local wind speed	KHOA http://www.khoa.go.kr/oceangrid/khoa/takepart/openapi/openApiObsSurveyDataInfo.do	API/TXT file
Rainfall	KMA Ground observation https://apihub.kma.go.kr/	API
River	WMIS watershed precipitation daily http://www.wamis.go.kr:8080/wamisweb/rf/w4.do http://wamis.go.kr/ENG/RF_DUBRFOBS_PAST.do	API/web tabulated
	WAMIS river water level http://www.wamis.go.kr:8080/wamisweb/rf/w9.do http://wamis.go.kr/ENG/WL_DUBWLOBS_PAST.do	API/web tabulated
	WAMIS river flow http://www.wamis.go.kr:8080/wamisweb/rf/w15.do http://wamis.go.kr/wkw/wkw_flwsrrs_lst.do	API/web tabulated

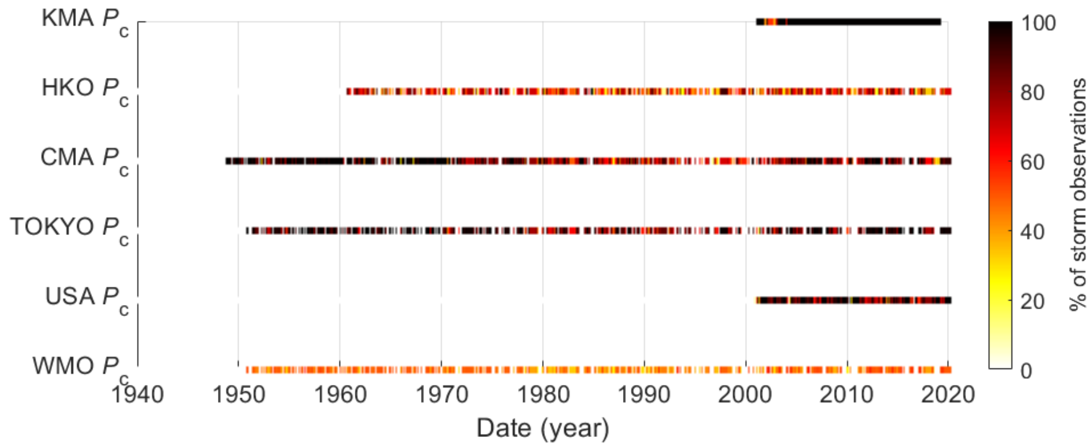
1.2. Tropical Cyclone Data Processing

The IBTrACS project [21, 22] stands as the most comprehensive worldwide repository of TC information. It consolidates historical data from various agencies, forming a cohesive and publicly accessible dataset known as the “best-track dataset.” This dataset was collaboratively developed with the World Meteorological Organization (WMO) Regional Specialized Meteorological Centres and various global organizations and individuals. KMA best-track data were added to the IBTrACS dataset in 2024.

Differences exist among data published by different agencies in the WNP, which are caused by variations in measurement technology and recording frequency [22]. To visualize these differences, an exploratory analysis of temporal coverage among multiple sources of storm data is conducted. Figure 1 shows a comparison of the fraction of (a) V_w and (b) P_c observations associated with a storm that are recorded in datasets from multiple agencies providing information for West-Pacific region storms. The historical storm observation fraction plots (Figure 1) reveal that the USA data source has the longest history record of wind velocity (V_w) dating back to 1945, while CMA holds the longest record history of central pressure (P_c) from 1949 to the present. However, the CMA data lacks storm size data, which is available from other sources.



(a)



(b)

Figure 1. Temporal Historical Storm Observation Coverage, Expressed as Ratios of Track Points That Include (a) V_w and (b) P_c for Each Storm in The Available Datasets. Visualization strategy based on [23]. USA: US National Hurricane Center, Joint Typhoon Warning Center, Central Pacific Hurricane Center and other USA agencies); TOKYO (WMO Regional Specialized Meteorological Center at Tokyo); CMA (Chinese Meteorological Administration Shanghai Typhoon Institute); and HKO (Hong Kong Observatory)

We set a latitude-longitude bounding box around the study region and extracted TCs that passed through it. The bounding box and extracted TC tracks are shown in Figure 2. We interpolate the extracted TC data to a finer spatial and temporal resolution, as illustrated in Figure 3.

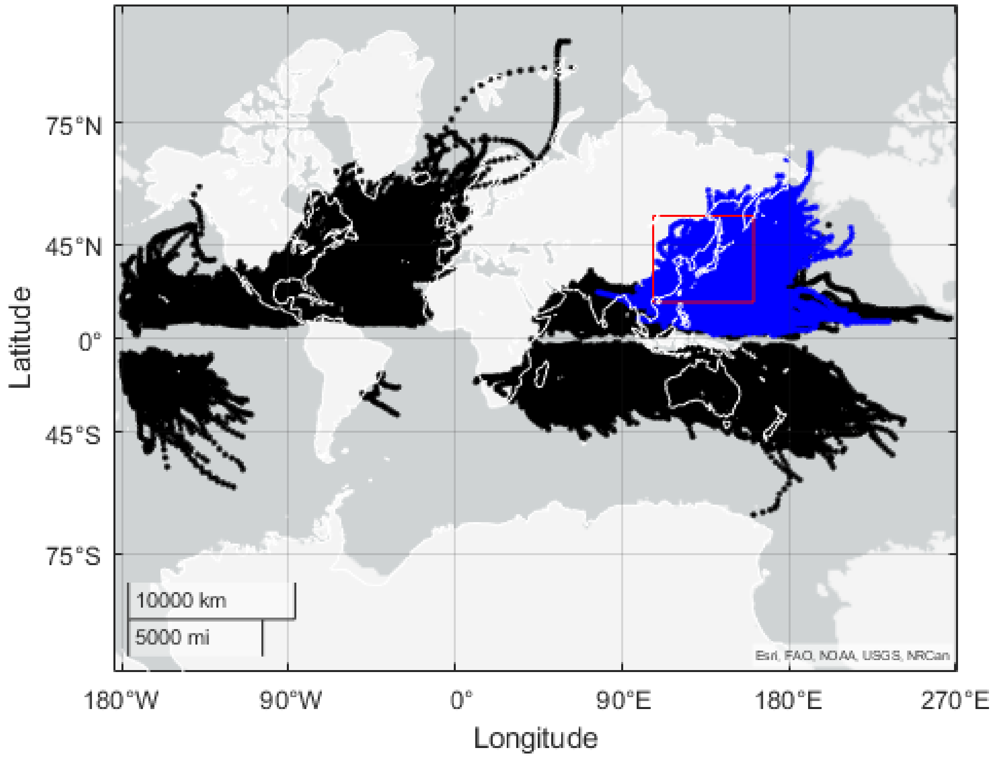


Figure 2: Spatial Bounding Box and Extracted TC Tracks

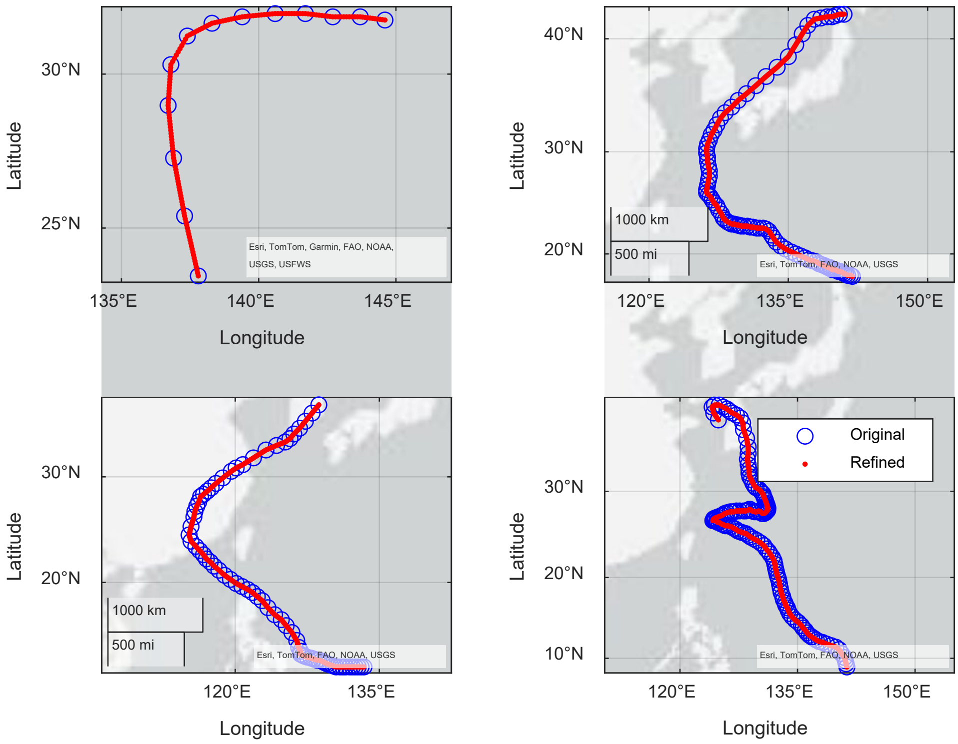


Figure 3: Example of Storm Track Spatio-Temporal Interpolation

2. TROPICAL CYCLONE-INDUCED MULTI-HAZARD ANALYSIS

In this study, local observational records are utilized to conduct a multi-hazard joint probability analysis for TC-induced non-tidal residuals (NTRs), wind, and rainfall. First, the tidal effects in the study region are investigated. Subsequently, a copula-based approach is applied to analyze the compound behavior of the three variables. Figure 4 shows the location of city sites involved in this analysis.

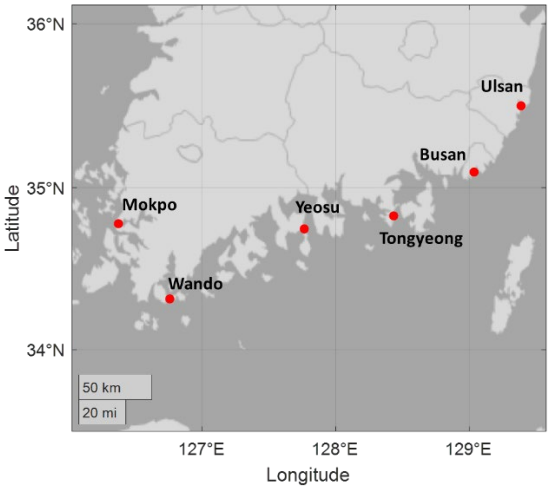


Figure 4. Gauge Locations

2.1. Tidal Effects on Observed Sea Water Level Data in South Korea

The O-sWL data play an important role in this multi-hazard analysis, as they are used as a source of TC surge. It is noted that O-sWL data in South Korea generally exhibit wider ranges than those in well-studied North Atlantic regions like the Gulf Coast or Florida [19, 24], primarily due to stronger astronomical tides. These strong tidal effects can be attributed to South Korea's higher latitude and complex coastal bathymetry, especially near locations such as Mokpo, Yeosu, Wando, and Tongyeong. As a result, it is useful to distinguish between total water levels and storm surge components. Figure 5 presents examples of predicted (hourly and daily maximum) and observed O-sWL data over six months, showing strong diurnal and semidiurnal tides, along with a semimonthly variation linked to lunar cycles [25, 26].

Semimonthly tidal variations introduce substantial noise when directly calculating the correlation between observed sea water level (O-sWL) and other variables (e.g., wind speed and rainfall). Therefore, NTRs are used for analysis. In this work, NTRs are obtained by subtracting the predicted tidal component from the observed O-sWL and represent the portion of O-sWL that effectively reflects the storm surge component [26]. Because the predicted tidal component data (needed for NTR calculation) from KHOA are only available after 2012, this study uses local observational records from 2012 onward for the multi-hazard analysis.

2.2. Trivariate Analysis

In this study, we perform a TC-conditional trivariate analysis considering TC-induced NTR, wind, and rainfall. For each KHOA gauge site, wind speed and observed sea water level (O-sWL) data were batch downloaded. Rainfall data from KMA ground observations were also obtained and matched with wind speed and O-sWL data from the nearest KHOA gauge site. For each site, TC track data from IBTrACS passing within a 500 km radius were extracted to identify TC events. The corresponding NTR, wind, and rainfall records were then extracted only within the event window of each identified TC event, rather than from the full observational record. Daily maximum NTR, daily maximum wind speed, and daily total rainfall corresponding to each TC event were then identified and paired according to matching calendar dates. It is noted that gauge records for some TC events are unavailable due to temporary instrument malfunctions or other issues. In the rest of this section, the results of selected city sites are presented for discussion.

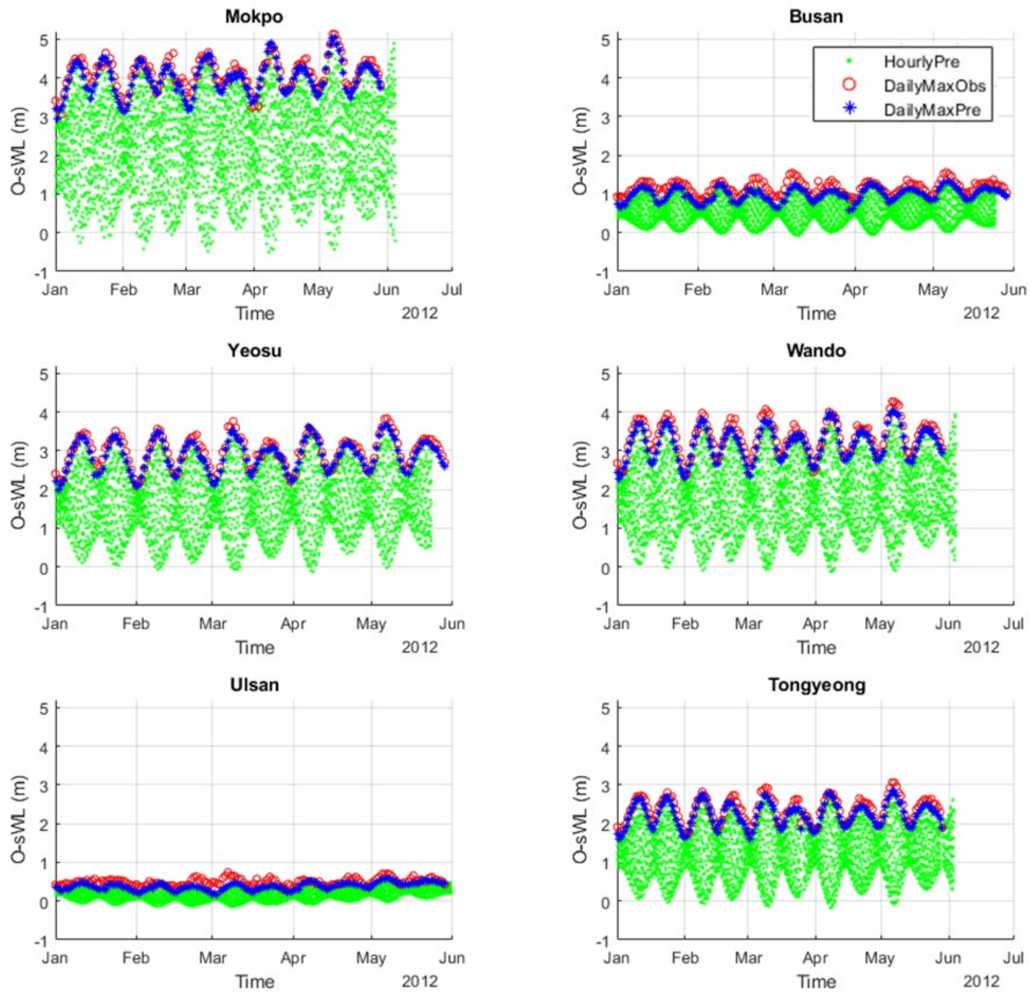
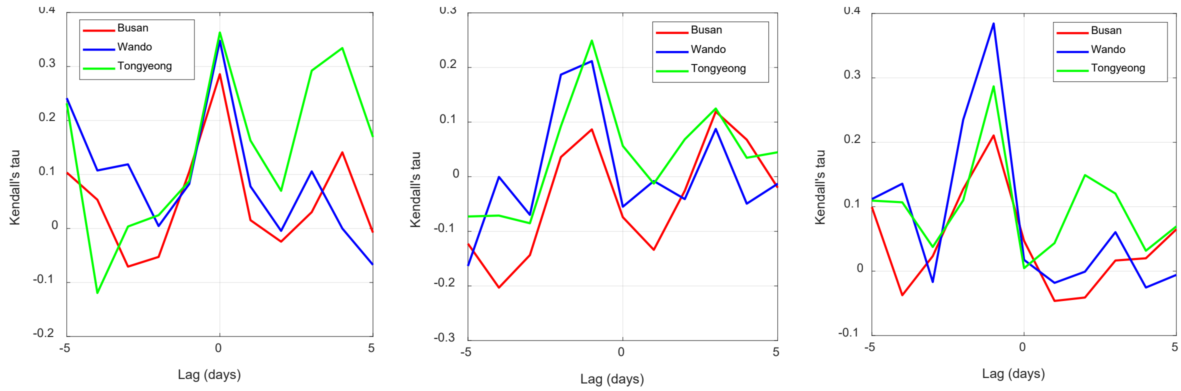


Figure 5. Predicted (Hourly and Daily Maximum) and Observed O-sWL Data Reflecting Astronomical Tidal Effects

A correlation analysis was performed among the TC-induced NTR, wind and daily total rainfall. In particular, a lag-correlation analysis was conducted, and the results are shown in Figure 6. Here, Kendall's tau is a rank correlation metric (in the range of [-1,1]) typically used in copula analysis. The lag (in days) represents the temporal offset of one variable relative to the other. For example, in the NTR-rainfall plot, a lag of +1 day indicates that the correlation is calculated between daily NTR observations (days 1:n-1) and daily total rainfall observations (days 2:n).

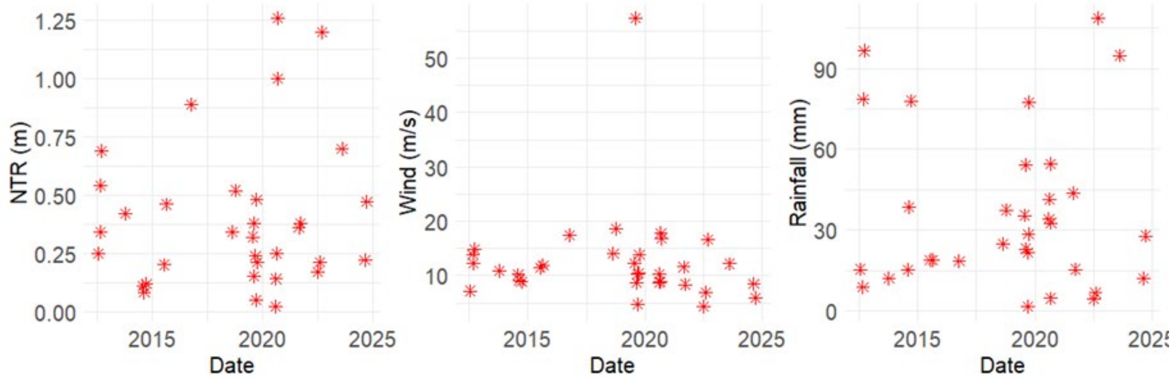
These results suggest that TC surges and winds intensify concurrently as a TC approaches and makes landfall, leading to the strongest correlation at zero lag. In contrast, rainfall often peaks earlier than the maximum surge and wind speeds, resulting in correlations that peak at a lag of -1 day. This temporal offset potentially reflects the spatial structure and movement of the TC: heavy rainfall is typically concentrated in the leading rainbands of the storm, whereas maximum winds and storm surge occur closer to the time of closest approach or landfall.

Figure 7 presents the TC event peak samples extracted for each variable at selected sites to support the subsequent trivariate analysis. Unlike the daily total rainfall used in the lag-correlation analysis shown in Figure 6, the trivariate analysis uses the peak 24-hour moving-sum rainfall within each TC event to maximize the potential correlation with the other event-level peak variables.

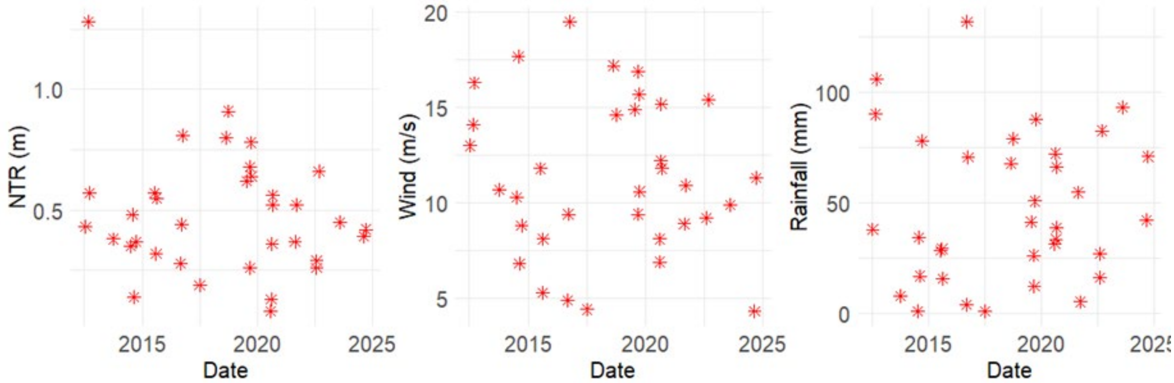


(a) NTR-Wind **(b) NTR-Rainfall** **(c) Wind-Rain**

Figure 6. TC-Induced Hazard Correlation



(a) Busan



(b) Wando

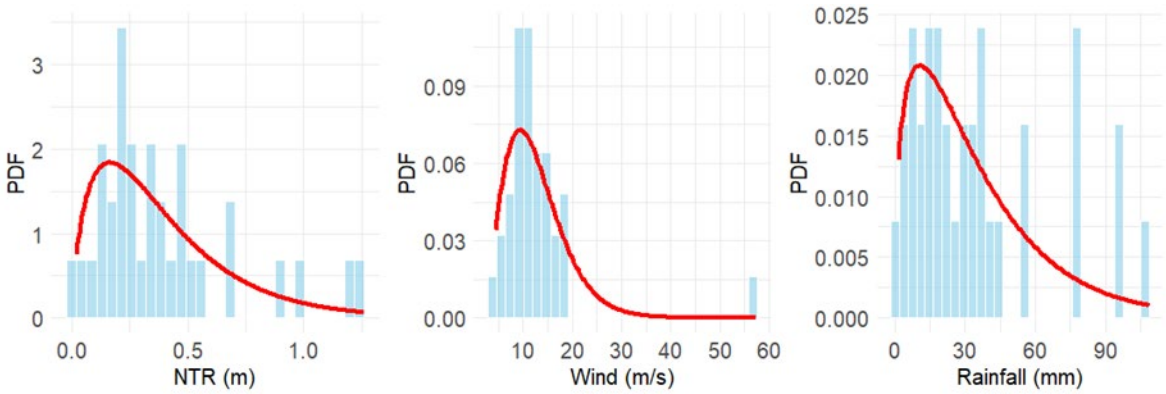
Figure 7. TC Event Peak Samples Extracted for Each Variable at Selected Sites

In this study, because TC-induced NTR, wind, and rainfall exhibit positive correlations and the focus of this work is on investigating their compound effect, a three-dimensional Gumbel copula is employed to construct the joint distribution model. The Gumbel copula is a member of the Archimedean copula family. Archimedean copulas have been widely applied in coastal and ocean engineering studies [27, 28]. The Gumbel copula is particularly suitable for modeling positive correlations and upper-tail dependence. Gamma distributions are employed as the marginal distributions for each variable, and the fitted probability density function (PDF) curves are shown in Figure 8. The fitted three-dimensional Gumbel copula based joint distribution is visualized by plotting pair-wise PDF contours with the scatter plots of sample data, as shown in Figure 9.

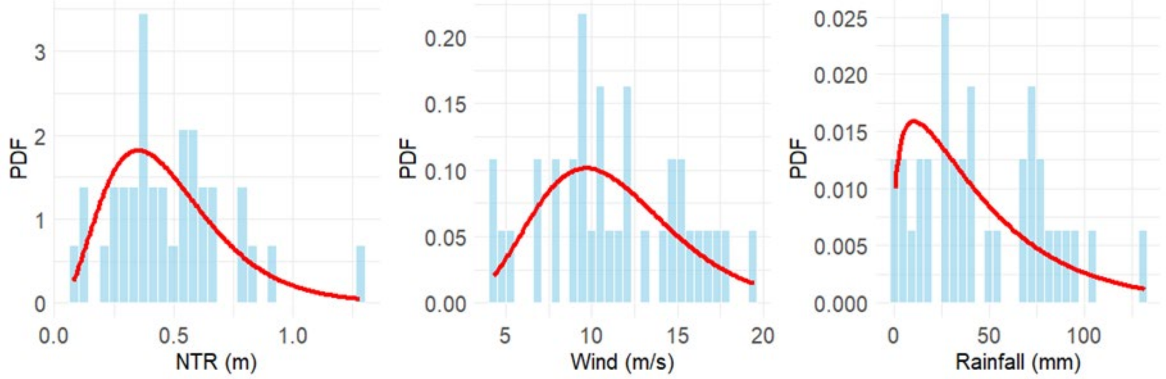
As shown in Figure 8, the marginal distributions of TC event peak NTR, wind speed, and TC peak rainfall are generally right-skewed, with most events concentrated at low-to-moderate magnitudes and a small number of high-intensity events forming upper tails. The fitted distributions reasonably reproduce the overall empirical patterns, although some deviations are observed in the tails, reflecting the uncertainty associated with limited samples of extreme TC events.

Figure 9 further illustrates the pair-wise dependence among the three variables. The dependence varies by both variable pair and site. Overall, moderate to strong dependence is observed for some variable pairs, with the strongest dependence occurring between NTR and wind at Wando, where Kendall's $\tau = 0.58$. This indicates a relatively strong association between wind forcing and storm surge response at this site. In comparison, the NTR-rainfall and wind-rainfall pairs show relative weaker dependence.

Overall, these results suggest that the dependence structure of TC-induced compound hazards is site-specific and that wind plays an important role in modulating elevated NTR, particularly at Wando. The sparse occurrence of high-magnitude events outside the main probability density regions also highlights the importance of using a copula-based framework to characterize joint extremes beyond the central portion of the distributions.



(a) Busan



(b) Wando

Figure 8. Marginal Analysis of Each Variable

To evaluate the compound effect in TC-induced multi-hazard analysis, joint exceedance events are computed, tabulated, and compared with single-hazard exceedance events defined from the marginal distribution of each individual hazard. That is, the n-year return period severity values for each individual hazard are calculated using the marginal distributions. Then two trivariate exceedance probabilities are computed relative to these same marginal n-year hazard severity levels using the fitted trivariate joint distribution, which accounts for dependence among the three hazards rather than assuming independence. Following the trivariate analysis approach proposed by [29], we estimate the exceedance probabilities of two types of joint events, which can be derived using DeMorgan's Rules as:

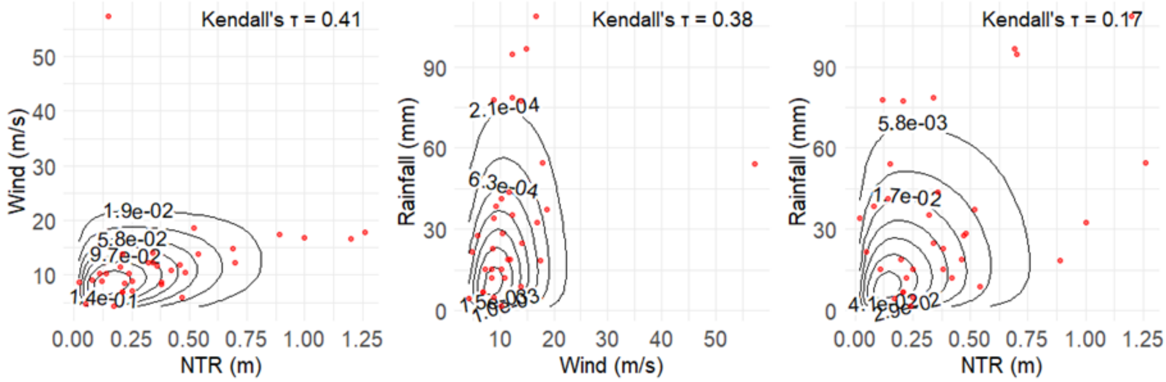
(1) The probability of exceeding any one of the thresholds for TC-induced NTR, wind, or rainfall (i.e., the union joint event):

$$EP_{\cup} = P(X_1 > x_1 \cup X_2 > x_2 \cup X_3 > x_3) = 1 - F(x_1, x_2, x_3) \quad (1)$$

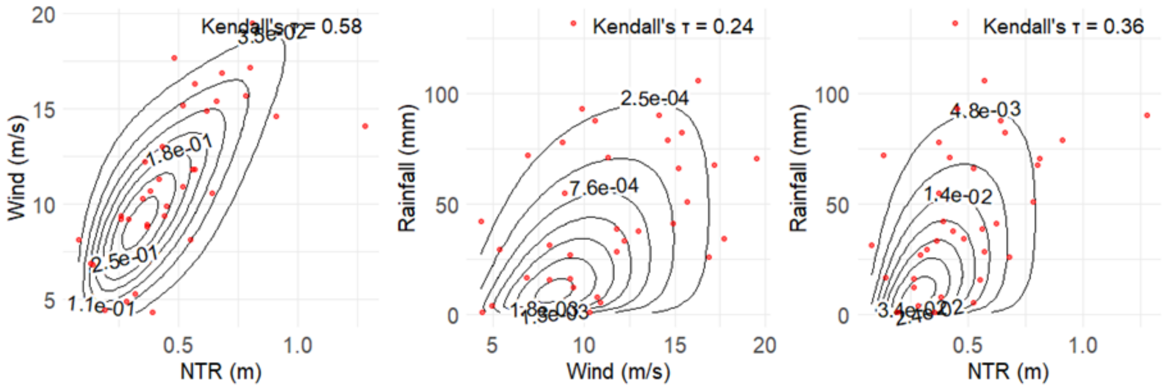
(2) The probability of exceeding all of the thresholds for TC-induced NTR, wind, or rainfall (i.e., the intersection joint event):

$$EP_{\cap} = P(X_1 > x_1 \cap X_2 > x_2 \cap X_3 > x_3) = 1 - F(x_1, \infty, \infty) - F(\infty, x_2, \infty) - F(\infty, \infty, x_3) + F(x1, x2, \infty) + F(x1, \infty, x3) + F(\infty, x_2, x_3) - F(x_1, x_2, x_3) \quad (2)$$

The calculated exceedance probabilities are converted into return periods to allow direct comparison with the single-hazard return period thresholds. The return period calculations account for the TC occurrence rate within the 500 km capture zone surrounding each gauge site. The return periods of single-hazard events, derived from marginal analyses, and those of joint-hazard events derived from the trivariate analysisare listed in Table 2 and compared at the same marginal severity levels. The threshold value for each type of TC hazard (NTR (η), wind speed (w), and daily total rainfall (p)) is included for reference. The results show how accounting for dependence through the trivariate joint cumulative distribution function changes the estimated return periods relative to treating the hazards as independent marginal events.



(a) Busan



(b) Wando

Figure 9. Pair-Wise PDF Plot and Scatter

Both the return periods for the union and intersection joint exceedance events reflect the positive correlations among NTR, wind, and rainfall. For example, at Wando, the combination of single-hazard severity thresholds corresponds to an intersection-type compound event with a return period of no more than 30 years. In contrast, if the correlations among hazards were ignored (i.e., the marginal distributions were treated as independent), the same intersection-type compound event would be estimated to have a return period of approximately 1,000 years, demonstrating how correlation significantly influences joint exceedance estimates. It is also important to note the spatial variability among sites. In Busan, the return period of the intersection joint exceedance event is much longer than that at Wando, which can be attributed to the relatively weaker correlations among NTR, wind, and rainfall near the site.

Table 2: Return Periods of Single Hazard Thresholds and Corresponding Trivariate Joint Exceedance Events

Return period (years) of a single hazard	Return period (years) of union joint event $EP_{\cup}$	Return period (years) of intersection joint event $EP_{\cap}$
Busan		
10 ($\eta = 1.20\ m, w = 27.6\ m/s, r = 115\ mm$)	4.1	87
100 ($\eta = 1.78\ m, w = 37.0\ m/s, r = 174\ mm$)	40	923
Wando		
10 ($\eta = 1.09\ m, w = 21.0\ m/s, r = 159\ mm$)	5.0	29
100 ($\eta = 1.48\ m, w = 26.7\ m/s, r = 247\ mm$)	49	293

3. CONCLUSION AND DISCUSSION

This study investigates the data sources, modeling approaches, and methodologies available for assessing TC-induced coastal hazards in South Korea. TC-related observational and reanalysis data were collected from various agencies and visualizations were created to demonstrate the availability of historical storm information.

A trivariate TC-conditional multi-hazard analysis was conducted using local gauge records, including NTR, wind speed, and rainfall observations. Strong positive correlations were found among these variables during TC events, underscoring the importance of accounting for their interdependence and compound effects in TC hazard assessments in South Korea. Ignoring these correlations in single-hazard analyses may lead to underestimations of the hazard frequencies.

However, the limited length of available records, particularly O-sWL and wind speed data, may limit the accuracy of statistical analyses, especially when estimating long-return-period events. Considering the limitations of historical data and the potential impacts of changing climate conditions in the region, JPM-based approaches provide a more robust strategy for improving coastal hazard quantification in South Korea. However, the application of JPM requires the development of efficient surrogate models for estimating TC responses (such as storm rainfall and storm surge), which are not yet available.

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