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Temporally Coherent Modeling of Tropical-Cyclone Compound Flooding for Reliable Coastal Hazard Estimation

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Tropical cyclone-induced coastal flooding arises from the interaction of multiple processes, including storm surge and wave-driven run-up, whose relative timing governs the severity of inundation. Conventional statistical approaches typically rely on static event maxima, implicitly assuming co-occurrence of extremes and neglecting their temporal evolution, which can lead to biased estimates of design-level hazards. This study applies the Multivariate Spatio-Temporal Maxima with Temporal Exposure (MSTM-TE) framework to address this limitation by explicitly incorporating temporal coherence into the modeling of compound extremes. Using a long-term synthetic tropical cyclone dataset for Guadeloupe archipelago of the French Antilles, full time series of key metocean variables are reconstructed to generate physically consistent storm realizations, from which total water level is derived using analytical formula as an integrated measure of coastal flooding. Results show that the MSTM-TE framework reduces both bias and variability in return-level estimates compared to conventional approaches. Analysis of reconstructed storm evolution further reveals a systematic alignment between peak flooding and wave-energy forcing, indicating that wave run-up dominates extreme total water levels while surge modulates their magnitude. These findings demonstrate the importance of preserving temporal structure in compound extreme modeling and provide a robust framework for coastal hazard assessment under limited observational data.

Keywords: Tropical cyclone, spatio-temporal extremes, synthetic storm, return value.

1 Introduction

Tropical cyclones (TCs) are among the most destructive natural hazards affecting coastal regions, producing severe impacts through strong winds, heavy rainfall, and coastal flooding. Over recent decades, nearly 2,000 cyclone-related disasters have resulted in approximately 779,000 fatalities and economic losses exceeding USD 1.4 trillion worldwide (World Meteorological Organization 2023). Among these impacts, coastal flooding is consistently the most critical, often driven by the combined effects of storm surge and wave processes (Rappaport 2014; Fritz et al. 2009).

A defining feature of TC-induced flooding is its compound nature, arising from the interaction of multiple interdependent processes that evolve over time. In particular, storm surge and wave run-up operate on different temporal scales: surge develops gradually through large-scale ocean response, while wave-driven processes respond rapidly to local atmospheric forcing (Mori et al. 2014; Elahi et al. 2023). The relative timing (temporal phasing) of these components plays a critical role in determining the severity of coastal inundation (Bevacqua et al. 2020).

Despite this, most conventional statistical approaches to compound extremes rely on static event maxima, implicitly assuming that peak values of different variables co-occur. This assumption can produce physically unrealistic combinations and introduce bias in the estimation of design-level hazards, particularly for long return periods where extrapolation is required (Coles 2001; Wahl et al. 2017). As a result, existing frameworks often fail to capture the temporal dynamics and dependence structure that govern real-world compound flooding events.

To address this limitation, this study adopts the Multivariate Spatio-Temporal Maxima with Temporal Exposure (MSTM-TE) framework (Sando et al. 2024), which explicitly incorporates temporal coherence into the simulation of extreme events. Rather than modeling only event-level maxima, the framework reconstructs full time series of key metocean variables, enabling the generation of physically consistent synthetic storms that preserve both statistical dependence and temporal evolution. This allows compound hazard metrics to be evaluated in a manner consistent with the underlying storm dynamics.

In this study, the MSTM-TE framework is applied to a long-term tropical cyclone dataset, where coastal flooding risk is quantified using total water level (TWL), defined as the sum of sea surface height and wave run-up. This integrated metric captures both low-frequency surge effects and high-frequency wave contributions, providing a physically interpretable measure of inundation potential.

The objectives of this study are twofold:

1. To evaluate whether temporally coherent modeling improves the statistical reliability of extreme TWL estimates, particularly under limited data conditions; and

2. To investigate the physical mechanisms of compound flooding, with emphasis on the temporal alignment and relative contributions of wave-driven and surge-driven processes.

By bridging statistical extreme value modeling with physically consistent storm reconstruction, this work aims to provide a more robust framework for assessing compound coastal flooding hazards under tropical cyclone forcing.

2 Data and Methodology

2.1 *Framework Overview*

A key feature of the MSTM-TE framework is the separation of the representation of storm intensity from its temporal evolution. The framework consists of two complementary components: (i) Multivariate Spatio-Temporal Maxima (MSTM), describing the extremal magnitude of each storm, and (ii) Temporal Exposure (TE), capturing the normalized temporal evolution of each variable throughout the storm lifecycle.

For each event, MSTM is defined as the vector of storm-level maxima across variables, while TE represents the corresponding time series scaled by their peak values, yielding dimensionless exposure patterns between 0 and 1. This separation allows synthetic storms to be generated by statistically modeling extreme magnitudes and recombining them with realistic temporal structures**.**

The overall procedure consists of three stages: (1) extraction and modeling of extreme storm characteristics, (2) conditional simulation of synthetic storm maxima, and (3) reconstruction of spatio-temporal storm evolution to compute TWL.

To assess its effectiveness, the MSTM–TE framework is evaluated against benchmark approaches that neglect key aspects of the problem: a static multivariate model that ignores temporal evolution, and a location-specific model that additionally neglects spatial dependence.

2.2 *Study Area and Data*

This study focuses on Guadeloupe, an island in the Lesser Antilles that is frequently exposed to TCs propagating along the North Atlantic hurricane corridor. Its narrow insular shelf and direct exposure to Atlantic wave conditions amplify hydrodynamic responses to storm forcing, making it a representative setting for compound coastal flooding analysis.

The analysis uses a synthetic TC hindcast database developed by the French Geological Survey (BRGM), representing approximately 1000 years of cyclone activity. The dataset consists of 685 storm events, each associated with spatially distributed time series of key metocean variables across a high-resolution computational grid (18,890 nodes) surrounding the island. To account for spatial heterogeneity in storm behavior, the dataset is partitioned into east and west clusters based on the longitude of maximum significant wave height (Hs), such that events peaking east of 61.5°W define the east cluster, while those peaking west of this boundary define the west cluster.

From the full domain, four coastal locations were selected to represent typical sandy beach environments, where wave-driven processes play a dominant role in flooding (see Figure 1).

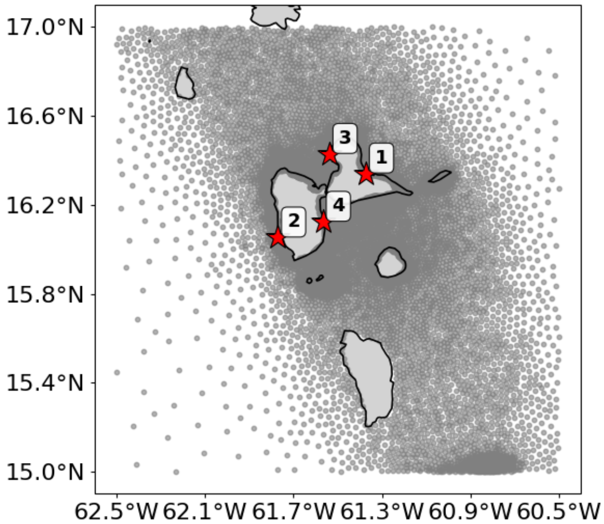


Figure 1. Map of the Guadeloupe region. Grid locations from which the datasets were sourced (grey dots) and the four study locations used in the analysis (red stars) are shown.

The primary risk metric TWL is defined as:

$$TWL = Ssh + R, \tag{1}$$

where Ssh represents the sea surface height and R denotes wave run-up. The run-up component is parameterized as a function of offshore wave conditions following Stockdon et al. (2006):

$$R = 1.1\left[0.35\beta_f\sqrt{\frac{gH_sT_p{}^2}{2\pi}} + \sqrt{\frac{gH_sT_p{}^2}{2\pi}\left(0.563\beta_f{}^2 + 0.004\right)}\right], \tag{2}$$

where H_s is the significant wave height (in meters), T_p is the peak wave period (in seconds), and β_f is a dimensionless parameter representing the foreshore slope. In this study, a representative sandy-beach slope, $\beta_f = 0.1$, is adopted following Melet et al. (2018).

Within this framework, extreme events are characterized using storm-level maxima of the key variables $\left(H_s, T_p, Ssh\right)$, as well as a compound wave-energy proxy $H_sT_p^2$. These variables form the basis for subsequent multivariate extreme value modeling and simulation. In this study, twol model configurations are considered: (1) a trivariate formulation based on $\left(H_s, T_p, Ssh\right)$, and a bivariate formulation based on the reduced set $(H_sT_p^2, Ssh)$.

2.3 *Extreme Value Modeling*

Once the time series are extracted and summarized through storm-level maxima, their extreme behavior is modeled through a combination of marginal tail estimation and multivariate dependence modeling.

For each variable, exceedances above a high threshold u_d (0.6 in this study) are modeled using the generalized Pareto distribution (GPD). Let $Y_d = S_d - u_d$denote exceedances of storm-level maxima. The conditional distribution is given by:

$$P(Y_d \leq y \mid Y_d > 0) = 1 - \left(1+\frac{\xi_d y}{\sigma_d}\right)^{-\frac{1}{\xi_d}}, y > 0, \tag{3}$$

where $\sigma_d$and $\xi_d$are scale and shape parameters. The fitted marginals are then transformed to a common Laplace scale to standardize variables.

Dependence in the joint tail is modeled using the Heffernan-Tawn (HT) conditional extremes model, following Heffernan and Tawn (2004). Conditioning on one variable $Y_d = y$ that exceeds a dependence threshold ψ_d, the remaining variables satisfy:

$$Y_{d'} \mid (Y_d = y) \approx \alpha_{d'|d}\, y + y^{\beta_{d'|d}} Z_{d'|d}, d' \neq d, \tag{4}$$

where $\alpha_{d'|d}$and $\beta_{d'|d}$control scaling and dependence structure, and $Z_{d'|d}$is a residual term.

To reduce sensitivity to threshold selection, the model is fitted across multiple dependence thresholds, specifically at the 0.6, 0.7, and 0.8 quantiles of the conditioning variable, and results are aggregated to obtain a more robust representation of extreme behavior.

2.4 *Simulation of Synthetic Storm Extremes and Evolution*

Synthetic storm events are randomly generated using a conditional simulation procedure that preserves both marginal distributions and dependence structure.

Storms are first classified according to a dominant variable, defined as the component exceeding its dependence threshold while remaining larger than all others. For each simulated event:

1. A dominant variable is sampled based on its empirical frequency;
2. An extreme value is drawn from its marginal distribution;
3. Remaining variables are simulated conditionally using the HT model.

The resulting vectors are transformed back to the physical domain, producing synthetic storm-level maxima consistent with historical extremes.

Each simulated MSTM vector is paired with an empirical TE sequence corresponding to the same dominant variable, thereby replicating the full intra-storm spatio-temporal evolution across all variabbles. This produces full time series for all variables, preserving intra-storm temporal structure.

2.5 *Evaluation*

The performance of the MSTM–TE framework is evaluated in terms of its ability to reproduce reliable estimates of the metric TWL. Specifically, return level estimates derived from MSTM-TE are compared against two benchmark approaches: a static multivariate model (MSTM-E), which preserves dependence between variables but neglects temporal evolution, and a location-specific model (LSE), which models extremes independently at each location.

Return levels are defined through the annual exceedance probability as

$$P(X > x_T) = \frac{1}{T p_a p_e}, \tag{5}$$

where T denotes the return period (100 years in this study), p_a is the annual storm occurrence rate (0.685 in this study), and p_e is the probability of exceeding the dependence threshold (i.e., $1 - \psi_d$). The return value x_T is the corresponding quantile of TWL.

Model performance is assessed using two key metrics: bias, defined as the deviation of estimated return levels from reference values, and variance, defined as the dispersion of estimates across simulated ensembles. To ensure robustness, evaluation is conducted across multiple ensemble realizations of synthetic storms, enabling comparison of both central tendencies and variability in predicted extremes.

3 Results and Discussion

3.1 *Temporal Structure of Compound Extremes*

Reconstructed storm time series generated by the MSTM-TE framework reveal a clear and systematic temporal alignment between TWL and wave-driven forcing. In particular, peak TWL is observed to occur predominantly at or near the maximum of the compound wave-energy variable $H_s T_p^2$, which governs wave run-up dynamics. This behavior is consistently reproduced across both observed (historical) and simulated storm ensembles, indicating that the framework successfully captures the temporal structure underlying compound extremes (see Figure 2).

Only a small fraction of events exhibit deviations from this alignment, with peak TWL occurring at times offset from the maximum wave-energy forcing (approximately 2-3% of storms). However, even in these cases, TWL maxima remain confined to periods when both surge and wave contributions are elevated. This indicates that extreme coastal flooding does not arise from independent maxima of contributing processes, but rather from their temporal co-occurrence within the storm lifecycle.

This result provides a direct physical explanation for the limitations of conventional static-maxima approaches. By implicitly assuming that peak surge and wave conditions coincide, such methods may generate combinations that are not dynamically consistent with real storm evolution. In contrast, the MSTM-TE framework preserves intra-storm temporal structure, ensuring that simulated extremes reflect physically plausible interactions between components. As a result, the timing of processes emerges as a key determinant of extreme TWL, highlighting the necessity of incorporating temporal dynamics in compound extreme modeling.

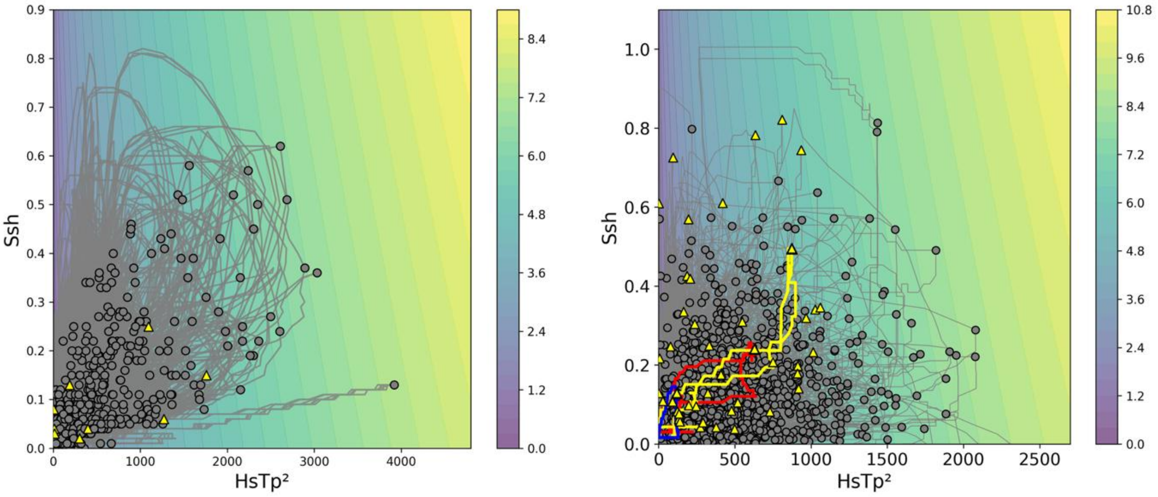


Figure 2. Joint time series trajectories of storms (East-cluster storms) for Location 1 in ${H_s T_p}^2 - Ssh$ space, with the colorscale representing the magnitude of the resulting TWL for observed (left) and simulated ensembles (right). Grey discs indicate the timing of peak TWL per storm that co-occurs with peak ${H_s T_p}^2$, and yellow triangles indicate the timing of peak TWL that does not co-occur with peak ${H_s T_p}^2$ (the colored trajectories in the right panel show representative storms exhibiting this behavior).

3.2 *Improvement in Extreme Value Estimation*

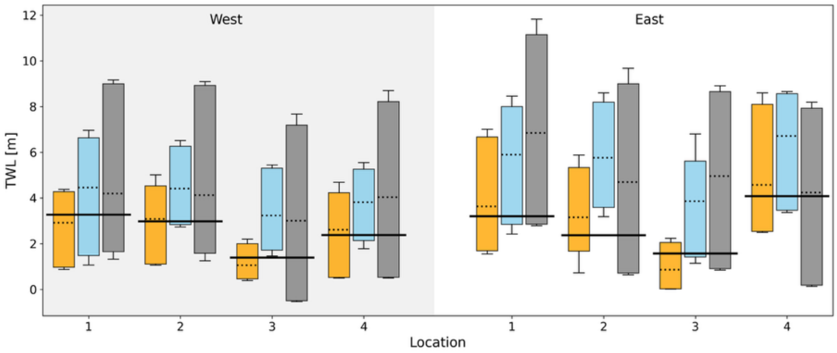
The impact of temporal coherence on extreme value estimation is evaluated by comparing TWL return levels derived from the MSTM-TE framework with those obtained from benchmark approaches. Across all study locations (Figure 1) and model configurations, a clear and consistent performance hierarchy emerges: MSTM-TE produces the most accurate and stable estimates, followed by the static multivariate model (MSTM-E), while the location-specific approach (LSE) exhibits the largest spread and systematic deviations (see Figure 3).

The improved performance of MSTM-TE is reflected in both reduced bias and lower variance of return level estimates. In contrast, approaches based on static maxima tend to either overestimate or underestimate extremes due to the implicit assumption that peak values of different variables occur simultaneously. This leads to the construction of physically inconsistent compound events, which propagate into biased tail estimates.

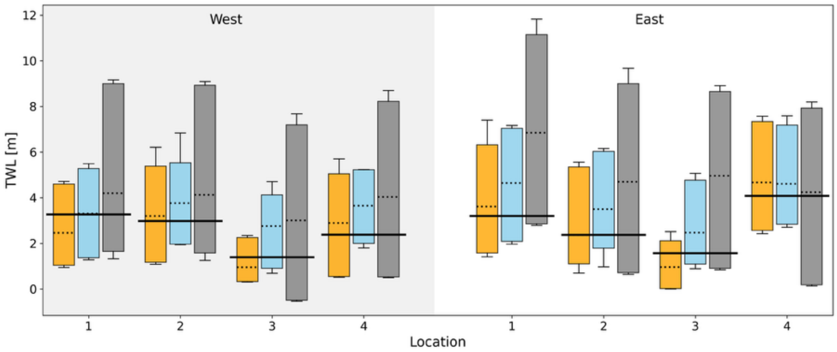
The results indicate that incorporating temporal structure directly improves the statistical reliability of extreme value analysis. By reconstructing the co-evolution of storm components, the MSTM-TE framework ensures that simulated events reflect realistic timing relationships, thereby avoiding artificial amplification or suppression of extremes. This effect is particularly evident for long return periods, where small inconsistencies in dependence structure can lead to large deviations in extrapolated values.

In addition to improved accuracy, the framework captures spatial variability in TWL extremes more effectively than benchmark models. For instance, locations with reduced wave exposure, such as Location 3, exhibit systematically lower return levels, a pattern that is preserved in MSTM-TE simulations but largely obscured in location-specific approaches. This highlights the importance of jointly accounting for spatial dependence and temporal coherence when assessing coastal hazard.

These findings demonstrate that the statistical benefits of the MSTM-TE framework arise directly from its physically consistent representation of compound processes, linking improved extreme value estimation to the underlying dynamics of storm evolution.



(a) Trivariate (H_s, T_p, Ssh) configuration



(b) Bivariate $(H_s T_p{}^2, Ssh)$ configuration

Figure 3. Box–whisker plots of 100-year return value estimates of TWL obtained from MSTM–TE (yellow), MSTM–E (blue), and LSE (grey), shown for west-cluster storms (left) and east-cluster storms (right). Panels (a) and (b) correspond to the trivariate and bivariate analyses, respectively. Estimates are based on an ensemble of 100 independent subsets, each comprising 1000 synthetic tropical cyclones. For each method, boxes represent the central 95% range (2.5th–97.5th percentiles) across ensemble subsets, the central line denotes the median, and whiskers extend to the minimum and maximum values within each ensemble. The black horizontal line indicates the ground-truth return value estimated directly from the full TC dataset.

3.3 *Physical Drivers of Extreme TWL*

To further understand the mechanisms governing extreme TWL, the relative contributions of sea surface height and wave run-up are examined. Contributions are quantified by decomposing TWL into its Ssh and R components at the estimated return level for each ensemble subset. The results show that wave run-up consistently dominates the total response across all study locations, while storm surge acts as a secondary component that primarily modulates the magnitude of TWL rather than its timing (see Figure 4). This finding is consistent with the temporal alignment identified in Section 3.1, where peak TWL coincides with periods of maximum wave-energy forcing.

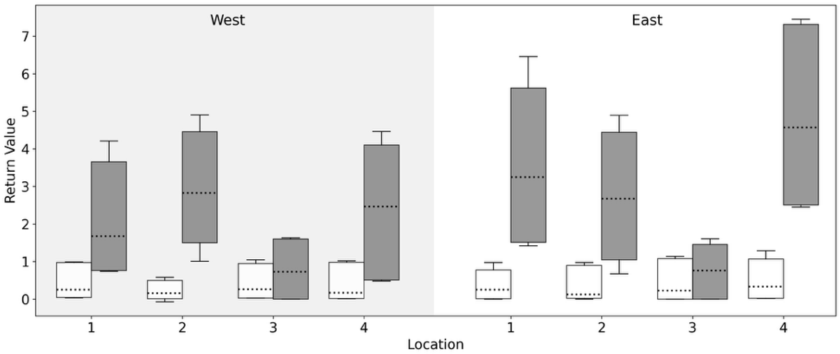


Figure 4. Box–whisker plots showing the contributions of sea surface height (white boxes) and wave run-up (grey boxes) to the 100-year return value of TWL across study locations. Results are shown for the bivariate configuration. Box–whisker specifications are the same as in Figure 3.

This behavior can be explained by the structure of the underlying dependence between variables. Wave-related components exhibit constrained joint variability, with peak wave period (T_p) saturating in the upper tail and contributing primarily through its interaction with wave height. In contrast, sea surface height retains greater independence, allowing it to vary more freely but with a weaker influence on the timing of extreme events. As a result, the effective dimensionality of the system is reduced, with extreme TWL governed by a dominant wave-driven axis and a secondary surge-driven axis.

This reduced structure provides a natural justification for simplifying the model representation. A bivariate formulation based on the compound wave-energy variable $H_sT_p^2$, paired with Ssh, is found to reproduce the statistical behavior of TWL extremes with comparable accuracy to the full trivariate model. This indicates that the key dynamics of compound flooding can be captured through a physically informed dimensionality reduction, where $H_sT_p^2$ encapsulates the dominant contribution of wave forcing to run-up processes.

The ability to reduce model complexity without sacrificing accuracy has important practical implications. It enables more efficient simulation and analysis while maintaining physical interpretability, making the approach particularly suitable for applications where data availability or computational resources are limited. More broadly, these results reinforce the interpretation that extreme coastal flooding is primarily controlled by wave-energy dynamics, with surge acting as a secondary but still essential component of the compound system.

4 Conclusions

This study applied the MSTM-TE framework to model tropical cyclone-induced compound coastal flooding and evaluated its performance in estimating extreme total water levels. The results demonstrate that explicitly preserving temporal coherence within storm evolution is essential for reliable extreme value analysis, as it avoids the unrealistic combination of independently occurring maxima that characterizes conventional approaches. By incorporating this temporal structure, the MSTM-TE framework produces more physically consistent simulations and achieves improved statistical performance, reducing both bias and variance in return level estimation compared to static multivariate and location-specific methods.

The analysis further reveals that extreme total water levels are predominantly driven by wave-energy forcing, with storm surge acting as a secondary factor that modulates the magnitude of the response rather than its timing. This finding provides a clear physical interpretation of compound flooding dynamics and explains the strong alignment observed between peak flooding and wave-driven processes. In addition, the results show that the effective dimensionality of the system can be reduced without loss of predictive capability. A simplified representation based on the compound variable $H_sT_p^2$ successfully captures the dominant behavior of extremes, offering a reduced-complexity alternative that retains both statistical accuracy and physical interpretability.

These findings highlight the importance of integrating temporal dynamics and physical consistency into statistical models of compound extremes. The proposed framework provides a practical and scalable approach for improving coastal hazard assessment under tropical cyclone forcing, particularly in data-limited environments.

Acknowledgments

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