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Temporally Coherent Modeling of Compound Coastal Flooding and Its Role in Extreme Water Level Estimation

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Contents

Motivation

<u>Tropical Cyclone (TC)-Induced Coastal Flooding</u>

- *<u>Compound</u>* extreme event [1]
- Design depends on return level estimates
- Limited historical data
  - Insufficient to estimate long-period return levels empirically

→ Statistical extreme value modeling (extrapolation)

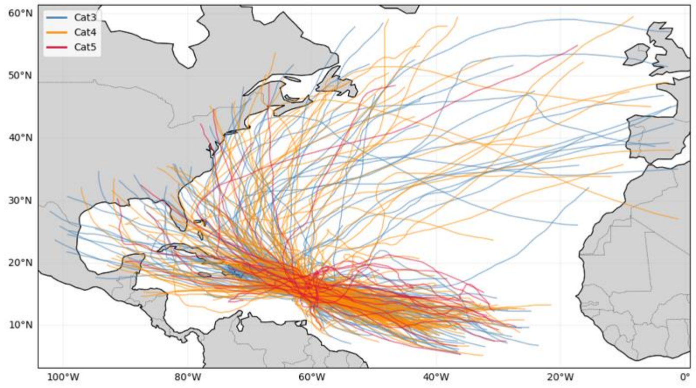


Fig. 1. Historical tropical cyclone trajectories

<u>Challenges in Conventional Approaches</u>

(1) Compound behavior
- Interaction of multiple variables

(2) Spatio-temporal structure
- Storms evolving across space and time

(3) Data limitation
- Rarely observed joint extremes (unreliable extrapolation)

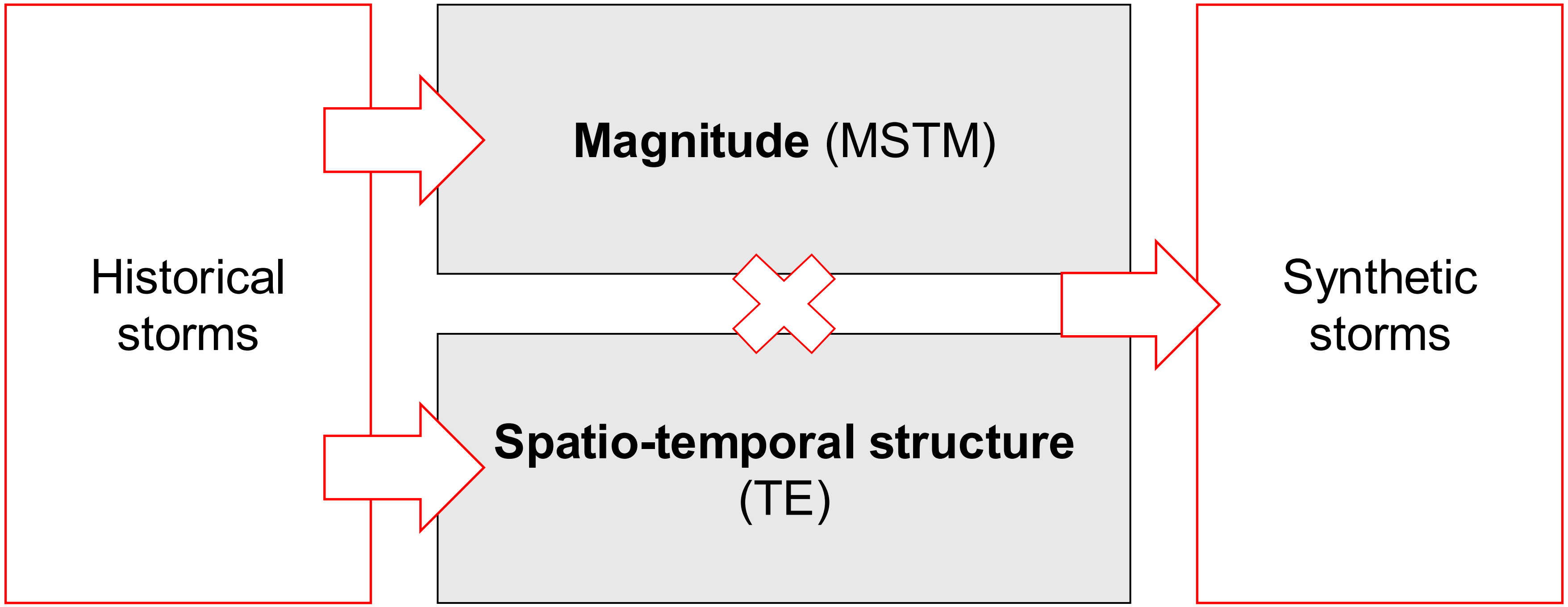
→ Estimation of rare extremes and spatio-temporal reconstruction required

[1] Di Bacco, M., Contento, A., & Scorzini, A. R. (2024). Exploring the compound nature of coastal flooding by tropical cyclones: A machine learning framework. *Journal of Hydrology*, *645*, 132262.

Prior Research

Multivariate Spatio-Temporal Maximum and Temporal Exposure (MSTM-TE) [2]

- An extreme-value framework incorporating spatial and temporal exposure (relative intensity)



[2] Sando, K., Wada, R., Rohmer, J., & Jonathan, P. (2024). Multivariate spatial and spatio-temporal models for extreme tropical cyclone seas. Ocean Engineering.

Research Objectives

Remaining questions:

Applying the framework to a real-world hazard:

- Whether temporally coherent simulations can produce unbiased return-level estimates under limited observational data
- How the differences in spatio-temporal exposure influence the governing mechanisms of compound extremes

Objectives:

(1) To determine the role of spatio-temporal structure in achieving reliable risk assessment of compound extremes

(2) To identify how joint behavior and temporal exposure govern the mechanisms of compound extremes

Contents

Study Domain and Dataset

Study Domain and Locations

- Guadeloupe region
  - Northeastern Caribbean Sea (60.5°W-62.5°W; 15°N-17°N)
- Four study locations on the main island

Dataset

- **1000-year** period containing **685 TCs** that pass within a 300 km radius of the archiopelago
  - Clustered into East (466 storms) and West (219 storms) based on the location of maximum wave height to fulfill the modeling assumption [2]
- 18,890 node spatial mesh
- High-resolution time series of key metocean variables

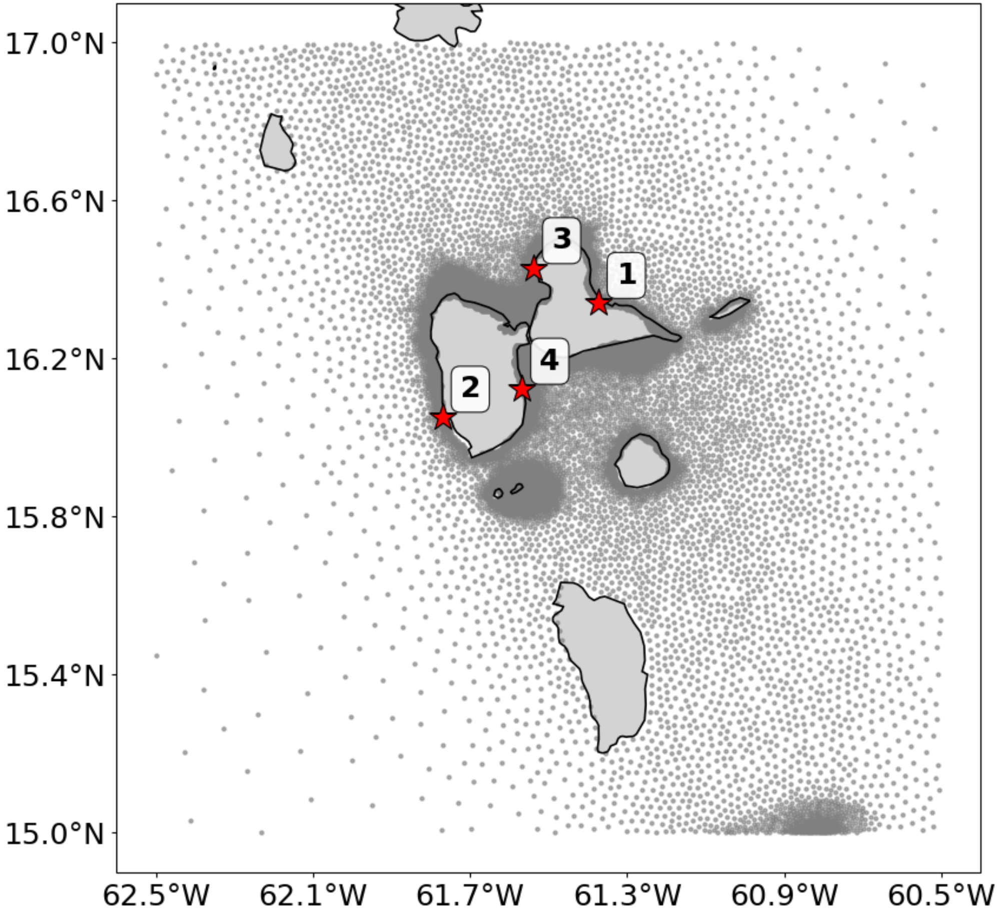


Fig. 2. Map of the Guadeloupe region showing the mesh grid nodes (grey dots) and the four study locations (red stars).

[2] Sando, K., Wada, R., Rohmer, J., & Jonathan, P. (2024). Multivariate spatial and spatio-temporal models for extreme tropical cyclone seas. Ocean Engineering, 309, 118365.

Risk Assessment Metric & Variables

Risk assessment metric (Total Water Level)

$$TWL = Ssh + R$$

- Sea surface height (Ssh)
- Wave run-up (R)

Wave run-up [3]

$$R = 1.1\left[0.35\beta_f\sqrt{\frac{9.81H_sT_p{}^2}{2\pi}} + \sqrt{\frac{9.81H_sT_p{}^2}{2\pi}\left(0.563\beta_f{}^2 + 0.0004\right)}\right]$$

- $\beta_f = 0.1$: foreshore slope [4]
- H_s: significant wave height
- T_p: peak wave period

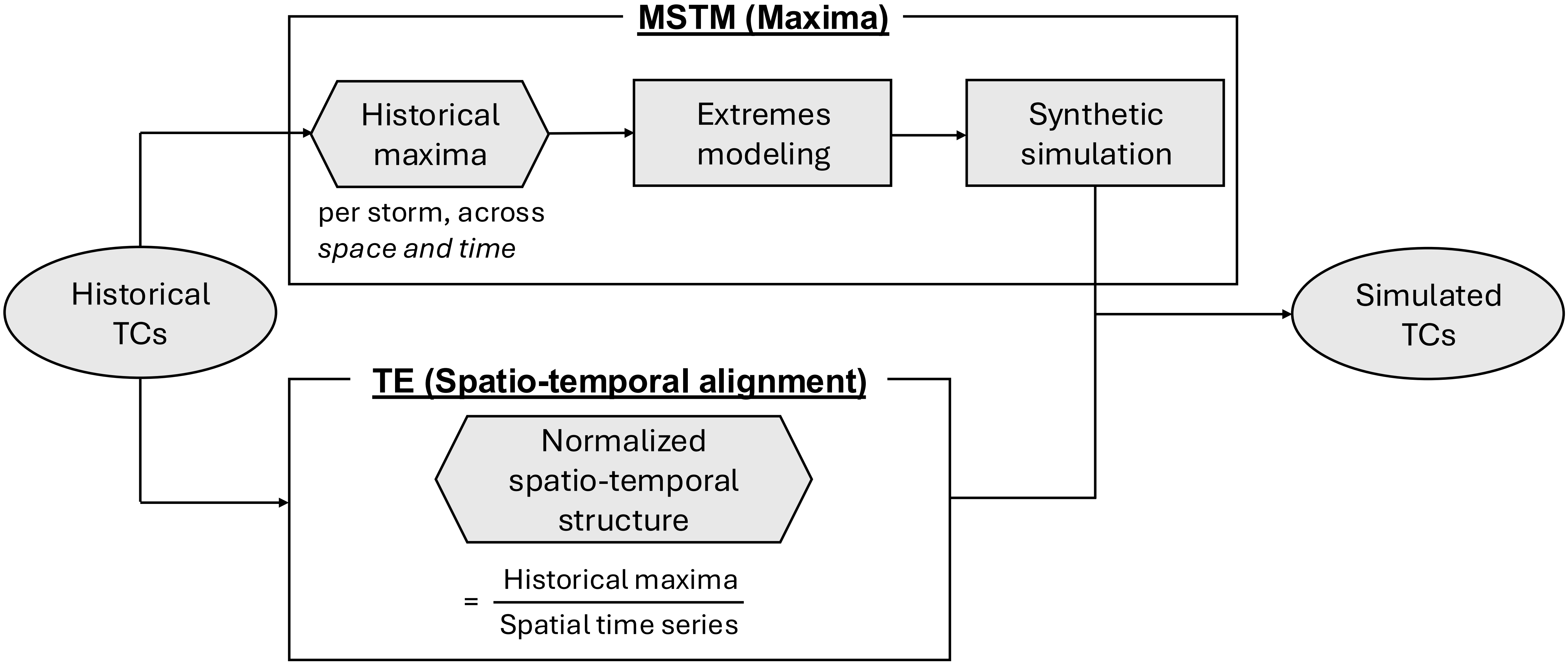
Variables

Risk metric as a function of:

- Sea surface height (Ssh)
- Significant wave height (H_s)
- Peak wave period (T_p)

[3] Stockdon, H. F., Holman, R. A., Howd, P. A., and Sallenger, A. H.: Empirical parameterization of setup, swash, and runup, Coastal Engi- neering
[4] Melet, A., Meyssignac, B., Almar, R., & Le Cozannet, G. (2018). Under-Estimated Wave Contribution to Coastal Sea-Level Rise. Nature Climate Change.

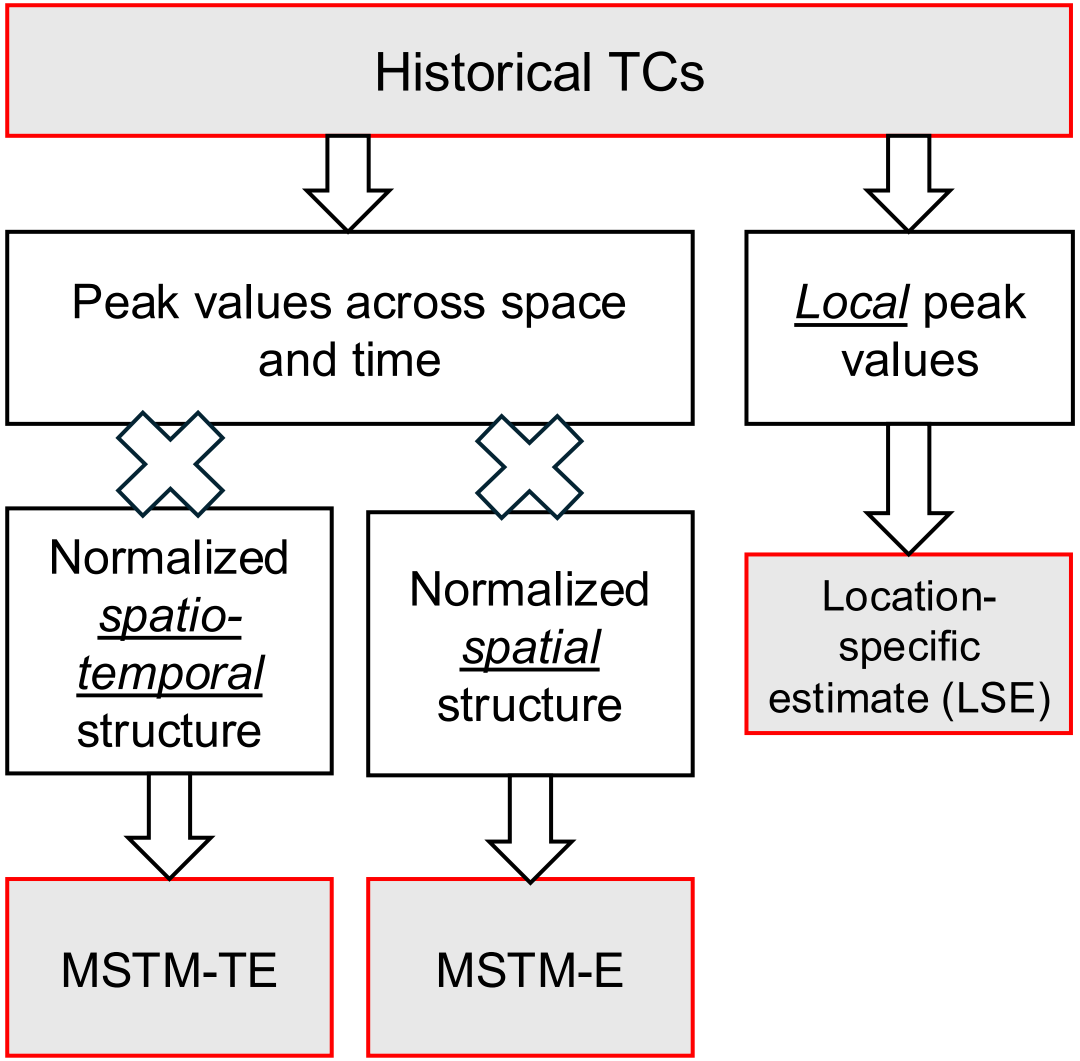
Methodology Overview [5]



[5] Chung, M., Wada, R., Rohmer, J., and Jonathan, P.: Temporally Coherent Modeling of Tropical Cyclone Compound Flooding for Reliable Coastal Hazard Estimation, EGUsphere [preprint].

Performance Evaluation

Performance evaluated across four frameworks:



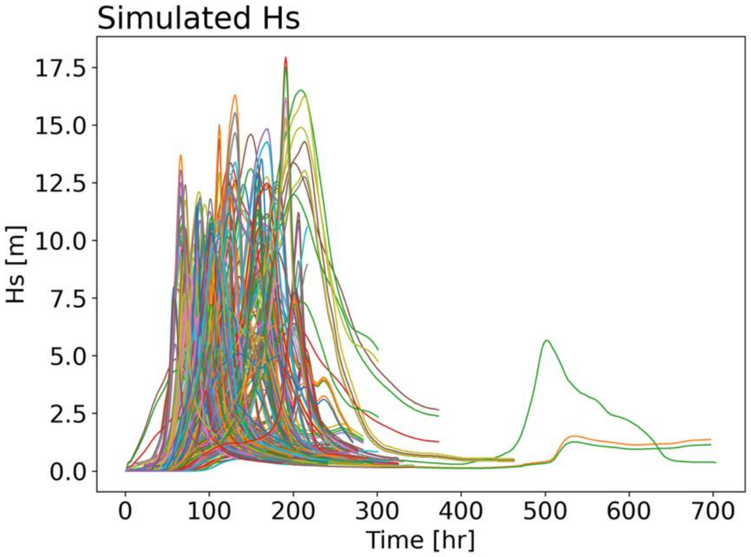
	MSTM-TE	MSTM-E	LSE
Spatial preservance	✓	✓	✕
Temporal preservance	✓	✕	✕

Evaluation based on:

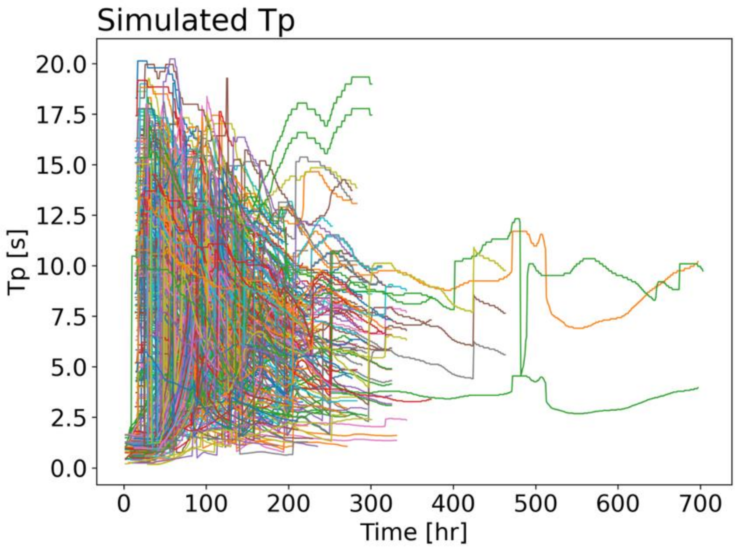
- **Bias**: difference between simulated return levels and ground truth
- **Variance**: how much the return level estimates fluctuate across simulations

Contents

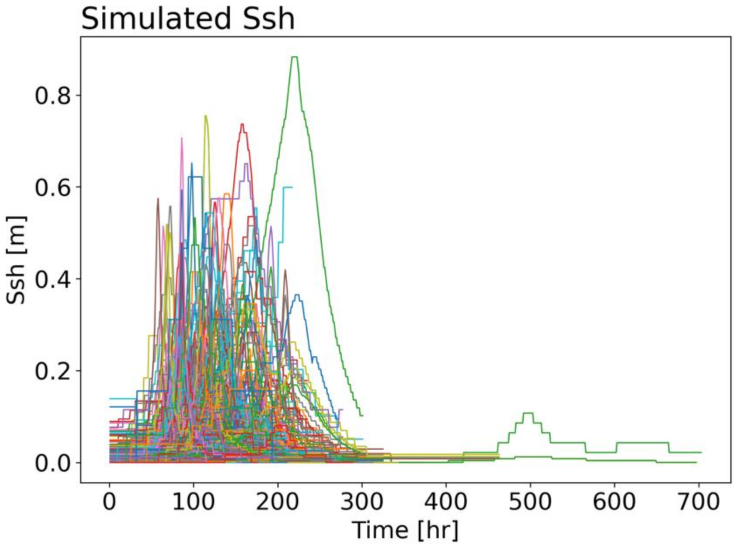
Simulated Time Series



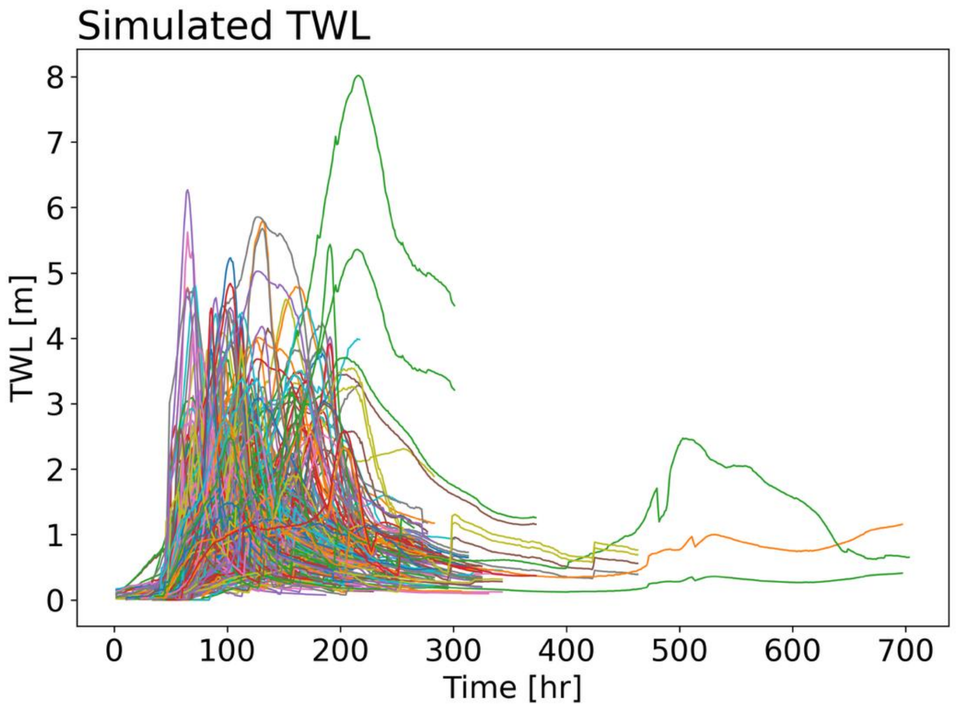
(a) H_s time series



(b) T_p time series



(c) Ssh time series



(d) TWL time series

Fig. 3. Full time series of the simulated variables for the East cluster at Location 1

Return Value Estimation

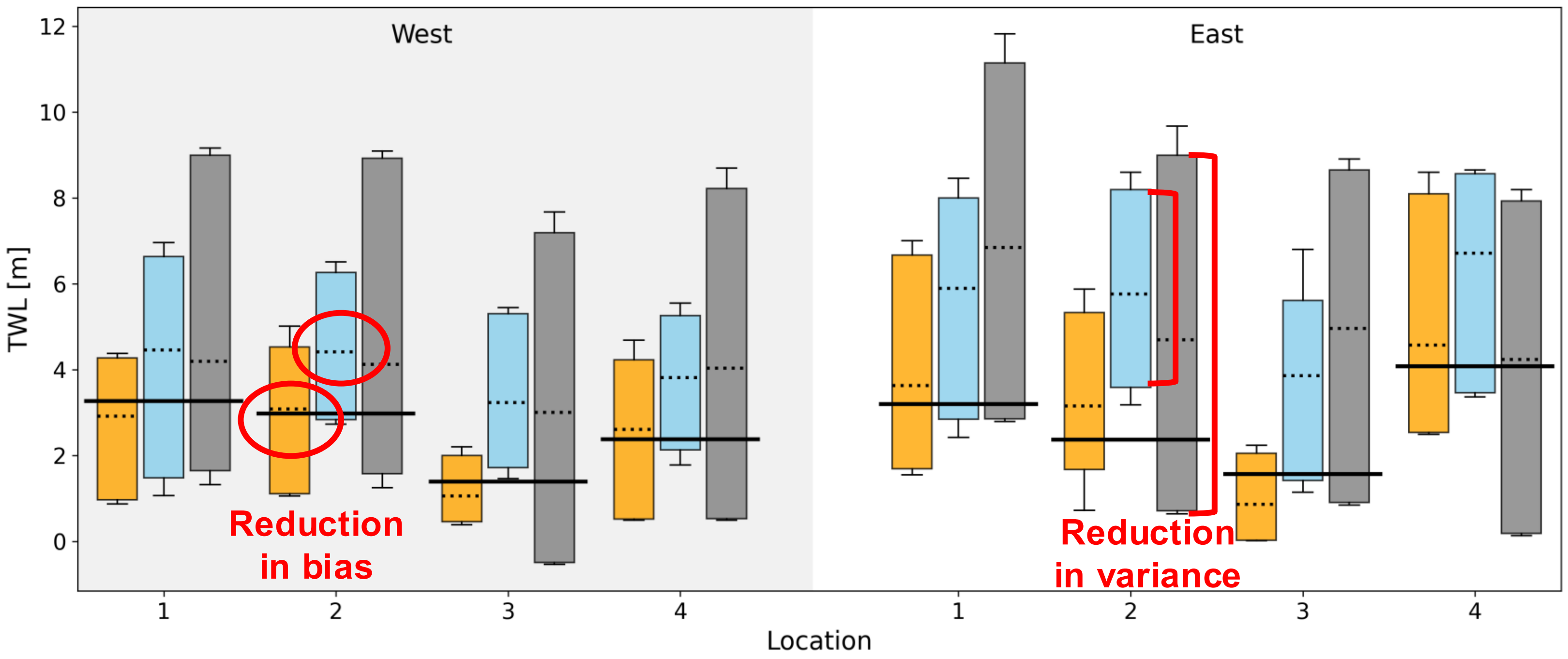


Fig. 4. Box–whisker plots of TWL return-level estimates for a 100-year return period modeled by west-cluster storms (left) and east-cluster storms (right). The black horizontal: the ground truth. The horizontal dotted line within each box: the mean value.

Across all study locations:

MSTM-E (blue)

- Reduces *variance* compared to LSE (grey)

MSTM-TE (yellow)

- Reduces *bias* compared to MSTM-E (blue)

→ Spatio-temporal coherence improves return level accuracy

Dominant Driver of Coastal Flooding

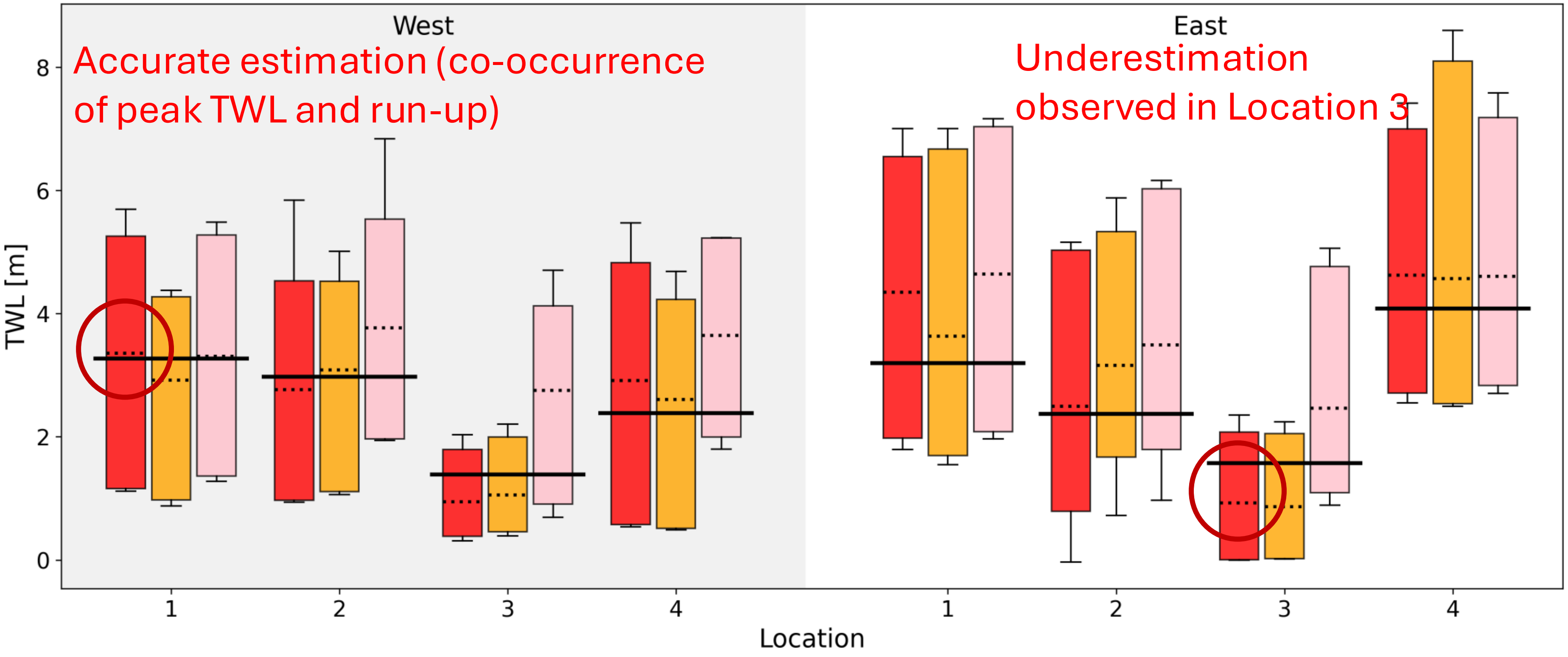


Fig. 5. Box–whisker plots of TWL return-level estimates for a 100-year return value estimates of TWL obtained from the **simplified timing-aligned framework (red)**, the MSTM-TE framework under **the trivariate configuration (yellow),** and the **bivariate configuration (pink)**.

Red: TWL at time of peak run-up

Yellow: MSTM-TE (T_p, H_s, Ssh)

Pink: MSTM-TE ($H_s T_p{}^2, Ssh$)

→ The mechanism of compound extremes is governed by local exposure patterns

Contents

Conclusion

(1) Temporal structure is essential for reliable risk assessment

(2) Wave-driven run-up dominantly governs extreme flooding

(3) Exposure governs the mechanism of compound extremes

Accurate design-level risk assessment must account for:

- Dominant physical processes (wave-driven run-up)
- Spatio-temporal structure
- Local exposure