Probabilistic reanalysis of storm surge extremes in Europe

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Practical motivation

- The impacts of sea-level rise will be largely felt through changes in extremes.
- Floods resulting from extreme sea levels are among the costliest and deadliest natural hazards.
- Numerical models project dramatic changes in sea-level extremes by the end of the 21st century.

How can the risks be managed?

Cost-effective risk mitigation strategies: balance expected damage with protection costs.

What is needed?

Knowledge of extreme event probabilities and their changes with time.
How do we estimate event probabilities?

Event probabilities are unobservable quantities that need to be inferred indirectly from sea-level measurements.

**Extreme value theory (EVT)**

- The distribution of extremes is always in the same family, regardless of the distribution of the overall data.
  - EVT is analogous to the central limit theorem for means, but it does not guarantee convergence.
  - Block maxima (e.g., annual maxima) can only converge to the GEV distribution.
  - To estimate event probabilities we need to determine the specific distribution within the GEV family, which involves estimating the GEV parameters (location, scale, shape).
Challenges in applying classical EVT

In sea-level research, EVT has primarily been applied on a **site-by-site** basis, namely by fitting a GEV separately at each tide gauge site. The challenges with this approach are:

- Number of events in the tide gauge record is small
  
  ![Large estimation uncertainty](image)

- Tide gauge record is sparse in space
  
  ![No estimates at many ungauged locations](image)

![Location of tide gauges and number of annual maxima for 1960-2013](image)
Extremes are spatial

Extreme values and their probabilities tend to be similar among neighbouring locations and regions. There are two types of spatial dependence:

1. Locations with correlated annual maxima

   They are affected by the same events

We capture this dependence using a max-stable process (the infinite-dimensional generalization of a GEV)

Annual maxima at 3 tide gauge sites

Tide gauge data from GESLA (Woodworth et al., 2017)
Extremes are spatial

The second type of spatial dependence is called **climatological dependence** since it is related to event probabilities:

2. Locations with correlated GEV($\mu, \sigma, \xi$) parameters

   $\Rightarrow$ *They have similar event probabilities*

We capture this type of dependence using **Gaussian processes**

*Model data from Muis et al. (2016)*
Aim: exploit spatial dependence to enable sharing of information across tide gauge sites

In our model, $\theta_i$ learns not only from data at the $i$-th site but from data at all other sites through the hyperparameters $\psi$. 
Advantages of spatiotemporal modeling

Advantage 1: reduction in estimation uncertainty

Standard errors in estimates of 50-yr return levels at tide gauge locations
Advantages of spatiotemporal modeling

Advantage 2: interpolation of event probabilities

50-yr return levels and SE’s as estimated by the Bayesian model
Advantages of spatiotemporal modeling

Advantage 3: interpolation of annual maxima

Estimated surge levels induced by cyclone Xaver in December 2013

Estimated annual maxima (black) compared with observed values at Delfzijl and Cuxhaven (green and magenta)

The probabilistic reanalysis of storm surge extremes has been deposited in Zenodo: https://doi.org/10.5281/zenodo.3471600

The code for the Bayesian hierarchical model is also available from Zenodo: https://doi.org/10.5281/zenodo.3442167

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