covXtreme: open-source software for modelling extreme data sets

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Motivation

• In risk analysis, the **modelling of the extremes of natural phenomena** such as rainfall, temperature, winds and waves is needed

• Particularly interested in the largest events that we **might have seen or could possibly see**

• Statistical methods can be used to model these largest events and provide the basis for design criteria

• Want to be able to also **incorporate information about important covariates** e.g., direction or season that influence these natural phenomena

• Focus on oceanographic applications but covXtreme can be used more generally for **non-stationary multivariate extreme value analysis**
Motivation

• Offshore operations require the probability of failure of manned structures and ships to be at the level of $p=1e-4$ per annum, corresponding to the so called 1 in 10 000 year criterion

• This requires the understanding of the extreme natural environment:
  • Extreme behaviour of waves, winds and currents individually
  • Joint behaviour of waves, winds and currents
  • Impact of covariates such as direction and the time of year

• Want to be able to propagate and quantify uncertainty related to modelling extremes of oceanographic data
Motivation
Oceanographic data
Motivation

• Statistical tool should handle the following features:
  • Accurate estimation of the tails of a data set
  • Capture covariate effects such as direction and season
  • Account for the interaction between multiple variables
  • Careful handling of uncertainty

• As a result, we have developed covXtreme, a open source MATLAB software for the estimation of extreme conditions
covXtreme

- covXtreme steps the user through a series of stages that result in the completion of a **full hazard risk analysis**
- MATLAB code is written in a **flexible modular way**
- Accompanied by an **user guide** that steps through two case studies
- A range of user settings can be specified - default settings are also provided
- Previous use of the code include Ross et al. [2018], Ross et al. [2020], Guerrero et al. [2021] and Barlow et al. [2023], example applications include surges, waves and neurology
Previous applications of covXtreme

**Surge trajectories** [Ross et al., 2018]

**Brain signals** [Guerrero et al., 2021]
covXtreme

- **Stage 1**: selection of extreme events from an environmental data set or simulation of a data set: selection of independent events
- **Stage 2**: selection of covariate bins, for example wave height as a function of direction: capture covariates for upcoming marginal modelling
- **Stage 3**: estimation of marginal models with respect to covariates: non-stationary modelling as a function of covariate bin
- **Stage 4**: joint estimation of oceanographic variables, for example the behaviour of wind speed when wave height is large: account for interaction between multiple variables
- **Stage 5**: estimation of environmental contours for risk assessment: interpretable summary for design engineers
How covXtreme has been useful in Shell?

- Development of code bases such as covXtreme maintains Shell’s reputation as a leader in the sector
- Application of covXtreme has yielded cost savings and improved safety offshore
- covXtreme is used for testing and scoping of improvements to Shell’s proprietary risk analysis software
- Established track record of covXtreme through extensive testing using relevant case studies
- Ability to do an efficient system analysis of offshore risk
- Use in upskilling and training of new staff and working with academic and industry partners
How does covXtreme fit in LF Energy’s landscape?
How could this code be useful more generally?

- **Educational** tool for the offshore sector: users can be data scientists, statisticians and practitioners
- **covXtreme motivates and explains** how natural hazard analysis problems are solved
- **First openly available tool** that brings together important elements of an risk analysis:
  - modelling a single variable
  - modelling multiple variables
  - incorporating the effect of covariates
  - system based response estimates
- **covXtreme has the key functionality to solve a typical risk analysis problem in a pragmatic manner**
Public engagement and future development

• covXtreme is **openly available through GitHub**: https://github.com/sede-open/covXtreme

• Journal article detailing methodology behind covXtreme is under review

• Presentations at statistics conferences e.g., RSS Conference (2023)

• Being **actively used by existing collaborators**

• External partners can build additional functionality into the code

• Opportunity to publicise with existing community and potentially interested communities, for example the flood risk sector
Potential future applications of covXtreme

- Pluvial and fluvial flooding
- Coastal risk of flooding
- Accounting for regime shifts in data sets e.g., financial or temperature data
- Operational maintenance of platforms, ships and wind turbines
Summary

• covXtreme enables **quick analysis of extreme data sets**

• **Computationally efficient and pragmatic** software for hazard risk analysis

• Non stationary **marginal and dependence modelling** with comprehensive uncertainty quantification

• **Improved quantification and communication** of risks associated with extreme events
References


Case Study: Hs and Tp

Example application of covXtreme: modelling the relationship between significant wave height (Hs) and peak period (Tp)
Stage 1: extraction of storm peaks
Stage 1: extraction of storm peaks
Stage 2: selection of bins
Stage 2: joint behaviour of Hs and Tp
Stage 3: marginal model

- Set a bin dependent threshold $\psi_b$ to define extreme events
- For data below the threshold fit a **Gamma distribution**
- For data above the threshold fit a **generalised Pareto (GP) distribution**:
  - Threshold $\psi_b$ with scale $\nu_b$ and shape parameter $\xi$
- Likelihood above the threshold:

$$
\ell(\dot{x}_i \mid \xi, \nu, \psi, \lambda) = \log \prod_{b=1}^{B} \prod_{i:A(i)=b; \dot{x}_i > \psi_b} f_{GP}(\dot{x}_i \mid \xi, \nu_b, \psi_b) + \lambda \left( \frac{1}{B} \sum_{b=1}^{B} \nu_b^2 - \left[ \frac{1}{B} \sum_{b=1}^{B} \nu_b \right]^2 \right)
$$
Stage 3: marginal model (Hs)

GP scale and Gamma parameters  

GP shape parameter
Stage 3: marginal model assessment (Hs)
Stage 3: marginal return values (Hs)
Stage 4: dependence model

Conditional dependence model of Heffernan and Tawn [2004]:

\[(Y_2 | Y_1 = y) = \alpha_b y + y^{\beta_b} W_b\]

- \(Y_2 = T_p, Y_1 = Hs\) on Laplace scale
- for \(y >\) sufficiently large threshold \(\phi\)
- \(\alpha_b \in [-1, 1], \beta_b \in (-\infty, 1]\)
- \(W_b \sim \text{DeltaLaplace}(\mu_b, \sigma_b, \delta)\)
Stage 4 - simulations from the dependence model
Stages 3 and 4: conditional return values (Tp|Hs)
Stages 3 and 4: dealing with uncertainty

Two sources of uncertainty:
- Bootstrap resampling
- Non exceedance probability threshold:
  $\phi \sim \text{Uniform}(\phi_{LB}, \phi_{UB})$
Stage 5: contour estimation

- Estimation of risk profiles
- Three different contour methods:
  - Exceedance (Exc)
  - Heffernan and Tawn (HTDns)
  - Huseby (Hus)
- Number of control factors