A Unified Framework for Analyzing Non-Stationary Joint Extremes Using Transformed-Stationary EVA

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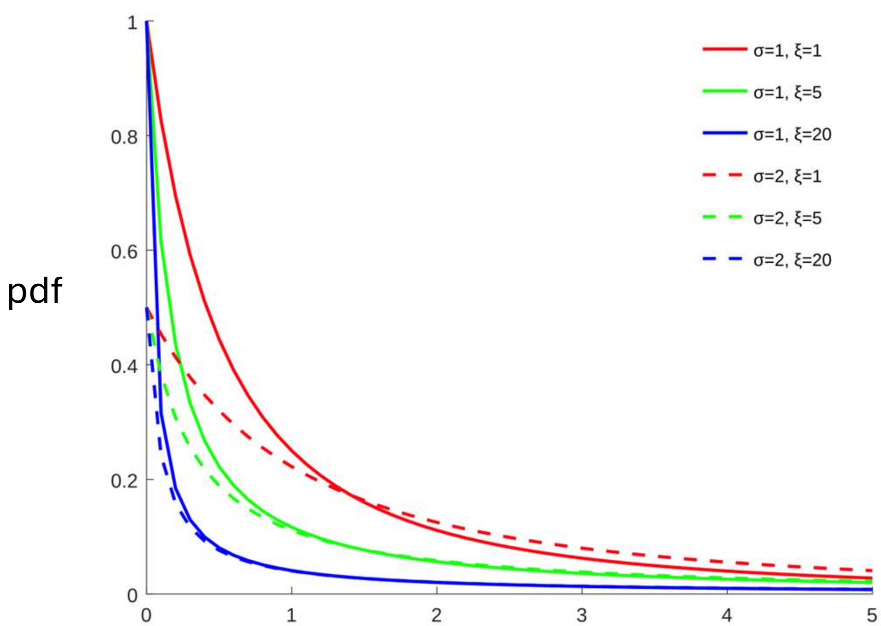
EOatSEE
Earth Observation advanced science tools for Sea level Extreme Events

25/September/2025
Santander, Spain

Probabilistic study of extremes

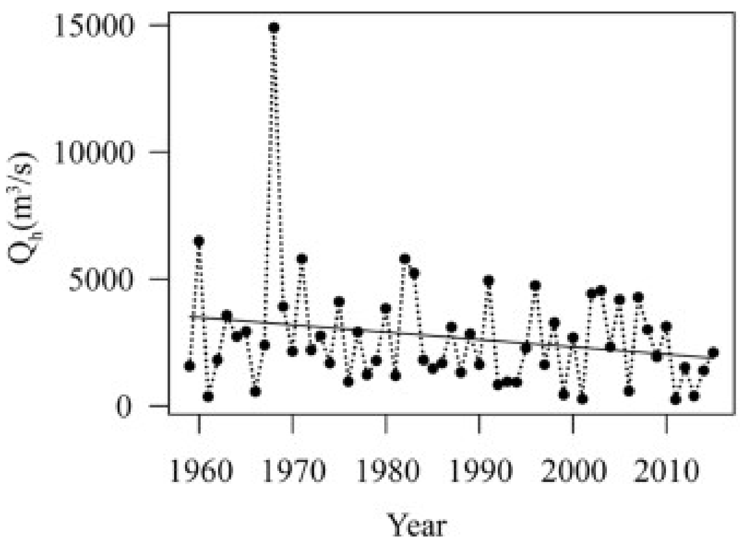
- Risk assessment of natural hazards : flooding, drought, etc.
- The theory : **extreme value analysis (EVA)**



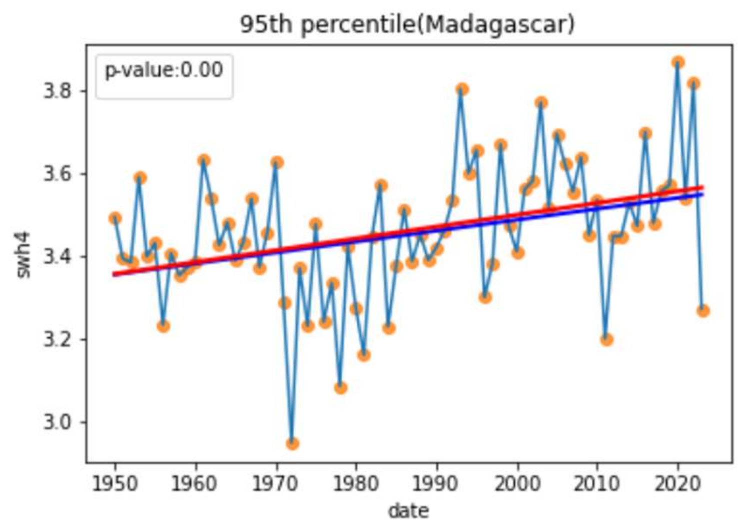
Stationarity requirement

- The classical EVA require stationarity of the underlying series
- Many datasets, especially those related to natural hazards, indicate non-stationarity

Huai River discharge
Feng, et al. 2020



Significant Wave Height in Madagascar
Mentaschi et al. 2023



Transformed-stationary Extreme Value Analysis: tsEVA

- *A freely available toolbox in GitHub : https://github.com/menta78/tsEva*

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL072488

Key Points:
- Extreme waves will change along a large portion of the coasts generally increasing in the S. Hemisphere and decreasing in the N. Hemisphere
- The projected changes of extreme waves can be explained with a projected intensification of climatic patterns such as AAO, ENSO, and NAO

Supporting Information:
- Supporting Information S1

Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns

Lorenzo Mentaschi[1], Michalis I. Vousdoukas[1,2], Evangelos Voukouvalas[1], Alessandro Dosio[1], and Luc Feyen[1]

[1]Joint Research Centre, European Commission, Ispra, Italy, [2]Department of Marine Sciences, University of the Aegean, Mitilene, Greece

Abstract In this study we conducted a comprehensive modeling analysis to identify global trends in extreme wave energy flux (WEF) along coastlines in the 21st century under a high emission pathway (Representative Concentration Pathways 8.5). For the end of the century, results show a significant increase up

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DOI: 10.1038/s41467-018-04692-w OPEN

Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard

Michalis I. Vousdoukas[1,2], Lorenzo Mentaschi[1], Evangelos Voukouvalas[3], Martin Verlaan[4,5],

Environmental Research Letters

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20 March 2018

LETTER

Extreme heat waves under 1.5 °C and 2 °C global warming

Alessandro Dosio[1,4], Lorenzo Mentaschi[1], Erich M Fischer[2] and Klaus Wyser[3]

1 European Commission, Joint Research Centre, Ispra, Italy
2 Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland
3 Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
4 Author to whom any correspondence should be addressed.

nature climate change

Analysis https://doi.org/10.1038/s41558-022-01540-0

Cost-effective adaptation strategies to rising river flood risk in Europe

Received: 12 May 2021

Accepted: 24 October 2022

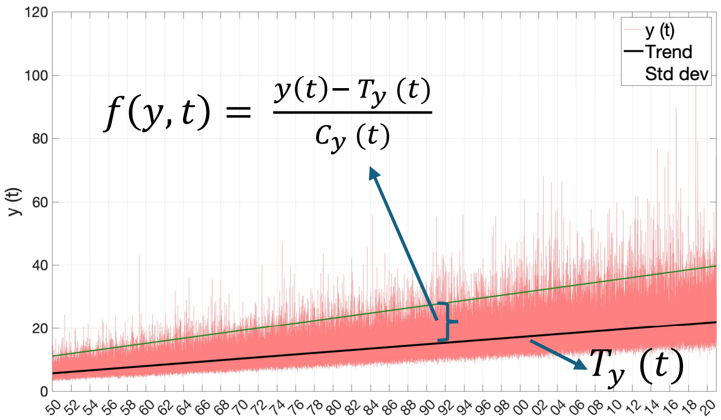
Published online: 6 February 2023

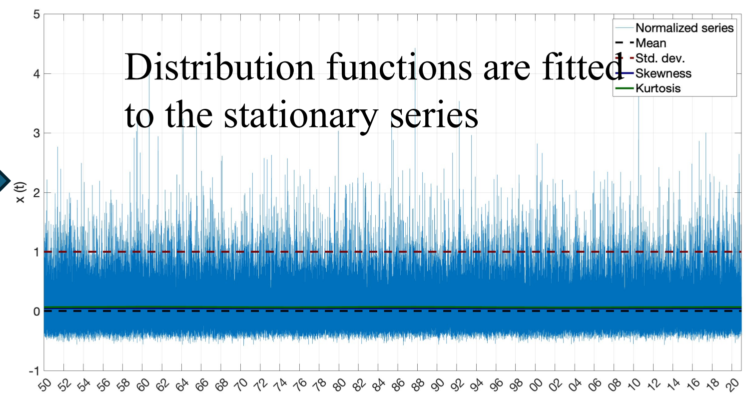
Check for updates

Francesco Dottori[1,4], Lorenzo Mentaschi[1,2], Alessandra Bianchi[3], Lorenzo Alfieri[4] & Luc Feyen[1]

River flood risk in Europe could rise to unprecedented levels due to global warming and continued development in flood-prone areas. Here, we appraise the potential of four key adaptation strategies to reduce flood risk across

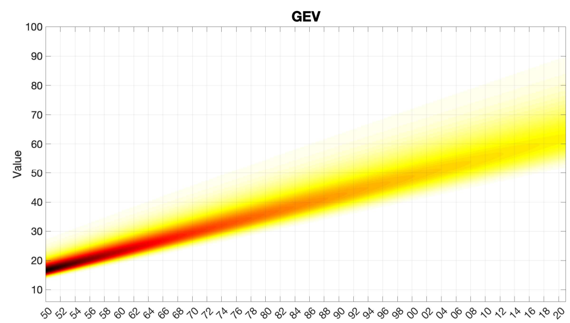
tsEVA methodology



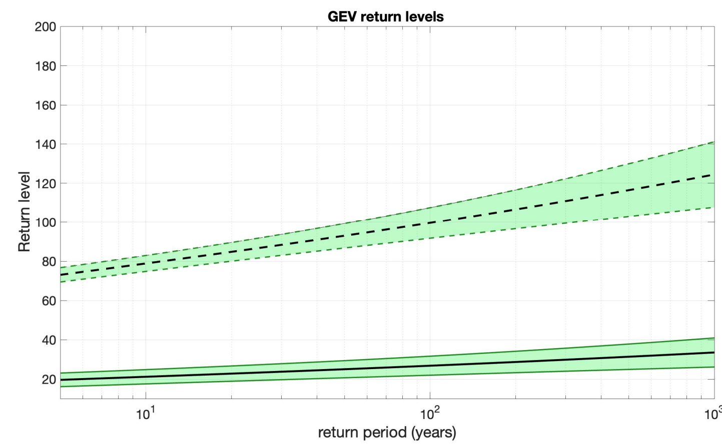


Transformation using time-varying normalization:

- A wide range of transformations
- Diagnosis of the type of non-stationarity
- No priori parametric assumption
- Different stage for non-stationary detection and fitting of EVD



Using a back-transformation, non-stationary distribution parameters are obtained



Return levels as a function of time

Extension of tsEVA for multivariate extremes : compound events

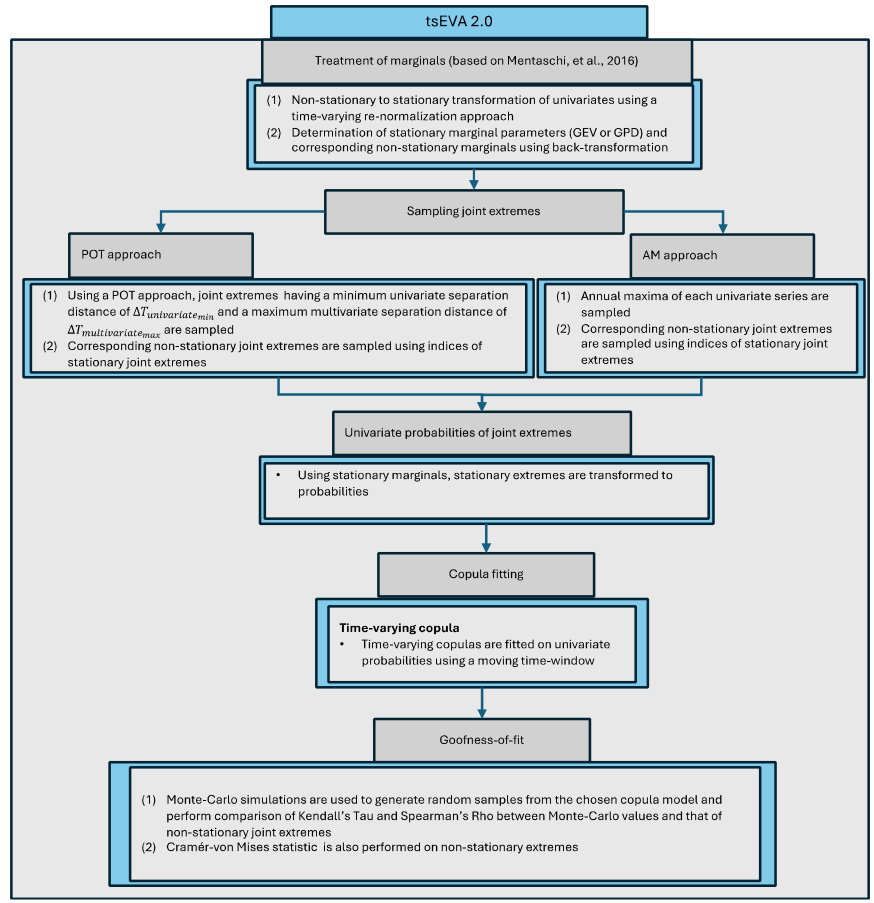
(1) Each univariate is separately stationarized

(2) Joint extremes are sampled using POT or AM approaches

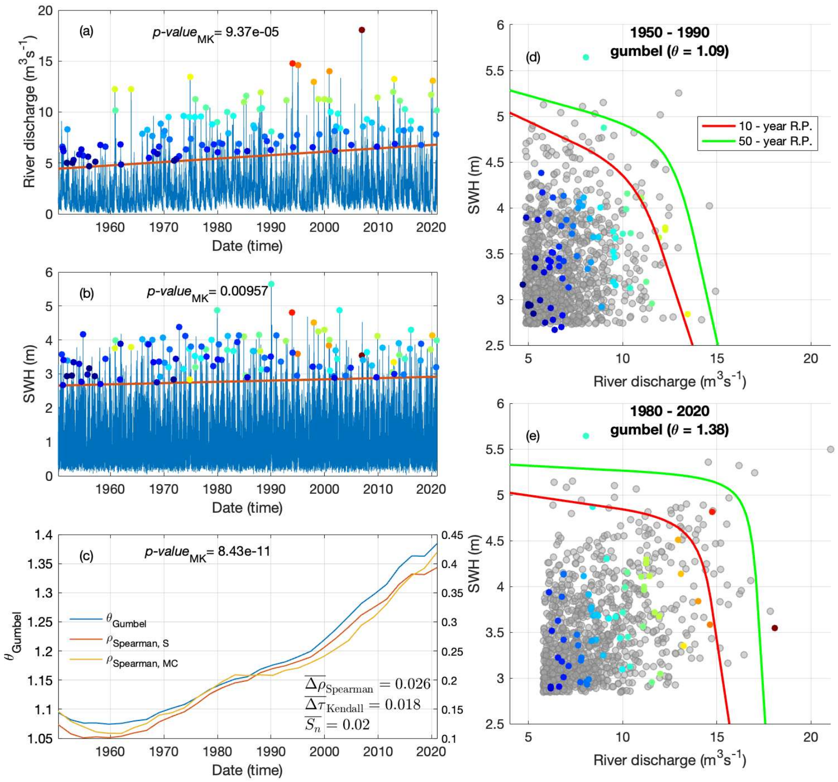
(3) Joint extremes are converted to probabilities using an appropriate CDF

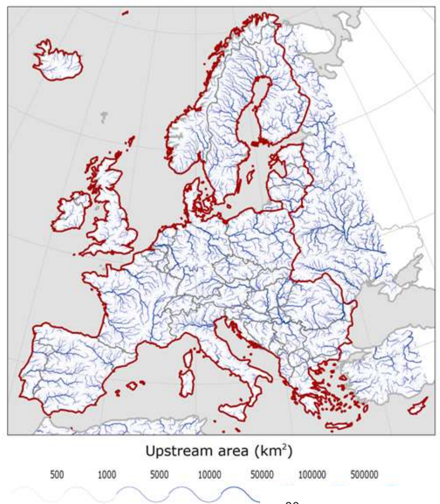
(4) A time-varying copula is then fitted on these set of probabilities based on pair-wise Kendal-taus and C-vine for multivariate Gumbel

(5) Goodness-of-fit of the copula model is assessed using Cramer-von Mises metric and Monte-Carlo strategies

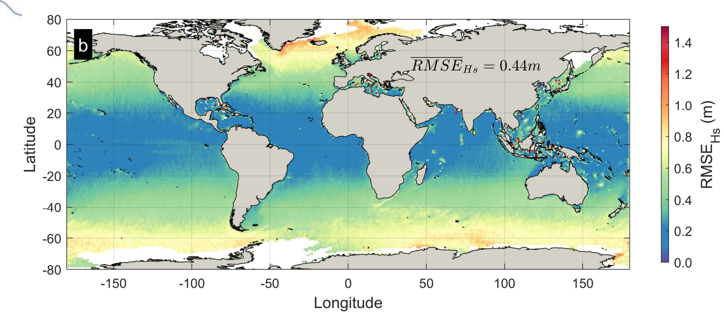


Bivariate application of tsEVA





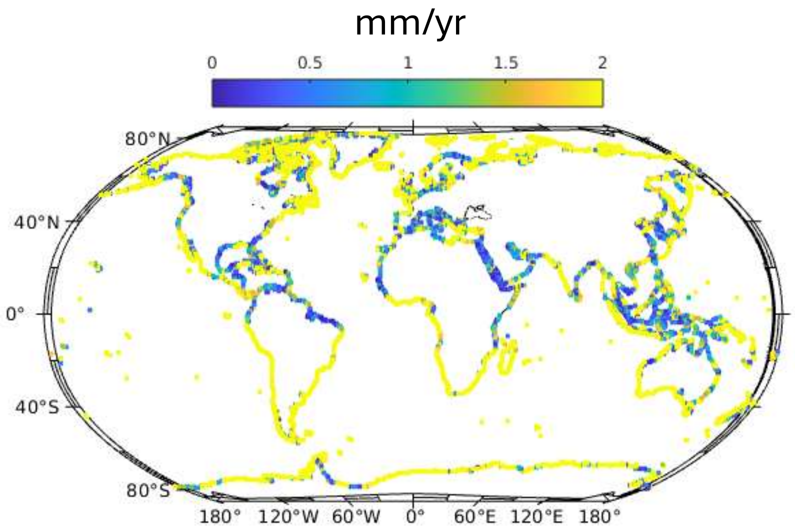
River data from Tilloy et al., 2025 (Hydrological Reanalysis)

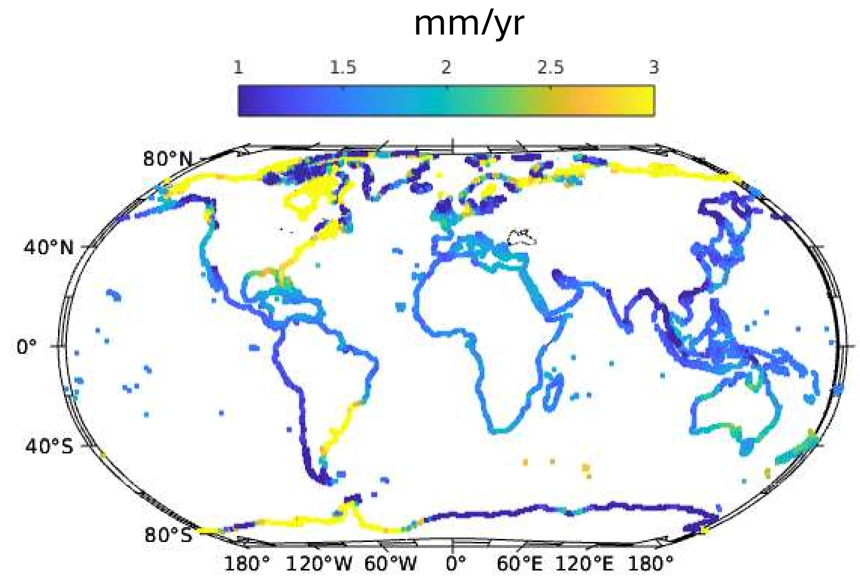


3-hourly wave data from Mentaschi et al., 2023

- GPD for margin and a time-varying Gumbel copula (40-year time window) to model dependence

Bivariate application of tsEva





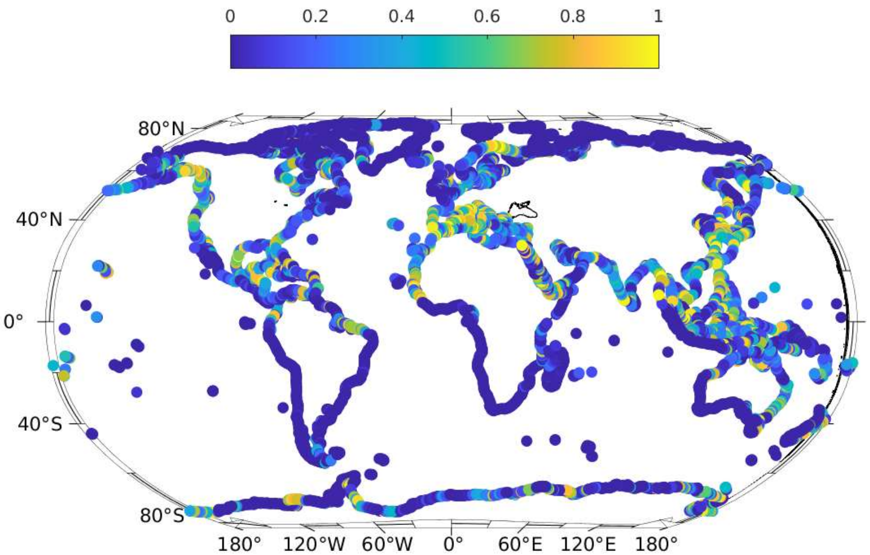
Trend of extremes of SWH

Trend of extremes of surge hindcast + SLR

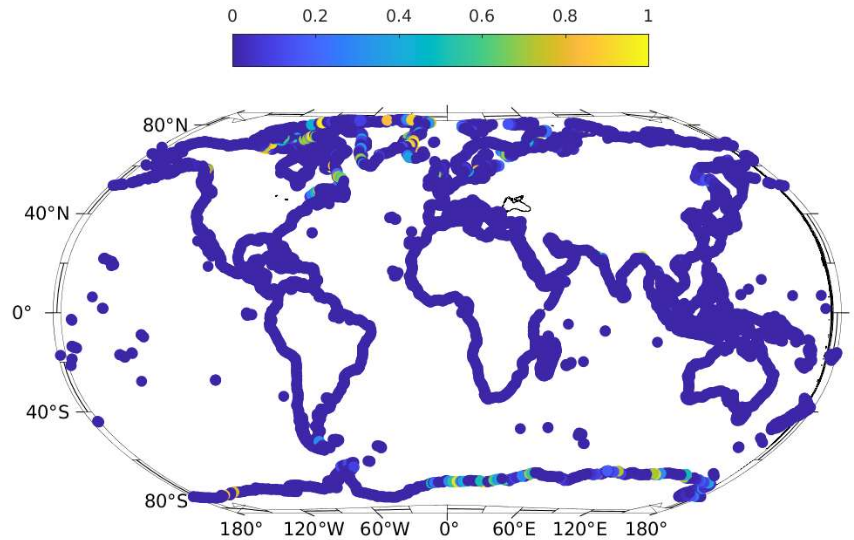
Trend of the 99th percentile

Data source: Mentaschi, et al., 2023 forced by ERA-5 & bias-corrected by altimetry
~ 130 k coastal grid points

Bivariate application of tsEva



SWH

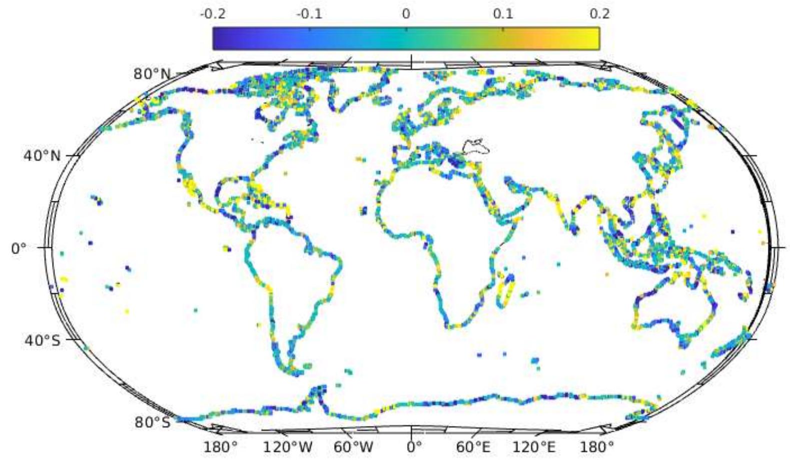


Surge hindcast + SLR

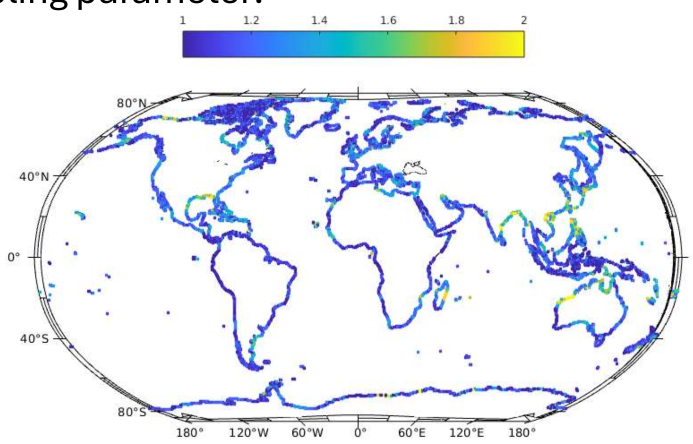
P-value (Mann-Kendal test)

Data source: Mentaschi, et al., 2023 forced by ERA-5 & bias-corrected by altimetry
~ 130 k coastal grid points

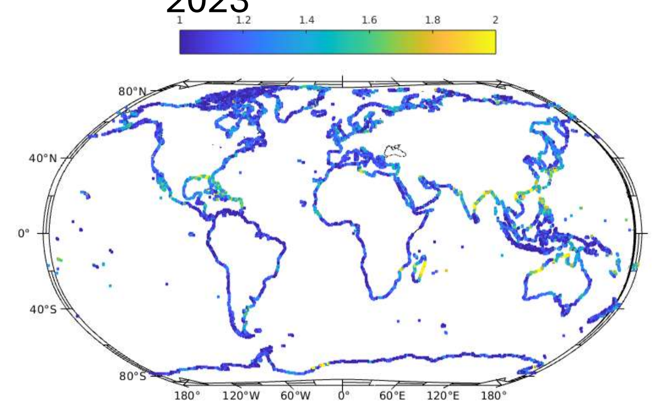
Bivariate application of tsEva



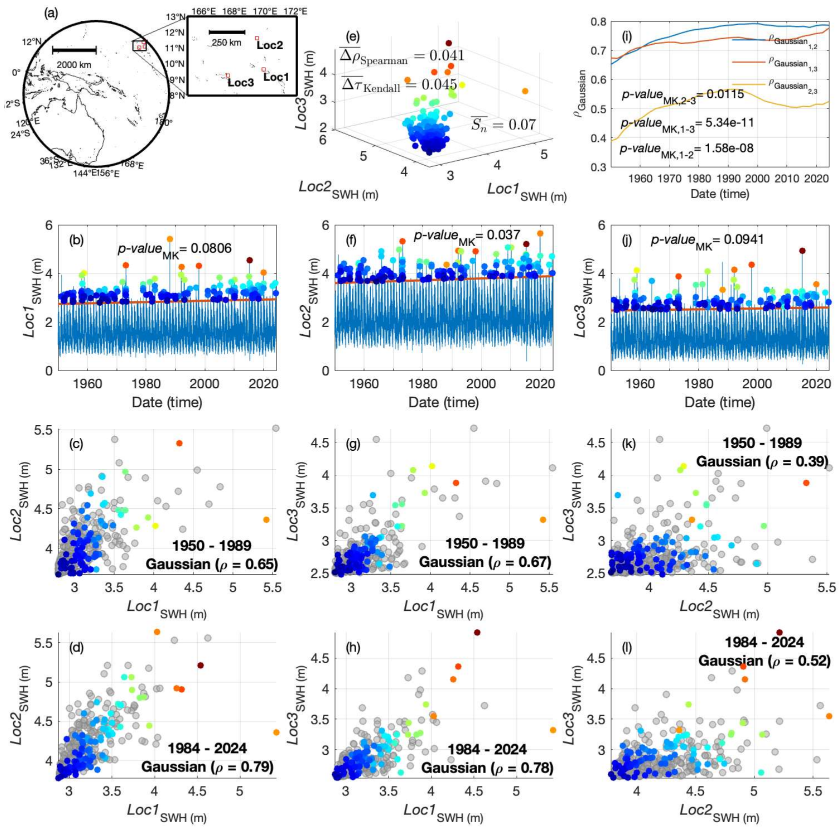
Coupling parameter:
1950

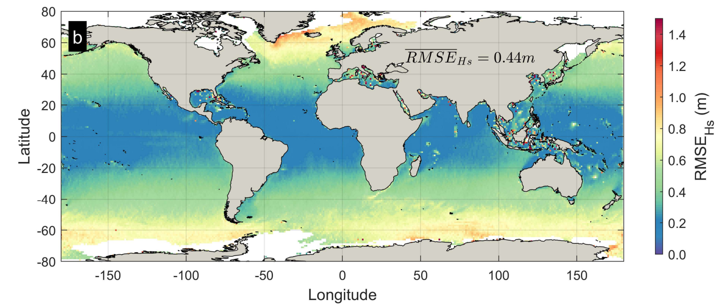


Coupling parameter:
2023



Trivariate application of tsEVA



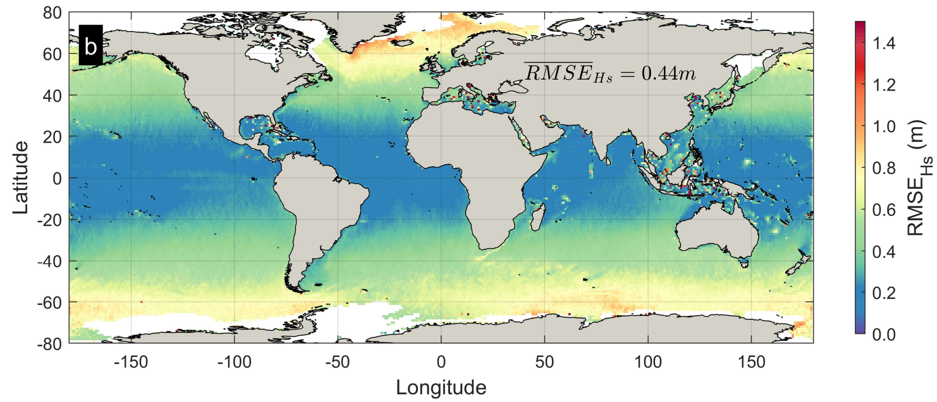


3-hourly SWH from Mentaschi et al., 2023 (1950 – 2024)

- Generalized Pareto Distribution (GPD) for univariate margins and a time-varying Gaussian copula (40-year time window) to model dependence

Five-variate application of tsEVA

HERA hydrological reanalysis : Tilloy et al., 2025



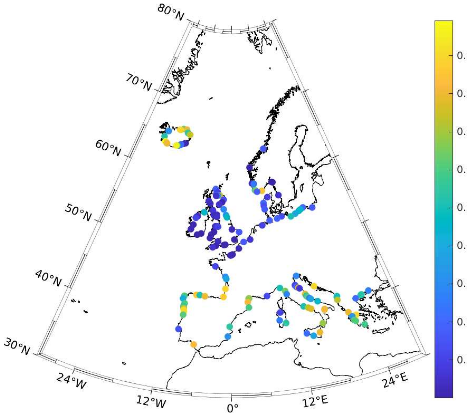
3-hourly SWH from Mentaschi et al., 2023 (1950 – 2024)

- All river mouthes (>10 m3/s) across Europe were identified
- Surge (+SLR)and SWH from nearest point were extracted
- Wave runup based on Stockdon, et al., 2006
- Instanteneous hourly wind speed and precipitation from ERA-5

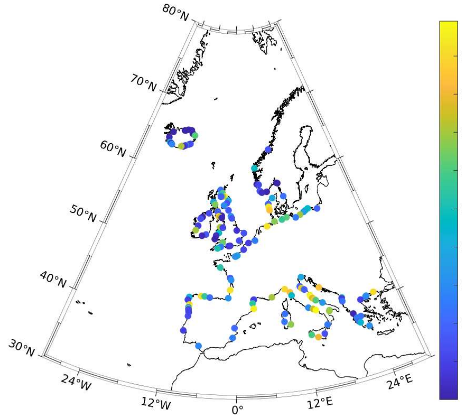
160 grid points yielded full fiver-variate dataset

Five-variate application of tsEVA

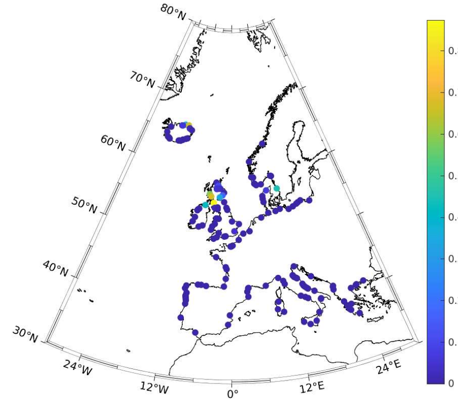
wind speed



SWH

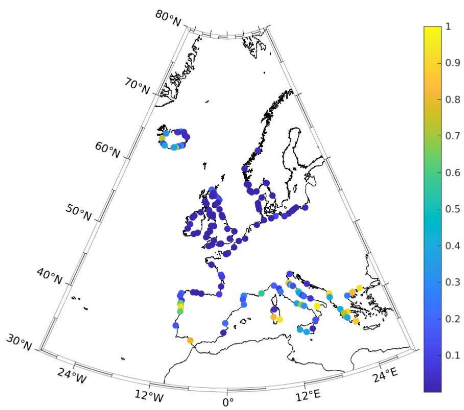


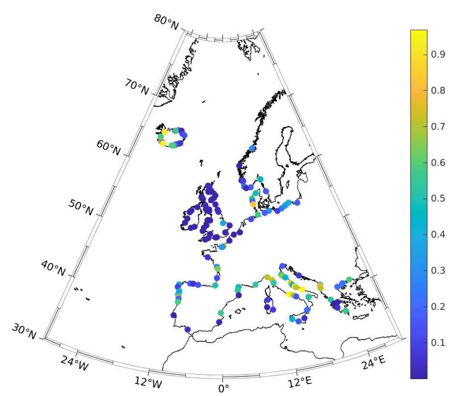
Water level



P-value of the Mann-kendal test

Precipitation

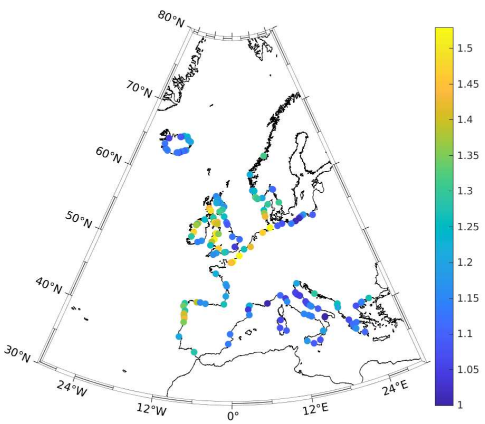




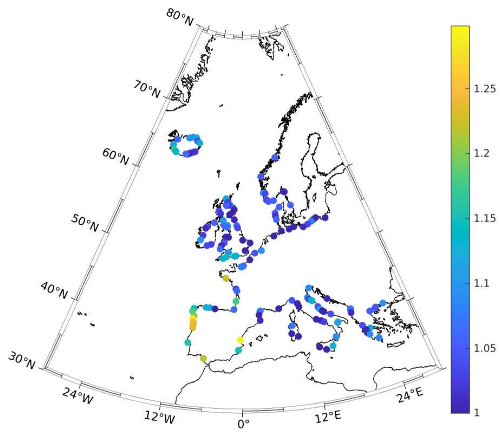
River discharge

Five-variate application of tsEVA

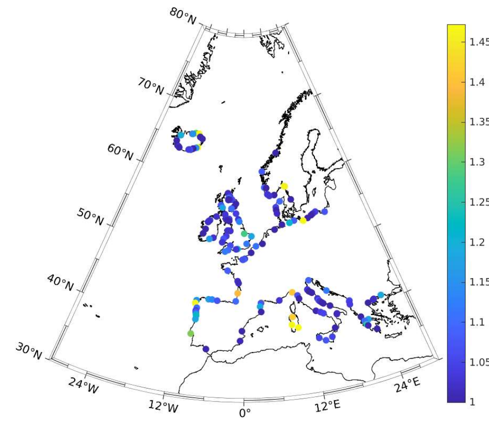
Precipitation & river discharge



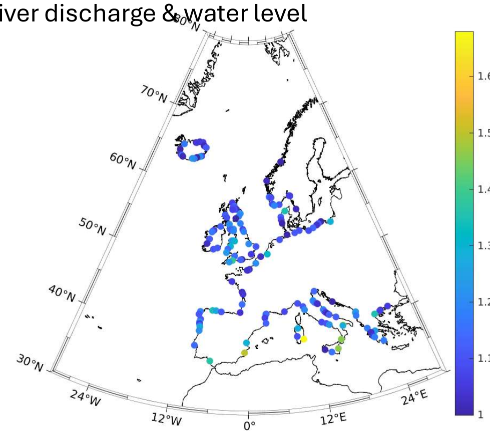
Precipitation & wind speed



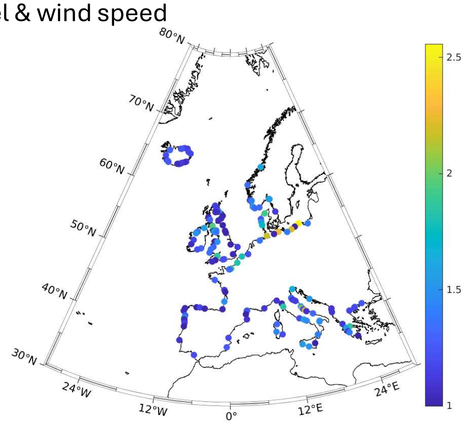
Precipitation & water level



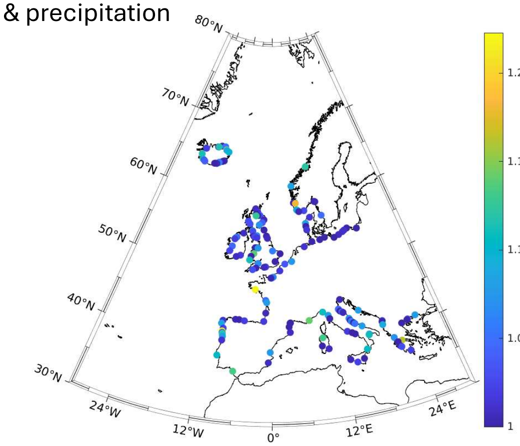
River discharge & water level



Water level & wind speed



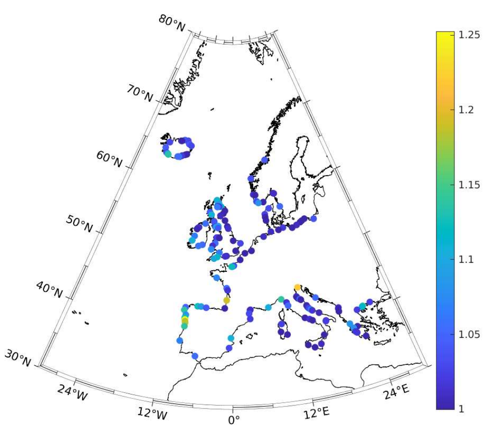
SWH & precipitation



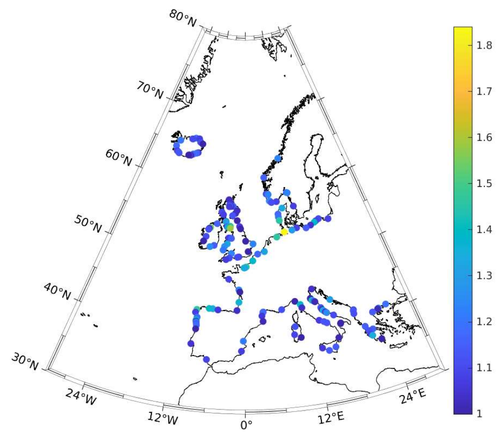
Coupling parameter (Gumbel copula)

Five-variate application of tsEVA

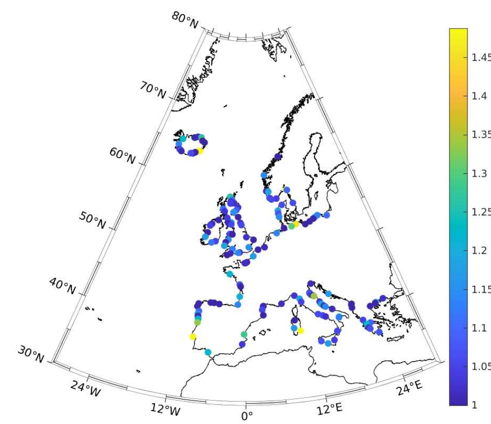
Wave & river



Wave & water level



Wave & wind



Coupling parameter
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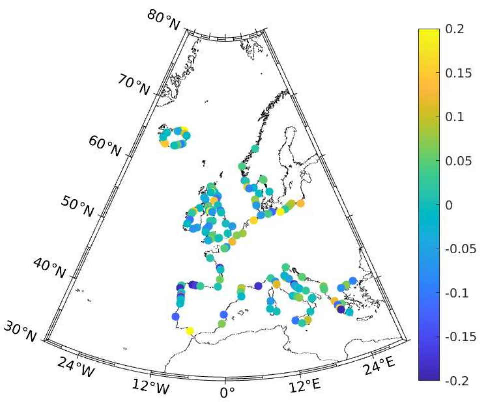
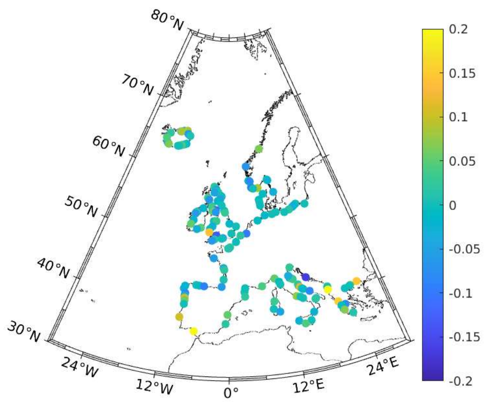
Five-variate application of tsEVA

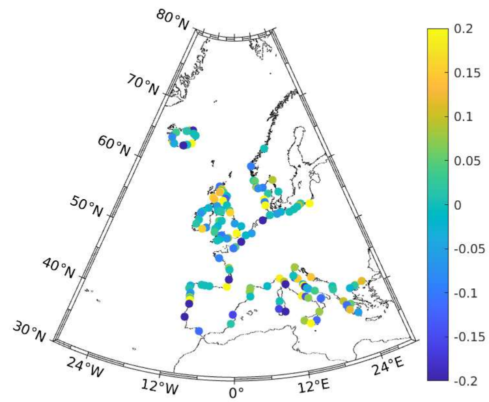
SWH & water level



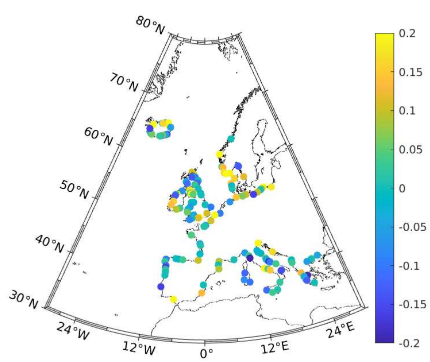
SWH & precipitation



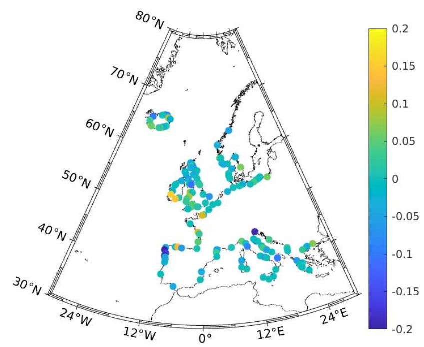
SWH & river discharge



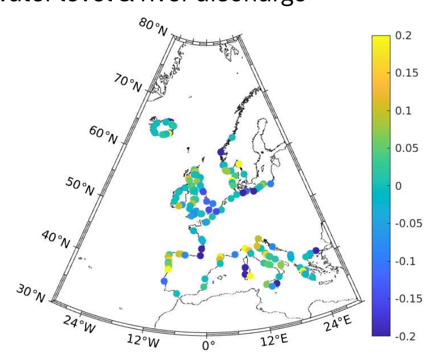
SWH & wind speed



Water level & precipitation



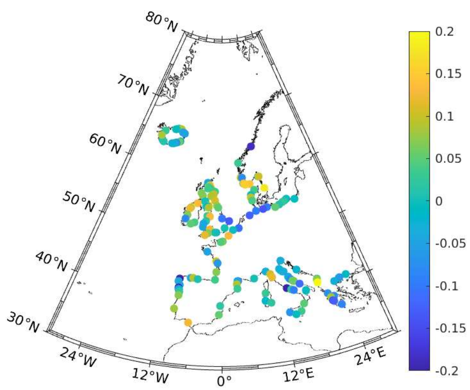
Water level & river discharge



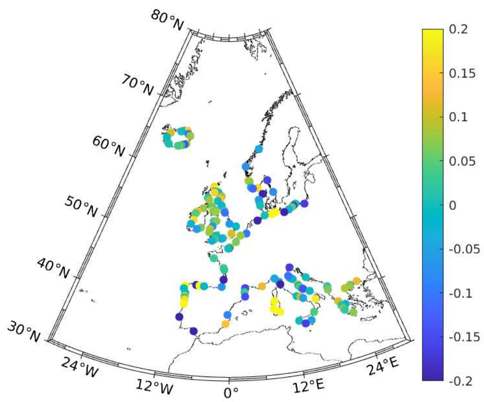
Change of coupling parameter (Gumbel copula)

Five-variate application of tsEVA

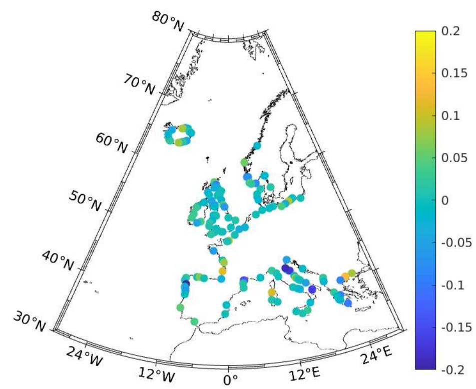
Water level & wind



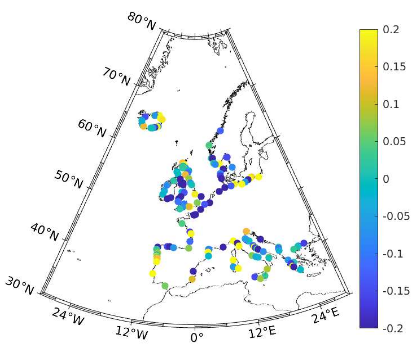
Precipitation & river discharge



Precipitation & wind



River discharge & wind



Change of coupling parameter (Gumbel copula)

Summary

•tsEVA 2.0 extends univariate non-stationary EVA to **multivariate extremes**, combining tsEVA with copula theory to model evolving dependencies

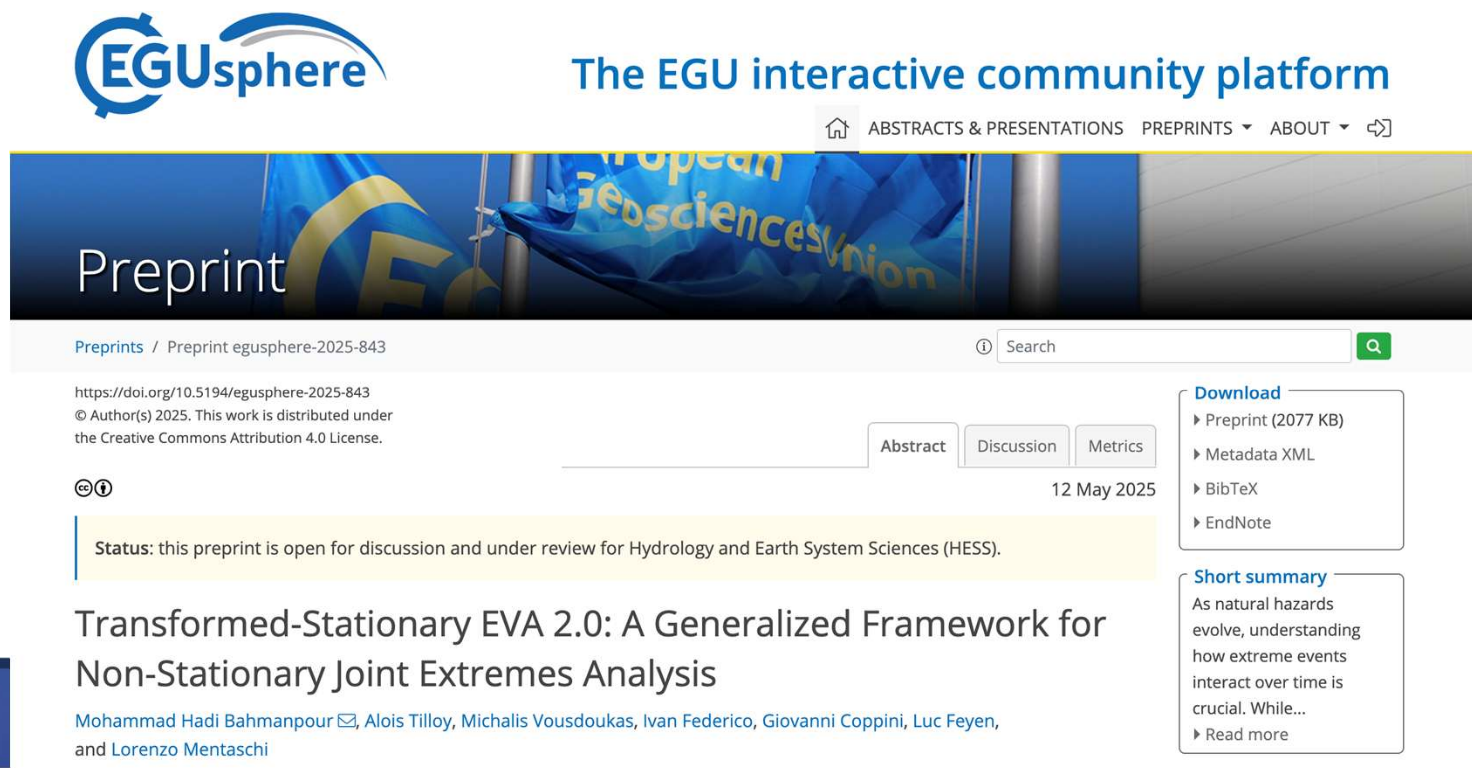
•Supports **block-maxima (GEV)** and **POT (GPD)** approaches, with **time-varying copulas** capturing both marginal and dependency non-stationarity; includes built-in **goodness-of-fit metrics** and joint return period estimation

•Application on different dataset indicated importance of considering non-stationarity both at the marginal as well as a dependency parameter highlighting the importance of accounting for **dynamic compound hazards**

Directions for future work:

•Integrate **climate model projections** to assess future non-stationary joint extremes and support **risk-informed adaptation strategies**

•Use ML approaches in the implementation of tsEVA



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Abstract | Discussion | Metrics

12 May 2025

Status: this preprint is open for discussion and under review for Hydrology and Earth System Sciences (HESS).

Transformed-Stationary EVA 2.0: A Generalized Framework for Non-Stationary Joint Extremes Analysis

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Short summary
As natural hazards evolve, understanding how extreme events interact over time is crucial. While...
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