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BOOK OF ABSTRACTS

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The impact of spatio-temporal resolution in simulating storm surges along European coasts

Miguel Agulles[1*], Marta Marcos[1,2], Ángel Amores[1,2] and Tim Toomey[4]

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In this work we investigate the patterns of storm surges along the European coastlines using numerical simulations (see Fig. 1). We pay special attention at the role of the spatio-temporal resolution of the available atmospheric forcing fields, and generate a new high-resolution storm surge hindcast of 82 years (1940-2021) covering all European coasts. To do so, the SCHISM numerical model (Zhang et al., 2016) and ERA5 atmospheric reanalysis are used. The outputs are compared against 145 tide gauges retrieved from GE LA 3.0 dataset (Haigh et al., 2022). Key metrics such as the variability, magnitude and duration of the events will be assessed as well as the effect of spatial and temporal resolution of the atmospheric fields (i.e., wind and mean sea level pressure) in the storm surge accuracy.

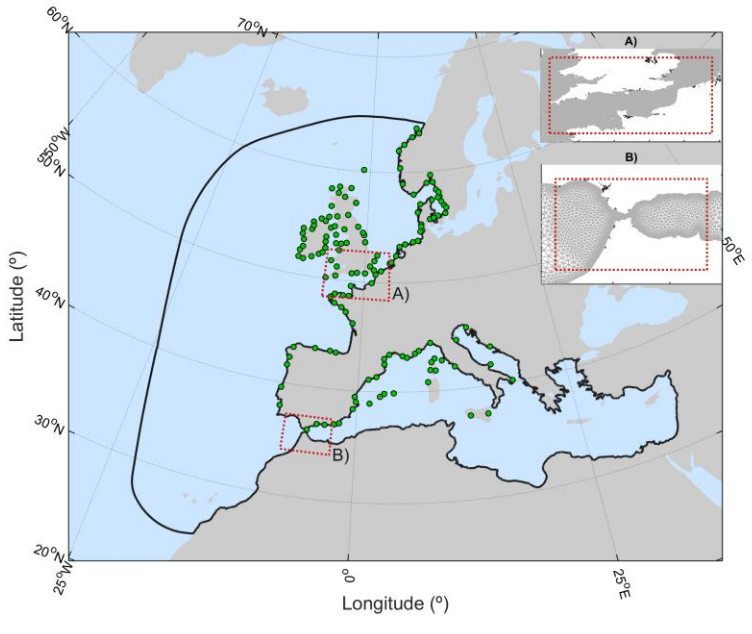

Fig. 1: *Study site. Mesh contour of the numerical model (in back), locations of the tide gauges (green dots) and straits with refined grid (red squares), for The English Channel (A) and the Gibraltar Strait (B).*

For instance, among other analysis, to evaluate the performance of the simulations under extreme events, we conducted a quantile-quantile comparison between simulated and observed storm surges at 16 tide gauge's locations (red dots Fig. 2).

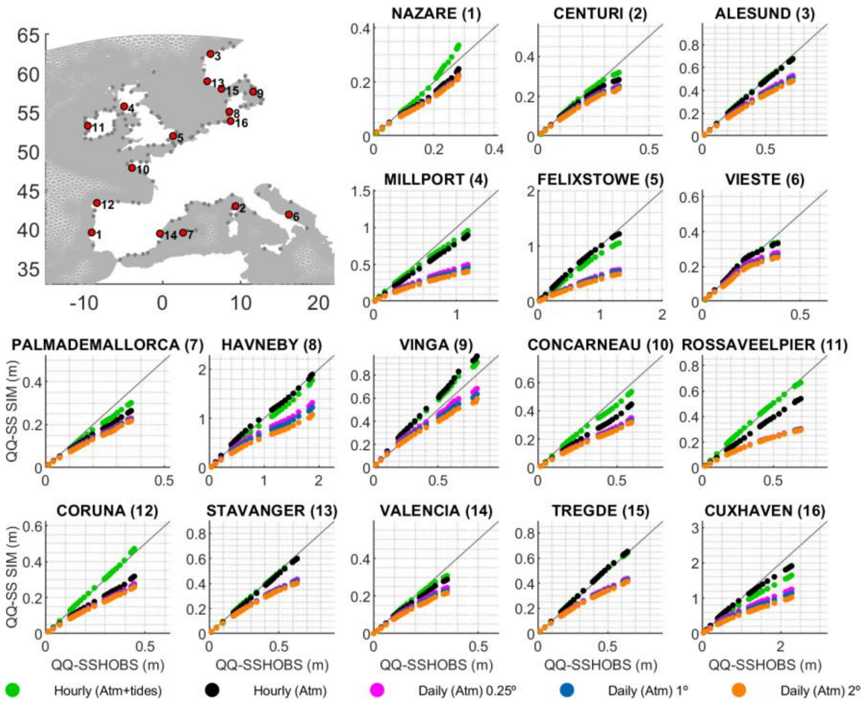

Fig. 2: *Quantile-quantile plot of surges that compares simulations (y axis) and observations (x axis). The simulations are depicted in different colors: SIM1 (green), SIM2 (black), SIM3 (magenta), SIM4 (blue) and SIM5 2º (orange)*

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Comparing extreme sub-daily rainfall projections from temperature-scaling and convection-permitting climate models across an Alpine gradient

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Understanding projected changes in sub-daily extreme rainfall in mountainous basins can help increase our capability to adapt to and mitigate against flash floods and debris flows. Here we compare the changes in extreme rainfall projections from apparent Clausius-Clapeyron (CC) temperature scaling against those obtained from convection-permitting climate model simulations. Temperature and precipitation projections are obtained from an ensemble of convection-permitting climate models (CPM), which are suitable to the task given their ability to explicitly represent deep convection and to resolve the mountainous topography. The CPM data provided by the CORDEX-FPS Convection project at 1-hour temporal and remapped to 3 km spatial resolution, cover historical and far-future (2090-2099) time periods under the extreme climate change scenario (RCP8.5). Due to the computational demands however, CPM simulations are still too short (typically 10-20 years) for analyzing extremes using conventional methods. We use a non-asymptotic statistical approach (the Metastatistical Extreme Value, MEVD, Marani and Ignaccolo, 2015) for the analysis of extremes from short time periods, such as the ones of CPM simulations. We use hourly precipitation and temperature data from 174 stations in an orographically complex area in northeastern Italy as a benchmark.
Results from our analysis reveal that the apparent CC temperature scaling method demonstrates effective performance when applied to 1-hour extreme rainfall projections and for high return periods. However, its accuracy decreases as the precipitation duration increases, highlighting potential limitations in accurately predicting changes in longer-duration extreme rainfall. Variations in performance are also noted when considering different return periods, as we find CPM changes depending on them, contradicting traditional CC-scaling. Furthermore, we show that elevation is a key factor influencing temperature variations, with higher elevation locations experiencing more pronounced temperature increases with respect to lowland areas. This affects more the results for 1 hr extreme rainfall projections, whereas it is less relevant for 24-h duration. These findings identify some serious limitations of traditional CC scaling and emphasize the need for a nuanced understanding of the scaling method's applicability under various conditions.

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Process-Driven Modeling of Compound Rainfall and Storm Surge Extremes for Coastal Texas

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Coastal Texas is no stranger to different natural hazards, including riverine and coastal flooding, heavy rainfall, and strong winds. While these events can be catastrophic on their own, they can have an even larger impact when they occur together, as in the case of compound extremes. It is therefore critical to account for the joint occurrence of these extremes toward a more accurate representation of the risk for these coastal communities.

Here we present a process-driven modeling approach that allows the development of high-resolution (~4 km and hourly) design storms that capture the observed dependence between rainfall and storm surge. Analyses are performed for six watersheds in eastern and central Texas for different annual exceedance probabilities. We hypothesize that not all storms have the same compounding characteristics, with the expectation that tropical cyclones (TCs) exhibit a different dependence structure than non-TC events. Hence, we stratify the records into TC- and non-TC events based on the TC tracks. We perform analyses from 1979 to 2021 using the Analysis of Period of Record for Calibration (AORC) dataset and existing water level records based on the National Oceanic and Atmospheric Association (NOAA) and U.S. Geological Survey (USGS) archives. While the precipitation record is continuous during the study period, this is not the case for the water level records; to address this issue, we use the long record at Galveston Pier 21 to infill missing data at all other locations. We then extract the storm surge time series at each location after accounting for different cycles in the record, from mean sea level variability to tidal contributions.

To identify extreme events, we use the peak-over-threshold (POT) approach and select a given number of events (n-events) per year on average based on a trade-off between sample size and goodness-of-fit of the marginals. We then attribute these events to either TCs or non-TCs. We find that precipitation and storm surge extremes are strongly correlated (uncorrelated) for TC (non-TC) events. Therefore, we treat the non-TC extremes as independent (i.e., non-compounding); we build two sets of bivariate models (Bender et al., 2016) for the TC events, where one model is conditioned on storm surge extremes and the other on precipitation extremes. Both models follow the framework proposed by Jane et al. (2020). This approach allows us to estimate the basin- and storm-averaged precipitation and the corresponding storm surge values for a given annual exceedance probability. Then, we use the historical TC and non-TC events to provide us with a way to downscale the design, basin- and storm-averaged value to the hourly and 4-km resolution. Moreover, we also provide a data-driven approach to account for the lag between precipitation and storm surge peaks.

The proposed methodology enables us to capture the compounding between precipitation and storm surge across coastal Texas. We show that there are strong differences between TC and non-TC events. Moreover, these differences would be lost if we did not account for different generating mechanisms (i.e., TC and non-TC events) and treated all events as coming from a single population. The proposed framework is flexible and can be customized for different regions and different flood processes, representing an empirical methodology to develop design storms for compound extremes for different annual exceedance probabilities.

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Analyzing patterns of extreme heat events in Europe using extreme value theory

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Understanding the frequency and intensity of extreme heat events is crucial for policy formulation and infrastructure planning. In this study, we analyse patterns of extreme heat events of Europe, utilizing the temperatures of air at 2m above the surface (land, sea or inland waters) between 1940 and 2023 from the ERA5 dataset. A method is derived that is based on the point process approach of extreme value theory to compute the likelihoods of patterns of heat events within a year. In contrast to existing literature, the group of heat days within a year is evaluated instead of individual heat days. This will allow us to compute the return level of mean excesses of temperatures within a group of heat days of any length, and the return period which is the expected waiting time of next occurrence of some specific year with unusual excesses of heat days. We therefore extend the classical approach of considering return levels of one heat day only.

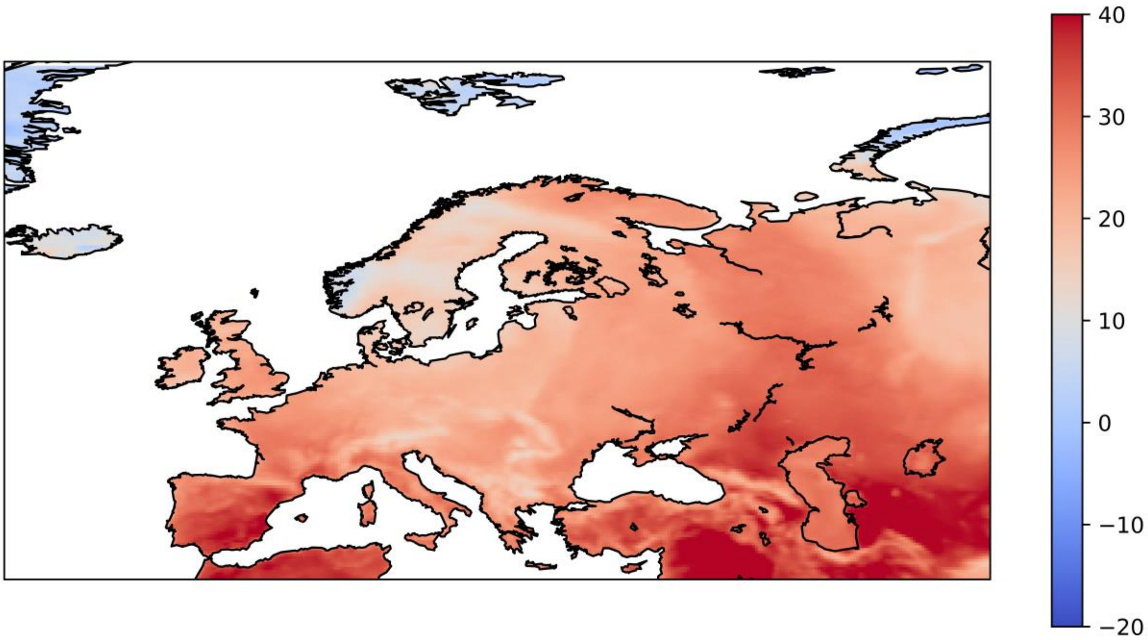

Fig. 1: *The temperature at 2m above the surface over Europe, 10 August 2023.*

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A Matter of Scale: Thermodynamic and Large-Scale Constraints in Extreme Rainfall Under a Changing Climate

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Changes in the hydrological cycle and, in particular, in rainfall extreme events induced by global warming are expected to pose significantly increased hazards in the coming decades. However, changes in the probability of occurrence of intense precipitation remain poorly understood even in observations. Here we investigate the thermodynamic and large-scale constraints to the generation of extreme rainfall at both hourly and daily scales. To this aim, we address some of the ambiguities intrinsic to the traditional definition of the dependence of extreme rainfall on temperature as mediated by the Clausius-Clapeyron (CC) relation. For this purpose, we use a non-asymptotic extreme value distribution (Marani and Ignaccolo, 2015) as a basis for our analysis. In this framework, the distribution of extremes emerges from the distribution of the ordinary events, here allowed to vary under climate change. The distribution of annual maxima is expressed as a function of the probability distribution of all events (that may be inferred using most of the available data, rather than just on yearly maxima) and of the number of event occurrences per year. The rationale here is that a warming of the atmosphere will affect the distribution of all rainfall events, i.e. the shape of the ordinary event distribution, rather than just rainfall extremes as in traditional CC arguments. Based on this approach, we then analyze the relation between the parameters of the probability distribution of ordinary precipitation events and temperature at the daily and hourly scales, using observational data in Padova, Italy (where almost 300 years of observations are available) and multiple stations in the continental US.

While local temperature is widely considered to be a major driver of change in rainfall regimes, changes in large-scale circulation are also expected to play a significant role in shaping future rainfall regimes. In order to represent the effects of large-scale circulation, and analyze changes that remain unexplained by local temperature, we compute here the Vertically Integrated Moisture Convergence, derived from the ECMWF Reanalysis v5 (ERA5) dataset.

Our results indicate that hourly precipitation is mainly controlled by thermodynamics, with the scale parameter of the probability distribution of hourly precipitation intensity showing a CC dependence. Conversely, at the daily scale, we show that precipitation variability is not explained by temperature changes but is rather driven by other factors such as large-scale circulation. These results support the need for an integrated approach, which quantitatively accounts for both local thermodynamics and large-scale circulation to estimate future changes in daily precipitation extremes under a climate change.

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Global estimation of storm surge seasonality and the effect of interannual variability

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Extreme storm surges exhibit significant seasonal and interannual variability influenced by large-scale climate modes studies (Kirezci et al., 2020). However, the dominant climate modes influencing these extremes are poorly understood due to insufficient observations with long records. Therefore, the goal of our work is to investigate the seasonality of storm surge extremes and the influence of inter-annual variability at the global scale.
To achieve this goal, we use storm surge levels derived from the Global Tides and Surge Model (GTSM) forced with the extended ERA5 climate reanalysis data spanning 1950-2020 (Hersbach et al., 2020). Our methodology consists of two main steps. First, we split the dataset into months (January – December)Next, we conduct extreme value analysis on selected thresholds and explore their connections with climate modes.
Preliminary findings indicate that extreme surge events are more frequent and pronounced at higher latitudes during SON, with notable peaks in DJF. This is particularly significant in the North Sea and funnel-shaped coastlines such as Rio de la Plata, Arafura Sea, and Hudson Bay. In contrast, regions like the South China Sea, the Bay of Bengal, the Yellow Sea, and southern Australia experience more frequent surge extremes from JJA to SON with variations in peak season.
Equatorial regions, especially around Africa, have negligible surge extremes except for occasional tropical cyclones from late DJF, with peaks in MAM in Mozambique and Madagascar. Similarly, there are occasional tropical cyclone events in parts of the Caribbean with peaks in JJA.
The study findings have broader implications for understanding the global distribution and spatio-temporal temporal variation of extreme surge events, which could provide guidance on future climate change impacts. Overall, the preliminary findings underpin the need to further explore the drivers of storm surge variability.

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On The Prediction of Extreme Sub-Hourly Precipitation via Temperature Variations: Case Study of Veneto Region, Italy

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Temperature variations play an important role in driving future extreme precipitation and its potential impact. In order to adapt to the ongoing climate-change it is therefore essential to adjust the design precipitation amounts used in engineering and risk management. Sub-hourly extremes are particularly concerning, because they have significant impacts (urban floods, flash floods, debris flows), because they are observed changing more in response to changes in temperature, and because they are not currently reproduced by climate models.
Recently, the TEmperature-dependent Non-Asymptotic statistical model for eXtreme return levels (TENAX) was proposed to predict future sub-hourly return levels only based on past observations and on future shifts in daily temperature (Marra et al.2024). Here, we propose an extension of the TENAX model to better characterize the future shift in daily temperature at a seasonal level. The evaluation of the proposed model is assessed with a case study of Veneto region, Italy. Using an hindcast approach, we then assess its accuracy in predicting unseen return levels only based on changes in daily temperature during the wet days.

Keywords: Precipitation, Temperature, Return level prediction, TENAX

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Future risk of hyperthermia in French Guiana: assessing extreme humid heat with multi-model analysis

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The IPCC sixth assessment report describes future climate scenarios with increased humid heat across the entire tropical belt (result extracted from Mora et al., 2017). Heat, coupled with high humidity, can lead to hyperthermia, *i.e.* an increase in human body temperature beyond dangerous thresholds. In the most severe cases, it can be deadly, even for young and healthy adults.
The ongoing development of Global Climate Models (GCMs) and downscaling methods, both dynamical (regional climate models) and statistical ones, allows us to analyze humid heat in low or medium-resolution climate projections. French Guiana is a coastal and equatorial overseas territory located in northern South America. Unfortunately, this small territory is covered by only few grid points from GCMs, calling for dedicated downscaling efforts.
Here we show the projections of a thermal comfort index for French Guiana, determined from statistical downscaling of CMIP6 GCMs. The NOAA Heat Index (Steadman, 1979; Rothfusz, 1990) estimates the apparent temperature felt by a human being. We compute it from daily temperature and relative humidity data. A previous study revealed that maximum temperature and minimum relative humidity are the best daily indicators for Heat Index computation in French Guiana (Longueville et al., 2022). Previous research has shown systematic biases in the CMIP6 ensemble over the tropical Atlantic/northern South America region. In particular, an Intertropical Convergence Zone shifted too far south during the boreal winter results in an overly dry wet season over French Guiana (Longueville et al., 2022). Consequently, we perform bias corrections using quality-controlled long observational time series from three stations in French Guiana, and adapted to take non-stationarity due to climate change into account (Michelangeli, Vrac, et Loukos, 2009). Extreme humid heat events are characterized by levels and return periods calculated with Generalized Extreme Value distributions.
The intensity and frequency of humid heat extremes may increase massively in French Guiana by the end of the 21st century. Figure 1 shows that historical decennial extreme Heat Index levels may be reached almost every year, particularly under the most pessimistic emissions scenario (SSP5-8.5). Such frequencies raise the question of local adaptation strategies and associated challenges (*e.g.,* future energy demand due to increased use of air conditioning).

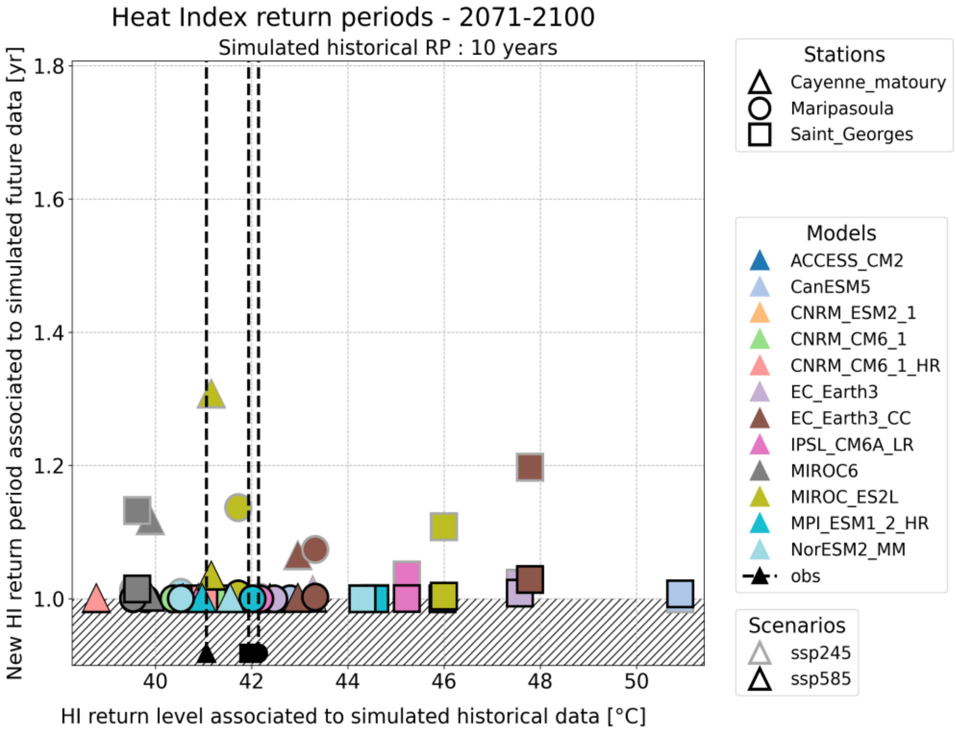

Fig. 1*: Future frequency of historical decennial extreme events in term of Heat Index level. The considered future period is 2071-2100, the historical one is 1988-2014. Here we considered only 12 CMIP6 GCMs.*

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Design of life levels of Extreme Temperature by 2100

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In a context of climate change, design levels for environmental extremes have to be redefined.
This work describes a new Bayesian methodology to design life levels in a non-stationary context, with an application to extreme temperature excess by 2100 at a local scale.
The usual risk indicator, the annual return level, is only defined in a stationary context. Since it's defined as a level corresponding to an annual probability of excess, its value can't be defined for a period of interest. It is necessary to select another risk indicator able to cover an entire time period. The Equivalent Reliability, which defines the probability of the maximum event during the period, was chosen because its probability of excess over a period is the same as the total probability of excess over a period for a stationary return level (Liang 2016 et Hu 2018).
The method used to estimate the Equivalent Reliability is adapted from the statistical method by Robin and Ribes (2020). A generalized extreme value distribution is used, where the non-stationarity in the parameters is given by a covariate, the European annual mean temperature, as a proxy of climate warming. To estimate the parameters, this Bayesian framework uses a prior based on Global Climate Models output which is then constrained using local meteorological observations. An estimation of the posterior parameters' distributions was produced using the No-U-Turn Sampler MCMC algorithm implemented in Stan (Holman 2014).
The predictive estimate, including uncertainty over the parameters' full distribution, was adapted to Equivalent Reliability. It accounts for a larger range of possible extreme values than the median estimate, while providing a unique value fit for design calculation.
An application was done on the Rhone Valley on France over the period 2050-2100.

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Fast return-level estimates for flood insurance via an improved Bennett inequality for random variables with differing upper bounds

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We are motivated by the problem of estimating the future insurance costs due to flooding for a portfolio. The UK government's 2015 solvency regulation (Swain and Swallow, 2015) requires specific information on the 200-year return level, the level of insurance payout over a year that is expected to be exceeded once in every 200-years on average; other return levels, from the 2-year to the 1000-year and above, are also of interest to insurers. Insurance losses due to flooding can be estimated by simulating and then summing a large number of independent losses for each in a large set of hypothetical years of flood events (Taylor and Carter, 2020). Replicated realisations of total losses for each year, combined over the set of years, provide Monte Carlo return-level estimates and associated uncertainty. The procedure, however, is highly computationally intensive. We develop and use a new, Bennett-like concentration inequality to provide conservative but relatively accurate estimates of return levels at a fraction of the computational cost. Motivated by the variability in the total insured value of insurance risks within a portfolio, we incorporate both individual upper bounds and variances and obtain tractable concentration bounds. Simulation studies and application to a representative portfolio demonstrate a substantial tightening compared with Bennett's bound. We then develop an importance-sampling procedure that repeatedly samples the loss for each year from the distribution implied by the concentration inequality, leading to conservative estimates of the return levels and their uncertainty computed orders of magnitude more quickly.

Fig. 1*: Extensive flooding caused by storms in Winter 2015/16 at Caton near Lancaster (UK). Courtesy of Jon Tawn.*

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Inference for multivariate extremes via a semi-parametric angular-radial model

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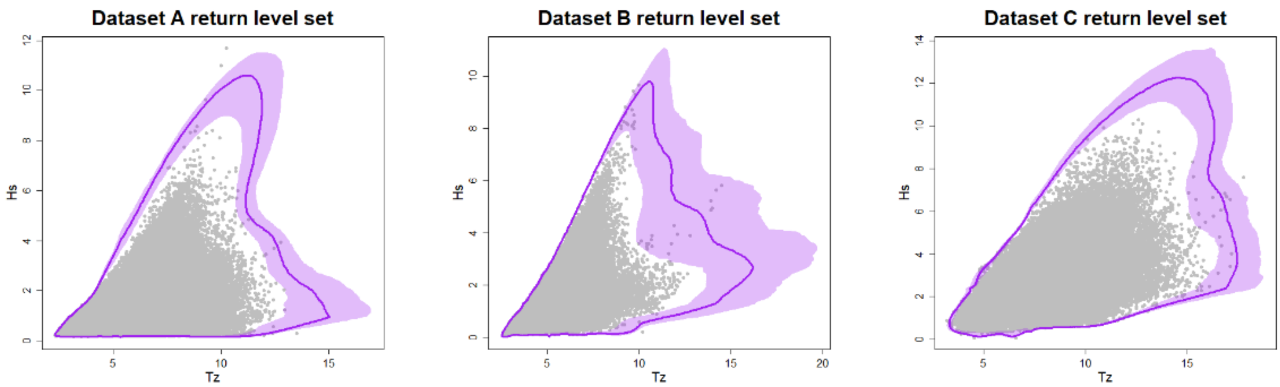

Fig. 1*: Estimated median 10 year return level sets (purple lines) for metocoean data sets A (left), B (centre), and C (right). The shaded region for each return level set denotes the 95% bootstrapped confidence region.*

Multivariate extreme event modelling plays a pivotal role in a wide range of applications, including flood risk analysis, metocean engineering, and financial risk assessment. A wide variety of statistical techniques have been proposed in the literature; however, many such methods are limited in the forms of dependence they can capture, or make strong parametric assumptions about data structures. These limitations can result in severe under- or over-estimation in practice, motivating novel developments.

In this work, we introduce a novel inference framework based on a semi-parametric angular-radial (SPAR) model (Mackay & Jonathan, 2023). The model involves a transformation to polar coordinates, and modelling the tail of the radial variable, conditional on angle. This reframes the problem of modelling multivariate extremes as one of modelling univariate extremes with angular dependence. The SPAR framework also includes many existing models for multivariate extremes as special cases and establishes a unified paradigm for evaluating joint tail behavior. Furthermore, unlike many existing techniques, no assumptions are required about either the form of the

margins or dependence structure, and the SPAR model can be applied on the original scale of the data, without a marginal transformation.
To demonstrate its uses, the proposed methodology is applied to a range of metocean time series from locations off the coast of North America. Understanding the joint extremes of metocean variables is important in the context of ocean engineering for assessing the reliability of offshore structures. In practice, joint measures of extremes risk, known as return level sets, are often used to aid with this assessment. We show that the proposed modelling framework can accurately capture the complex joint extreme behaviours of these metocean variables, allowing one to obtain realistic and practically applicable estimates of return level sets (Murphy-Barltrop et al., 2024).

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10,000 years of extratropical cyclone events at global scale - a dataset of extreme water levels

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Tropical and extratropical cyclones are among the most devastating natural hazards, causing extreme events of coastal flooding. In order to reduce their potential impacts, an understanding of global coastal flood risk is required. Traditionally, large scale flood risk assessments calculate return periods of coastal water levels by fitting a Generalized Extreme Value distribution to observed or simulated water levels (Dullaart et al., 2021; Muis et al., 2016; Wahl et al., 2017). However, given the limited record length of these datasets, extrapolation to derive return periods of low probability is necessary, thereby introducing substantial uncertainties in the statistics of extreme events (van den Brink et al., 2004).
While a global synthetic event dataset has been developed for tropical cyclones (Bloemendaal et al., 2020), enabling more accurate estimation of water level return periods up to 10,000 years, statistics of extratropical cyclone water levels still rely solely on climate reanalysis datasets (Dullaart et al., 2021). These datasets provide data for only the past 50 years. This short observation period means that extratropical cyclones in many coastal regions may not be registered in the available datasets, resulting in inaccurate risk estimates of the low probability extremes.
This study aims to address this challenge by generating a dataset of 10,000 years of extratropical cyclone induced extreme water levels. By combining ensemble members and lead times from the ECMWF seasonal prediction system SEAS5 we obtain approximately 10,000 years of meteorological forcing (Johnson et al., 2019; van den Brink et al., 2004). The meteorological forcing is then used to force the hydrodynamic Global Tide and Surge Model (Muis et al., 2016), resulting in a 10,000-year global dataset of extreme water level timeseries attributed to extratropical cyclone events. Subsequently, we analyse the influence of this dataset on the statistics of extreme water levels and compare it with those obtained from the climate reanalysis dataset ERA5.

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Assessment extreme wind hazards in France

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In anticipation of updating the Eurocode wind map, which recommends the reference wind speed for new building construction, a preliminary study was conducted to analyze the available wind data. The aim was to identify best practices for developing the future map of extreme wind in France.
Since the previous study, weather stations have around twenty years of additional wind observation. Firstly, wind data were normalized to remove environmental factors such as roughness, orography, *and* obstacles, enabling the comparison of observed wind speeds under identical conditions across various meteorological stations. For this study, we have assumed that those normalized coefficients have not changed since 2003, which is a strong assumption since we know, for example, that some stations have been moved, also the height of measurement was not normalized at the 10m reference height.
For each of the selected 100 weather stations, our study characterized wind speeds for various return periods (10, 50, 100, and 500 years) based on extreme value theory. We selected the appropriate statistical laws, choosing between Gumbel (annual maximum with 2 parameters) and GPD (peak over threshold with 3 parameters), using the Bayesian Information Criterion (BIC) test and 95% confidence intervals. The violin boxplot presented in Figure 1 illustrates the dispersion of wind speeds for all selected stations. The uncertainties increase with the return period.
Wind speeds were assessed by comparison with the national wind map estimated by the CSTB in 2003. The significance of the differences was assessed on the basis of the estimated confidence intervals.

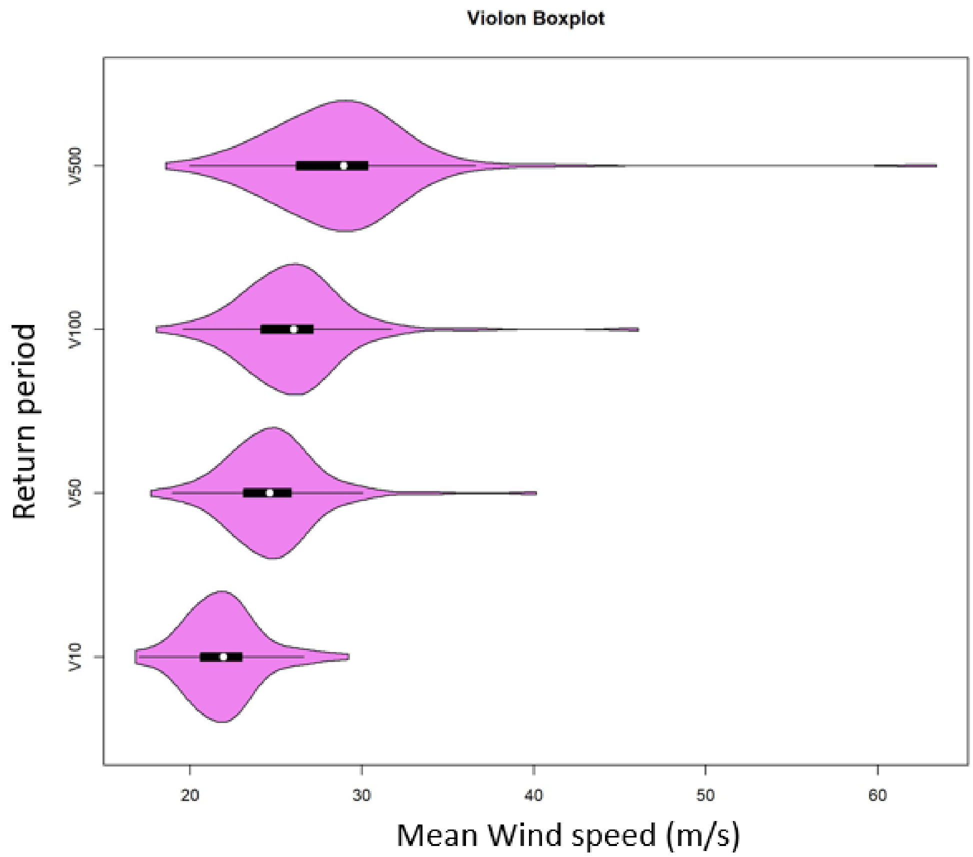

Fig. 1*: Dispersion of mean wind speed (m/s) estimated for each studied return period event for the 100 selected stations located over France.*

Future extreme wind speed assessment in France

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Our study aims to analyze the evolution of mean and normalized wind speeds in France for two fixed levels of global warming, 2 and 4°C relative to the pre-industrial era (1861-1900). We utilized one regional model, WRF-IPSL and WRF-CNRM, for two global circulation models, IPSL-CM5A-MR and CNRM-CM5 with the 8.5 RCP scenario (Vautard et al., 2021). To determine the 30-year time windows for these 2 and 4-degree warming levels, we followed the procedure described in Shi et al. (2018). For the IPSL-CM5A-MR simulation, the periods are 2017-2046 (2°C) and 2053-2082 (4°C), while for the CNRM-CM5 simulation, the periods are 2031-2060 (2°C) and 2071-2100 (4°C). The reference climatological period is 1976-2005.
Despite significant progress in regional climate modeling, biases persist in the produced simulations. To address this issue, we adopted the debiasing methodology known as CDF-t explicit (Michelangeli et al., 2009; Vrac et al., 2012). All modeled data, whether from WRF-IPSL or WRF-CNRM, were debiased for 100 meteorological weather stations (cf.
Fig. *2*) where normalized mean wind speed data are available. Subsequently, the 50-year return levels were estimated using the Gumbel law. The difference between the 50-year return warming level and the reference period (1976-2005) was used to assess future changes.
Our initial findings indicate an absence of geographical structure, leading us to conclude that climate warming does not structurally impact extreme winds in France in the future.

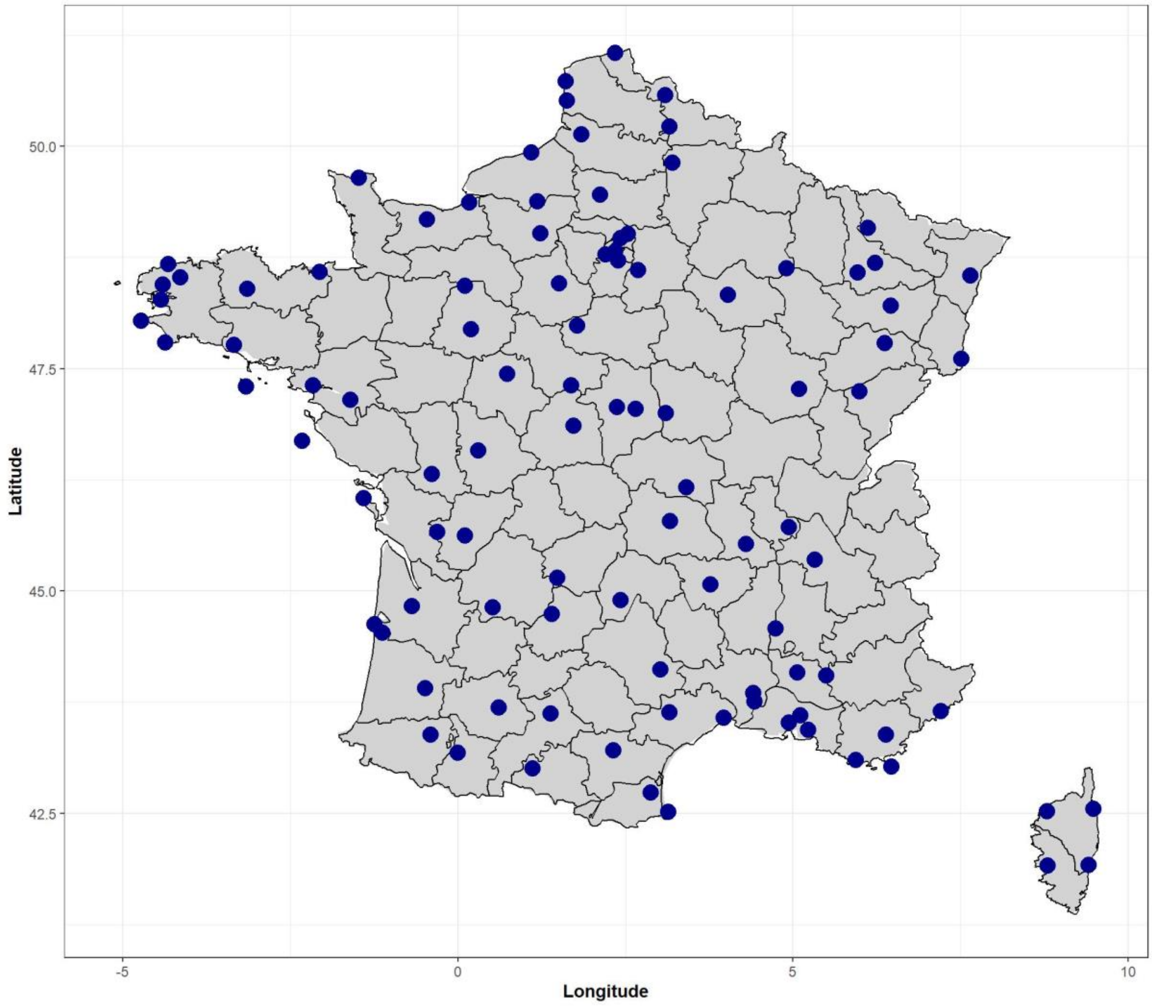

Fig. 2: *100 weather stations selected in our study*

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Spatial patterns in Extreme Sea Level return period in the Northern Adriatic Sea

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Floods are among the most common hazards affecting worldwide coastal areas, showing an increasing frequency driven by climate change. An accurate assessment of the occurrence probability of Extreme Sea Levels (ESLs) is crucial in coastal area management. Several works involved the application of different methodologies to process historical SL time series worldwide (Caruso and Marani, 2022) for estimating the probability of ESLs occurrence. In the Northern Adriatic Sea, ESLs analyses commonly refer to the Venice – Punta della Salute (PS) station, which boasts the longest SL time series in the Mediterranean Sea, extending back to 1923. However, during extreme events, significative differences emerge in SL peaks recorded within the Northern Adriatic coast, stemming from the combined influence of synoptic and medium-small scale meteorological phenomena (see Figure 1).

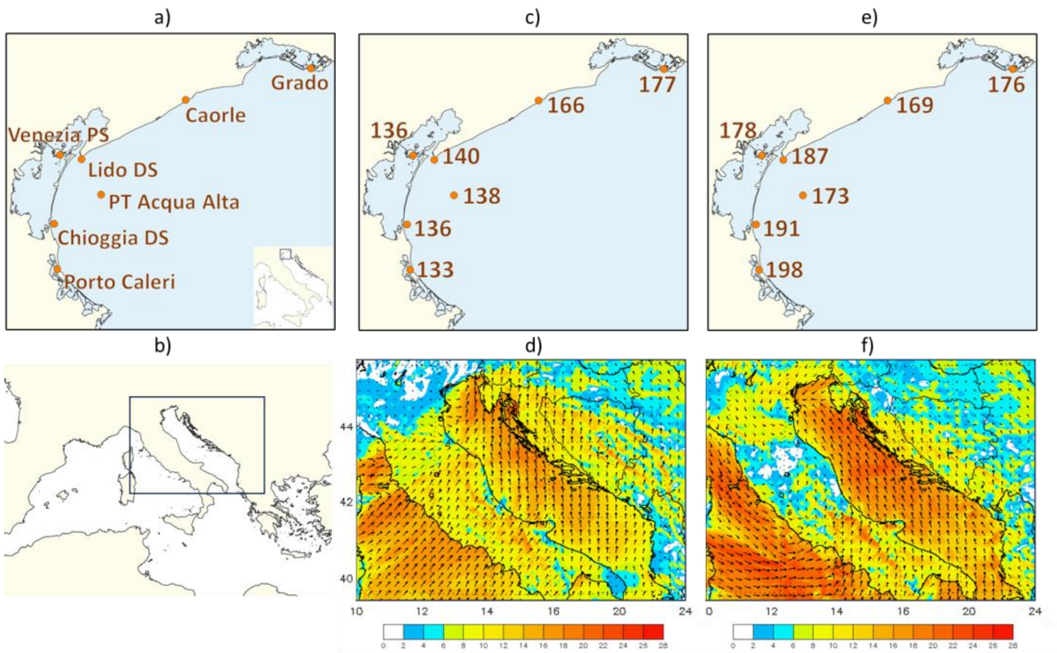

Fig. 1: *a) Location of SL monitoring stations we used; b) Clipping area of the 'MOLOCH' weather field (ISPRA hydro-meteo-sea forecasting system). c) SL maxima registered during the event of 5th of November 2023 and d) corresponding synoptical wind forecasting field (MOLOCH 0300UTC), characterized by S-SE wind in Adriatic Sea and SW wind in Northern Adriatic Sea; e) SL maxima of 22th of November 2022 and f) corresponding synoptical wind*

forecasting field (MOLOCH 0900UTC), characterized by SE wind in Adriatic Sea and NE wind within the Northern coastline.

In this study, we investigate whether spatial patterns observed at the event-scale lead to any spatial patterns in the return period of ESLs. We opted for the peaks-over-threshold approach using the Generalized Pareto Distribution (GPD), due to its more efficient use of temporally limited observations (Caruso and Marani, 2022). To ensure comparability of ESL return time among the stations, hourly SL data from 2000 to 2023 were used for all sites. Before fitting the models, we detrended the SL data by subtracting the yearly average mean SL from each observation. We note that, since October 2020, the movable dams of the Mo.S.E. system rise across the Venice Lagoon inlets in case of surge events, to prevent the flooding of the city of Venice and the other urban settlements located within the lagoon. Therefore, ESLs at Venice-PS station from 2020 to 2023 were computed using a numerical model (Carniello et al, 2005).

The ESLs resulted the highest at Porto Caleri (Po Delta) for all the return periods greater than 2 years, and the lowest at the PT Acqua Alta station, ranging from 177 to 192 cm for a 50-years return period (see Table1). The Grado station exhibited distinct ESLs for return periods of 2, 10 and 20 years.

Table 1: *ESLs for return period of 2, 10, 20, 50 years for the seven studied stations. The interval of confidence is also reported.*

gauge	2 yr		10 yr		20 yr		50 yr	
Grado	147	(140-154)	167	(155-178)	174	(159-190)	183	(162-205)
Caorle	142	(135-150)	164	(150-177)	172	(154-190)	182	(157-207)
PT Acqua Alta	136	(130-142)	156	(144-169)	165	(148-183)	177	(150-203)
Venice - PS	143	(135-151)	164	(151-176)	171	(156-186)	180	(160-200)
Lido DS	140	(134-145)	162	(147-177)	172	(152-192)	184	(156-212)
Chioggia DS	141	(134-147)	162	(149-176)	171	(154-189)	183	(157-209)
Porto Caleri	146	(139-153)	170	(156-183)	179	(161-198)	192	(166-218)

These ESLs spatial patterns are likely influenced by: i) the location of the PT Acqua Alta (15 km offshore from the Venetian coast), which experiences negligible wave and wind setup; ii) the common synoptic pattern of Sirocco (SE) wind in the Adriatic sea and Bora (ENE) in the Northern Adriatic Sea (see Figure 1f), leading to higher SLs at the Northern coast of the Po Delta. Similarly, higher ESLs at Grado can be addressed to the Sirocco (SE) and Libeccio (SW) pattern (see Figure1d). Nevertheless, the return period of ESLs assessed for the Venice PS station seem to be representative of the Northern Adriatic coast, when considering the confidence interval estimations.

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Characterization of streams and rivers in terms of hydrological alteration and flow regime: a principal component approach

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Quantitative and temporal characteristics of river flow are necessary for the definition of the hydrological regime of a section or a number of sections. To pursue this goal, hydrograms are normally used and analysed. However, it is clear that the hydrological regime can vary in time and the definition of this alteration is essential for a number of reasons, the clearest being the need of control and monitoring of the alteration itself. A number of techniques exists to take account of this alteration which normally depends on a quite huge number of parameters with different temporal and spatial scale (e.g. Boni *et al.*, 1993-A, Poff and Ward, 1989; Poff, 1996; Poff *et al*., 1997). In the meantime, the type of flow regime of a section which describes the physical processes and the dynamics regulating the flow of the river is essential as suggested in literature (e.g. Bussettini et al., 2014). Particularly, in a global contest where droughts and floods alternate with higher frequency, it is necessary to deal with intermittent rivers and rivers with changing permanent regimes. This said, a number of questions might arise: is there a relationship between the hydrological alteration of a section and the type of flow regime of the section itself? And if so, which are the most representative and influencing parameters of this alteration? The following study is a preliminary approach to answer, though initially, these questions.
A pool of 72 daily discharge series has been used located in the Italian territory in order to have a realistic representation as the study area and representative for four clusters of flow regime types (intermittent, snow, stable and permanent). Then, the IHA has been estimated in each if its 33 components for each series. In order to evaluate the role and influence of the parameters to explain the hydrological alteration the Principal Component Analysis is used (Alcaraz *et al.*, 2023). Preliminary results show that 1) the biplot of the PCA differs according to the cluster, meaning that the most representative parameters of alteration depends on the type of flow regime, as expected: indeed, different flow regime means different physical dynamics of the section; 2) secondly, it is possible to define for each cluster a smaller pool of parameters from the 33 original ones which can quantitatively and statistically be considered well-representative of the whole pool of parameters of alteration, with limited loss of information and smaller uncertainty. This aspect is crucial: a smaller number of parameters are necessary to be computed and they can be considered a good proxy of the alteration processes of the specific flow regime so that the procedure of estimation is easier. Sensitivity analysis on the clustering procedure will be considered. Limits on the procedure include the validation of the results: it is important to prove whether the selected parameters really reproduced the physical dynamics of the different flow regime

sections. Further analysis will be considered in the future using different validation strategies.

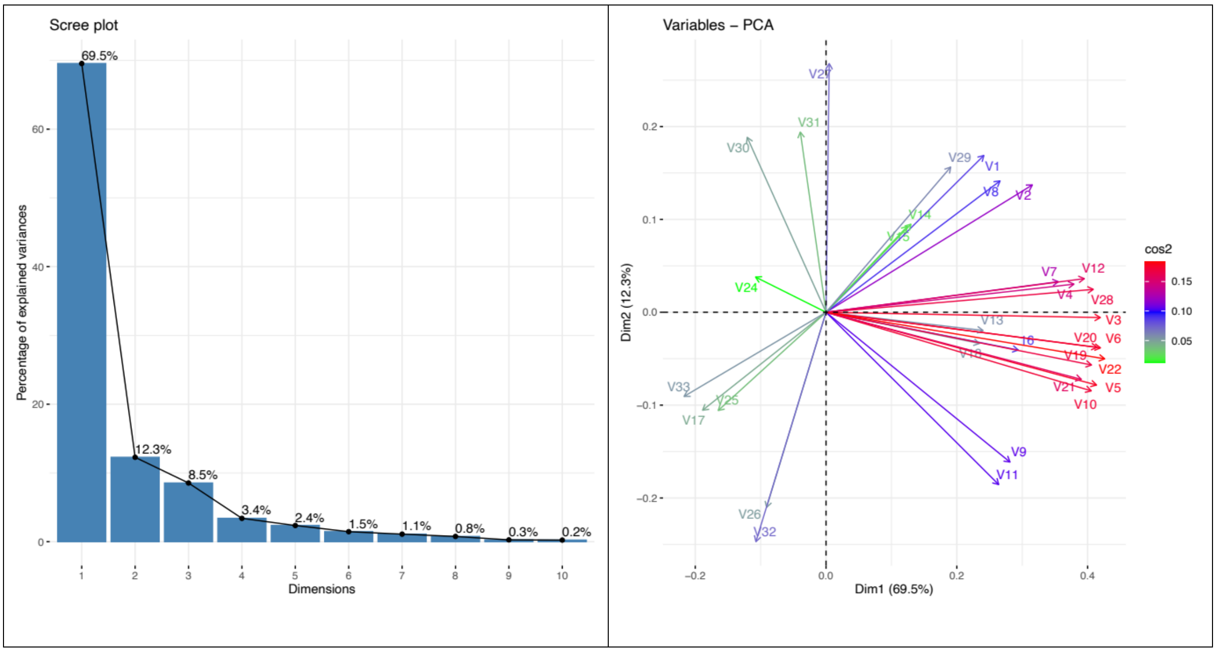

Fig. 1*: In the left box, it can be seen that in case of intermittent regime the first two principal components show a cumulative percentage of around 81 %; in the right box, the differ colors reflect the magnitude of the vectors.*

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Structured multivariate and spatial extreme value models for environmental science

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Environmental extremes exhibit spatial, temporal and multivariate dependence. Our work focuses on exploiting justifiable assumptions about dependence structure, e.g., graphical models or vine copulas, which have the potential to improve the inference for multivariate extremes (Engelke and Ivanovs, 2021; Hobæk Haff et al., 2016) or making stationarity assumptions for spatial extremes (Wadsworth and Tawn, 2022).
The framework we will work in involves conditional extreme value models (Heffernan and Tawn, 2004). It involves conditioning on one variable being extreme, then looking at the joint behaviour of all other variables to make inferences. Specifically, the joint behaviour of residuals of the other variables is independent of the conditioning variable. It is a versatile modelling framework that works in both cases of asymptotic dependence (AD; the largest values of the variables can occur together) and asymptotic independence (AI; the largest values cannot occur together). This is important since other commonly used methods for inference assume that the variables are AD, which only works in some applications (Davison et al., 2012).
In the multivariate case the computational complexity increases rapidly with the dimension of the problem, with the conditional extreme models facing issues of the curse-of-dimensionality. Hence our approach is to assume some structure on the joint distribution of the residuals by imposing a Gaussian copula model (Towe et al., 2018), a graphical model or vine copula structure, which are novel as these structures can be applied to arbitrary combinations of pairwise AD and AI cases in the multivariate variable.
In the spatial case current methods for conditional spatial extremes focus on a single extreme event whether the process is AD or AI. Our work looks to extend this to multiple extreme events occurring over large spatial regions, which gives much greater flexibility than present models in the AI case and captures features other models for AD processes have, without imposing AD over all distances between sites.

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CLIMADA - the open-source and -access global platform for globally consistent probabilistic multi-hazard risk modelling and options appraisal

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Using state-of-the-art probabilistic modelling CLIMADA (Aznar-Siguan and Bresch, 2019) allows to estimate multi-hazard socio-economic impacts as a measure of risk today, the incremental increase from economic development and the further incremental increase due to climate change. The Economics of Climate Adaptation (ECA) methodology as implemented in CLIMADA (Souvignet et al., 2016; Bresch, 2016) provides decision makers with a fact base to understand the impact of weather and climate on their economies, including cost/benefit and multi-criteria perspectives on specific risk reduction and resiliency measures (Bresch and Aznar-Siguan, 2021) as well as risk transfer solutions (Steinmann et al., 2023). The CLIMADA platform is well suited to operate on diverse spatio-temporal scales, e.g. from impact-based warning applications (regional to local, timescale of days, c.f. Röösli et al., 2021; Geiger et al., 2024) to providing an open and independent global (yet still high-resolution) view on physical risk (including tail risk quantification, c.f. Meiler et al., 2023). We will present on-going work on multi-hazard risk analysis (Stalhandske et al., *preprint*) and new attempts to implement multi-criteria perspectives on options appraisal in a truly replicable fashion, illustrated by select adaptation economics case studies from different regions of the world.

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Past to future changes in probabilities of very rare compound meteorological extremes

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The UK drought of 1975–1976 was one of the most acute droughts in its modern climatological history, and led into the 1976 summer heatwave, which remains one of the UK's most significant heatwaves in terms of persistence. The resulting impacts were significant and widespread affecting people's lives, the environment and agriculture, exacerbated by the compound nature of the event. Cereal crops were badly affected, there was an acute potato shortage, and arid soil conditions severely impacted grass growth, milk yields fell requiring out of season supplementary feeding of dairy cows. In mid-June, drought orders affected roughly one-third of the country with the drought at its most severe in August 1976. Subsequent epidemiological reviews suggest that there was a particularly high number of deaths in comparison to other heatwaves. In response to the 1976 event, the UK parliament passed the Drought Act 1976 to ensure the strategic and long-term planning of the management of water resources and to provide emergency powers to turn off domestic and industrial water supplies.

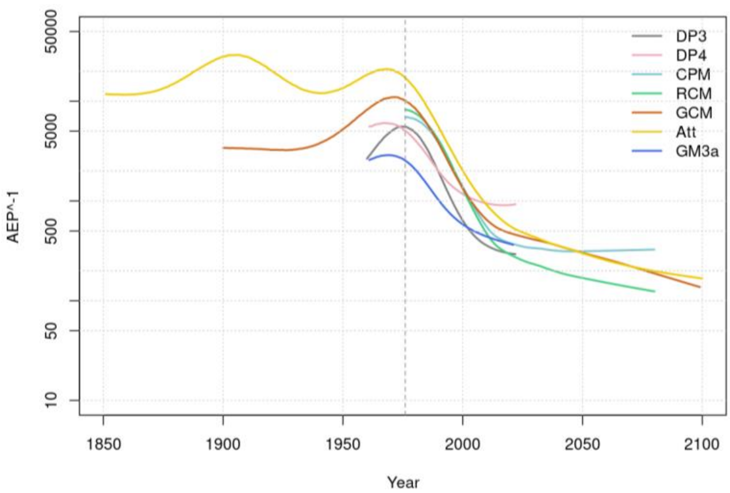
Despite several decades of a warming climate, the heatwave/drought of 1975–1976 remains one of the most impactful in UK history. 1976 was not actually the hottest (2018) or driest (1995) summer on record for the UK but in terms of a joint event it was exceptional. Dry conditions started in spring of 1975, with significant rainfall deficit extending through the winter into spring of 1976. The 9-month period ending in August 1976 is the driest on record for the UK and for England, for data back to 1836. For summer mean temperature, 1976 was the third-warmest for England (16.9°C) in a 139-year series.

This study considers the compound (or multivariate) hazard of a prolonged (December to August) rainfall deficit ending in a hot summer (June to August). Past and future likelihoods are determined using both observations and climate model data from a number of different modelling systems. These include recent high-resolution (2km) convection permitting climate projections, regional climate models (12km), coarser-resolution global multi-model ensembles (~60km, coupled and atmosphere only), attribution ensembles and large ensembles of initialised decadal hindcasts.

Characterising the probability and the changing probability of such an event is very difficult particularly when the joint magnitude is so far outside of what has been observed or even what has been produced by the large sample of climate model data used here. Climate change means that the margins of both variables are changing with time which will need to be modelled accurately. The climate models themselves contain biases compared to observations which will also need to be characterised. Furthermore, due to this event being a compound event the extremal dependence between the two variables will need to be modelled if accurate probabilities are going to be determined. Such dependence can often be a function of quantile, particularly for temperature (Wadsworth & Tawn 2022), requiring a modelling approach that allows for such structure. As both variables show non-stationarity through time, both need transforming to be stationary to ensure any extremal dependence is not contaminated by trends (e.g., a warming trend can incorrectly be seen as increasing extremal dependence).

To address these challenges non-stationary quantiles and Genralised Pareto distributions (GPDs) are fitted via a generalised additive model (GAM) framework, with covariates to capture the evolution through time and the bias between the observations and climate model data (c.f. Brown, 2020). Using these time-dependent quantile and GPD functions the data from both sources can be transformed to common stationary margins. The extremal dependence between high temperatures and low rainfall extremes is explicitly modelled through the use of the conditional extreme value model of Heffernan and Tawn (2004) which has the flexibility to accommodate both asymptotic dependence and independence, that is, whether two variables become increasingly dependent or independent as the probability of occurrence decreases. This modelling approach requires no a priori knowledge of the form of asymptotic dependence, determining this from the data. Here we model the extreme distribution of the JJA temperature conditional on the DJF-MAM-JJA rainfall deficit for both the observations and a given climate model simultaneously.

Such joint statistical modelling of observed and climate model data has two important benefits. The first is that difficult-to-determine characteristics, such as the GPD shape parameter and the change of extreme properties through time, are expedited as one can choose for them to be common for both data types thus benefiting from greater sample size. The second is that it can accommodate biases between the two data types parametrically. When it is required to return stochastically generated data (as probabilities) back to observed units the corresponding inverse transformations can be made with the corresponding quantiles and GPD parameters for the year of interest. The approach of this method is to transform non-stationary data to stationary probabilities, simulate large amounts of joint extremes in this stationary space and then de-transform back to non-stationary observed units at the desired covariates from which timeseries of joint exceedance probabilities can be empirically calculated.



Example (left) of the estimated observed time evolution of the likelihood of a 1976 joint heatwave-drought event when observations are jointly modelled with climate model data. Climate model data are: decadal hindcasts(DP3 & DP4), convective permitting model (CPM), regional climate model (RCM), global coupled model (GCM), attribution simulations (Att) and atmosphere only global model (GM3a). Given the rarity of the event and its compound nature we find notable agreement between the different parings of observations and climate model data with return periods for the 1976 event in 1976 ranging from 2500 to 17,000 years falling to 270 to 930 years for it occurring in 2022. This change is mainly being driven by the increasing likelihoods of hot summers with the spread between model pairings mainly due to differing changes in likelihood of drought between climate model data types. Neglecting to explicitly model the extremal dependence can lead to a x20 underestimation of the likelihood for 1976 type events.

Producing such information on such high impact compound extreme weather events is increasingly becoming a requirement for Climate Services to facilitate effective adaptation to future climate change. To meet this demand careful modelling of their extremal properties, as presented here, will be needed. This talk will also explore how this multi-model approach might be combined to give a single “best” estimate of the future risk from such events.

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The extreme marine events of October and November 2023 in the North Adriatic Sea

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From October 24th to November 6th, the Northern Adriatic Sea experienced a cluster of sequential tidal peaks, resulting in the second-longest recorded duration of the sea level (SL) exceeding 110 cm over ZMPS for a single event (Baldan et al., 2023).
Based on statistical analyses on multiple series of consecutive events performed by Baldan et al. (2023), we found that the persistence of SL ≥ 110 cm recorded between October 24th and November 6th resulted in the second longest event recorded along the Venetian coast (almost 34 hours), even in the absence of extreme SL peaks, differently by the events occurred on November 12th, 2019 (189 cm recorded at Punta della Salute, PS) and November 22nd, 2022 (173 cm at Piattaforma Acqua Alta, PT-CNR AAOT).

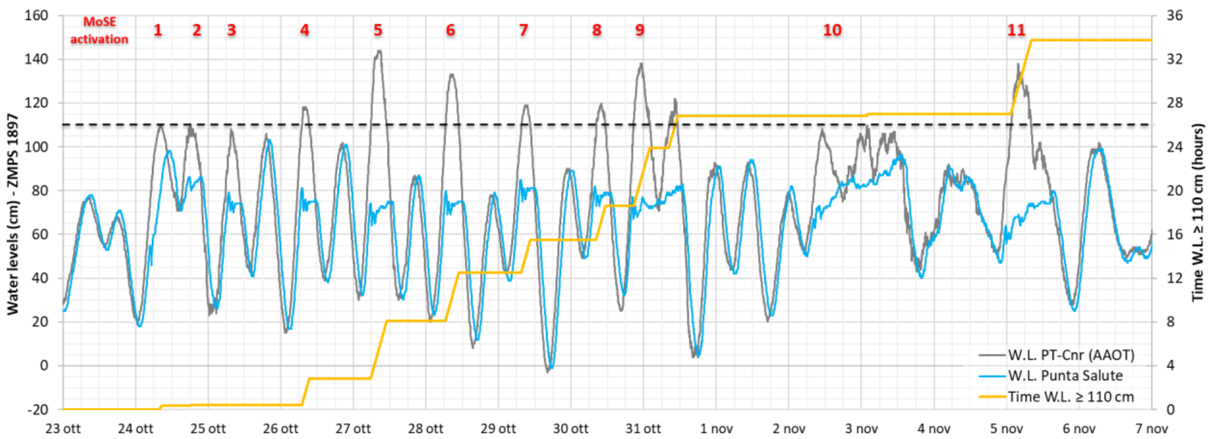

Fig. 1*: October 23rd – November 7th, 2023. SLs measured seaward at PT-CNR (AAOT), compared to those recorded at PS. Red numbers stand for the Mo.S.E. system operations; yellow line for the cumulated period of SL ≥ 110 cm.*

Furthermore, the recent event featured an unusual wind pattern, occasionally triggering intense winds from West and Southwest (Libeccio) in the North Adriatic Sea, resulting in a maximum sea level gradient opposite to the well-known Bora wind regime conditions (see Figure 2).
Such a perseverance of Southwestern winds is not common in the Northern Adriatic Sea, where Libeccio usually alternates with winds blowing from the first and second

quadrants (i.e., Bora and Sirocco winds respectively, see Massalin et al., 2006). This atypical condition, caused by the anomalous persistence of the African anticyclone over the Eastern Mediterranean Sea coupled with a deep low pressure area over the North Atlantic and Western Europe, which produced a sequence of low pressure systems reaching Italy from the Western Mediterranean Sea, resulted in significant SL differences recorded within the Northern Adriatic Sea, i.e., between PT-CNR (AAOT), Grado and Trieste, up to 30 cm on October 27th and 40 cm on November 3rd and 5th. In the latter case the maximum SLs were 138 cm at PT-CNR (AAOT), 177 cm at Grado and 165 cm at Trieste respectively, with an instantaneous maximum difference of some 50 cm overnight between PT-CNR (AAOT) and Grado.

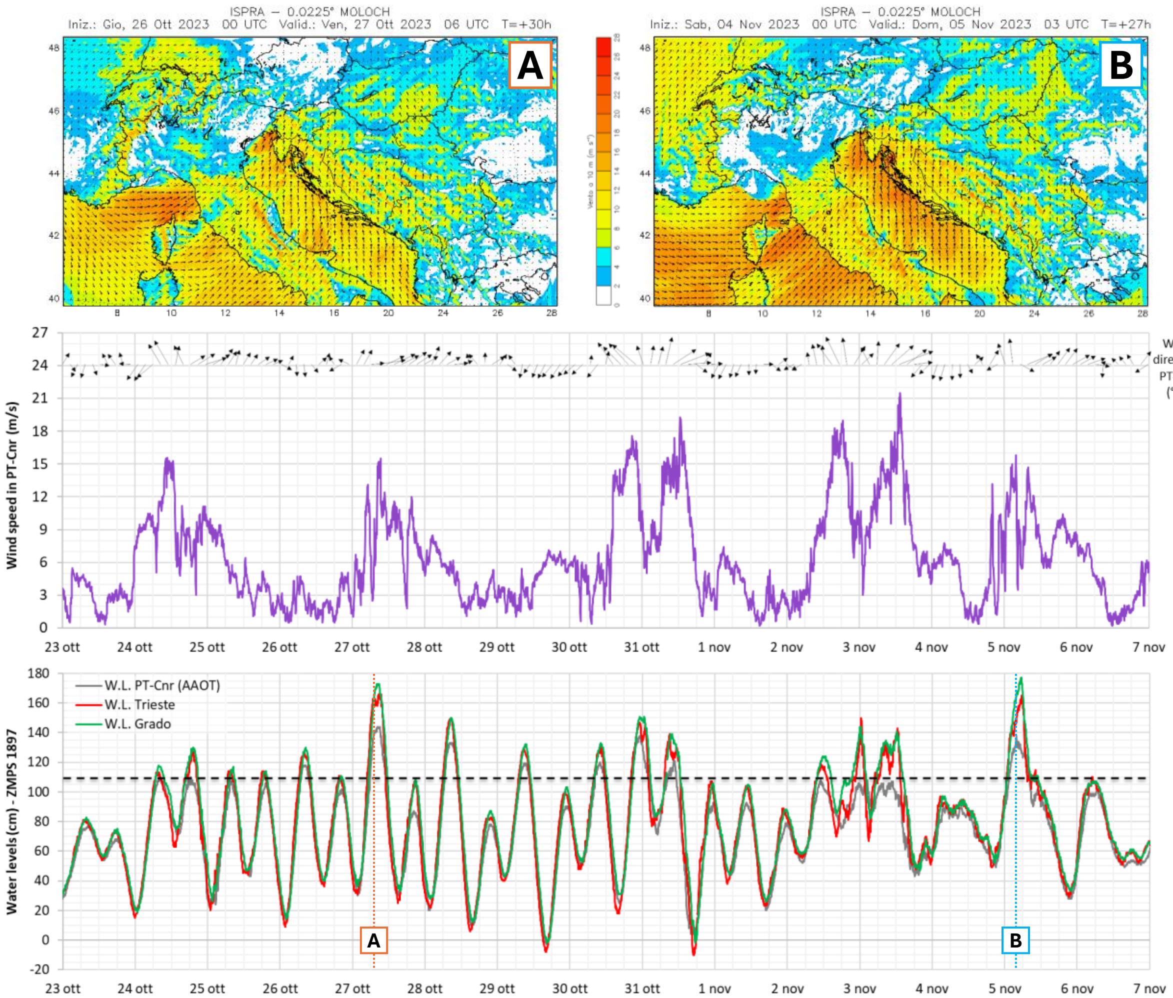

Fig. 2: *Wind speed and direction forecast by the Moloch atmospheric model on 27/10/23 7:00 (A) and 5/11/23 4:00 (B), compared to wind speed and direction measured at PT-CNR (AAOT). The lower panel shows SLs measured at PT-CNR (AAOT), Grado, and Trieste within the period October 23rd – November 7th, 2023.*

The analysis of this event highlights how, in the examination of extreme events, it is crucial to consider not only the magnitude of the events, but also their duration and any medium-small-scale dynamics, that can be accurately described only in the presence of a widespread meteo-marine monitoring network.

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Bayesian mixture models for heterogeneous extremes

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In this research we propose a novel approach for describing the behaviour of extreme values in the presence of heterogeneity. In practical scenarios, observed maximum values often deviate from a single parametric (e.g., Generalized Extreme Value) distribution. Instead, a grouping structure may manifest in the extremes, giving rise to grouped block maxima. Examples include summer and winter rainfall maxima or maximum losses observed in bull and bear market conditions. Incorrectly assuming a single group when multiple groups exist can result in model misspecification and lead to inaccurate risk estimation for rare events based on return levels.
Mixture models provide a valuable approach for capturing heterogeneity in data distributions. We propose to exploit this property in the context of block maxima. Specifically, we assume that each block, from which the maximum is extracted, belongs to a group. A latent variable is employed to indicate group allocation. Allowing for an infinite number of groups enables the characterisation of every possible block behaviour. In practice, the resulting number of mixture components will be finite, but will not need to be fixed in advance. Maxima arising from grouped blocks exhibit a consistent grouped structure, resulting in heterogeneity in extremes. As the block size increases, the distribution of such block maxima converges to an infinite mixture of GEV distributions.
A Bayesian treatment of heterogeneous extremes involves setting a prior on the discrete mixing measure associated with the infinite mixture model. We adopt the stick-breaking prior, with a choice of parameters that yield the Dirichlet process (DP), which constitutes the basis of Bayesian methods. Covariates can be incorporated into the model to inform the distribution of the mixing measure via a Dependent Dirichlet process. We illustrate the application of our proposed model using both simulated and real-world data.

Stochastic temporal downscaling in Northeast Italy using convection-permitting climate models: from hourly to sub-hourly timescales

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The statistical properties of rainfall at short durations are pivotal for many hydrological applications. Commonly available rainfall records nor km-scale model, i.e. Convection-Permitting Models (not provide rainfall data at the sub-hourly scales needed for many applications, such as hydrological modelling in small or urban catchments or landslide or debris-flow models. Motivated by the above considerations, in this application a statistical downscaling technique is proposed for inferring the rainfall correlation structure at sub-hourly scale by using hourly statistics from CPM simulations. The proposed approach is based on the theory of stochastic processes, which establishes statistical relationships between coarse-scale predictors and fine-scale predictands. To validate the temporally downscaled results against observations, here we use, as a benchmark, high-resolution rainfall records from a dense network of rain gauges in northeastern Italy considering aggregation timescales ranging from 5 minutes to 24 hours. We then explore how the downscaling method developed here, coupled with the Complete Stochastic Modelling Solution (CoSMoS; Papalexiou, 2018) framework, may be used to generate sub-hourly rainfall sequences that reproduce the observed short- and long-timescale variability. Applied to statistics for each month in a year, to reproduce seasonality, the proposed downscaling method appropriately reproduces the observed correlation structure at desired fine-scale resolution. Consequently, the rainfall generator used here, by exploiting the downscaled information from CPM runs, allows to generate rainfall records at the desired scale that may be used for evaluating risk and risk change scenarios, for example associated with debris flows.

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Spatio-temporal data fusion of threshold exceedances

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Air pollution poses a significant risk to public health. Heavy and extremely heavy episodes of high particle matter pollution (PM) are linked to increased hospitalisations due to the exacerbation of cardiovascular and respiratory conditions.
Mitigating the effects of PM pollution is a priority for national and regional authorities; however, air quality management requires PM concentration data at high spatial and temporal resolutions. While high-quality monitoring networks are available in the UK, they can have low spatial and temporal coverage. Alternative data are available from remote-sensing or reanalysis sources but are less reliable than in-situ monitoring stations. Data fusion has been proposed to combine desirable properties of different data sources, but applications to air pollution have widely focused on the mean concentrations, effectively smoothing the data and underestimating episodes of extreme pollution and the risk posed by them.
We propose a bespoke modelling approach within a Bayesian hierarchical structure that enables the fusion of threshold exceedance data measured over different spatiotemporal supports. Our model treats data at each location as observations of smooth functions over space and time, which allows us to predict at any space-time location. We demonstrate the reliability of our approach through a simulation study and apply the model to produce a spatio-temporal interpolation of in-situ PM2.5 data in the UK.

A European Perspective on Joint Probabilities Within Multi-Hazards

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Natural hazards rarely occur in isolation. Frequently, one hazard triggers another, such as an earthquake triggering a tsunami. Likewise, the likelihood of a hazardous event can be amplified by the occurrence of a previous event, such as a drought amplifying the likelihood of a wildfire. However, two extremes can also co-occur as a compound event, leading to even higher combined impacts.
While the field of compound events is advancing rapidly, studies often focus solely on climatic extremes occurring at the same time, excluding non-climate-related hazards or previous triggering and amplifying conditions. Therefore, this research aims to better understand the dependencies between different (pre-conditioning) hazard magnitudes, geographic features, and historic natural hazard footprints, accounting for both climatic and geological hazards.
With the use of a newly created Python vine-copula package, we model the relationships within two different hazard groups. The first group consists of drought, heatwave, and fuel indicators to calculate the likelihood of wildfires. The second group includes earthquakes, precipitation, and slope data to calculate the likelihood of landslides. While the first group is considered a compound event, the second group can be classified as a multi-hazard, with different triggering or amplifying relationships. For both groups, we attempt to use the same method to model synthetic/stochastic events that include a potential hazard footprint for wildfires and landslides on a local/European scale. This model allows users to evaluate potential hazard combinations and footprints in their regions, enabling better preparedness for potential multi-hazard events.

Global application of a regional frequency analysis on extreme sea levels

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Inundation from storm tides and ocean waves is one of the greatest threats coastal communities endure; a threat that is increasing with sea-level rise and changes in storminess. Stakeholders require high resolution hazard data to make informed decisions on how best to mitigate and adapt to coastal flooding. We present a novel approach to estimating global Extreme Sea Level (ESL) exceedance probabilities, using a Regional Frequency Analysis (RFA) approach. The methodology is an extension of the regional framework from Sweet et al. (2022), with innovations made to incorporate wave setup and apply the method globally. The research combines observed and modelled hindcast data to produce a high-resolution (~1 km) dataset of ESL exceedance probabilities, including wave setup, along the entire global coastline, excluding Antarctica.

The RFA approach offers several advantages over traditional methods, particularly in regions with limited observational data. It overcomes the challenge of short and incomplete observational records by substituting long historical records with a collection of shorter but spatially distributed records. This spatially distributed data not only retains the volume of information but also addresses the issue of sparse tide gauge coverage in less populated areas and developing nations.

This study provides a valuable resource for quantifying global coastal flood risk, offering an innovative global methodology that can contribute to preparing for, and mitigating against, coastal flooding.

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How projected changes in storm properties shape changes in the statistics of sub-daily precipitation extremes?

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Sub-daily intense precipitation can trigger natural disasters, particularly in mountainous areas and urban basins. The analysis of extreme precipitation values under a changing climate is critical for improving risk management, as it can help quantifying the future probability of observing extreme precipitation events. Kilometer scale convection-permitting climate models (CPMs) realistically represent convective precipitation processes and complex terrain, thus improving the description of sub-daily extreme precipitation. They are however limited in the length of the simulations. To this end, non-asymptotic extreme value approaches proved effective in reducing uncertainty even from short datasets. Further, these methods can provide insights about the underlying changes in precipitation processes, thanks to the separation of precipitation intensity distribution from event occurrence in their formulation.
In this study, we apply the Simplified Metastatistical Extreme Value approach (SMEV) to i) evaluate the projected changes in extreme sub-daily precipitation in an orographically-complex region in the North Italy area; and ii) analyze the relation between changes in the statistics of extremes and changes in the characteristics of the underlying storms.
We focus on an ensemble of 9 CPMs from the CORDEX-FPS project, with a spatial resolution of 3 kilometers and a temporal resolution of 1 hour. We investigate three time slices: historical (1996-2005), near future (2041-2050), and far future (2090-2099) under the RCP8.5 emission scenario. Utilizing a dry hiatus of 24 hours to identify storm events in the time series at each grid point, we employ a two-parameter Weibull distribution to model precipitation frequencies of maximum intensities for the heaviest events. Return levels are estimated up to a 1% yearly exceedance probability (100-year return time) for precipitation durations spanning from 1 to 24 hours. Several storm properties are assessed at each grid point (intensity, total duration, seasonality, decorrelation-time). We estimate future changes in return levels, distribution parameters, and storm properties by contrasting the two future periods with the historical one.
Across the domain, we find a general increase in extreme precipitation at all durations, with stronger enhancements at short durations and rarer probabilities (Figure 1). The spatial patterns vary with duration and time slice. The change in the distribution

parameters shed light on the change in the return levels: the scale parameter has positive change at short durations, while the shape parameter indicates increasing tail heaviness across all durations. The combined effect for increased scale and increased tail heaviness explains the enhanced change found at short duration return levels. Preliminary results on the changes in storm characteristics reveals that properties typical of convective events seems more related with the heavier future tails. Further investigation could lead to advancements in our understanding of the interplay between physical processes and statistics of extremes.

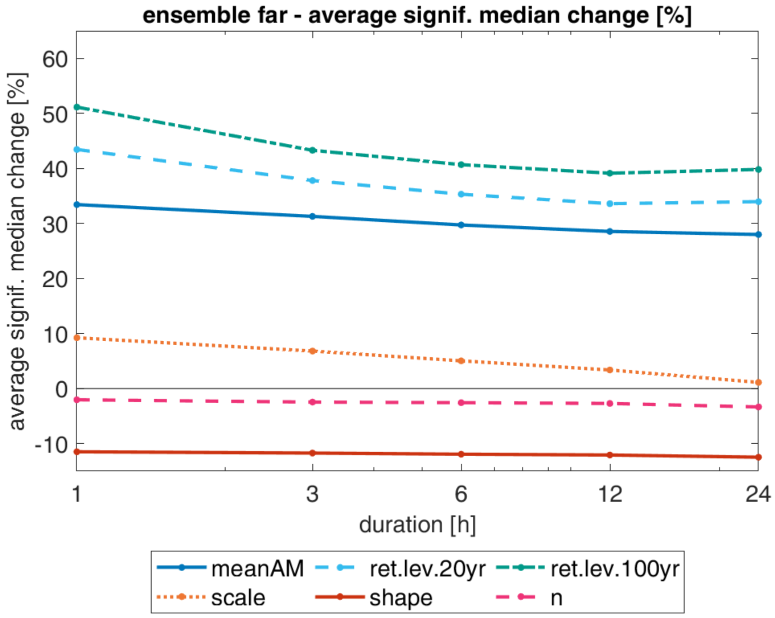

Fig. 1*: Average significant change in extreme precipitation (Annual Maxima AM, 20yr return level, 100yr return level), in the distribution parameters (scale and shape) and in the yearly number of events, for the 5 precipitation durations from 1 to 24 h.*

This research has been supported by the Fondazione Cassa di Risparmio di Padova e Rovigo (Excellence Grant 2021 to the Resilience Project). This study has also been carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D. D. 1243 2/8/2022, PE0000005)

Disentangling Natural and Anthropogenic Drivers of Changes in Extreme Sea Levels since 1850

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Extreme sea levels (ESL) have been increasing over the 20th century, and it has been demonstrated that in most regions, mean sea levels (MSL) are the main driver of the observed changes (Menendez and Woodworth, 2010). While it is now well understood that an increasing portion of the observed changes in global MSL can be attributed to anthropogenic forcing (Dangendorf et al., 2015; Slangen et al., 2016), there have been no attempts to attribute observed changes in local ESLs to individual forcings yet. Here, we assess ESLs at the tide gauge of Sewell's Point in Virginia using nonstationary extreme value statistics based on a generalized pareto distribution. The threshold parameter shows a significant linear trend of about 4.6 mm/yr that is mostly reflective of the underlying MSL rise at that location (~4.2 mm/yr over the period 1928 to 2005). We use single forcing experiments from the Climate Model Intercomparison Project 5 (CMIP5) in combination with independent estimates of observed vertical land motion (VLM) to attribute the MSL changes (and related changes in the threshold parameter) to natural (volcanic eruptions, solar forcings, etc.) and anthropogenic (greenhouse gases, aerosols) forcings. The modelled MSL in combination with VLM matches the observed MSL trend, such that we can model changes in the threshold parameter as a function of modelled MSL using single forcing experiments over the period 1850 to 2005. In total the 100-year event has been increasing by 0.67 m from 3.37 m in 1850 to 4.04 m in 2005. As a result, the return water level corresponding to a return period of a hundred years under present day conditions, corresponded only to a once in a 1,200-year event in 1850. VLM has been the most dominant driver of this reduction in the return periods. Greenhouse gases have also significantly contributed, although the resulting trends have partially been offset by aerosol forcing. Natural forcings contributed the least to the observed changes. Our framework represents an important step towards the attribution of observed changes in ESLs.

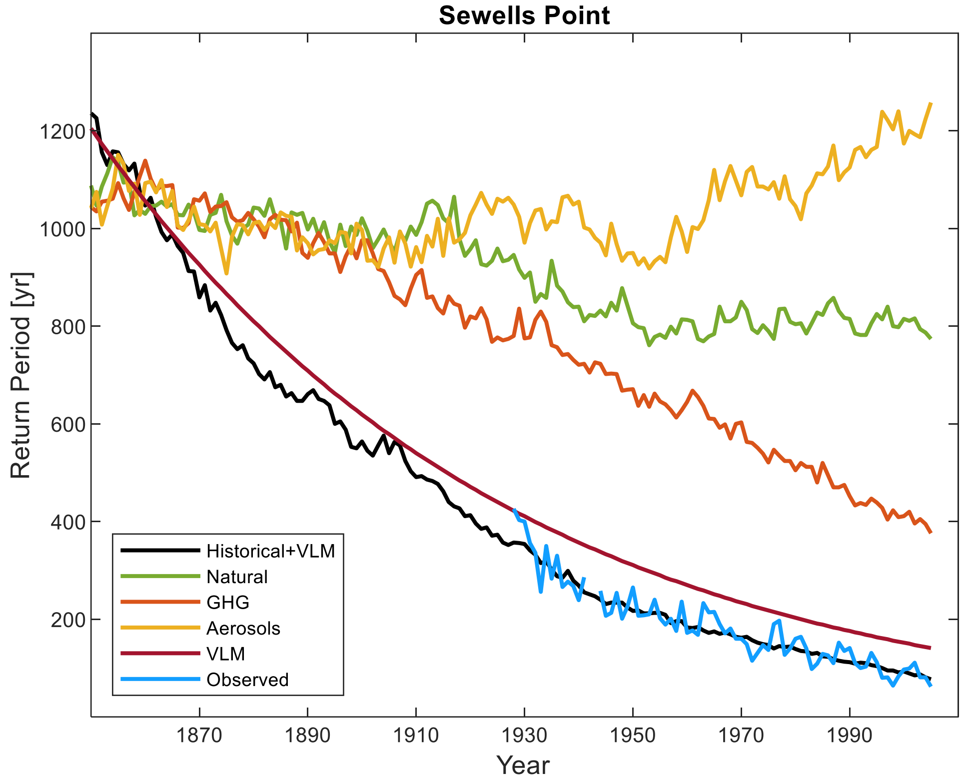

Fig. 1: *Modelled and observed changes in the return period of a water level corresponding to a return period of a 100-year event under present day conditions using different single forcing experiments from CMIP5 over 1850 to 2005.*

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Regional Frequency Analysis of extreme waves in the Mediterranean Sea

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Regional Frequency Analysis (RFA) is a well settled tool that implies to pool together time-series of different sites, to form homogeneous regions from a climatological point of view (Hosking & Wallis, 1997). Such approach yields vast dataset that can be used to extrapolate low frequency extremes with reduced uncertainty. While RFA has reached prominence among the meteorologist and hydrologist communities, to date very few applications deal with maritime stressors and hazard, such as storm surge and ocean waves (see, e.g., Campos et al., 2019, and references therein). As regards the latter, no prior researches were developed in the Mediterranean Sea (MS), and some aspects still need to be clarified. The goal of the research is twofold: first, to form homogeneous regions based on the major directional wave patterns within the MS; except for Sartini et al., (2018), waves directionality has so far not be accounted for, although this is a crucial aspect for the design of coastal and off-shore engineering projects. Second, to assess how the inter-site dependence may affect the confidence intervals of the return period curves. As a matter of fact, one assumption of RFA is that the regions obtained should embed uncorrelated sites, a condition hard to be met in real cases; violating this assumption may lead to serious underestimation of return level confidence intervals, although this is often overlooked.
On this note, we form homogeneous regions in the MS by taking advantage of hindcast data reconstructed over the whole basin, and extrapolate long-term return levels of significant wave height (H_S), for both omni-directional data and for data belonging to the main directional fetches.
The work-flow is as follows: first, we cluster the hindcast nodes based on the dominant seas as pointed out in De Leo et al., (2024), for varying numbers of clusters. The initial set of regions is subsequently refined to ensure spatial continuity, and statistical tests are carried out to check on the homogeneity of the regions and remove possibly discordant sites. Next, we pool together omni-directional and directional annual maxima H_s series and compute the respective regional moments for the Generalized Extreme Value distribution, which are then used to extrapolate the H_s values for varying return periods (T_R). Finally, confidence intervals for the H_s-T_R curves are computed through a bootstrap approach, either accounting for inter-site dependence or not.
The optimal set of regions resulting from the analysis above can be appreciated in Figure 1. Results of the H_s-T_R levels (Figure 2) show that, although the RFA lead to a reduction the uncertainty of the estimates (that is, narrower confidence intervals or CI), this is over-estimated when not accounting for cross-correlation between AM series.

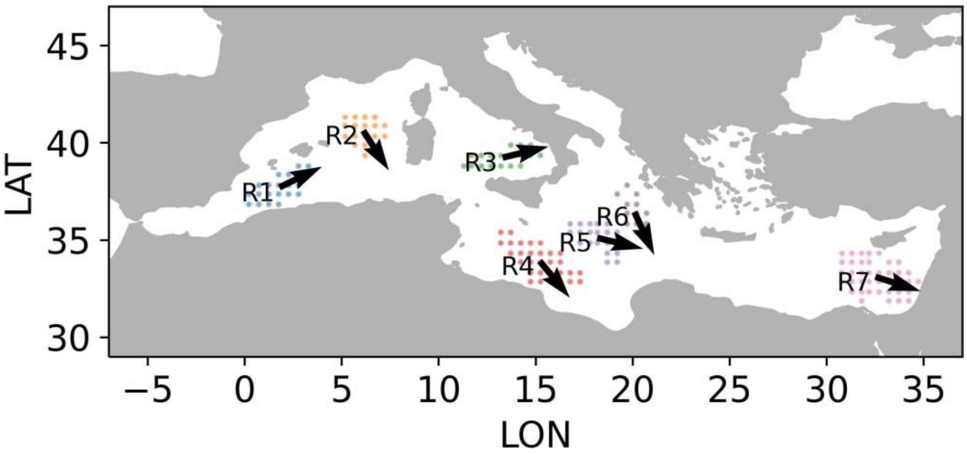

Fig. 1*: Regions highlighted through the RFA in the MS. Black arrows indicate the direction of the main fetchs.*

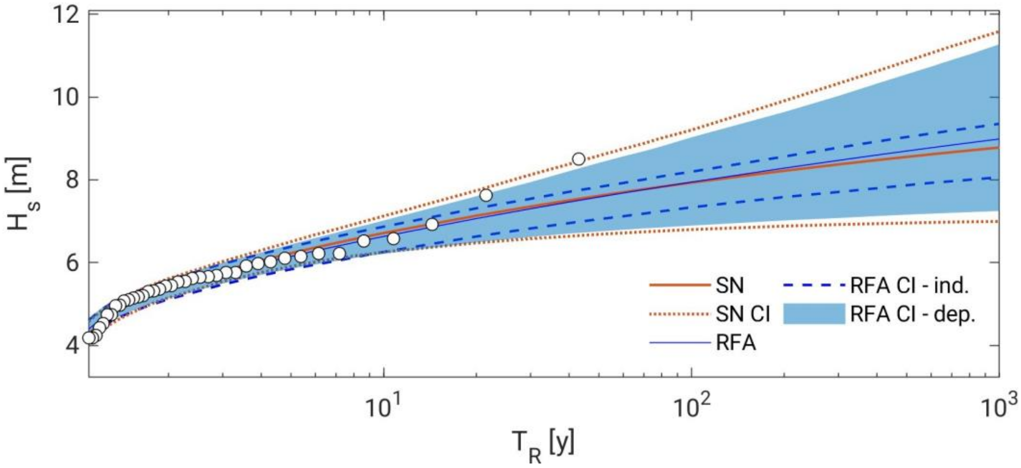

Fig. 2: *H_s-T_R curves for site no. 6 in the first region (R1). Brown and blue curves indicate the classical Extreme Value Analysis approach and the RFA, respectively. Dashed blue lines denote CI obtained without accounting for inter-site dependence, while the shaded area denotes CI obtained accounting for it. Directional analysis.*

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A regionalized framework for the Metastatistical Extreme Value Distribution applied to sub-daily rainfall.

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The estimation of extreme rainfall based on short records is of considerable interest, above all in the context of rapidly changing rainfall regimes. Regionalization techniques, by trading space for time, allow to partially overcome the lack of long observational records. The recently-introduced Metastatistical Extreme Value (MEV) distribution, which infers the probability distribution of annual maxima from all observed rainfall events, also contributed towards improving our ability to estimate large quantiles based on short observational time series. Here we combine established regionalization techniques, aggregating data from multiple adjacent stations complying with set homogeneity criteria, with MEVD-based methodologies to explore how their joint use may further reduce the uncertainty with which large extremes may be estimated. In the present work we focus on observations from the Veneto Region Environmental Protection Agency (Italy), which includes a round 200 stations, with an average distance of 15 km and deployed in a wide range of elevations and in different rainfall regimes, providing time series with a time resolution of 5 minutes. To evaluate possible improvements with respect to regionalization techniques based on traditional extreme value theory, such as the Generalized Extreme Value (GEV) distribution, we comparatively apply the proposed MEVD-based regionalization approaches and GEV-based methods. The results show the benefits arising from the regionalization technique, which enhances the robustness of the models by increasing the consistency of the observed data population thanks to trivially identifiable homogeneous regions. The proposed regionalization approach based on the metastatistic distribution brings to a significant reduction of the estimation uncertainty for very high ratios between the forecasting return period value and the length of the calibration sample when compared to traditional methods.

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Modelling Extreme Water Level and its Components for Infrastructure Design: the case of Hoek van Holland

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Sea Level Rise (SLR) is expected to increase impacting the frequency and intensity of coastal flooding. This combination of the increasing level of urbanization and population growth in coastal regions calls for a better probabilistic representation of Extreme Water Levels (EWLs), and the mechanisms generating them, and their components, i.e., astronomical tide and storm surge. As a matter of fact, EWLs drive the maintenance and design of flood protection systems and long-term adaptation strategies.
Here, we present a comparative study of different probabilistic models for EWL available in the literature, i.e., univariate extreme value analysis (EVA), bivariate copulas, and Joint Probability Method (JPM), each relying on different initial assumptions. We adopt Hoek van Holland (NL) as a case study. This site holds significant importance for the Netherlands as it serves as the entrance to the port of Rotterdam, the largest port in Europe. Additionally, it is where the Maeslant storm surge barrier, a crucial component of the Delta Works, designed to safeguard the southern regions of the Netherlands from sea-related threats, is located.
Our results show that EVA and JPM provide a similar probabilistic characterization of EWL, while bivariate copulas tend to underestimate EWL's higher quantiles.
In the following Figure 1, the main framework of the approach is given. The homogenized Water Level (WL) data have been divided into the tidal and Non Tidal Residual (NTR) components. For the latter one the wind speed and Sea Surface Pressure (S.S.P) as the main drivers are analyzed to define the duration of storm events. In the probabilistic part of the analysis three different approaches are compared. On the one hand, the JPM which is oriented by the extreme NTR and the NTR and tides are assumed independent. On the other hand copulas and EVA are EWL oriented, as they have been calculated with Peak Over Threshold (POT), differing in the implementation method as in the first the dependence between tides and NTR is taken into consideration, whilst in the EVA method statistical distributions are fitted directly to the EWL for extrapolation in higher return periods.

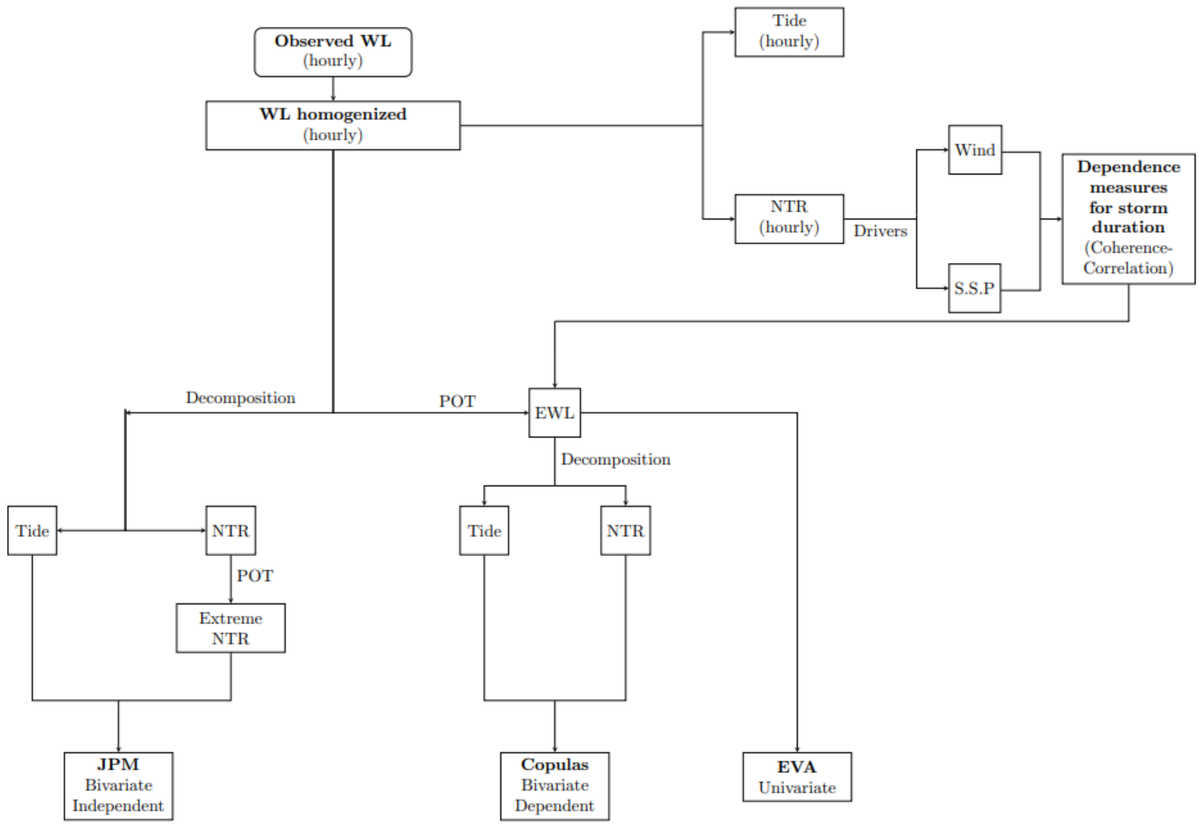

Fig. 1: *Flow diagram of the framework of the methodology adopted in the research paper.*

Sea level rise drives increase in water level extremes in the German Bight

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Water level extremes in the German Bight pose a major threat to coastal structures and can lead to the loss of human life. It is crucial to develop a better understanding of the occurrence probabilities and intensities of these extreme events, especially under the influence of sea level rise (SLR) (Calafat et al., 2022).
For this purpose, we propose the framework of Vector Generalized Linear Models (VGLM) (Yee, 2015) to describe the monthly maxima of water levels at more than 50 tide gauge stations in the German Bight. We use the Generalized Extreme Value Distribution (GEV) and model all three distribution parameters (μ, σ, ξ).
Anticipating an annual cycle in water level extremes, we introduce a series of harmonic functions as a first batch of covariates (Rust et al., 2009; Fischer et al., 2019). By doing so, we are able to test the hypotheses that the overall magnitude (annual cycle in μ), spread (annual cycle in σ) and the generating process (annual cycle in ξ) of water level extremes might change throughout the year.
By furthermore introducing SLR in the form of Legendre polynomials (Rust et al., 2013; Fischer et al., 2019) as a second batch of covariates, we are able to model a potential dependence of water level extremes in the German Bight on SLR.
Allowing for interaction-terms between the harmonic functions and SLR in a last step, we are able to quantify a possible change in the annual cycle of water level extremes with SLR.
The model selection is based on a stepwise-forward approach and subsequent verification, using k-fold cross-validation in conjunction with the Quantile Skill Score (Bentzien and Friederichs, 2014). The main preliminary results are:

1. the annual cycle is important for the overall magnitude and the spread of water level extremes
2. ξ remains constant throughout the year and over time
3. the linear and quadratic orders of SLR are relevant for the overall magnitude of water level extremes
4. a change in the annual cycle of water level extremes with SLR could be detected

By further evaluating and verifying the results from the proposed modeling approach, we are able to gain a deeper understanding of how water level extremes change throughout the year and with SLR.
Following a thorough verification, future work will include the combination of the proposed modeling approach and SLR-projections to enable estimation of future water level extremes in the German Bight.

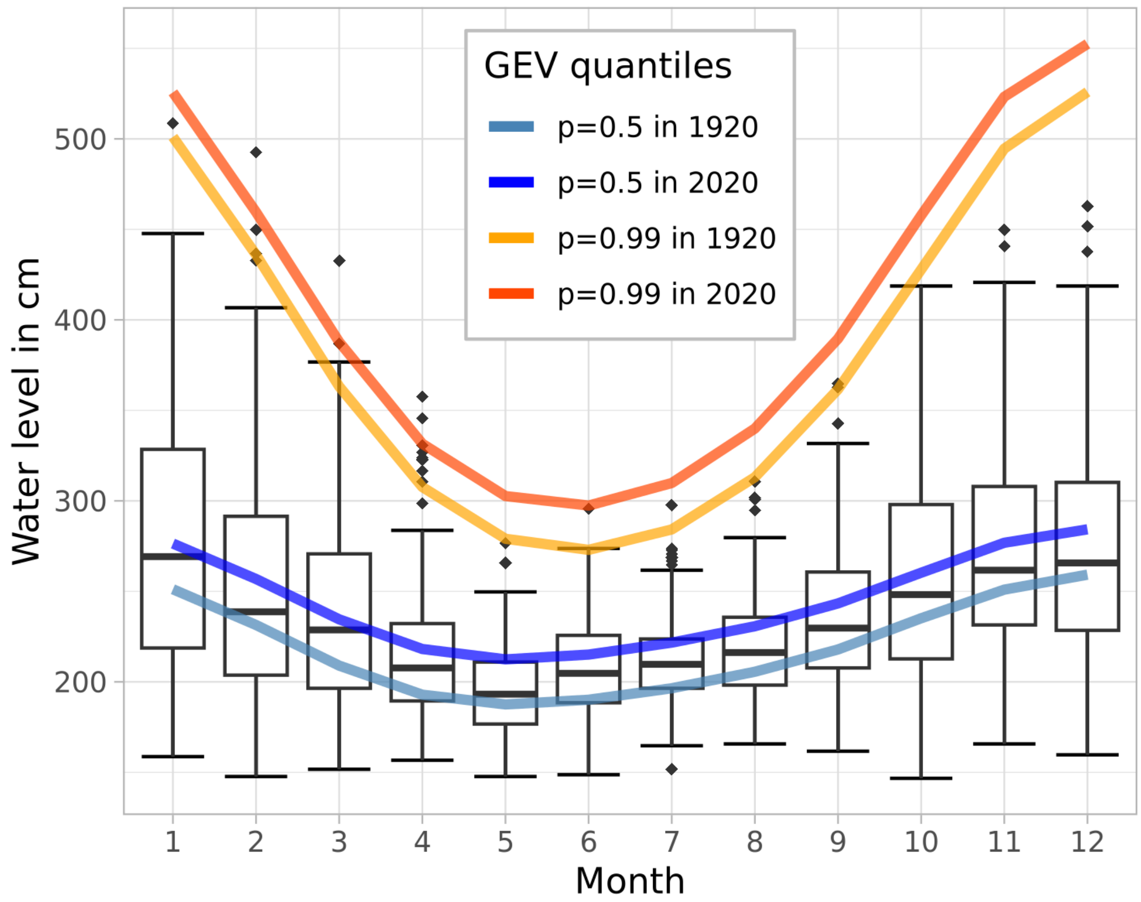

Fig. 1: *Boxplot of monthly maxima at tide gauge station Cuxhaven (1900 – 2023). Colored lines indicate quantiles from the GEV model for an early time stamp (light colors) and a late time stamp (saturated colors) in the time series.*

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Geometric mixture of generalized extreme value distributions: Application to the estimation of return levels of river flows and wind speeds

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In extreme value theory, the generalized extreme value (GEV) distribution and the generalized Pareto (GP) distribution are the main statistical models widely used to characterize extreme values of univariate random variables having unknown probability distributions. In practice, the GEV distribution is estimated through the block maxima (BM) approach whereas the GP distribution is estimated through the peak over threshold (POT) approach. However, the estimated extreme value distributions are very sensitive to the block size used in the BM approach and to the threshold used in the POT approach. To address these limitations, we introduce the geometric mixture generalized extreme value (GMGEV) distribution. The GMGEV distribution is max-stable, and such, it is a valid asymptotic distribution for maxima. In addition, we propose a statistical modeling approach called the equivalent block maxima (EBM) approach through which the parameters of the GMGEV distribution can be estimated. Specifically, the EBM approach consists to construct the GMGEV distribution with all estimated GEV distributions from the BM approach whose parameters are not statistically different. Illustrations on simulated data show the ability of our extreme value modeling strategy to provide consistent estimators for extreme quantiles. Finally, we apply the proposed strategy to estimate centennial, millennial and deca-millennial return levels associated with river flows and wind speeds in France.

Analysing non-stationary damage risks from spatially correlated coastal extreme events

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A singular extreme event can induce coastal flood risk over vast areas, regardless of geographical proximity. Hurricane Ian (2022) generated impactful extreme sea levels along Florida's west coast, from Key West to Fort Myers, and simultaneously impacted northeastern Florida, South Carolina, and North Carolina. This spatial footprint is not unique; the same regions have previously experienced simultaneous extreme events in the past (Enriquez et al., 2020).
Understanding the spatial dependencies of extreme water levels is crucial for accurately estimating flood risk metrics, such as expected annual economic losses. Reliable information on correlated loss probabilities is essential for developing insurance schemes and public adaptation funds. The importance of accounting for the spatial dependencies of floods has been shown for rivers: models neglecting the spatial dependencies of river water levels underestimate the economic damage, while losses are overestimated when complete spatial dependence is assumed (Lamb et al 2010; Jongman et al 2014). While previous studies have underscored the importance of spatial dependencies in assessing damage from river floods, similar attention has not been paid to coastal regions.
The spatial dependencies of extreme storm surges and extreme sea levels have been identified in previous studies (Enriquez et al., 2020; Li et al., 2023), utilizing observations and reanalysis at a global scale. In those works, stationarity is assumed. However, the spatial footprints of extreme events may vary depending on selected time periods due to seasonal variations in atmospheric circulation patterns, modulating extreme storm surges and the associated spatial correlations.
Here, we present the non-stationary spatial footprints of both, extreme storm surges and extreme sea levels. We then used this information to derive non-stationary event-based datasets using a multivariate statistical model that reflects the identified spatial structures (Li et al., 2023). Utilizing stationary and non-stationary event-based datasets, we estimated flood damage losses along the Gulf of Mexico coasts. Results illustrate seasonal changes in damage losses compared to stationary assumptions. Neglecting spatial correlations of extreme water levels underestimates potential flood losses at the coast, emphasizing the necessity of considering spatial correlations when modeling extreme sea levels and estimating damage losses.

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Non-stationary models for extremal dependence with an application to heavy rainfall data

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Being asymptotically justified by limit theorems, parametric models for max-stable processes and Pareto processes have become popular choices to model spatial extreme events. Apart from few exceptions, existing literature mainly focuses on models with stationary dependence structures. In this talk, we propose a novel non-stationary approach that can be used for both Brown-Resnick type and extremal-t type processes – two of the most popular model classes in spatial extremes – by including covariates in the corresponding variogram and correlation functions, respectively. We apply our new approach to extreme precipitation data in two regions in Southern and Northern Germany and compare the results to existing stationary models in terms of Takeuchi's information criterion (TIC). Our results indicate that, for this case study, non-stationary models are more appropriate than stationary ones for the region in Southern Germany. In addition, we investigate the effect of random covariates on the theoretical properties of the limit processes conditional under investigation. We show that these can result in both asymptotically dependent and asymptotically independent processes. Thus, conditional models do not suffer from the usual restrictions of classical max-stable and Pareto models.

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Estimating the number of closures of storm surge barriers in the future

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Coastal flooding is already one of the most dangerous and costly natural hazards that humanity faces globally and yet it will become even more frequent and challenging to manage because of climate change and other factors. In densely populated estuarine settings, a storm surge barrier is often an attractive and economical solution for flood protection (Figure 1). There are currently more than 50 storm surge barriers in operation today around the world protecting tens of million people and trillions of pounds of property and infrastructure. However, with accelerating rates of sea-level rise being observed and changes in storminess, surge barriers are starting to have to close increasingly frequently, and changes have begun to be seen in the months when closures are typically occurring. Increased used of barriers in the future has critical implications for barrier management, maintenance, and operation. We have developed, validated, and applied a statistical approach to assess how the number of storms surge barrier closures will likely increase in the future and change in frequency throughout the year, considering the Eastern Scheldt storm surge barrier in the Netherlands and the Thames barrier in the UK as representative examples. We descried a flexible method we have developed, using advanced extreme value statistics, for estimating the likely number of closures of storms surge barrier in the future, and frequency throughout the year, that can be used for different climate change scenarios and accounting for different forecast errors. Next, we validate the method, demonstrating it accurately predicts past closure statistics for the Eastern Scheldt barrier and the Thames barrier. Then we apply the method to estimate potential future numbers of barrier closures considering different projections of SLR, along with changes in tides, storm surges and river discharge. We show that there is a rapid acceleration in number of barrier closures in the future, with the strong influence of the lunar nodal cycle, at both case study barriers. Finally, we illustrate how the tool can be used to help guide future barrier management, maintenance, operation, and upgrade/replacement and inform adaptative flood management approaches. The approach we have developed could easily be extended to other storm surge barriers around the world.

Fig. 1*: Schematic diagram showing an illustration of a storm surge barrier*.

On the projected changes in the frequency of flooding across the contiguous United States

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The understanding of the physical processes responsible for historical changes in flood characteristics is crucial for improving preparedness and for mitigating the impacts of this natural hazard. Here we assess future changes in flooding in terms of its frequency by applying an attribution-and-projection approach to the frequency of floods at thousands of streamgages across the contiguous United States. We conduct the analysis at the seasonal level, with the seasons representing proxies for different flood-generating mechanisms and processes. We first use a peak-over-threshold approach to select flood events and develop Poisson models to describe the year-to-year changes in the seasonal number of flood events. In terms of predictors, we consider basin- and season-averaged precipitation and temperature, which are fundamental climate drivers responsible for flooding.

After having developed the statistical models for each basin and each season, we move to the assessment of future changes in the frequency of flood events by examining how the projected changes in the climate predictors are expected to impact this flood characteristic. To do this, we use projected climate drivers calculated from 36 global climate models and four scenarios of the Coupled Model Intercomparison Project Phase 6, providing valuable insights into the way that the frequency of flood events is projected to change for a range of emission scenarios.

Non-stationarities in spatial extremal dependence of precipitation processes

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This research aims to characterise the spatiotemporal features of extremal precipitation data over the Piave river basin in northeast Italy. The data comprises hourly observations over 33 years (1990–2023) recorded at 65 sites across the river basin. Empirical evidence suggests that both the extremal dependence structures and the marginal behaviours of precipitation events over the Piave basin vary throughout the year (reflecting seasonal patterns) and spatial dependence appears to weaken as events become more extreme. Furthermore, we observe differing extremal dependence structures for precipitation extremes when precipitation accumulation is considered over different time scales (e.g., hourly to daily accumulation). We investigate possible factors affecting the marginal distributions, the spatial dependence and the interplay between them. Capturing these features is essential to provide a realistic description of extreme precipitation processes in order to better estimate the risks associated with them. The study investigates and compares the performance of recently proposed multivariate extreme value models in capturing temporally non-stationary and non-asymptotically dependent extremes. We explore the efficacy of using various climatic covariates to capture seasonal effects affecting the extremal precipitation distribution.

Approximate Bayesian inference for analysis of spatiotemporal flood frequency data

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Extreme floods cause casualties and widespread damage to property and vital civil infrastructure. Predictions of extreme floods, within gauged and ungauged catchments, is crucial to mitigate these disasters. In this presentation, we introduce the Bayesian framework of Jóhannesson et al (2022) for predicting extreme floods, using the generalized extreme-value (GEV) distribution. A major methodological challenge is to find a suitable parametrization for the GEV distribution when multiple covariates and/or latent spatial effects are involved and a time trend is present. Other challenges involve balancing model complexity and parsimony, using an appropriate model selection procedure and making inference based on a reliable and computationally efficient approach. The statistical model is a Bayesian latent Gaussian model (BLGM) with a novel multivariate link function designed to separate the interpretation of the parameters at the latent level and to avoid unreasonable estimates of the shape and time trend parameters. Structured additive regression models, which include catchment descriptors as covariates and spatially correlated model components, are proposed for the four parameters at the latent level. To achieve computational efficiency with large datasets and richly parametrized models, we exploit a highly accurate and fast approximate Bayesian inference approach, referred to as Max-and-Smooth (Hrafnkelsson et al., 2021), which can also be used to efficiently select models separately for each of the four regression models at the latent level. The framework, based on the aforementioned BLGM and Max-and-Smooth, is applied to annual peak river flow data from 554 catchments across the United Kingdom. The framework performed well in terms of flood predictions for both ungauged catchments and future observations at gauged catchments. The results show that the spatial model components for the transformed location and scale parameters as well as the time trend are all important, and none of these should be ignored. Posterior estimates of the time trend parameters correspond to an average increase of about 1.5% per decade with range 0.1% to 2.8% and reveal a spatial structure across the United Kingdom. When the interest lies in estimating return levels for spatial aggregates, we apply a novel copula-based postprocessing approach of posterior predictive samples in order to mitigate the effect of the conditional independence assumption at the data level, and we demonstrate that our approach indeed provides accurate results. See results in Jóhannesson et al. (2022).

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A Bayesian multivariate extreme value mixture model

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Impact assessment of natural hazards requires the consideration of both extreme and non-extreme events. Extensive research has been conducted on the joint modeling of bulk and tail in univariate settings; however, the corresponding body of research in the context of multivariate analysis is comparatively scant. This study extends the univariate joint modeling of bulk and tail to the multivariate framework. Specifically, it pertains to cases where multivariate observations exceed a high threshold in at least one component. We propose a multivariate mixture model that assumes a parametric model to capture the bulk of the distribution, which is in the max-domain of attraction (MDA) of a multivariate extreme value distribution (mGEVD). The tail is described by the multivariate generalized Pareto distribution, which is asymptotically justified to model multivariate threshold exceedances. We show that if all components exceed the threshold, our mixture model is in the MDA of an mGEVD. Bayesian inference based on multivariate random-walk Metropolis-Hastings and the automated factor slice sampler allows us to incorporate uncertainty from the threshold selection easily. Due to computational limitations, simulations and data applications are provided for dimension d=2, but a discussion is provided with views toward scalability based on pairwise likelihood.

Amortized neural Bayes estimators with application to the spatial modeling of environmental extreme events

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Rare, low-probability events often lead to the biggest impacts. Therefore, the development of statistical approaches for modeling, predicting and quantifying environmental risks associated with natural hazards is of utmost importance. However, popular statistical models for spatial extreme events lead to computationally prohibitive likelihood-based inference, especially when data are observed at many spatial locations and when non-extreme data must be censored. In this talk, I will show how neural Bayes estimators can be exploited to provide significant time savings to make inference for such models. This novel estimation approach exploits recent advances in deep learning to perform fast and statistically efficient inference with intractable models in a likelihood-free and amortized manner. The proposed methods will be illustrated by application to extreme Red Sea surface temperature data and air pollution data from Saudi Arabia.

Heat Waves and Connections to Climate Variability and Change Across the United States

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Heat waves continue to greatly impact the globe and are projected to continue to increase in frequency, intensity, and duration under climate change. Here heat waves are analyzed from historical stations across the U.S. with daily maximum temperature data from 1950-2023. We apply a covariate-based extreme value analysis (EVA) point process approach that accounts for natural climate variability and climate change influences on extreme temperatures. Statistical attribution is also applied to these observational data to explore changes in likelihood associated with the different modes of climate variability and change. We find pronounced shifts in heat wave frequency, magnitude, duration, and timing within the hot season with regional variations across the U.S. Much of these changes indicate increased detrimental impacts of heat waves on society. These observed changes in heat wave characteristics are correlated with both modes of natural climate variability and long-term change. Statistical attribution of heat waves suggests substantial increases in the probability of events in the climate of today versus the climate at the beginning of the study period as a result of long-term climate change.

Dominant sources of uncertainty for downscaled climate: a military installation perspective

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While Department of Defense (DoD) infrastructure is no stranger to extremes, recent events have been unprecedented, with climate change acting as a growing risk multiplier. To assess the level of exposure of DoD installations to extreme weather and climate events, site-specific climate information is needed. One way to bridge the scale gap between outputs from existing global climate models (GCMs) and sites is climate downscaling. This makes the information more relevant for impact assessment at the DoD installation and facility scale. However, downscaling GCMs is beset by a myriad of challenges and sources of uncertainty, and downscaling methods were not designed with specific infrastructure planning and design needs in mind. Here, we evaluate state-of-the-science dynamical and statistical downscaling methods for climate variables (i.e., temperature and precipitation) at the daily scale. We also combine downscaling approaches in novel ways to optimize computational efficiency and reduce uncertainty. Furthermore, we examine the sensitivity of the downscaled outputs to the choice of reference data and quantify the relative uncertainty related to downscaling approach, reference data, and other factors across the climate variables and aggregation scales. Results show that empirical quantile mapping (eqm), a statistical approach, consistently performs well and has less sensitivity to the choice of reference data. Moreover, a hybrid approach that leverages the eqm improves the performance of a dynamical downscaling approach. Our findings highlight that the choice of reference data dominate uncertainties in temperature downscaling, while their role is more muted for precipitation but still non-negligible.

Developing a spatial regression modeling framework for insured flood losses in Houston, Texas

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Flood events in Houston, Texas, are responsible for major economic impacts to public infrastructure and residential properties. Events such as Hurricane Harvey in 2017 have led to billions of dollars in reported flood insurance claims through the National Flood Insurance Program (NFIP), and studies have shown that economic burden from flood losses is often felt unequally across the city. Despite growing interest, there is currently limited research investigating how hydrologic and socio-economic drivers influence the location and magnitude of reported NFIP flood insurance claims. Furthermore, few studies take into account the effect of spatial dependency in existing flood loss models. Here we present a statistical spatial regression modeling framework of NFIP flood insurance claims and claim amounts in Houston, Texas, at the census tract level for 13 flood events from 2010 to 2019. We determine a statistical relationship between these losses and various hydrologic and socio-economic factors related to each community, and we perform eigenvector spatial filtering (ESF) to account for spatial dependency and to improve model skill. We find that communities with high policy densities within high-risk flood zones that experienced severe flooding resulted in the largest number of reported claims and total claim amounts. When considering social demographics, we find that census with higher median incomes and a higher percentage of elderly residents, regardless of race, are linked to more insurance claims. Additionally, we find that census tracts with predominantly White, non-Hispanic and Hispanic populations are linked to higher claim amounts than census tracts with a predominantly Black, non-Hispanic population. Our modeling framework allows us to evaluate future changes in flood losses due to climate-change driven flooding and changes in flood insurance policy density, with implications for flood risk management and insurance.

Assessing the future spatial dependence of extreme sea level events along the global coastline

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When single flood episodes affect a large spatial area simultaneously, the impacts can be largely amplified. A recent example of such widespread coastal disasters is the extratropical cyclone (ETC) Xaver in which flooding devastated eight countries in the northwestern Europe and caused 1.9 billion euro economic losses. To derive accurate risk estimates and develop effective adaptation strategies, it is important to understand the spatial dependence of extreme sea level events, i.e. the spatial footprints and the joint probabilities of extreme water levels in different locations. To date, there exists no studies looking into how the dependence structure may change in the future due to sea level rise and changes in storminess. In this contribution, we aim to assess historic and future changes in spatial dependence of extreme sea level events along the global coastline. For the historic changes, we use 40-year reanalysis water level data to assess the non-stationarity in spatial footprints at seasonal to decadal time scales. The joint probabilities are estimated by applying a multivariate dependence model (Heffernan & Tawn, 2004) to the 40-year time series. For the future changes, we use the global projections of extreme water levels derived from the hydrodynamic Global Tide and Surge Model (GTSM) forced with a climate model ensemble (Muis et al., 2023). We then apply the same approaches to the future water levels to estimate the spatial footprints and joint probabilities. With the multivariate dependence model, it is possible to statistically extend the decadal extremes to 10,000-year synthetic events. These synthetic events preserve the dependence structure as found in the original dataset. These events can be used for improving coastal flood risk assessments by providing more accurate estimates of current and future risks.

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Extreme quantile treatment effect estimation using extreme value theory and power transformation

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Extreme event attribution (EEA) assesses the impact of human activity on the likelihood and severity of extreme weather or climate events. In its simplest form, it relies on comparing the tails of the distribution of the weather variable of interest in a factual world (with human intervention) with that of a counterfactual world (without human intervention). By considering human intervention a binary treatment, we can resort to the potential outcomes framework (POF) for causal inference to quantify the effect of human activity on the tails of the distribution of the weather variable. For an (anthropogenic) intervention, the POF defines causal effect as the difference between the outcomes that would be observed with versus without the intervention. Since our focus is on the tails of the weather variable distribution, a natural way to do this is through quantile treatment effect (QTE), which is defined as the difference between the marginal quantile of the response variable in the two worlds. Classical QTE estimators struggle to estimate extreme QTE since their asymptotic property no longer holds when the quantile index tends to 0 or 1 (Zhang, 2018). However, over the last few years, different authors have proposed improvements and alternatives to classical QTE estimators to accommodate extreme QTE.

To add to the existing literature, we here proposed a two-step strategy to estimate extreme QTE. First, we estimate conditional extreme quantiles by either the generalised Pareto distribution for threshold exceedances with parameters described through generalised additive models or the power transformation method of Wang & Li (2013), which uses information from covariates and extrapolates the conditional non-extreme quantile into extremes using Weissman's estimator. Second, we use a propensity score-free estimator and an advanced inverse probability weight estimator (Ma et al., 2022) to obtain the marginal extreme quantile treatment effect. The transformation equation between conditional and marginal quantiles may not have exact roots, so we rewrite the equation into an optimisation problem with L1 type convex function.

We illustrate the performance of our methods using three different simulation scenarios that differ in the heaviness of the tail of the data-generating process. Our preliminary results show that our estimators exhibit competitive performance compared to those proposed by Firpo (2007), Zhang (2018), Bhuyan et al. (2023), and Deuber et al. (2023). Our ongoing work is focused on uncertainty assessment, asymptotic properties, and an application to estimate extreme QTE of human activity on rainfall in Australia using post- and pre-industrial data.

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Validation of an analytical expression of tornadoes probability against observed events

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Tornadoes are hazardous and extreme weather events whose small spatial scale, short duration, nonlinear and chaotic dynamics prevent simulation in operational weather forecasts and reproduction in climate models. However, since they are frequent causes of damage and victims, there is a widespread need for approaches that can lead to estimating their frequency and their occurrence. To match this request a set of analytical formulas have been proposed (Ingrosso et al., 2023) for computing the probability P of tornadoes on the basis of the meteorological variables that have been shown to have a role in their occurrence (Ingrosso et al., 2020): W_{MAX} (updraft maximum parcel vertical velocity), WS_{700} (the wind shear in the lower troposphere), LCL (the lifting condensation level), SRH_{900} (low-level storm relative helicity). An example is the formula

$$\log_{10}(\mathrm{P}) = -6.6 + \frac{\mathrm{W_{MAX}}}{3.1 + 5.2 \cdot \mathrm{W_{MAX}}/\mathrm{WS_{700}}}$$

In this contribution we show to which extent the probability estimated using this type of formulas agree with the actual occurrence of tornadoes at interannual time scales.

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Advantages and limitations of non-asymptotic extreme value modelling methods

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Extreme events in the Earth system involving the water cycle, such as floods, droughts, and storms, have large impacts on human society and on its infrastructure. Understanding and robustly quantifying such extremes is now more important than ever, as we prepare for an accelerating climatic change over the next century. Here, past changes in the frequency of extreme events in a number of geophysical processes will be examined, illustrating what can be learned about extremes and their changes using a recently-developed tool, the Metastatistical Extreme Value Distribution (MEVD). This approach, by relaxing some assumptions of the traditional Extreme Value Theory, increases the amount of information used in large quantile estimation, thereby generally reducing estimation uncertainty. This is particularly useful when only short observational time series are available, and, in a time of climate change, when statistical stationarity may be assumed to hold for just short periods of time. Results from a wide spectrum of applications will be reviewed, from observed hourly and daily rainfall, to rainfall generated through Convection Permitting Models, to flood peak discharge, to hurricane intensity, to storm surge sea levels, to drought intensity, to the intensity of historical epidemics. The review will show strengths and limitations of the MEVD approach as compared with traditional methods related to the Generalized Extreme Value Distribution.

Bias-correction and downscaling of precipitation from global climate models across the Colorado River Basin

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Extreme precipitation events are responsible for numerous hazards (e.g., floods, landslides), claiming a high toll in terms of fatalities and economic damage (Gründemann et al., 2023). Because of these major impacts, the projection of extreme precipitation under future climatic scenarios is essential to improve mitigation strategies. In this framework, hydrologic and hydraulic models play a key role in transforming precipitation into runoff, evaluating the resultant discharge, and assessing its impact in terms of flooding. Nonetheless, for precipitation to serve as input for hydrologic models, it necessitates high-resolution data both in space and time (i.e., sub-daily and few kilometers). Current global climate models (GCMs) do not provide outputs at such high resolution and are affected by biases, thus requiring downscaling and bias-correction procedures (McSweeney et al., 2015; Schmidli et al., 2006).

This work focuses on the examination of different bias-correction and downscaling techniques to generate precipitation outputs with a temporal and spatial resolution of one hour and 4-km, respectively, useful for decision making at the local scale. As a case study, we focus on the Colorado River Basin in the western United States, and in particular on the Hoover Dam and Glen Canyon Dam that led to the creation two of the largest reservoirs in the United States, i.e. Lake Mead and Lake Powell. These reservoirs play a critical role for water supply, flood control and hydropower, and have been the topic of extensive interest in the news because of their extremely low levels in recent years.

Here we assess whether the current precipitation conditions are expected to continue into the future or whether they will revert to their design conditions. This work aims at providing insights into a question with global relevance, as many reservoirs are facing the same issue with severe implications. More broadly, the outcome of this research aims at providing key information for several applications (e.g., risk analysis and dams and reservoirs design and management) as an appropriate water resource management is necessary to cope with extreme events and changes in precipitation amounts.

As reference, we use the Analysis of Record for Calibration (AORC) dataset (Kitzmiller et al., 2018); it provides information about precipitation and other meteorological variables across the contiguous United States from 1979 to the present with high spatial and temporal resolution (i.e., 4 km and hourly). Moreover, we have access to daily outputs from 20 climate models, with a spatial resolution between 25 km and 200 km for both historical simulations and four future scenarios or Shared Socioeconomic Pathways (i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5). We perform statistical bias correction and downscaling using some of the most widely used approaches. The use of different techniques allows us to assess the strengths and weaknesses of each method in relation to the case study, and their suitability for applications to the energy sector.

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Reconciling extreme precipitation-temperature scaling with extreme value analysis

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We present a statistical model for extreme sub-hourly precipitation return levels based on our understanding of the underlying physics. The TEmperature-dependent Non-Asymptotic statistical model for eXtreme return levels (TENAX, Marra et al., 2024) represents the exceedance probability of extreme intensities using temperature as a covariate, and explicitly models the probability density of temperatures observed during precipitation events. Using the total probability theorem, these two modules are linked to provide a physics-based estimate of the marginal distribution of the precipitation intensities. Return levels are then estimated using a non-asymptotic method.
We present the theory behind TENAX and we show that it reproduces sub-hourly return levels with the same accuracy of purely statistical methods. We then show that TENAX explains known properties of the extreme precipitation-temperature scaling relation for which it was not explicitly designed.
Assuming that the physics of convection remains unchanged in time and that convection remains the dominant process for sub-hourly extremes (i.e., no change in the magnitude module), TENAX can be used to project future sub-hourly return levels only based on the projected changes in daily temperature during rainy days. In hindcast, we demonstrate that TENAX trained on past observations predicts "future" unseen return levels only based on projections of daily temperatures.
TENAX codes are freely available online to the statistical hydrology community and any interested researcher and practitioner (Marra and Peleg, 2023).

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Temporal clustering of storm surges

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Successive storm surges (even when they are only moderate) can have greater impacts than a single storm surge event, especially when communities are still recovering from previous shocks. These occurrences are known as temporal clusters, leading to compounding effects. Accurate risk assessment and emergency response planning require an understanding of the frequency of such temporal clusters. To date, no comprehensive analysis of temporal clustering has been conducted at the global scale to identify hotspots and potential changes in clustering. The study aims to quantify the variability of temporal clustering over short time scales (intra-annual) along global coastlines using in-situ observations from more than 1,000 tide gauges.
The first step in finding temporal clusters includes properly identifying individual storm surge events from the hourly water level time series. Traditional methods of de-clustering often are ineffective when moderate events are of interest. We apply a new methodology that returns a “standard event duration” for each tide gauge station based on the correlation between events. Using these de-clustered events, we apply various methods based on event counts, statistical analysis of inter-arrival times, and other indicators such as the Ripley’s K function to identify temporal clusters and geographical hotspots where the occurrence of events deviate from a Poisson distribution. We use different cluster definitions, spanning from 30 days to one year. Furthermore, we explore the relationship between clusters and event intensity, using different thresholds to analyze it. Preliminary results show that the Baltic Sea, Japan, and the Gulf of Mexico are more prone to clustering events. We also find that clustering is stronger for events with moderate magnitude.

Challenges and Opportunities in the Detection of Trends in Subdaily Heavy Precipitation in the United States

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Increasing empirical evidence has been showing that, over the last decades, the frequency of daily heavy precipitation has risen in some regions of the United States (U.S.); less evidence has instead been presented at subdaily resolutions. In this study, we describe the challenges and opportunities associated with the detection of trends in subdaily heavy P in the U.S. using Version 2 of the Hourly Precipitation Data (HPD) from the National Climatic Data Center (NCDC). This dataset comprises records from 1897 gages, which we found to be affected by several issues preventing their use in trend studies, including long periods with missing observations, changes of instruments, and different signal resolutions (largely, 0.254 and 2.54 mm). Despite this, after proper checks, we were able to identify 370 gages with ≥40 years of statistically homogenous data in 1950-2010 that cover the U.S. with a good density. To improve the ability to detect trends, we designed a framework that quantifies the degree to which the observed over-threshold series above a given empirical q-quantile are consistent with stationary count time series with the same marginal distribution and serial correlation structure as the observations. We also applied the false discovery rate test to account for spatial dependence and multiplicity of the local tests. Analyses were performed for the signals aggregated at Δt = 1, 2, 3, 6, 12, and 24 h and for q = 0.95, 0.97, and 0.99, finding that most gages exhibit increasing trends across all Δt's and that their statistical significance increases with Δt and decreases with q, but only for $\Delta t \geq 2$ h. This might indicate that the physical generating mechanisms of precipitation have changed in a way that leads to larger accumulations over durations >1 h but similar intensities within 1 h. An alternative possible explanation for these outcomes is instead that the coarse signal resolution (2.54 mm) reduces the power of the test for trend detection as Δt decreases. Investigating these issues will be the subject of our immediate future work.

Accounting for eustatic sea level rise in joint analyses of waves and sea levels for the design of maritime structures

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Joint probability analyses of waves and sea level can be used to estimate the probability of occurrence of the hydraulic loads on harbour structures (flooding, overtopping, stability of the armour of a rubble mound breakwater, loads on a caisson…), taking into account the dependence between the two phenomena. As a result, contour lines of the joint exceedance return period of significant wave height and sea level can be drawn, along which pairs can be selected for the design, depending on the response of the structure to be considered.
However, eustatic sea level rise due to climate change modifies the bivariate probabilities: each year, the probability of exceedance of a given wave height / sea level pair increases, while its joint return period decreases. A simplified and conservative approach is to add to the considered pair the increase expected at the end of the project lifetime: at that time, the joint return period is the one to be used for design. Conversely, at the beginning of the lifetime, it will be much higher.
It is proposed to deal with this issue by using the probability of encounter over the whole lifetime of the project. By making it dependent on a joint probability that varies each year with the expected rise, it is possible to determine the rise from the baseline situation (without eustatism) to be taken into account in order to obtain an encounter probability of the design event that is identical to that of the stationary case.
This approach optimises the adaptation of the design of maritime or port structures to cope with the expected sea level rise in the coming decades. It can also be useful for a finer estimation of the hazard associated with exceeding the altimetry of a given quay or platform, such as in the case of the *Aqua Alta* in Venice.

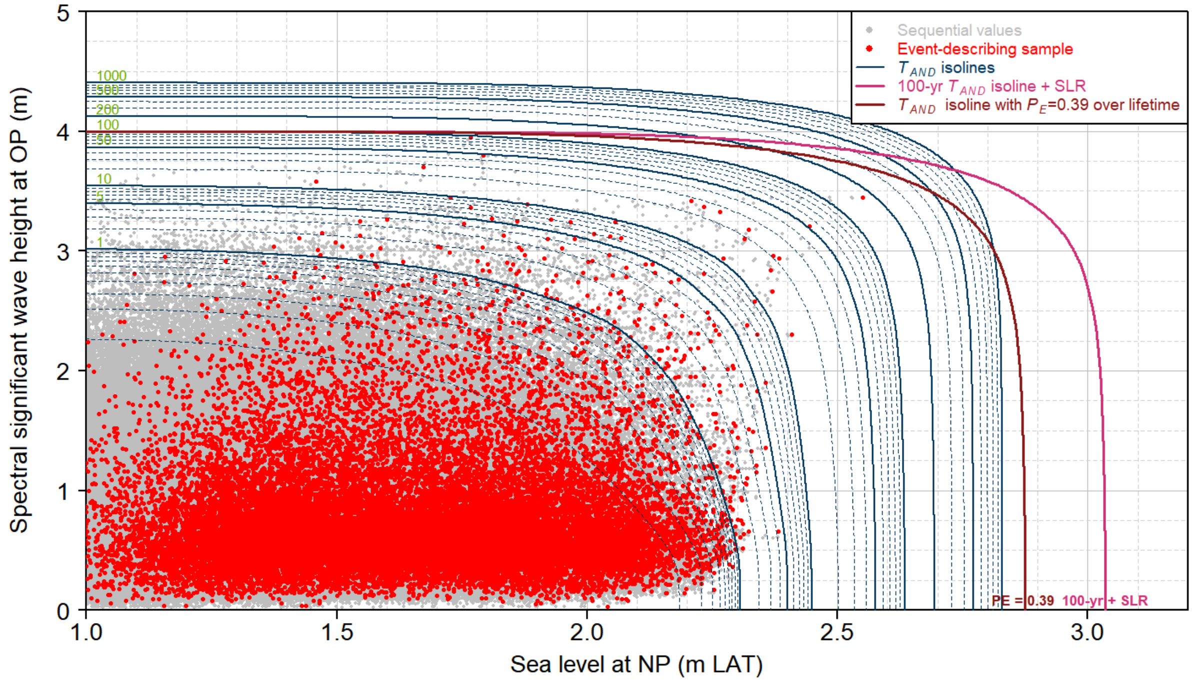

Fig. 1*: Contour lines of joint exceedance return period of sea level and significant wave height (blue lines) and inclusion of sea level rise for the 100-yr joint return period.*

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Signal of change in ordinary and extraordinary precipitation extremes over Italy

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In Italy, few national-scale analyses were performed to investigate possible changes in the frequency and intensity of extreme rainfall events (Libertino et al., 2019; Mazzoglio et al., 2022) while several studies at the regional level have been carried out in the last two decades (see e.g. Bonaccorso et al., 2005; Persiano et al., 2020; Treppiedi et al., 2021; Avino et al., 2024). This lack of comprehensive studies is the consequence of the extreme fragmentation that characterizes the Italian hydrologic data, that does not allow a nationwide comparison among the results.
Using the Improved Italian – Rainfall Extreme Dataset (I^2-RED; Mazzoglio et al., 2020), a collection of short-duration (1 – 24 h) annual maximum rainfall depths measured by more than 5000 rain gauges from 1916 up to 2022, we investigated the possible presence of trends in rainfall extremes over the whole country.
In a first step, the Mann-Kendall test was applied to all the time series with at least 30 years of data (more than 1600). The results confirm that rainfall extremes of different durations are not increasing uniformly over Italy and that different trend signs emerge even in neighboring areas. Considering that the time series considered cover different time periods and, thus, this may affect the results obtained in wide areas, we extended the analysis by using an approach that can cope with data fragmentation, both in space and in time.
We first divided Italy using a coarse grid size of the order of 20 km resolution. Then, for each cell we applied a quantile regression, by pooling together all the time series available within a certain search radius, without imposing limitation to the length of the time series used. For each rainfall duration, several quantiles were tested again trend: q = 0.5 (i.e., the median), 0.9, 0.95, and 0.99. By using this approach, a common period (1960-2022) can be used in each part of the Italian territory, allowing to obtain results that can be directly compared.
With this approach, positive variations in short-duration annual maxima have been found all over the country, especially when considering 1 h extremes. When moving to longer durations (24 h), negative trends emerge over large areas. An additional result found is that the quantile regression shows that lower quantiles (0.5) are characterized by smaller variations with respect to higher quantiles (such as 0.95 or 0.99).

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Towards the development of community-level projections of flood extremes: An Iowa case study

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Developing localized flood information is critical to improving resilience and preparedness of communities across the world under climate change due to nonstationary changes in flood risk. This risk is brough about by changes in the flood hazard itself along with changes in vulnerability and exposure (e.g., Michalek et al., 2023; Tanoue et al., 2016). However, localized information of changes in flood risk are generally not available, not actionable for decision makers, and the information we do have at this scale is generally categorized to have low to medium confidence (IPCC, 2022). Therefore, we present a case study examining localized flood projections for the state of Iowa, located in the central United States. To develop high resolution flood projections, we utilize the hillslope-link model (HLM) TETIS (see Quintero and Velasquez (2022)) that provides information at every stream in our domain, and force it with outputs of global climate models (GCMs) from the Coupled Model Intercomparison Projects 5 (CMIP5) and 6 (CMIP6).

We first examine how current flood frequency information is presented for ungauged communities in Iowa (Michalek et al., 2022). Currently, Iowa uses regional regression equations developed with stream gage observations to estimate annual exceedance probability (AEP) discharges. They divide Iowa into three regions and only one region uses a climate predictor (i.e., precipitation) within the regional regression equations (all the other predictors are static and related to basins' characteristics, such as their size and soil characteristics). This makes it difficult to account for climate change as it is not possible to incorporate future changes in the climate drivers. Therefore, we run the HLM to develop historical annual maximum discharges everywhere in Iowa and compare them with those by the regional regression approach. Our results indicate that using a hydrologic model to determine AEP discharge matches the regression performance in the region that includes a climate predictor, highlighting the viability of using physically based models in this context.

Next, we utilize climate models outputs from CMIP5 and CMIP6 to estimate flood projections until the end of the century under various emission scenarios (Michalek, Quintero, et al., 2023). For CMIP5, under Relative Concentration Pathway 8.5 (RPC8.5) there are significant increasing trends in annual maximum discharge for the eastern and central parts of the state by 2100. No trends are found under RCP4.5.

We then shift our focus to climate models from CMIP6 to examine flood projections (Michalek, Villarini, et al., 2023). First, we explore the viability of using the High-Resolution Model Intercomparison Project (HighResMIP) outputs, which have projections until 2050 with 25- or 50-km spatial resolution. We perform 12 types of bias correction and statistical downscaling (BCSD) to explore the impact on flood projections. We find the median annual maximum discharge is projected to increase between 10-30% for most Iowa communities by 2050.

We complement the results from the HighResMIP with those from the native CMIP6 products. We develop flood projections under four Shared Socioeconomic Pathways (SSPs) from 1981 to 2100 (A. T. Michalek et al., 2023). Under SSP370 and SSP585, we detect increasing trends in the yearly median annual maximum discharges for most Iowa communities by 2100. Moreover, we find that climate models producing larger increases in variance typically produce larger changes in the mean. Next, we couple our projections with inundation maps developed for ten Iowa communities to examine uncertainty partitioning from a flood hazard and risk perspective. Climate model uncertainty is dominant in the late 21st century, while internal climate variability dominates the earlier part of the 21st century and directly translates to flood risk.
Finally, we use downscaled results to examine the impact of different BCSD methods on estimating projected changes in flood frequency extremes (A. Michalek et al., 2024). We examine 1%, 0.5%, and 0.2% floods by fitting a Generalized Extreme Value (GEV) distribution to annual flood peak projections from CMIP6. Our results suggest the choice of BCSD impacts the magnitude of the projected changes, with the SSPs exerting limited sensitivity compared to the choice of downscaling method. Future work aims at expanding this community level framework to other domains.

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Extreme Natural Hazards and National Security – A U.S. Department of Defense Perspective

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Extreme heat, floods, rising sea levels, droughts, wildfires and more frequent and intense storms and other natural disasters are reshaping the U.S. Department of Defense' (DOD) operating environment, and degrading military readiness. In recent years, DOD has been forced to absorb billions of dollars in recovery costs from extreme weather events. This includes $1 billion for rebuilding Offutt Air Force Base, Nebraska after historic floods in 2019, $3 billion to rebuild Camp Lejeune, North Carolina after Hurricane Florence in 2018, and $5 billion to rebuild Tyndall Air Force Base, Florida after Hurricane Michael also in 2018 (see Fig. *3*). DOD bases impacted by natural disasters and extreme weather events from 2017-2021 resulted in more than $13B in damages. The number of personnel days the National Guard spent on firefighting increased from 14,000 in fiscal year 2016 to 176,000 days in fiscal 2021 which is more than twelve-fold in just five years, and it is a major redirection of time, attention, and resources. Extreme natural hazards impact military readiness including warfighter training, mission execution, tactical planning, acquisition and sustainment of platforms and installations, and national and global security.

Fig. 3. Left panel: A Nebraska Army National Guardsman descends from a helicopter during response efforts near Columbus, Nebraska after historic floods., March 14, 2019. Right panel: Hangers once used to keep aircraft out of the elements lie scattered across the Tyndall Air Force Base flight line following Hurricane Michael, Oct. 10, 2018.

As recently as July 2023, extreme rainfall at West Point Military Reservation (WPMR), New York, caused extensive inundation and damages to roads, grounds, and buildings across WPMR, including ranges and training areas. The total damages are estimated at $207M. DOD analyses of rainfall observations of this short-duration high-intensity event indicate associated annual recurrence intervals (ARI) ranging from 100 to over 1000 years depending on the rainfall duration (see Table 1).

Table 1. Summary of July 2023 Rainfall Event at WPMR

Rainfall duration (hours)	Rainfall (inches)	Annual Exceedance Probability (AEP)	ARI (years)
3	6.96	< 0.1% AEP	> 1000
6	7.7	0.13% AEP	750
24	9.5	0.7% AEP	150

In addition to existing 1% AEP 24-hour rainfall-induced inundation maps, DOD is currently mapping 1 % AEP 6-hr and 0.2 % AEP 24-hr and 6-hr rainfall-induced flooding exposure and resulting inundation at DOD sites globally.

Impacts from extreme natural hazards are compounded by climate change. Climate change has been identified by DOD as a critical national security threat and threat multiplier. In 2017, during and after Hurricane Harvey, about 11,000 National Guardsmen, a total of 1,638 active-duty service members and 1,254 DOD civilian employees and contractors were deployed to support rescue and recovery operations. A significant portion of Harvey's extreme rainfall and resulting impacts have been attributed to climate change (Frame *et al.*, 2020; Tenberth *et al.*, 2018). Wide-ranging literature projects future increases in frequency and intensity of extreme events with climate change. The need to operate in more extreme environments may alter where and how warfighters train for future conflict. The DOD Climate Assessment Tool (DCAT) enables military departments and their installation personnel to deliver consistent screen-level exposure assessments, including exposure to historical extreme natural hazards and future projections of climate hazards, and identify regions or installations for additional in-depth analysis. The DOD Regional Sea Level (DRSL) database provides future projections of sea levels and extreme water levels that are used to develop inundation mapping at coastal and tidally influenced DOD sites globally.

This presentation will highlight some of the recent impacts from extreme natural hazard to DoD infrastructure, systems, people, organizations, missions, operations, or activities. DOD tools and analyses on non-stationarity detection, extreme natural hazards, and climate change exposure will be presented. Challenges and opportunities in incorporating projecting future changes to extreme natural hazards including compounding and cascading impacts to DOD will be discussed.

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Extreme daily rainfall events in Italy: should we update the probability of failure of existing hydraulic infrastructures?

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Every year, extreme rainfall events not only lead to tragic loss of human lives but also cause significant economic damage across the globe. Risk reduction strategies often involve the implementation of structural measures that are designed to safeguard both individuals and territories against extreme events with a fixed annual exceedance probability, generally quantified in terms of return period (Volpi and Fiori 2014). Despite the extensive reliance on these mitigation strategies, there remains the potential for overload events, i.e. events of magnitude exceeding the design values of the structures, occurring through their design life. Such occurrences are linked to the probability of failure, often referred to as residual risk.

In this study, we propose a systematic procedure aimed at continuously revising the design variables over the design life of hydraulic infrastructures (Figure 1). In fact, at the time of design, only historical data are available to define the quantile value, whereas new observations can be collected after construction and during the life of the work. Assuming a 30-years observations period to estimate the quantile and to design a hydraulic protection structure or infrastructure projects (as illustrated in Figure 1, step 1) aligns with established practices in time series statistical analysis. After the selection of the best probability distribution function and the evaluation of its parameters (Figure 1, step 2; Moccia et al. 2021), we can determine the design variable for a fixed return period and establish the design life of the structure, thus deriving the probability of failure (Figure 1, step 3). After the realization, new records of the design variable become available and can be integrated into the original sample to enhance its robustness for statistical analysis (Figure 1, step 4), allowing the definition of an updated probability of failure.

In this work we apply the aforementioned methodology to daily rainfall observations from the National System for the Collection, Elaboration and Diffusion of Climatological Data (SCIA, Desiato et al. 2007) recorded by 2282 rain gauges in a time period ranging between 1860 and 2022 over the Italian territory. However, we maintain that this methodology is also applicable to other hydrological variables (such as peak flows) and different time scales (including sub-daily).

Results show that in terms of differences between the expected and the updated probabilities of failure, ΔR, there is a general tendency to have a higher probability of failure than the expected for 64% of the analyzed samples. An increase in the probability of failure is associated with a reduction of the return period related to the design variable, implying that the design event has a higher probability of occurrence with potentially dramatic consequences on people and territory at risk.

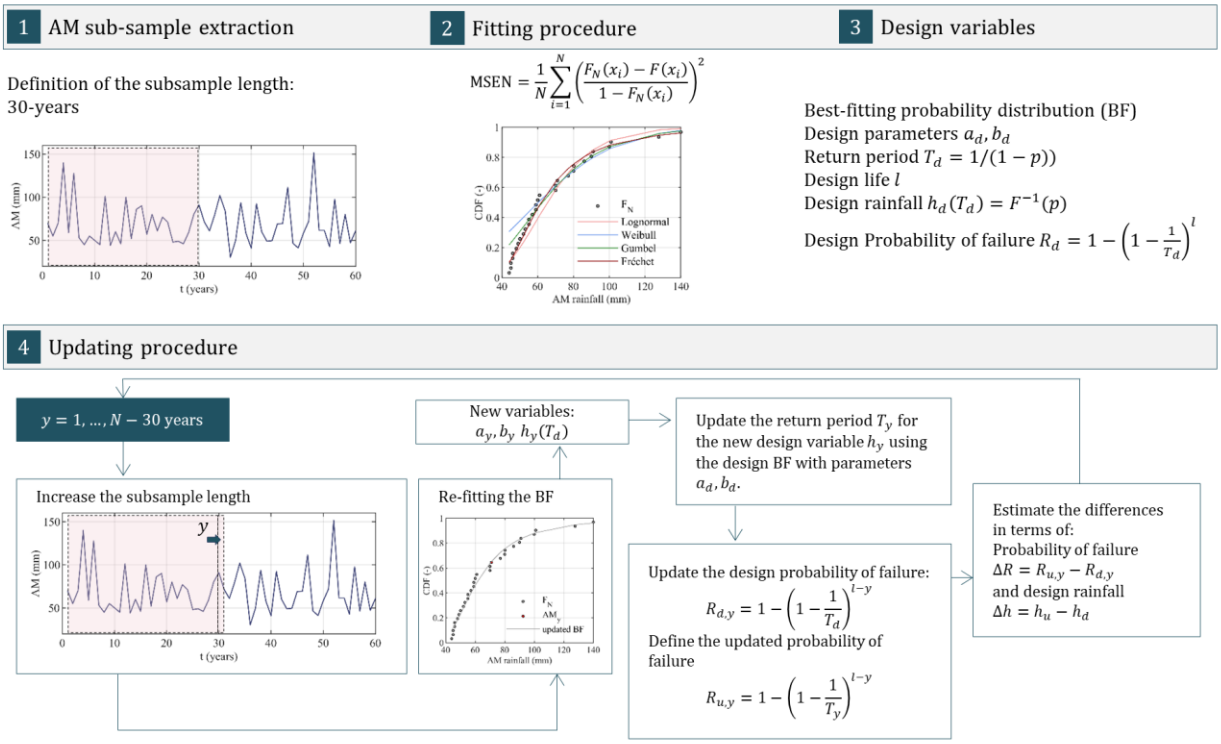

Fig. 1: Detailed updating procedure of the probability of failure of a hydraulic infrastructures.

This proactive methodology enables us to evaluate the occurrence of rare but conceivable events, thereby contributing to a more comprehensive understanding of the potential vulnerability of existing hydraulic infrastructures. Through this proposed approach, local, regional, and national managers can quantify and update the level of risk associated with hydraulic structures. This allows decision-makers to formulate investment plans for addressing any required extraordinary maintenance and defining risk-based priorities for interventions. Furthermore, the development of dynamic risk maps facilitates the monitoring of critical areas across the territory.

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Flood Risk Analysis in Galveston, Texas (USA), using Long-Term Observed Data and Building Elevation Mapping

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On September 8, 1900, a 4.79-m storm tide struck Galveston, Texas (USA), inflicting 6,000-8,000 fatalities on the Island and causing the deadliest disaster in U.S. history. Galveston responded with legendary resiliency, building a 16-km seawall and raising the inhabited island more than 5 meters.

To help prepare modern-day Galveston (population ~ 50,000) from hurricane-induced storm surges, the U-Surge Project has constructed a comprehensive flood dataset going back to 1837, which includes high water marks from 95 hurricanes and tropical storms. Statistical methodologies estimate the height of the 500-, 200-, 100-, 50-, 25- and 10-year storm surge events.

To better understand the impact of storm surge flooding in this vulnerable location, Flood Information Systems has built an island-wide building elevation map, which provides accurate first floor information data for more than 16,000 buildings. These data were created by obtaining elevation certificates from the local government, conducting field work, and analyzing street-level imagery. These data provide unique perspectives on both the long-term flood risk, as well as addressed-based flood forecasting during future hurricane events.

This project provides a prototype that can be followed in other flood-prone cities. U-Surge has created preliminary flood histories for 46 U.S. cities along the Gulf and Atlantic Coasts. In addition, we are using the Galveston building elevation dataset to train Artificial Intelligence (AI) to automate and improve efficiency of the data-construction process for future projects.

Fig. 1: *Galveston, Texas, after a 4.79-m storm tide struck on September 8, 1900. Photo: Rosenberg Library*

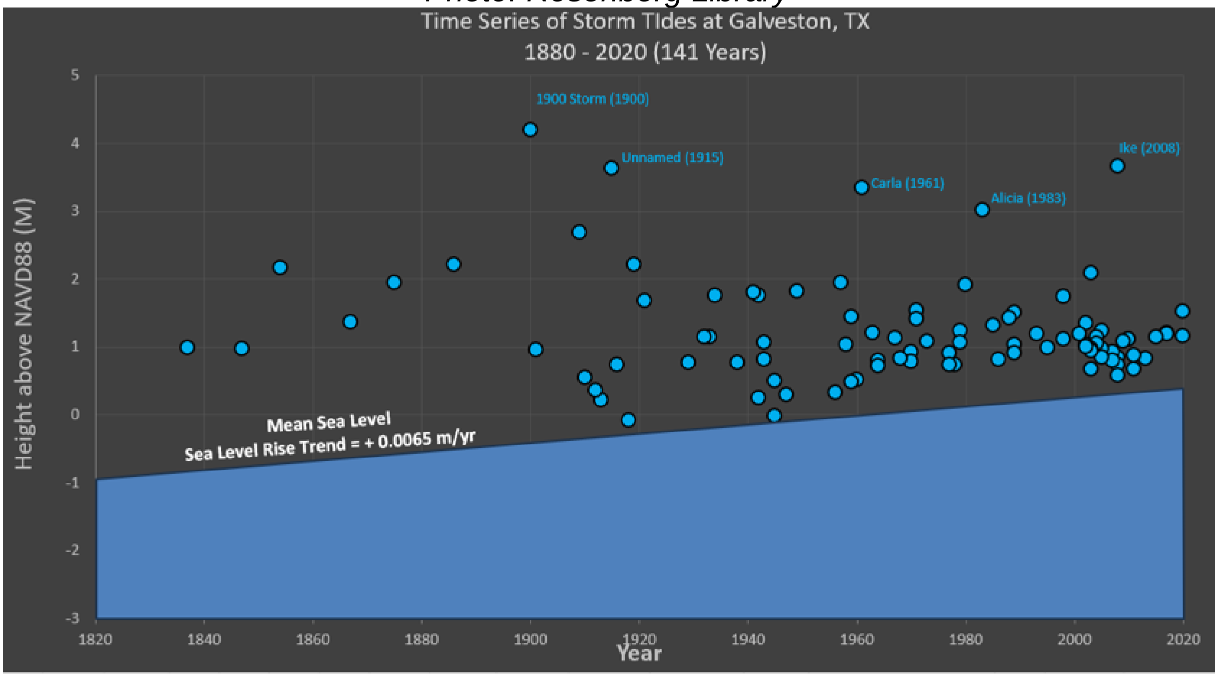

Figure 2: *Time series of storm tides at Galveston, Texas, since 1837. This graph depicts highwater marks for 95 hurricanes and tropical storms. Data: U-Surge Project*

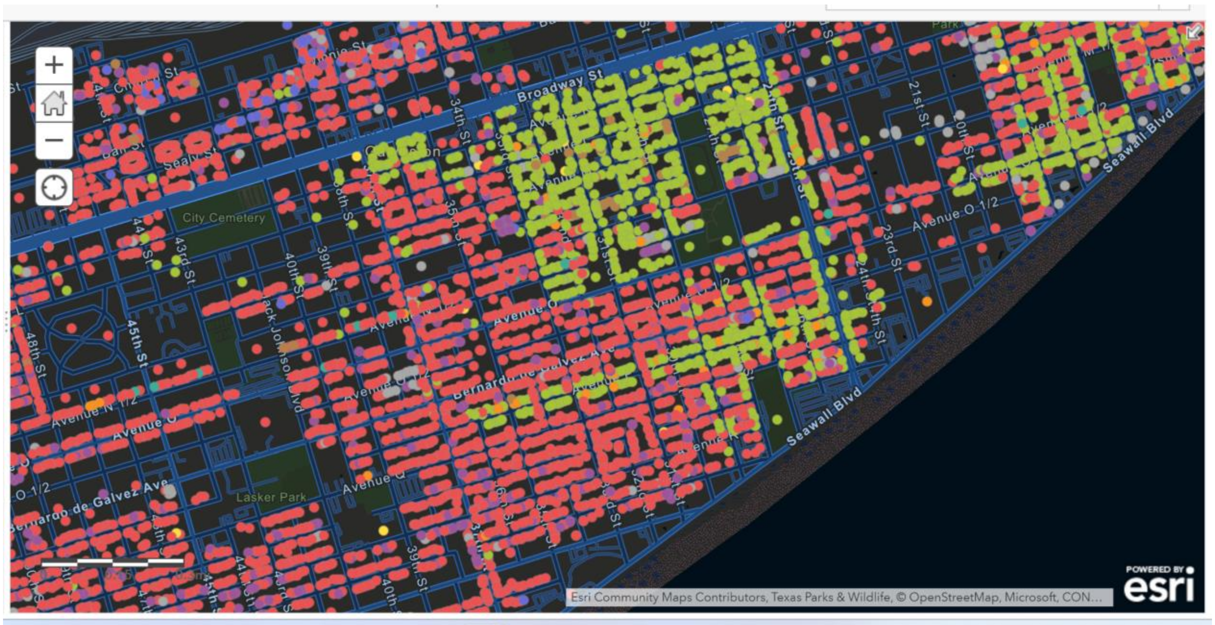

Fig. 3: *Building elevation map for Galveston, Texas, provided by Flood Information Systems. Such granular maps provide unique insights into flood risk.*

Unified reduced bias estimation of the residual dependence index: Pareto meets Fréchet

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Unlike univariate extremes, multivariate extreme value distributions cannot be specified through a finite- dimensional parameter family of distributions. Instead, the many facets of multivariate extremes are mirrored in the inherent dependence structure of component-wise maxima which in principle must be dissociated from their marginal distributions.

Statistical procedures for eliciting extremal dependence typically rely on standardisation of the unknown marginal distributions, through which process pseudo-observations of either Pareto or Fréchet distribution are often considered. The relative merits of either of these choices for transformation of marginals have been discussed in the literature, particularly in the context of domains of attraction of a multivariate extreme value distribution. This talk is set within this context as we will introduce a class of reduced-bias estimators for the residual dependence index that eschews consideration of this choice of marginals. The proposed unifying class of reduced bias estimators includes but is not limited to variants of the Hill estimator. Adapted conditions of regular variation lay the groundwork for obtaining their asymptotic properties, whose effectiveness is borne by a simulation study.

The leading application is aimed at discerning asymptotic independence from monsoon-related rainfall occurrences at several locations in Ghana.

Jump tails and high tide flooding in estuaries

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Flood events in estuaries are driven by both ocean and river source extremes. The distributions of water levels in these settings often exhibit heavy and discontinuous (jump) tails characterising different flood event mechanisms (e.g., Merz et al., 2022). Separating estuary flood events according to their driving mechanisms is necessary for extreme values analysis since the assumptions inherent in common parametric and joint probability approaches produce smooth asymptotic tails and consequentially, mischaracterise the heights and frequencies of exceedance levels. The statistical problem presented by jump tails is mirrored in the different management responses required for ocean versus river source flood events. Here we describe an appropriate technique for handling jump tails in water level distributions that can also be used to quantify the specific contributions of different sea level and estuary processes to nonstationary high water (HW) levels over recent epochs.

To separate ocean versus river source extremes, we isolated river flood events in tide gauge records for four large Australian estuaries: the Tweed, Hunter and Hawkesbury in New South Wales on the east coast, and the Swan in Western Australia. The river flood events were identified from heavy tails in computed non-tidal residual distributions. The limits for heavy tails were defined from extremal index estimators based on the interquartile range (Jordanova and Petkova, 2017). Ocean driven water levels were represented by HW level maxima, excluding those HW levels occurring during identified river floods. The river floods were represented by hydrographs and compared within and between systems.

For the ocean driven HW levels (excluding river floods), we derived joint probability distributions from the convolutions of three defined sea level components (mean sea level, predicted HW, and skew surge) at estuary entrance sites. We also defined two estuary level components (‘propagation’ and ‘deviation’) to compute joint probability distributions at nodes located upriver within each system. From the total HW level probabilities, the heights of HW exceedance levels recurring at 1-, 5-, and 10-year Average Recurrence Intervals (ARIs) were obtained. The HW exceedance levels at each ARI were compared between two recent 19-year epochs: 1986-2004 vs 2005-2023 (inclusive). We then quantified the respective contributions of each of the sea level and estuary level components to changes in HW exceedance levels between these epochs.

The relative importance of each component varied between and within systems. Changes in the estuary level components both added to and subtracted from changes in sea level components at the ocean boundary. We show the value of using nonparametric approaches for separating the effects of ocean and river forcing on extreme water levels represented by heavy and discontinuous tails. The approach is useful for estimating the individual and total effects of changes over time in mean sea level, tides, surges, estuary morphology, and hydraulics on high tide flooding in estuaries.

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How the last hot summers in France led to rethink future extremes estimation

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Since about 20 years, after the 2003 heat wave, methodologies have been developed at EDF R&D to take climate change into account in the estimation of hot temperature extremes. Rare high temperature levels are indeed required to adapt the cooling systems in the nuclear power plants so that they can further safely produce electricity. This holds for running plants, but this is true for new projects as well, and in this later case, the anticipation of future temperature extremes targets farther time horizons until the end of the century.
Climate models are not designed to reliably represent very rare local extremes, and the current bias adjustment methods do not handle the highest values in a reliable way either. Therefore, a dedicated methodology has been set up to estimate future extremes. It relies on the computation of a reduced variable whose extremes can be considered as stationary (Parey et al. 2013, Parey et al. 2019). Indeed, we have shown that once the trends in mean and standard deviation have been removed, the extremes of the reduced variable can be considered as stationary. A dedicated stationarity test has been developed accordingly. Consequently, future extreme temperature levels can be estimated from the corresponding extreme of the reduced variable, and the future changes in mean and standard deviation given by the climate projections at the desired horizon. When estimating hot extremes, only summer days are considered, and the projected changes are then for the mean and standard deviation of summer temperature.

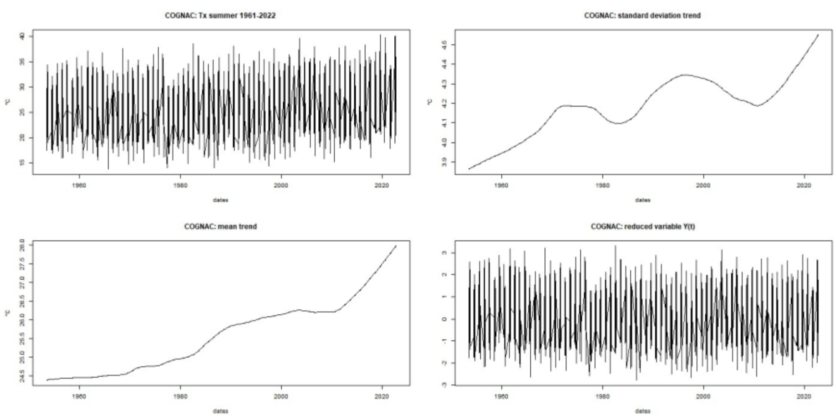

Fig. 1*: an example of the computation of the reduced variable: summer temperature time series (top left), mean trend (bottom left), standard deviation trend (top right), reduced variable (bottom right).*

The first step in such estimation study consists in validating the methodology with historical data. This had been done in Parey et al. 2019 and has recently been reconsidered. To do so, observed daily maximum temperature time series have been downloaded from the Météo-France database for use in the study. The chosen time series are the longest (at least 50 years) and the most homogeneous. Then, different ways have been used to compute a 100-year Return Level for the current climate, that is over the period 1991-2020:

- A direct application of the statistical extreme value theory to the summer temperatures of the period in a stationary context, that is in neglecting the trend. This assumption is reasonable given the short length of the considered period, and this same length led us to favor the peak over threshold approach rather than block maxima;
- A similar direct application of the statistical extreme value theory, but in a non-stationary context: a time varying threshold is used to select the highest values and the Return Level is computed for the period 1991-2020 by use of a Return Level definition adapted to the non-stationary context;
- The use of the proposed approach based on the reduced variable and the stationarity of its extremes as previously described, using summer mean and standard deviation as observed or projected by climate models.

When comparing the results, it turns out that generally, the three types of estimation are consistent, but for some stations, the observed maximum, which may occur in 2022, is of the order of magnitude of the 100-year Return Level, or even higher. This led us to study more carefully the link between the highest values of the reduced variable and the other characteristics of the summer, such as the average summer temperature or the intra-summer variability. A clear correlation is found between the summer average temperature or the summer variability and the value of the reduced variable: the highest values generally occur during the warmest or the most variable summers. Founding a similar link with the summer temperature average and its variability is not a surprise, because we had shown that in France in summer, the mean and the variance are positively correlated (Parey et al. 2010). Then, the hottest summers are generally more variable, and more susceptible to experience larger deviations away from the mean state and the variance around it. Furthermore, the intensity of the links seems to depend on the geographical location. Those considerations let us think that it may be better to consider only the changes in mean and standard deviation of the hottest (and more variable) summers when reconstructing the temperature 100-year Return Level from that of the reduced variable.

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The application of the Cramer-von Mises test for the estimation of extreme high-water levels

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Extreme high-water levels (EHWL) pose significant risks to coastal communities and coastal infrastructure. In the UK, Nuclear Power Plants are located at the coast, as this offers a source of cold water used in the reactor cooling process. The Office for Nuclear Regulation (ONR) guidance suggests that coastal defences need to be built to withstand an extreme water event with a 10^{-4} annual occurrence probability, i.e., an event that occurs on average once every 10,000 years (Office for Nuclear Regulation, 2021). Therefore, the accurate estimation of present and future EHWL levels is crucial for effective coastal management and adaptation to climate change.

In 2018, the Environment Agency (EA) published the Coastal Flood Boundary Conditions (CFB18), which provide estimates of EHWL along the UK coastline and at selected tide gauge sites. These estimates are often used as part of risk assessments for coastal infrastructure. These estimates have been obtained by applying the Skew Surge Joint Probability Method (SSJPM), which fits a Generalized Pareto Distribution to the skew surge Peaks Over Threshold (POT). Traditionally, threshold selection relies on the visual inspection of parameter stability and mean residual life plots. This is a qualitative approach introducing bias for coastal modelers.

In this study, we propose the use of the Cramer-von Mises test (CvM) as part of the process for EWHL estimates. In particular, the CvM is applied for the selection of thresholds of exceedances. The CvM offers a quantitative measurement for the goodness of the GPD fit, reducing bias in EHWL, and potentially improving the accuracy of extreme water level estimation. We apply the SSJPM coupled with the CvM to the UK tide gauge network and compare the results to those obtained by the CFB18. Our results demonstrate the effectiveness of the CvM when applied with the SSJPM, providing results that are comparable to those presented by the CFB18. By mitigating bias introduced by threshold selection, our approach provides more reliable estimates of extreme water levels, essential for effective coastal flood risk management.

This study contributes to the advancement of methodologies for estimating extreme water levels and provides valuable insights for coastal communities, policymakers, and stakeholders. The findings underscore the importance of incorporating robust statistical techniques into coastal hazard assessments.

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Issues concerning application of extreme value analysis on an authoritative level

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The Danish Coastal Authority (DCA) has since 1986 regularly been publishing "High Water Statistics" (HWS) based on data from tide gauge stations distributed along the 7000 km long and diverse Danish coastline. The number of stations with statistics have gradually increased up to c. 70 where ten stations have >100 years of data and with the Port of Esbjerg holding the longest series dating back to 1874.

The HWS are applied e.g. in the design of coastal protection and harbor construction work; in risk reduction related to the implementation of the EU Floods Directive, and they are applied to decide whether house owners etc. are eligible for insurance pay-outs from flooding due to storm surges exceeding a 20 years' event. Due to their high societal impact a high level of confidence must be reflected in HWS and work methods must be both transparent and lucid.

Extreme value analysis involves methodological choices and selections. Here, a detailed description of criteria applied must be documented in order to avoid unnecessary criticism and conflicts with stakeholders of diverging interests and agendas. It is thus desired to make choices and selections as theoretically well-founded and objective as possible and – in case they cannot be objective, at least make them general!

In the most recent HWS (DCA, 2024), analyses are generalized by choosing the General Pareto Distribution (GPD) with a peak-over-threshold (POT) for all stations. This generally leads to higher return values in individual stations compared to previous statistics based on other distributions. The threshold selection is not trivial and it is certainly difficult to set up a general set of rules for this decision. The guidelines of Coles (2001) inform to set the threshold when the free parameters of the GPD stabilize with a constant or linear tendency, respectively. Furthermore, Coles instructs to set the threshold as low as possible to grant a larger dataset. The guidelines are very general and flexible, however, and a range of additional considerations needs to be taken into account. For instance:

- Is it desirable to set the threshold as low as possible even if it yields five or six extremes per year? The data has a nice fit, but six extremes a year just is not very extreme.
- In some cases, which is actually more profound in the larger datasets, the free parameters never really stabilizes; where then to set the threshold?
- In many cases the parameters stabilize multiple times and one may argue to pick the latest point of stabilization. However, this is also the one that yields the smallest dataset and the largest uncertainties. Furthermore, these multiple stabilizations have varying lengths (in terms of increasing threshold) and it becomes a subjective estimate when to call an actual stabilization.

A more general issue is that the GPD generally fits the data well except for the most extreme events (in the order of one to six events depending on the size of the dataset)

which are almost always underestimated. As it is most often the rare events, one really wants to gain knowledge about, suggestions about how to resolve this matter must be addressed; e.g. in the case where the most extreme events may relate to specific weather events and follow a different distribution than more frequent events.
Based on the HWS and considerations stated above, the paper presents current efforts by the DCA in order to increase our understanding of those conditions that influences the HWS regarding both the natural processes governing extreme water levels and the applied methods.
One main goal is to qualify an automation and standardization in the production of the HWS. Among a range of different methods following Arns *et al* (2013), one obstacle is thus an automation of the threshold selection, where several options considered are presented, compared and discussed: One is to simply explore whether it is possible to set up a general set of rules for the selection based on *qq*-plot and the parameter stability plots; another option develops machine learning algorithms, and yet another option considered is a selection based on quantiles. Automation and standardization is important since it leads to transparency but it may to some extent jeopardize the quality of analyses.

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Extreme sea levels in a context of climate change applied to French offshore wind farms

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French wind farms are recent installations at sea. Extreme sea levels brought by climate change will probably impact their maintenance and design in the future. In this study we compare on France's three coasts: the English Channel, the Atlantic Ocean and the Mediterranean Sea, local variations through *in situ* data analysis, reanalysis and future predictions in order to better evaluate profitability and risk for French offshore wind farms.
Sea level rise is well describe but questions remain for sea level extremes, especially at local scale. We propose an innovative method to detect extreme sea levels based on the analysis of Reinert et al. (2021). We developed an adaptive method that can be apply on different datasets and on different locations. We use reanalysis (ERA5), historical datasets, long term *in situ* data from tide gauge stations (since 1900 for the longest timeseries), local database called Resourcecode and future climate projections with RCP4.5 and 8.5 scenarios. Our study cover all French coasts and multiple scores and comparisons are made between all datasets taking the *in situ* data as reference.
Extreme sea levels local variations are important as mentioned by Reinert et al. (2021) varying by more than 3 mm from North to South. We quantify extreme sea levels at the local scale of each French wind farm and by comparing the three oceanic coasts of France. Another aspect of this study is based that at global scale the sea level rise is evolving in the same order as the extreme sea levels (Calafat et al., 2022). We wonder how these local variations differ from the global sea level rise and how physical processes can impact their evolutions. Our results show the importance to study extreme sea levels at local scale and propose a new method to detect extreme events.

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Non-stationary GEV models for the design of offshore structures in a changing climate

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The design of offshore structures has traditionally incorporated historical wave data from hindcast models in order to account for extreme events. However, climate change is altering oceanographic patterns, leading to an increased frequency and intensity of extreme events. In this presentation, we explore the impact of this evolving climate on the design of offshore wind farm, particularly for high quantiles such as 100-year return levels. However, significant uncertainties plague these estimations, impacting the design, maintenance and safety of offshore structures.

Is well-know that the wave height alone is not sufficient to estimate extreme responses of offshore structures, such as floating wind turbines, as the whole sea-state will impact the response (Raillard et al., 2019). In this talk, we will thus consider several variables that describe a sea-state (e.g., significant wave height (Hs), peak wave period (Tp), wave direction (Dp)). Leveraging the recent developments in non-stationary models for extreme values modeling (Reinert et al., 2021; Youngman, 2019), we will present a methodological approach to estimate the return levels of these variables and to quantify the influence on covariates on such values. A focus will be made on how the proposed methodology mitigate the uncertainties in the estimation on the 100-yr return level.

The application of such method will be carried out on climate projections (Meucci et al., 2024), downscaled to the local scales of several site of interest along the French coast, using the classical CDF-transform (Michelangeli et al., 2009). The local climatology was given by recent hindcast wave data from the Resourcecode database (Accensi et al., 2021). A particular attention will be given to the ability of the model to capture the potential trends and/or decadal variabilities on several sea-state parameters such as significant wave height, wave period and direction.

These preliminary results show that sea-states are tending towards a seasonal shift linked to climate change, as predicted by Ruosteenoja et al. (2020), who announce shorter winters and longer summers in northern Europe. The fact that sea-states are following this shift can also suggests a change in intensity, as predicted by Breton et al. (2022) for atmospheric conditions based on historical data and climate projections. These trends show the power of climate change on the deregulation of previously known sea-states, which will affect French offshore wind farms, particularly in terms of design, but also maintenance and aging.

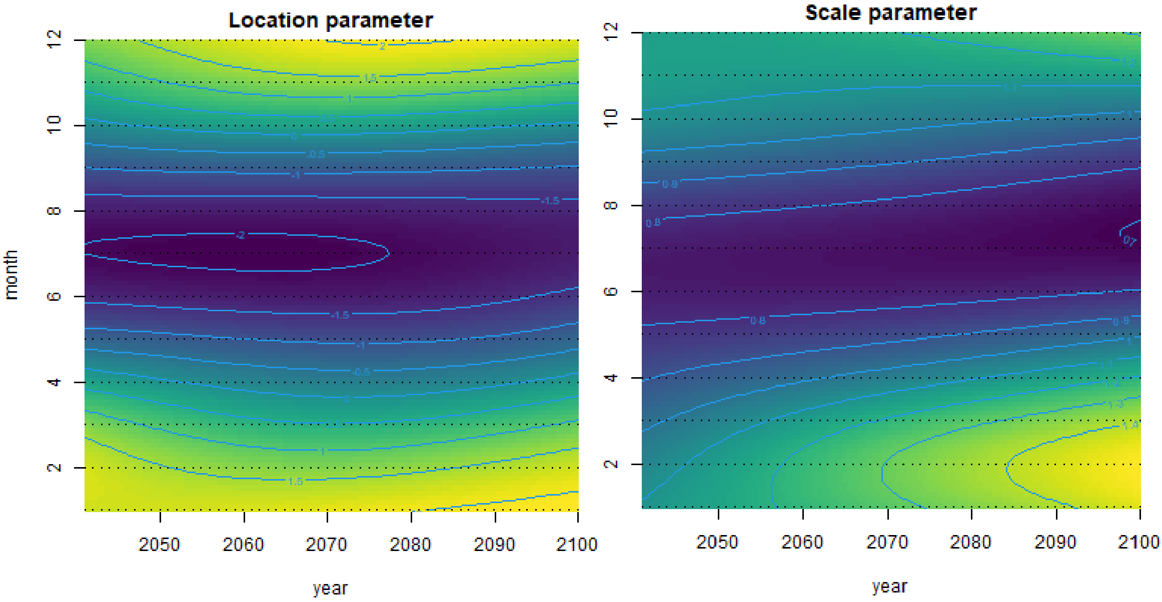

Fig. 1: *Estimation of GEV parameters for non-stationary GEV models fitted on future significant wave height climate.*

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Updating IDF curves in the context of climate change: approaches, limitations, and uncertainty assessment

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Climate-proofing the design of infrastructures and buildings is becoming an absolute priority for communities, designers, and policymakers. At the national and continental scale, for example, the second generation of Eurocodes (to be released from 2026) will report updates to the values currently included in the National Annexes (by now outdated) for loadings associated with extreme temperatures, wind, and snow, and the definition of change factors to account for future variations in weather forcing. Regarding extreme precipitation events, Intensity-Duration-Frequency (IDF) laws have traditionally informed, at local level, the design process of urban drainage systems (where precipitation quantiles corresponding to low return periods are of interest) and hydraulic risk protection assets (where values associated with high return periods are considered). In recent years, various investigations have proposed innovative methods for updating IDF curves in the context of climate change (Martel et al., 2021; Padulano et al., 2019). Despite the peculiarities of different studies, all acknowledge the current weaknesses of physically-based climate modeling in reproducing extremes, especially for sub-daily durations preventing the adoption of raw precipitation outputs and most propose the application of bias correction approaches not on the entire precipitation series but directly to the sample of annual maxima derived from observations and modeling for both the present and future periods. This can be due to various reasons; among others, historical series related to only maximum precipitation, even for sub-daily durations, are often more easily retrievable in many areas compared to the entire precipitation series (e.g. Hydrological Yearbooks in Italy). Additionally, applying corrections directly to maximum precipitation values allows for "optimizing" performances on the values of interest, avoiding the need to account for constraints related to adjusting the entire series including wet and dry parts, low precipitation values. The adoption of such a simulation chain presents several elements of complexity and potential bottlenecks, such as: i) identifying the best distribution for fitting annual maximum values and evaluating the parameters to obtain physically consistent results; ii) selecting the bias correction method while considering the trade-off between different needs, such as the accuracy of the output in reproducing the reference period, ease of use, and explicit or implicit preservation the climatic signal, returned by the raw climate simulation chains in certain characteristic values, like the mean, variance, and quantiles; iii) selecting input climate models and evaluating the plausibility of their responses; estimating the uncertainty associated with the results; and especially iv) effectively communicating these results to end-users. To enhance knowledge on these issues, ongoing research aims to address the following questions: a) under which assumptions and conditions bias correction approaches can preserve the climate signal in crucial characteristics; b) how these results can be influenced by the choice of the probability distribution and the regionalization of related parameters;

c) how invariant the analysis results are to the order in which different post-processing stages are conducted? For example, working directly on the probability distribution of maximum values or first performing bias correction on the entire series and then extracting the maxima to fit the probability distribution; d) for many years, various national and international initiatives have made precipitation data available only up to the daily scale due to previously discussed constraints and limitations; the increase in understanding of atmospheric dynamics and the growing computational power has now made outputs on finer scales credible and thus available. How informative are daily scale anomalies when moving to sub-daily ones? e) For several real test cases, beyond scenario analyses, local updating of IDF laws is required; a correct estimation of uncertainty necessitates considering input data from various climate simulations under different greenhouse gas concentration scenarios, using different bias correction approaches. What is the spread associated with these estimates and how can it be properly communicated to policymakers to guide the design process?
Specifically, the work considers five state-of-the-art approaches for updating IDF curves: the canonical parametric quantile mapping (Wood et al., 2004), quantile-quantile downscaling (Hassanzadeh et al., 2014), equidistance quantile mapping following Alzahrani et al. (2022), detrended quantile mapping, and quantile delta mapping (Cannon et al., 2015) where either only the mean value or all quantiles are explicitly preserved. In the first phase of the work, the two-parameter Gumbel distribution function is used; in this case, it can be easily demonstrated that the first three methods "collapse" into a single approach. For the first two phases of the work (a and b), biases and climate scenario signals are used, while for the other phases, on a daily scale, an ensemble of 14 models (at the resolution of 12 km) under three concentration scenarios made available by the EURO-CORDEX initiative is used (only for a few of them are hourly data available). The real test case is the city of Vilnius (Lithuania) where the municipal administration is working on updating the design criteria for urban drainage works.

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A deep learning approach to modelling joint environmental extremes

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The geometric representation for multivariate extremes, where data is split into radial and angular components and the radial component is modelled conditionally on the angle, provides an exciting new approach to modelling environmental data. Through a consideration of scaled sample clouds and limit sets, it provides a flexible, semi-parametric model for extremes that connects multiple classical extremal dependence measures; these include the coefficients of tail dependence and asymptotic independence, and parameters of the conditional extremes framework. Although the geometric approach is becoming an increasingly popular modelling tool for environmental data, its inference is limited to a low dimensional setting ($d \leq 3$). We propose here the first deep representation for geometric extremes. By leveraging the predictive power and computational scalability of neural networks, we construct asymptotically-justified yet flexible semi-parametric models for extremal dependence of high-dimensional data. We showcase the efficacy of our deep approach by modelling the complex extremal dependence between metocean variables sampled from the North Sea.

Revisiting the flood frequency in the River Avon catchment using reconstructed historical events

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The Bristol Avon and its tributaries is a major river system in the South West of England flowing through the cities of Bath and Bristol. Flow in the river system is measured at a number of gauging stations with record lengths up-to 80 years long. However, the magnitude of the largest events is often estimated, and there is evidence, such as flood marks and newspaper articles, detailing large events occurring prior to the onset of systematic gauging. In this study we discuss recent efforts and challenges in reconstructing historical flood events using hydraulic models when combined with historical evidence. In particular, the study will assess the impact of including these highly uncertain estimates into statistical analysis of annual maximum series of peak flow through a censored maximum-likelihood framework. The results show that, in general, including the information of large historical events can impact the model parameters resulting in higher design floods. These results will potentially have important implications for flood risk management in the region.

Estimation of extremes of long precipitation series via the block quantile method

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Efficient estimation of quantiles of partial maxima of a time series is one of the main components in statistical analysis of extremal phenomena occurring in climatology, demography, economics and other areas. We construct several new estimators for quantiles of maxima of a stationary sequence using a novel block quantiles method that combines the ideas of the classical Gumbel block maxima method, adaptive selection of the proper tail model and some regression techniques. Moreover, when applied to random samples our method allows the estimation of extreme quantiles of the underlying distribution function.
Traditionally, hydrological extremes are modelled by extreme value distributions with positive shape parameter (Koutsoyiannis, 2004), though recently the appropriateness of using this model has been questioned (Marani & Ignaccolo 2015). In our work, we consider long precipitation series (usually more than 120 years of consecutive observations) from several places around the world. Using the block quantiles method, we show that applying the Weibull-type model (representatives of which are normal, gamma and Weibull distributions) for the estimation of extreme quantiles of this data performs better than the classical Generalized Pareto model. However, the block quantiles method coupled with the Weibull-type model, the metastatistical approach of Marani & Ignaccolo (2015) and the classical methods of statistics of extremes applied to estimation of the maxima of these data show almost the same performance.

Joint work with A.C. Davison (EPFL, Switzerland)

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Assessing the Influence of Storm Surge Duration and Intensity on Extreme Coastal Water Level Impact

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Coastal water levels are driven by a combination of processes such as tides, storm surges, mean sea level, and sea level anomalies. While understanding the magnitude of extreme events is often what's used to assess the severity of an event, events that persist for a longer period of time also have the potential to cause severe damage. The spatio-temporal pattern in the duration and magnitude of flooding events is thus crucial to understand for assessing impacts on coastal areas. The focus of this study is to investigate the influence of storm surge events on extreme water level occurrences across the United States (US) coast, identifying whether the duration of storm surge events contributes significantly to the intensity of extreme water levels.

In this study, hourly verified water level datasets from National Oceanographic and Atmospheric Administration (NOAA) tide gauges across the US coastline are used. A Peak Over Threshold (POT) approach with a 99.5 percentile is used to extract both extreme water levels and storm surge events, decomposed from the water level signal. We employ a mean lower threshold to identify a storm surge event, alongside measuring their duration, while the extreme duration is only considered as the time the storm surge is over the threshold. The duration of the extreme water level is measured by the total number of hours it remains over the extreme water level threshold during the entire storm surge event.

We found that not all extreme storm surges lead to extreme water levels, however, in this analysis, we characterize only the storm surge conditions leading to extreme water levels. When extreme water levels and extreme storm surge events coincide, water level impacts are evaluated through a normalization method applied to the intensity and duration of extreme water levels coinciding with storm surges. Subsequently, a generalized additive model (GAM) is applied to evaluate the individual as well as joint influences of the storm surge duration and intensity on the impact of extreme water levels at different locations. At the same time, a non-stationary Generalized Pareto Distribution (GPD) is used to understand the temporal variations of duration and intensity for different stations. This multi-scale approach will offer new insights into how variations in storm surge duration or intensity may amplify the effects of extreme water levels on diverse coastal regions.

Uncertainties in compound flooding: Event vs Response based approaches

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Assessing flooding from compound events has become essential to inform decision-makers and develop adaptation strategies as these events can exacerbate flood impacts compared to single-driver events. Significant attention has been directed to improving the statistical characterization of the magnitude of compound events and developing efficient compound flood models. However, little attention has been placed on the variability of the temporal evolution of extreme events at event timescales and the uncertainties associated with it in flood hazard estimates.
Here, we use a new data-driven statistical framework to assess compound events from precipitation and storm surges, which can also generate synthetic rainfall fields and water level time series accounting for the variability of tides and mean sea level.
This statistical framework accounts for the dependencies between drivers and their characteristics depending on the storm type that caused them (i.e. tropical cyclones, extratropical cyclones, and convective).
Using the generated synthetic events as boundary conditions of a flood model (SFINCS), we assess the uncertainties in flood extent and water depth associated with the variability of the temporal evolution of compound events of equal magnitude for the case study of Gloucester City, New Jersey. These uncertainties are very large when estimating flood hazards using the event-based approach, in which a “most likely” event is defined based on the magnitude of the flood drivers. Estimated flood hazard maps are highly dependent on the selected temporal evolution of the “most-likely” event, which is generally assumed constant for varying event magnitudes.
A better characterization of the flood hazard is produced using the response-based approach, i.e. simulating flooding from a large number of events and estimating the empirical distribution of water depths at each model cell. However, this approach is computationally demanding compared to the event-based approach, placing emphasis on the sampling of events to reduce computational costs. We show how the sample size can affect response-based flood hazard estimates and provide a comparison of the two approaches.

Modeling moderate and extreme urban rainfall at high spatio-temporal resolution

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Precipitation modeling is of great interest for flood risk analysis. While severe floods can result from extreme rainfall events, some of them can appear due to moderate ones. This is particularly true when such moderate events persist over a long period of time or when the ground is already saturated with water. The flood risk is even greater in urban areas where water absorption is reduced by impervious surfaces. This shows the importance of analysing both extreme and moderate rainfall events and their variability in terms of space and time in urban areas.
Significant rainfall events, known as Mediterranean episodes, are common in Montpellier, in the south of France. In our study we focus on 17 rain gauges in Montpellier in the water catchment of the Verdanson, a tributary of the Lez (see Figure 1). The rainfall measurements from these stations are provided by the urban Observatory of the HydroScience Montpellier (OHSM) (see Finaud-Guyot et al., 2023). They cover a period of 4 years with a high temporal resolution of 5 minutes. In terms of spatial granularity, we also have a high resolution with a distance between two stations ranging from 77 to 1531 meters. We propose to model the spatio-temporal characteristics of these rainfall data in order to better understand the rainfall behaviour over this area. To extend our analysis to a longer period but with a less fine resolution, we combine these data with the French COMEPHORE mosaic from Météo France (see Tabary et al., 2012).

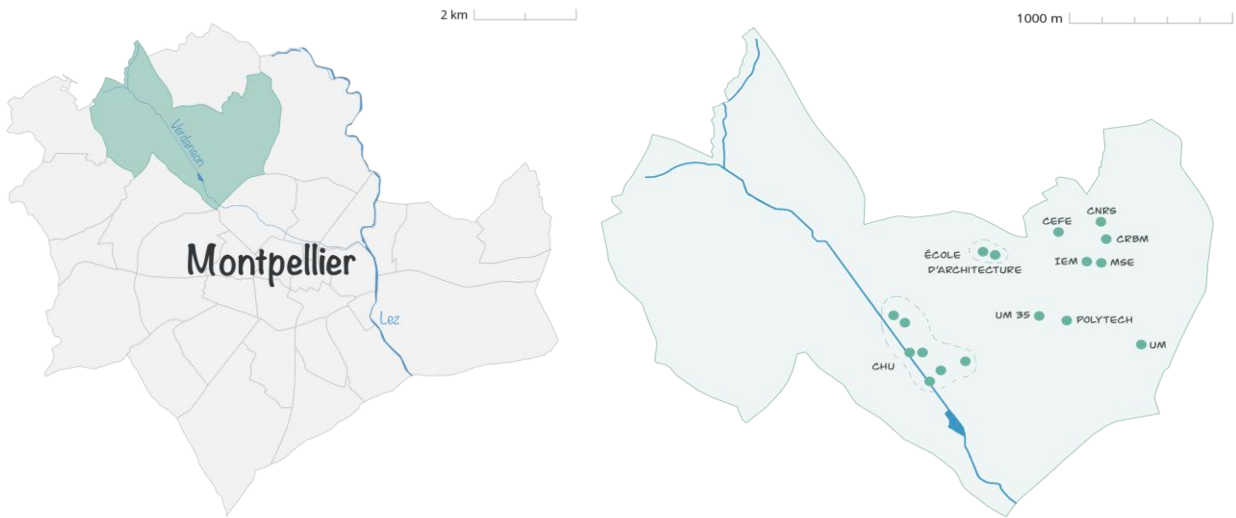

Fig. 1: *Study area in Montpellier and the 17 rain gauges location*

For our univariate modeling approach, we consider moderate and intense rainfall simultaneously using the Extended Generalized Pareto Distribution (EGPD) introduced in Naveau et al., 2016. This family of distributions allows us to avoid explicit threshold selection to distinguish extreme from moderate rainfall events, which is often difficult in extreme statistics. This approach also simplifies parameter estimation. Our analysis on both datasets (OHSM and COMEPHORE) shows a robust fit with the EGPD, indicating a strong suitability for representing univariate distributions.
The spatio-temporal dependence is then modeled by using a spatio-temporal Brown-Resnick process and by incorporating advection, which refers to the transport of properties such as heat or moisture by the horizontal movement of air masses. The Brown-Resnick process establishes a direct relationship between the spatio-temporal extremogram and the spatio-temporal variogram. Both of which provide insight into the spatio-temporal dependence behavior and they measure the similarity or dissimilarity between process values at different locations and time points. While the variogram measures variability across the entire distribution, the extremogram focuses on the extreme part of the distribution. These autocorrelation indices show the overall variability of the rainfall distribution even for short spatial distances and short observation periods. Contrasting our dependence model with a simpler separable model highlights the importance of including advection, which is estimated using an optimization method.

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Heat Stress, Climate Change and Mortality

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We propose a novel method to assess mortality from extreme heatwave events. The first stage uses an epidemiological model to represent daily mortality from a specific city or region as a function of current-day and up to 3 days lagged temperature and dewpoint, together with a long-term trend. The meteorological component of the model is then extrapolated to a long-term series of "virtual deaths" using observational temperature and dewpoint data. The effect of heatwaves is characterized by the most extreme elements of this series, typically, the 7-day period within each year that has the largest total of virtual deaths. We then use extreme value theory to relate this variable to an underlying climate signal, typically summer temperatures over a grid box covering the city or region of interest. The resulting series can be extrapolated both forwards and backwards in time by relating to climate models from the CMIP6 climate model archive. The backward extrapolations help us to make attribution statements (e.g., what proportion of the increase in extreme deaths over the last 100 years can be attributed to climate change), while the forward extrapolations allow us to make projections (with uncertainty bounds) for future heatwave mortality. The results show the sharpest increase under the 5-8.5 SSP climate scenario with more modest increases for other climate scenarios; see Figure 1 for an example based on mortality data from the California South Coast (Los Angeles area). Future work will examine other mortality series and alternative measures of heat stress such as hospital admissions.

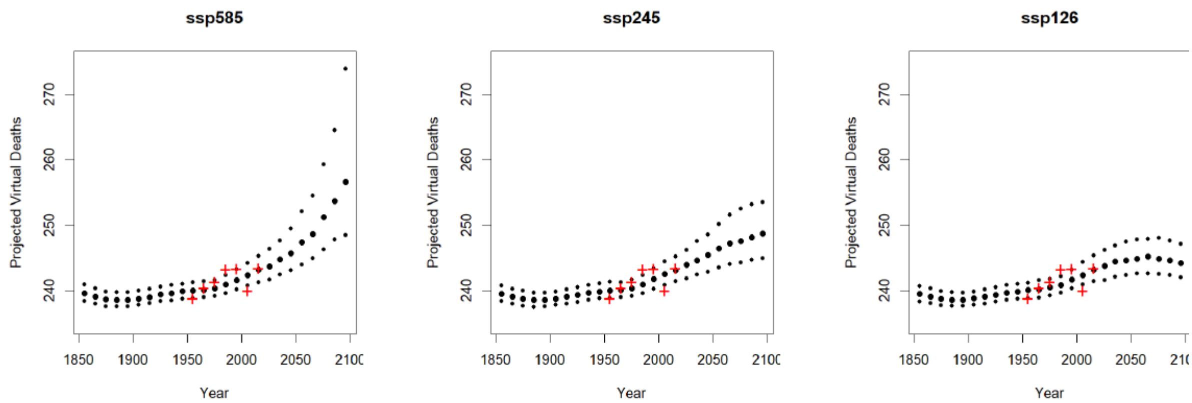

Fig. 1: *California South Coast: Decadal means and percentiles from the projective distribution for each decade from 1851-1860 through 2091-2100. Red crosses: observed values from 1951-1960 through 2011-2020. ssp585, ssp245, ssp126 refer to three IPCC scenarios for future emissions. The variable being plotted is mean number of deaths per day over the most extreme 7 days in each year, averaged over 10 years.*

Estimating Metocean Environments Associated with Extreme Structural Response

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Any ocean structure, be it an offshore oil platform, floating wind turbine, or coastal defence, will have forces induced on it by the surrounding ocean environment. This environment is highly complex and multi-dimensional, consisting of wind, wave and current components. The modelling of the extremes of this environment using multivariate extreme value models (Heffernan and Tawn, 2004; Jonathan et al., 2014) is therefore crucial when performing structural risk analysis, as extreme environmental conditions will naturally induce the largest forces on a platform. When combined with physical models for the short-term environment (Taylor et al., 1997) and wave-structure interactions (Morison et al., 1950), extreme value models for the evolving ocean environment can be used to estimate structure failure probabilities.

Environmental contours (Ross et al., 2020) are used as an alternative to assessing structure failure probabilities when full simulation from the above 'forward approach' isn't computationally feasible. In one respect, contour methods are advantageous over the forward approach in that they characterise the environment only and so do not require modelling of the structural response. Therefore, combined with appropriate assumptions for the ocean-structure interaction, these can in principle be used to assess any structure in that environment. Popular methods, e.g., IFORM (Winterstein et al., 1993), have formed the basis of historic metocean design. Unfortunately, the assumptions these methods make regarding the interaction between structure and environment are often infeasible for certain structure types.

We introduce a novel representation for the statistics of environmentally induced response forces calculated using the forward approach, in the form of the environmental density conditioned on attaining a given response force. We then illustrate the estimation of this density via efficient simulation from structural response models. It is proposed that this density can serve as an alternative to traditional environmental contours, by indicating which points in the environment space are most likely to induce critical response levels and thus are most relevant to test against. It also captures the stochasticity of the response force for a given environment, which contours do not. We explore the sensitivity of this representation for varying classes of structure type and assess its capabilities when compared to the IFORM environmental contour construction method.

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Extreme Exceedances for Moving Average Drought Indices

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The Standardized Precipitation Index (SPI) is used to measure meteorological drought operationally by drought monitors throughout the world. The SPI uses a moving average structure to quantify drought severity by normalizing accumulated precipitation relative to historical climatology. This makes the index particularly useful due to its simplicity and relation to drought definitions based on a sustained period of below-typical water availability for a given season. For this reason, the SPI has spawned numerous other normalized drought indices that also rely on a moving average structure to measure anomalies in other hydrologic variables.

Despite abundant research on moving average time series, there is no available study of this specific case: quantifying the extreme behavior of moving average sequences where the moving window is long relative to the time interval (annual). This is exactly the case for normalized drought indices like the SPI. This study examines the probability of annual exceedances from such a process, leveraging the inherent moving average structure of the SPI. To accomplish this, a stochastic model was used to simulate 10 million years of daily or monthly SPI values which were then used to fit the distribution of annual exceedance probabilities.

Prior extreme value theory for moving averages (Davis and Resnick, 1991; Rootzen, 1986) appears to break down under the specific conditions of the normalized drought indices outlined here. The resulting distribution of annual extremes follow a Generalized Normal distribution, rather than the Generalized Extreme Value (GEV) distribution, as expected from extreme value theory. This is due to clustering of extremes, which violates assumptions underlying extreme value theory.

This study provides the theoretical expected annual return periods for the SPI and similar drought indices with common accumulation periods (moving window length), ranging from 1 to 24 months (Fig. 1). We show that the annual return period differs depending on both the accumulation period and the temporal resolution (daily or monthly). The likelihood of exceeding an SPI threshold in a given year decreases as the accumulation period increases. Return periods and temporal persistence from the idealized moving average series were ultimately compared with real-world precipitation gauge data to determine the extent to which natural persistence and clustering of extremes causes deviation from the theoretical values.

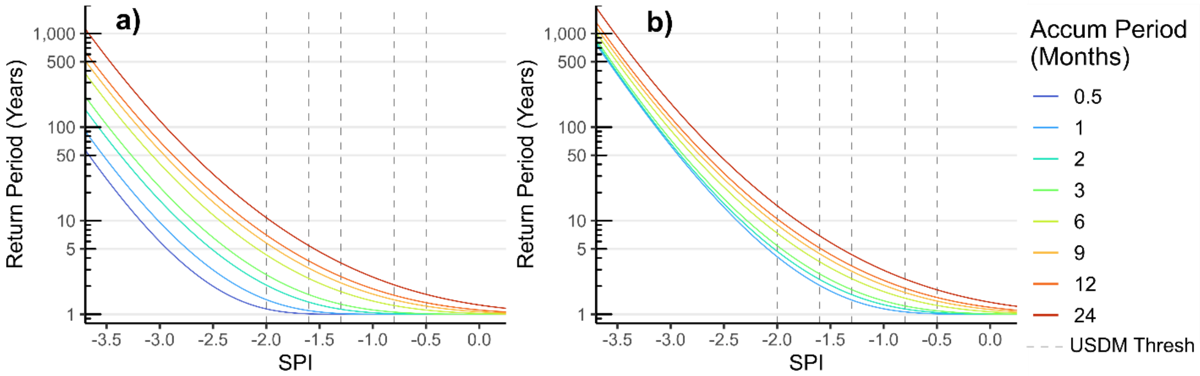

Fig. 1: *Return periods for (a) daily and (b) monthly sequences with accumulation periods indicated by color and measured in months. Vertical grey lines correspond to US Drought Monitor thresholds.*

In addition to explicitly quantifying annual extreme exceedances from a particular class of time series models, this study provides insight into drought indices used worldwide. These findings suggest that practitioners should exercise caution when discussing or comparing annual exceedances across indices with different accumulation periods or resolutions.

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Evaluating long-term variations of global storm surge energy

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Storm surge is one of the deadliest natural hazards. Long-term variation and changes in storm surge involve the process of synoptic extreme events in coastal areas on climate timescales. This study investigates the temporal and spatial evolution of the storm surge energy using the accumulated energy of storm surge on a yearly basis in observations. The merit of the annual storm surge energy includes integrating frequency and strength of individual surge events (Ji, T. et al., 2021; Marcos al., 2017). A total of 1381 tide gauge stations, with hourly sea level records, from the GESLA 3.0 data set are selected in our analysis, which form a quasi-global distribution of data. Each station has at least 25 years of valid data during the research period 1966 to 2019. We apply wavelet transform to decompose the energy into different frequency bands, namely those related to weather and sub-seasonal regimes. These two bands are 3–10 days (synoptic) and 10–90 days (sub-seasonal), as shown in Figure 1. The linear trend and periodic variation in storm surge energy are investigated. To reduce the effect of localization and high-dimension of data on global and regional scale analysis, long tide gauge sites are grouped by the clustering approaches by considering the interannual variation of total storm surge energy. From the clustered sites, representative time series of the energy are created for each individual region across the globe covering the period 1966 to 2019. The uncertainty of regional representative records is further addressed by including more stations but with a short time of valid data. Climatic indices are linked to regional time series to identify the driving factors of the regional variations. For example, our preliminary results show that ENSO and NAO have significant influence on the variation of energy along the Pacific and Atlantic coasts, respectively. In this workshop, we will present our latest results in both regional and global scales, trying to highlight coherent patterns in storm surge energy in a changing climate.

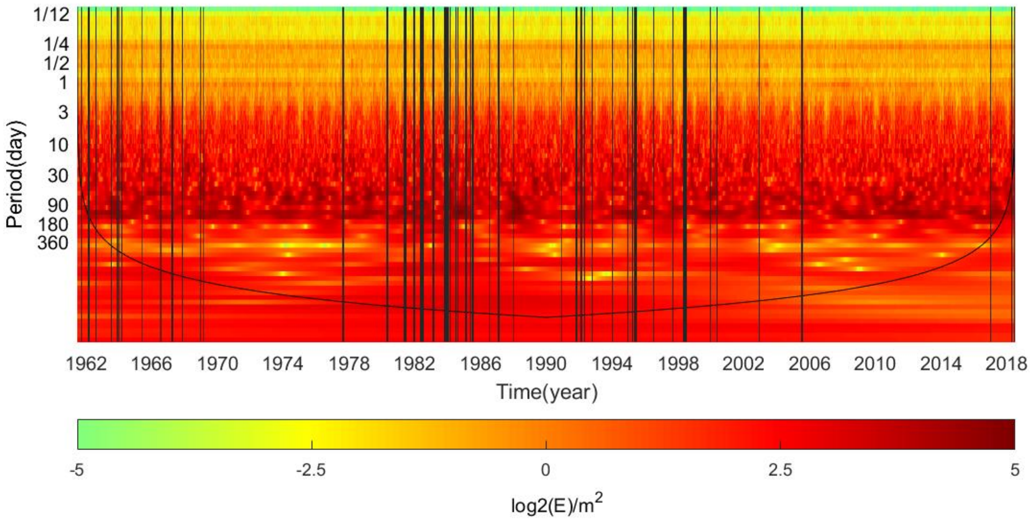

Fig. 1: *Wavelet spectrum derived from the hourly storm surge record in Hong Kong during 1962-2018. Black straight lines indicate missing data at corresponding time. The black curve line depicts the cone of influence beneath which data is dubious due to edge effect. Color represents the strength of energy in each band.*

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Comparing Joint Design Events from Event-Based and Response-Based Approaches for Approximating Return Levels Along Atlantic and Gulf Coast River Flood Transition Zones

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The frequency of coastal flooding is increasing, causing billions of dollars in damage to property and infrastructure and leaving millions of people at risk of dangerous flooding events. Traditional approaches for evaluating the risk of flooding are event-based, using a one-to-one relationship between a forcing and its response, equating the probability of some design event, like the 100-year river discharge, with the probability of its outcome (e.g., the 100-year water surface elevation). However, flooding along rivers at the coast is often subject to compounding processes such as elevated river discharge and high coastal water levels driven by storm surges and tides, such that the 100-year flood may be mischaracterized if bivariate processes are not included (e.g., Serafin et al., 2019). Prior research has found that flood transition zones, where both inland and coastal processes combine to drive flooding, can be over 40 km in length and may begin anywhere between 0.5 and 150 km upriver of the river mouth (Jane et al., 2022).

Our work compares the magnitude of the 100-year water surface elevation across the flood transition zone and the isoline of river and coastal conditions driving it from an event-based approach to a response-based approach for rivers in the southern United States. In order to include bivariate processes and their respective dependencies into an event-based approach, we consider the AND hazard scenario, where both processes are considered extreme, and develop an isoline of all river discharge and coastal water level events corresponding to the 100-year joint return period. From that isoline, we quantify the "most-likely" bivariate return period event across all joint events. On the other hand, a response-based approach evaluates the variable of interest (in this case, the water surface elevation along-river) to define the probability of occurrence rather than the flood drivers, and the drivers related to the resulting water surface elevation can then be extracted and explored. This approach allows for spatial variability in flood drivers, meaning the same forcing conditions do not have to generate the same probability of water surface elevation everywhere. The computational efficiency of our previously developed hybrid modeling framework allows for the application of a response-based approach.

The hybrid modeling framework links a statistical and numerical model through surrogate modeling to evaluate joint design events. This framework consists of statistically simulating synthetic joint boundary conditions of river discharge and coastal water level, running a subset of the statistically simulated boundary conditions through a Hydrologic Engineering Center – River Analysis System (HEC-RAS) steady flow model to output along-river water surface elevations. This subset of conditions is then used to generate surrogate models for the efficient extraction of water surface elevations from all of the synthetically simulated upstream discharge and downstream coastal water levels. We then empirically extract along-river return levels, like the 100-year water level, at a high spatial resolution and investigate whether they are driven by river discharge, coastal water level, or a combination of both processes.

Using these two approaches, we characterize any variation in the magnitude of the water surface elevation across the flood transition zone and evaluate how the joint-probability isoline of river and coastal conditions for a return period spatially varies across the flood transition zone. By characterizing the joint events driving return levels across our study sites, we gain deeper insights into the complex dynamics driving flood transition zones. Ultimately, comparing the “most-likely” event identified through our analysis with a response-based approach enhances our ability to conduct effective flood risk assessment and management strategies.

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Future wave climate in the Mediterranean Sea from a large ensemble of GCM-RCMs

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The generation and propagation of waves towards the coastal regions during storm events, in combination with storm surges, are a major coastal hazard. Although the Mediterranean Sea is characterized by a fetch-limited environment, the generation and/or passage of extra-tropical cyclones over its surface often originates powerful waves. An illustrative example includes recorded significant wave heights higher than 8 m during the Gloria storm in 2020 (Amores et al., 2020), that caused extensive damage in the eastern coasts of Spain. As climate numerical models consistently converged towards a global warming climate over the past few decades, it is thus crucial to evaluate how wave climate will be responding to future climate conditions.
This study investigates wave climate projected across the Mediterranean region using an ensemble of high-resolution wave numerical simulations of unprecedented size. Projected shifts in the wave distribution are evaluated, specifically focusing on wave extremes, along with the statistical significance related to the use of a multi-model ensemble.
The wave numerical simulations were forced using 16 GCM-RCMs of the European Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX), providing wind fields with 3-h (7 simulations) and 6-h (9 simulations) temporal resolutions and 0.11º (~8-11 km) spatial resolution, for both the historical and future periods (historical: 1979-2005; mid-century: 2034-2060; end-century: 2074-2100). The wave generation and propagation were performed integrating WaveWatch III (version 5.16; The WAVEWATCH III®Development Group 2019; hereinafter WW3) and SCHISM (Zhang et al., 2016) spectral wave models. These simulations (indicated in Table 1) are combined with the 17 EURO-CORDEX GCM-RCMs dataset from Lira-Loarca et al. (2023), resulting in an ensemble of 33 GCM-RCMs wave numerical simulations. Outputs provide wave bulk parameters at approximately 10 km spatial resolution and 3-h temporal resolution (1-h for the 3-h forcing wind fields).
The assessment of the overall future wave climate is performed through the examination of the seasonal variability, by considering the December-February (Winter), March–May (Spring), June-August (Summer), and September-November (Fall), focusing on significant wave height (H_s), peak period (T_p), peak direction (D_p) wave parameters and using mean and 0.95 quantile. We incorporate the inherent variability within the ensemble to characterize the outcomes. Furthermore, we focus on H_s changes in 10 to 100-year return levels by mid and end century. The return level computation is performed fitting a Generalized Extreme Value (GEV) distribution to sets of H_s annual maxima. As well as a multi model approach considering each model independently for the return level computation (as performed for the mean and 0.95

quantile), we assemble wave extremes from all models as a coherent and unique distribution of extremes similarly to the Unprecedented Simulated Extreme Ensemble (UNSEEN) approach (Kelder et al., 2020). The latter allows to tackle the limited number of years provided by each model separately and the resulting wide confidence intervals of return levels. The merging of extreme distribution from different models requires a previous bias-correction process. This is performed using a reference wave hindcast (Lira-Loarca et al. 2022) and widely used bias-correction methods (e.g Pierce et al., 2015), but adapted to our distribution of wave extremes.

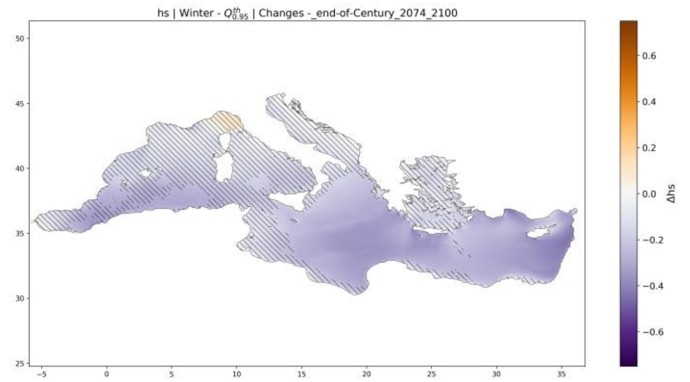

Figure 5: Difference in Hs quantile 0.95 between historical and end-century periods, for winter. Hatched areas indicate non-robust signal.

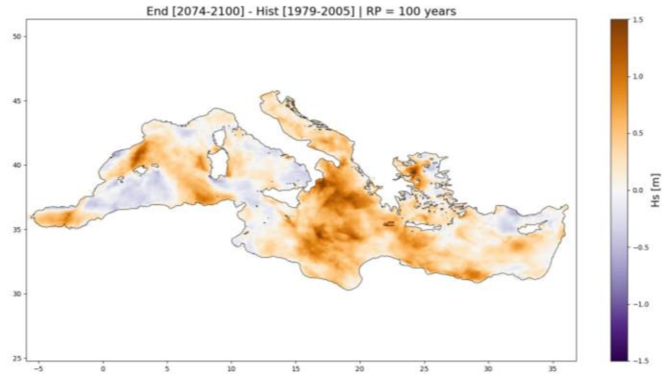

Figure 4: Difference in 100-year Hs return levels between historical and end-century periods.

Our study reveals varying degrees of model consensus across different regions of the Mediterranean. While some areas exhibit a higher dispersion between models in the projected changes towards the end (mean and 0.95 quantile), other zones show significant agreement among multiple models. For example, our analysis indicates a projected reduction in wave climate intensity during winter towards the end of the century in the Central Mediterranean see Figure 1), consistent with findings from previous studies focused on wave trends. However, the return level analysis indicates an intensification of wave extremes towards the end of the century in several areas of the Mediterranean basin. Despite limitations inherent to bias-correction methods and return level computation, our findings highlight the contrasting outcomes between analyzing the entire statistical distribution versus focusing solely on the tail, underscoring the importance of considering both aspects in wave climate projections.

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Impact of changes in extreme water levels on storm surge barrier maintenance

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Sea-level rise, changes in storminess and population growth are increasing the risks of coastal flooding. The impacts are amplified in coastal cities due to the high concentration of inhabitants, infrastructure and services. In these low-lying areas with long exposed coastlines, storm surge barriers can provide flood. Maintenance is vital to ensure these complex and unique structures remain reliable and comply with legal protection standards. To ensure safe working conditions, water level thresholds are defined above which maintenance work must stop. This study evaluates the changes in past and future extreme water levels to inform management, maintenance and operation strategies of storm surge barriers.
The Maeslant barrier in the Netherlands is used as a case study. Results show that 13% of maintenance threshold exceedances occurred during the maintenance season, which could interrupt work. The effect of sea-level rise and natural inter-annual tidal cycles on future threshold exceedances is also assessed. Findings reveal that the maintenance window could shift earlier in the year and narrow until exceedances occur regularly all year-round. As sea-levels rise, tides play an increasingly dominant role in maintenance threshold exceedances, which in turn will significantly influence maintenance work. This analysis highlights that maintenance strategies at the Maeslant barrier need to be adapted for the barrier to remain operational until its design life of 2100. This analysis can be applied to other existing barriers to assess future intervention points and for barriers in the design phase to verify the implications of design decisions on planned maintenance.

Fig. 1: *Maeslant Barrier in Rotterdam undergoing maintenance work.*

Precipitation Extremes Projected to Increase and to Occur in Different Times of the Year

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The study of extreme precipitation events is crucial for a multitude of sectors, from the design and maintenance of hydraulic infrastructures to water resource management. At the same time, climate change is altering the characteristics of extreme precipitation, requiring ever greater efforts to get a more comprehensive view of the problem. However, there is sometimes an implicit assumption of stationarity in analyzing these features: the seasonality of precipitation extremes is generally not projected to change when the main focus is on the magnitude and vice versa. Here we assess how the seasonality and magnitude of precipitation extremes are jointly projected to change under different climate scenarios. We perform analyses at the global scale using nine global climate models and four different emission scenarios. We also treat seasonality as a circular variable, thus being able to model different modes in the timing of extreme precipitation. As greenhouse gas emissions increase, we find that the severity of extreme precipitation is projected to increase worldwide. In terms of seasonality, we identify large areas of the globe where these events might occur later in the actual wet season, and this is more evident moving to high emission scenarios.

Including pump reliability: introducing extremes during non-extreme conditions

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As a result of sea level rise it will become increasingly difficult to freely discharge superfluous river inflow from low-lying deltas such as the Netherlands. Large pumping stations have been suggested to discharge the excess water if high sea water levels prevent the natural outflow (e.g. De Bruijn et al., 2022). Recent estimates of the required pumping capacity (when natural discharge is not possible anymore) range from 8,700 m3/s (in case of sufficient buffer capacity) to 15,500 m3/s to discharge a 1:10,000 extreme river discharge from the Rhine and Meuse (Ministry of Infrastructure and Water Management, 2024). However, the effect of pump reliability was not taken into account yet in these first assessments.
In the Netherlands, flood risk assessments often make use of synthetic storms with standard shapes described by several (dependent) stochastic variables such as max wind speed, wind direction, duration and storm setup (e.g. Diermanse et al., 2013). A similar approach was applied for the assessment of the required pumping capacity, with a standard shaped flood wave with ten day duration and a peak discharge described with an extreme value distribution.
Introducing operational pump reliability complicates the extreme value analysis as extreme water levels in the water system are not only caused by extreme hydrological conditions but also by pump failure. During (partial) unavailability of the full pump capacity, less extreme conditions can lead to severe floods. Additionally, the normative timescale is determined by the available buffer capacity. It is uncertain of these characteristics are sufficiently captured by the standard-shaped flood waves.
Therefore an approach using long (synthetic) time sequences (e.g. Te Linde et al., 2010) might be better suited as it includes all relevant extreme events. In this presentation we will compare both methods in the assessment of the required pump capacity.

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Climate Change and Flooding Across the United States

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There is a growing recognition that flooding has been changing in recent decades across different parts of the contiguous United States (CONUS), with climate change acting as a risk multiplier. However, the standard practice in the design of our physical infrastructure assumes stationarity, which implies that what we experienced in the past will manifest itself again in the future and is at odds with the recognition of a changing climate. Given that many engineering projects are designed to be in operation for several decades or longer, how do we provide basic information to develop best practices for addressing non-stationarity issues in flood frequency estimation and risk management in a world in which the past may no longer be representative of the future?

This presentation will provide a path forward on how we can incorporate climate change to design our infrastructure for the future, not for the past. At the core of the proposed approach there is the need to gain insights into the factors responsible for the year-to-year changes we observe in the historical discharge records. The improved understanding of the physical processes responsible for flood events has challenged the traditional notion that floods result from a single-population causative mechanism. This paradigm stresses the fact that all floods are not created equal and is based on the premise that different flood agents are responsible for different events, moving us closer to a process-driven flood frequency analysis.

Here we use parsimonious statistical models to show that much of the interannual variability in annual maximum daily discharge can be described in terms of aggregated climate variables (i.e., basin- and season-averaged precipitation and temperature). Instead of modeling the annual maximum time series directly, which would imply that all the flood peaks are coming from the same population, we model the seasonal maxima as a way of capturing different flood generating mechanisms; we then use a Monte Carlo approach to mix the seasonal models to get to the annual maximum time series, allowing us to move toward a process-driven flood frequency analysis. Furthermore, we employ Bayesian networks to make causal statements about the relationship between flood peaks and climate predictors.

This approach not only more accurately describes the flood records but also represents an alternative way to investigate how flooding is projected to change in a warmer climate: we can use climate model outputs to examine how the drivers of these major flood agents are projected to change and then use this information to infer how flood frequencies are bound to change. The goal is to learn from the past and to then use this information to provide better insights into future changes in flooding, providing a scientific basis for the engineering design of flood mitigation alternatives and the management of the water resources.

To do this, we assess future changes in flooding across the CONUS using outputs from 28 global climate models and four scenarios of the Coupled Model Intercomparison Project Phase 6. We find that the CONUS is projected to experience an overall increase in flooding, especially under higher emission scenarios; there are subregional differences, with the Northeast and Southeast (Great Plains of the North and Southwest) showing higher tendency towards increasing (decreasing) flooding due to changes in flood processes at the seasonal scale.

On the Attribution and Future Projections of Daily Precipitation Extremes across the United States

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There is high confidence that anthropogenic emissions have exacerbated the magnitude and frequency of extreme precipitation events at the global scale and are expected to continue to do so into the future. However, previous event attribution studies on precipitation extremes across the contiguous United States (CONUS) are more equivocal about the role of anthropogenic forcing in altering the odds of observed extremes. Most of the existing attribution studies focus on specific precipitation events of varying duration and spatial extent. Furthermore, the different extreme value statistics and approaches employed make it difficult to compare the results among existing studies. There is still a need for a comprehensive assessment of the role of greenhouse gas emissions (GHG) in altering the probability of daily precipitation extremes across the CONUS.

Attribution statements are influenced by the extreme value statistics used for modelling the extreme events. Block maxima or peak over threshold (POT) approaches are often employed for the frequency analysis of extreme events. While the block maxima approach does not sample all observed extremes, the selection of a suitable threshold is a major challenge in POT approaches: a higher threshold reduces the available sample size, while the lower threshold violates the assumption of the extreme value distribution. Therefore, the choice of the threshold is dictated by the sample size and the assumptions of extreme value statistics. To address this issue, we use an extended generalized Pareto distribution (ExtGPD), which enables sampling the entire time series without specifying a threshold.

Here, we conduct a comprehensive assessment of anthropogenic emissions in altering the odds of observed daily precipitation extremes across CONUS. We also examine the projected changes in the extremes under four different emission pathways. We make use of the ExtGPD, which jointly models low precipitation with a generalised Pareto distribution and heavy rainfall with a different Pareto tail. One advantage of the ExtGP is that the always difficult threshold selection step is completely bypassed. Since ExtGPD samples the entire record, we use it to evaluate whether global climate models can capture the observed extremes during the historical period. In our work, we use gridded Climate Prediction Centre (CPC) precipitation observations, 12 global climate models from the detection and attribution intercomparison project and 22 global climate model projections.

Our results show that anthropogenic emissions exacerbate observed precipitation extremes. We found that an alternate scenario of well-mixed GHG emissions increases the magnitude of extreme daily precipitation across the Midwest, Southeast, Northeast, and the U.S. West Coast. Similarly, an alternate scenario with only natural forcing would have reduced the magnitude of extreme daily precipitation across CONUS, especially in the arid western regions. In short, we observe a major role of GHG emissions in increasing precipitation extremes in temperate climatic regions. Our results highlight an unambiguous linkage between anthropogenic emissions and daily precipitation extremes across CONUS.

Looking into the future using the ExtGPD, we find that daily precipitation extremes are projected to increase, especially for increasing GHG emissions. This is true for different global climate models and for CONUS as a whole, but particularly strong across the Northeast, Southeast, Midwest, and West Coast. Also, the intensity of precipitation extremes increases manifold in higher emission scenarios, underscoring the benefits of limiting anthropogenic emissions in reducing the magnitude of future extremes.

Complete Time-series Analysis for hydrological design and risk assessment

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Complete Time-series Analysis (CTA) is discussed here as a tool for hydrological design and risk assessment, alternative to the classical approach based on Annual Maxima (AM) that constitutes the basis of traditional extreme value analysis. Indeed, AM are usually analyzed to catch the tail of the distribution of the parent process, where the latter is the process of interest (as shown in Figure 1). The rationale behind CTA is to exploit all the information provided by observational data, with the objective of better estimating the return period in a wider range of values, not only at the largest extremes that are the focus of extreme value theory. Small to moderate return period values are still of interest in several practical problems, such as pluvial flooding. Besides, it is important to stress that CTA provides different return period estimates with respect to annual maxima by considering all the occurrences of the dangerous values (e.g. exceedance of the random variable above/below any threshold value of interest) within the observed record (Volpi et al., 2019). CTA potentiality and limitations are discussed by means of illustrative examples, including the analysis of an exceptionally long time-series (Volpi et al., 2024).

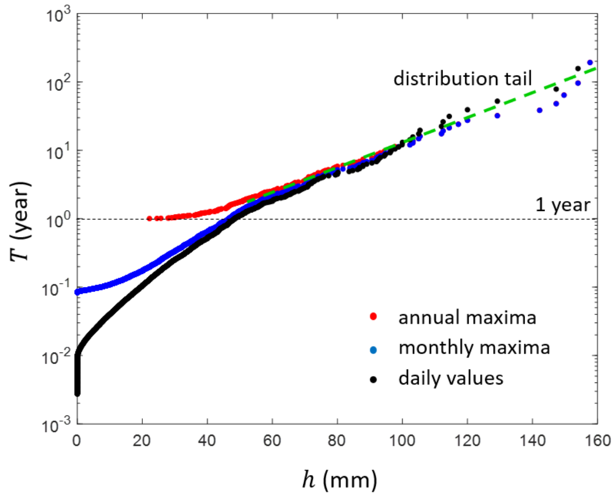

Fig. 1: *Empirical probability distribution of the rainfall annual and monthly maxima and of the ordinary daily value in terms of return period T (from Volpi et al., 2024).*

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Storm surge return levels and trends along the U.S. coastline

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Obtaining robust and spatially continuous estimates of storm surge and extreme water level return periods for coastal flood risk assessments and adaptation planning remains a challenge. These return periods may also be non-stationary due to changes in storminess as a result of global warming and natural climate variability. Continental and global scale hydrodynamic numerical model hindcasts have been used for that purpose but are subject to uncertainties related to the underlying bathymetry and relatively coarse atmospheric forcing. Regional Frequency Analysis is an alternative approach to derive the desired information at ungauged locations by pooling observational data from larger regions which are assumed to be coherent. While easy to implement, this method relies on subjective choices to define regions and also suffers from unsubstantiated statistical assumptions.

Here we produce and analyze a new dataset of storm surge and extreme water level return periods using a Bayesian Hierarchical Model (BHM) (Calafat and Marcos, 2020) that leverages spatial dependences in storm surge data to enable sharing of information across space. The BHM produces more robust return level estimates at tide gauges compared to the traditional at-site approach, while also providing return levels as well as annual maxima storm surge time series with associated uncertainties at ungauged locations. From the Bayesian estimates, we infer spatial patterns of return levels along the entire coast and reconstruct footprints of individual extreme events. Compared to existing information currently used in large-scale coastal impact assessments, our return level estimates are higher at most locations with smaller confidence levels.

The BHM also considers a non-stationary location parameter allowing us to identify regionally coherent long-term trends in extreme storm surges. We find hotspots of positive trends since 1950 (intensified since the 1970s) in southwest Alaska, the northeast Gulf of Mexico, and U.S. northwest and southeast coasts. Negative trends exist in the Gulf of Alaska and U.S. west coast. With trends being in the order of 1 mm/yr they are smaller in magnitude than the observed mean sea level trends in the same regions over the same periods. However, when compared to the trends in the main drivers of mean sea level rise (i.e., barystatic, sterodynamic, glacial isostatic adjustment, and inverse barometer) the storm surge trends are as large or even larger than the trends in several of the mean sea level components. And while future sea level projections always include the contributions from all of the main mean sea level drivers, trends in storm surges are typically ignored.

Overall, the results indicate that contemporary and future coastal risk assessments may underestimate the flood hazard component with potential implications for misguided design and adaptation planning.

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Storm surge barriers, the unknown challenges and the impact of climate change on their management and maintenance

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Storm surge barriers are moveable constructions in an estuary or river branch that can be temporarily closed. They are designed to protect against extreme water levels caused by storm surges and/or high tides. During normal conditions, moveable storm surge barrier gates are open to provide a connection to the sea enabling shipping and tidal exchange. In storm conditions, the barrier gates close preventing the rise of water levels behind the barrier and thus protecting the area inland from flooding.

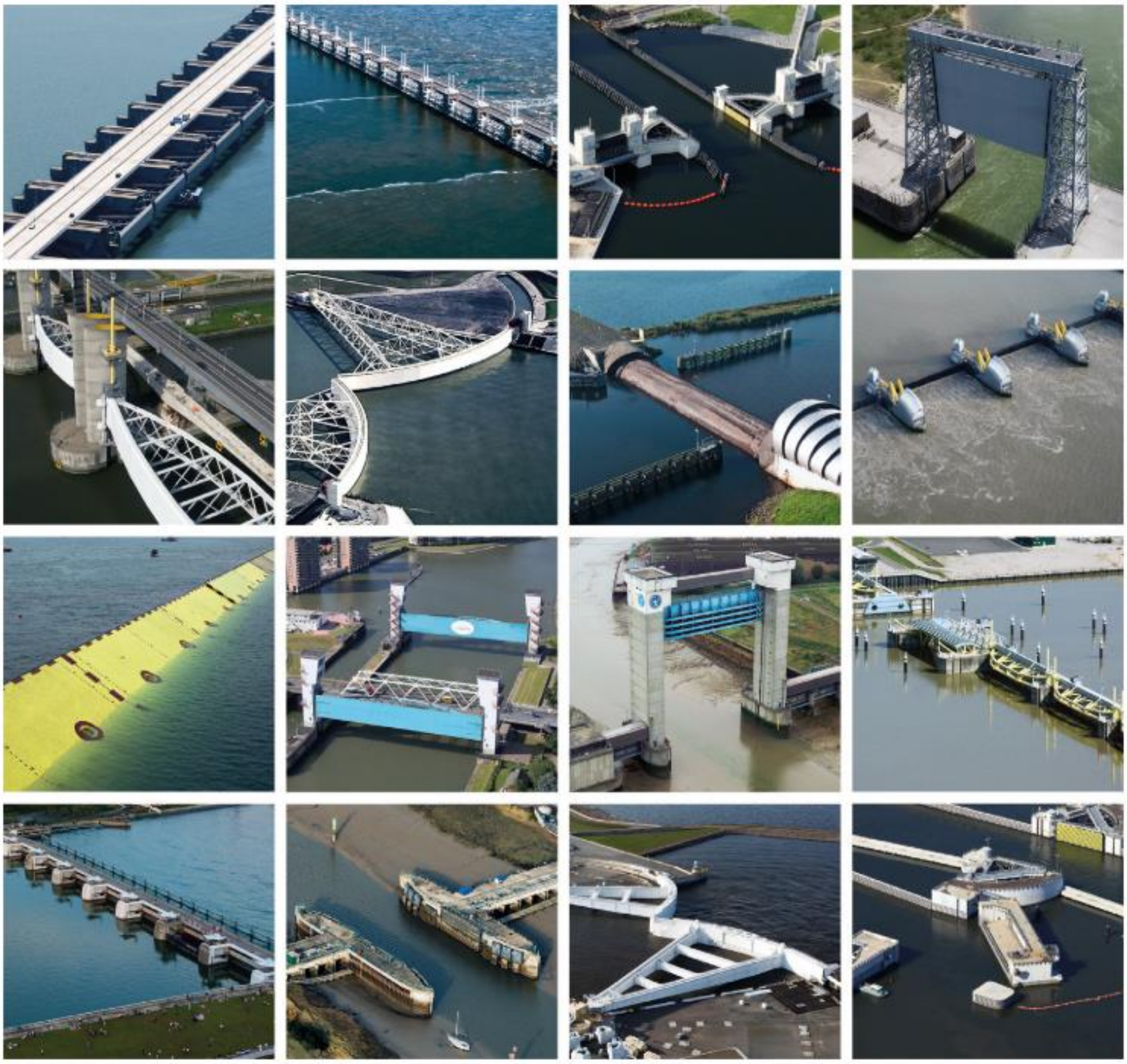

Fig. 1: *Overview of exemplary movable Storm Surge Barriers worldwide.*

Sea-level rise and changes in storminess, together with population growth and coastward migration, are raising the risks of coastal flooding. So, storm surge barriers are increasingly becoming major components of flood risk management solutions worldwide. Due to their complex, unique and costly nature, storm surge barriers require specialist management, maintenance and operation. The reliability of a barrier must comply with legal and policy requirements. Extreme storm conditions do not occur regularly, this means many storm surge barriers are not operated often. This limited use has multiple effects for maintenance, management and operation. (1) limited opportunity to gain technical and organisational experience (2) low possibility to find out about unique and specific maintenance problems and the effect of maintenance on specific parts and (3) low frequency of intended operation means that testing the barrier in an integrated manner is limited.

There are currently over 50 storm surge barriers in operation around the world, well known examples include the Maeslant Barrier in the Netherlands, the MOSE Barrier in Italy, the Thames Barrier in England, the Marina Barrage in Singapore and the Hurricane Storm Damage Risk Reduction System in New Orleans, USA to name a few. I-STORM (www.i-storm.org) is an international knowledge sharing network for all people who have a role in achieving reliable storm surge barriers. It looks to facilitate knowledge exchange and collaboration between members to help them deal with common challenges at an international level and enable continuous improvement in storm surge barrier design, management, maintenance and operation.

Also capturing lessons learned on management, maintenance and operations is to the use of all involved. And especially for those that consider to design and construct new barriers worldwide incorporating these lessons learned is to the benefit of the reliability of these new barriers as well to the cost effectiveness of future maintenance and operations. More and more it’s obvious that we’re in it together and worldwide collaboration is needed to protect those living in low laying areas now and in the future.

In collaboration with teams working at the barriers, research has been conducted to better understand the implications of climate change on the management, maintenance and operation of storm surge barriers. The occurrence of weather windows when maintenance work can be carried out has been determined by evaluating past and future extreme water levels (Trace-Kleeberg et al., 2023). This study emphasises the relevance of close cooperation between academia and industry to highlight the challenges and motivate change within organisations to address the impacts of climate change on the management, maintenance and operation of storm surge barriers.

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Dynamics of extreme risk and resilience for distributed stormwater infrastructure: Insights from 8,000 large culverts in Northeastern USA

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During extreme rainfall events, floodwaters inundate many road networks - disrupting mobility, jeopardizing traffic, and impacting roads' structural integrity. It is estimated that approximately 75% of flood-related fatalities occur when individuals drive into or attempt to walk through floodwaters (Ashley & Ashley, 2008; Jaeger et al., 2019). Furthermore, anticipated changes in the loading brought on by climate and land-use change may cause additional capacity deficits in stormwater infrastructure, potentially leading to enormous financial losses (Gassman et al., 2017; Joseph Perrin & Dwivedi, 2006). Within this context, the economic impact of culvert failures is significant. For example, the average cost of replacing a culvert in the USA, according to one study, could amount to approximately $ 800,000, with the highest recorded cost being $ 4.2 million (Perrin and Dwivedi, 2006).

Therefore, it is highly desirable to have a unified, uncertainty-aware framework that produces insights into the risk and resilience of the distributed culvert infrastructure - utilizing high-resolution DEM and other readily available geospatial features. Decision makers are additionally interested in knowing how the culvert failure risks change (a) with the location and size of the catchment, i.e., the dynamics of risk in space, and (b) with land use change and shifts in precipitation patterns due to climate change - i.e., dynamics in time. Here we propose such a framework.

We aim to present results from the application of this framework on 8,000 large culverts in the Northeastern United States (as shown in Figure 1). Our framework builds on previous work (Truhlar et al., 2020) that calculates the hydraulic capacity of culverts to find the return period of peak storm discharge they can handle in Hudson Valley, New York State. However, we additionally leverage (1) Monte Carlo simulations to treat uncertainties, (2) a higher-resolution DEM that is able to resolve small streams and geolocate culverts, (3) large geospatial datasets of catchment characteristics influencing discharge generation, and (4) past and projected rainfall fields. Within this framework, we run extensive simulations to understand the interconnected and compound risks and generate insights on the corresponding resilience of the infrastructure. We also analyze dependencies between resilience and (a) different types of road networks, (b) watershed characteristics like average slope and the order of the stream, (c) land use characteristics, and (d) the rarity of the extreme rainfall event. We finally comment on the scalability of this framework in understanding spatial and temporal dynamics of risks to distributed stormwater infrastructure serving connected road networks over large areas.

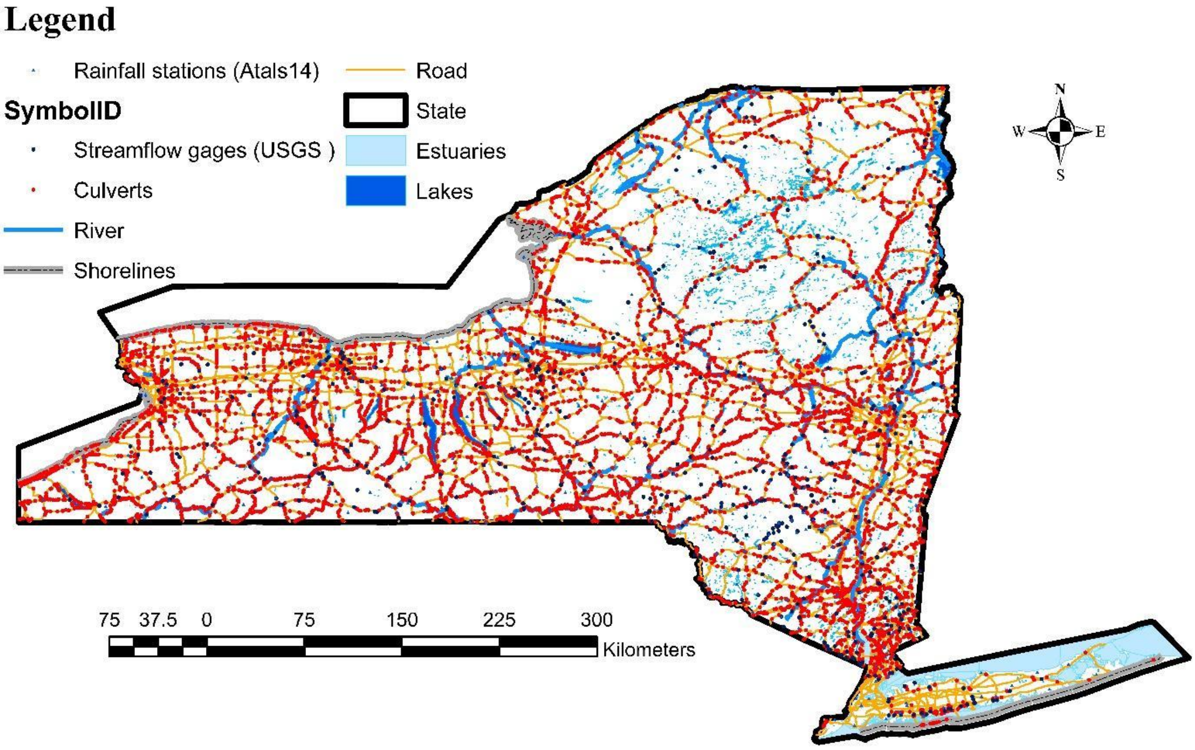

Fig. 1: *New York state map showing culvert locations, road networks, water bodies, streams, and rainfall stations.*

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Flexible models for coherent estimation of Rainfall extremes

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Intensity duration frequency (IDF) curves are one of the most commonly used tools in water resources engineering for planning, designing, or operating water resource projects against floods. These curves explain the relationship between extreme precipitation intensities (amount of rainfall), duration (few minutes to several hours or days), and frequency (annual exceedance probability). The IDF relationship describes the characteristics of extreme rainfall measured at different durations, and its study has a long history (Bernard 1932). These curves are used to describe the expected frequency of extreme rainfall measured at different durations. To ensure coherent estimates of exceedance probabilities across durations, these curves are subject to adequate shape constraints.

Most existing methods employed to estimate IDF curves assume that extreme rainfall accumulations over different durations are independent of each other (see for example Lutz et al. 2020, Fauer et al. 2021), but this assumption may not always be valid. This problem is addressed in our work by proposing a Markovian model which accounts for dependence and is computationally feasible. Our approach is based on a first-order Markov assumption that incorporates the dependence between consecutive rainfall durations through the use of bivariate extreme models, while the marginal distributions are duration-dependent Generalized Extreme Value (d-GEV) distributions. The proposed model is applied to annual maximum intensity data over relevant rainfall durations, with an example from Germany.

We performed an extensive simulation study by considering two different IDF models, one that considers the dependence between rainfall durations using the first-order Markov process, and the classical approach with duration-dependent GEV (d-GEV). We conclude that Markov processes are worth considering for IDF curve estimation when focusing on short durations if the model's asymptotic dependence can be assumed to be properly captured.

keywords: Rainfall extremes; intensity-duration-frequency curve; Markov process; duration-dependent-GEV

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