Proposer of the vote of thanks and contribution to the JRSS-C Discussion of ”Inference for extreme spatial temperature events in a changing climate with application to Ireland”

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Proposer of the vote of thanks and contribution to the Discussion of "Inference for extreme spatial temperature events in a changing climate with application to Ireland" by Healy, Tawn, Thorne, Parnell

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The authors astutely develop a non-stationary generative statistical model for spatial temperature extremes under climate change, allowing for Monte-Carlo estimation of spatial risk measures. Based on asymptotic theory for threshold exceedances of spatial risk functionals, the model combines data from irregularly spaced weather stations with simulations of a physical climate model on a regular spatial grid.

Their work addresses the general need for comprehensive non-stationary statistical assessment of the frequency, magnitude and extent of extreme weather. This task is complex since temperature, the key variable of global warming, exhibits strongly heterogeneous trends across three-dimensional space and time. Numerical simulations from physical models provide a wealth of "big" data but come with strong limitations: simulation is deterministic and not probabilistic, and is performed on relatively coarse spatial grids, *i.e.*, not point-based at weather-station level; large biases of simulations with respect to the true climate are possible; computational cost is high and prevents simulating even moderately large numbers of full space-time chronicles and extreme-event catalogs. Instead, the proposed approach transfers information about spatial temperature heterogeneity in sparsely observed areas from physical simulations to a statistical model to obtain a point-based Stochastic Weather Generator (SWG) not suffering from such limitations. It showcases that SWGs are key tools to enhance data provided by physical simulations. They can be calibrated at low computational cost for various purposes: emulation of physical models, downscaling from gridded large-scale input data to point-based distributions, and stochastic simulation of large samples of rare events.

The paper leverages flexible state-of-the-art methods from Extreme-Value Theory (EVT) for dependent peaks-over-threshold rather than traditional methods based on annual location-wise maxima, so that information from data is better preserved and interpretation facilitated (Huser et al., 2024). Though, this comes at a price: threshold exceedances of aggregated spatial risk often do not correspond to marginal threshold exceedances at all locations, such that models incorporating covariates must be fitted for both the bulk and the tail of marginal distributions. The authors solve the problem by conducting multiple quantile regression for the bulk model. Another option resides in subasymptotic models, also called *Extended Generalized Pareto Distributions*, that flexibly capture the full range of data while preserving coherence with asymptotic models in both tails (Papastathopoulos and Tawn, 2013; Naveau et al., 2016; Yadav et al., 2023). This helps to avoid the increased uncertainty and modelling overhead due to the split modelling below and above an explicit fixed threshold.

The proposed model uses large-scale physical covariates (*e.g.*, temperature means) to propagate large-scale signals to local (point-based) temperatures. Provided that the causal influence of covariates on the temperature response can be ascertained, such models would allow simulating future extreme temperatures, with future covariates obtained from climate-change scenarios and physical simulations. Tools for causal inference in extremes of time series (Bodik et al., 2024) could be promising to confirm causal effects of large-scale variables.

Another possibility to strengthen causal interpretations could be to closely compare SWG-based results and physical-model simulations to assess their general coherence.

It is challenging to reliably extrapolate covariate effects when future covariate values fall outside the range of training data. Statistical methodology should be extended to appropriately design and validate covariate models for this purpose. Physically plausible model structures should be ensured for tail extrapolation, especially in the non-stationary climate-change setting. An interesting innovation is the estimation of extreme-temperature models by including a physically motivated finite upper bound of the distribution (Zhang and Boos, 2023; Noyelle et al., 2023, 2024).

The paper focuses on *spatial* dependence. For assessing climate-change impacts, it appears equally important to improve how temporal dependence of weather extremes is taken into account, especially regarding the persistence of moderate and extreme anomalies, and compounding effects. This could improve the understanding of how biotic processes in fields such as agriculture, ecology, and epidemiology could respond to unprecedented and cumulated extreme events. For example, droughts often build up through the temporal persistence of several conditions: relatively high temperatures, low precipitation, high wind speeds and low humidity. One could study asymptotics of probabilities $\Pr(S_n \geq u)$ for partial sums $S_n = \sum_{k=1}^{n} X_{t+k}$ of time series X_t as $n \to \infty$, with an extreme quantile u of S_n. Results from Large-Deviation Theory (Touchette, 2011) could be useful.

A highly dynamic research area today involves the intersection of EVT with artificial-intelligence (AI), and specifically deep learning, for tasks such as parameter estimation, prediction and stochastic simulation. Due to the high complexity of the Earth system, numerical and statistical approaches to modelling and simulation are particularly concerned (Beucler et al., 2023), and hybridising physical and statistical models to take the best of both worlds shows great promise. There is growing interest in using EVT to design AI model components appropriate for extrapolation beyond the observed data range, for example in Generative Adversarial Networks for heavy-tailed data (Allouche et al., 2022) or Variational Autoencoders (Lafon et al., 2023; Zhang et al., 2023).

To conclude, I congratulate the authors on an excellent contribution providing relevant innovations and raising important questions.

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