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A multivariate extreme wave and storm surge climate emulator based on weather patterns

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ABSTRACT

Coastal floods often coincide with large waves, storm surge and tides. Thus, joint probability methods are needed to properly characterize extreme sea levels. This work introduces a statistical downscaling framework for multivariate extremes that relates the non-stationary behavior of coastal flooding events to the occurrence probability of daily weather patterns. The proposed method is based on recently-developed weather-type methods to predict extreme events (e.g., significant wave height, mean wave period, surge level) from large-scale sea-level pressure fields. For each weather type, variables of interest are modeled using Generalized Extreme Value (GEV) distributions and a Gaussian copula for modelling the interdependence between variables. The statistical dependence between consecutive days is addressed by defining a climate-based extremal index for each weather type. This work allows attribution of extreme events to specific weather conditions, enhancing the knowledge of climate-driven coastal flooding.

1. Introduction

Coastal flooding results from non-linear interactions of multiple oceanographic, hydrological, geological and meteorological processes (e.g., astronomical tide, monthly sea-level anomalies, storm surge, wave set-up, wind set-up, fluvial discharges, precipitation and land subsidence). Coastal flooding can result from an exceptional intensity of a single process (e.g. storm surge), but more often results from the combination of elevated values of more than one of the aforementioned processes, namely a compound event. As defined by the IPCC SREX report (Seneviratne et al., 2012) and Leonard et al. (2014), the main characteristics of a compound event are: (1) the extremeness of the impact rather than the individual components, (2) the multivariate nature of the impact and (3) the components statistical dependence. In this paper, we examine extreme non-tidal total water level (TWL) defined as the linear summation of storm surge (SS) and wave run-up, which is functionally related to significant wave height, Hs, and mean period, Tm (Stockdon et al., 2006). Because synoptic atmospheric circulation patterns control the magnitude of SS, Hs and Tm, all three variables show strong statistical dependence.

The processes responsible for extreme waves and storm surge are non-stationary. They vary seasonally, interannually and on longer time scales, possibly due to climate change (Milly et al., 2008). Recently, many extreme value models were developed to deal with non-stationarity and multivariate extremes, including conditional approaches (Heffernan and Tawn, 2004; Gouldby et al., 2014), stationary and non-stationary bivariate copula methods (Bender et al., 2014; Wahl et al., 2012, Masina et al., 2015) and higher-dimensional copulas (Corbella and Stretch, 2013; Ben Alaya et al., 2014; Wahl et al., 2016). Despite its predictability, the astronomical tide is also a component that adds non-stationarity to the estimation of TWL (Dixon and Tawn, 1999; Coles and Tawn, 2005), and often requires dependency correction between consecutive events using an extremal index (Leadbetter, 1983; Tawn 1992; Coles, 2001; Batstone et al., 2013).

Statistical models of extreme coastal flooding have been developed by combining highly energetic wave conditions (defined by large values of Hs and Tm) and high water levels (high tides and storm surge), with a time-dependent peak over threshold extreme value model (Serafin and Ruggiero, 2014) that accounts for seasonal and interannual variability based on sea-level pressure (SLP) and sea-surface temperature (SST) indices.

Recently, Camus et al. (2014a) developed a method to obtain daily SLP-based predictors that explain the inter-daily variability

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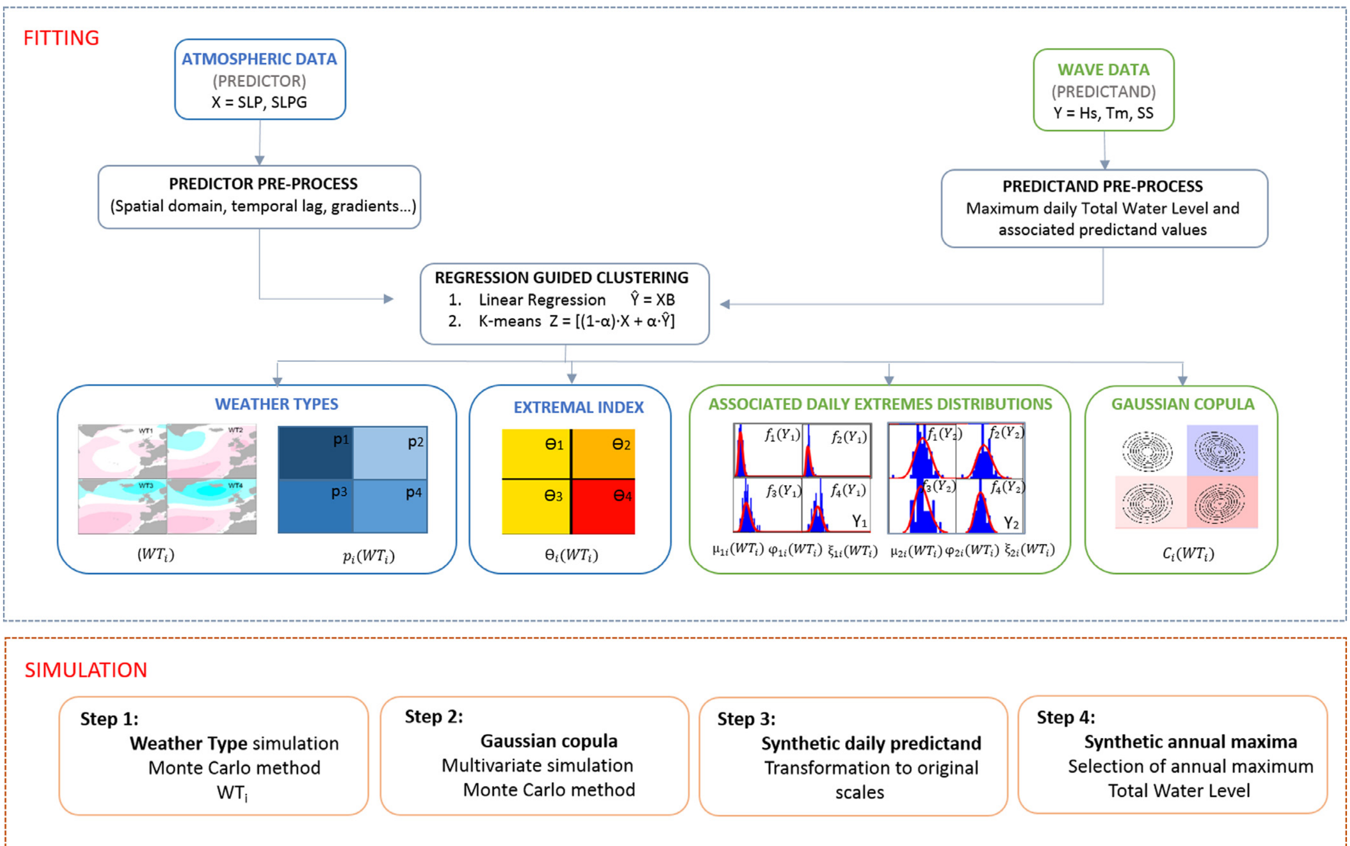

Fig. 1. Proposed methodology to obtain a multivariate climate-dependent extreme model.

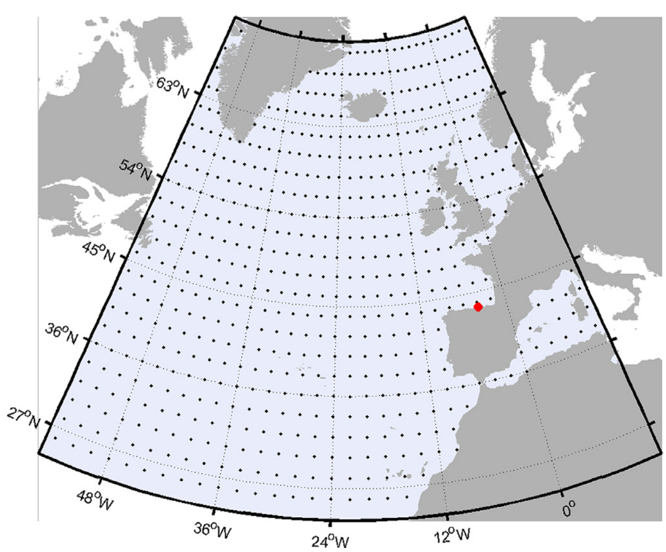

Fig. 2. Selected spatial domain of SLP predictor (black points). The red point shows the study site at Santander (Spain). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of wave climate. Based on these daily predictors, Camus et al. (2014b) presented a weather-type statistical downscaling framework for wave climate at daily scale. Statistical-downscaling methods based on weather types typically apply regional-scale predictors such as a collection of SLP patterns to estimate the local predictand, e.g. wave height, mean period and/or wave direction. Other applications of weather-types methods allow downscaling of multivariate directional spectra (Espejo et al., 2014) and precipitation extremes (Garavaglia et al., 2010).

In this paper, we propose a weather-types framework (Camus et al., 2014b) to model daily multivariate events using Generalized Extreme Value (GEV) marginal distributions for each predictand variable and Gaussian copulas for the correlation between variables. The statistical dependence between consecutive days is addressed by defining a climate-based extremal index for each weather type. We use the coastal flooding index, TWL, to characterize the extremeness of the compound events.

A benefit of the weather-type framework is the ability to trace back weather patterns responsible for large local flooding events. The water level contribution from the astronomical tide is deterministic, and the surge-tide interaction practically negligible in the area of study, therefore it is not considered in this paper. However, the framework could be easily extended to consider time scales of variability of the astronomical tide (e.g. seasonal, spring-neap, 4.4-yr, 8.85-yr and 18.6-yr cycles) and its inclusion in the Monte Carlo simulation of the hydraulic boundary conditions.

The paper is organized as follows: Section 2 describes the methodology, Section 3 presents the application of the method, and finally, Section 4 contains the summary and the conclusions.

2. Methodology

The proposed methodology is an extension of Rueda et al. (2016) to multivariate analysis. The methodology is composed of several steps:

1. Collect and pre-process historical data of predictor (SLP) and predictands (Hs, Tm, and SS).
2. Define weather types from synoptic SLP patterns.