Applied Ocean Research 65 (2017) 192–205

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Multivariate statistical modelling of future marine storms

J. Lin-Ye[a,*], M. García-León[a], V. Gràcia[a], M.I. Ortego[b], P. Lionello[c], A. Sánchez-Arcilla[a]

[a] Laboratory of Maritime Engineering, Barcelona Tech, D1 Campus Nord, Jordi Girona 1-3, 08034 Barcelona, Spain
[b] Department of Civil and Environmental Engineering, Barcelona Tech, C2 Campus Nord, Jordi Girona 1-3, 08034 Barcelona, Spain
[c] Centro Euro-Mediterraneo sui Cambiamenti Climatici, Via Augusto Imperatore, 16, Lecce, Italy

ARTICLE INFO

Article history:
Received 6 February 2017
Received in revised form 4 April 2017
Accepted 12 April 2017

Keywords:
Wave storm
Catalan Coast
Hierarchical Archimedean copula
Generalized Pareto distribution
Non-stationarity
Generalized additive model

ABSTRACT

Extreme events, such as wave-storms, need to be characterized for coastal infrastructure design purposes. Such description should contain information on both the univariate behaviour and the joint-dependence of storm-variables. These two aspects have been here addressed through generalized Pareto distributions and hierarchical Archimedean copulas. A non-stationary model has been used to highlight the relationship between these extreme events and non-stationary climate. It has been applied to a Representative Concentration Pathway 8.5 Climate-Change scenario, for a fetch-limited environment (Catalan Coast). In the non-stationary model, all considered variables decrease in time, except for storm-duration at the northern part of the Catalan Coast. The joint distribution of storm variables presents cyclical fluctuations, with a stronger influence of climate dynamics than of climate itself.

1. Introduction

Extreme events characterization is a key piece of information for an efficient design and construction of any coastal infrastructure. Natural extreme events, such as hurricanes, tsunamis or earthquakes, can lead to considerable economic losses [64]. From all these hazards, marine storms cause most of the damage to non-seismic coasts. This situation may eventually be aggravated as a consequence of Climate-Change, which affects the intensity and frequency of extreme wave-conditions [82,33].

Changes in climate can affect several coastal hazards: flooding [34,80], erosion [35,9,44], harbour agitation [62,66] and overtopping [65]. A robust statistical characterization of storms is, thus, required to assess coastal risks and to forecast storm impacts [60,29]. The stationary climate assumption, common approach in the last decades for designing infrastructures, does no longer hold valid in a context of Climate-Change. Hence, there is a pressing urge for methodologies that consider non-stationarity, not only in trends, but also in higher statistical moments such as variance.

Usual statistical distributions for extremes such as the Generalized Pareto Distribution (GPD) or the Generalized Extreme Value distribution have three parameters: location, scale and shape. Rigby and Stasinopoulos [55] proposed a generalized additive model for these three parameters to predict river flow-data from temperature and precipitation on the Vatnsdalsa river (Iceland). Yee and Stephenson [83] developed a methodology that allows extreme value distributions to be modelled as linear or smooth functions of covariates. One of the examples they presented was the modelling of rainfall in Southwest England. Du et al. [15] carried out frequency analyses using meteorological variables, where they tested several combinations of co-variates with generalized additive models for location, scale and shape, and concluded that meteorological co-variates improve the characterization of non-stationary return periods. Méndez et al. [47] used a time-dependent generalized extreme value distribution to fit monthly maxima series of a large historical tidal gauge record, allowing for the identification and estimation of time scale such as seasonality and interdecadal variability. Méndez et al. [48] extended the former methodology to significant wave-height, while considering the effect of storm duration.

For design purposes, the most analysed variable in marine storms is the significant wave height (H_s), usually considered to be independent from other wave storm-components such as peak-period (T_p), or storm-duration (D). Nevertheless, these variables are known to be semi-dependent [14]. Univariate analyses on singular variables, such as H_s, cannot thus describe coastal processes adequately [59], leading to misestimation of coastal impacts and risks.

The relationship among storm variables can be modelled with statistical techniques such as parametric probability distributions [19], asymptotic theory [86], joint modelling [5], or copulas [25,74], among other techniques. Copulas were proposed by Sklar [67], and

---

[*] Corresponding author.
E-mail address: jue.lin@upc.edu (J. Lin-Ye).

http://dx.doi.org/10.1016/j.apor.2017.04.009

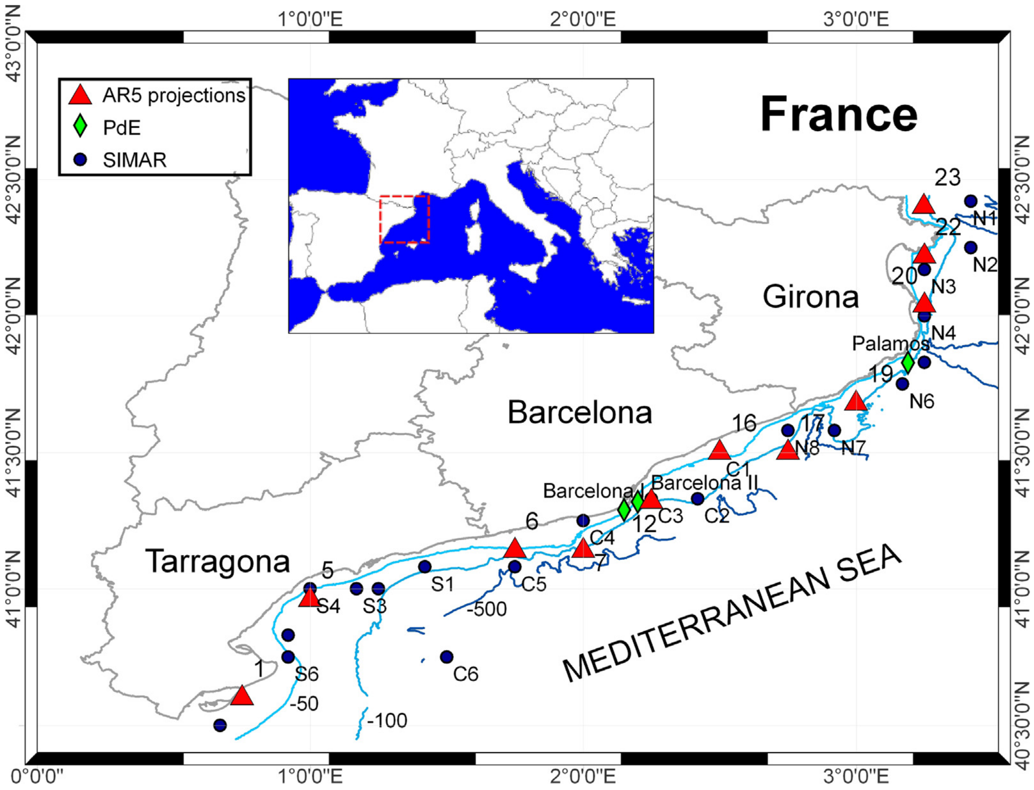

Fig. 1. Map of the Catalan Coast, area located in the northwestern Mediterranean. The bathymetry is in meters, showing how all nodes where the proposed model applies (AR5 nodes) are in deep water, except nodes 1 and 16. AR5 nodes are represented by red triangles, buoy (PdE) nodes are green rhombuses, and SIMAR nodes are solid black points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

have recently attracted attention from coastal engineers [13,58]. Wahl et al. [79] applied fully nested Archimedean copulas to wave storms off the German coast. They first characterized the highest energy point and its intensity and then incorporated the significant wave height. Complementary to these methodologies, Gómez et al. [28] has implemented a time varying copula to analyse the relationship between air temperature and glacier discharge, which is non-constant and non-linear through time. In this case, both marginal and copula parameters depend on time, and a full Bayesian inference has been applied to obtain these parameters.

Based on this, the present work characterizes the extreme wave climate under a Representative Concentration Pathway 8.5 Climate-Change scenario (RCP8.5, i.e. an increase of the radiative forcing values by year 2100 relative to pre-industrial values of 8.5 W/m^2; Stocker et al. [68]) for a fetch-limited environment (Catalan Coast). The study is based on a set of geographical nodes which are equidistant along the Catalan Coast. Only eleven nodes out of the total twenty-three are used in this paper, since they represent well the main features and spatial variability of the storm distributions (see Fig. 1, red triangles). Two of the eleven nodes are in intermediate waters, while the rest are in deep waters. The subsequent analysis is performed assuming, first, stationary, and then, transient conditions.

Section 3 describes the methodology and the theoretical background. Section 2 presents the study area. Section 4 lists main results, which are discussed in Section 5. The conclusions are summarized in Section 6.

2. Study area

The Mediterranean Sea (see Fig. 1) is a semienclosed basin, constrained by the European, Asian and African continents. It has a narrow connection to the Atlantic Ocean (Gibraltar Strait), as well as an access to the Black Sea. In terms of waves, the Mediterranean Sea can be splitted into different partitions [46]. This paper deals with the Catalan Coast, which can be found at the northwestern Mediterranean sector. This area has, as its main morphological features, (a) mountain chains which run parallel and adjacent to the coast, (b) Pyrenees Mountains to the north, and (c) the Ebre river valley to the south. These orographic discontinuities, along with the major river valleys, serve as channels for the strong winds that flow towards the coast [30].

The most frequent and intense wind in the Catalan Coast is the Tramuntana (north), appearing in cold seasons. It is the major forcing for the northern and central Catalan Coast waves. However, from latitude 41° N southward, the principal wind direction is the Mistral (northwest), which is formed by the winds that flow downhill the Pirinees or between the gaps of the mentioned mountains. A secondary wind, the Ponent (west), comes from the depressions in northern Europe. It is the second most frequent one, with limited intensity. Eastern winds are the ones with larger fetch for intense sheer stress, corresponding to low pressure centres over the northwestern Mediterranean. During the summer, there are southern sea-breezes and eastern winds, triggered by an intense high-pressure area on the British Islands.

The northwestern Mediterranean Sea is a fetch-limited environment, primarily driven by wind-sea waves [6,62]. The distance that waves travel, from the storm genesis to the Catalan Coast, is at most one-sixth that of a wave that reaches the Atlantic European coasts [24]. Therefore, the corresponding wave-periods, in the northwestern Mediterranean, are much shorter.

The present climate presents a mean significant wave height $\bar{H}_s$ of 0.72 m from Barcelona City northward, and 0.78 m southward. Maximum H_s ranges between 5.48 m in the southern coast to 5.85 m at the northern coast [61,6]. Casas-Prat and Sierra [10] projected future wave climate at the Catalan Coast through Regional Circula-