



Spatio-temporal modelling of extreme wave heights in the Mediterranean Sea



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ABSTRACT

This study reveals characteristics of the Mediterranean Seas wave climate by illustrating the results of a spatial assessment of extreme significant wave heights. The assessment was based on a 37-year wind and wave hindcast database covering the entire area at 10-km resolution. A point-wise GEV (Generalized Extreme Values) model was employed to generate the assessments results. Overall, the spatial model proved capable of providing an accurate description of extreme return levels of significant wave heights and their spatial variability, especially on a basin-wide scale and with greatest precision on the mesoscale. However, return level estimates are found less reliable in certain coastal areas because the traditional point-wise approach is not refined enough to address the entire wave spectrum of an area as complex as the Mediterranean Sea. Therefore, MSLP (Mean Sea Level Pressure) fields were incorporated as covariates to improve localized assessment. These covariates represent meteorological forcing and allow analysis of the role of different cyclonic regimes in defining wave features and their spatial variability. Finally, the broad temporal span and high spatial resolution of the hindcast database allow for EOF (Empirical Orthogonal Function) and CCA (Canonical Correlation Analysis) analysis of wind and waves fields. This analysis validates spatial wave distribution assessment, revealing that the main processes governing the Mediterranean Seas wave climate can be attributed to four main modes.

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1. Introduction

The modelling of spatial extremes of geophysical variables represents a complex framework both in terms of statistical approach employed and in terms of the availability of datasets with high spatio-temporal resolution. Several studies focusing on spatial extremes have been carried out making use either of spatial interpolation techniques or multivariate methods providing directly return levels. Among the latter, for instance (Padoan et al., 2010; Padoan, 2013) make use of max-stable processes (Pickands, 1981; Haan, 1984), which can be considered as an extension to the infinite-dimensional setting, similarly to Buishand et al. (2008), while Bayesian extreme value models are applied by Cooley et al. (2007), Davison et al. (2012), Shaby and Reich (2012) and Fuentes et al. (2013). In Gardes and Girard (2010) a nearest neighbour estimators method is employed.

On the contrary, methods based on smoothing or interpolation techniques have been largely used, as done by Szolgay et al. (2009),

Blanchet and Lehning (2010), Sang and Gelfand (2010), while in Carreau and Girard (2011) a weighted log-likelihood approach is adopted. In Ceresetti et al. (2012) a kriging method based on neural network interpolation is described. Another approach is that of regional frequency analysis, as performed by Weiss et al. (2014) when analyzing extreme significant wave heights.

The need to adopt high-resolution downscaled wind fields is of crucial importance for the proper modelling of wave climate and wave extremes, especially on a spatial scale; indeed, a coarse wind input can lead to missing sharp wave features which unavoidably translates into underrated return level estimates concerning of significant wave heights (Cavaleri and Bertotti, 2003; Lionello et al., 2008; Cavaleri, 2009; Sartini et al., 2016). As a consequence, the use of suitable high-resolution wind forcing is essential for wave modelling in closed or semi-closed areas with basins and complex coast distribution responsible for diversified wave features (Cavaleri and Bertotti, 2004).

The present study is conceived within this framework in order to study spatial variability exhibited by extreme significant wave heights in the entire Mediterranean Sea and to improve the understanding of processes governing wave climate in the area, based on

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37 years of high resolution wave hindcast dataset. More precisely, in the present contribution we investigate the following topics: i) the wave climate assessment of extreme significant wave heights in the Mediterranean Sea on the basis of spatial extremes; ii) the performances of different spatio-temporal models and iii) the role carried out by meteorological forcing in defining spatial extremes at basin scales.

Indeed, the modelling of spatial extremes in such a complex area requires the involvement of different temporal-spatial scales in order to ensure an exhaustive representation of wave climate. The study employed both a point-wise and a spatial model to evaluate the influence of possible spatial dependencies from a defined covariate in solution reliability. Since spatial effects can be assessed in terms both of basin scale and local one, it can be reasonably assumed that both the high temporal and the spatial resolution of wave hindcast data here employed in relation to the computational domain size can ensure that average spatial effects are captured. In this way the marginal distribution variability over the whole area of study is characterized properly, while local spatial effects will require the adoption of a suitable dependence function. Furthermore, the effect of inference statistics has been described by covariance structures incorporated into the spatial model.

The manuscript is organized as follows: first, a brief description of wave hindcast data and models is provided in Section 2.1. Results provided by point-wise and spatial models are discussed on the basis of spatial assessment reliability in Sections 3.1–3.3; the role of meteorological forcing is also presented in Section 2.3 as well as some findings on the area's general wave climate. Finally, some conclusion are given and discussed.

2. Methods

2.1. Waves and weather hindcast data

To perform the study, a 37-year wave/wind hindcast reanalysis database spanning the years 1979 to 2015 at and hourly frequency covering the whole Mediterranean basin at about 0.1° resolution in longitude and latitude was employed. More precisely, the database was produced by means of an integrated modelling chain developed at the University of Genoa and used for several applications (including operational forecasts, see <http://www.dicca.unige.it/meteocean/>); it consists of the non-hydrostatic mesoscale atmospheric model Weather Research and Forecast (WRF-ARW) version 3.3.1 (Skamarock et al., 2008) for wind downscaling and the third generation wave model WavewatchIII, version 3.14 (Tolman, 2009). A 10-km resolution Lambert conformal grid, covering the Mediterranean Sea, Southern Europe and Northern Africa, was adopted to downscale the atmospheric reanalysis fields with the WRF-ARW model. Specifically, initial and boundary conditions for WRF simulations were obtained by the CFSR (Climate Forecast System Reanalysis) global reanalysis database (Saha et al., 2010) at 0.5° × 0.5° horizontal resolution (corresponding to about 50 km), on 37 pressure levels. Full details about the WRF-ARW model setup as well as the parameterization schemes adopted are given in Mentaschi et al. (2015). The wind fields provided by the WRF model were used to drive WaveWatchIII simulation, on a computational domain covering the Mediterranean Sea with a regular grid at 0.1273 × 0.09 degrees resolution, corresponding to approximately 10 km at 45°N latitude. Wave hindcast validation (Mentaschi et al., 2015) was performed by means of buoys data provided by RON (Rete Ondametrica Nazionale) and by REDEXT (Red Exterior) (Fig. 1, panel 1), while the atmospheric component of the modelling chain was used and assessed for several applications (Bove et al., 2014; Casola et al., 2015). Further validation concerning the reliability of wave hindcast database in performing robust wave climate assessment regarding extreme return values was achieved by using buoy

field data (Sartini et al., 2015b) and other wave hindcast databases (Sartini et al., 2016).

2.2. The models

2.2.1. The point-wise model

Generalized Extreme Value (GEV) distribution (Coles, 2001) was employed in a non-stationary version (Menéndez et al., 2009; Izaguirre et al., 2010; Mínguez et al., 2010) to model monthly maxima of significant wave heights.

The model relies on the assumption that maxima are independent and identically distributed; thus, given a Z_n as an independent maxima sample over n observations, the GEV non-exceedance probability is given by:

$$F(z) = \begin{cases} \exp \left\{ - \left[1 + \xi(t) \left(\frac{z - \mu(t)}{\psi(t)} \right) \right]_+^{-1/\xi(t)} \right\} & \xi(t) \neq 0 \\ \exp \left\{ - \exp \left[- \left(\frac{z - \mu(t)}{\psi(t)} \right) \right] \right\} & \xi(t) = 0, \end{cases} \quad (1)$$

where $\mu(t) > 0$, $\psi(t) > 0$ and $\xi(t)$ represent respectively time-dependent location, scale and shape parameters expressed as harmonics containing both periodic contribution representing seasonal effects, long-term trends in linear form and covariate effects, as described in Mínguez et al. (2010) and Sartini et al. (2015a). More precisely, the shape parameter governs the tails behaviour of the distribution, where the sub-families described by $\xi(t) = 0$, $\xi(t) > 0$ and $\xi(t) < 0$ follow into the distributions:

- Gumbel or type I extreme value distribution

$$F(x; \mu(t), \psi(t), 0) = e^{-e^{-(x-\mu(t))/\psi(t)}}, \quad (2)$$

- Fréchet or type II extreme value distribution

$$F(x; \mu(t), \psi(t), \xi(t)) = \begin{cases} e^{-y^{-\xi(t)}} & y > 0 \\ 0 & y \leq 0 \end{cases} \quad (3)$$

where $y = 1 + \xi(t)(x - \mu(t))/\psi(t)$

- Reversed Weibull or type III extreme value distribution

$$F(x; \mu(t), \psi(t), \xi(t)) = \begin{cases} e^{-(-y)^{\xi(t)}} & y < 0 \\ 1 & y \geq 0 \end{cases} \quad (4)$$

where $y = -(1 + \xi(t)(x - \mu(t))/\psi(t))$.

Three harmonics were introduced in order to model the annual, the semi-annual and the quarterly cycle within a year for location $\mu(t)$ and scale $\psi(t)$ parameters, while constituents have been limited to the second order for the shape one $\xi(t)$. Parameters estimate are assessed by means of the likelihood method.

Return levels of significant wave heights corresponding to a given probability of non-exceedance $1-q$ and a time span $[t_a, t_b]$ are obtained by integrating

$$1 - q = \exp \left\{ -k_m \int_{t_a}^{t_b} \left[1 + \xi(t) \left(\frac{\bar{x}_q - \mu(t)}{\psi(t)} \right) \right]^{-1/\xi(t)} dt \right\}, \quad (5)$$

where $1/k_m$ is the length of time-block maxima and $\mu(t)$, $\psi(t)$, $\xi(t)$ are the time-dependent GEV parameters.

2.2.2. The spatial model

In the present work a simple multivariate GEV model was used for performing spatial extremes on monthly maxima of significant wave heights. Basically, by restricting the attention to a two-dimensional problem, since one covariate per simulation was considered, the vector of componentwise maxima is defined as:

$$M_n = (M_{x,n}, M_{y,n}) \quad (6)$$

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