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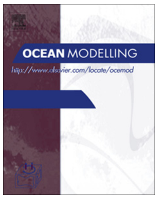

A physical-based statistical method for modeling ocean wave heights

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ABSTRACT

This study proposes a computationally inexpensive statistical method for modeling ocean wave heights, focusing particularly on modeling wave heights in near-shore areas. A multiple linear regression is used to predict significant wave heights (H_s) using predictors derived from the sea level pressure (SLP) field, including the use of squared SLP gradients to represent geostrophic winds. One time step lagged H_s is also included as a predictor, which could be interpreted as the first order derivative in the spectral energy balance governing equation. Further, based on the frequency/directional dispersion theory of waves, the swell component is accounted for by using a set of selected principal components derived from the squared SLP gradient vectors (including magnitudes and directions). The effect of non-Gaussian (non-negative) variables is also assessed by applying two types of transformation to the data.

The proposed method is evaluated and shown to have good skills for the study area (Catalan coast). This method can be used to project possible future wave climate change for use in coastal impact assessment studies. It is used in this study to project the wave climate for the study area that corresponds to 5 sets of regional climate model (RCM) atmospheric projections, which were made by different RCMs forced by the same global circulation model (GCM), or by the same RCM forced by two GCMs. For the season analyzed (winter), the results show that the uncertainty due to using different GCMs to drive the same RCM is greater than that due to using different RCMs driven by the same GCM.

1. Introduction

Nowadays, climate change is a hot research topic because of its possible impacts on our society and on the environment in the near future. The greenhouse effect might contribute not only to an increase of the global temperature, but also to changes in the atmospheric pressure and wind patterns at both global and regional scales, affecting the frequency and intensity of storms at a given location (e.g. Bengtsson et al., 2006, 2007, 2009; Weisse and von Storch, 2010). Changes in any characteristics of storms will affect ocean wave climate both locally (wind-sea) and remotely (swell waves). This might produce several coastal impacts such as a possible increase of coastal erosion, inundation, structure failure, decrease of harbour operability, etc. (e.g. Casas-Prat and Sierra, 2012; Hemer, 2009; Slott et al., 2006; Zacharioudaki and Reeve, 2011). In this context, the IPCC (2000) established different greenhouse gas emission scenarios. Several regional and global circulation models (RCMs and GCMs) have been developed and used to project changes in the atmosphere patterns (temperature, pressure, wind, precipitation, etc.) and to estimate the sea level rise corresponding to these scenarios. However, even in the IPCC fourth assessment report (IPCC, 2007) limited attention has been paid to wave climate projections, especially on regional scales that are essential to perform coastal impact assessment.

Average population densities are significantly higher in the near-coastal zone than inland areas (Small and Nicholls, 2003). Thus, evaluating the impact of climate change on coastal areas where wave climate plays an important role, is of great importance. To infill this gap, in the recent years some studies have been carried out to project future wave climate conditions using numerical wave models forced by surface winds as simulated in RCMs and GCMs. Some examples are: Mori et al. (2010), Hemer et al. (2013a,b) and Semedo et al. (2011, 2013) at the global scale and Lionello et al. (2008), Grabemann and Weisse (2008), Charles et al. (2012), Hemer et al. (2012) and Casas-Prat and Sierra (2013) at a regional scale. This approach, named "dynamical downscaling" is very time-consuming; and many combinations have to be taken into account in order to consider all the sources of uncertainty (greenhouse scenario, inter-model variability… see Déqué

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et al. (2007) for more details). Thus, statistical downscaling approaches have been developed as an alternative for making projections of wave climate (e.g. Callaghan et al., 2008; Camus et al., 2011; Gunaydin, 2008; Mori et al., 2013; Wang and Swail, 2006; Wang et al., 2010). This method is based on building an empirical relationship between atmospheric variables and wave climate parameters using observations or reanalysis data, and assumes that this relationship will hold under the projected future climate conditions. Although the physical processes are notably simplified with a more or less simple relationship, if the main wave features are properly captured, comparable (or even better) results can be obtained when compared to dynamical downscaling (Wang et al., 2010). Apart from the significant reduction of required computational time and memory, the statistical approach has the advantage of being flexible regarding the selection of the forcing variable(s). For example, one can use atmospheric variables that are well simulated by climate models, such as sea level pressure, as predictors to project ocean waves (Wang et al., 2010); whereas for a numerical wave modeling one has to use the 10-m wind data, although they are usually not as well simulated by climate models (e.g. McInnes et al., 2011).

Wang and Swail (2006) and Wang et al. (2010) used a multiple linear regression to represent the relationship between the predictand, significant wave height (H_s), and two SLP-based predictors that mainly represent local wave generation. They obtained reasonably good results at the global and the North Atlantic scales but the swell component of waves is insufficiently represented in their model. Wang et al. (2012) recently developed a more skillful model which accounts for the swell component by using the principal components (PCs) of the aforementioned SLP-based predictors and lagged values of the predictand. In this study, we aim to improve the representation of swell in the model, focusing on modeling (deep water) near-shore regional waves with finer spatial (0.125°) and temporal (3 h) resolutions that are suitable for studying regional coastal impacts of climate change and adaptation. Based on the work of Wang and Swail (2006) and Wang et al. (2010, 2012), we develop a new approach taking into account the physical theory of directional and frequency decomposition of swell waves (e.g. Holthuijsen, 2007). The new model is then applied to 5 sets of projections of the atmosphere by four different RCMs (forced by one or two GCMs; see Table 1), to explore the inter-model variability and to project future changes in wave climate, as done by Casas-Prat and Sierra (2013) with dynamical downscaling.

The study area is situated in the NW Mediterranean Sea, focusing on the Catalan coast (highlighted in red in Figs. 1 and 2). The new method is therefore adapted to the features of this zone, providing the area with a range of wave projections that are of sufficiently high spatial and temporal resolutions for coastal impact assessments in the context of climate change. In general, we aim to develop a computationally inexpensive method of general applicability. Thus, our method can easily be adapted for use in other regions.

The remainder of this paper is structured as follows. Section 2 describes the main features of the atmospheric and wave climate of the study area, and Section 3, the datasets used to calibrate and validate the statistical model and to project the future wave climate conditions in this area. Section 4 describes how the statistical method is developed and applied to the study area. Along with some discussion, Section 5 presents the results of model evaluation, and future wave projections are discussed in Section 6. Finally, Section 7 summarizes the main conclusions of this study, along with some discussion.

Table 1
Subsets of SLP data used to project H_s.

Acronym	RCM	GCM	$\Delta t(h)$
HIR_E	HIRHAM5	ECHAM5	1
RAC_E	RACMO2	ECHAM5	3
REM_E	REMO	ECHAM5	1
RCA_E	RCA3	ECHAM5	3
RCA_H	RCA3	HadCM3Q3	3

2. Study area

Although we focus on the wave climate along the Catalan coast, in order to account for swell waves (see Section 2.2), a larger domain (than merely the Catalan sea area) is considered as the “study area”, which is illustrated with a black square in Fig. 1 and shown enlarged in Fig. 2. In determining the boundaries of this study area, we consider: (1) the maximum fetch affecting the Catalan coast and (2) the shadow effects produced by the Balearic islands (more details in Section 2.2). We will produce therefore wave climate projections for the whole study area (not only for the Catalan coast). However, the results are less reliable/accurate for grid points near the domain boundaries, especially those that are close to the Gibraltar strait, since no exchange with the Atlantic Ocean is considered in the datasets used.

Having a better knowledge of the main aspects of atmospheric and (corresponding) wave climate is important to better design the statistical model, and to properly interpret the modeling results. Therefore, a review of those aspects has been undertaken and is presented in the subsections below.

2.1. Atmospheric climate

Several reviews and studies have been carried out in the recent years in order to better describe the characteristics of the complex Mediterranean climate (e.g. Bolle, 2003; Campins et al., 2011; Lionello et al., 2006; Nissen et al., 2010). Like other areas in a similar latitude, the Mediterranean region is a transitional zone with a large environmental meridional gradient between humid mountains in the North and hot and arid regions in the South and is affected by both tropical and mid-latitude systems (Campins et al., 2011; Lionello et al., 2006). However, the presence of a relatively large and deep mass of water makes the Mediterranean quite unique (Bolle, 2003), ranging its orography from depths to altitudes of the order of 5000 m and being communicated to the Atlantic through the Gibraltar strait. This water mass not only represents a heat reservoir and source of moisture for land areas but is also a source of energy that can be transformed into cyclone activity (Lionello et al., 2006). According to Nissen et al. (2010), 69% of the wind storms are caused by cyclones (low pressure systems) located in the Mediterranean region while the remaining 31% have their origin in the North Atlantic or Northern Europe.

Although forced by planetary scale patterns, the complexity of the basin (e.g. sharp orography) produces many subregional and mesoscale features with a large spatial and seasonal variability (Campins et al., 2011). Winter and summer have contrasting patterns because of the different cyclogenetic mechanisms taking place (Campins et al., 2011). Therefore, statistical analysis of climate data should be preferably performed for each season separately. During summer, cyclones/heat-lows are short-lived, weak and shallow, mainly caused by thermal contrasts and orographic effects (Campins et al., 2011). On the contrary, during winter, cyclones are well-developed depressions and tend to be deeper, longer-lived, more mobile and intense. Spring and autumn can be considered as transitional seasons between both extremes (Campins et al., 2011). Their different physical origins turn into different spatial distributions of low pressure system centres as well.