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High resolution downscaled ocean waves (DOW) reanalysis in coastal areas

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ABSTRACT

Large-scale wave reanalysis databases (0.1°–1° spatial resolution) provide valuable information for wave climate research and ocean applications which require long-term time series (>20 years) of hourly sea state parameters. However, coastal studies need a more detailed spatial resolution (50–500 m) including wave transformation processes in shallow waters. This specific problem, called downscaling, is usually solved applying a dynamical approach by means of numerical wave propagation models requiring a high computational time effort. Besides, the use of atmospheric reanalysis and wave generation and propagation numerical models introduce some uncertainties and errors that must be dealt with. In this work, we present a global framework to downscale wave reanalysis to coastal areas, taking into account the correction of open sea significant wave height (directional calibration) and drastically reducing the CPU time effort (about 1000×) by using a hybrid methodology which combines numerical models (dynamical downscaling) and mathematical tools (statistical downscaling). The spatial wave variability along the boundaries of the propagation domain and the simultaneous wind fields are taking into account in the numerical propagations to performance similarly to the dynamical downscaling approach. The principal component analysis is applied to the model forcings to reduce the data dimension simplifying the selection of a subset of numerical simulations and the definition of the wave transfer function which incorporates the dependency of the wave spatial variability and the non-uniform wind forcings. The methodology has been tested in a case study on the northern coast of Spain and validated using shallow water buoys, confirming a good reproduction of the hourly time series structure and the different statistical parameters.

1. Introduction

Wave retrospective analysis or *reanalysis* databases have become a powerful source of information for wave climate research and ocean applications over the last decades. These databases have good spatial coverage and provide continuous time-series of offshore wave parameters, over significant periods of time (more than 40 year-long), allowing the description of wave climate in locations where instrumental data is unavailable. However, i) they are not quantitatively perfect, ii) waves are poorly described at shallow water areas because the spatial resolution is not sufficiently detailed and iii) wave transformations due to the interaction with the bathymetry are not usually modeled.

The first problem related to the inaccuracy of the reanalysis wave data is corrected by means of calibration methods using instrumental observations (Mínguez et al., 2011a). The two other ones require modeling of the transformation processes and the increase of the spatial resolution (Camus et al., 2011b). This process, known as downscaling, is extremely important for design purposes in coastal engineering or for the evaluation of coastal wave energy resources.

Three different downscaling methods have been proposed: i) a dynamical approach consisting of nesting a wave propagation model for coastal areas which simulates wave transformation processes (refraction, bottom friction, shoaling, diffraction, breaking) from deep water to shallow water (Rusu et al., 2008); ii) a statistical approach establishing an empirical relationship between open ocean significant wave heights and a nearshore significant wave height in shallow water (e.g. using artificial neural networks, Browne et al., 2007; Kalra et al., 2005); iii) a hybrid approach which combines dynamical downscaling (numerical models) and statistical downscaling (an interpolation scheme, neural networks) in order to reduce the computational effort.

Dynamical downscaling is the most accurate approach providing a long time series with high spatial and temporal resolutions which allow a better statistical characterization of wave climate and extreme wave analysis. Statistical relations can be an effective method for nearshore height estimation with a little computational effort and an easy implementation. In applications where many simplifications must be adopted in numerical calculations due to the open ocean forcing and the bathymetry information available, the statistical methods can be more accurate than the numerical models (Browne et al., 2007). However, the main drawback is the requirement of coastal wave records at the location of interest to define the statistical model. Regarding hybrid methodologies, the most common

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ones consist of developing a transfer function for the transformation of offshore wave conditions to nearshore locations through the numerical propagation of a number of sea state conditions which characterize deep water wave climate (dynamical downscaling), see for instance Groeneweg et al. (2007) and Stansby et al. (2007). The representative cases are defined by means of several combinations of offshore wave and/or wind conditions at a specific location, without considering the spatial variability of these forcings. In order to correctly define the transfer function, a large number of sea states need to be simulated numerically, especially if the number of offshore wave parameters increases and therefore, the number of parameter combinations (Chini et al., 2010). Breivik et al. (2009) defined a linear downscaling based on 1-year hourly dynamical simulations, nested to the outputs of a third-generation wave model and forced by high resolution winds. However, the coastal wave height is estimated by means of a simpler linear relation with the height at a coarse-resolution open-ocean reanalysis grid, including the wave direction dependency via the definition of four regression models corresponding to four different directional sectors.

In addition to these hybrid methods, more sophisticated methodologies have been developed to obtain high resolution nearshore wave statistics. Galiskova and Weisse (2006) proposed three different statistical models based on linear regression, canonical correlation analysis and analogs to define a relation between instantaneous medium-scale wave fields from a hindcast database and higher resolution wave data in shallow water obtained dynamically. The empirical relations established are used to reconstruct certain percentiles of the significant wave height. Another statistical–dynamical approach, developed by Herman et al. (2009), uses a combination of a numerical model, principal component analysis and a neural-network method. This methodology reconstructs the spatial wave fields in shallow water as a function of the wave conditions, wind conditions and the sea level at a certain location because the forcings are highly uniform in the study area. These two methodologies require propagating several years of dynamical downscaling to generate the statistical model and its validation (Galiskova and Weisse, 2006; Herman et al., 2009).

The hybrid methodology proposed in Camus et al. (2011b), hereafter CMM, consists of the selection of a small number of representative wave conditions at deep water using the Maximum Dissimilarity Algorithm (MDA, see the analysis of selection algorithms of multivariate sea states presented in Camus et al., 2011a), the propagation of the selected cases using any state-of-the-art wave propagation model and the reconstruction of the wave time series at shallow water by means of the interpolation algorithm based on the radial basis functions (RBFs). The computational time required is significantly less than the other hybrid methodologies proposed because MDA covers the whole diversity of the offshore conditions with a reduced number of cases. Moreover, the RBFs allow establishing the statistical relation as a function of more offshore parameters.

The aim of this paper is to develop a methodology to generate hourly coastal wave time series trying to emulate the characteristics of the coastal wave reanalysis databases obtained by means of dynamical downscaling but reducing the computational time. In the application that will be shown, the computational time effort is reduced to three orders of magnitude (1000×) compared to the classical non-stationary simulations of a coastal wave reanalysis. The wave climate in deep water is transferred nearshore following the basis of the hybrid CMM methodology. However, in this previous paper, the offshore wave and wind conditions were defined at one location in deep water, assuming uniform forcings. In the present work, the dynamical propagations are nested to the outputs of a global/regional wave model. Therefore, the spatial wave variability along the boundaries of the propagation domain is taken into account and also the simultaneous wind fields in order to consider local wave generation. The CMM methodology needs to be improved and extended to deal with higher dimensional data. Although the MDA and RBF techniques are capable of dealing with multivariate data, the data dimension is reduced applying the principal component analysis (PCA), eliminating the information redundancy and facilitating the selection and the interpolation processes.

The generation of a coastal wave reanalysis database (downscaled ocean waves, DOW) by means of the proposed methodology requires the use of the wind and offshore wave reanalysis databases as forcings in order to obtain high temporal coverage. In this work, the long-term global NCEP/NCAR surface winds (Kalnay et al., 1996) and wave reanalysis GOW (Reguero et al., 2011) are used. Wave reanalysis models are a simplification of reality and they are also forced by discrete fields consisting of surface winds at different times. The wave generation outputs are calibrated to correct the differences when comparing with instrumental data (Mínguez et al., 2011a). Therefore, a global framework is proposed, which includes the previous calibration of the wave reanalysis data in deep water, in order to present a methodology with a wider application.

The proposed global framework and the case study for the application of the methodology are presented in Section 2. The deep water wave reanalysis database is described in Section 3. The steps involved in the proposed methodology: calibration, selection, propagation, and time series reconstruction are described in Sections 4, 5, 6, and 7 respectively. The selection and reconstruction processes are described in more detail because most innovative adaptations of the methodology to generate coastal wave reanalysis database are implemented. The validation of the methodology is detailed in Section 8. Finally, some conclusions are given in Section 9.

2. Global framework

The development of the DOW database implies several steps, which are summarized in Fig. 1. The steps of the proposed global framework are: a) analysis of the reanalysis databases available in the study area b) calibration of the reanalysis databases in deep water with instrumental data; c) selection of a limited number of cases which are the most representative of wave and wind hourly conditions in deep water; d) propagation of the selected cases using a wave propagation model; e) reconstruction of the time series of sea state parameters at shallow water; f) validation of the coastal wave data with instrumental data; and g) characterization of wave climate by means of a statistical technique.

The proposed methodology is applied to the northern coast of Spain (Fig. 2). The GOW Iberia grid with a resolution of $0.5°\times0.5°$, the GOW Cantabrico grid with a resolution of $0.1°\times0.1°$ and the wind NCEP/NCAR database with a spatial resolution of 1.9° are shown in Fig. 2. The instrumental data located in the study area are: Bilbao moored buoys located in deep water at a depth = 600 m and near the coast at a depth = 53 m (belonging to Puertos del Estado), Pasaia acoustic doppler current profiler at a depth = 25 m (belonging to EUSKALMET) and Virgen Mar (depth = 32 m) and Santoña (depth = 28 m) moored buoys (belonging to Vigia Network from the Government of Cantabria). Although there a lot of information available, these data are spatially scarce and discontinuous in time, as can be seen in the time series of the GOW reanalysis gridpoint (marked with a circle) and the time series of the Bilbao buoys (lower panel of Fig. 2) during the year 2006.

The spatial domain has to be defined before applying the proposed methodology. This domain is nested to the outputs of the wave generation model, the GOW reanalysis database in our case study. Stationary wave simulations are assumed in order to consider the subset propagations as independent, which is a requirement of the proposed methodology. Therefore, the domain has to be small enough so that the wave propagation across this area occurs at a faster rate than the change in offshore forcing at the domain boundary. These restrictions are obviously inaccurate for global or basin-scale models but are reasonable for a smaller domain (Rogers