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On the ability of statistical wind-wave models to capture the variability and long-term trends of the North Atlantic winter wave climate

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ABSTRACT

A dynamical wind-wave climate simulation covering the North Atlantic Ocean and spanning the whole 21st century under the A1B scenario has been compared with a set of statistical projections using atmospheric variables or large scale climate indices as predictors. As a first step, the performance of all statistical models has been evaluated for the present-day climate; namely they have been compared with a dynamical wind-wave hindcast in terms of winter Significant Wave Height (SWH) trends and variance as well as with altimetry data. For the projections, it has been found that statistical models that use wind speed as independent variable predictor are able to capture a larger fraction of the winter SWH inter-annual variability (68% on average) and of the long term changes projected by the dynamical simulation. Conversely, regression models using climate indices, sea level pressure and/or pressure gradient as predictors, account for a smaller SWH variance (from 2.8% to 33%) and do not reproduce the dynamically projected long term trends over the North Atlantic. Investigating the wind-sea and swell components separately, we have found that the combination of two regression models, one for wind-sea waves and another one for the swell component, can improve significantly the wave field projections obtained from single regression models over the North Atlantic.

1. Introduction

Changes in wave climate have received much attention in recent years due to their impact on coastal and offshore structures and ecosystems. Numerous wave climate simulations under different future scenarios of greenhouse gases (GHGs) emissions have been generated at both global and regional scales using numerical wave models. The North Atlantic is one of the most widely studied regions. Many earlier works have pointed to changes in wave height climate as a consequence of global warming. For example, Mori et al. (2010) projected future decreases in the wave heights over the North Atlantic at mid-latitudes by using wind fields generated by the MRI-JMA General Circulation Model (GCM) run under the A1B scenario. Likewise, Hemer et al. (2012) projected future decreases in wave heights during winter and changes in wave directions over all the North Atlantic by using the ECHAM5 GCM and CSIRO Mk3.5 GCM wind fields, both under the A2 forcing scenario. Semedo et al. (2013) projected decreases in both wave heights and periods over the North Atlantic during the winter season by using ECHAM5 GCM wind fields under the A1B scenario. Fan et al. (2013) projected decreases of wave heights during winter over the North Atlantic and increases over the north-eastern sector by using a three member ensemble forced by CM2 GCM, HadCM3 GCM and ECHAM5 GCM wind fields under the A1B scenario. In a subsequent paper, Fan et al. (2014) used the same model ensemble to obtain winter trends for the wind-sea and swell components separately. Andrade et al. (2007) projected decreases of wave heights and clockwise changes in wave directions and investigated their effects along the Portuguese coast. More local studies also exist in the region. In particular, Charles et al. (2012) projected very

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similar winter wave height decreases over the Bay of Biscay by using the ARPEGE-Climat GCM under three different future climate scenarios (B1, A1B, A2). All the simulations referred above are based on dynamical models forced with the surface wind fields from atmospheric models. The simulated wave parameters defining the wave climate are significant wave height (SWH), mean wave period (MWP) and mean wave direction (MWD), as well as their separation into local (wind sea) and remotely-forced (swell) waves. Both components can be properly modeled when using global wind-wave models. Regional models can also be suitable to model the swell component, although they require to be nested into larger domains to account for remotely generated swell; in turn, they usually provide higher spatial resolution.

Alternative approaches to explore wave changes in future climates cover a wide variety of statistical methods that can be classified into three main types (Wilby et al., 2004): (i) regression methods, (ii) weather generators and (iii) weather typing schemes. Each method has its own advantages and shortcomings. Briefly, weather generators are stochastic models that replicate the statistical properties of the observed sequences of events, such as mean value and variance (Ailliot et al., 2014; Wilks, 1998). Weather typing schemes establish the relationship between atmospheric and wave parameters based on a division in weather classes, as shown for instance in Camus et al. (2014). Among these, the analogue method (Lorenz, 1969; Zorita and Von Storch, 1999) and the Monte Carlo method are also weather typing methods.

Among the regression methods, the redundancy analysis used by Wang et al. (2004) to simulate future SWH changes is a first example. Some of the most frequently used regression methods are based on transfer functions, which represent the relationship between observed wave parameters, usually SWH, and atmospheric variables such as the squared wind speed ($W = u^2+v^2$), sea level pressure (P) and/or the squared sea level pressure gradient (G) representing the geostrophic wind (that is the sum of the squared zonal and squared meridional SLP gradients). The atmospheric parameters obtained from model output under increased GHG scenarios can then be used to estimate the changes in the wave field through the statistical relationship between them obtained for the present-day period, assuming that such relationship holds also for the future period. Examples of application of such methodology can be found in Wang and Swail (2006), who used global anomalies of P and G as predictors in different regression models to simulate future SWH. Likewise, Wang et al. (2010) compared both dynamical and regression models to simulate future SWH changes over the North Atlantic at hourly (dynamical) and seasonal (statistical) scales. They tested the inclusion of W as a predictor in a set of regression models, but they concluded that it was preferable to use P and G predictors to simulate future changes on SWH due to the bias in the winds produced by the atmospheric models. Wang et al. (2012) and Wang et al. (2014) improved the regression model predictability by establishing a predictor-predict and relationship at 6-hourly time scale and including the lagged-dependent variable and the Principal Components (PCs) of P and G at 6-hourly time scale as predictors, which result in a better representation of the swell. More recently, Casas-Prat et al. (2014) have developed a more complex regression model that better accounts for the swell component to simulate future changes in the wave climate of the Western Mediterranean. In a similar way to atmospheric variables, large scale climate indices can also in principle be used as proxies for the statistical projections of waves (Woolf et al., 2002; Tsimplis et al., 2005; Feng et al., 2014a). The obvious constraint is that they must be correlated for present-day climate with both wind sea and swell wave parameters (Shimura et al., 2013; Martínez-Asensio et al., 2016).

The statistical techniques offer low computational effort relative to dynamical modeling, which in turn permits the generation of larger ensembles resulting in a better understanding and quantification of uncertainties. Wang and Swail (2006) carried out an analysis of the uncertainty in SWH projections over the North Atlantic by running a set of statistical simulations forced with atmospheric variables simulated by three different climate models (CGCM2, HadCM3 and ECHAM4/OPYC3) and three different scenarios (IS92a, A2 and B2) at a seasonal scale. They found that the uncertainty associated with the GCM used to feed the statistical model was much larger than that associated with the emission scenarios covering the period 1990-2049. Recently, Wang et al. (2015) reached the same conclusion by analyzing larger ensembles of statistical projections of 6-hourly SWH using Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations of 6-hourly SLP. Similar conclusions were pointed out by Charles et al. (2012) by comparing their results with those available in the literature. Hemer et al. (2013) went further into the uncertainty analysis by taking into account five independent studies projecting future changes in wave climate (namely those carried out by Wang and Swail, 2006; Mori et al., 2010; Hemer et al., 2012; Semedo et al., 2013; and Fan et al., 2013). They considered a total of four climate scenarios (A2, A1B, B2 and IS92a), six GCMs (ECHAM5, CSIRO-Mk3.5, GFDL-CM2.1, HadCM3, ECHAM4 and CGCM2), an ensemble mean of three CGCM2 simulations produced with different initial conditions, two ensemble means of 18 and 23 CMIP3 members, a set of three dynamical wave models (WaveWatch III, SWAN and WAM), one statistical model and three wave parameters (SWH, MWP and MWD). They found that the method used to obtain regional wave climates (the regional climate model, the downscaling technique, the dynamical wave model approach and the use of different predictors in statistical models) is also a high source of uncertainty.

In our study the performance of a set of transfer function statistical models to project the future wave climate over the North Atlantic Ocean is studied. Our aim is to compare a wide set of these statistical models against a reference dynamical model and quantify their performances. The chosen statistical models are based on some of the most widely used transfer functions; the set was complemented by other, more specific models as well as by models based on large scale climate indices.

A wind-wave hindcast and an atmospheric reanalysis are used to calibrate all the statistical models for the period 1958–2002. Altimetry SWH observations are used to validate both the dynamical and statistical models. Then, the atmospheric output of a climate model (ECHAM5) run under the A1B emission scenario for the period 2000–2100 is used to obtain the changes in the atmospheric parameters used as predictors in statistical models and hence for the prediction of the winter SWH fields of the future. ECHAM5 is considered one of the best CMIP3 GCMs in simulating the recent past climate conditions in terms of inter-annual variability over the North-East Atlantic (Pérez et al., 2014).

The 6-hourly surface winds output from the ECHAM5 climate model is used to force a dynamical regional wave model to project winter SWH, MWP and MWD fields. The differences between the dynamical and statistical approximations of the future wave field as well as their respective limitations are discussed.

The paper is organized as follows: the dynamical and statistical models and their forcing are presented in Section 2. The models are validated for present-day climate in Section 3. Projections of wave climate are presented in Section 4. In the last section results are discussed and conclusions are outlined.

2. Data set and methodology

The set of dynamical and statistical simulations and the procedure to generate all of them is schematically shown in Fig. 1, while the details are given in the sections below.