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Statistical multi-model climate projections of surface ocean waves in Europe

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ABSTRACT

In recent years, the impact of climate change on sea surface waves has received increasingly more attention by the climate community. Indeed, ocean waves reaching the coast play an important role in several processes concerning coastal communities, such as inundation and erosion. However, regional downscaling at the high spatial resolution necessary for coastal studies has received less attention. Here, we present a novel framework for regional wave climate projections and its application in the European region. Changes in the wave dynamics under different scenarios in the Northeast Atlantic Ocean and the Mediterranean are analyzed.

The multi-model projection methodology is based on a statistical downscaling approach. The statistical relation between the predictor (atmospheric conditions) and the predictand (multivariate wave climate) is based on a weather type (WT) classification. This atmospheric classification is developed by applying the k-means clustering technique over historical offshore sea level pressure (SLP) fields. Each WT is linked to sea wave conditions from a wave hindcast. This link is developed by associating atmospheric conditions from reanalysis with multivariate local waves. This predictor–predictand relationship is applied to the daily SLP fields from global climate models (GCMs) in order to project future changes in regional wave conditions. The GCMs used in the multi-model projection are selected according to skill criteria. The application of this framework uses CMIP5-based wave climate projections in Europe. The low computational requirements of the statistical approach allow a large number of GCMs and climate change scenarios to be studied.

Consistent with previous works on global wave climate projections, the estimated changes from the regional wave climate projections show a general decrease in wave heights and periods in the Atlantic Europe for the late twenty-first century. The regional projections, however, allow a more detailed spatial characterization of the projected changes under different climate scenarios. For example, changes in significant wave heights for the RCP8.5 scenario for the 2070–2099 time period indicate a general decrease of about 10 cm in Southern Europe (Portuguese, Spanish and French coasts) with respect to present conditions. This decrease is due to a higher occurrence of dominant and moderate Azores high pressure systems over the North Atlantic Ocean and a decrease in the persistence of intense low pressure systems at high latitudes.

1. Introduction

Reliable estimates of future wave climate parameters (i.e. significant wave height, mean wave period, mean wave direction) are essential for several applications such as coastal planning and design of coastal and offshore structures. Future wave climate is often estimated by extrapolating trends in historical data (e.g. Menendez et al., 2008). This approach, however, does not seem appropriate for the next century. Larger concentrations of greenhouse gases may lead to changes that are not captured in historical trends. In this context, global climate models (GCMs) have become valuable tools to estimate climate changes for different future climate scenarios. However, GCMs do not simulate ocean surface waves. Furthermore, the resolution of GCM-derived surface wind fields is often too coarse to force regional wave models.

There are two different approaches to generate regional wave climate projections. Dynamical downscaling, based on nesting of

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numerical models, is perhaps the most widely used methodology (e.g. Erikson et al., 2015; Hemer et al., 2013a; Mori et al., 2010; Semedo et al., 2013). An alternative approach is statistical downscaling, which can be conducted, for example, by means of regression methods (e.g. Wang et al., 2014) or weather pattern-based approaches (e.g. Camus et al., 2014a). Laugel et al. (2014) showed that statistical projections can reproduce wave climatology as well as dynamical projections. Wang et al. (2010) found substantial similarity between both approaches in projected future changes. However, statistical methods were reported to perform better in reproducing the observed climate and interannual variability. Moreover, dynamical approaches are very computationaly expensive. Therefore, most dynamical wave climate projections studies are based on only one or a few GCMs (e.g. Laugel et al., 2014; Mori et al., 2010; Semedo et al., 2013). On the other hand, statistical approaches are much cheaper, thus, allowing the study of a large number of simulations. Analysis of multiple GCMs and climate scenarios is extremely important because cascading uncertainties can make outputs from two simulations very different. Furthermore, a large ensemble gives more robust projections and a measure of uncertainties (Gleckler et al., 2008).

In this work, a weather type (WT) statistical downscaling for multivariate ocean wave climate is presented. This method is based on a statistical downscaling framework able to reproduce the seasonal and interannual variability of wave climate (Camus et al., 2014a) and takes into account the skill of GCMs to define an optimal ensemble of models (Perez et al., 2014a). Application of this method is demonstrated through wave climate projections in the European region with a spatial resolution up to 0.125° (less than 15 km along the coast).

The paper is presented in five sections. Following the introduction, Section 2 presents the databases (reanalysis, wave hindcast and GCMs) used in this study. Section 3 explains the methodology that has been developed, describing the WT classification, the downscaling technique, and the selection of the ensemble of GCMs. The study is completed with presentation of the results in Section 4 and the conclusions in Section 5.

2. Data

2.1. Historical atmospheric data

Reanalyses are designed to provide global gridded representations of the atmosphere–ocean–land surface–sea ice system over a long historical period of time. The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR, Saha et al., 2010) is a reanalysis dataset that represents an improvement in the field due to its high resolution and advanced data-assimilation techniques. Beginning in 2011, CFSR is extended by NCEP's Climate Forecast System Version 2 (CFSv2, Saha et al., 2014) operational model. We use near-surface winds, ice coverage, and sea level pressure fields from CFSR and CFSv2. CFSR and CFSv2 outputs are available at an hourly time resolution from 1979 onward. Global winds and ice coverage at a horizontal resolution of ~0.3° (~0.2° for CFSv2) were used as forcing for a wave hindcast. SLP fields at a 0.5° horizontal resolution were used to create a WT classification.

2.2. Historical wave data

In this study, we have conducted a wave hindcast from 1979 to 2013 with hourly resolution to provide historical wave data. This hindcast uses WaveWatch III wave model (version 4.18, Tolman, 2014) in a multigrid configuration. The multigrid is composed of several regular grids with two-way nesting: a global grid (1° latitude × 1.5° longitude), a grid covering the Atlantic Ocean (0.5° × 0.5°) and a grid in the area close to the European coastline (0.125° × 0.125°). Small grids covering the archipelagos of Cape Verde, Canary Islands and Azores (0.125° × 0.125°) are also used to improve the modeling of wave shadowing effects. Winds and ice coverage were interpolated from CFSR and CFSv2 data. The bathymetry, land-sea mask, and obstruction grids for unresolved boundaries for each grid were obtained using the automated generation software for WaveWatch III (Chawla and Tolman, 2008). We used this software with etopo1 bathymetry (Amante and Eakins, 2009) and coastlines from the global self-consistent, hierarchical, high-resolution geography database (GSHHG, Wessel and Smith, 1996).

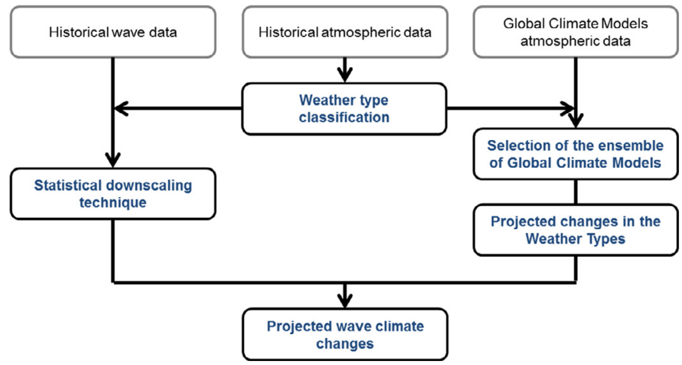

Fig. 1. Flowchart representing the methodology to obtain wave climate projections.

Wave spectra in WaveWatch III were defined by 32 frequencies ranging non-linearly from 0.0372 Hz to 0.714 Hz with a factor of 1.1 and 24 direction bins. WaveWatch III was implemented using the parameterization TEST451 (Ardhuin et al., 2010) because the wave heights obtained with TEST451 (e.g. Rascle and Arhuin, 2013) have smaller biases than those obtained with older parameterizations. Validation against buoys and altimeter data (not shown) confirmed a good agreement of this hindcast with observations. For example, the comparison between altimeter measured and modeled significant wave heights on the European grid shows a 0.95 correlation and a scatter index of less than 0.2. The best agreement is found in the Atlantic Ocean while the worst agreement is found in some semi-enclosed basins such as the Alboran Sea and the Adriatic Sea.

2.3. Global climate models atmospheric data

We analyzed daily SLP fields from CMIP5 GCMs to study changes in atmospheric circulation. Data from historical experiments from 1975 to 2004 was used to characterize recent past conditions. Data from representative concentration pathways (RCPs, Moss et al., 2010) from 2010 to 2100 were used to represent future conditions. These time periods were chosen because they overlap with data available from most GCMs. The three selected RCPs included one mitigation scenario leading to a very low forcing level (RCP2.6), one medium stabilization scenario (RCP4.5) and one very high baseline emission scenario (RCP8.5) leading to high greenhouse concentration levels (van Vuuren et al., 2011). All the simulations available (at the time this work was conducted) for these scenarios were analyzed. This resulted in a total of 42 GCMs with 137 historical simulations, 56 RCP2.6 simulations, 98 RCP4.5 simulations and 72 RCP8.5 simulations. The CMIP5 data used in this study were obtained via the Earth System Grid-Center for Enabling Technologies (ESG-CET, http://pcmdi9.llnl.gov/).

3. Methods

3.1. Framework

Fig. 1 summarizes the methodology to obtain regional wave climate projections. This methodology requires three sources of data: historical wave data, historical atmospheric data and GCM simulated atmospheric data. First, an automated WT classification is performed using the historical atmospheric data from a reanalysis. This