Ocean Modelling 59–60 (2012) 31–40

Contents lists available at SciVerse ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Review

Exploring the interannual variability of extreme wave climate in the Northeast Atlantic Ocean

Cristina Izaguirre, Melisa Menéndez, Paula Camus, Fernando J. Méndez *, Roberto Mínguez, Inigo J. Losada

Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, Spain

A R T I C L E I N F O

Article history:
Received 27 June 2012
Received in revised form 18 September 2012
Accepted 26 September 2012
Available online 13 October 2012

Keywords:
Weather types
Generalized extreme value distribution
Climate variability
Synoptic classification
Self organizing maps
Extreme wave climate

A B S T R A C T

The extreme wave climate is of paramount importance for: (i) off-shore and coastal engineering design, (ii) ship design and maritime transportation, or (iii) analysis of coastal processes. Identifying the synoptic patterns that produce extreme waves is necessary to understand the wave climate for a specific location. Thus, a characterization of these weather patterns may allow the study of the relationships between the magnitude and occurrence of extreme wave events and the climate system.

The aim of this paper is to analyze the interannual variability of extreme wave heights. For this purpose, we present a methodological framework and its application to an area over the North East (NE) Atlantic Ocean. The climatology in the NE Atlantic is analyzed using the self-organizing maps (SOMs). The application of this clustering technique to monthly mean sea level pressure fields provides a continuum of synoptic categorizations compared with discrete realizations produced through most traditional methods.

The extreme wave climate has been analyzed by means of monthly maxima of the significant wave height (SWH) in several locations over the NE Atlantic. A statistical approach based on a time-dependent generalized extreme value (GEV) distribution has been applied. The seasonal variation was characterized and, afterwards, the interannual variability was studied throughout regional pressure patterns. The anomalies of the 50-year return level estimates of SWH, due to interannual variability have been projected into the weather types of SOM. It provides a comprehensive visual representation, which relates the weather type with the positive or negative contribution to extreme waves over the selected locations.

Contents

1. Introduction . . . 32
2. Data . . . 32
  2.1. Sea level pressure data . . . 32
  2.2. Wave data . . . 32
3. Methods . . . 33
  3.1. Summary of the approach . . . 33
  3.2. Principal component analysis . . . 33
  3.3. Time-dependent extreme model . . . 34
  3.4. Self-organizing maps . . . 35
4. Results . . . 35
  4.1. Extreme wave climate analysis . . . 35
  4.2. NE Atlantic weather types . . . 36
  4.3. Extreme waves and atmospheric relationships . . . 36
5. Conclusions . . . 39
Acknowledgements . . . 39
References . . . 39

* Corresponding author. Address: Environmental Hydraulics Institute IH Cantabria, c/Isabel Torres No. 15, Parque Científico y Tecnológico de Cantabria, 39011 Santander, Spain. Tel.: +34 942 201616; fax: +34 942 266361.

E-mail addresses: fernando.mendez@unican.es, mendezf@unican.es (F.J. Méndez).

1463-5003/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ocemod.2012.09.007

1. Introduction

The most severe conditions of wave climate are of paramount importance on natural coastal processes (i.e. sediment transport or the development of the seaweed meadows), coastal management and engineering design (maritime works, ship design, route definition, offshore structures design, operability,...). Thus, there is a need for appropriate methods to describe these phenomena.

During the last decades, the study of the extreme wave climate has increased significantly. The statistical modeling of the extreme wave height including seasonal and interannual variability have been studied by numerous authors (Wang and Swail, 2001; Caires et al., 2006; Méndez et al., 2006; Menéndez et al., 2009; Izaguirre et al., 2010; Hemer, 2010). However, there is not a clear conclusion about the atmospheric situations that cause the interannual fluctuations on extreme wave heights. From this point of view, the aim of this work is to analyze the variability in the state of the atmosphere, and to investigate if these variations can explain or help to understand the complex relationships between wave forcing at a regional scale, and their effect in the interannual variability of the extreme wave climate at a local spatial scale.

In the earliest 70's synoptic climatology was established as a climatological subfield with the publication of 'Synoptic climatology: methods and applications' (Barry and Perry, 1973). After that seminal work, a lot of techniques have been applied to explore and analyze the climatology in order to understand and simplify data of geophysical variables. Several statistical methods have been developed to relate synoptic-scale atmospheric circulation to local environmental responses (analyzing variables like temperature, precipitation or pressure fields). The main advantage of the statistical techniques is that a large amount of complex data fields (with spatial and temporal dimensions) can be processed automatically to output a simple and readable synthesis, minimizing the human factors.

The principal component analysis (PCA) is one of the most popular techniques. PCA is especially useful to reduce the number of dimensions and identify patterns in environmental data. The data sample is projected in a space with minor dimension where the vectors of the new orthogonal base maximize the variance of the data sample. This technique removes the data dependency and data redundancy with the minimum lost of variance, which is sometimes required by the assumptions of many statistical methods.

The clustering methods try to reduce the amount of data by categorizing or grouping similar data together. These methods are used to partition the sample data into clusters defined by centroids or reference vectors representing the data in a more compact and manageable way. The self-organizing maps (SOMs) is one of the most powerful data mining techniques for clustering high-dimensional data due to its graphical visualization properties. The cluster centroids are forced with a neighborhood mechanism to a space with smaller dimension (usually a two-dimensional lattice) preserving the topology of data in the original space. Therefore, the clusters are spatially organized in the lattice of projection which gives an intuitive analysis of the information contained in the data.

Several applications of these techniques can be found in the wave climate field trying to explain relations of sea states with atmospheric patterns. Bacon and Carter (1993) showed the relationship between wave heights and the north–south atmospheric pressure in the North Atlantic (the so-called North Atlantic Oscillation, NAO). Later on, Kushnir et al. (1997) found a link between the wintertime monthly significant wave height (SWH) and monthly average sea level pressure (SLP) using a canonical correlation analysis. Wang and Swail (2001, 2002) applied a PCA on both the SLP and extreme wave height anomalies in the Northern Hemisphere to analyze their correlation and, Woolf et al. (2002) shows that a large fraction of the wave height anomalies in the northeastern sector of the Atlantic is associated to a single pattern of pressure anomalies that resembles the NAO. Moreover, Izaguirre et al. (2010) found that NAO and the East Atlantic (EA) pattern are the most influential patterns in the North Atlantic, enhanced by the analysis of interannual variability with the PCs of SLP anomalies: first two PCs have similar patterns to NAO and EA indices and show important contribution to the extreme wave height in the northeast Atlantic and Mediterranean region. Le Cozannet et al. (2011) analyzed the influence of teleconnection patterns in the interannual variability of the frequency of sea state modes in the Bay of Biscay, obtained from a K-means classification.

Following the hypothesis that interannual variability of the extreme wave height is induced by patterns in the atmospheric circulation, the aim of this work is to present a methodological framework to explain the relationship between extreme wave height anomalies and the synoptic situation that produces it by means of a graphical representation. To achieve this goal, a SOM analysis is carried out to process the principal components (PCs) of SLP of the NE Atlantic area, to characterize the climatology on a bidimensional lattice. The extreme wave height statistics at six different locations over the studied domain is modeled by applying a time-dependent GEV model including seasonal and interannual variability. The topology preservation property of the SOM allows defining a function on the SOM lattice corresponding to average value of extreme wave height for the reanalysis SLP dates corresponding to each of the clusters. The interannual variability of the extreme wave climate at each location projected into the climatological lattice is used to study the relationship with the synoptic states and to analyze how extreme wave probability distributions change due to changes in climatic conditions.

The paper is organized as follows. Section 2 provides a description of the SLP and the wave data used. In Section 3 we present the methodology, describing the data mining techniques, PCA and SOM, and the statistical modeling of the extreme wave height. The NE Atlantic weather types issued from the SOM analysis, extreme wave climate variability and the relationship between both are presented in Section 4. Finally, some conclusions are given in Section 5.

2. Data

2.1. Sea level pressure data

The sea level pressure fields used in this work come from the reanalysis dataset of the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR; Kalnay et al., 1996). The SLP data consist of 6-h fields on a Gaussian grid with T62 resolution (about 210 km, for more details see Kalnay et al., 1996). The period of the reanalysis used in this study spans from 1948 to 2008.

The spatial domain under study spans from 25°N to 70°N and 60°W to 10°E (see Fig. 1) using a $5^\circ \times 5^\circ$ spatial resolution grid where the SLP data are interpolated. The area is selected to capture the action center of the NAO, which is the most prominent oscillation mode in the North Atlantic. Monthly mean sea level pressure (MSLP) is extracted for the regridded spatial domain. In summary, the monthly MSLP data consist of a record of 744 monthly values from 1948 to 2008, each defined at 150 grid points.

2.2. Wave data

The wave data used in this work come from the global ocean wave reanalysis database GOW (Reguero et al., 2012). GOW reanalysis has been generated with the third generation model