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Extreme wave parameters under North Atlantic extratropical cyclones

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ABSTRACT

A characterization of extreme wave parameters during extratropical cyclones in the Northern hemisphere is made from WAM wave model hindcasts. In February 2007 two extratropical storms were observed in the North Atlantic and the wave fields associated with them are modeled in this paper. Wave buoy and satellite altimetry data were used to validate the WAM hindcast results. The distribution of the Benjamin–Feir index (BFI), kurtosis and the ratio of maximum wave height to significant wave height (abnormality index) around the eye of the two extratropical cyclones is studied. It is found that under these conditions the BFI and kurtosis are significantly larger mainly in the fourth quadrant and also when the wind direction is aligned with the wave propagation direction. In these regions the probability of occurrence of abnormal waves is higher.

1. Introduction

Extreme waves occurring in the ocean and closed seas are dangerous to human activities and personal safety. Despite the scarcity of these events, they can be associated with severe consequences such as considerable damages to ships, offshore structures and potential loss of human life (Faulkner and Buckley, 1997; Guedes Soares et al., 2008). In a sea state described by linear theory, the probability distribution of wave heights follows a Rayleigh distribution (Longuet-Higgins, 1952). However, full scale data (Guedes Soares et al., 2011) and experiments (Onorato et al., 2004; Cherneva et al., 2009) have shown that when extreme sea states are more expectable the statistics of large wave heights do not follow this distribution and nonlinearity plays a role. In fact, several studies have shown that in some cases the Rayleigh distribution tends to under predict the actual observed heights (Longuet-Higgins, 1980; Goda, 2000; Tayfun and Fedele, 2007; among others) and alternatives on the Rayleigh distribution have been proposed in order to improve its accuracy for large waves. Comparisons with empirical data by Forristall (1984), Petrova and Guedes Soares (2011), Casas-Prat and Holthuijsen (2010) and Alkhalidi (2012), among others have reached the general conclusion that the asymptotic distributions of Tayfun (1990) and Boccotti (1981, 1989, 2000) appear to be the most accurate ones in predicting large wave heights. Later, Alkhalidi and Tayfun (2013) found a generalized model that describes large wave heights well and noticeably better than the original Boccotti distribution and other models proposed for describing wave heights affected by third-order nonlinearities.

Abnormal, rogue or freak waves are transient very high waves in relation to the sea state in which they occur, which started being identified when the abnormality index, (Dean, 1990), i.e. the ratio of maximum wave height (H) to significant wave height (Hs) would be larger than two ($H/\mathrm{Hs} > 2$). Additional conditions have been proposed by various authors as reviewed by Kharif et al. (2008), but that condition has remained as the common one. Abnormal wave occurrences have been reported from field observations in the Sea of Japan (Yasuda and Mori, 1997), the North Sea (Guedes Soares et al., 2003) and in a hurricane in the Gulf of Mexico (Guedes Soares et al., 2004; Veltcheva and Guedes Soares, 2012).

Several physical mechanisms have been suggested as responsible for the formation of these extreme waves: linear superposition of waves or spatial–temporal focusing (Kharif and Pelinovsky, 2003), interaction of waves with currents (Lavrenov, 1998), modulational instability (Benjamin–Feir instability) in crossing seas (Trulsen and Dysthe, 1997). The nonlinear enhancement of freak wave generation was explained in terms of the number of waves in a time series and the surface elevation kurtosis by Mori and Janssen (2006). This enhancement occurs with finite kurtosis (for a Gaussian time series kurtosis is zero) and can reach a three-fold increase in the ratio of freak wave occurrence. Kurtosis is a fourth-order moment of a probability density function and is related to third order nonlinear interactions (Longuet-Higgins et al., 1963). Based on the probability of occurrence calculations from North

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Sea wave measurements it was shown that the kurtosis coefficient can be used as an indicator for the occurrences of abnormal waves (Guedes Soares et al., 2011).

Directional dispersion influences the evolution of kurtosis in deep water and a decrease of kurtosis was found for directional sea states in numerical and experimental settings (Gramstad and Trulsen, 2007; Waseda, 2006; Onorato et al., 2009). Mori et al. (2011) then studied the dependence of kurtosis on the BFI and directional spread in directional sea states.

The relationship between the probability of occurrence of abnormal waves and BFI and kurtosis gives spectral wave models like WAM the opportunity of being applied for forecasting sea states with high probability of occurrence of abnormal waves.

Despite of the latest advances on the subject little information has been published about extreme waves generated under realistic conditions of extratropical storms. Young (2006) provided a directional spectrum description under hurricane conditions based on cyclones records. He showed that for almost all quadrants of the storms the dominant waves are remotely generated swell and that nonlinear wave–wave interactions play a major role in the spectral balance. Later, the abnormal waves generated under idealized typhoon conditions were examined in Mori (2012). From his work it was concluded that freak waves have a greater potential of occurring in the fourth quadrant of the typhoon.

The present work intends to gain insight about the extratropical cyclones conditions which allowed for the generation of extreme waves by using a spectral wave model. The paper is structured as follows. Section 2 is devoted to the data and methods giving different details about the wave measurements (buoys and satellite altimetry), a description about the wind forcings used. The WAM model description and wave model set up configuration are presented in Section 3. The considered extratropical cyclones are briefly described in Section 4. This is followed by the validation of the hindcast in Section 5. Section 6 presents the results and discussions focused on the spatial–temporal distributions of the main extreme wave parameters and the wave spectra characteristics in the cyclone area. General conclusions of the work were provided in Section 7.

2. Data and methods

2.1. Wave measurements

The wave hindcast was validated against two moored wave buoys data (Fig. 1) from UK Metoffice which are distributed by the JCOMM-Joint Technical Commission for Oceanography and Marine Meteorology Project (Bidlot, 2012). These moorings consist of directional wave buoys Fugro Oceanor Seawatch transmitting hourly data on the standard suite of meteorological parameters.

For the assessment of the WAM hindcast, altimetry data (JASON1) from GLOBWAVE (Ash et al., 2012) were used. The GLOBWAVE data set is homogenized with a high quality control which allows making use of these data with a spatial coverage that is ideal for a wave hindcast validation. For JASON1 the calibrations are taken from Durrant et al. (2009).

The WAM significant wave height (Hs) was compared against the GLOBWAVE L2P data (Ash et al., 2012). The GLOBWAVE data employed suitable quality control and calibration of the data streams from the various missions as described in Queffeulou and Croize-Fillon (2012). Only the calibrated Hs data flagged as “probably good measurement” were used in the present study. The method employed to filter these data is the following: WAM model results are interpolated linearly to the position and time of the satellite observations.

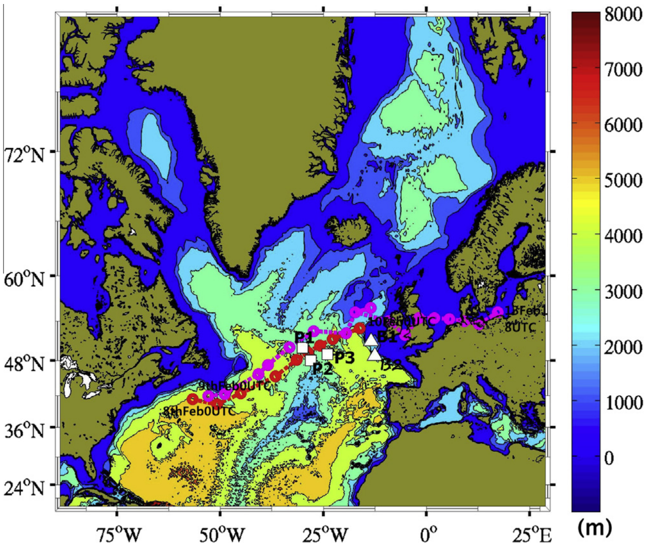

Fig. 1. Study region and the WAM model bathymetry grid (depth in meters). P1, P2, P3 – WAM output locations (white squares); B1, B2-wave buoys locations (white triangles). The cyclones tracks: 1st cyclone (red dashed line); 2nd cyclone (magenta dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Wind forcing

The reanalysis used for this study come from the Climate Forecast System Reanalysis (CFSR) from NOAA (Saha Suranjana et al., 2010). The CFSR is a third generation reanalysis product. It is a global, high resolution, coupled atmosphere–ocean–land surface–sea ice system designed to provide the best estimate of the state of these coupled domains over a time period. The CFSR includes coupling of atmosphere and ocean during the generation of the 6 h guess field, an interactive sea-ice model, and assimilation of satellite radiances. The CFSR global atmosphere resolution is about 38 km with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. It is also coupled to an ocean circulation model (as opposed to using a prescribed Sea Surface Temperature (SST) over the ocean as was done earlier).

The subset of ds093.1 – NCEP Climate Forecast System Reanalysis (CFSR) selected hourly time-series products was used, with a temporal resolution of 1 h, coverage from January 1979 to December 2010 and the two spatial resolution products: 0.5° and 0.31°. For further details about this data base a complete validation of a thirty year wave hindcast using the CFSR winds can be found in Chawla et al. (2013).

2.3. Methods

The BFI and kurtosis fields obtained from the hindcast were linearly interpolated to a latitude–longitude grid centred at the cyclone’s centre position. The position of the cyclone’s centre was obtained from the NSIDC’s (National Snow and Ice Data Center) database of northern hemisphere cyclone location and characteristics (Serreze, 2009). This data set contains half-a-century of daily extratropical cyclone statistics, such as centre location and sea level pressure (SLP). Cyclone locations and characteristics were obtained by applying the updated Serreze et al. (1997) algorithm to daily Sea Level Pressure data at six hour intervals (Serreze and Barrett, 2008). The SLP source data are part of the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) Reanalysis data set.