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Wave height analysis from 10 years of observations in the Norwegian Sea

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ABSTRACT

Large waves pose risks to ships, offshore structures, coastal infrastructure and ecosystems. This paper analyses 10 years of in-situ measurements of significant wave height (H_s) and maximum wave height (H_{max}) from the ocean weather ship *Polarfront* in the Norwegian Sea. During the period 2000 to 2009, surface elevation was recorded every 0.59 s during sampling periods of 30 min.

The H_{max} observations scale linearly with H_s on average. A widely-used empirical Weibull distribution is found to estimate average values of H_{max}/H_s and H_{max} better than a Rayleigh distribution, but tends to underestimate both for all but the smallest waves. In this paper we propose a modified Rayleigh distribution which compensates for the heterogeneity of the observed dataset: the distribution is fitted to the whole dataset and improves the estimate of the largest waves. Over the 10-year period, the Weibull distribution approximates the observed H_s and H_{max} well, and an exponential function can be used to predict the probability distribution function of the ratio H_{max}/H_s. However, the Weibull distribution tends to underestimate the occurrence of extremely large values of H_s and H_{max}.

The persistence of H_s and H_{max} in winter is also examined. Wave fields with $H_s > 12$ m and $H_{max} > 16$ m do not last longer than 3 h. Low-to-moderate wave heights that persist for more than 12 h dominate the relationship of the wave field with the winter NAO index over 2000–2009. In contrast, the inter-annual variability of wave fields with $H_s > 5.5$ m or $H_{max} > 8.5$ m and wave fields persisting over $\sim$2.5 days is not associated with the winter NAO index.

1. Introduction

Large ocean waves pose significant risks to ships, offshore structures, coastal infrastructure and coastal ecosystems. The development of offshore installations for oil and gas extraction and for renewable energy exploitation requires knowledge of the wave fields and any potential changes in them. Waves are also important in understanding aspects of ocean dynamics such as surface wind stress, and near-surface mixing which in turn affects the air–sea fluxes of gases and heat (Melville and Matusov, 2002). Waves play a role in the mixing and dispersal of pollutants (Giarrusso et al., 2001) and also contribute to the levels of underwater noise (Leighton 1997) thus affecting the behavior of many cetaceans.

Most information presently available for wave fields is presented in terms of the significant wave height (H_s). H_s is defined as the average height of the highest one-third of the waves, which in the deep ocean equates to four times the square root of the zeroth moment of the narrow-band wave spectrum (Sverdrup and Munk, 1947; Phillips, 1977). Knowledge of the maximum peak-to-trough wave height (H_{max}) is not usually available although these largest waves have the most significant impact on ocean engineering, safety and financial concerns.

Lack of data has made it necessary to estimate H_{max} from its expected statistical relationship with H_s. Assuming that the statistics of stochastic ocean waves are stationary, H_{max} estimates have been made using the Rayleigh distribution (Longuet-Higgins, 1952; Sarpkaya and Isaacson, 1981). However, in some cases where H_{max} observations did exist, this method has been found to overestimate the largest individual wave heights (Forristall, 1978; Tayfun, 1981; Krogstad, 1985; Massel, 1996; Nerzic and Prevosto, 1997; Mori et al., 2002; Casas-Prat and Holthuijsen, 2010). Some of the discrepancy is known to be due to the effect of the spectral bandwidth, i.e. the gathering of wave components around the peak energy component (Tayfun, 1981; Ochi, 1998; Vandever et al., 2008). The nonlinearity of wave-wave interaction has also been found to affect the crest height and trough depth distributions, but not the individual wave height (Tayfun, 1983; Casas-Prat and Holthuijsen, 2010). In contrast to

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observations, recent laboratory experiments and theoretical model studies show that the nonlinearity affects the wave height distributions, and that this effect depends on the state of wave development (Slunyaev and Sergeeva, 2012; Ying and Kaplan, 2012). What has now been confirmed both from theories and measurements is that the nonlinear wave interactions have significant impact on the ratio of the maximum wave height to significant wave height (H_{max}/H_s) (Janssen, 2003; Mori and Janssen, 2006).

Forristall (1978) and Gemmrich and Garrett (2011) have shown that the Weibull distribution provides a better estimate of the observed largest wave heights, i.e. those with the lowest probability of being exceeded. Because the parameterization of the Weibull distribution depends on the local sea state, it is not easy to apply in practice. Forristall (1978) suggests an empirical fit to the Weibull distribution based on the number of waves in the observational record. The significant improvement in estimating H_{max} was confirmed using clustered or ensemble wave height distributions by Forristall (2005), Casas-Prat and Holthuijsen (2010) and Waseda et al. (2011). However, the lack of long-term H_{max} observations means that neither of the statistical distributions has been fully evaluated in all conditions.

In this paper we investigate H_s, H_{max} and the persistence of wave fields using 10 years of 30-min sea surface elevation records from a Ship-Borne Wave Recorder (SBWR) at Ocean Weather Station (OWS) Mike in the Norwegian Sea. We systemically evaluate the capability of the Rayleigh distribution and the corrected method by Forristall (1978) in estimating H_{max}/H_s, and the resulting H_{max}, against the 30-min records. The long-term distributions of wave heights and persistence are also explored.

The paper is structured as follows. The data and methodology are described in Section 2, along with the statistical definitions to be used. A new parameter, “run length”, is introduced to describe the persistence of wave fields that exceed given thresholds. Section 3 examines the short-term statistics of the observations of H_{max}/H_s and H_{max}, and how they vary from theoretical predictions. The long-term (10-year) distributions of H_s, H_{max}, H_{max}/H_s and run length are then discussed. In Section 4, the temporal variability of the wave field is correlated with the winter NAO index to show which aspects of the winter wave climate are affected by the large-scale changes in the overall sea level pressure field, as opposed to being caused by individual storms. Our conclusions are given in Section 5.

2. Data and methodology

2.1. Ship-borne wave recorder (SBWR) data

Ocean Weather Station Mike (OWS Mike, 66°N, 2°E in the Norwegian Sea, Fig. 1) was occupied by an ocean weather ship for more than 60 years until the ship *Polarfront* was withdrawn at the end of 2009. The sea surface elevation was measured by a ship-borne wave recorder (SBWR) and wave height data from this system are available from 1980 to the end of 2009.

The SBWR was developed by the UK National Institute of Oceanography (later to become part of the National Oceanography Centre) in the 1950s and is considered a very reliable system (Graham et al., 1978; Holliday, et al., 2006). The SBWR uses the surface-following properties of the platform to capture the longer wavelength waves, and pressure sensors mounted in the hull to measure shorter wavelength waves. *Polarfront* was a relatively small ship (49 m length) and spent most of the time drifting beam-on to the waves, but the response of the ship to the waves tends to flatten the measurement of the wave crests and sharpen the troughs (Magnusson et al., 1999). A short, 30-h comparison between observations obtained by the SBWR on *Polarfront* and those from a wave-rider buoy showed good agreement, with the SBWR underestimating H_s by 0.4 m on average (Clayson, 1997).

From 1980 until the end of 1999, only the integrated wave parameters (e.g. H_s and average period) were recorded by the SBWR system: these have been analysed briefly elsewhere (Yelland et al., 2009). However, for the last 10 years of operation (2000–2009, the period investigated in this paper) the SBWR system also recorded the sea surface elevation every 0.59 s for the 30-min sampling periods, with sampling occurring once every 90 min before the 250th day of 2004, and once every 45 min thereafter.

The height of an individual wave is defined as the vertical distance between a wave trough and the following wave crest. For each 30-min record, the highest individual wave is identified as H_{max}, and H_s is calculated from four times the square root of the zeroth-order moment of the wave frequency spectrum within 0.02–0.85 Hz.

2.2. Data quality

The reliability of the measurement of individual waves is of significant importance in the analysis of extreme waves. Significant uncertainty can be introduced in to the sea surface elevation measurement depending on: the type of platform used; the way the platform interacts with the waves; the type of measuring instrument; the instrument's ability to measure very steep changes of the sea surface e.g. waves that are about to break; the relationship between a point measurement and the multi-dimensional wave profile. These issues are discussed in detail by Liu and MacHutchon (2006), Christou and Ewans, (2011a,2011b) and Forristall, (2005) and affect all in-situ measurements to some extent.

The performance of SBWRs mounted on light vessels and other ships has been validated against data from wave buoys in terms of H_s and spectrum by Graham et al. (1978), Crisp (1987) and Pitt (1991). In the case of *Polarfront* the only validation was the 30-h comparison with a wave buoy made by Clayson (1997). The lack of validation comparisons is a general problem for wave measurements made from numerous platforms and instruments (Christou and Ewans, 2011a). In the case of the SBWR on *Polarfront* we cannot exclude the possibility of systematic biases such as the 0.4 m underestimate as found by Clayson (1997).

In normal operations, *Polarfront* was allowed to drift without engine propulsion, provided it remained within a 32 km radius around the location known as OWS Mike. Once outside this radius the ship steamed slowly back to station with a speed of up to 5 m/s at most. The ship stayed on station all year round, except for 3 days out of every 28 when it returned to port. These days on passage to port and back were not included in the analysis: this removed about 11% of the available 30-min wave records. Further quality control was applied by examining various wave parameters (e.g. H_{max}, H_{max}/H_s, maximum wave period) to identify extreme and/or potentially un-realistic values. All of these records were then checked by visually examining the wave trace over the whole of the 30-min record. A total of 524 physically unrealistic wave traces were identified in this fashion: most of these events were associated with unusually large changes in ship speed and direction. It should be noted that when an unrealistic trace was detected, the entire 30-min record was removed from the analysis.

In total, the quality control led to a rejection of 10,678 out of 81,888 (13%) 30-min wave records. This procedure left 17,389,559 individual waves in a total of 71,210 records obtained over 2915 days between 2000 and 2009.

2.3. Statistical distributions of waves

Longuet-Higgins (1952) suggests that, in the deep ocean, individual waves with a narrow-band wave spectrum follow a Rayleigh