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Changes in significant and maximum wave heights in the Norwegian Sea

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ABSTRACT

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. The 30-minute Ship-Borne Wave Recorder measurements of H_{max} and H_s are shown to be consistent with theoretical wave distributions. The linear regression between H_{max} and H_s has a slope of 1.53. Neither H_s nor H_{max} show a significant trend in the period 2000–2009. These data are combined with earlier observations. The long-term trend over the period 1980–2009 in annual H_s is 2.72 ± 0.88 cm/year. Mean H_s and H_{max} are both correlated with the North Atlantic Oscillation (NAO) index during winter. The correlation with the NAO index is highest for the more frequently encountered (75th percentile) wave heights. The wave field variability associated with the NAO index is reconstructed using a 500-year NAO index record. H_s and H_{max} are found to vary by up to 1.42 m and 3.10 m respectively over the 500-year period. Trends in all 30-year segments of the reconstructed wave field are lower than the trend in the observations during 1980–2009. The NAO index does not change significantly in 21st century projections from CMIP5 climate models under scenario RCP85, and thus no NAO-related changes are expected in the mean and extreme wave fields of the Norwegian Sea.

1. Introduction

Large ocean waves pose significant risks to ships and offshore structures. 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. Most information presently available for wave fields is presented in terms of the significant wave height (H_s), which is defined as the average height of the highest one-third of the waves or, alternatively, as four times the square root of the zeroth moment of the 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 greatest impact on ships and offshore structures.

The *OWS Polarfront*, the last weather ship in the world, made measurements of H_s for 30 years using a Ship-Borne Wave Recorder (SBWR). The ship was located at Ocean Weather Station Mike (OWS Mike, 66°N, 2°E, see Fig. 1) in the Norwegian Sea. Waves observed using SBWRs at other stations have been systematically validated against wave buoys in terms of H_s and spectrum by Graham et al. (1978), Crisp (1987) and Pitt (1991). However in this study we also use H_{max} from the SBWR which has not previously been validated against other wave measuring devices. By analysing the statistical relationship between H_s and H_{max} as measured by the SBWR and comparing it with the known theoretical and empirical relationships we indirectly provide confidence for the validity of the H_{max} measurements.

The wind field over the North Atlantic is related to the North Atlantic Oscillation (NAO), a major large-scale atmospheric pattern in this region (Hurrell, 1995; Hurrell and Van Loon, 1997; Osborn et al., 1999). The status of the NAO is represented by the NAO index, determined from the non-dimensional sea level pressure difference between the Icelandic Low and the Azores High. The NAO is particularly important in winter, and Bacon and Carter (1993) were the first to note the link between this large weather pattern and the wave climate over the North Atlantic. An increase in H_s in the North Atlantic over the second half of the 20th century was found be associated with the NAO index variability (Bacon and Carter, 1993; Kushnir et al., 1997; Wang and Swail, 2001, 2002; Woolf et al., 2002; Wolf and Woolf, 2006). In addition, linear regressions between the inter-annual H_s anomalies and the NAO index have been established for various methods of wave height estimation (e.g. in-situ measurements, visual observations, satellite altimetry and numerical models) (Bacon and Carter, 1993; Gulev and Hasse, 1999; Woolf et al., 2002; Wang et al., 2004; Tsimplis et al., 2005). Hindcasts from numerical models suggest that the influence of the NAO extends to the largest 1% of H_s in the North Atlantic during winter (Wang and Swail, 2001, 2002). Izaguirre et al. (2010) using satellite H_s data also indicated that along the Atlantic coast of the Iberian Peninsula the extreme wave climate is significantly associated with the NAO.

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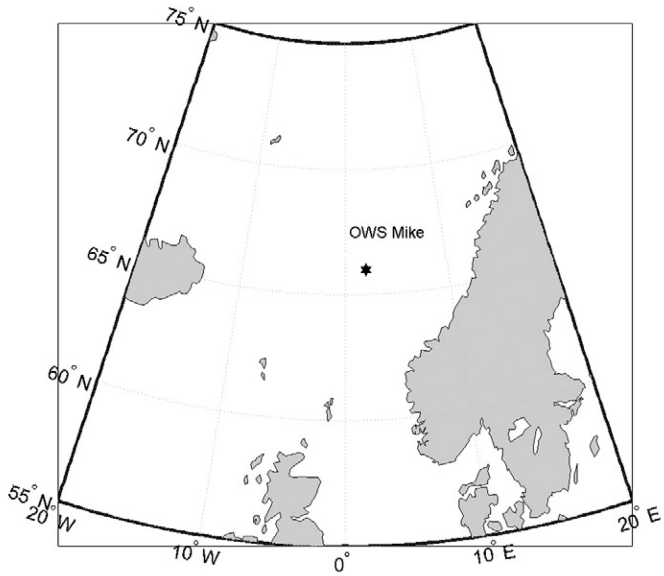

Fig. 1. Location of Ocean Weather Station Mike (66°N, 2°E).

Thus there is a well-established relationship between H_s and the NAO index during winter. The two terms, H_{max} and H_s are both characteristics of the wave field and both increase with increasing winds or increasing durations of a consistent wind. H_s is governed by the mean conditions; however H_{max} is not fully determined by the mean conditions but is also affected by local conditions as well as randomness. H_{max} is the pertinent parameter for describing risks associated with operation of ships or offshore structures, hence it is important that we analyse both these measures of the wave field in a consistent manner to show how they differ.

In this paper, we investigate H_s and H_{max} using 10 years of 30-minute surface elevation records from the SBWR at OWS Mike in the Norwegian Sea. First we assess the validity of the dataset by comparing the observational distributions of H_{max} and the H_{max}/H_s ratio with the corresponding theoretical distributions. We establish that the H_s and H_{max} data obtained from the SBWR behave as expected on the basis of theoretical distributions that have been tested against other wave measuring systems. Thus this provides evidence that the H_{max} from the SBWR are reliable. We then explore the relationships of the inter-annual changes in H_s and H_{max} with the NAO index. We also use a 500-year NAO index record to reconstruct the range of values that H_s and H_{max} may have had over the same period.

The paper is structured as follows. The data processing and methodology are described in Section 2, along with the statistical definitions to be used. In this section a comparison of the expected distributions for H_s and H_{max} with the observed distributions is made. In Section 3, the temporal variability of H_s and H_{max} are described, and is correlated with the winter NAO index. The results are discussed in Section 4 where also the natural variability of the wave field over the past 5 centuries is estimated from a reconstruction of the NAO index. Outputs from the most recent CMIP5 models are also used to infer changes in the NAO index under climate change scenarios, and hence assess the likely overall change of the wave fields in the 21st century. 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, with 2000 m water depth) was occupied by weather ships for more than 60 years until the ship *Polarfront* was withdrawn at the end of 2009. Sea surface elevation has been 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 principles of operation of the SBWR are described in detail by Tucker and Pitt (2001). Using 13 years of data from three different weather ships stationed on the UK continental shelf, Graham et al. (1978) demonstrated that H_s values from the SBWR were 8% larger than those from WaveRider buoys on average, with closer agreement at larger wave heights. Crisp (1987) examined the wave spectra, and found that the frequency response of the SBWR differed from that of the WaveRider. Pitt (1991) developed an empirical frequency-response correction for the SBWR and this reduced the overestimation of H_s to 5%. A short, 30-hour comparison between observations obtained on *Polarfront* and those from a WaveRider buoy also found good agreement, but in this case the SBWR underestimated the H_s slightly, by 0.4 m on average (Clayson, 1997). Hence H_s data from the SBWR are well validated.

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 on *Polarfront*: 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-minute sampling periods, with sampling occurring once every 90 min before the 250th day of 2004, and once every 45 min thereafter. Tests made by sub-sampling data in the latter period to replicate the earlier 90-minute observational interval showed that the change in the observation interval in 2004 has no impact on the results discussed in the rest of this paper.

Polarfront was allowed to drift freely within a 32 km radius around OWS Mike. Once outside this radius the ship returned on station with a speed of up to 5 m/s. Some of the 30-minute records obtained whilst the ship was steaming were found to contain unrealistically large elevations. All spurious elevations when the ship was steaming were excluded from the analysis during quality control. The wave data during the periods when the *Polarfront* returned to port, 3 days out of every 28-day period, were omitted because the ship was not on station. A summary of the data record, after application of quality control, is provided in Fig. 2.

The height of an individual wave is defined as the vertical distance between a wave trough and the following wave crest. There are 17,389,559 individual waves in a total of 71,210 thirty-minute wave records obtained over 2915 days between 2000 and 2009. For each 30-minute record, the highest individual wave is identified as H_{max},

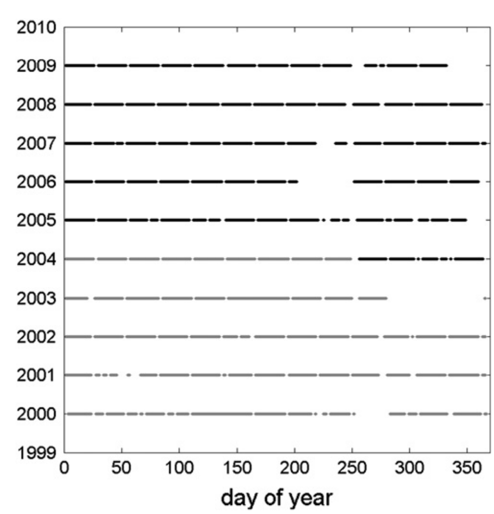

Fig. 2. Quality-controlled SBWR data from OWS Mike during 2000–2009. Grey lines indicate that the observing frequency was every 90 min, and black every 45 min.