Enhanced freak wave occurrence with narrow directional spectrum in the North Sea

T. Waseda,[1] M. Hallerstig,[1,2] K. Ozaki,[1] and H. Tomita[3]

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[1] Wind and wave records obtained from the Kvitebjorn platform (2.3°E, 61.0°N, 190 m deep) in the northern North Sea from 2003 to 2005 were analyzed. Among the 2723 20-min records taken during storm conditions, 57 cases included freak waves exceeding twice the significant wave height. Comparisons between various wave parameters and the freak wave occurrence index did not show any significant correlation. Thus, the in situ wave record was used to select the days when relatively more or less freak waves were observed. The days were classified into freakish and non-freakish days, respectively. On freakish days, the Icelandic low was enhanced. Hindcasts performed by a third-generation wave model suggest that this synoptic atmospheric pressure difference produces approximately 7.6 degrees narrower directional spreading of the wave spectra during freakish days at the Kvitebjorn platform. This result is consistent with the physical mechanism of freak wave generation through nonlinear self-focusing in random wave fields. **Citation:** Waseda, T., M. Hallerstig, K. Ozaki, and H. Tomita (2011), Enhanced freak wave occurrence with narrow directional spectrum in the North Sea, *Geophys. Res. Lett.*, *38*, L13605, doi:10.1029/2011GL047779.

1. Introduction

[2] The occurrence probability of freak waves is considered to increase as the wave spectrum narrows in both the frequency bandwidth and directional spreading. Recent studies have attempted to relate the probability of freak wave occurrence to the shape of the wave spectrum and have provided evidence from numerical, experimental, and theoretical perspectives [*Gramstad and Trulsen*, 2007; *Dysthe et al.*, 2008; *Onorato et al.*, 2009a, 2009b; *Waseda et al.*, 2009a, 2009b]. Following these fundamental studies, research has attempted to relate possible freak wave incidents to particular meteorological conditions. Recent hindcast simulations of the sea conditions during a marine accident near Japan by *Tamura et al.* [2009] highlighted the interesting process of swell-wind-wave interaction. This process resulted in the formation of an extremely narrow wave spectrum, i.e., the genesis of a freakish sea state. The meteorological precursor to this incident was the Baiu front and a passing mid-latitude depression. Another analysis of a historical marine accident in the 1980s [*In et al.*, 2009] also suggested that the narrowing of the wave spectrum coincides with the possible occurrence of freak waves. In this case, a gale system was moving slowly toward the east. These studies suggested that the formation of a narrow wave spectrum may be preconditioned by certain meteorological states.

[3] The observed freak waves in the North Sea can be explained partly by the weakly nonlinear process of self-focusing [*Slunyaev et al.*, 2005]. In this study, we analyze northern North Sea (NNS) wave records in an attempt to characterize the basic meteorological conditions likely to produce freakish sea states in which nonlinearity plays an important role.

2. Waves in the Northern North Sea

2.1. Wind and Wave Records

[4] The surface elevation time series, made available to us by S. Harver of Statoil, were obtained by Saab radar from the Kvitebjorn platform (hereafter KBP) in the NNS (2.335°E, 61.0050°N and 190 m depth). Continuous hourly wind records and sporadic 20-min wave records at selected high sea states (0.13 s sampling rate) covered the period from December 2003 until May 2005. The records were taken from September to April. Records in 2004 and 2005 mostly came from the winter months. In this section, all 2723 records are analyzed to characterize the mean statistical properties of the waves at the KBP.

2.2. Elevation Time Series and Spectral Geometry

[5] The 20-min surface elevation record η shown in Figure 1 (bottom) contains the most abnormal wave found among all the records. The zero-up-crossing (ZUC) significant wave height H_s is 5.6 m and the corresponding maximum wave height $H_{\max}$ is 14.7 m, yielding an abnormality index $AI \equiv H_{\max}/H_s = 2.6$ and a large kurtosis $\kappa_4 = \langle\eta^4\rangle/\langle\eta^2\rangle^2$ of around 3.93. The energy spectrum $E(\omega) = 1/T\left|\int_0^T \eta(t)\exp(-i\omega t)dt\right|^2$ is estimated from the time series as an averaged periodogram with 64 degrees of freedom (Figure 1, top). The geometrical properties of the spectrum in the frequency domain are derived as follows: the Benjamin-Feir index is defined as $BFI = k_0 m_0^{1/2} Q_p \sqrt{2\pi}$, where $m_0 = \int_0^{\omega_n} E(\omega)d\omega$ and $Q_p = 2\int_0^{\omega_n} \omega E^2(\omega)d\omega/m_0^2$, and the peakedness factor γ is curve-fit to the JONSWAP spectrum; ω_n is the Nyquist frequency. For the record shown in Figure 1, $BFI = 1.75$ and $\gamma = 28.3$, implying an extremely narrow spectrum. Another important parameter, the directional spreading $\sigma_\theta = [2(1 - (a^2 + b^2)/m_0^2)^{0.5}]]^{0.5}$ where $a = \int_0^{2\pi}\int_0^\infty \cos\theta F(\sigma, \theta)d\sigma d\theta)$ and $b = \int_0^{2\pi}\int_0^\infty \sin\theta F(\sigma, \theta)d\sigma d\theta$, is not available from the observation.

[6] Among the 2723 records, we identified 57 cases in which the ZUC maximum wave height exceeded twice the significant wave height, i.e., $AI_{zuc} > 2.0$. A typical 20-min record from the ocean contains about $N = 150$ waves. From

[1]Department of Ocean Technology Policy and Environment, Graduate School of Frontier Sciences, University of Tokyo, Kashiwa, Japan.
[2]Geophysical Institute, University of Bergen, Bergen, Norway.
[3]Department of Physics, Sophia University, Tokyo, Japan.

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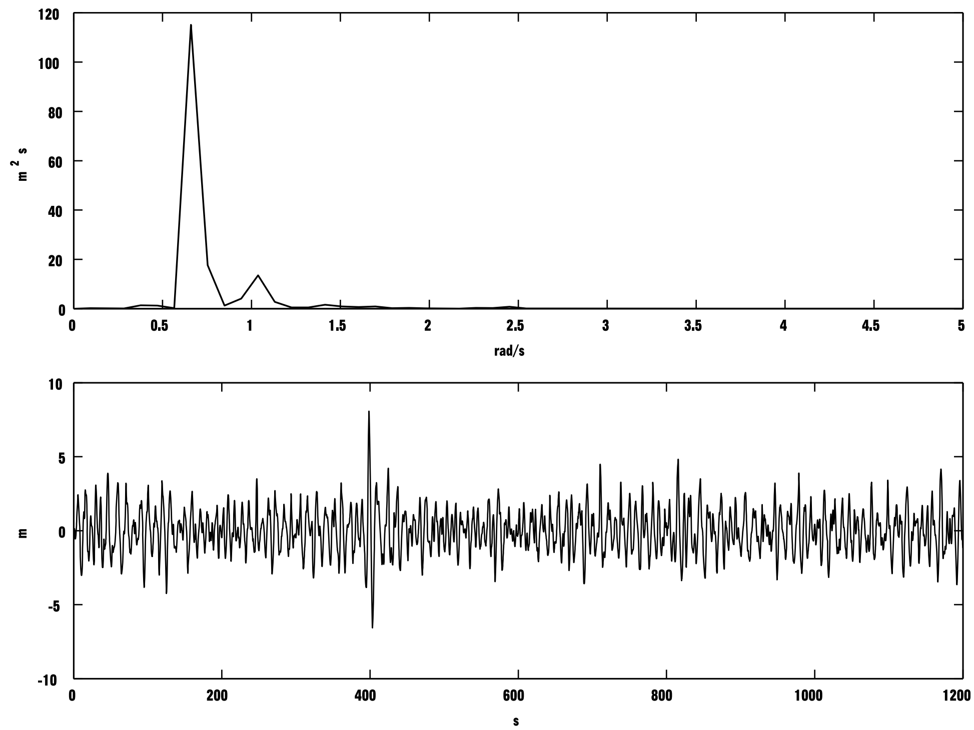

Figure 1. (top) Energy spectrum and (bottom) surface elevation time series.

the Rayleigh distribution of wave height, the probability of finding a record with $AI > 2.0$ is about 4.8 % [*Tomita and Waseda*, 2006]. Hence the data from the KBP are substantially less freakish (57/2723 = 2.1%). When the zero-down-crossing (ZDC) wave was used instead, 62 $AI_{zdc} > 2.0$ events were found, of which 16 coincided with the $AI_{zuc} > 2.0$ events.

[7] The use of the *BFI* [*Janssen*, 2003] allows for correlation of the spectral geometry of the observed or forecasted frequency spectrum to the occurrence probability of the freak wave P_{freak} [*Mori and Janssen*, 2006]. These two studies suggest that nonlinear correction to P_{freak} can be parameterized by the kurtosis κ_4, which is a function of the *BFI* that indicates the relative significance of nonlinearity and dispersion. For all the KBP records, the estimated values of κ_4 ranged between 2.5 and 4.2, whereas the *BFI* ranged between 0.15 and 2.7. However, the two parameters were practically uncorrelated, with a correlation coefficient of −0.03. For example, while there was a case with large $BFI = 1.75$, $\kappa_4 = 3.9$, and $AI = 2.6$ (Figure 1), the largest $BFI = 2.72$ case corresponded to a non-freakish state (small $\kappa_4 = 2.9$ and $AI = 1.49$). In addition, the JONSWAP peakedness parameter γ was estimated for each time record (4.4 ~ 26.2) but had poor correlation with the kurtosis κ_4 (−0.02). Directional wave information may correct the P_{freak} but these data were not available from the observations. We also estimated the correlation between *AI* and the locally measured wind speed W_{local} and found it to be poor (0.007). Therefore, the conventional analysis linking the occurrence of freak waves to either the wave spectral parameters or to local meteorological conditions failed.

2.3. Exceedance Probability

[8] Exceedance probability of the normalized wave height (H/H_s) was estimated from the records following similar analyses by *Forristall* [1978] and *Stansell* [2004]. For each 20-min record, the significant wave height H_s was estimated and the ZUC wave heights were normalized. Those normalized wave heights were accumulated (total of 412,411 waves) and the exceedance probability was estimated (Figure 2). The distribution agrees quite well with the Forristall distribution, which is an empirical fit of the Weibull distribution to the North Sea wave record; $F = 1 - \exp(-(x/a)^c)$ where $a = 0.7218$ and $c = 2.126$. The exceedance probability estimated from the cumulated records did not deviate from that estimated from the subset classified in ranges of H_s at meter intervals. The averaged regressed Weibull coefficients were $a = 0.70$ and $c = 1.9$ with negligible variance. The analysis suggested that the KBP record is consistent with the data analyzed by *Forristall* [1978] (see Figure 2). Therefore, the Rayleigh distribution overestimates the occurrence of freak waves.

[9] A similar tendency of lowered probability at the tail of the distribution was found in tank experiments [*Onorato et al.*, 2009a, 2009b; *Waseda et al.*, 2009a]. However, when the spectrum was extremely narrow in angular spreading, the quasi-resonance became active and the tail of the probability density function increased [*Waseda et al.*, 2009b].

3. Classification of Freakish and Non-freakish Days

[10] The conventional analysis method presented in Section 2 has limitations. The assumption for the analysis is that the parent distribution of the wave remains the same throughout the entire observation period. However, the wind field and effective fetch change with time, along with the wave spectrum and the associated probability distribution. In addition, during the freakish sea state, the chance that the wave record will include freak waves is itself stochastic. Therefore, in evolving sea states, the true wave statistics

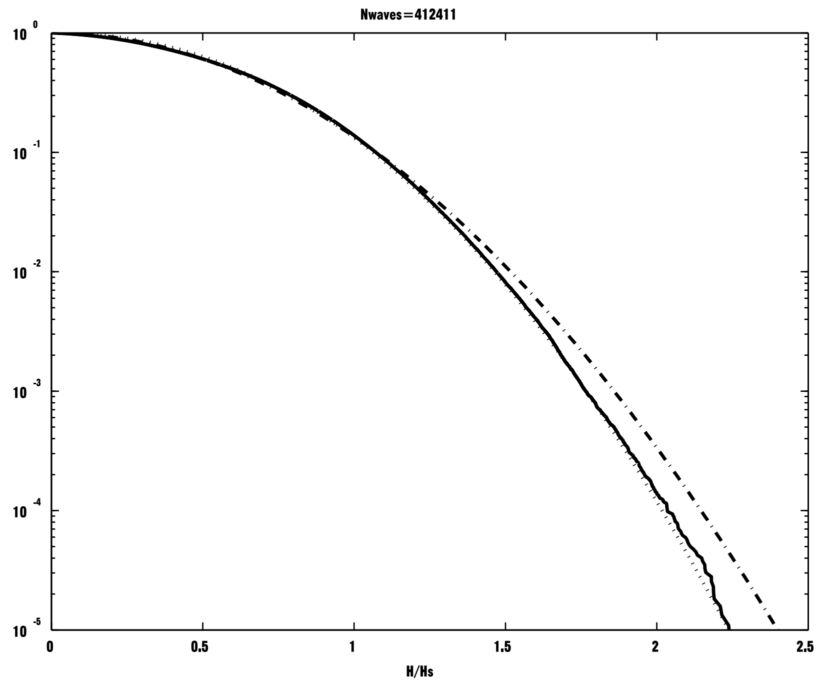

Figure 2. Exceedance probability of H/H_s, log-linear; Rayleigh distribution (dash-dotted line), Forristall distribution (dotted line) and observations (solid line).

cannot be inferred from each record by associating the derived spectral parameters with the freak wave index.

[11] We propose an alternative method. The percentage of records containing freak waves in a day will give us an indication of how freakish the sea state was during that day. We can then classify the observed dates into freakish and non-freakish days. The probability that a given record contains a freak wave is about 2.4% for a record with about 150 ZUC waves. Thus, given that each day has 72 records, the expected number of records that contain a freak wave for an average sea state in the NNS is 1.7. If more than two records contain freak waves in a day, that day is classified as freakish. If there are one or less freak waves in a day, the day will be classified as non-freakish.

[12] Observations of the KBP wave records will be used to classify the dates to be investigated into freakish and non-freakish days. We employed both sophisticated multivariate analysis and an ad hoc method. In the ad hoc method, a freakish day (hereafter, FD) is defined as a day when any of the available 20-min records satisfies $AI_{ZUC} > 2.0$. During the winter of 2004 and 2005, 37 days were classified FD and 64 days were classified as non-freakish (hereafter, NFD). As will be shown in Section 4, the mean sea level pressure showed statistically significant differences between FD and NFD averages. This preliminary analysis motivated us to refine the classification scheme.

[13] A shortcoming of the ad hoc method is that it does not consider the number of available 20-min wave records in a day, even though the record number per day can be from one to 72. The two multivariate methods compensate for the missing information.

[14] A linear discriminant analysis based on 16 explanatory variables (e.g., daily mean, standard deviation, maximum and minimum values of significant wave height, maximum wave height, wind speed, and number of observed waves) was conducted. Ten explanatory variables were found to regress best onto the response variable, which we chose to be the maximum AI of the day. The training sets were chosen to be days with more than two data sets with $AI > 2.0$ for freakish days. For non-freakish days, they were chosen as days with more than 58 records but without any case with $AI > 2.0$. As a result, 44 days were classified as FD and 57 days were classified as NFD.

[15] The weighting method provides an estimate the expected number of freak wave cases for the missing data. For example, if M observations were missing in a day, the expected number of cases of freak waves in a day can be estimated as $M \times P(AI > 2.0)$ plus the actual number of observed cases. The empirical fit to the Weibull distribution from the records was used for the probability $P(AI > 2.0)$. As a result, 24 days were classified as FD and 77 days were classified as NFD.

[16] The arbitrary parameters in the two multivariate methods varied and the results presented above are our best estimates. However, misclassifications may still be possible. To make the best estimate, we took the common denominator of the three classifications. The results identified 10 days as freakish and 35 five days as non-freakish; the rest of the days were ambiguous.

4. SLP Difference Between Freakish and Non-freakish Sea States

[17] We boldly hypothesized that the freakish sea state is forced deterministically by a unique weather system. Here, we investigate the possibility that the increased occurrence probability of freak waves at the KBP is associated with particular synoptic atmospheric conditions.

[18] Daily mean National Centers for Environmental Prediction (NCEP) reanalysis products were analyzed: the sea level pressure (SLP) at 2.5 degree resolution, wind speed at 10 m height (U_{10}), surface air temperature at 2 m height

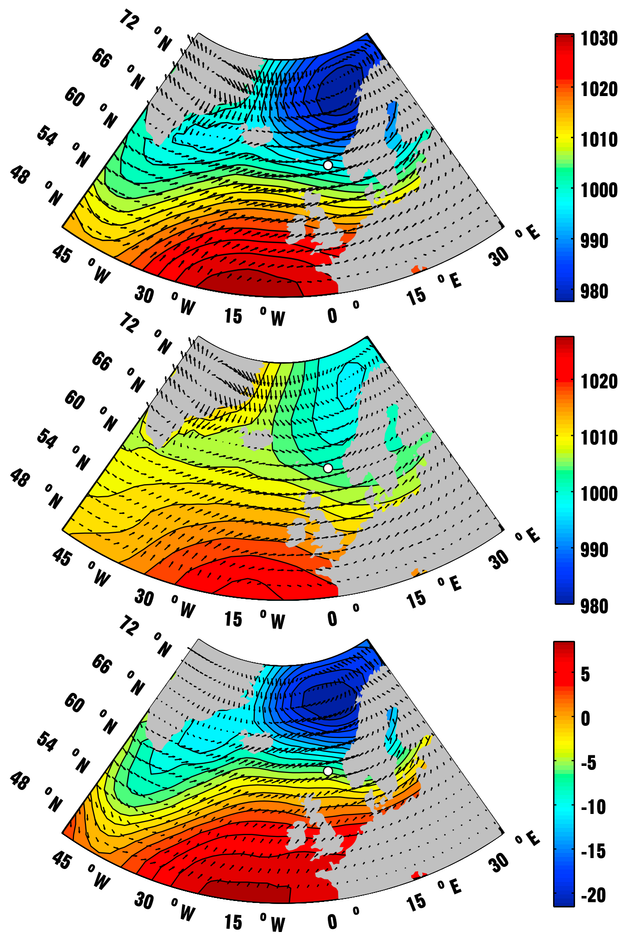

Figure 3. (top) *SLP* for FD, (middle) *SLP* for the NFD and (bottom) sea level pressure difference between the NFD and FD (ΔSLP). Contours indicate *SLP*s, and their difference. The arrows indicate mean wind speeds and their difference.

(*SAT*), and sea surface temperature (*SST*) at approximately 0.1 degree resolution.

[19] NCEP reanalysis variables (*SLP*, U_{10}, *SAT* and *SST*) were conditionally averaged for the NFD and the FD. For most variables, the difference in the means between the classified cases were negligibly small, moderate but insignificant (from the null hypothesis test), or both small and insignificant. The only exception was the *SLP* (Figure 3). The difference between the FD (top) and NFD (middle) cases suggests that when a freak wave was observed at the KBP (white dot in Figure 3), with 99% significance level using the z-test, both the Icelandic low and the Azores high were enhanced (note that ΔSLP is defined as $P_{FD} - P_{NFD}$). Therefore, the westerly wind at the KBP was strengthened in the FWD cases.

[20] We were surprised that there was a statistically significant enhancement of the Iceland-Azores sea level pressure (*SLP*) gradient for the FDs. If freak wave occurrence is random, it is hard to conceive that the conditionally averaged *SLP*s would differ significantly because they are based on how often a freak wave was observed during a day. To ensure that the result was not an artifact of the analysis, we randomly selected 10000 combinations of 36 days from the record and compared the mean *SLP* to that of the rest of the record (65 days). About 20% of the random combinations showed a *SLP* difference at nearly 95% significance level, but no case reached the significance level of the difference shown in Figure 3. This result suggests that the difference in the pressure gradient shown in Figure 3 was not a rare coincidence.

5. Narrowing of the Directional Spectrum in the Freakish Sea State

[21] The mean SLP difference between FD and NFD was statistically significant, particularly in regions including the KBP. The corresponding wave field in the NNS differed between FD and NFD as simulated by Wave Watch 3 (WW3) forced by NCEP wind data. The wave hindcast simulation was conducted in the region 37.5°W to 37.5°E and 37.5°N to 75°N at 1/4 degree resolution during 1 August 2004 to 30 April 2005 (hereafter, NNS-WW3). The modeled wave field compared reasonably well with the Fleet Numerical Meteorology and Oceanography Center (FNMOC) WW3 simulation, obtained from the U.S. Global Ocean Data Assimilation Experiment (GODAE) portal, but showed lower wave height than observations at the KBP. Various wave parameters derived from the directional wave spectrum of the NNS-WW3 were averaged over the classified FD and NFD. The significant wave height was 2.0 m larger for FD (6.0 m) in regions around the KBP. The mean period was around 1.6 s larger and the peak period was 2.0 s larger for FD (10.4 s and 8.7 s). Because the wavelength increased with wave height, the steepness was nearly the same (0.10); the difference was 0.0093. The difference in the frequency bandwidth $Q_p \sim 2.2$ was small (0.013). Therefore, both the nonlinearity and dispersion effects were comparable between the FD and NFD. The most prominent difference was found in the directional spreading (Figure 4). At the KBP, the average directional spreading was about 7.6 degrees lower for FD (28.8 degrees) than for NFD (36.4 degrees). The region of the reduced directional spreading extended to a wider surrounding area where the maximum reduction was about 10 degrees. We have shown that when freak waves were observed more often at KBP, the directional spreading of the wave spectrum was narrower than on other days.

6. Discussion

[22] The wave records from an oil platform in the NNS were used to classify the days with and without freak waves. The results revealed that when the Iceland-Azores *SLP* gradient strengthened, more freak waves were observed at the KBP. From the hindcast simulation of the wave field, the average spectral characteristics of the FD showed narrower directional spreading than those of the NFD (Figure 5). For both cases, about 30% were mixed swell-windsea condition. Although not validated quantitatively yet, the result implies that the probability of freak wave occurrence is inhomogeneous in space, and that under certain synoptic meteorological conditions, a region with high probability of freak waves can form.

[23] In addition, local winds may influence the wave occurrence. Correlation of the local wind with AI showed that the maximum wind speed in a day correlated better (correlation coefficient = 0.46) than the mean wind speed

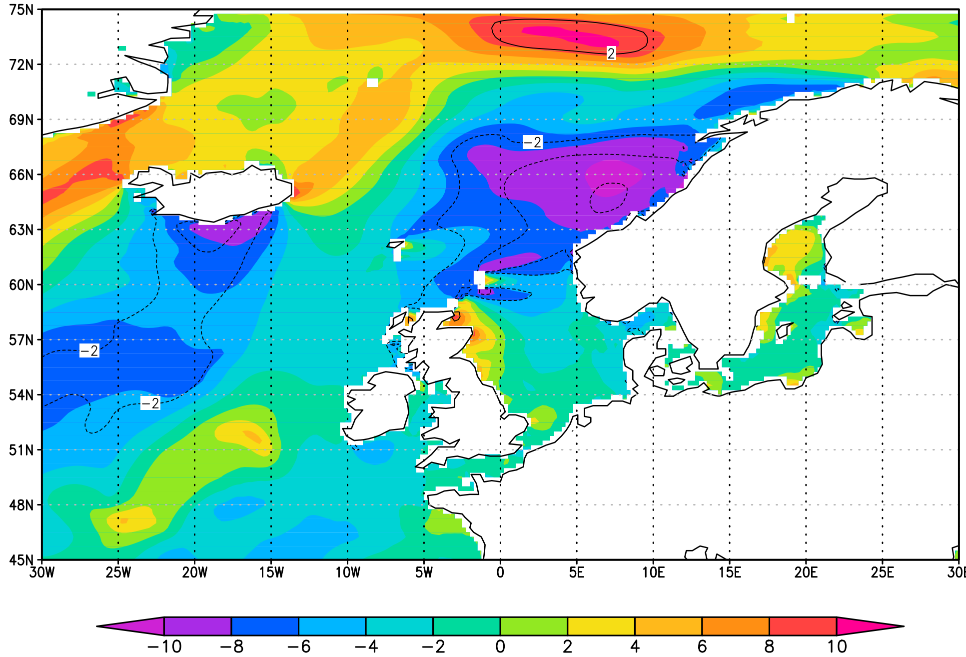

Figure 4. Difference in the directional spreading, FD - NFD (color contour) and the statistical significance levels at $z = \pm 2$, ± 3, *and* ± 4 (contour line).

(correlation coefficient = 0.007). A region near KBP was identified as having high sea wind from satellite data [*Sampe and Xie*, 2007]. It is therefore plausible that the gust may have prolonged the lifetime of the freak wave, as suggested by *Kharif et al.* [2008].

[24] The focused analysis of NNS wave records revealed that straightforward comparison among wave and environmental parameters may hinder understanding of freakish sea states. This concept as well as the usefulness of the opera-

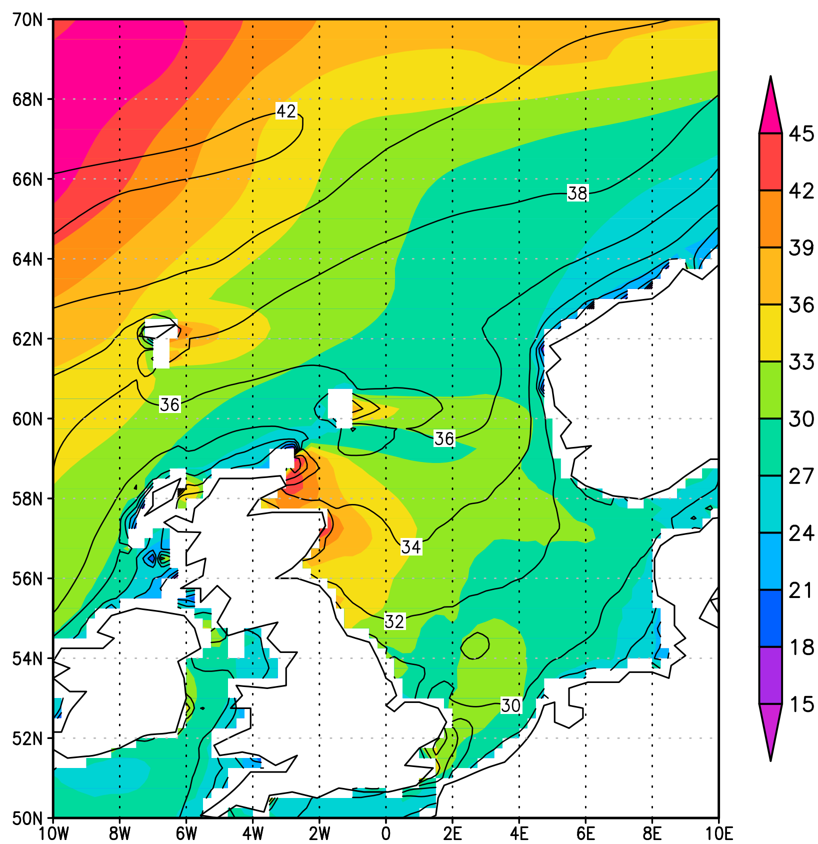

Figure 5. Directional spreading for FD (color contour) and NFD (contour lines).

tional forecast such as the ECMWF freak wave warning system should therefore be revisited.

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M. Hallerstig, K. Ozaki, and T. Waseda, Department of Ocean Technology Policy and Environment, Graduate School of Frontier Sciences, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8563, Japan. (waseda@k.u-tokyo.ac.jp)

H. Tomita, Department of Physics, Sophia University, Tokyo 190-0002, Japan.