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Rogue Wave Observations Off the US West Coast

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ABSTRACT. Rogue waves can cause significant damage to vessels and offshore structures and are linked to the loss of hundreds of lives at sea. They represent extreme statistical events with wave heights exceeding twice the significant wave height. The authors investigated a wave buoy data set collected off the US West Coast with 7,157 rogue waves observed over a total of 81 years. It yields comprehensive statistics regarding the likelihood of rogue wave occurrence in the open ocean, coastal ocean, and shallow water. The highest recorded rogue wave had a trough-to-crest height of 18.95 m. The average likelihood of occurrence is 63 per year in coastal waters and 101 per year in the open ocean. An extrapolation to conditions in the world ocean yields an average likelihood of encountering rogue waves along the main shipping routes in the North Atlantic of 0.8–1.2% per day for rogue waves exceeding 11 m in height. The results can be used to test rogue wave forecasting models and will help to improve the forecasting of hazardous ocean conditions.

INTRODUCTION

Rogue waves are commonly defined as waves with a trough-to-crest height exceeding the significant wave height (approximately the average of the highest one-third of waves that occur in a given period) by a factor of two or more and are, therefore, statistically extreme ocean gravity waves. While their absolute wave height may not always be large, they become a major hazard for vessels and offshore structures in rough seas. In folklore, rogue waves have served as an explanation for the disappearance of ships for centuries, but they have also been linked to several recent incidents and the loss of hundreds of people in heavy seas (Lawton, 2001; Kharif and Pelinovsky, 2003; Didenkulova et al., 2006; Liu, 2007). The existence of rogue waves has been verified only recently by scientific evidence, such as two striking observations in the North Sea: in 1984, a ~ 13-m-high wave was observed at the Gorm Platform (Sand et al., 1990), exceeding the significant wave height by more than a factor of two, and in 1995, the "New Year's Wave" was measured at the Draupner Platform (Taylor et al., 2006) with a trough-to-crest height of 25.6 m in seas of 12 m. In spite of an increasing number of recent rogue wave observations (e.g., Paprota et al., 2003; Dysthe et al., 2008; Didenkulova and Anderson, 2010) more data are needed to establish the differences in rogue waves statistics between shallow and deep water, and coastal and open ocean, and to improve our understanding of the mechanisms under which rogue waves are predominantly formed.

WAVE DATA

In this study, we use wave amplitude data collected between 1993 and 2010 at 16 different Datawell Directional Waverider buoys (type Mk-II and Mk-III) off the US West Coast (Table 1, Figure 1). The buoy locations are representative of deepwater open-ocean conditions, shallow water, and the coastal ocean of varying water depths sheltered by islands or the coast (Table 1), which will be considered separately. The Coastal Data Information Program (CDIP), Integrative Oceanography Division, operated by Scripps Institution of Oceanography, San Diego, CA, furnished the data. All buoys contain accelerometers that are mounted along each of their three principal axes. The displacements in the vertical and horizontal directions are calculated independently by double integration. The horizontal orientation

Table 1. Wave buoys of the Coastal Data Information Program used in this study

	Buoy	Name	Position	Time On (years)	Water Depth (m)	Max. Rogue Wave Height (m)
Open Ocean	029	Point Reyes, CA	38°12.23’N, 125°58.45'W	8.5	550	16.1
	067	San Nicolas Island, CA	33°13.28’N, 119°52.84'W	5.3	335	13.2
	071	Harvest, CA	34°27.24’N, 120°46.83'W	7.9	549	19.0
	094	Cape Medocino, CA	40°17.45’N, 124°44.42'W	6.2	319	18.8
	157	Point Sur, CA	36°20.47’N, 122°06.13'W	1.0	366	12.5
Coastal Ocean	028	Santa Monica Bay, CA	33°51.27’N, 118°37.97'W	9.5	363	7.0
	091	Point Loma, CA	32°37.93’N, 117°26.66'W	4.0	186	6.4
	107	Goleta Point, CA	34°20.00’N, 119°48.21'W	5.9	183	7.0
	111	Anacapa Passage, CA	34°10.04’N, 119°26.10'W	5.9	113	8.2
	156	Monterey Canyon, CA	36°45.65’N, 121°56.81'W	2.4	168	8.1
Shallow Water	036	Gray’s Harbor, WA	46°51.53’N, 124°14.63'W	11.0	40	16.7
	076	Diablo Canyon, CA	35°12.23’N, 120°51.56'W	5.6	23	11.3
	128	Humboldt Bay, CA	40°45.18’N, 124°18.76'W	4.7	40	12.8
	131	Rincon, CA	34°21.33’N, 119°28.53'W	1.5	22	3.4
	141	Port Hueneme, CA	34°06.00’N, 119°10.03'W	0.6	21	5.5
	142	San Francisco Bar, CA	37°46.80’N, 122°35.83'W	2.2	16	6.7

is determined with a fluxgate compass. Pitch and roll measurements are determined by magnetic flux changes and are coupled with the accelerations to determine horizontal displacement.

The Waverider buoys can measure waves with periods of 1.6–30 s and wave heights up to 40 m, with a displacement error < 3%. The data were recorded at a rate of 1.28 Hz and the horizontal and vertical resolution is 0.01 m. The maximum horizontal displacement of the buoy from its deployment location is ~ 1.7 times the water depth. In earlier years, the buoys transmitted 42 min of data every 3 h. This value gradually increased to continuous coverage in later years with the exception of errors and communication failures.

Transmission-related errors and data spikes of more than 6 m s^{-1} or spikes with ratios of $a/H_s > 2.0$, where a is the wave amplitude, were removed. The magnitude of the vertical and horizontal displacements had to agree within a factor of 1.5, and the wavelengths of the rogue wave and predominant background wave field had to agree within a factor of 2.0. The wave height could not exceed the water depth, and each rogue wave had to contain at least five data points. Filter performance was checked manually for all rogue waves and all questionable data were removed. The resulting uncertainty is < 3%. The total amount of logged and usable data, hereafter referred to as “time on,” is 80.8 years for all buoys combined.

ROGUE WAVES

Rogue waves are usually defined as waves with a trough-to-crest wave height H exceeding the significant wave height H_s by at least a factor of two (Dysthe et al., 2008; Stansell, 2004; Donelan and Magnusson, 2005; Müller and Garrett, 2007). Other authors use a ratio of $H/H_s \geq 2.2$ (Heller, 2006) or $H/H_s \geq 2.3$ (Wolfram et al., 2001), or a ratio of wave crest height to significant wave height of $\xi/H_s > 1.25$ (Müller and Garrett, 2007; Dysthe et al., 2008). In this study, we will mainly use the definition $H/H_s \geq 2.0$, but we will also calculate statistics for $H/H_s \geq 2.2$ and $\xi/H_s > 1.25$.

The significant wave height H_s is calculated over a 30-min sliding interval as $H_s = 4\ std(a)$, where a is the surface

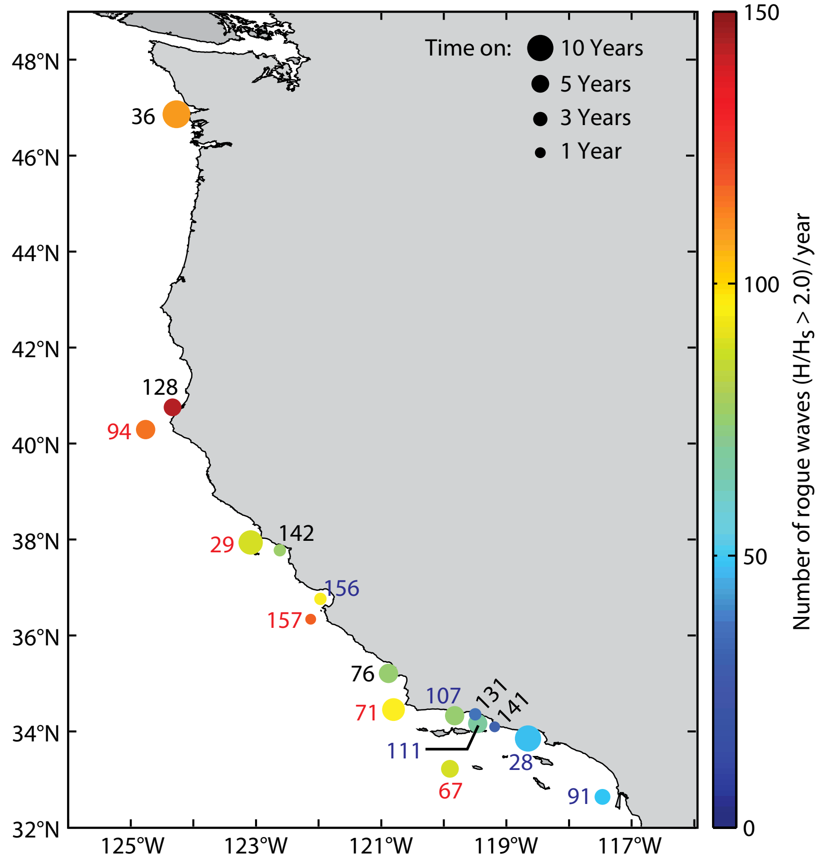

Figure 1. Map of the US West coast with locations of the Coastal Data Information Program (CDIP) buoys used in this study (Table 1). The text shows the mooring number, and the text color indicates open-ocean moorings (red), coastal moorings (blue), and shallow-water moorings (black). The average number of rogue waves per year for a ratio of wave height to significant wave height $H/H_s \geq 2.0$ is given by the colored dots, with the amount of available data indicated by their size.

elevation relative to the mean sea surface height and *std* is the standard deviation. Rogue waves are often thought to be extremely large and destructive, but because they are defined relative to the significant wave height, the majority of the rogue waves are only a few meters high. While these waves may cause significant damage to smaller vessels, the buoys also recorded 69 waves of more than 11 m in height. The largest rogue wave found in the data occurred at buoy 71 (Harvest, CA) on February 24, 2008, 21:19 UTC and is shown in Figure 2a. It is the second of two rogue waves immediately following each other. The trough-to-crest heights of the two waves are 16.7 m and 18.95 m, the zero-crossing wave period is 15.5 s, and the H/H_s ratios are 2.4 and 2.3. The magnitudes of the horizontal displacements are 23.0 m and 16.8 m. Horizontal and vertical displacements indicate an approximately circular wave motion (Figure 2b). The directions of the rogue waves agree with the hourly directional wave spectra provided by the Coastal Data Information Program within < 20° (Figure 2c).

ROGUE WAVE STATISTICS

The average number of rogue waves per year is calculated by comparing the number of rogue waves found at each buoy to its total "time on" and to the total number of waves. In a total of 80.8 years of data and 6.1 x 10^8 waves at all moorings, 7,157 rogue waves with a ratio of $H/H_s \geq 2.0$ were observed, averaging 88.6 rogue waves per year, or about one in 84,500 waves (Table 2). For a ratio of $H/H_s \geq 2.2$, a total of 687 rogue waves were counted, yielding an average of 8.5 rogue waves per year or one in 880,000 waves. The maximum observed ratio of H/H_s was 2.57 for a 4.1-m-high wave at buoy 128. The maximum rogue wave height was 18.95 m at buoy 71 (Figure 2).

The statistics vary significantly when open ocean, shallow water, and coastal ocean are considered separately (Table 2). While in the open ocean and shallow water, about 100 rogue waves of $H/H_s \geq 2.0$ and 9 to 11 rogue waves of $H/H_s \geq 2.2$ occur per year, they are less frequent in the protected coastal waters with 63 and 6 rogue waves per year for $H/H_s \geq 2.0$ and $H/H_s \geq 2.2$, respectively.

Figure 1 shows regional differences in the likelihood of rogue wave occurrence. The colors show the average number of rogue waves at each of the 16 buoys, indicating that the greatest likelihood of rogue wave occurrence is at the exposed deepwater and northern buoys, while the lowest likelihood of occurrence

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is at the sheltered coastal buoys in Southern California Bight. Table 1 shows the maximum rogue wave height found at each buoy.

Figure 3a plots the exceedance probability of rogue waves as a function of the normalized crest height ξ/H_s, and Figure 3b plots the normalized wave height H/H_s for the coastal ocean (dotted curves) and open ocean (dashed curves). Waves with $\xi/H_s \geq 1.25$ or $H/H_s \geq 2.0$ are rogue waves. The observed probabilities are compared to the distributions by Forristall (2000) and Naess (1985), respectively, yielding mostly higher likelihoods than the wave buoy observations.

The number of rogue waves per year is plotted in Figure 4a for waves within a wave height increment of 1.0 m. Rogue waves with a height of 3.0 m are the most common, and a total of 69 rogue waves with $H \geq 11$ m have been found in the data. These numbers are indicative of the most common wave height at the mooring locations, as large rogue waves will not likely occur in areas with small H_s.

Figure 4b plots the average likelihood of encountering a rogue wave in a 24-h period as function of the significant wave height H_s, with solid lines indicating H/H_s increments of 0.1 and significant wave height increments of 1.0 m. The data comprise a total of 28.3 years from the five open-ocean moorings located in unprotected waters off the US West Coast (Table 1). The figure shows that the rogue wave likelihood is almost independent of H_s and is predominantly a function of H/H_s, which is consistent with Stansell (2004). For large H/H_s ratios, it increases slightly with H_s as indicated in Figure 4b.

In order to determine the probability P of encountering a rogue wave

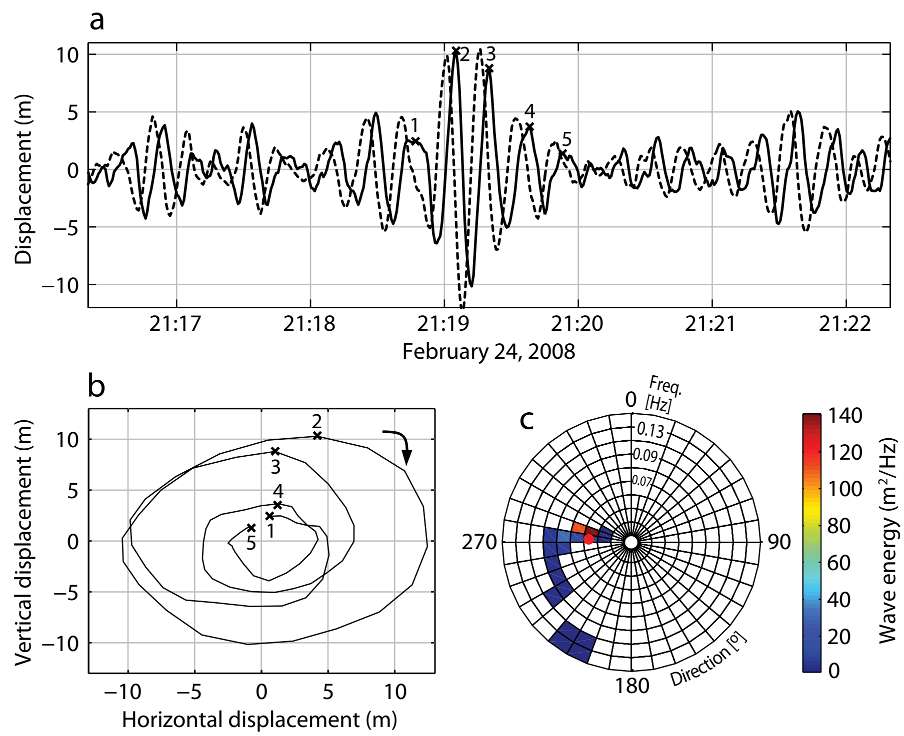

Figure 2. Two rogue waves at mooring 71 (Harvest, CA) on February 24, 2008, 21:19 UTC. (a) Wave amplitude (solid line) and magnitude of horizontal displacement in wave direction (dashed line). Locations 1 to 5 correspond to panel (b). The trough-to-crest wave height of waves 2 and 3 is 16.7 m and 18.95 m, respectively, and the zero-crossing period is 15.5 s. (b) Horizontal and vertical displacements indicate rotational motion. (c) Directional wave spectrum showing the wave energy density of the background wave field as function of direction (°) and frequency (Hz). The direction and frequency of the rogue waves are marked with red dots.

Table 2. Rogue wave statistics

		Open Ocean	Shallow Water	Coastal Ocean	Total
Total Time (years)		28.3	25.0	27.5	80.8
Total Number of Waves		2×10^8	1.8×10^8	2.2×10^8	6.1×10^8
Average Wave Period (s)		4.5	4.3	3.8	4.2
Number of Rogue Waves	$H \geq 2.0H_s$	2843	2567	1747	7157
	$H \geq 2.1H_s$	926	800	519	2245
	$H \geq 2.2H_s$	258	278	151	687
	$\xi \geq 1.25H_s$	1072	737	630	2439
Likelihood	$H \geq 2.0H_s$	1.4×10^{-5}	1.4×10^{-5}	7.7×10^{-6}	1.2×10^{-5}
	$H \geq 2.1H_s$	4.7×10^{-6}	4.4×10^{-6}	2.3×10^{-6}	3.7×10^{-6}
	$H \geq 2.2H_s$	1.3×10^{-6}	1.5×10^{-6}	6.7×10^{-7}	1.1×10^{-6}
	$\xi \geq 1.25H_s$	5.4×10^{-6}	4.1×10^{-6}	2.8×10^{-6}	4.0×10^{-6}
Number of Rogue Waves Per Year	$H \geq 2.0H_s$	100.6	102.7	63.4	88.6
	$H \geq 2.1H_s$	32.8	32.0	18.8	27.8
	$H \geq 2.2H_s$	9.1	11.1	5.5	8.5
	$\xi \geq 1.25H_s$	37.9	29.5	22.9	30.2

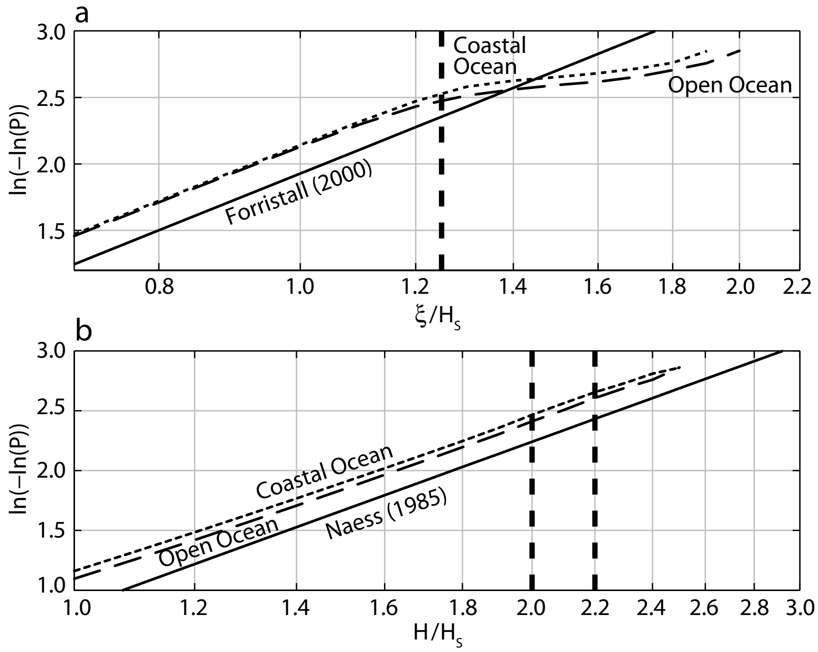

Figure 3. Exceedance probability P plotted as $ln(-ln(P))$ and as a function of (a) normalized crest height ξ/H_s and (b) normalized wave height H/H_s for the coastal ocean (dotted curves) and open ocean (dashed curves). The distributions by Forristall (2000) and Naess (1985) are plotted for comparison. Values above those lines indicate a lower probability.

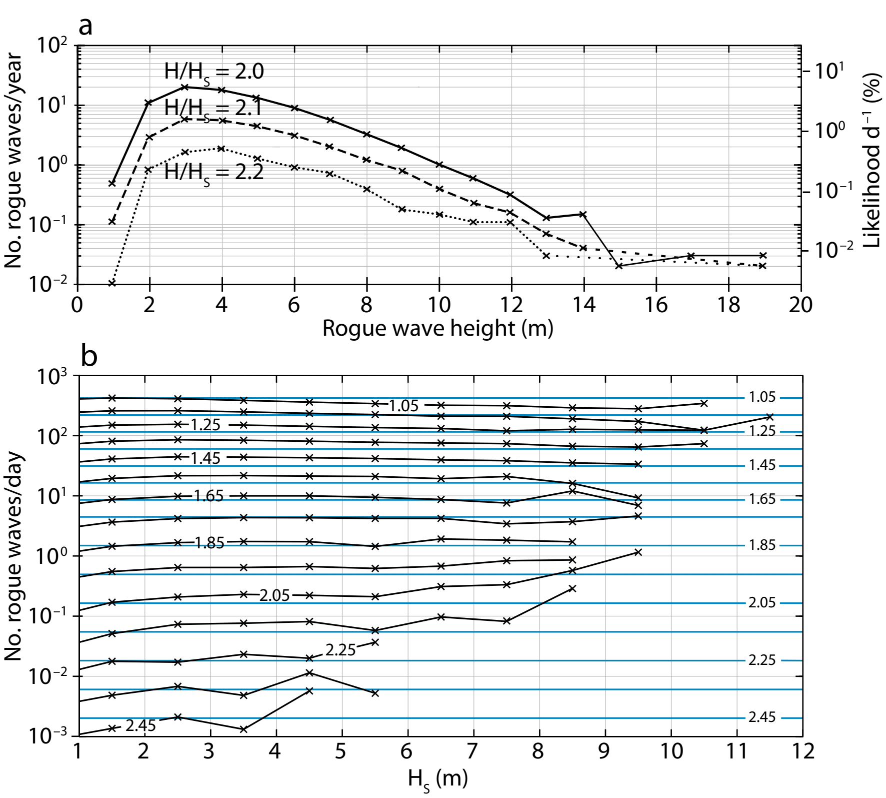

Figure 4. (a) Number of rogue waves per year for wave height increments of 1.0 m for H/H_s = 2.0, 2.1, and 2.2. The likelihood of encountering a rogue wave within a 24-h period is shown on the right-hand axis. (b) Number of rogue waves per day for significant wave height increments of 1.0 m and H/H_s increments of 0.1 calculated from the open-ocean moorings (black lines) and from the linear approximation as described in the text (blue lines).

in the open ocean, the data have been approximated with $P = 535e^{6.5(1-H/Hs)}$ for $H/H_s \leq 1.75$ and $P = 17{,}000e^{11(1-H/Hs)}$ for $H/H_s > 1.75$ conservatively predicting the number of rogue waves in a 24-h interval for H/H_s–increments of 0.1. The results are plotted in Figure 4b as dashed lines.

We use this approximation derived from the open-ocean moorings off the US West Coast to estimate the likelihood of rogue waves of a certain size in the world ocean using daily level-3 QuikSCAT wind speed data for the years 2000 to 2008 with a 25-km resolution, even though several other factors such as directionality, nonlinearity, or nonstationarity may influence the results, as discussed below.

Daily values of the significant wave height are calculated for each location as function of wind speed u_{10} (Sverdrup and Munk, 1947) as $H_s = k\, u_{10}^2\, g^{-1}$, where g is the gravitational acceleration and the constant $k = 0.15$ is derived for open-ocean conditions in the North Atlantic. More recent results (Emeis and Turk, 2009) closely match this equation. Based on the statistics of H_s at each location, the H/H_s-ratio required to exceed a certain wave height is determined, and the time-averaged rogue wave likelihood is calculated.

Figure 5a is a world map of the extrapolated likelihood of encountering rogue waves in the open ocean within a 24-h period for rogue waves defined as $H/H_s \geq 2.0$ and $H/H_s \geq 2.2$ and with wave heights of $H \geq 5$ m and $H \geq 11$ m. The areas of the highest likelihood generally correspond to areas of high wind speeds in the Southern Ocean, North Atlantic, and North Pacific. Rogue waves with $H \geq 5$ m are about twice as common in the Southern Ocean as in the North Atlantic and North Pacific, while rogue waves with $H \geq 11$ m have similar likelihoods in all three oceans. Rogue waves with $H \geq 5$ m and defined as $H/H_s \geq 2.0$ have a likelihood of up to 9% for a 24-h period. If a rogue wave definition of $H/H_s \geq 2.2$ is used, the maximum likelihood is 1.1%, which is similar to the likelihood of rogue waves with $H \geq 11$ m and $H/H_s \geq 2.0$.

RESULTS AND DISCUSSION

We identified a total of 7,157 rogue waves defined as $H/H_s \geq 2.0$ over a total measurement period of 80.8 years for all buoys combined. The likelihood of rogue waves is 63.4 per year in the sheltered coastal ocean and 100.6 per year in the open ocean, and is more or less independent of the significant wave height. In the coastal ocean, this likelihood is equivalent to an average of one rogue wave in 129,300 waves, or 7.7×10^{-6} and a return period of 5.75 d. In the open ocean, the likelihood is 1.4×10^{-5} and a return period of 3.6 d. These numbers are significantly lower than previous observations showing a likelihood of 2.9×10^{-4} and a return period of 7.6 h (Stansell, 2004), as well as the observations of small waves in very shallow water (Didenkulova and Anderson, 2010) with a likelihood of 2.5×10^{-4} and a return period of 2.1 h. Gaussian wave height statistics predict a likelihood of 3.4×10^{-4}, which is also significantly larger than our observations. On the other hand, several studies show that Gaussian statistics over-predict the wave height probability distribution in comparison with observations (Kharif and Pelinovsky, 2003; Paprota et al., 2003; Forristall, 2000, 2005; Forristall

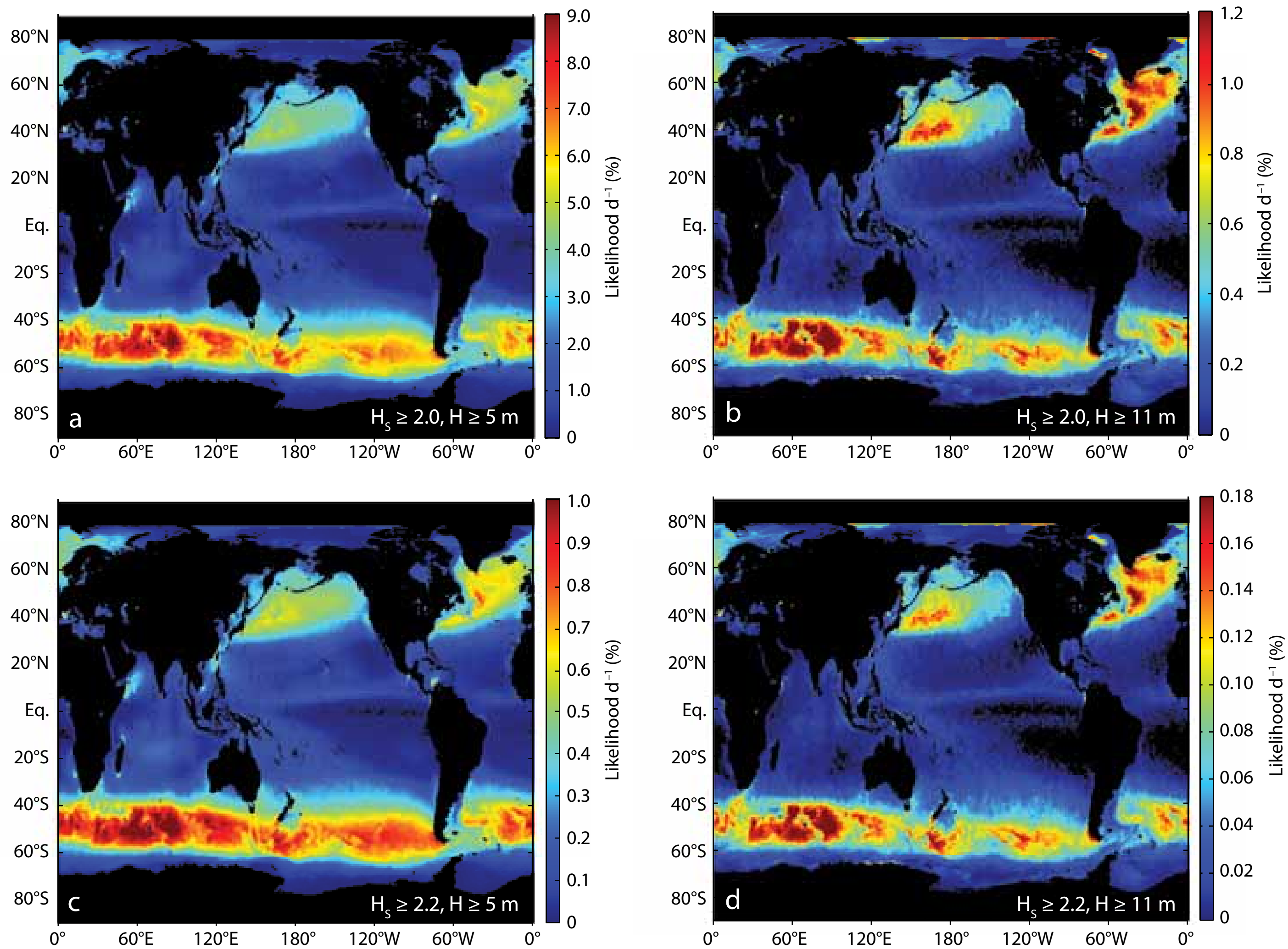

Figure 5. Map showing the average likelihood of encountering a rogue wave within a 24-h period in the open ocean. (a) Likelihood for waves with $H/H_s \geq 2.0$ and $H \geq 5.0$ m, (b) $H/H_s \geq 2.0$, $H \geq 11.0$ m, (c) $H/H_s \geq 2.2$, $H \geq 5.0$ m, and (d) $H/H_s \geq 2.2$, $H \geq 11.0$ m.

et al., 2004), while others argue that they underestimate the likelihood (Stansell, 2004). Different environmental conditions, such as very shallow water, are likely to account for part of the differences among the statistics, but the discrepancy may be also due to the fact that wave buoys, as used in this study, yield statistics less than Gaussian, while wave lasers provide statistics higher than Gaussian (Forristall, 2005; Magnusson et al., 2003). The wave period can differ between these Eulerian and Lagrangian measurement methods by up to 38% (Longuet-Higgins, 1986). Low buoy measurements are often explained by buoys submerging in the wave crest or sliding sideways away from the highest point of the crest (Forristall, 2000). Lower crest height statistics are also caused by a buoy traveling with the direction of the wave in the crests and backward in the trough, so that it spends more time in the crests, leading to an overestimation of the mean sea surface elevation and an underestimation of the crest heights (Forristall, 2000).

Another factor that makes the comparison with other data sets difficult is the calculation of the significant wave height, which has been traditionally determined as the average of the highest one-third of the waves ($H_{1/3}$), resulting in values that are typically 5% lower than the modern description of four times the standard deviation of the sea surface elevation (e.g., Forristall, 1978). This figure is equivalent to a 5% less-restrictive rogue wave definition, such as $H/H_s \geq 1.9$ instead of $H/H_s \geq 2.0$, and therefore results in a much larger number of rogue waves (by a factor of two to three) and a shorter return period.

The sheltering of islands and often fetch-limited conditions may cause the significantly shorter return period of rogue waves in the open ocean compared to the coastal ocean. However, there are also indications (Figures 3a and 4b; Stansell, 2004) that rogue waves generally occur more frequently at higher significant wave heights, such as in the open ocean. Also, a systematic difference in buoy measurements of small and large rogue waves may have an effect due to the different vertical accelerations and displacements of the buoys.

Most of the observed rogue waves are relatively small, with wave heights of 3–4 m. While these waves can significantly damage small vessels, they do not affect large ocean-going vessels, which generally have a design wave height of ~ 11 m (Smith, 2007). Winds of > 26.8 m s^{-1} are required to generate a significant wave height exceeding 11 m, but rogue waves of 11-m height can already occur at significant wave heights of 4.4–5.5 m, or wind speeds of 17.0–19.0 m s^{-1}, and can therefore be found in many regions of the world ocean (Figure 5).

In 2007, a total of 490,517 ship journeys directly connecting two ports were made by 16,363 ships of more than 10,000 GT, making up 93% of the world's total capacity of cargo ships (Kaluza et al., 2010). In the heavily frequented North Atlantic, several shipping lines pass through an extended area of high rogue wave likelihood (Figure 5), such as the route between Rotterdam, Netherlands, and New York, USA, with about 3,000 ship journeys per year. To illustrate the potential risk of encountering a rogue wave along this shipping route, we assume an average ship speed of 23 knots. While it takes 5.7 d to complete the journey, the vessel spends ~ 2 d in the region with a 0.9% likelihood of encountering rogue waves with heights exceeding 11 m (Figure 5b). Thus, an average of 54 vessels may be hit by a rogue wave of more than 11-m height each year on that route alone. Ships predominantly traveling in the North Atlantic will encounter 20–30 of these rogue waves during their service lives of 25 years.

Several additional factors play a role that may have an influence on the buoy data used in this study or the likelihood of rogue wave occurrence in many parts of the world ocean. For example, the study does not consider wind fetch (Waseda, 2006), wind speed fluctuations (Abdalla and Cavaleri, 2002), directionality (Abdalla and Cavaleri, 2002), nonstationarity (Müller and Garrett, 2007; Mori and Janssen, 2006), nonlinearity (Onorato et al., 2006; Janssen and Herbers, 2009), group and crest length (Gramstad and Trulsen, 2007), water depth (Baldock and Swan, 1996), wave focusing by meteorology (Donelan and Magnusson, 2005), topography, currents, or wave-current interaction (Janssen and Herbers, 2009; Smith, 1976; Lavrenov, 1998; White and Fornberg, 1998; Baschek, 2005). While the latter two may have significant influence in regions with strong velocity gradients, such as fronts or the Agulhas current off South Africa, the results of this study nevertheless demonstrate that rogue waves present a significant threat for vessels and offshore structures in extended parts of the world ocean.

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