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Extreme Ocean Wave Conditions for Northern California Wave Energy Conversion Device

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Extreme Ocean Wave Conditions for Northern California Wave Energy Conversion Device

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Abstract

The work described in this document was performed in support of the marine hydrokinetic (MHK) reference model effort led by Sandia National Laboratories. The goal of the reference model effort is to develop a representative set of models for the MHK industry that establish baseline cost of energy and identify key areas for technology improvement. The focus of this report is extreme ocean wave, wind, and surface current conditions at the Northern California deployment site chosen for the Reference Model 3 point-absorber wave device. Archived data records from wave buoys at the reference site are analyzed in accordance with the recommendations of applicable design standards to calculate the 100-year wave height and period as well as extreme wind conditions.

ACKNOWLEDGMENTS

Data were furnished by: the National Data Buoy Center (NDBC) operated by the National Oceanic and Atmospheric Administration; the Coastal Data Information Program (CDIP), Integrative Oceanography Division, operated by the Scripps Institution of Oceanography, under the sponsorship of the U.S. Army Corps of Engineers and the California Department of Boating and Waterways; and the OSCAR Project Office operated by Earth and Space Research.

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INTRODUCTION

The response of a wave energy conversion device to extreme ocean conditions must be analyzed to properly design the mooring system and provide appropriate strength margins in the structural design of the device. For the purpose of extreme event analysis, the ocean sea-state can be characterized with average wave parameters such as significant wave height and peak wave period. Significant wave height, H_s, is described as the mean of the highest one-third of waves in the wave record but it is typically derived from the energy spectrum. Peak period, T_p, is the inverse of the frequency at which the energy spectrum obtains its peak value. Wave height and period must be considered jointly and therefore the set of extreme conditions is described by a curve rather than a single point. Although surface winds likely have some correlation with the wave height, this report treats the extreme value statistics for wind independently.

DESIGN STANDARDS

The design standards and recommended practices of Det Norske Veritas (DNV) provided guidance in defining the extreme environmental conditions. The offshore standard on position mooring [1] includes a list of required design documentation for device certification. Among the items listed, the following environmental conditions are required:

- Combinations of significant wave heights and peak periods along the 100-year contour line for a specified location;
- 1 hour mean wind speed with a return period of 100 years;
- Surface and subsurface current speed with a return period of 10 years;
- Current profile;
- Water depths (including tide and storm surge);
- Soil conditions;
- Marine growth, thickness and specific weight;
- Wave spectrum; and
- Wave energy distribution.

This document seeks to address the first three items in the above list. It is recommended that anyone making use of this document would address the remaining items in the list and also refer to the design standard documents themselves.

DATA SOURCES

For the Eureka – Northern California site, the following data sources were utilized to generate extreme event models for wave, wind, and surface current conditions. National Data Buoy Center (NDBC) station 46022 provided hourly wave and wind data from 1982 through 2009. The significant wave height is calculated from the wave displacement spectrum captured during the 20-minute sampling period. Because the spectrum is divided into frequency bins, the peak wave period corresponds to the center frequency of the bin with the maximum spectral density.

Wind speed was measured 5 meters above the water surface and two data channels were recorded: (1) the 8-minute average wind speed and (2) the peak 5-second gust speed measured during the 8-minute sample period. Coastal Data Information Program (CDIP) stations 094 and 128 provided daily maximum wave heights (measured crest-to-trough) from May 2007 to September 2010. Although these data span only three years, they serve as a point of comparison. Ocean surface currents for the region (126.2W–124.2W, 40.2N–42.2N) from 1992 through 2010 were obtained from the Ocean Surface Current Analyses – Real Time (OSCAR) Project Office. In these data, the mean and median current speeds were recorded every five days. Figure 1 illustrates the geographic location of these data sources.

There are periods of missing data for NDBC station 46022. The duration of these gaps varies from hours to months. Figure 2 indicates a substantial drop in the number of data points in the November–January time frame. It is also seen that significant wave height tends to be higher in the winter months. Given these two facts, it is possible that a large storm was missed due to data dropout. There are, however, at least four large storms seen in the available data that contribute to the extreme value statistics.

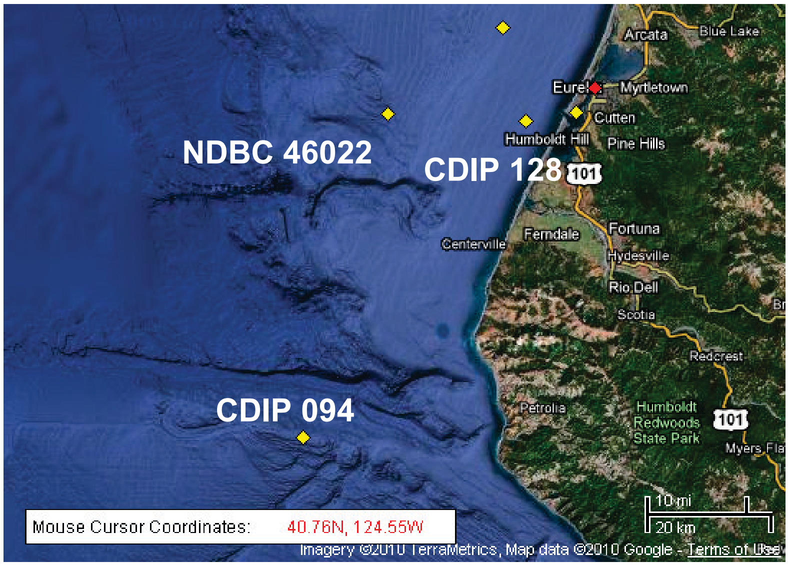


Figure 1. NDBC and CDIP stations near Eureka, California, used in extreme event analysis.

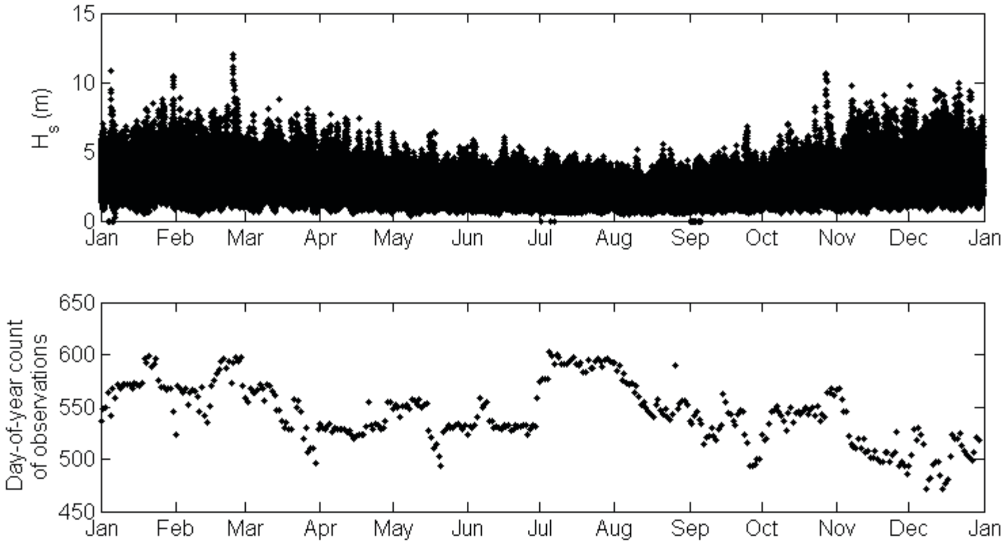


Figure 2. Seasonal variation of wave height and count of observations for NDBC buoy 46022.

100-YEAR CONTOUR FOR WAVE SEA STATE

Sea states with return periods of 100 years are defined by combinations of significant wave height and peak period along the 100-year contour line. The 100-year contour is found using the inverse FORM technique [2], which requires the joint probability distribution of H_s and T_p.

The inverse FORM technique consists of four steps:

1. Calculate the marginal distribution of H_s and fit a three-parameter Weibull distribution given by

$$P[H_s < h] = F_{Hs}(h) = 1 - \exp\left[-\left(\frac{h-\gamma_{Hs}}{\alpha_{Hs}}\right)^{\beta_{Hs}}\right].$$

2. Calculate the marginal distribution of T_p conditioned on H_s and fit a parameterized lognormal distribution.

   where

$$P\left[T_p < t \middle| h\right] = F_{Tp|Hs}(t) = \Phi\left(\frac{\ln t - \mu}{\sigma}\right)$$

$$\mu = E[\ln T_p|h] = a_0 + a_1 h^{a_2} \text{ and}$$

$$\sigma = std[\ln T_p|h] = b_0 + b_1 e^{b_2 h}.$$

3. Determine the 100-year contour line by transforming the standard normal variables U_1 and U_2 into H_s and T_p.

$$H_s = F_{Hs}^{-1}(\Phi(U_1));\ T_p = F_{Tp|Hs}^{-1}(\Phi(U_2))$$

along circle

$$\sqrt{{U_1}^2 + {U_2}^2} = \beta$$

where

$$\beta = \Phi^{-1}\left(1 - \frac{T_{SS}}{365 \times 24 \times T_r}\right).$$

4. "Inflate" the contour line to "compensate for approximating the true stochastic response by its median value." The parameter α_o^2 is commonly chosen in the range 0.10 to 0.20.

$$\beta^* = \beta / \sqrt{1 - \alpha_o^2}$$

The last equation in step 3 prescribes the relationship between the return period T_r and the radius of the circle in standard normal coordinates. The other factors in this equation account for the sea state duration T_{SS} of the data and conversion of units from sea state hours to return period in years.

For NDBC buoy 46022, joint distribution parameters are given in Table 1. These parameters were fit to available data using the least square method. Visual check of fit is given in Figures 3 and 4. Figure 5 is the resulting 100-year contour with circles marking the location of sea states given in Table 2.

Table 1. Hs-Tp Joint Distribution Parameters for NDBC Buoy 46022.

Weibull parameters	γ_{Hs}	α_{Hs}	β_{Hs}
	0.4010	2.007	1.667
Lognormal mean	a_0	a_1	a_2
	-0.0034	2.137	0.1193
Lognormal std. dev.	b_0	b_1	b_2
	0.0000	0.4456	-0.1826

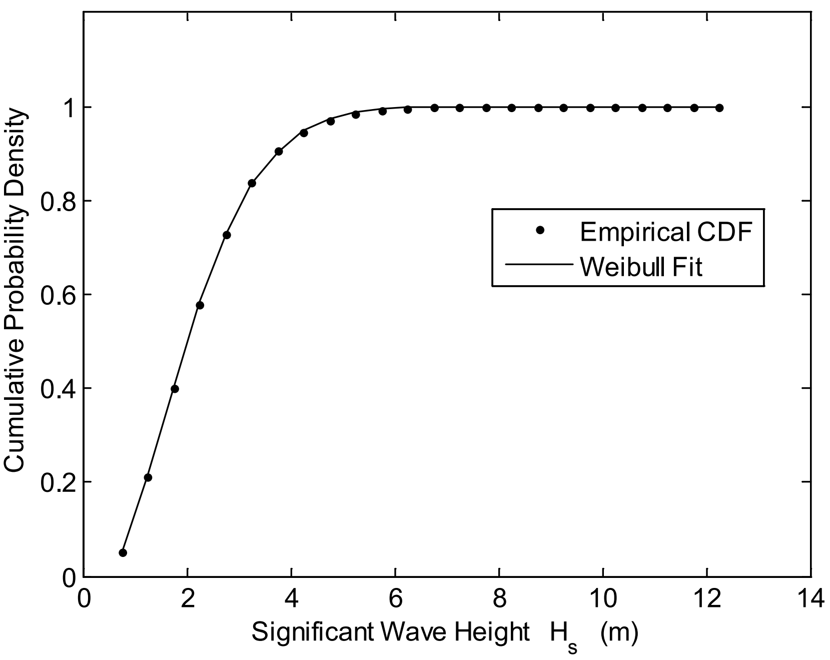


Figure 3. Cumulative distribution function of significant wave height for NDBC buoy 46022.

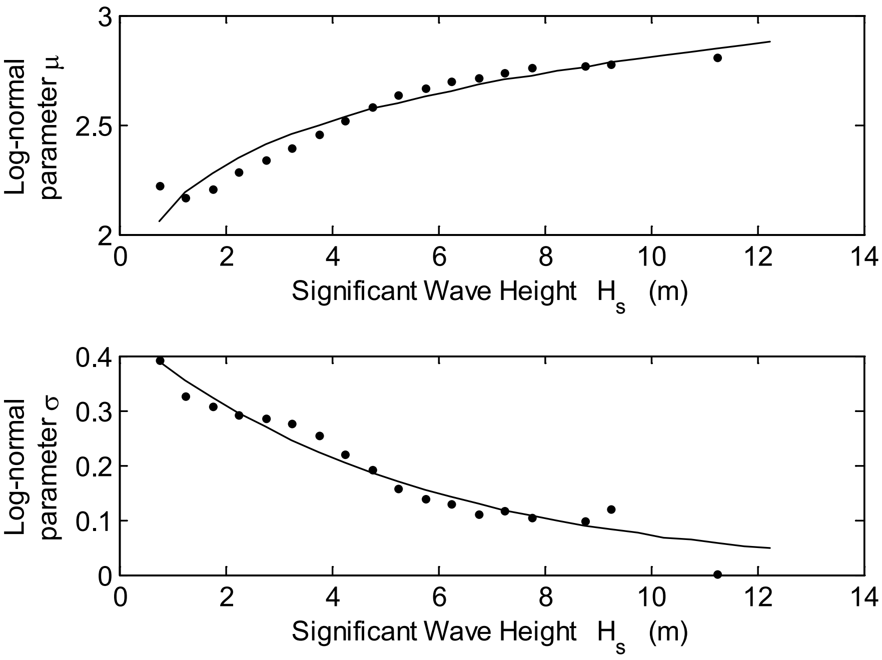


Figure 4. Lognormal parameters of Tp conditioned on Hs for NDBC buoy 46022.

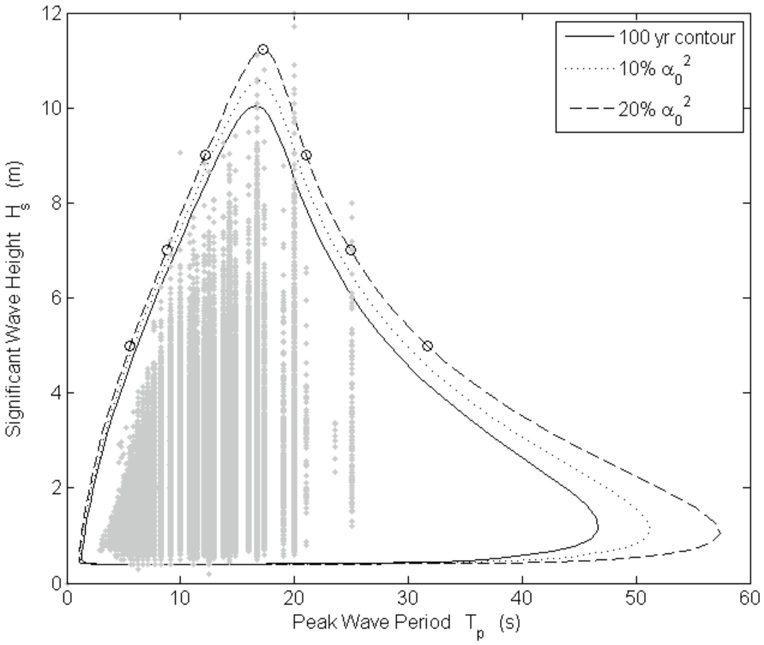


Figure 5. 100-year contour for NDBC buoy 46022.

Table 2. Design Sea States Identified on 100-year Contour.

Significant wave height Hs (m)	5	7	9	11.22	9	7	5
Peak period Tp (s)	5.57	8.76	12.18	17.26	21.09	24.92	31.70

Time series data for an extreme sea state can be generated with a random-phase/amplitude model by assuming a wave spectrum with the given significant wave height and peak period. The wave spectrum for a wind sea is often represented by either the Pierson-Moskowitz (PM) spectrum or the JONSWAP spectrum. In some cases, it is necessary to use a two-peak spectrum to account for both wind sea and swell. Equations for these spectra can be found in Reference 3. The random-phase/amplitude modeling approach is described in Reference 4.

EXTREME INDIVIDUAL WAVE HEIGHT

DNV's recommended practice for Environmental Conditions and Loads states that, when more detailed information is lacking, the 100-year extreme individual wave height H_{100} may be taken as 1.9 times the significant wave height $H_{s,100}$ [3]. The most probable wave period corresponding to the extreme wave height is generally expressed as

$$T_{H\,\max} = a \cdot H_{\max}^{b}$$

where a and b are empirical coefficients. However, it was not clear from the recommendation how to determine these coefficients. From available information, it seems reasonable to assume the extreme wave's period falls in a range around the 100-year contour peak.

The 100-year extreme individual wave at the reference site is estimated to be $H_{100} = 1.9 \times 11.22 = 21.3$ meters with a wave period in the range of 15 to 19 seconds. For comparison, the nearby CDIP stations 094 and 128 recorded a few maximum individual waves with heights around 15 meters with periods around 16 seconds (during three years of available data).

WIND

DNV's offshore standard on position mooring states that the wind load should be treated as a steady component in combination with time-varying gusts that generate low-frequency motion [1]. The steady component is normally represented by a 1-hour average wind speed 10 m above the water surface with a 100-year return period. The wind speed data from station 46022 are 8-minute averages at 5 m recorded hourly.

Following the recommendations of Reference 1, a Gumbel distribution was fit to the *square* of the annual maximum wind speed. (Because wind loads are proportional to the square of wind speed, fitting to the square can produce better results.) The Gumbel distribution (with the random variable squared) is given by

$$F_{U^2,\,\text{max},\,1\,\text{year}} = \exp\{-\exp[-a(u^2 - b)]\}.$$

The wind speed with return period T_r is then given by

$$U_{T_r} = \left[F_{U^2,\,\text{max},\,1\,\text{year}}{}^{-1}(1 - 1/T_r)\right]^{1/2}.$$

Using available data from NDBC station 46022, the fit parameters were $a = 0.0132$ and $b = 393.85$, which results in a 100-year wind of 27.2 m/s. A visual check of fit is given in Figure 6.

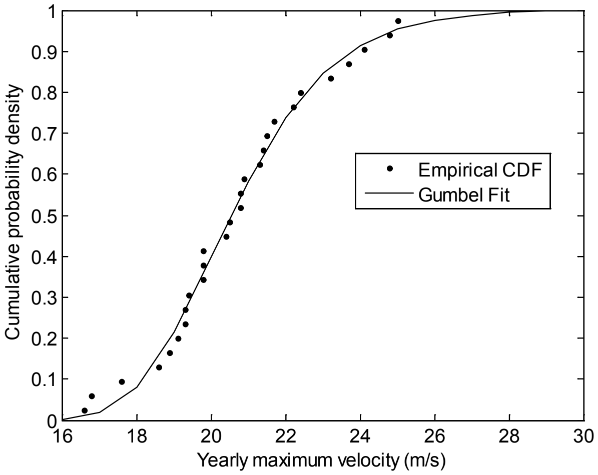


Figure 6. Cumulative distribution function of wind velocity yearly maximums for NDBC station 46022.

CURRENT

DNV's offshore standard on position mooring states that a surface current speed with a 10-year return period should normally be used as a basis for design [1]. If current speed data are not available, the following equation applies in open areas with wind-generated currents at the still water level.

$$V_{C_{Wind}} = 0.015 \cdot U_{\text{1hour, 10m}}$$

To convert from 5-meter to 10-meter wind speed measurements, a power law profile was assumed with exponent 0.12 (open sea with waves). Thus, the 100-year wind of 27.2 m/s at 5 meters corresponds to 29.6 m/s at 10 meters. Assuming the above equation is valid for the site conditions, the 100-year wind-generated surface current is expected to be around 0.44 m/s.

Although a specific methodology was not specified in the DNV design standards, it was assumed that the extreme event analysis applied to wind data would also be appropriate for current data. Using the OSCAR surface current data, a Gumbel distribution was fit to the yearly maximums and resulted in fit parameters $a = 20.874$ and $b = 0.22$. The 10-year and 100-year surface currents are 0.33 m/s and 0.44 m/s respectively. Again, it is the 10-year current DNV recommends using for design. A visual check of the cumulative distribution function fit is given in Figure 7.

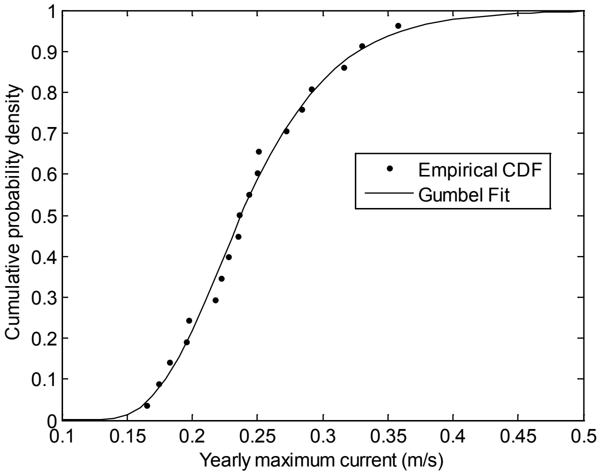


Figure 7: Cumulative distribution function of surface current yearly maximums.

According to Reference 3, the variation of wind generated current with depth can be taken as either a linear profile

$$v_{c,\,\mathrm{wind}}(z) = v_{c,\,\mathrm{wind}}(0)\left(\frac{d_0 + z}{d_0}\right) \qquad \text{for} - d_0 \le z \le 0$$

or a slab profile

$$v_{c,\,\mathrm{wind}}(z) = v_{c,\,\mathrm{wind}}(0) \quad \text{for} - d_0 \le z \le 0.$$

Depth variation of tidal currents may be modeled as a power law:

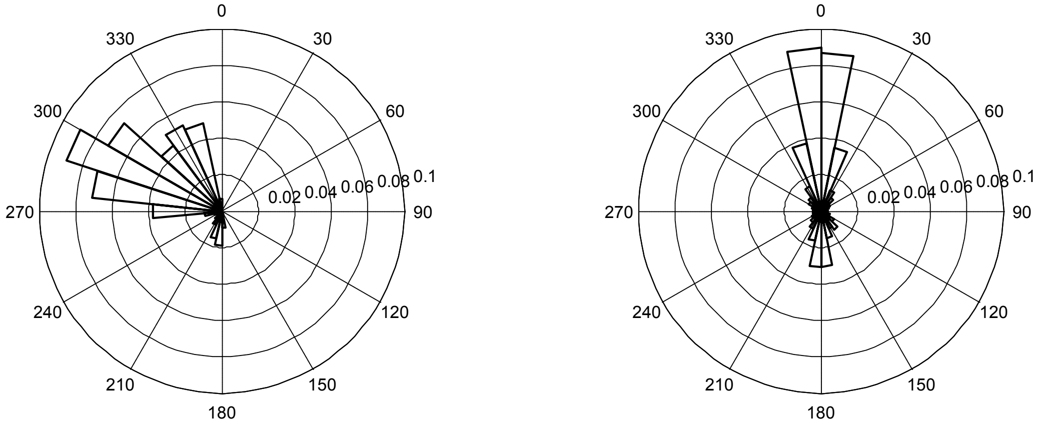
$$v_{c,\,\mathrm{tide}}(z) = v_{c,\,\mathrm{tide}}(0)\left(\frac{d+z}{d}\right)^{\alpha} \qquad \text{for } z \le 0.$$

DIRECTION OF WAVES, WIND, AND CURRENT

DNV's standards specify that the direction of waves, wind, and current should be considered in two combinations: collinear and noncollinear. In a collinear environment, wind, waves, and current all act in the same direction. In a noncollinear environment, the directions should match available data or have the following orientation when data are not available [1]:

1. Wave towards the unit's bow (0°);
2. Wind 30° relative to the waves; and
3. Current 45° relative to the waves.

For the Eureka, California, site, wave and wind direction statistics were available and are shown in Figure 8. The dominant wave direction is from the west-northwest (roughly perpendicular to the shore line) and the dominant wind direction is from the north.



Wave direction rose

Wind direction rose

Figure 8. Wave direction rose (CDIP 094) and wind direction rose (NDBC 46022).

CONCLUSION

Extreme conditions for ocean waves, wind, and surface currents have been calculated according to DNV standards for the Northern California deployment site near Eureka. The reader should note there were gaps in the data during the stormy winter season, and that the data history covers 30 years or less. Both of these factors increase the uncertainty in the extreme event calculations. The author is reasonably confident in the extreme wave statistics but would like to obtain additional data sources for the wind and ocean current statistics.

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[3] Det Norske Veritas, *Environmental Conditions and Environmental Loads*, Recommended Practice DNV-RP-C205, 2007. Amended April 2010. Web access November 28, 2010.

[4] L.H. Holthuijsen, *Waves in Oceanic and Coastal Waters*, Cambridge University Press, 2007, ISBN 978-0-521-86028-4.

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