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Technical note

Predicting significant wave height off the northeast coast of the United States

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Abstract

To develop a simple method to predict the significant wave height, we analyze 18 years of hourly observations from 12 different buoys that are off the northeast coast of the United States. Water depths ranged from 19 to 4427 m for these moored buoys. We find that, on average, all of these buoys exhibit a region of constant wave height for 10-m wind speeds between 0 and 4 m s^{-1}. That wave height does, however, depend on water depth. For wind speeds above 4 m s^{-1}, the wave height increases as the square of the wind speed; but the multiplicative factor is again a function of water depth. We synthesize these results in a prediction scheme that yields the significant wave height from simple functions of water depth and 10-m wind speed for wind speeds up to 25 m s^{-1}.
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Keywords: Buoy data; Fully developed sea; Ocean waves; Significant wave height; Wave modeling

1. Introduction

The significant wave height, $H_{1/3}$, is the average of the highest one-third of all waves occurring during a period. It is the most frequently reported wave statistic and, thus, appears often in ocean engineering and studies of sea surface physics. For example, the expected $H_{1/3}$ environment is a design consideration for ships and ocean structures (Tucker and Pitt, 2001, p. 164f.). Among examples of its many applications in sea surface physics, $H_{1/3}$ is a scaling depth that predicts the region over which bubbles are ejected and ocean turbulence is generated when waves break (e.g., Thorpe, 1995). $H_{1/3}$ is also used to predict the wave steepness and, in turn, the air–sea drag coefficient (Taylor and Yelland, 2001; Fairall et al., 2003). Likewise, Woolf (2005) uses $H_{1/3}$ in his parameterization for the air–sea gas transfer velocity. And finally, our own specific interest in the significant wave height is that Andreas's (1992, 2003, 2004; Andreas and DeCosmo, 2002) algorithm to predict the effects of sea spray on the air–sea heat fluxes requires $H_{1/3}$.

The works cited above use the typical fully developed or equilibrium sea approximation (Kinsman 1965, p. 390f.; Carter, 1982; Tucker and Pitt 2001, p. 100):

$$H_{1/3} = 0.0246\, U_{10}^2 \tag{1}$$

to predict the significant wave height (in meters), where U_{10} is the wind speed (in m s^{-1}) at a reference height of 10 m. But our recent mesoscale simulations of Atlantic storms (Perrie et al., 2005), which incorporated the Andreas (2003) spray algorithm, hinted that Eq. (1) predicts waves that are too high. If this were true, the Andreas algorithm would predict latent heat fluxes mediated by spray that are too large.

We therefore looked at 18 years of hourly wave data from 12 different moored buoys off the northeast coast of the United States to investigate this issue. Fig. 1 shows 1 year of such data from a buoy in 4427 m of water, 150 nautical miles east of Cape Hatteras. The figure includes the hourly data as a function of U_{10}, data averaged in U_{10} bins, the model we have fitted to these averages, and what Eq. (1) predicts. All 18 data sets resemble Fig. 1: In all

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cases, Eq. (1) overpredicts the average buoy measurements of $H_{1/3}$ for high wind speeds and predicts wave heights approaching zero as the wind speed approaches zero, while the data show that waves are always present, even in light winds. In the remainder of this paper, we fill in the details of this analysis and report our new parameterization for $H_{1/3}$. Andreas and Wang (2006) have reported our preliminary results.

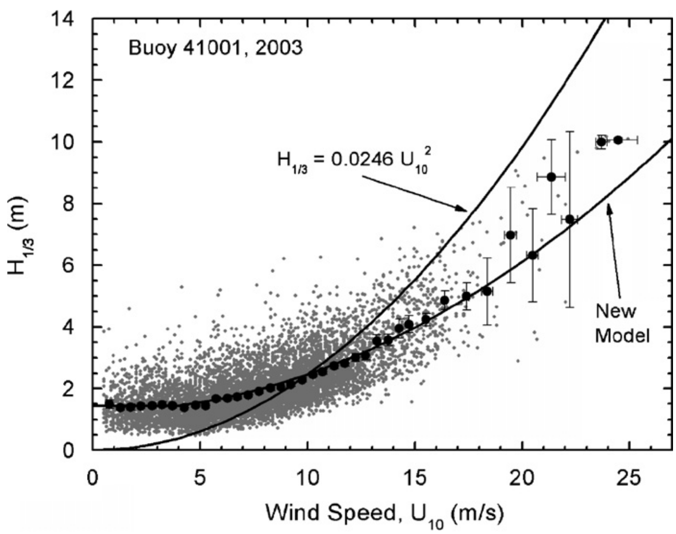

Fig. 1. Hourly significant wave heights (gray circles) for 2003 from NOAA buoy 41001, which was 150 nautical miles east of Cape Hatteras in water 4427 m deep. Black circles are wave heights averaged in wind speed bins that are 0.5 m s^{-1} wide; error bars are ± 2 standard deviations in the bin means. The curve marked ''New Model'' is our fit to these averages, Eq. (6). The curve labeled ''0.0246 U_{10}^2'' is a typical prediction for significant wave height in a fully developed sea.

2. Measurements

The US National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) operates scores of buoys in the oceans surrounding the United States. These buoys measure a host of meteorological and oceanographic variables; their hourly data, among other statistics, are archived at the NOAA NDBC website, www.ndbc.noaa.gov. From this website, we obtained 18 years of data from 12 different buoys off the northeast coast of the United States. Fig. 2 shows the locations of these buoys; Table 1 lists the specific aspects of the data sets we used in this study. From these data sets, we took only two variables, the wind speed and the significant wave height, $H_{1/3}$.

The buoys that provided the data for this study are pitch, roll, and heave buoys that use accelerometers and inclinometers to infer the wave spectrum through techniques such as those described in Tucker and Pitt (2001, p. 71ff.; cf. Gilhousen, 1987). Microprocessors on each buoy do all the wave calculations, including finding $H_{1/3}$; only the relevant wave statistics are transmitted to shore.

Each of the buoys that we used measures wind speed with a propeller-vane at a height of 5 m. To standardize our analysis, we converted this reported wind speed, U_5, to the standard 10-m value, U_{10}, by assuming that all observations were in near-neutral stratification. In such conditions,

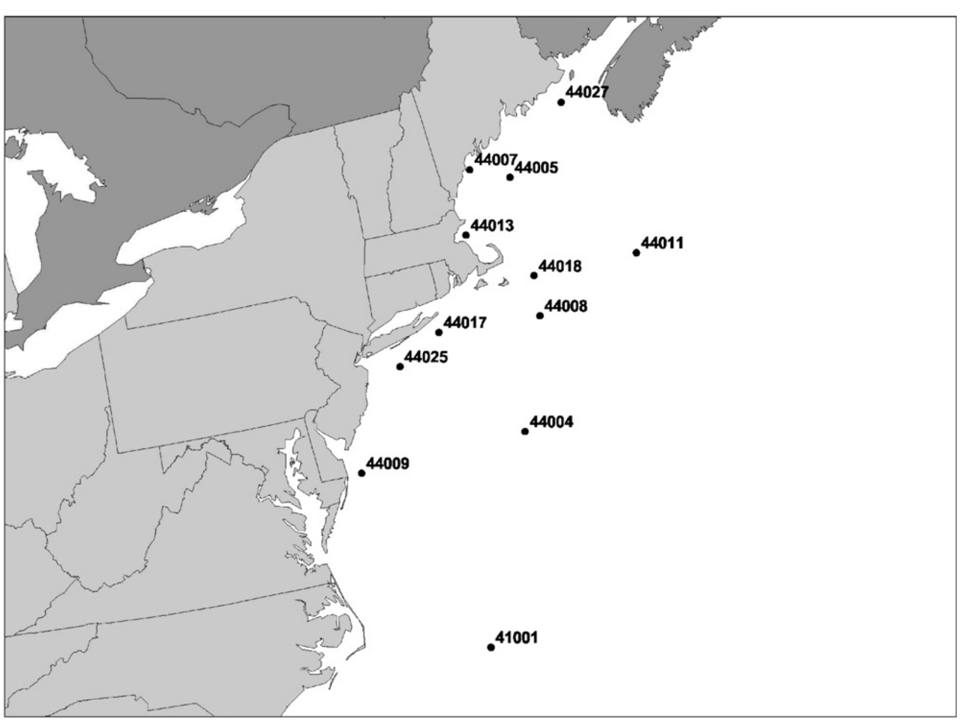

Fig. 2. All data that we used in this study came from NOAA National Data Buoy Center buoys off the Atlantic coast of the United States.

Table 1
Buoys used in this study and data years

Buoy	Year	Latitude (deg.)	Longitude (deg.)	Water depth (m)	Number of observations
41001	2002	34.68	72.66	4426.8	8349
41001	2003	34.68	72.66	4426.8	7454
44004	2002	38.47	70.56	3124.4	8524
44004	2003	38.47	70.56	3124.4	8007
44005	2003	43.18	69.18	21.9	6930
44007	2002	43.53	70.14	18.9	8598
44007	2003	43.53	70.14	18.9	8246
44008	2002	40.50	69.43	62.5	8688
44008	2003	40.50	69.43	62.5	7478
44009	2003	38.46	74.70	28.0	8113
44011	2003	41.11	66.62	88.4	4587
44013	2002	42.35	70.69	55.0	8671
44013	2003	42.35	70.69	55.0	8492
44017	2003	40.70	72.00	44.8	8420
44018	2003	41.26	69.29	74.4	8534
44025	2002	40.25	73.17	36.3	8660
44025	2003	40.25	73.17	36.3	6629
44027	2003	44.27	67.31	182.0	5293

"Number of observations" shows how many screened hours of data were in each buoy record that we used in our analysis.

the wind speed at height z obeys

$$U(z) = \frac{u_*}{k} \ln(z/z_0), \tag{2}$$

where u_* is the friction velocity; k ($=0.40$), the von Kármán constant; and z_0, the roughness length. The wind speeds at 5 and 10 m are, thus, related by

$$U_{10} - U_5 = \frac{C_{\mathrm{DN10}}^{1/2} U_{10}}{k} \ln(10/5) \tag{3}$$

or

$$U_{10} = \frac{U_5}{1 + \frac{C_{\mathrm{DN10}}^{1/2}}{k} \ln(5/10)}, \tag{4}$$

where we use the usual definition of the neutral-stability drag coefficient at a reference height of 10 m, $C_{\mathrm{DN10}} = (u_*/U_{10})^2$.

To complete Eq. (4), we use Large and Pond's (1982) result:

$$10^3 C_{\mathrm{DN10}} = 1.14 \text{ for } U_{10} \leqslant 10\,\mathrm{m\,s^{-1}}, \tag{5a}$$

$$10^3\, C_{\mathrm{DN10}} = 0.49 + 0.065\, U_{10} \text{ for } 10\,\mathrm{m\,s^{-1}} < U_{10}. \tag{5b}$$

Although Eq. (5) requires U_{10}, we use U_5 to compute C_{DN10} because this is the only available wind speed. Of course, we could have iterated among Eqs. (4) and (5) to find U_{10}; but for neutral stratification, U_5 is typically only about 6% less than U_{10}. Consequently, using U_5 instead of U_{10} in Eq. (5) causes no inaccuracy in Eq. (4) for $U_{10} \leqslant 10\,\mathrm{m\,s^{-1}}$ and biases our computed U_{10} values low by less than 1% for wind speeds above $10\,\mathrm{m\,s^{-1}}$. Hence, our approximating U_{10} by U_5 in Eq. (5) is not a problem.

Lastly, we screened the data files to eliminate missing or questionable data. If the reported wave height was $H_{1/3} \leqslant 0.1$ m, we excluded the hour from our analysis. This test basically eliminated missing data. If $U_5 < 0.5\,\mathrm{m\,s^{-1}}$, we also excluded the hour. This test eliminated hours with missing values for wind speed but also recognizes that propeller anemometers have some finite threshold starting speed. Propeller anemometers simply do not perform reliably in very light winds. Our visual screening of the data suggested that reported wind speeds below $0.5\,\mathrm{m\,s^{-1}}$ were of dubious quality.

3. Results

Fig. 3 shows another plot like Fig. 1 to emphasize the similarities in wave behavior despite $2\frac{1}{2}$ orders of magnitude difference in water depth between the two sites. All 18 years of data that we looked at yielded plots like those in Figs. 1 and 3. The average wave heights tend to be constant for 10-m winds less than 4–5 $\mathrm{m\,s^{-1}}$; and for winds nominally above $10\,\mathrm{m\,s^{-1}}$, the observed wave heights are much less than the typical prediction for a wind sea in local equilibrium, Eq. (1).

We have, therefore, fitted all 18 data sets with a parameterization that has the form

$$H_{1/3} = C(D) \text{ for } U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}, \tag{6a}$$

$$H_{1/3} = a(D)\, U_{10}^2 + b(D) \text{ for } 4\,\mathrm{m\,s^{-1}} < U_{10}. \tag{6b}$$

Here, $H_{1/3}$ is in meters when U_{10} is in $\mathrm{m\,s^{-1}}$, and D is the water depth.

To do this fitting, we first determined a depth-dependent constant value $C(D)$ by averaging all the wave heights for which $U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$ in a buoy record. Fig. 4 shows the resulting $C(D)$ value for each year of buoy data. The line

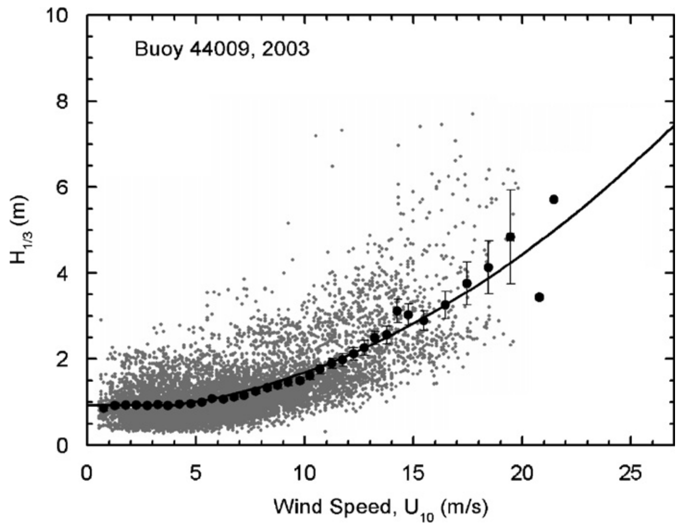

Fig. 3. Similar to Fig. 1, except this is 2003 data from buoy 44009, which was in only 28 m of water 26 nautical miles southeast of Cape May, NJ.

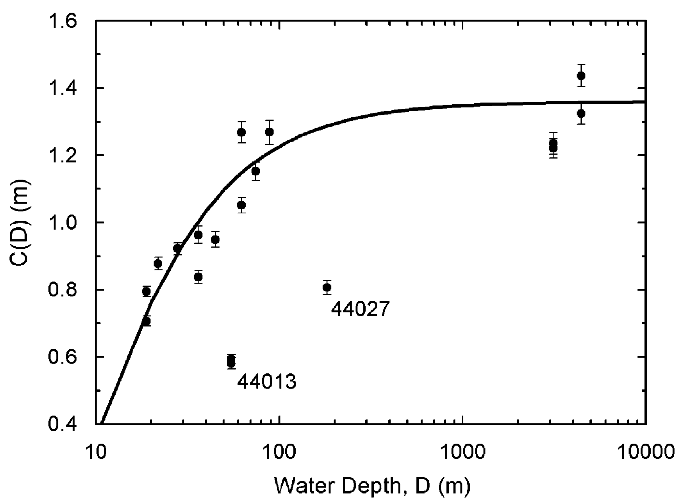

Fig. 4. The height of the constant $H_{1/3}$ region in each buoy record, obtained by averaging all wave heights for which $U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$. That is, the plot shows C in Eq. (6a) as a function of water depth D. The error bars are ± 2 standard deviations in the mean of C. The line is Eq. (7), and we ignored buoys 44013 and 44027 as outliers in obtaining this fit.

we fitted to these values is

$$C(D) = 1.36\ \tanh\left[\frac{\ln(D/6)}{1.9}\right], \tag{7}$$

which gives C in meters when D is in meters. In obtaining Eq. (7), we ignored three points in Fig. 4: the 2 years of data from buoy 44013 and the data from buoy 44027. Both buoys are in protected locations and see waves from only small sectors of the open ocean. Buoy 44013 is outside Boston harbor; its only open-ocean fetch is about an 80° sector to the northeast. Buoy 44027 is near the mouth of the Bay of Fundy and similarly sees only about a 90° sector to the open ocean.

We have good reason to suspect that $H_{1/3}$ should go as the square of the wind speed in a wind sea—as Eq. (6b) suggests. Scaling arguments, as formulated, for example, by Kitaigorodskii (1973) and reiterated in Komen et al. (1994, p. 174f.) and Tucker and Pitt (2001, p. 100), suggest $H_{1/3}$ should depend on U_{10}^2 or u_*^2. We explore that suggestion with our data.

We found $a(D)$ and $b(D)$ in Eq. (6b) by two methods. Define $\overline{H_{1/3}}$ as the average of all wave heights in a yearly buoy record for which $U_{10} > 4\,\mathrm{m\,s^{-1}}$. Define $\overline{U_{10}^2}$ as the average of the squares of the corresponding wind speeds. Then,

$$a'(D) = \frac{\overline{H_{1/3}} - C(D)}{\overline{U_{10}^2} - 16} \tag{8}$$

yields $a(D)$ values in Eq. (6b) such that Eqs. (6a) and (6b) are guaranteed to be continuous at $U_{10} = 4\,\mathrm{m\,s^{-1}}$. An estimate for $b(D)$ then comes from

$$b'(D) = C(D) - 16\,a'(D). \tag{9}$$

Alternatively, we obtained $a''(D)$ and $b''(D)$ by simply doing a least-squares linear regression of $H_{1/3}$ versus U_{10}^2 for all $U_{10} > 4\,\mathrm{m\,s^{-1}}$. This fitting, however, does not necessarily require that Eqs. (6a) and (6b) meet at $U_{10} = 4\,\mathrm{m\,s^{-1}}$, although our fitting generally produced results for Eq. (6b) that almost matched Eq. (6a).

To arrive at a consensus value for $a(D)$ in Eq. (6b) for each buoy record, we simply averaged the $a'(D)$ and $a''(D)$ values. With this value, we then computed a $b(D)$ value that guaranteed Eqs. (6a) and (6b) to match at $U_{10} = 4\,\mathrm{m\,s^{-1}}$ from

$$b(D) = C(D) - 16\,a(D), \tag{10}$$

which gives b in meters.

Fig. 5 shows our best estimate of $a(D)$ for each buoy, with error bars based on $|a' - a''|$. The line we have fitted by eye is

$$a(D) = 0.0134\ \tanh\left[\frac{\ln(D/9)}{1.3}\right], \tag{11}$$

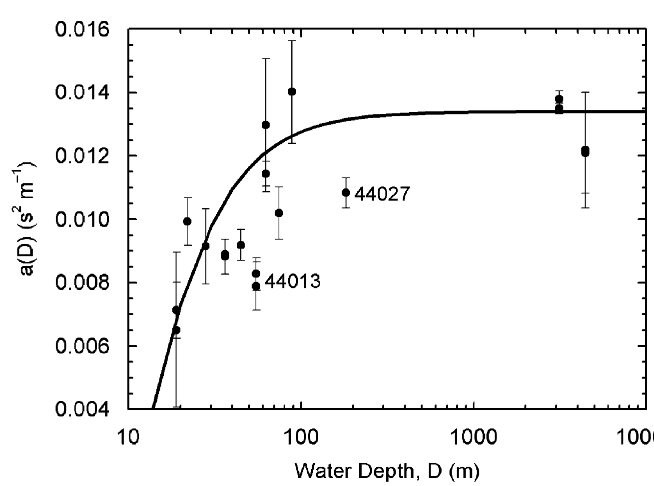

Fig. 5. The wind speed multiplier $a(D)$ in Eq. (6b) as a function of water depth, D. The error bars show $\pm|a' - a''|$, the absolute value of the difference in our two estimates of $a(D)$. The line is Eq. (11), although we ignored the points from buoys 44013 and 44027 as outliers in fitting this line.

which gives $a(D)$ in $s^2 m^{-1}$ for water depth D in meters. As with Fig. 4, we ignored the results from buoys 44013 and 44027, which again appear as outliers because of their protected locations.

Finally, Fig. 6 shows the values for $b(D)$ that we computed for each buoy. Here, the fitting line is required by Eq. (10) once we specify Eqs. (7) and (11), respectively, as our functions for $C(D)$ and $a(D)$. The error bars here are $\pm|b'-b''|$, where b' and b'' are the two statistical estimates of b that we described above. Again, the results from buoys 44013 and 44027 are outliers on this plot, but we did not explicitly ignore these to obtain the curve in Fig. 6: It comes automatically from Eqs. (10), (7), and (11).

The curves through the averaged data in Figs. 1 and 3 are examples of how well Eq. (6) and these values of a, b, and C represent the average behavior of the buoy data.

To check the usefulness of our parameterization, we used Eqs. (7), (11), and (10) to compute values for C, a, and b, respectively, for each buoy in our data set from its reported water depth (i.e., Table 1). We then used Eq. (6) to estimate $H_{1/3}$ for each hour when we had measurements of both wind speed and wave height. Fig. 7, which is typical of these comparisons, shows measured and modeled values of $H_{1/3}$ for 1 year of data (2002) from buoy 44008. The figure also shows the line for 1:1 correlation and the line obtained from least-squares regression for all the $H_{1/3}$ pairs shown. Essentially, the best fit produced by Eq. (6) is almost indistinguishable from the 1:1 line. Fig. 7 shows a distinct lower limit in modeled wave height because our algorithm will not predict $H_{1/3}$ values less than $C(D)$.

The correlation coefficient for the measured-modeled $H_{1/3}$ pairs in Fig. 7 is 0.760. Table 2 lists the correlation coefficients that we computed similarly for the other buoys in our data set. Most of the correlation coefficients are between 0.7 and 0.8; thus, our parameterization typically explains 50–60% of the variance in the observed $H_{1/3}$ values. Notice, the buoy with the shallowest water depth in our set, 44007 in 18.9 m of water, yielded the two lowest values for the correlation coefficient. Buoy 44007 was also the buoy nearest a shoreline. Buoy 44013, which we identified as an outlier in our set, yielded the next two lowest correlation coefficients. Ironically, though, buoy 44027, which is another outlier, produced the highest correlation coefficient; but the least-squared fit of the measured-modeled $H_{1/3}$ pairs for this buoy deviated most from 1:1.

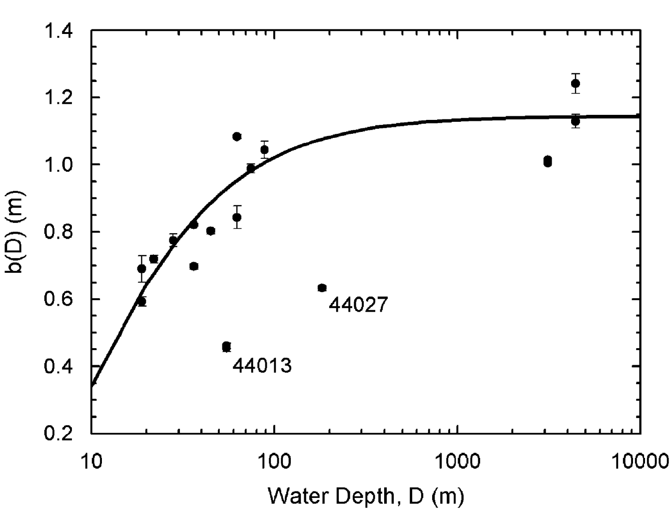

Fig. 6. The additive constant $b(D)$ in Eq. (6b) as a function of water depth, D. The error bars are $\pm|b'-b''|$, where b' and b'' are the two estimates of b described in the text. The curve is Eq. (10) with Eq. (7) for $C(D)$ and Eq. (11) for $a(D)$. Buoys 44013 and 44027 are again outliers.

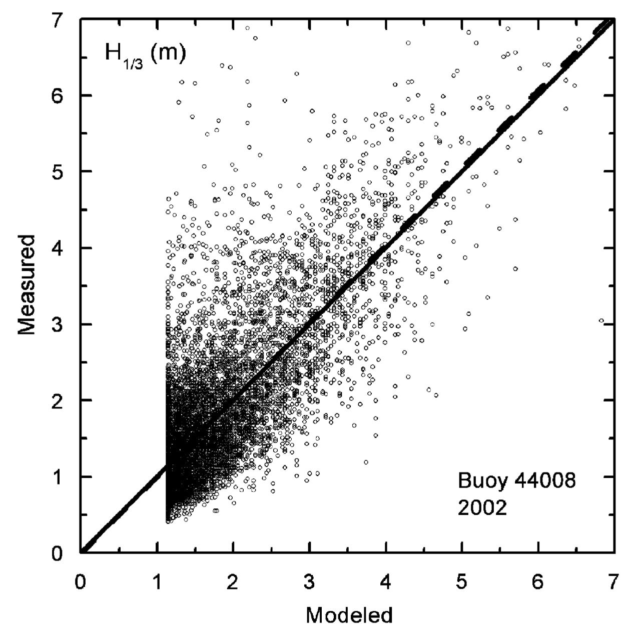

Fig. 7. Measured and modeled values of $H_{1/3}$ for buoy 44008 for all of 2002. This buoy is in 62.5 m of water 54 nautical miles southeast of Nantucket. The solid line is the 1:1 relation; the dashed line is the least-squares fit. The correlation coefficient for the plotted values is 0.760.

As other statistics for evaluating the accuracy of our parameterization, we also computed the bias error and root-mean-square error (RMSE) for each of our 18 data sets. We define the bias error as

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N}(H_{1/3,\text{mod}} - H_{1/3,\text{meas}}) \tag{12}$$

and the RMSE as

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(H_{1/3,mod} - H_{1/3,\text{meas}})^2\right]^{1/2}. \tag{13}$$

In each of these, N is the number of samples; $H_{1/3,\text{meas}}$, the measured hourly wave height; and $H_{1/3,\text{mod}}$, the corresponding modeled wave height, for which we used Eqs. (7), (11), and (10) and the reported water depth to calculate C, a, and b, respectively, and then used Eq. (6) to calculate $H_{1/3,\text{mod}}$.

Table 2 lists the bias and RMSE for each entire buoy record in our set but also breaks these error calculations into cases for which $U_{10} \leqslant 4\,\text{m s}^{-1}$—so we can assess the accuracy of Eqs. (6a) and (7)—and for which $U_{10} > 4\,\text{m s}^{-1}$—so we can

Table 2
Comparisons of the measured significant wave height for each buoy with heights calculated using Eqs. (6), (7), (10), and (11)

Buoy	Year	All data			$U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$			$U_{10} > 4\,\mathrm{m\,s^{-1}}$			ρ
		No.	Bias (m)	RMSE (m)	No.	Bias (m)	RMSE (m)	No.	Bias (m)	RMSE (m)	
41001	2002	8349	0.145	0.725	1201	0.035	0.533	7148	0.163	0.752	0.743
41001	2003	7454	0.043	0.471	1180	−0.079	0.326	6274	0.066	0.499	0.749
44004	2002	8524	0.134	0.584	1451	0.135	0.316	7073	0.134	0.639	0.774
44004	2003	8007	0.086	0.688	1358	0.121	0.356	6649	0.079	0.756	0.771
44005	2003	6930	−0.152	0.353	2018	−0.072	0.191	4912	−0.185	0.419	0.778
44007	2002	8598	0.036	0.244	2442	0.028	0.139	6156	0.040	0.285	0.590
44007	2003	8246	−0.007	0.252	3024	−0.060	0.186	5222	0.023	0.290	0.567
44008	2002	8688	−0.006	0.491	1928	0.096	0.254	6760	−0.036	0.558	0.760
44008	2003	7478	−0.076	0.502	1741	−0.120	0.437	5737	−0.062	0.522	0.736
44009	2003	8113	0.030	0.346	2239	−0.010	0.161	5874	0.045	0.417	0.702
44011	2003	4587	−0.160	0.652	1171	−0.060	0.369	3416	−0.194	0.749	0.738
44013	2002	8671	0.713	0.796	2070	0.538	0.432	6601	0.768	0.091	0.652
44013	2003	8492	0.672	0.788	2679	0.526	0.406	5813	0.739	0.964	0.646
44017	2003	8420	0.246	0.366	1707	0.118	0.239	6713	0.278	0.399	0.754
44018	2003	8534	0.164	0.528	1969	0.029	0.380	6565	0.205	0.572	0.718
44025	2002	8660	0.243	0.269	1651	0.167	0.166	7009	0.261	0.293	0.754
44025	2003	6629	0.142	0.313	1197	0.042	0.197	5432	0.164	0.338	0.755
44027	2003	5293	0.589	0.695	1820	0.481	0.427	3473	0.645	0.836	0.809

The results are for all the data for the year, for the data in the constant-height region (where $U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$), and for the region where the wave height goes as U_{10}^2 (i.e., for $U_{10} > 4\,\mathrm{m\,s^{-1}}$). The columns show the number of observations in each category, the bias error and the root-mean-square error (RMSE) in the parameterization, and the correlation coefficient (ρ) for the entire year of measured-modeled pairs.

assess Eqs. (6b), (10), and (11). Except for buoys 44013 and 44027, which we already identified as outliers, the bias errors for the year of data from each buoy are quite small—typically less than 0.2 m in absolute value. The bias errors in the constant-wave-height region (where $U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$) are even smaller: except for the three outliers, all are less than 0.17 m. For the region where wave height goes as U_{10}^2 (i.e., for $U_{10} > 4\,\mathrm{m\,s^{-1}}$), the bias errors are slightly larger than the errors calculated for the entire data years.

The measured wave heights do scatter quite a bit about our parameterized values, though, as reflected in both the RMSE and the correlation coefficients in Table 2. This scatter undoubtedly results because our simple two-variable parameterization does not include all the environmental variables that affect wave height—variables like fetch, swell, atmospheric stratification, and duration of the wind.

Still the bias and RMSE in Table 2 are surprisingly comparable to similar statistics calculated for validating much more complicated wave models. For example, Bouws et al. (1985) compared three operational shallow-water wave models for sites with water depths similar to our shallow-water sites and found bias errors with absolute values from 0.1 to 0.4 m and RMSE values of 0.4 to 1.5 m. Likewise, Janssen et al. (1997) used wind forecasts from the European Centre for Medium-Range Weather Forecasts in the wave model WAM to predict $H_{1/3}$ for about 40 days in the Southern Hemisphere. They compared their wave model predictions with satellite altimeter estimates of $H_{1/3}$ and reported bias and RMSE values not very different from ours. Admittedly, the tests by Janssen et al. were much more complex than ours because they predicted surface-level winds rather than using measured values. Nevertheless, our point is that, though very simple, our parameterization yields results that are not badly biased.

Several of the buoy records that we used in our study include observations of $H_{1/3}$ for 10-m wind speeds up to $25\,\mathrm{m\,s^{-1}}$. Where we had such data, Eq. (6) still provided an accurate description of the correlation between $H_{1/3}$ and U_{10}. Hence, we conclude that Eq. (6) is a reliable model for $H_{1/3}$ for U_{10} up to, at least, $25\,\mathrm{m\,s^{-1}}$.

4. Discussion

Our analysis implies that the assumption of an equilibrium sea, which is the basis for obtaining wave statistics from the Pierson–Moskowitz spectrum, for instance (e.g., Carter, 1982; Tucker and Pitt, 2001, p. 100), is rarely valid. This assumption yields parameterizations for the significant wave height that resemble Eq. (1). The multiplicative constant may vary among analyses (cf. Tucker and Pitt, 2001, p. 100; Taylor and Yelland, 2001), but the analysis always predicts that $H_{1/3}$ goes to zero as U_{10} goes to zero.

A very robust result of our analysis, in contrast, is that $H_{1/3}$ is independent of the local wind for $U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$ and is significantly larger, on average, than zero here. Fig. 4 shows that this lower limit for $H_{1/3}$ in light winds is a function of water depth. We presume that the waves constantly present, even in light winds, are from swell. The decrease in $C(D)$ with decreasing water depth may then be a consequence of energy dissipation when the swell feels the bottom (Komen et al., 1994, p. 200f.).

An alternative explanation for the existence of the waves in light winds may be convectively induced wind gusts that can significantly enhance air–sea momentum transfer even when the average wind speed is measured to be small. We discount this explanation, however. Using the parameterization for this process reported in Fairall et al. (1996, 2003), we estimate that the sensible heat flux at the sea surface would have to exceed $500\,\mathrm{W\,m^{-2}}$ to produce wind gusts that were capable of transferring the same momentum as a constant 4-$\mathrm{m\,s^{-1}}$ wind. Such a large sensible heat flux is virtually impossible in this region, though, even under the advection of very cold air.

We cannot yet say how general our model is. Because all of our buoys are off the US east coast, all have a shoreline to their west; and with winds predominantly from the west here, the wave field at the buoys was often fetch-limited. Hence, we cannot rule out the notion that the dependence we see on water depth may be an indirect effect of fetch.

Buoys off the US west coast, in contrast, would usually see a wave field with unlimited fetch under, predominantly, westerly winds. We have looked just briefly at two NOAA NDBC buoys off the US west coast and found that the measured wave heights tend, on average, to be above what our parameterization would predict. Still, though, we see the same two regimes as in the east coast buoys: For low winds, the wave heights are independent of wind speed and are distinctly non-zero; for higher winds, the wave heights increase approximately as U_{10}^2 but not as rapidly as Eq. (1) predicts. Consequently, our analysis provides a framework for developing wind-wave parameterizations in other locations.

5. Conclusions

Using in situ data from 12 buoys off the US east coast, we have developed a simple parameterization for the significant wave height as a function of just the water depth and the 10-m wind speed. Equations (6), (7), (10) and (11) constitute our parameterization. Our analysis revealed two wave height regimes in all of the buoy records. For $U_{10} \leqslant 4\,\mathrm{m\,s^{-1}}$, $H_{1/3}$ is independent of wind speed; for $U_{10} > 4\,\mathrm{m\,s^{-1}}$, $H_{1/3}$ goes as U_{10}^2 but does not reach the levels that an equilibrium-sea model predicts. $H_{1/3}$ depends on water depth in both regimes.

Our parameterization thus argues strongly against using an equilibrium wind sea approximation—such as Eq. (1)—in models and analyses that require an estimate of $H_{1/3}$ (e.g., Taylor and Yelland, 2001; Fairall et al., 2003; Woolf, 2005). This equilibrium approximation fails in two aspects: It underpredicts $H_{1/3}$ in light winds and overpredicts it in winds, nominally, above $10\,\mathrm{m\,s^{-1}}$.

Our parameterization has acceptable bias and RMSEs, at least for the east coast buoys that we studied. And because it requires only two input variables, wind speed and water depth, it is very simple compared to the sophistication common in other wave models (e.g., Komen et al., 1994; Moon et al., 2004), yet typically explains at least 50% of the variance in an observed record of significant wave height (Table 2). Finally, our parameterization does particularly well in predicting long-term averages of $H_{1/3}$ as a function of wind speed (Figs. 1 and 3).

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