Wind Product Inferred From CDIP Buoy Measured Wave Spectra

Kaley Mudd, Sophia Merrifield, Alli Ho, Jim Behrens, Andre Amador, John Lodise

CDIP · US Army Corps of Engineers · Scripps Institution of Oceanography · UC San Diego

Motivation

- Meteorological data is essential to understanding coastal marine weather conditions
- Offshore surface wind data improve weather forecasting, surface transport estimation, etc.
- In-situ wind sensors offshore are extremely sparse, relative to onshore, due to high cost and challenging environmental conditions
- Coastal Data Information Program (CDIP) wave monitoring buoy array stations can serve as proxy surface wind data sources where direct measurements are unavailable because of the precision, frequency band, persistence, and free availability of the data, both real-time and archived

Observational Data

Wave Data

The wave buoy records surface displacement and acceleration and applies a Fourier transform over 30-minute intervals to produce wave spectra. Wave energy and wave direction measurements are resolved into 64 bands with a frequency range of 0.0250-0.5800 Hz at CDIP station 185 at Monterey Bay, integrated into the National Data Buoy Center (NDBC) as station 46114.

Wind Data

Wind data were collected every 10 minutes at NDBC station 46042. The raw wind speeds are converted to the standard height of 10 meters following $U_{10}/U_a = (10/z_a)^{0.11}$ (Hsu et al. 1994) where z_a is the anemometer height of 3.8 meters. The wind speed and direction values are averaged over 30-minute intervals to match the temporal resolution of the wave spectra data.

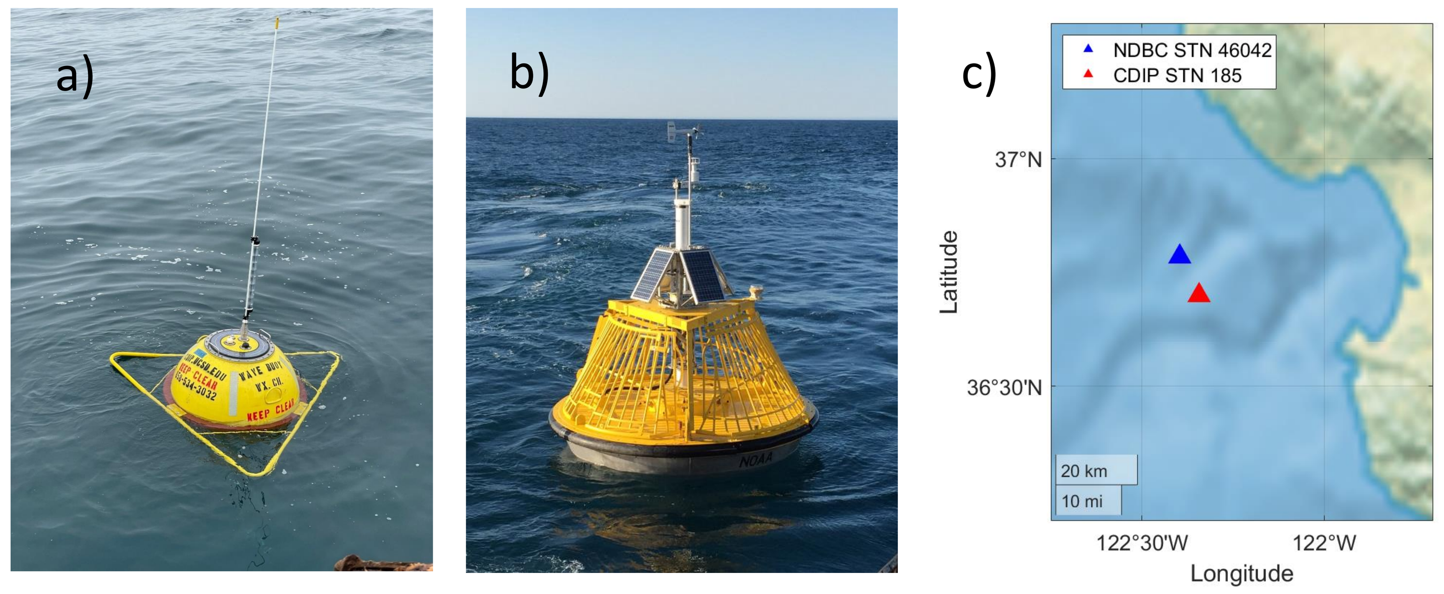

Figure 1. (a) CDIP station 185, Datawell Directional Waverider MKIII (b) NDBC station 46042, a standard 3-meter discus buoy w/ seal cage (c) Data stations used in this study. The buoys are separated by approximately 11 kilometers.

Theoretical Background

Short surface waves are closely coupled to the surface wind field, as the majority of momentum is transferred at these high frequencies. This region of the wave spectrum is called the 'equilibrium range' where wave energy E is determined by the balance of wind input S_{wind}, redistribution S_{nl}, and breaking S_{diss} via the following equation for spectra energy balance.

$$\frac{dE}{dt} = S_{wind} + S_{diss} + S_{nl} = 0 \qquad (1)$$

From this, Phillips 1985 derived the following analytic expression for the energy spectrum in this range.

$$E(f) = E_0 f^{-4} \quad \text{where } E_0 = \frac{4\beta I(p) u_* g}{(2\pi)^3} \qquad (2)$$

Where g is gravitational acceleration, f is cyclic frequency, and u_* is the wind friction velocity. I(p) is a direction spreading function set at 2.5, which is determined from a variety of observations (Thomson et al. 2013). β is a constant estimated empirically from wind speed and wave age observations. We use β = 0.012 (Juszko et al. 1995).

Method

Determining The Equilibrium Range

$E(f)f^4$ has a predicted slope of 0 in the equilibrium range. The frequency range is chosen by minimizing the RMSE between the predicted slope and the actual $E(f)f^4$ data for each possible frequency range.

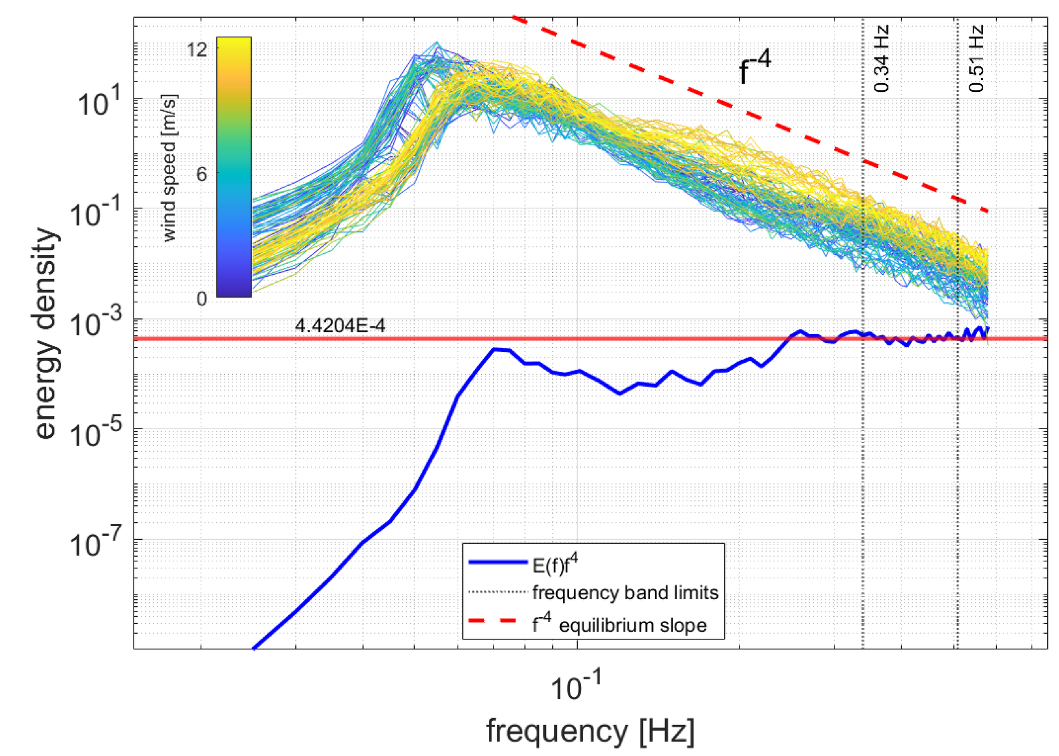

Figure 2. Wave spectra over time, colored by measured wind speeds. Frequency band fitting method example indicating E(f)f⁴ (blue), upper and lower limits of the fitted equilibrium range (vertical dotted black), predicted f^{-4} equilibrium slope (dashed red), and the average E(f)f⁴ value over that range (solid red).

Wave Spectra → Wind Friction Velocity

Wind friction velocity (u_*) at each time is calculated via equation (2) by using the average value of E(f)f⁴ across the fitted frequency range.

Wind Friction Velocity → U10

$$\tau = \rho u_*^2 = \rho C_D U_{10}^2 \qquad (3)$$

Where τ is the surface stress, ρ is the density of air, and C_D is a viscous drag coefficient. A value of C_D= 0.00114 suggested by Large & Pond 1981 is used.

Wind Direction

Wind direction is determined by averaging the wave direction values across the same frequency range used for determining wind speeds.

Results

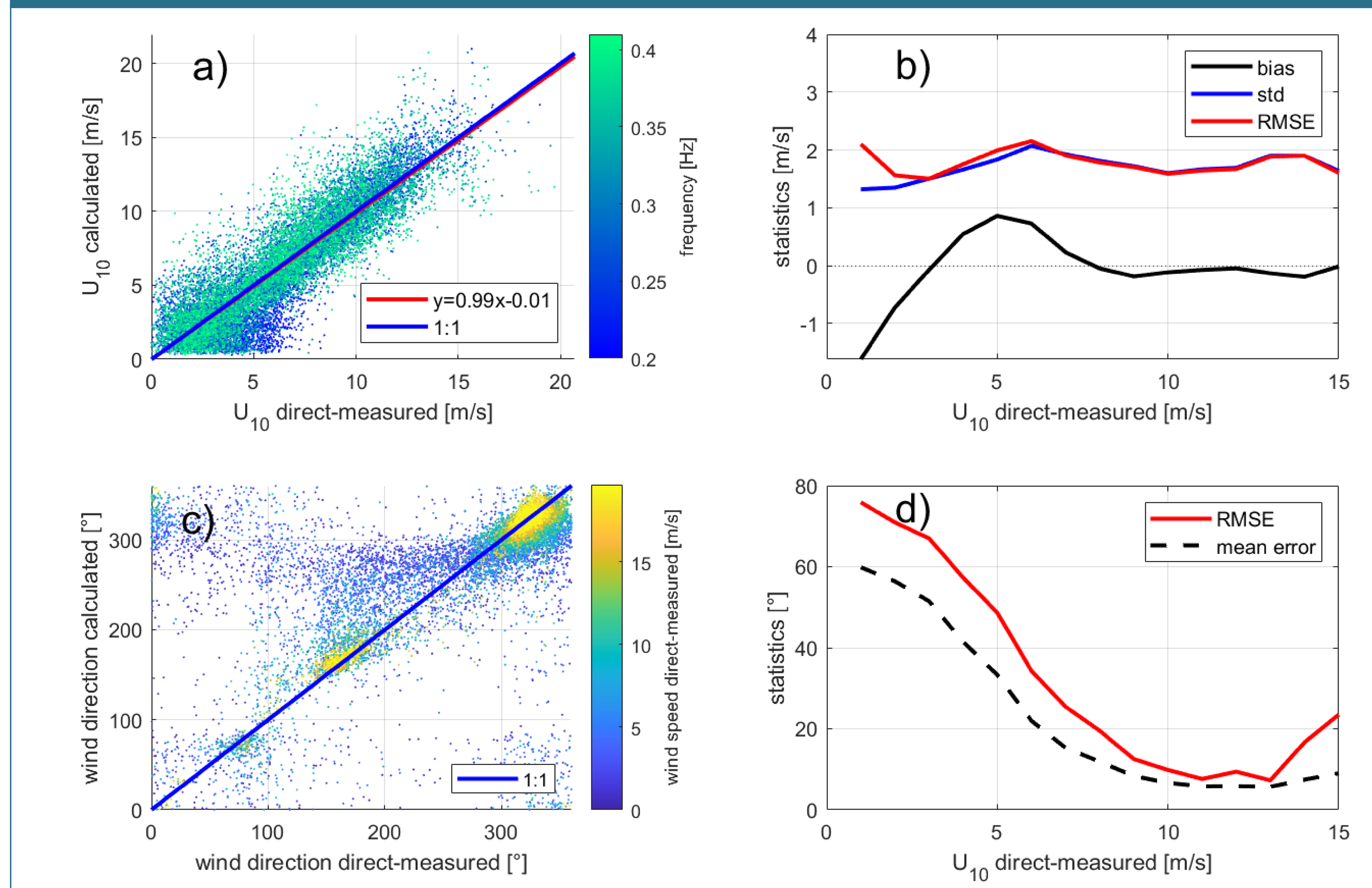

Figure 3. (a) Measured wind speeds plotted against calculated wind speeds (colored by the low limit of the equilibrium frequency range) and the regression function (red). The overall RMSE value is 1.8 m/s. (b) Bias (black), standard deviation (blue), and RMSE (red) values over all wind speeds. (c) Measured direction values plotted against calculated wind direction values (colored by direct-measured wind speeds). The overall RMSE is 42.0° with a mean error of 24.9°. (d) Direction RMSE and mean error for all wind speeds.

Results

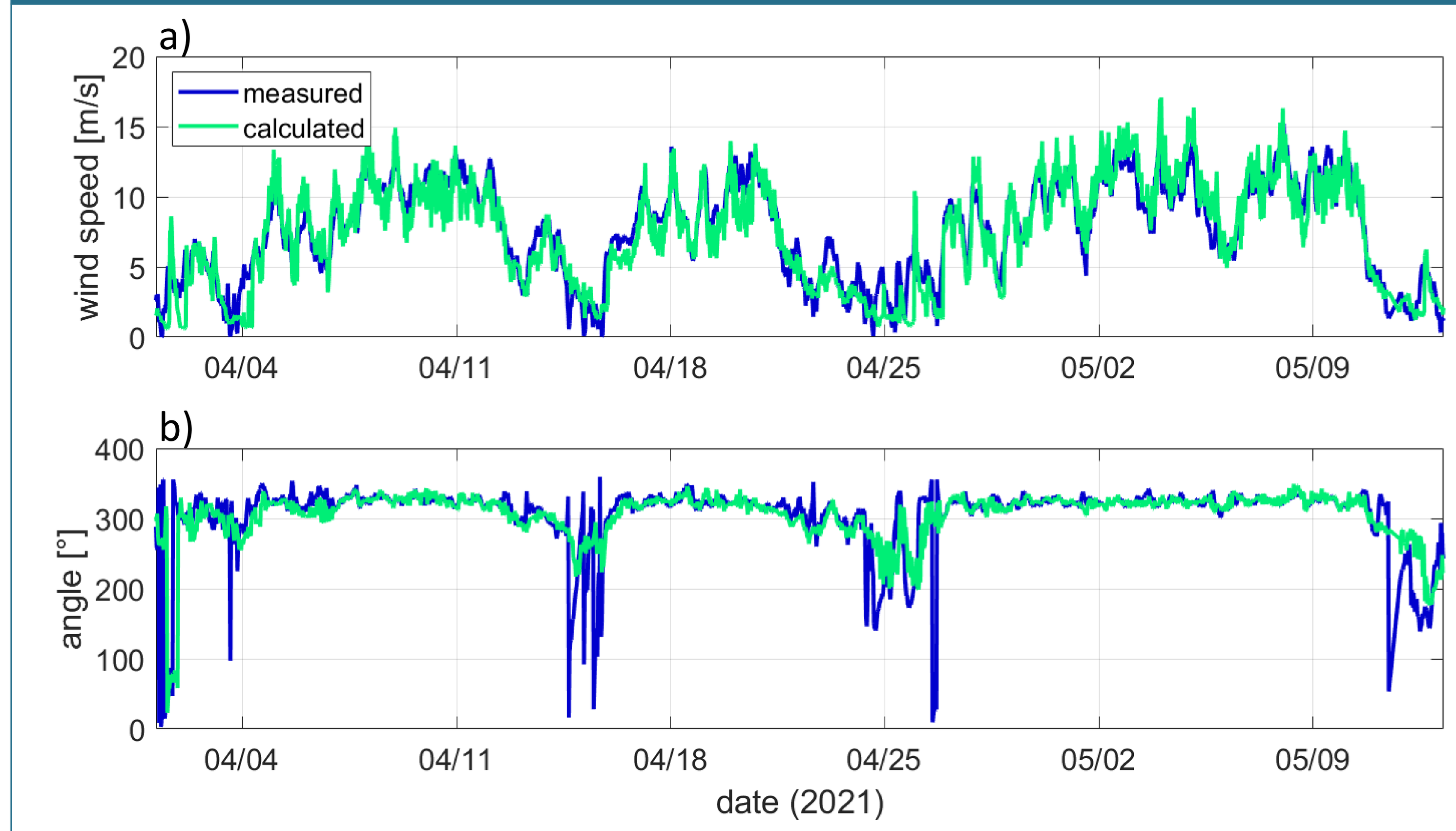

Figure 4. Time series comparison of direct-measured (blue) and calculated (green) wind speeds (a) and wind direction (b)

Conclusions

- Wave measurements can be used to estimate wind speeds with less than 2 m/s error in magnitude and 42° error in direction for wind speeds of 5-15 m/s
- The bias of the calculated wind speeds compared to measured wind speeds is near 0 for wind speeds of 5-15 m/s, and increases for higher or lower speeds
- It may be useful to determine a minimum and maximum cutoff for wind speeds and directions to decrease overall RMSE values
- This model can provide remote and short-term forecasts to be used by mariners, oil spill tracking information, and eventually be implemented into a publicly available CDIP online product

Discussion

Biofouling

- Biofouling causes the high frequency tail of wave spectra to deviate from the f^{-4} equilibrium slope (Thomson et al. 2015)
- Effects of minor biofouling are not expected to make significant impacts on the model as the fitting method should choose a portion of the spectra that is not impacted
- If biofouling is significant enough that there is no 18-band frequency range that falls in equilibrium, there may be impacts

Land Proximity

- Proximity to land may have an impact on the frequency range selection because nearshore buoys typically see diurnal wind and wave cycling
- The fitting method could account for these cycles, but it has not been explored

Form Factor

- Form factor may impact the model because of varied responsiveness to high frequency waves based on buoy size and shape

References

Hsu, S. A., Meindl, E. A., & Gilhousen, D. B. (1994). Determining the power-law wind-profile exponent under near-neutral stability conditions at sea. Journal of Applied Meteorology, 33(6), 757–765.

Juszko, B.-A., Marsden, R. F., & Waddell, S. R. (1995). Wind stress from wave slopes using Phillips equilibrium theory. Journal of Physical Oceanography, 25(2), 185–203.

Large, W., and S. Pond (1981), Open ocean momentum flux measurements in moderate to strong winds, J. Phys. Oceanogr., 11, 324–336

Thomson, J., D'Asaro, E. A., Cronin, M. F., Rogers, W. E., Harcourt, R. R., & Shcherbina, A. (2013). Waves and the equilibrium range at Ocean Weather Station P. Journal of Geophysical Research: Oceans, 118, 5951–5962. https://doi.org/10.1002/2013JC008837

Thomson, J., Talbert, J., de Klerk, A., Brown, A., Schwendeman, M., Goldsmith, J., Thomas, J., Olfe, C., Cameron, G., & Meinig, C. (2015). Biofouling effects on the response of a wave measurement buoy in deep water. Journal of Atmospheric and Oceanic Technology, 32(6), 1281–1286. https://doi.org/10.1175/jtech-d-15-0029.1