Wagging the tail: Comparing and correcting buoy observations of high frequency ocean waves in global datasets

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Abstract

A comparison across several buoy types (moored Datawell, moored NDBC, and two types of drifting buoys) suggests large differences in the high frequency portion of the observed wave energy spectra (0.2 to 0.6 Hz). When binned by wind speed, the moored Datawell buoys have much higher energy in the high frequency tail vs. other buoys. The moored Datawell buoys have better agreement with high-frequency energy levels predicted by a numerical wave model. The key to the difference appears to be the reference frame of the observations. The observations from the drifting buoys become more consistent with the moored Datawell buoys once the spectra are adjusted from the drifting reference frame to the fixed reference frame, though discrepancies still exist with the moored NDBC buoys. The adjustment calculation is a two-step process, in which the buoy-observed frequencies are first shifted to an intrinsic reference frame, providing wavenumber at each frequency, and then the drifter-observed spectrum is Doppler-shifted to the fixed reference frame. Two methods for estimation of buoy drift are tested; one is based on wind speed, and one is based on buoy positions.

Background

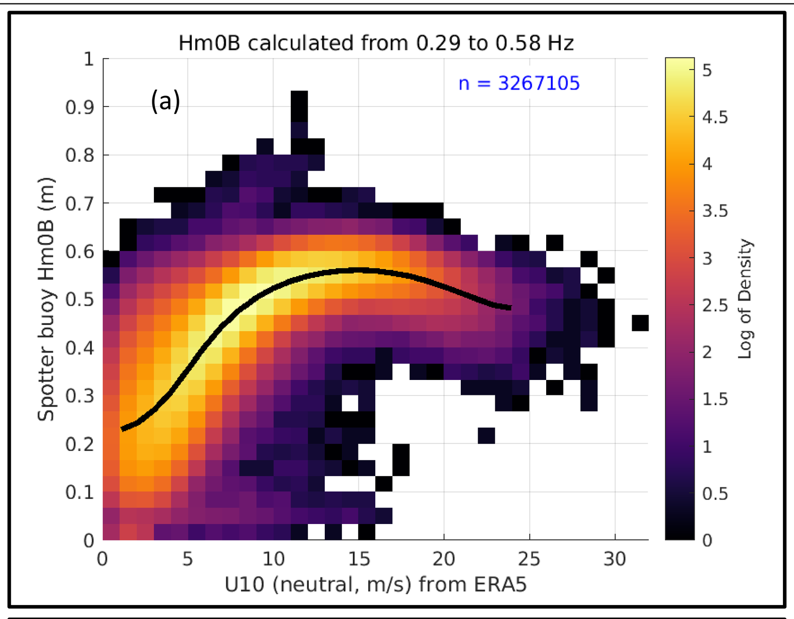
- Large new drifting wave buoy datasets (e.g., from Sofar, panels (a,d)), complement existing moored wave buoy datasets (e.g., NDBC, CDIP).
- Evaluation of high frequency wave energy from numerical ocean wave model WAVEWATCH III ('WW3', WW3DG 2019) against different buoy datasets yield inconsistent conclusions (panels b and c).
- These conclusions are robust and, broadly speaking, do not depend on parameter used. Rogers and Thomson (2026) compared high-frequency band height (panel b), energy at test frequency (panel c) and mean square slope (not shown here).

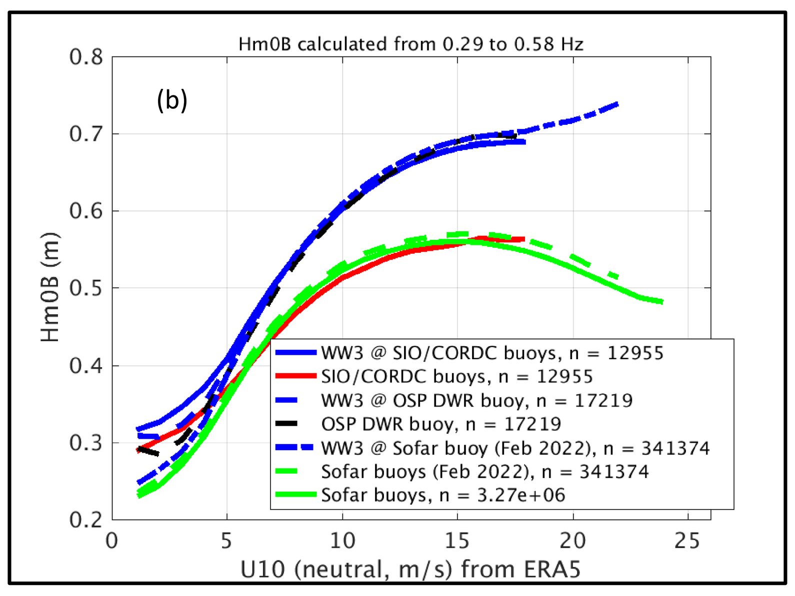
Panel (a) : High-frequency band height, $H_{m0B} = 4\sqrt{\int_{f_1}^{f_2} E(f)df}$, with f_1=0.29 Hz and f_2=0.58 Hz, as a function of wind speed, based on nine months of observations from Sofar drifting buoys.

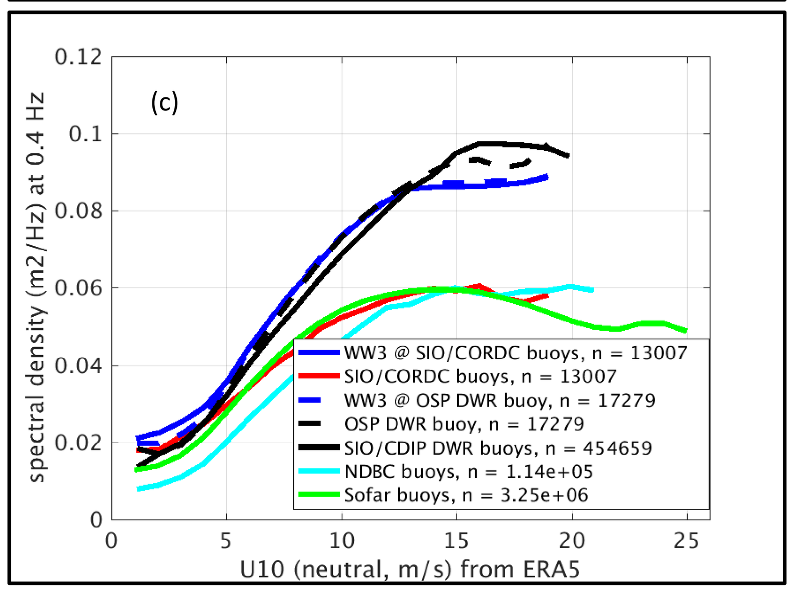
Panel (b) : Comparison of the mean trend lines of high-frequency band height, H_{m0B} vs. wind speed mean from ERA5 (ECMWF).

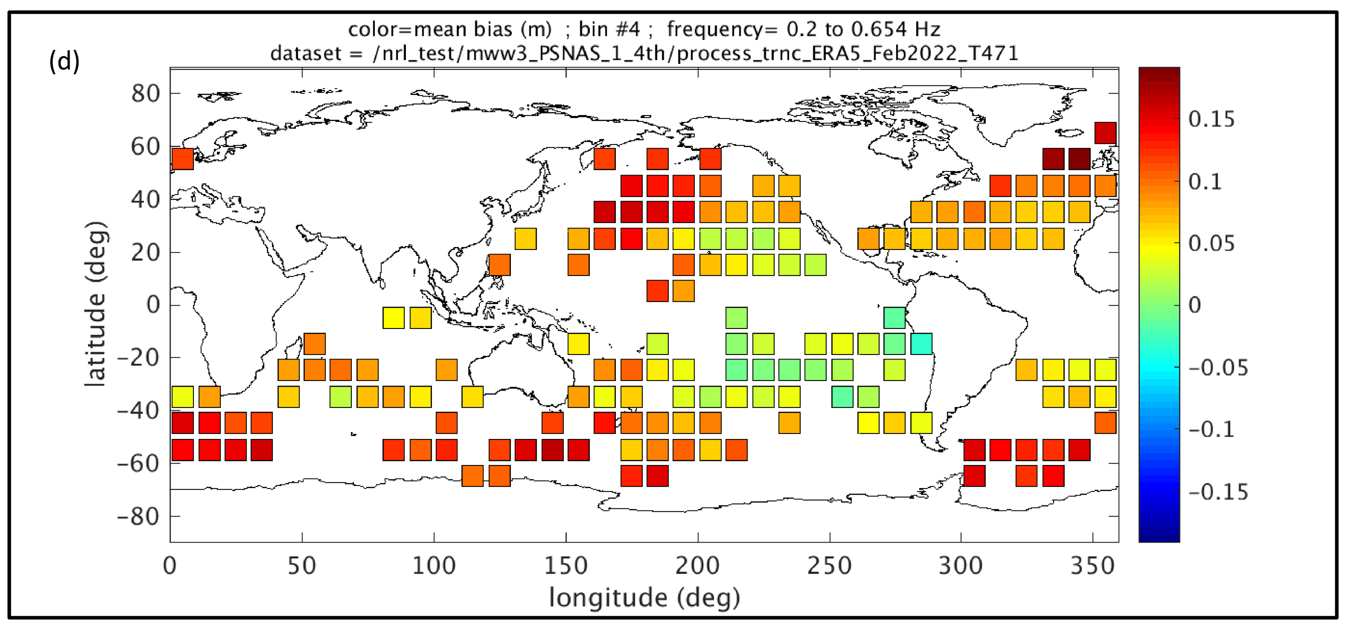
Panel (c) : Like panel (b), but showing the mean value lines of $E(f)$ at f=0.4 Hz.

Panel (d) : Bias (m) in H_{m0B} of WW3 hindcast with ERA5 forcing relative to Sofar buoys for the month of February 2022. H_{m0B} is computed using f_1 =0.2 and f_2= 0.654 Hz.









Hypotheses and Scope

Hypothesis 1. Discrepancy is caused by Doppler shift. In open ocean, a scenario where buoy drift is aligned with high-frequency wave direction is common, since both are strongly affected by wind. In this scenario, waves observed by drifting buoy will appear to have longer wave period than they do in a fixed frame of reference. This redshift, combined with spectral slope, $\partial E_d(f_d)/f_d$, results in energy level that is reduced relative to what we would expect a buoy to measure from a fixed frame of reference.

Hypothesis 2. Discrepancy is caused by differences in buoy response and/or incorrect application of corrections for buoy response.

In this poster, we explore Hypothesis 1.
Reframing this hypothesis: "*If we Doppler-shift the drifting buoy spectra, will they look more like the moored buoy spectra?*"

Methods

- Doppler-shift drifting buoy data set (9 months of Sofar Spotter data provided by P. Smit (Sofar), over 3 million spectra) to a fixed frame of reference.
- Test two methods of Doppler-shifting the spectra.

The Doppler equation relating absolute frequency ω and intrinsic frequency σ for the case of waves on currents: $\omega = \sigma + \vec{k}\cdot\vec{U}$.
However, this considers only two frames of reference: fixed (ω) and relative to currents (σ).
Here, we consider three frames of reference.
Thus, we use a more general expression for Doppler-shift: $2\pi f_2 = 2\pi f_1 + \vec{k}\cdot\overrightarrow{(U_1 - U_2)}$

Assumption: high frequency waves are aligned with the wind and currents, with no directional spread. Therefore, our Doppler-shift is simplified to: $2\pi f_2 = 2\pi f_1 + k(U_1 - U_2)$.

Our three frames of reference are:
1. Fixed, frequency is 'absolute' f_a, speed U is $U_{fixed} = 0$.
2. Relative to Lagrangian current (medium that waves are in), frequency is 'intrinsic' f_i, speed U is U_{Lagr} approximated as U_{slab}. This frequency determines wavenumber k as: $\sigma^2 = (2\pi f_i)^2 = gk$
3. Relative to drifter, frequency is f_d, speed U is U_{drift}.

Methods, continued

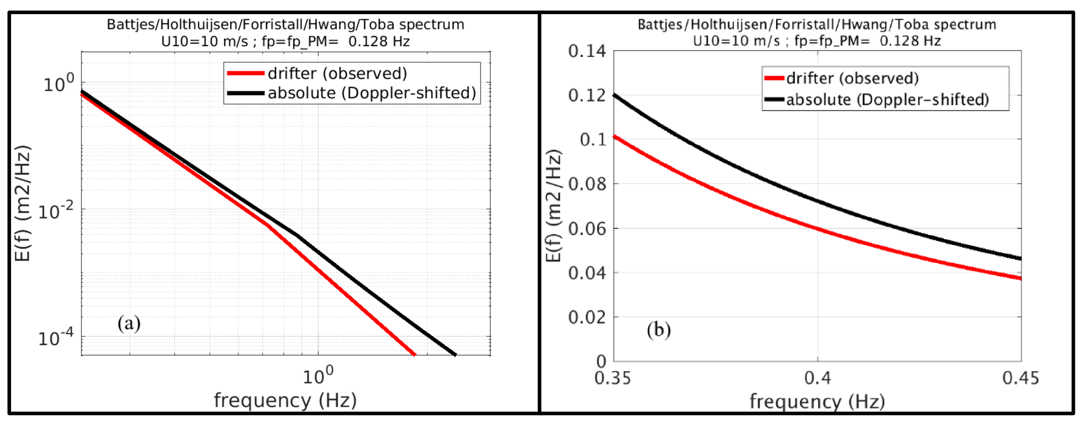


Figure: Example of a parametric spectrum, Doppler-shifted from a drifter frame of reference to a fixed frame of reference. (a) log plot and (b) linear plot

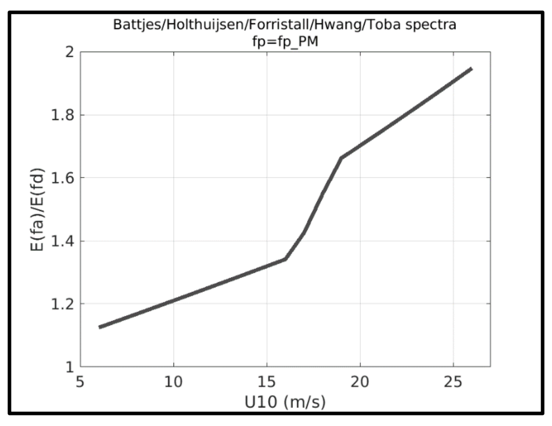


Figure: The ratio $E(f_a)/E(f_d)$ vs. U_{10} for the parametric spectra at 0.4 Hz.

Method 1 (wind-based drift estimate)

i. The intrinsic frequency f_i is computed from Doppler-shift: $f_i = f_d + k(U_{drift} - U_{slab})(2\pi)^{-1}$
  - $U_{drift} - U_{slab}$ is assumed to be 1% of wind speed $0.01U_{10}$, caused by windage (Houghton et al. 2021)
  - This step provides wavenumber k, which is required in the next step.

ii. The absolute frequency f_a is computed from Doppler-shift: $f_a = f_i + k(U_{slab} - U_{fixed})(2\pi)^{-1}$
  - U_{slab} is assumed to be 3% of wind speed, $0.03U_{10}$ (Samelson 2022)
  - Implied but not used: U_{drift} is 4% of wind speed, $U_{drift} = (0.01 + 0.03)U_{10}$

iii. The spectral density $E(f_a)$ is then computed using the relation $E(f_a)df_a = E(f_d)df_d$ (e.g., Collins et al. 2017).

iv. The discretization of f_a is made to be consistent with that of f_d via linear interpolation, i.e., $E(f_a)$ is remapped to a new grid.

Method 2 (location-based drift estimate)

i. Same as in Method 1, step i.

ii. The absolute frequency f_a is computed from Doppler-shift: $f_a = f_d + k(U_{dr,sp} - U_{fixed})(2\pi)^{-1}$
  - U_{drift} is computed from the buoy positional change, using finite differencing.
  - Only the component of the drift along the axis of the wind is used in the Doppler-shift: $U_{dr,sp} = (\overline{U_{10}}\cdot\overline{U_{drift}})/U_{10}$.

iii. Same as in Method 1, step iii.

iv. Same as in Method 1, step iv.

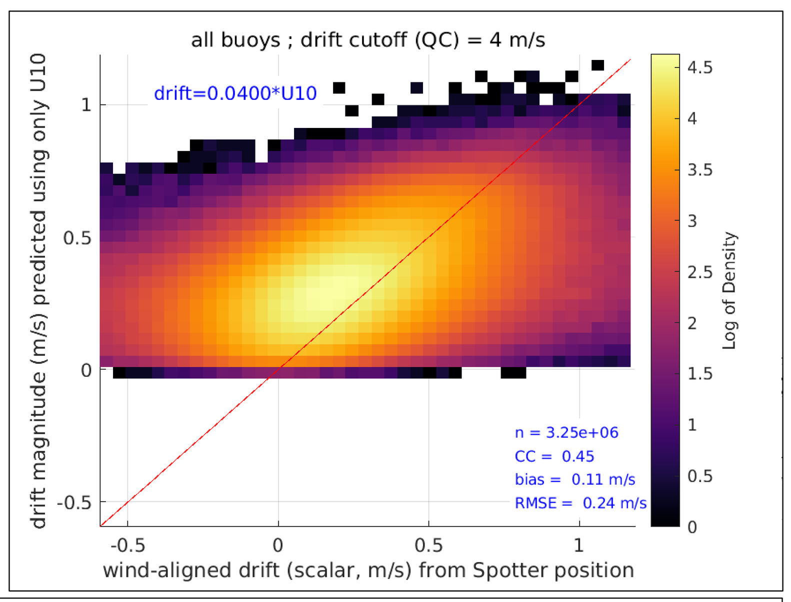
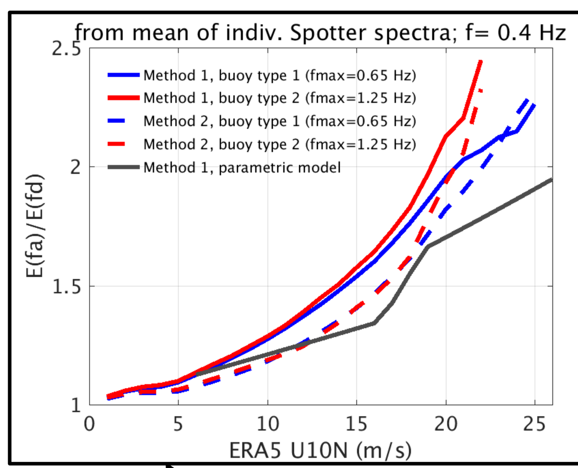


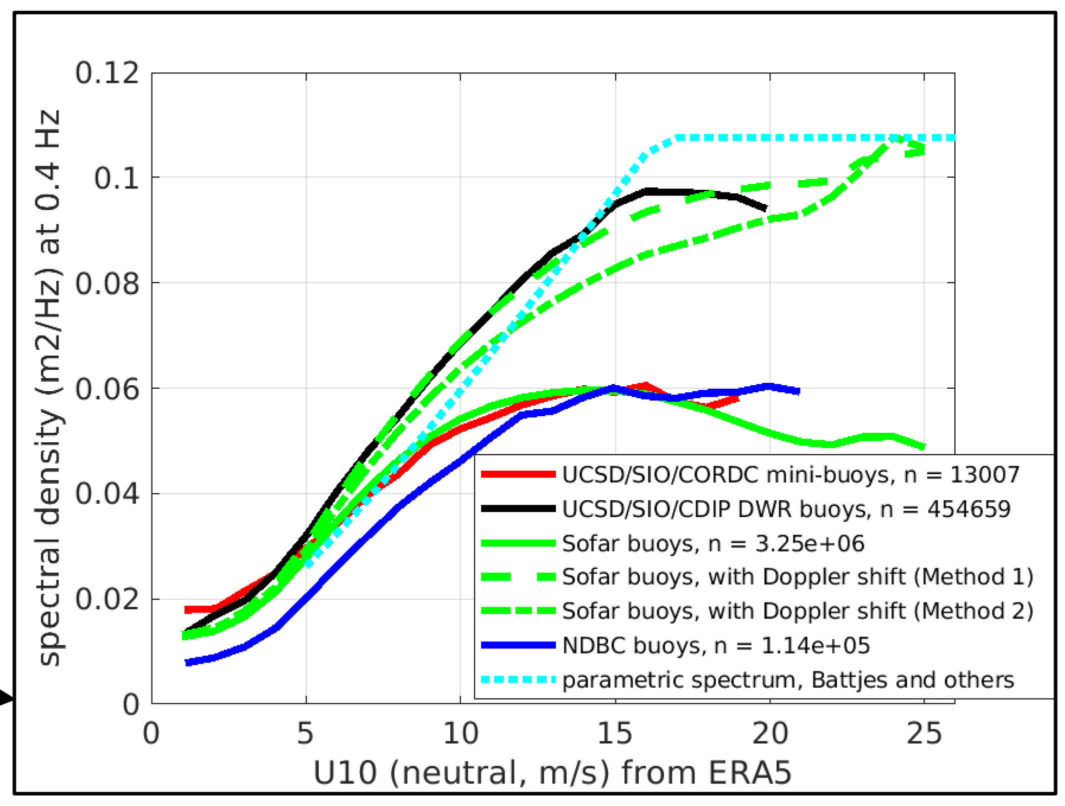
Figure: A two-dimensional histogram comparing two methods to estimate drift of the Sofar buoys (9-month dataset).

Results



The mean ratio $E(f_a)/E(f_d)$ vs. U_{10} for the Sofar buoys (9-month dataset), using two methods (1 and 2) and two buoy types (f_{max}=0.65 Hz and f_{max}=1.25 Hz).

$E(f)$ at f=0.4 Hz vs. U_{10} for several buoy datasets.



Discussion

- Since we assume wind direction = wave direction and ignore directional spread, our estimates of Doppler-shift are high, especially using Method 1.
- Hypotheses 1 and 2 can both be correct at the same time.
- On response functions: NDBC buoys are relatively large and have not been carefully calibrated for high frequencies. It is noteworthy that $E(f)$ from NDBC at low-to-moderate winds is lower than that of all other buoys.
- Since they are both moored, Doppler-shift cannot explain the discrepancy of DWR vs. NDBC.

Key Findings

- The agreement between drifting Sofar buoys and DWR buoys is greatly improved if spectra of Sofar buoys are Doppler-shifted.
- A more careful estimate of buoy drift (our Method 2) results in smaller Doppler shift than our Method 1.
- Since our methods are a high estimate of the Doppler effect, hypothesis 2 may still be required to fully close the gap between Sofar spectra and DWR spectra.

Recommendations and next steps

- Future work: we should develop new methods to account for directional spread. One approach is to apply a directional estimator: Drennan et al. (1994), Hanson et al. (1997), Colosi et al. (2023).
- Parametric spectra should not be developed using drifting buoys without accounting for Doppler shift.
- 3GWAM (WW3-type) models should not be calibrated or adjusted via data assimilation using both moored and drifting buoys without accounting for Doppler shift.
- Our analysis of drifting buoys should be extended to include other buoys (CORDC, mini-SWIFT).

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