Investigating gas exchange processes using noble gases in very high winds: observations of bubbles and turbulence beneath breaking waves

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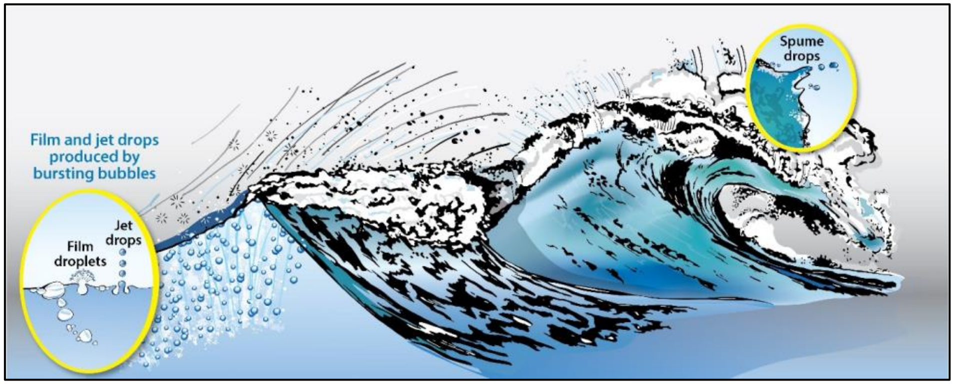
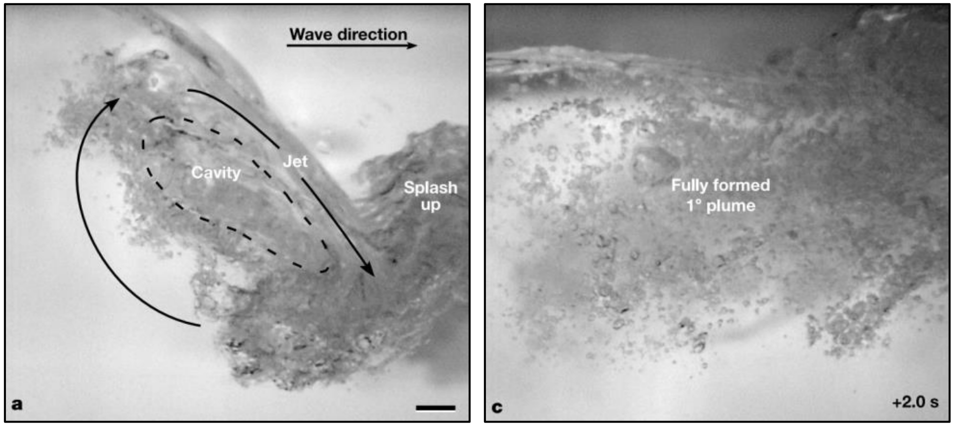
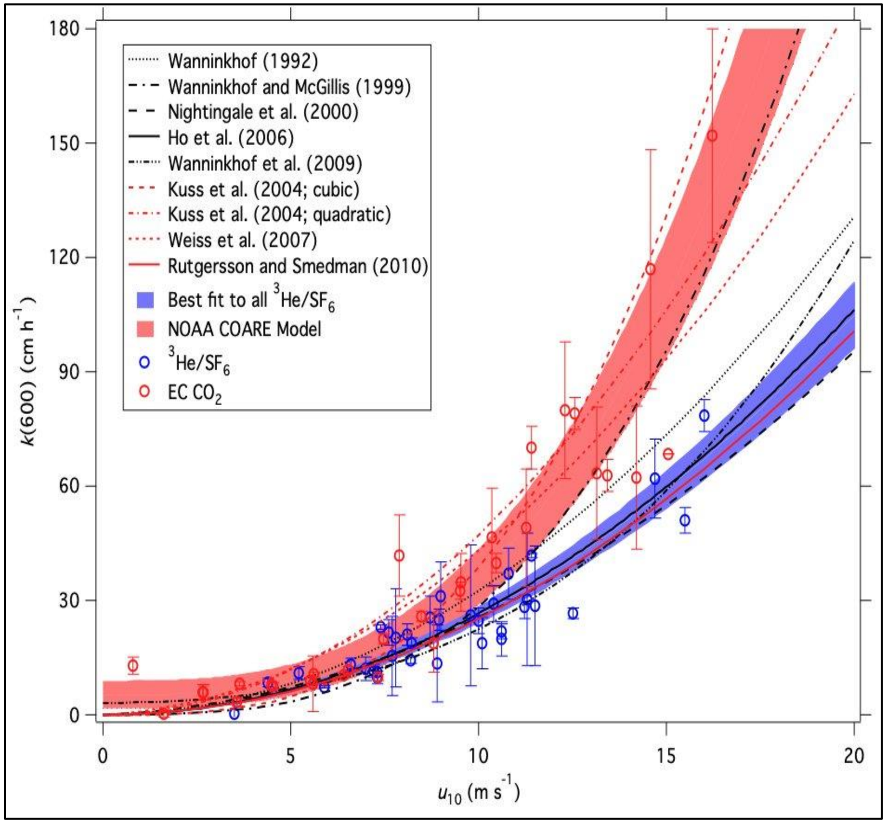
THE UNIVERSITY OF RHODE ISLAND

Breaking Waves, Gas Flux, and Uncertainty







Wave growth via wind-wave momentum flux culminates in physical destabilisation and breaking with varied intensity

Plunging, spilling breakers • Air entrainment, bubble plumes ⟶ gas flux

Uncertainty in gas flux in higher winds, but inert tracers can help

Noble gases ⟶ He, Ne, Ar, Kr, Xe

Up-scale ramifications for global climate change

Scientific Objectives

1. Conduct a series of laboratory experiments invading noble gases at different wind speeds, water temperatures, and wave conditions

   Alfred C. Glassell, Jr. SUrge STructure Atmosphere INteraction (SUSTAIN) facility
   Winds up to hurricane-force

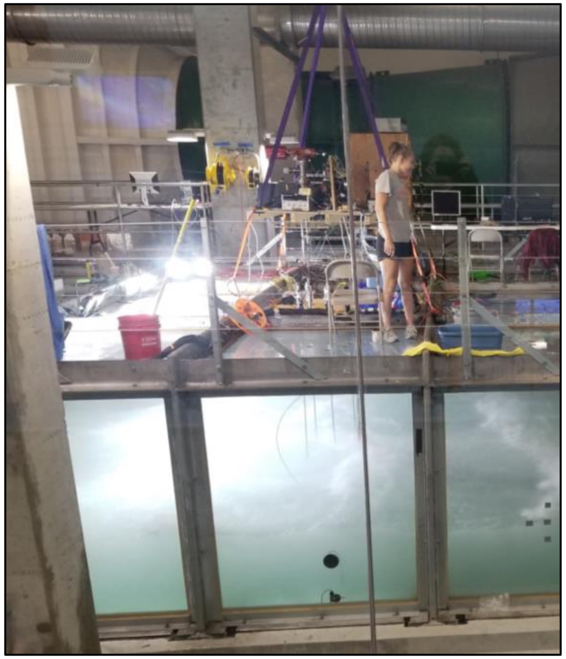
2. Measure and observe surface waves, sub-surface bubbles, sub-surface turbulence dissipation

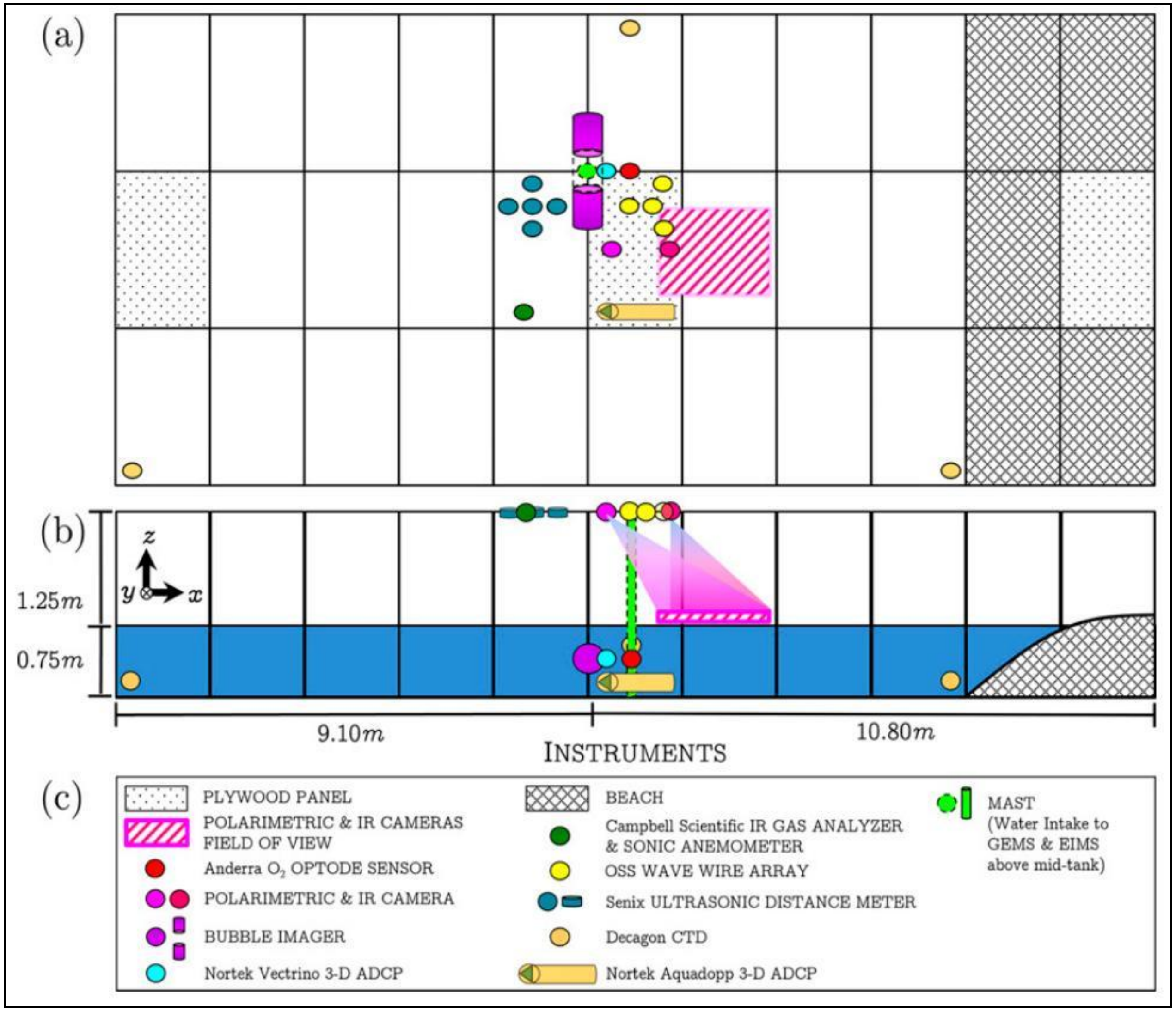
   Connect breaking waves, bubble distributions, and gas flux

3. Monitor and sample individual noble gas concentrations and their ratios, assess behavior, role of wind, waves, solubility

Laboratory Facility

SUrge STructure Atmosphere INteraction (SUSTAIN)





Experiments

35 experiments, July 10-15, 2018

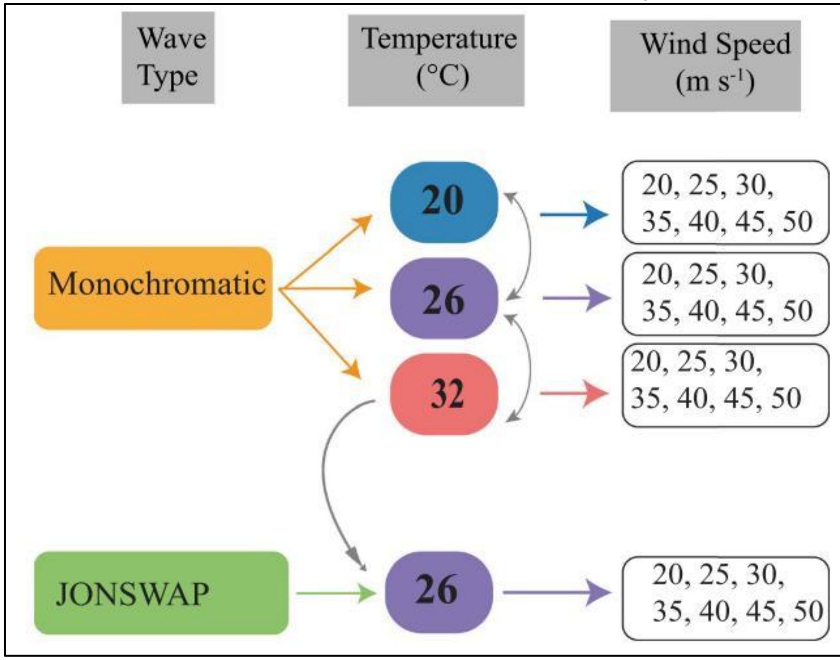


TABLE 1. Experimental conditions in SUSTAIN. The column headers refer to experiment number, water temperature (T_w), wave type either monochromatic or JONSWAP spectrum, dominant wave frequency (f) or peak period (T_p), amplitude (a) or significant wave height (H_s), and gas saturation conditions in the water.

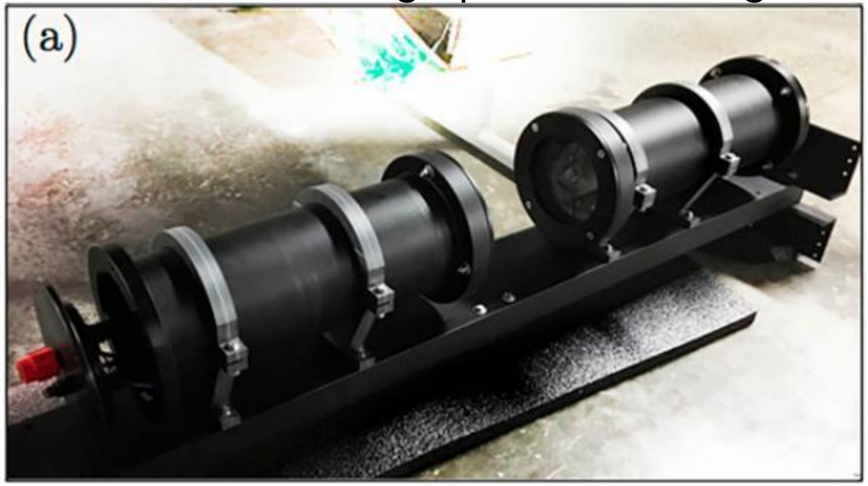
Expt No.	T_w (°C)	U_{10} (m s^{-1})	Wave type[a]	f (Hz) or T_p (s)	a (m) or H_s (m)	Gas saturation[b]
1–8	26	0–50	M	1.00 Hz	0.15 m a	US (prior to Exp. 1)
9–16	20	20–50	M	1.00 Hz	0.15 m a	US (prior to Exp. 9)
17	26	35	M	1.00 Hz	0.15 m a	SS (prior to Exp. 17)
18–24	32	20–50	M	1.00 Hz	0.15 m a	SS (prior to Exp. 18)
25	26	35	S	0.65 s T_p	0.5 m H_s	US (prior to Exp. 25)
26	26	40	S	1.00 s T_p	0.5 m H_s	
27–34	26	10.6–50	S	1.00 s T_p	0.15 m H_s	
35	32	20	M	1.00 Hz	0.15 m a	SS (prior to Exp. 35)
EQ[c]	—	10	S	0.65 s T_p	0.15 m H_s	—

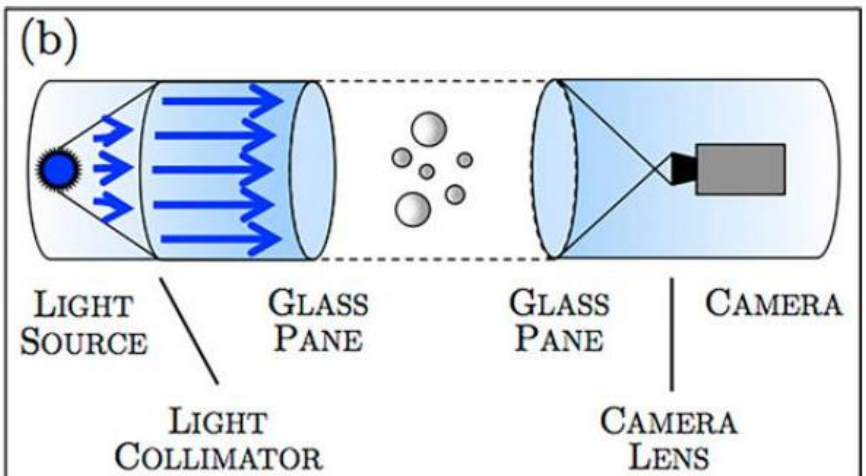
[a] M = Monochromatic; S = JONSWAP spectral.
[b] US = Undersaturated; SS = Supersaturated.
[c] EQ = Equilibration period.

Water temperature manipulated prior to some experiments to force super-saturation of noble gas (when warmed) or under-saturation of gas (when cooled)

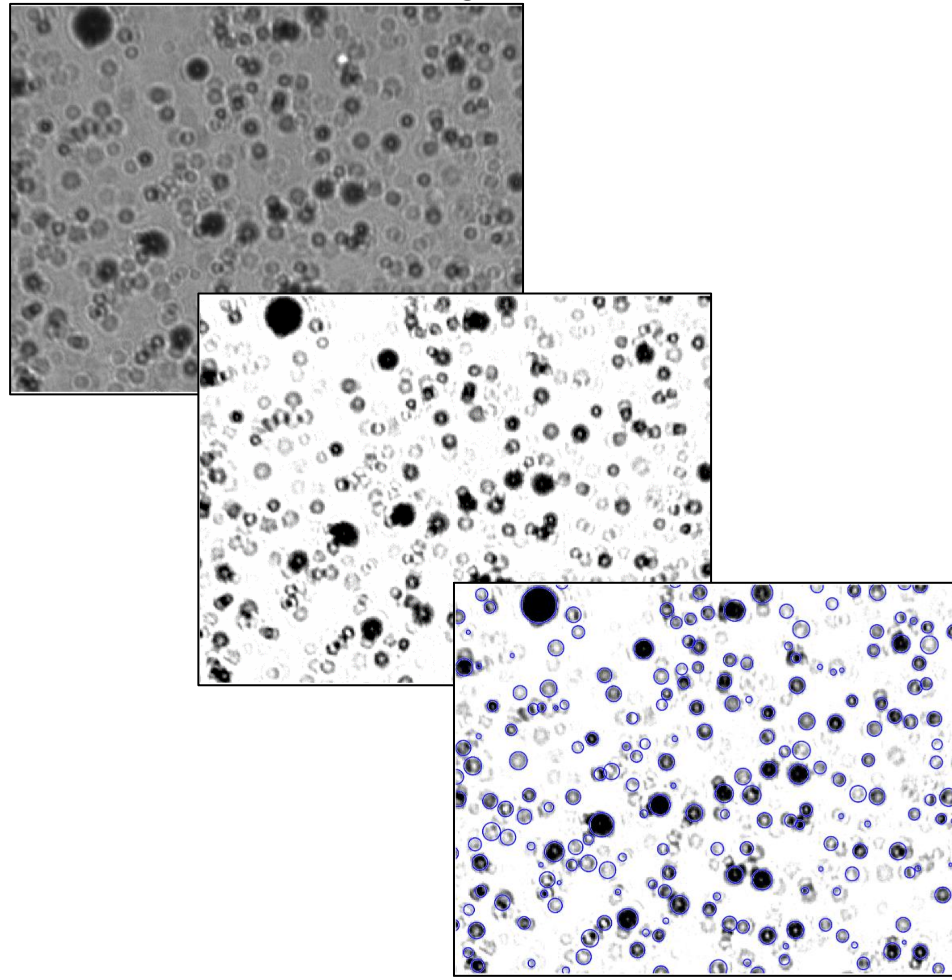
Experiments

SUSTAIN shadowgraph bubble imager





Circular Hough Transform (CHT)



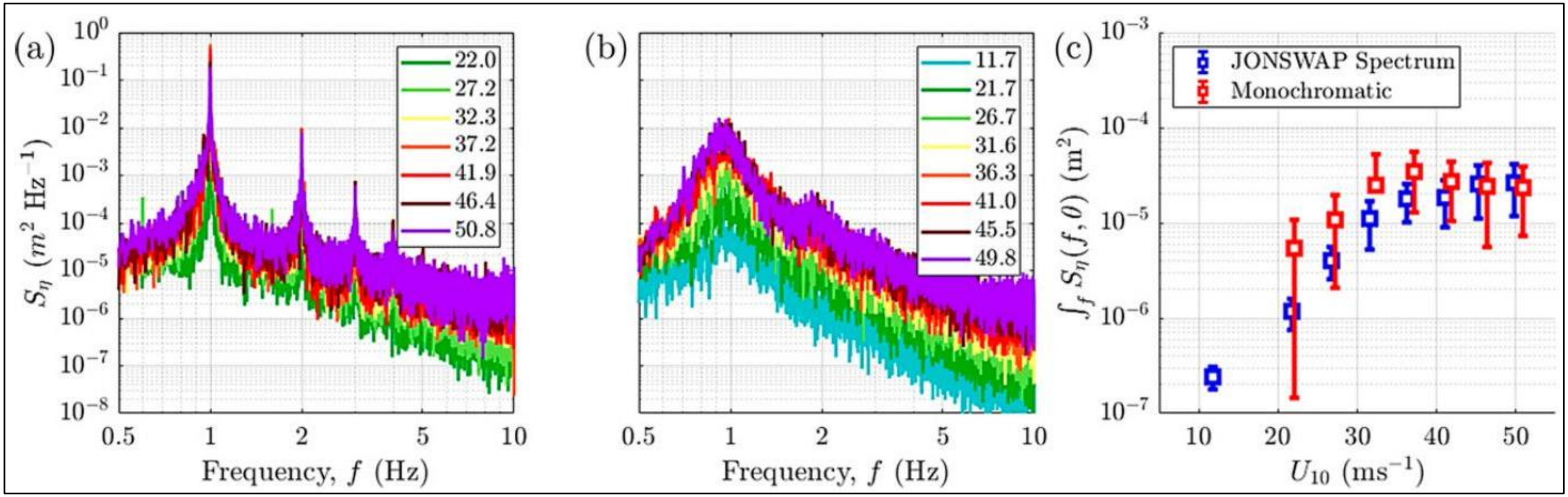
- Basler avA2300-gm area-scan camera
- Kowa LM50HC F1.4/f = 50mm lens
- Luxeon Rebel royal blue (470 nm) LED

- Quiescent background removal
- C-L adaptive histogram equalization
- Perform CHT for bubble centers, edges, stats

Results

Wave Spectra

Monochromatic JONSWAP Spectrum



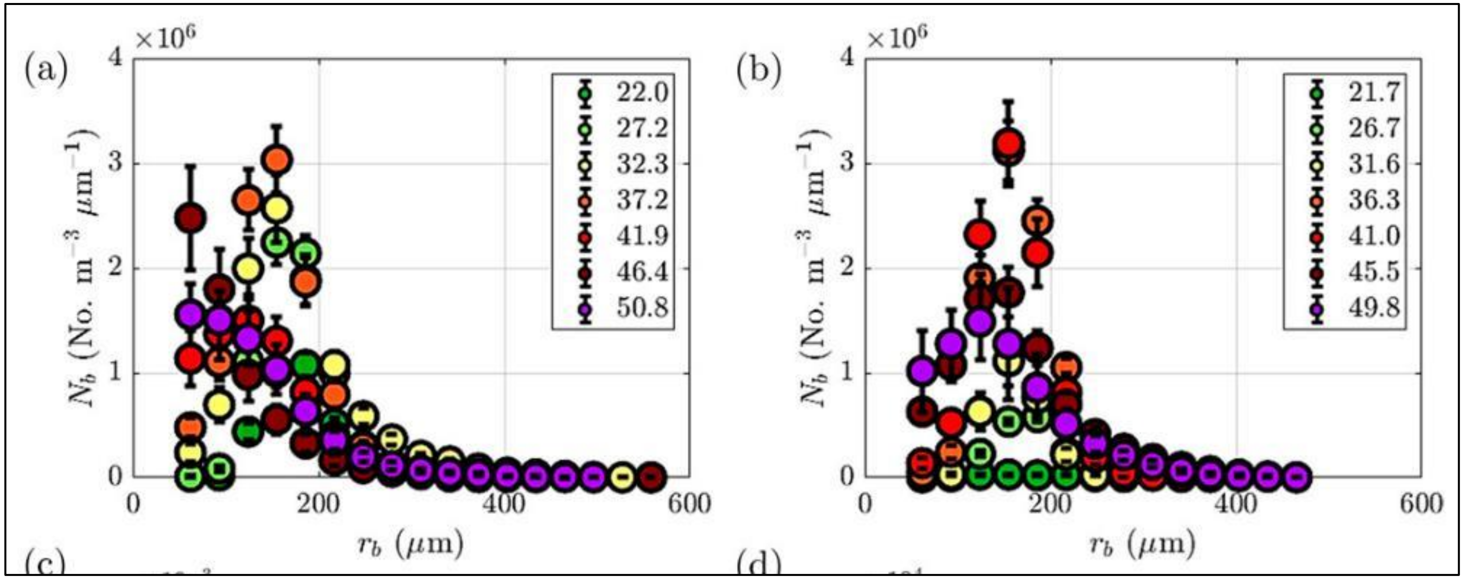
- Water temperature 25.7C and 25.9C, filtered sea-water from Biscayne Bay
- Average peak frequency 0.99 and 0.96 Hz, respectively
- Integrated wave spectral density: increases with U_{10N} until about 37 ms^{-1}
- At higher winds, monochromatic level-off, JONSWAP spectrum approaches

Results

Bubble Spectra

Monochromatic

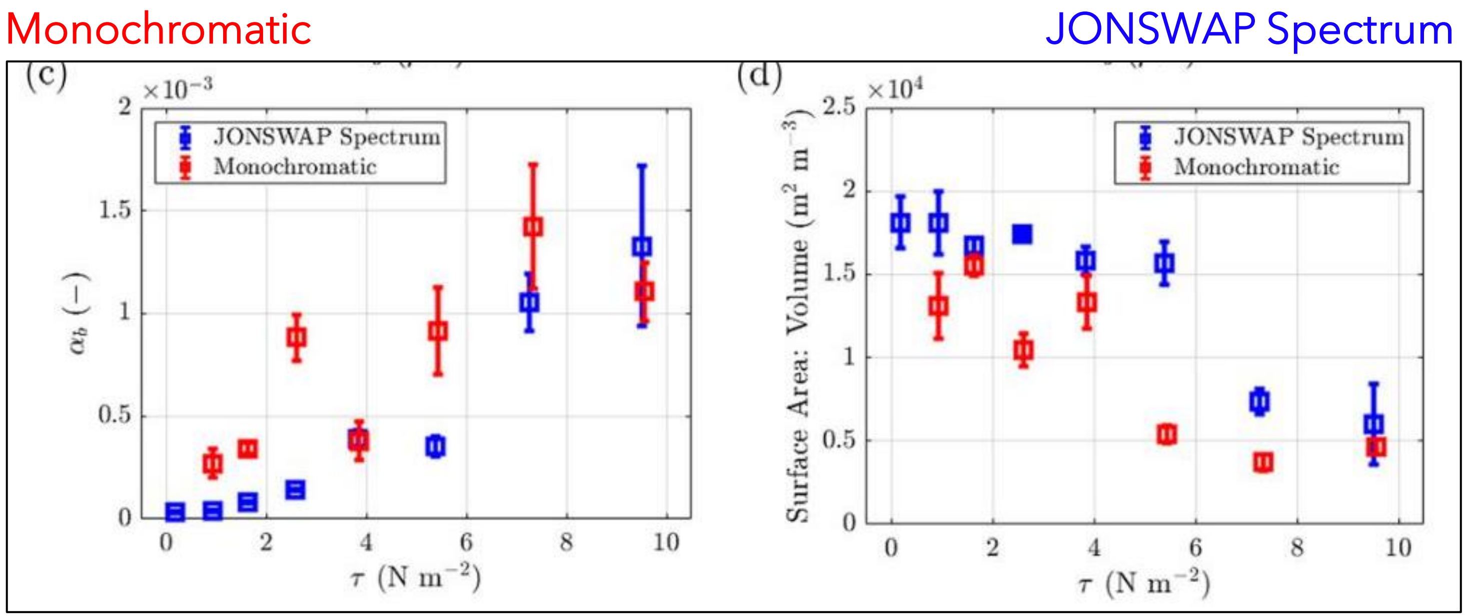
JONSWAP Spectrum



- Average bubble size distributions increase over low - moderate (U_{10N} < 37 ms^{-1})
- Number of bubbles increases more rapidly beneath monochromatic vs JONSWAP spectrum, both decrease at higher winds
- Bubble size decreases 8% faster with 1.7x greater bubble radius variance beneath monochromatic waves (23% steeper, 13% more asymmetric, 40% larger breaking intensity)

Results

Void Fraction and Surface Area to Volume Ratio



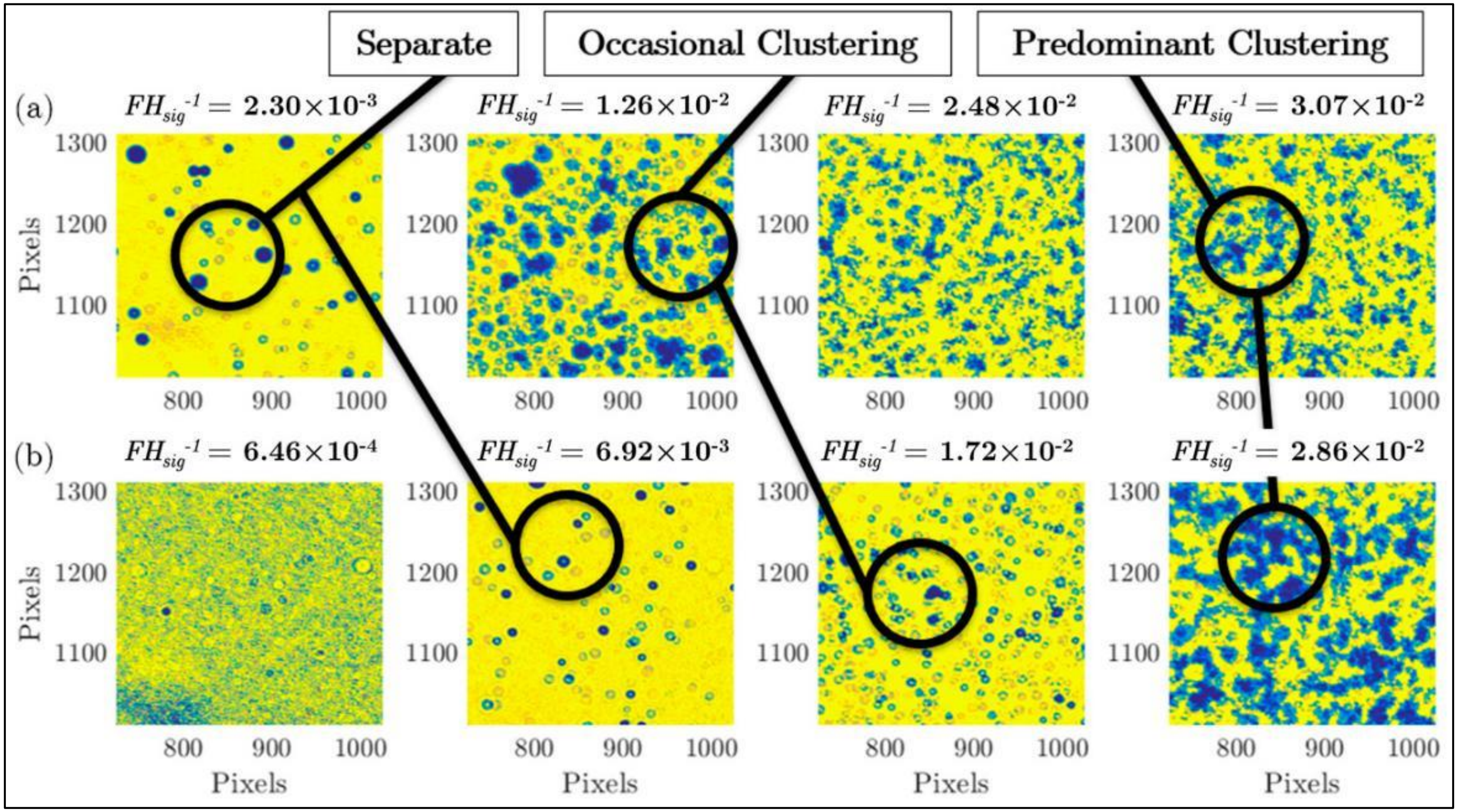
- Void fraction 3.2x larger on average in monochromatic waves vs JONSWAP
- Void fraction increases 1.5x faster per unit stress in JONSWAP though
- SA:V 1.6x larger in JONSWAP, but SA:V decreases 4.7x faster in monochromatic
- Larger void fractions and more rapidly decreasing SA:V with increasing stress in steeper monochromatic waves vs. JONSWAP spectrum

Results

Sub-Surface Bubble Evolution

Monochromatic

JONSWAP Spectrum



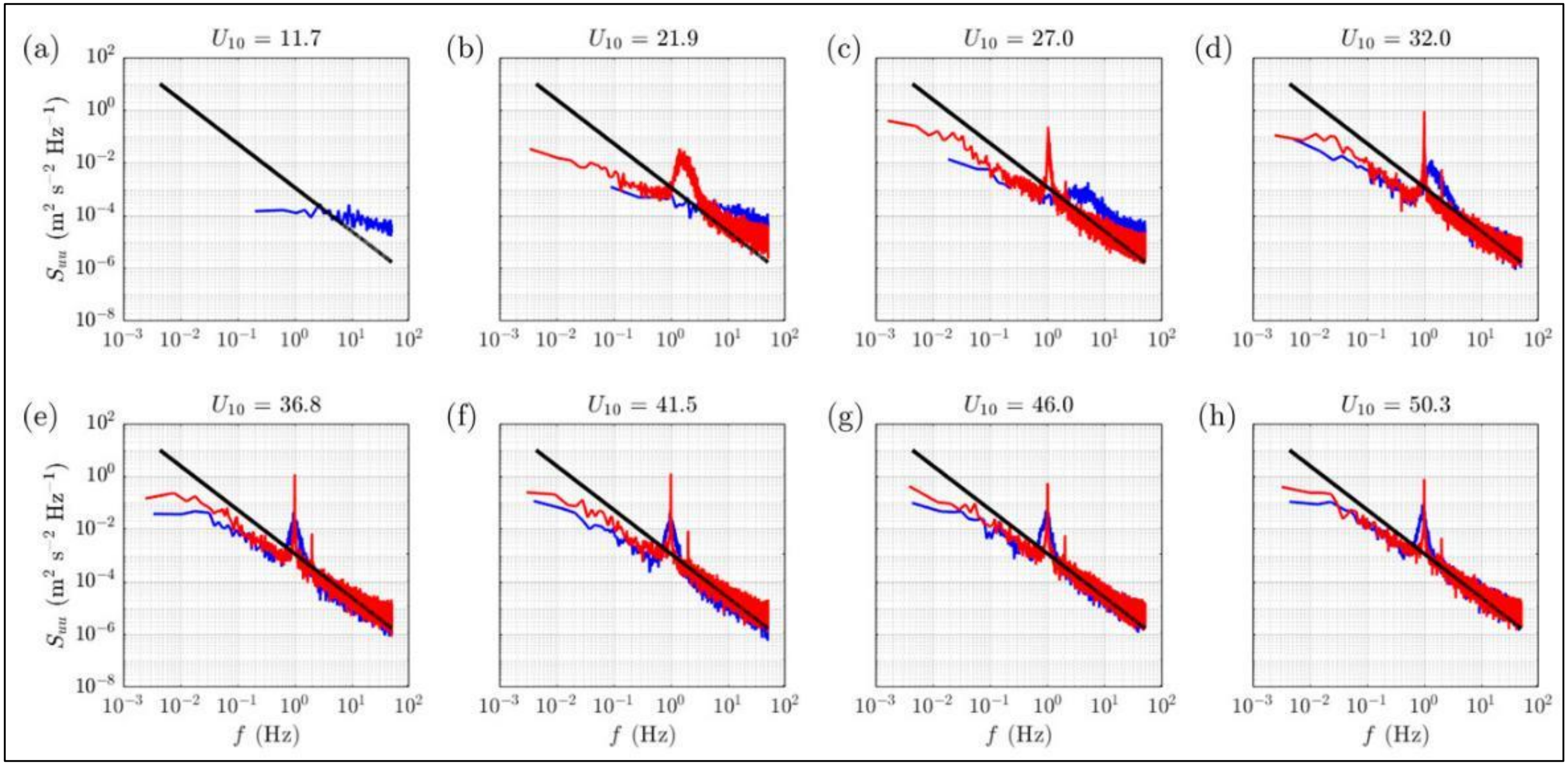
- Circular Hough Transform used in bubble center and edge detection
- Larger wave-scaled wind-wave energy input (wave-induced turbulence) in monochromatic waves vs. JONSWAP
- Separate bubbles transition to more clustered behavior in images, accuracy challenged in high winds

Results

Sub-Surface TKE & Dissipation

Monochromatic

JONSWAP Spectrum

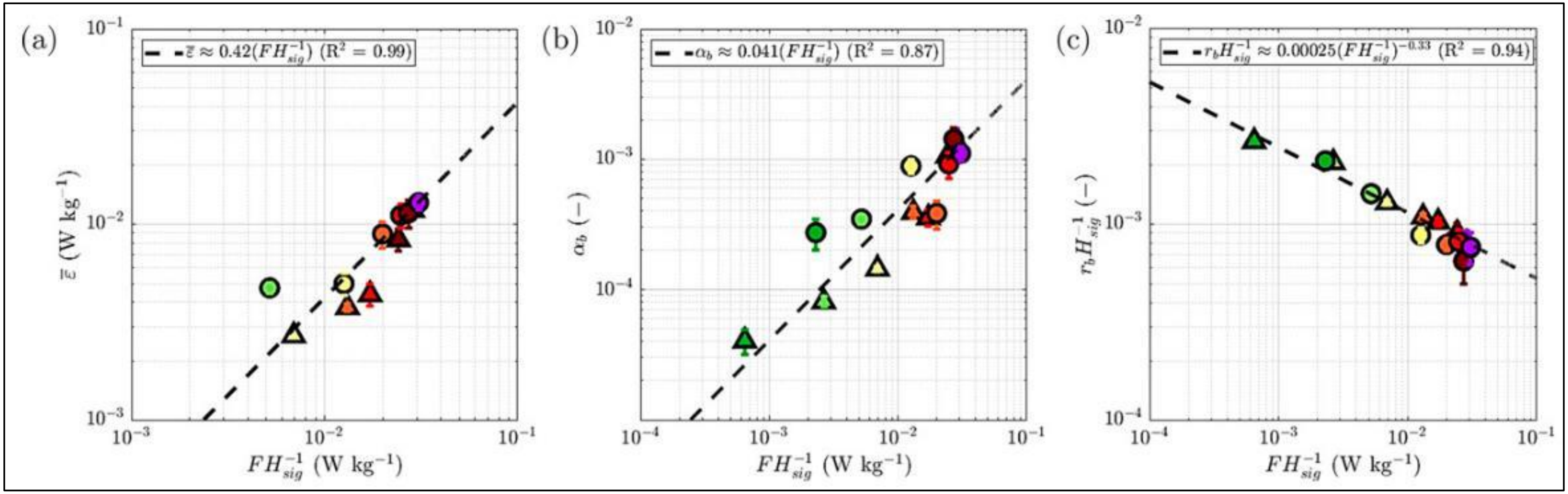


- TKE dissipation rate determined from sub-surface ADCP velocity spectra
- Dissipation rates larger (4.7×10^{-3} – 1.3×10^{-2} m^2 s^{-3}) in monochromatic vs JONSWAP (2.7×10^{-3} – 1.2×10^{-2} m^2 s^{-3}); higher ADCP SNR

Results

Sub-Surface TKE & Dissipation

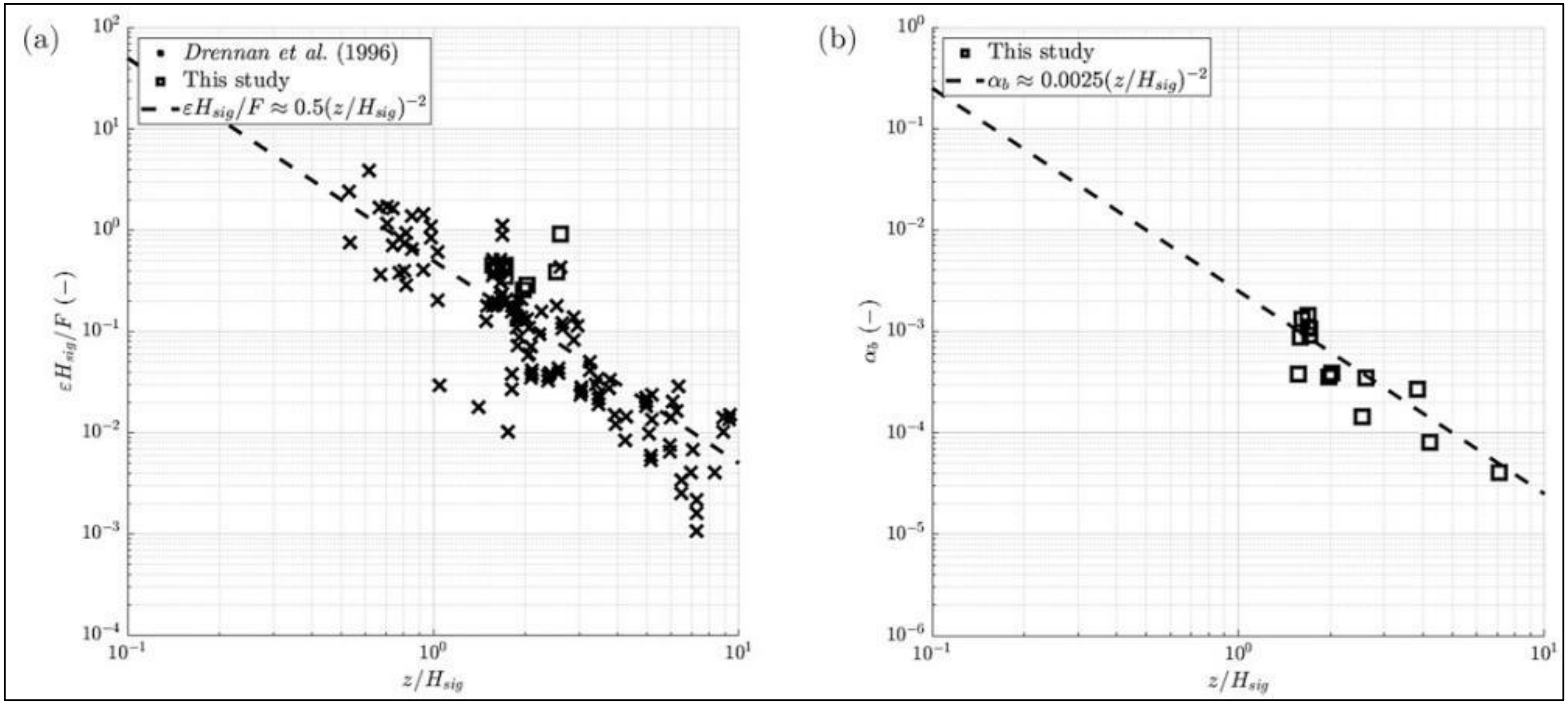
Monochromatic (*circles*) JONSWAP Spectrum (*triangles*)



- Dissipation rates increase with wave-scaled wind-wave energy input, which accounts for wind-wave alignment, wind speed, phase speed of waves
- Void fraction increases with wave-scaled wind-wave input
- Wave-scaled bubble radius decreases with wave-scaled wind-wave energy input

Results

Sub-Surface TKE & Dissipation



- Wind-wave input-scaled dissipation rate increases as significant wave height increases and/or proximity to the wavy surface increases
- Void fraction increases as well
- Laboratory findings lie amongst field data from SWADE and WAVES field campaigns where measured

Conclusions

Smith, Haus, and Stanley (2022)

1. Increasing wind stress and wave height result in greater volume of air entrainment, greater number of bubbles

2. Air entrainment greater, but bubble size smaller as wave-scaled wind-wave energy input increases

3. Sub-surface turbulence and dissipation larger beneath monochromatic vs JONSWAP spectrum waves

4. Wave-scaled dissipation rates agree with power-law fit scaling and observations in SWADE and WAVES campaigns

Stanley, Kinjo, Smith, et al. (2022)

5. Steady-state gas saturation anomalies and noble gas fluxes increased initially and then leveled off at high winds

6. Significant wave height and wave steepness better predict gas fluxes than wind speed, especially in JONSWAP spectrum waves that approximate real open ocean conditions

7. Important differences in gas flux when considering invasion vs. evasion for all noble gases, need to account for this in future parameterisations

References

Smith, A. W., Haus, B. K., & Stanley, R. H. R. (2022). Bubble-turbulence dynamics and dissipation beneath laboratory breaking waves. *Journal of Physical Oceanography*, *1*, 2159–2181. https://doi.org/10.1175/JPO-D-21-0209.1

Stanley, R. H. R., Kinjo, L., Smith, A. W., Aldrett, D., Alt, H., Kopp, E., Krevanko, C., Cahill, K., & Haus, B. K. (2022). Gas Fluxes and Steady State Saturation Anomalies at Very High Wind Speeds. *Journal of Geophysical Research: Oceans*, 1–19. https://doi.org/10.1029/2021jc018387