Imperial College London

UKRI Natural Environment Research Council

Breaking Wave Whitecaps:

Applying Laboratory-Derived Results to Field Observations

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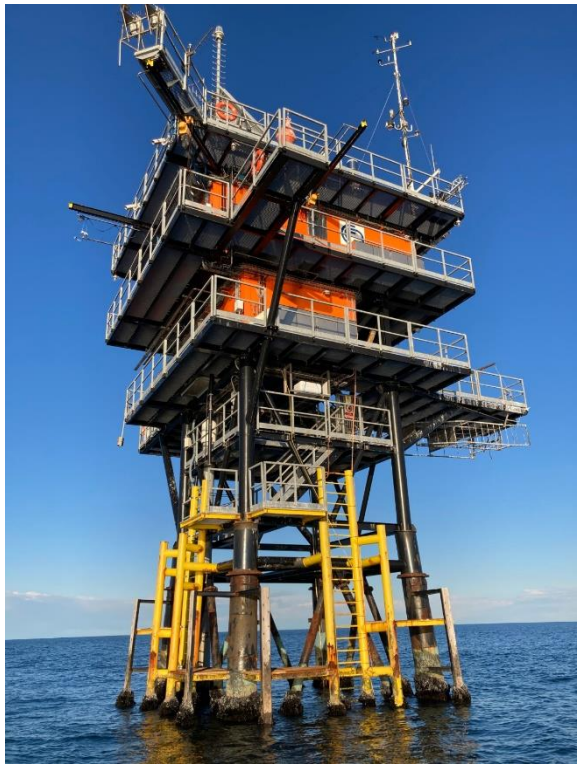
Oceanic Breaking Waves – Whitecaps

- Observing Breaking Wave Whitecaps



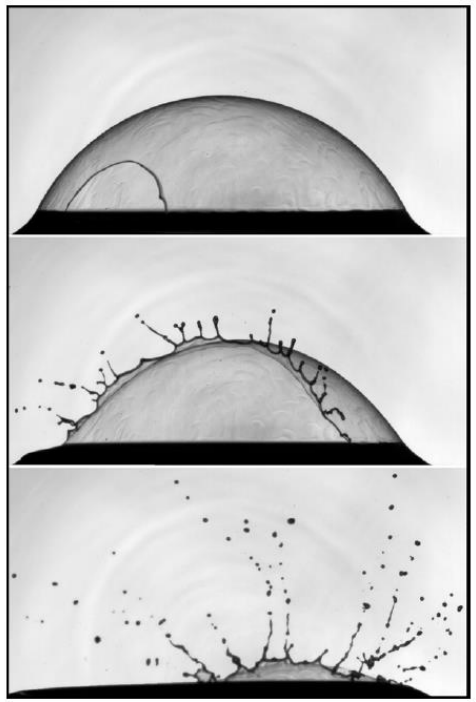
Acqua Alta Tower

Bubbles Efficiently Transfer CO_2 Between the Air and Water

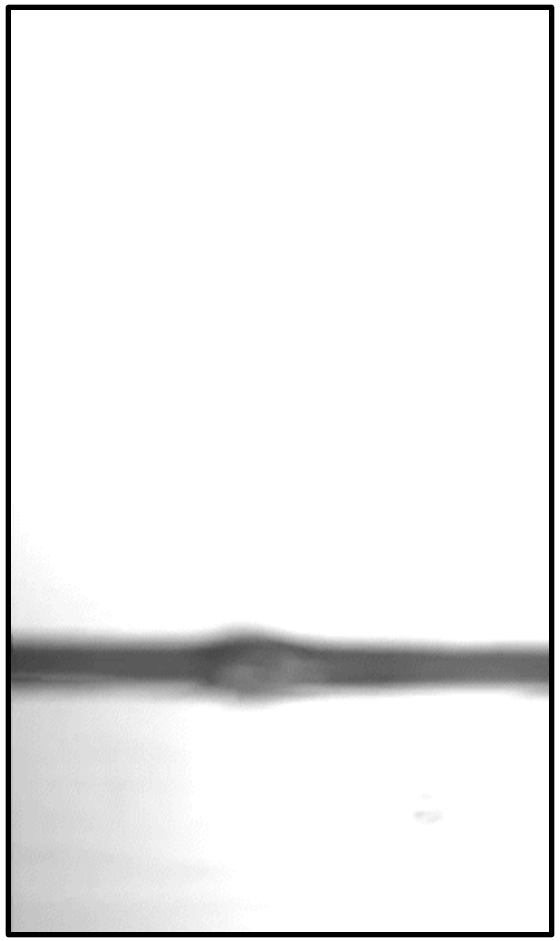
$$CO_{2(g)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)} \rightarrow H^+_{(aq)} + HCO^-_{3(aq)}$$

Limewater Demonstration – www.bbc.co.uk

Bubble Bursting is a Key Driver of Sea Spray Production Flux



Film Droplet Production
- L'huissier and Villermaux, *JFM*, 2012



Jet Droplet Production

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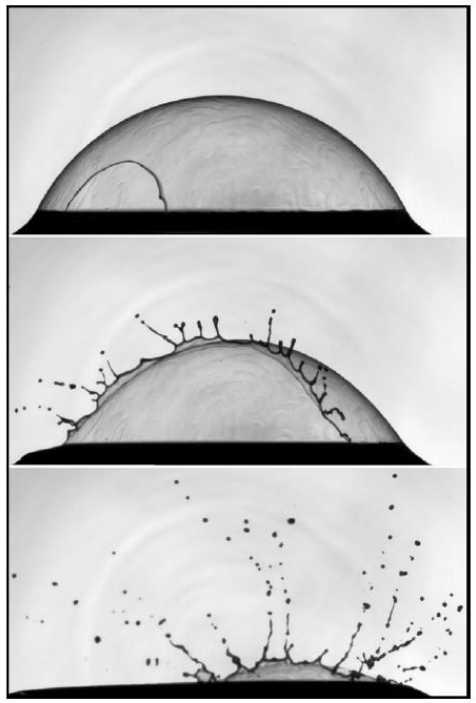
Bubble Bursting is a Key Driver of Sea Spray Production Flux



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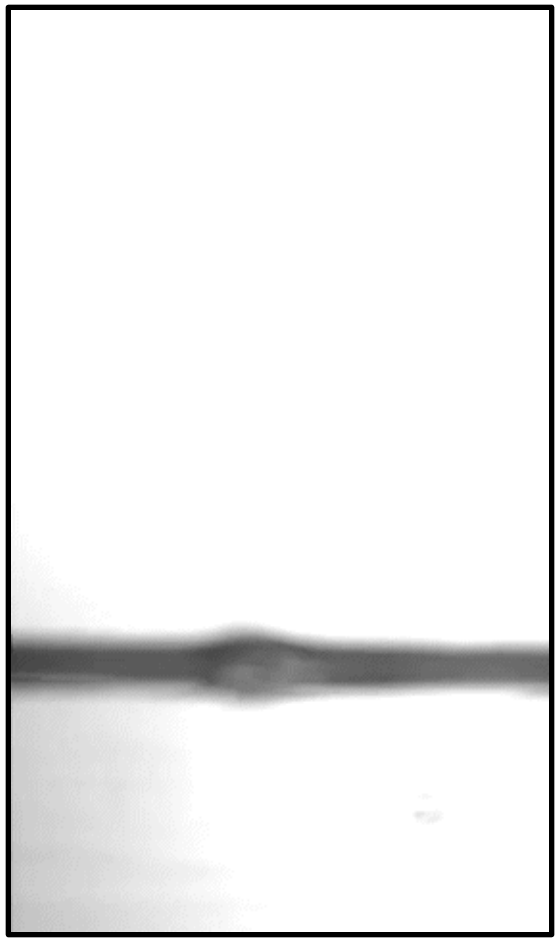

Jet Droplet Production

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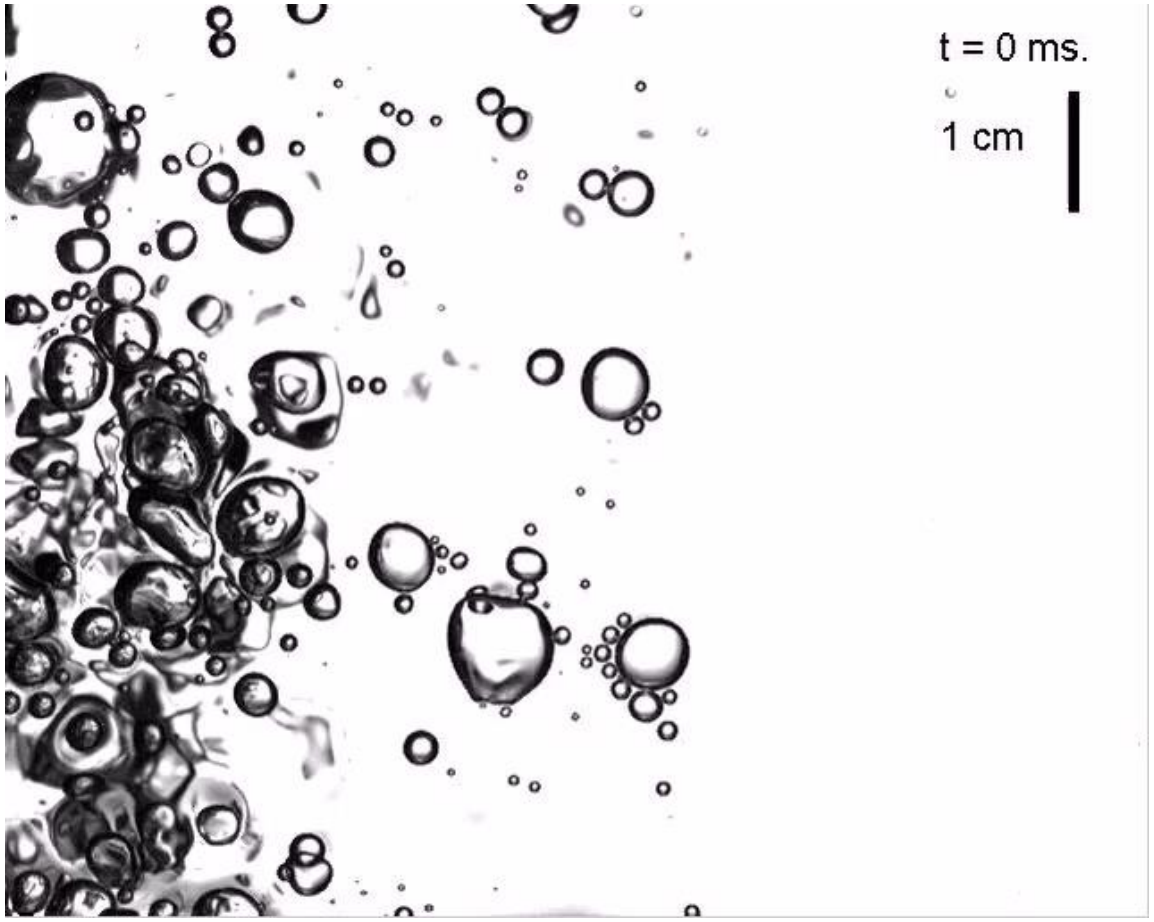
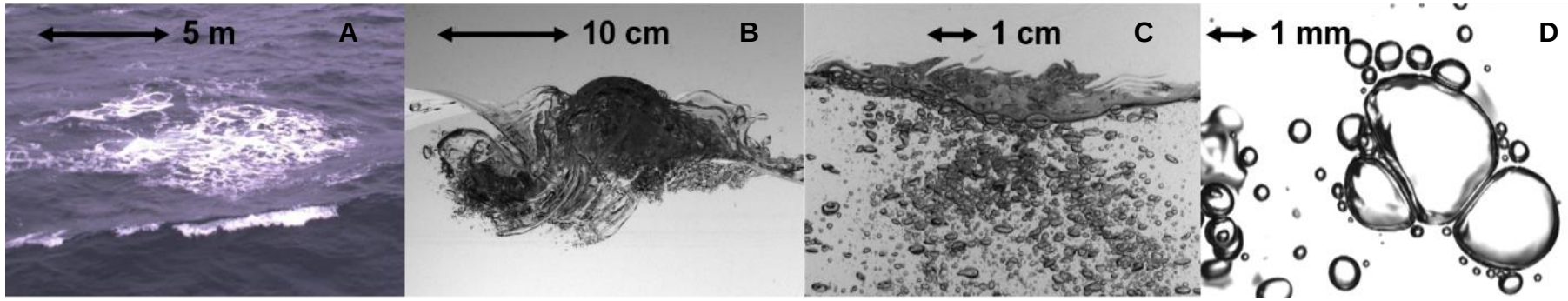


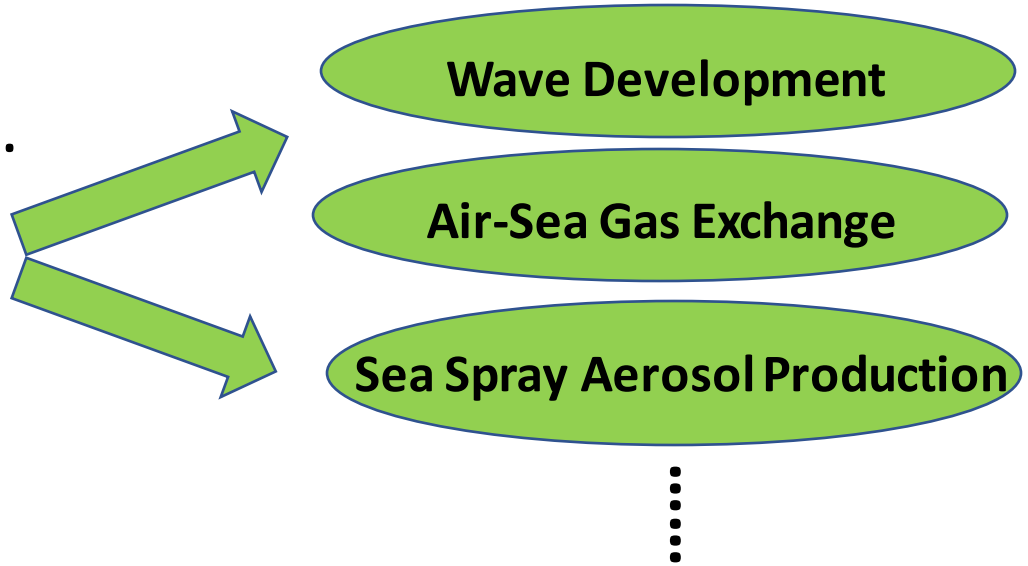
Foam Cell Evolution

Scripps Institution of Oceanography

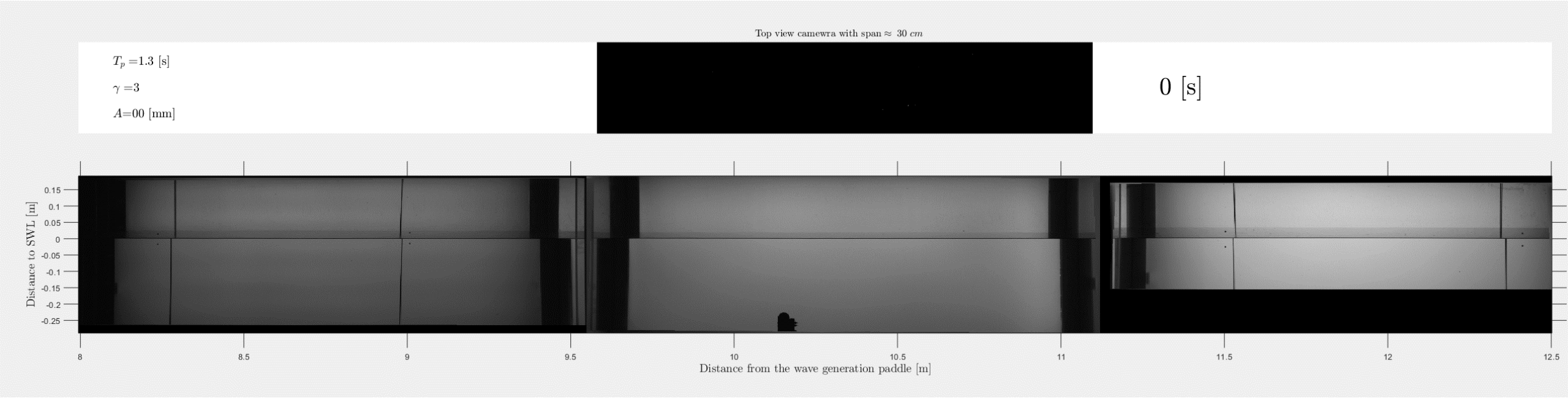
Breaking Waves and Bubble-Mediated Processes Span Multiple Orders of Magnitude in Space and Time

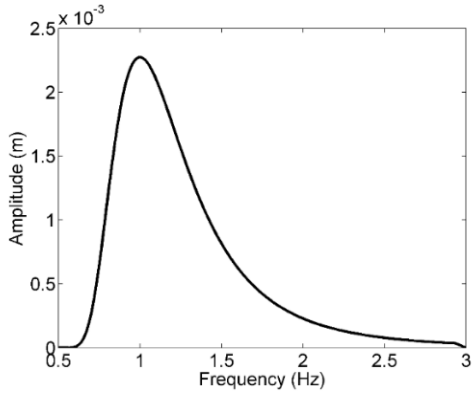


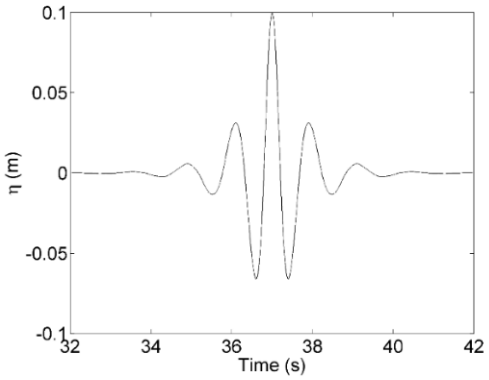
- Whitecap Scale and Generation Rate.
  - Volume Flux of Air.
    - Bubble Size Distributions.
      - Foam Cell Distributions.



Breaking Waves in the Laboratory

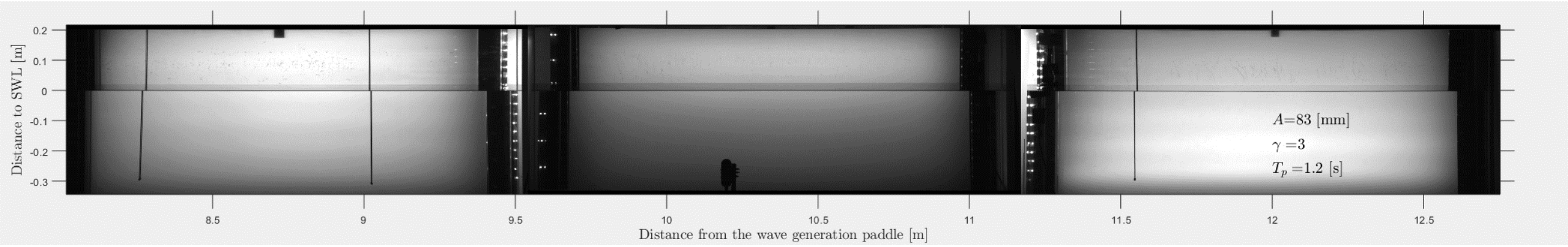


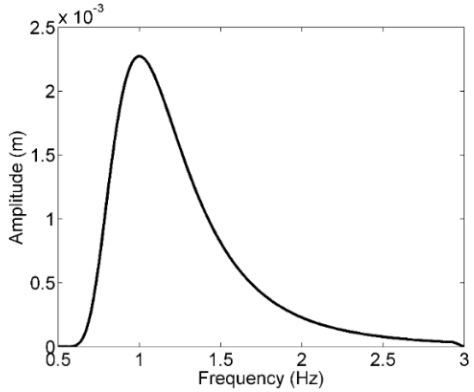




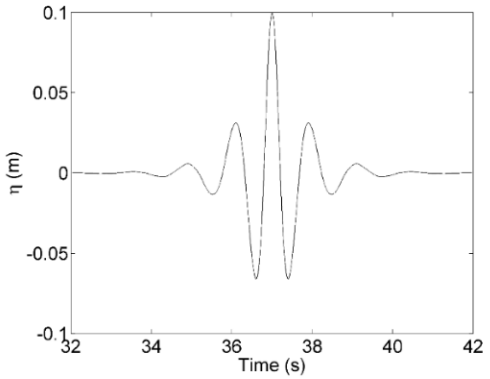
Wind-forced Breaking Waves in the Laboratory

Wind-forced breaking waves have shallower bubble plume injection depths.

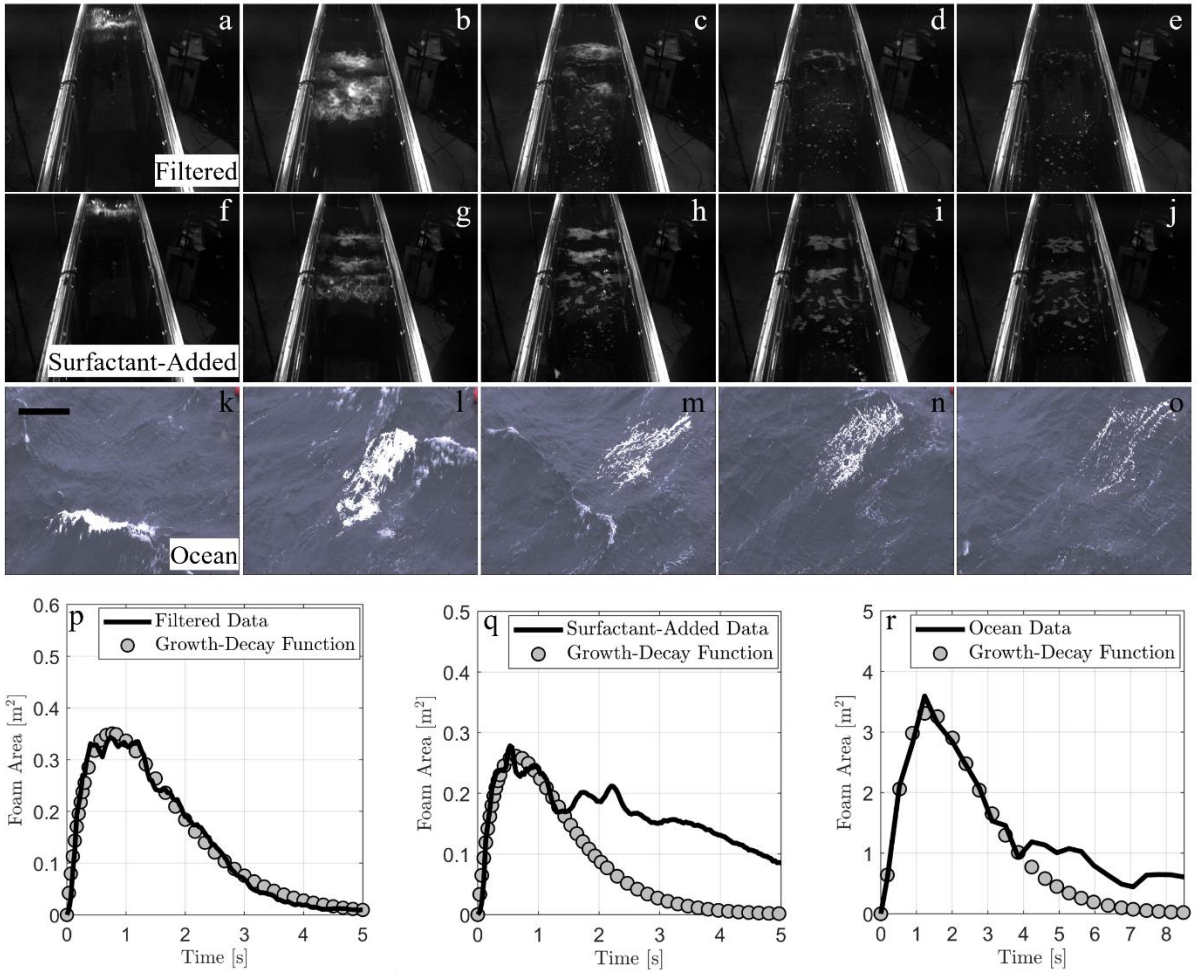




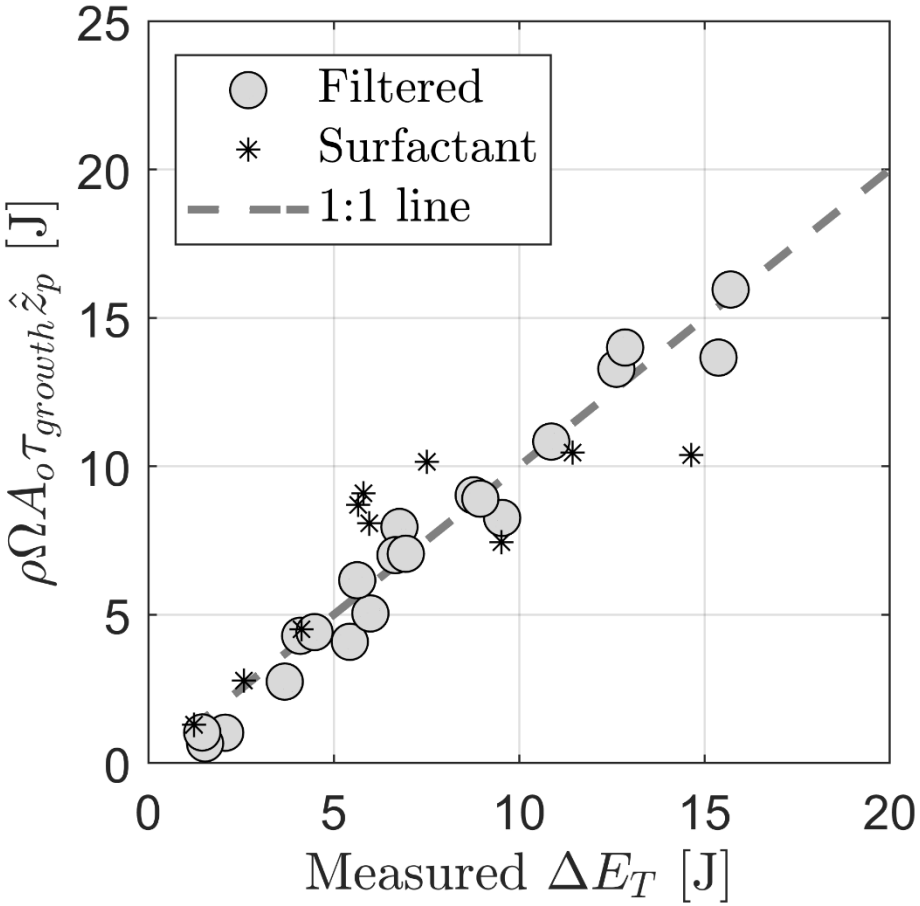
Wind



Foam Area Evolution Can Be Used to Estimate Energy Dissipation By Individual Laboratory Breaking Waves

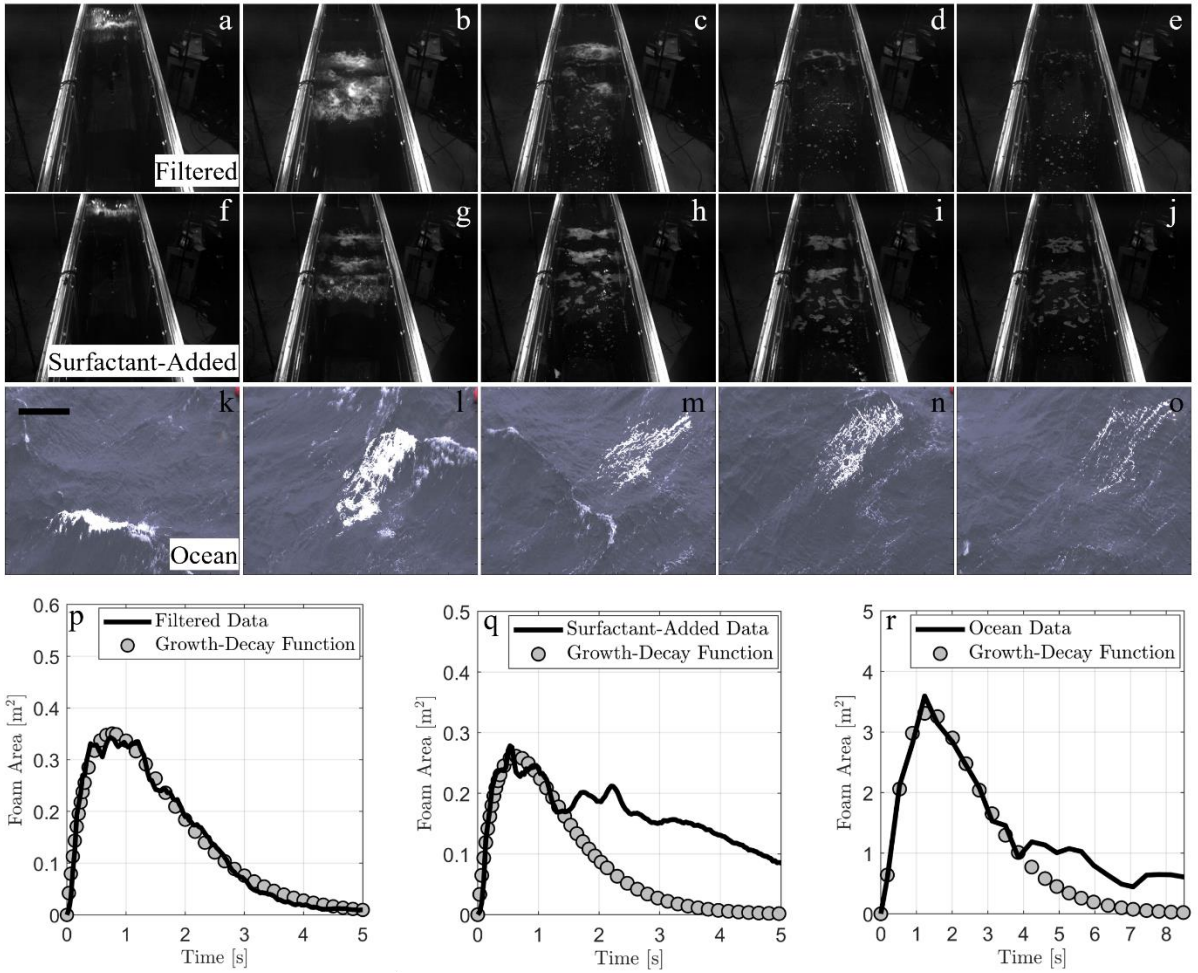


Callaghan et al., 2013, 2016, 2017

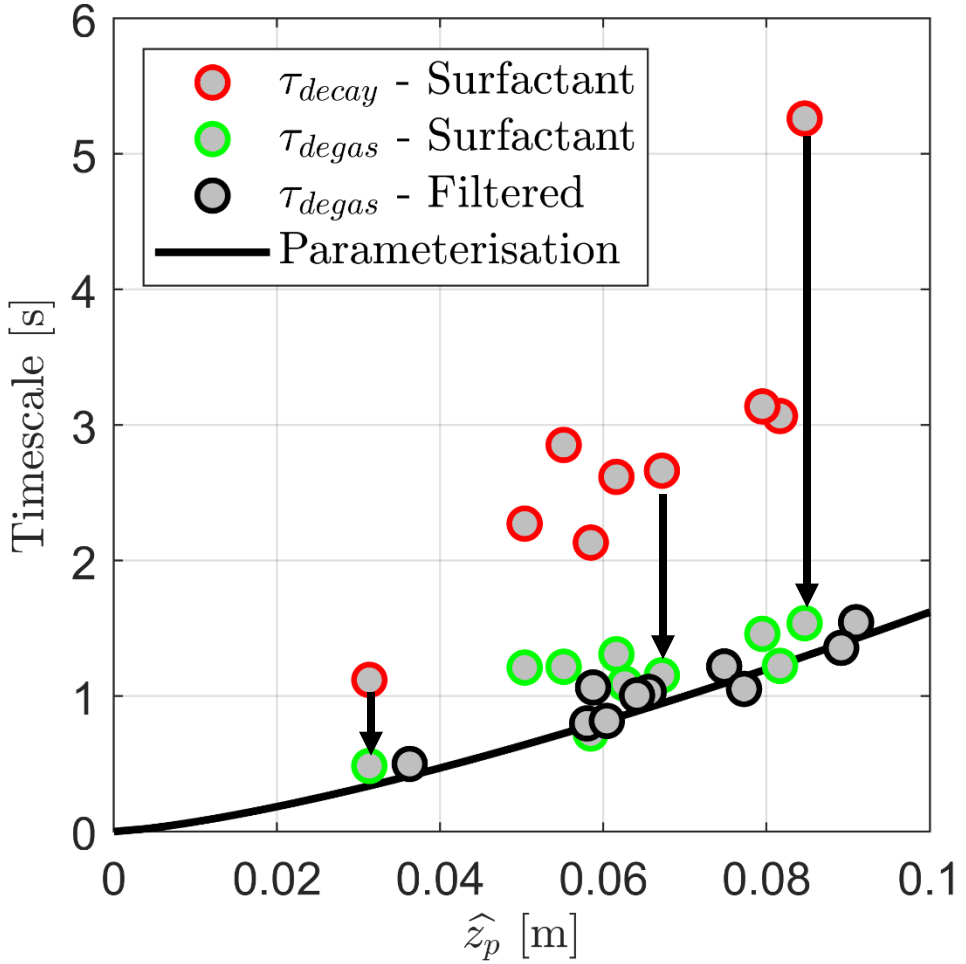


$$\Delta E_T = \Omega \rho A_o \tau_{growth} \hat{z}_p$$

Foam Area Evolution Can Be Used to Estimate Energy Dissipation By Individual Laboratory Breaking Waves

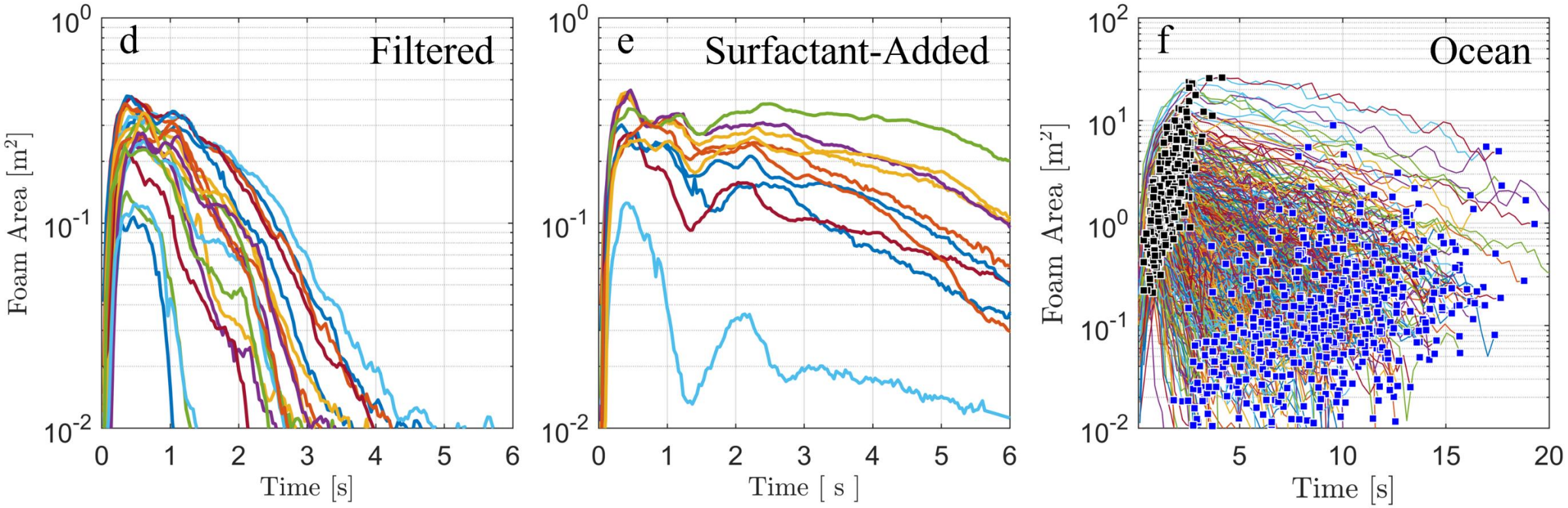


Callaghan et al., 2013, 2016, 2017



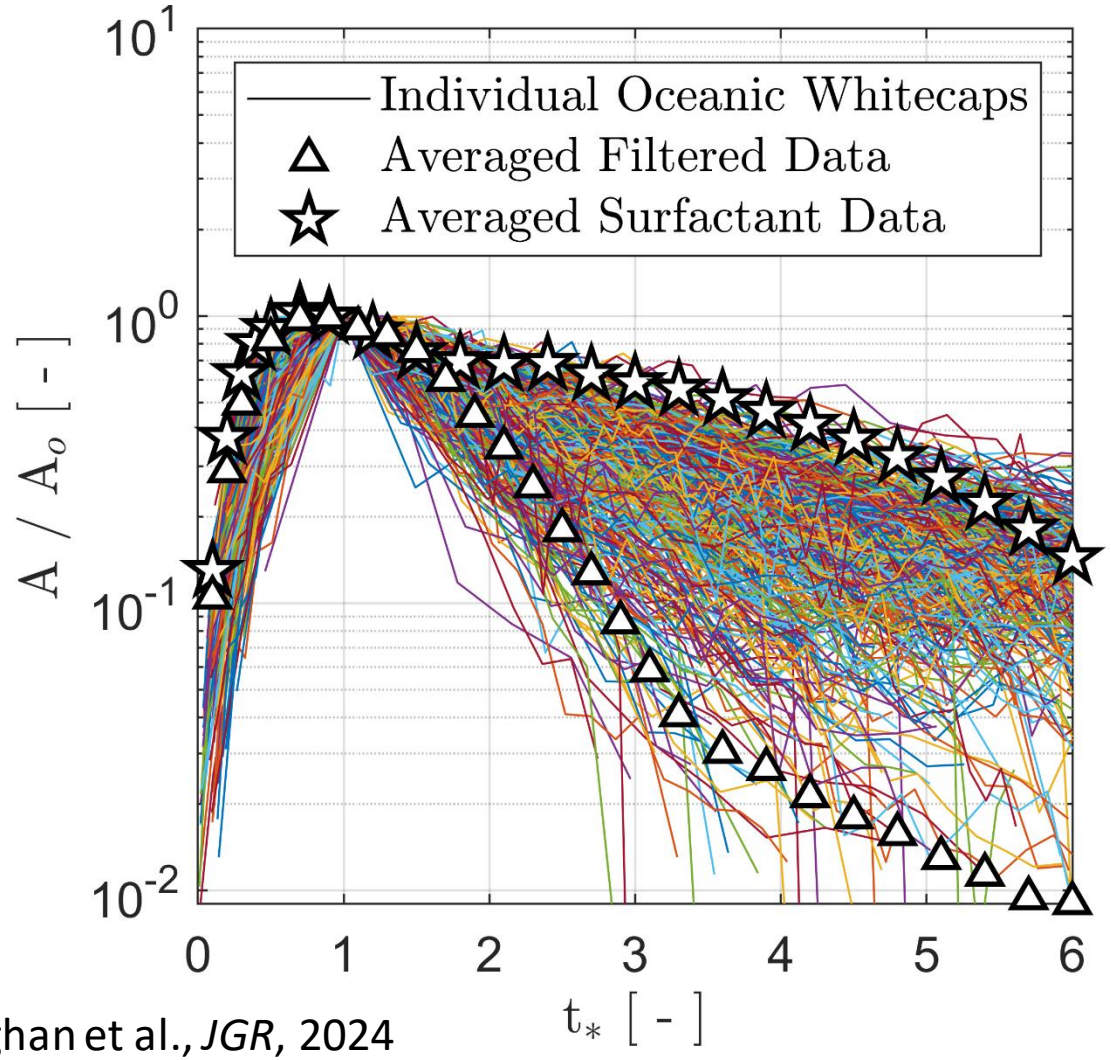
$$\hat{z}_{\mathrm{p}} = f(\tau_{degas})$$

Foam Evolution from Laboratory Breaking Waves and Oceanic Whitecaps Occurs at Different Scales



Callaghan et al., *JGR*, 2024

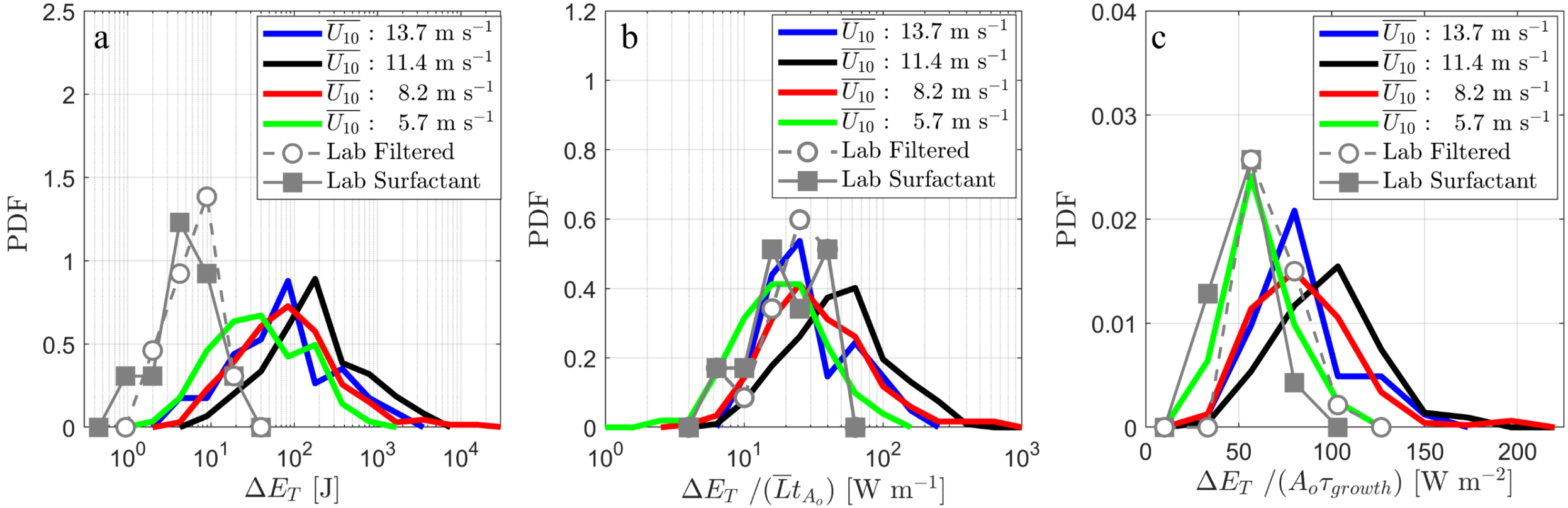
Scaled Foam Evolution from Laboratory Breaking Waves and Oceanic Whitecaps is Similar



Callaghan et al., *JGR*, 2024

Air-Sea Interaction Tower (ASIT) at the Martha's Vineyard Coastal Observatory

Estimates of Energy Dissipation by Individual Oceanic Whitecaps



Callaghan et al., *JGR*, 2024

Modelling Whitecap Coverage with ecWAM

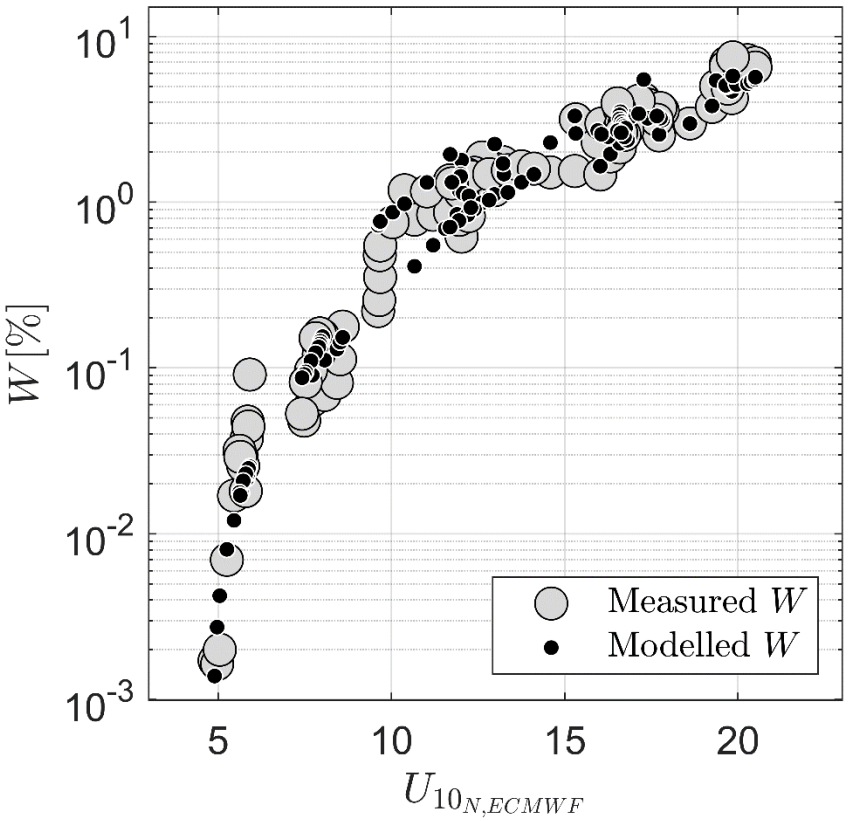
$$W = \frac{\xi\phi_{oc} - \phi_{th}}{\Omega\rho\hat{z}_p^*}(1+\delta^*)$$

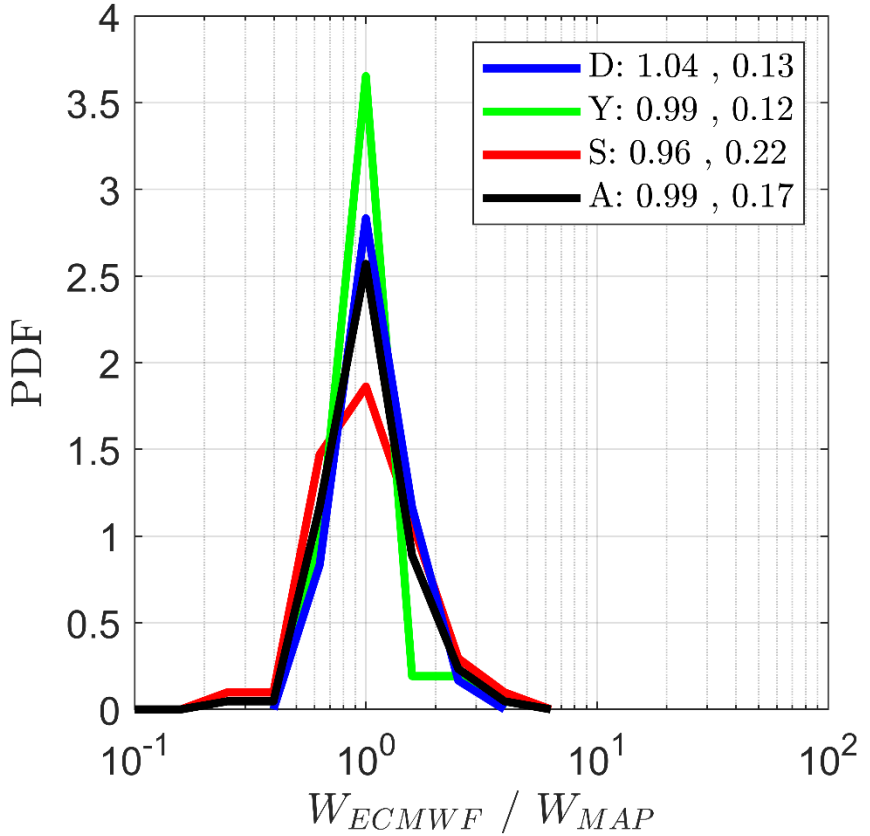
$$\xi = f\left(c_p/u_{10}\right)$$

$$\hat{z}_p^* = f\left(H_{s,ww}\right)$$

$$\delta^* = f\left(H_{s,ww}\right)$$

$$\phi_{th} = 2.7 \times 10^{-3}\ \mathrm{W\,m^{-2}}$$





D: $1 \leq c_p/u_{10} \leq 1.2$

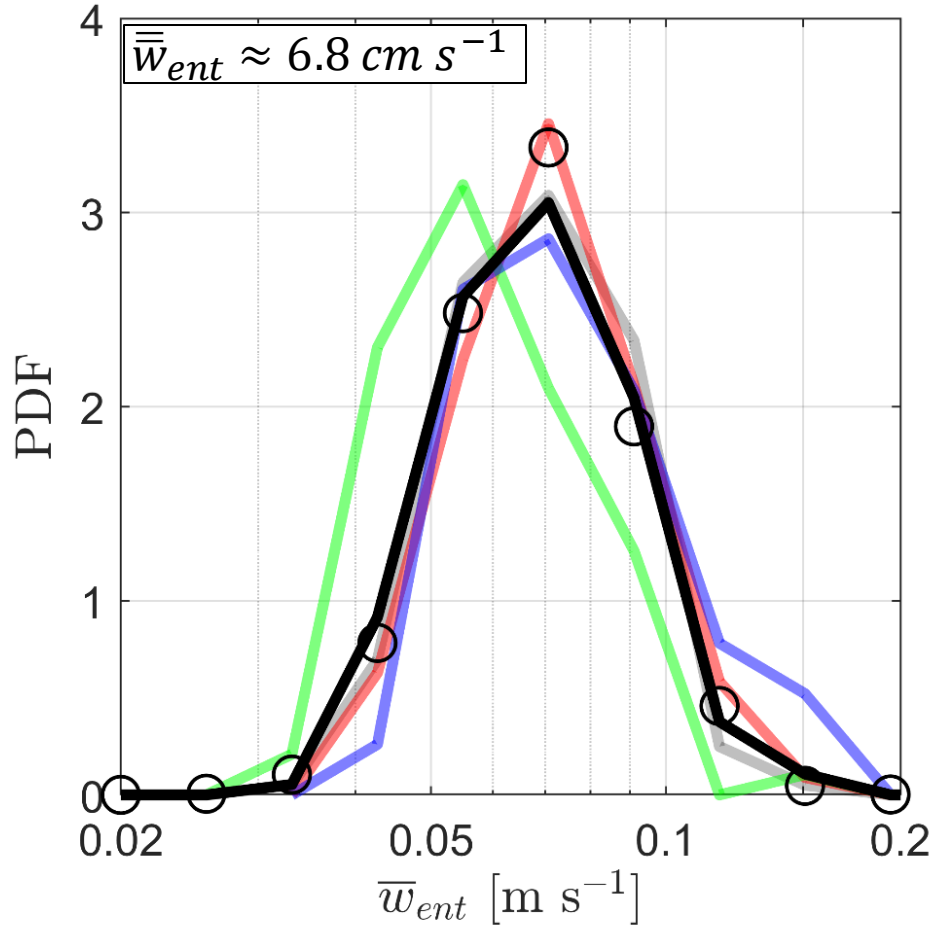
Y: $c_p/u_{10} < 1$

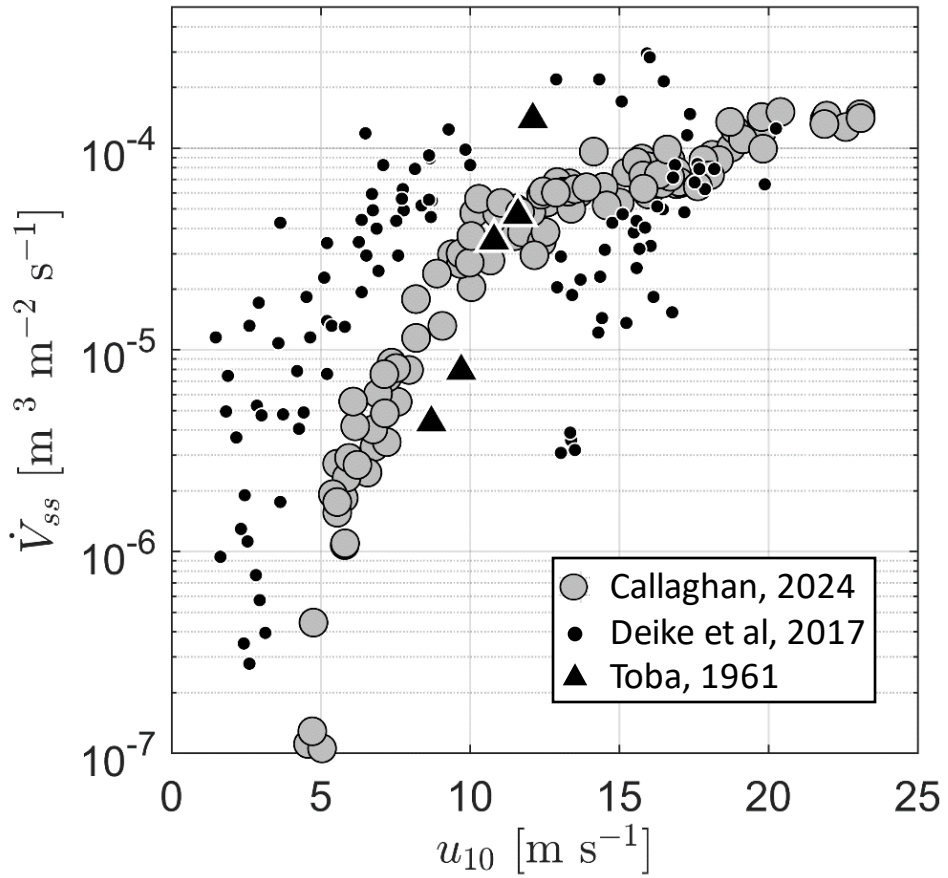
S: $c_p/u_{10} > 1.2$

Callaghan et al., *GRL, in review*

Modelling Air Entrainment Rate by Whitecaps

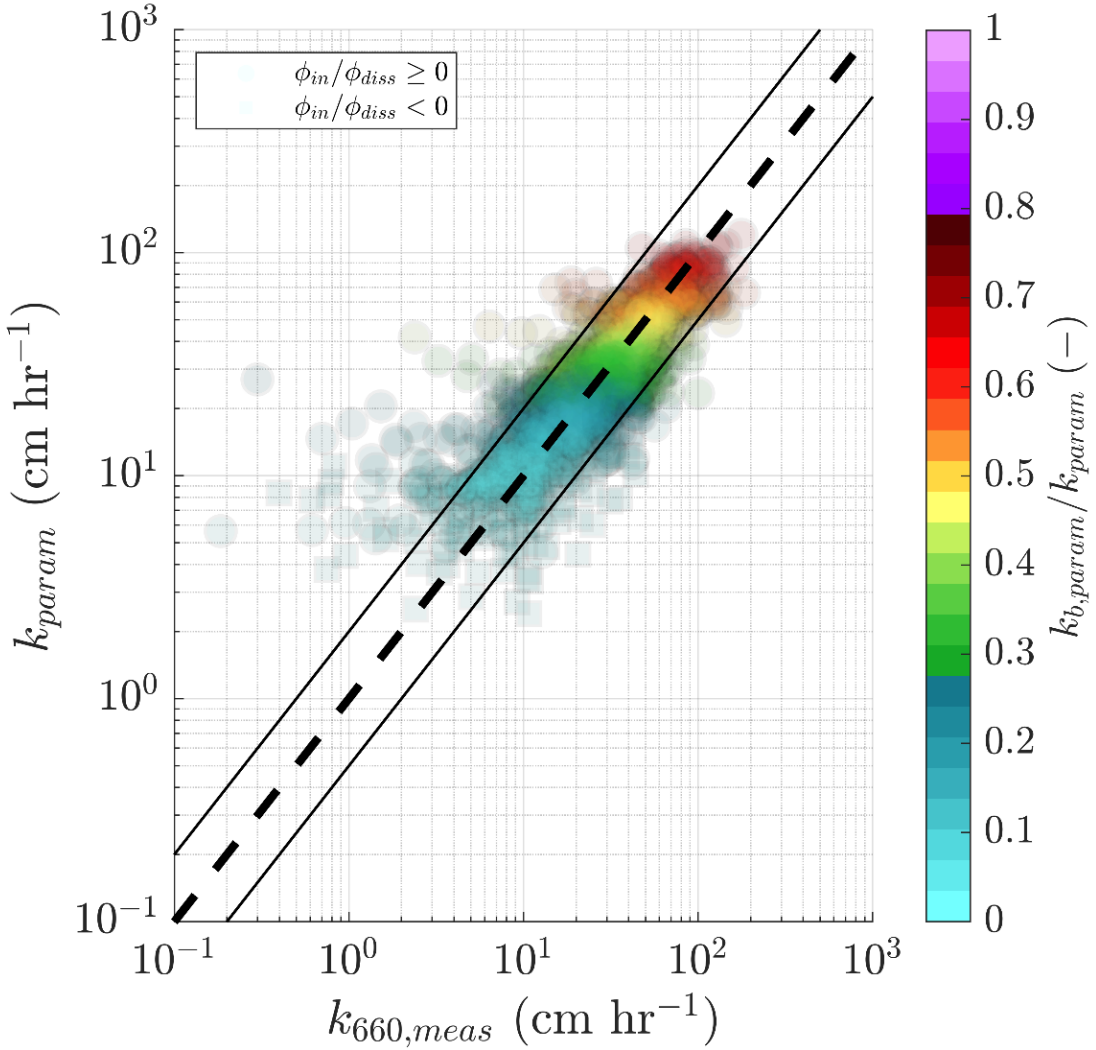
$$\dot{V}_{ss} = 2\alpha_{eff}\overline{\overline{w}}_{ent}W_{growth} \qquad \dot{V}_{ss} = 2\alpha_{eff}\overline{\overline{w}}_{ent}\left[\frac{W}{1+\delta^*}\right]$$

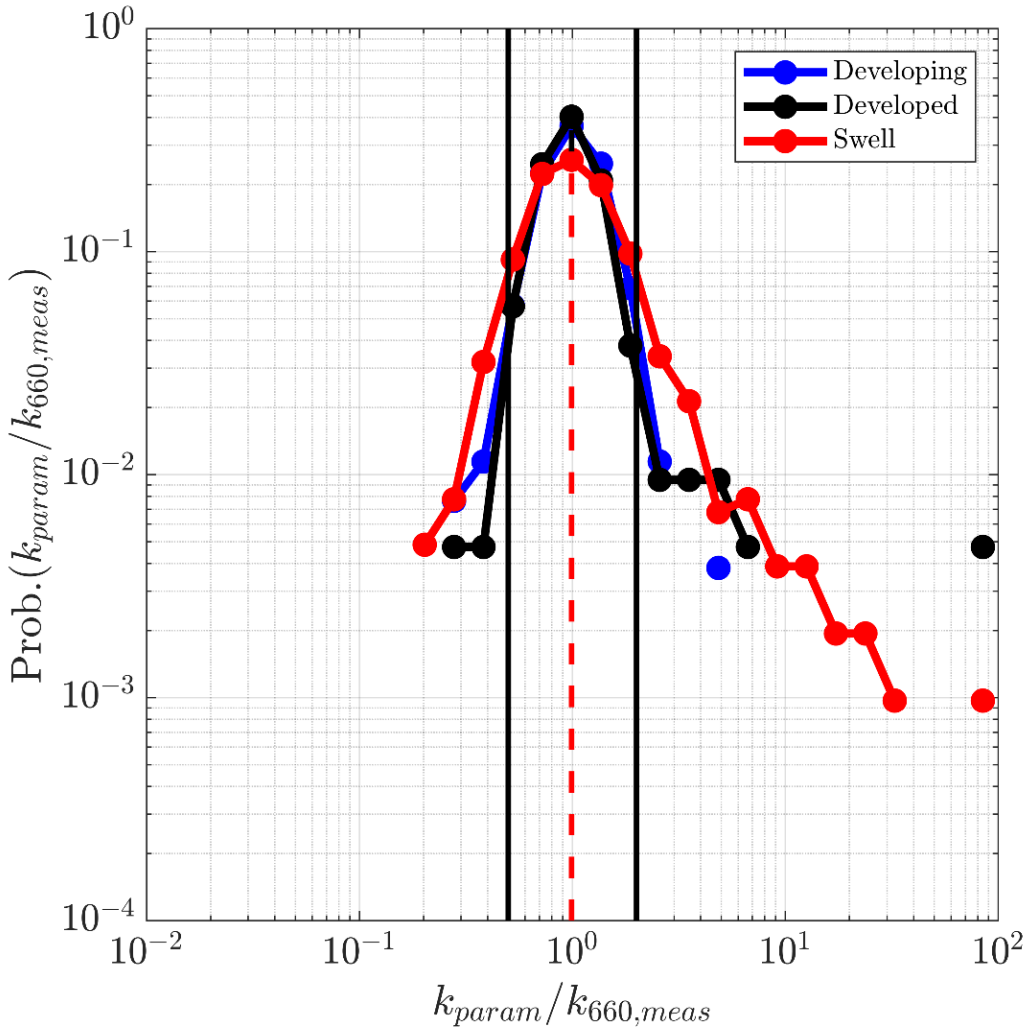




Callaghan, *GRL*, (*2024*)

Modelling CO_2 Gas Transfer Velocity (k) with ecWAM

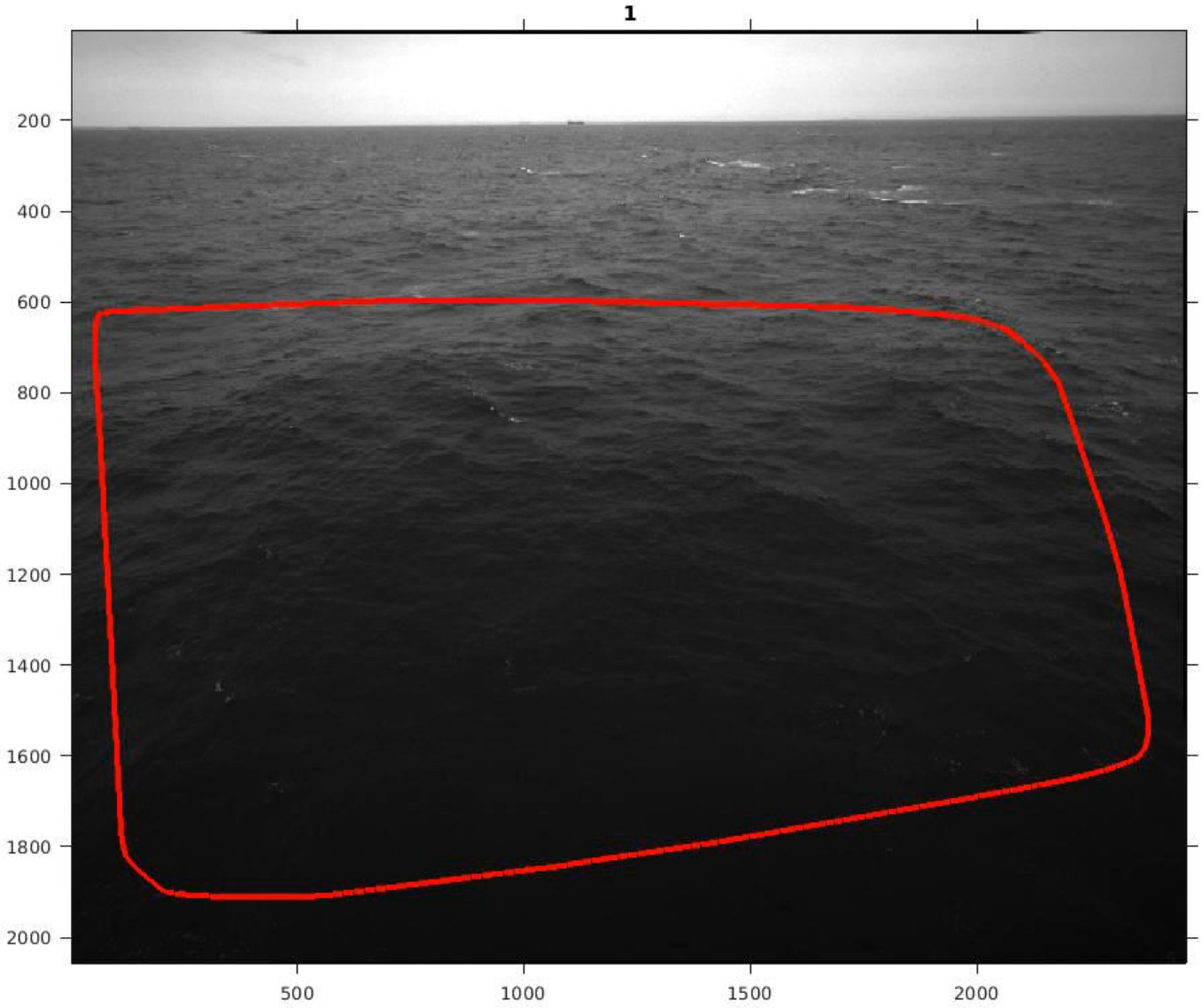




$$F_{CO_2} = k\,\Delta C$$

Smith et al., in prep.

Automated Whitecap Detection and Tracking (AWDAT)



- Collaborative effort between Imperial College London, ISMAR and Ca'Foscari University
- Individual whitecaps are detected, labelled and tracked in time and space.
- Enables statistical distributions of parameters for individual whitecaps to be generated.
- Can provide unprecedented detail on whitecap variability.
- Peach, Callaghan, Bergamasco, Benetazzo, Pistellato, Barbariol (*in prep.*), *A vision-based method for spatial and temporal tracking of individual whitecaps*.

Conclusions

- Breaking waves exert an important influence on weather and climate.
- Laboratory-derived results have demonstrated how whitecap foam evolution can be used to estimate energy dissipation by individual breaking waves.
- When applied to oceanic whitecaps, integrated results are in good agreement with measurements of whitecap coverage and other estimates of air-fluxes.
- ecWAM can reproduce estimates of W in good agreement with measurements.
- We have developed AWDAT to provide a detailed statistical description of very large populations of whitecaps.
- Further work will develop directional distributions of the rate of energy dissipated per unit sea surface area by whitecaps.