Modeling Air-Sea Gas Transfer Under Tropical Cyclone Conditions

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Introduction

- The gas transfer velocities for different gases converge under low wind speed conditions when normalized with the Schmidt number
- Substantial differences between various gases, except for relatively soluble gases like DMS, emerge under higher winds due to the contribution of the bubble-mediated gas transfer depending on the gas solubility
- Here, we use multiphase computational fluid dynamics (CFD) tools to gain an insight into gas transfer at the air-sea interface under tropical cyclone conditions

Sea Surface Under Tropical Cyclone Conditions

AOML Communications:
https://www.aoml.noaa.gov/news/hurricane-edouard/

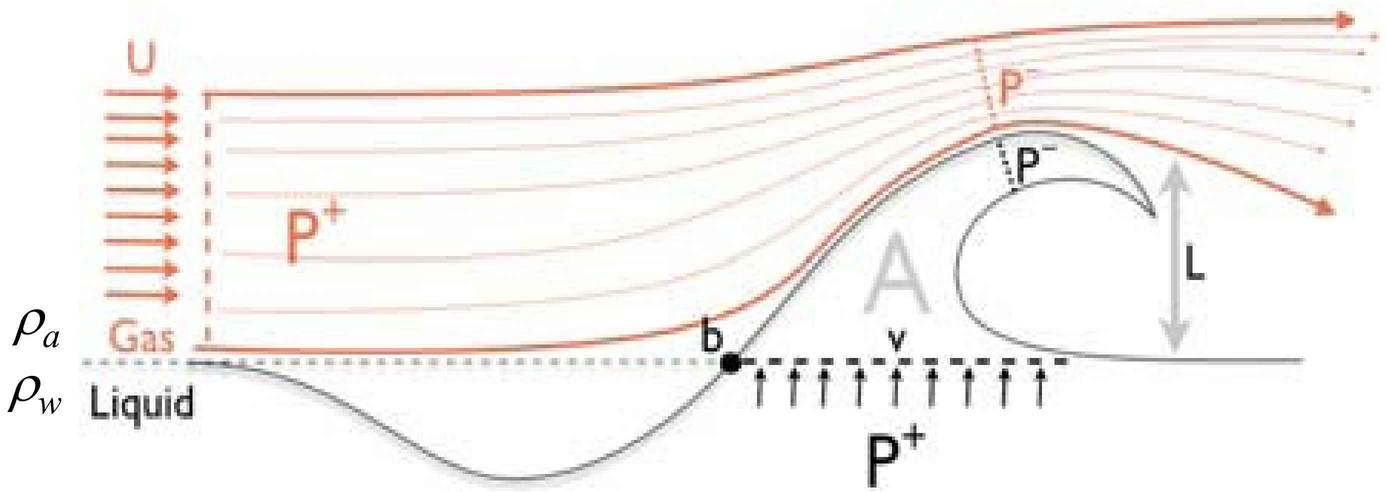
- “The whitecap coverage increases with wind but at very high wind speeds remains at a constant 4% level, while the white out coverage increases toward full saturation.” (Holthuijsen et al. 2012)
- The streaks on the photos cannot always be traced to whitecaps (breaking waves) and are a different process
- The white out material can be a result of the Kelvin-Helmholtz instability of the air-water interface in the presence of surface waves (Soloviev et al. 2017)

Quora

Direct Disruption of the Air-Sea Interface Under Tropical Cyclone Winds

- Koga (1981) and Soloviev and Lukas (2010) ascribed disruption of the air-sea interface under tropical cyclones to the Kelvin-Helmholtz (KH) instability
- There is analogy of the air-sea interface in very strong winds to the process of atomization in some engineering applications (fuel injection in combustion and rocket engines, food processing, inkjet printing, etc.)
- KH can take different forms like ‘fingers’, ‘sails’, ‘mushrooms’, etc.
- Here, we will follow engineering terminology and call the combination of all these modes as the KH type instability
- At the air-sea interface KH is additionally modulated by surface waves

Theoretical Consideration of KH Instability



Hoepffner, Blumenthal, and Zaleski (2011)

Acceleration of the air stream above a short wave induces a pressure drop:

$$\Delta P = P^{+} - P^{-} \sim \rho_a U^2 k L. \qquad (1)$$

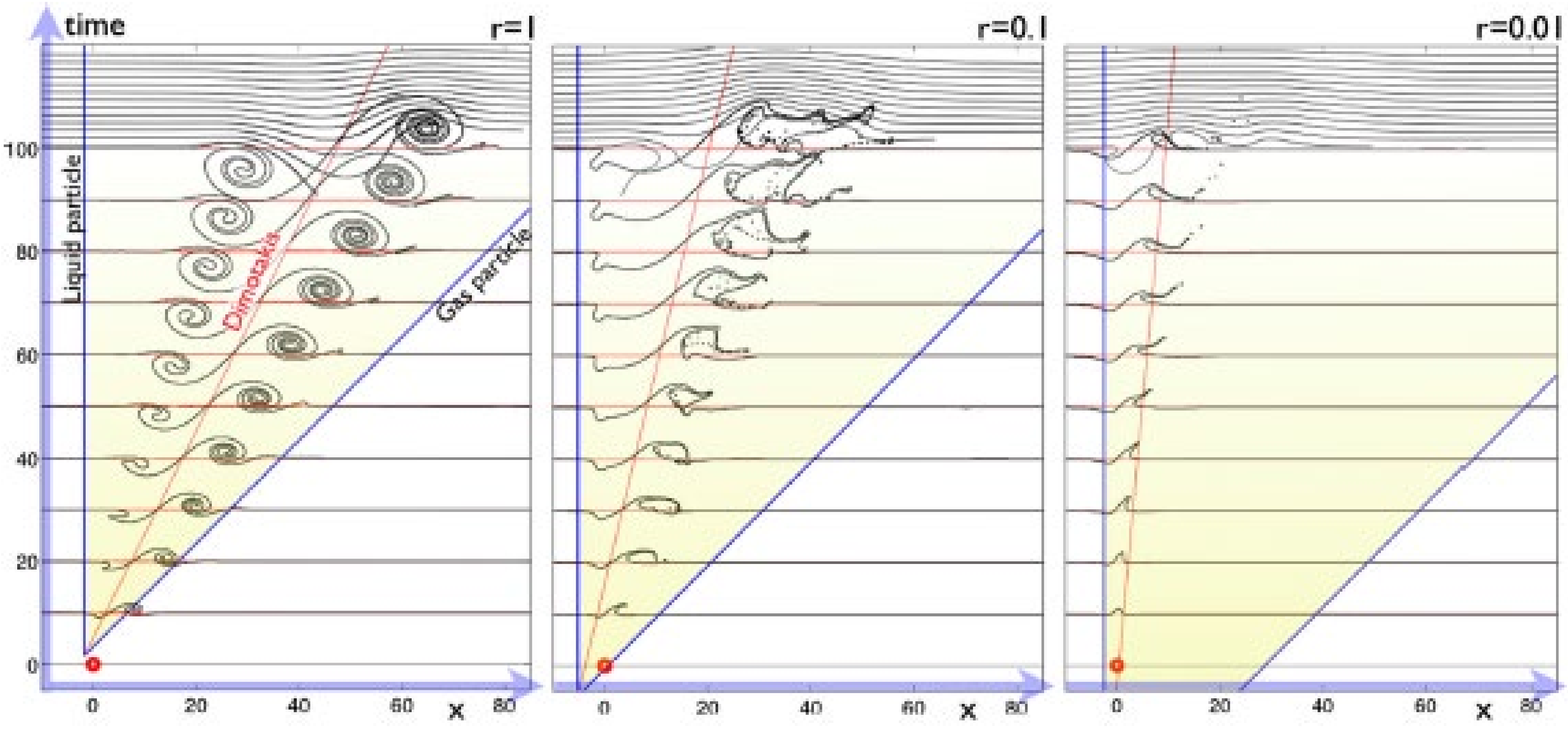
The instability breaks up the interface if ΔP exceeds the combined restoring force of gravity and surface tension:

$$\Delta P > (\rho_w g + \sigma_s k^2) L \qquad (2)$$

σ_s the surface tension, k the wavenumber.

Inequality (2) is satisfied for U_{10} > 30-35 m/s, which curiously coincides with transition to hurricanes.

KH Wave at an Interface with Large Density Difference Evolves in a Strongly Asymmetrical Structure with All Action on the Gas Side (Hopfner et al. 2011))

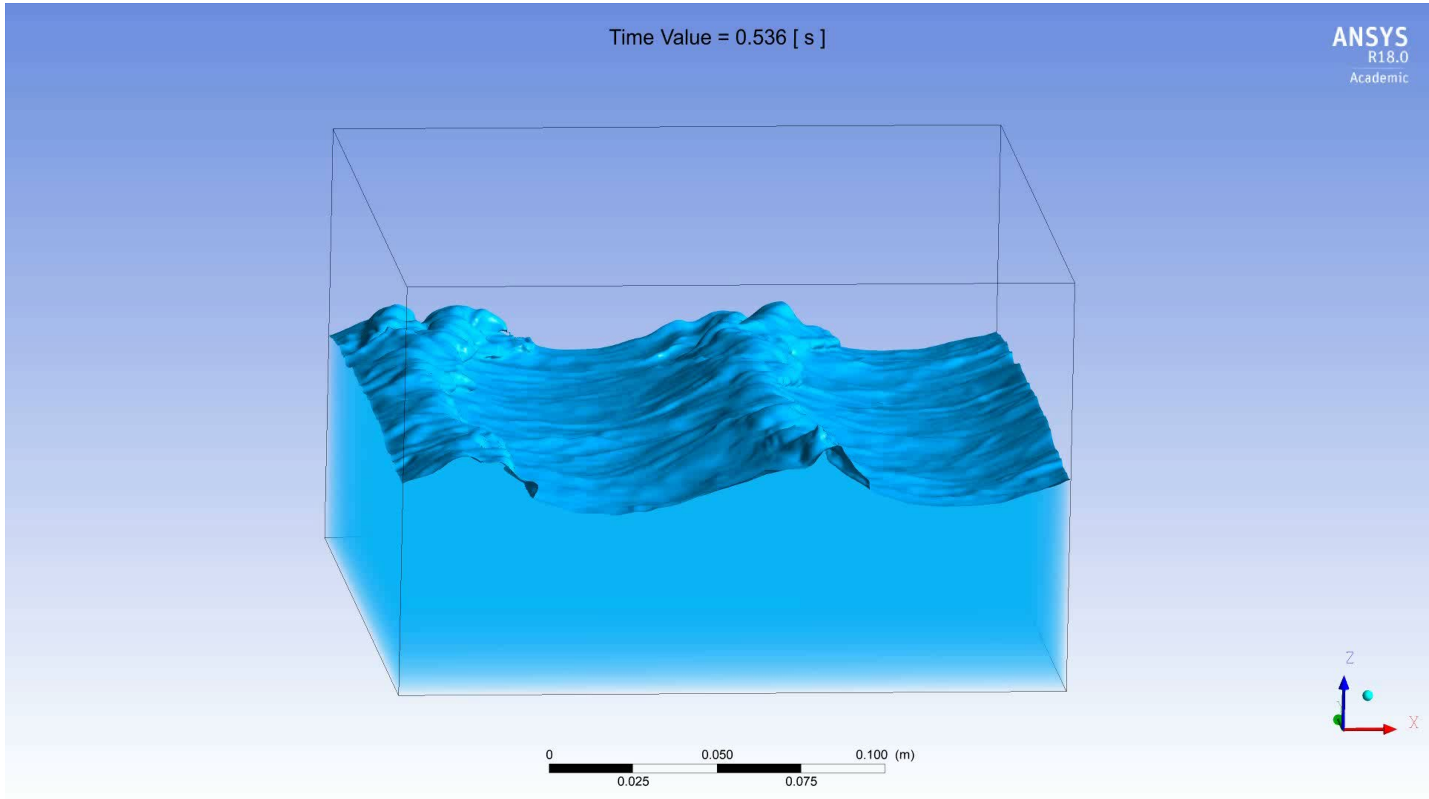


r = ρ_{gas}/ρ_{liquid}

Multiphase Computational Fluid Dynamics Model

- Wind stress of 4 Nm^{-2}, 10 Nm^{-2}, or 20 Nm^{-2} at the top of the domain to model Cat 1, 3, or 5 tropical cyclones, respectively
- Normal surface tension - 0.072 N/m
- Periodic boundary conditions

τ = 20 N m^{-2}

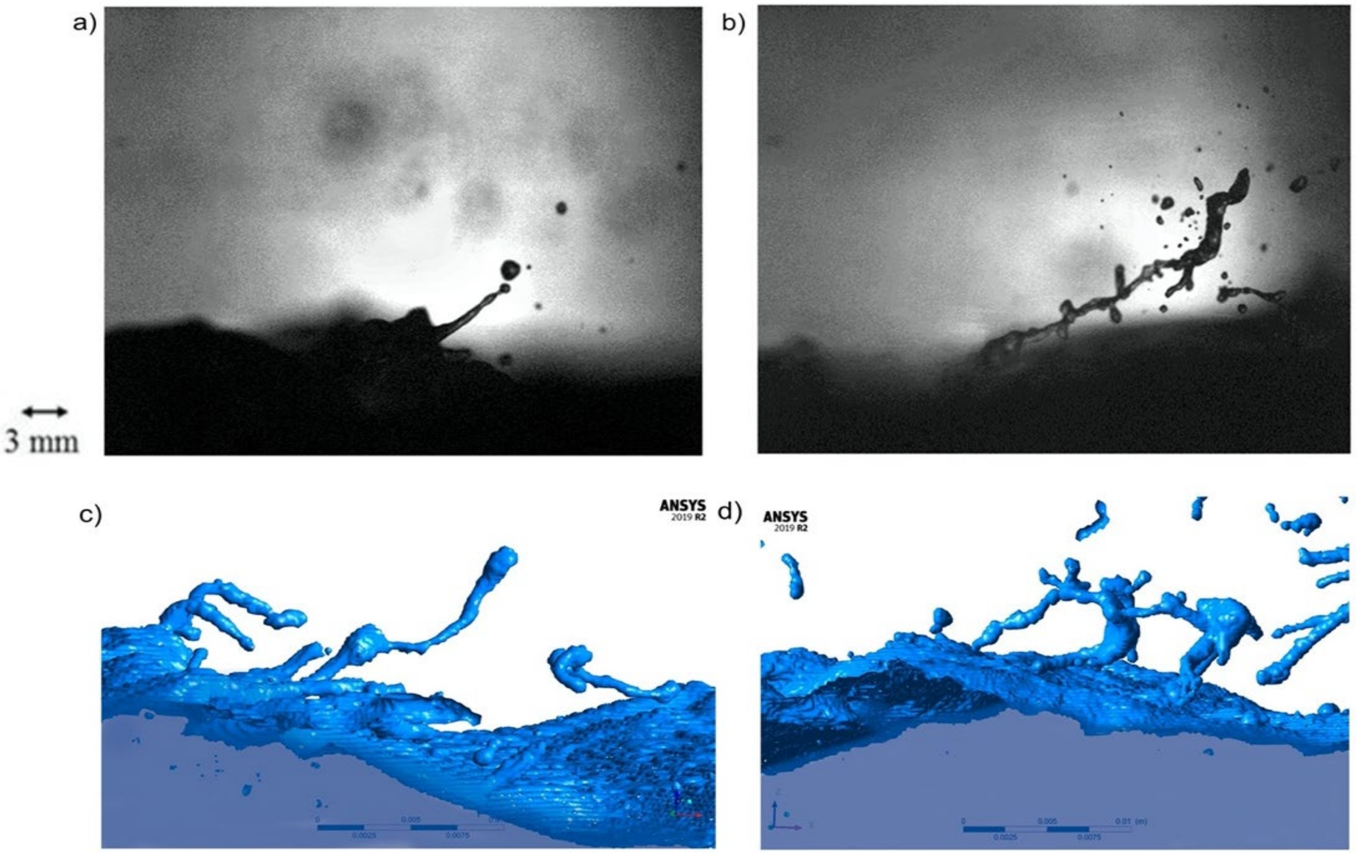


Asymmetry of the KH Instability at the Air-Water Interface Under Tropical Cyclone Winds

Clean surface | **Surfactants**

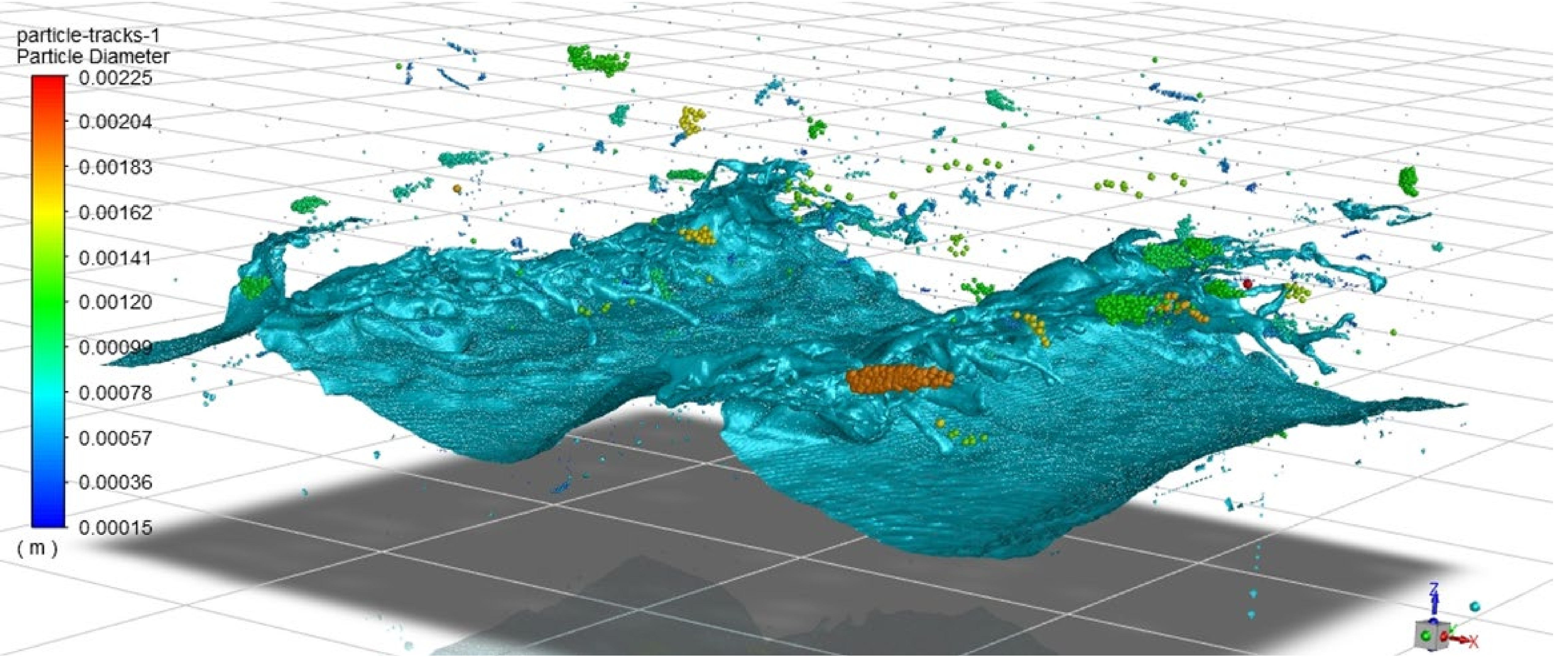
Laboratory (SUSTAIN)

Multiphase CFD model



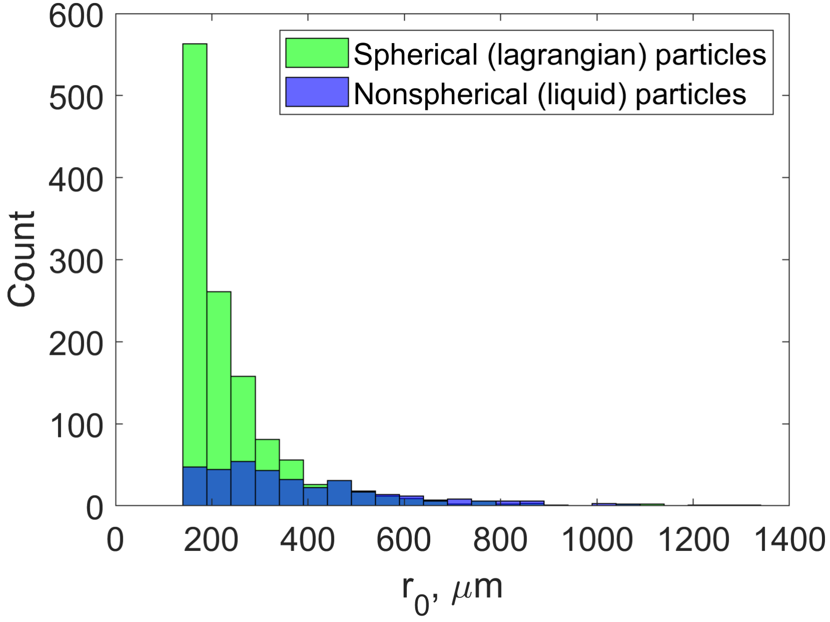
(a, c) No surfactant – finger-like structures formed
(b, d) Surfactants – branch-like structure formed (see Vanderplow et al. 2020)

Volume of Fluid to Discrete Phase Method (VOF to DPM) with Mesh Adaptation

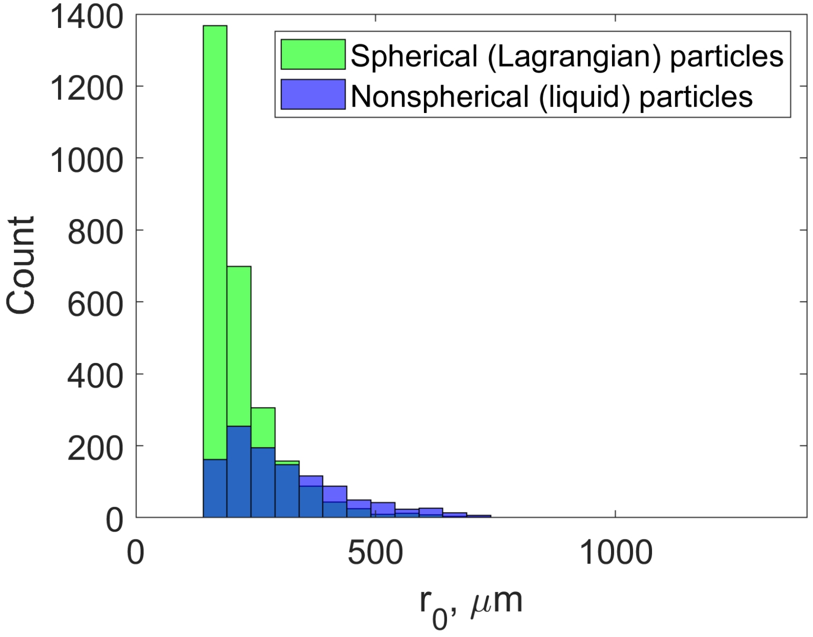


Spherical and Nonspherical Spume Particles

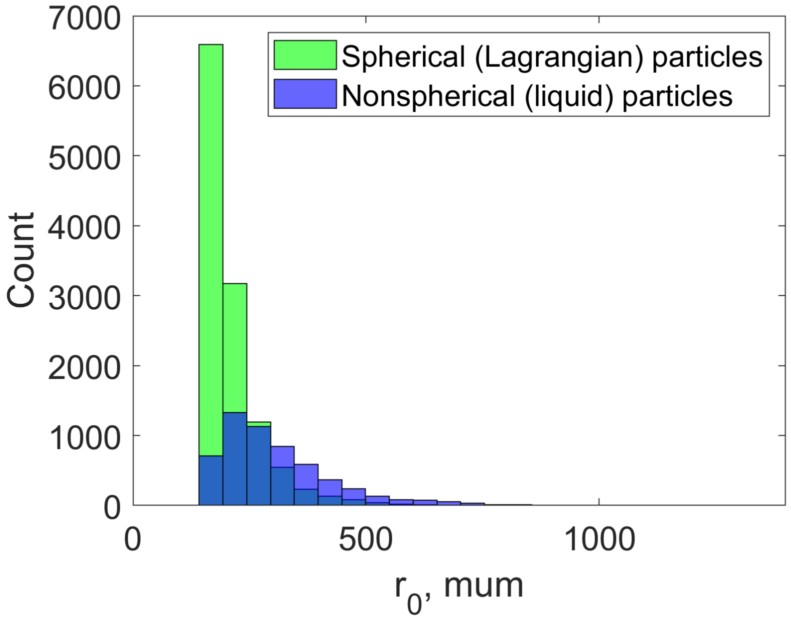
Category 1



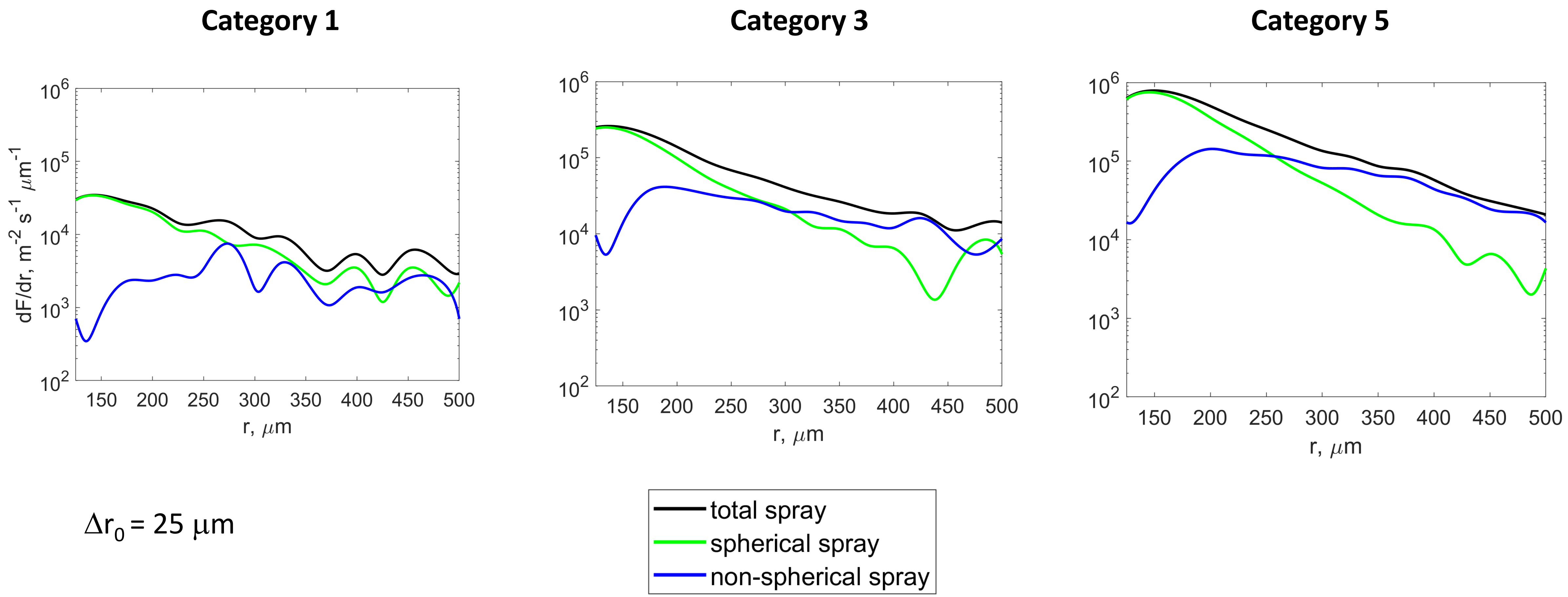
Category 3



Category 5

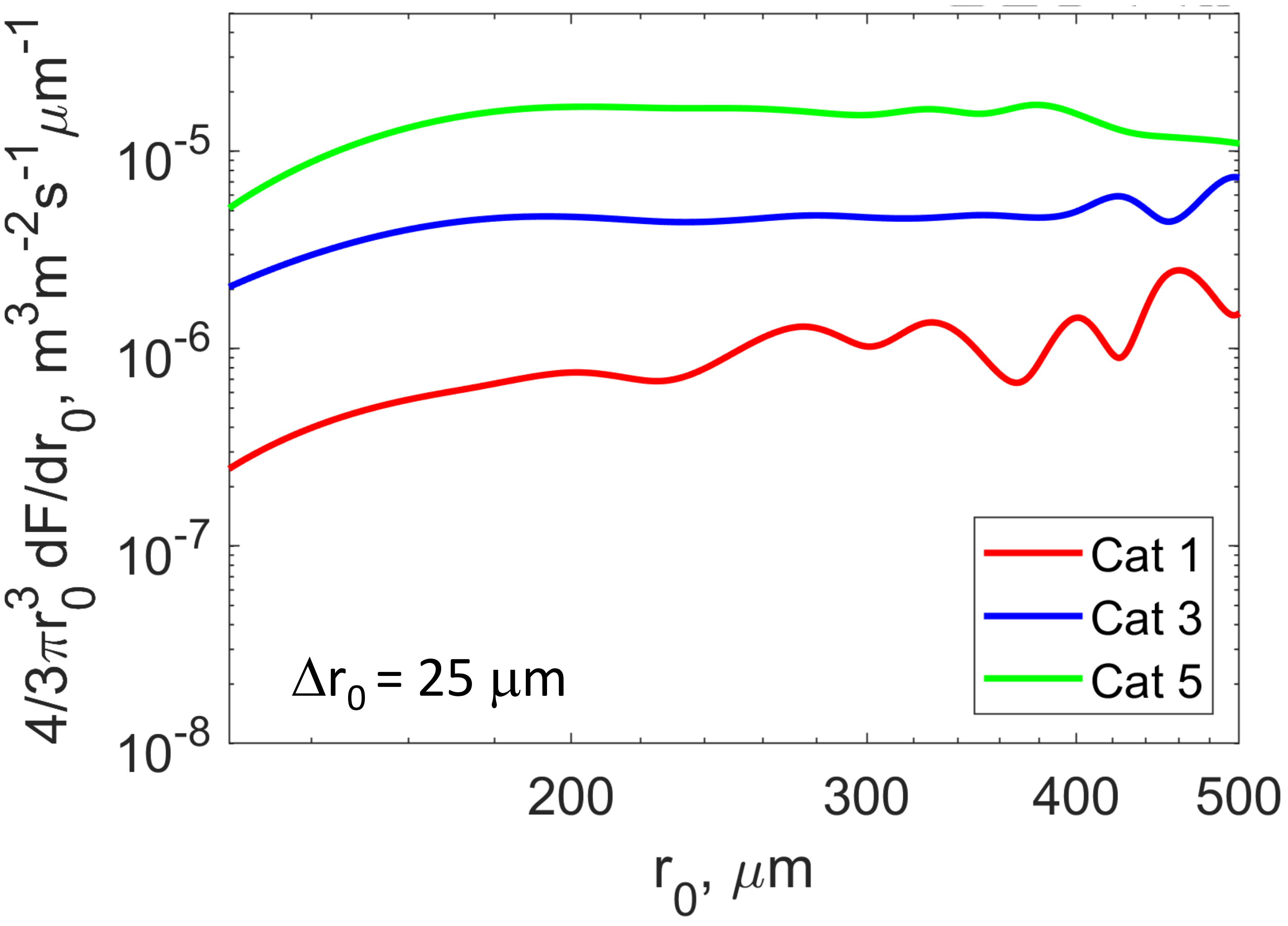


Spherical and Nonspherical Components of the Sea Spray Generation Function

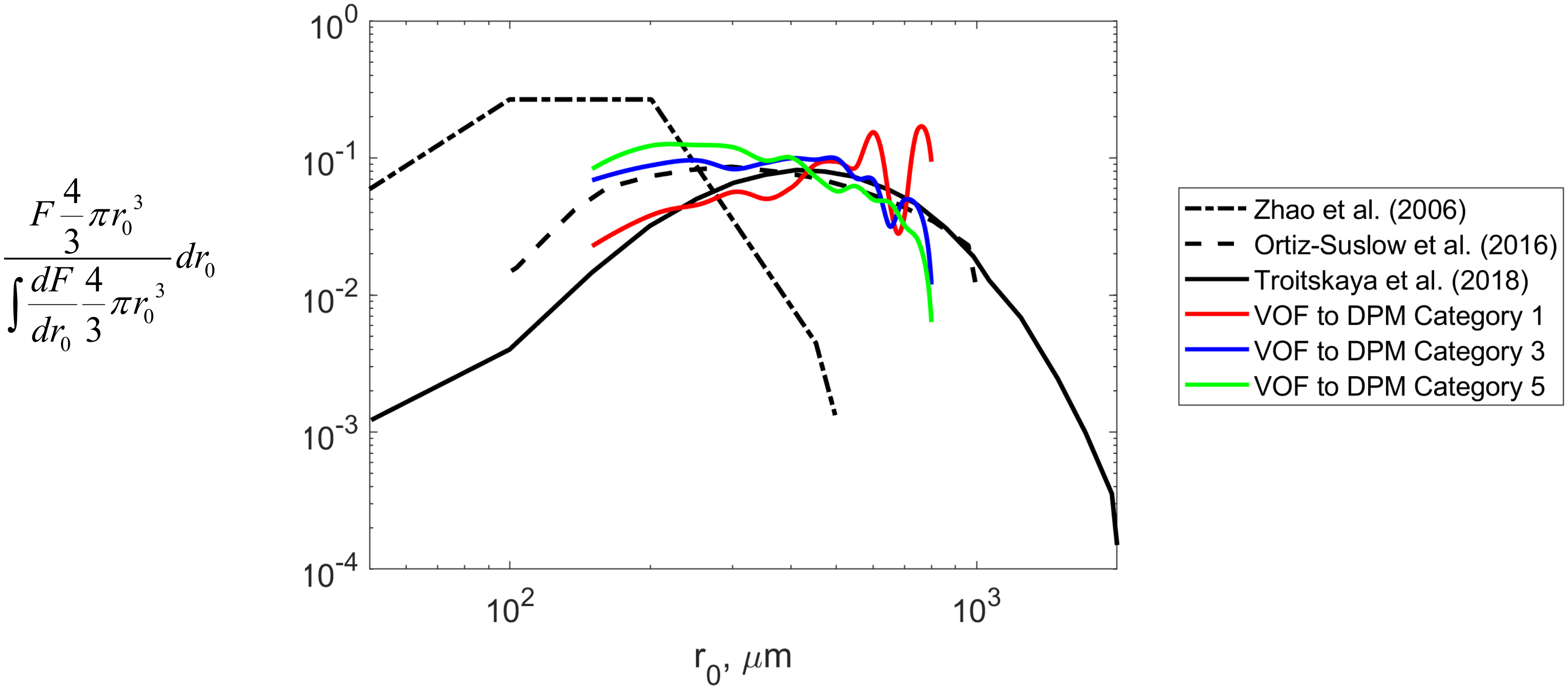


$\Delta r_0 = 25\ \mu m$

Sea Spray Generation Function in Terms of Volume Flux for Category 1, 3, and 5 Tropical Cyclones



Sea Spray Generation Function in Terms of Volume Flux for Tropical Cyclone Conditions

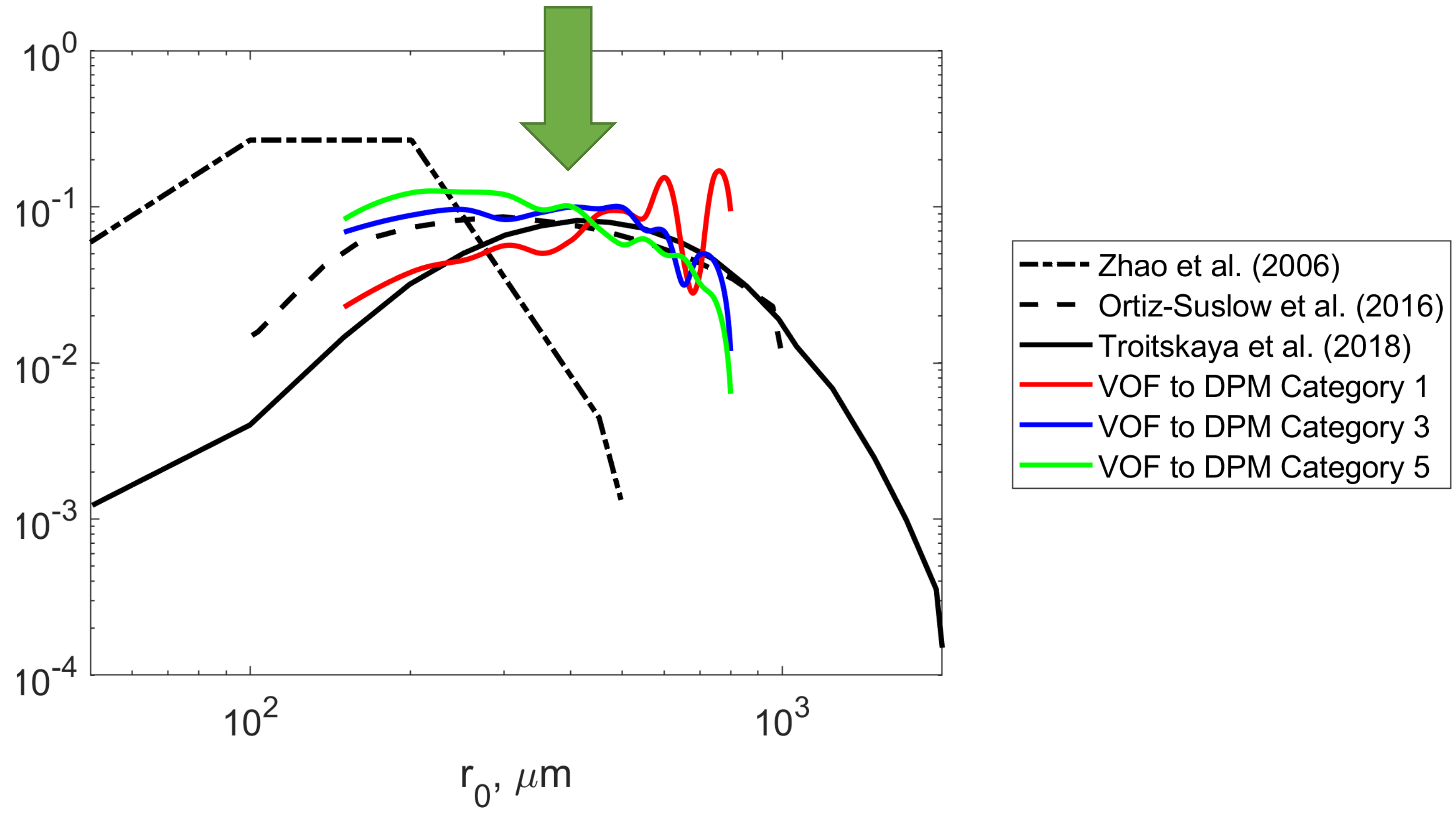


Multiphase SSGF superimposed on Sroka’s and Emanuel (2022) Figure 3.

Sea Spray Generation Function in Terms of Volume Flux for Tropical Cyclone Conditions

Peak spray contribution to momentum and energy flux around r_0 ~ 500 μm

$$\frac{F\frac{4}{3}\pi r_0^3}{\int \frac{dF}{dr_0}\frac{4}{3}\pi r_0^3} dr_0$$



Multiphase SSGF superimposed on Sroka's and Emanuel (2022) Figure 3.

Time-Scale of Gas Equilibration in Sea Spray Drops

following Andreas, Vlahos, and Monahan (2017)

For non-reactive gases, sea spray gas diffusion includes:

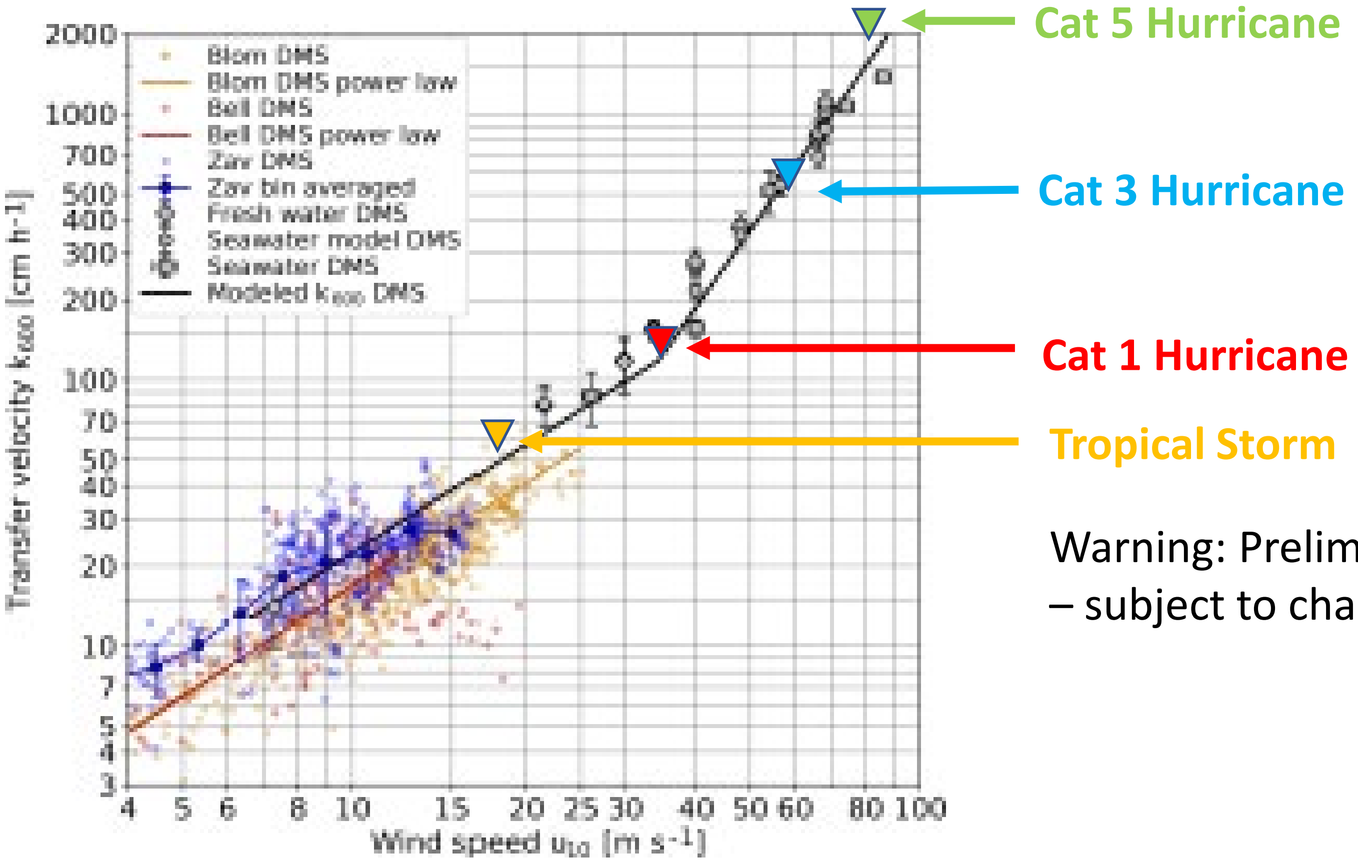
- diffusion between the deep interior of the droplet and its interior surface - largest time-scale (t_{aq})
- diffusion across the air-droplet interface
- diffusion between the air-side boundary layer and the bulk atmosphere

Tennekes and Lumley (1972) and Andreas et al. (2017): "…**fluid motion within the droplets could increase the effective gas diffusivity by several orders of magnitude**"

Spray drop radius r_0 (μm)	Terminal* velocity u_f (m s^{-1})	Surface motion in spray drop v_s (m s^{-1})	Effective gas diffusivity $r_0 v_s$ (m^{2}s^{-1})	Spray drop gas time scale t_{aq} (s)	Spray drop residence time t_f (s)	Ratio t_{aq}/t_f
50	0.254	3.1×10^{-3}	1.9×10^{-7}			
100	0.725	0.012	1.2×10^{-6}	0.0008	0.2069	**0.41%**
200	1.67	0.030	1.0×10^{-5}	0.0004	0.0898	**0.45%**
500	4.10	0.16	8×10^{-5}	0.0003	0.0366	**0.87%**

* For significant wave height = 0.3 m

VOF to DPM Multiphase Model Compared to Krall's (2019) Transfer Velocities of DMS at Kyoto and SUSTAIN Facilities



Warning: Preliminary results – subject to change

Computational transfer velocities of DMS superimposed on Krall's et al. (2019) Figure 10.

Conclusions

- The gas transfer velocities from our model are close the Krall et al. (2019) laboratory results for tropical cyclone winds
- The Kelvin-Helmholtz (KH) instability at the air-water interface, covering almost all sea surface under tropical cyclone conditions, is strongly asymmetrical, with most action on the air side of the interface
- KH mostly generates spume with less air bubbles, potentially reducing the effect of gas solubility
- The model can include the effect of surface tension on sea spray generation (Vanderplow et al. 2020) - implementation of surfactant effects on gas exchange under tropical cyclone conditions is under way

Acknowledgements:

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Thank you!