Modeling bubble mediated gas transfer by breaking waves

Luc Deike

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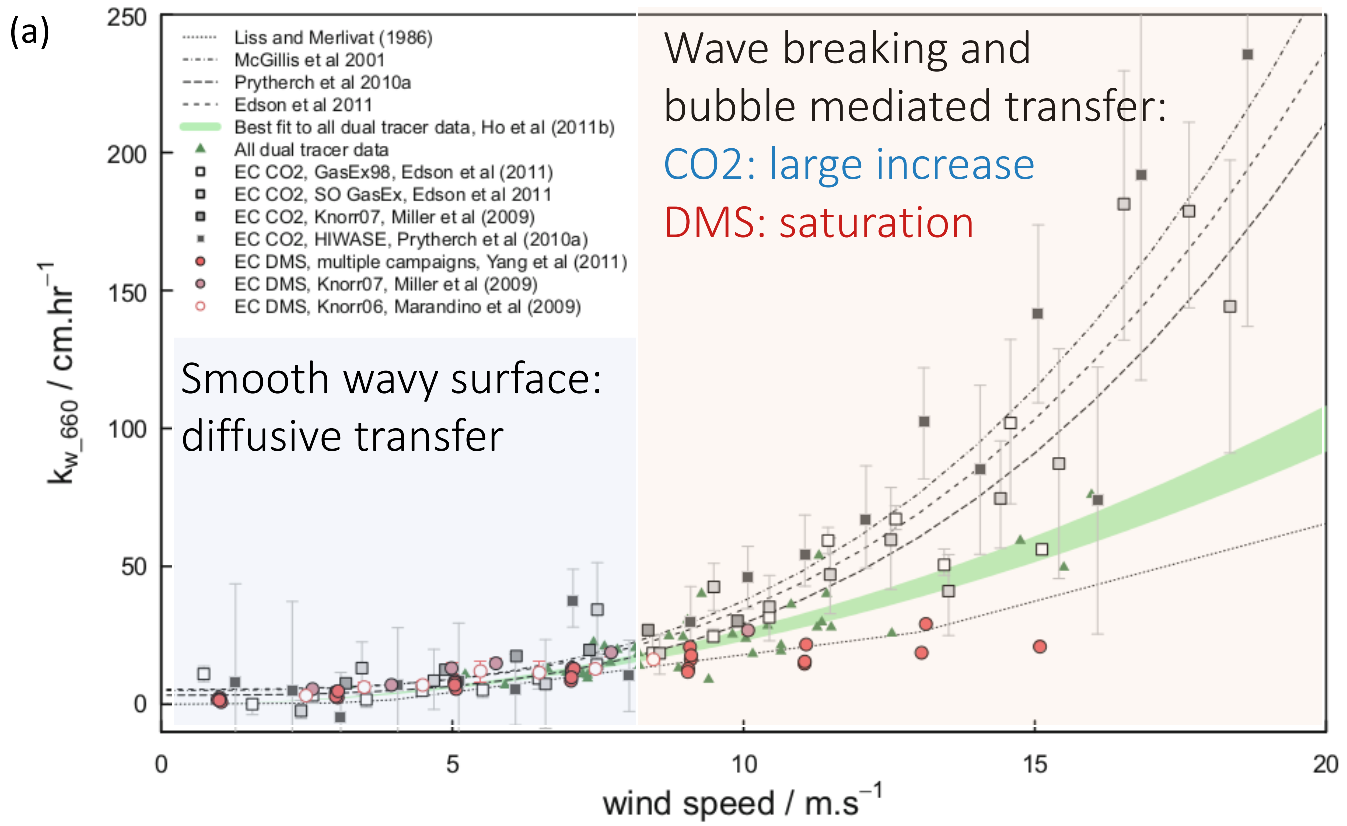
With W. Mostert, P. Kumar Farsoiya, D. Ruth, A. Riviere, S. Perrard, J. Wu,

B. Reichl[2] ([2] NOAA GFDL), S. Popinet[3] ([3] Sorbonne University).

Field measurement of the gas transfer velocity



- - Various parameterizations

$$k_w \propto Sc^{-n} U_{10}^{m}$$

$$m \approx 2$$

Garbe et al 2014
Brumer et al 2017
Bell et al 2017

Wind speed is not enough to describe the transfer of gas

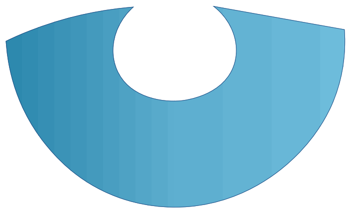
How can we incorporate the role of breaking and associated bubbles in gas transfer estimations?

A multi-scale approach for ocean-atmosphere interaction

O(1m-10km)

O(1mm-10m)

O(1μm-10mm)



L. Deike, Ann. Rev. Fluid Mech. 2022.

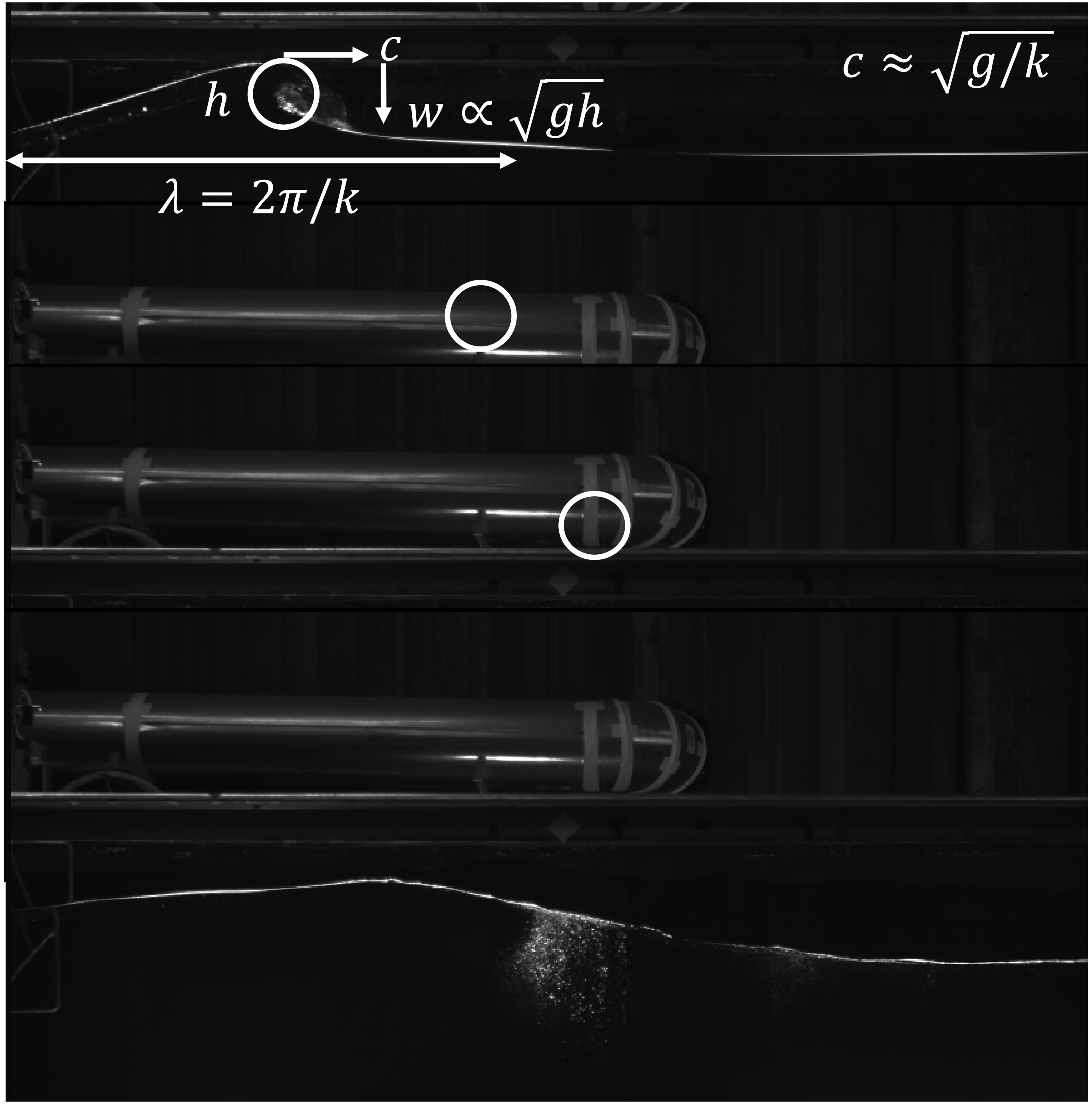
The scales of breaking waves

Laboratory experiments by W.K. Melville; J. Duncan; M. Banner, M. Perlin, etc…

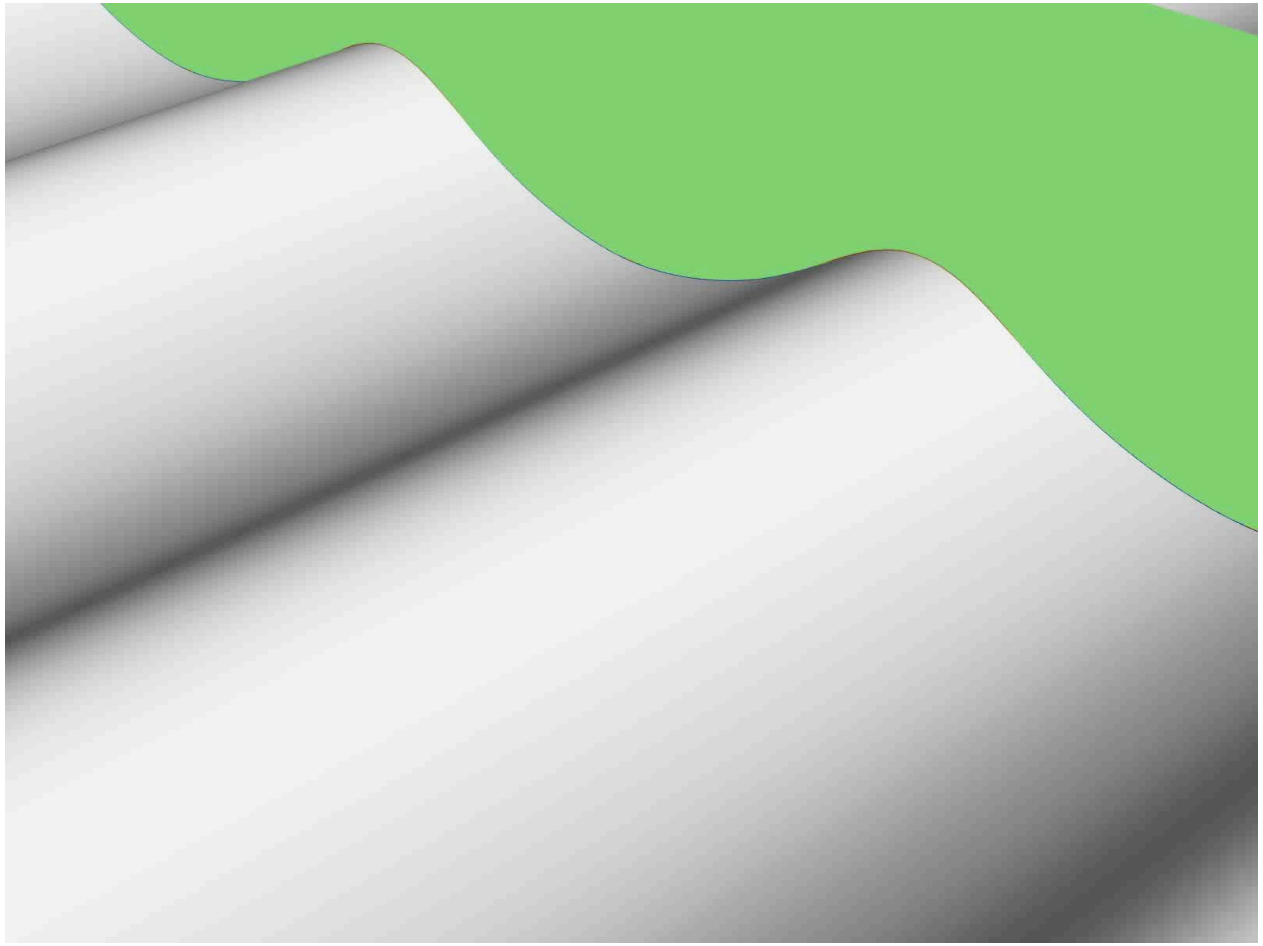
Energy dissipation rate by breaking: (Drazen et al 2008, Romero et al 2012, Deike et al 2015, 2016)

$$\varepsilon \propto \frac{w^3}{h}$$

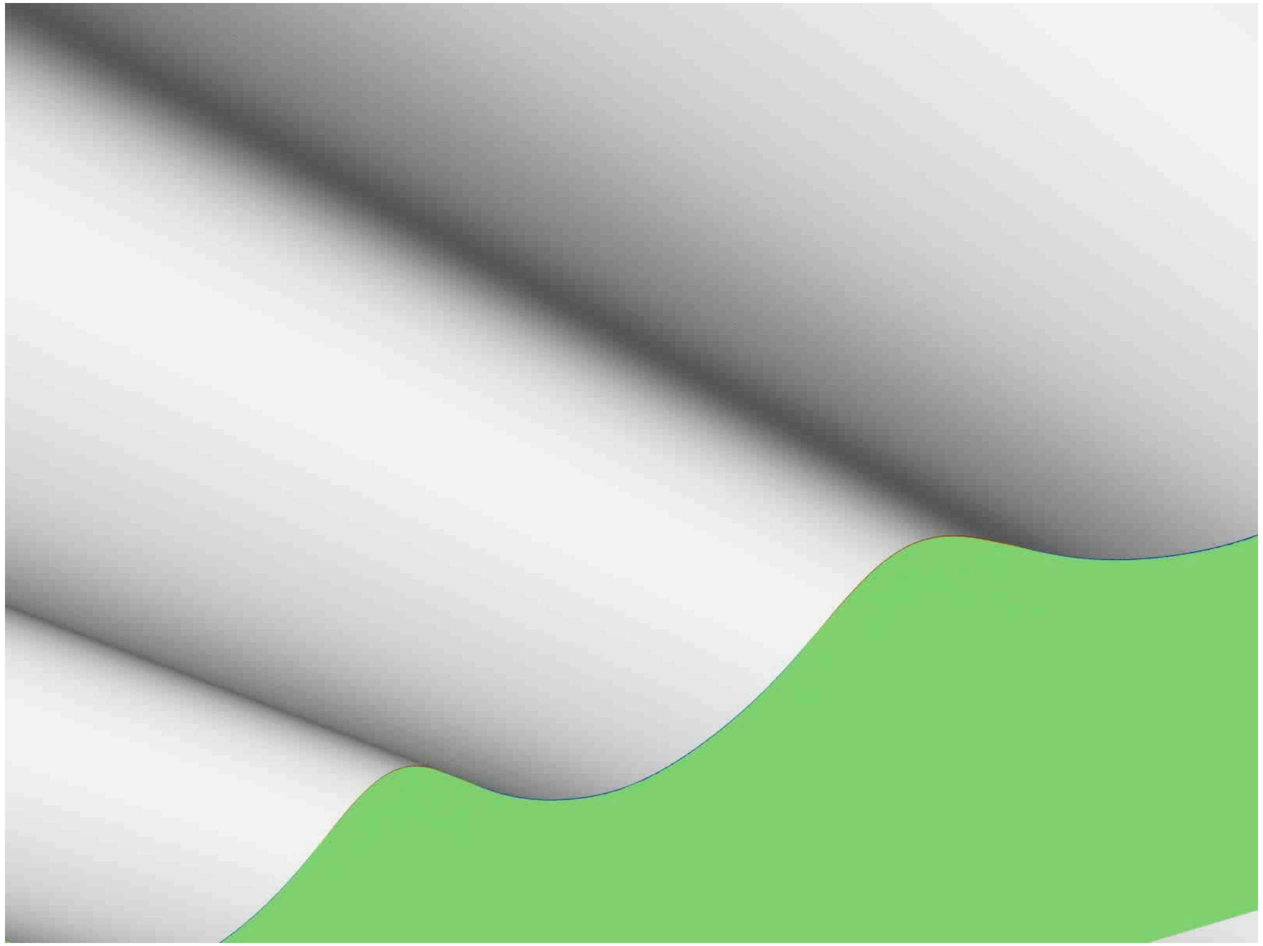
$$\epsilon_l \propto \frac{\rho}{g}(hk)^{5/2}c^5$$



Direct Numerical Simulations of breaking waves (DNS)



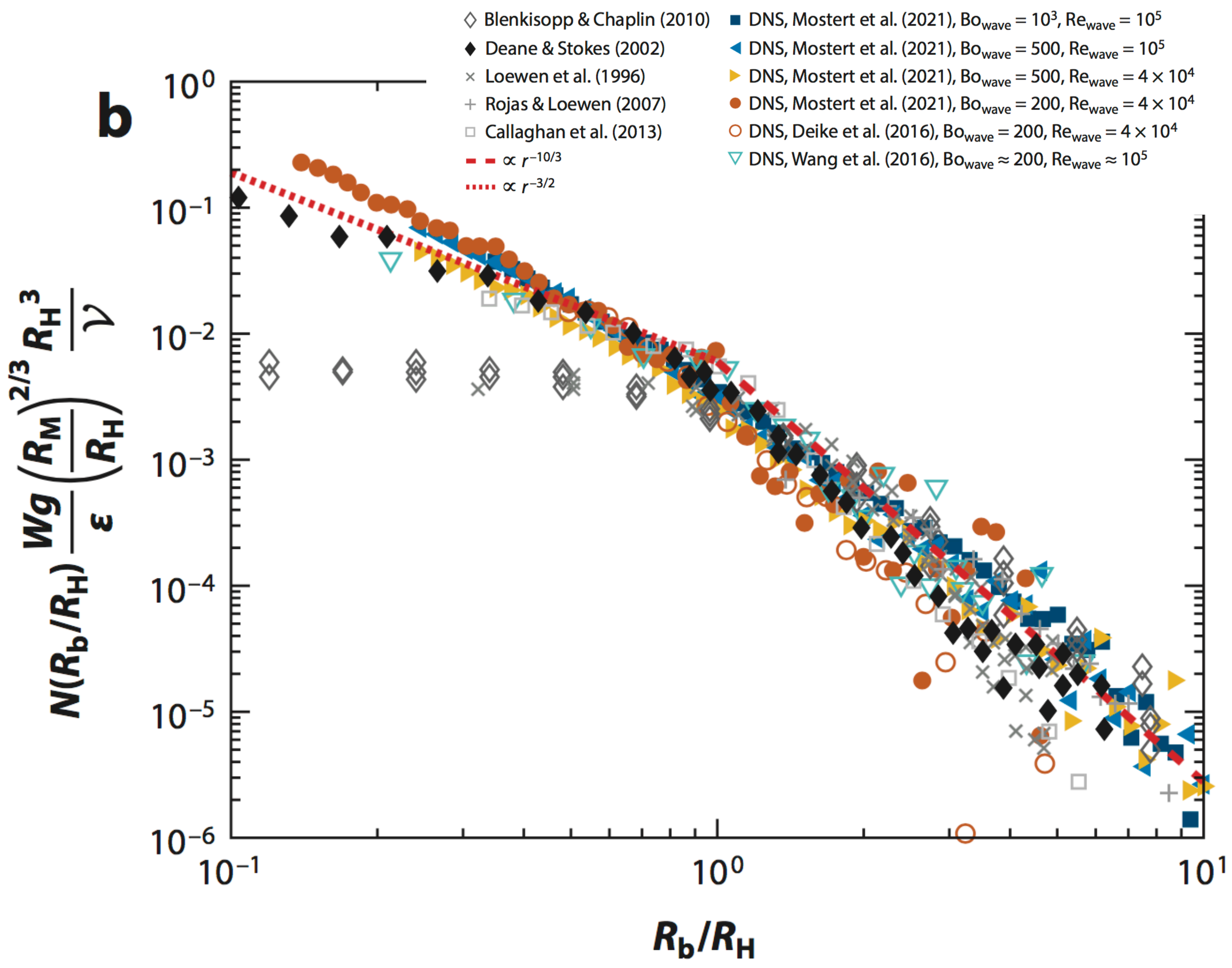
Basilisk Flow Solver Open source (S. Popinet) http://basilisk.fr



Deike, Melville and Popinet 2016,
Mostert, Popinet and Deike, 2022

Air entrainment, drops and bubble statistics

Bubble size distribution under a breaking wave



$100\mu m$ $1mm$ $10mm$

<u>Above the Hinze scale:</u>

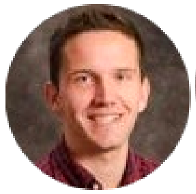
Inertial turbulent break-up *(Garrett et al 2000)*

$$n(R_b) \sim R_b^{-10/3}$$

<u>Below the Hinze scale</u>

- break-up of large bubbles and driven by capillary break-up of elongated filaments

$$n(R_b) \sim R_b^{-3/2}$$



See Mostert, Popinet and Deike 2022,
Ruth et al, in review,
Riviere et al, in review
And Dan Ruth's talk yesterday

A multi-scale approach for ocean-atmosphere interaction

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O(1mm-10m)

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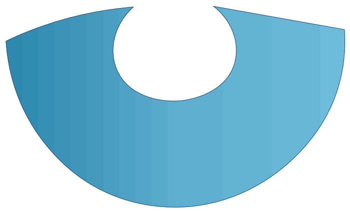


L. Deike, Ann. Rev. Fluid Mech. 2022.

Mass (gas) transfer of an individual bubble in a turbulent flow

Higbie' 1938 eddy renewal theory: $k_L \propto \sqrt{\frac{D}{\theta}}$

For a bubble/interface in a turbulent flow: $\theta \propto \frac{\eta_K}{u'_k}$

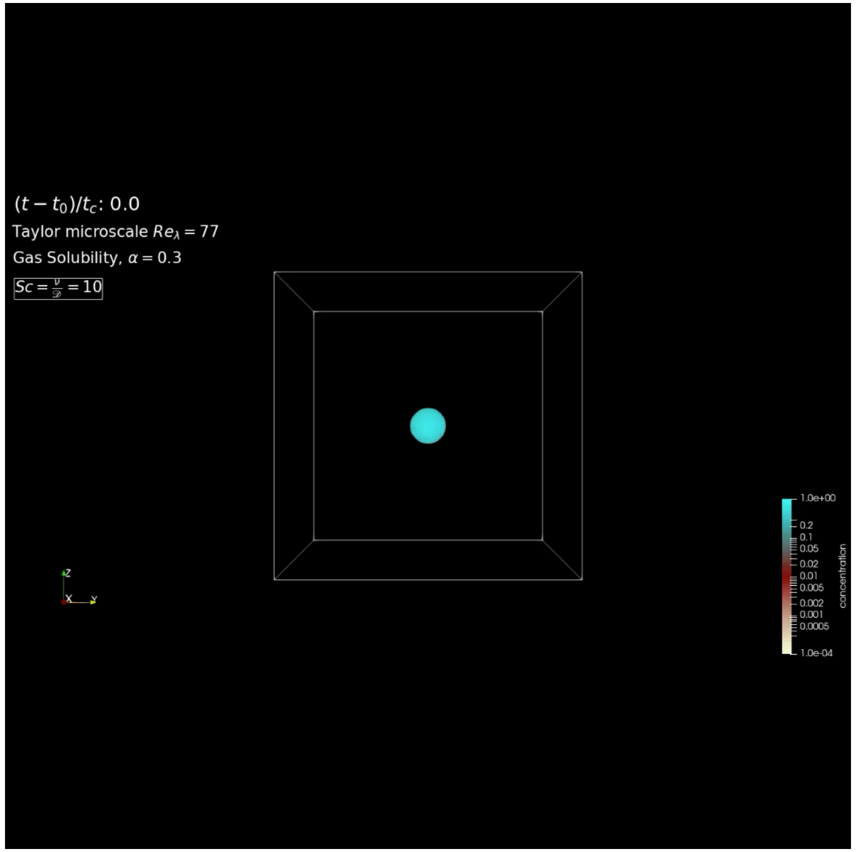
The transfer rate then reads:

$$k_L \propto \mathrm{Sc}^{-1/2}(\varepsilon\nu)^{1/4}$$

In non dimensional form

$$\mathrm{ShSc}^{1/2} \propto \mathrm{Re}^{3/4}$$

(see also Lamont and Scott 1970)



Kumar Farsoiya, Popinet and Deike, J. Fluid Mech. 2021
Kumar Farsoiya, Popinet and Deike, 2022, submitted

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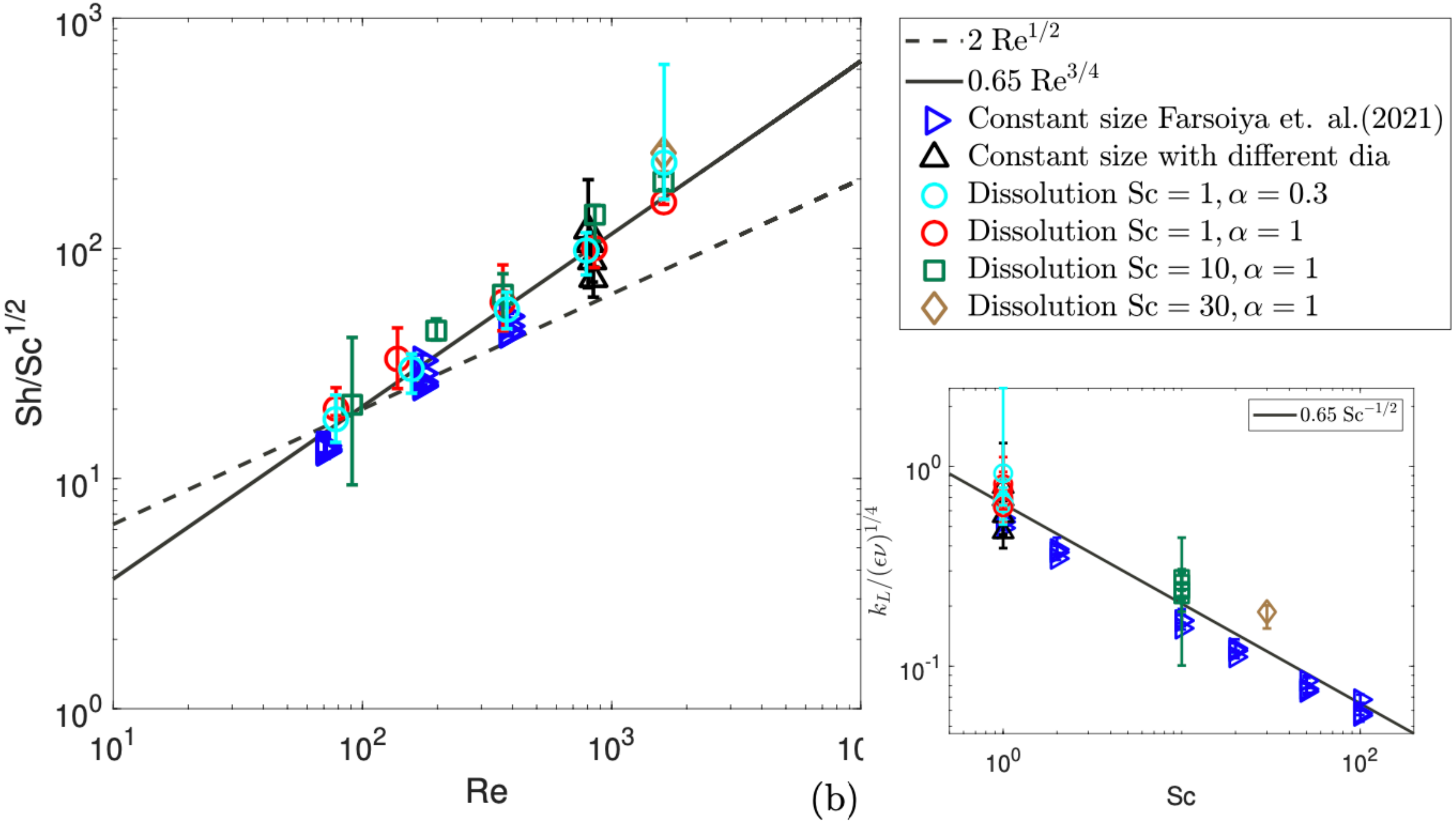

$$Sh/Sc^{1/2} \propto Re^{3/4}$$

$$k_L \propto Sc^{-1/2}(\varepsilon\nu)^{1/4}$$

Same high Re regime as Herlina (Monday's talk)

Kumar Farsoiya, Popinet and Deike, J. Fluid Mech. 2021
Kumar Farsoiya, Popinet and Deike, 2022, submitted

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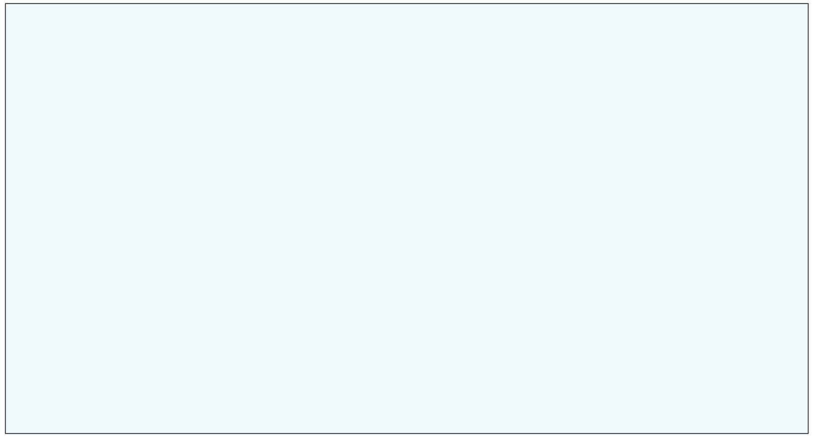

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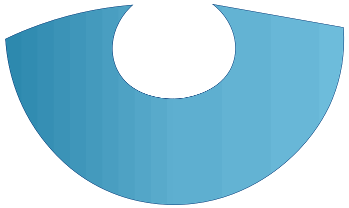
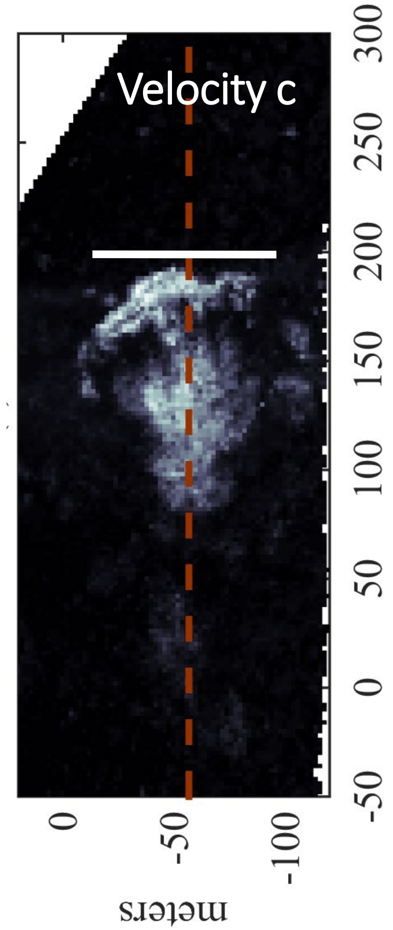


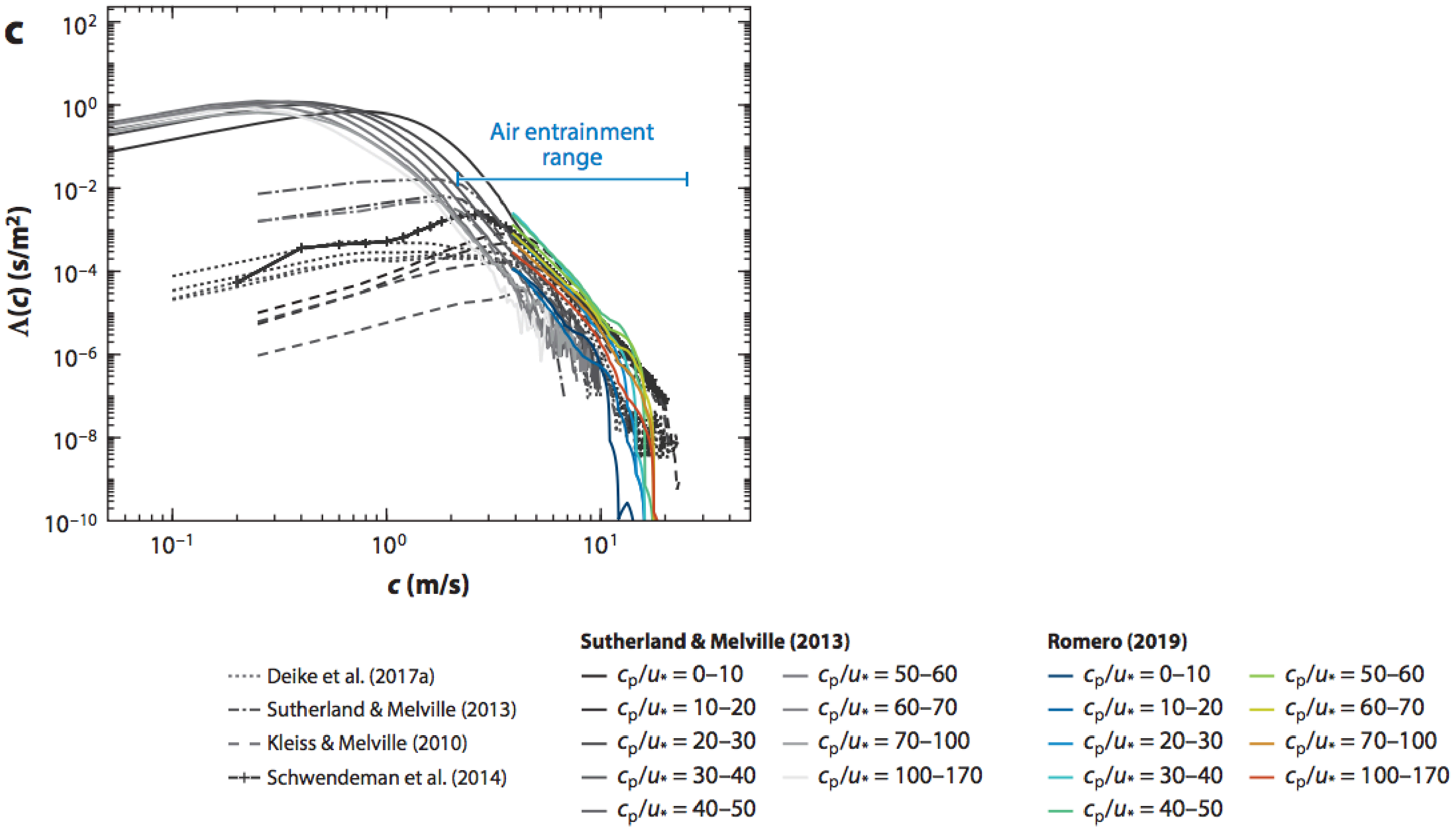
L. Deike, Ann. Rev. Fluid Mech. 2022.

Breaking wave distribution of length of breaking crest

Breaking and air entrainment statistics
Visible video: detect and measure the length of breaking crest **Λ(c),** moving at speed **c** and the associated breaking slope **S=hk** (via the wave spectrum) which control air entrainment (Phillips 1985, Melville et al 2016, Deike et al 2017)



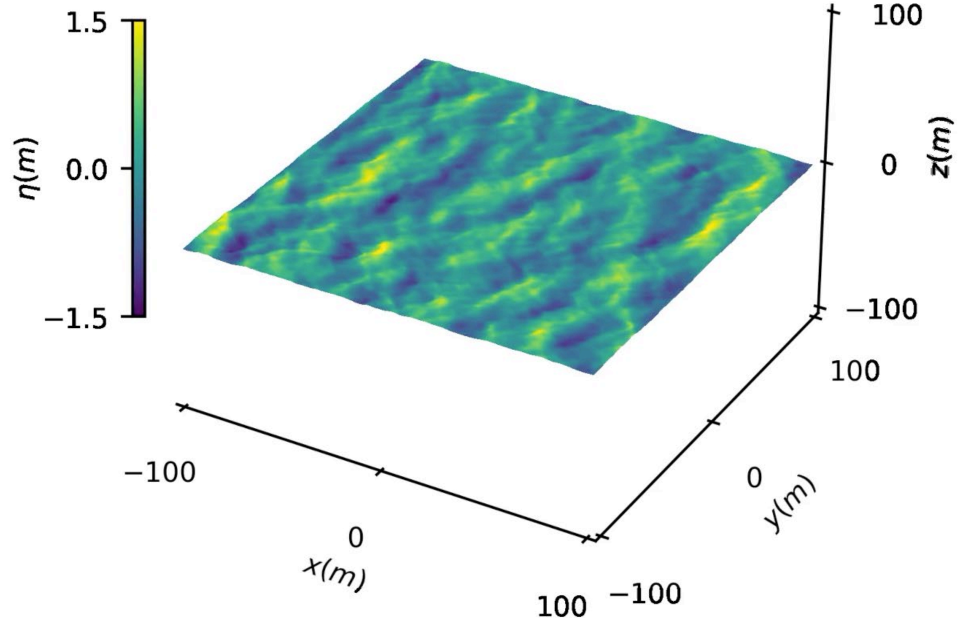
Airborne measurement of breaking waves, Melville et al 2016.

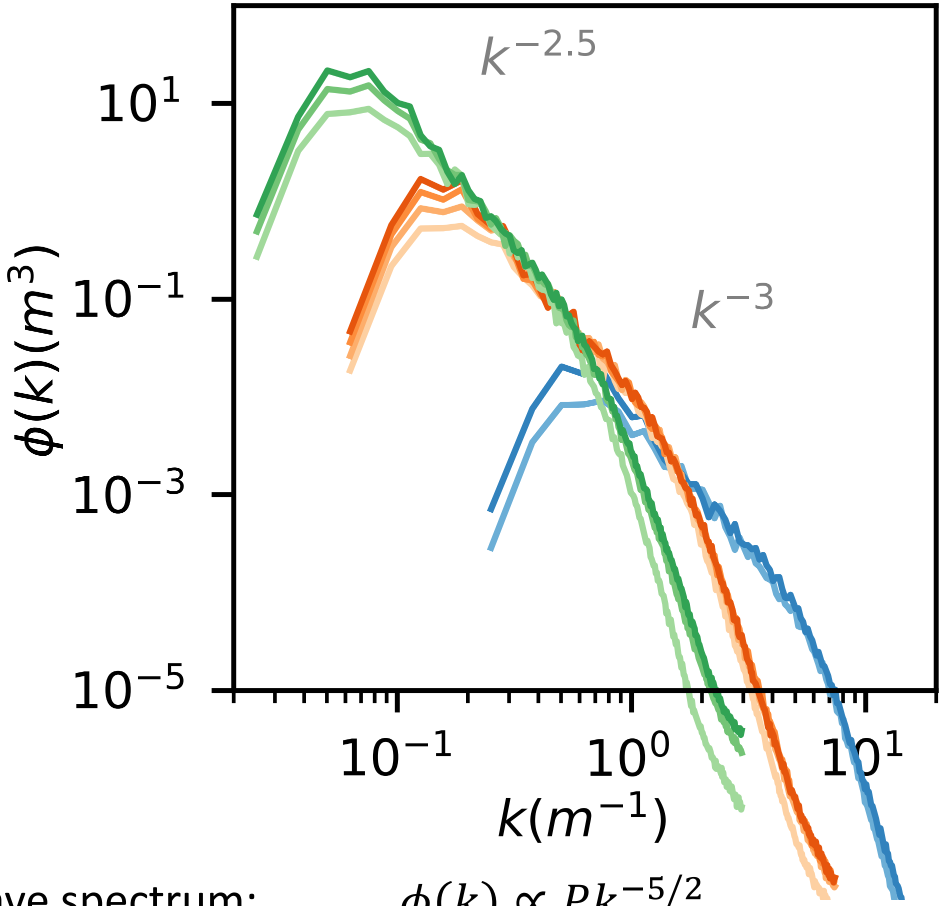


Deike et al 2017, Deike and Melville 2018; Deike 2022.

Modeling wind waves and wave statistics

Direct modeling of a wave spectrum using the multi-layer model

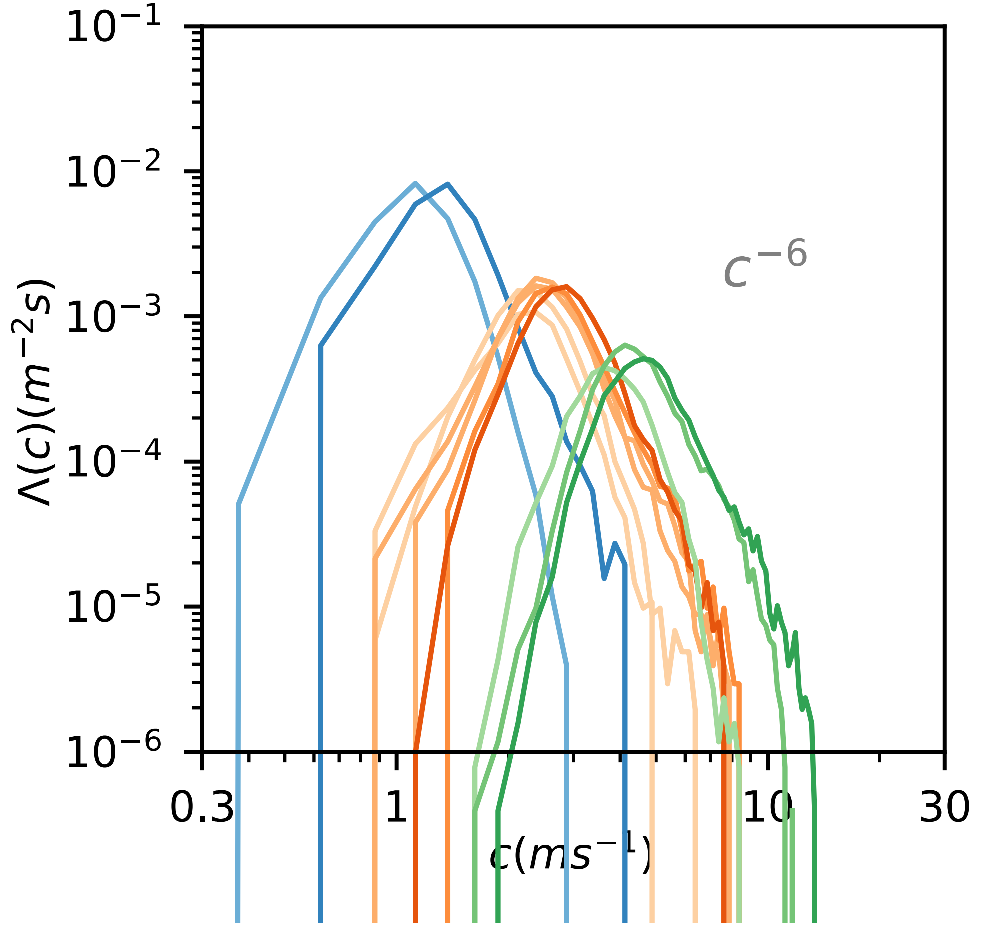




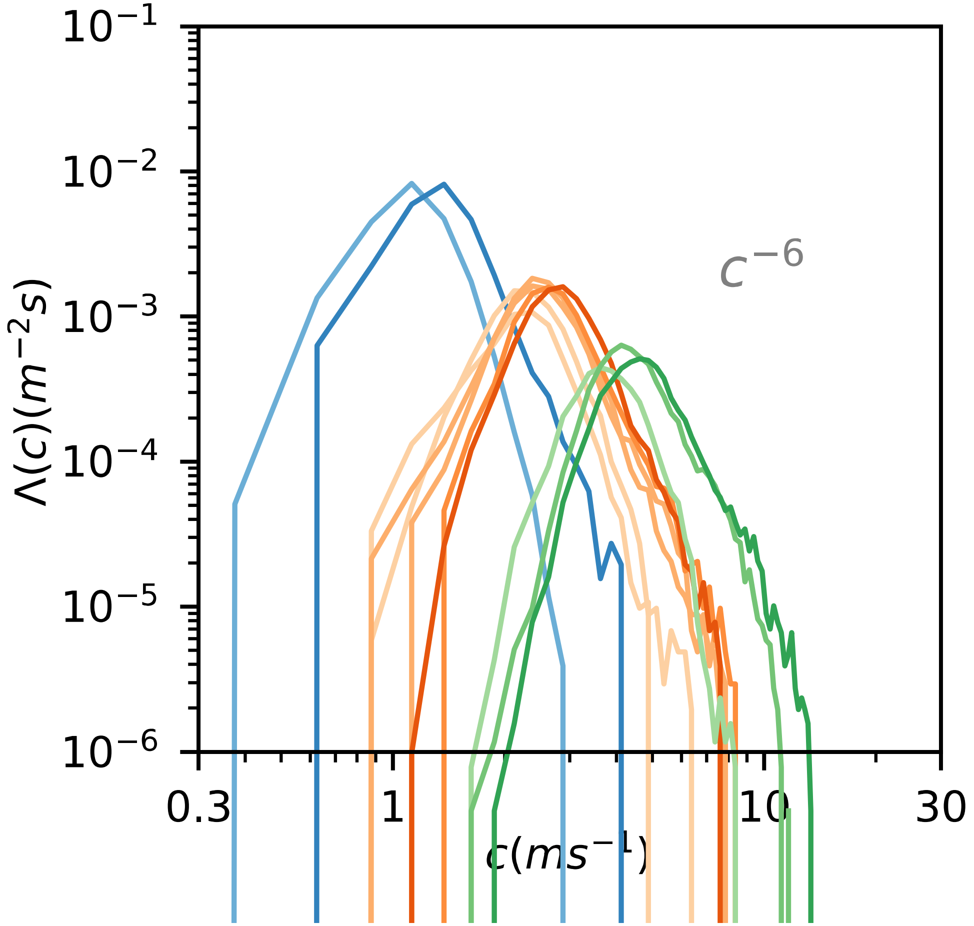
Wave spectrum: $\phi(k) \propto Pk^{-5/2}$

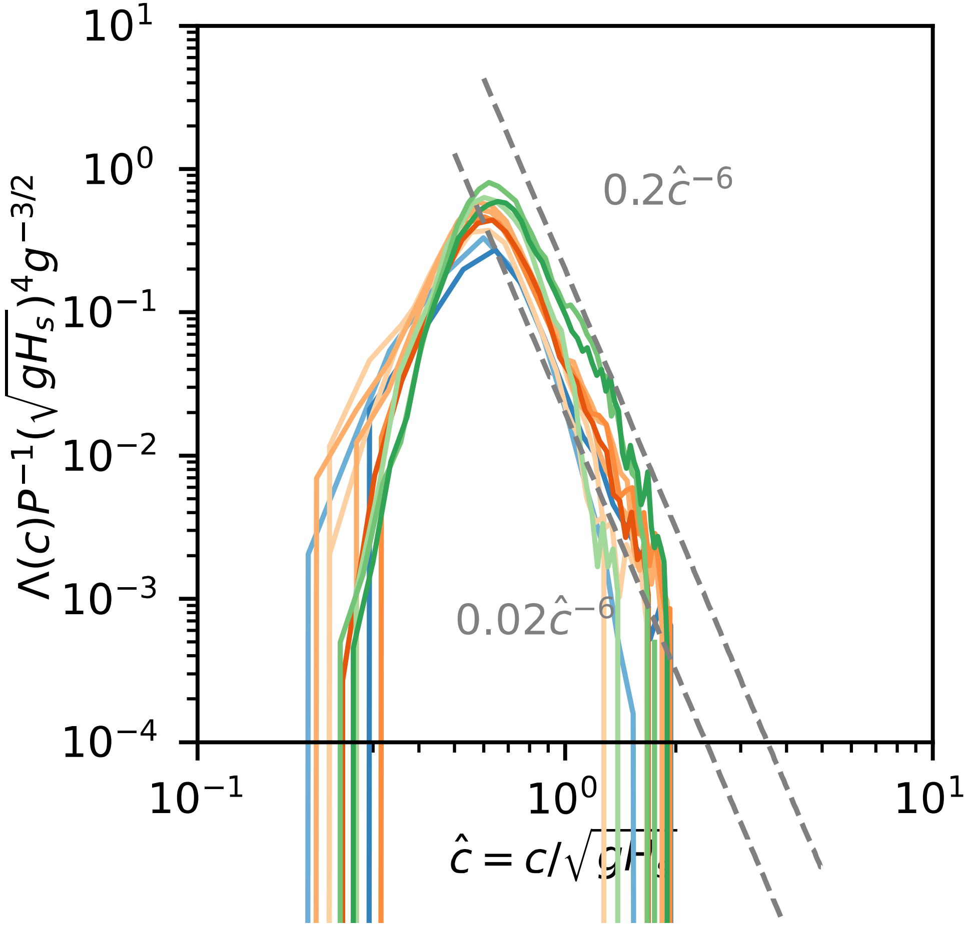
Modeling wind waves and wave statistics

Analysis of breaking kinematics statistics



Scaling the breaking wave statistics





Wu, Popinet and Deike, in prep

Ability to model the breaking statistics based on the wave spectrum!

(compatible to the spectral model from Romero 2019)

Breaking wave distribution of length of breaking crest

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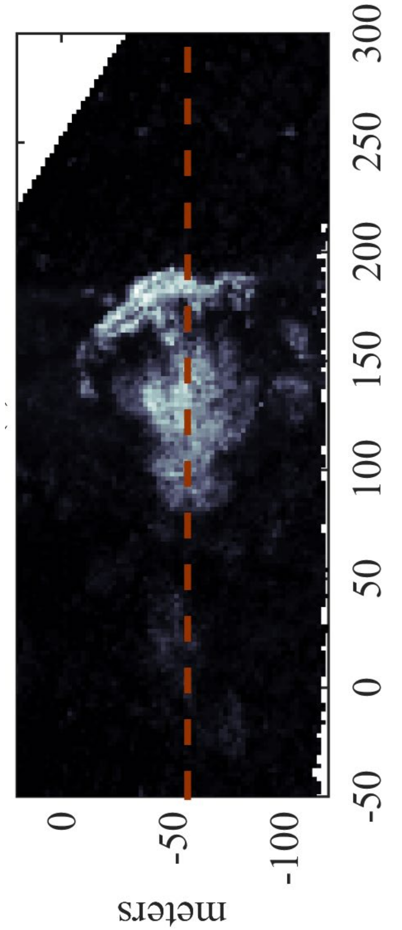
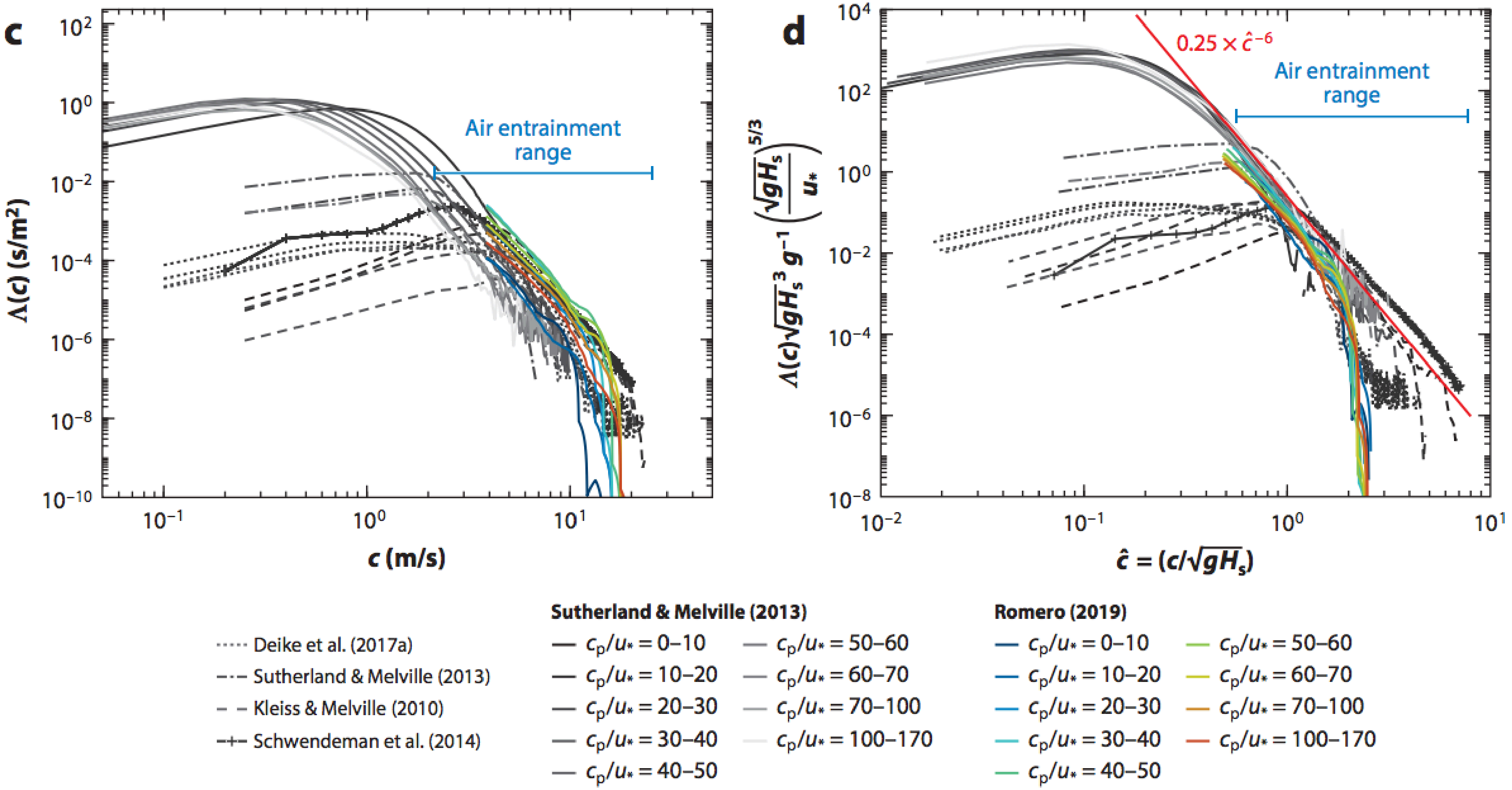
Visible video: detect and measure the length of breaking crest **Λ(c),** moving at speed **c** and the associated breaking slope **S=hk** (via the wave spectrum) which control air entrainment (Phillips 1985, Melville et al 2016, Deike et al 2017)



Airborne measurement of breaking waves, Melville et al 2016.



Deike et al 2017, Deike and Melville 2018; Deike 2022.

Air entrainment by an ensemble of breaking waves

$$V_A = \int v_l(c)\Lambda(c)dc, \quad \text{with } v_l(c) = V/(L_c \tau_b),$$

Entrained air by a breaking wave with speed ***c,*** slope ***hk***

Integration over all breaking events
(Deike et al 2016, 2017); follows Phillips 1985

Deike et al 2017

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Entrained air by a breaking wave with speed ***c*,** slope ***hk***

Integration over all breaking events
(Deike et al 2016, 2017); follows Phillips 1985

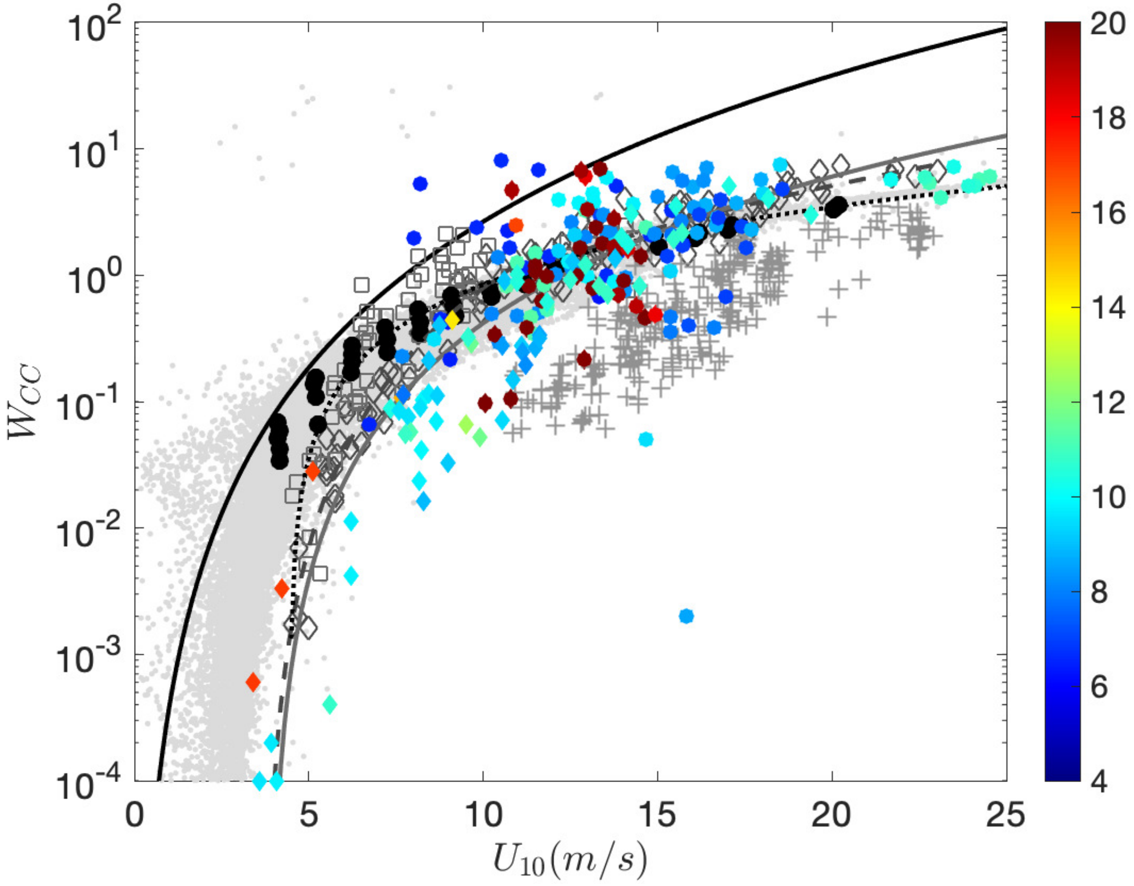
$$V_A = \int B\frac{b}{(hk)}\frac{c^3}{g}\Lambda(c)dc.$$

Similarly the size distribution of bubbles under an ensemble of breaking waves

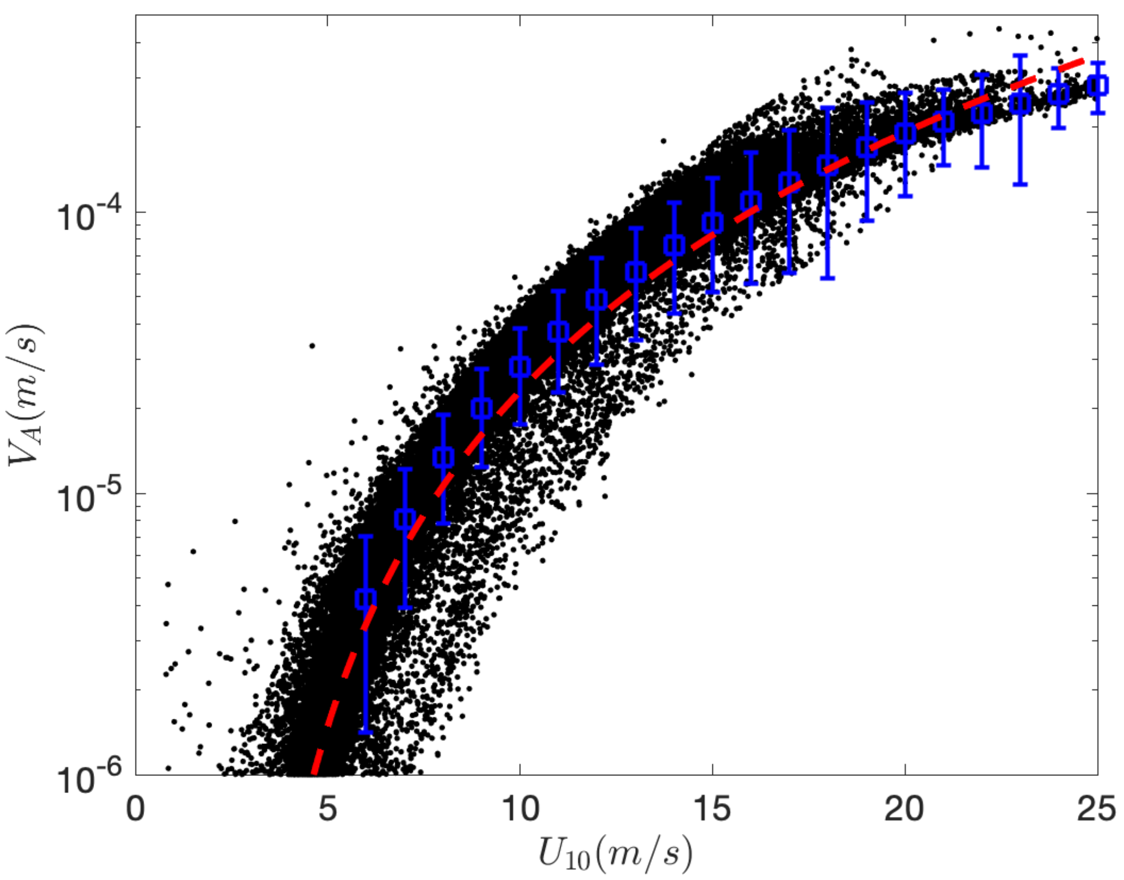
$$Q(R_b) = \int q_l(R_b,c)\Lambda(c)dc, \text{ with } q_l(R_b,c) = \frac{B}{2\pi}s(k)^{3/2}N(R_b)\frac{c^3}{g},$$

Deike et al 2017

Air entrainment and whitecap coverage



$$WCC \propto \int c^2 \Lambda(c) dc$$



$$V_A \propto \int c^3 \Lambda(c) dc$$

A multi-scale model for the total gas flux

$$F = -(k_b + k_{nb})\Delta C$$

Woolf and Thorpe 1991
Keeling 1993,

Non-breaking transfer, from classic parameterization (Edson et al 2011, Zappa et al 2007):

$$k_{nb} = A Sc^{-1/2} u_*$$

A multi-scale model for the total gas flux

$$F = -(k_b + k_{nb})\Delta C$$

Woolf and Thorpe 1991
Keeling 1993,

Bubble mediated flux k_b, **using individual bubble dynamics in turbulence results for rise velocity and transfer rates, integrated over the bubble size distribution and all breaking events**

$$k_b = \iint dc\, dR_b\, f_1(R_b, c)\Lambda(c), \text{ with}$$

Deike and Melville 2018;

A multi-scale model for the total gas flux

$$\mathrm{F} = -(k_b + k_{nb})\Delta C$$

Bubble mediated flux k_b, **using individual bubble dynamics in turbulence results for rise velocity and transfer rates, integrated over the bubble size distribution and all breaking events**

$$k_\mathrm{b} = \iint \mathrm{d}c\, \mathrm{d}R_\mathrm{b}\ f_1(R_\mathrm{b}, c)\Lambda(c), \text{ with}$$

$$f_1(R_\mathrm{b}, c) = \frac{q_1(R_\mathrm{b}, c)E(R_\mathrm{b})}{\alpha}\frac{4\pi R_\mathrm{b}^3}{3} = \frac{B}{2\pi}\frac{s(k)^{3/2}c^3}{g}\frac{4\pi R_\mathrm{b}^3}{3}\frac{N(R_\mathrm{b})E(R_\mathrm{b})}{\alpha}.$$

With:

$$\mathrm{E(R_b)} = \frac{z_0}{z_0 + He_q}$$

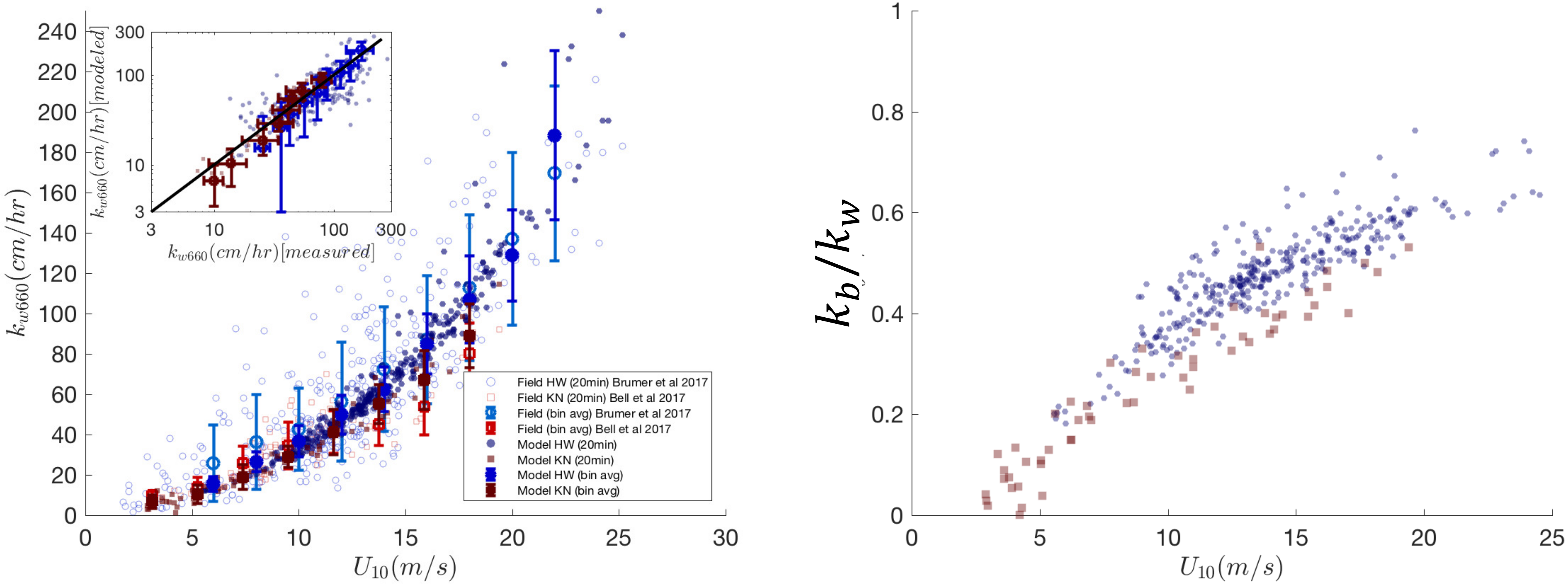
Efficiency factor

$$H_{eq} = \frac{4\pi}{3\alpha}\frac{R_b w_b}{k_L}$$

Equilibrium depth

Deike and Melville 2018;
Based on Keeling 1993

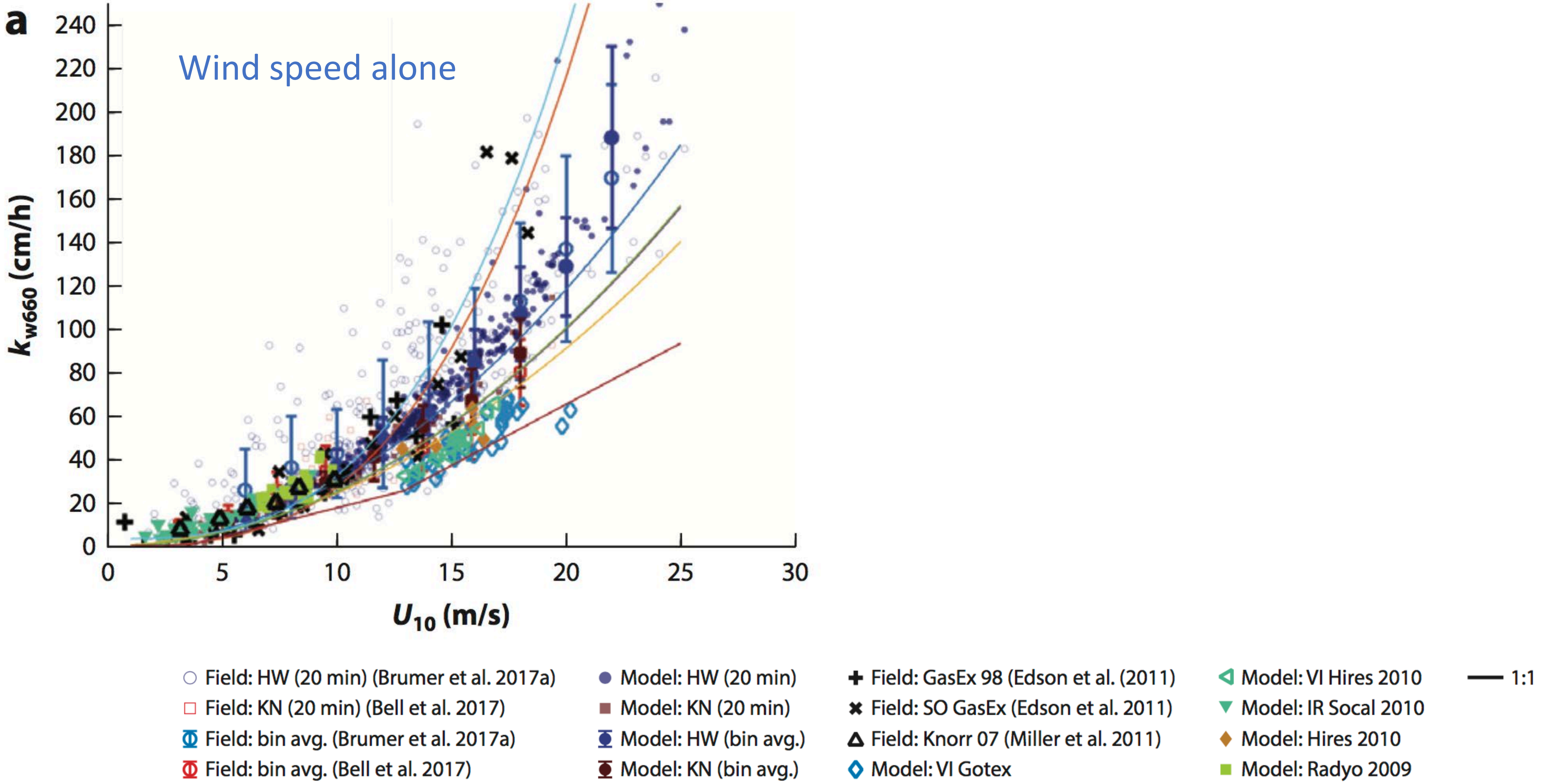
The model reproduces recent CO_2 gas transfer velocity field measurements



Data sets in the North Atlantic, *Brumer et al 2017* (HiWings), *Bell et al 2017* (Knorr 2011)
Bubble mediated gas transfer becomes dominant above 15 m/s

Deike and Melville 2018

Gas transfer velocity: a function of wind speed and sea-state



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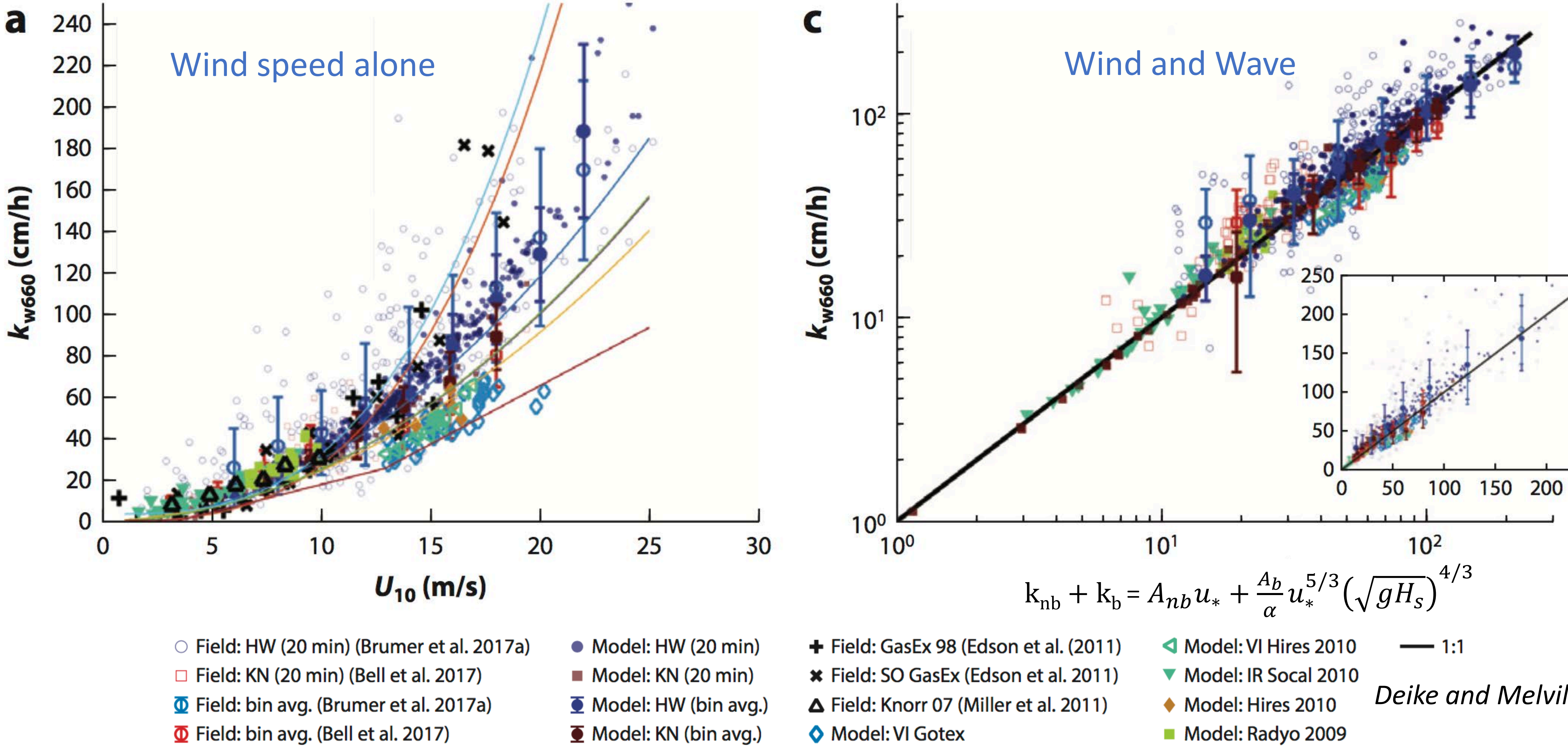
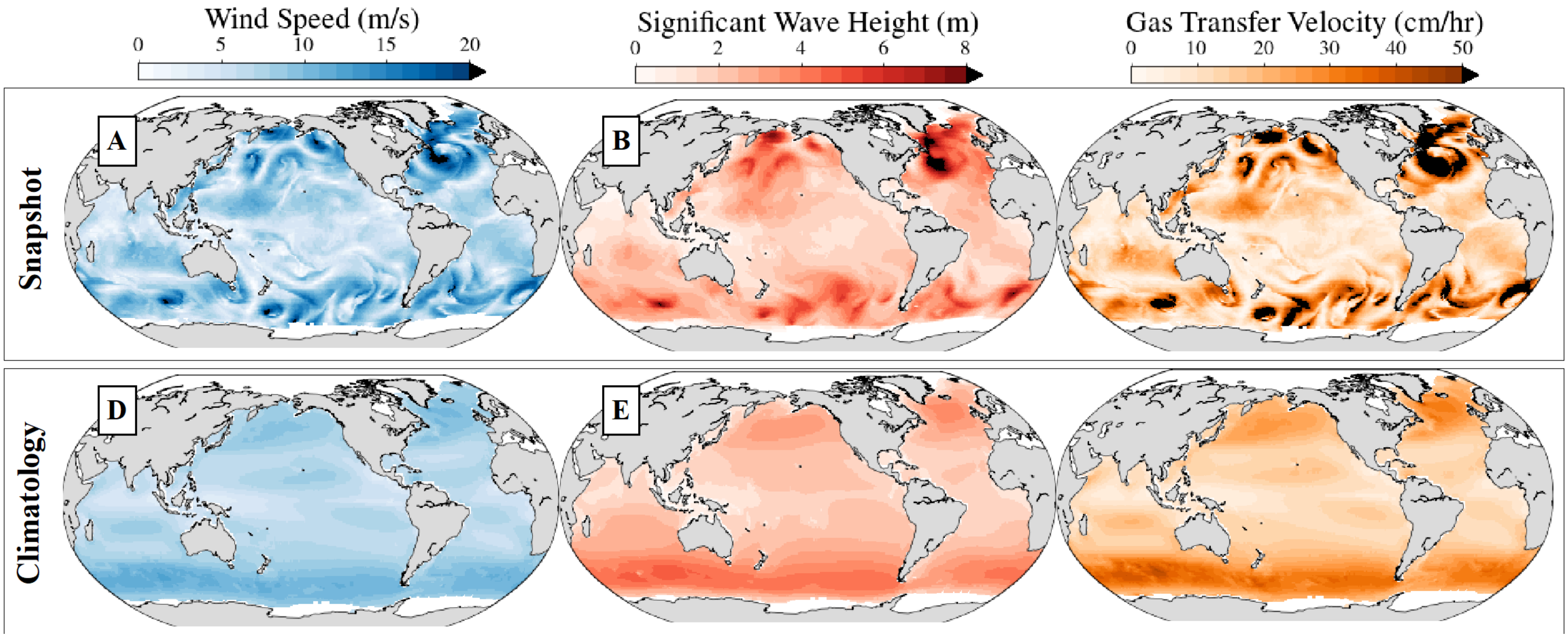


Deike and Melville 2018

Semi-empirical parameterization inspired from our theoretical model collapses all data for CO_2 (and DMS)

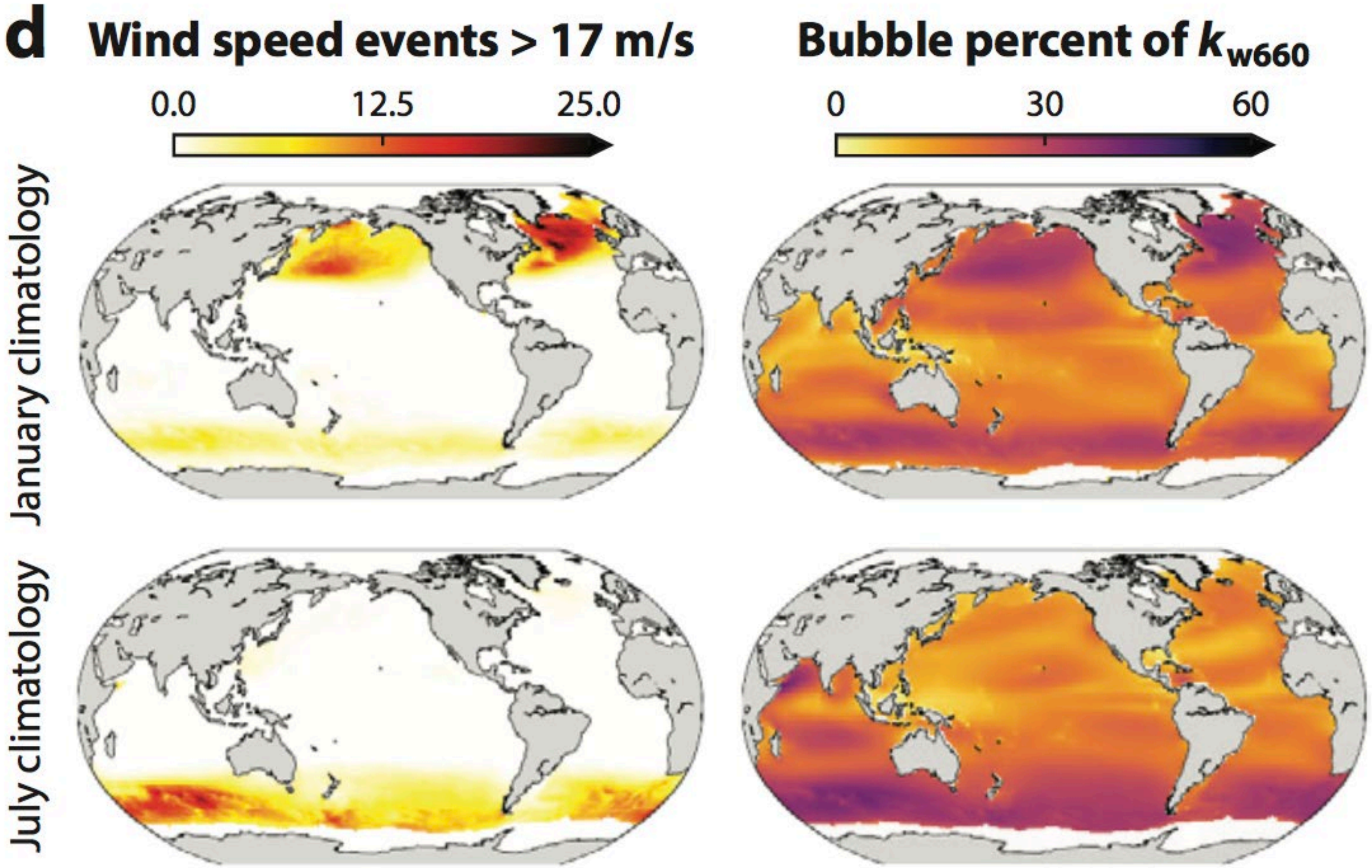
$$k_{w,660} = k_{w,660} \left(\frac{Sc}{660}\right)^{1/2} = k_{nb} + k_b = A_{nb} u_* + \frac{A_b}{\alpha} u_*^{5/3} \left(\sqrt{gH_s}\right)^{4/3}$$

Implementation of our wind-wave gas transfer parameterization: Global wave modeling (with Brandon Reichl, NOAA GFDL)



Reichl and Deike 2020

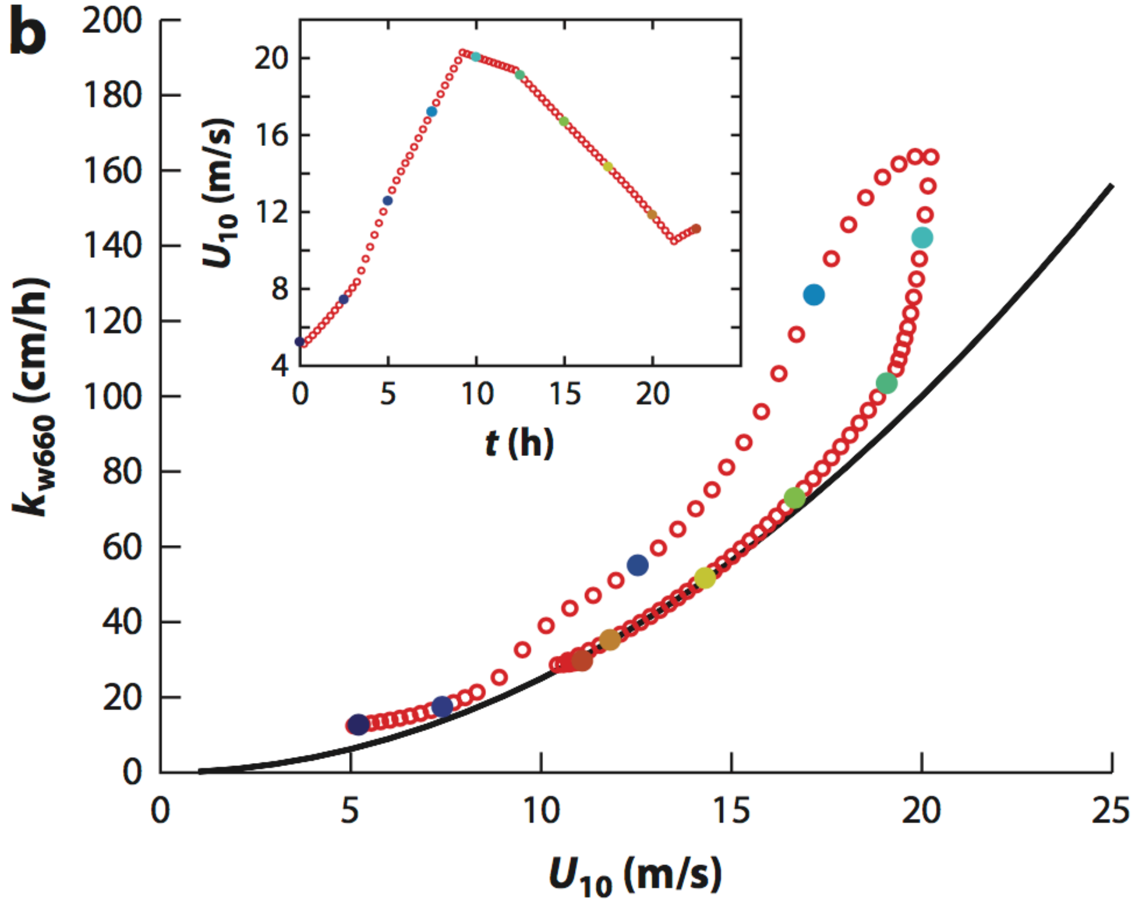
Understanding the role of sea-state variability during storms and its implications on regional and seasonal scales



Bubble accounts for 40% of the total CO2 flux and increase the spatial and temporal flux variability

Reichl and Deike 2020

Understanding the role of sea-state variability during storms and its implications on regional and seasonal scales



Deike 2022

Transfer velocity during storm intensification can be twice larger for the same wind speed value

Hysteresis cycles are sometimes the other way around

Conclusions and Perspectives

Multi-scale framework to describe air-sea mass exchange related to bubbles

From air entrainment, bubble distribution under breaking waves, to gas transfer under an ensemble of breaking waves

Can be applied locally and globally using wave modeling

Describes induced sea-state variability

Need to incorporate bubble collapse term (bubble asymmetric effect)

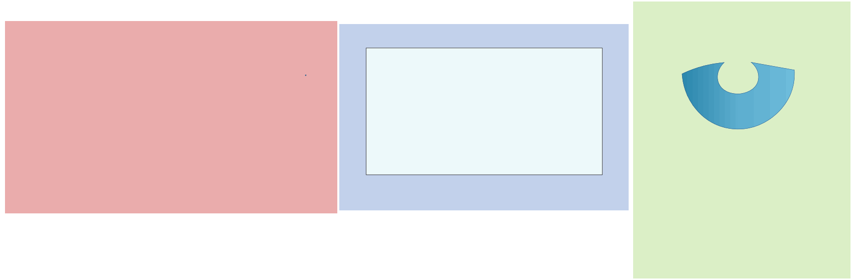
If you have gas fluxes/transfer velocity data, I would be happy to see if the present framework can model them!

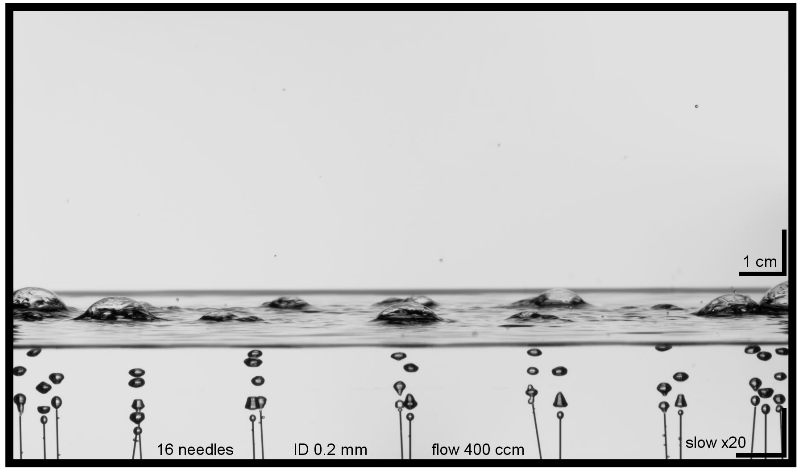
Similar ideas are being applied to sea spray production by bubble bursting

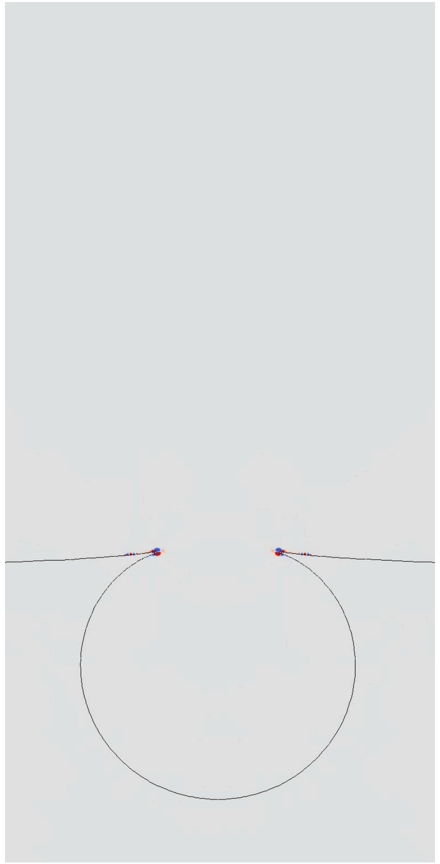
Sea spray by bubble bursting!

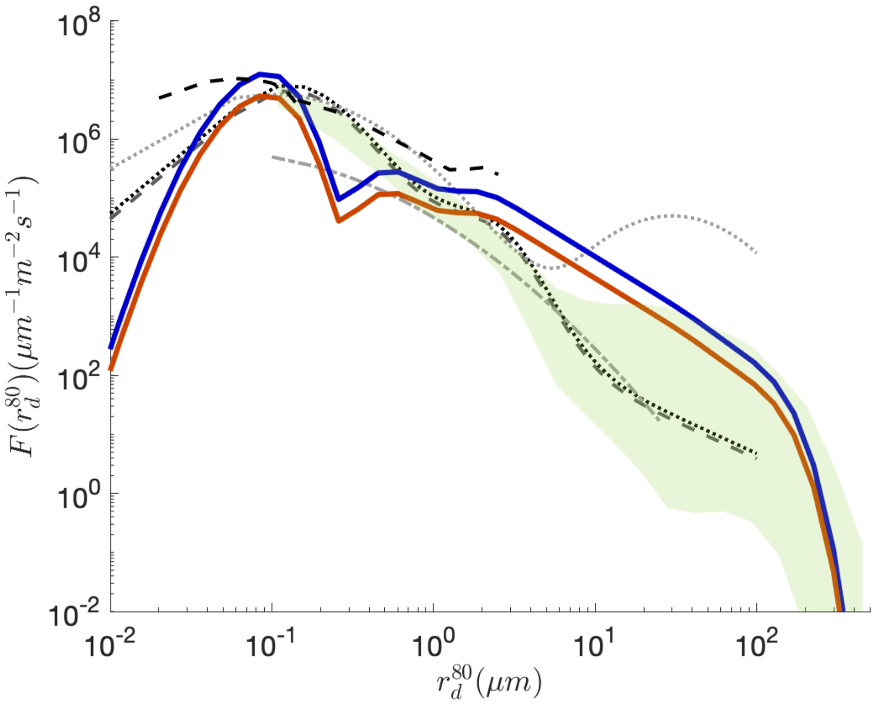
$$F_\mathrm{d}(r_\mathrm{d}) = \int Q(R_\mathrm{b}) \frac{n(R_\mathrm{b})}{\langle r_\mathrm{d} \rangle} p\left(\frac{r_\mathrm{d}}{\langle r_\mathrm{d} \rangle}\right) \mathrm{d}R_\mathrm{b}$$

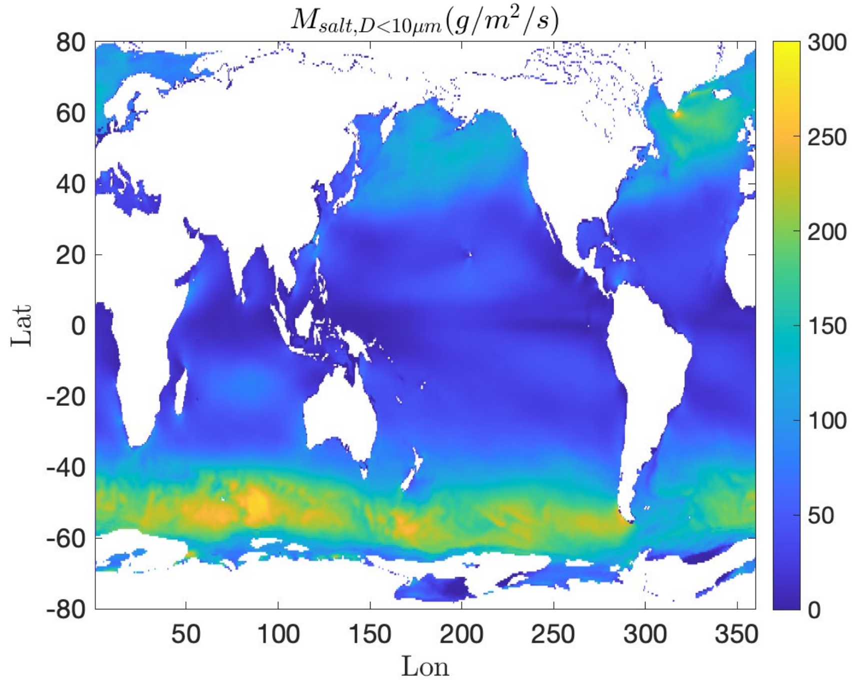
$$= \iint \frac{B}{2\pi} \frac{s(k)^{3/2} c^3}{g} \Lambda(c)\, \mathrm{d}c \frac{N(R_\mathrm{b}) n(R_\mathrm{b})}{\langle r_\mathrm{d} \rangle} p\left(\frac{r_\mathrm{d}}{\langle r_\mathrm{d} \rangle}\right) \mathrm{d}R_\mathrm{b}.$$











Conclusions and Perspectives

Multi-scale framework to describe air-sea mass exchange related to bubbles

Deike et al 2017 GRL, Deike and Melville 2018 GRL, Deike 2022 Ann. Rev. Fluid Mech

Describe air entrainment, bubble statistics and turbulence under breaking waves

(Mostert, Popinet and Deike, 2022, in press, Deike et al 2016, J. Fluid Mech.)

Bubble size distribution in turbulence can be explained by local and non-local production processes

(Riviere, Mostert, Perrard and Deike, 2021, Riviere, Ruth, Mostert, Deike and Perrard, 2022 under review.)

Individual bubble rise velocity and gas transfer in turbulence and under breaking waves

P. Kumar Farsoiya, S. Popinet and L. Deike (2021). JFM. D.J. Ruth, M. Vernet, S. Perrard and L.Deike (2021), JFM. And work in progress

Application to global models using spectral wave modeling

B. Reichl and L. Deike (2020). GRL, 47, 9. And work in progress

Sea spray production by bubble bursting: jet drop production

Deike et al 2018 PRF, Lai, Eggers and Deike 2018 PRL, Berny, Deike, Seon, Popinet 2020, 2021 PRF, GRL;

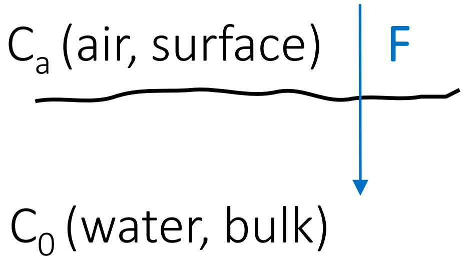
Towards understanding collective processes, role of contamination and temperature

Neel and Deike 2021 JFM, Shaw and Deike 2021 JFM, and work in progress

Wind wave modeling (J. Wu and L. Deike 2021 (PRF), and Wu et al submitted)

How is gas transfer modeled?

Gas solubility



$$F = -k_w\,(C_0 - C_a) = -k_w\,(C_0 - K_0 p_a)$$

Transfer velocity:

$$k_w \propto Sc^{-n} U_{10}^{m}$$

Wanninkhov et al 2009
Garbe et al 2014

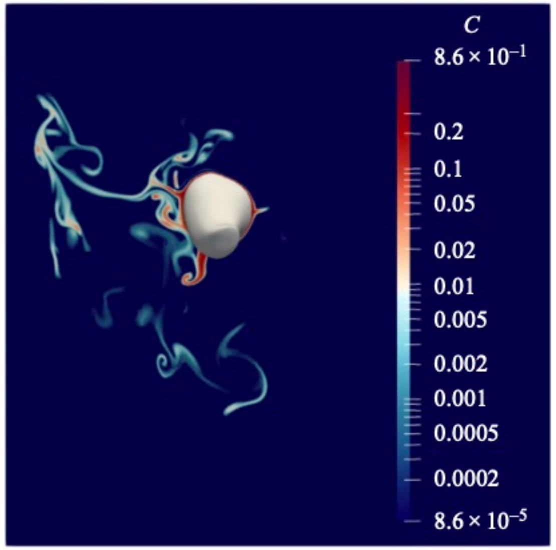
Schmidt number
$Sc = \nu / D$

Wind speed U_{10}

Is the wind speed good enough?

Mass (gas) transfer of an individual bubble in a turbulent flow

Exchange of a dilute gas and dissolution through a one fluid advection equation based on Bothe & Fleckenstein 2013, Haroon et al 2010.



Kumar Farsoiya, Popinet and Deike, J. Fluid Mech. 2021
Kumar Farsoiya, Popinet and Deike, 2022, submitted

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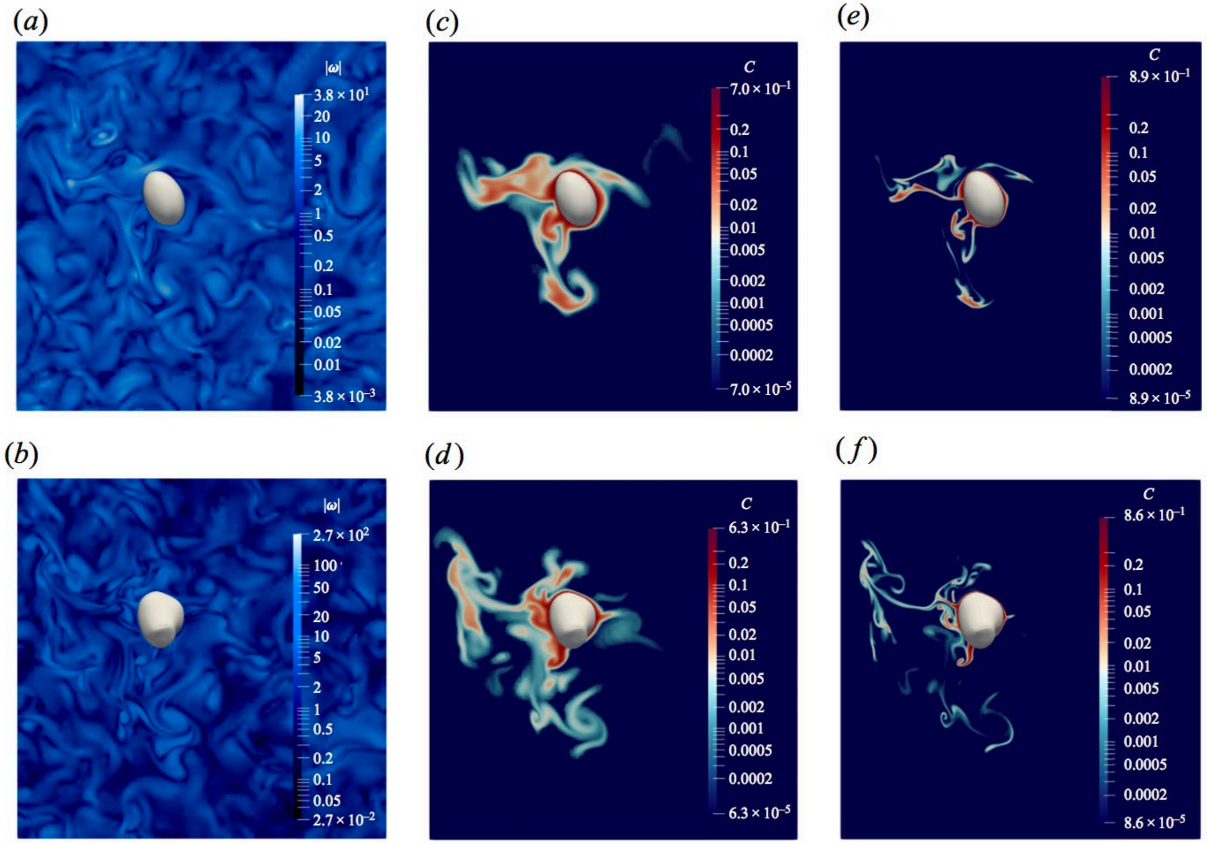
In non dimensional form

$$\mathrm{Sh}\mathrm{Sc}^{1/2} \propto \mathrm{Re}^{3/4}$$

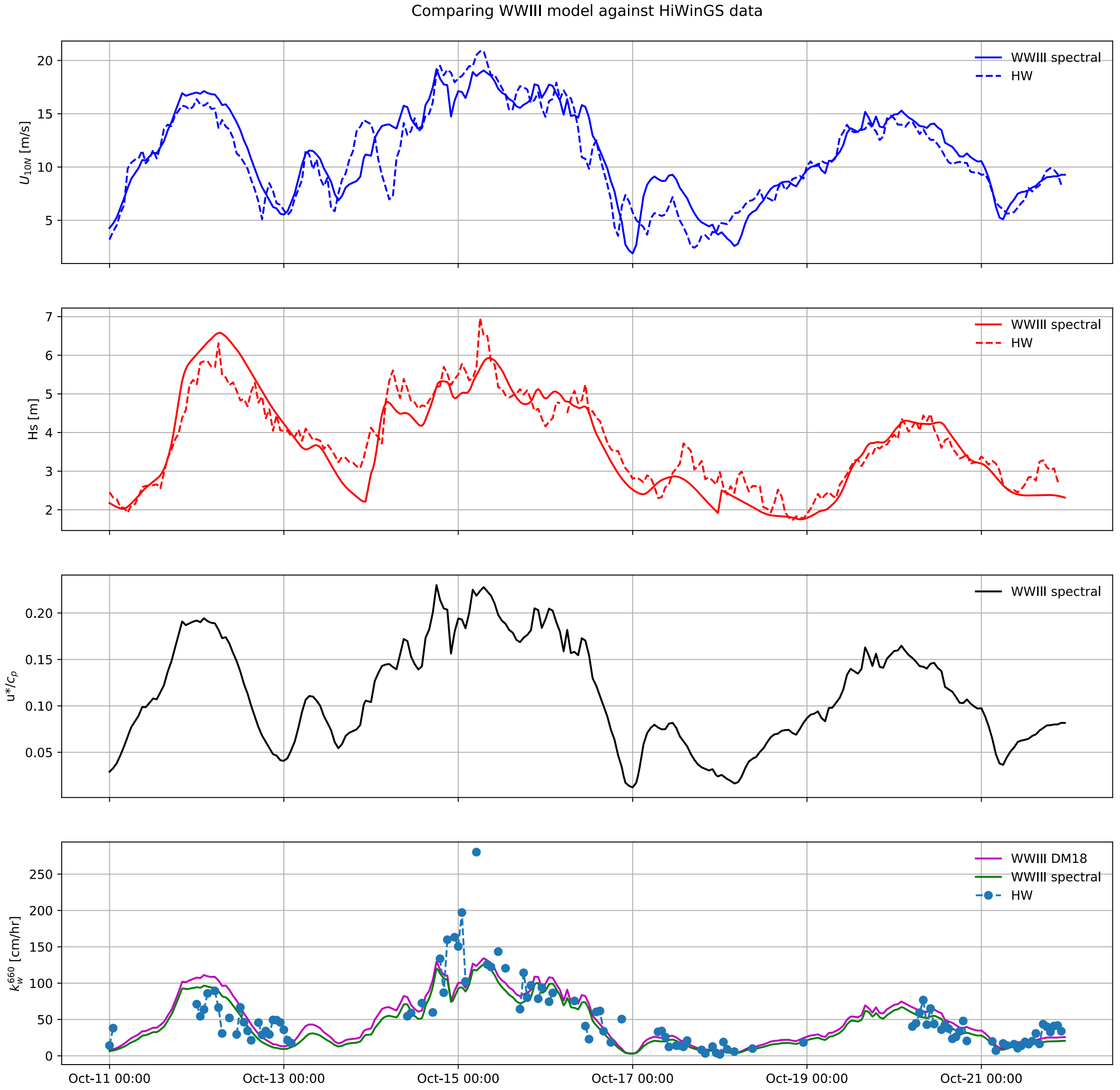
(see also Lamont and Scott 1970)

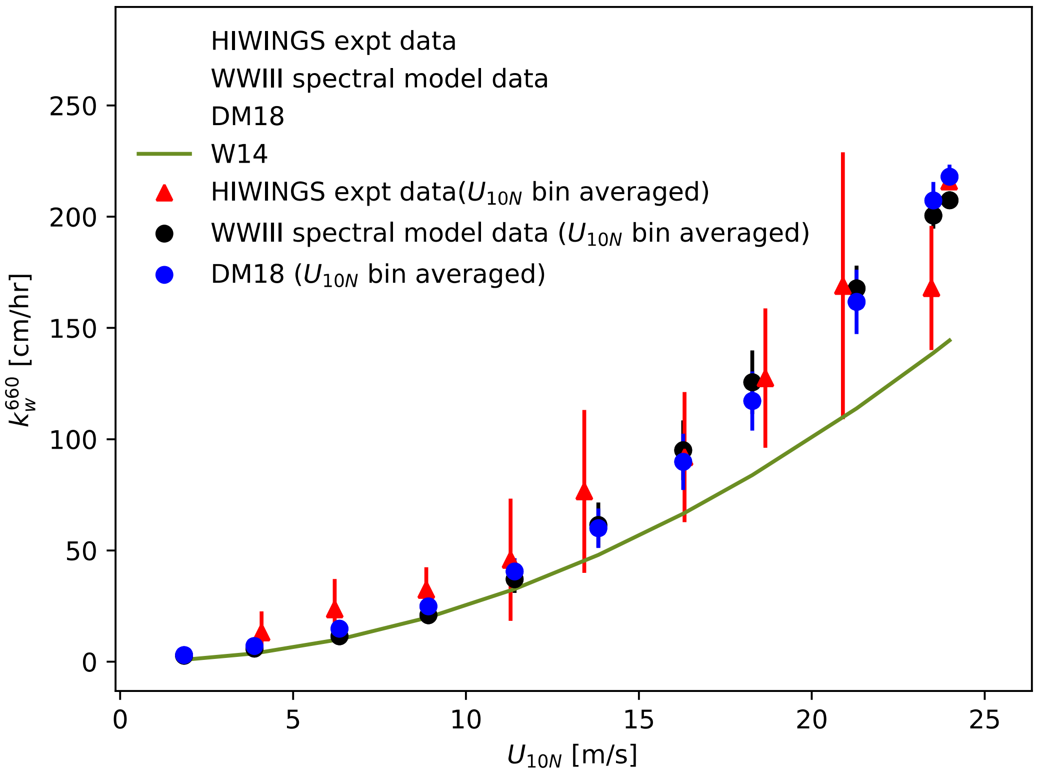


Vorticity   Sc=1 (Pe=200)   Sc=10 (Pe=2000)

Kumar Farsoiya, Popinet and Deike, J. Fluid Mech. 2021
Kumar Farsoiya, Popinet and Deike, 2022, submitted

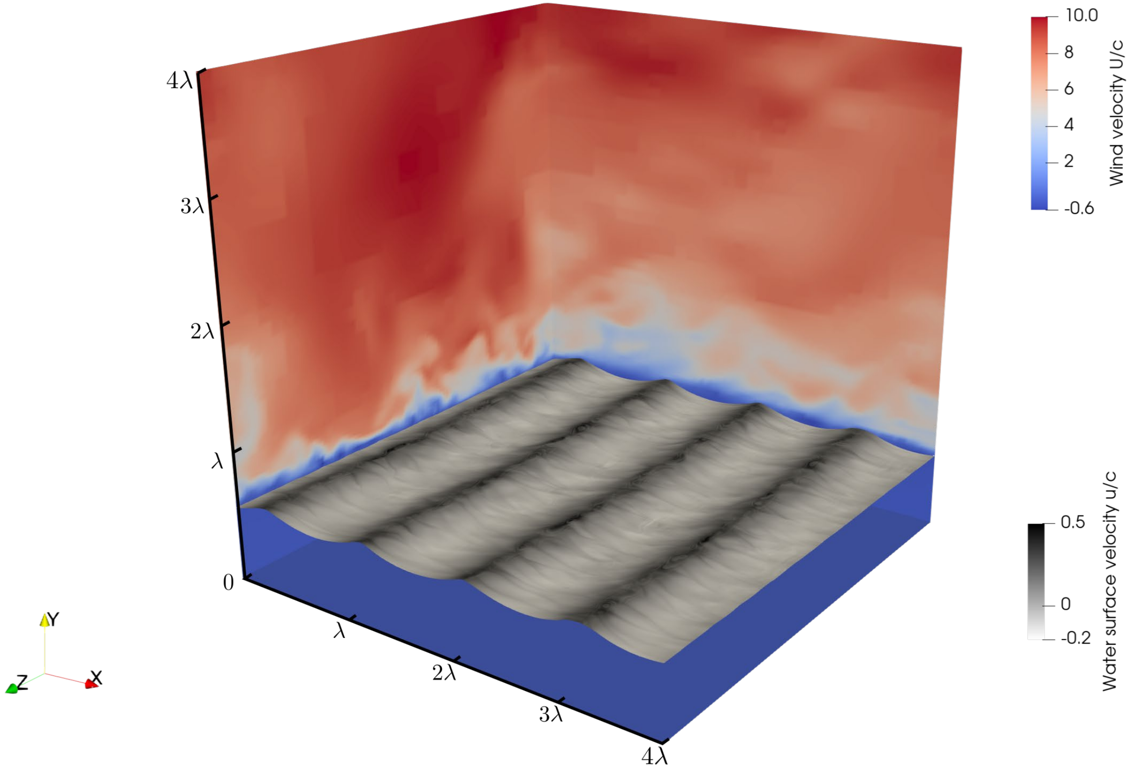
The model reproduces recent CO_2 k_w field measurements

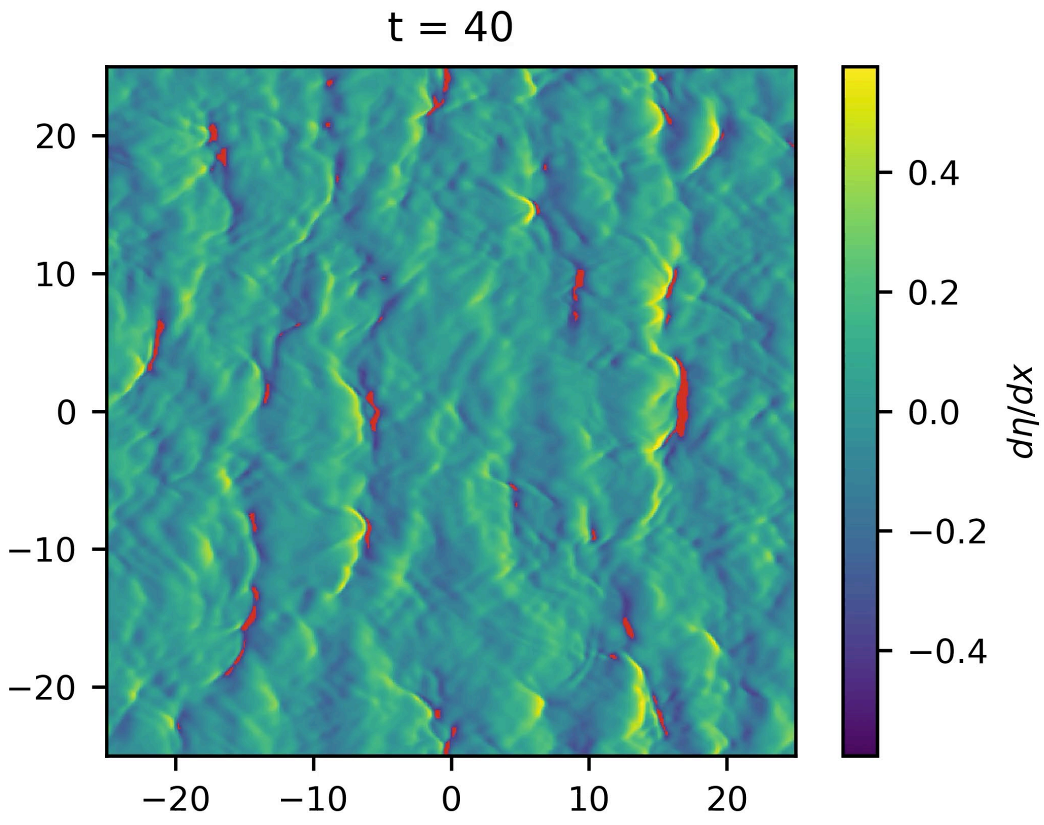




Modeling wind waves and wave statistics

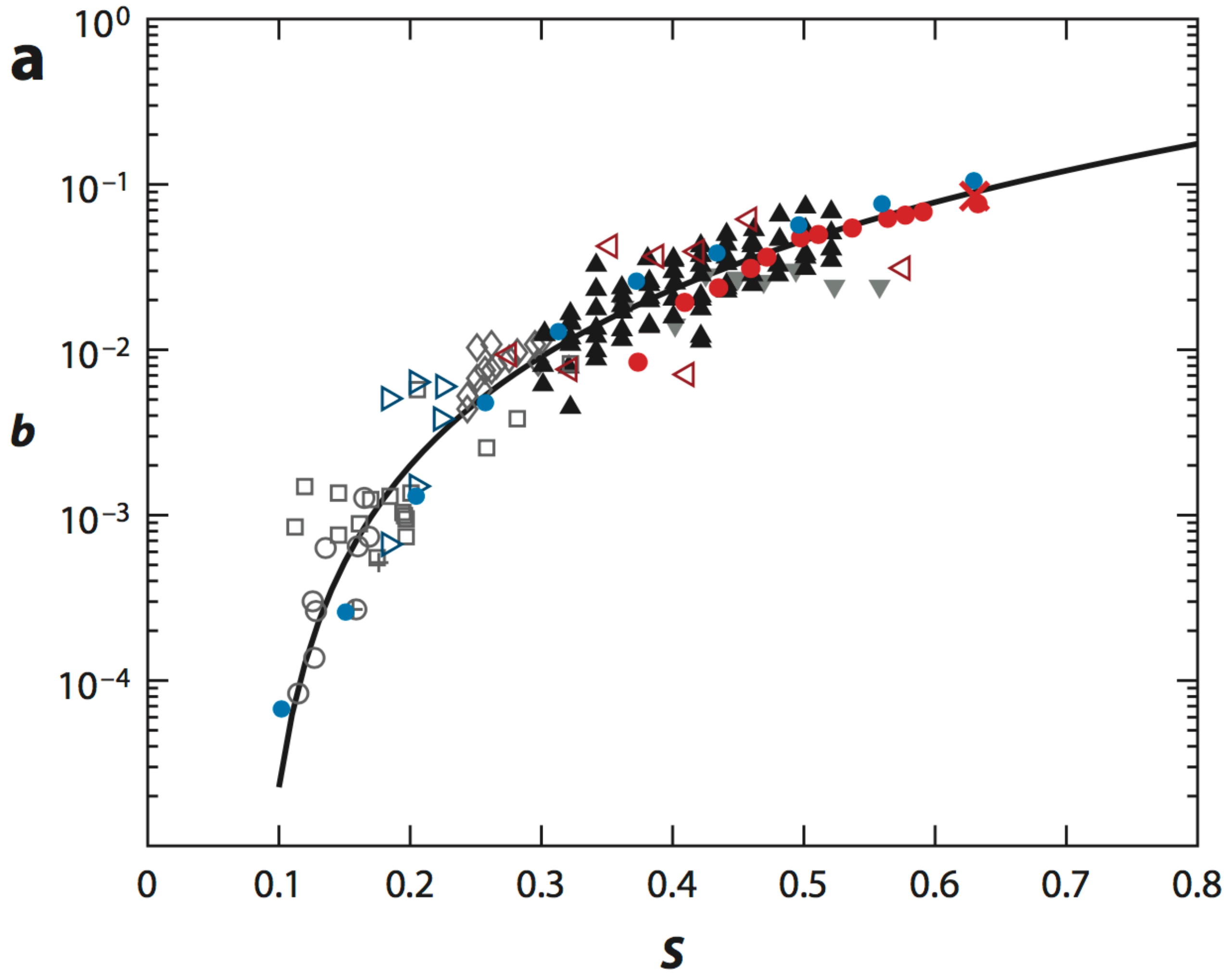
Wind wave growth via full DNS coupling
(Wu and Deike 2021, and Wu et al, submitted)



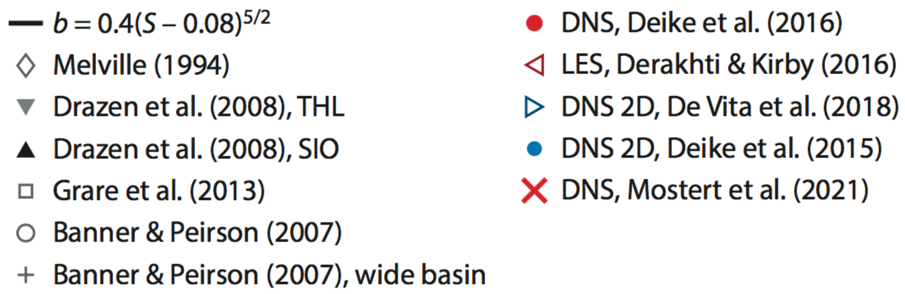


Direct modeling of breaking statistics using a multi-layer model
(Wu, Popinet and Deike, in prep)

Energy dissipation due to breaking from DNS are in good agreement with laboratory measurements



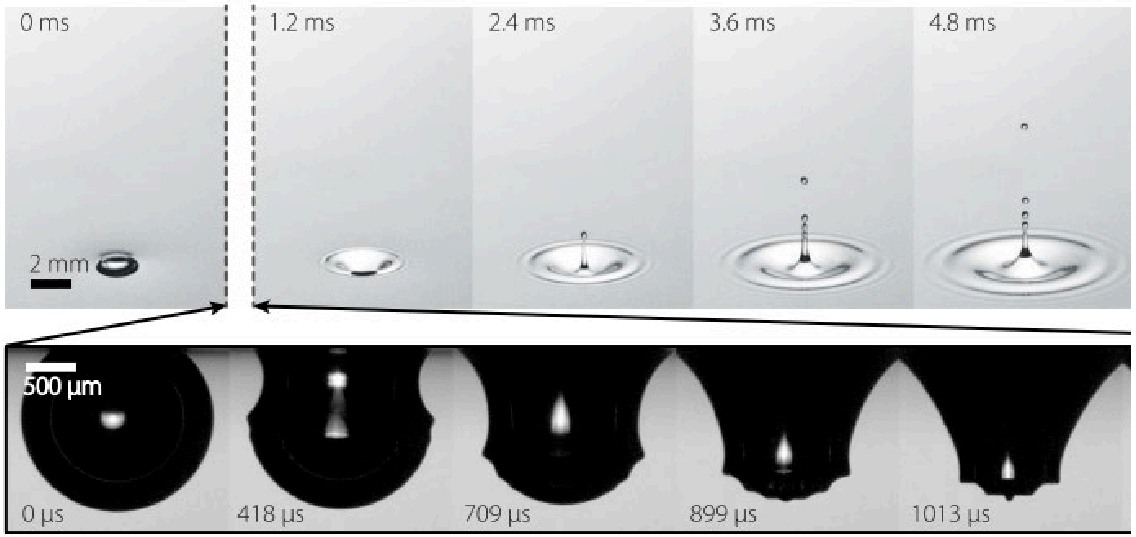
Adapted from Drazen et al 2008, Romero et al 2012



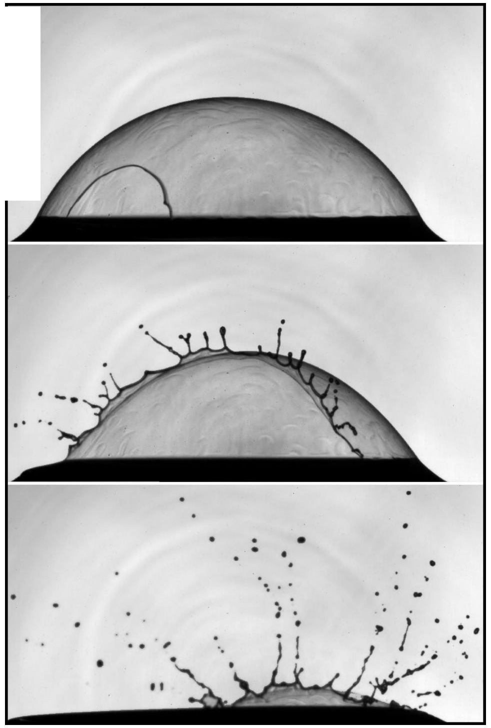
Validates the use DNS to study the multi-phase turbulent flow resulting from breaking

Scales of production of film and jet drops

Jet drops,
Ghabache et al 2014



Film drops,
Lhuissier and
Villermaux 2012



Visco-capillary length: $l_\mu = \mu^2/(\rho\gamma)$

Capillary length: $l_c = \sqrt{\gamma/(\rho g)}$