From wave breaking to air-sea fluxes of mass, heat, and momentum via bubbles and sea spray

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Laero
Laboratoire d'Aérologie

cnrs

Current Work - Waves impacts on extra-tropical cyclones

Project anr JCJC "WINDGUST" (PI: F. Pantillon)

Laero
Laboratoire d'Aérologie

Objectives:

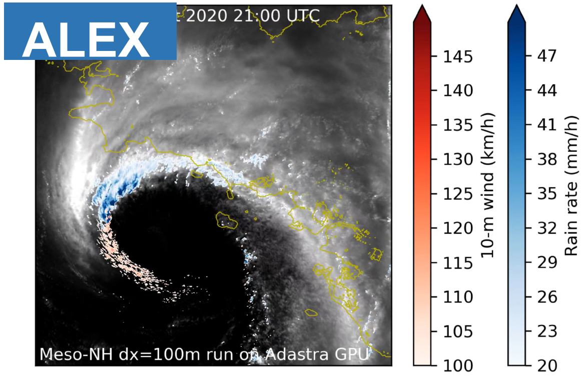
- Better understand fine-scale processes responsible for the formation of gusts
- Explore the feedback of local processes on midlatitude cyclone dynamics

Approach:

→ *Realistic coupled atmosphere-wave-ocean simulations*

→ *High-resolution (100 m - 2.5 km)*

2 case studies:



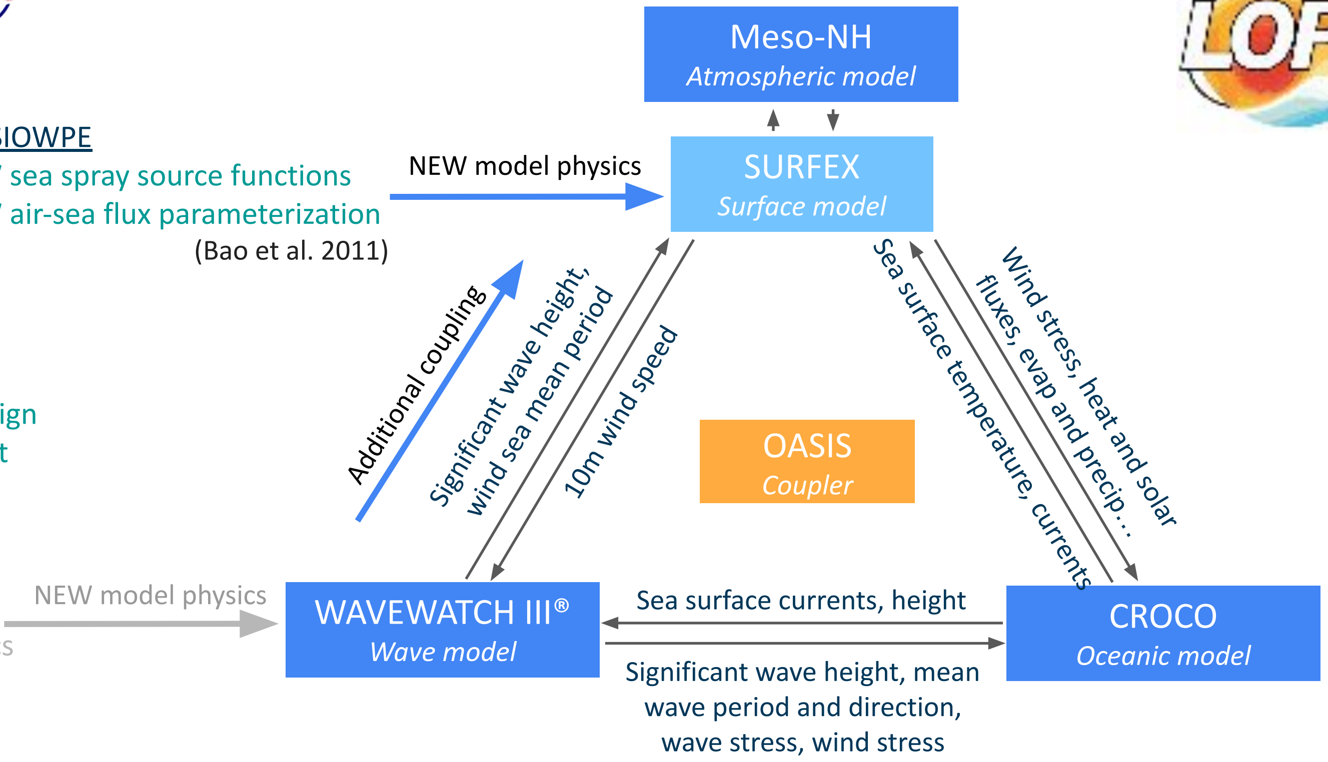
Previous Work - A coupled model framework with sea spray

FRANCE ENERGIES MARINES
anr®
ANR-10-IEED-0006-34
FRANCE 2030
LOPS

<u>CASSIOWPE</u>
Dataset collection
- Sea-spray
- Air-flow separation
- SUMOS field campaign
- SUSTAIN experiment

<u>CASSIOWPE</u>
NEW sea spray source functions
NEW air-sea flux parameterization
(Bao et al. 2011)

<u>DiMe</u>
Quantification of the spectral distribution of breaking statistics



PhD - The High Wind speed Gas Exchange Study (HiWinGS)

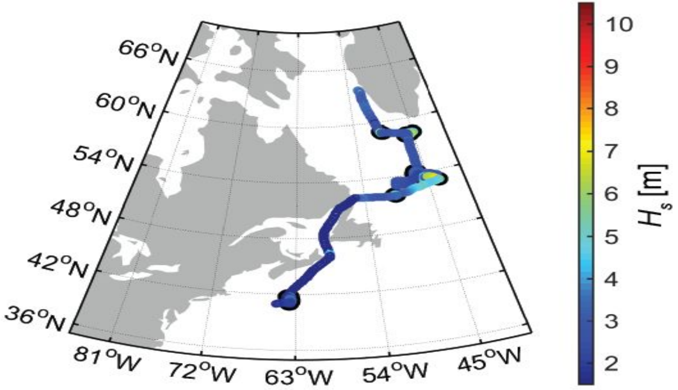
Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

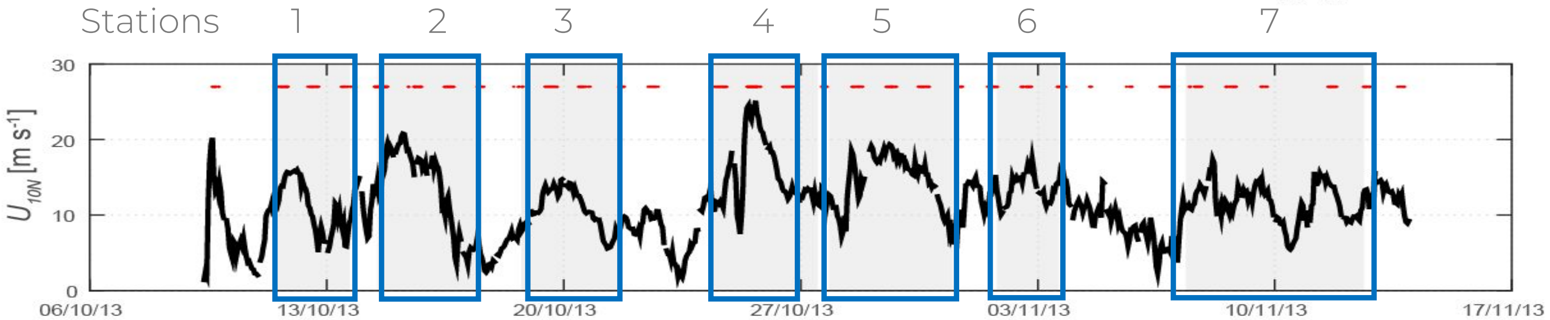
Where : Labrador Sea – Nuuk to WHOI

When : Oct 9 – Nov 14 2013

LDEO Measurements : Ship-Based **Visible Imaging**
Whitecap cover & breaking crest length distributions

Additional Measurements :
Wave field: Riegl Altimeter (continuous till station 4)
Wave Rider buoy (on station)
Meteorological and chemical fluxes (CO_2, DMS…)





U_{10N} > 15 m s^{-1} for 25% of the time & 48 hrs with U_{10N} > 20 m s^{-1} !

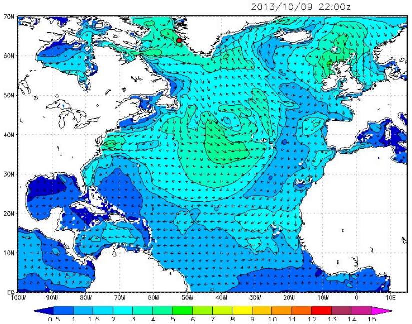
PhD - The High Wind speed Gas Exchange Study (HiWinGS)

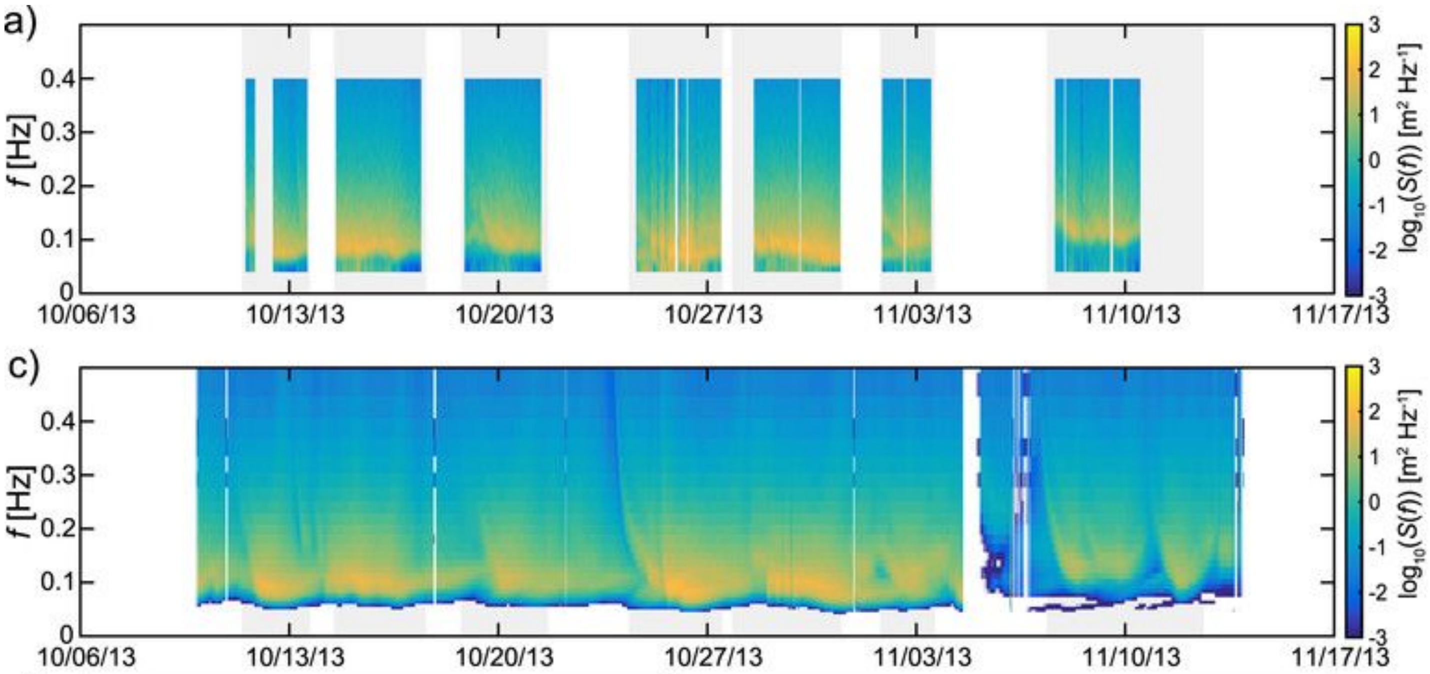
St. Jude Day Storm

PhD - The High Wind speed Gas Exchange Study (HiWinGS)

wave rider buoy

WAVEWATCH-III

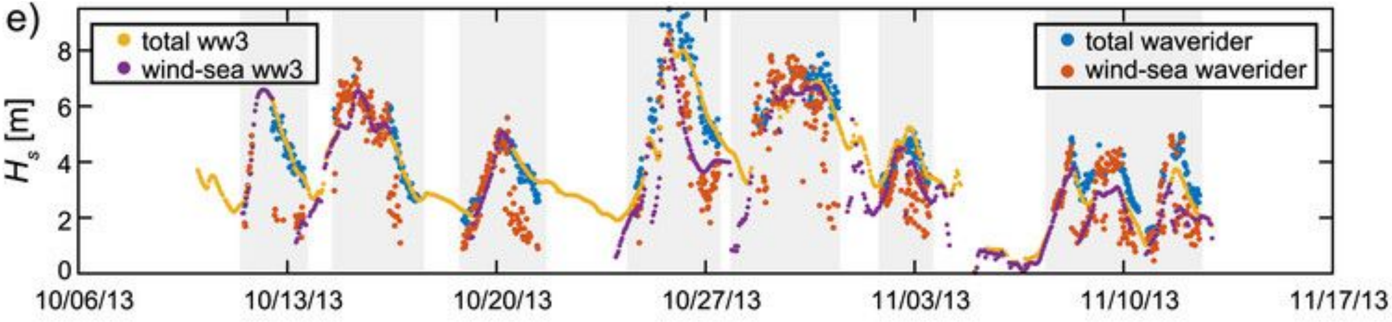


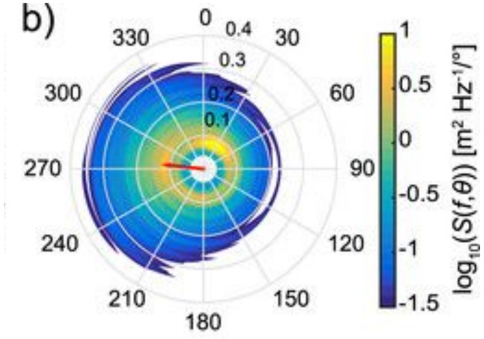


PhD - The High Wind speed Gas Exchange Study (HiWinGS)

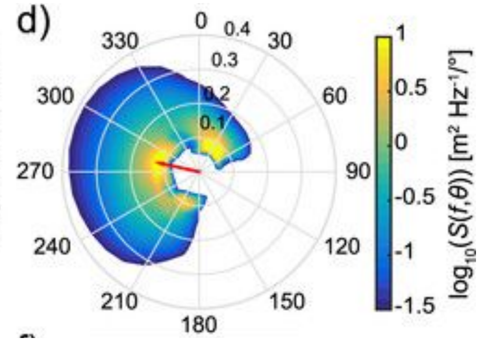
- wind sea dominated mixed seas

- Model hindcast closely mimics measurements



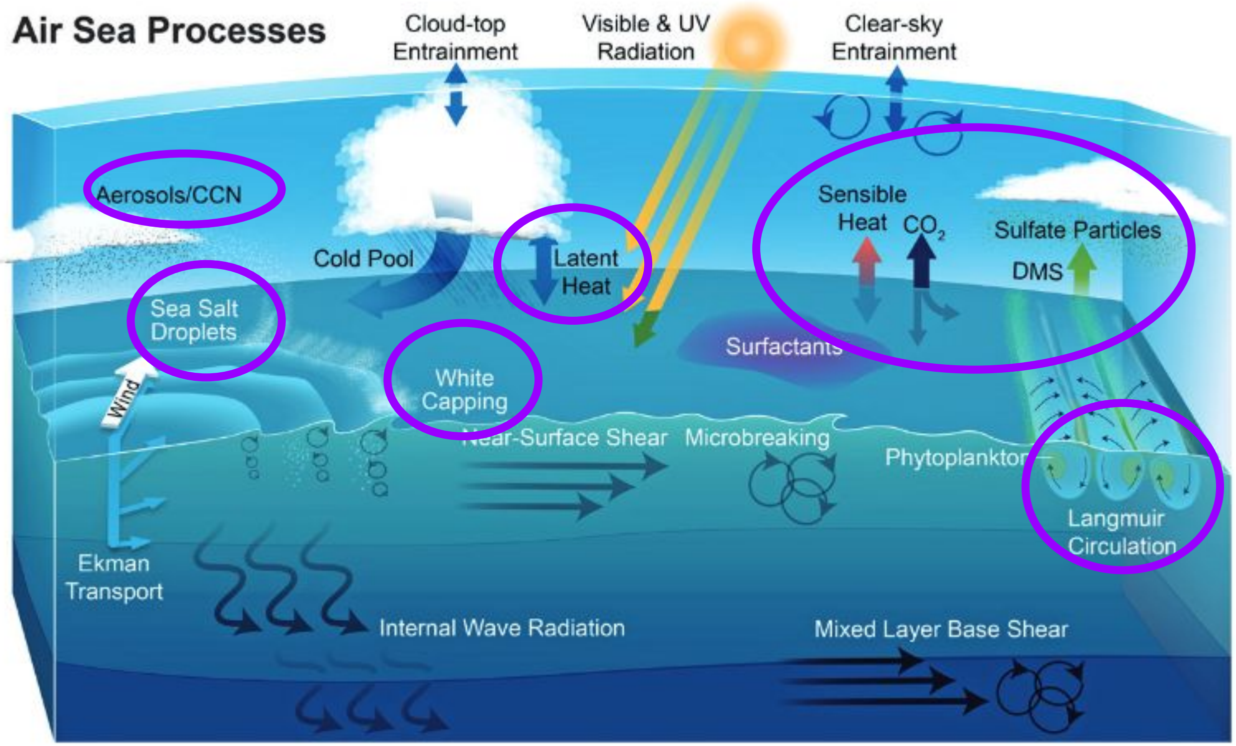


wave rider buoy



WAVEWATCH-III

Wave dependent air-sea processes



Clayson et al (2020)

Whitecaps

Whitecap parametrizations (1971 – 2004)

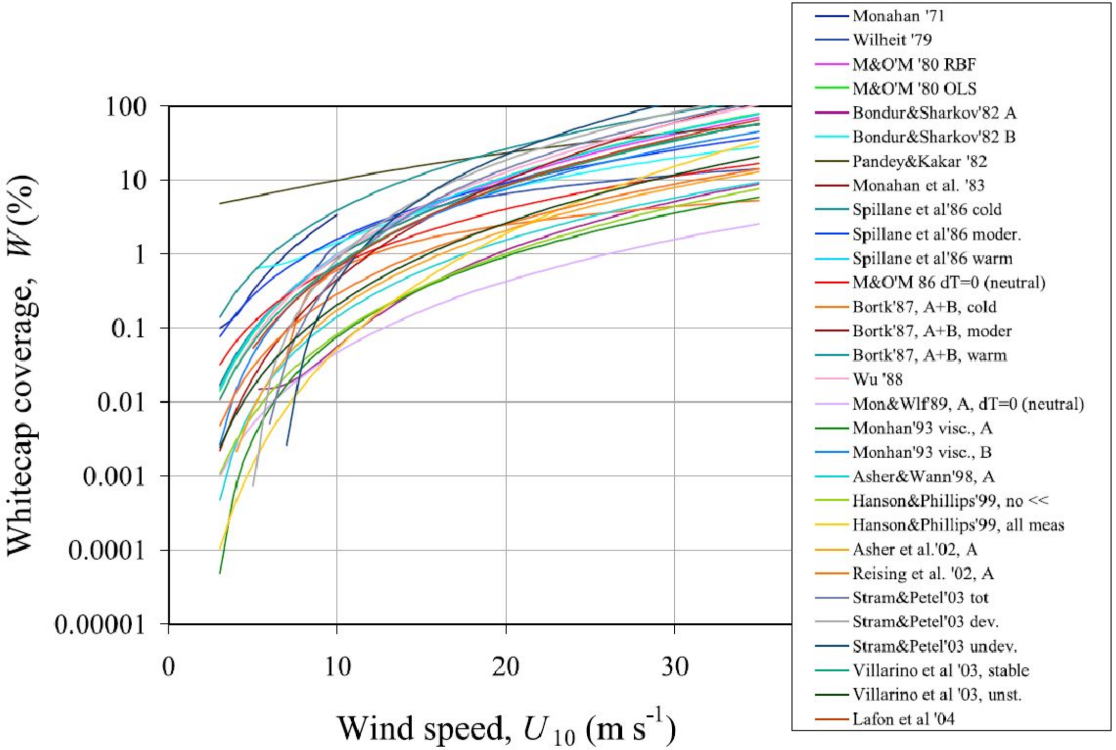
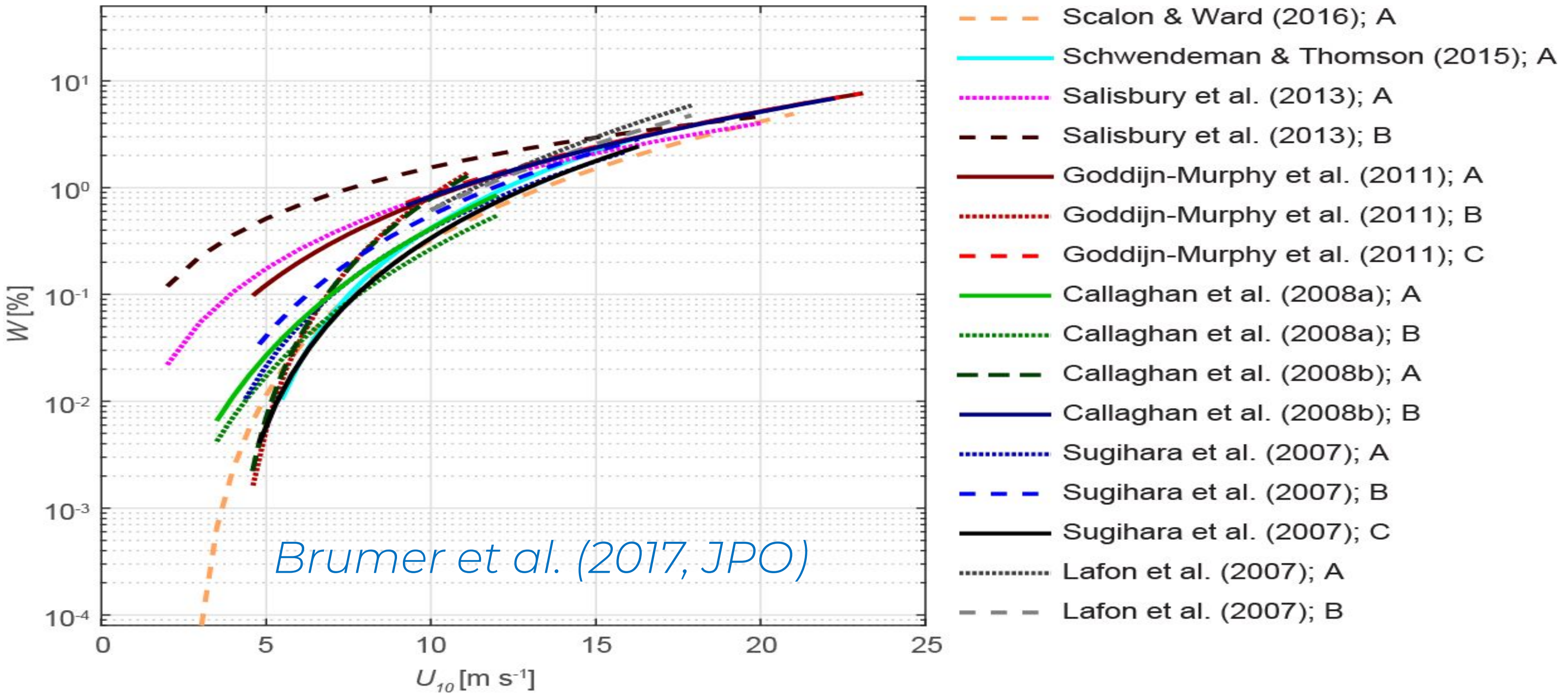


Figure 1. Various parameterizations for $W(U_{10})$ relation.

Anguelova and Webster (2006)

Whitecap parametrizations (2007 – 2016)

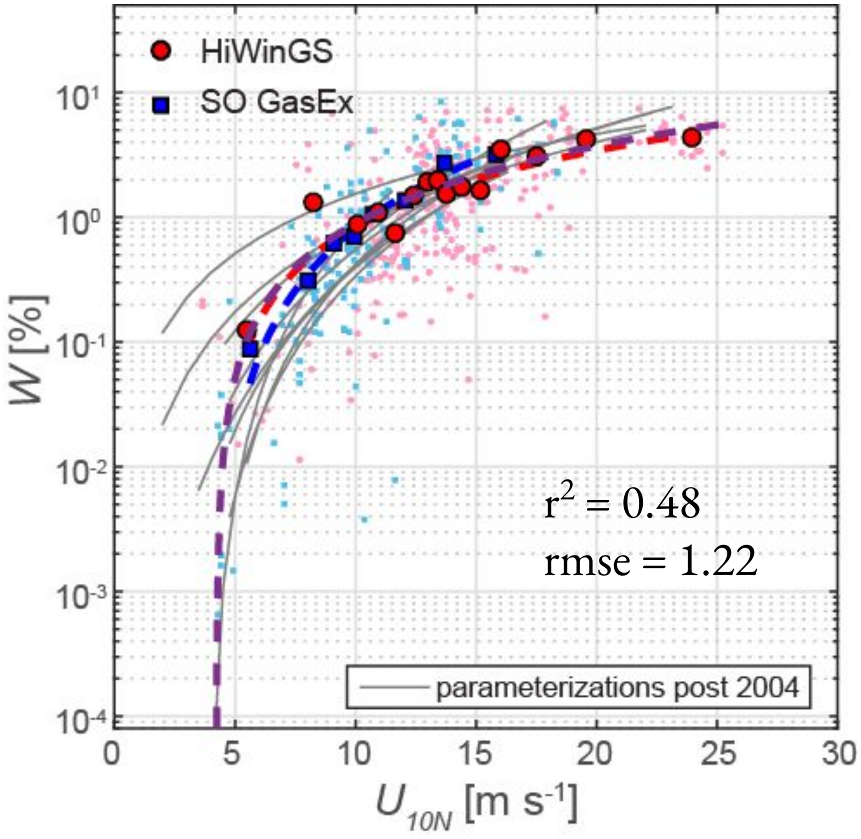


Whitecap parametrizations – HiWinGS & SO GasEx Results

Ship-borne high freq. visible imaging (motion corrected)

Good agreement between
the 2 datasets &
with previous studies

HiWinGS
→ extended validity to 25 m s^{-1}
→ saturation beyond 20 m s^{-1}?



Brumer et al. (2017, JPO)

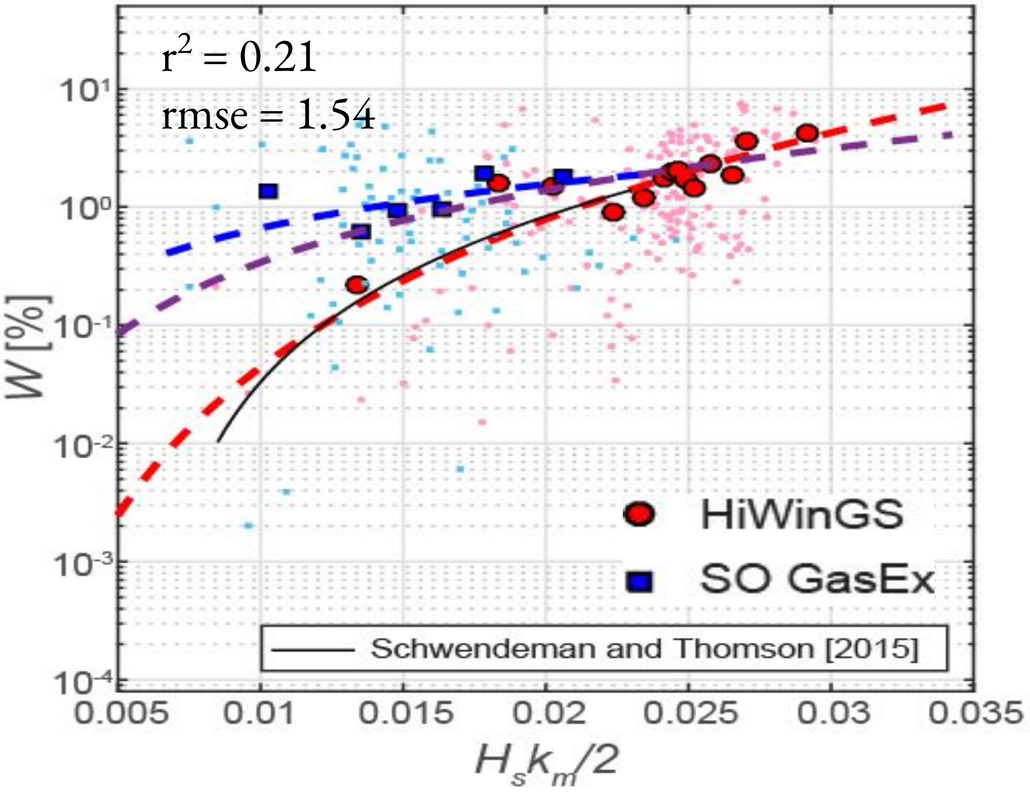
Whitecap parametrizations – HiWinGS & SO GasEx Results

Sea state dependence

1. wave steepness
   a. mss
   b. “Bulk”
2. Wave age

→ poor agreement between the 2 datasets & with previous studies

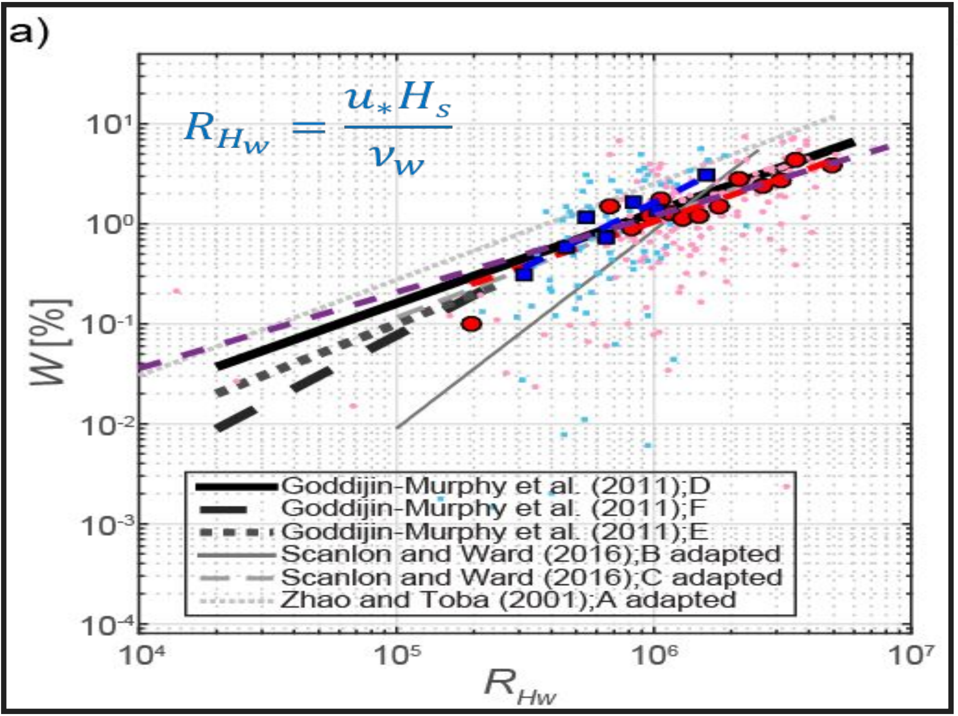
→ no improvement when considering only wind-sea partition



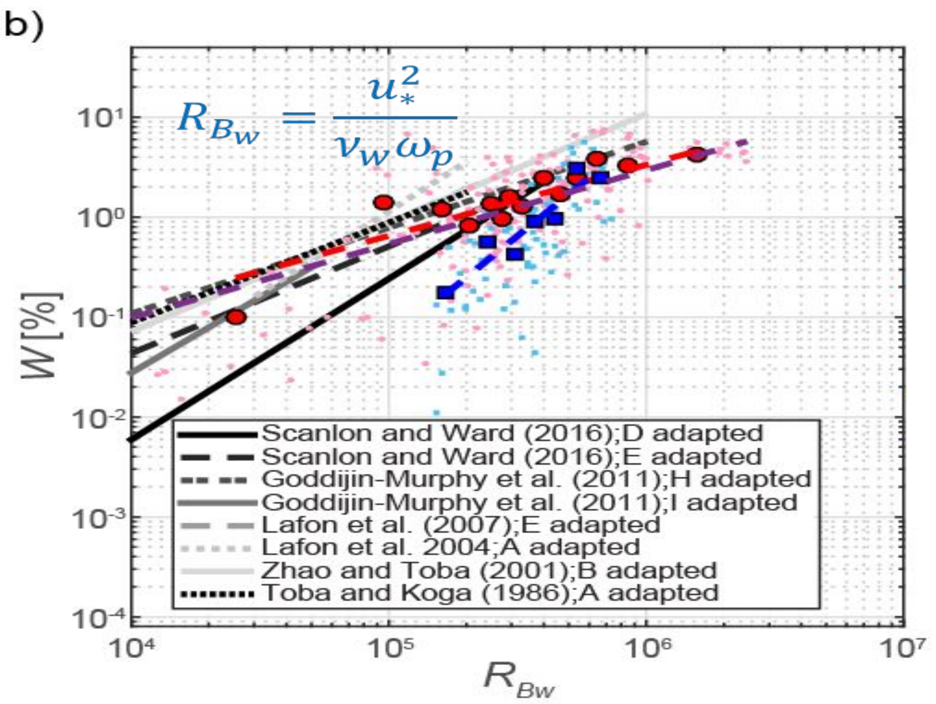
Brumer et al. (2017, JPO)

Whitecap parametrizations – HiWinGS & SO GasEx Results

Wave-wind Reynolds number



Breaking Reynolds number



Brumer et al. (2017, JPO)

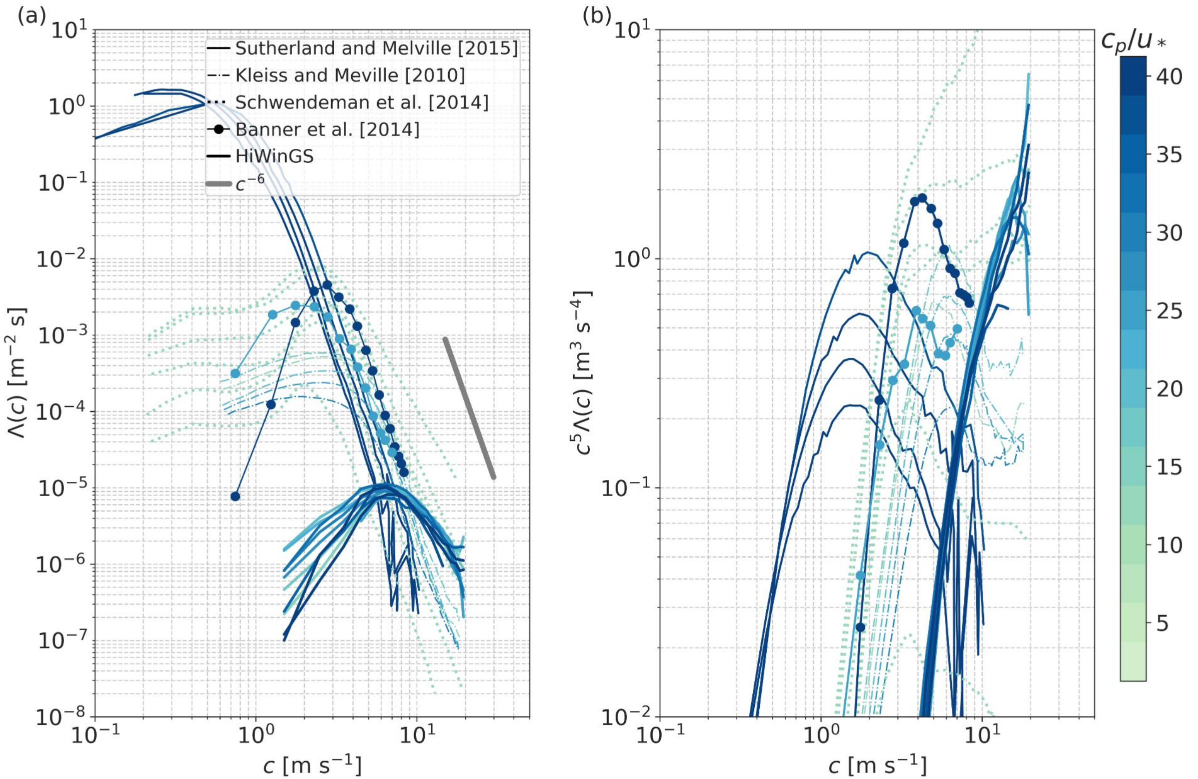
Breaking crest length distributions (Λ)

Λ framework links breaking scales (length & velocity) to upper ocean TKE dissipation rates *(Philips 1985)* + bubble flux (Deike et al. 2017)

NB: different image analysis techniques used by the different groups

HiWinGS

- much younger seas and higher winds than previously
- Poor fit to scaling proposed in literature



Brumer and Zappa (2020)

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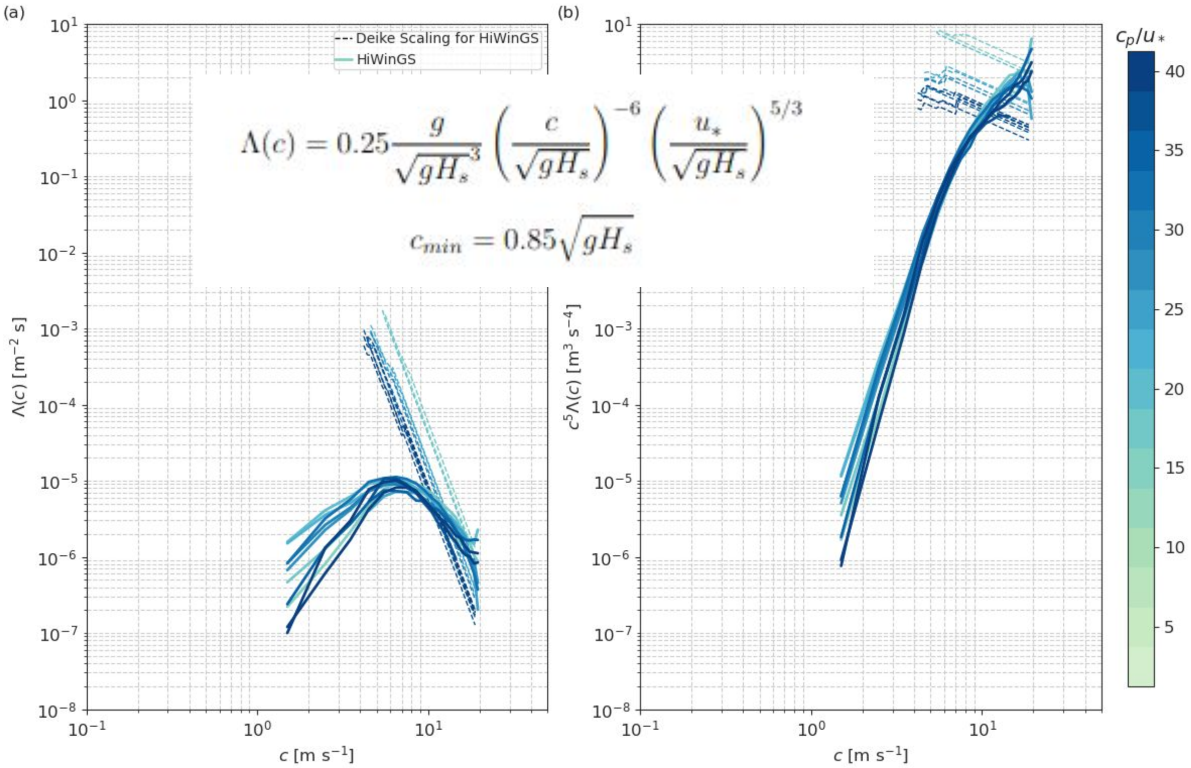


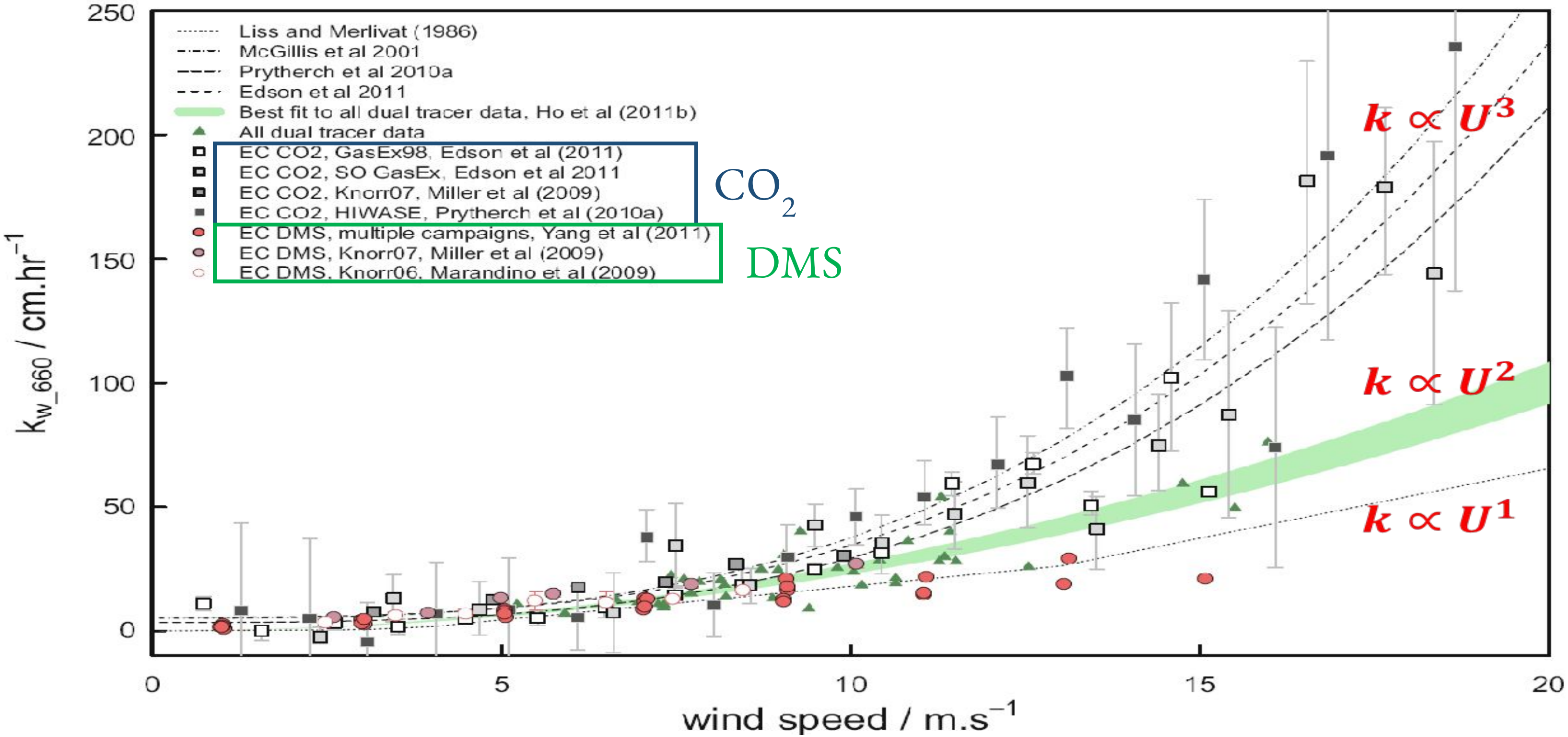
$$\Lambda(c) = 0.25\frac{g}{\sqrt{gH_s}^3}\left(\frac{c}{\sqrt{gH_s}}\right)^{-6}\left(\frac{u_*}{\sqrt{gH_s}}\right)^{5/3}$$

$$c_{min} = 0.85\sqrt{gH_s}$$

Brumer and Zappa (2020)

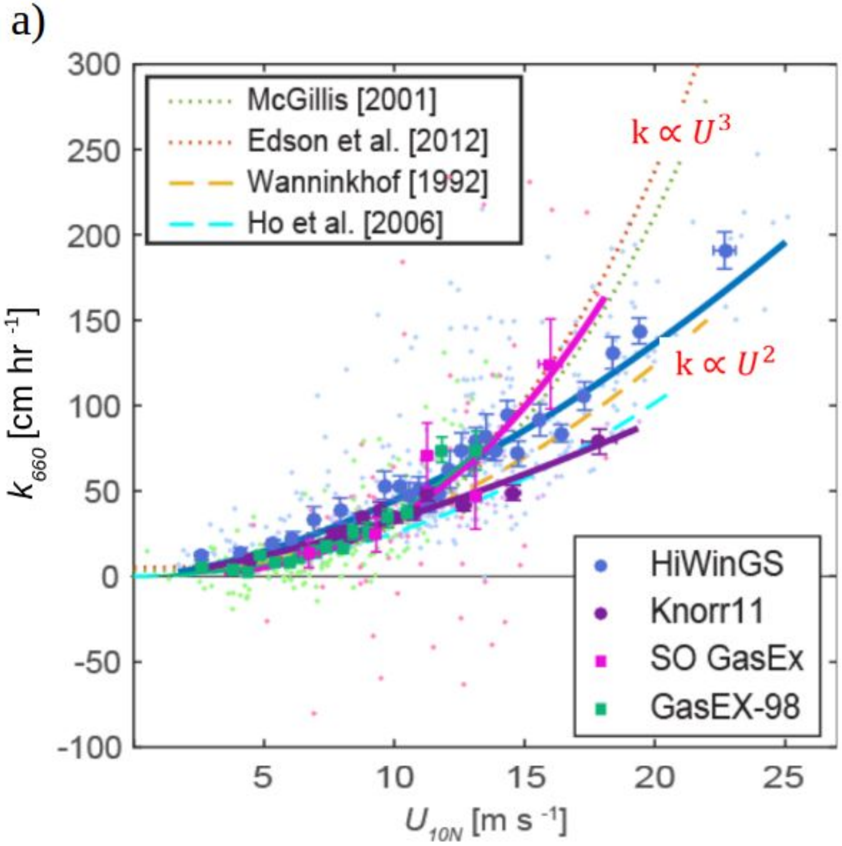
Gaz transfer

The k-conundrum



Garbe et al., (2014)

Single parameter parametrization – CO_2

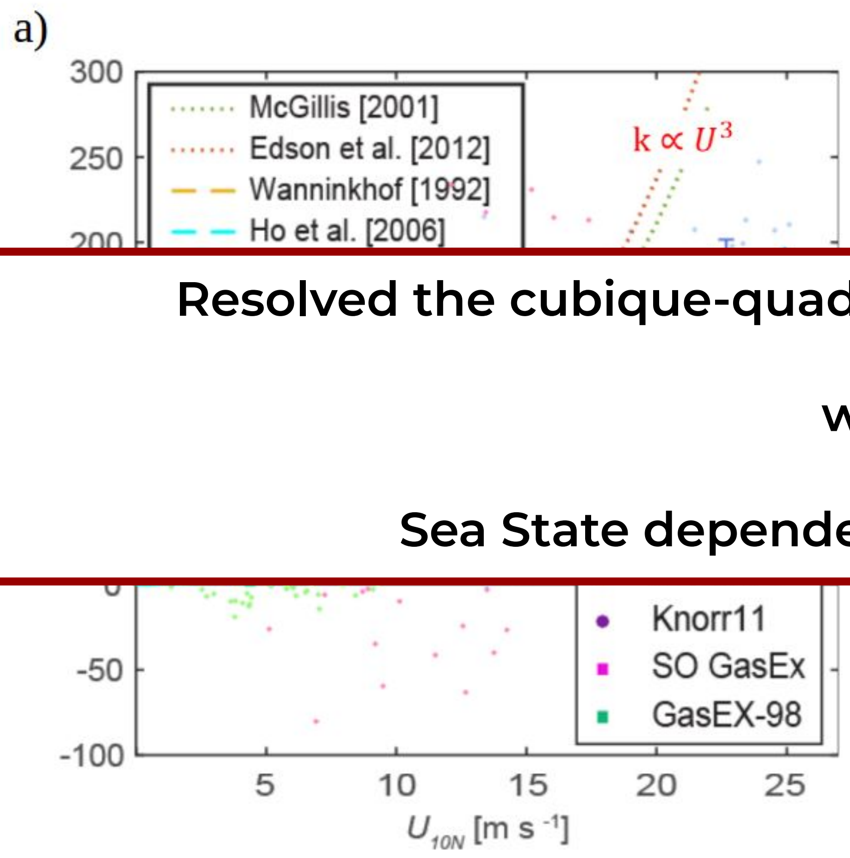


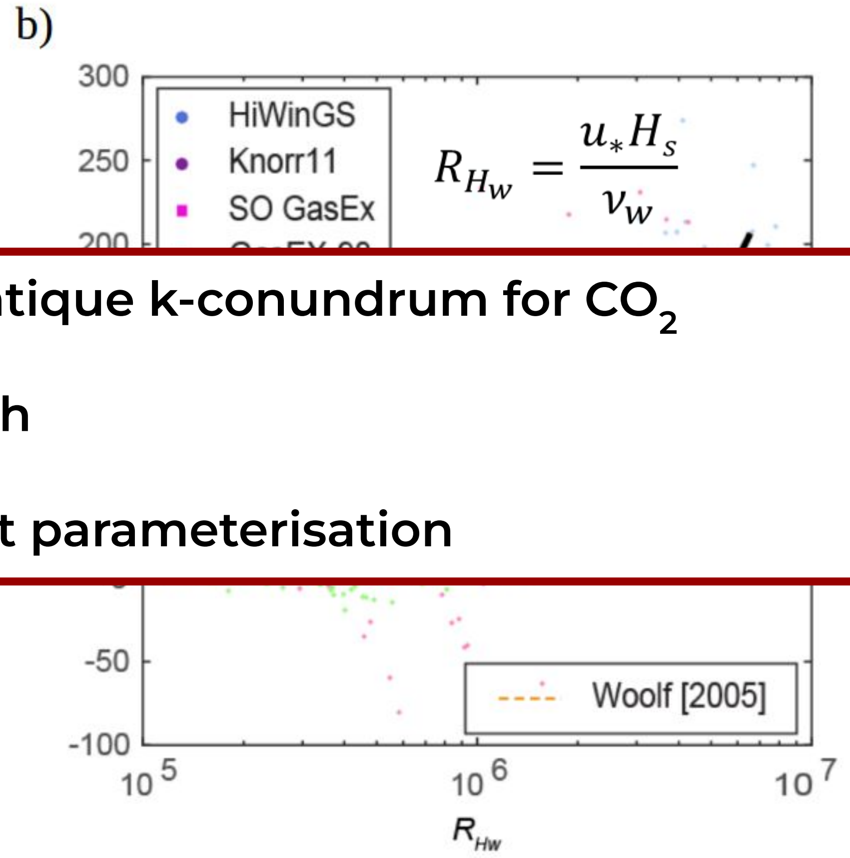
4 distinct
open ocean data sets

Large discrepancies in trends:

- GasEx-98 & SO GasEx close to cubic U_{10N} dependence
- HiWinGS & Knorr11 lower than quadratic dependence

Single parameter parametrization – CO_2



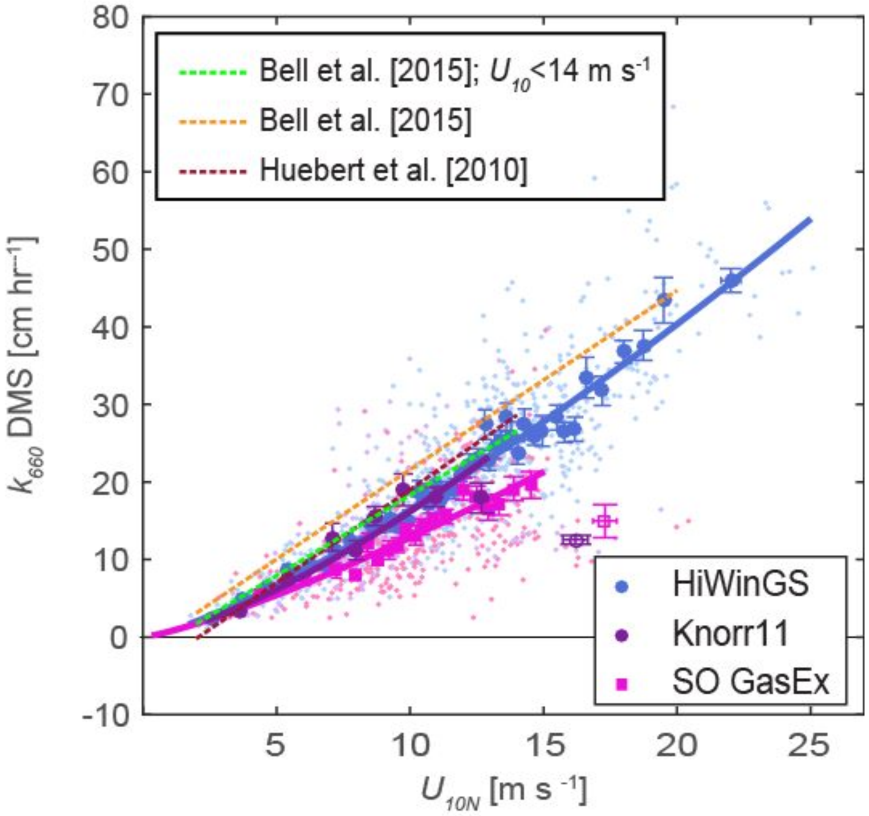


Resolved the cubique-quadratique k-conundrum for CO_2

with

Sea State dependent parameterisation

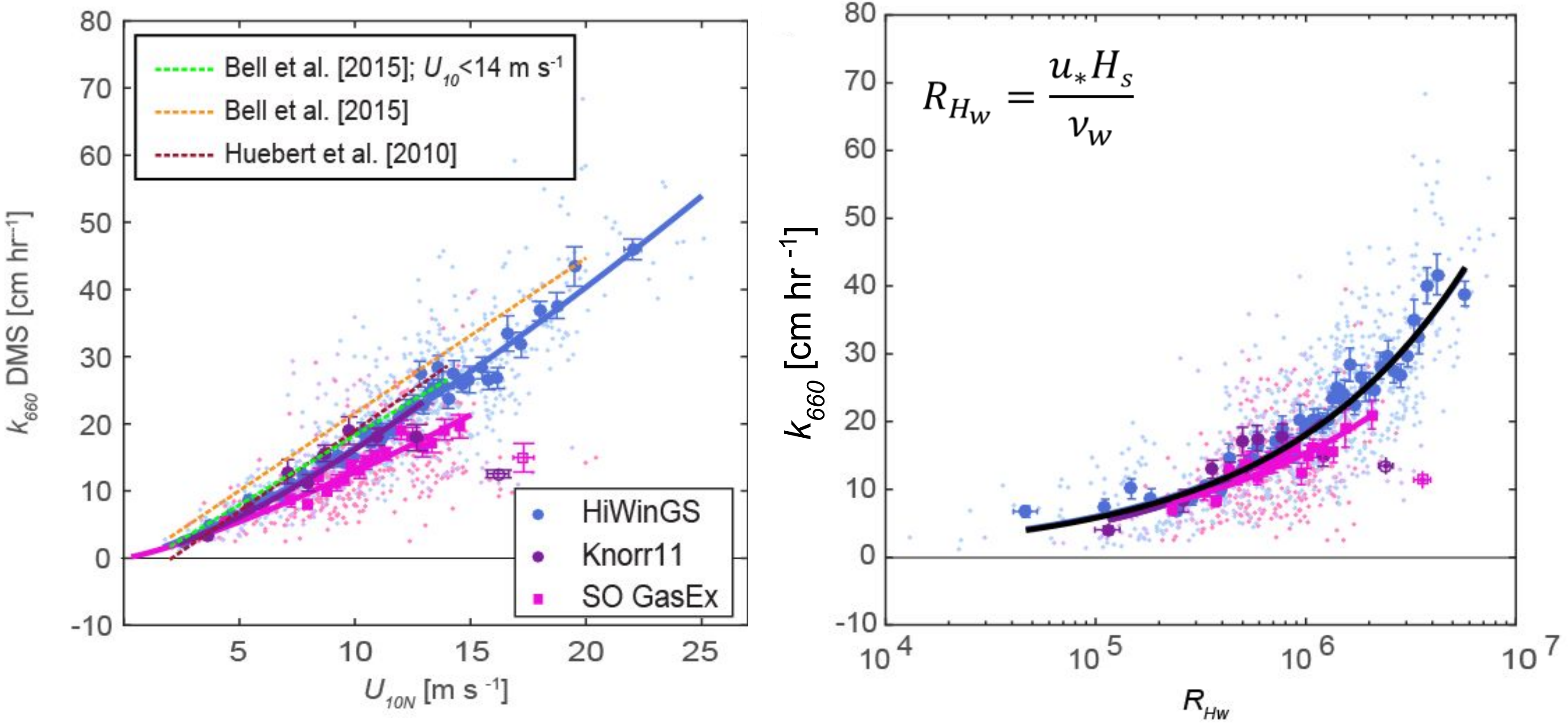
Single parameter parametrization – DMS



3 distinct
open ocean data sets

- near linear dependence for all
- SO GasEx lower than HiWinGS at all wind speeds
- outliers at U_{10N} > 15 m s^{-1} in SO GasEX and Knorr11 datasets

Single parameter parametrization - DMS



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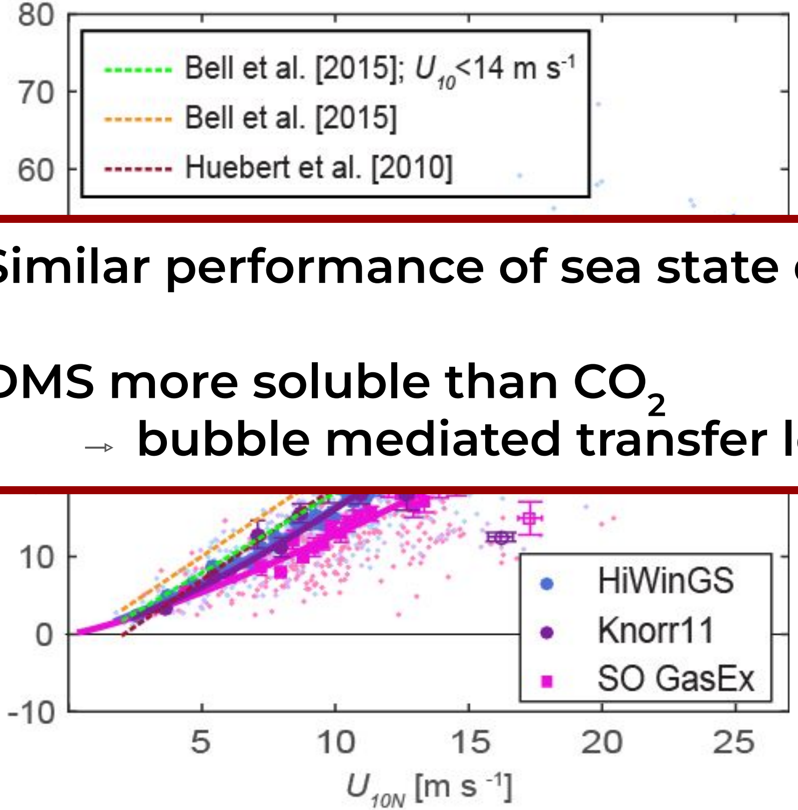
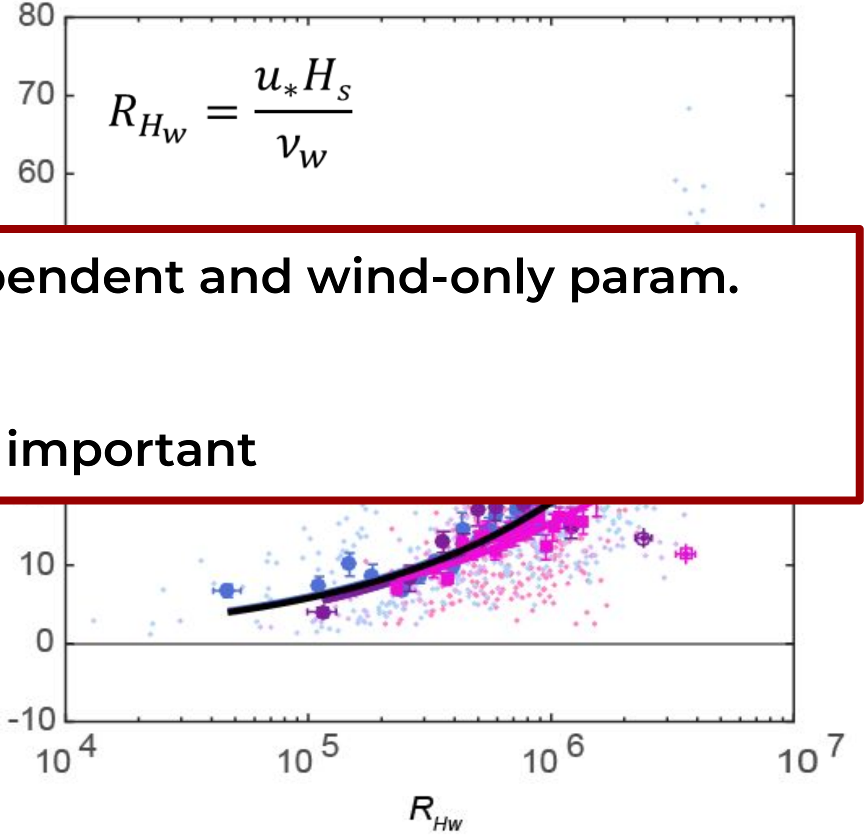




- Similar performance of sea state dependent and wind-only param.

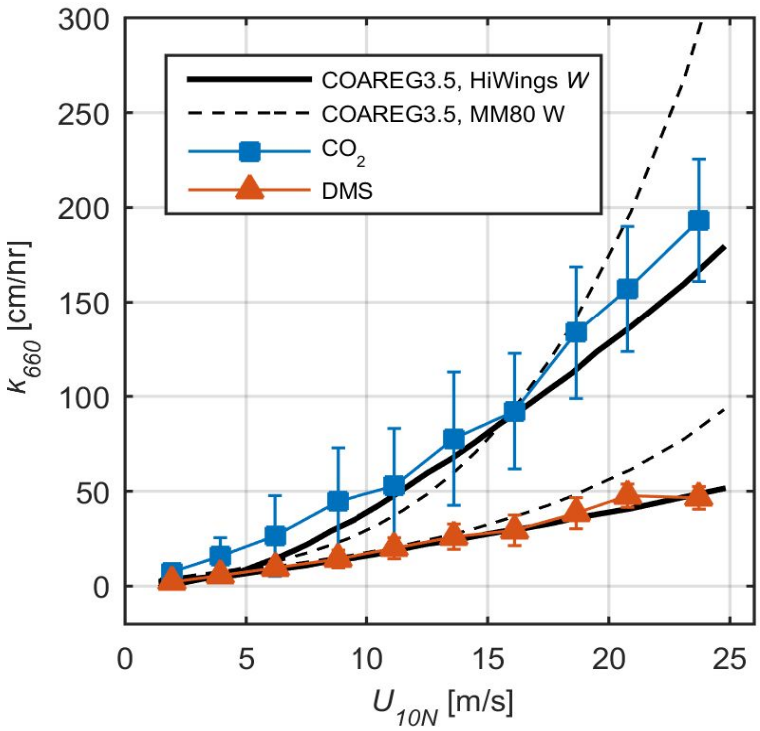
- DMS more soluble than CO_2
  → bubble mediated transfer less important

Mechanistic models

NOAA-COAREG *(Blomquist et al. 2017, Fairall et al. 2022)* :

$$k = \left[(k_w + k_b)^{-1} + s k_a^{-1}\right]^{-1}$$

Friction Velocity — Whitecap Coverage



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Friction Velocity   Whitecap Coverage

Deike and Melville (2018); Reichl and Deike (2020) :

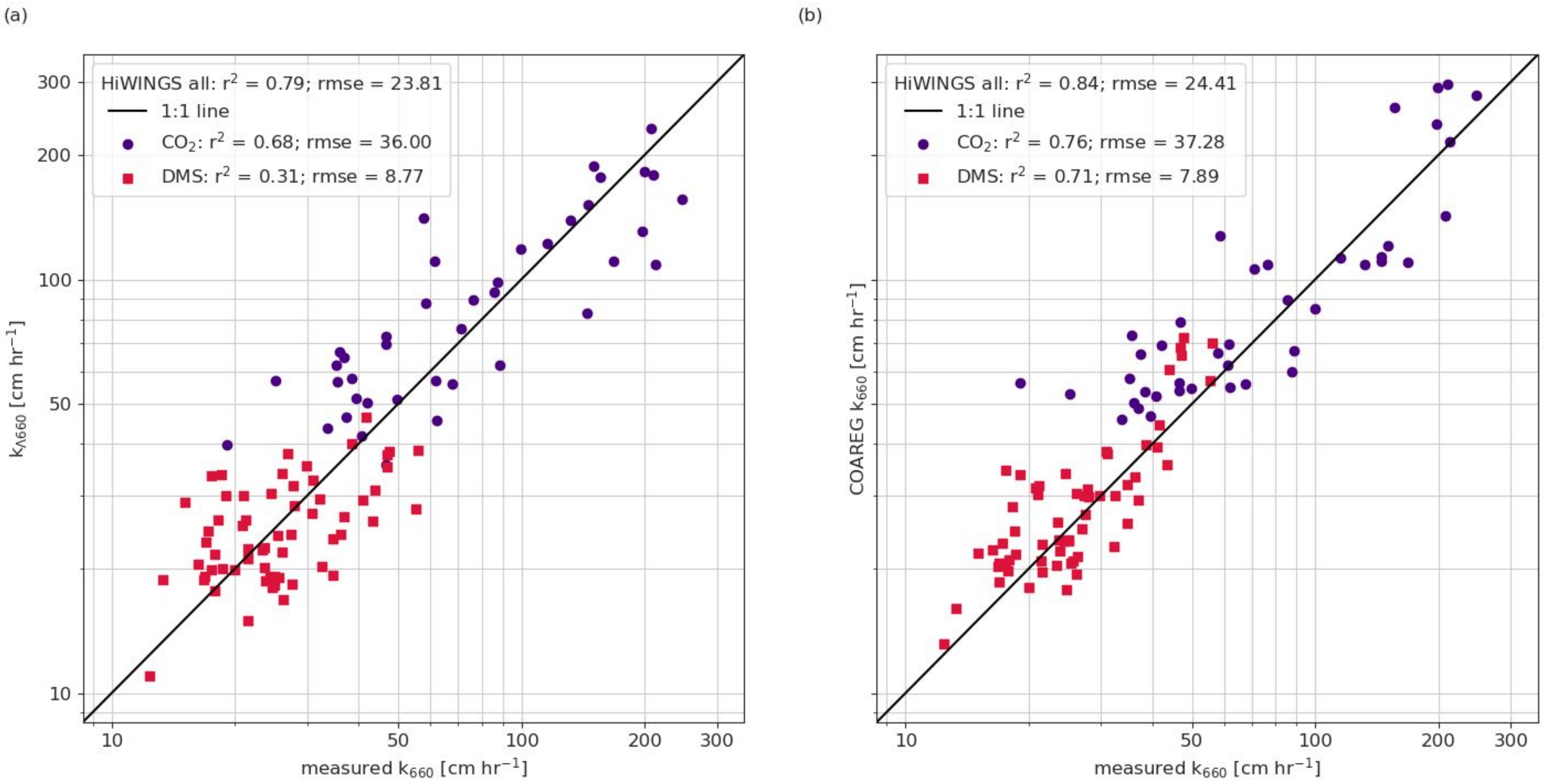
$$k_{\mathrm{w}}^{\mathrm{simple}} = k_{\mathrm{nb}} + k_{\mathrm{b}}^{\mathrm{simple}}, \text{ with } k_{\mathrm{b}}^{\mathrm{simple}} = \left[\frac{A_{\mathrm{B}}}{\alpha}\left(u_*^{5/3}\sqrt{gH_{\mathrm{s}}}^{4/3}\right)\right]\left(\frac{Sc}{660}\right)^{-1/2}$$

Alternative functional form:

$$k = k_\varepsilon + k_b$$

TKE Dissipation Rate   Whitecap Coverage & Volume of Air Entrained by Bubbles

Mechanistic models – COAREG & Λ dependent



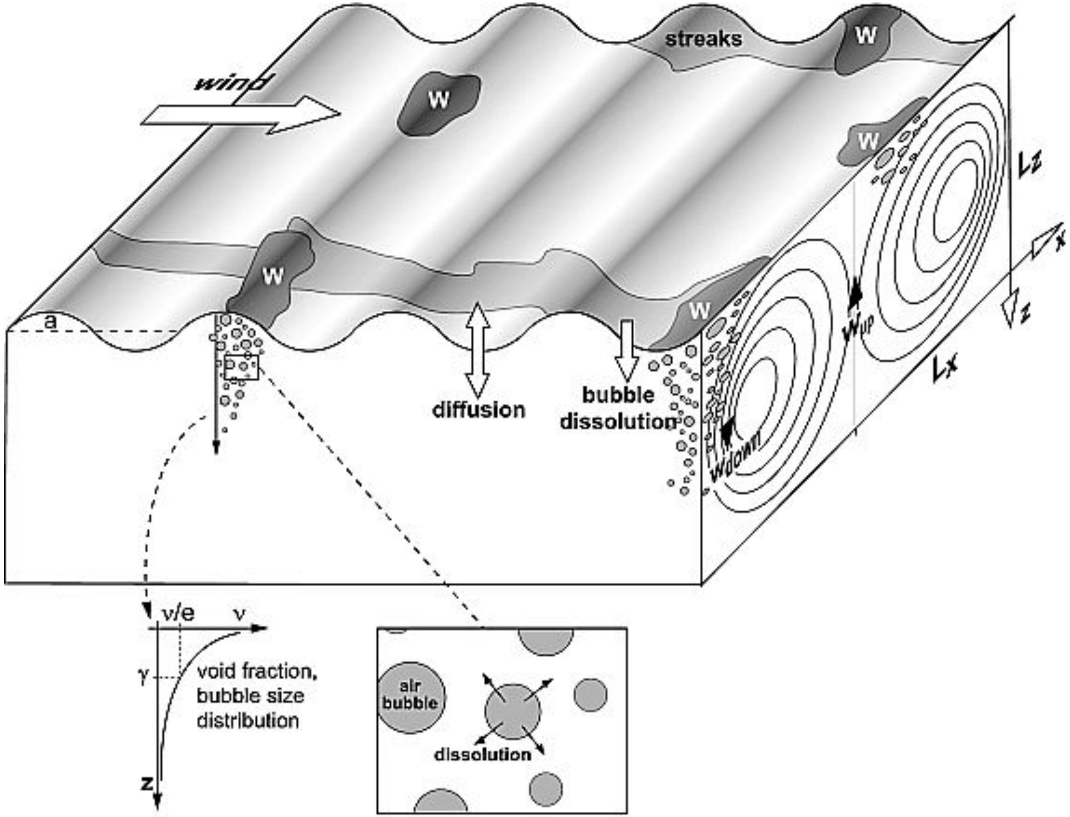
Brumer and Zappa (2020)

Impact of Langmuir cells

Langmuir cells enhance the contribution from bubbles by keeping them under water for longer thus increasing their dissolution

Chiba and Baschek (2010) model depending on:

- active white cap coverage
- duration of wave breaking,
- injected void fraction as function of depth and wave height
- cell sizes
- dowelling velocities



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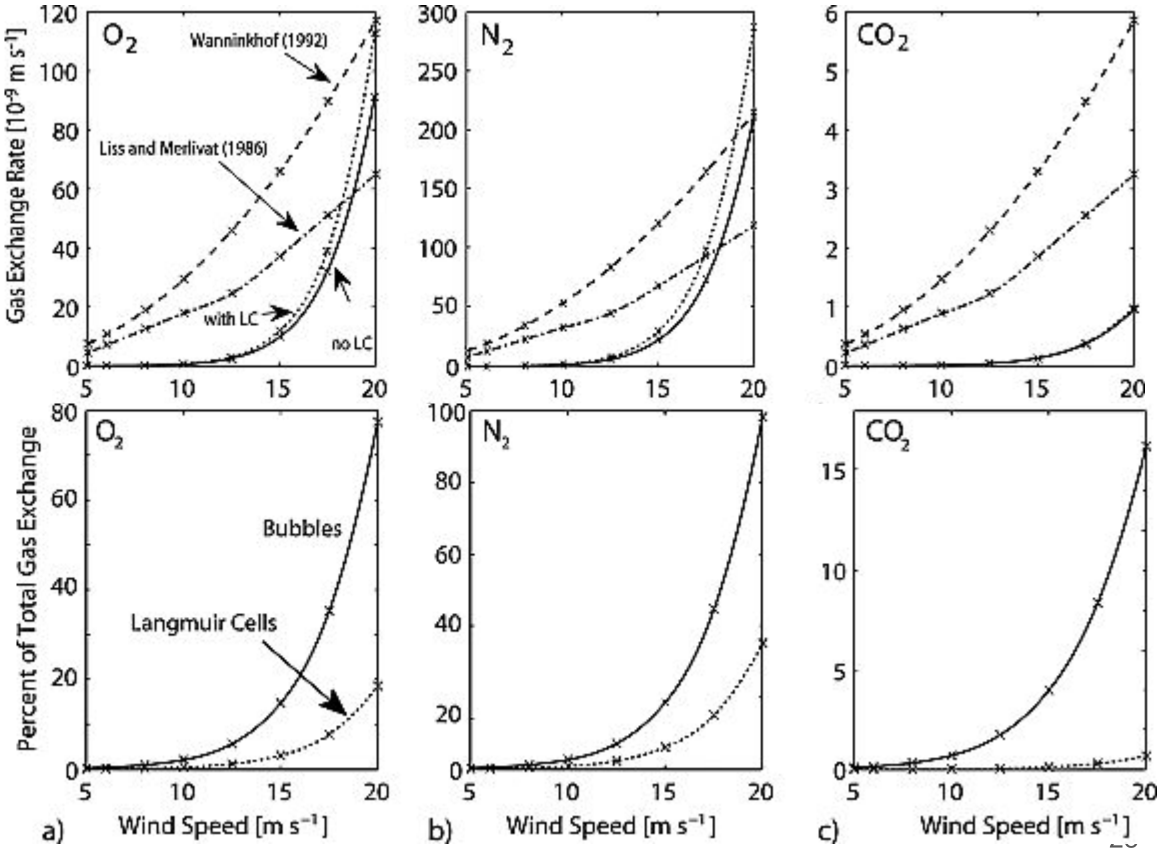
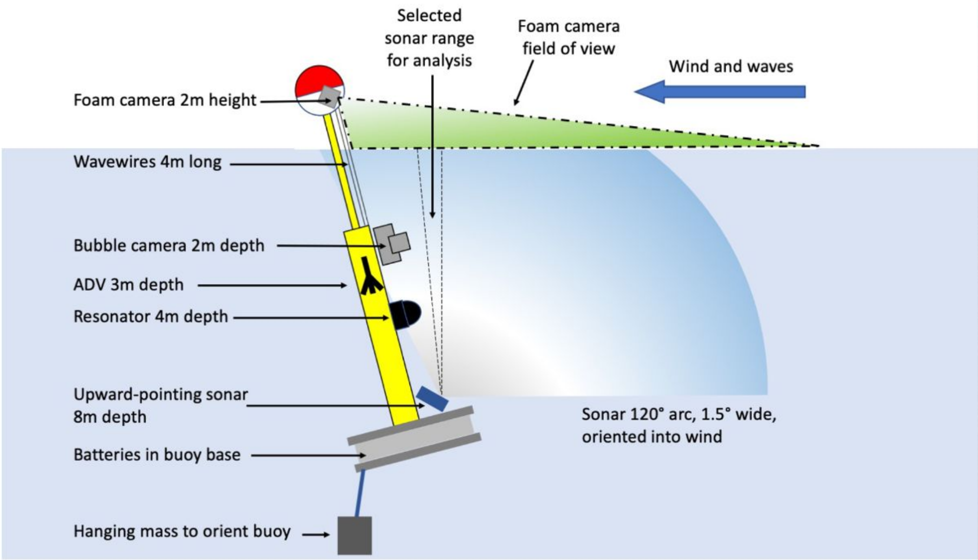
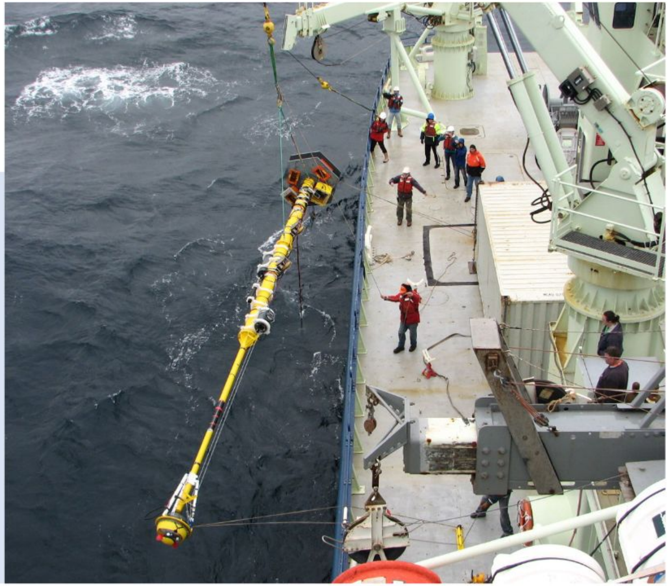


Bubbles

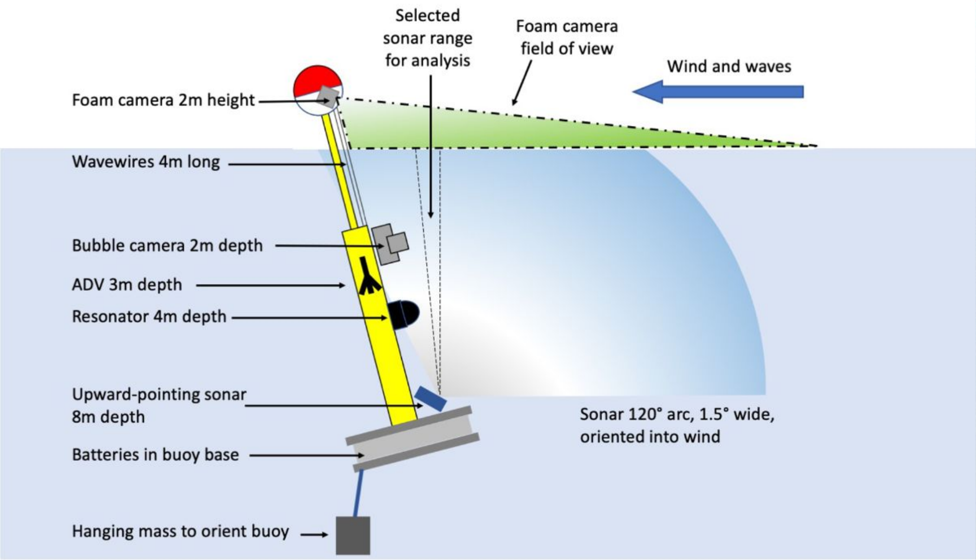
HiWinGS Results

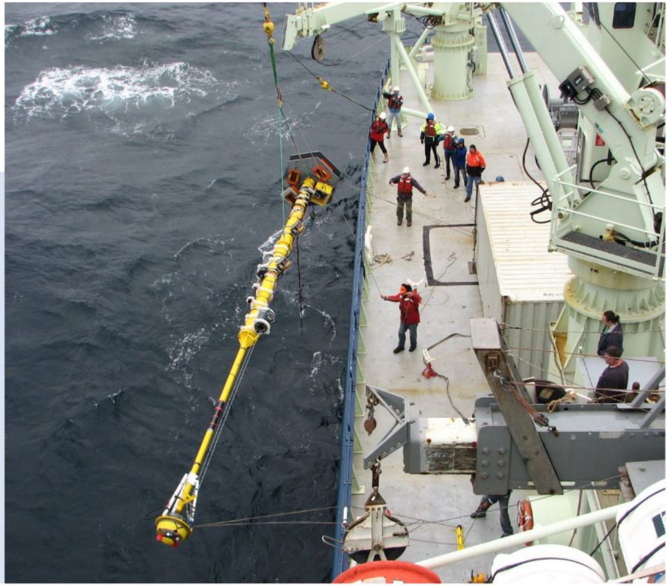




Czerski et al. (2022)

HiWinGS Results





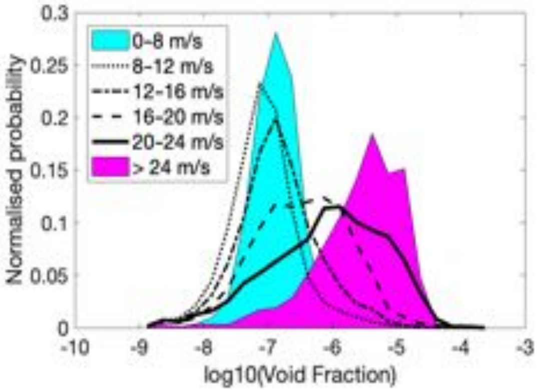
Czerski et al. (2022): "It has proven challenging to develop a robust relationship between sea state, water conditions and a quantitative description of subsurface bubble plumes."

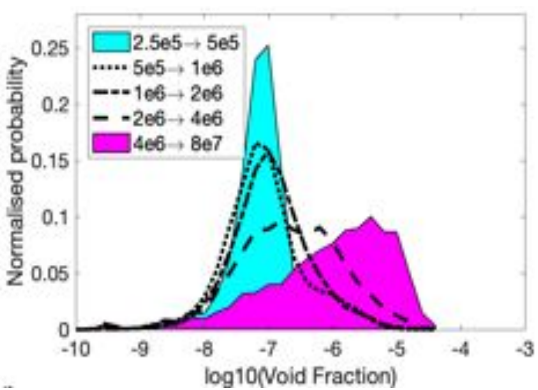
In situ measurements are rare and don't give the whole picture: shallow and deep plumes, horizontal advection, Langmuir entrainment

HiWinGS Results

Probability distribution of void fraction at 2 m depth

- Very similar below wind speeds of 16 m s^{-1} or a wind-wave Reynolds number of 2 x 10^6 in all conditions
- Increases significantly above either threshold.





HiWinGS Results

Probability distribution of void fraction at 2 m depth

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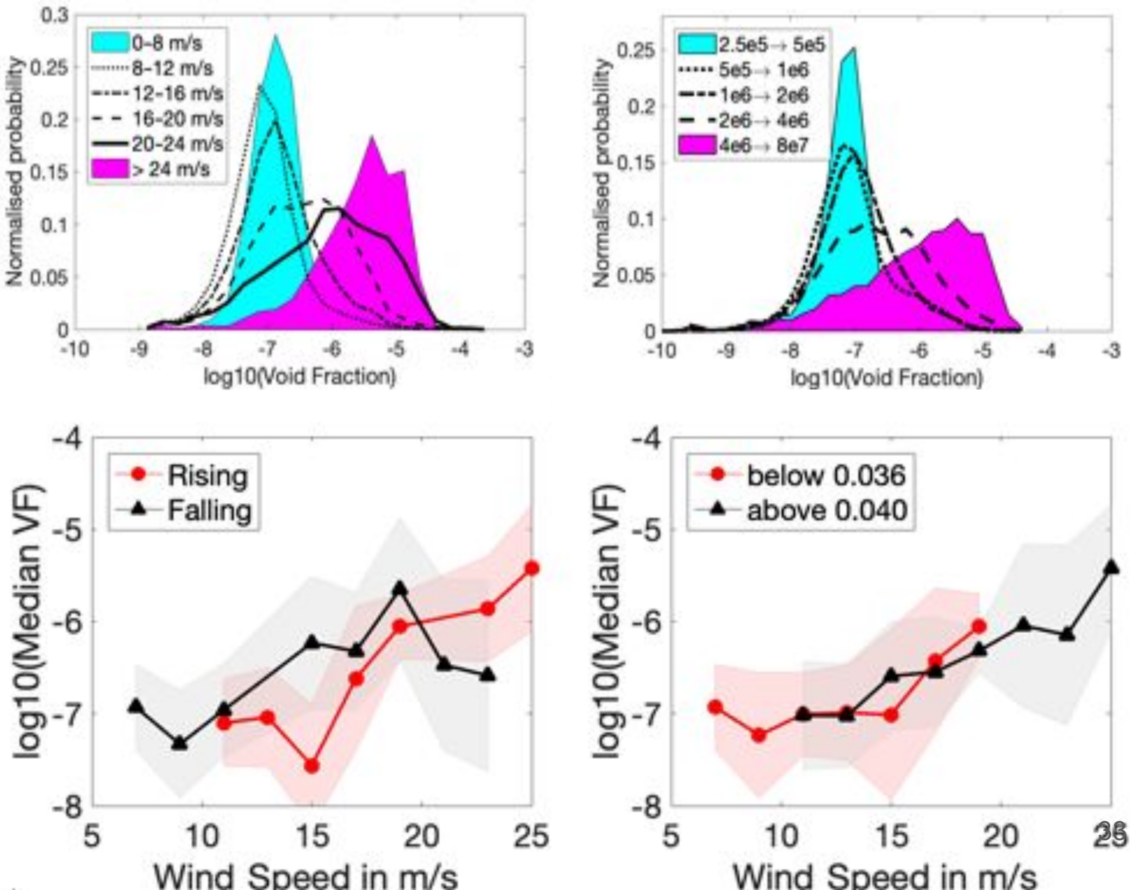
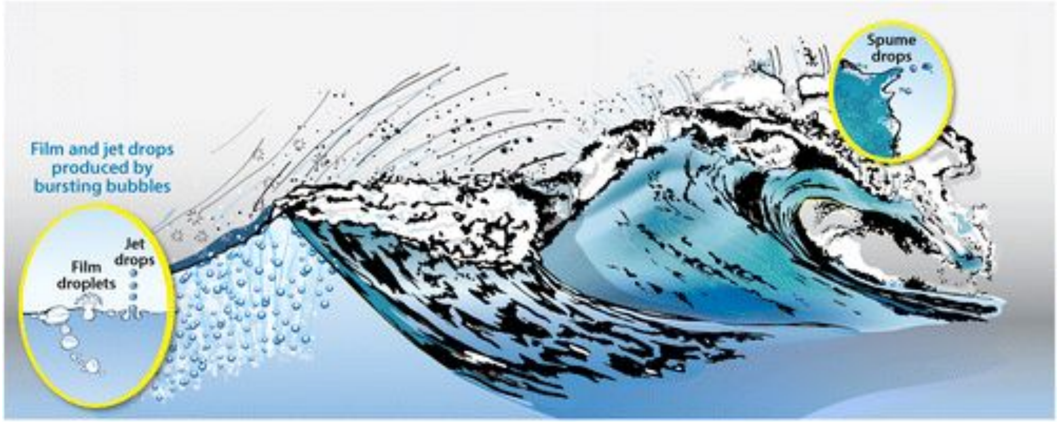
Void fractions at 2 m depth

- significantly different during periods of rising and falling winds
- no distinction with wave age



Sea Spray

Types of sea spray



Veron F. 2015.
Annu. Rev. Fluid Mech. 47:507–38

- Bubble-Generated
  - Film Drops (r_0 = 0.01–2 μm)
  - Jet Drops (r_0 = 2–200 μm)
- Spume Drops (r_0 = 10–2300 μm)

Sea Spray Aerosols

Sea Spray Aerosols Source Functions

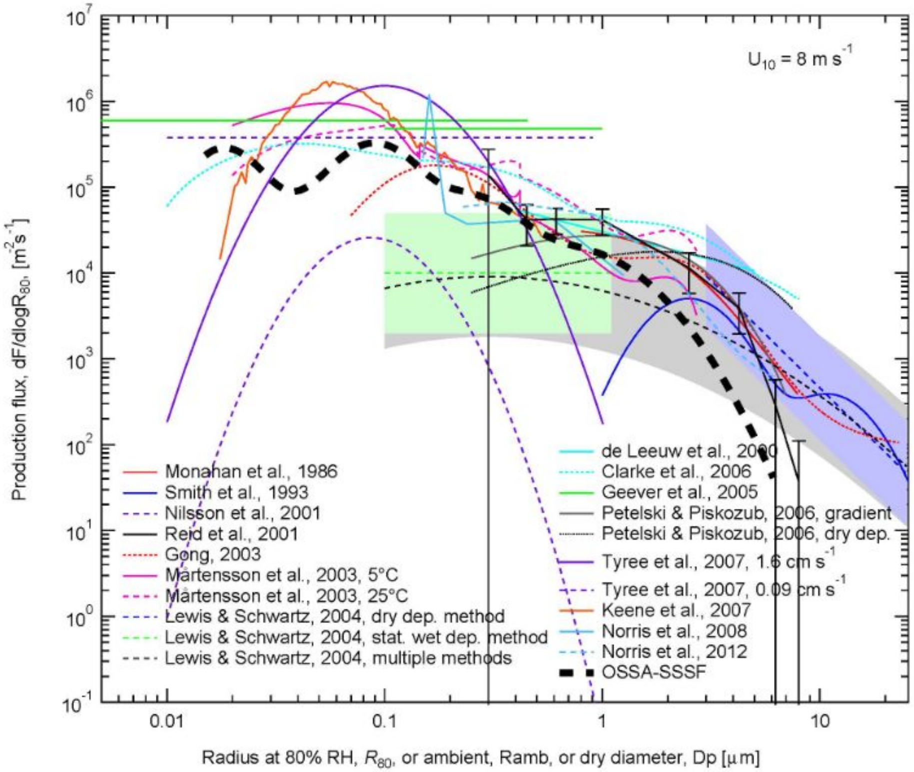
$$\frac{dF}{dr_0} = f_1(U_{10}, W, ...)f_2(r_0)$$

Dependence on environmental parameters

Size Spectrum

Wave dependent parameters considered:

- Whitecapping
  (Shi et al., 2020; Hartery et al., 2020)
- Wave age
  (Varlas et al., 2021)
- Wave Steepness
  (Bruch et al. 2021)
- Wave dependent Reynold numbers
  (Norris et al. 2013; Ovadnevaite et al. (2014); Shi et al., 2016; Bruch et al. 2021)



Ovadnevaite et al. (2014)

Rising vs Falling winds

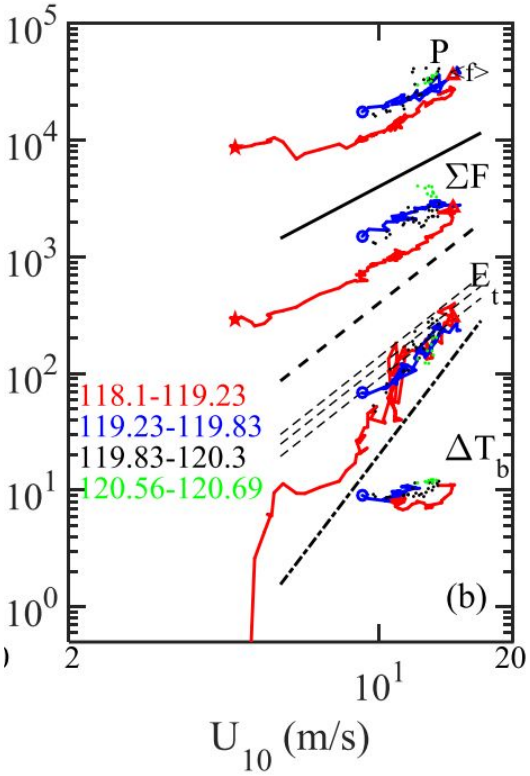
Breaking Wave Experiment: BREWEX on-board FLIP

- U10 ranging between 1.9 and 15.6 m/s
- Simultaneous measurements of:
  - sea spray aerosol (∑F)
  - Wind - waves dissipation (Et)
  - microwave brightness temperature (Tb)
  - underwater acoustic (P) → bubble detachment or splitting ("screaming infant microbubbles")

→ Distinct properties in rising winds (red) & falling winds (blue)

→ Higher SSA volume in falling winds / older seas

→ Similar trend is found in the short scale roughness



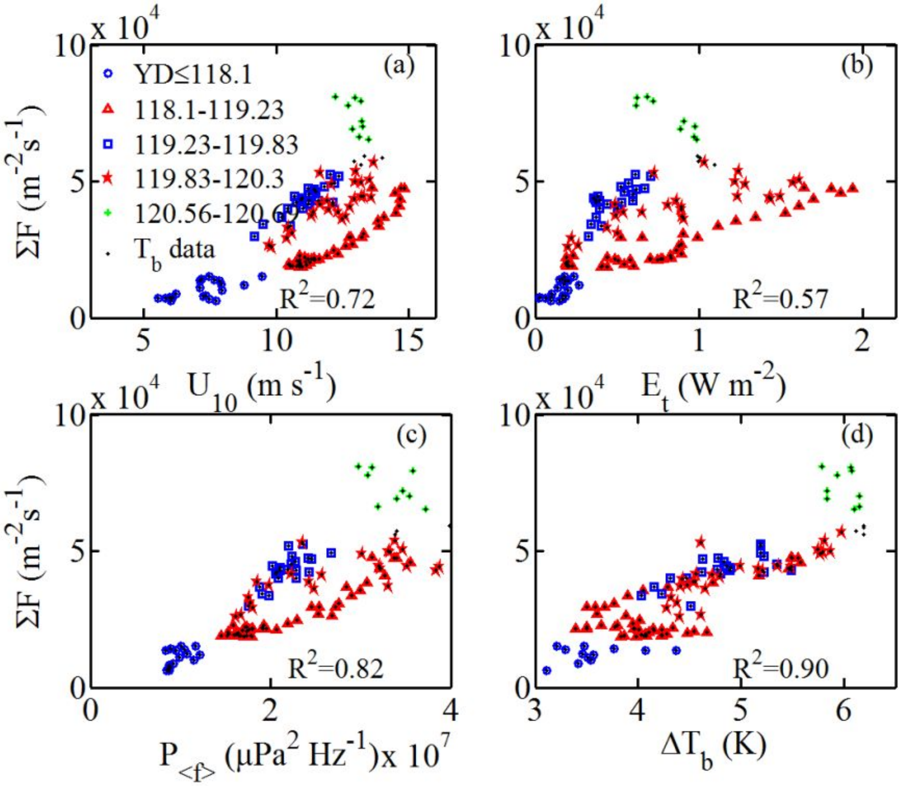
Hwang et al. (2019)

Rising vs Falling winds

- length scale of wave breaking shorter in mixed seas than in wind seas

- Breaking more violent in rising winds
  → entrains larger air cavities
  → short lifetime
  → not broken down to smaller bubbles
  → inefficient SSA generation

- Wind wave TKE dissipation is not a good candidate for single-variable parameterization

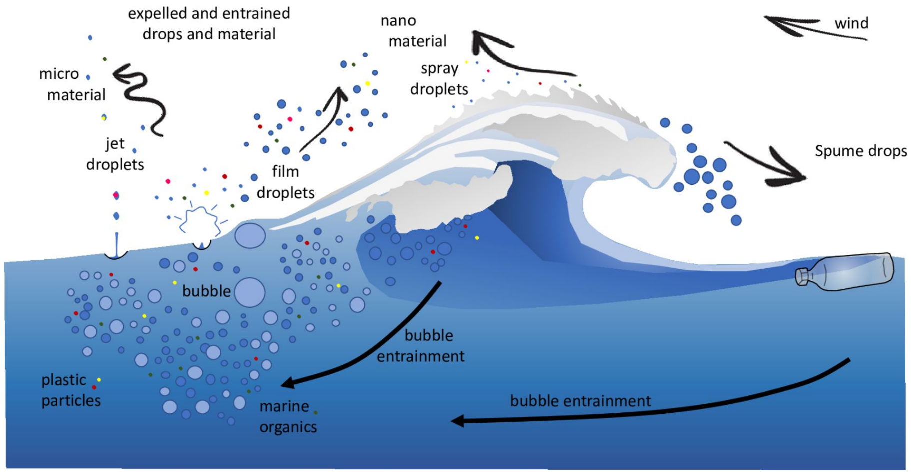


Hwang et al. (2019)

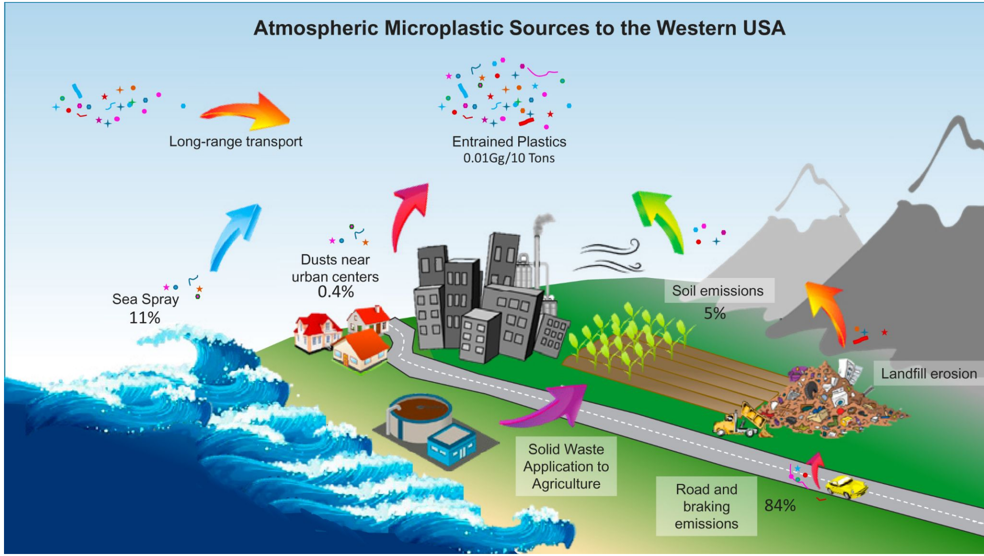
Water to Air Plastics Exchange

Negative mass balance of entering (4-13 Tg/y) vs. detected marine plastic debris (0.3 Tg)
→ “missing” plastic *(Eriksen et al. 2014)*

Air mass back trajectories consistent with local emissions in remote marine atmosphere (North Atlantic)
→ Sea Spray ejection of plastics *(Trainic et al. 2020)*



Allen et al. (2020)



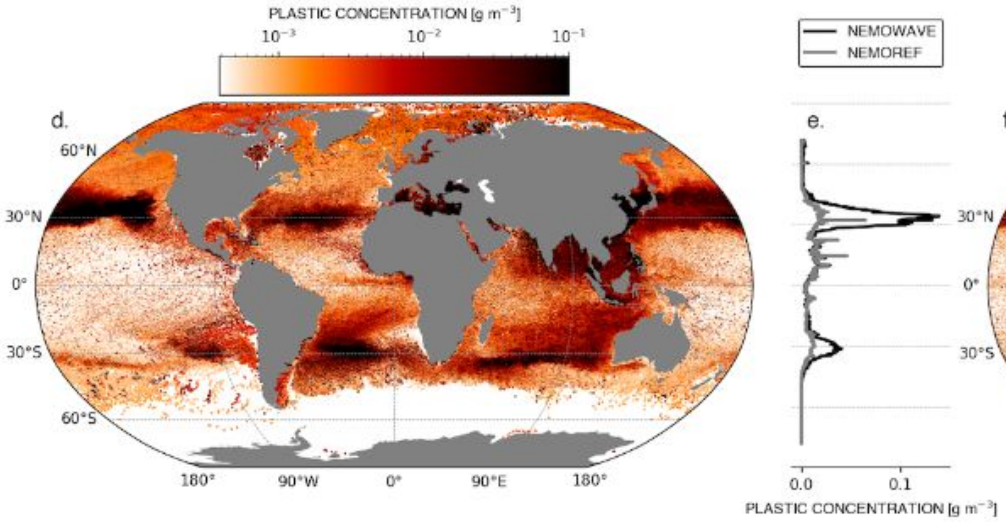
Brahney et al. (2021)

BubblePlast

GOALS:

1. **Qualitative and quantitative characterization of water-to-air transfer of MP/NPs**
2. **Improve atmospheric and ocean models of MPs/NPs, and their coupling**

Evaluate the influence of waves on MPs and NPs surface concentrations
Test and adapt sea state vs. wind-only ocean-atmosphere SSA source functions for MPs/NPs



Bajon et al. (2024)

Dropplets

Sea Spray Generation Functions

More recent ones varying shape spectrum

$$\frac{dF}{dr_0} = f_1(U_{10}, W, \ldots) f_2(r_0)$$

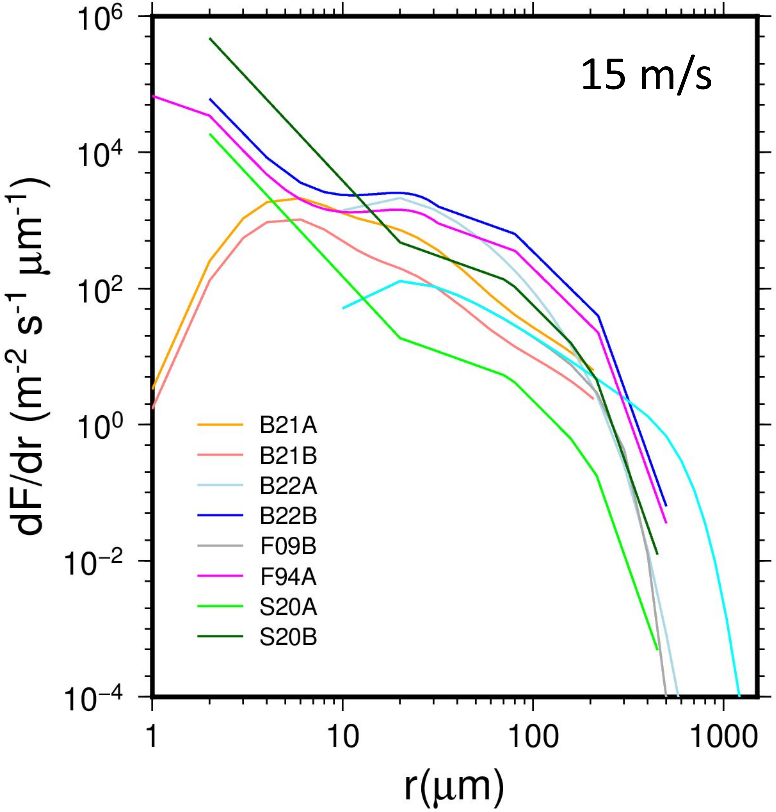
Dependence on environmental parameters → f_1; Size Spectrum → f_2

Environmental parameters considered:

- Wind speed or friction velocity
  (e.g. Fairall et al., 1994)
- Wave Breaking Dissipation
  (Fairall et al., 2009; Lenain & Melville, 2017; Deike, 2021, Barr et al. 2022)
- Whitecapping
  (Shi et al., 2020)
- Wave dependent Reynold numbers / wave age
  (Troitskaya et al., 2018)

NB:

- Scarce in situ measurements for $r_0 > 20$ µm
- Scaling of results of lab experiments not straightforward



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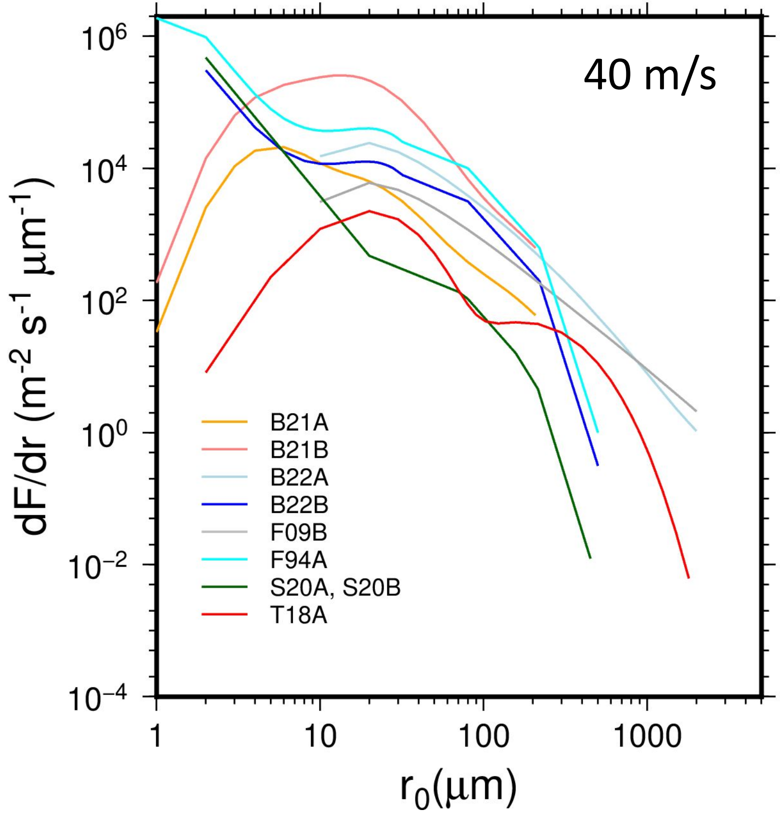
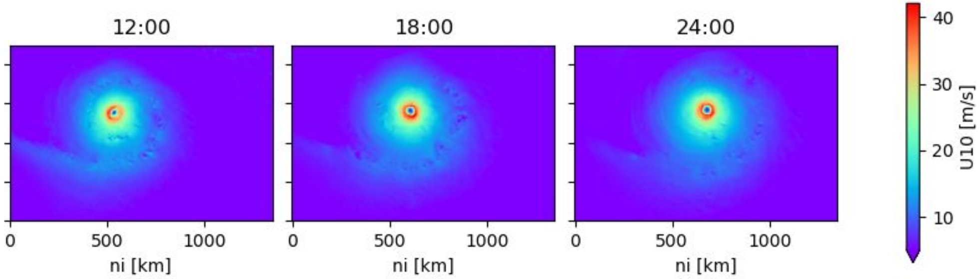
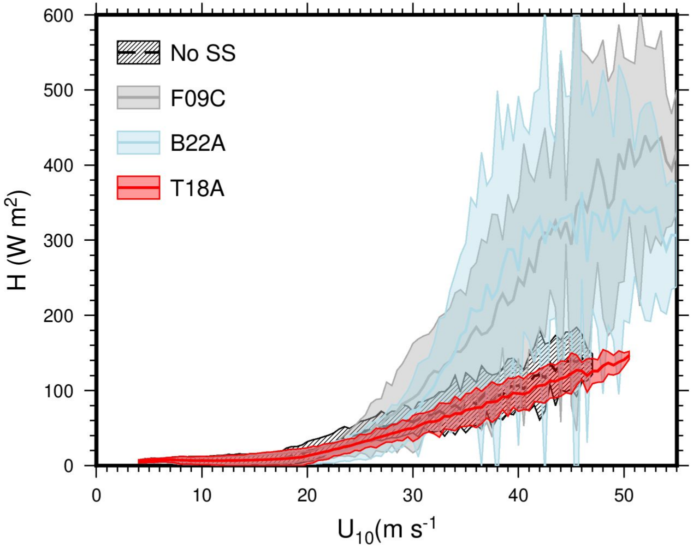
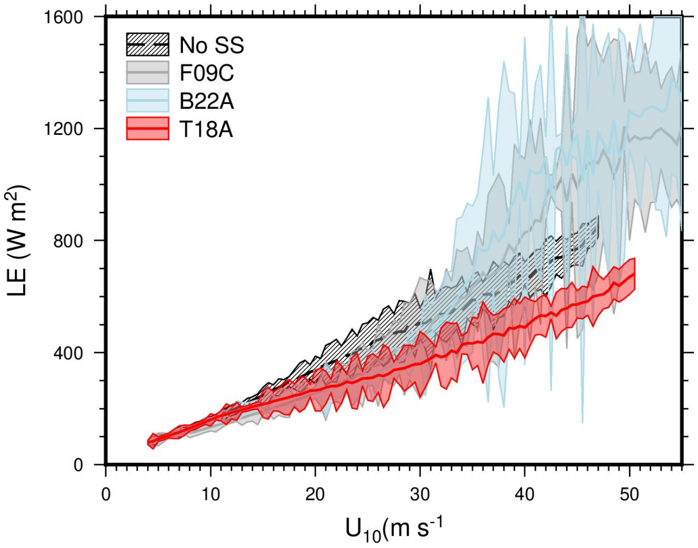


Sea spray impacts on heat fluxes

Coupled wave-atmosphere simulations of an idealize translating vortex





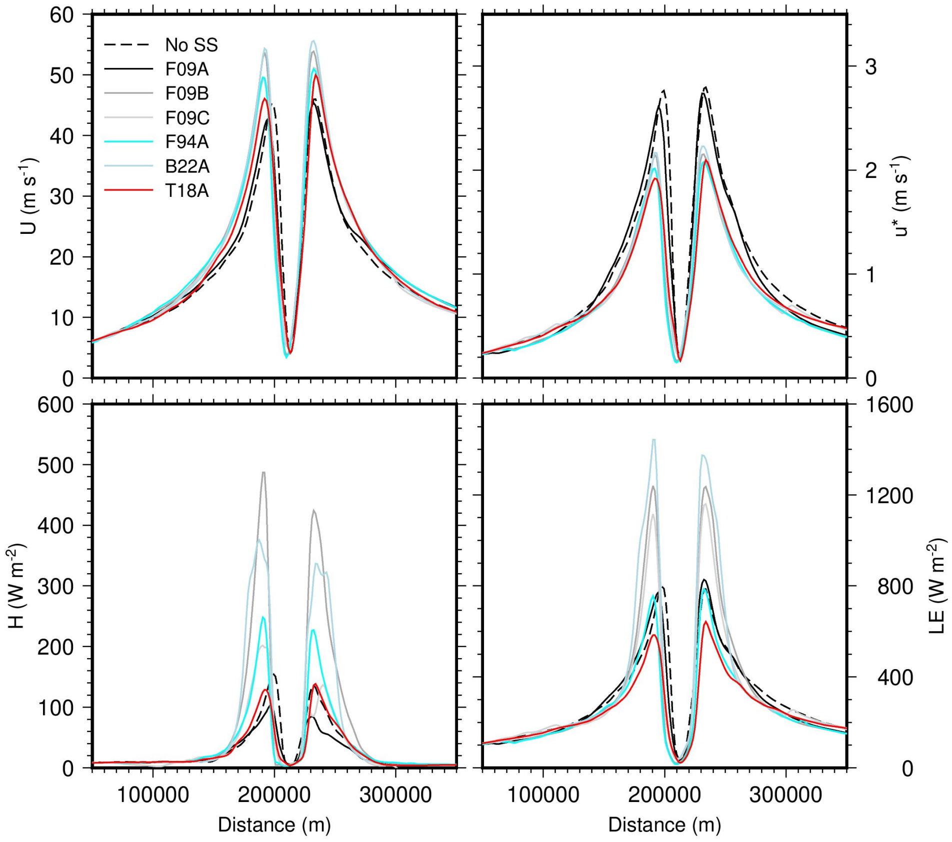


Sea spray impacts on heat and momentum fluxes

Coupled wave-atmosphere simulations of an idealize translating vortex

Following Bao et al. (2011)

- Sea Spray increases intensity for all SSGFs
- Distinct impacts on heat fluxes, mostly enhanced but for T18

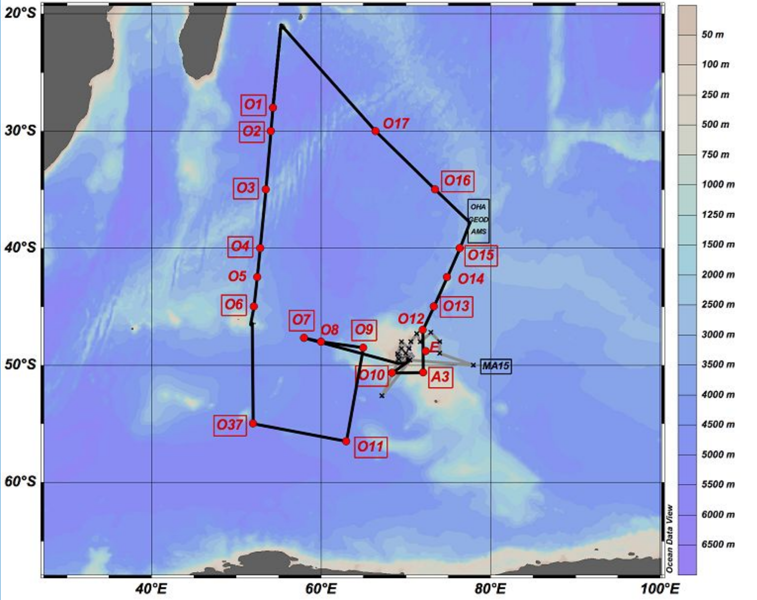


Exploratory Project IDEA

Goals :

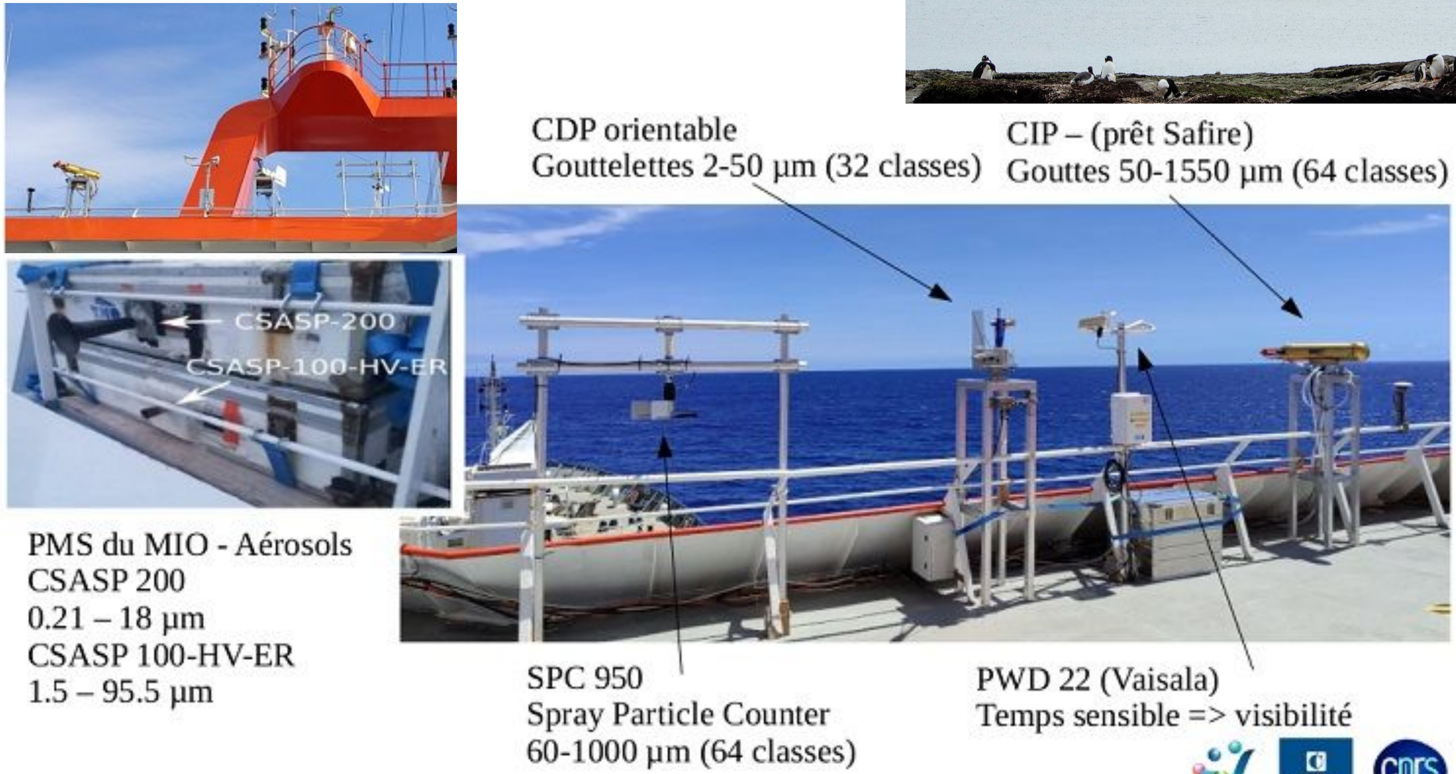
1. Evaluate the benefits of **introducing sea spray explicitly into microphysical schemes**, as opposed to current surface schemes.
   → coupled ideal & realistic simulations WAVEWATCH-MesoNH with LIMA
   → adapting sea spray param.

2. Sample the full size distribution of sea spray as an extension to ongoing aerosol sampling onboard the Marion-Dufresne (MAP-IO project)
   → OBSAUSTRAL 2024 (11 jan. – 08 mar.)



Exploratory Project IDEA

OBS-Austral 2024



IDEA – F. Burnet et al

Going Beyond

Coupled modeling

- Insure **coherent**
  - measured and modeled sea state parameters & breaking statistics
  - coupling strategy in terms of spatio-temporal resolution & parametrizations
    - Measurements & bulk approach assume homogeneity over ~15 minutes & fetch dependent footprint (not really quantified)
    - Used in climate to 100 m scale atmospheric modeling

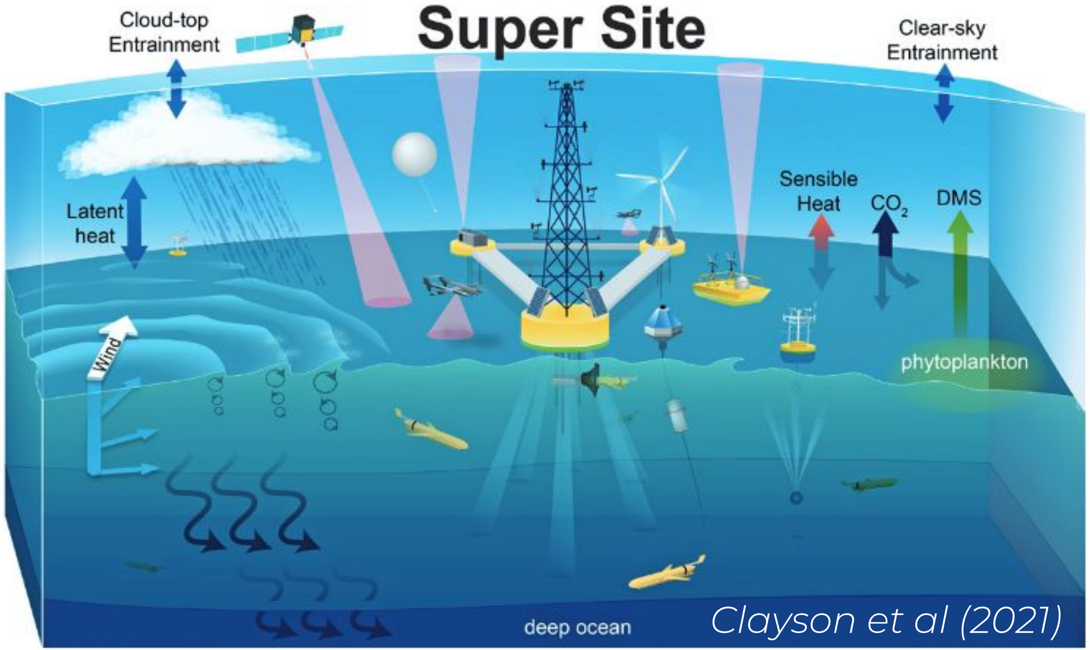
- Improve practical **mechanistic models**

- Seek appropriate **coupling variables** to better represent variability (beyond Hs, Tp, alpha)

Observations

- More **comprehensive** field observations targeting varied geophysical conditions; wave & breaking measurements are still too often excluded
- **Unifying** measurements and analysis techniques
- **Revisiting historic datasets** complemented by wave model hindcasts

Observations



- multi-year suites of measurements at specific locations to simultaneously
- characterize physical and biogeochemical processes at high spatial and temporal resolution

Thank you!