The wave-mediated ocean-atmosphere system

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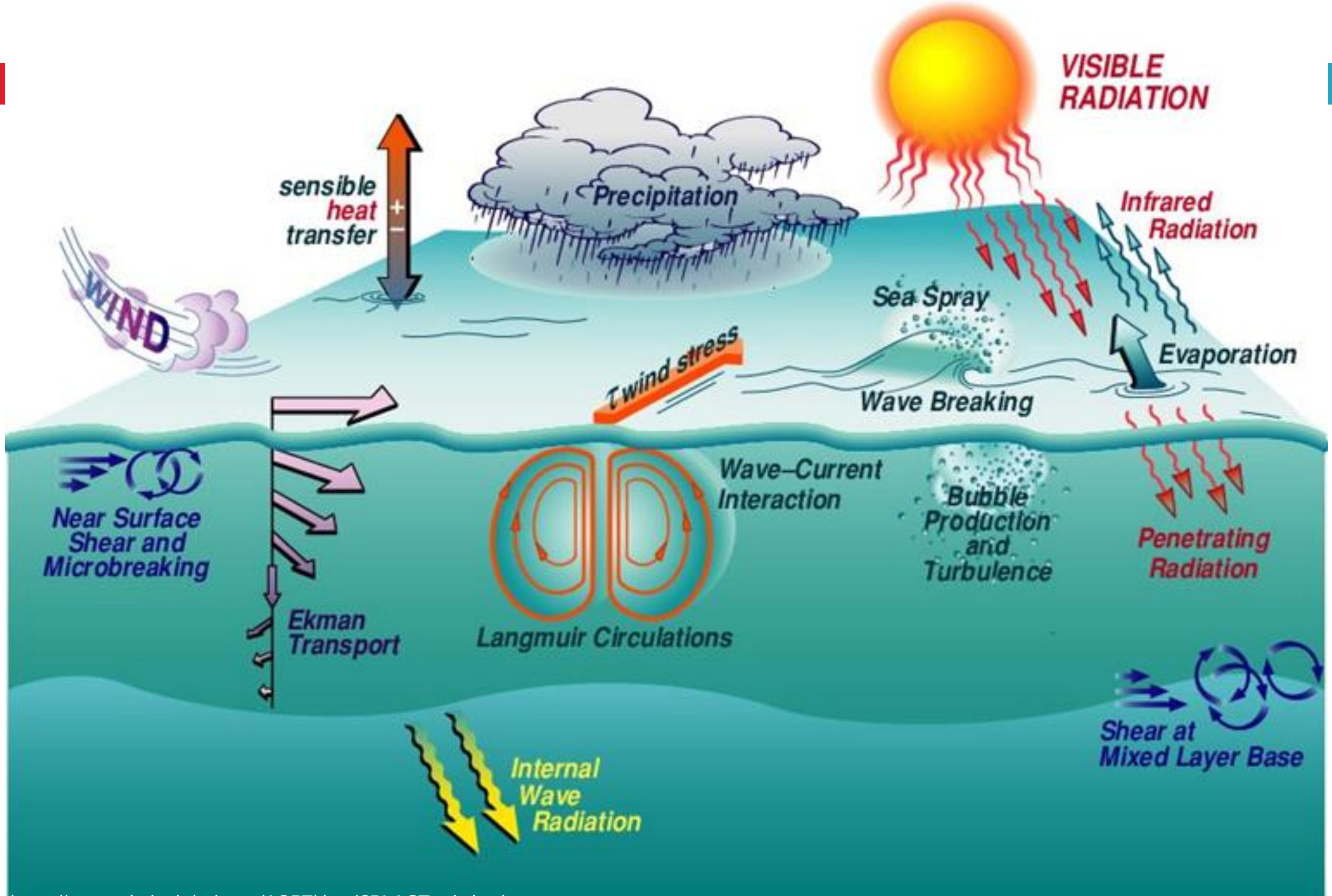
Norwegian Meteorological Institute

Small-scale mixing processes in the upper ocean



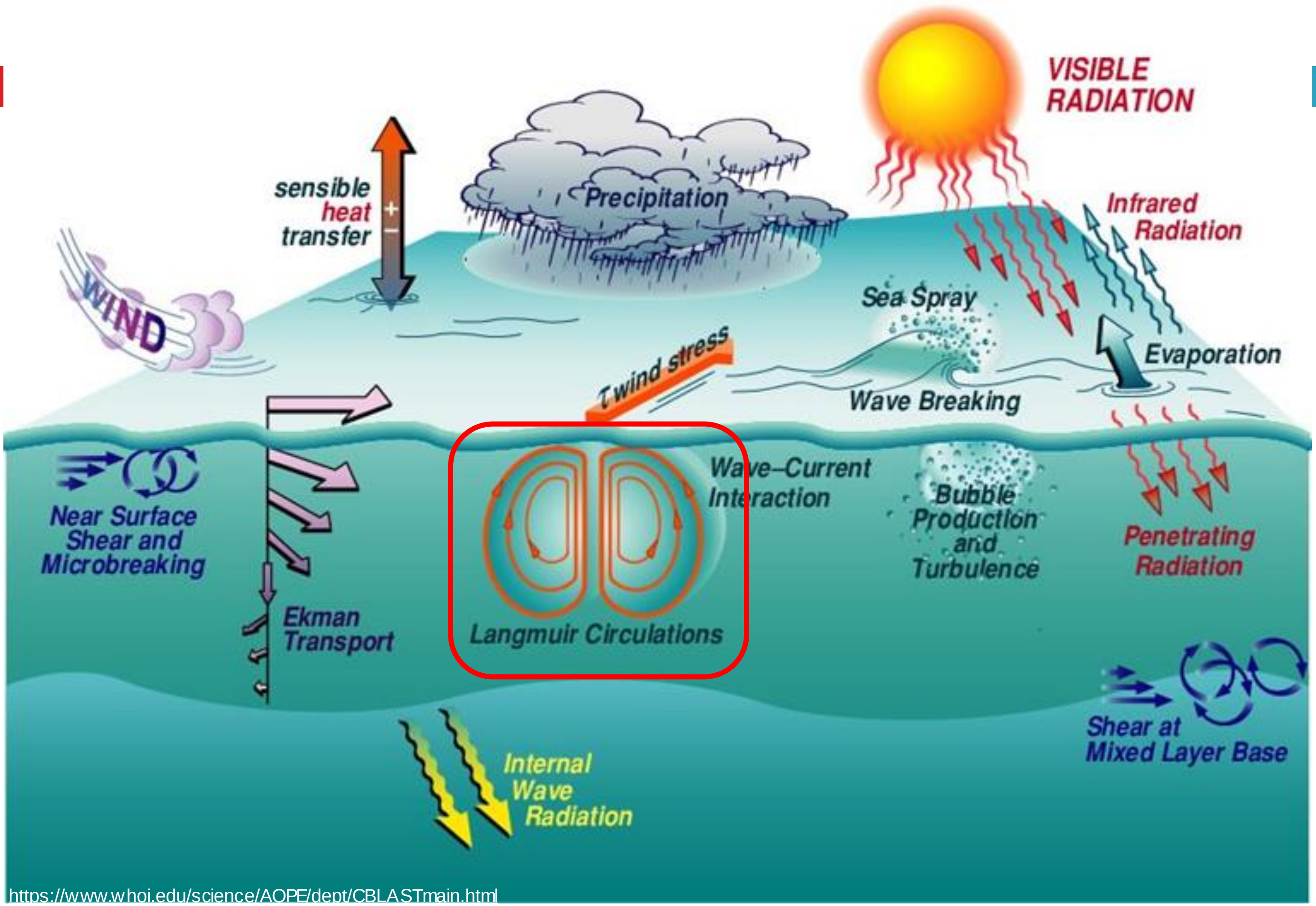
https://www.whoi.edu/science/AOPE/dept/CBLASTmain.html

Turbulent kinetic energy budget

$$\frac{De}{Dt} = \underbrace{-\overline{\mathbf{u}_h'w'}\cdot\frac{\partial \mathbf{u}_h}{\partial z}}_{1} \underbrace{-\overline{\mathbf{u}_h'w'}\cdot\frac{\partial \mathbf{u}_s}{\partial z}}_{2} + \underbrace{\overline{w'b'}}_{3} \underbrace{-\frac{\partial}{\partial z}\left\{\overline{w'u_i'u_i'} + \frac{1}{\rho_0}\overline{w'p'}\right\}}_{4} - \underbrace{\varepsilon}_{5}$$

1. Shear production
2. Stokes production
3. Buoyant production
4. Turbulent transport
5. Dissipation

Wave-driven mixing processes in the upper ocean



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$$\frac{De}{Dt} = -\underbrace{\overline{\mathbf{u}'_h w'} \cdot \frac{\partial \mathbf{u}_h}{\partial z}}_{1} - \underbrace{\overline{\mathbf{u}'_h w'} \cdot \frac{\partial \mathbf{u}_s}{\partial z}}_{2} + \underbrace{\overline{w'b'}}_{3} - \underbrace{\frac{\partial}{\partial z}\left\{\overline{w'u'_i u'_i} + \frac{1}{\rho_0}\overline{w'p'}\right\}}_{4} - \underbrace{\varepsilon}_{5}$$

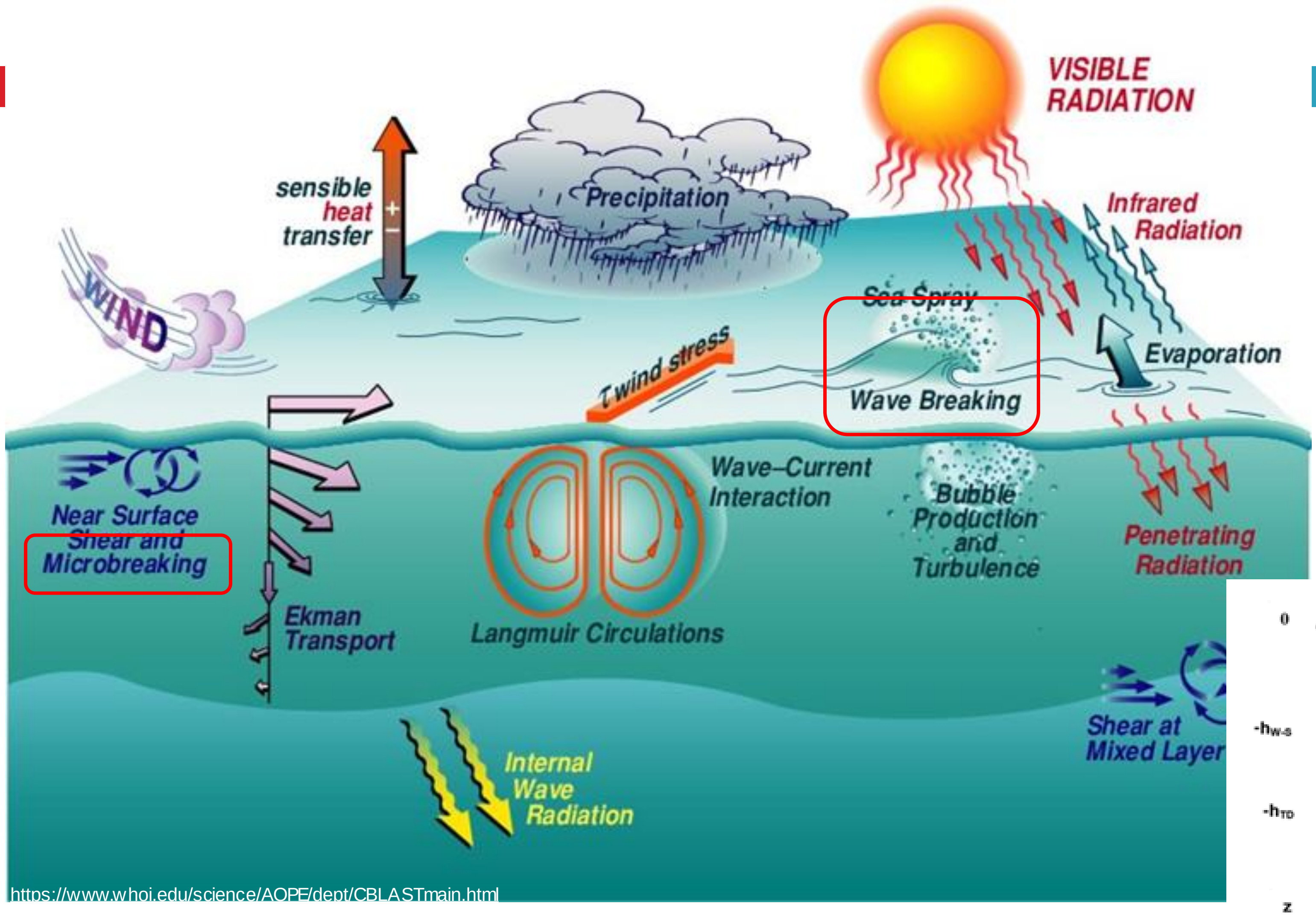
1. Shear production
2. **Stokes production (wave-averaged)**
3. Buoyant production
4. Turbulent transport
5. Dissipation

Langmuir turbulence

- Occurs due to interaction between waves (Stokes drift) and vorticity
- Enhances mixing in OSBL
- Transports properties vertically across OSBL
- May deepen mixed layer depth

Sullivan and McWilliams (2010)

Wave-driven mixing processes in the upper ocean



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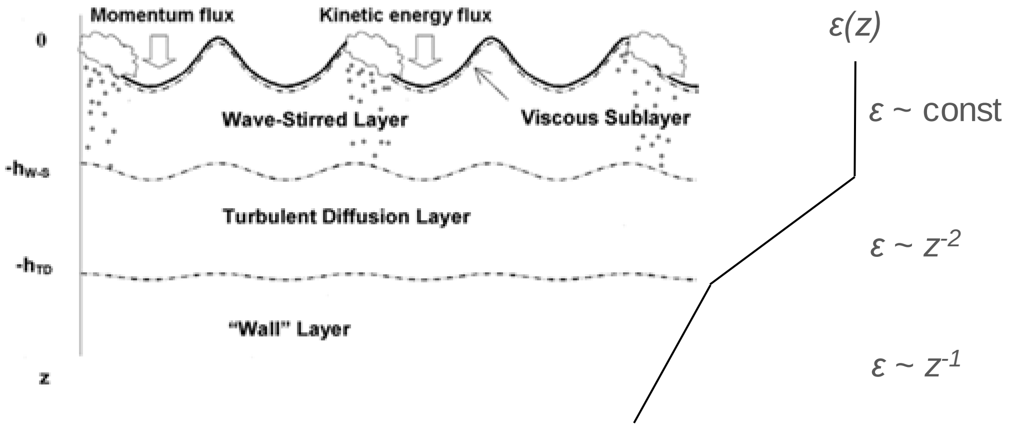
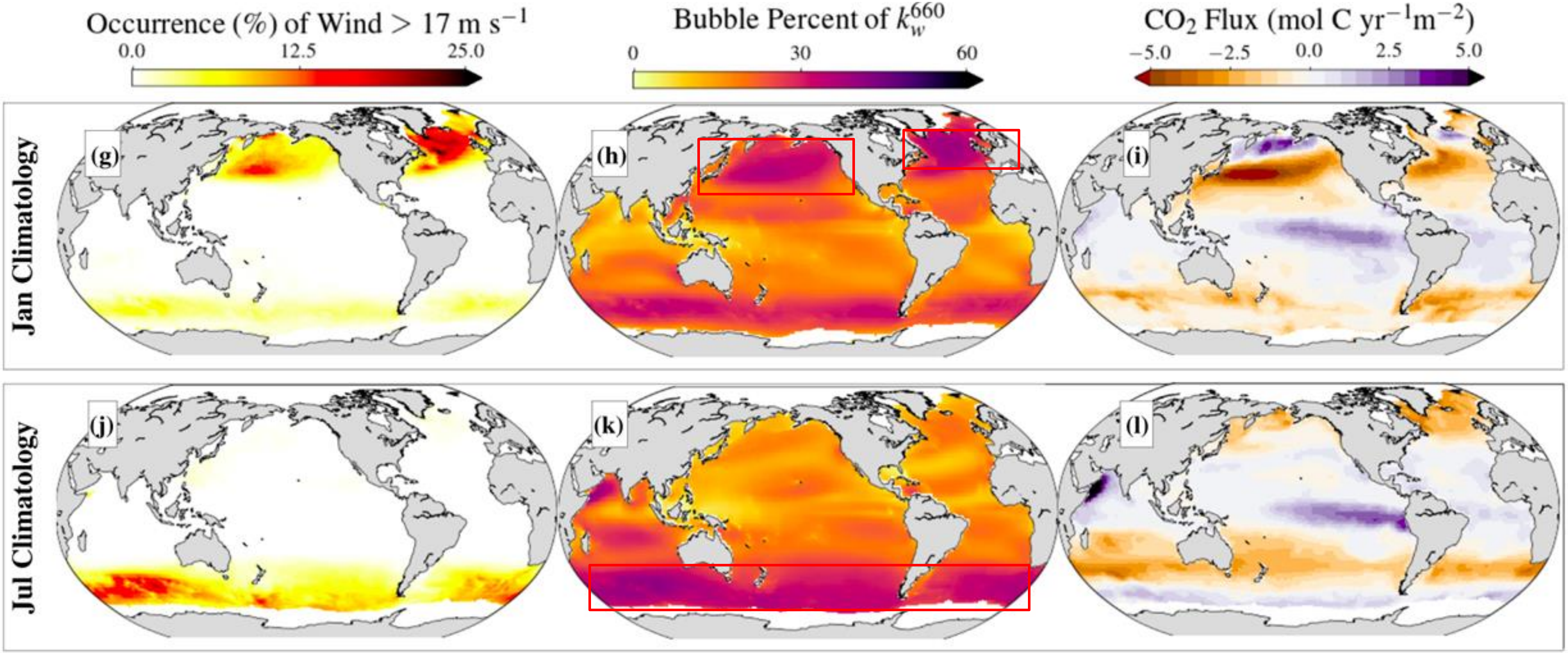
1. Shear production
2. Stokes production
3. Buoyant production
4. Turbulent transport
5. **Dissipation**

Enhanced dissipation due to wave breaking (Craig and Banner, 1994)



Soloviev and Lukas (2014)

The bubble-mediated CO_2 flux



~40% of the net global air-sea CO2 flux is mediated by bubbles

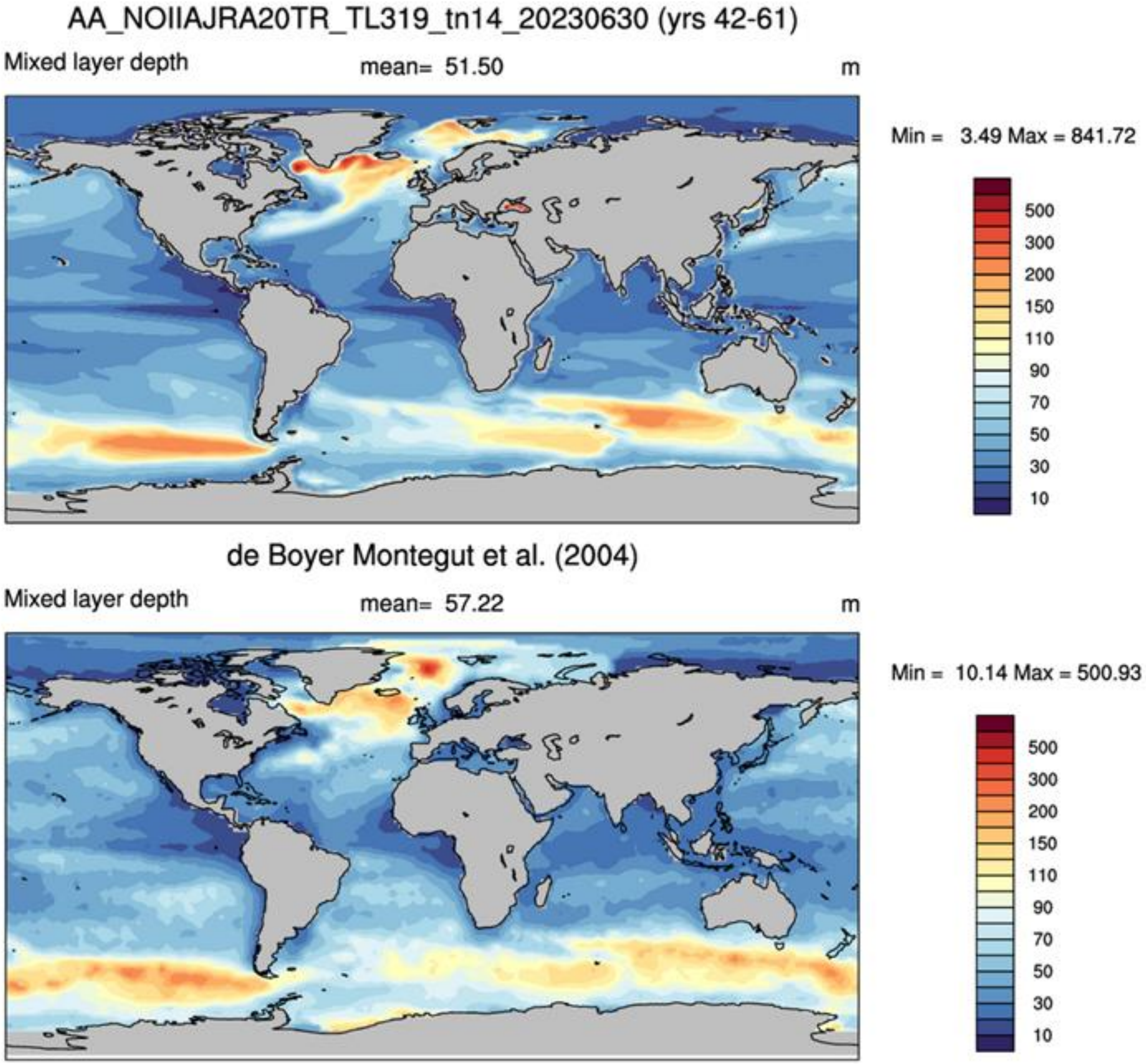
Bubble contribution has significant spatial variability

Reichl and Deike (2020)

Langmuir turbulence parameterised in climate models

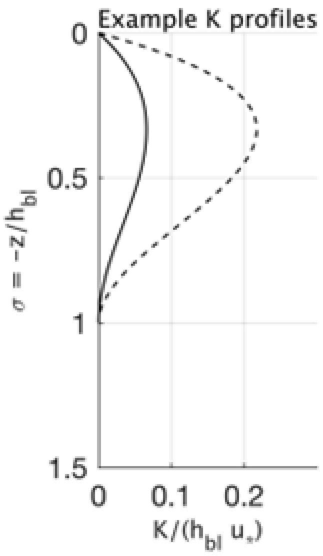
6

The mixed layer depth of the global ocean component of the Norwegian Earth System model (NorESM) - too thin



Langmuir turbulence parameterised in climate models

Add a bit of mixing based on the Langmuir enhancement factor in the KPP scheme …



See Alfatih Ali's poster

Langmuir mixing parameterization in KPP

- In the KPP scheme, the turbulent eddy diffusivity of a property X within the ocean surface boundary layer $0 < z < h$ is parameterized as

$$K_x(z,t) = h(t)\,w_x(z/h,t)\,G(z/h).$$

- The ocean boundary layer depth h is determined as the shallowest depth at which the bulk Richardson number $\mathrm{Ri_b}(z)$ rises above a critical value Ri_c:

$$\mathrm{Ri_b}(z) = \frac{(B_r - B(z))|z|}{|\mathbf{u}_r - \mathbf{u}(z)|^2 + V_t^2(z)}.$$

- LT effects are parameterized following McWilliams and Sullivan (2000) through an enhancement factor $\mathcal{E}(La_t)$ applied to the turbulent velocity scale as

$$w_x = (\kappa u_*/\phi)\mathcal{E}(La_t) \quad \text{where} \quad \mathcal{E}(La_t) = \left[1 + C_w/La_t^{2\alpha}\right]^{1/\alpha}$$

- The LT-enhanced unresolved turbulence shear: $V_t^2(z) = \frac{C_v N(z)(\kappa u_*/\phi)\mathcal{E}(La_t)|z|}{\mathrm{Ri}_c \kappa^2}\left(\frac{-\beta_T}{c_s \epsilon}\right)^{\frac{1}{2}}$

Table: Description of the four experiments where CNTL is the control run without wave effects. VR12PAR refers to the experiment where Stokes drift profile is **parameterized** from wind, while VR12 and LF17 experiments are coupled with WAVEWATCH III.

Parameterization	Exp.	Enhancement factor $\mathcal{E}(\mathrm{La_{SL}})$	Unresolved shear	Wave coupling
Large et al. (1994)	CNTL	1	V_t^2	No coupling
Van Roekel et al. (2012)	VR12	$\sqrt{1 + (1.5\mathrm{La_{SL}})^{-2} + (5.4\mathrm{La_{SL}})^{-4}}$	V_t^2	WAVEWATCH III
Li et al. (2017)	VR12PAR	same as VR12	same as VR12	Parameterized Stokes profile
Li and Fox-Kemper (2017)	LF17	same as VR12	V_{tL}^2	WAVEWATCH III

- LT enhancement of the buoyancy entrainment at the base of the boundary layer (Li and Fox-Kemper, 2017):

The unresolved turbulence shear is modified:

$$V_{tL}^2(z) = \frac{C_v N(z) w_s(z)|z|}{\mathrm{Ri_c}}\left[\frac{-\overline{w b_e} h}{w_s(z)^3}\right]^{\frac{1}{2}}$$

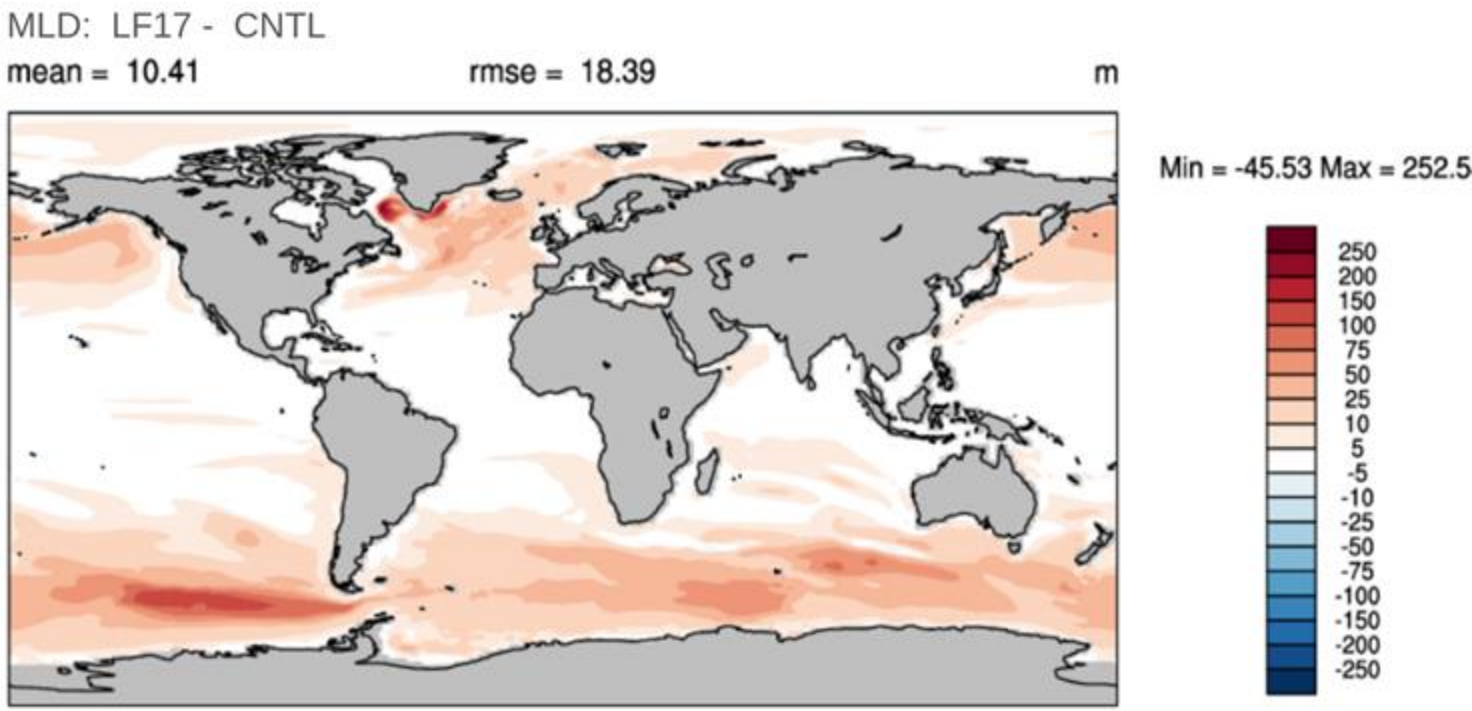
Enhanced entrainment buoyancy flux:

$$-\overline{w b_e} = \frac{u^{*3}}{h}\left(0.17 + 0.083\mathrm{La_{SL}^{-2}} - 0.15\frac{h}{\kappa L}\right)$$

Langmuir turbulence parameterised in climate models

Add a bit of mixing based on the Langmuir enhancement factor in the KPP scheme …

and things improve …

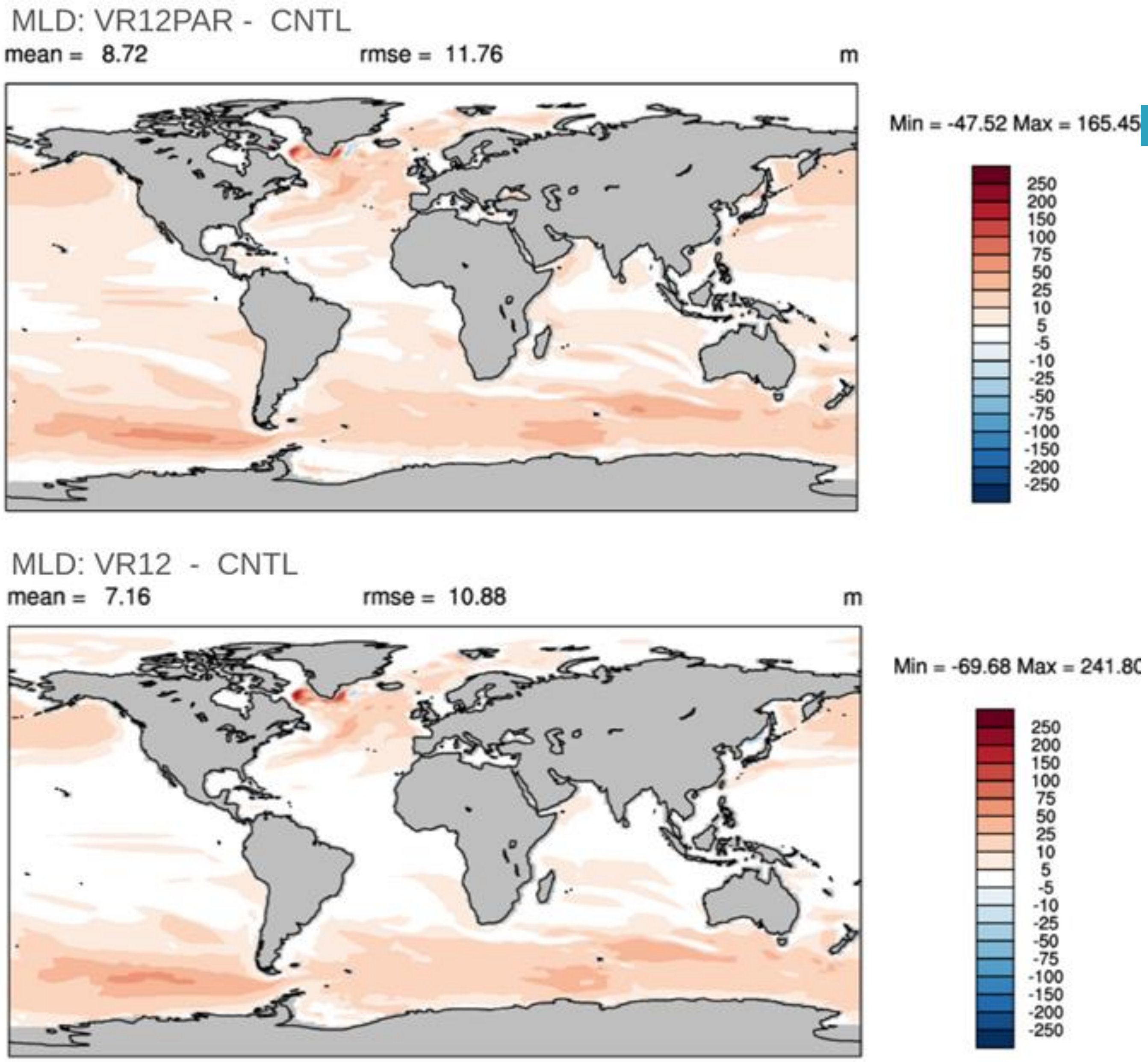


Langmuir turbulence parameterised in climate models

Add a bit of mixing based on the Langmuir enhancement factor in the KPP scheme …

and things improve *on average* …

but, do we really need wave models for that?



Stokes drift profile parameterised from local wind

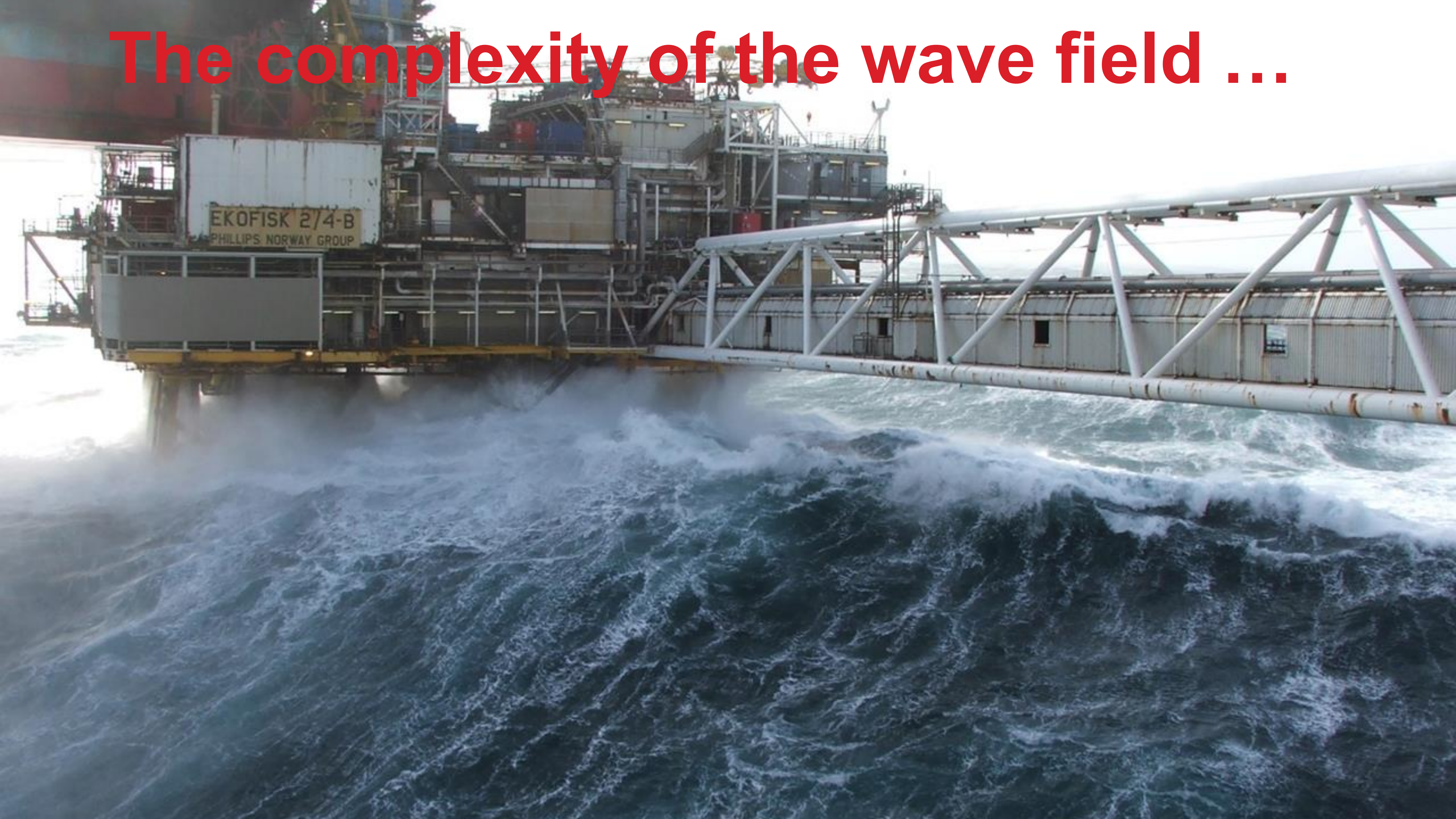
vs

Stokes drift profile from wave model

Intermediate conclusion

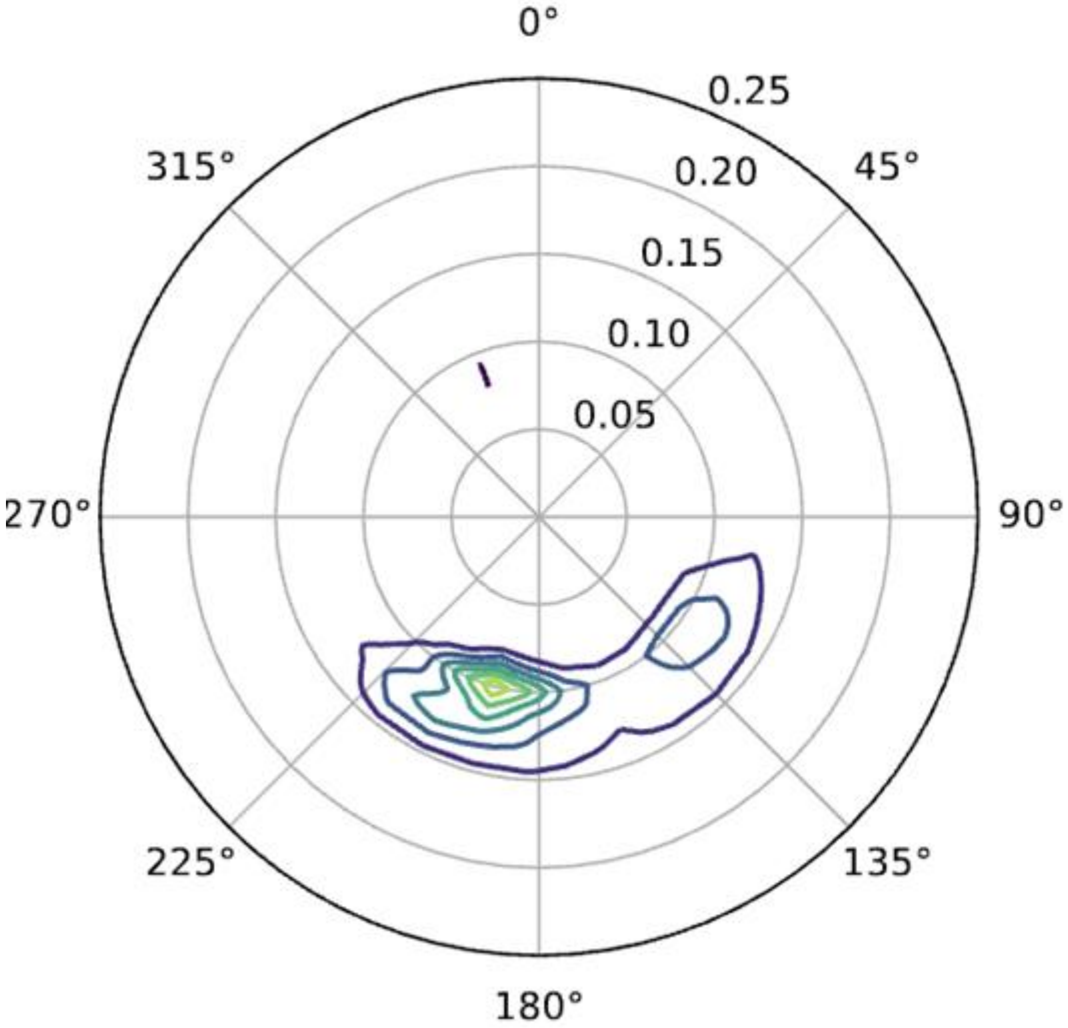
- Wave models are necessary and essential for certain types of coupled systems, like the IFS, because they determine the *evolution* of the weather systems
- But, wave models are necessary to *inform*, but may not be *affordable or necessary* for all sorts of coupled models where only *mean quantities* need to be correct

The complexity of the wave field …



The complexity of the wave field …

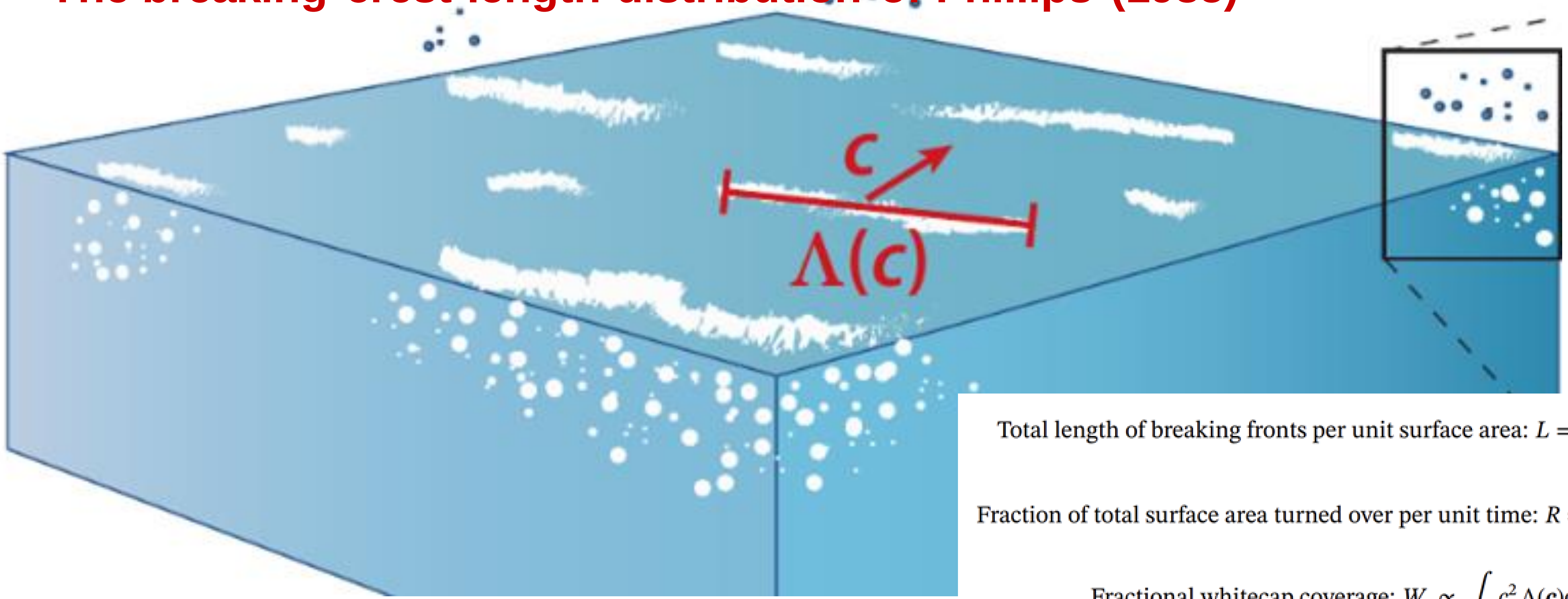
… reduced to this



The richness of the wave field …

- cannot possibly be captured by the two-dimensional spectrum
- can we continue to parameterise the processes responsible for the air-sea interaction the way we have?
- and if so, can we do better by turning to new types of measurements?

The breaking crest length distribution of Phillips (1985)



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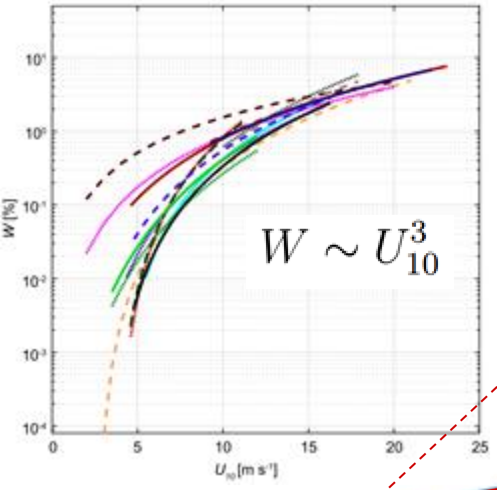
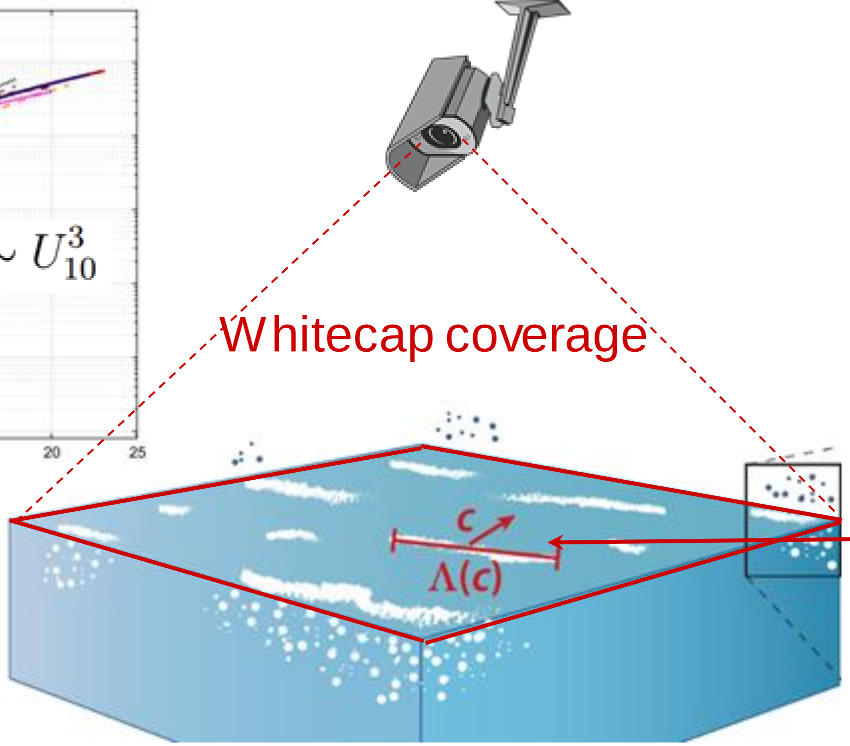
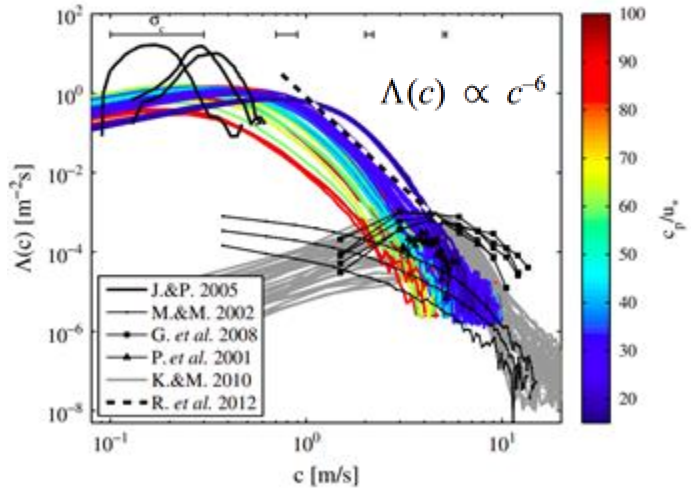
Deike (2022)







Breaking crest length distribution Λ(c)
Phillips (1985)

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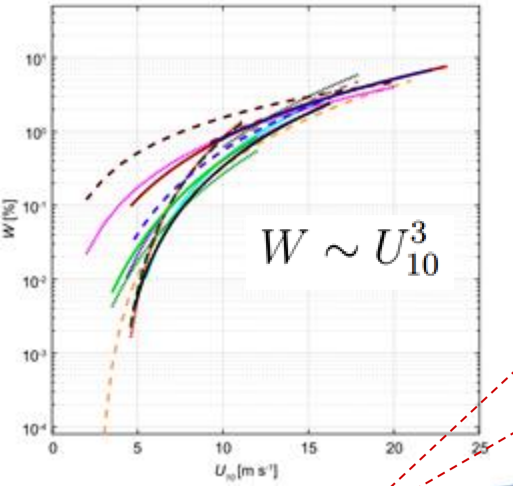
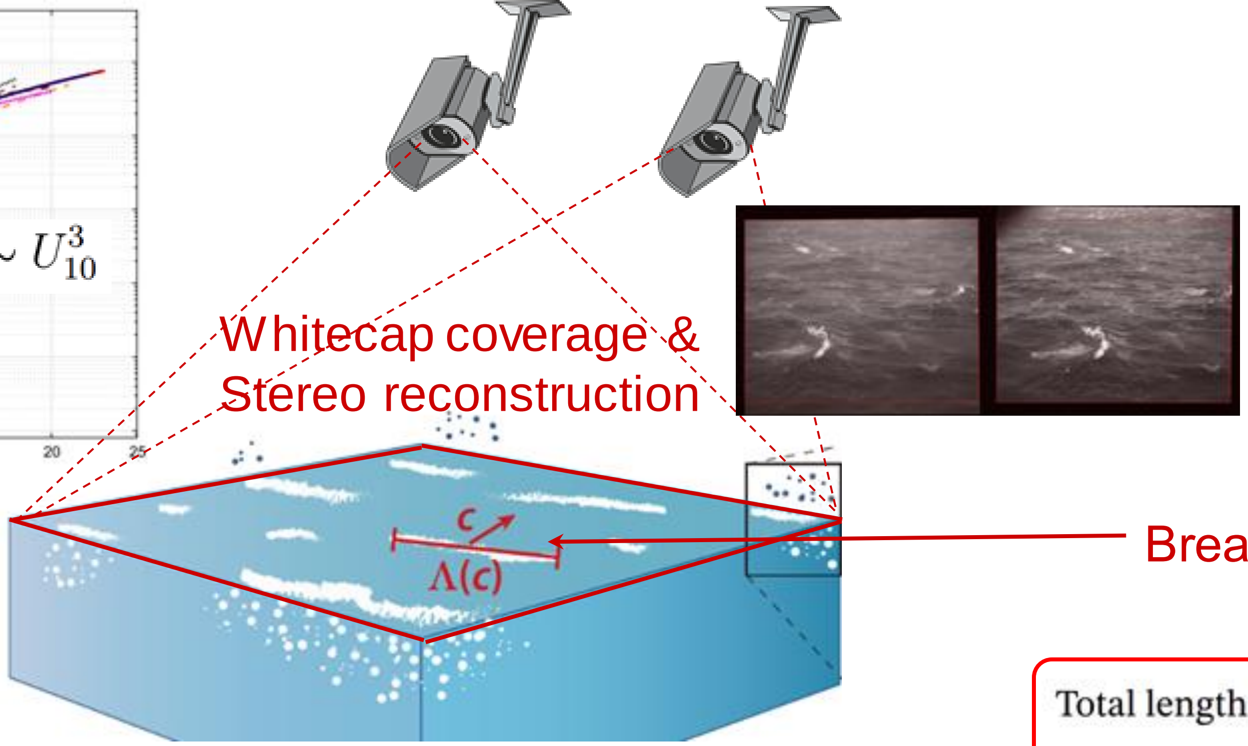
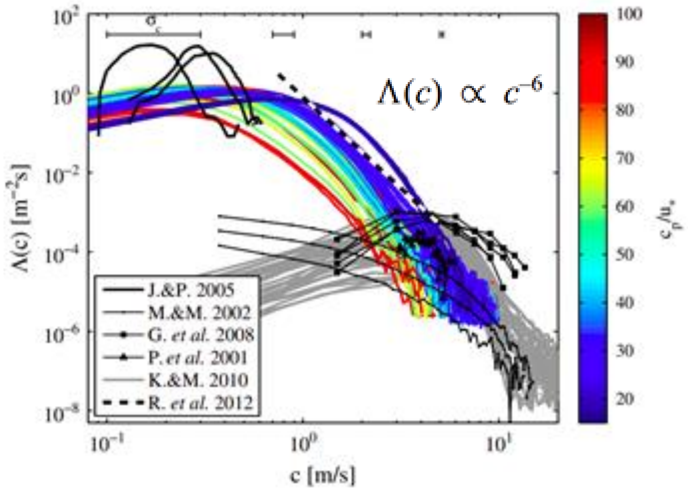
Brumer et al. (2017); Deike (2022); Sutherland and Melville (2013); Romero (2019)







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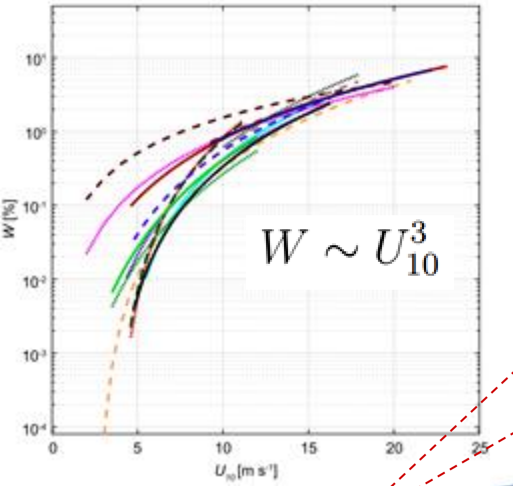

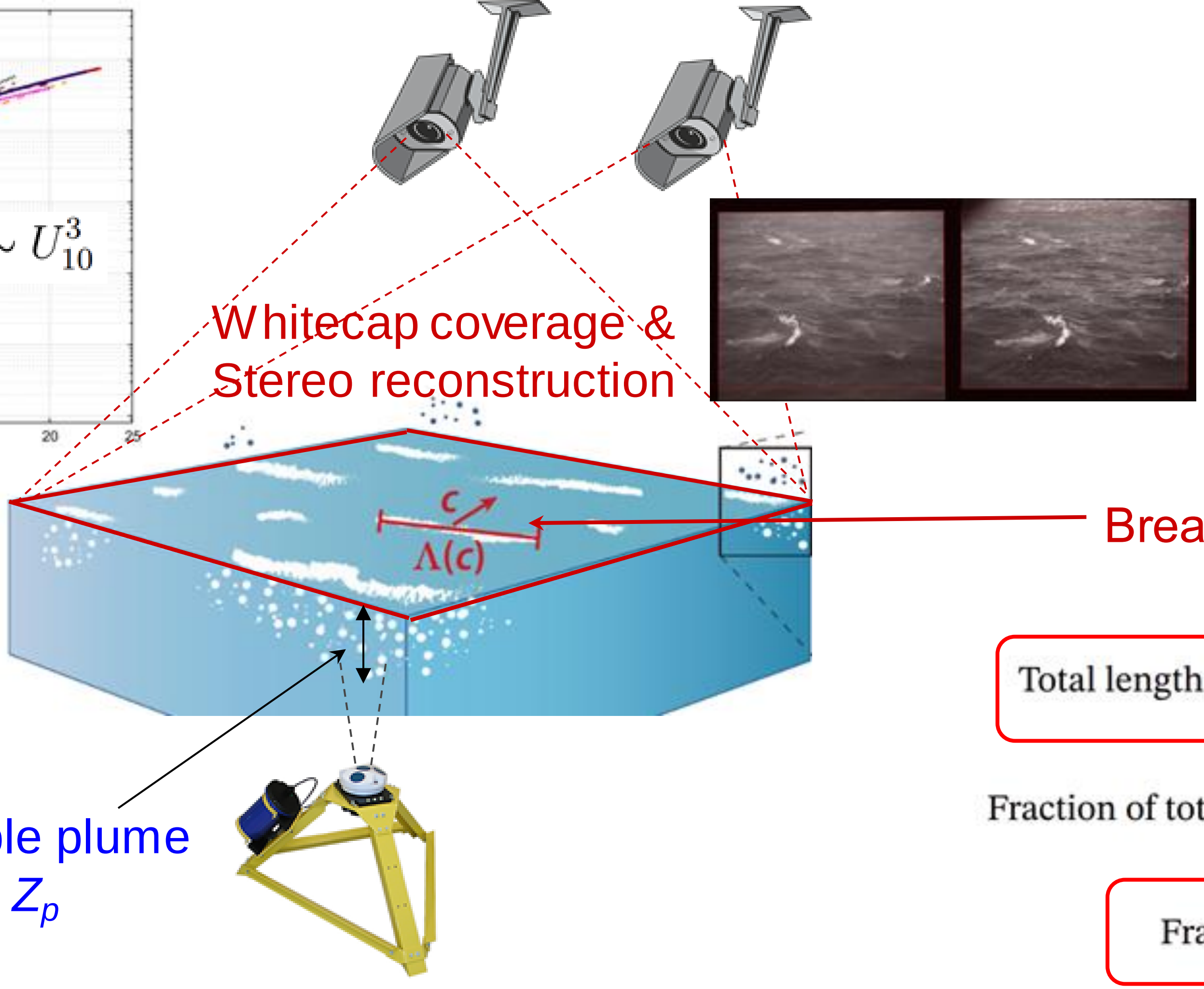

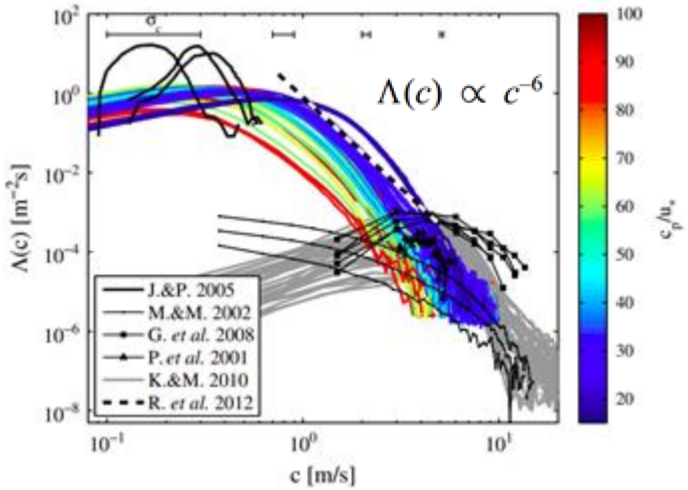

ADCP Bubble plume depth Z_p

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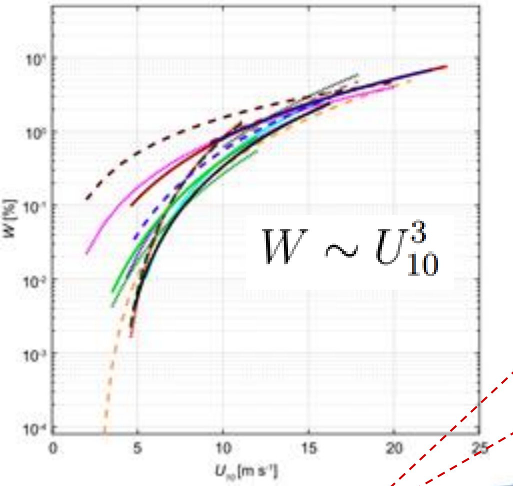

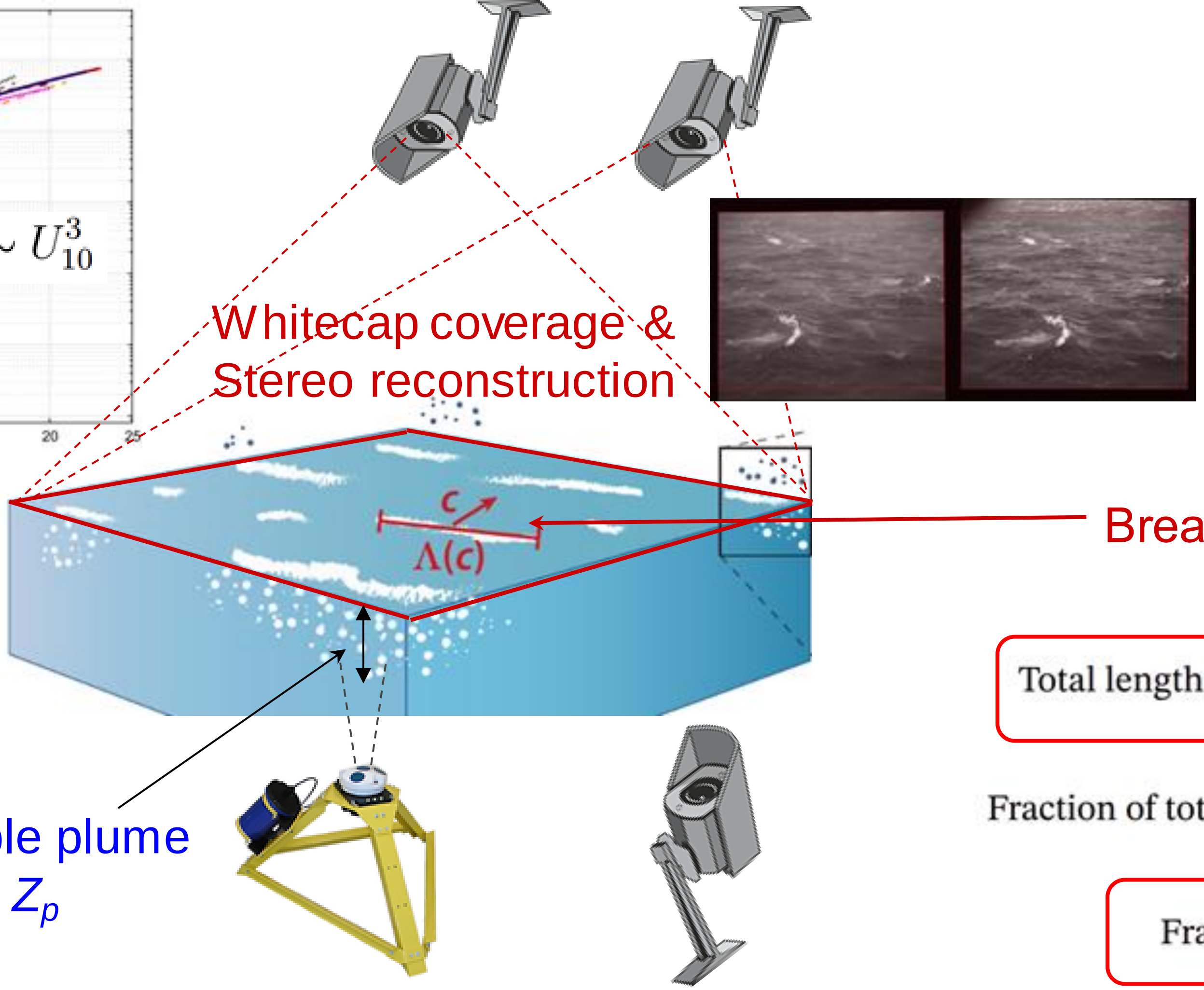

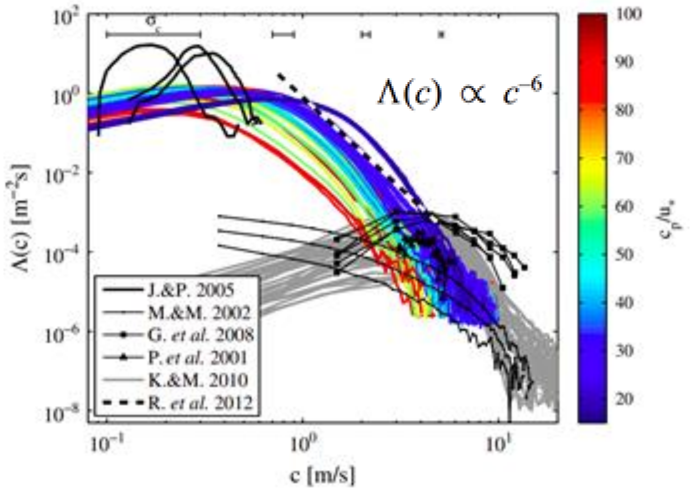

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Subsurface camera for bubble size distribution

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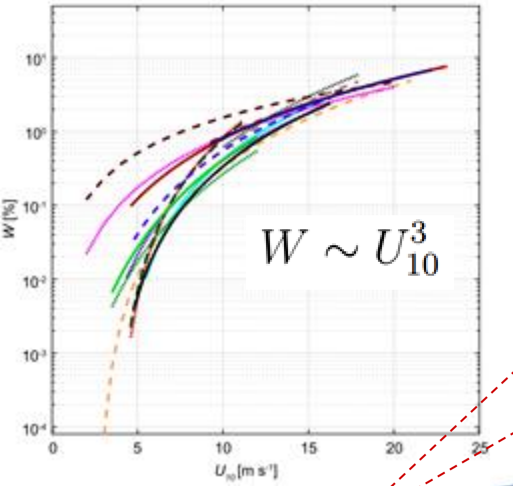

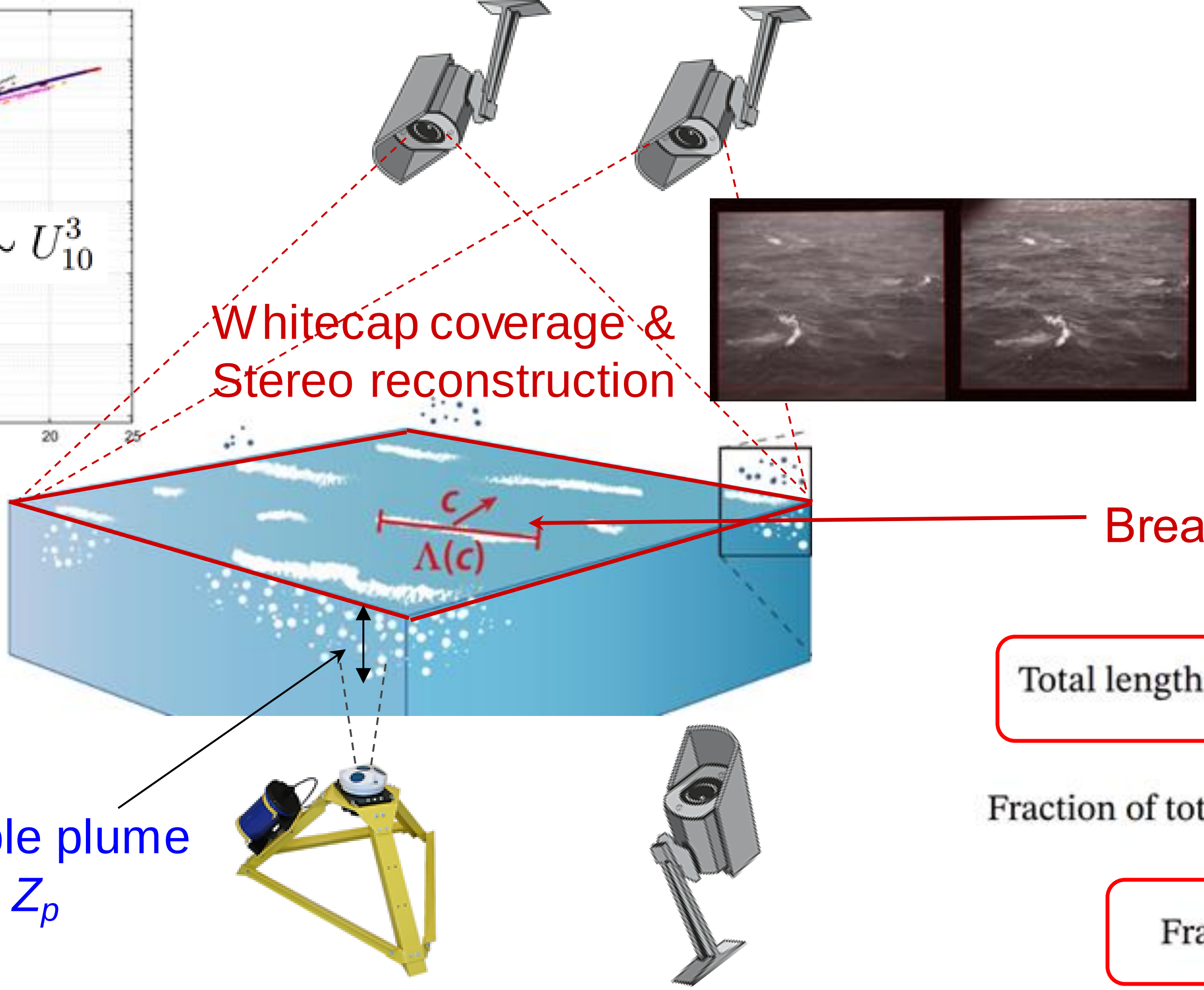

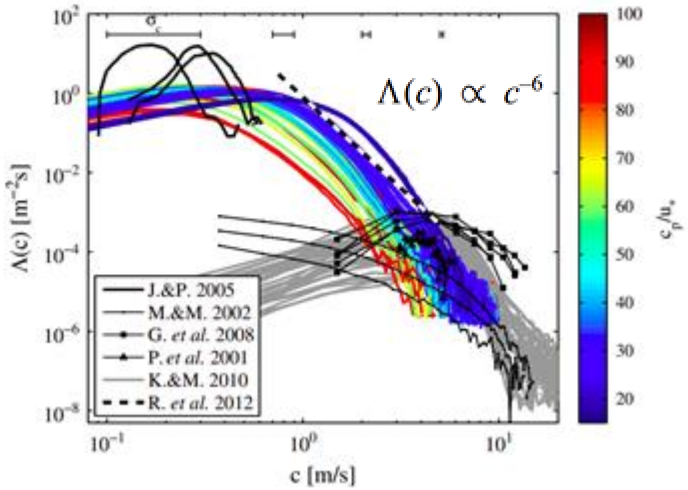

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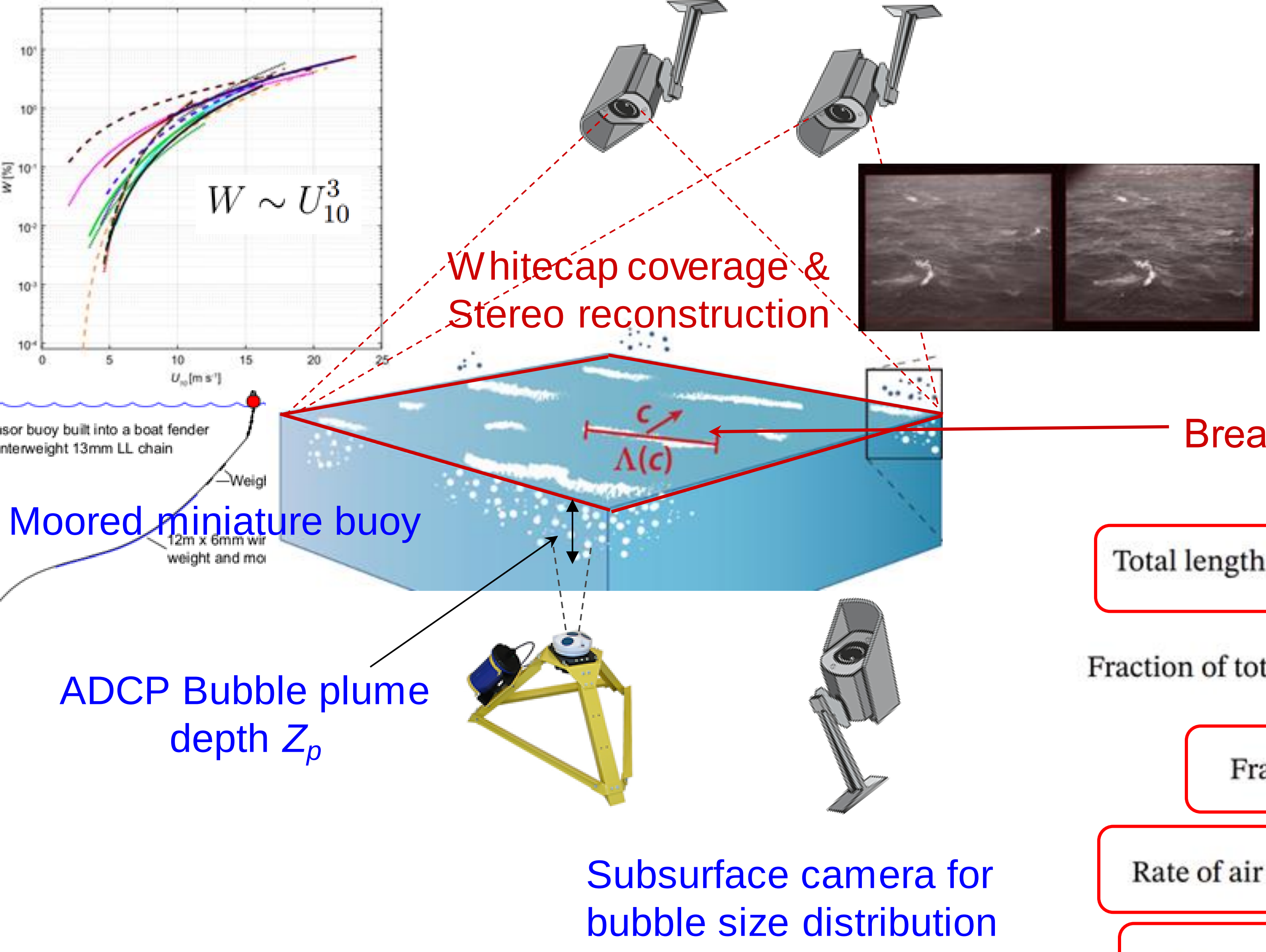

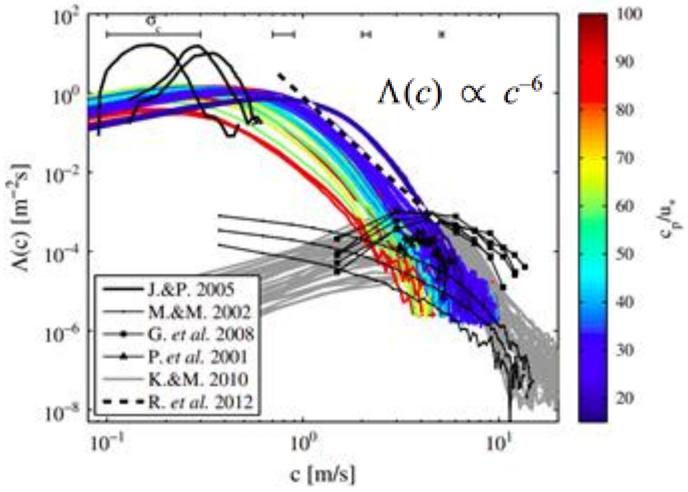

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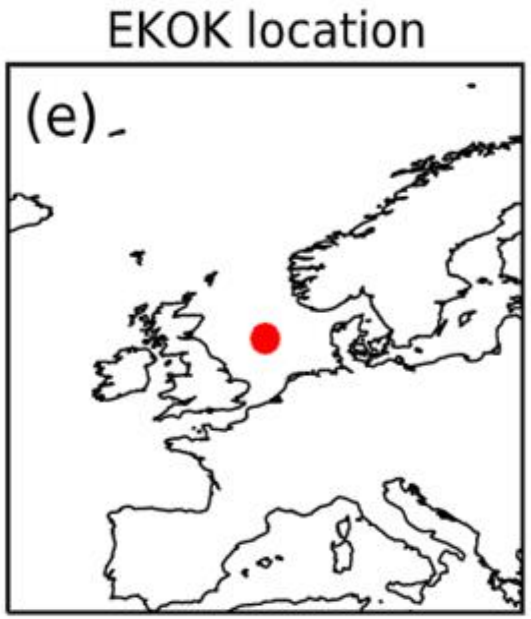
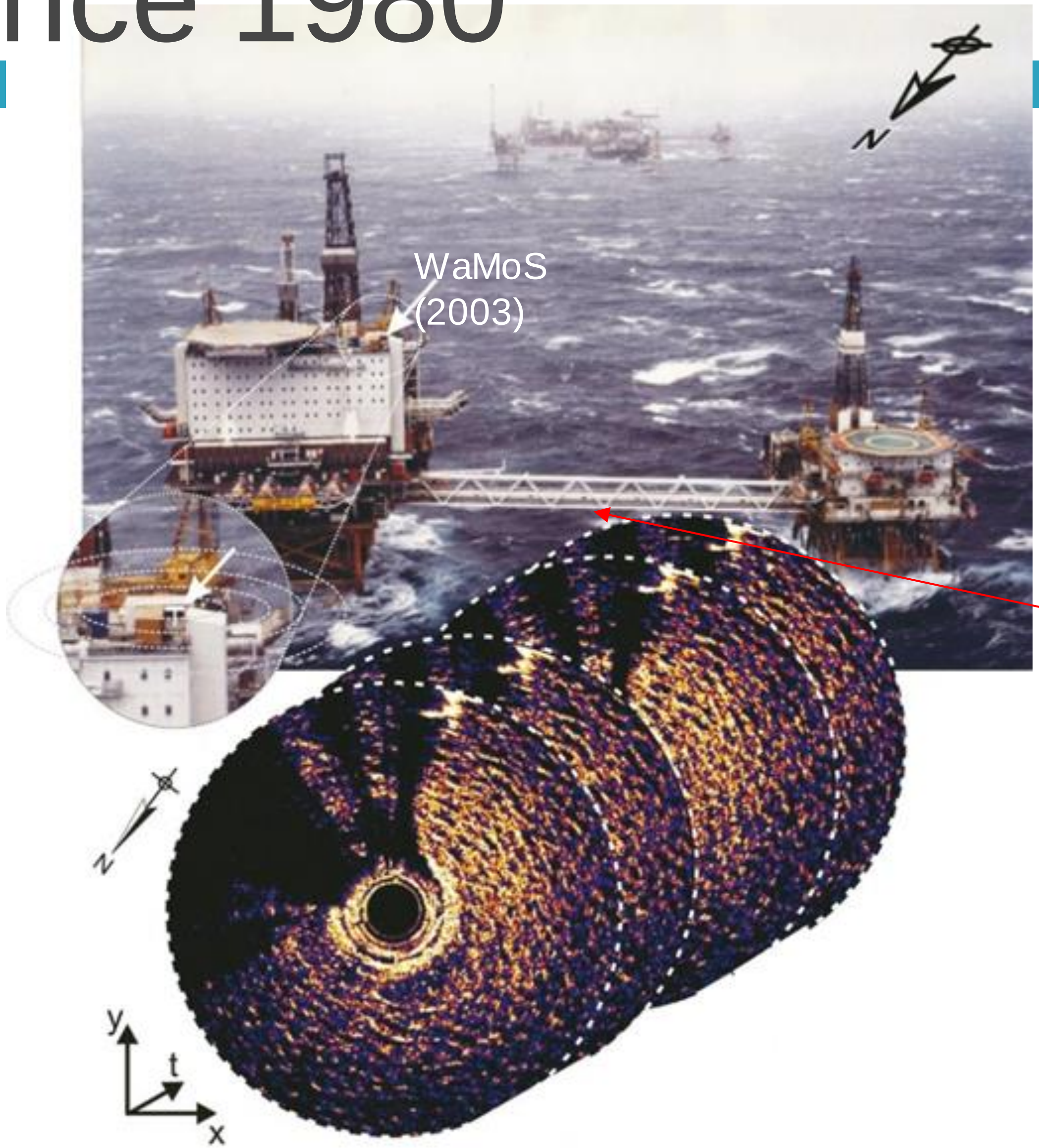
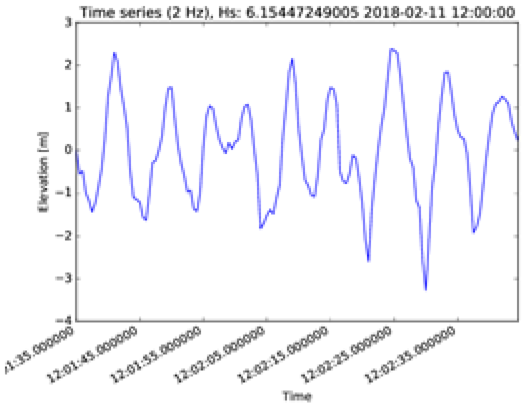
Ekofisk - an open-ocean wave laboratory since 1980



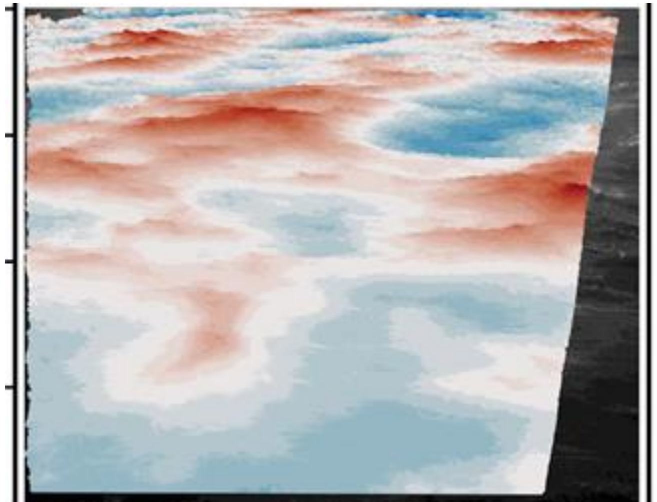


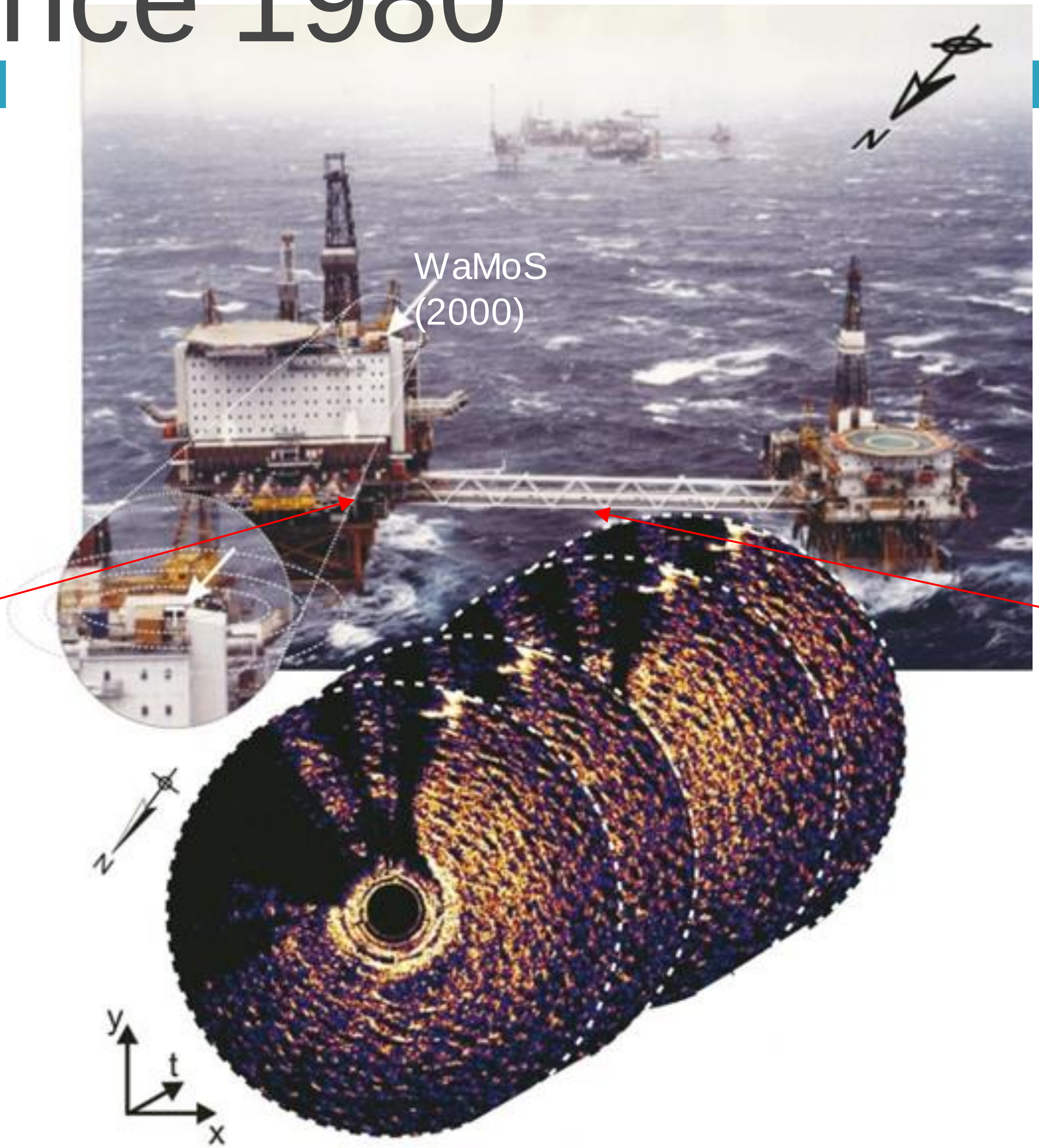
LASAR (2003)



Ekofisk - an open-ocean wave laboratory since 1980

Stereo video (2017)





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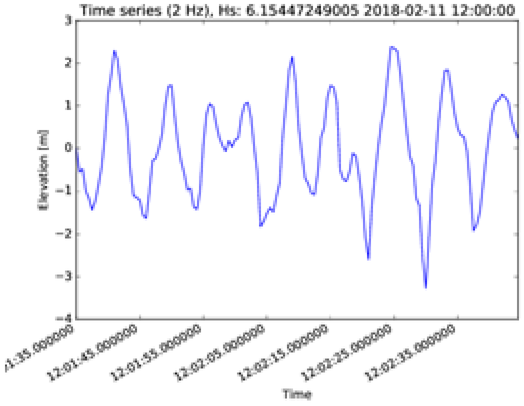
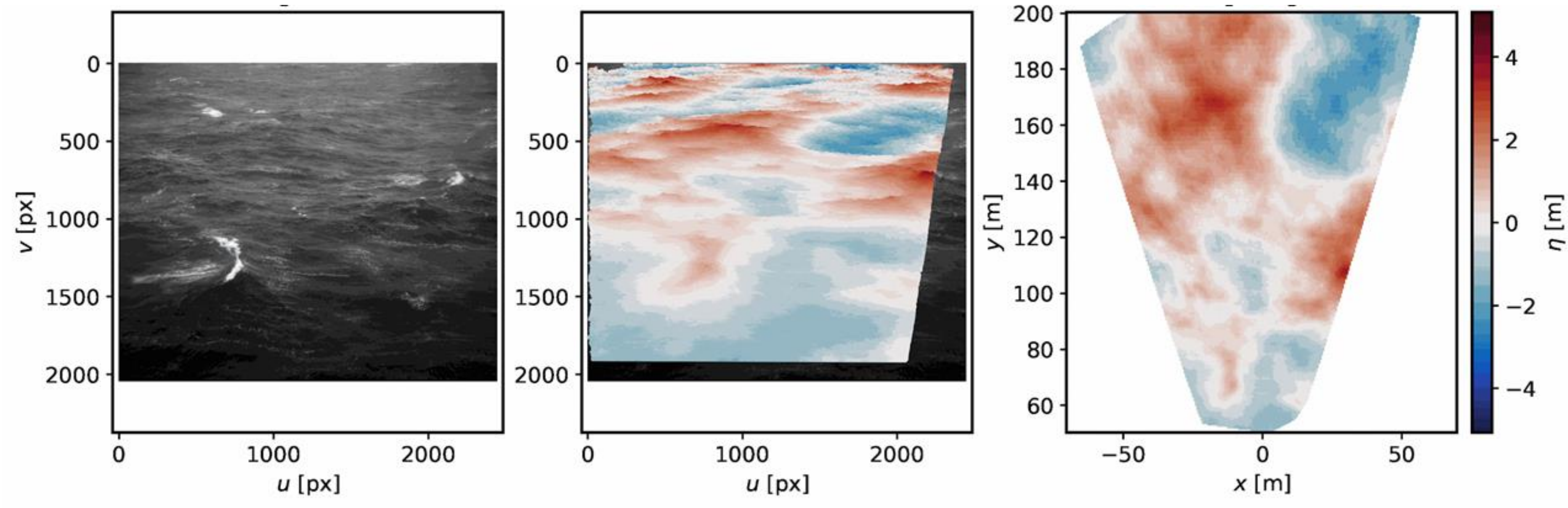
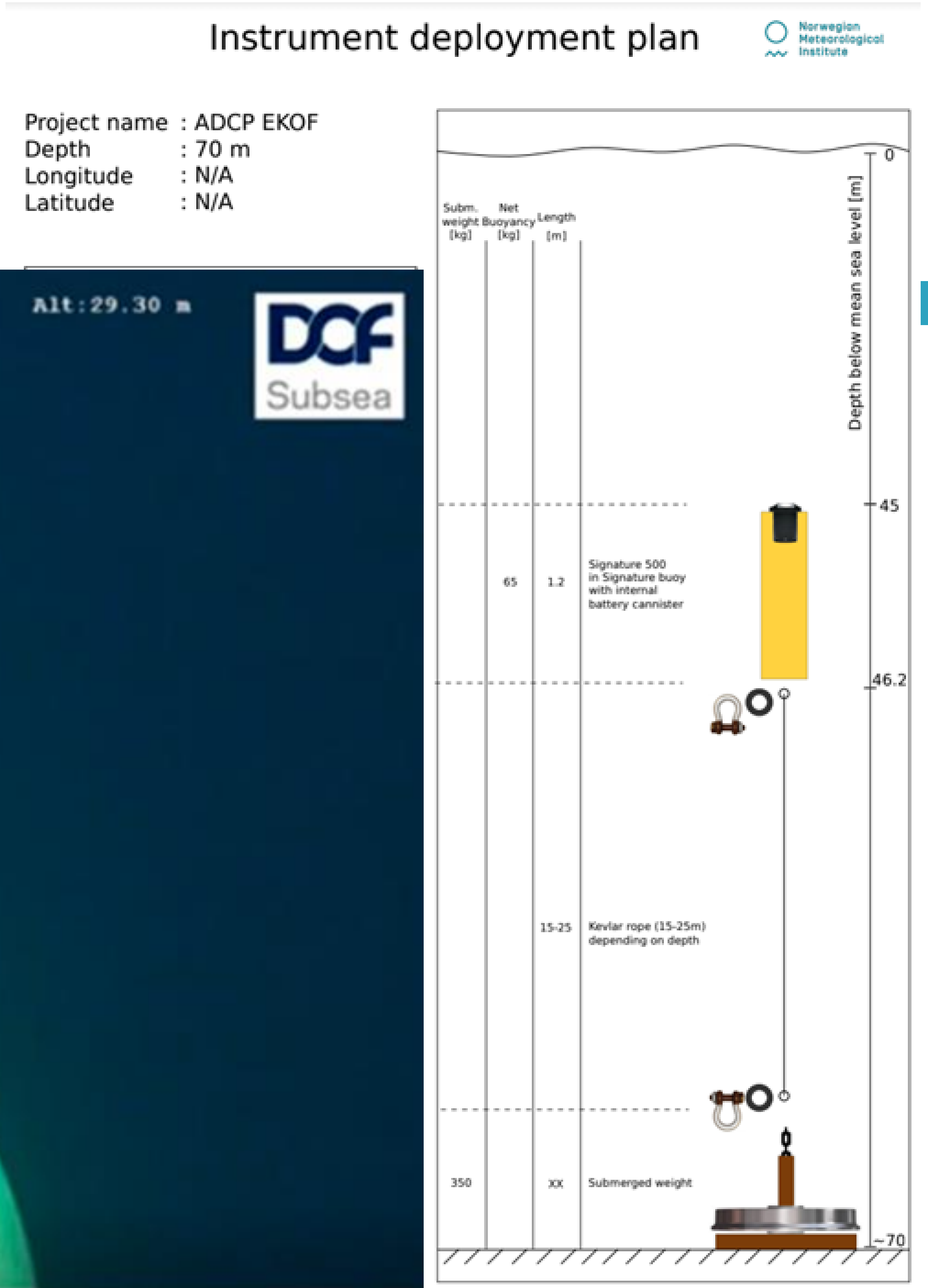
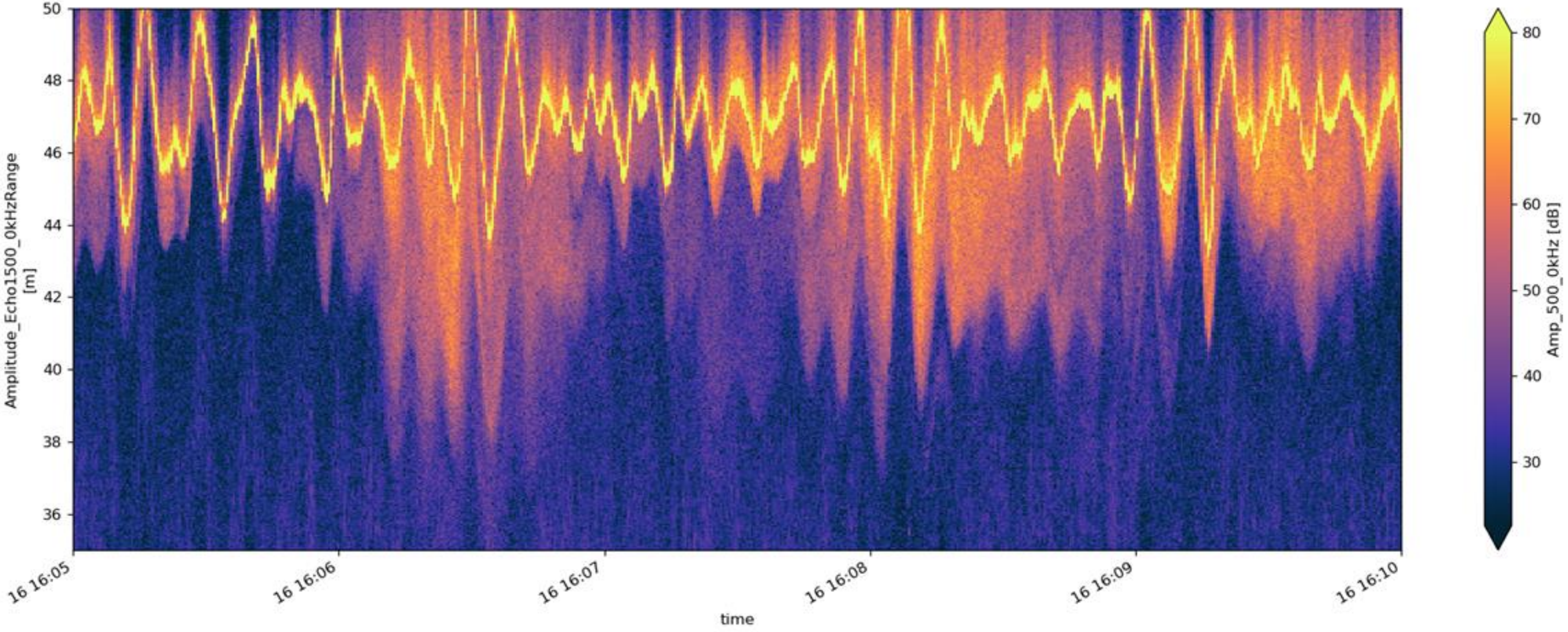


Since 2017: Stereo measurements (5 Hz)



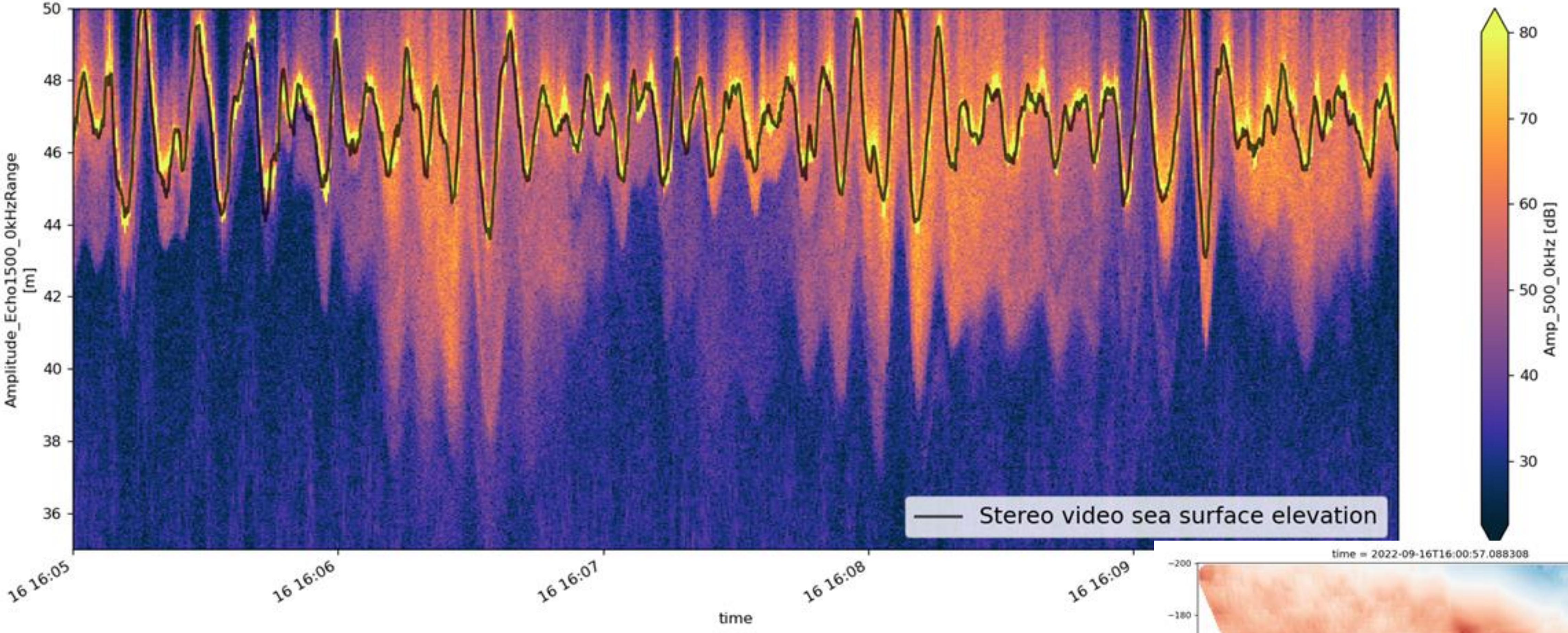
2022: Deployment of ADCP in the stereo camera field of view

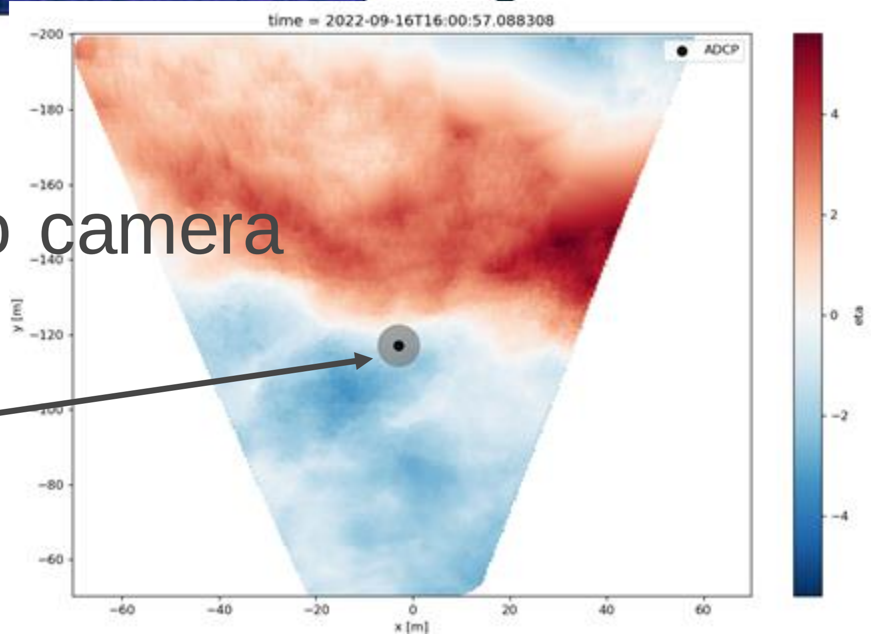




The fifth beam of a Nortek 500 ADCP

- 5 minute time series of raw echosounder image
- Brighter yellow indicates stronger backscatter, bubble plumes clearly visible

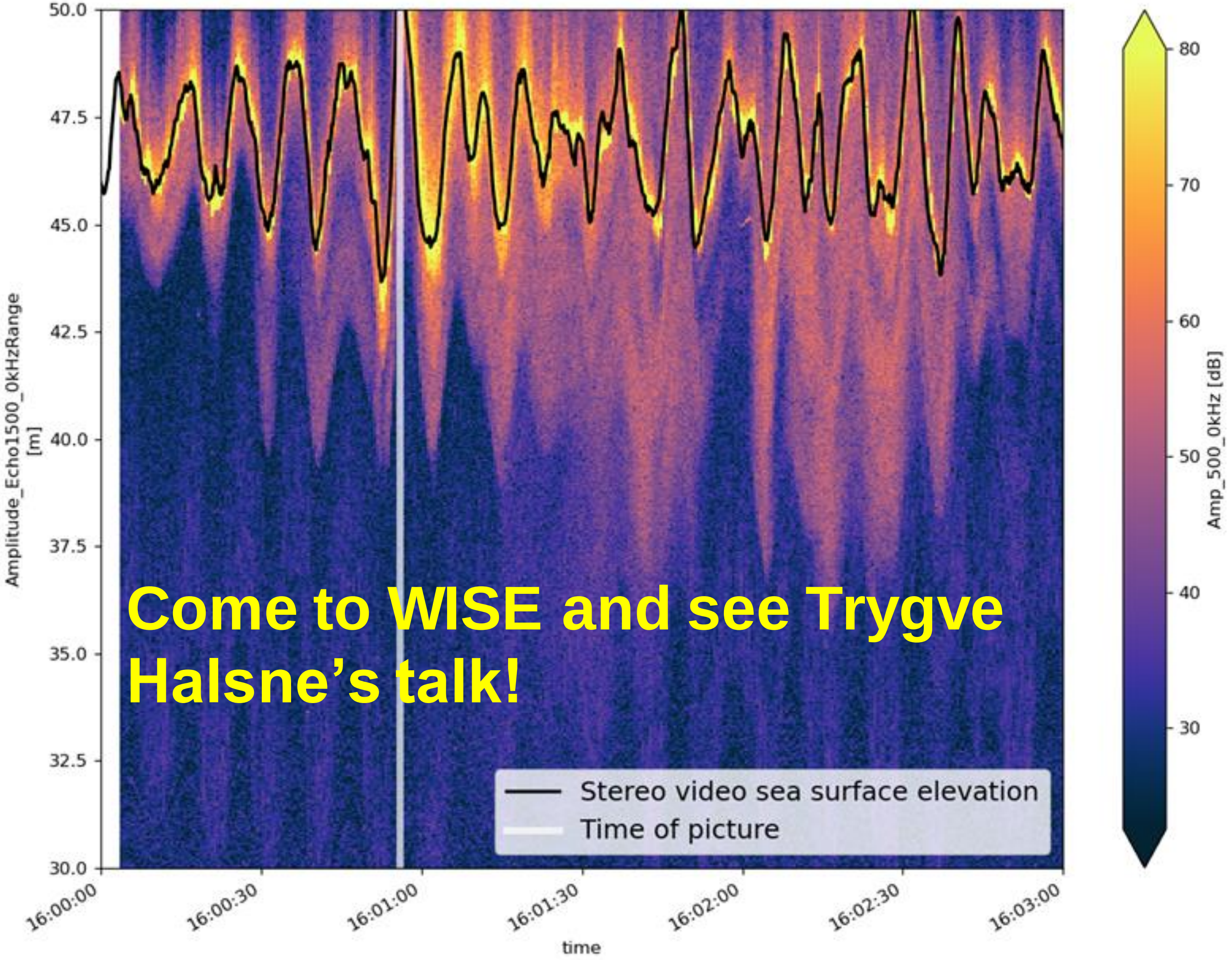




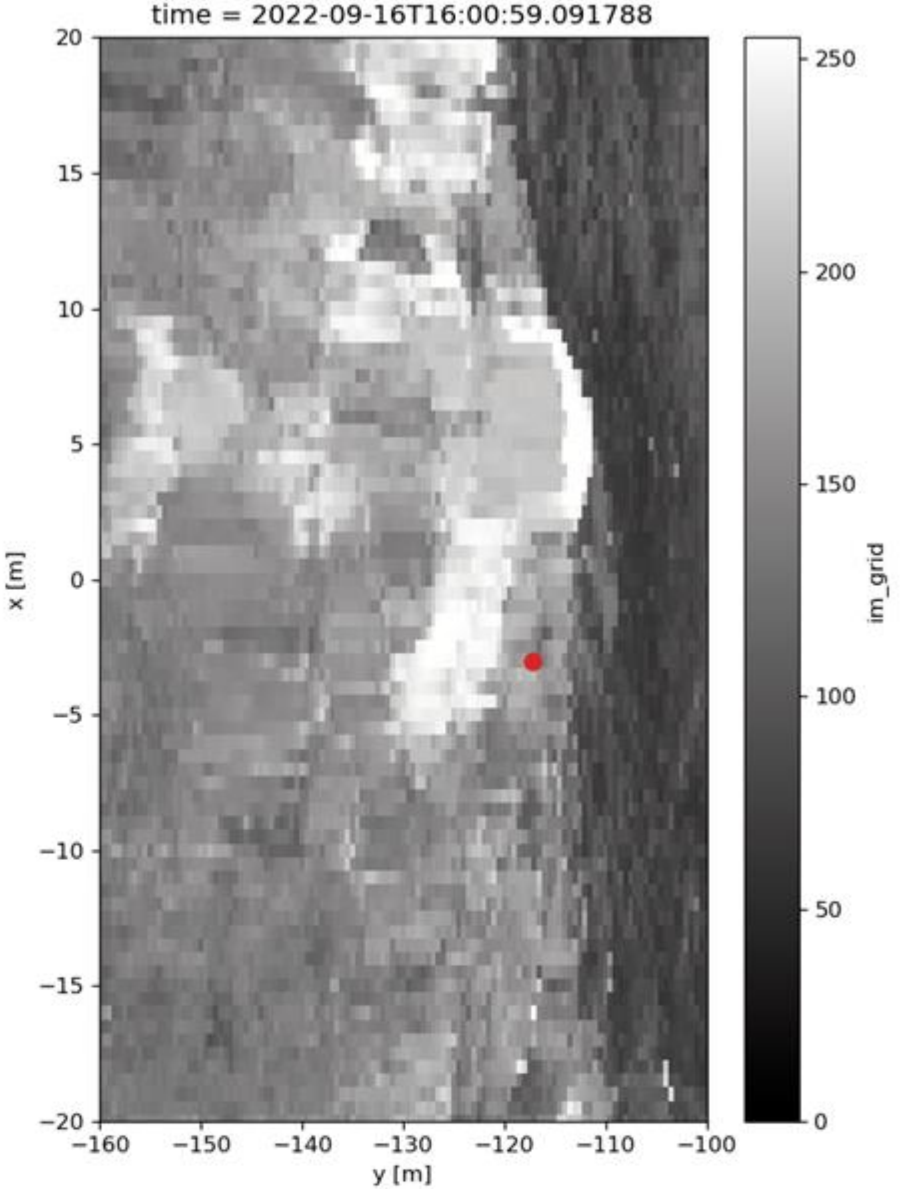
The fifth beam of a Nortek 500 ADCP & a stereo camera

- 5 minute time series of raw echosounder image
- Brighter yellow indicates stronger backscatter
- ADCP located here

Identified wave breaking events in the vicinity of the ADCP



Come to WISE and see Trygve Halsne's talk!



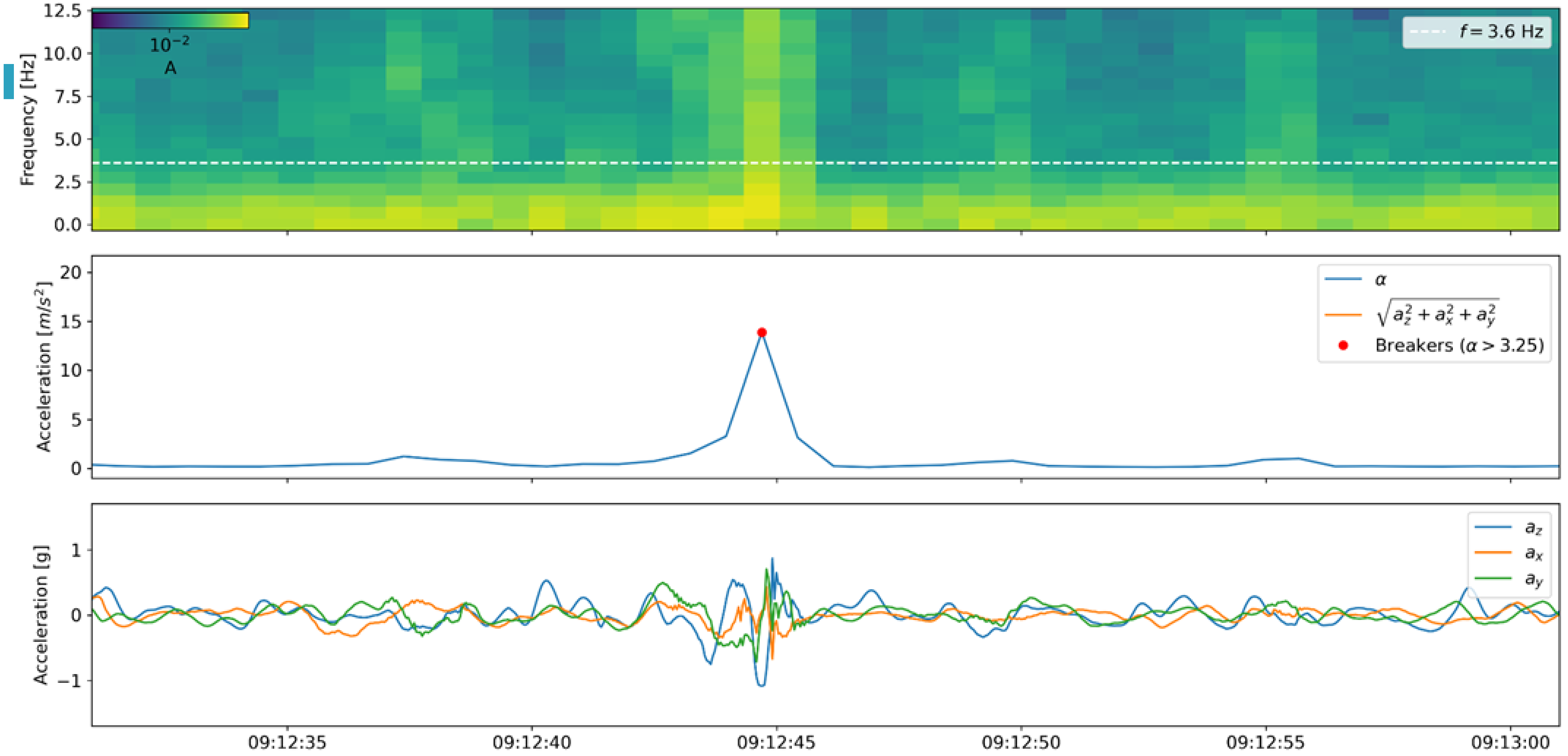
Wave propagation direction →

April 2024: Deployment of SFY miniature wave buoys in the stereo camera footprint

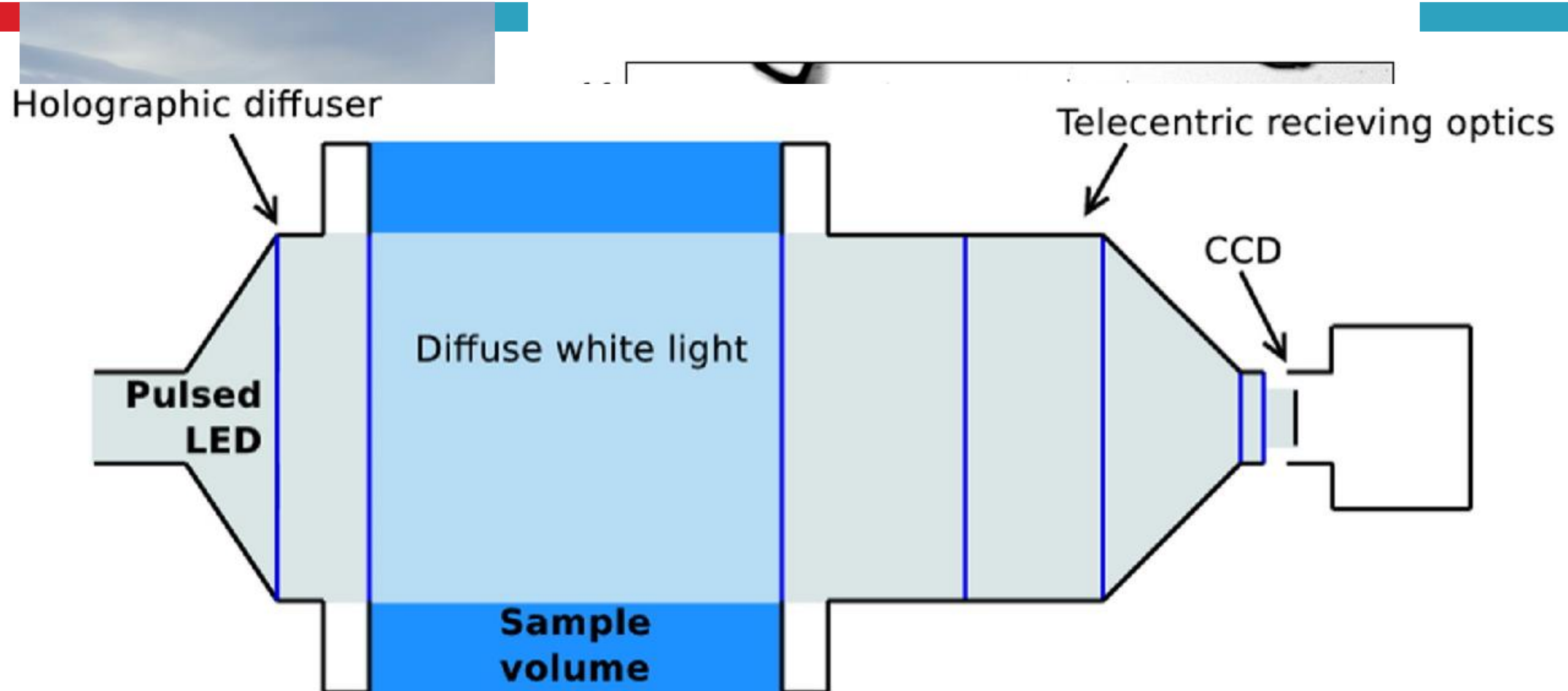
- Sample rate: **52 Hz sampling rate**, filtered (FIR) and downsampled from *208 Hz input to AHRS algorithm*.
- Output:
  - Absolute vertical acceleration
  - horizontal acceleration, but not oriented in fixed direction over time
- Batteries:
  - Alkaline C-cells: safer than Lithium in ocean-water.
- Transmits at configured interval, or when memory is full. I.e. every 20 minutes at 52 Hz.
- Telemetry: **Cellular network**, GSM, LTE.
- Georeference and time: GPS/GNSS/GLONASS
- Onboard storage: SD-card
- Cost of parts: **About 2000 NOK / 200 USD.**

Hardware, code and processing: https://github.com/gauteh/sfy

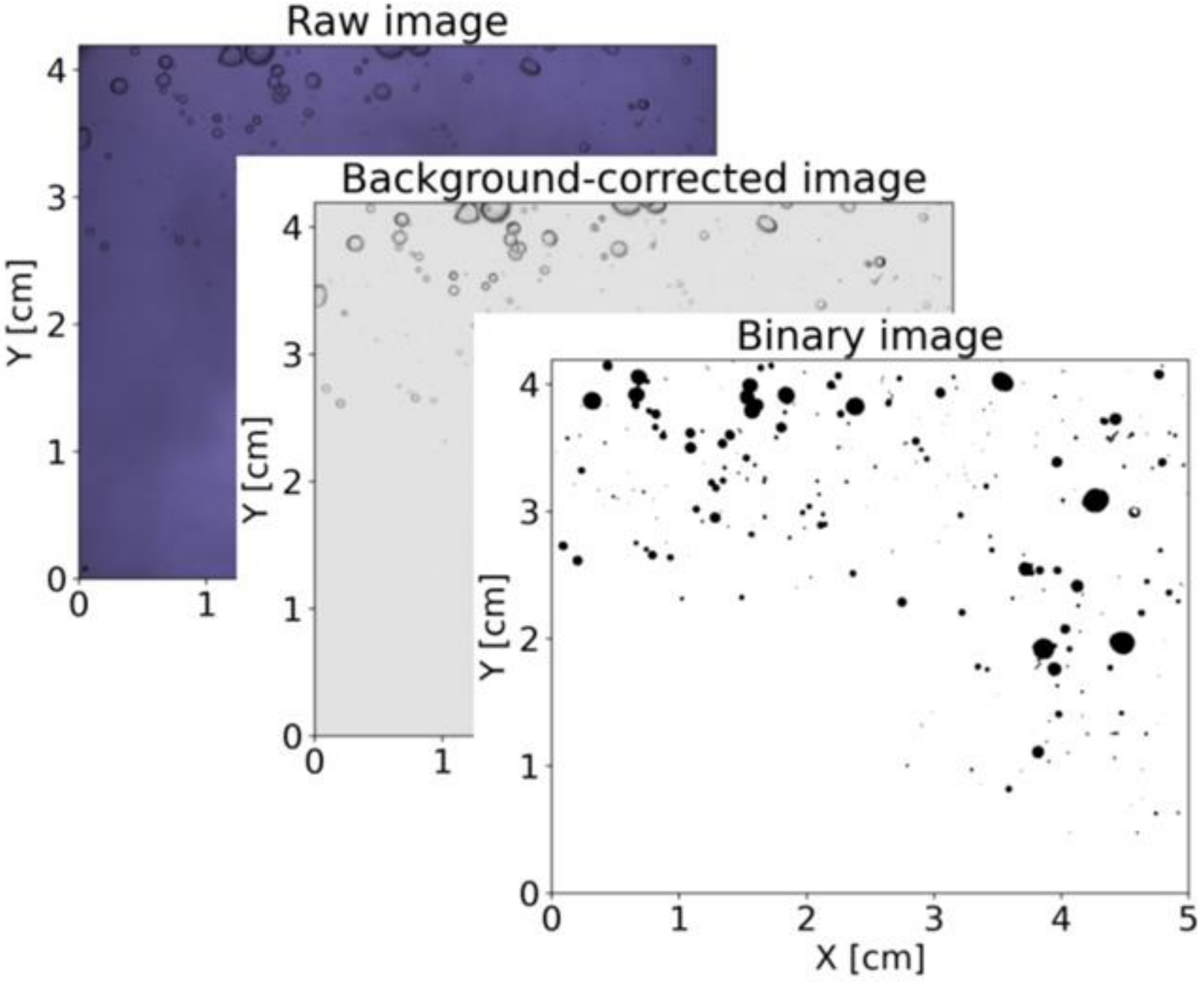
SFY: Capable of detecting individual breaking events

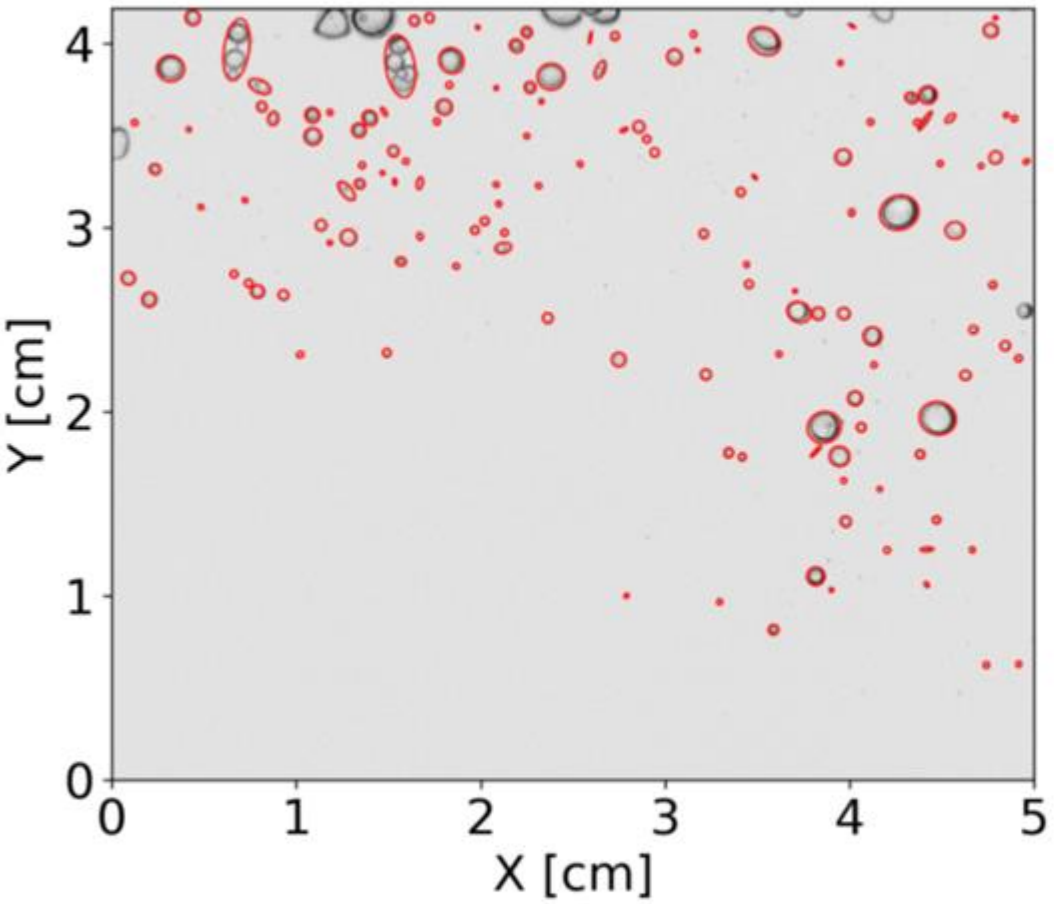


Sintef's Spartacus buoy equipped with telecentric lens for bubble size distribution



From telecentric images to bubble size distribution





Conclusion

The time is ripe.

- We have the components to go and measure the properties postulated to be proportional to the momenta of Phillips’ breaking crest length distribution.
- We can now combine new types of instruments in open-ocean conditions and help inform a new generation of wave models,
- but also, even more importantly, the parameterisations that need to go into coupled earth system models.