Modulation of air-sea fluxes by microscale breaking waves.

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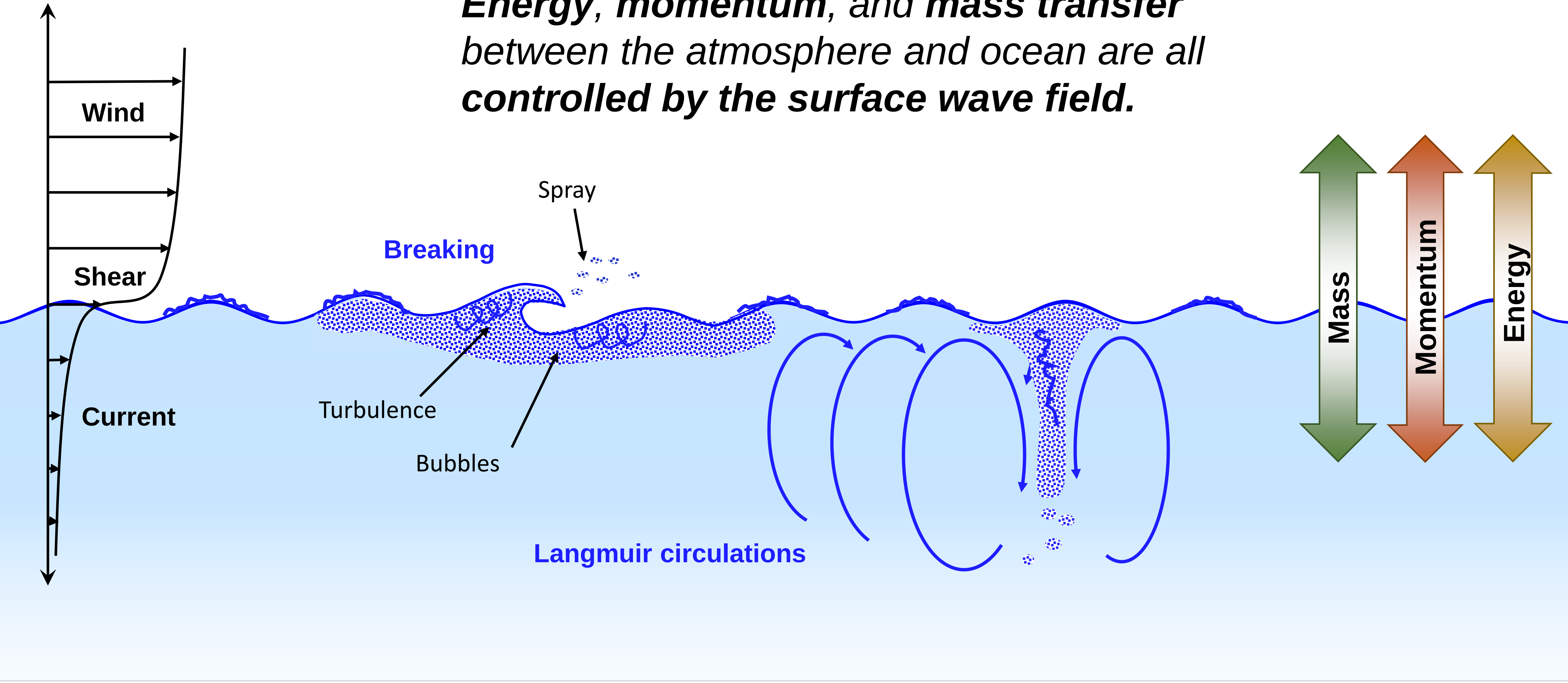
08/09/2016

Air-sea gas flux 2016

Modulation of fluxes at the air-sea interface by surface waves

Energy**, **momentum**, and **mass transfer** between the atmosphere and ocean are all **controlled by the surface wave field.



Experimental configuration

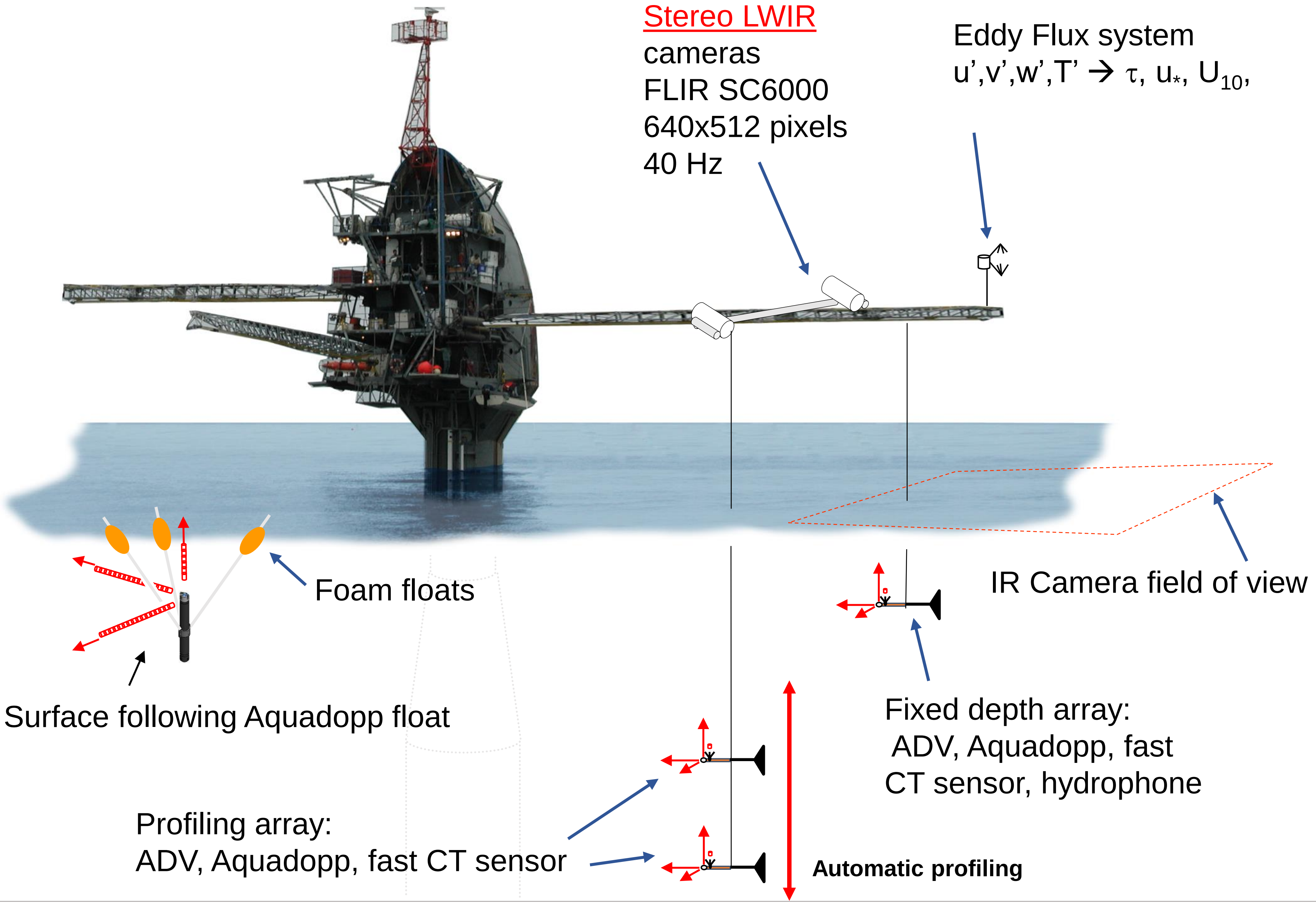
FLIP
- Stable
- **Minimal air-flow or wave field distortion**
- Long booms

3 Experiments:
- Hawaii, Southern California, Northern California

70 20-minute records:
Wind speed
U_{10} = 1.6 – 16 m/s

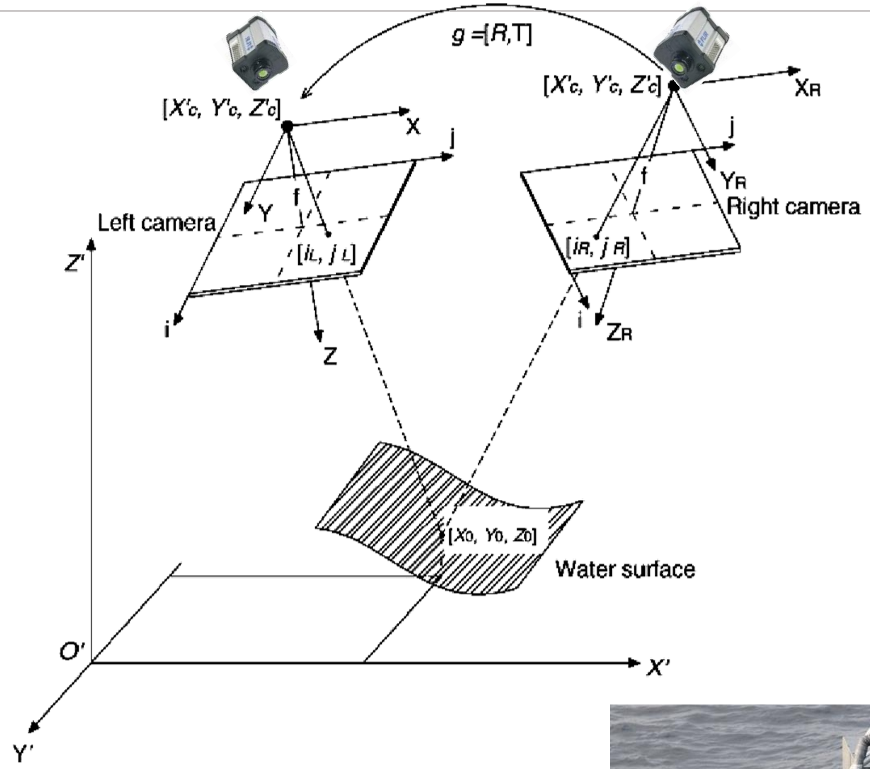
Significant wave height
H_s = 0.7 – 4.7 m

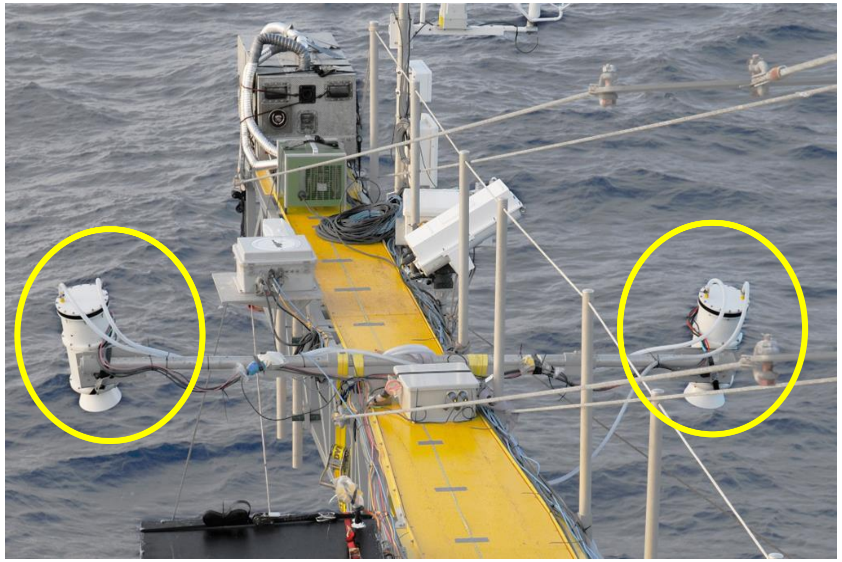
Wave age
c_m/u_* = 16 – 150



Stereo infrared

- 2x FLIR SC6000 Long wave infra red (LWIR)
- Surface temperature structure is used as a passive tracer over short Δt
  - active breakers
  - remnants of past breakers
  - surface signature of turbulence
- FOV ~3 m x 4m; 6 mm resolution



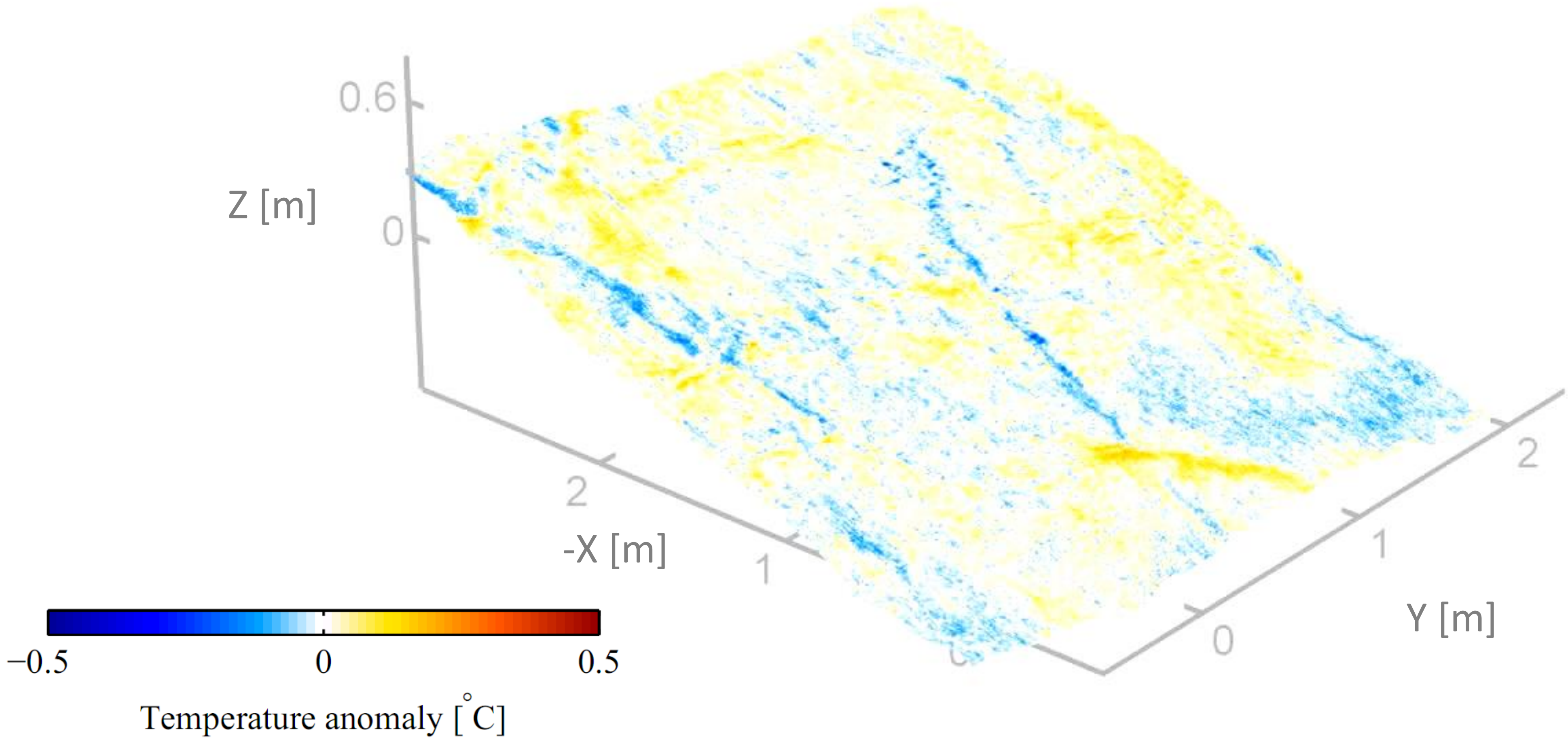


8µm to 9.2µm IR wavelengths

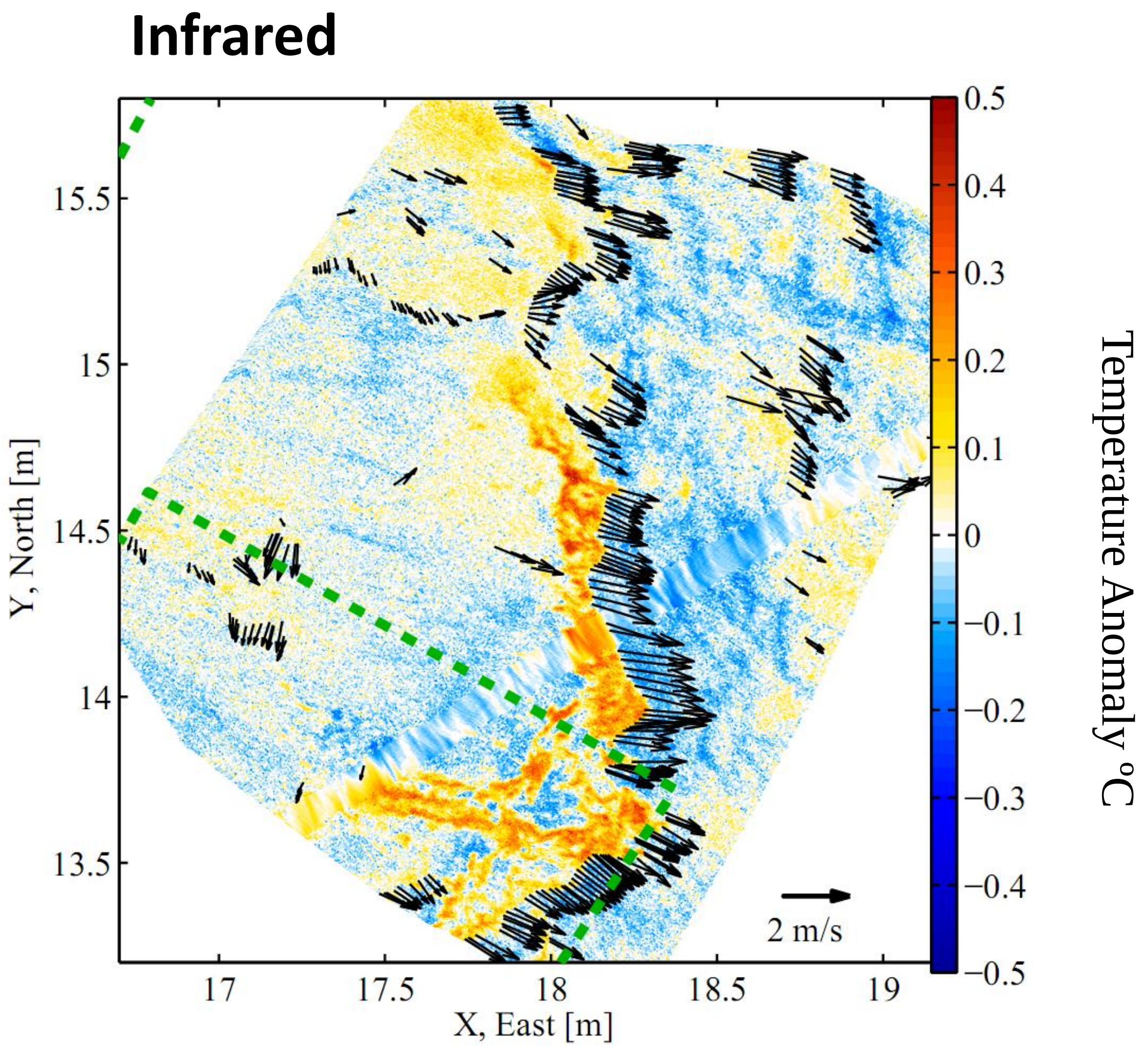
$2x10^{-5}$m penetration depth

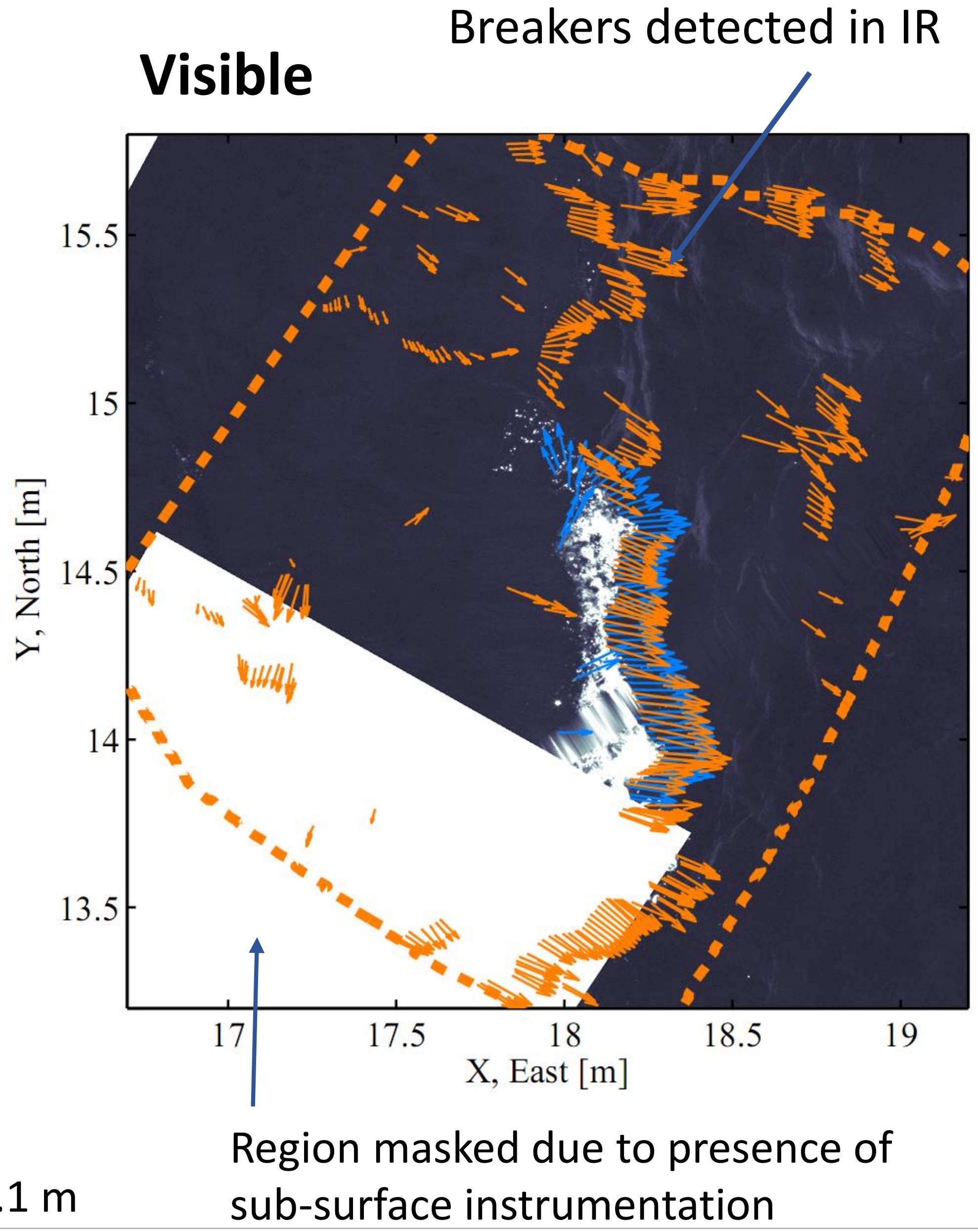
Stereo infrared surface reconstruction

Reconstructed surface, 2009/09/08 11:07:29.5. U10 = 7.7 m/s, Hs = 2.4 m



Breaking wave detection





Images taken December 6, 2010, 22:02:32.75 [UTC], U10 = 6.5 m/s, Hs = 1.1 m

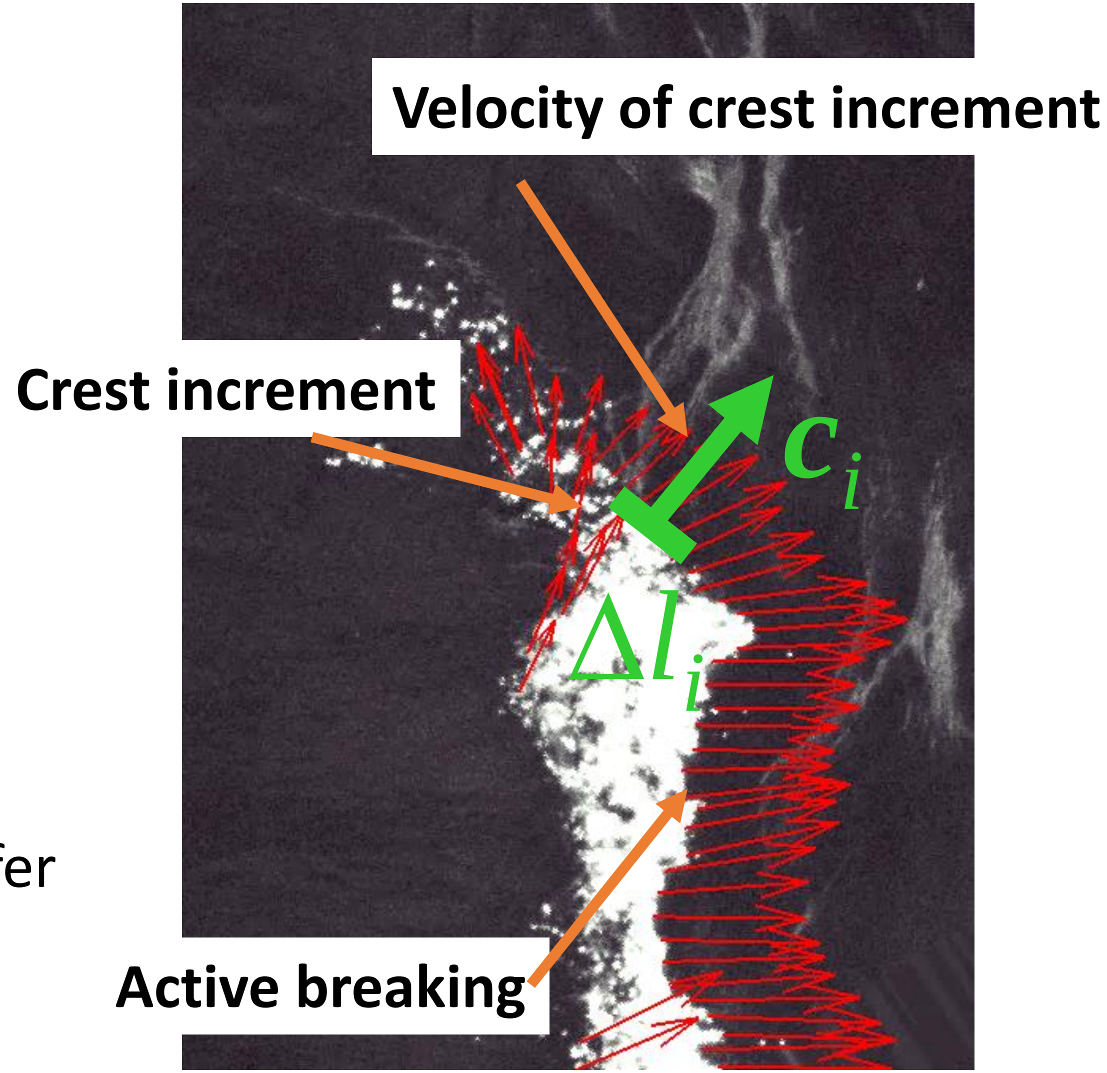
Breaker crest length distribution Λ(c) [Phillips 1985]

$\Lambda(c)$ = Distribution of breaker crest length per unit area of sea surface per unit increment of breaking crest speed c.

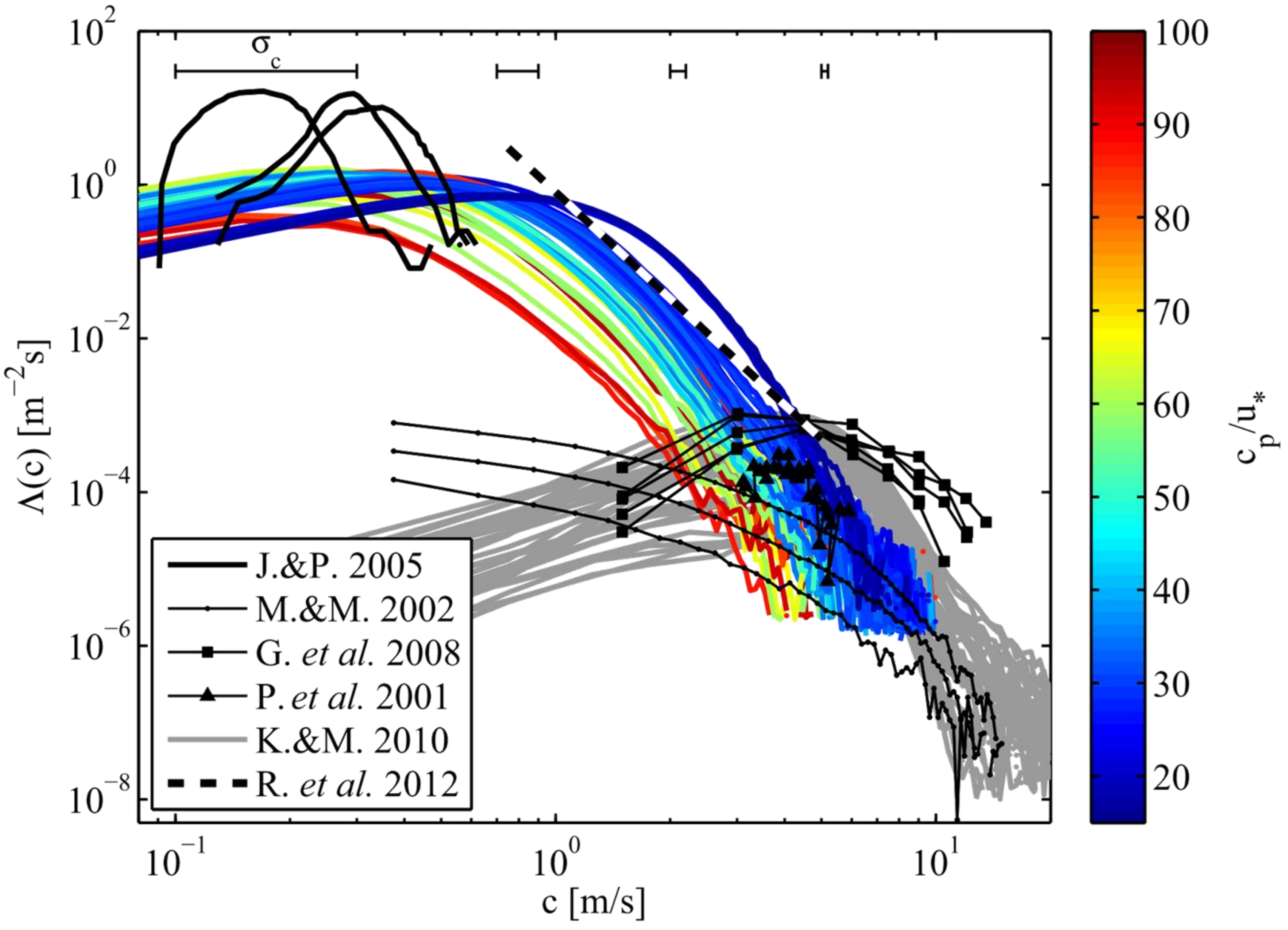
$$L = \int \Lambda(c)dc$$ **= Total crest length per unit area** [m^{-1}]

$$R = \int c\Lambda(c)dc$$ **= Fractional overturn per unit time** [s^{-1}]

Related to heat and gas transfer



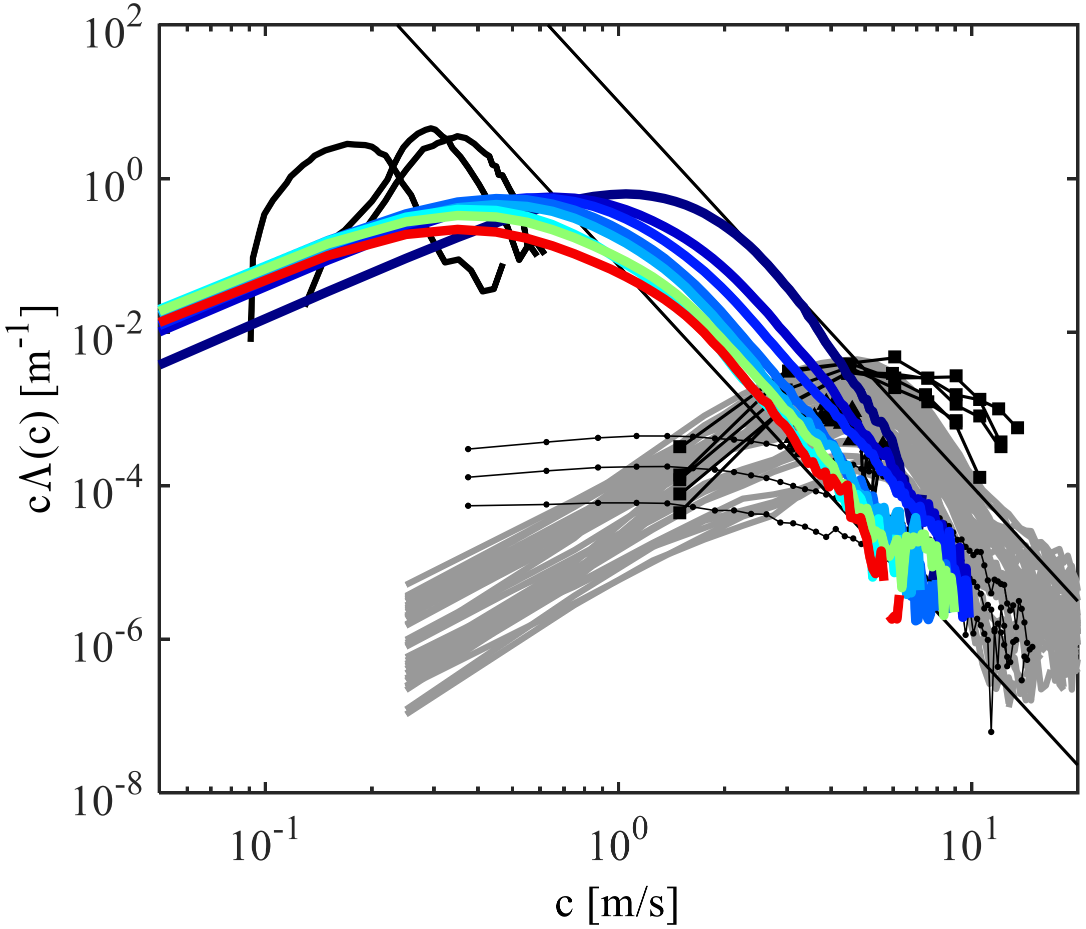
Breaker crest length distribution. Λ(c)



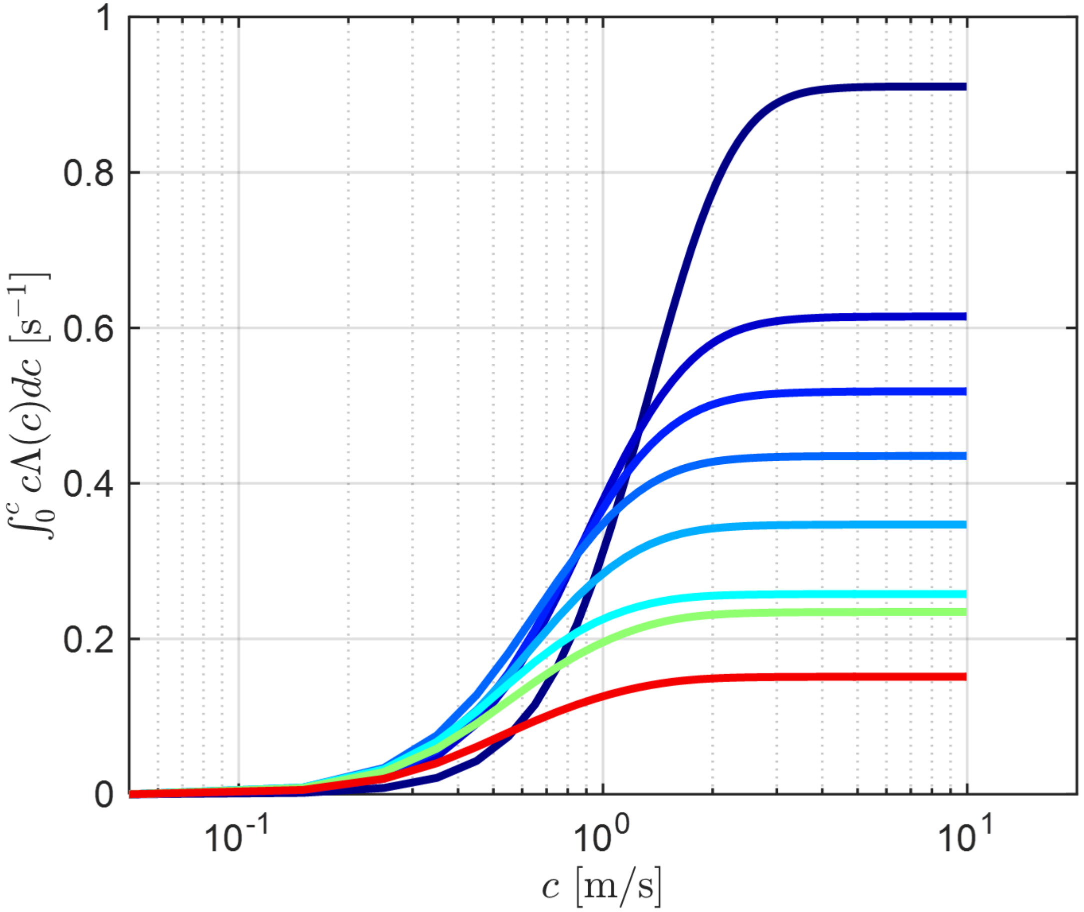
Surface renewal

$$R = \int c\Lambda(c)dc$$ = **Fractional overturn per unit time** [s^{-1}]

First moment of Λ(c)



Cumulative integral of first moment of Λ(c)



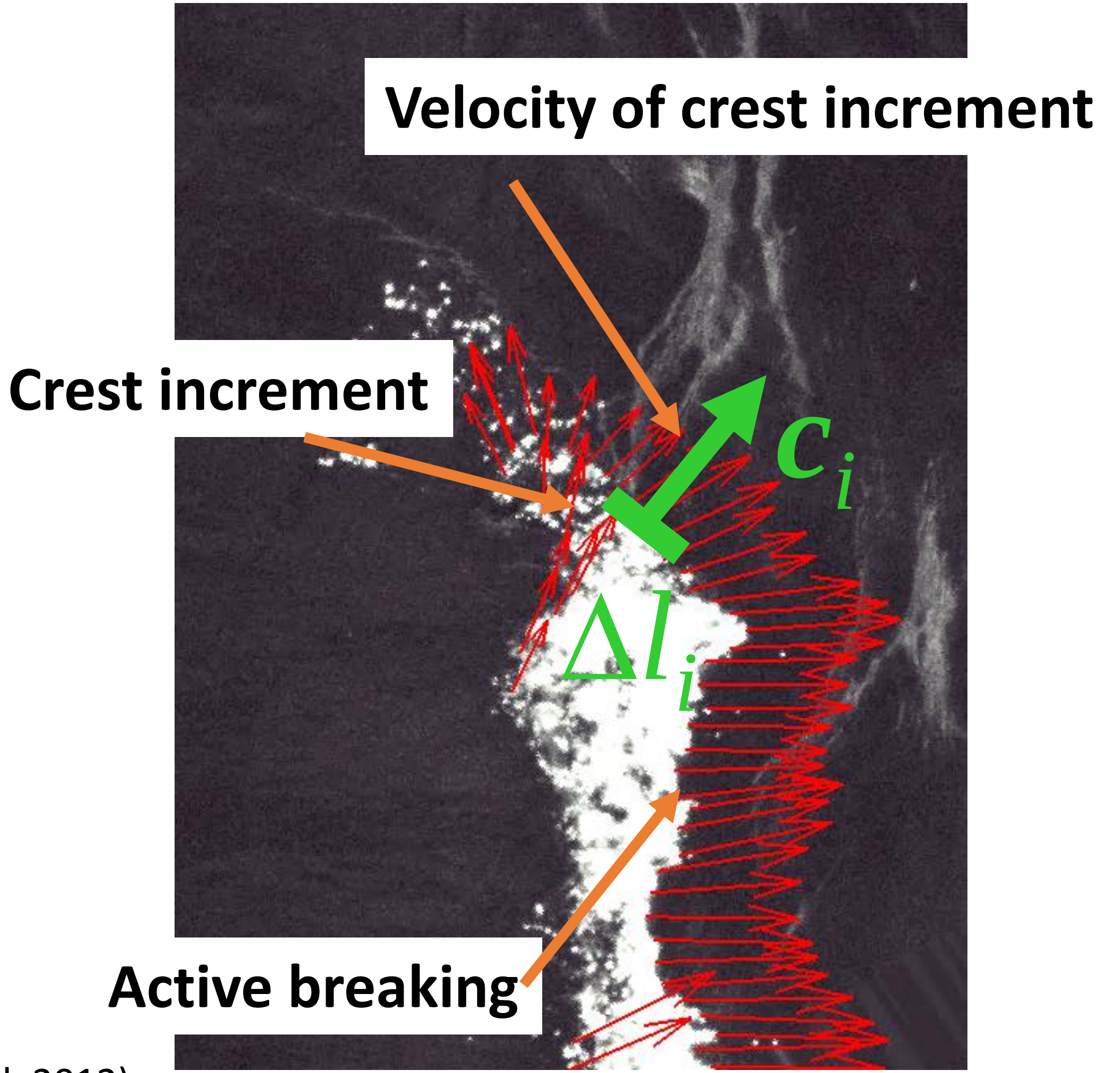
Stress and dissipation from Λ(c)

$\Lambda(c)$ = Distribution of breaker crest length per unit area of sea surface per unit increment of breaking crest speed c.

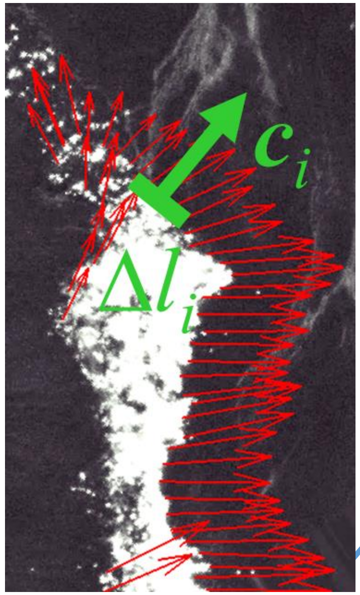
$$\boldsymbol{F_m} = \frac{\rho_w}{g}\int b c^3 \boldsymbol{c}\Lambda(\boldsymbol{c})\mathrm{d}\boldsymbol{c}$$ = **Stress** [N/m²]

$$F_E = \frac{\rho_w}{g}\int b c^5 \Lambda(c)dc$$ = **Dissipation** [W/m²]

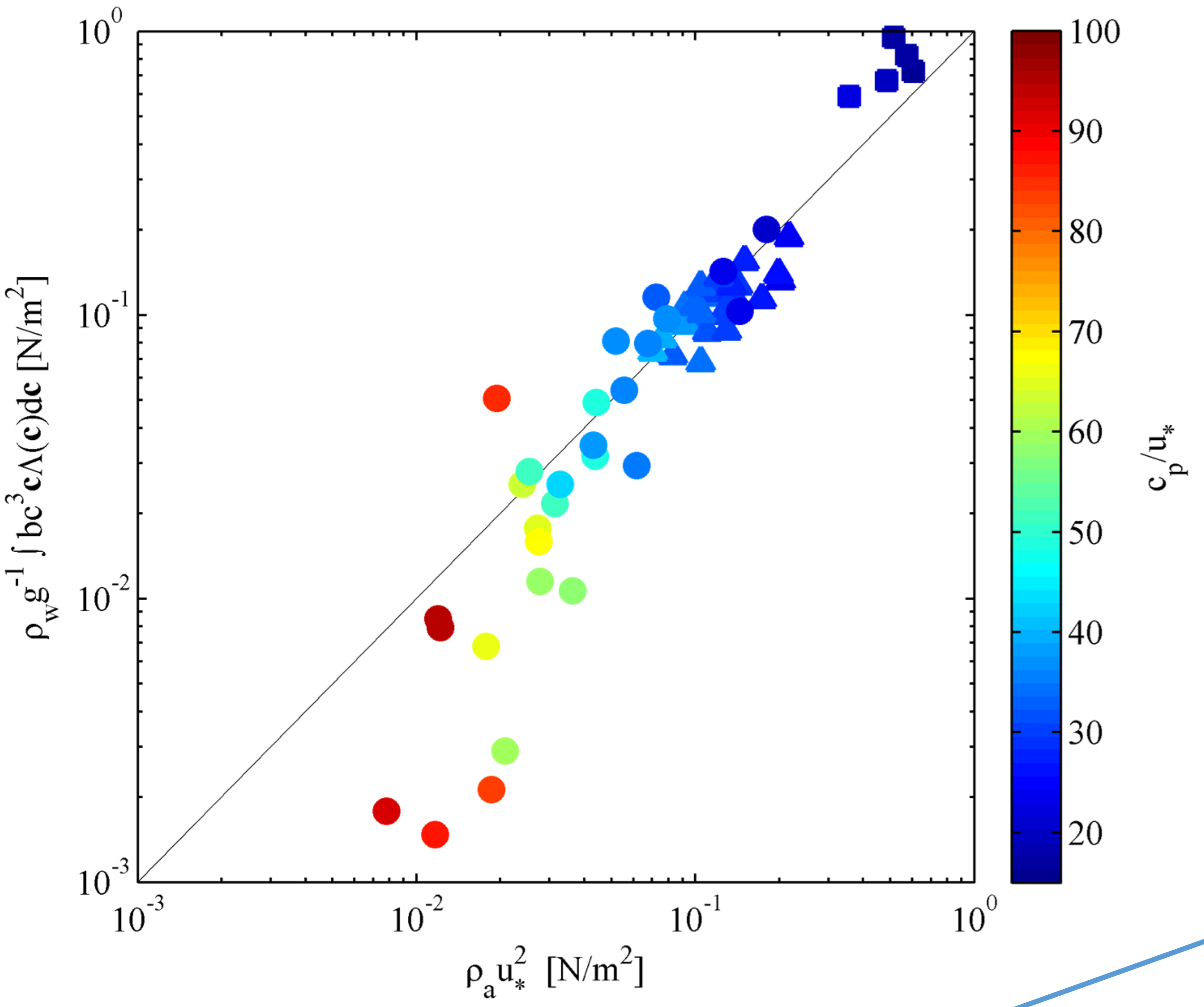
Breaking strength parameter
Depends on wave slope
Parameterized as a function of spectral saturation (Romero et al. 2012)

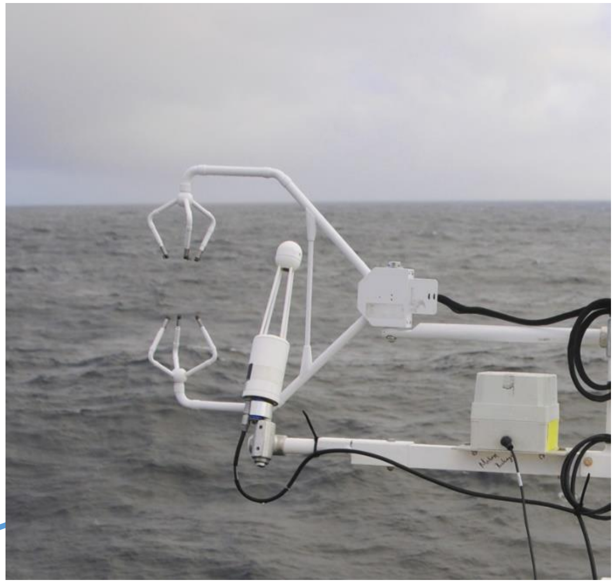


Momentum flux



Momentum flux by breaking





Measured wind stress

Measuring TKE dissipation near the sea surface is challenging:

- Waves + turbulence have motions at the same spatial and temporal scales
- Instrument wakes
- Intermittent processes
- …

Vorticity $\omega = \nabla \times \boldsymbol{u}$ for separation of irrot. waves from turbulence

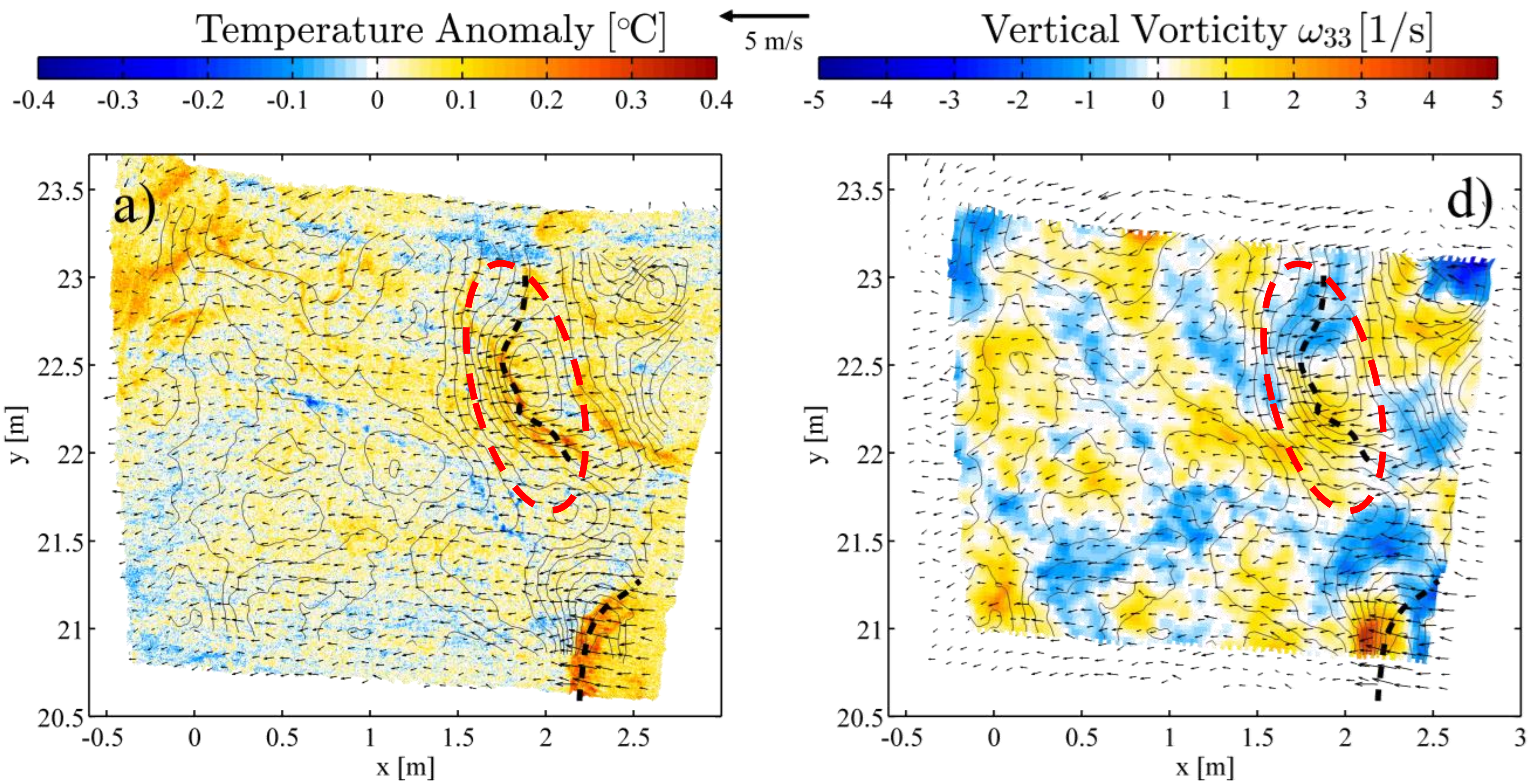
Helmholtz decomposition:

$$\boldsymbol{u} = \underbrace{-\nabla\phi}_{\boldsymbol{u_I}} + \underbrace{\nabla \times \boldsymbol{A}}_{\boldsymbol{u_R}}$$

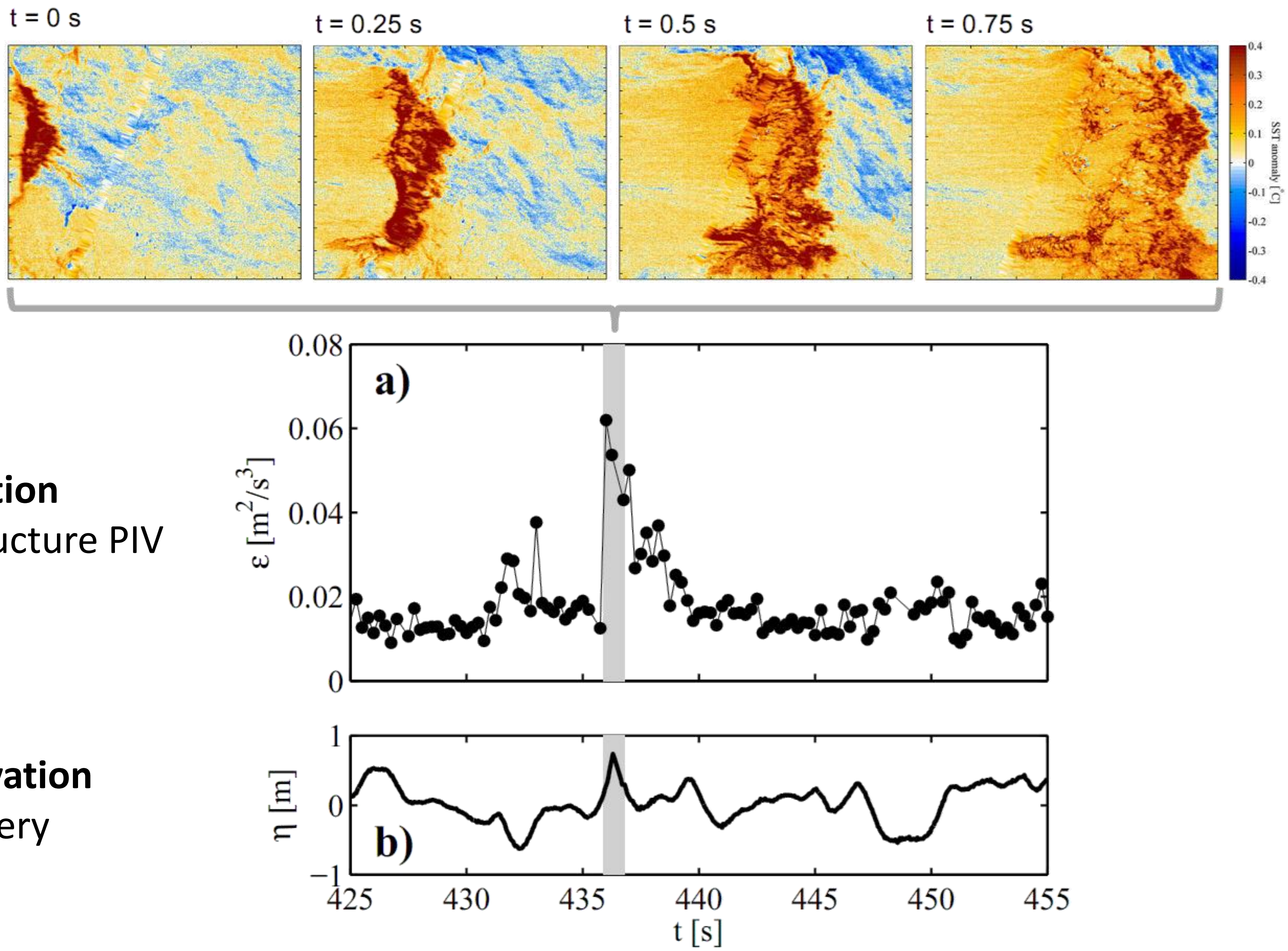
Irrotational velocity

Rotational velocity

Vorticity field contains no irrotational wave component



Energy dissipation by wave breaking

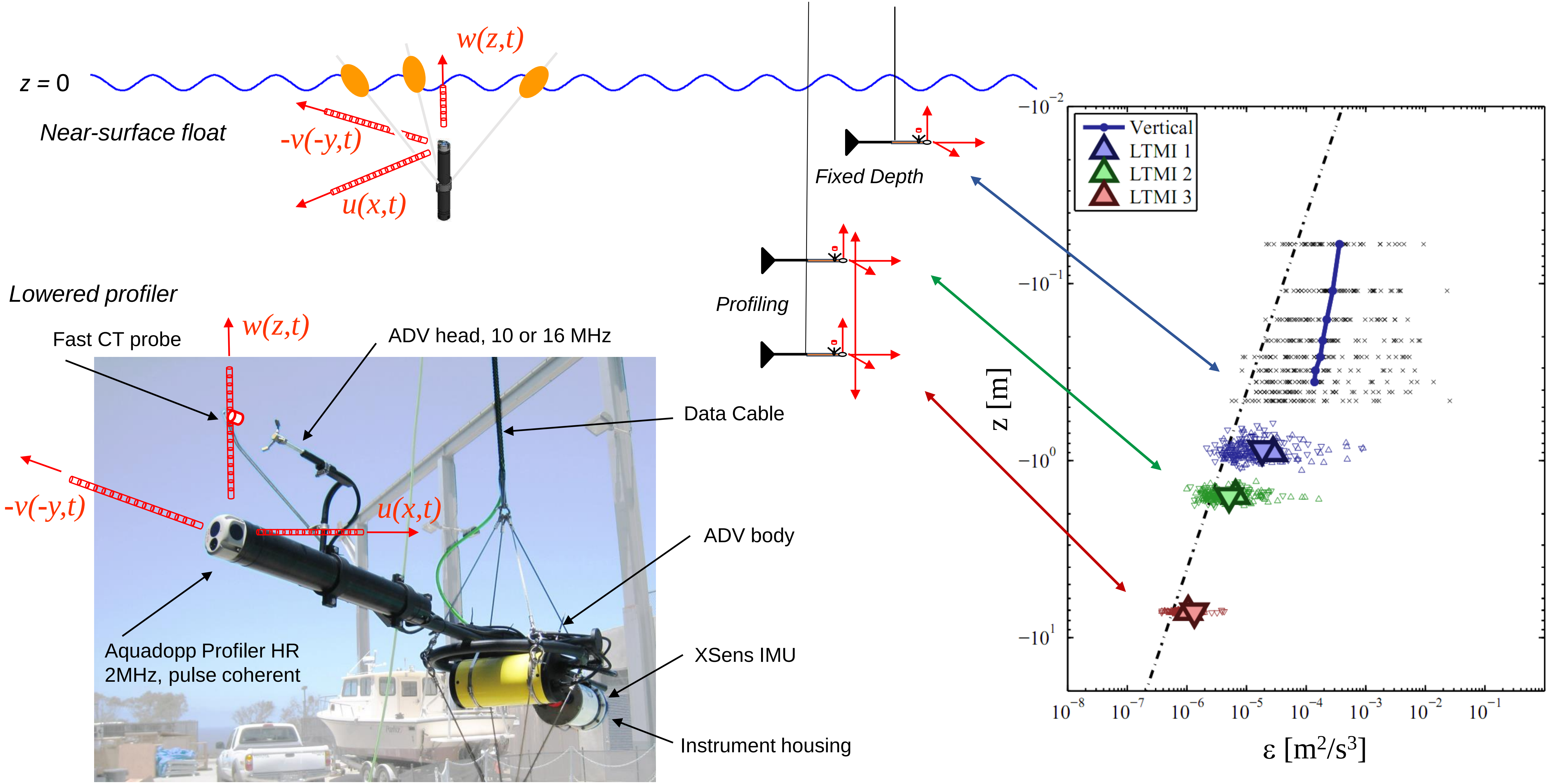


TKE Dissipation
Thermal structure PIV

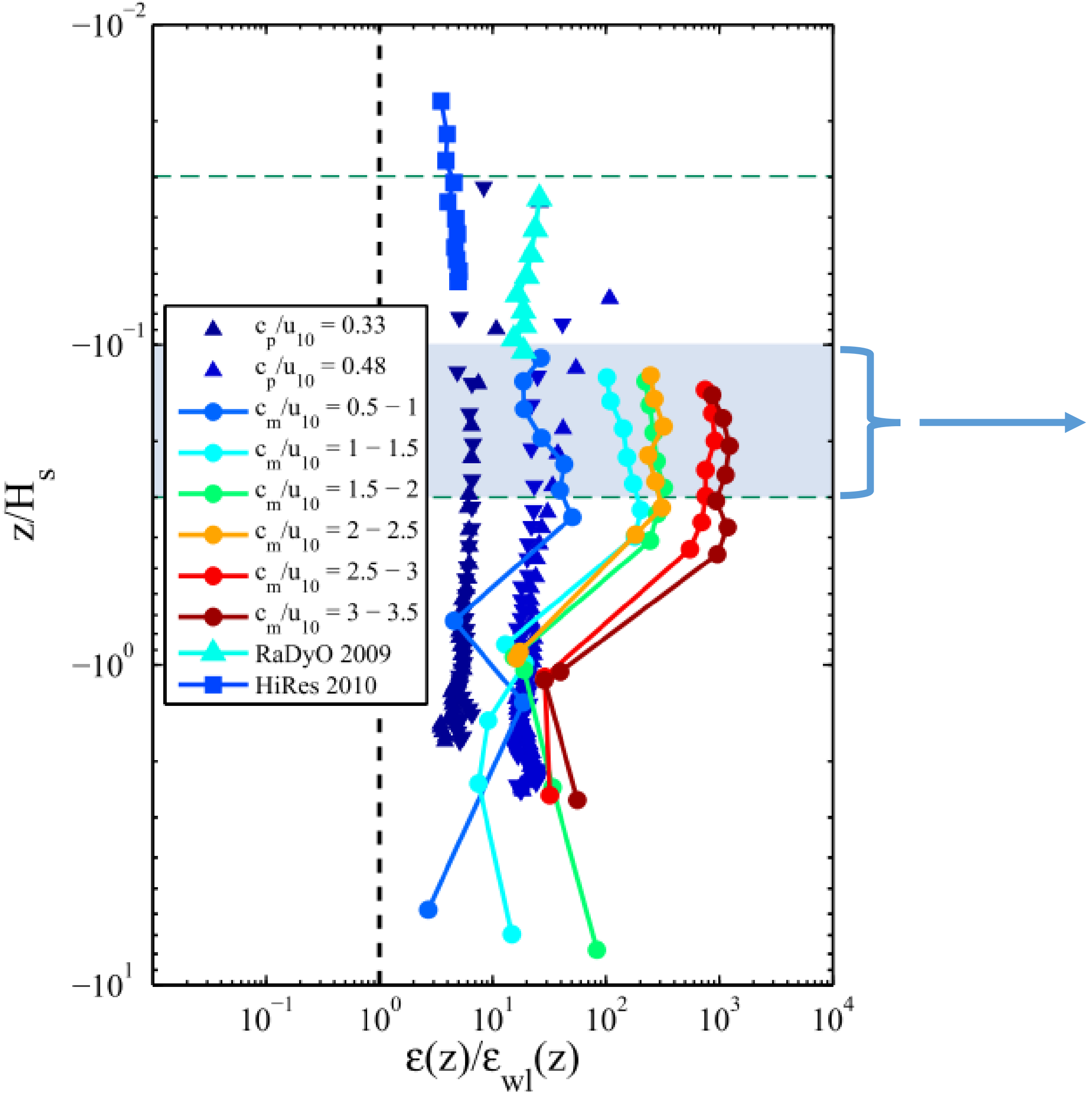
Surface elevation
Stereo imagery

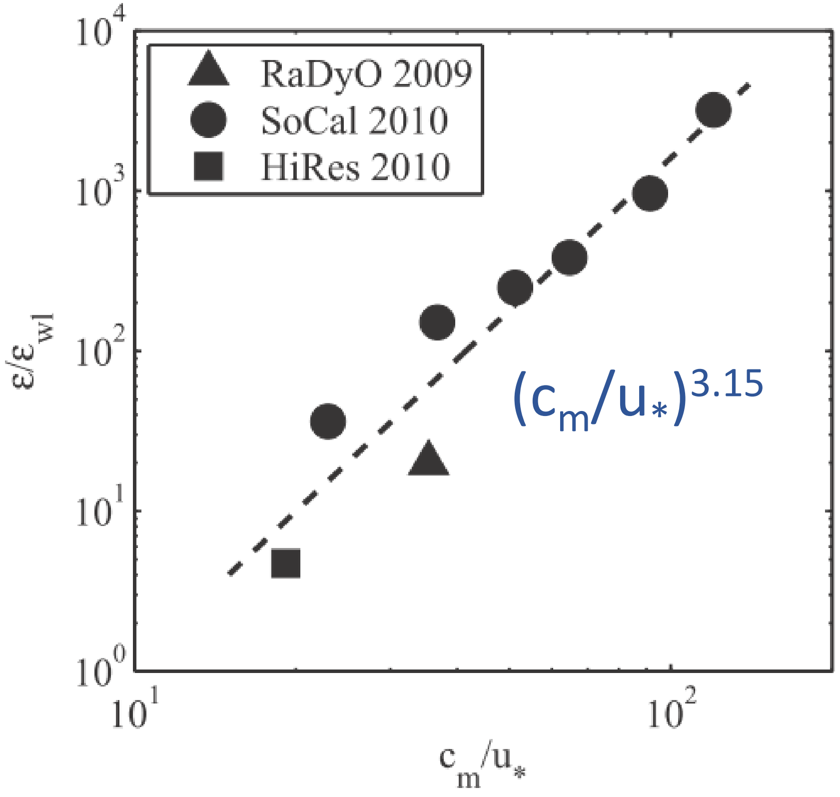
U_{10} = 6.5 m/s
H_s = 1.1 m
T_p = 4.9 s

Sub-surface TKE dissipation



Comparison with wall-layer



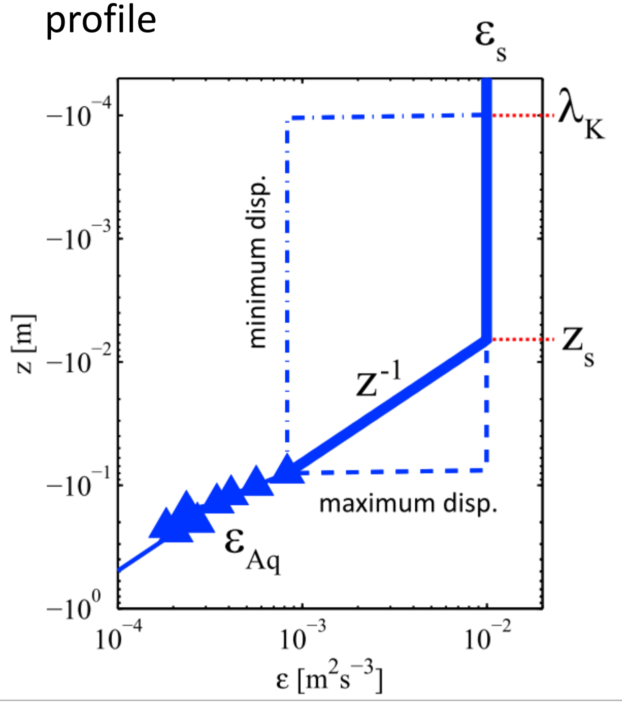


$(c_m/u_*)^{3.15}$

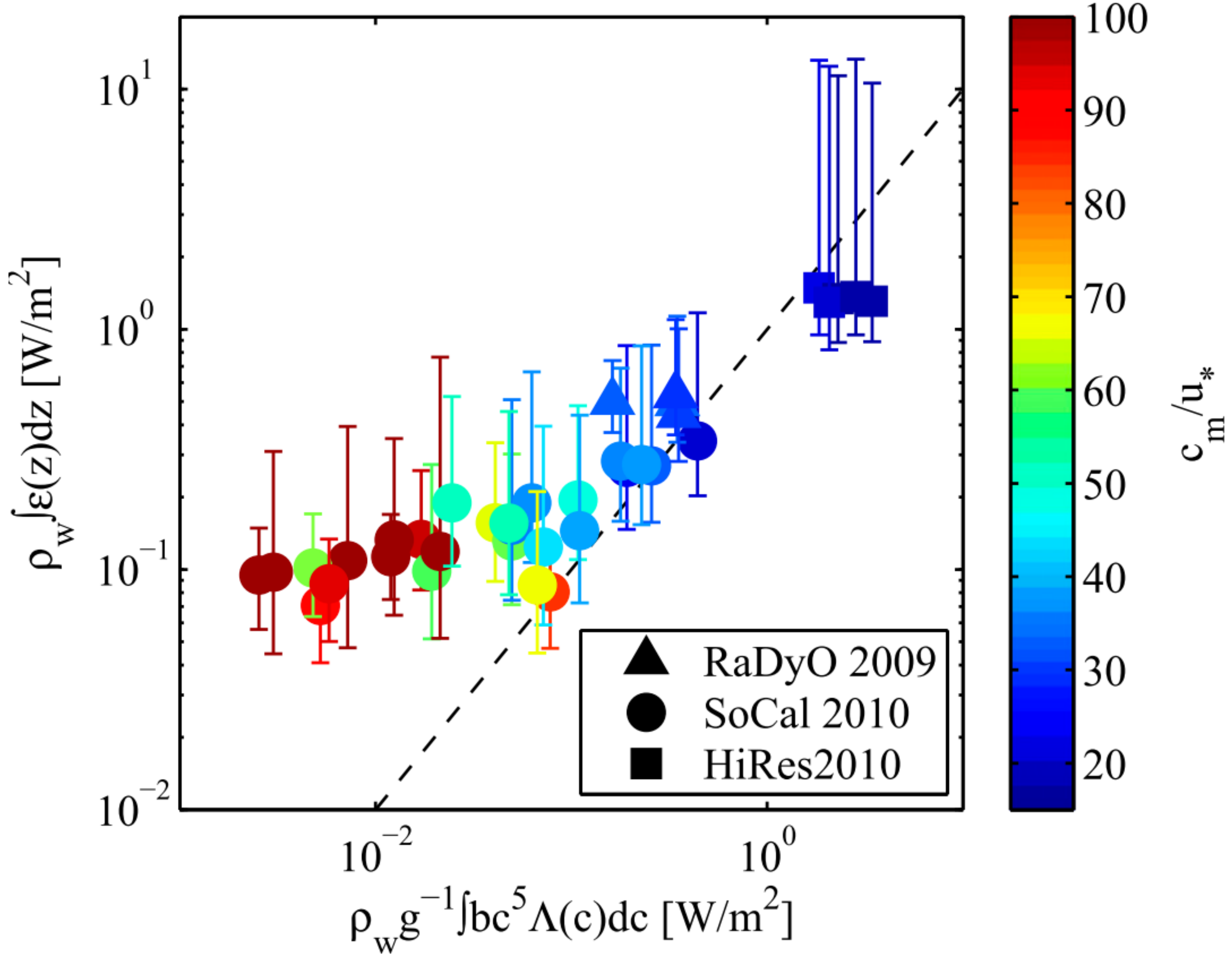
Dissipation by breaking vs. total near-surface TKE dissipation

- Agreement in young waves
- Disagreement in light winds / old waves

Sub-surface measurements connected to surface measurements using a z^{-1} profile



Integrated sub-surface dissipation

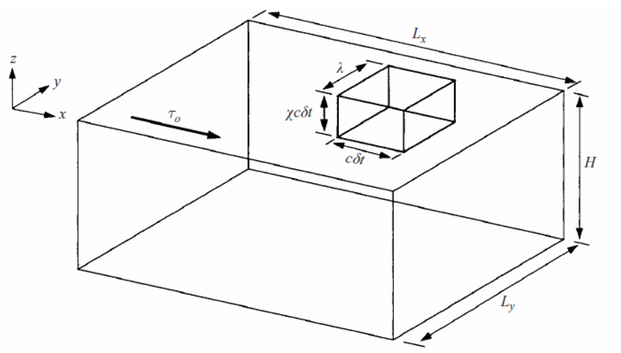


Dissipation by breaking

Turbulence profile comparison with LES

Sullivan, McWilliams, and Melville 2007

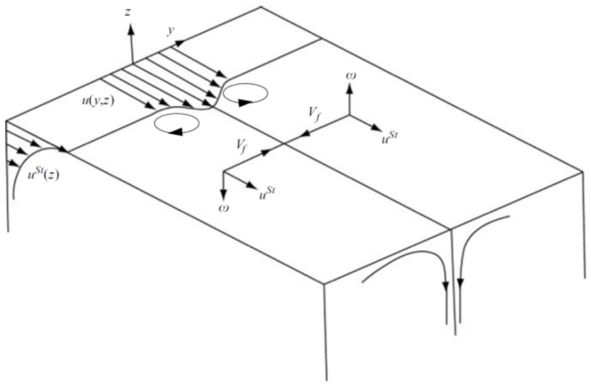
Breakers applied as body forces

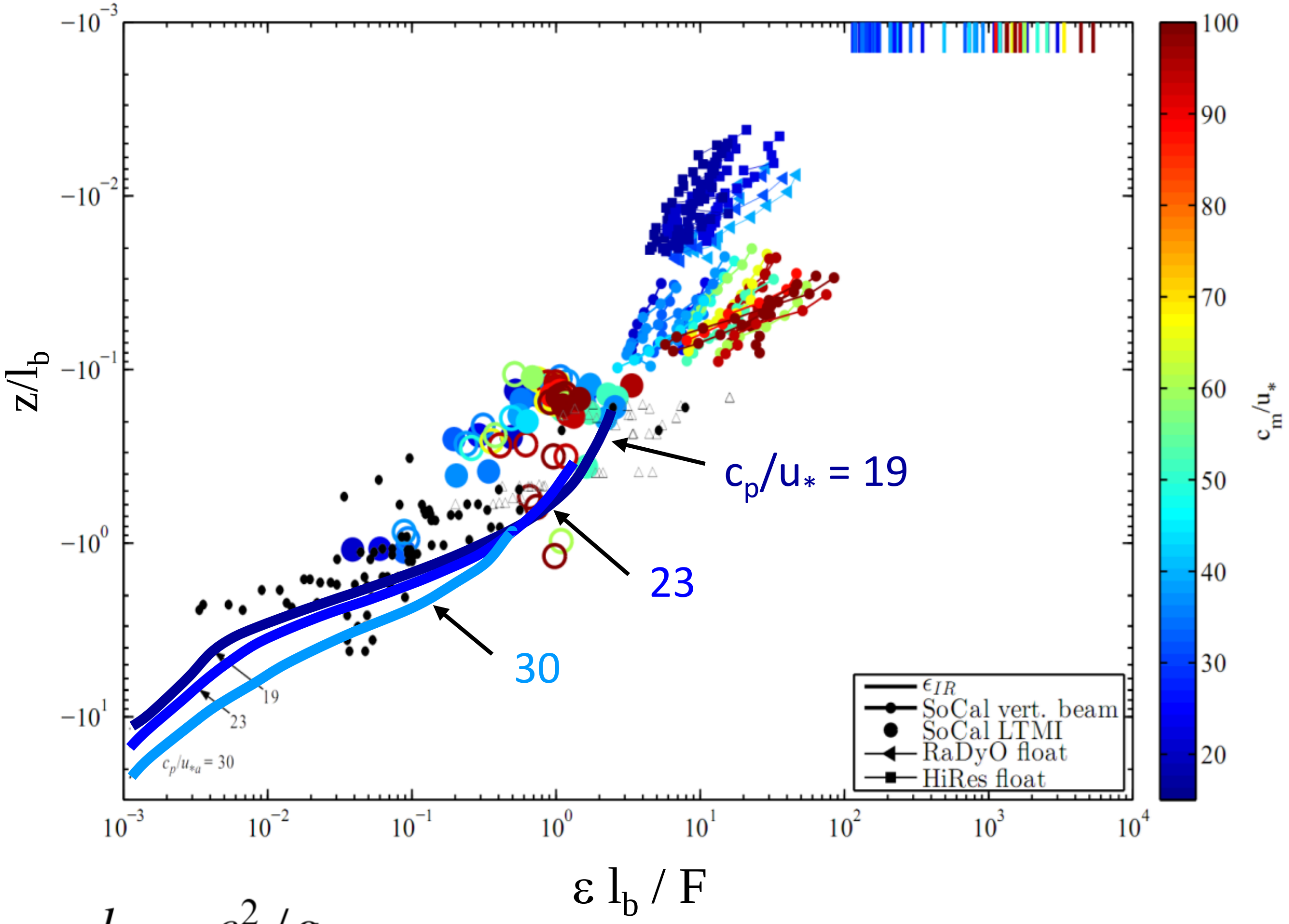


Body force shape functions from Melville, White, and Veron, 2002

Breaker distribution from Melville and Matusov 2002

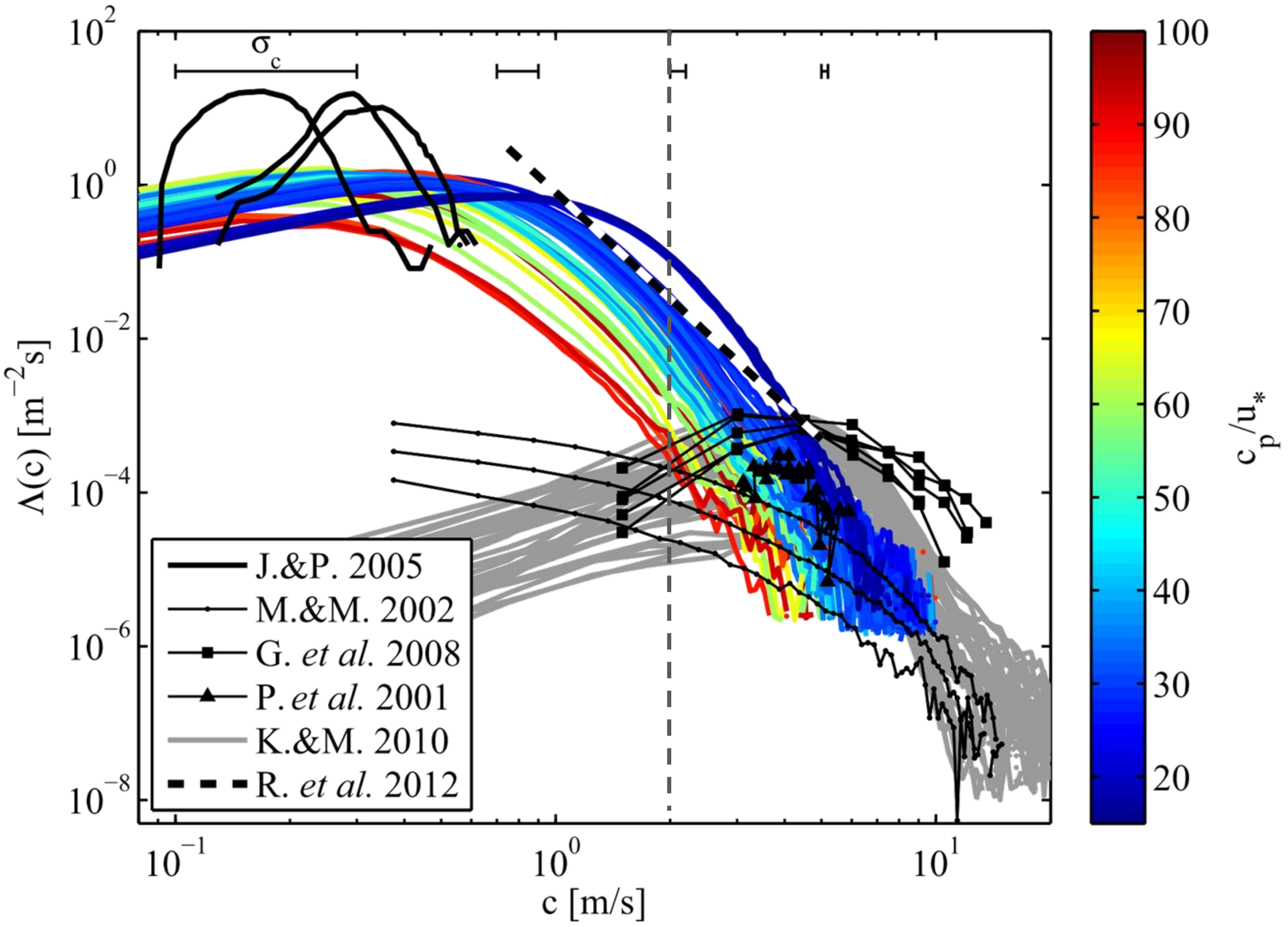
Langmuir Circulations





$$l_b = c_p^2/g$$

Breaker crest length distribution. Λ(c)



Conclusions

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- **Small scale breaking is dynamically important (surface renewal, stress, and dissipation)**.
- When small scale breaking is included, **wave dissipation can be balanced with dissipation by breaking** and **measured wind stress can be balanced by momentum flux by breaking** over a broad range of conditions.
- **Energy is dissipated very near the surface; the majority of energy is dissipated at depths < H_s** from the sea surface.

- Developed a **new method to measure TKE dissipation at the wavy sea surface**.

psutherland.ca/publications.html

- Sutherland, P., and W. K. Melville, **2015**. Measuring turbulent kinetic energy dissipation at a wavy sea surface. *Journal of Atmospheric and Oceanic Technology*, 32, 1498–1514.
- Sutherland, P., and W. K. Melville, **2015**. Field Measurements of Surface and Near-Surface Turbulence in the Presence of Breaking Waves. *Journal of Physical Oceanography*, 45, 943-965.
- Sutherland, P. & Melville, W. K. **2013.** Field measurements and scaling of ocean surface wave-breaking statistics. *Geophysical Research Letters, 40*, 3074-3079

Acknowledgements

- Luc Lenain, Nick Statom
- Captain and crew of R/P FLIP
- Workshop organisers!