IMPERIAL

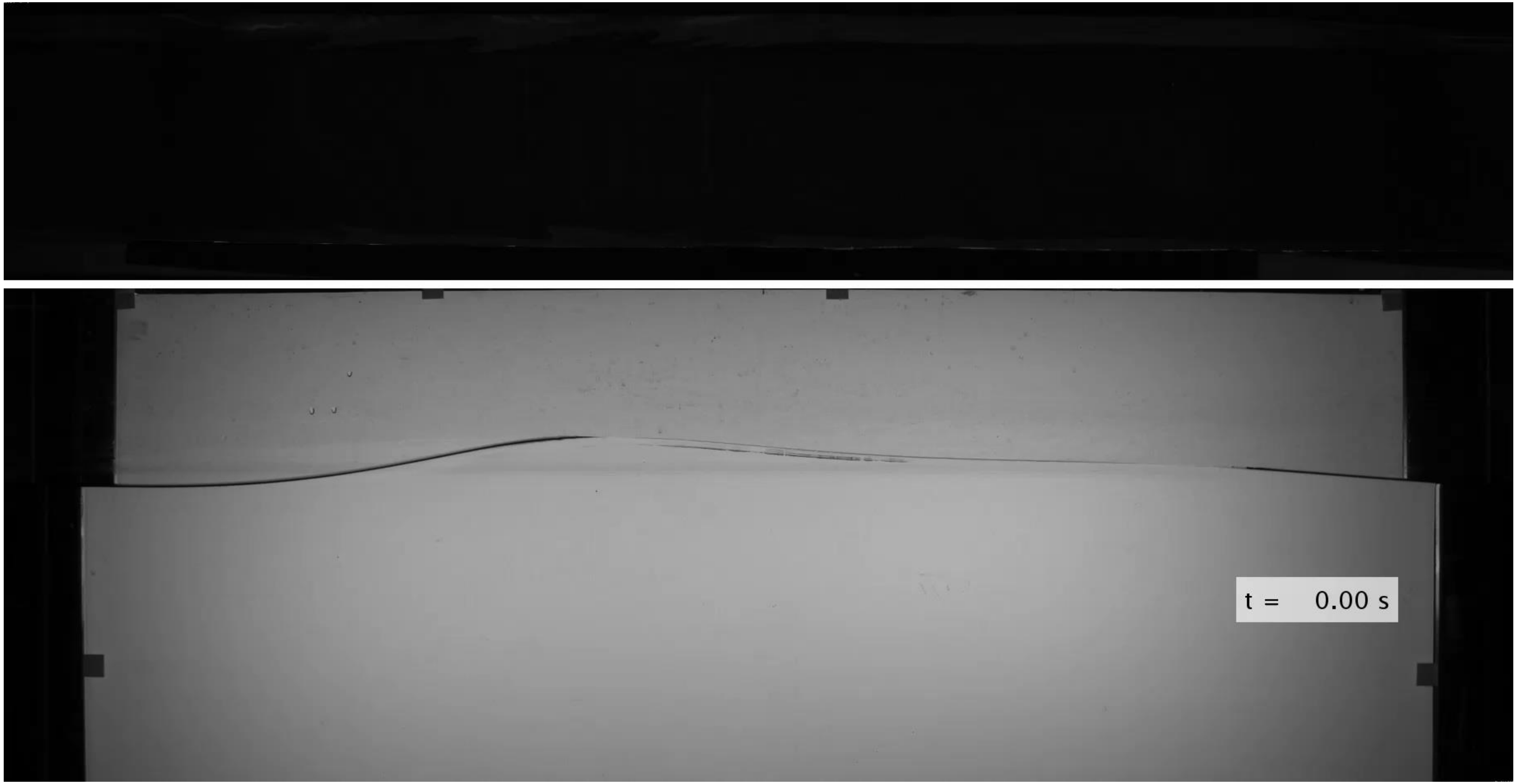
Automated Tracking and Characterization of Oceanic Wave Breaking

Zhanyuan Tian

Adrian Callaghan, Daniel Valero (ICL)
Filippo Bergamasco, Mara Pistellato (Ca' Foscari)
Alvise Benetazzo, Francesco Barbariol (ISMAR)

Background
Importance of Wave Breaking in Air-Sea Interaction Studies

[1]



[1] SIREN Experiment from Imperial

Background
Remote Sensin

Whitecap Tracking - original - frame: 902

2008

Gemmrich, J. R., Banner, M. L., & Garrett, C

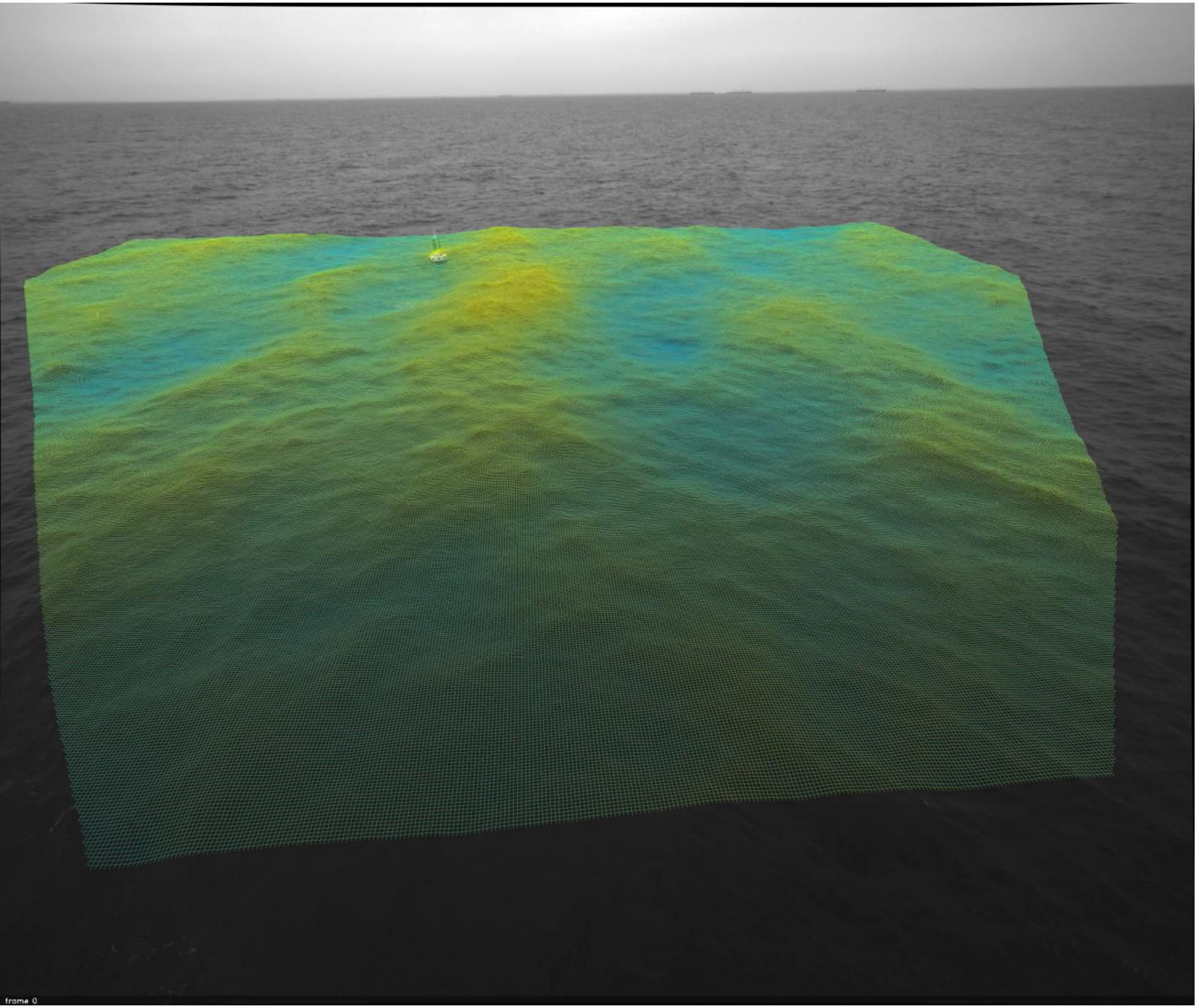
Kleiss, J. M., & Melville, W. K

2025

Akaawase, B., Romero, L., & Benetazzo,

Background
Wave Field Observation

[2]



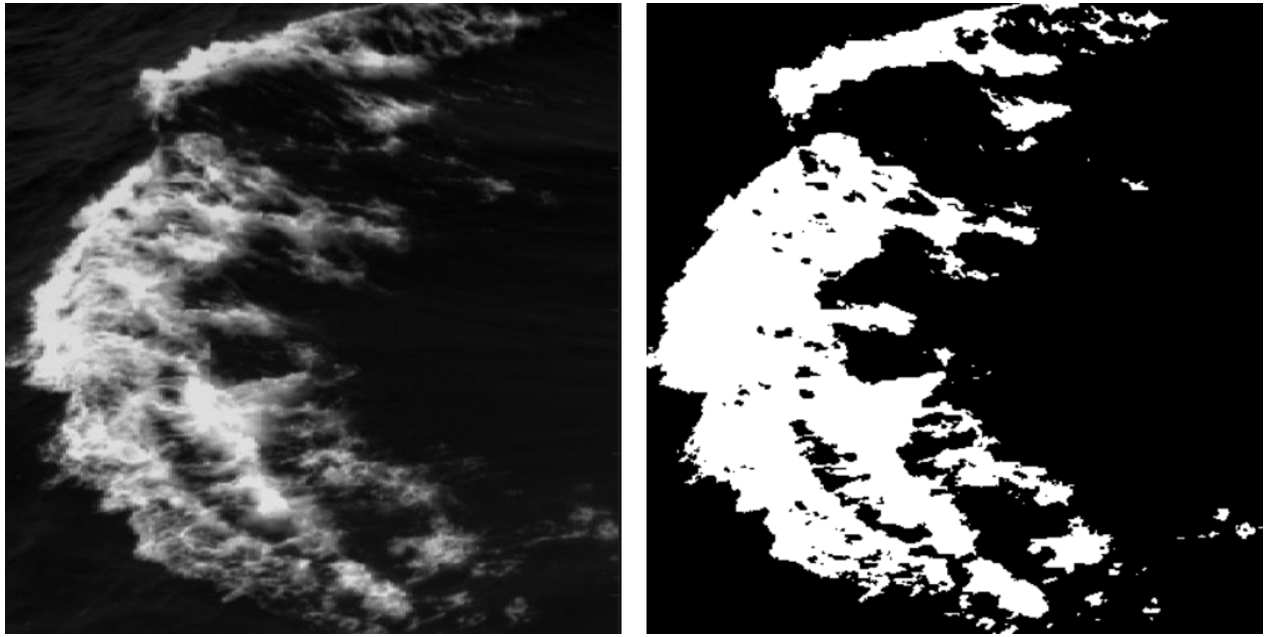
[1]

[1] Peach, J. 2025. Photo credit: Silvio Davison
[2] Benetazzo, A., Bergamasco, F., Yoo, J., Cavaleri, L., Kim, S. S., Bertotti, L., Barbariol, F., & Shim, J. S. (2018).

Background

Automated Whitecap Detection and Tracking Algorithm (AWDAT) [1]

(1) Binarize each frame based on the grayscale of the image (AWE method).



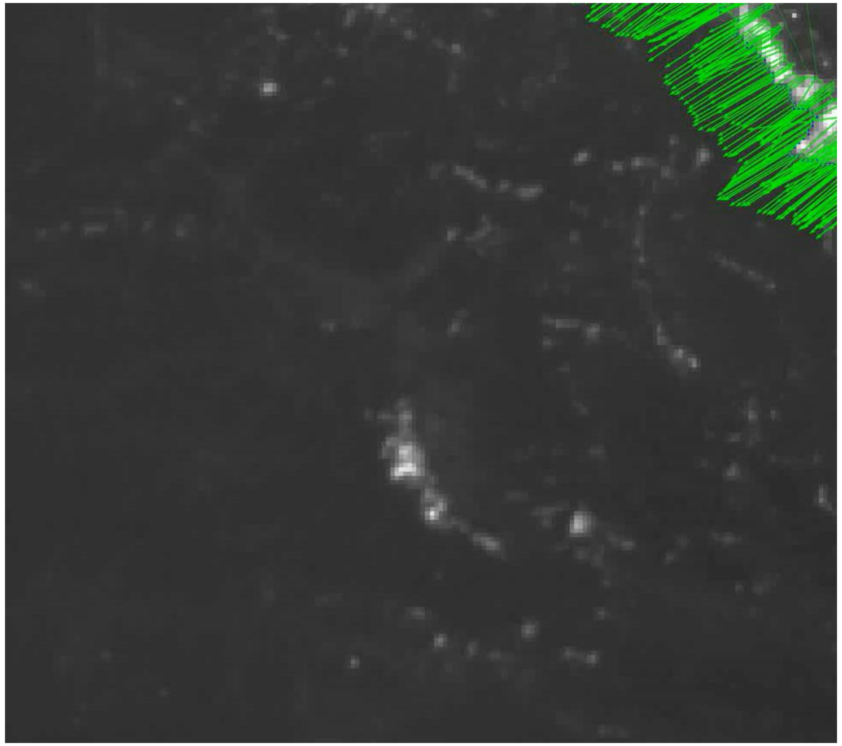
[1] Peach, J., Callaghan, A. H., Bergamasco, F., Pistellato, M., Barbariol, F., and Benetazzo, A. (2025)

Background

Automated Whitecap Detection and Tracking Algorithm (AWDAT)

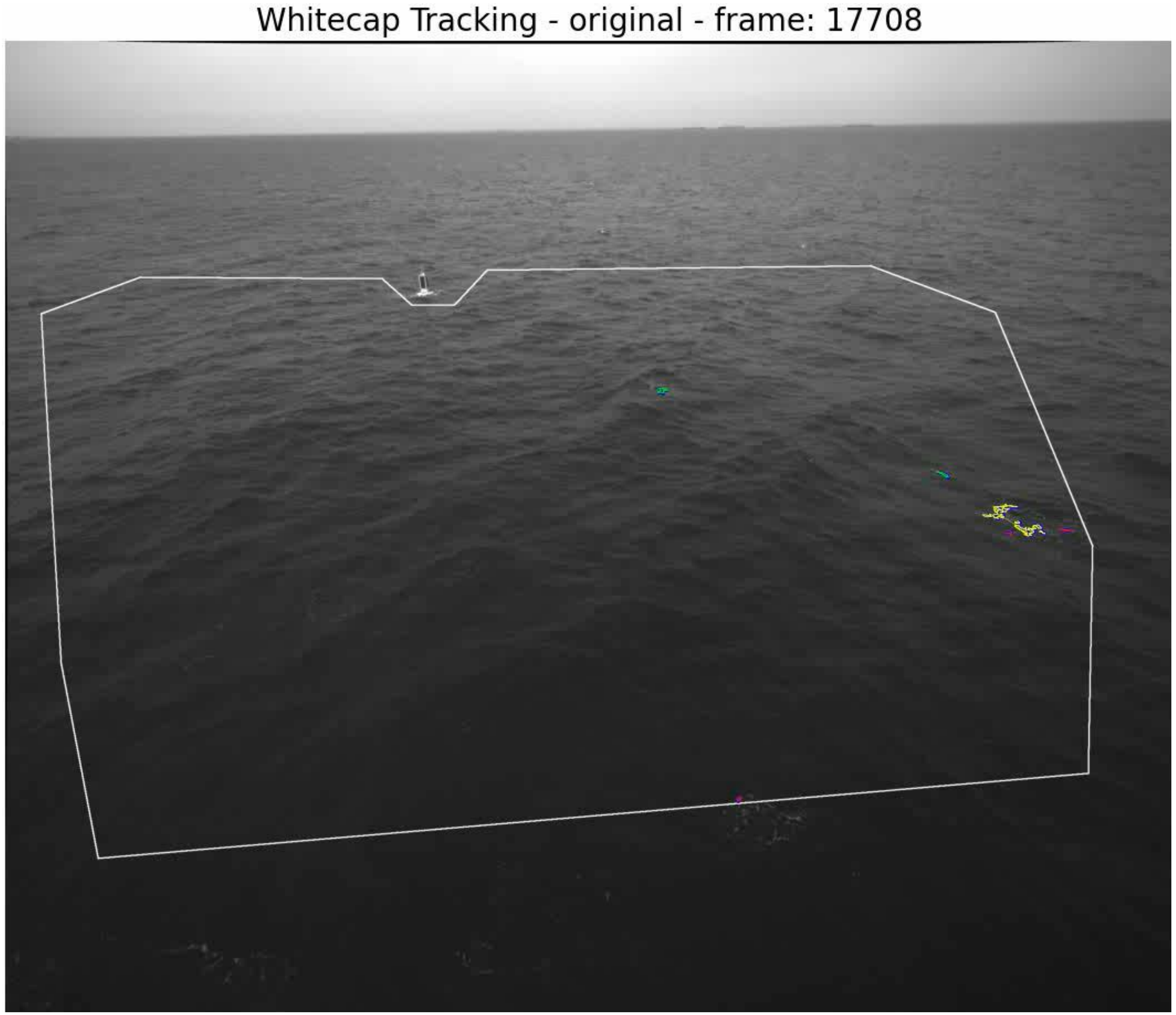
(1) Binarize each frame based on the grayscale of the image (AWE method).

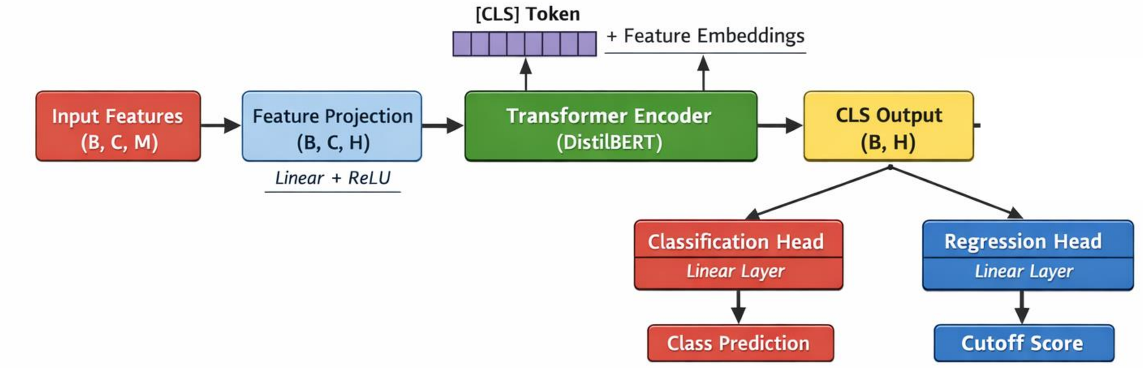
(2) Apply an optical flow algorithm to track whitecap boundary across consecutive frames.



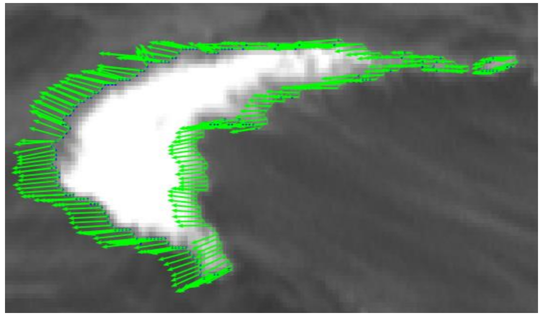
Background

Automated Whitecap Detection and Trac

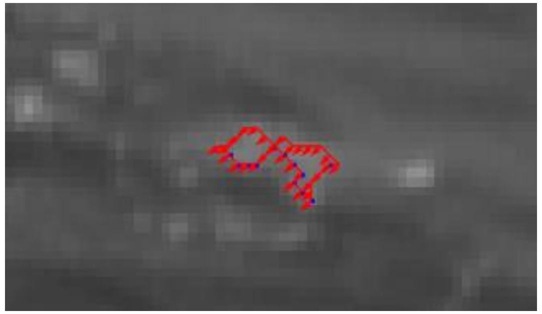




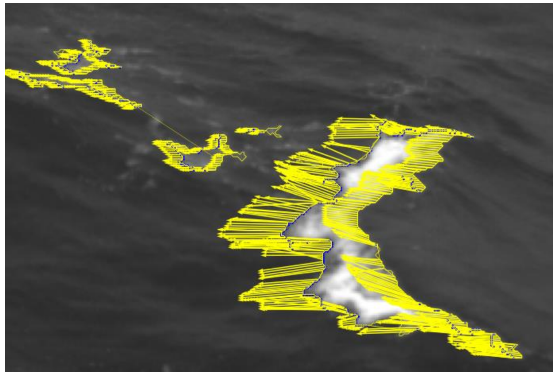
(3) Use a fine-tuned neural network to classify active breaking events from other detections.



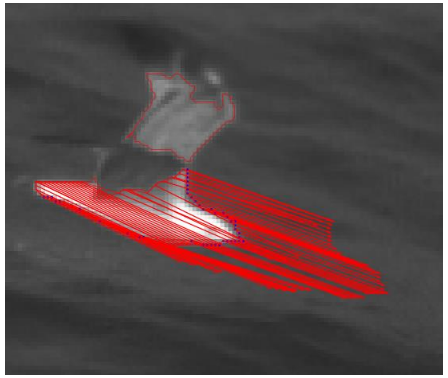
Active breaking



Residual foam

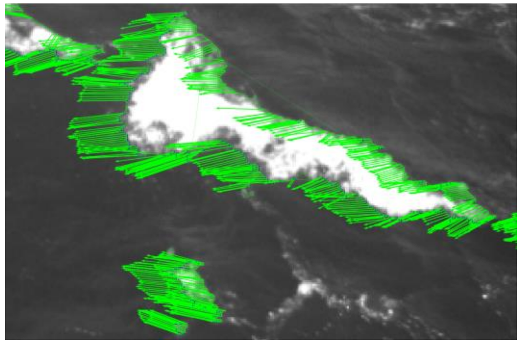


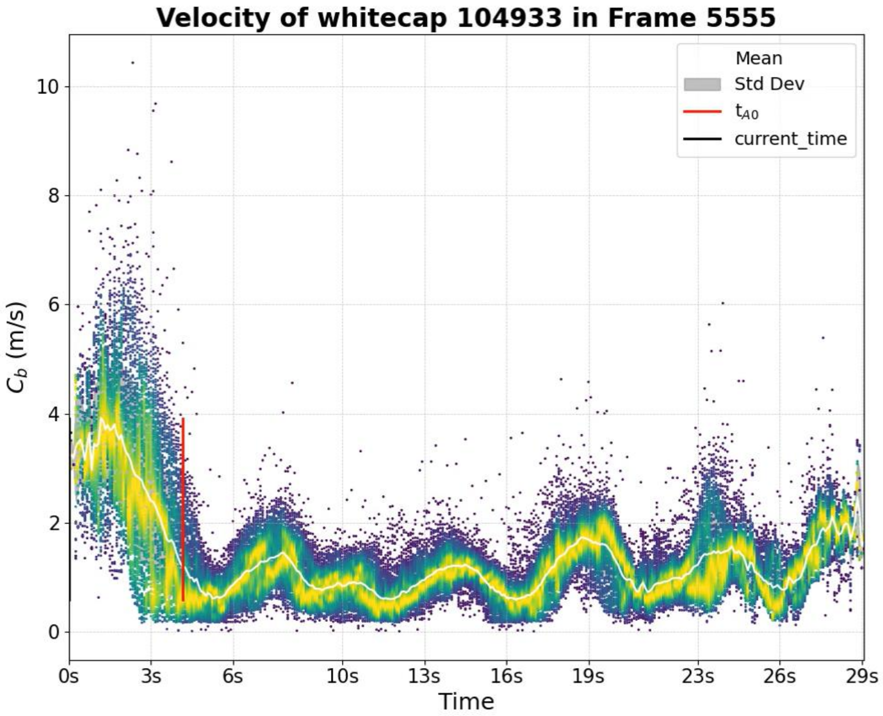
Overlapping

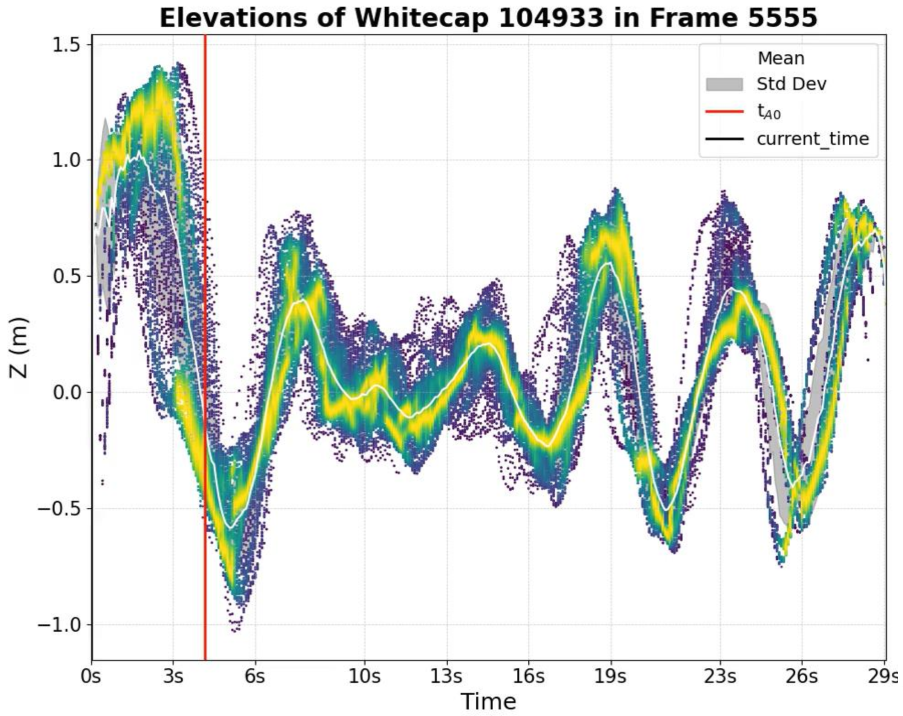


Bird?

Individual Breaking Analysis

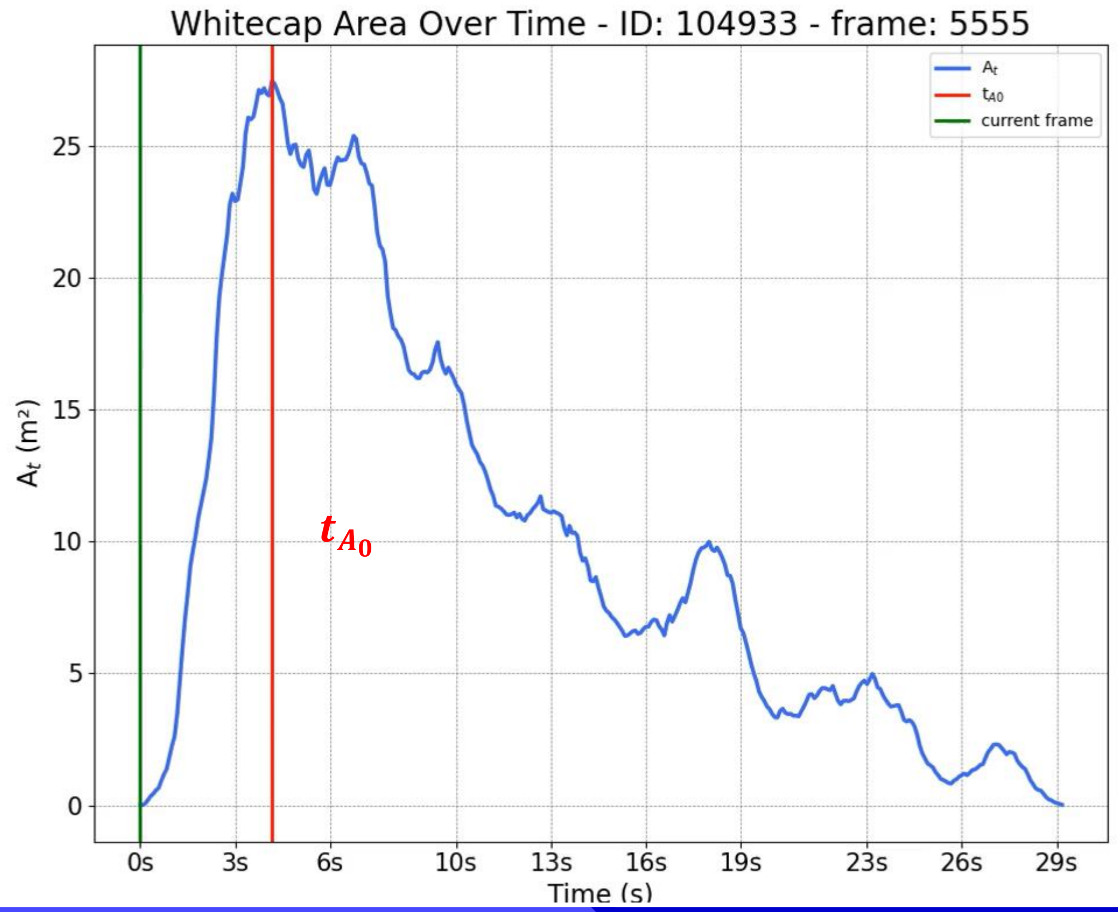






Energy Dissipation
Individual Breaking Analysis

$$\Delta E_T = \Omega \rho A_0 \hat{z}_{p,\infty} \tau_{growth}$$ [1]



Ω: turbulence strength parameter,

A_0 : maximum area of the whitecap,

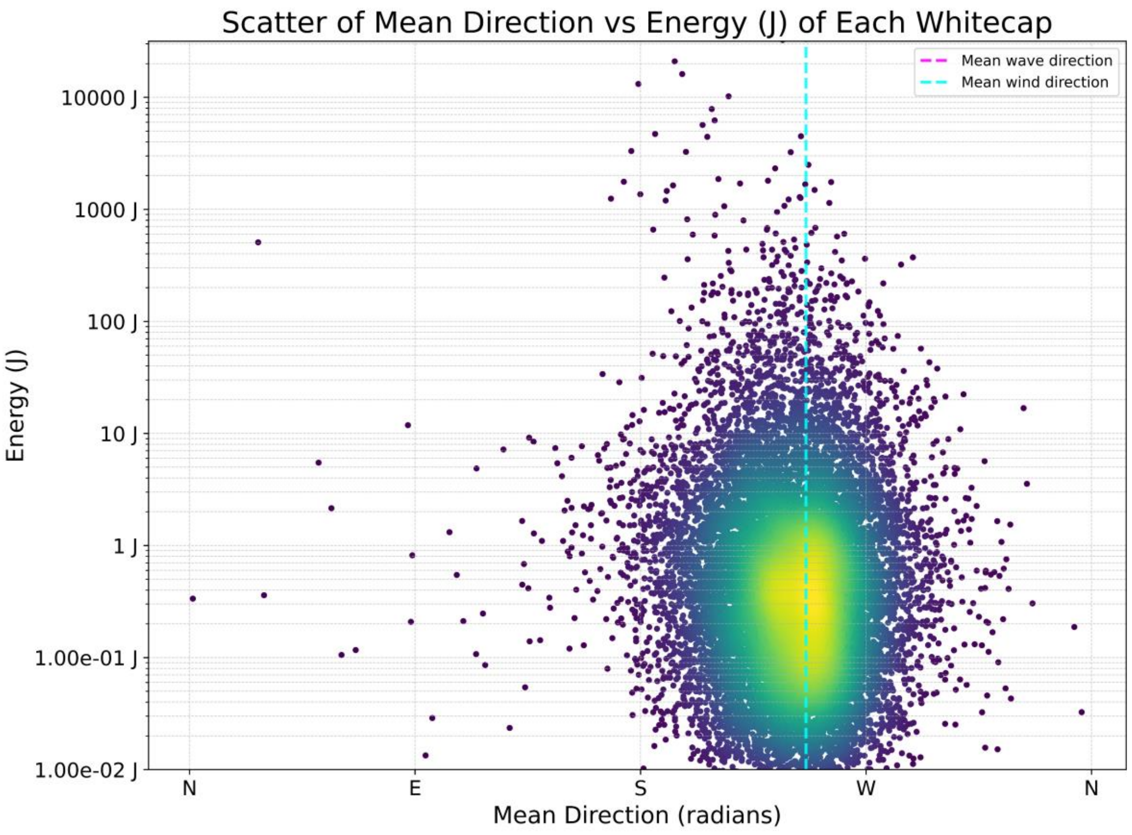
z_p : estimated bubble plume injection depth

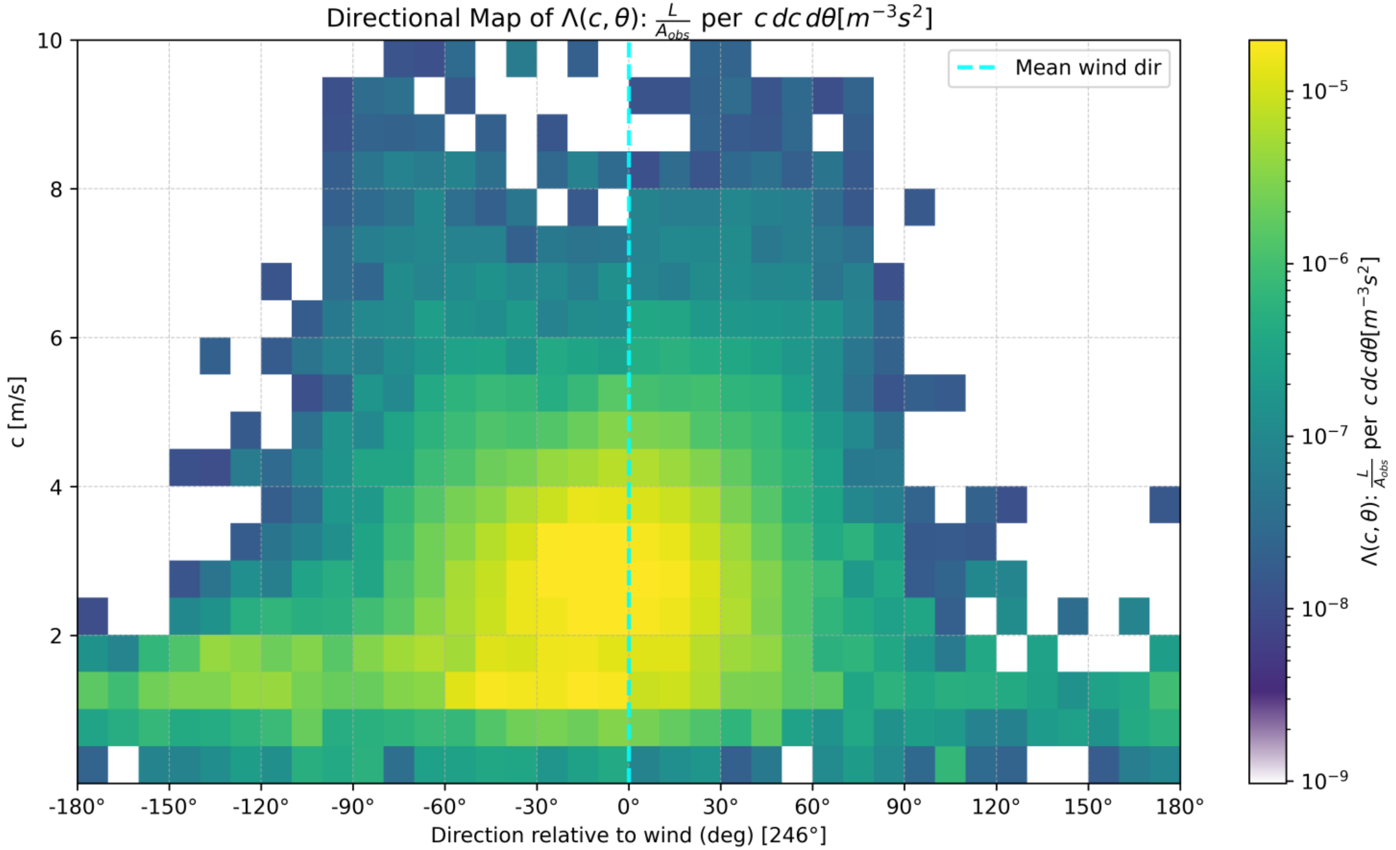
τ_{growth} : characteristic growth timescale.

[1] Callaghan, A., Deane, G., and Stokes, M. (2016)

Energy Dissipation
Distribution of Whitecap Energy

$$\epsilon_{ss} = \frac{\rho}{g} \int b(c) c^5 \Lambda(c) dc$$

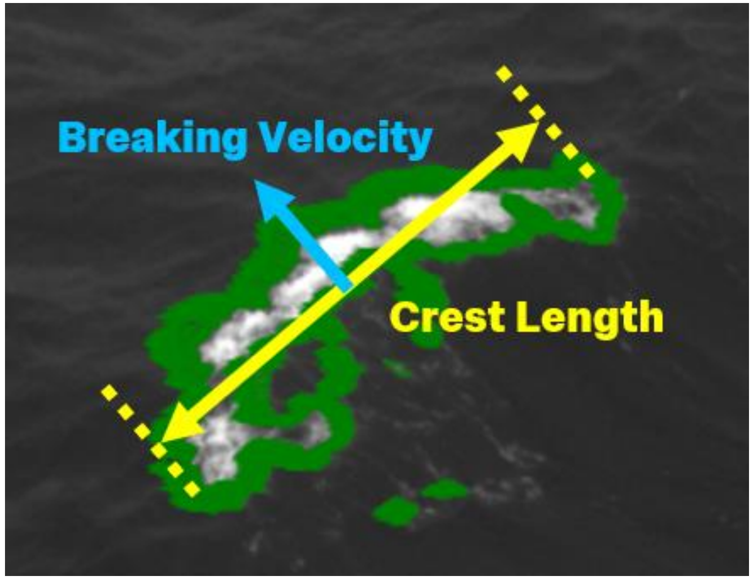




What else can we do?

Breaking Statistics

Phillips(1985) – Lambda Distribution



$\Lambda(\mathrm{c})$ – The total length of breaking wave crests in certain bin width $\mathrm{c_i}$

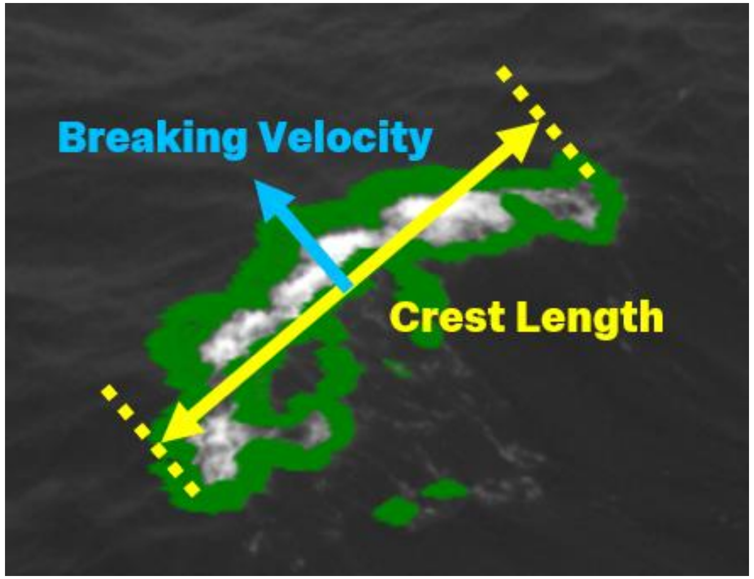
$$\Lambda(\mathrm{c})\Delta\mathrm{c} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}(\overline{\mathrm{L}}_{\mathrm{i}}\mathrm{t}_{\mathrm{A}_{0,\mathrm{i}}}) \mid \mathrm{c_i} - \frac{\Delta\mathrm{c}}{2} < \mathrm{c_i} < \mathrm{c_i} + \frac{\Delta\mathrm{c}}{2}}{\mathrm{A_{obs}T_{obs}}}$$

- Third moment of $\Lambda(\mathrm{c})$: entrained air
- Forth moment of $\Lambda(\mathrm{c})$: momentum transferred
- **Fifth moment** of $\Lambda(\mathrm{c})$: the energy dissipation per unit area

$$\epsilon_{ss} = \frac{\rho}{g}\int \mathrm{b(c)c^5\Lambda(c)dc}$$

Breaking Statistics

Phillips(1985) – Lambda Distribution



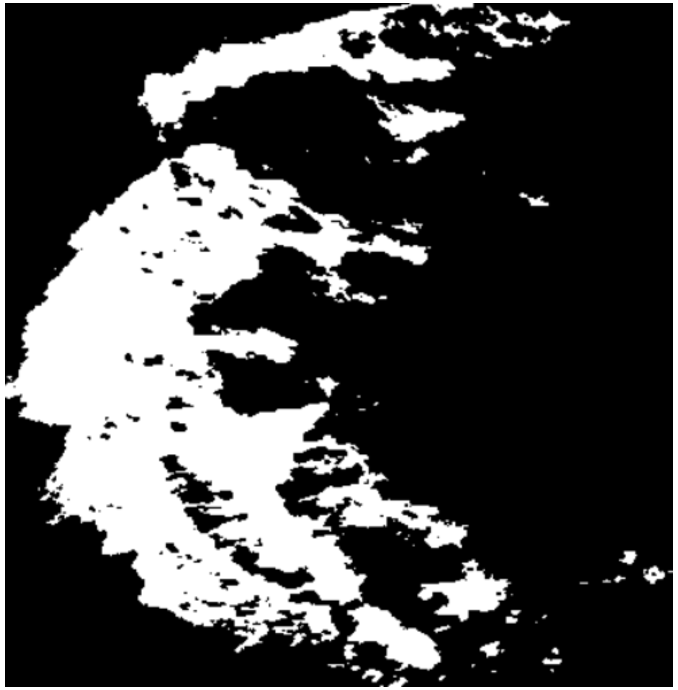
$\Lambda(\mathrm{c})$ – The total length of breaking wave crests in certain bin width $\mathrm{c_i}$

$$\Lambda(\mathrm{c})\Delta\mathrm{c} = \frac{\sum_{i=1}^{N}(\bar{L}_i t_{A_{0,i}}) \mid c_i - \frac{\Delta c}{2} < c_i < c_i + \frac{\Delta c}{2}}{A_{obs}T_{obs}}$$

- **First moment** of $\Lambda(\mathrm{c})$ (or second moment if assume $\tau \propto c$) : the fractional area of breaking waves $\mathrm{W_g}$.

$$\mathrm{W_g} = \int \tau \mathrm{c}\, \Lambda(\mathrm{c})\mathrm{dc}$$

, where $\mathrm{W_g} = \frac{\sum A_0 \tau_{growth}}{A_{obs}T_{obs}}$



- Third moment of $\Lambda(\mathrm{c})$: entrained air
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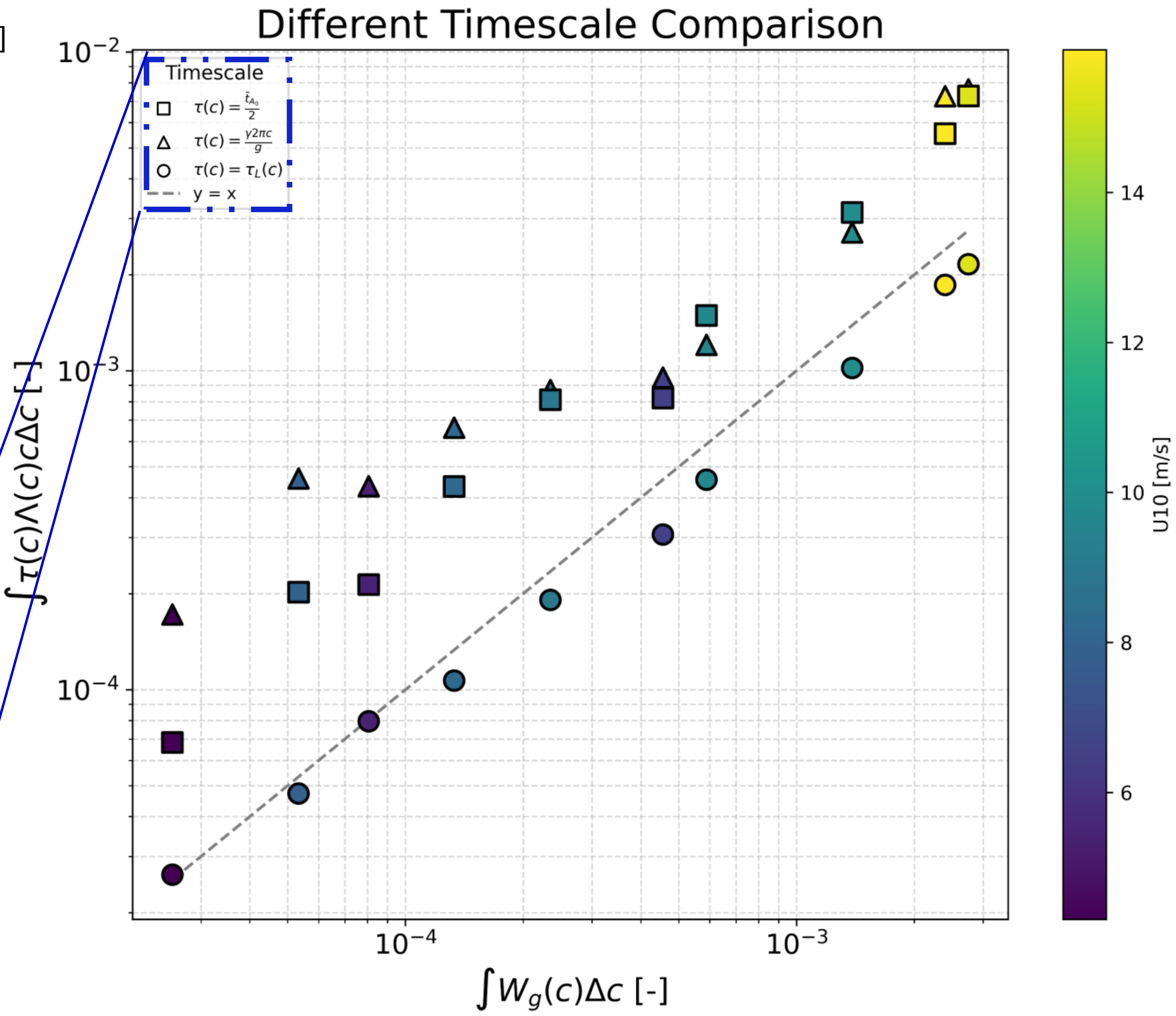
$$\epsilon_{ss} = \frac{\rho}{g}\int b(c)c^5\Lambda(c)dc$$

Breaking Statistics
Timescale Comparison

$$W_g = \int \tau(c) c\, \Lambda(c) \Delta c$$

Whitecap 33850 Tracking - original - frame: 19551

[3]



Bubble persistence time:

(1) $\tau = \gamma \frac{2\pi c}{g}$ $(\gamma = 0.56)$ [1] △

[2]

(2) $\tau = t_{A_0} / 2$ □

(3) $\tau(t) = \int_{t}^{t_{A_0}} \frac{A(\hat{t})}{A_{so}(\hat{t})} d\hat{t}$ ○

$\tau(t)$	Time → Averaged	τ	Velocity Bin → Averaged	$\tau(c)$
Per Frame		**Per Whitecap**		**Per Bin**

[1] Deike, L., Lenain, L., & Melville, W. K. (2017)
[2] Kleiss, J. M., & Melville, W. K. (2011)
[3]Cao, R., Padilla, E. M., Chen, X., & Callaghan, A. H. (2026)

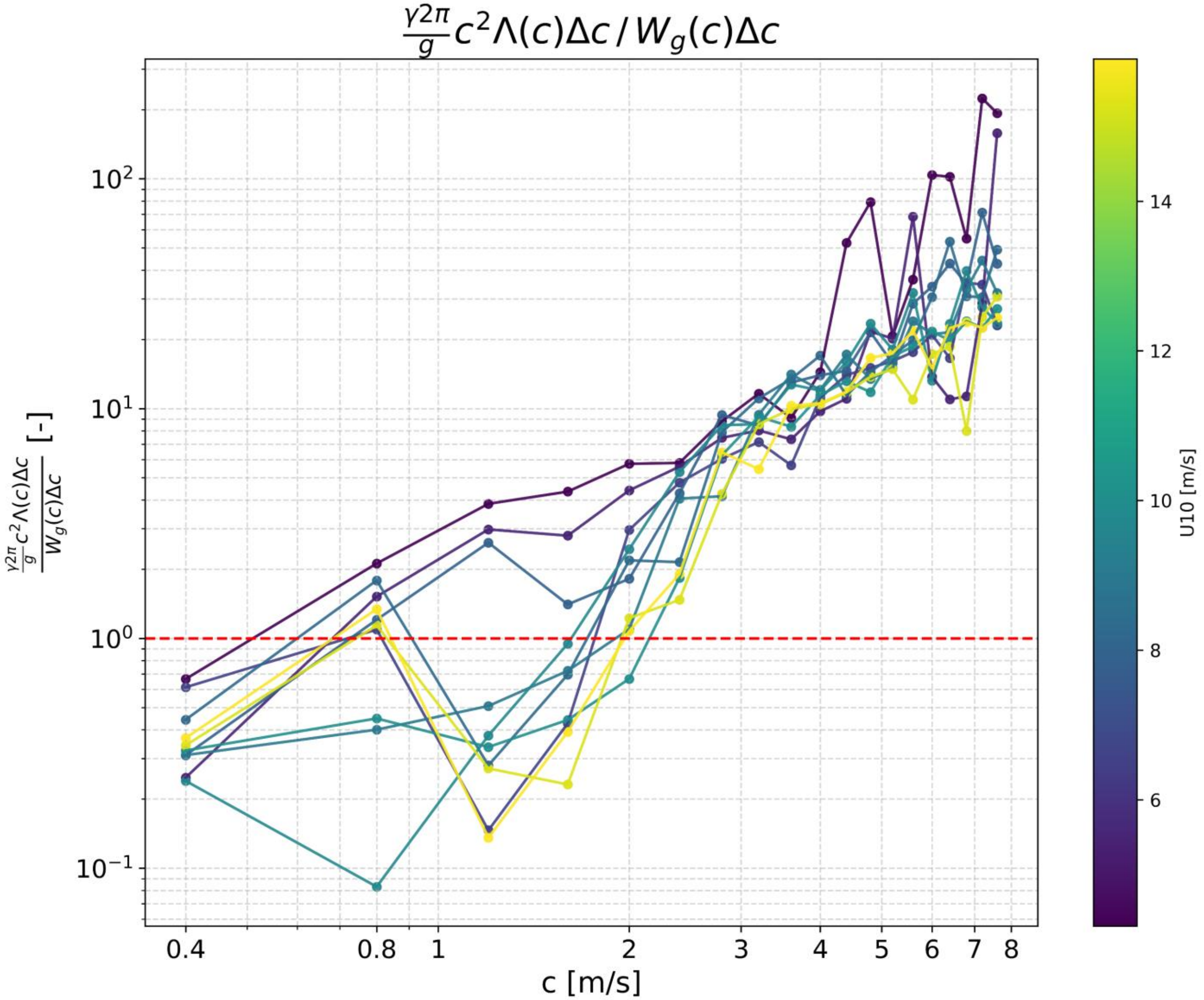
Breaking Statistics
Timescale Comparison

$$W_g = \int \tau(c)c\,\Lambda(c)\Delta c$$

$$\int W_g(c)\Delta c = \int \tau(c)c\,\Lambda(c)\Delta c$$

$$\text{Does } \frac{\tau(c)c\,\Lambda(c)}{W_g(c)} = 1\,?$$

$$\boxed{(1)\ \tau = \gamma\frac{2\pi c}{g}\ (\gamma = 0.56)}$$



Breaking Statistics
Timescale Comparison

$$W_g = \int \tau(c) c\, \Lambda(c) \Delta c$$

$$\int W_g(c) \Delta c = \int \tau(c) c\, \Lambda(c) \Delta c$$

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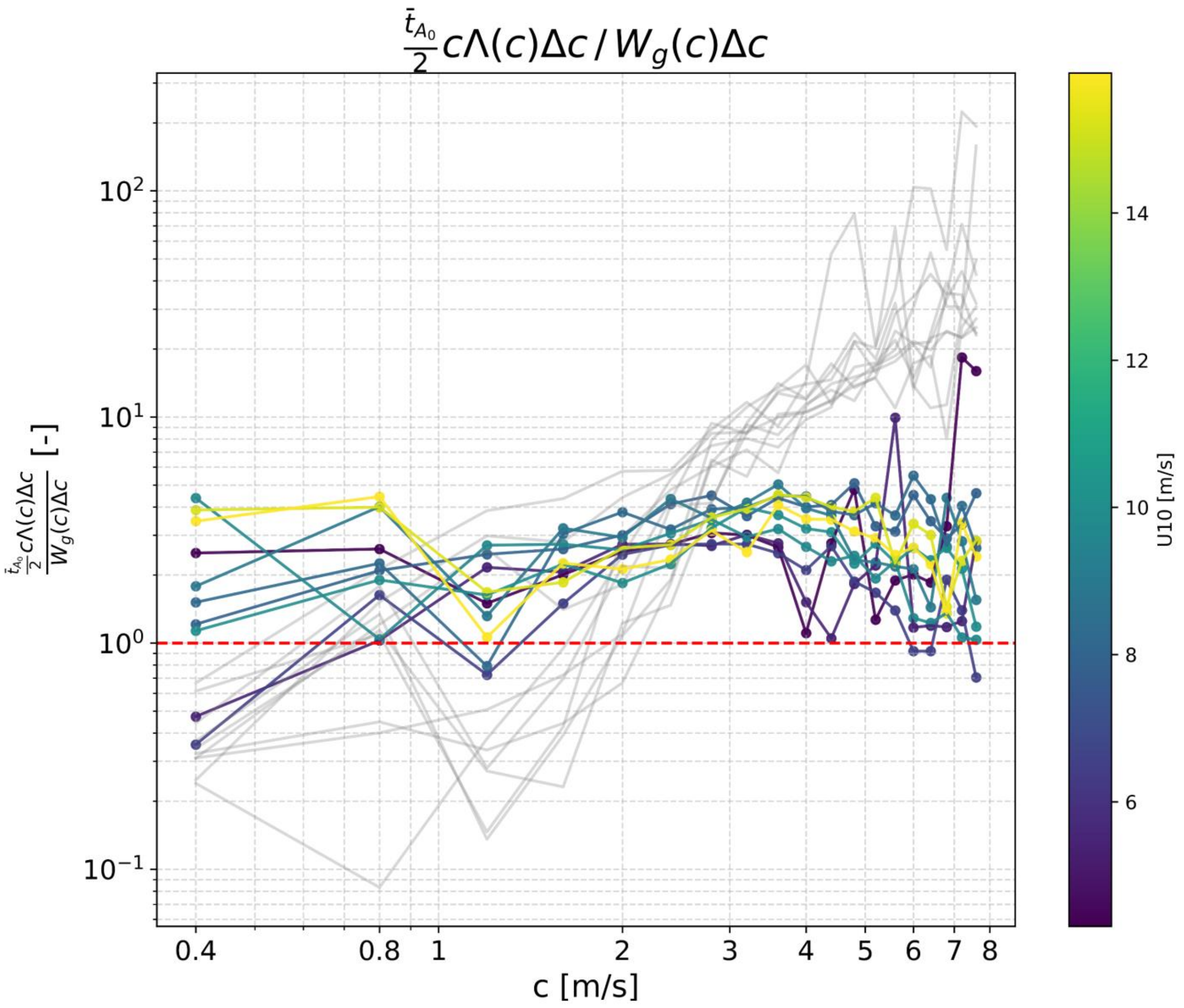

Breaking Statistics
Timescale Comparison

$$W_g = \int \tau(c) c\, \Lambda(c) \Delta c$$

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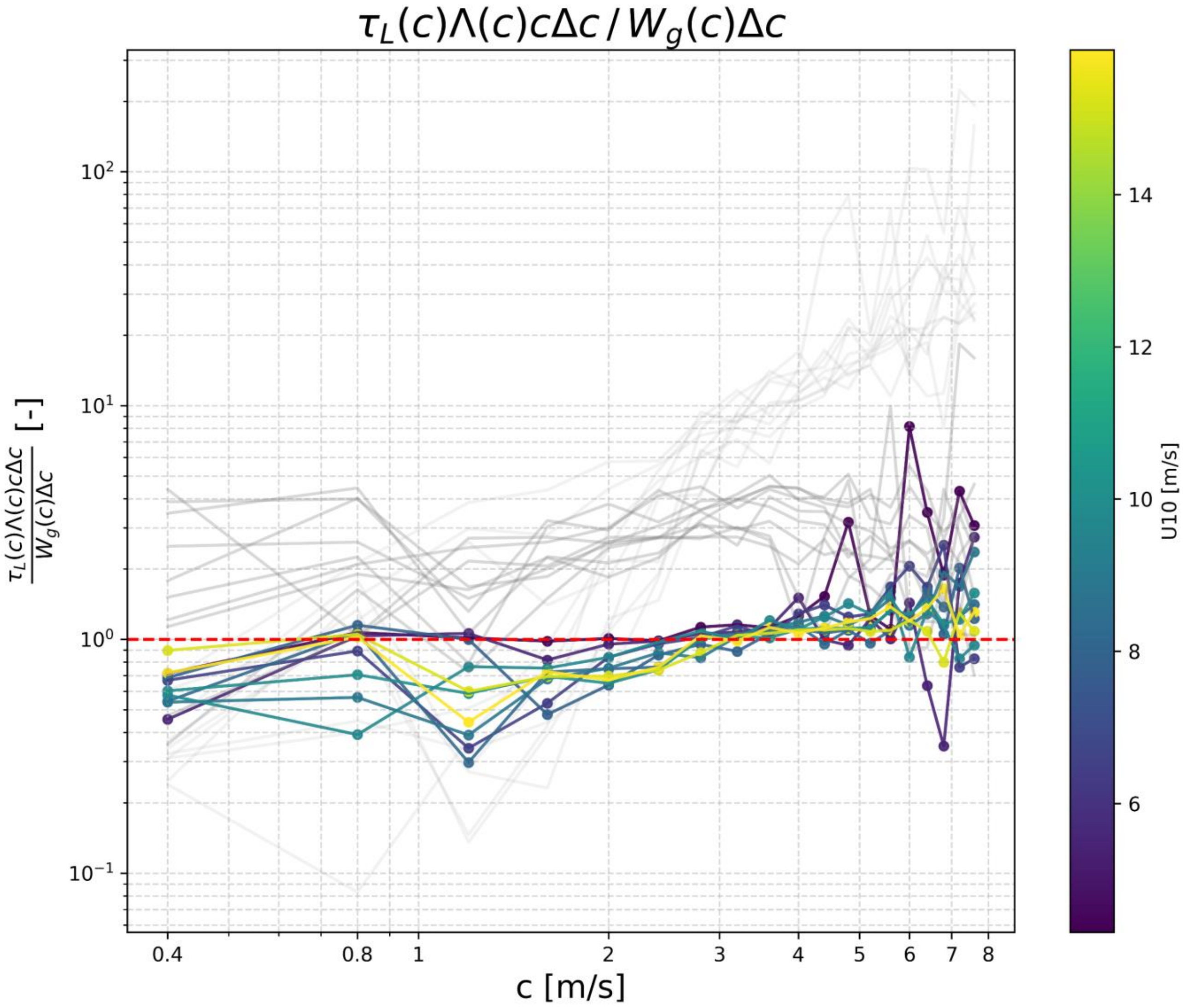
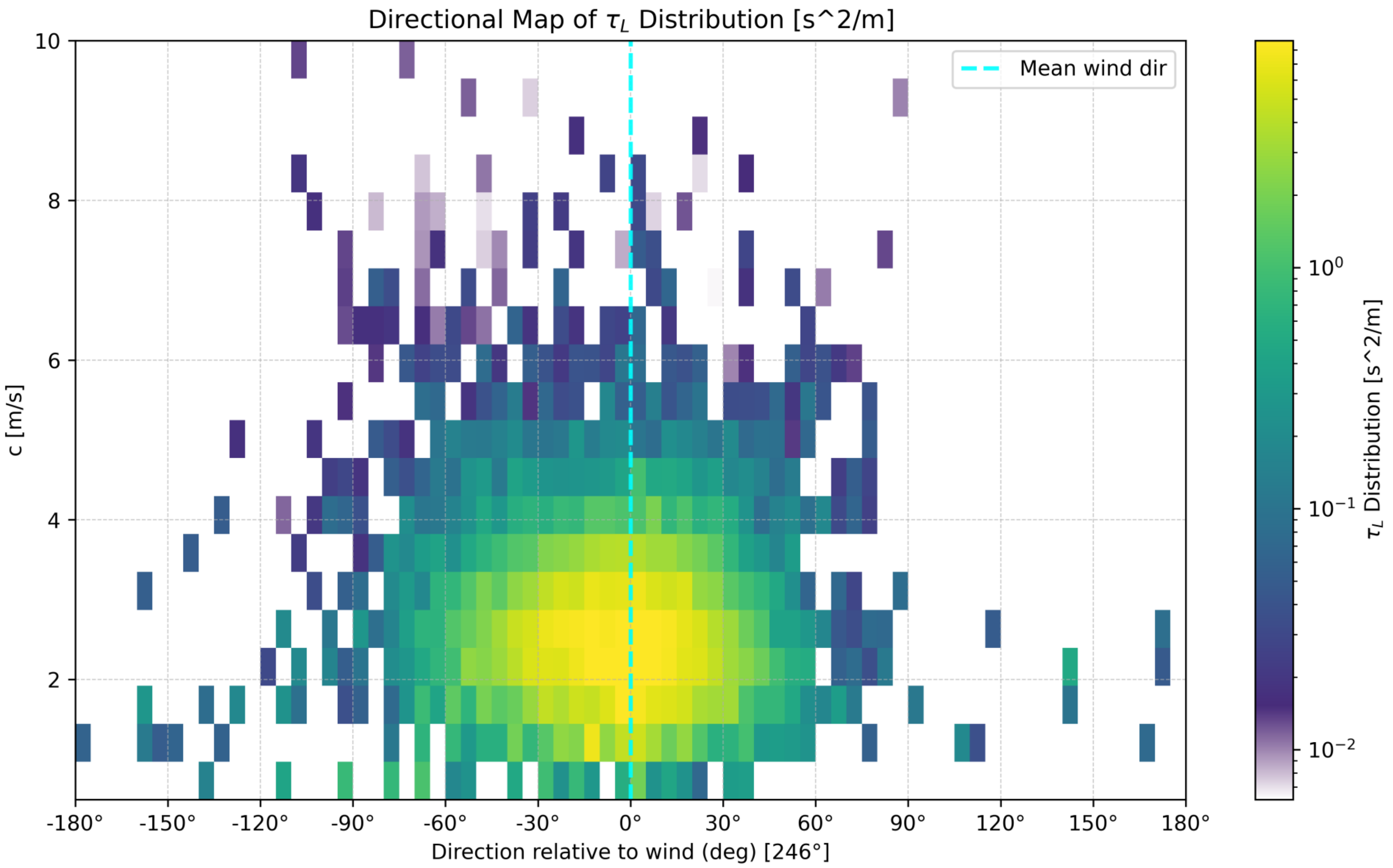
(1) $\tau = \gamma \dfrac{2\pi c}{g}$ $(\gamma = 0.56)$

(2) $\tau = t_{A_0} / 2$

$$\boxed{(3)\ \tau = \int_{t}^{t_{A_0}} \frac{A(\hat{t})}{\boldsymbol{A_{so}}(\hat{t})} d\hat{t}}$$



Breaking Statistics
Tau Directional Distribution (U10 = 15.9 m/s)



Conclusions

- A new whitecap tracking algorithm was developed to separately track individual wave-breaking events.
- The evolution of velocity and elevation throughout the lifespan of breaking waves was calculated.
- Bubble persistence time distributions were re-examined in directional and velocity space, and whitecap coverage was evaluated using the Lambda distribution.

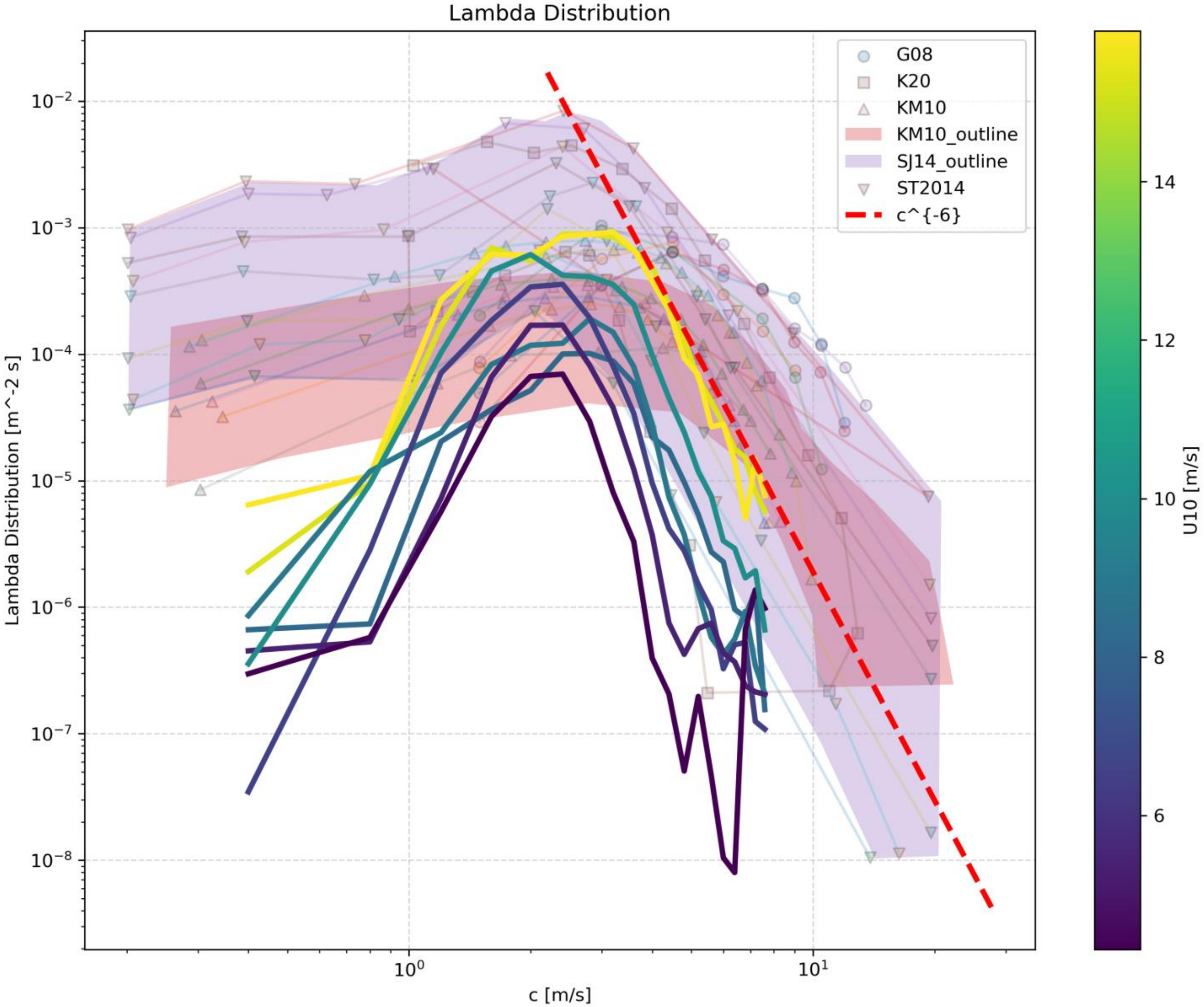
Future Work

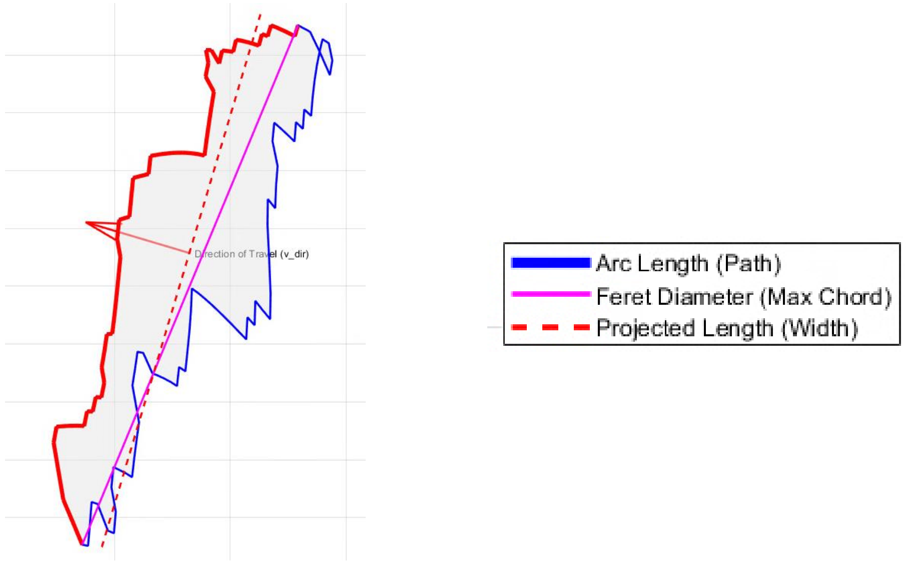
- Investigation of the directional distribution of energy dissipation associated with whitecaps.
- Estimation of breaking strength for individual wave-breaking events.

The end

Thanks!

Breaking Statistics
Lambda Distribution





$$\Lambda(c)\Delta c = \frac{\sum_{i=1}^{N}(\bar{L}_i t_{A_{0,i}}) \mid c_i - \frac{\Delta c}{2} < c_i < c_i + \frac{\Delta c}{2}}{A_{\text{obs}} T_{\text{obs}}}$$

$\bar{L}_i$: time-averaged crest length of event i

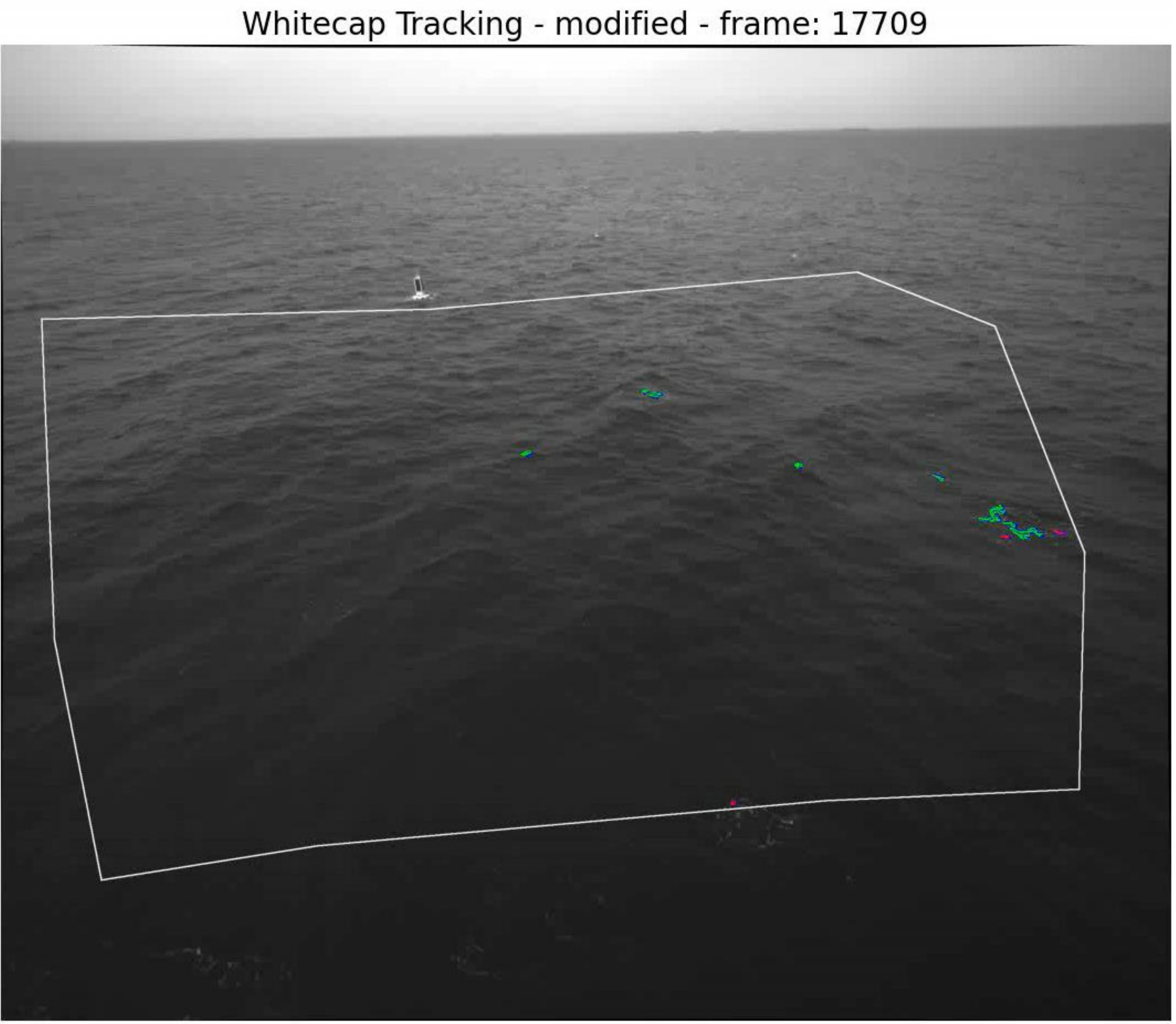
$t_{A_{0,i}}$: breaking duration

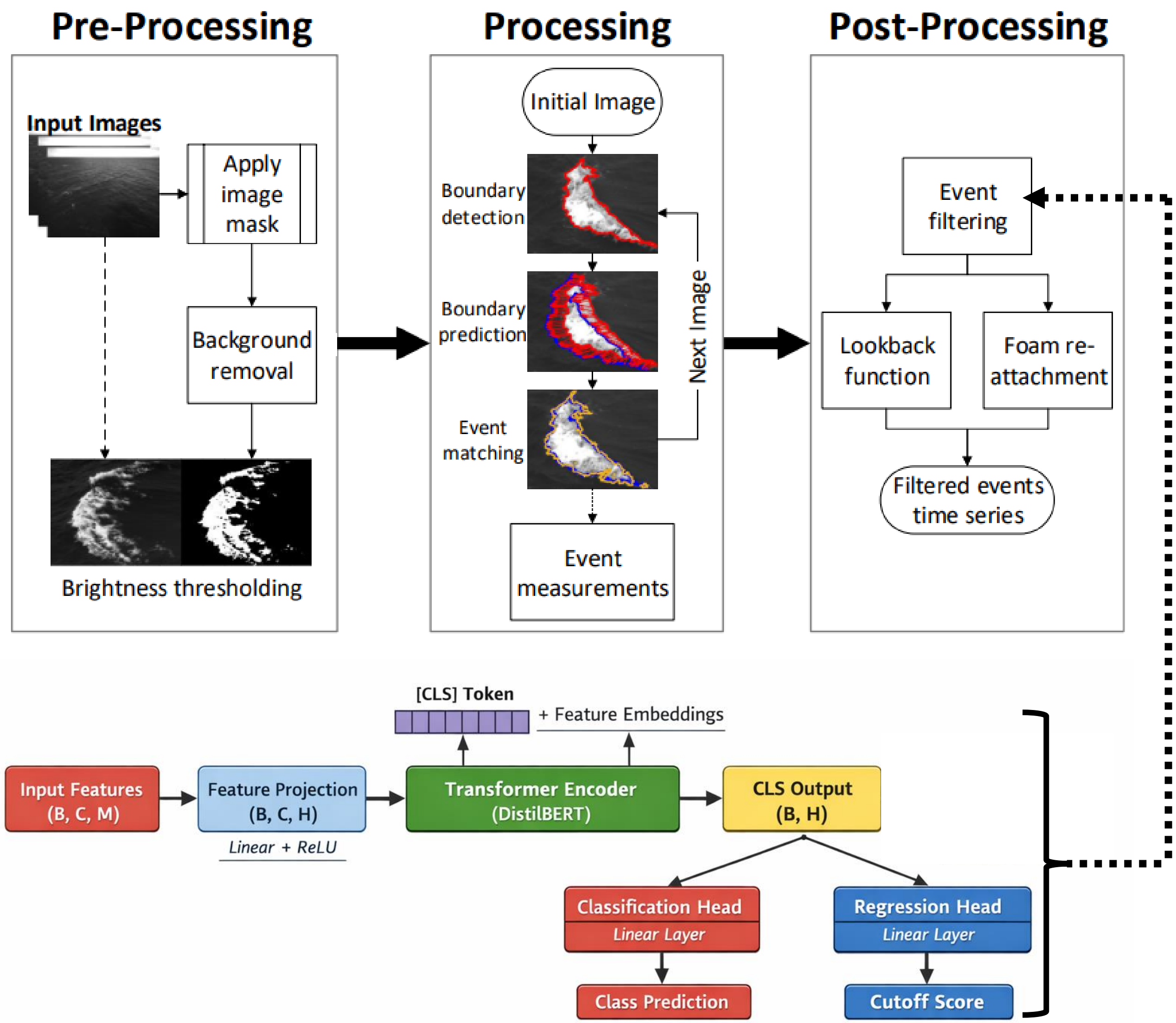
c_i: breaking velocity

A_{obs}: observation area

T_{obs}:observation duration

Automated Whitecap Detection And Tracking algorithm (AWDAT) [1]





[1] Peach, J., Callaghan, A. H., Bergamasco, F., Pistellato, M., Barbariol, F., and Benetazzo, A. (2025). A vision-based method for spatial and temporal tracking of individual whitecaps from breaking ocean waves. IEEE Transactions on Geoscience and Remote Sensing, pages 1–1

Lambda Distribution

Phillips(1985) – Framework for Field Observation of Dissipation

[1]

$\Lambda(c)$ – The total length of breaking wave crests per unit per unit velocity bin

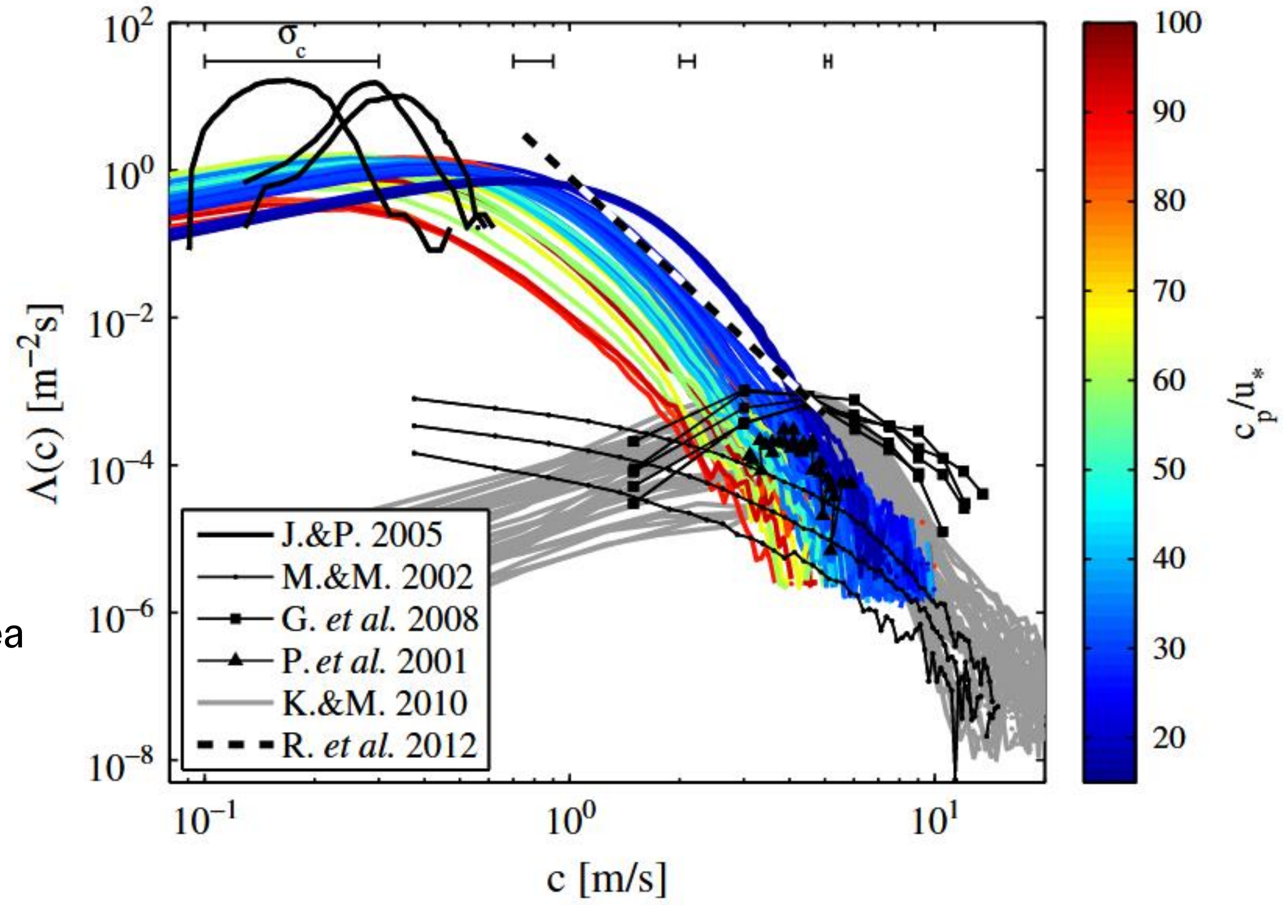
$$\Lambda(c) = \frac{4\gamma\beta^3 \, I(3p) \, u_*^3 g}{b} c^{-6}$$

- **First/second moment** of $\Lambda(c)$: the fractional area of the sea surface occupied by the actively breaking waves.

$$W_g = \int \color{red}{Tc} \, \Lambda(c)dc$$

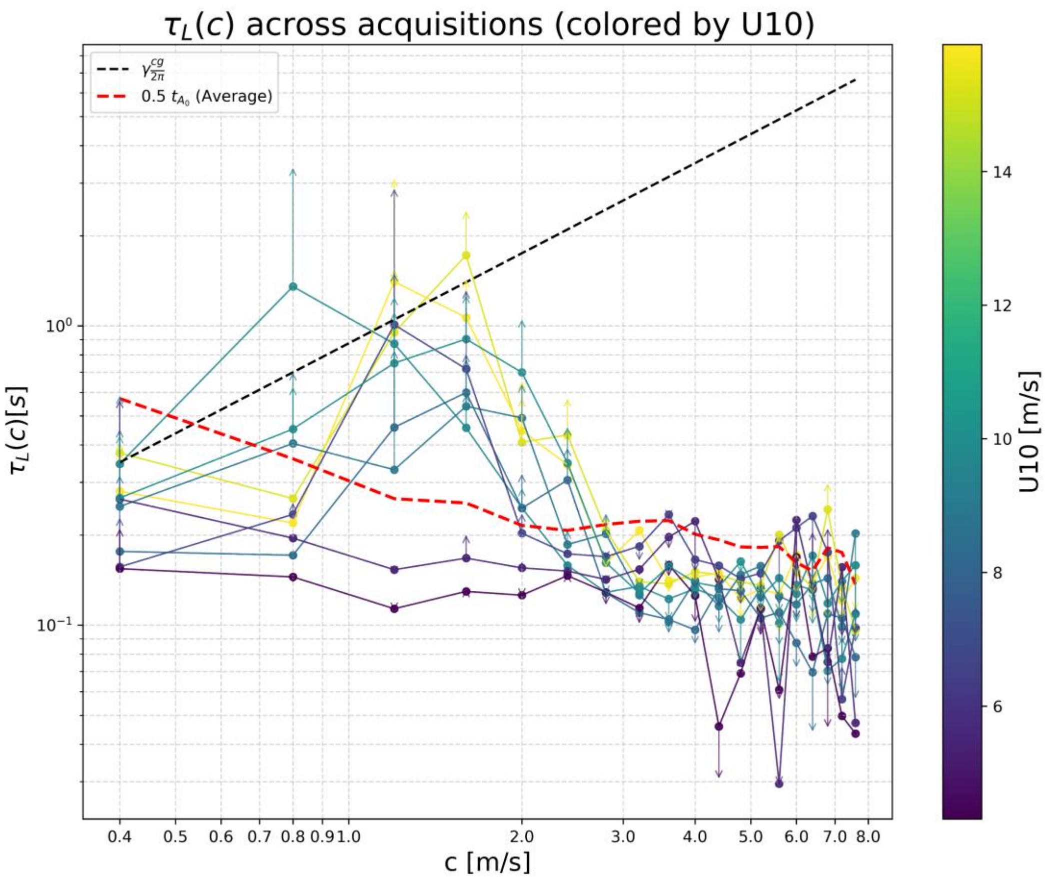
- Third moment of $\Lambda(c)$: the entrained air per unit area per time
- Forth moment of $\Lambda(c)$: the momentum transferred per unit area
- **Fifth moment** of $\Lambda(c)$: the energy dissipation per unit area

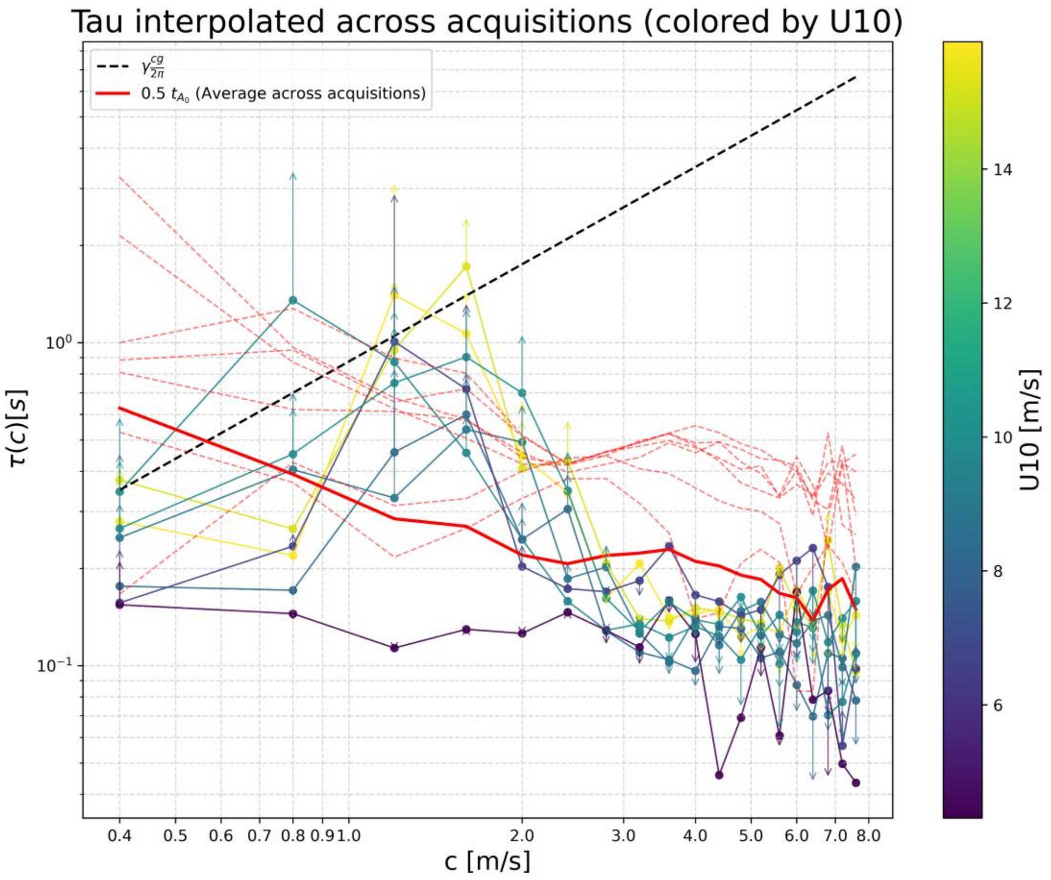
$$\epsilon_{ss} = \frac{\rho}{g} \int b(c) c^5 \Lambda(c) dc$$



[1] Sutherland, P., & Melville, W. K. (2013).

Breaking Statistics
Tau Distribution





Energy Dissipation
Lambda Directional Distribution

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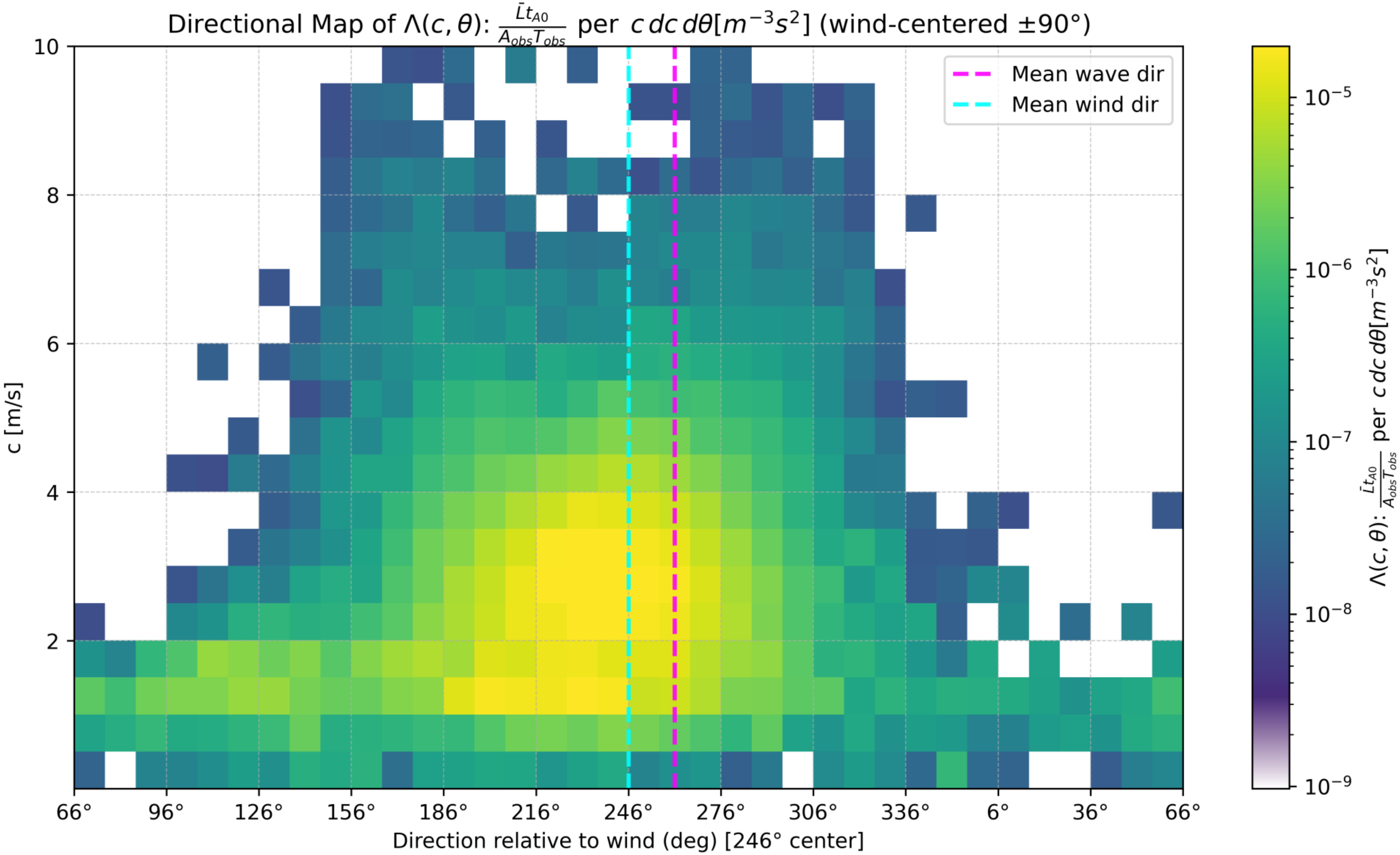
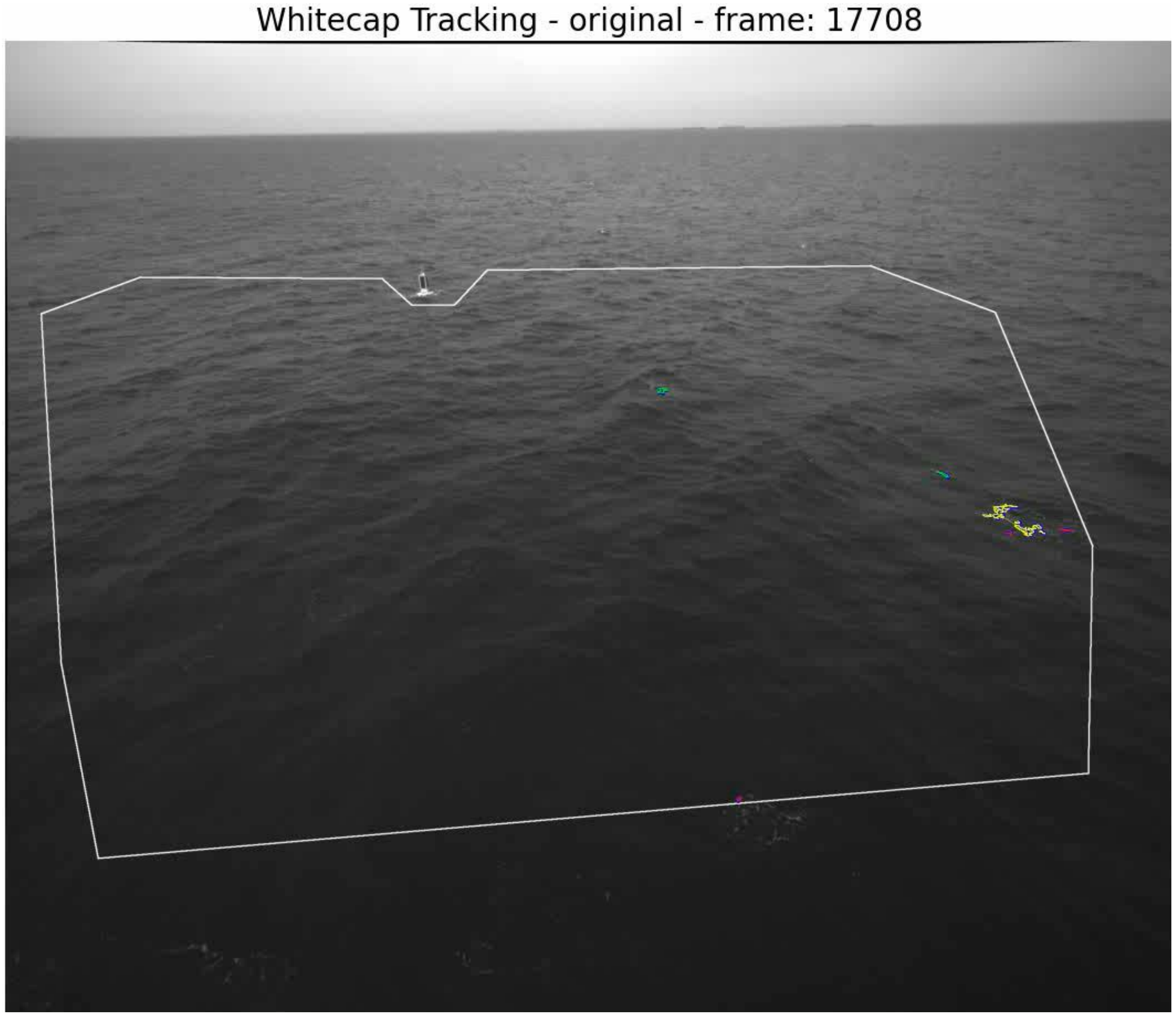
$$\Delta E_T = \Omega\rho A_0\hat{z}_{p,\infty}\tau_{growth}$$

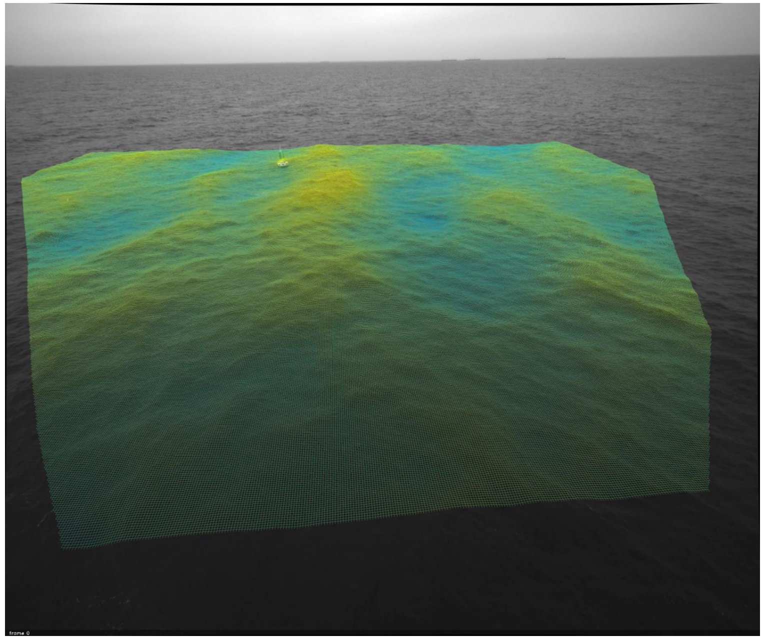


Background

Automated Whitecap Detection and Tracking Algorithm (AWDAT)



(1) Binarize each frame using the AWE thresholding method.
(2) Apply an optical flow algorithm to track whitecap features across consecutive frames.
(3) Use a fine-tuned neural network to classify active breaking events from other detections.
(4) Use Wave Acquisition Stereo System (WASS) to perform stereo reconstruction and project image points into 3D world coordinates.

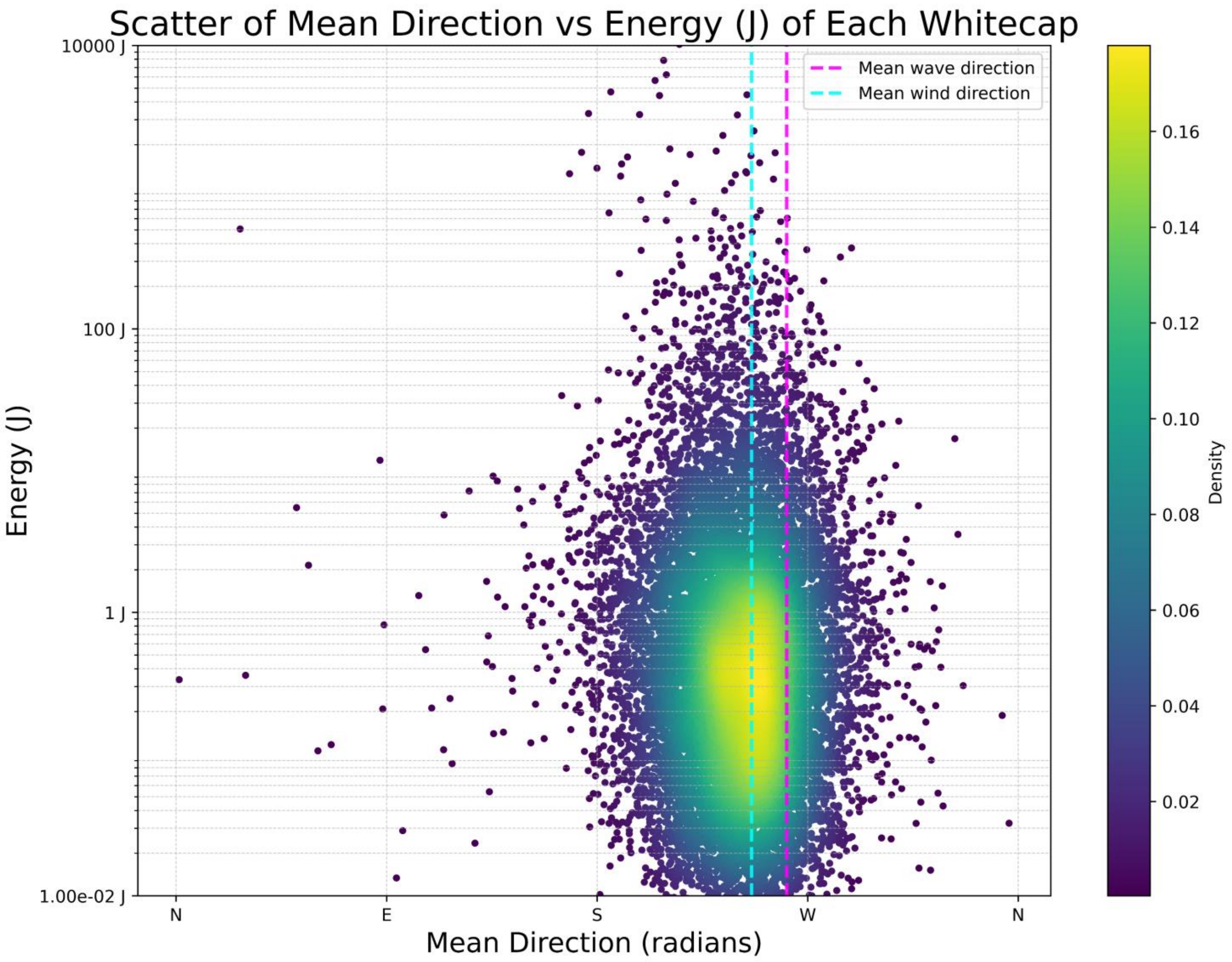


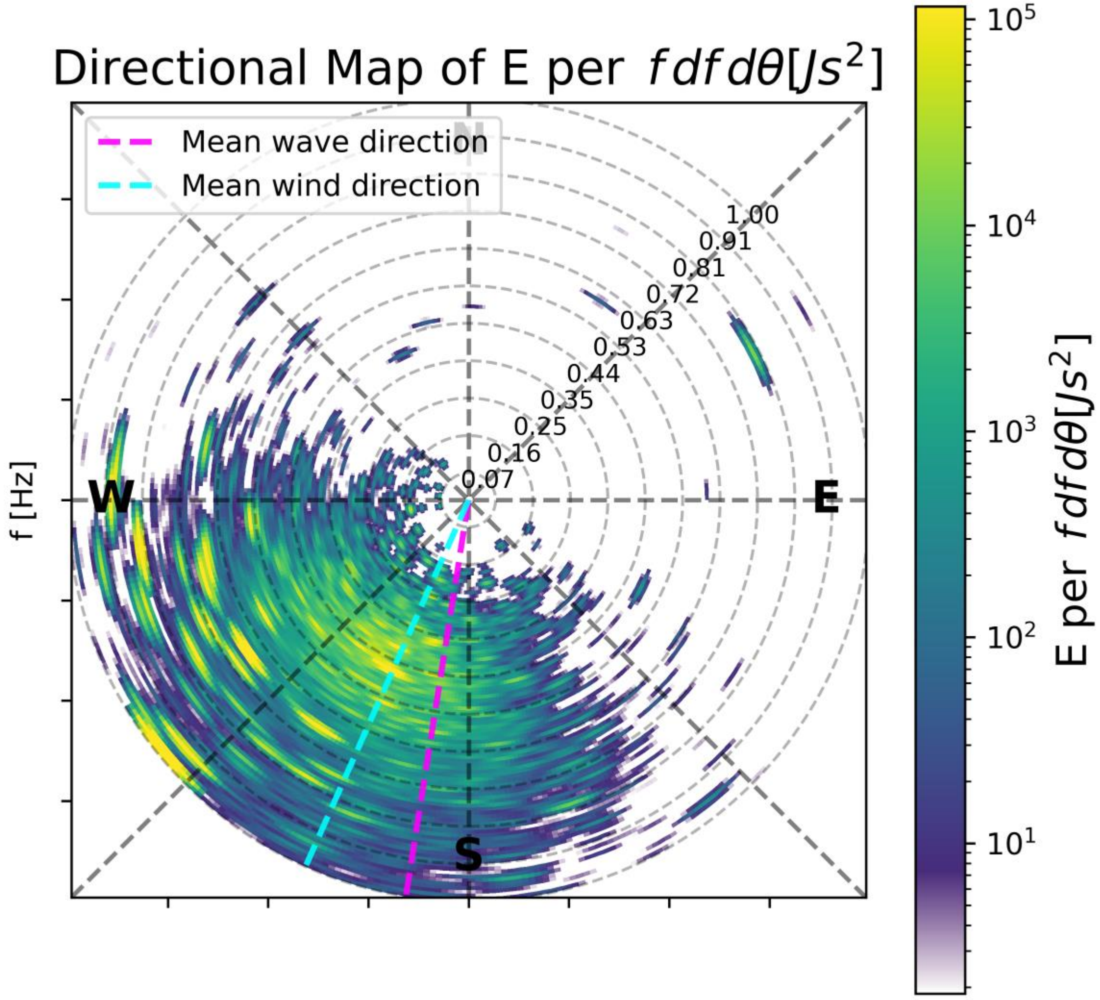
[1]

[1] Benetazzo, A., Bergamasco, F., Yoo, J., Cavaleri, L., Kim, S. S., Bertotti, L., Barbariol, F., & Shim, J. S. (2018).

Energy Dissipation

Distribution of Whitecap Energy





Whitecap 33830 Tracking - original - frame: 19567