In-situ Airflow Measurements over Surface Waves using PIV

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Take-home messages

- In-situ airflow measurements over surface waves show a critical layer in the vertical wave-coherent velocity field
- The phase of the vertical velocity eigenfunction shows agreement with Miles' linear theory[1]
- The calculated dimensionless wave growth rate using the wave momentum flux is in agreement with other studies

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1. Motivation

Energy input into the ocean by wave growth

1. **Turbulent eddies** generate ripples
2. **Asymmetric boundary layer thinning & thickening** causes sheltering events downwind of wave crests
3. **Pressure difference** transfers energy from wind to wave
4. **Wind speed equals wave speed** at critical height
5. **Waves cause airflow shear instability** leading to wave growth

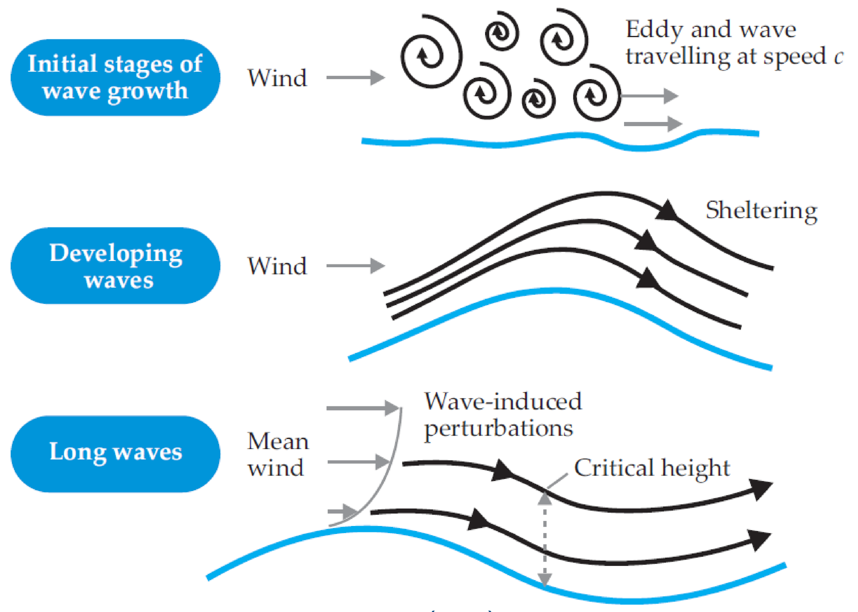


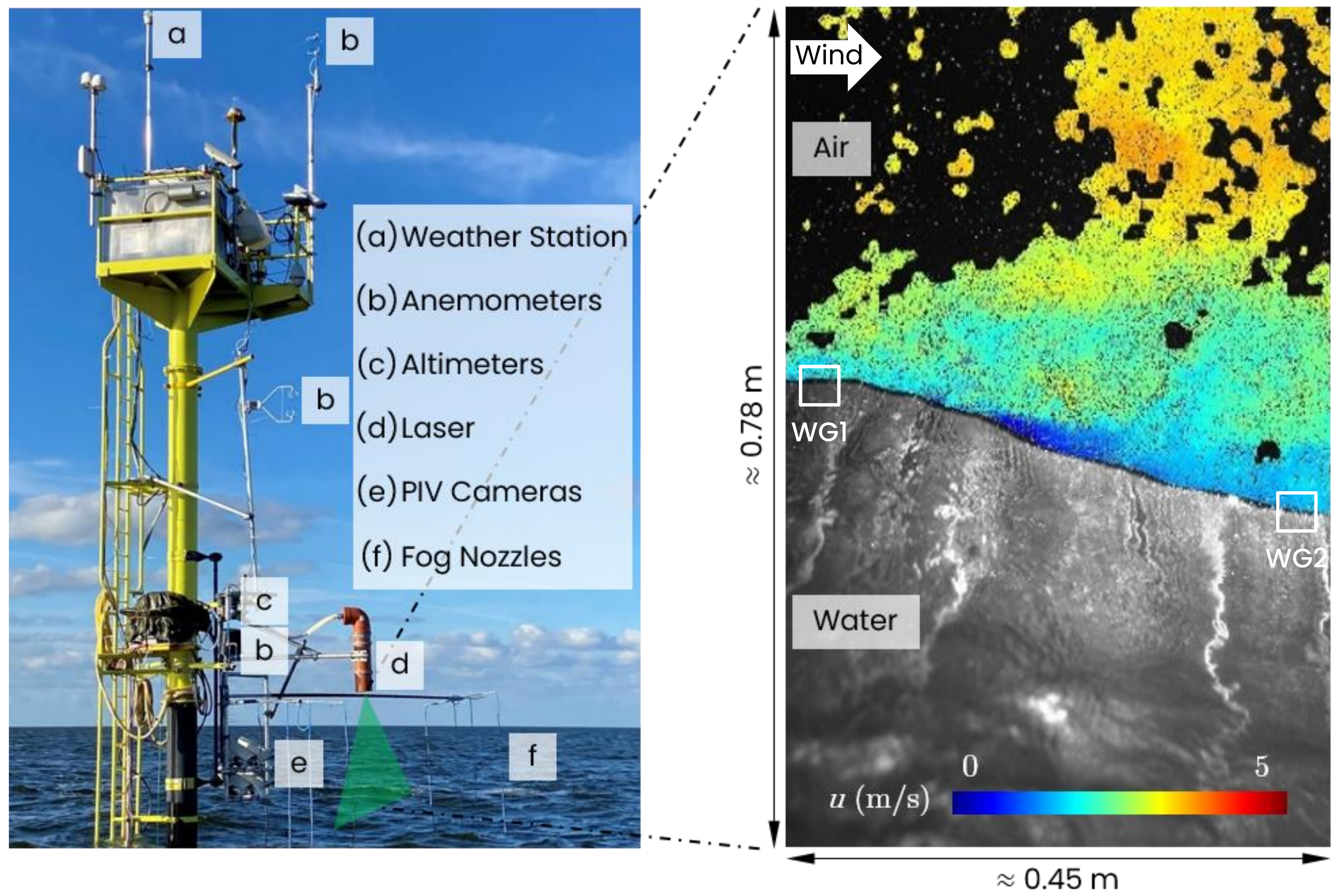
Image: Donna Padian; Pizzo, N. et al. (2021). How does the wind generate waves? *Physics Today*

Assumption: Critical layer theory[1] may be important for intermediate wave ages, while sheltering mechanisms dominate energy transfer for young and old waves

2. Methods

Experimental set-up

- Remote-controlled, high-resolution (130 µm/px), **rotating Particle Image Velocimetry** (PIV) system installed in the Szczecin Lagoon (Baltic Sea coast, Germany)
- **Fetch**: 20-25 km, **PIV frequency**: 14 velocity fields/s



Experimental conditions

- **Power spectral density** estimation of water surface elevation time series to detect **peak frequency**
- **Cross-spectral analysis** of two adjacent wave gauges (WG1 & WG2) to calculate **intrinsic wave speed** and **wind drift**
- **Wind drift velocity 1.6 % of wind speed** at 10 m height

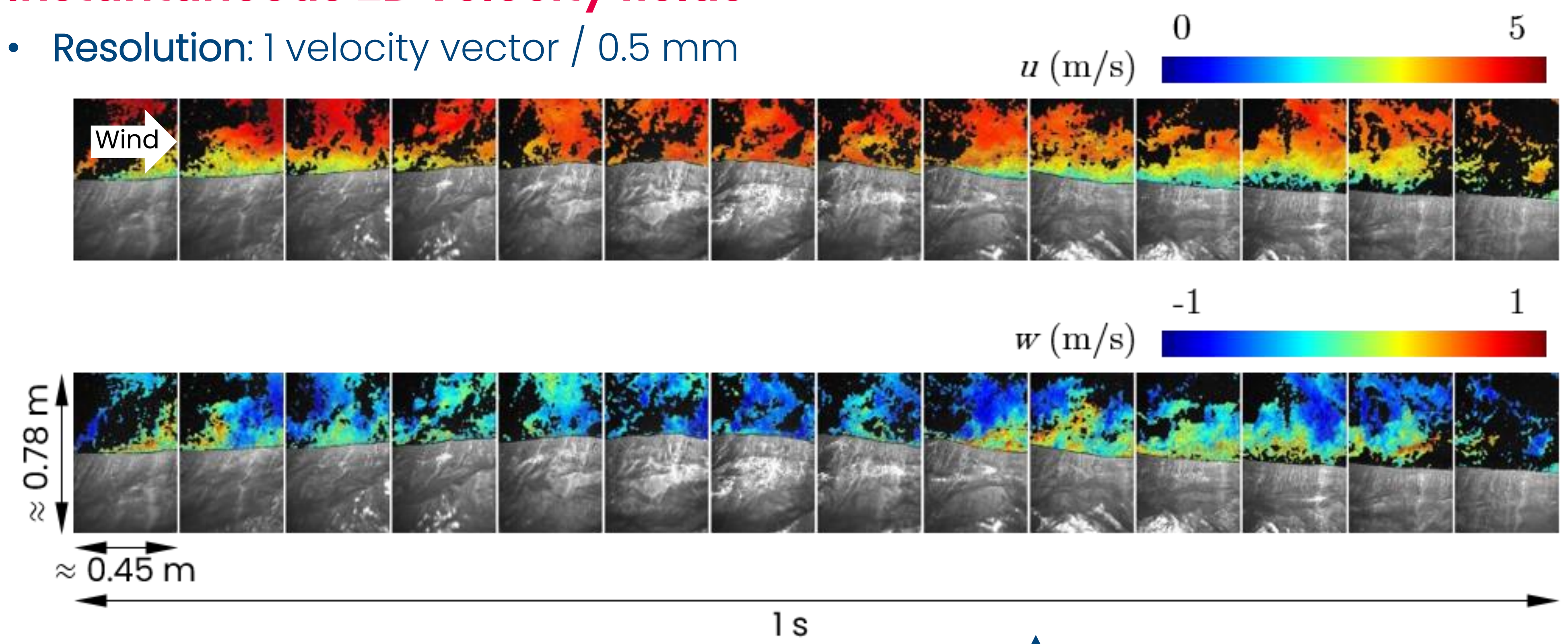
Wind speed at 10 m (m/s)	Peak frequency (Hz)	Wave speed (m/s)	Wind drift (m/s)	Wave-length (m)	Slope ak_p (-)	Wave age c_p/u_* (-)
5.69	0.55	2.94±1.19	0.09±1.03	5.53	0.08	14.16

Small slope & intermediate wave age

3. Results

Instantaneous 2D velocity fields

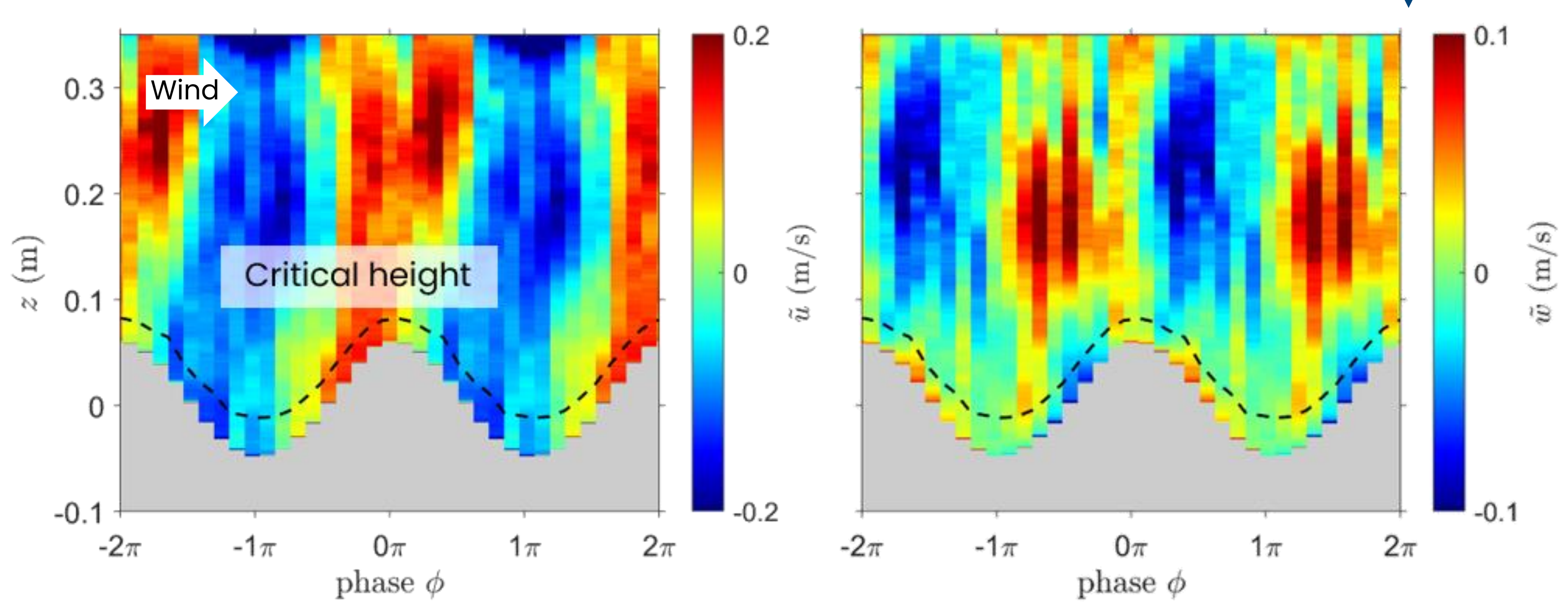
- **Resolution**: 1 velocity vector / 0.5 mm



Sheltering events downwind (upwind) of wave crests

Wave-coherent velocity fields

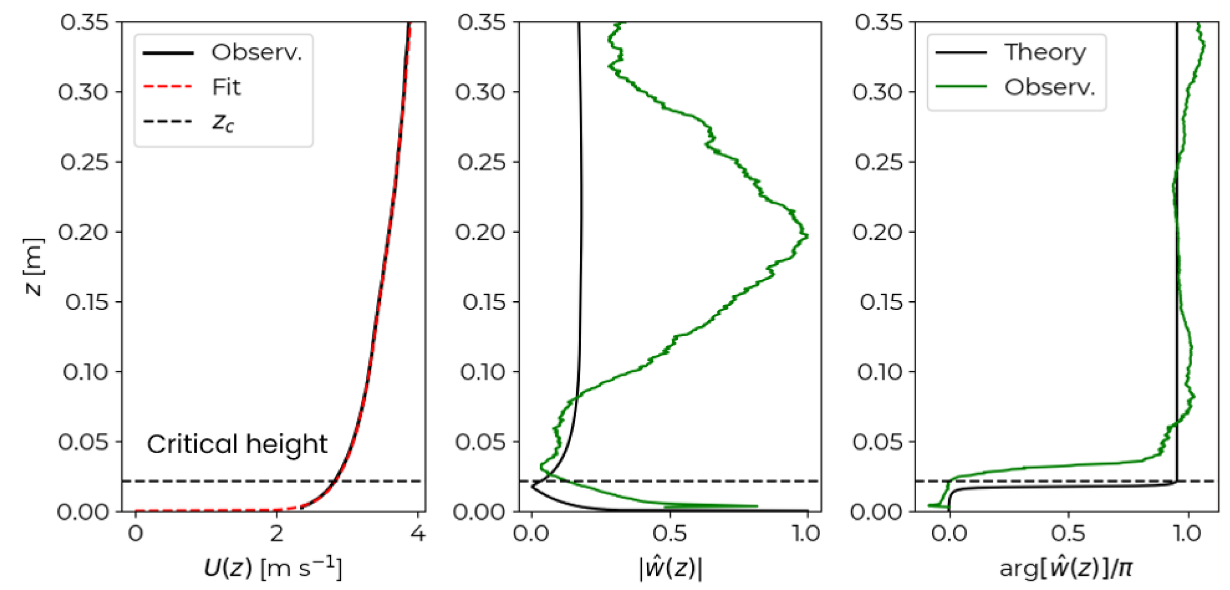
- **Triple decomposition** of an instantaneous quantity: $q_i = \langle q \rangle + q_i' = \bar{q} + \tilde{q} + q_i'$
- Wave phase detection by applying **Hilbert transforms** to WG1 & WG2 and subsequent linear interpolation
- Phase-averaging velocity fields into **18 bins** in the interval 0 to 2π



Wave-coherent vertical velocity is phase shifted at critical height, within critical layer airflow follows wave orbital motion

Comparison to linear theory[2]

- **Observed** eigenfunction: $\hat{w}(z) = \int_0^{2\pi} \tilde{w}(\varphi, z) e^{-i\varphi} \frac{d\varphi}{\pi}$
- **Theory** (Rayleigh equation): $\hat{w}'' - \left(k^2 + \frac{U''}{U-c}\right)\hat{w} = 0$

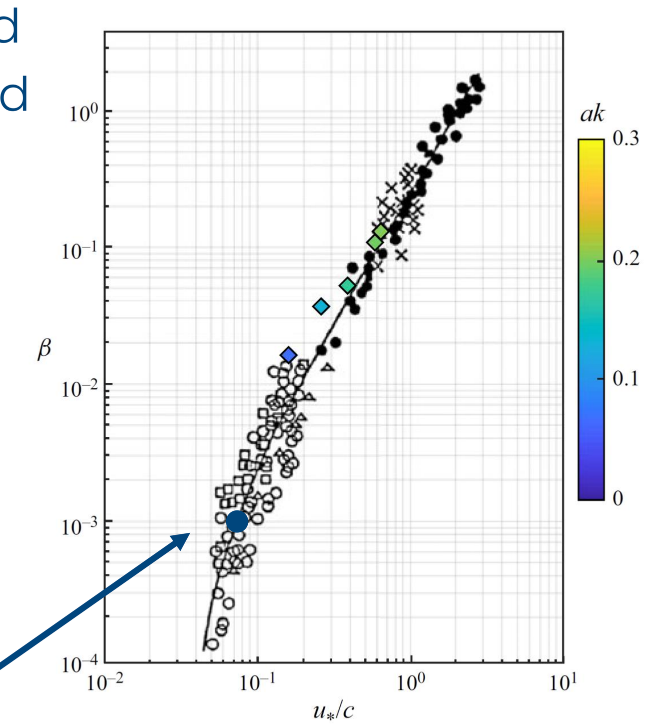


Phase of vertical velocity eigenfunction **is consistent with Miles' linear theory[1]**, while its shape shows some agreement

Wave growth rates

- **First approach**: Growth rate obtained by applying linear theory to observed wind profile is similar to what is expected[3] (optimal phase shift for wave growth π/2)
- **Second approach**: Wave-coherent momentum flux, wave age, and wave slope are all essential parts of the wave growth process[4]:

$$\beta = 4\pi \frac{\rho}{\rho_w} \frac{\tau_w}{\rho u_*^2} \frac{u_*^2}{c^2} \frac{1}{(ak)^2} - 8\pi Re^{-1}$$



Wave growth rate is in agreement with other studies

4. Conclusions

- There must be a **pressure difference to make waves grow**, but the mechanism that causes this asymmetry is still unclear, it cannot be explained by Miles' critical layer theory[1] alone
- Future work needs to **look at different scenarios using simulations** (see QR code) that can calculate pressure fields

[1] Miles, J. W. (1957). On the generation of surface waves by shear flows. *Journal of Fluid Mechanics*
[2] Carpenter, J. et al. (2022). Evidence of the critical layer mechanism in growing wind waves. *Journal of Fluid Mechanics*
[3] Komen, G. J. et al. (1994). *Dynamics and modelling of ocean waves*. Cambridge University Press.
[4] Buckley, M. et al. (2020). Surface viscous stress over wind-driven waves with intermittent airflow separation. *Journal of Fluid Mechanics*

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