EarthScope DAS RCN Workshop
June 12, 2023

Observational frontiers in physical oceanography enabled by fiber-optic sensing

Ethan F. Williams

Zhongwen Zhan
Joern Callies
Caltech

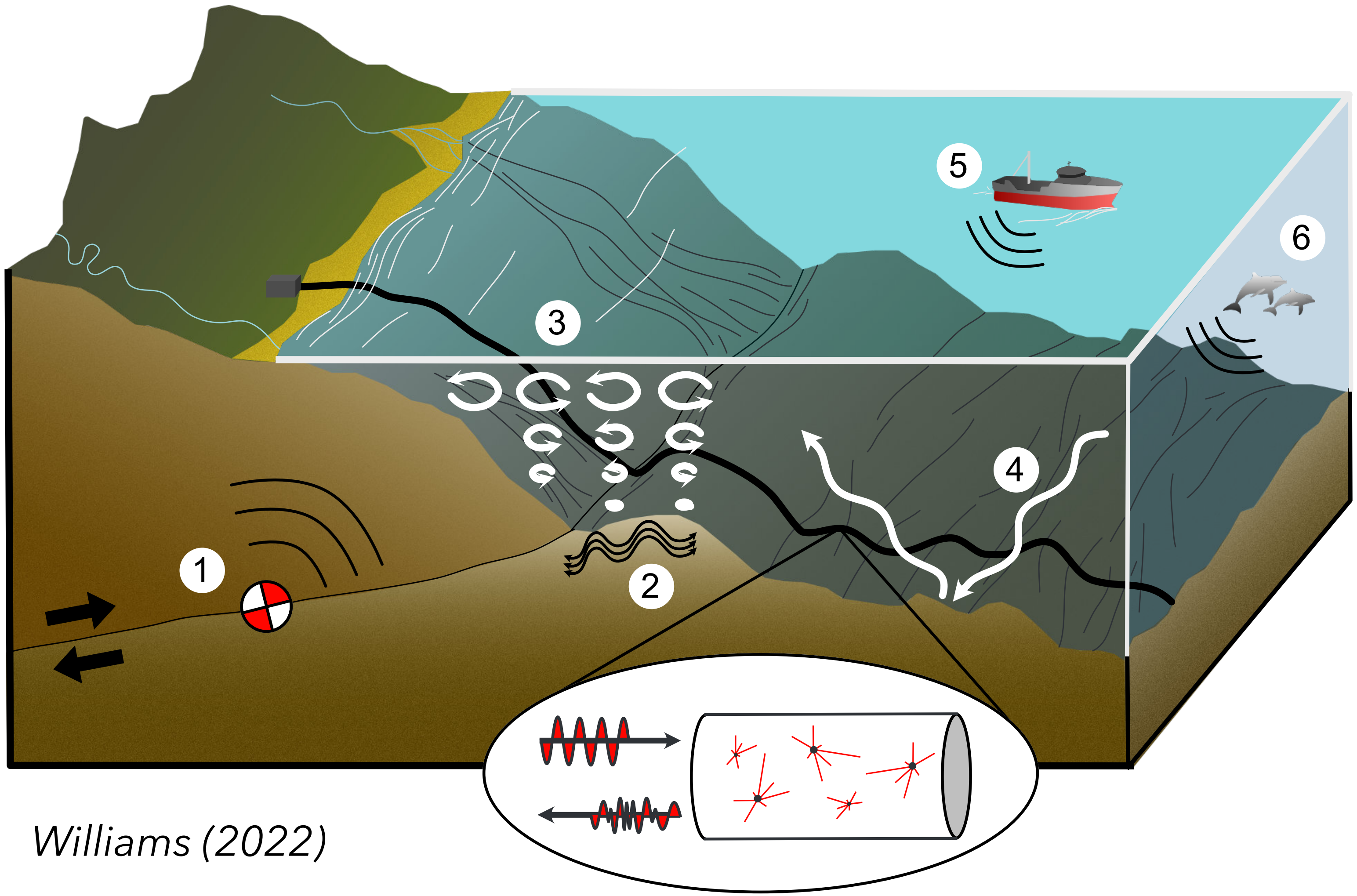
Arantza Ugalde
Mariona Claret
Josep L. Pelegri
Institut de Ciències del Mar

Hugo F. Martins
Carlos Becerril
M. Rosario Fernandez-Ruiz
Miguel Gonzalez-Herraez
Sonia Martin-Lopez
Universidad de Alcalá

Kraig B. Winters
Scripps Institution of Oceanography

Brad Lipovsky
University of Washington

Ocean-bottom distributed acoustic sensing (OBDAS)



Williams (2022)

1. Earthquakes
2. Ambient seismic noise
3. Surface gravity waves
4. Internal gravity waves
5. Anthropogenic noise
6. Marine mammal vocalizations

1. Surface waves on DAS

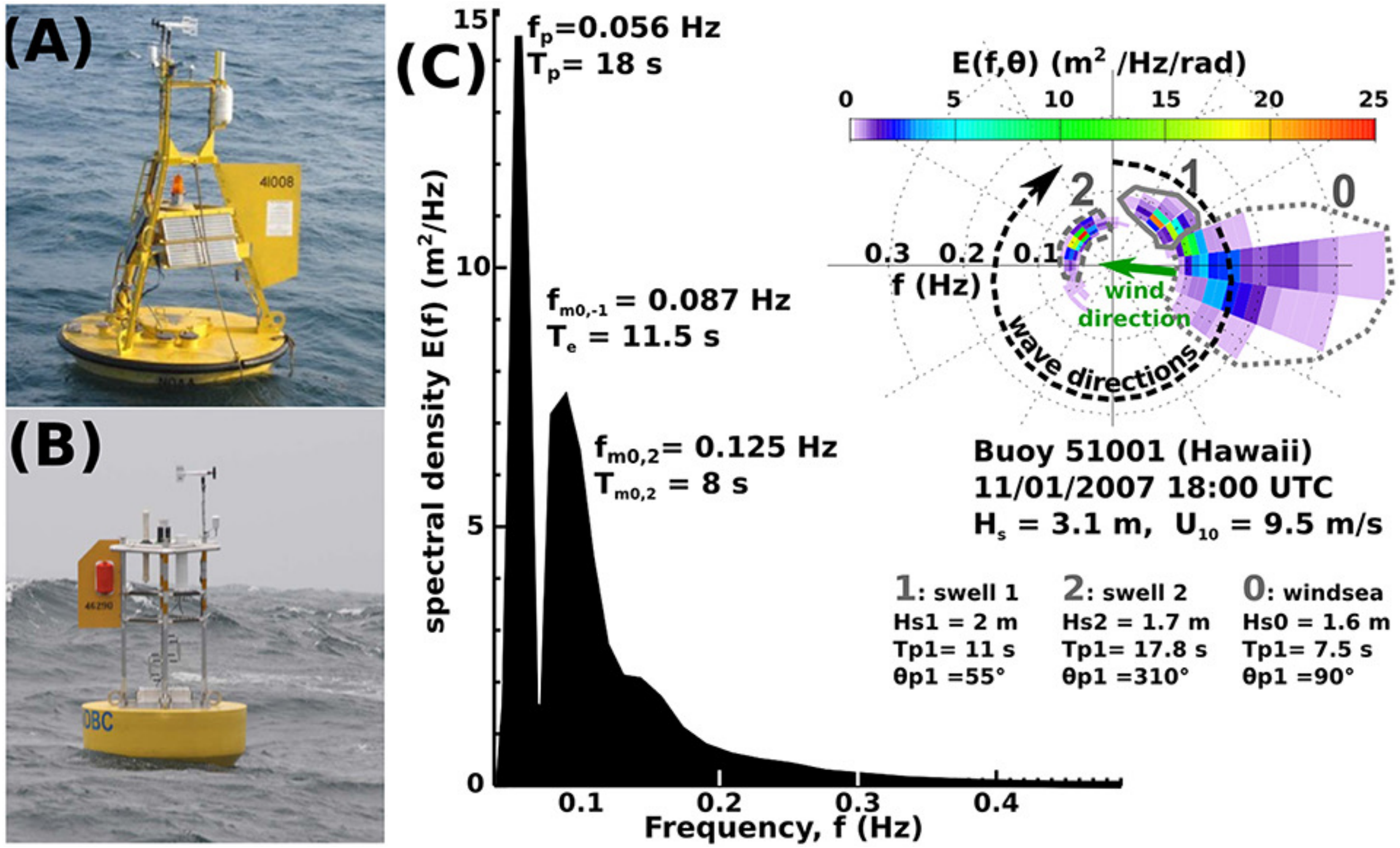
- Observations of wind waves and swell in Gibraltar
- Measures seafloor strain proportional to pressure
- Recover flow velocity from dispersion using interferometry

2. Internal waves on DAS

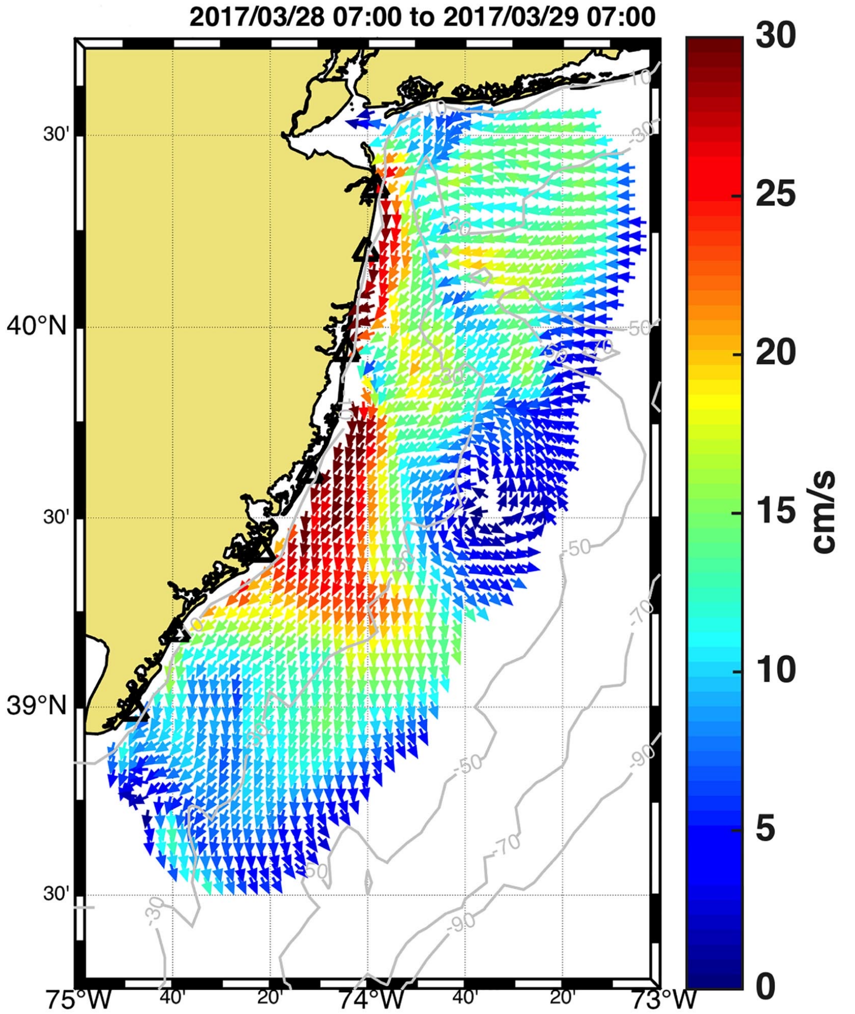
- Large-amplitude interal waves in the Strait of Gibraltar
- Nonlinear internal tide on the slope of Gran Canaria
- Predominately sensitive to temperature, not pressure


Ocean surface gravity waves

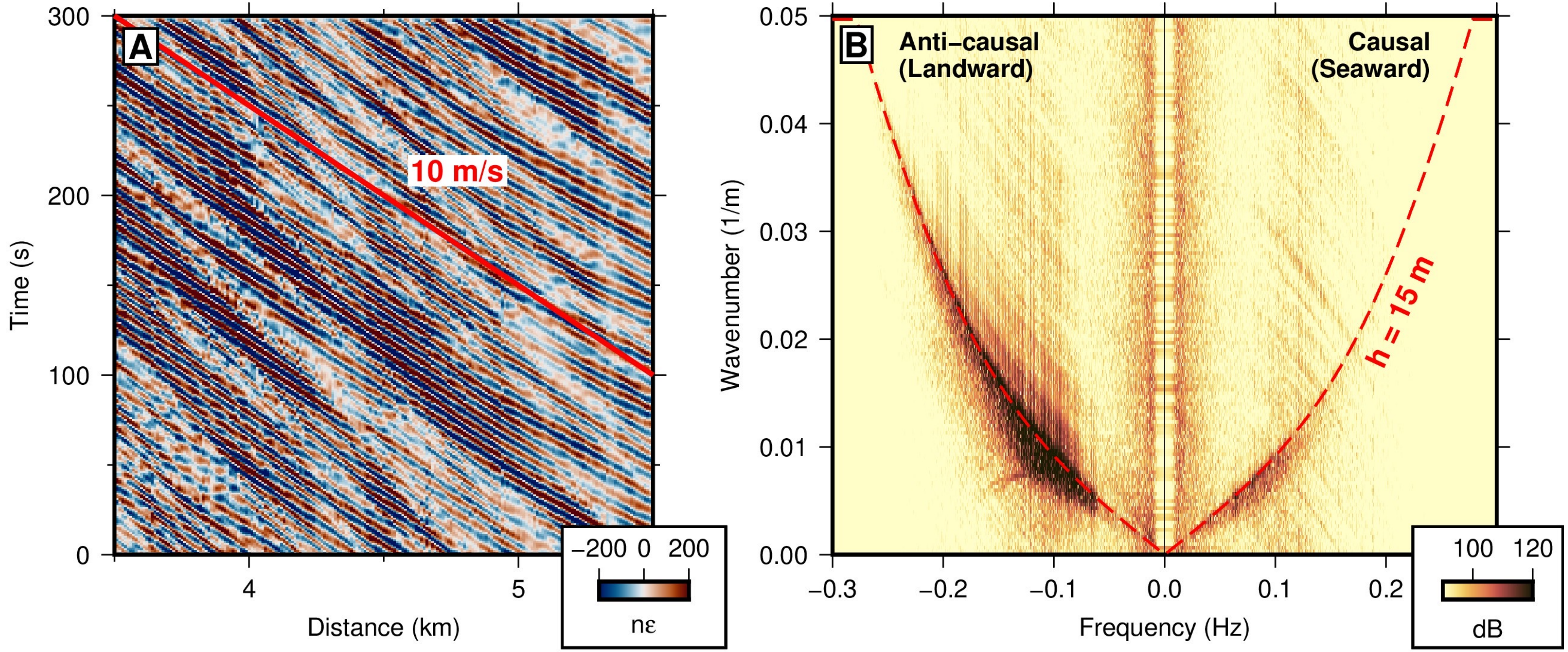
Measuring waves and coastal currents



Ardhuin, 2020



Ocean surface gravity waves in DAS data



Williams et al. (2022)

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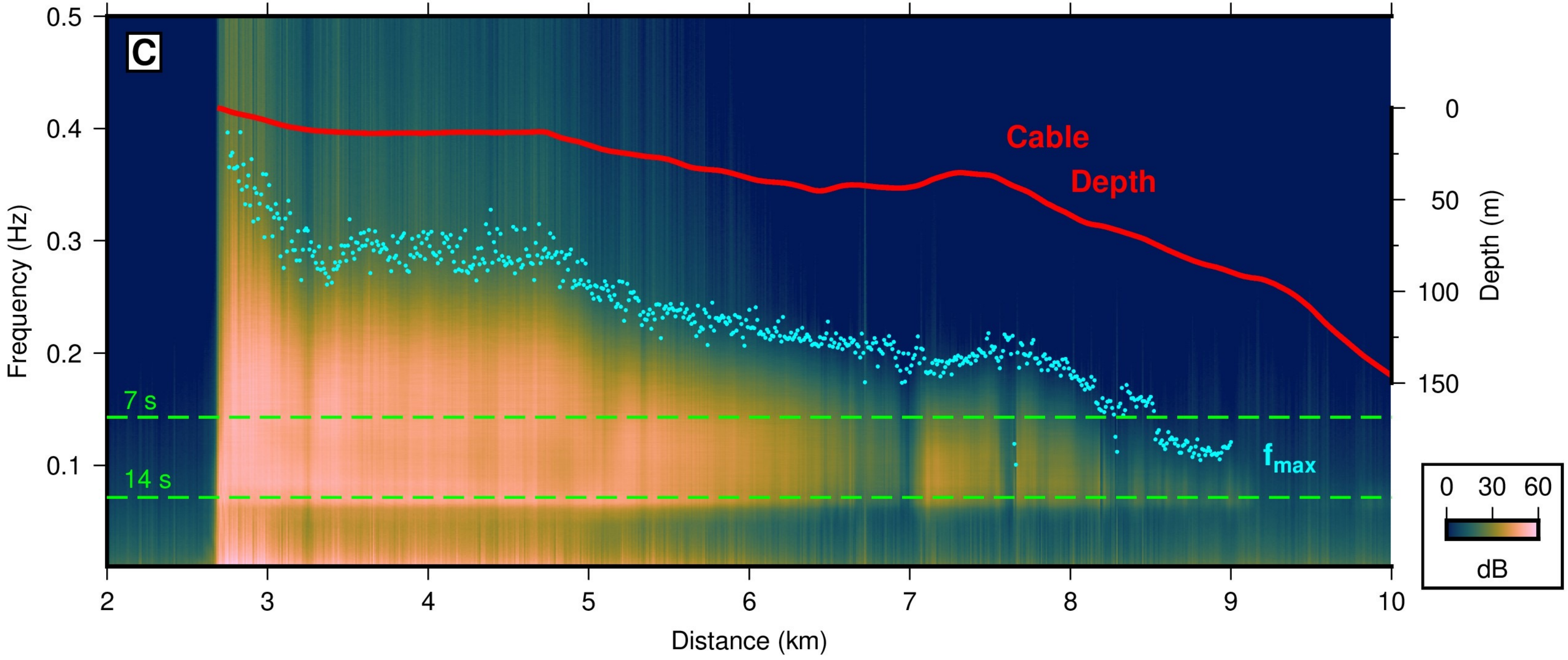
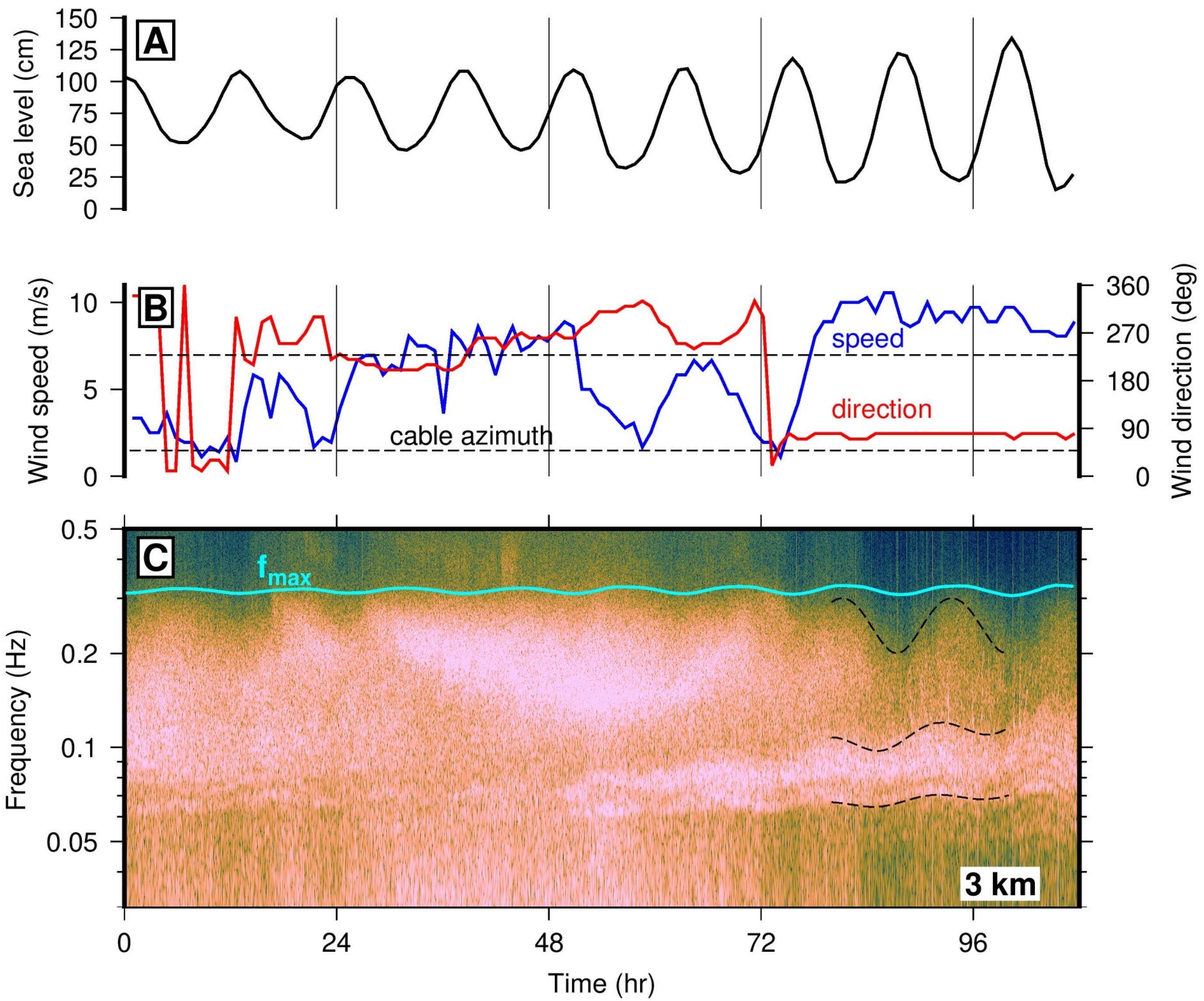


Bimodal spectrum: swell and wind waves

Amplitude and bandwidth modulated by bathymetry

Williams et al. (2022)

OSGW in the Gibraltar DAS dataset



Wave frequency and amplitude strongly modulated by tides (more than linear theory can predict)

Strongly enhanced high-frequency wave energy when wind blows along cable azimuth towards Spanish coast

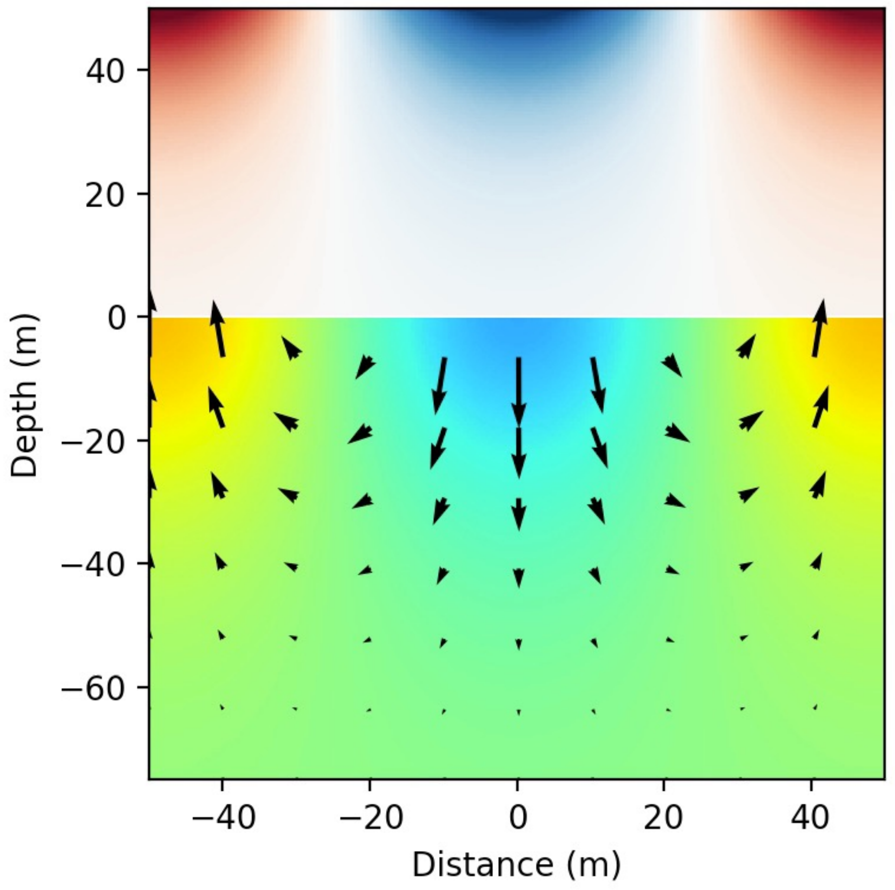
Swell is characteristically dispersive

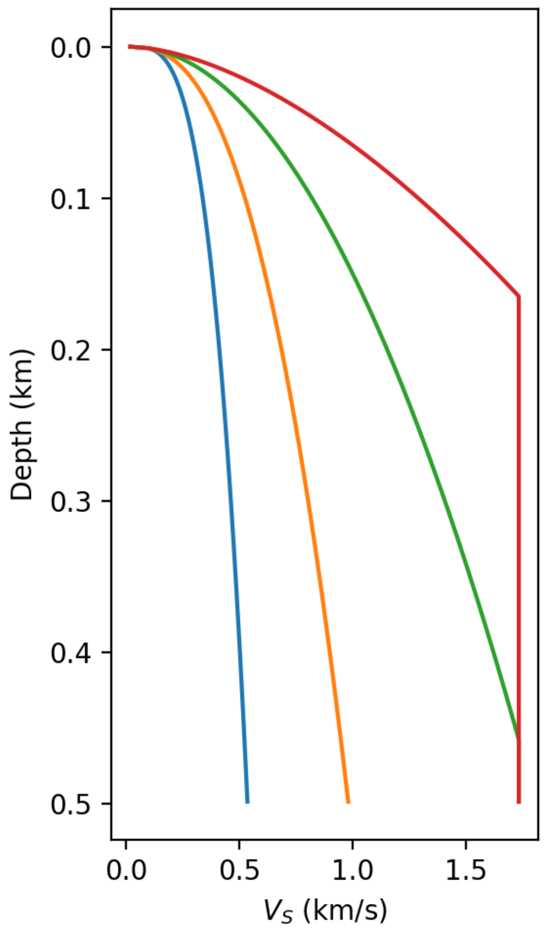
Williams et al. (2022)

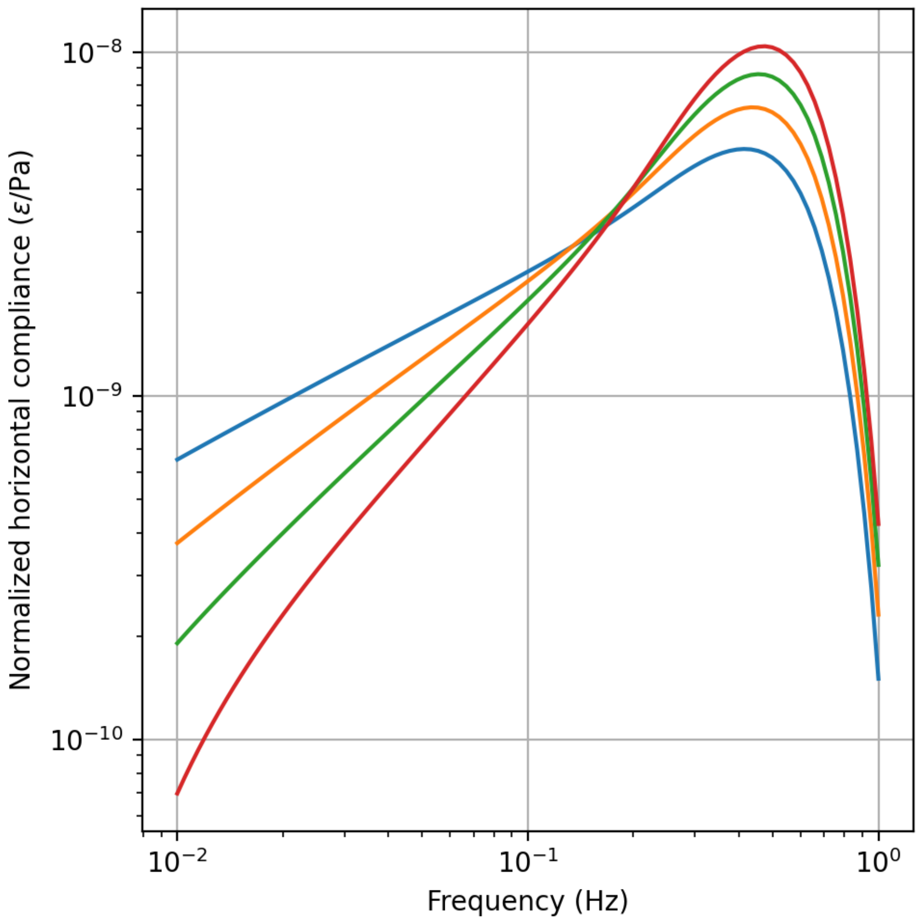
Towards extracting ocean wave statistics from DAS data

1. Physics-based transfer function from sea surface displacement to DAS strain

$$\eta_x = k\frac{u_x}{\tau_{zz}} = \frac{\varepsilon_{xx}}{p_d} = \frac{\lambda + 2\mu}{2\mu(\lambda+\mu)}$$

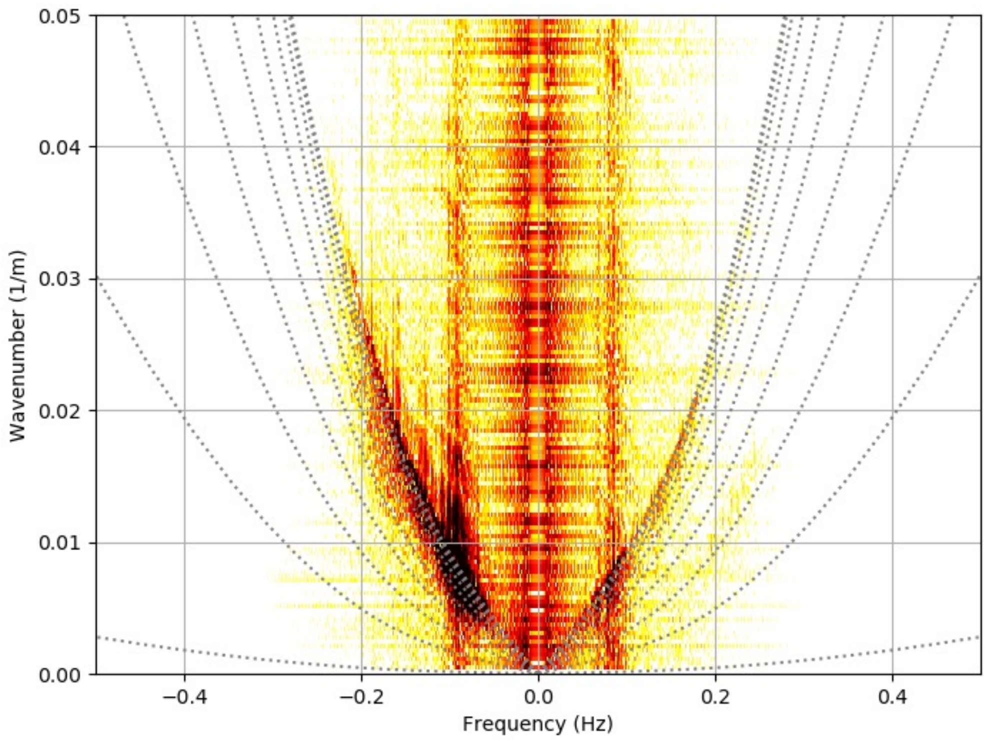


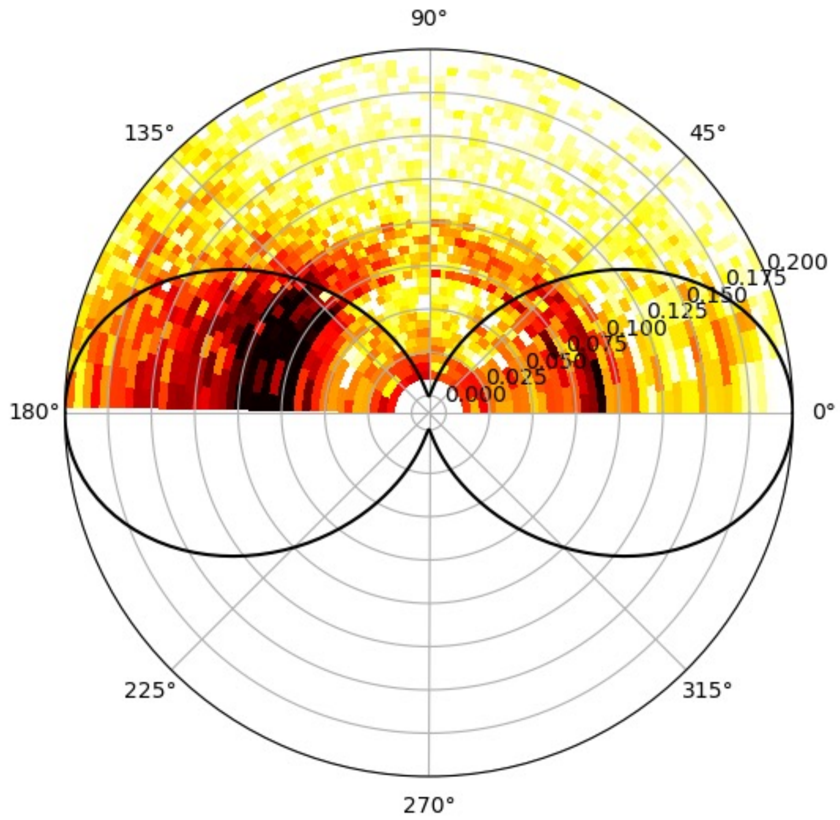




Towards extracting ocean wave statistics from DAS data

2. Array-based estimation of wave directional energy distribution ("spreading")





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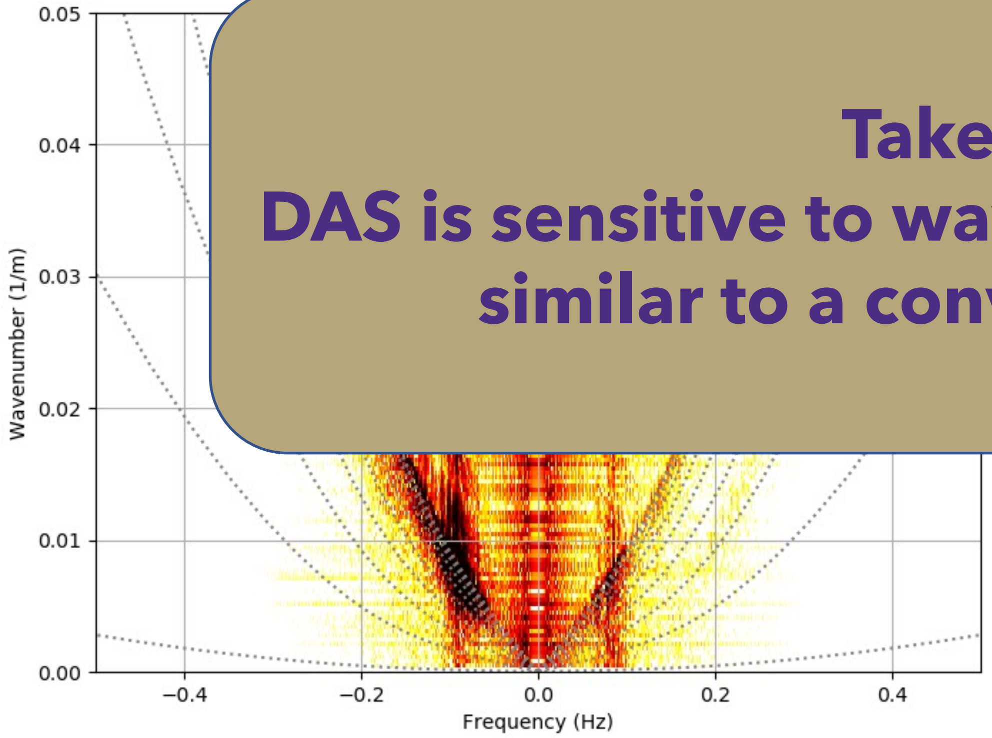
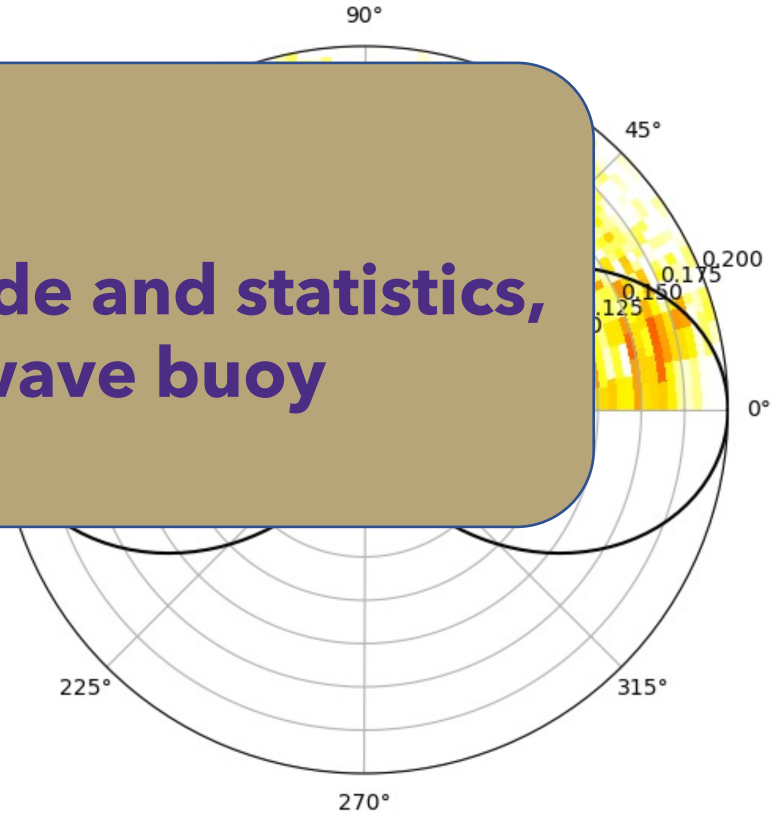
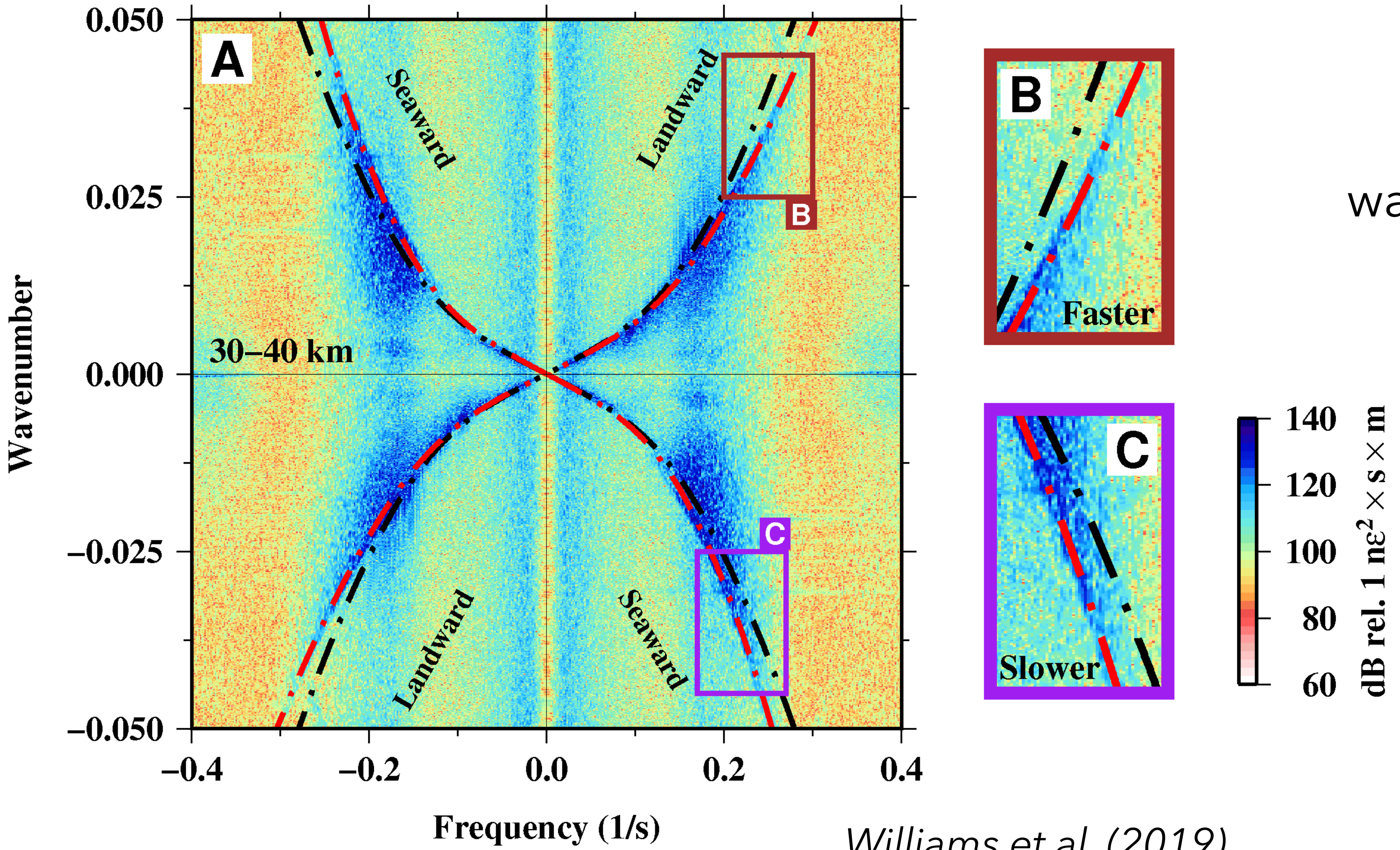




Take-away #1:
DAS is sensitive to wave amplitude and statistics, similar to a conventional wave buoy

Williams et al. (2019)

Spatio-temporal ocean flow monitoring with DAS

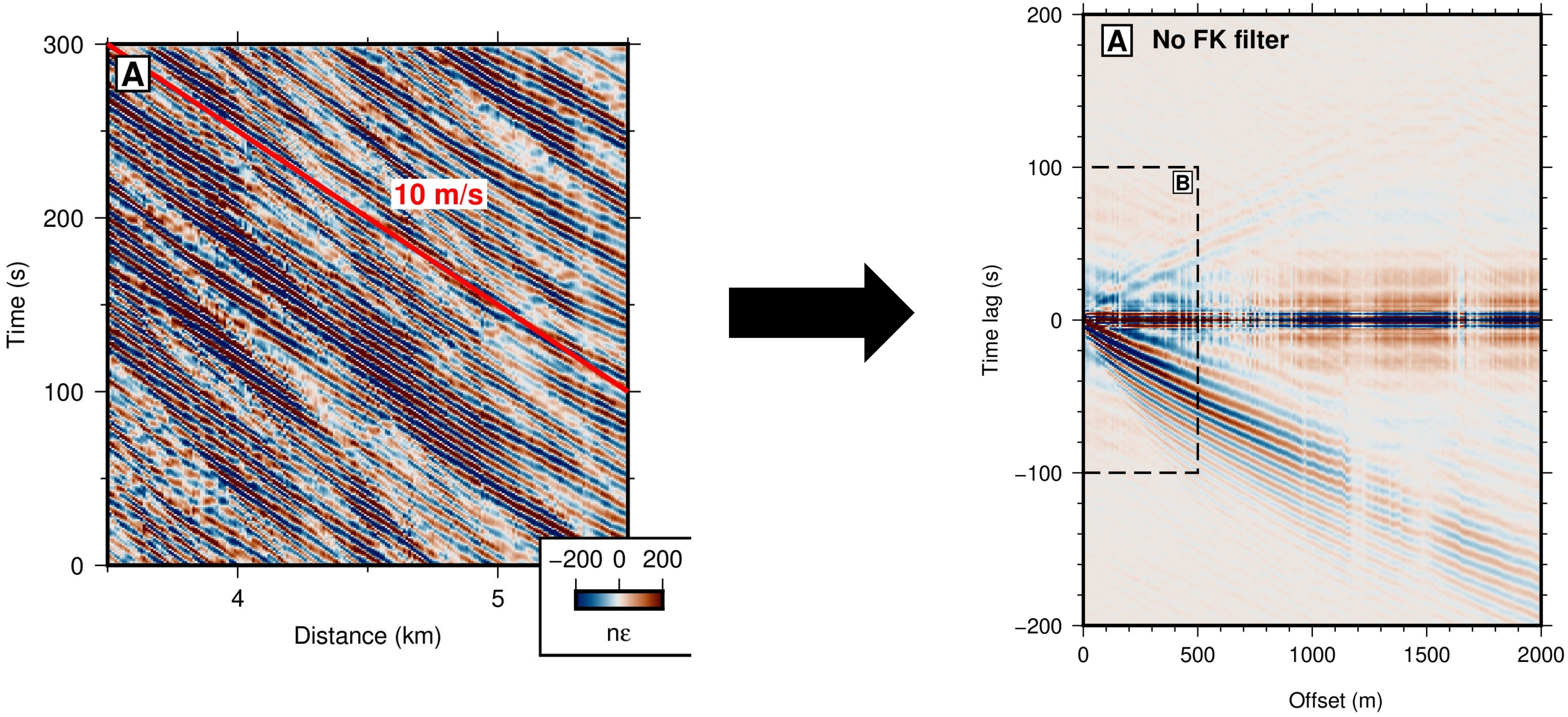


Williams et al. (2019)

Doppler shift: waves propagating with the current are faster and waves propagating against the current are slower

$$c(\omega) = \pm\sqrt{\frac{g}{k}\tanh kh} + U$$

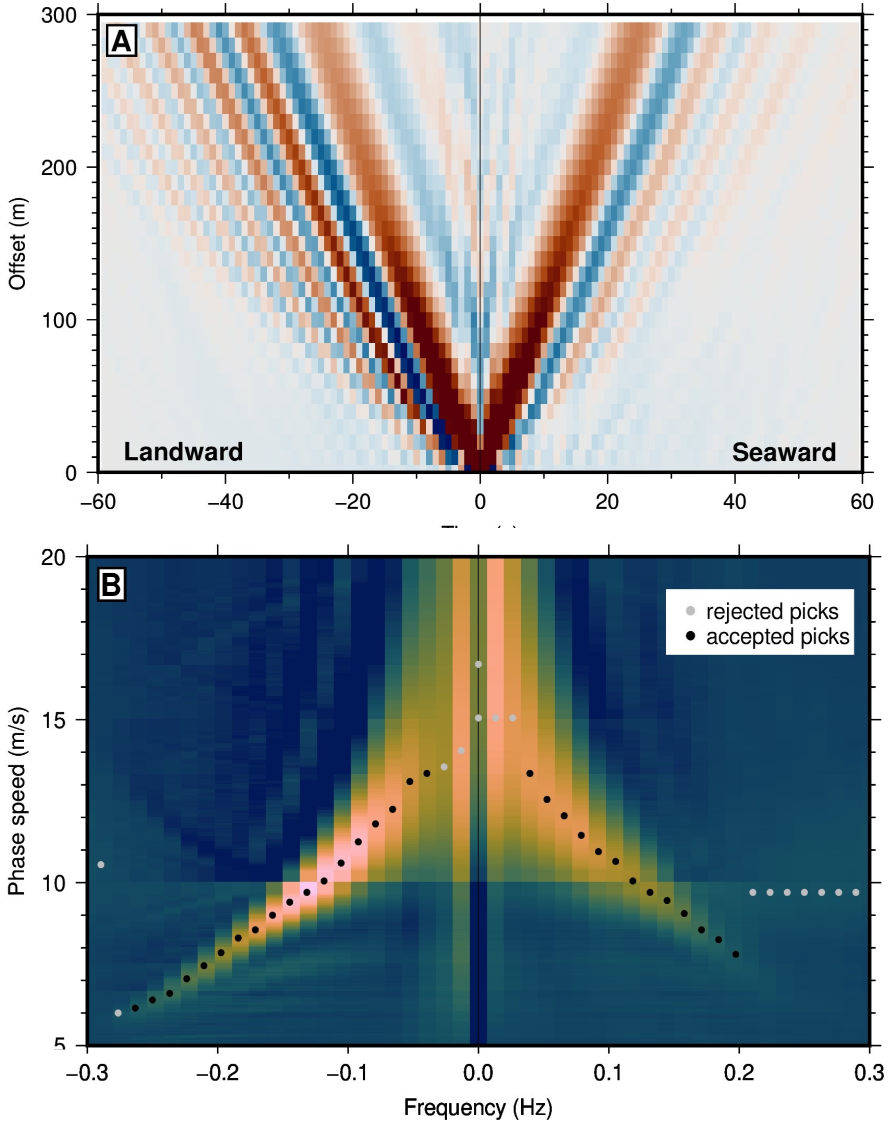
Ambient noise interferometry with OSGW



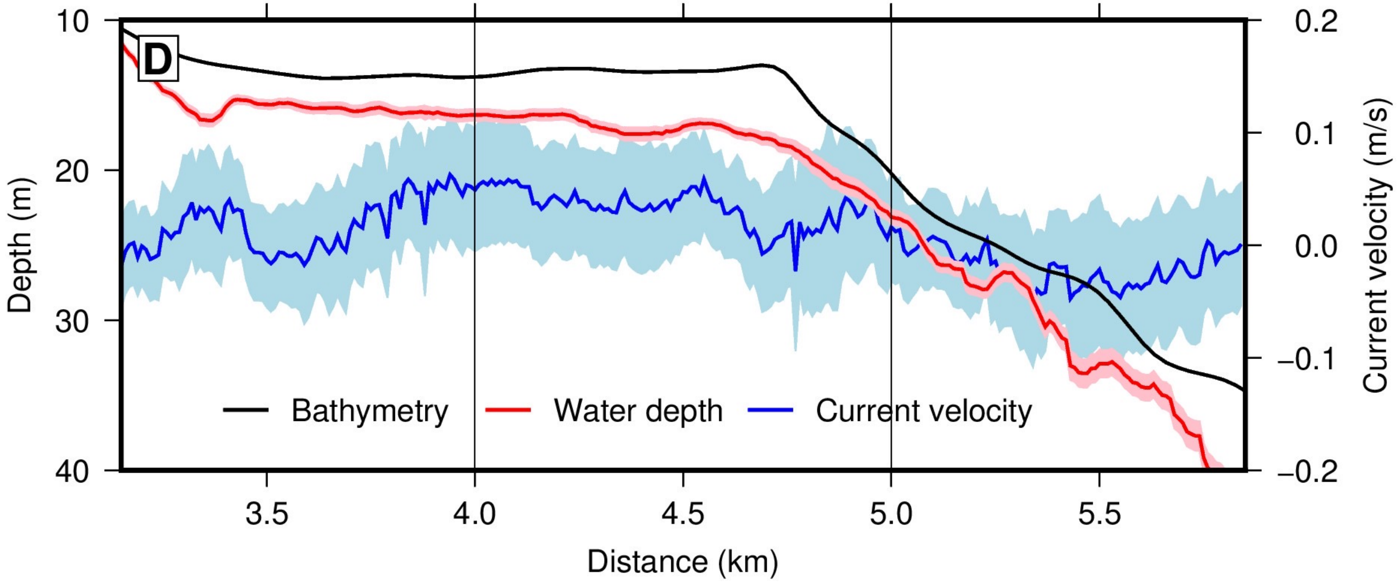
Williams et al. (2022)

Step 1: Invert for mean state

Williams et al. (2022)



For each direction, measure dispersion on subarrays and fit to wave-current model



Recovers two paramers: Cable depth and time-averaged current velocity

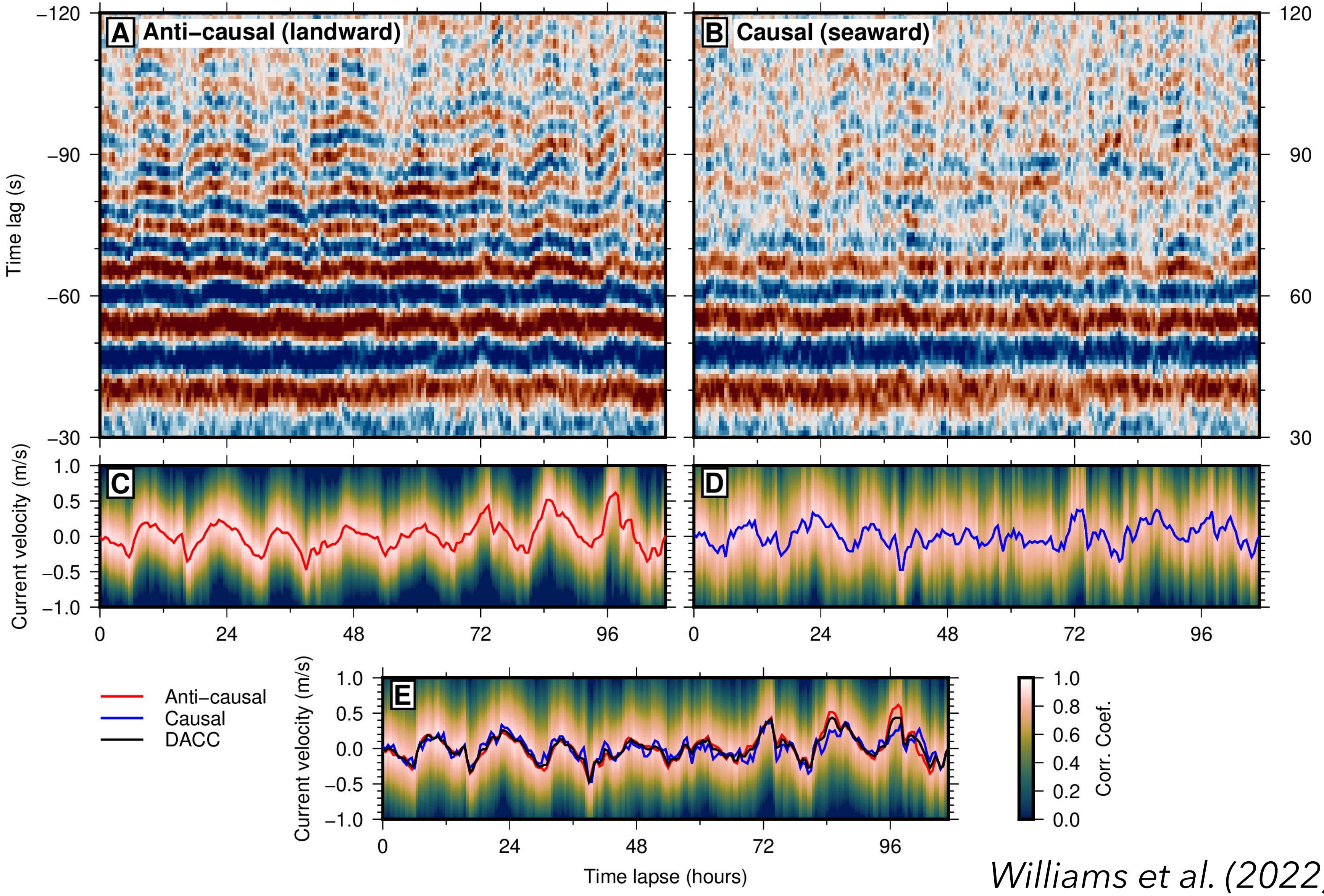
Williams et al. (2022)

Step 2: Time-lapse waveform stretching

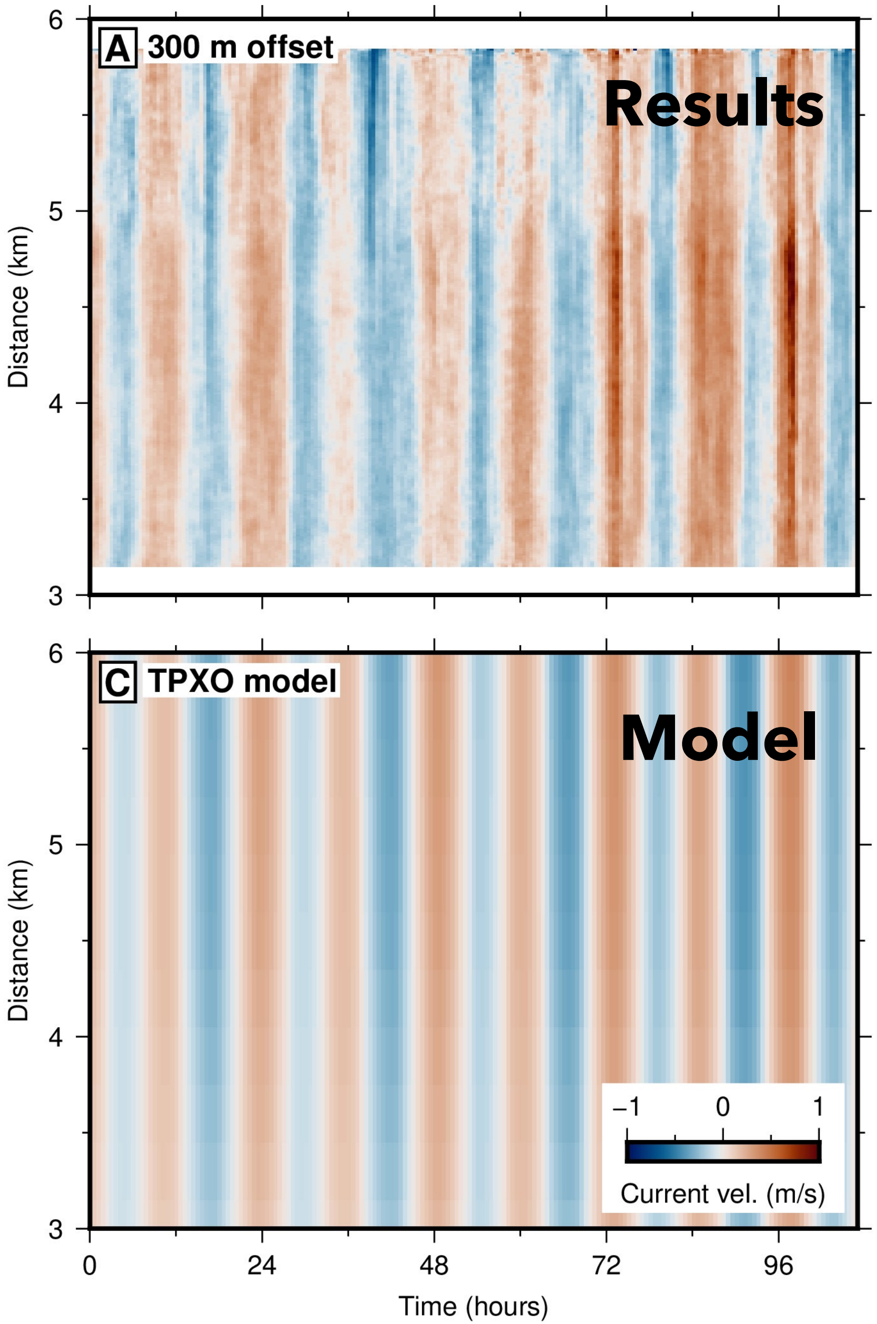
Semidiurnal variation in travel-times of cross-correlations, strongly frequency dependent

Waveform stretching provides a good fit (CC>0.9) with simple depth-averaged wave-current interaction model

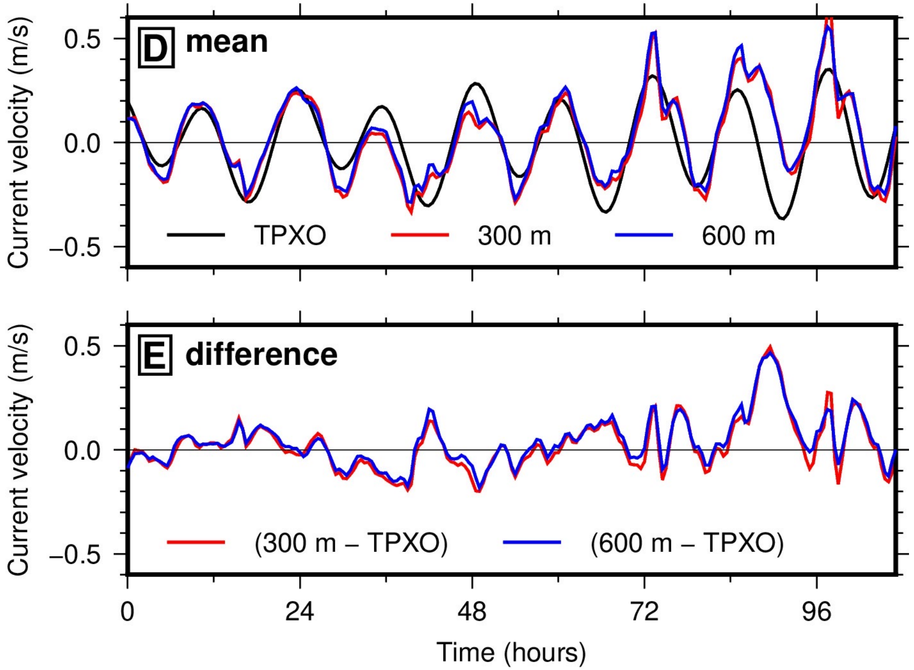
Reveals tidal current with velocity ~0.5 m/s



Williams et al. (2022)



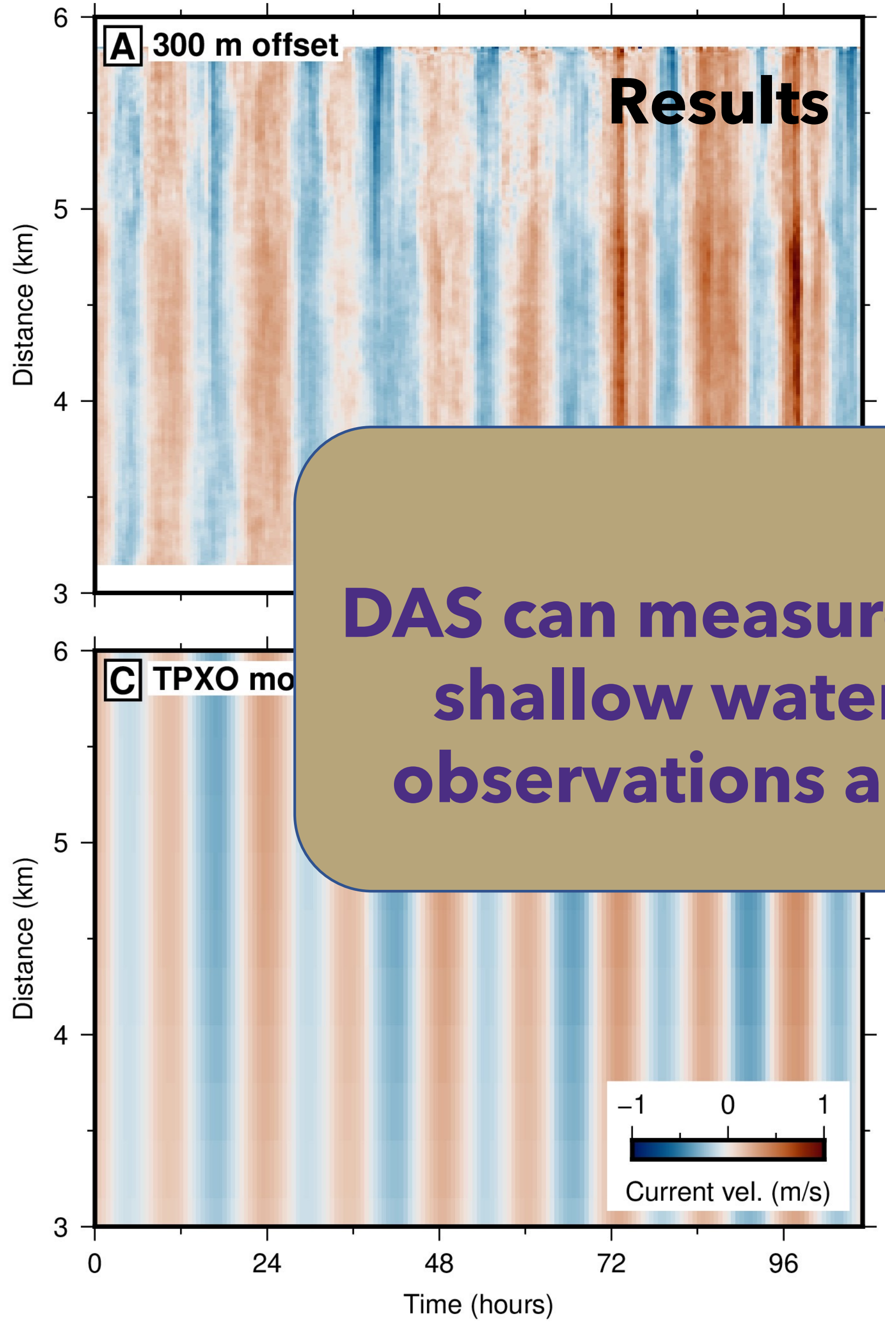
Successfully recovers the amplitude and phase of the tidal current in the Strait of Gibraltar



Captures some sharp features not explained by tidal harmonics: internal waves?

Williams et al. (2022)

Results



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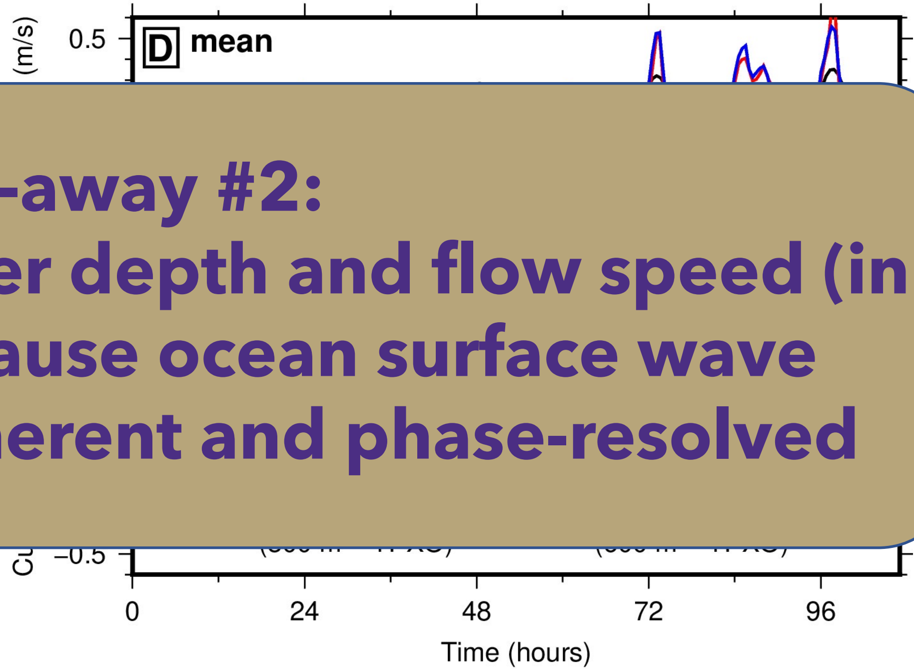


Take-away #2:
DAS can measure water depth and flow speed (in shallow water) because ocean surface wave observations are coherent and phase-resolved

Captures some sharp features not explained by tidal harmonics: internal waves?

Williams et al. (2022)

DAS is sensitive to both strain and temperature

DAS measures change in optical path length, which includes physical deformation (strain) and changes in the refractive index

$$\frac{\Delta\phi}{\phi} \propto \frac{\Delta x}{x} + \frac{\Delta n}{n}$$

$$\frac{\Delta x}{x} = \varepsilon + \alpha_T \Delta T \qquad \frac{\Delta n}{n} = \psi\varepsilon + \xi\Delta T$$

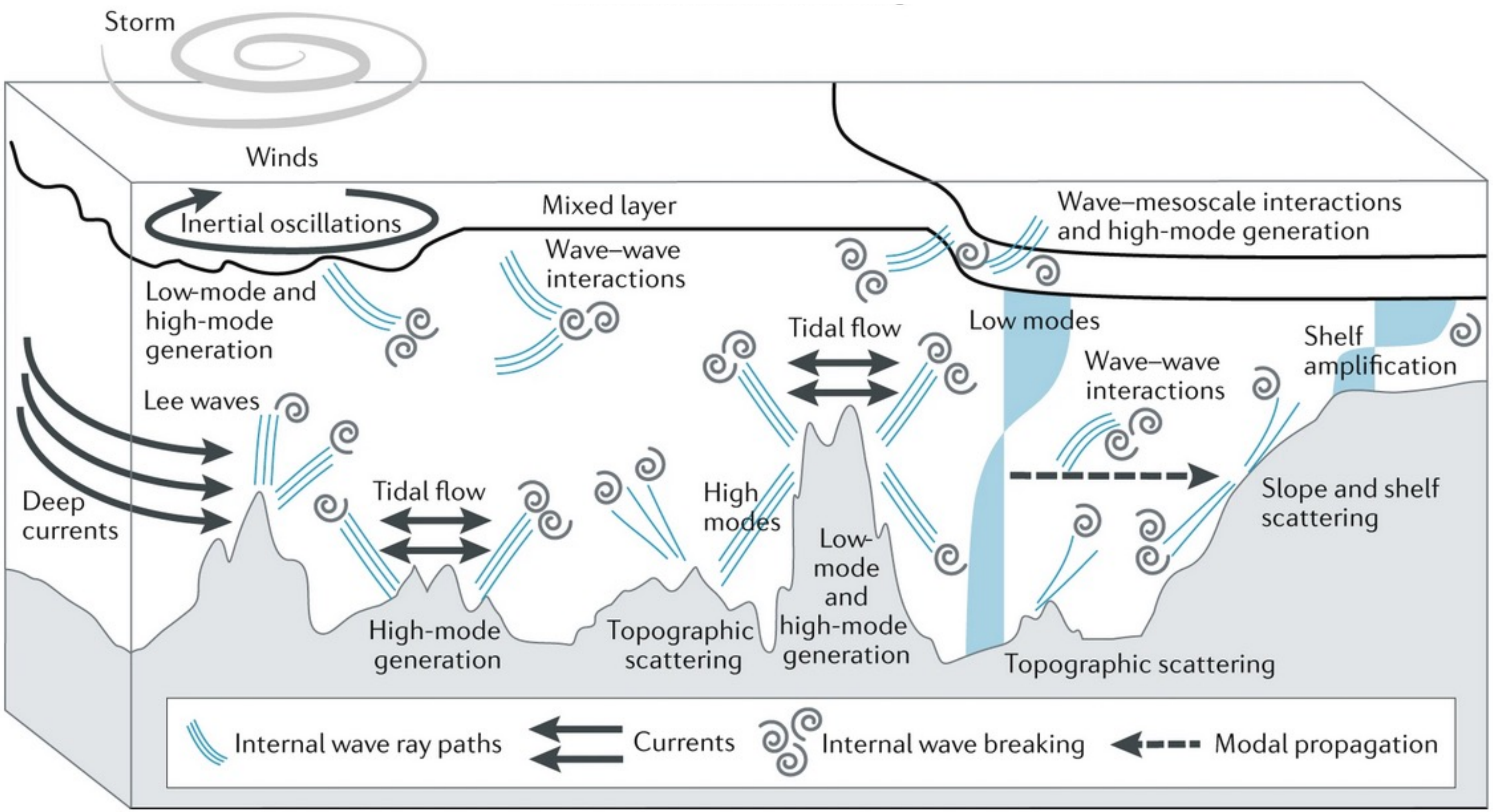
$$\Delta\phi \propto (1+\psi)\varepsilon + (\alpha_T + \xi)\Delta T$$

$$= 0.78\,\varepsilon + 7.3\times10^{-6}\,\Delta T$$

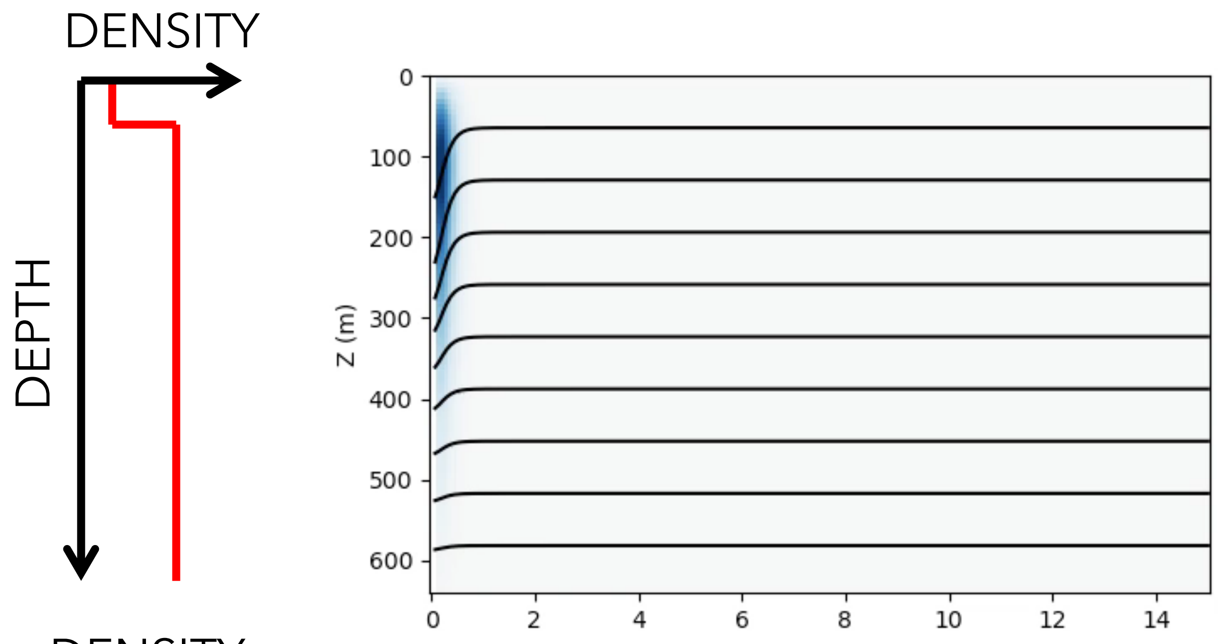
1 °C = 10^{-5} strain

DAS measurements of temperature and strain are indistinguishable without a-priori physical understanding

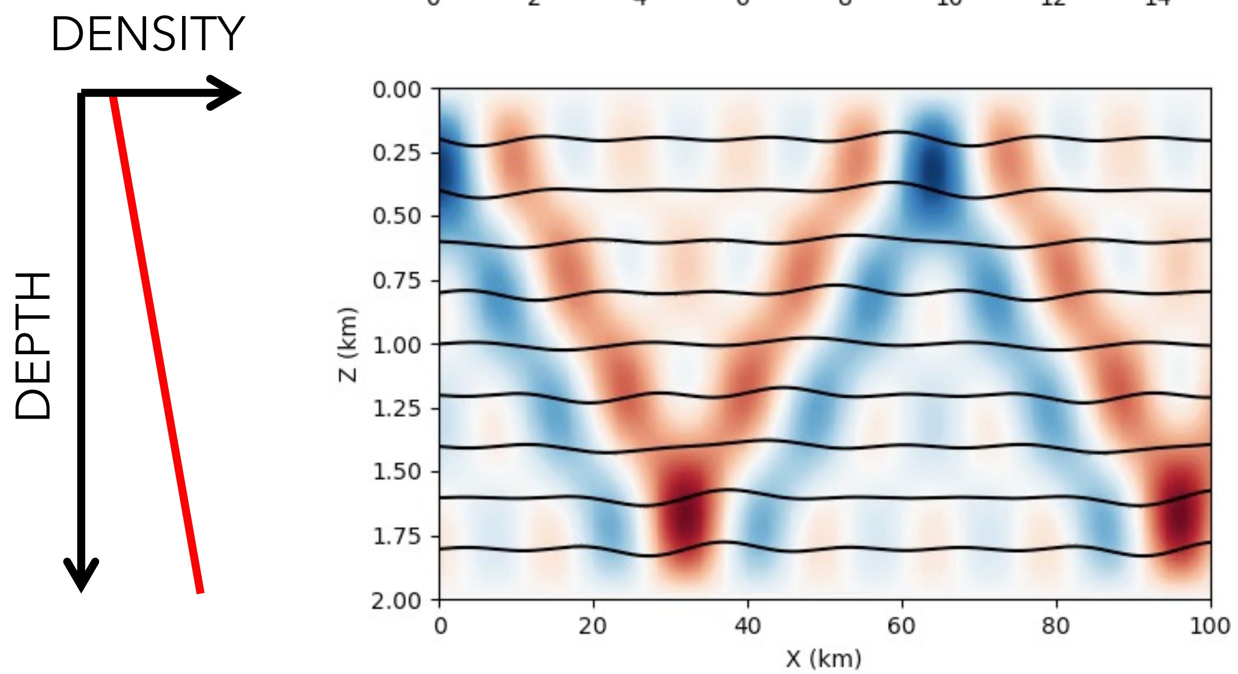
Internal gravity waves in the ocean



MacKinnon et al. (2017)



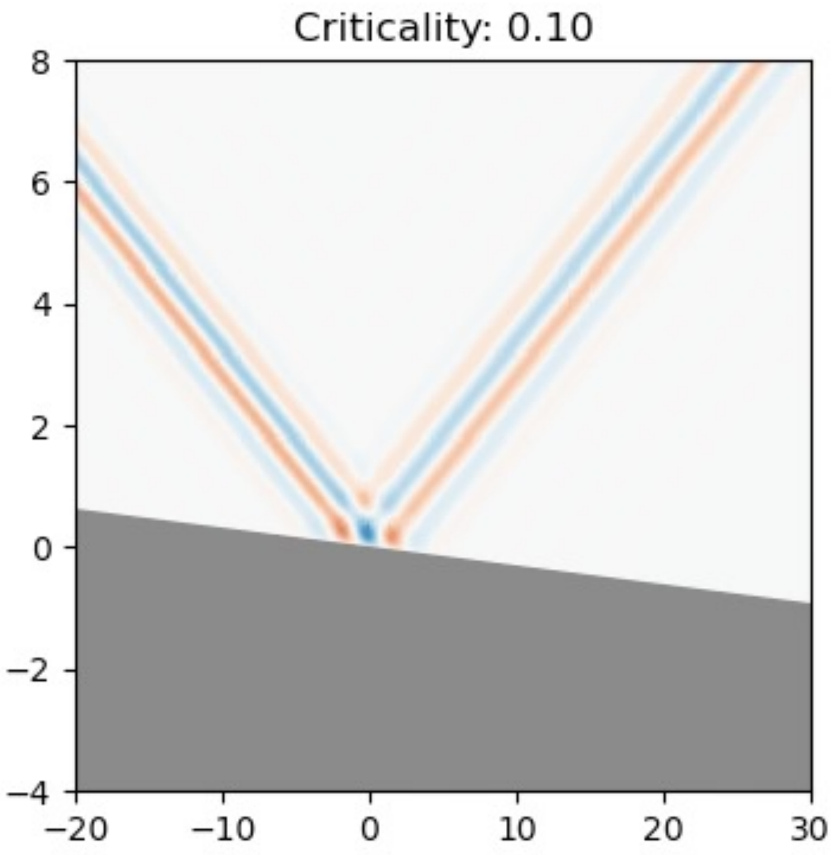
A.
Internal soliton trains in a two-layer ocean

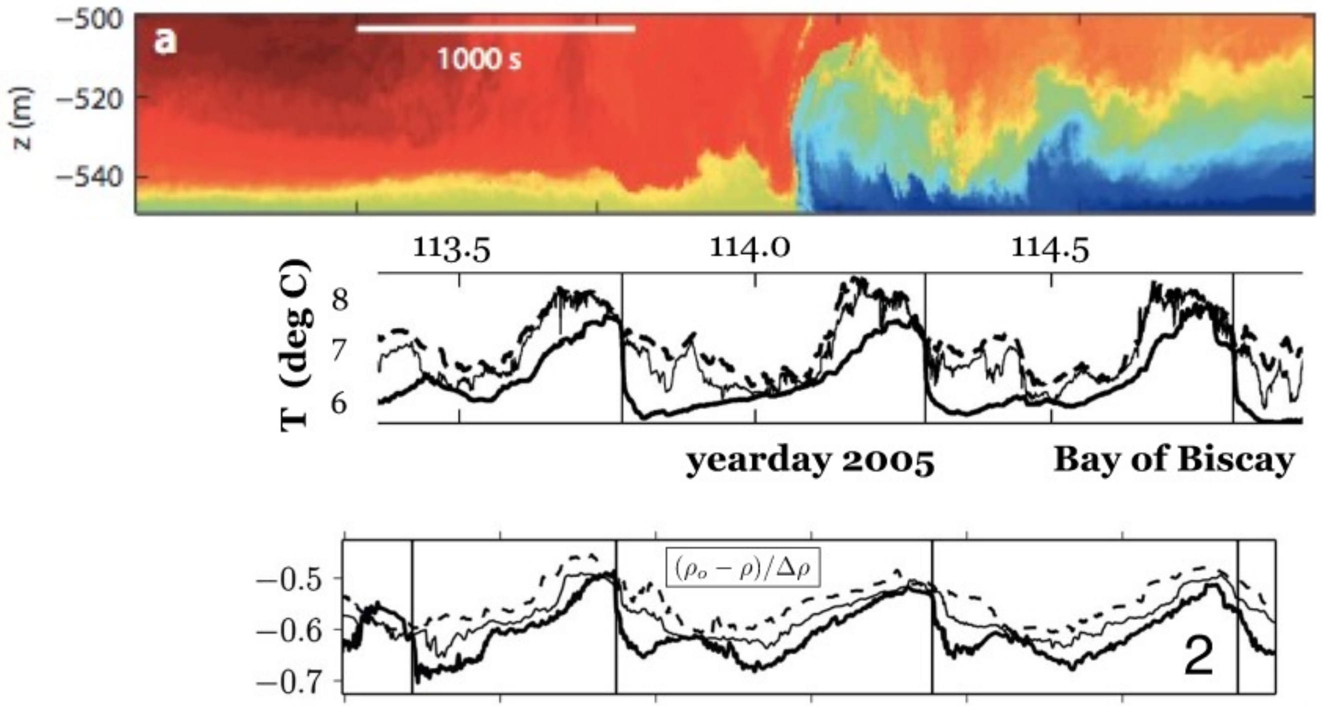


B.
Internal tide beams in a uniformly stratified ocean

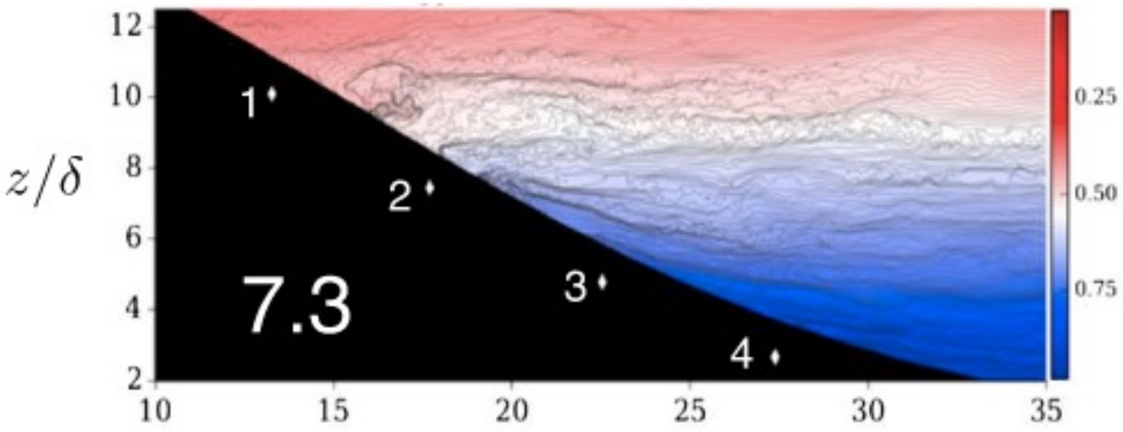
Internal tides on steep submarine slopes

van Haren (2006, 2012)



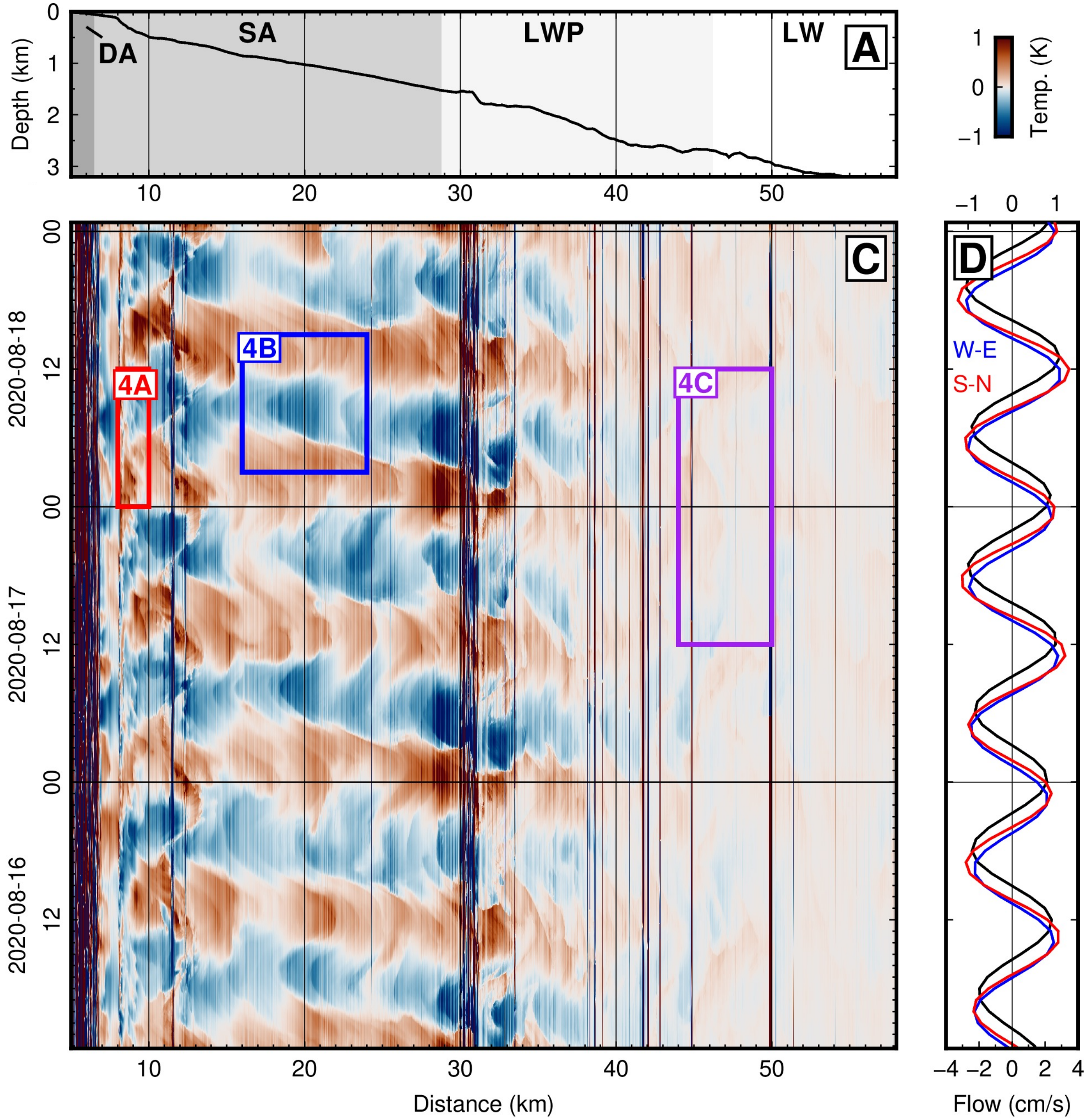


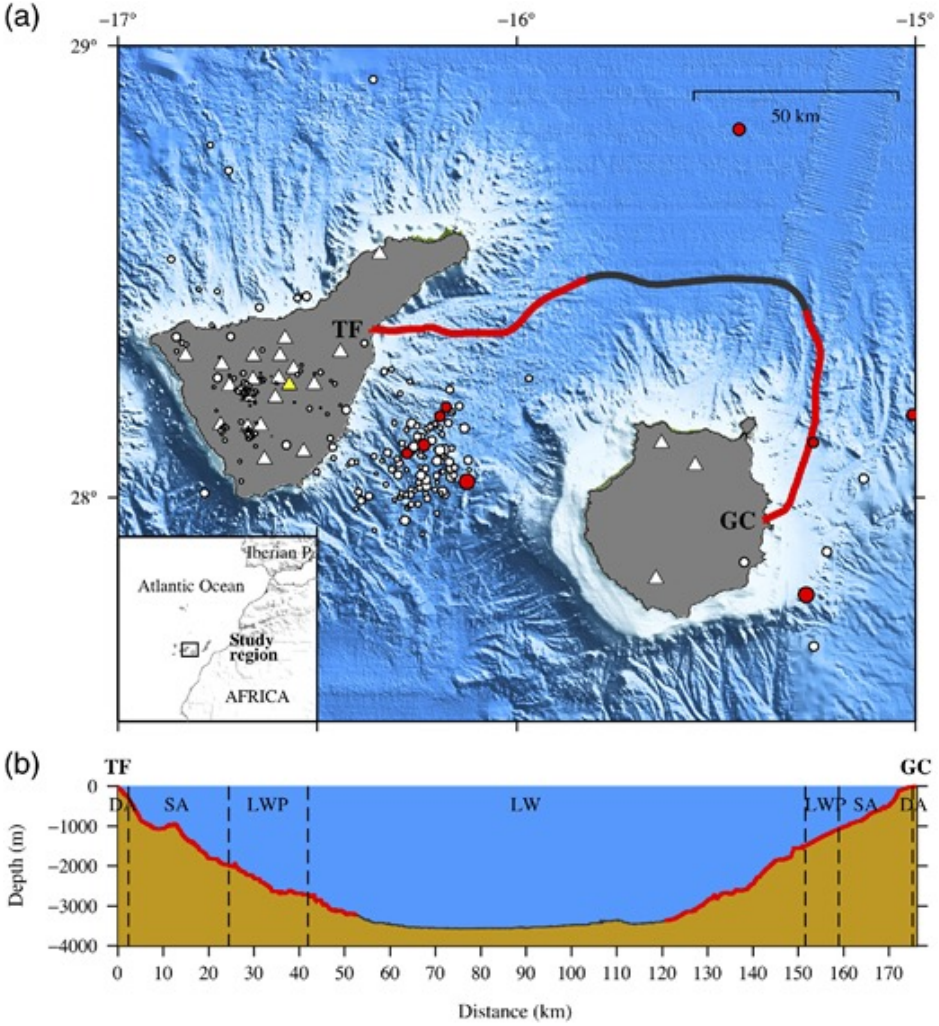
Winters (2015)



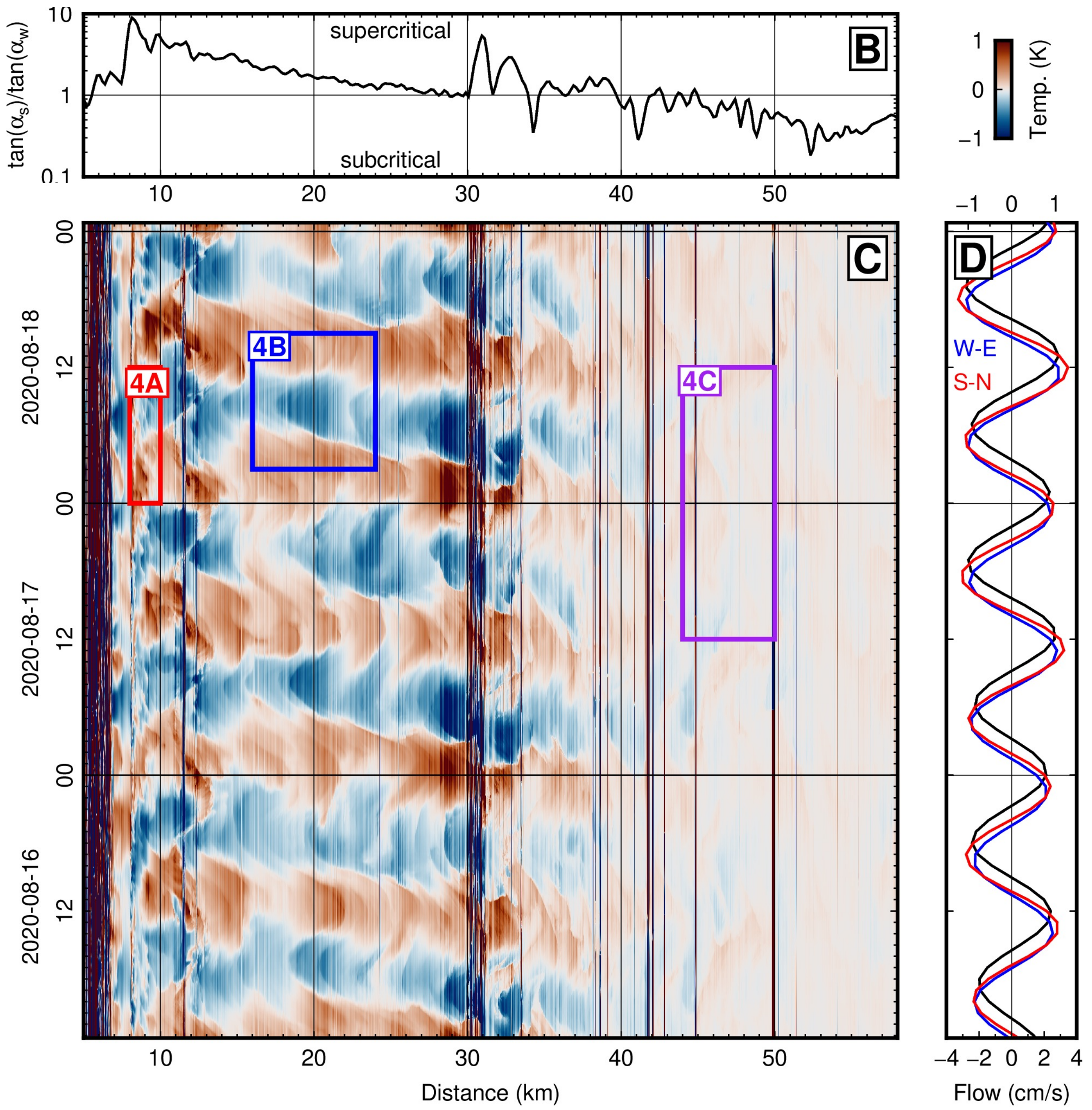
Bore-like temperature fronts generated by reflection of the internal tide on near-critical slopes

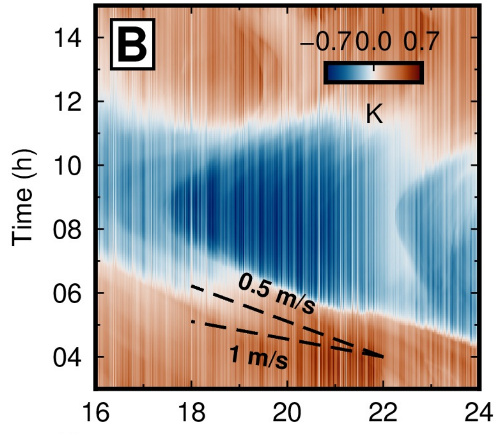
Nonlinear internal tides at Gran Canaria



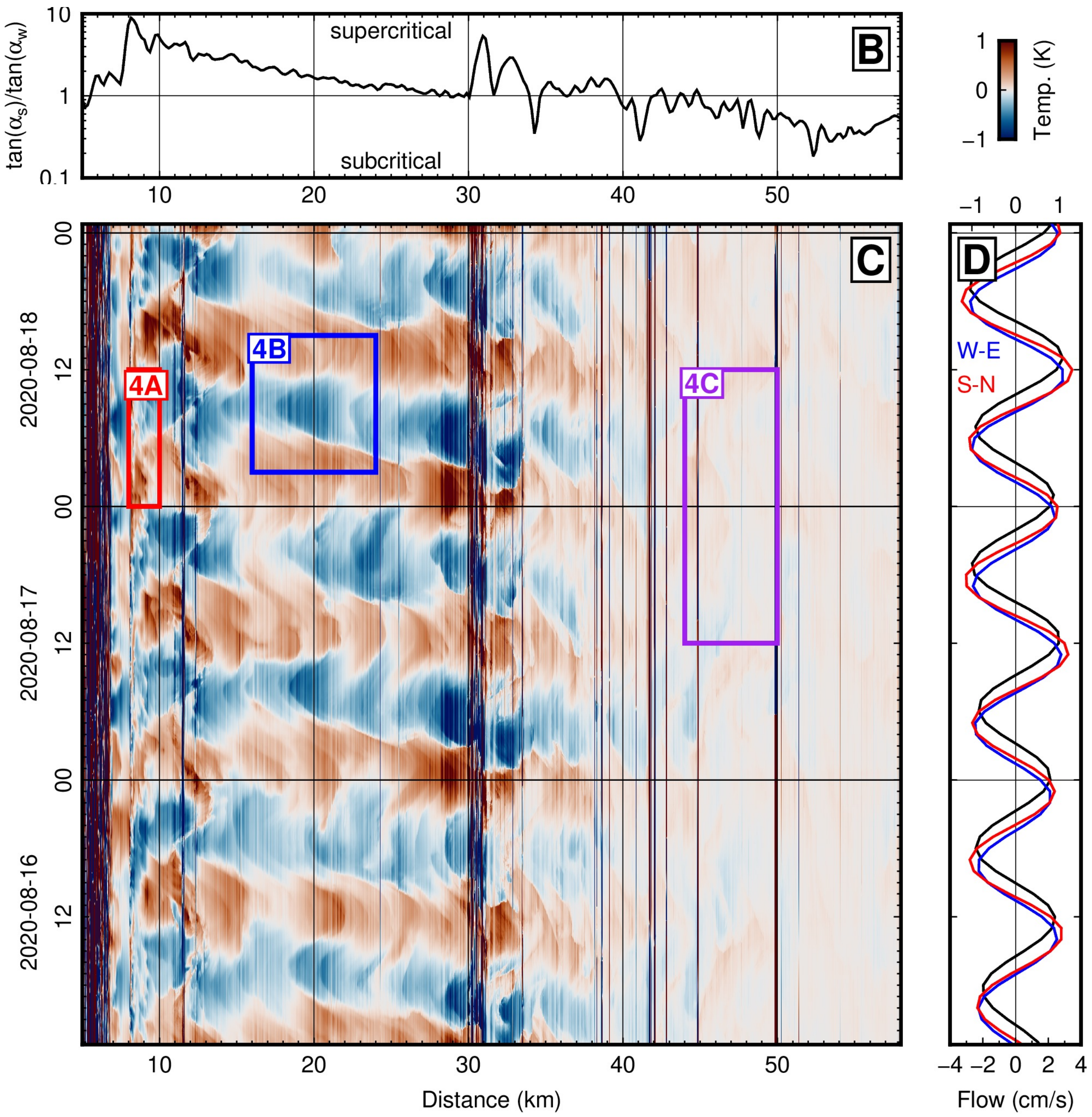


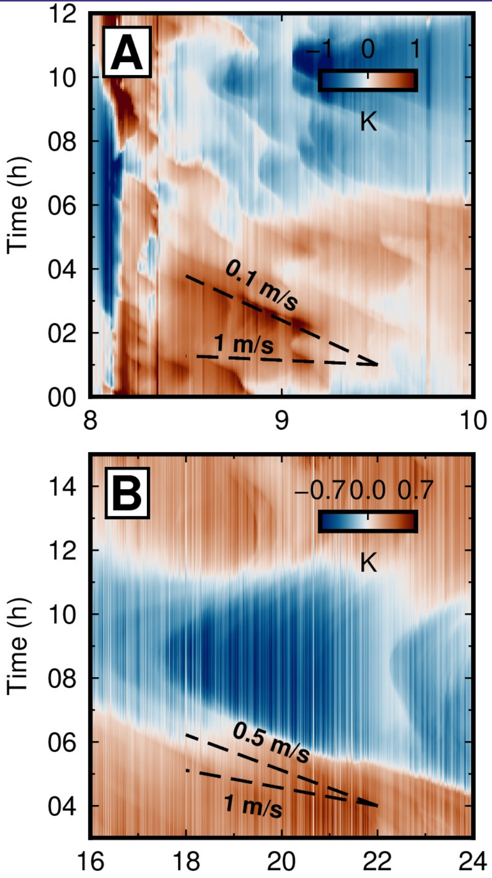
Ugalde et al. (2022)





Sharp (1-2 K) cold fronts propagate up near-critical slope, slow, and recede down-slope as weaker warm fronts





Slow and divide into many smaller fronts on supercritical slope in shallower water

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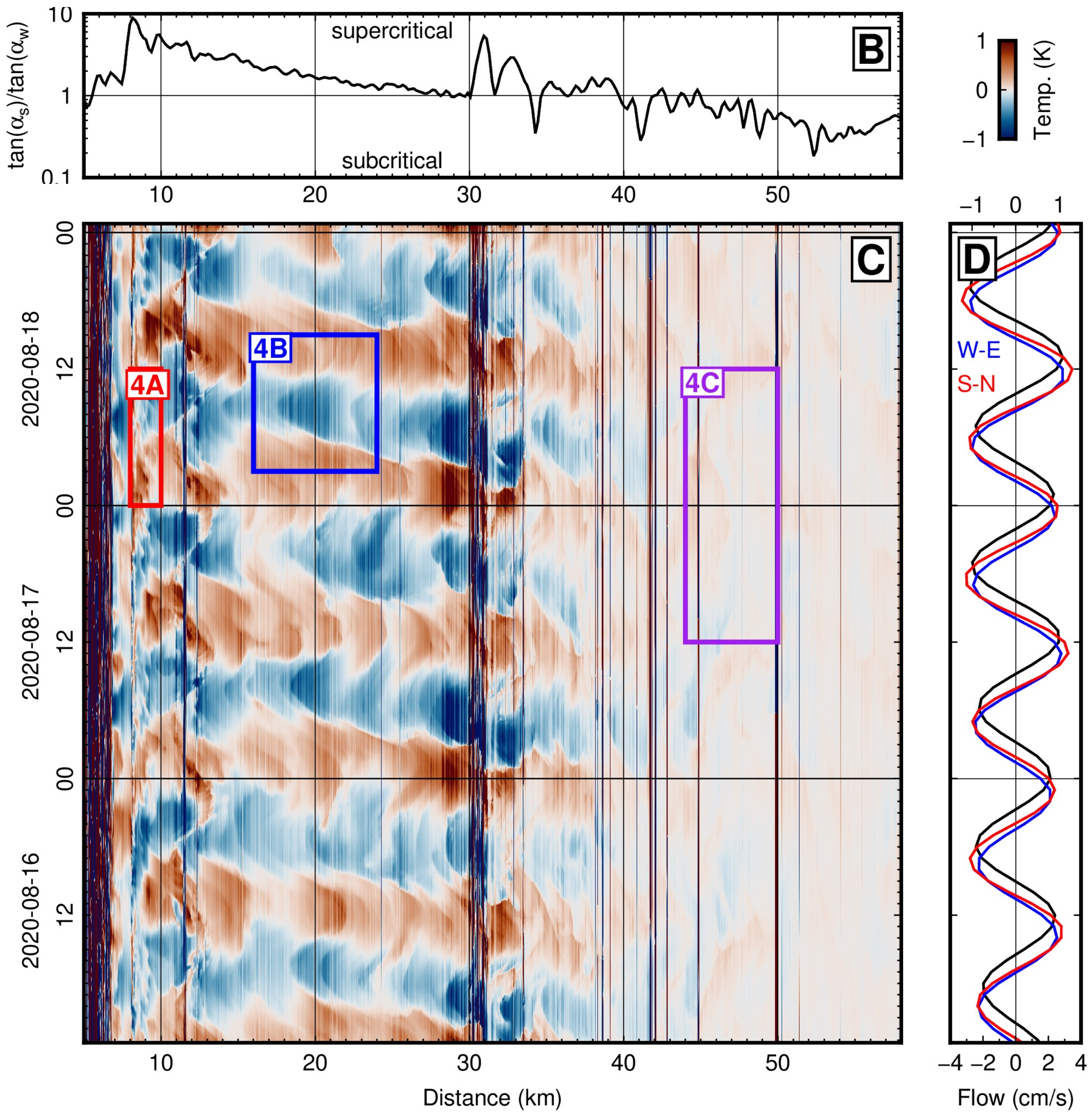

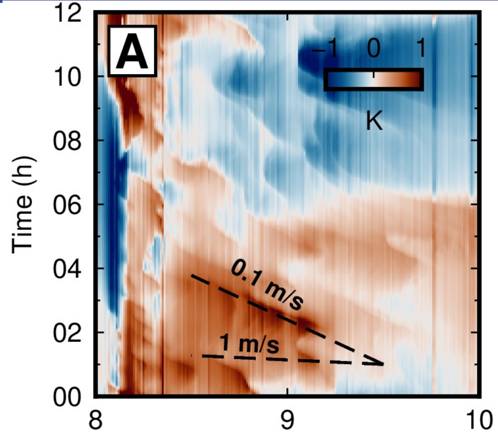

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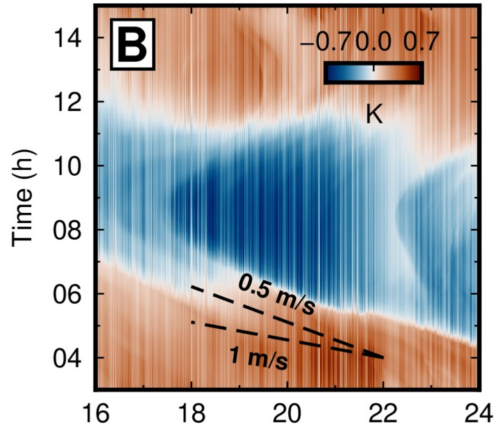

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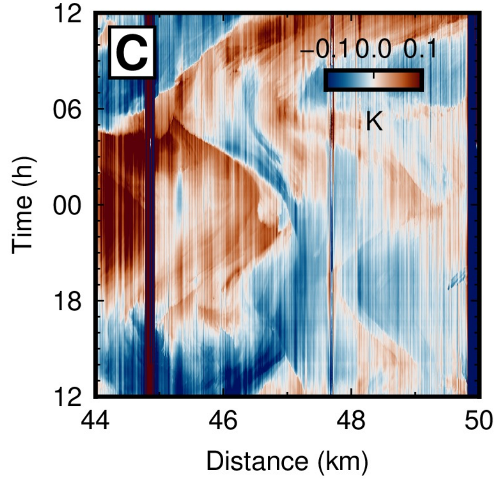
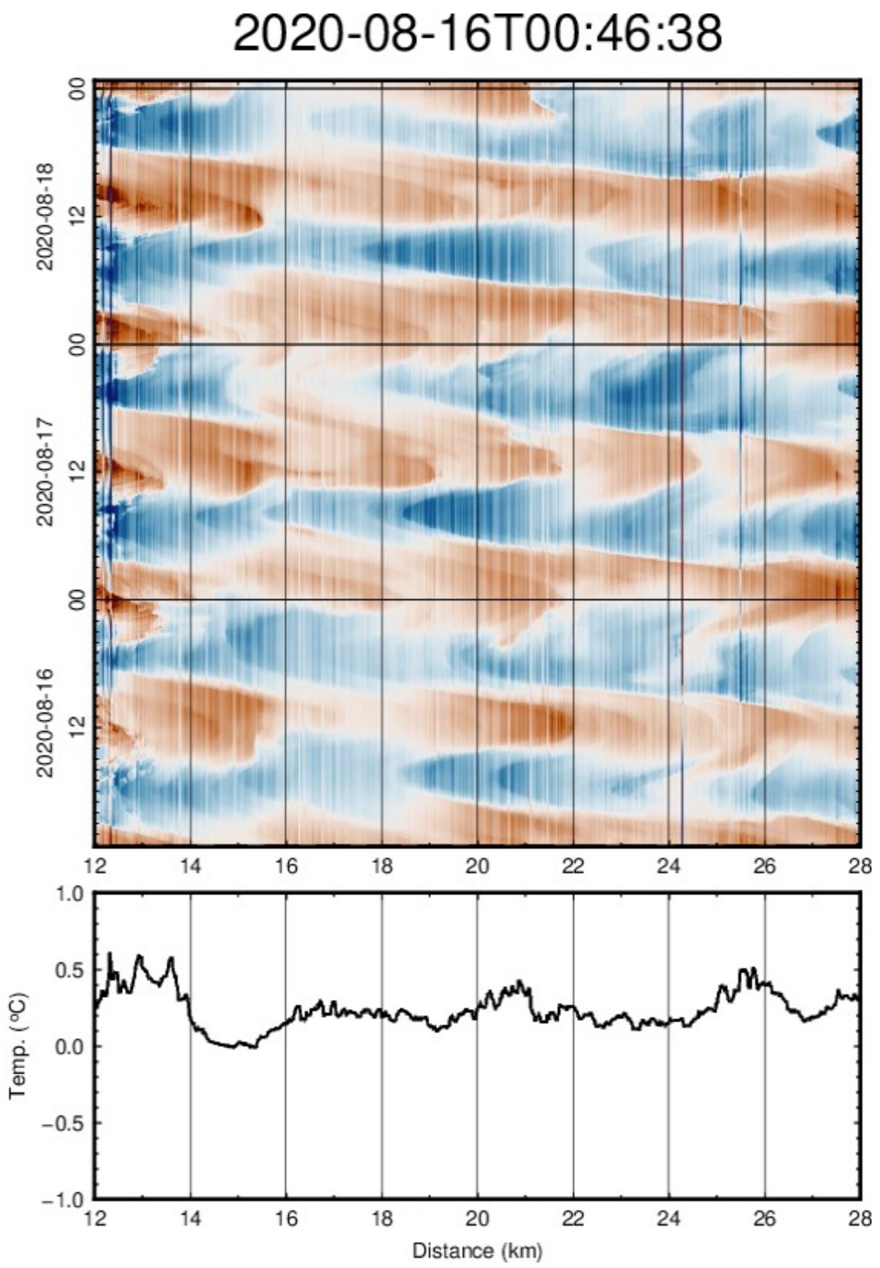
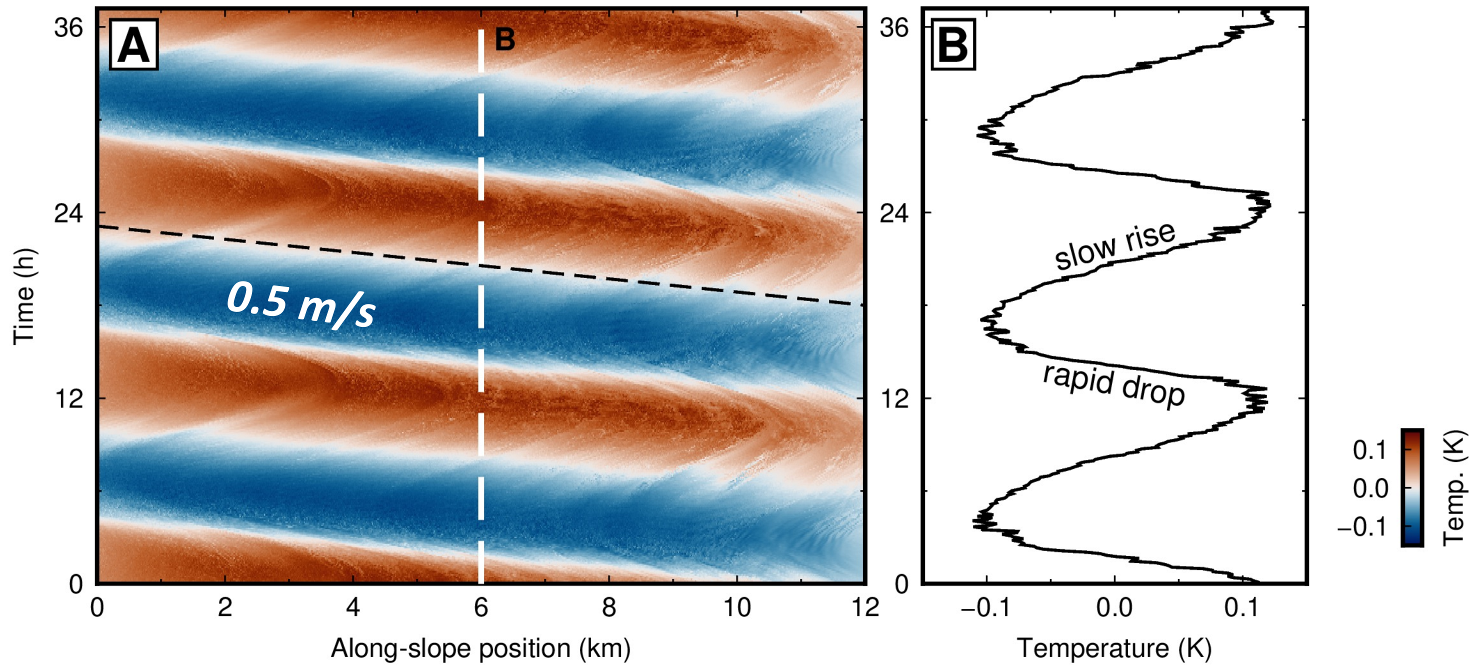
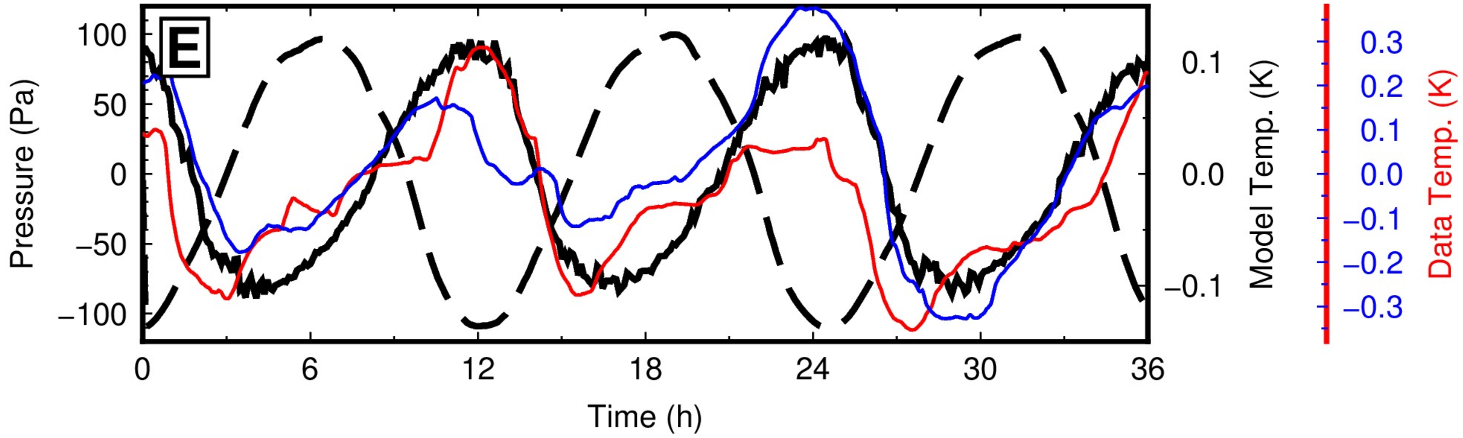


Sharp but weaker (0.1-0.4 K) fronts persist on subcritical slope in deep water, advected horizontally

Model by Kraig Winters and Mariona Claret







Temperature or strain?

✓ 1. Amplitude is too large to be strain
- 2 K (or 20 μ**ε**) similar to peak dynamic strain recorded <1 km from Ridgecrest EQ
- 2 K (or 20 μ**ε**) coherent over 10+ km => 20+ cm integrated displacement if strain
- Given steel strength element (E = 200 GPa), would require 20 MPa oscillating stress

✓ 2. Signal disappears when cable is buried
- OSGW pressure-induced strain observed ~1-100 n**ε** on buried cable segment
- Thermal diffusivity of geological materials is low, semidiurnal thermal skin depth is 10-50 cm

✓ 3. Temperature supported by modeling
- Internal tide amplitude, asymmetric shape, and up-slope propagating frontal velocity reproduced by temperature in an idealized model
- By contrast, pressure perturbations are smaller, symmetric, and much longer wavelength, dominated by pycnocline displacement and almost independent of the near-bottom flow

✓ 4. Change in cable type consistent with temperature
- From SA to LWP cable, frequency-dependent change in sensitivity fit with thermal model
- Difference in Young's modulus (steel/aluminum ~200 GPa to polypropylene ~2 GPa) would expect order of magnitude broadband change in extensional strain from same forcing

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Take-away #3:
Where subsea cables are unburied, DAS is sensitive to temperature fluctuations from internal waves and tides

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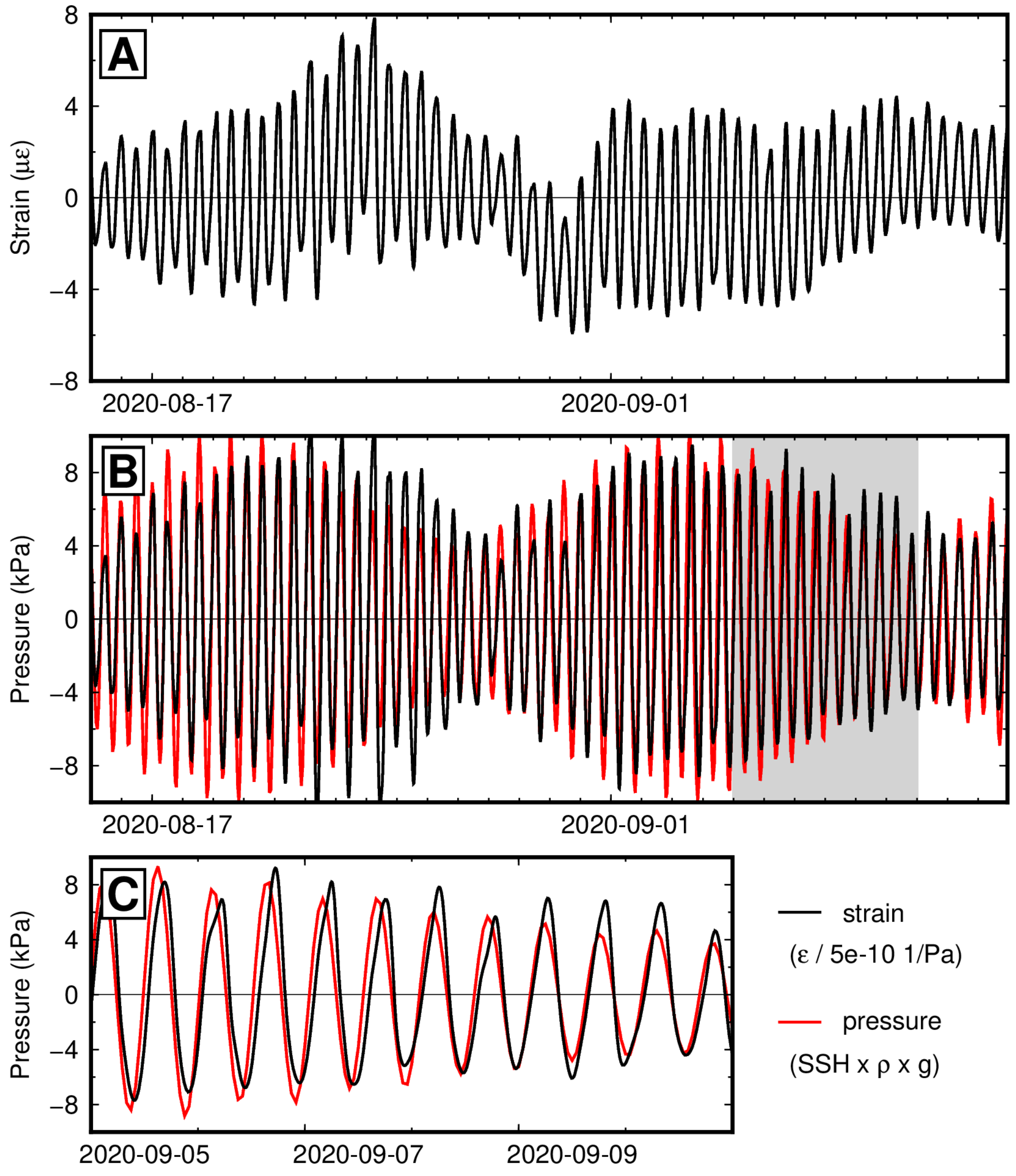
Hidden signature of the barotropic tide?

Spatially averaging over the slope results in a regular and symmetric tidal signal:

- Phase and amplitude match with prediction, including fortnightly lunar tide (M_f)
- Could be direct pressure loading of the cable (Poisson effect) or seafloor strain from ocean tidal loading (compliance)
- Apparent sensitivity ~5×10^{-10} strain/Pa ?



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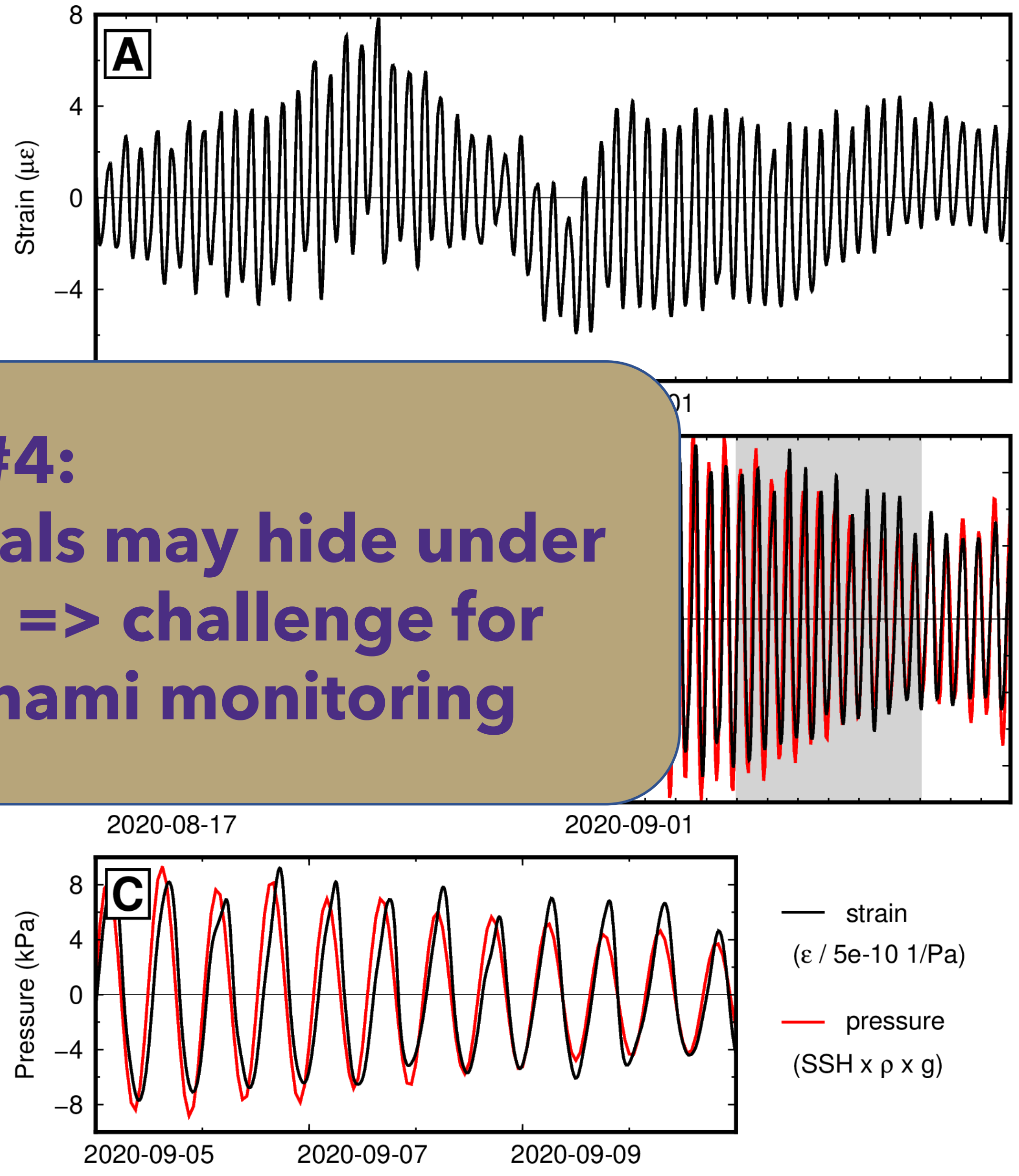
Take-away #4:
Weak mechanical strain signals may hide under larger temperature signals => challenge for seafloor geodesy and tsunami monitoring



Conclusion: Broad scope of applications for DAS in oceanography

Take-aways:

1. DAS is sensitive to wave amplitude and statistics, similar to a conventional wave buoy
2. DAS can measure water depth and flow speed (in shallow water) because ocean surface wave observations are coherent and phase-resolved
3. Where subsea cables are unburied, DAS is sensitive to temperature fluctuations from internal waves and tides
4. Weak mechanical strain signals may hide under larger temperature signals => challenge for seafloor geodesy and tsunami monitoring