Enhancing Climate Resilience with Distributed Acoustic Sensing (DAS): from Land to the Sea

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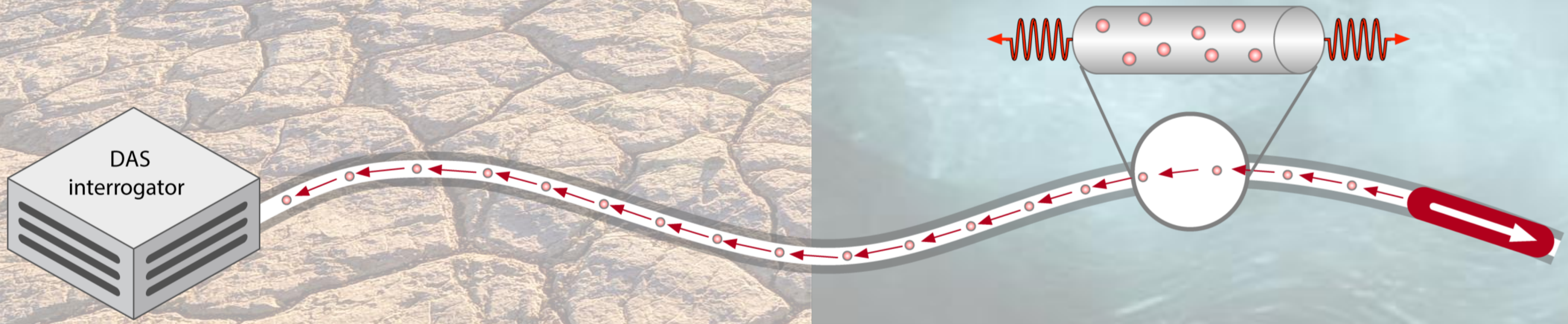


Seminar @ National Central University, 12/04/2025

Water is all around us in all its forms

A vital and strategic resource for sustaining life on Earth

Atmosphere

Ocean

Lake

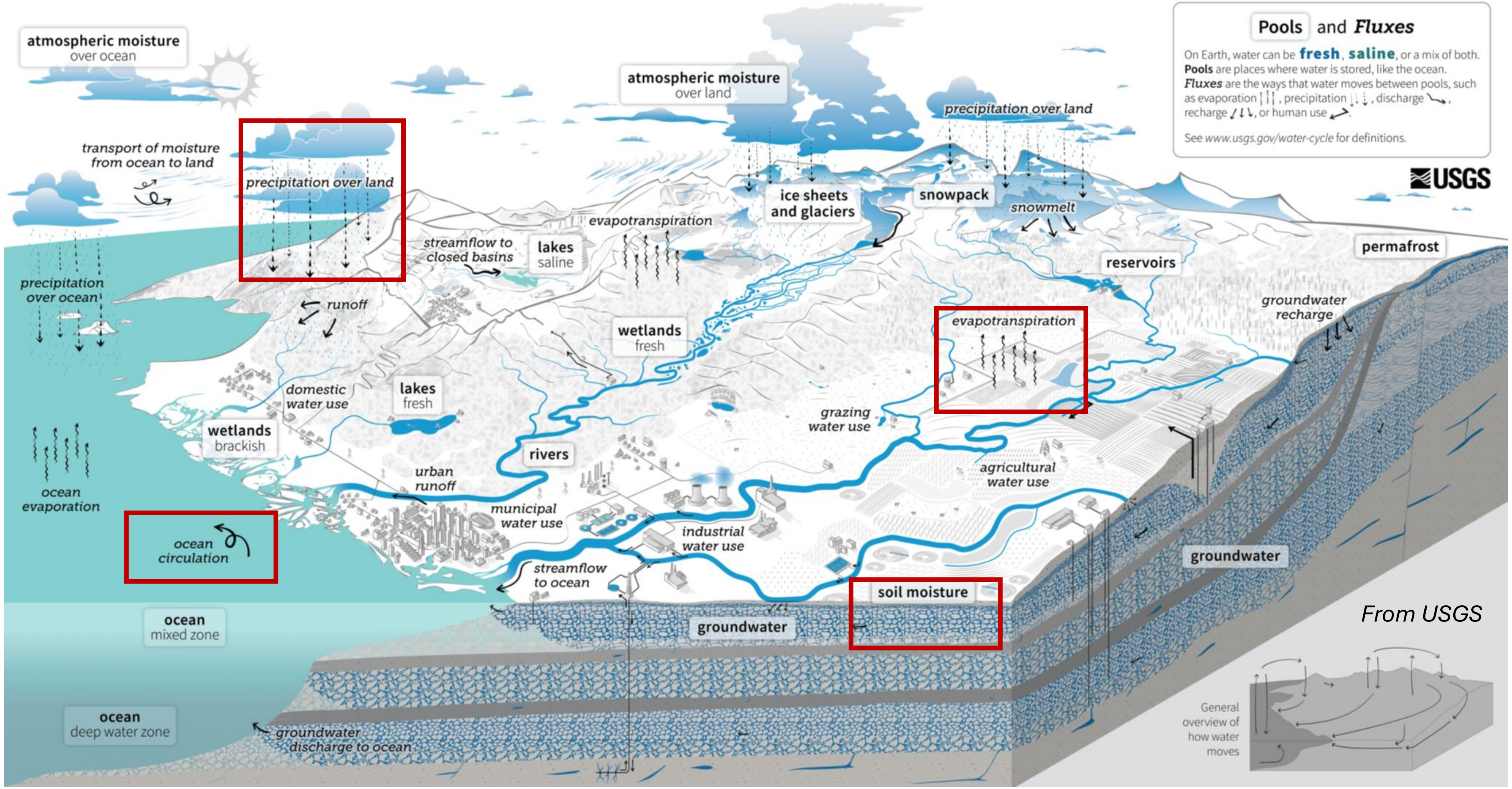
River

Stream

Glacier

The water cycle

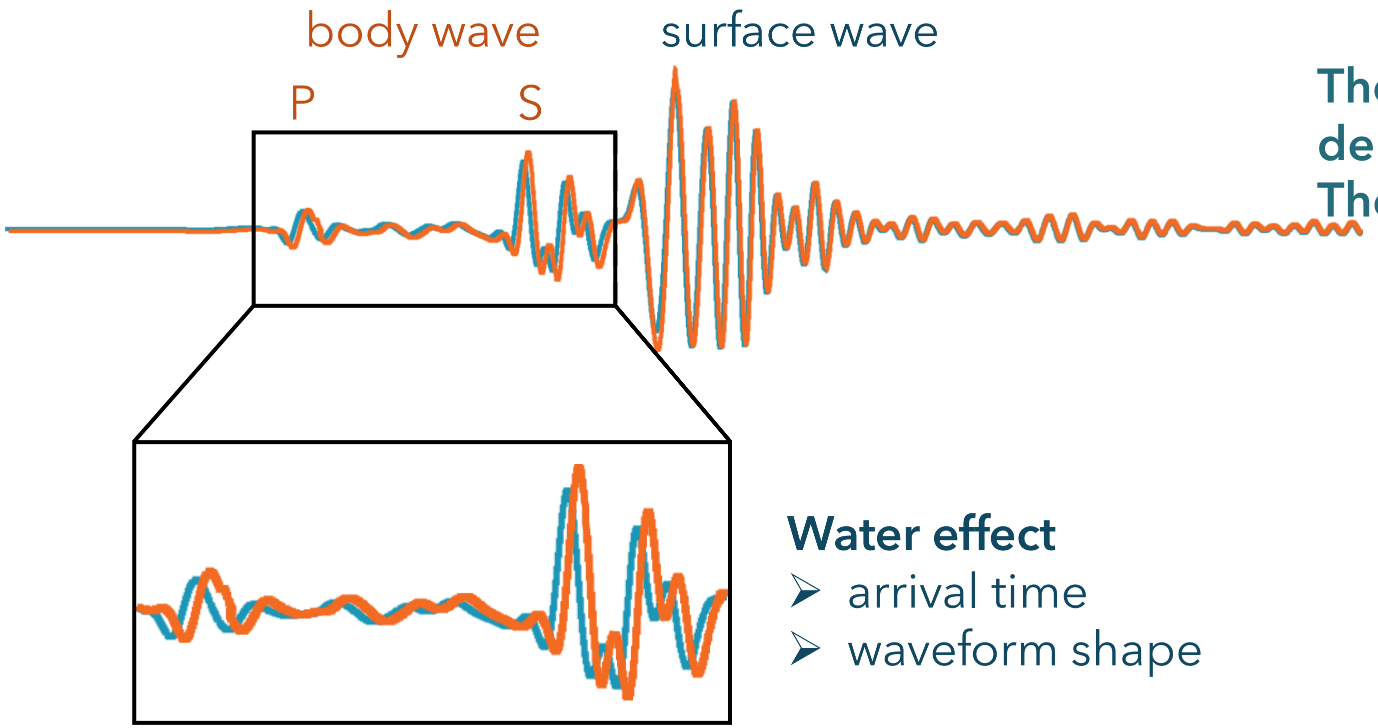
In the face of climate variability, quantifying the responses of Earth's water cycle across time and space is crucial for the sustainable management of water resources.



From USGS

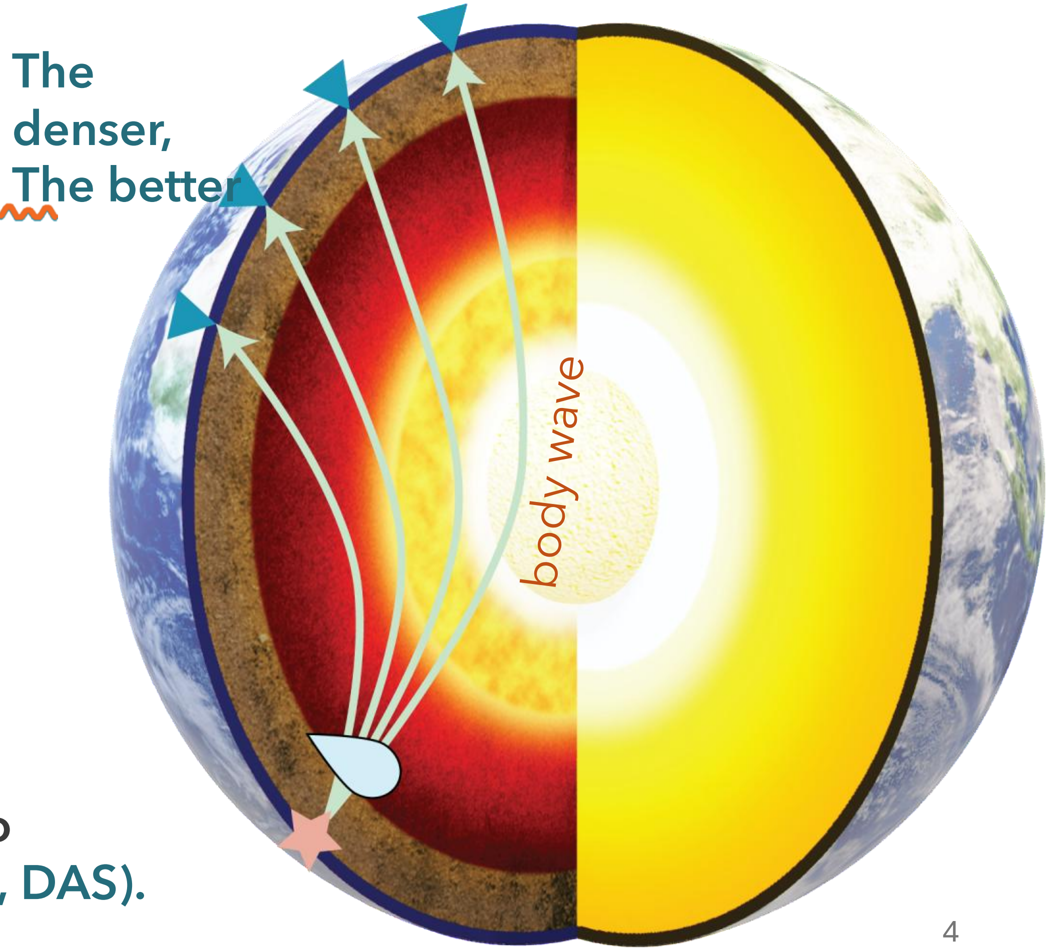
Seismology: a powerful water-sensing tool

Provide water signatures of the regions it samples, particularly the long- & short-term behavior of the water cycle in the subsurface and ocean.



Water effect

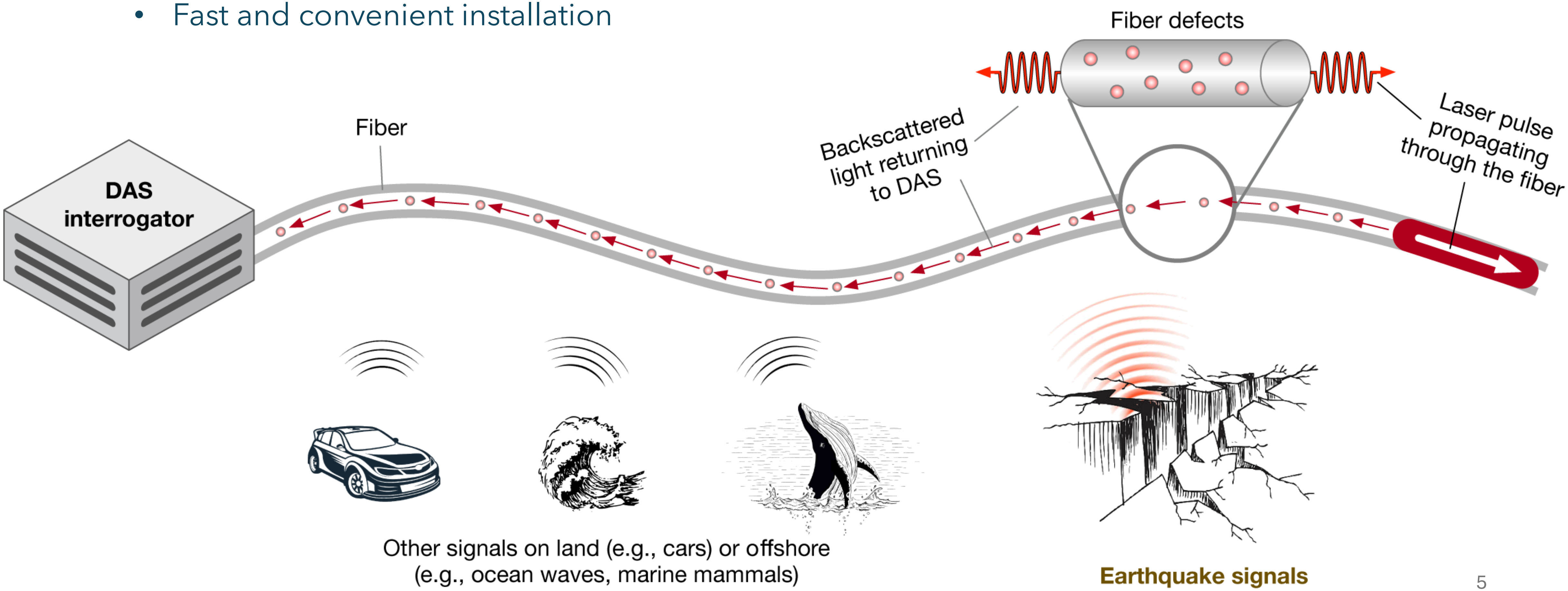
- ➢ arrival time
- ➢ waveform shape



Enhancing and exploiting the subtle waveform signatures to characterize water reservoirs with dense seismic arrays (e.g., DAS).

Distributed Acoustic Sensing (DAS)

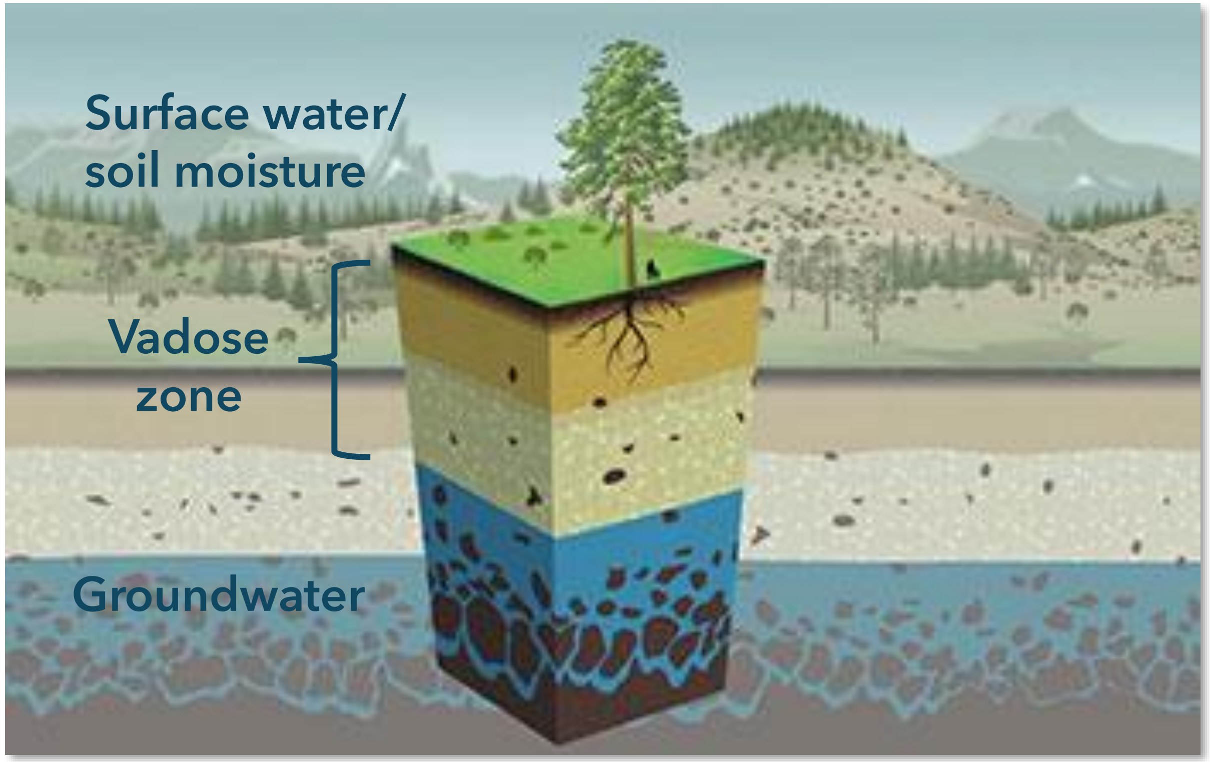
- Ultra dense spacing (meter-scale)
- Large aperture (~100 km long)
- Fast and convenient installation



Part I. DAS for vadose zone hydrology

Function as a backup water reservoir in semiarid regions, thus crucial for strengthening the resilience of our ecological and agricultural systems.

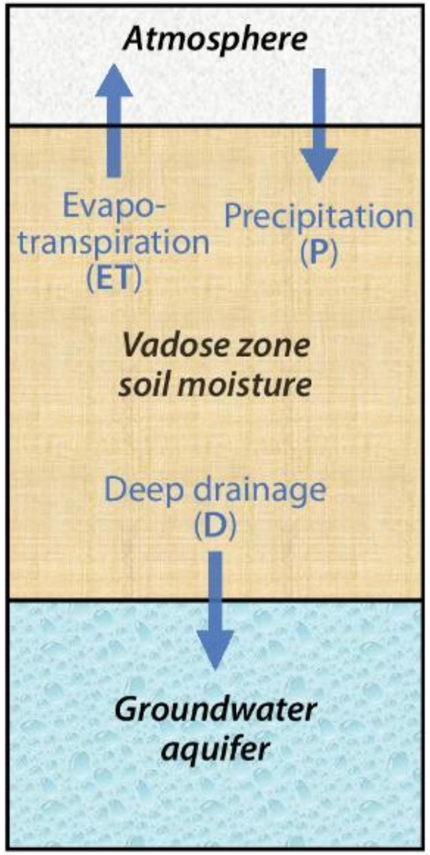
Critical Zone



https://www.nsf.gov/news/special_reports/announcements/090120.04.jsp

Observational bottleneck for vadose zone

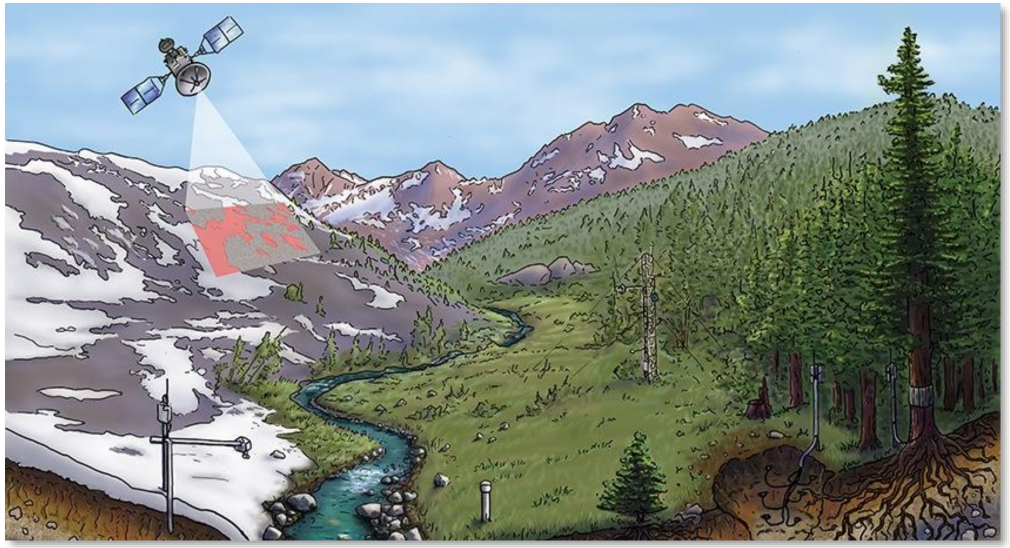
The inability to observe vadose zone soil moisture at large spatiotemporal scales hinders quantitative characterization of vadose zone water dynamics in face of climate variability.



Shen et al., 2024

Challenging to quantify the long-term, large-scale vadose zone soil moisture dynamics at depth.

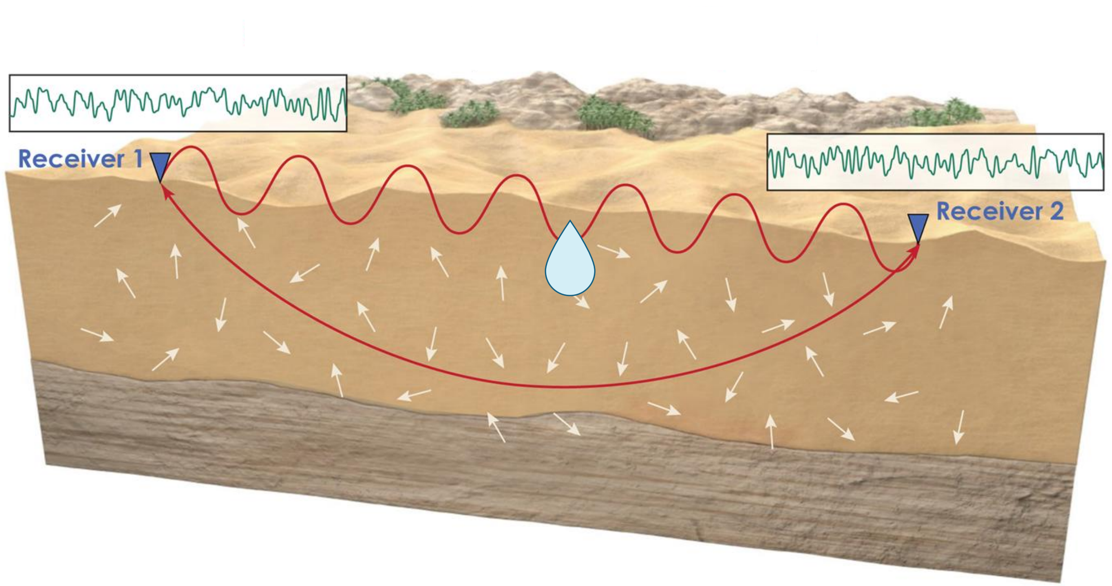
- **Satellite-based tools**
  - SMAP/SMOS
  - GNSS-based techniques
  - Gravimetric measurements
- **Ground-based tools**
  - *In-situ lysimeters*
  - *Cosmic-ray neutron sensors*
  - *Ground penetrating radar*
  - *Time domain reflectometry*
  - *Electromagnetics et al.*

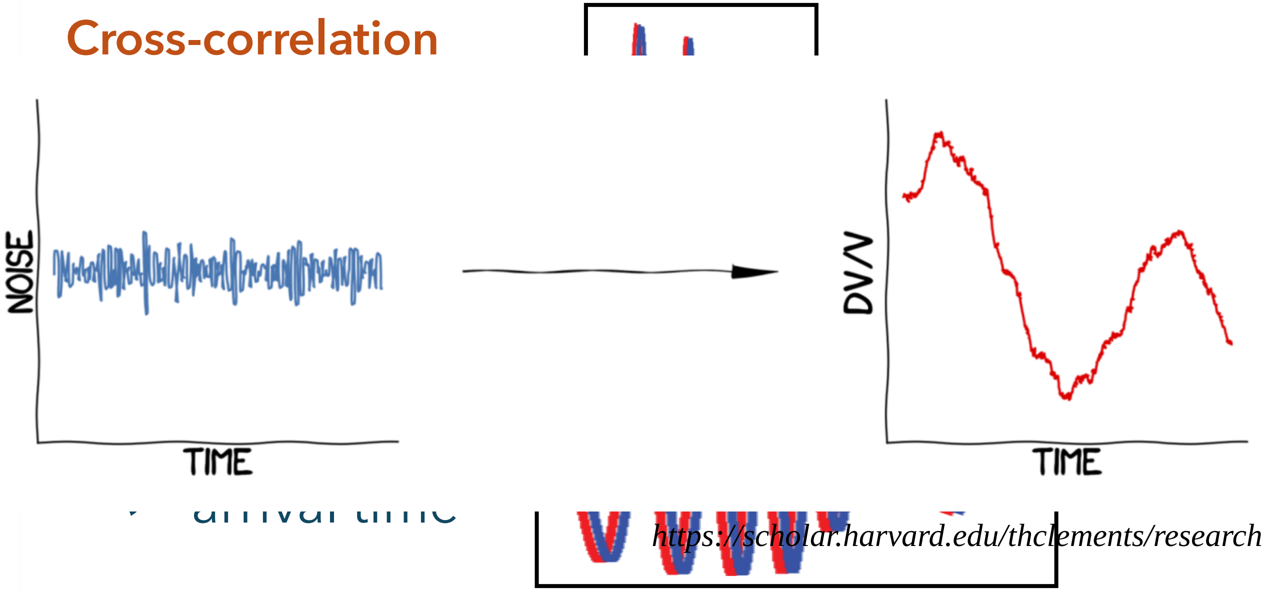


https://www.nsf.gov/news/newsmedia/ENV-discoveries/CZO-discovery-series.jsp

Time-lapse seismology

Water content change perturbs seismic velocity, thus can be inferred by repeatedly measuring the arrival time variation of surface waves propagating between two stations on a regular basis.





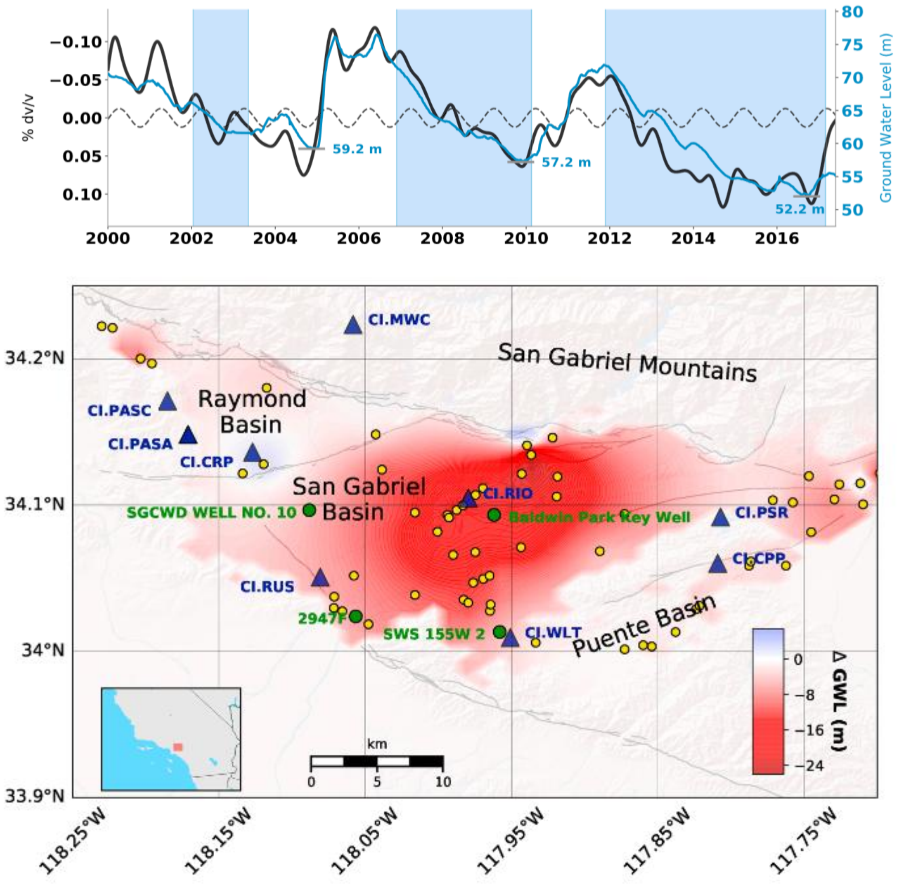
https://scholar.harvard.edu/thclements/research

Seismic velocity changes (dv/v) ⟷ water content

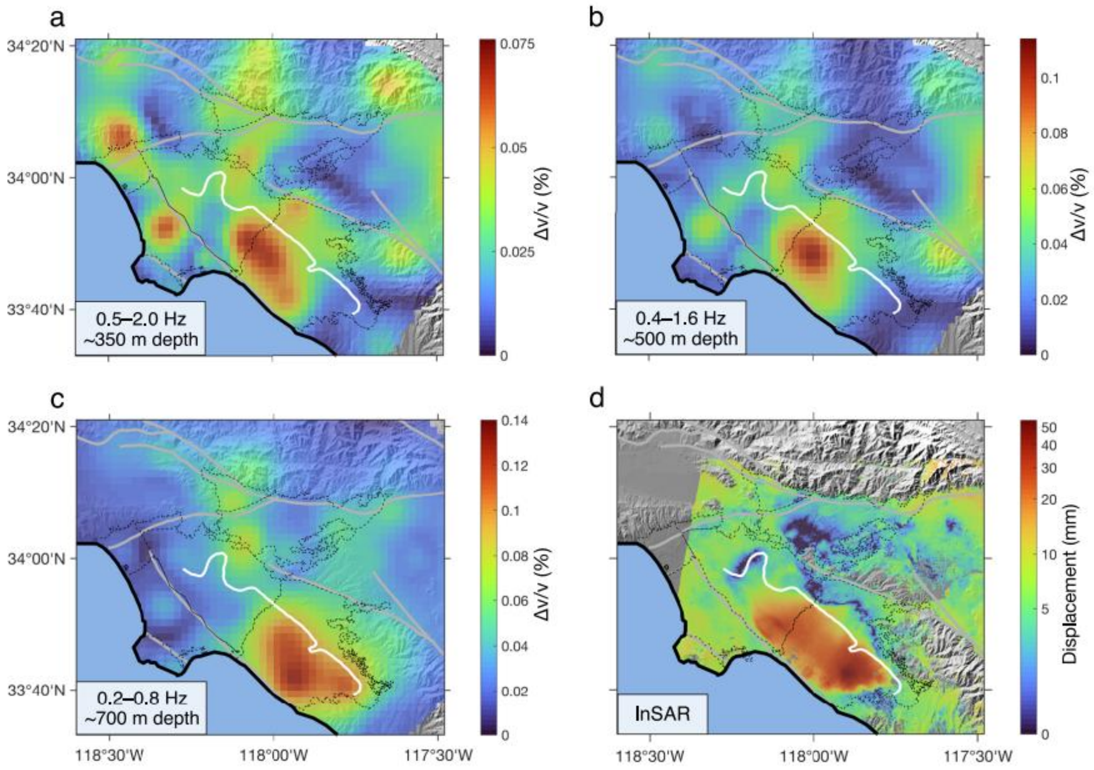
- temporal resolution
- depth sensitivity

Shown promise in groundwater studies

Limited by the conventional seismic network spacing, time-lapse seismology can only probe water at depths of hundreds of meters, not shallow enough for vadose zone soil moisture.



Clements & Denolle, 2018



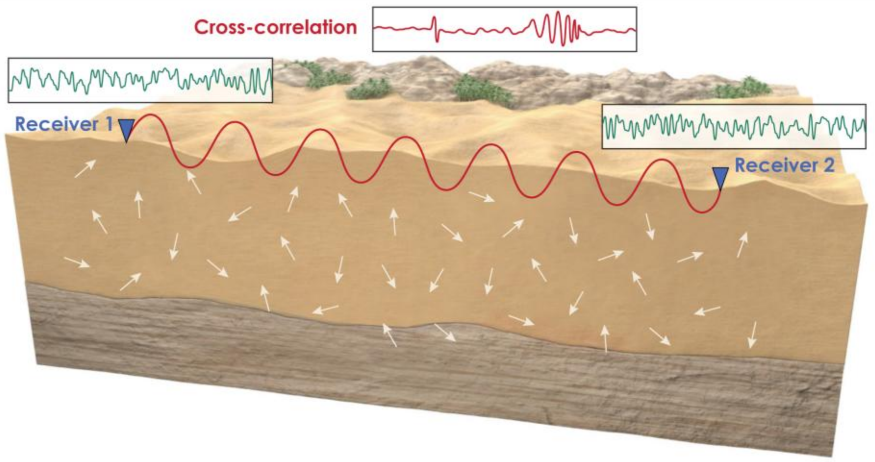
Mao et al., 2021

Fiber-optic seismic sensing principle

The meter-scale channel spacing of DAS enables to fill in the observational gap for vadose zone.

Continuous DAS data ➡ Shallow seismic velocity change (dv/v) ➡ Vadose zone soil moisture change

Time-lapse seismology



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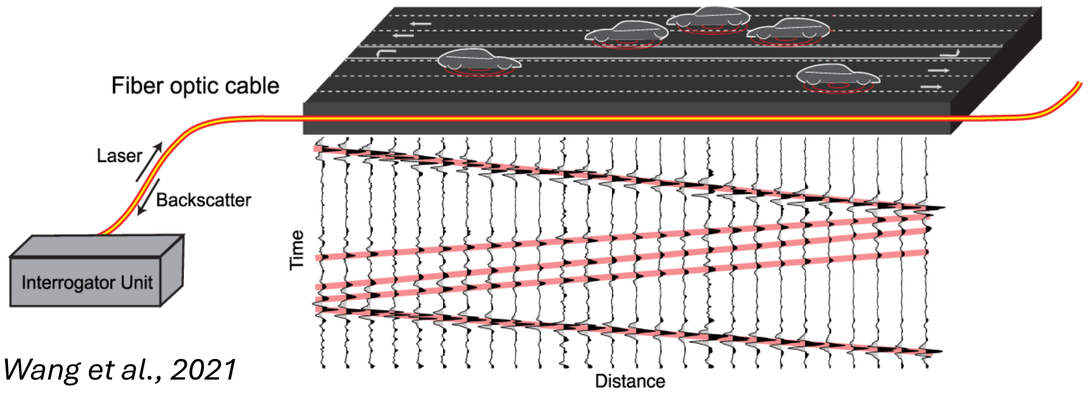
Filling the gap: DAS



Wang et al., 2021

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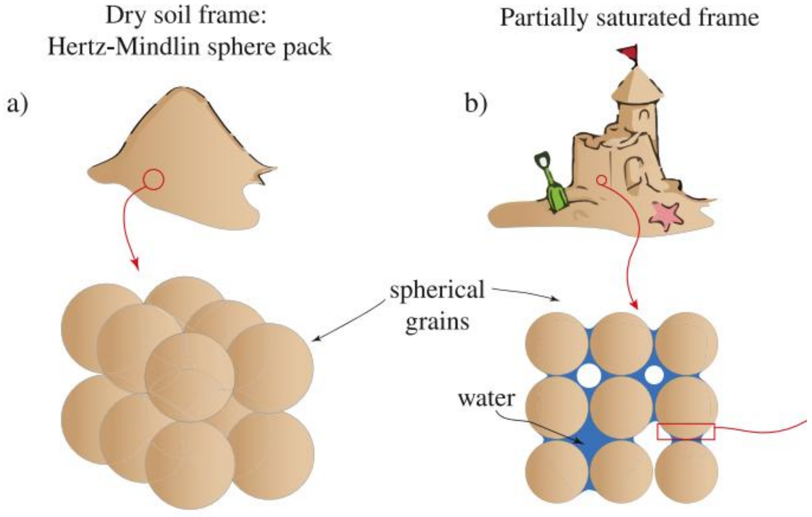
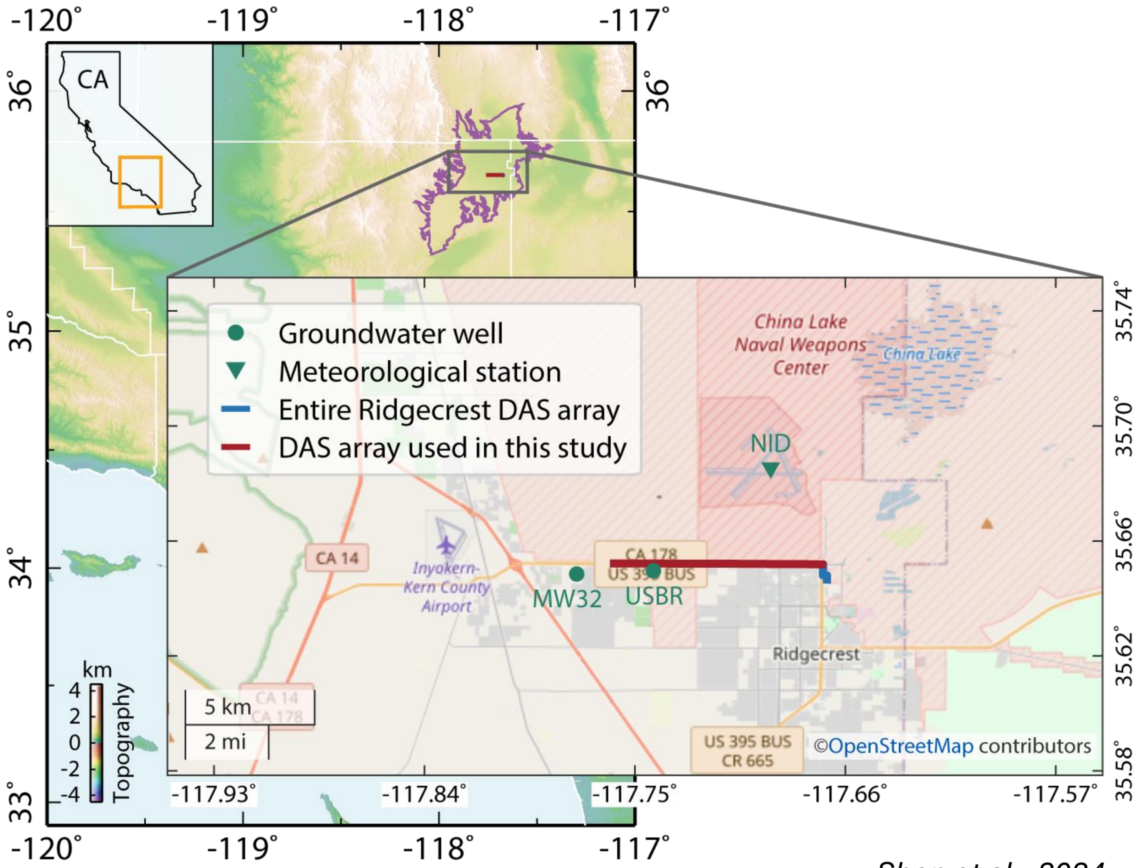
Rock physics

Mapping observed dv/v to vadose zone soil moisture changes



Solazzi et al., 2021

Study region: Ridgecrest (DAS array), CA



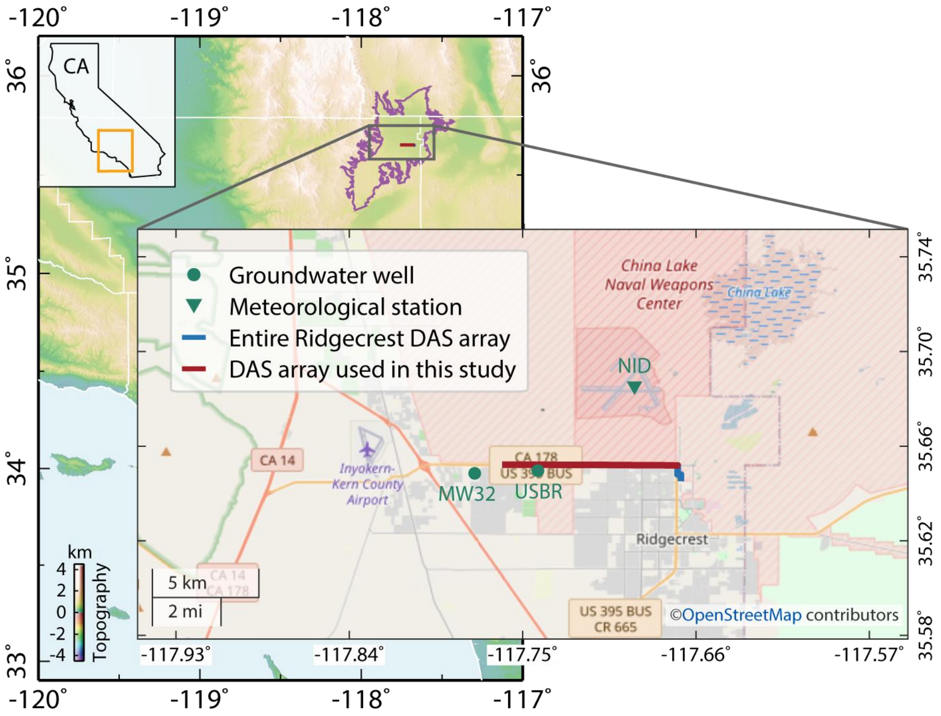
Shen et al., 2024

Ridgecrest DAS array

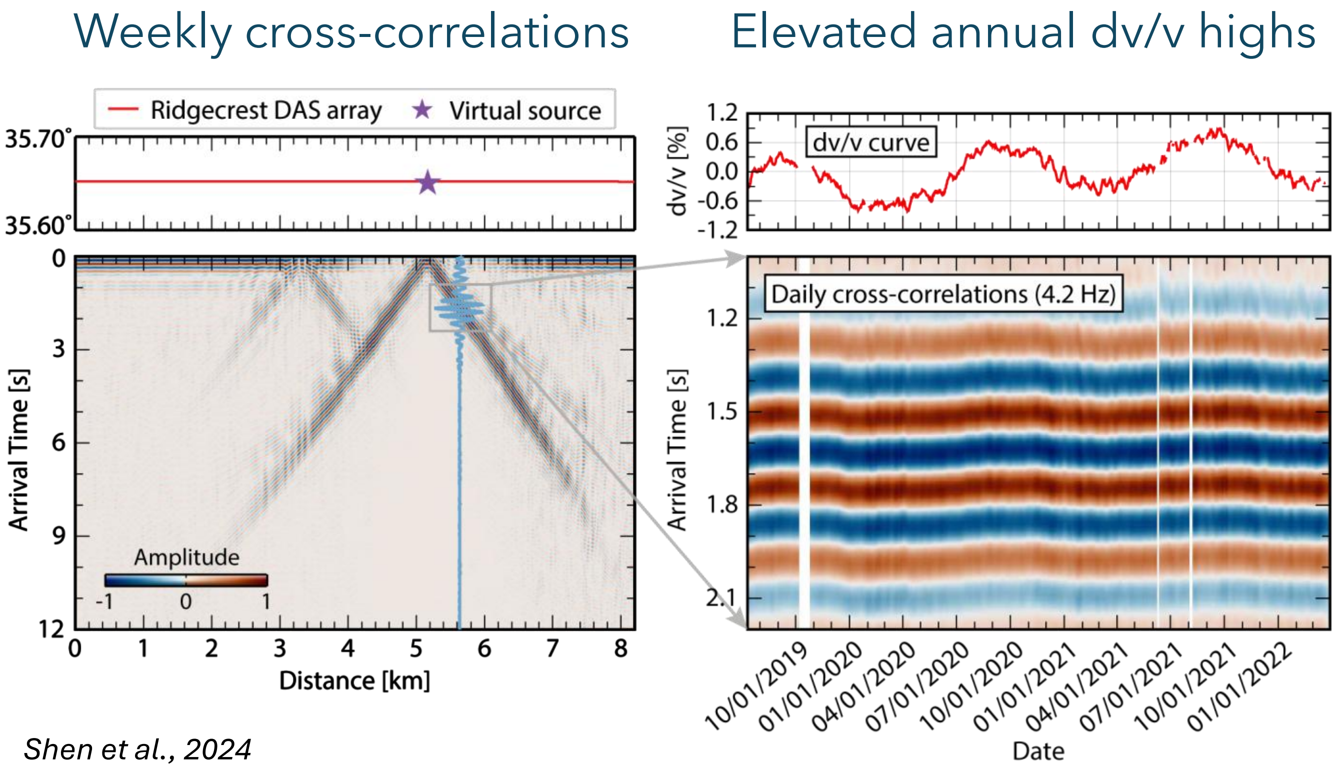
- North of the Mojave desert
- 10-km long with 8-m spacing
- Continuous acquisition since July 2019
- ~80 TB data (2019.07 – 2022.03)

Here, groundwater has been critically overdrawn to meet agricultural and municipal demand, but the impact of drought on water stored in the vadose zone soil is unclear.

Fiber-optic seismic sensing on Ridgecrest DAS

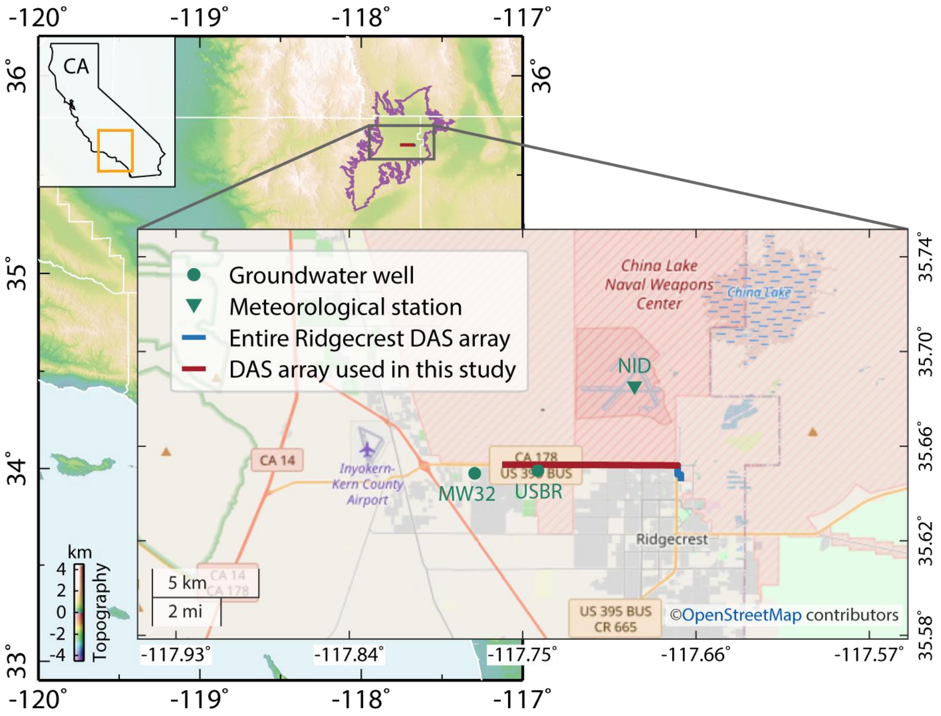


Example of time-lapse seismology on one DAS channel pair

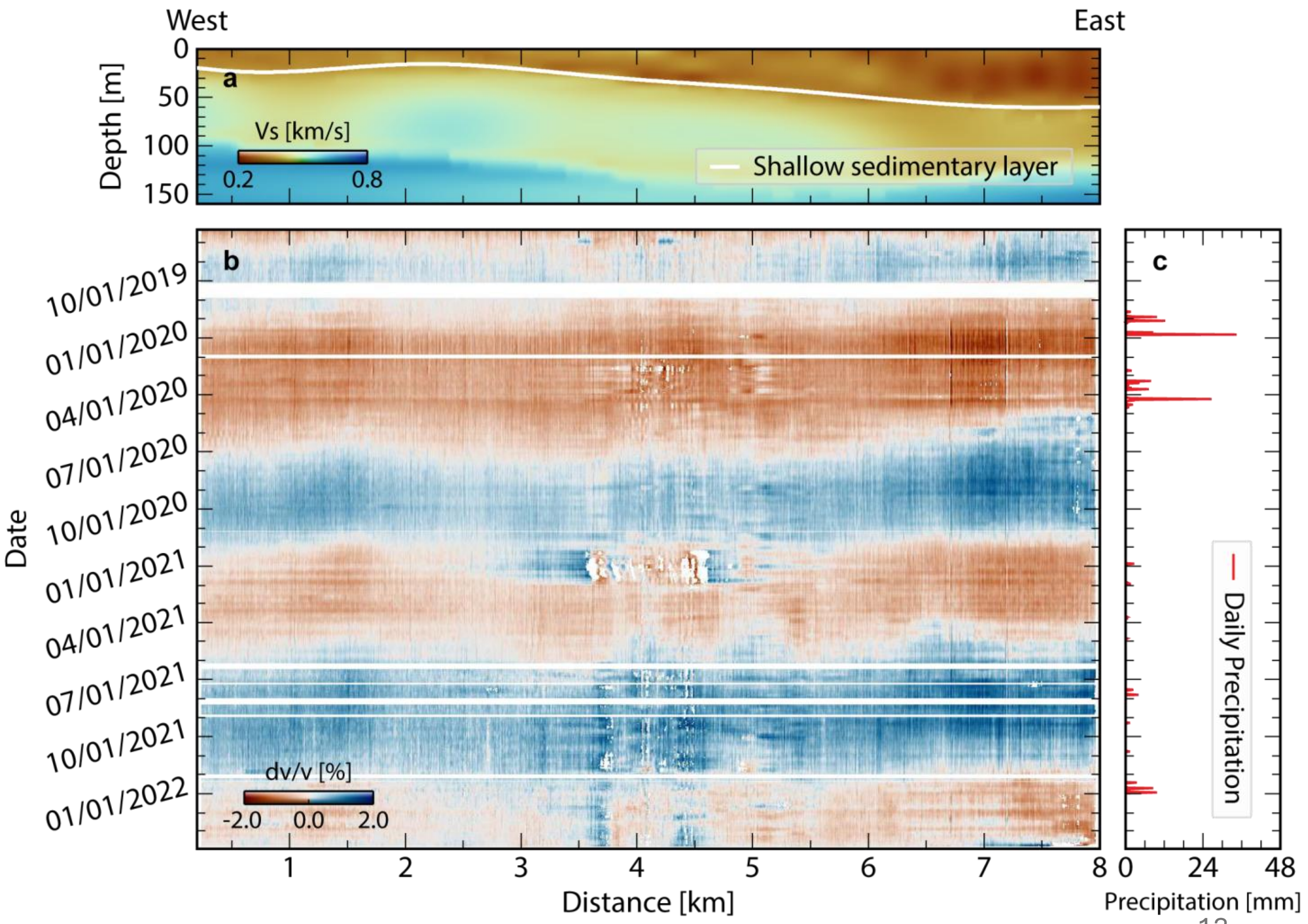


Shen et al., 2024

Observation of vadose zone soil moisture dynamics



Space-time view of seismic velocity change (dv/v)



Shen et al., 2024

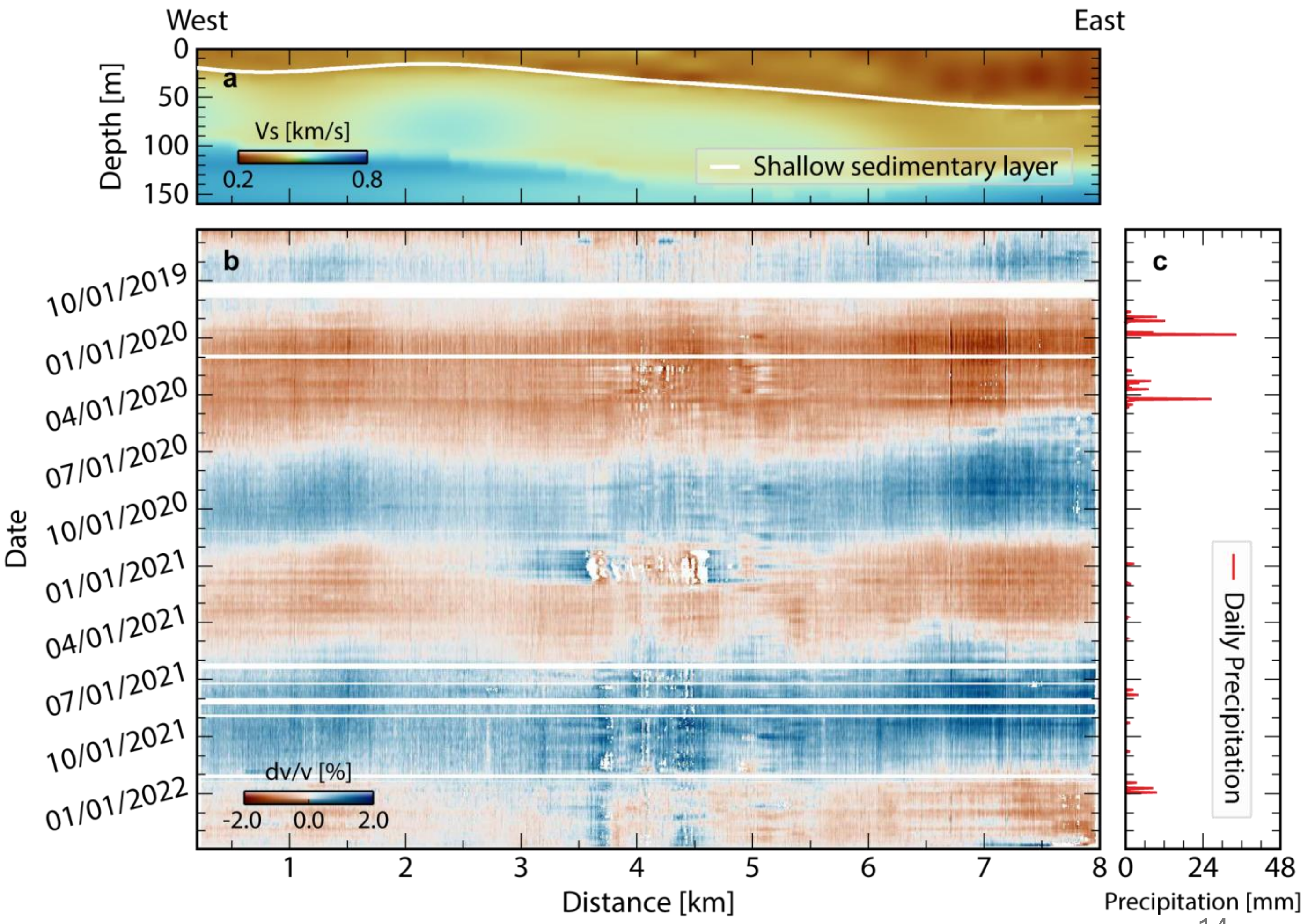
Observation of vadose zone soil moisture dynamics

Spatial dimension

- *dv/v amplitudes strikingly correlate with shallow sedimentary thickness*

How about other frequencies?

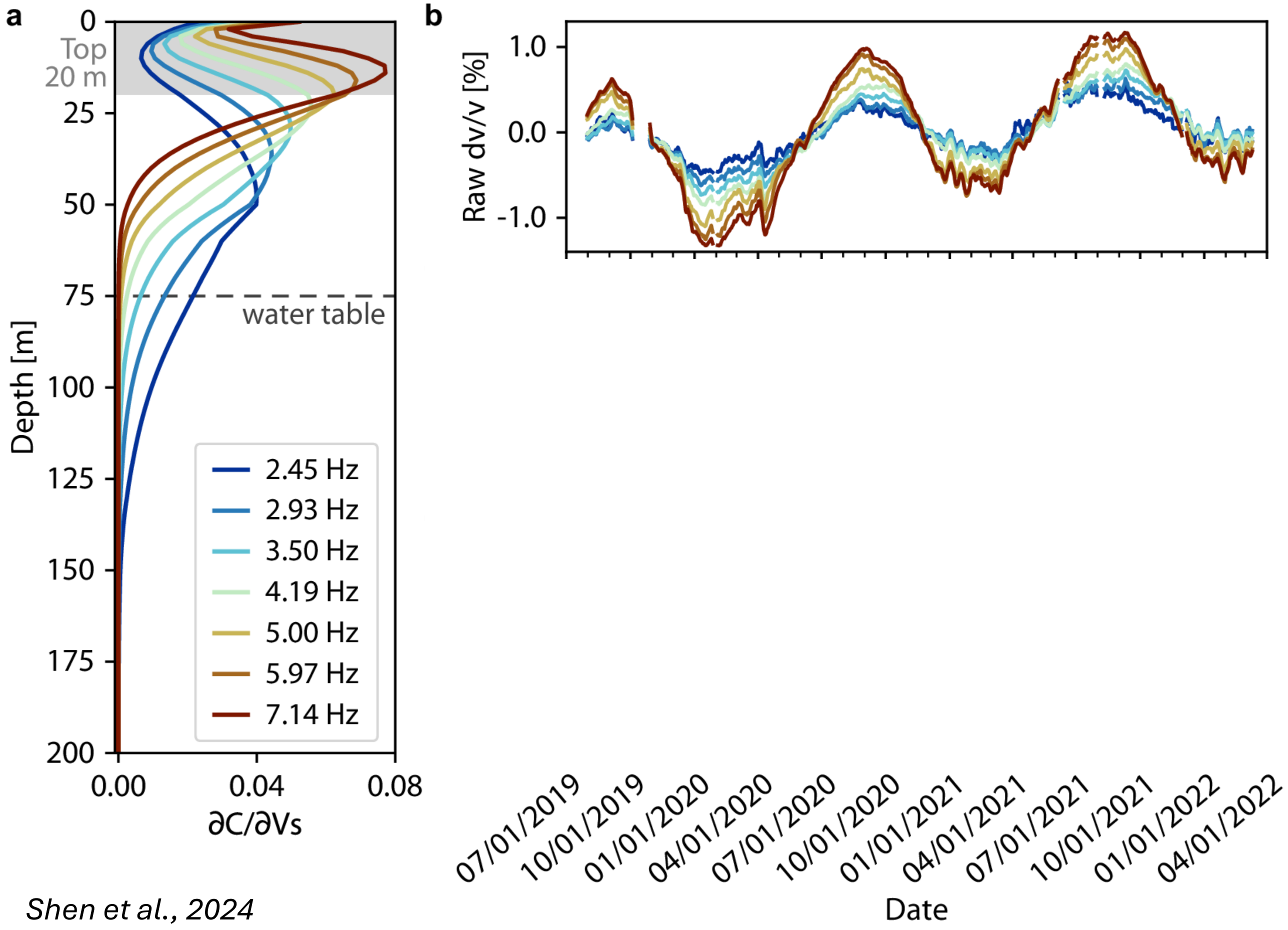
Space-time view of seismic velocity change (dv/v)



Shen et al., 2024

Observation of vadose zone soil moisture dynamics

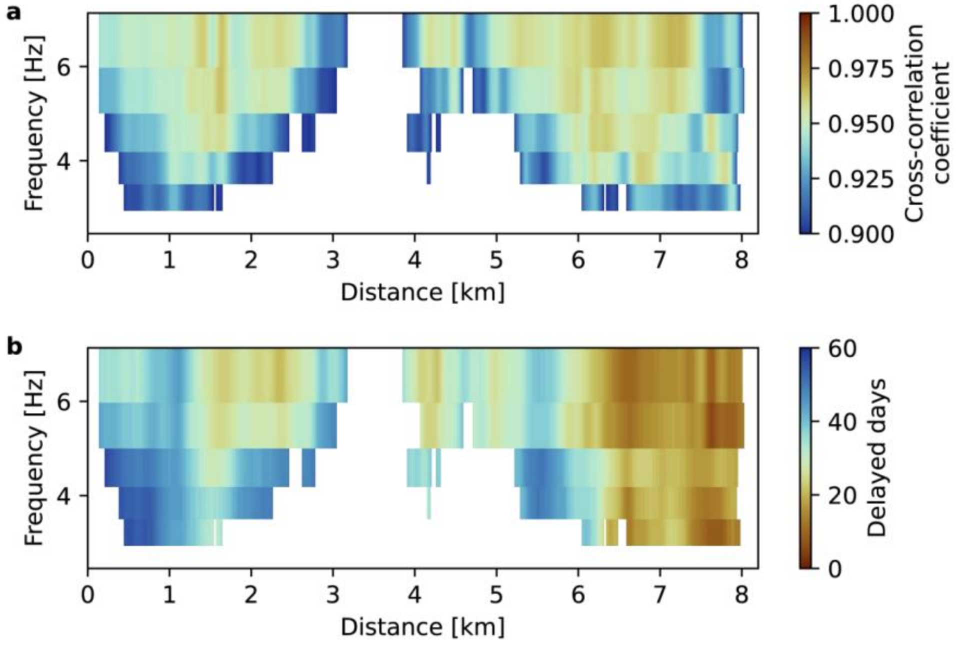
Multi-frequency analysis of dv/v observations suggests a primary dv/v contribution from the top 20 m



Shen et al., 2024

Removing seasonal thermoelastic effects

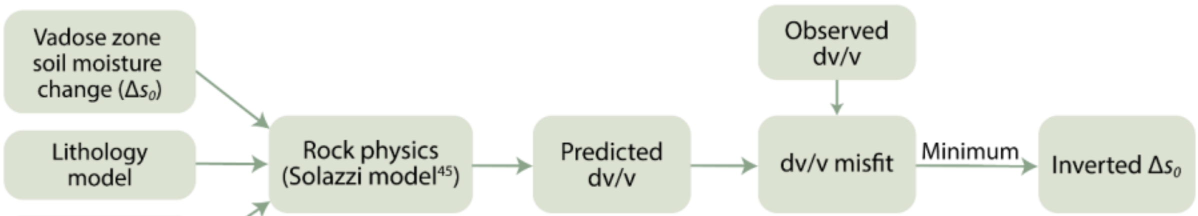
$$\left(\frac{dv}{v}\right)_{\text{thermo}} = a\delta T(t-\tau)$$



Averaged thermal diffusivity: 1.49×10^{-6} m^2/s

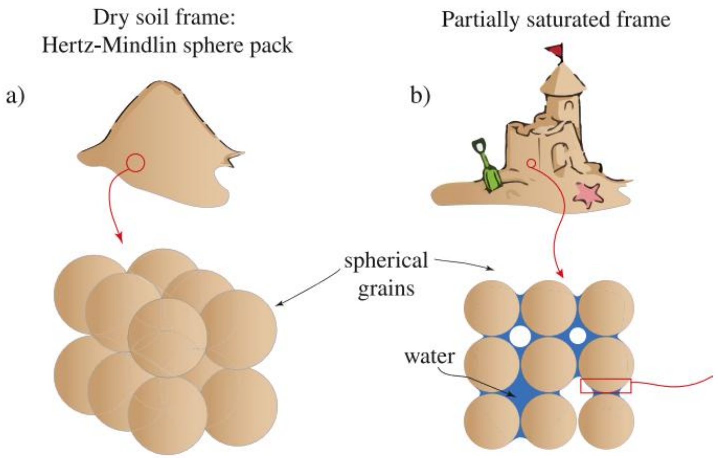
Quantification of vadose zone soil moisture dynamics

Input



$$\mathbf{V}_{P,j} = \sqrt{\frac{\mathbf{K}_j + \frac{4}{3}\boldsymbol{\mu}_j}{\boldsymbol{\rho}_j}}; \mathbf{V}_{S,j} = \sqrt{\frac{\boldsymbol{\mu}_j}{\boldsymbol{\rho}_j}}$$

Rock physics (Solazzi model):



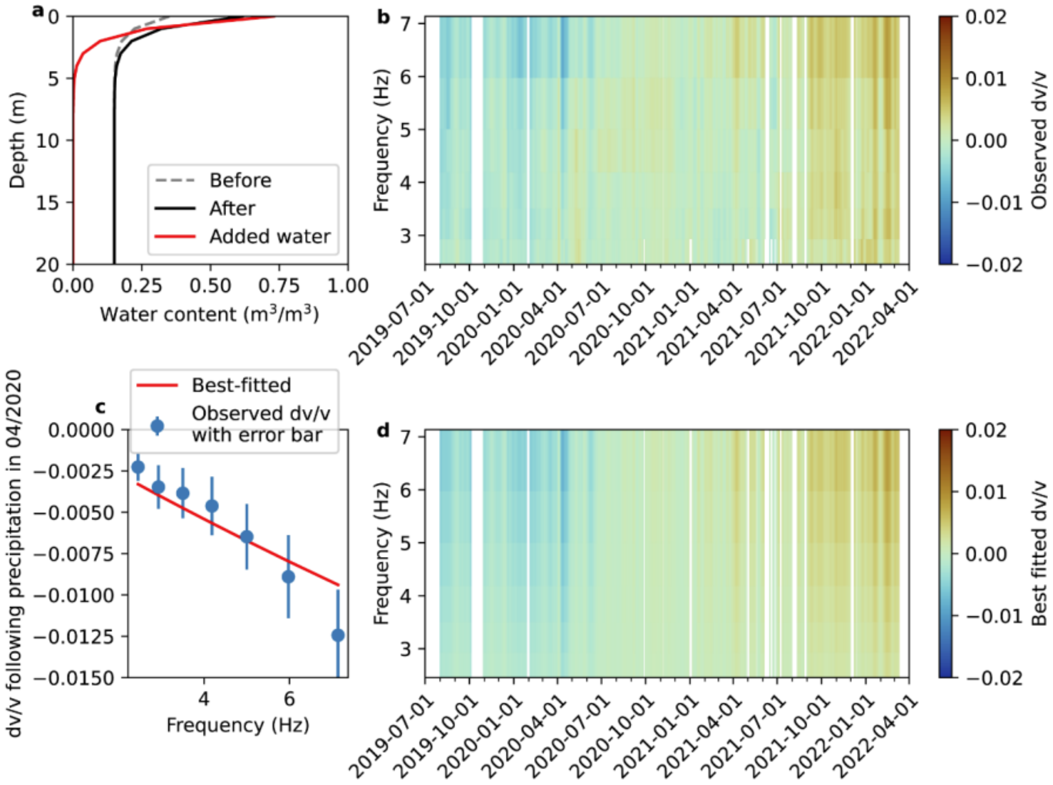
Hertz-Mindlin theory

$$\mathbf{K}_{d,j} = \left[\frac{N^2\left(1-\boldsymbol{\phi}_j\right)^2 \boldsymbol{\mu}_{Se,j}^2}{18\pi^2\left(1-\boldsymbol{\nu}_{Se,j}\right)^2}\mathbf{P}_{e,j}\right]^{\frac{1}{3}}$$

$$\boldsymbol{\mu}_{d,j} = \frac{2+3f-(1+3f)\boldsymbol{\nu}_{Se,j}}{5(2-\boldsymbol{\nu}_{Se,j})}\left[\frac{3N^2(1-\boldsymbol{\phi}_j)^2\boldsymbol{\mu}_{Se,j}^2}{2\pi^2(1-\boldsymbol{\nu}_{Se,j})^2}\mathbf{P}_{e,j}\right]^{\frac{1}{3}}$$

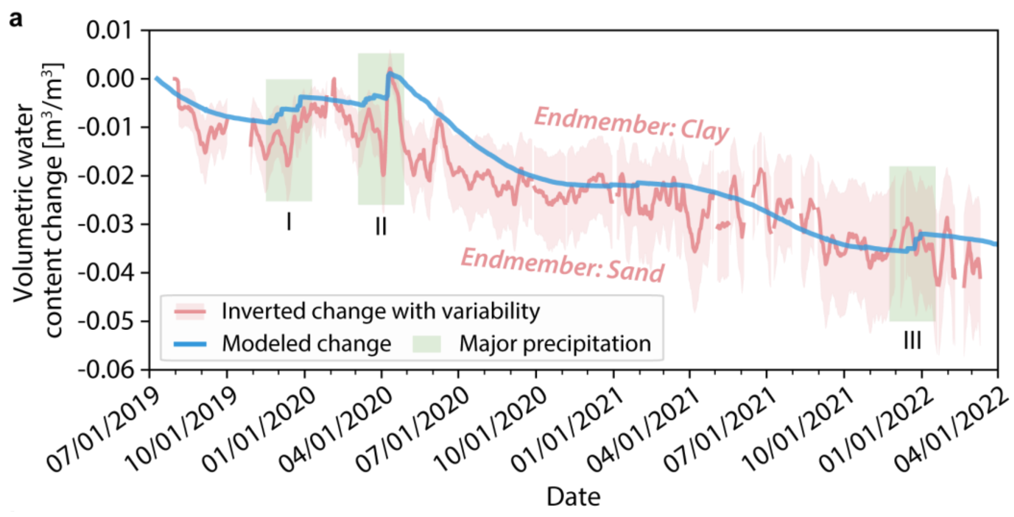
Solazzi et al., 2021

$$\Delta \mathbf{s}(z) = \Delta s_0 e^{-\frac{z}{\lambda}}$$

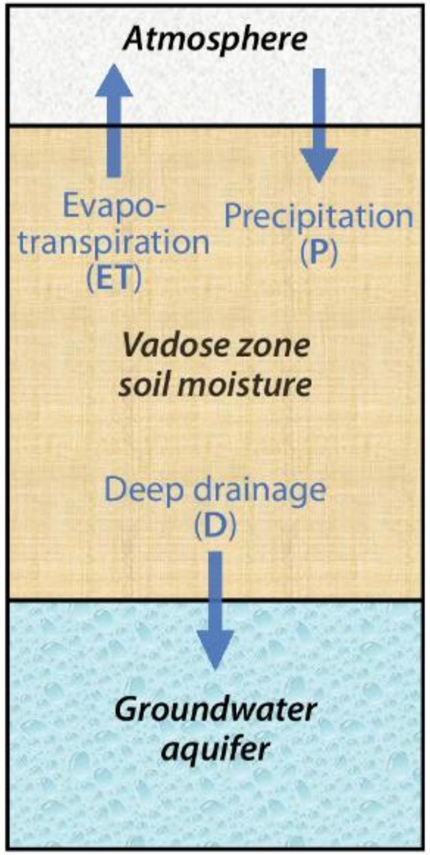


Shen et al., 2024

Long-term vadose zone soil moisture loss



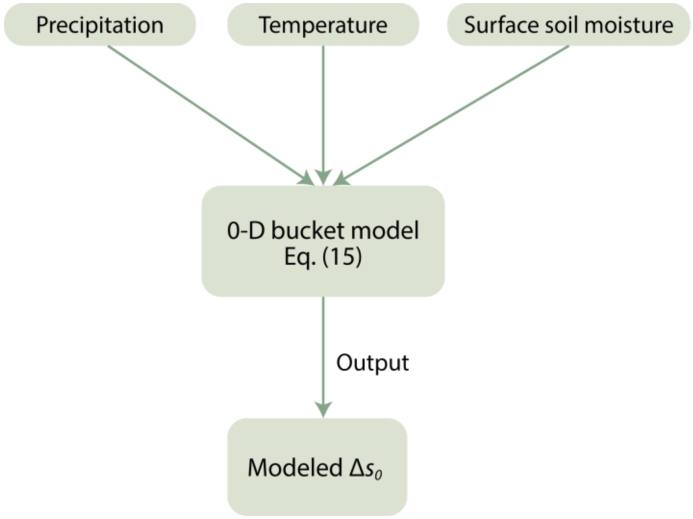
Validation I. 0-D hydrological modeling



Water balance

$$\Delta z\left(\theta_{fc} - \theta_w\right)\frac{ds}{dt} = \mathbf{P}(t) - \mathbf{E}(s,t) - \mathbf{Q}(s,t)$$

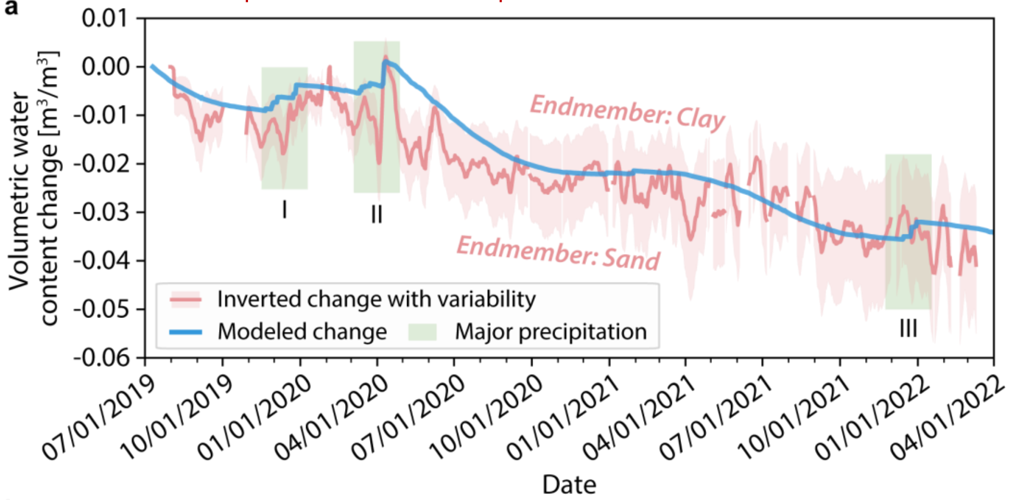
Input data from SMAP



Shen et al., 2024

Long-term vadose zone soil moisture loss

Still, quantitative discrepancies still exist in finer details.

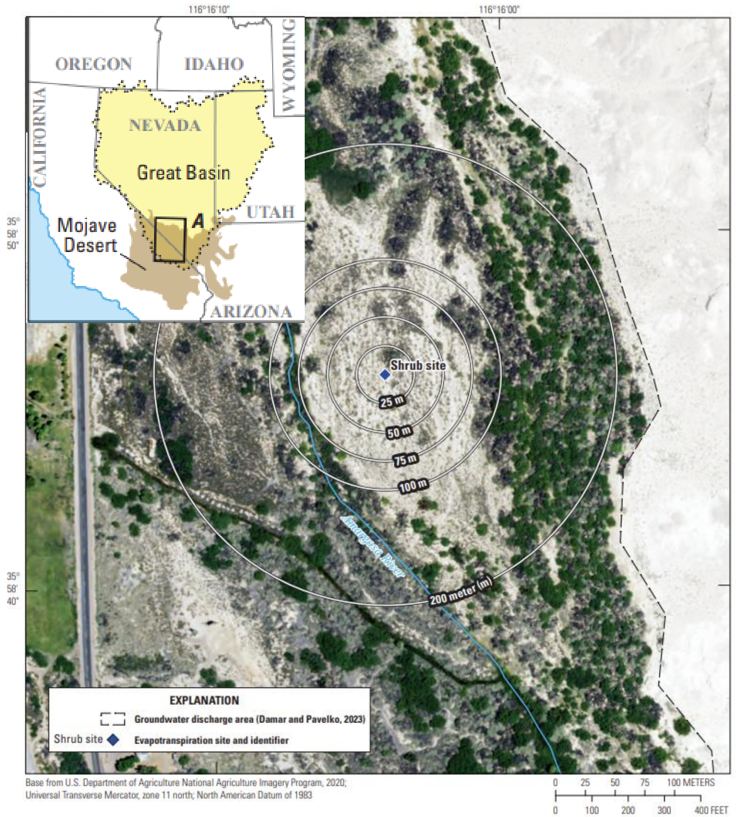


Shen et al., 2024

Extrapolating annual water loss to entire Mojave desert: equivalent to a Hoover Dam

Validation II.
Eddy-covariance based measurements

Annual ET rate: 0.25 m/yr (ours) vs. 0.2 m/yr (data)



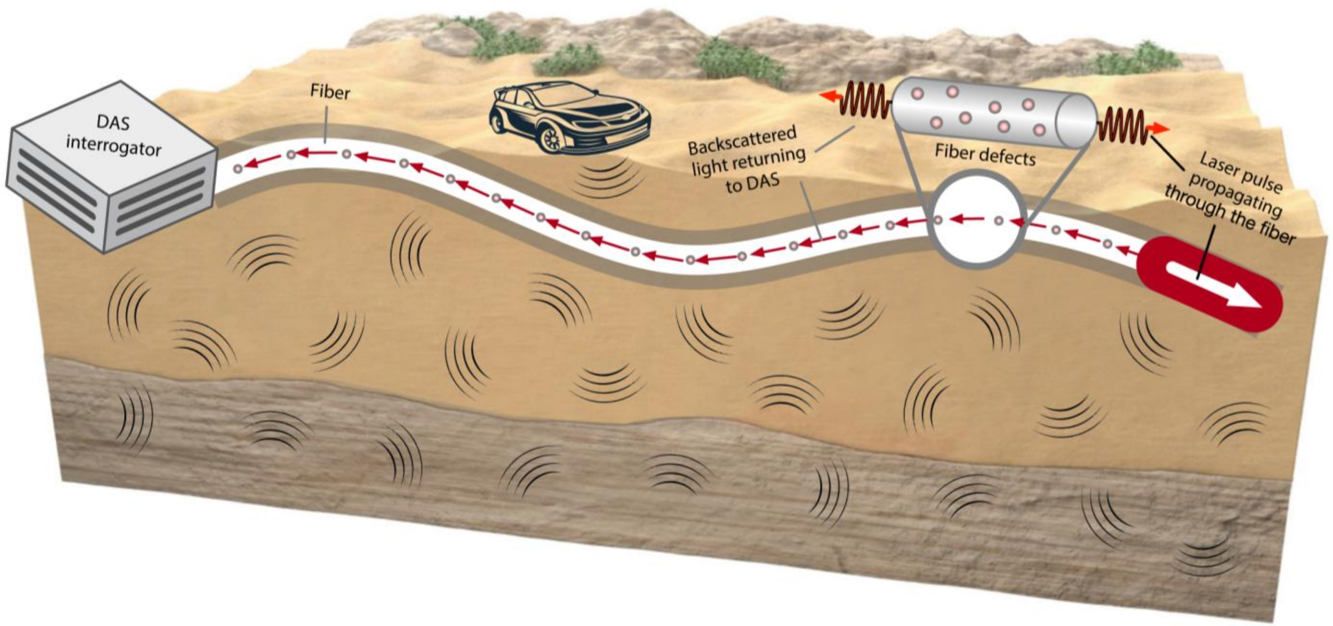
Photograph by Michael T. Pavelko, U.S. Geological Survey (May 23, 2017)

Photograph by Michael T. Pavelko, U.S. Geological Survey (May 23, 2017)

Pavelko et al., 2023

Part I. Summary

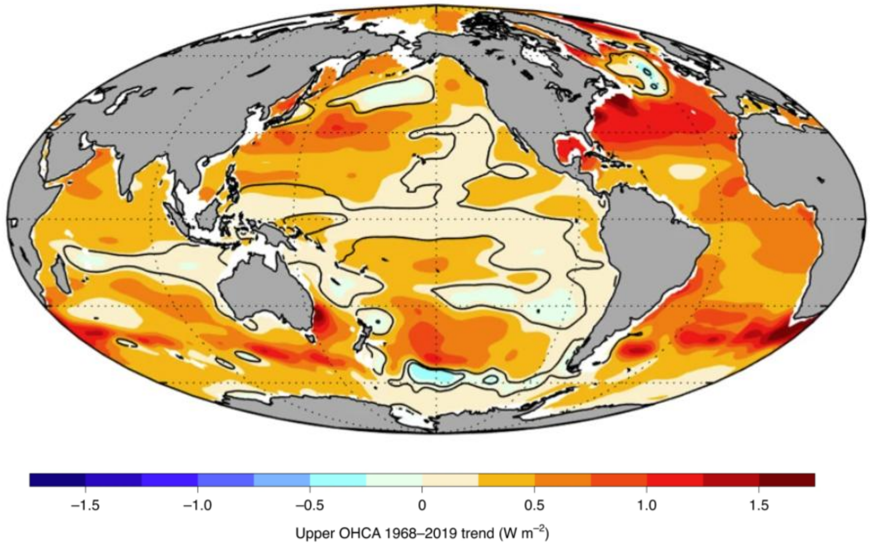
- With Ridgecrest DAS array, we demonstrate that fiber-optic seismic sensing can robustly capture the response of vadose zone soil moisture to episodic precipitation and long-term droughts.
- Our results highlight the promise of DAS as a large-scale, long-term, and cost-effective observational tool to enhance our climate resilience in semi-arid regions.



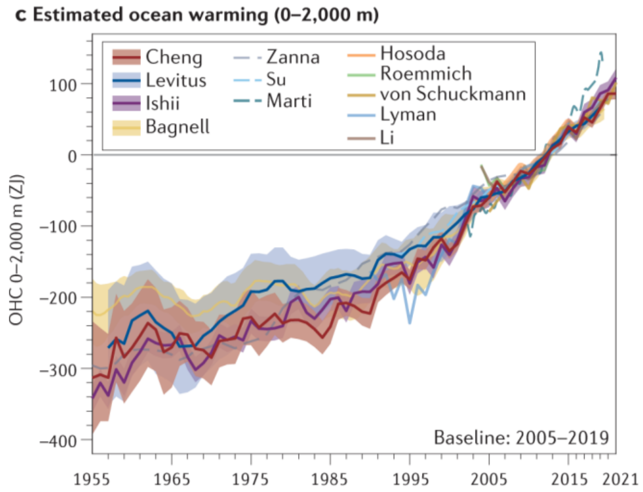
Part II. DAS for ocean temperature changes

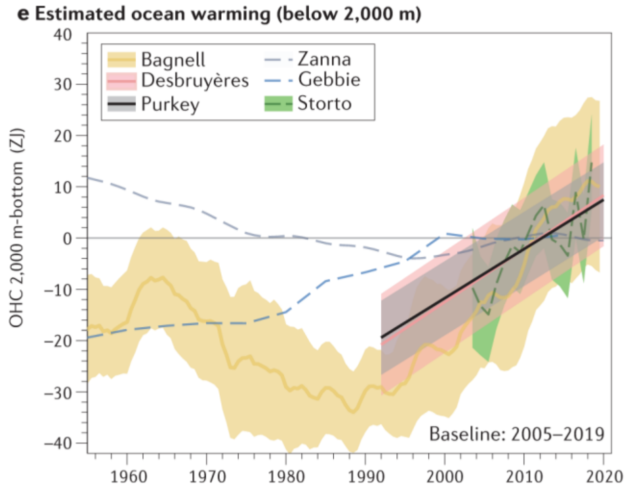
The ocean absorbs >90% of the global warming heat due to green gases, but accurate estimate of global ocean temperature is challenging.

Warming trend dominates global ocean



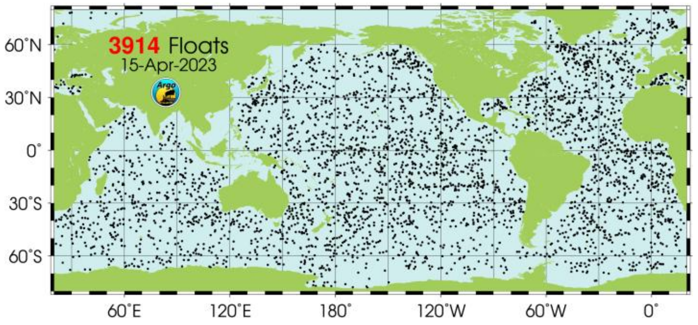
Johnson & Lyman, 2020



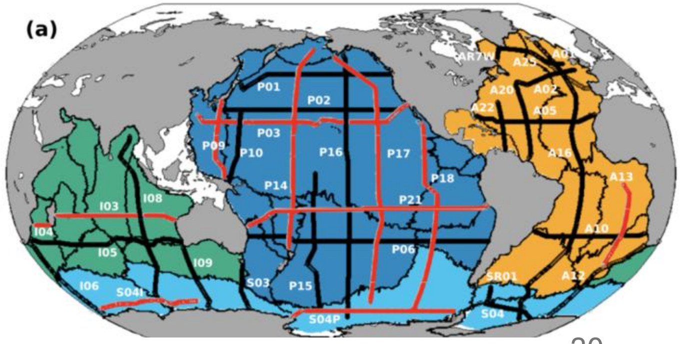


Cheng et al., 2020

Argo floats (0-2000 m)



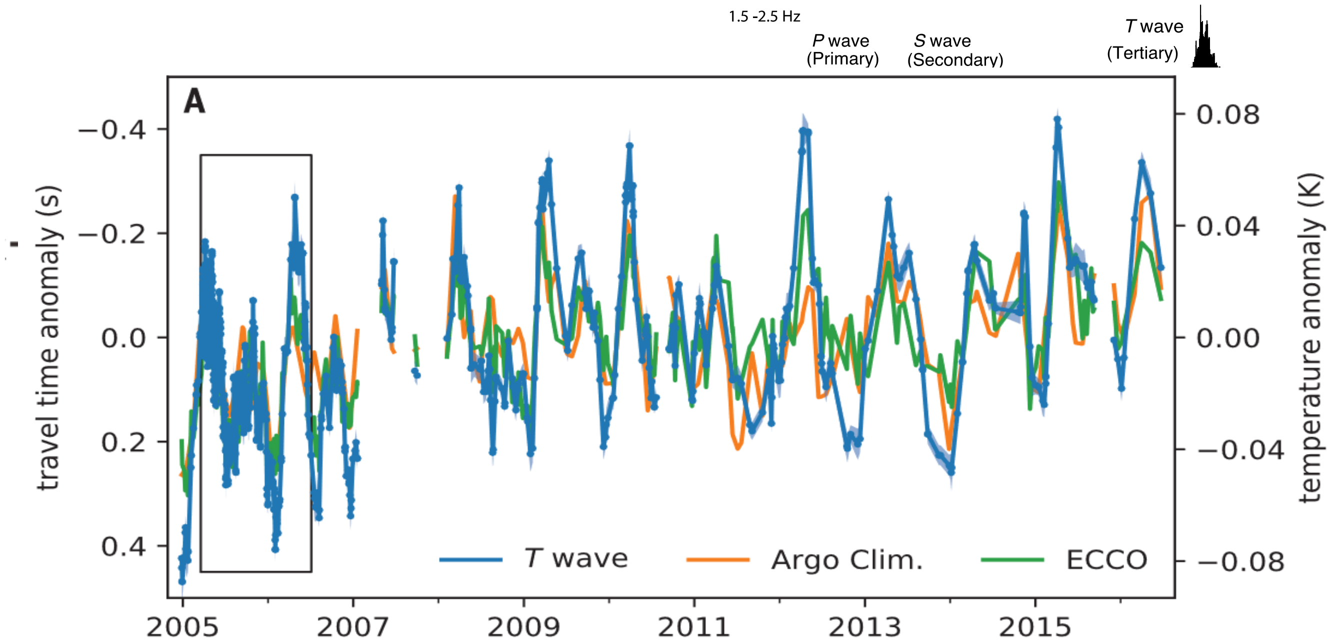
Hydrographic data (>2000 m)



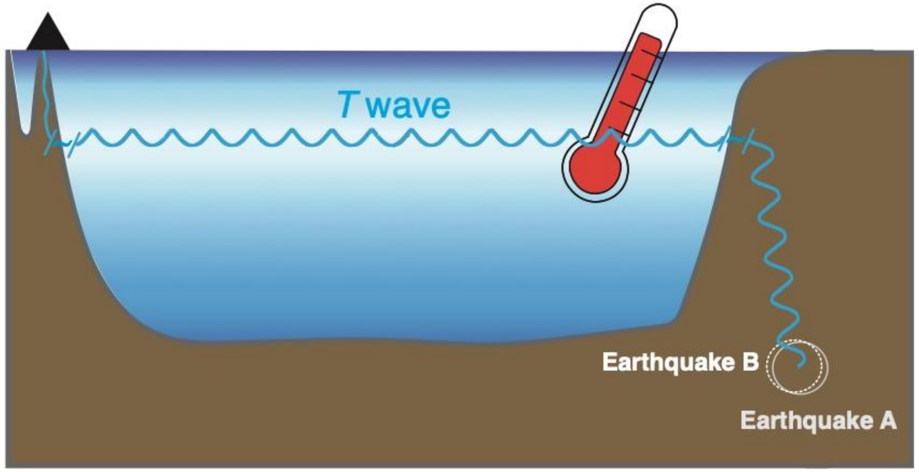
Desbruyères et al., 2016

T-wave & seismic ocean thermometry (SOT)

- ❑ T(tertiary) wave: long-distance with little energy loss



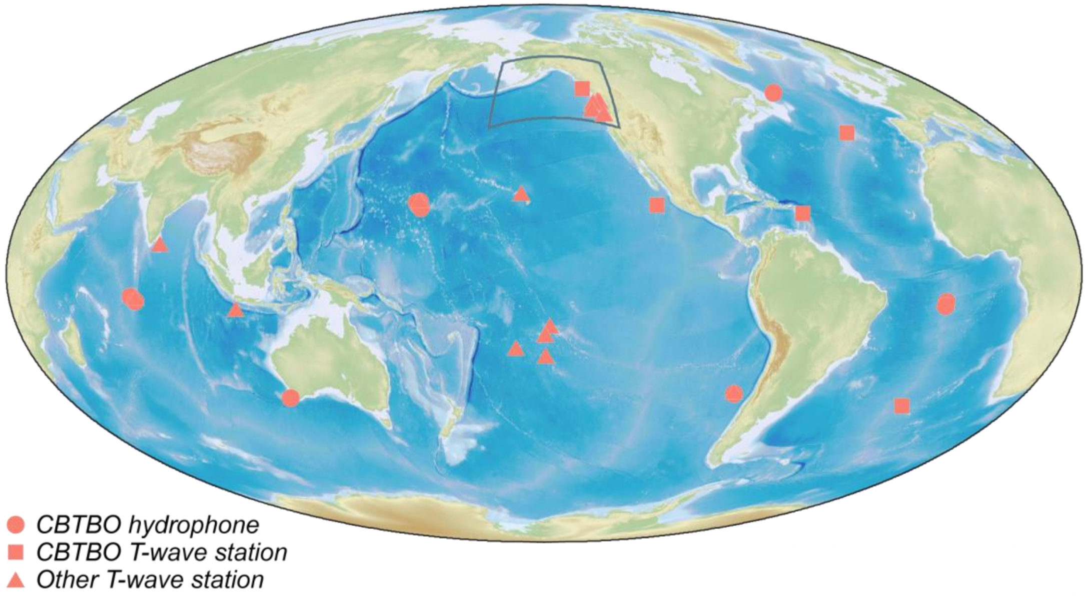
Wu et al. 2020



Current T-wave stations are sparse

Can DAS help improve the spatial resolution of global SOT?

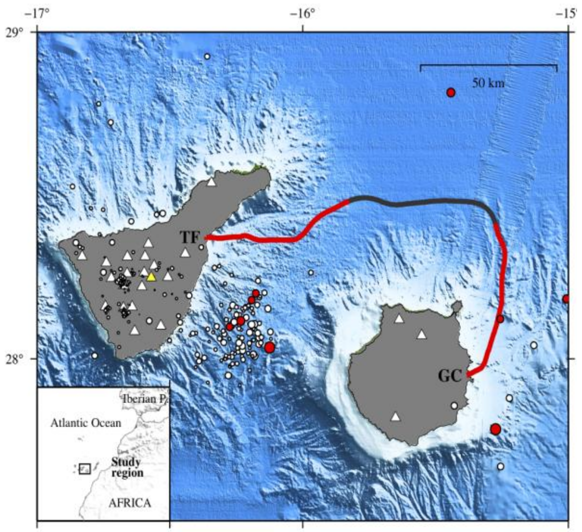
Global T-wave stations



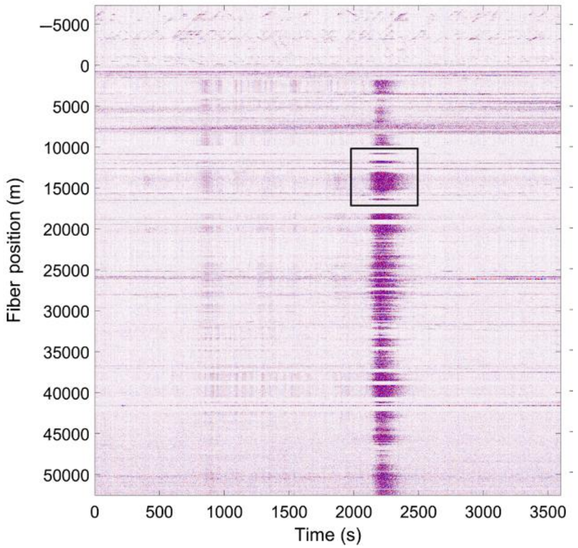
Shen et al., 2024

T-waves can be observed on submarine DAS, but how good it is in detecting small repeating EQs?

Canary Islands



Mw6.9 T-wave

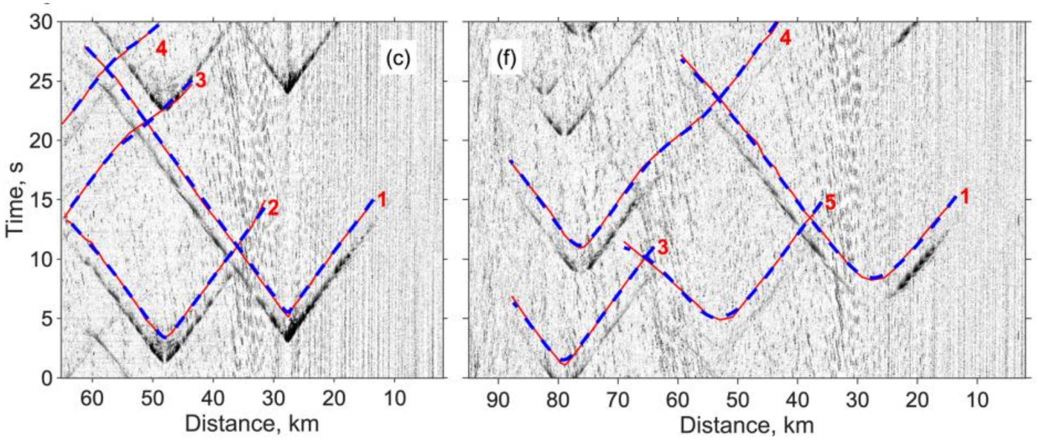


Ugalde et al., 2021

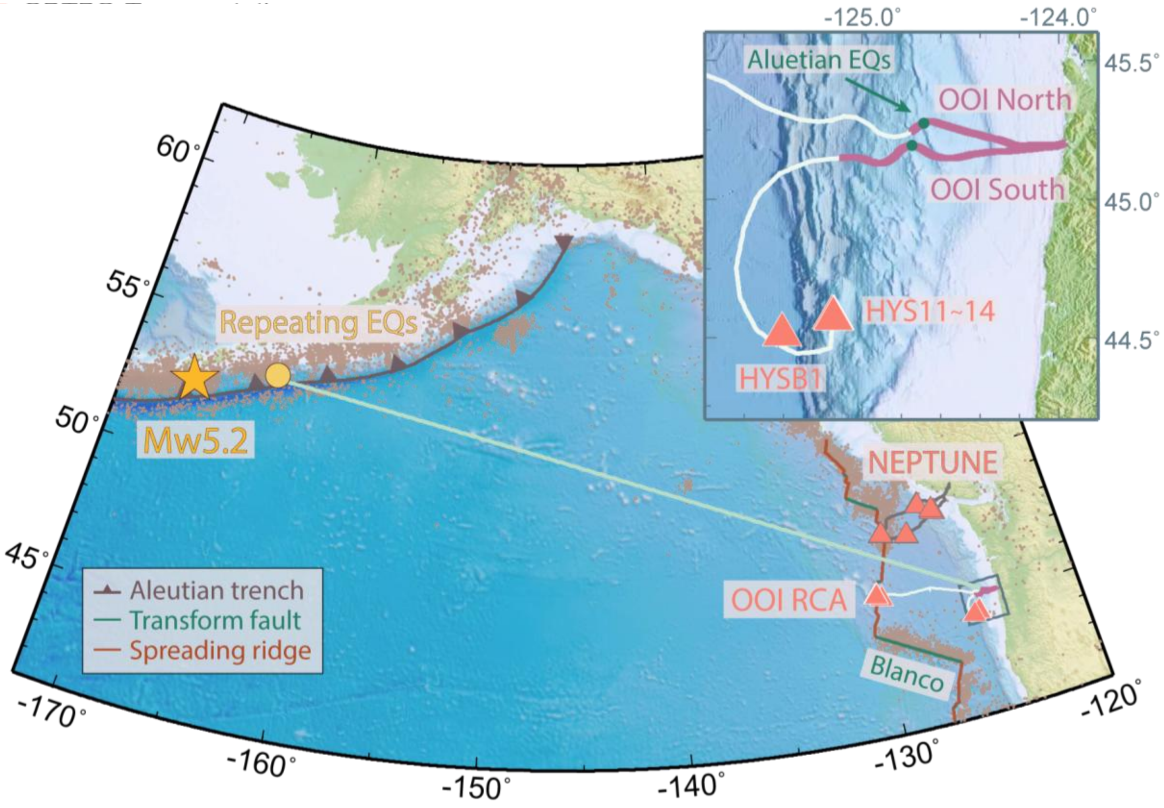
OOI DAS: a community experiment

- ❑ 2021 Nov. 1 ~ Nov. 5
- ❑ Two backbone cables:
  - OOI North (65 km; 2-m spacing)
  - OOI South (96 km; 2-m spacing)

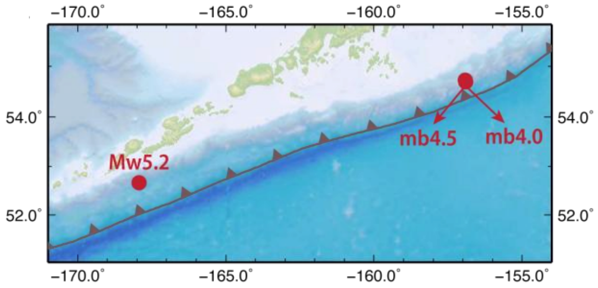
Whale calls

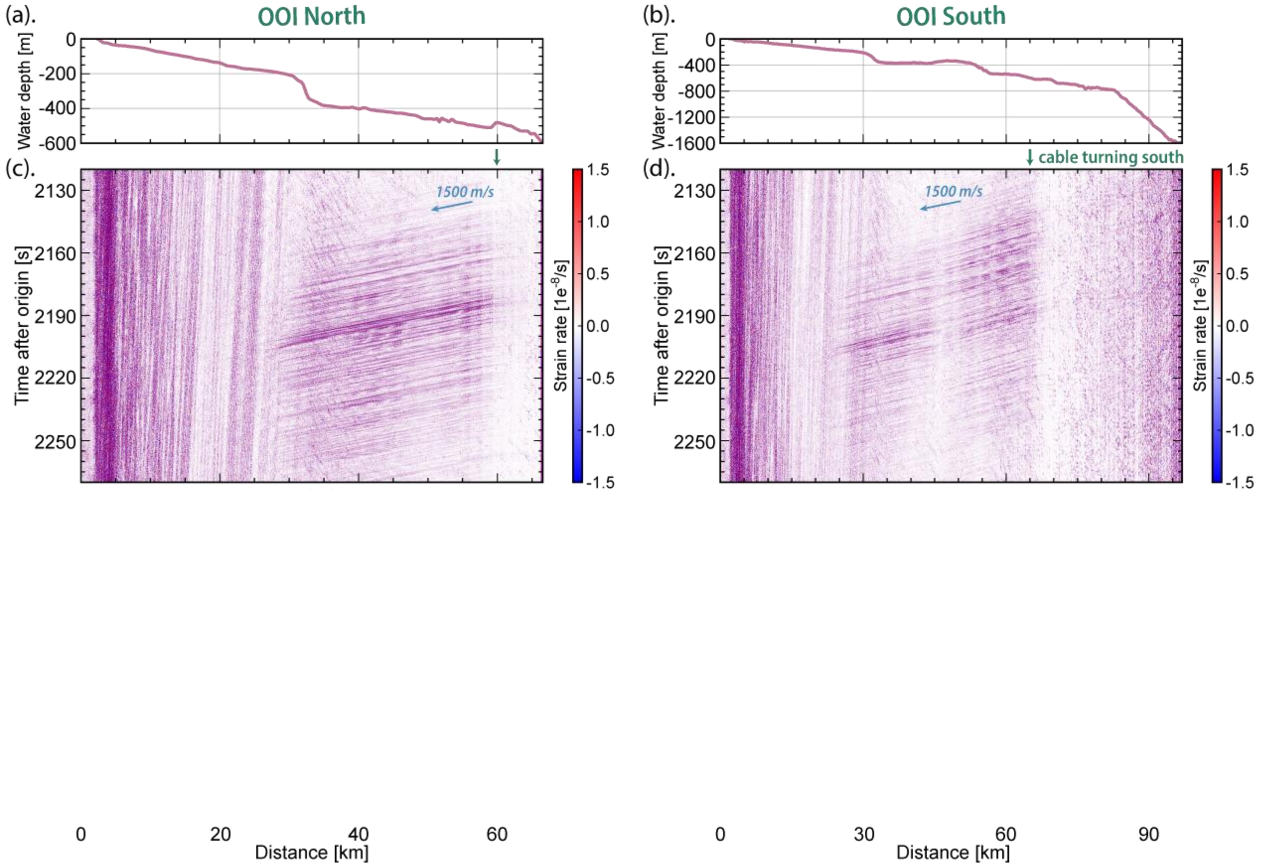


Wilcock et al., 2022



T-wave observations on OOI DAS

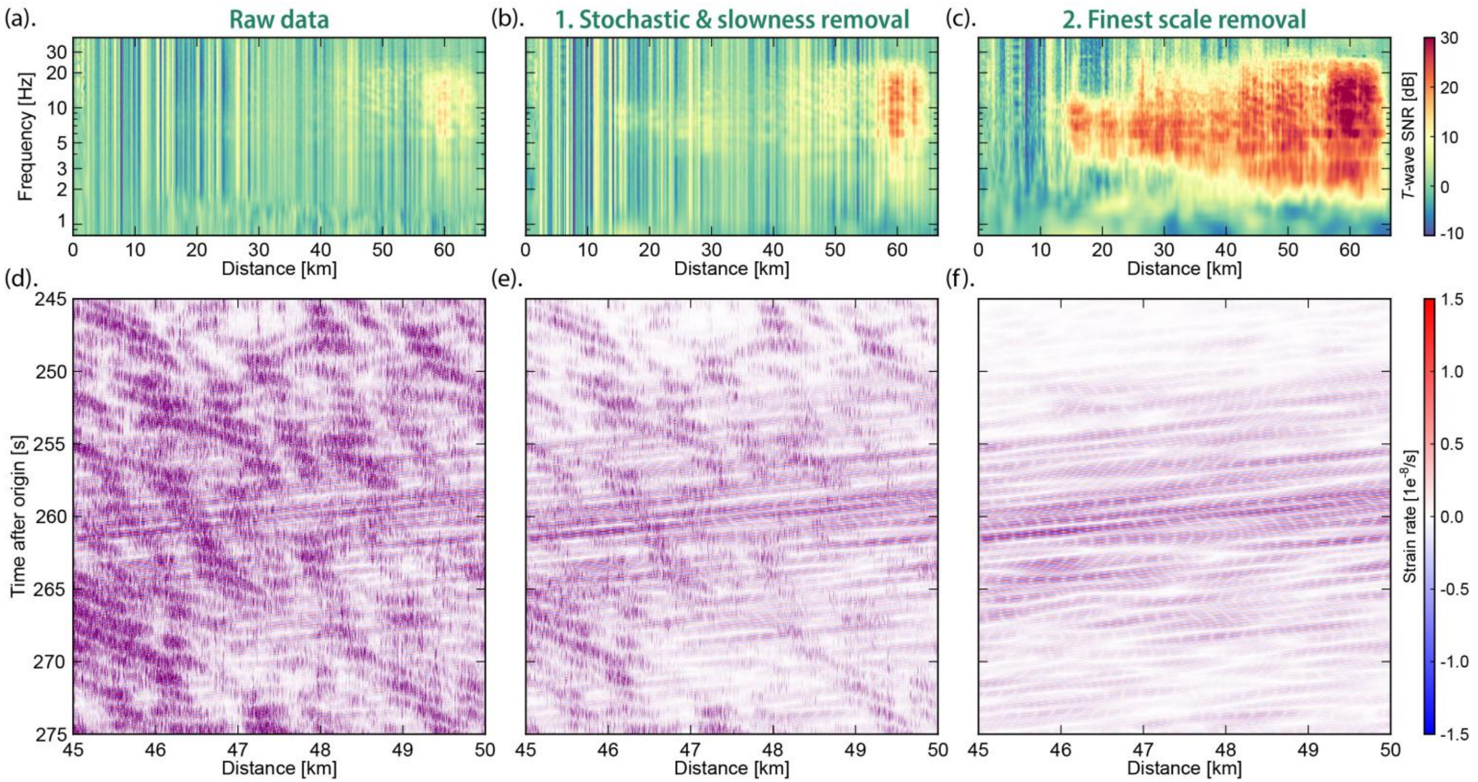




Shen et al., 2024

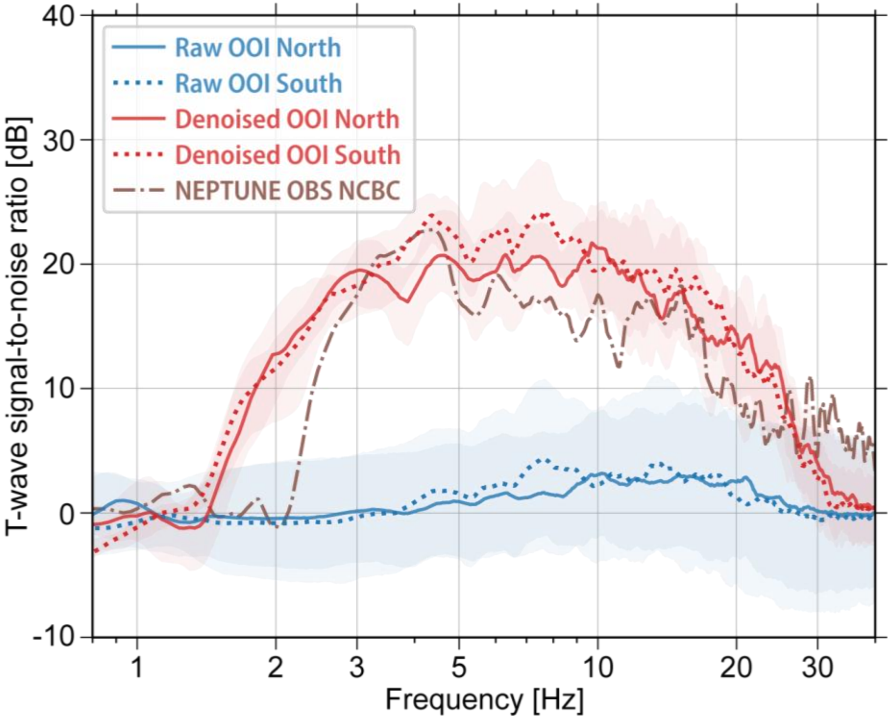
Enhancing T-waves: curvelet denoising

- **Curvelets:** suitable for DAS smooth wavefield
- **Stochastic & Slowness removal:** background random noise & coherent noise
- **Finest-scale removal:** spiky incoherent noise



T-wave SNR

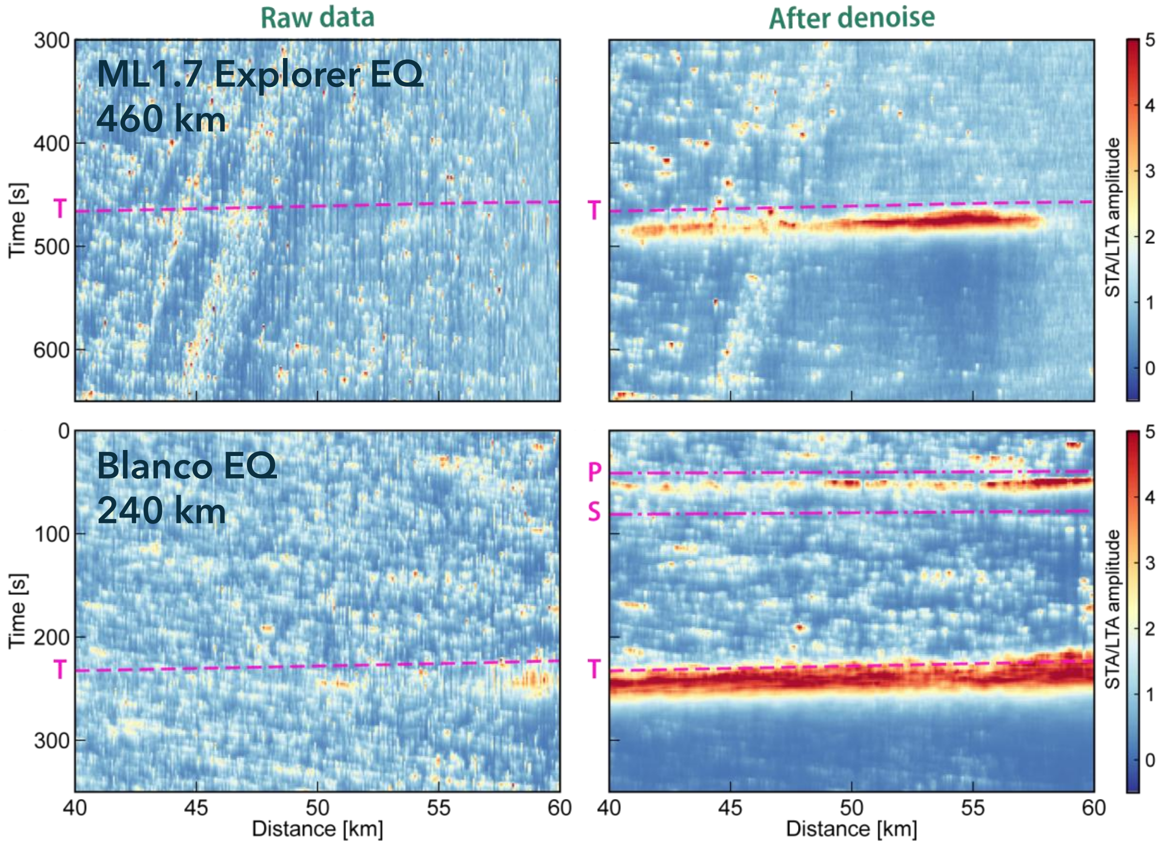
Comparable to OBS



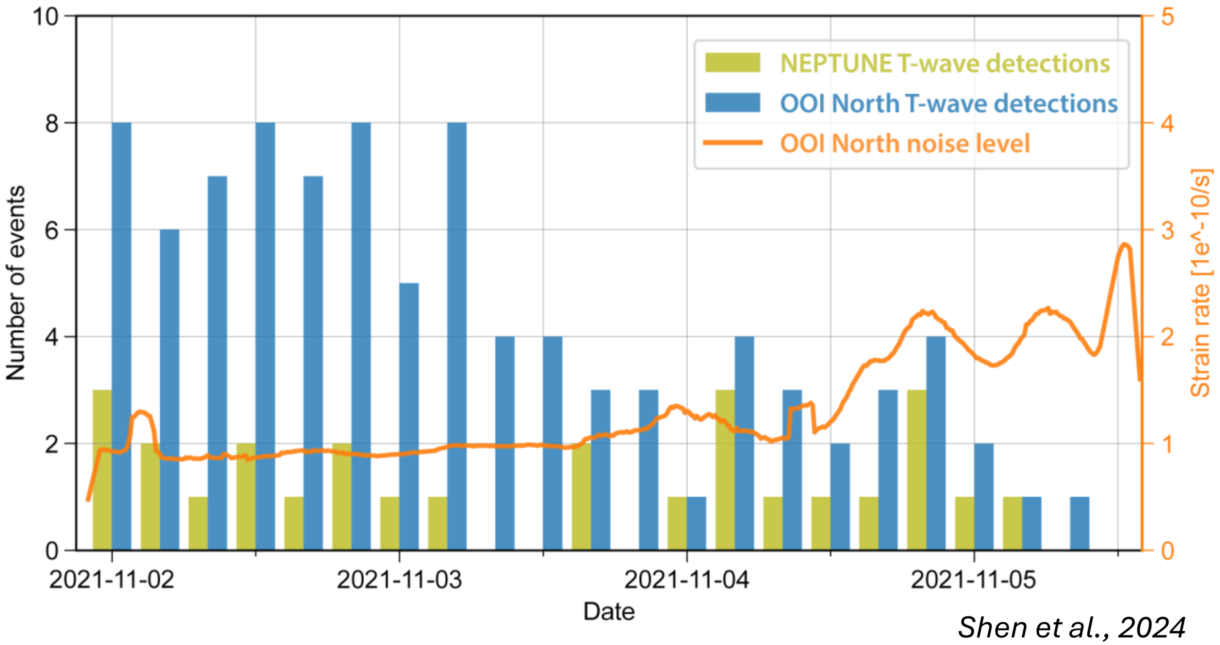
Shen et al., 2024

Improved EQ detectability using DAS

Detection examples

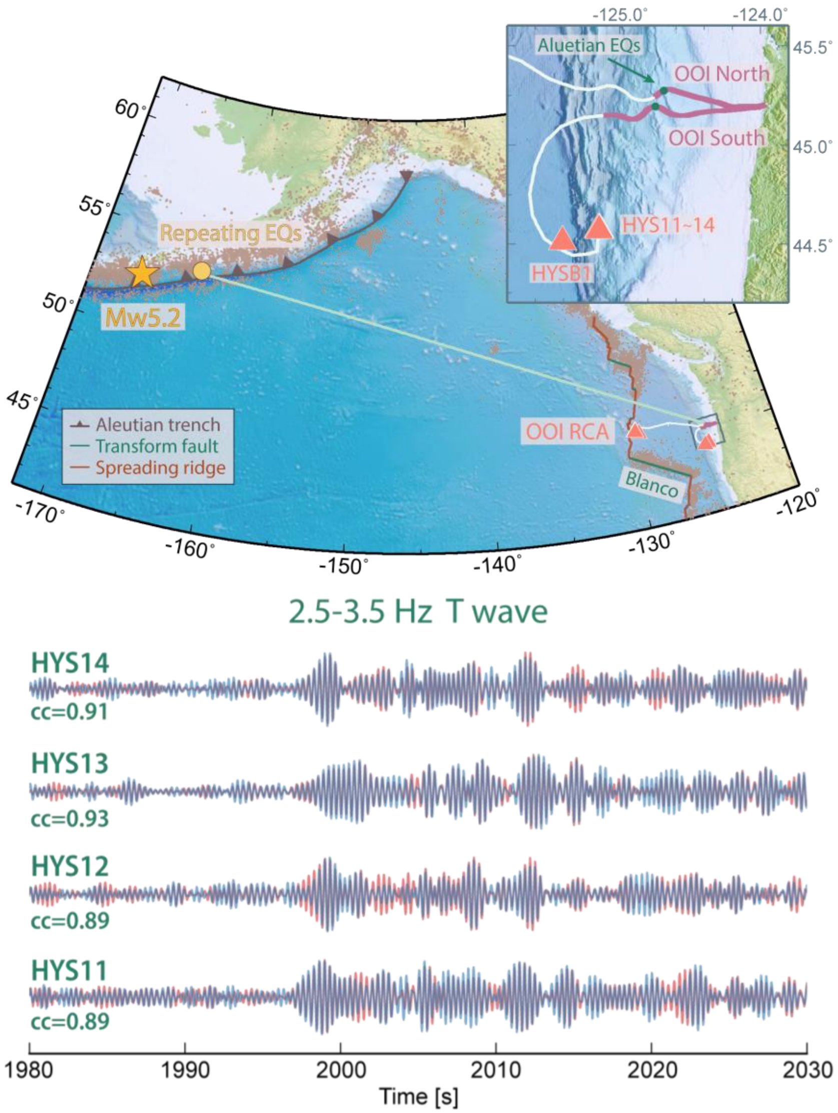


- A total of 92 EQ events detected
- 3x more than cabled OBS
- Modulated by ocean noise level



Shen et al., 2024

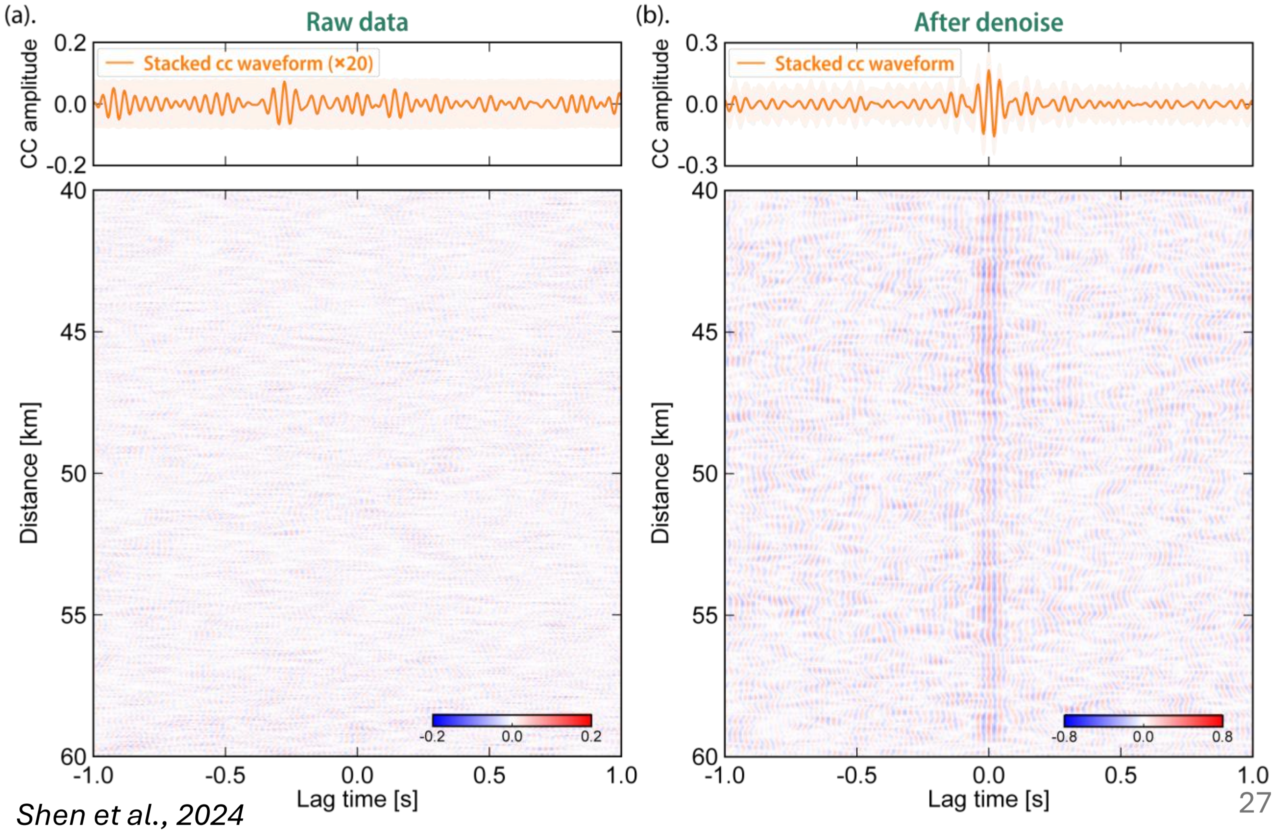
Aleutian-OOI: a feasible ocean path for SOT



Generating Pseudo-repeating earthquake:

real noise + scaled T-wave from the Mw5.2 EQ

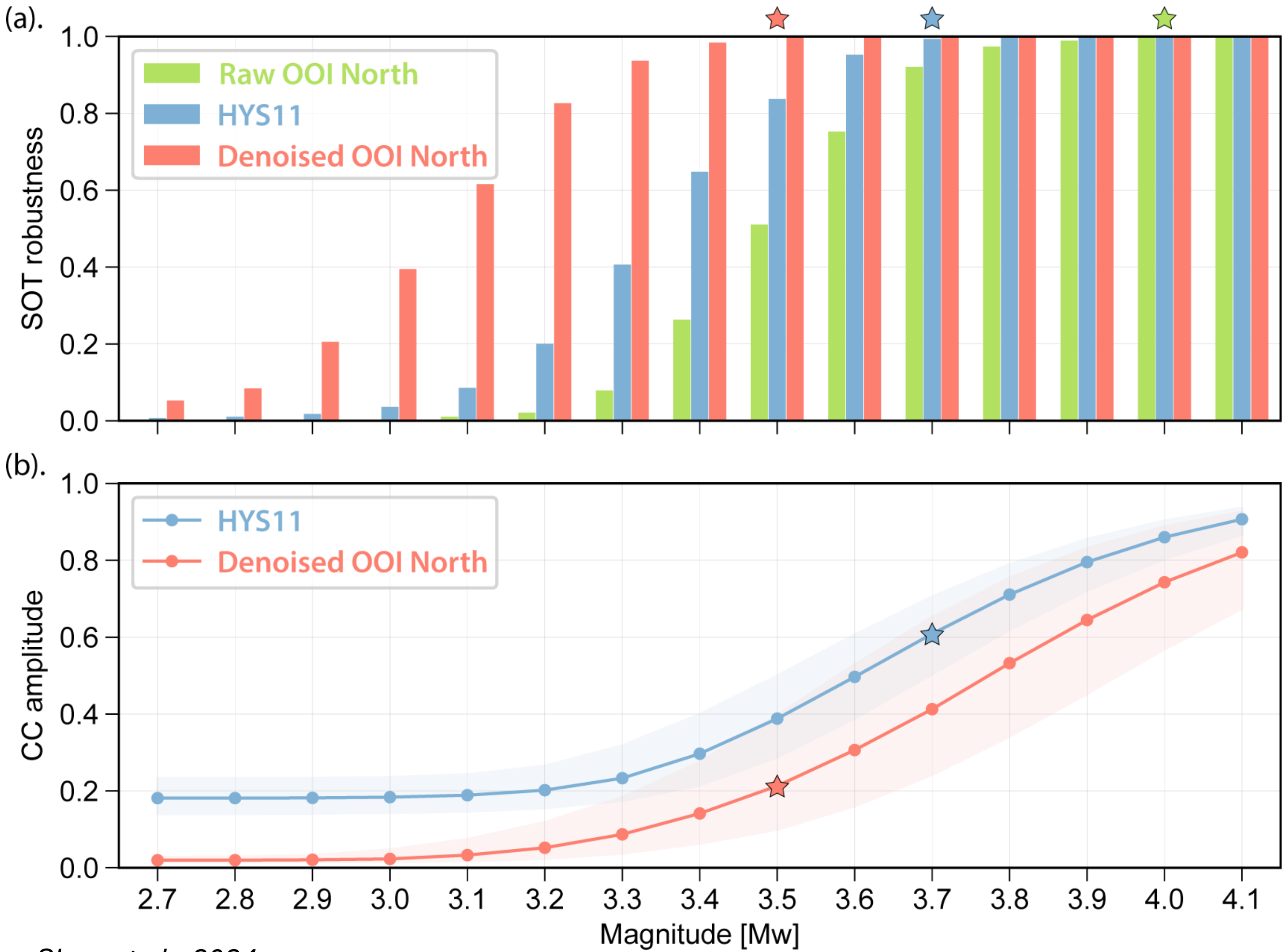
Example for a Mw3.5 pseudo-repeating pair



Shen et al., 2024

SOT performance: DAS vs. OBS

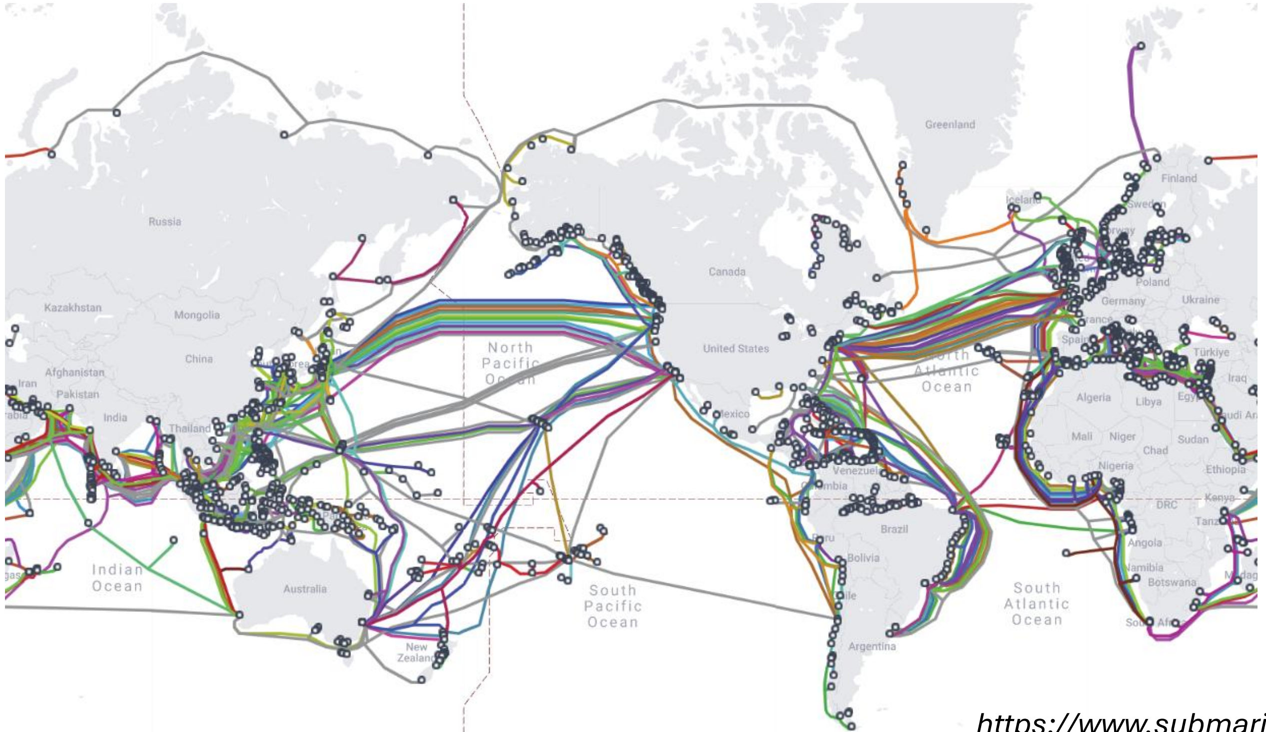
- ❑ 20 random noise -> 190 pairs
- ❑ SOT robustness: percentage of pseudo-repeating EQ pairs producing ground truth time shift (0 s)
- ❑ Smallest magnitude for SOT:
  - ➢ OBS HYS11: Mw3.7
  - ➢ Denoised DAS: Mw3.5
- ❑ DAS can provide 4x more small repeating pairs for SOT than OBS



Shen et al., 2024

Part II. Summary

- DAS can detect 3x more earthquakes than cabled OBSs after denoising, making more small repeating earthquakes useable for seismic ocean thermometry.
- Our results highlight the promise of submarine DAS as a long-term and large-scale complementary tool to enhance our capability to monitor ocean warming.



https://www.submarinecablemap.com/

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