Turbulent seismoacoustic signals from a hurricane landfall

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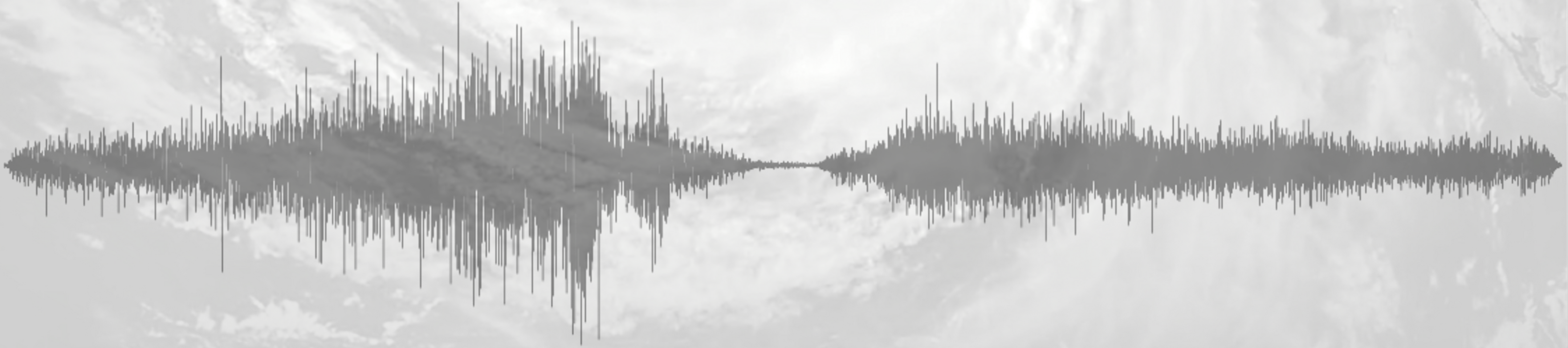
Whole Earth Seminar at UC Santa Cruz, October 1

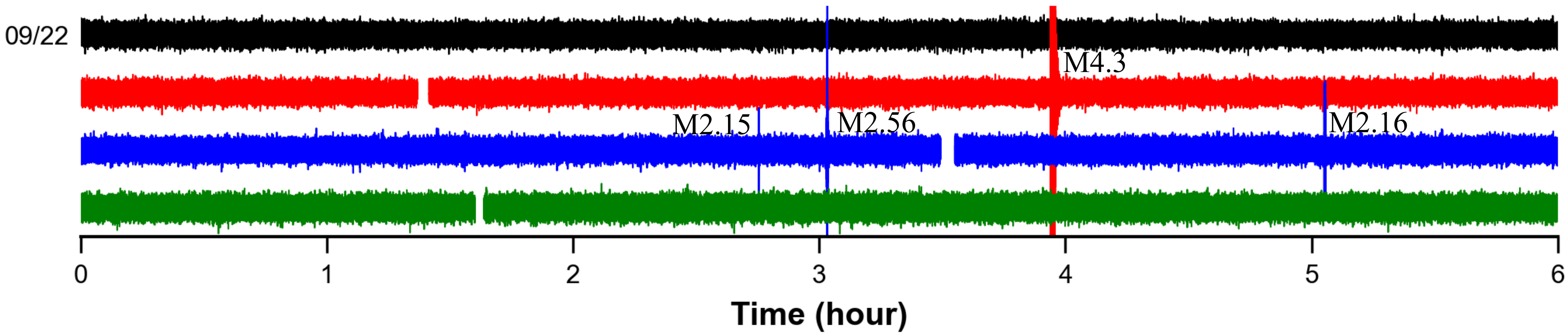


Environmental Seismology

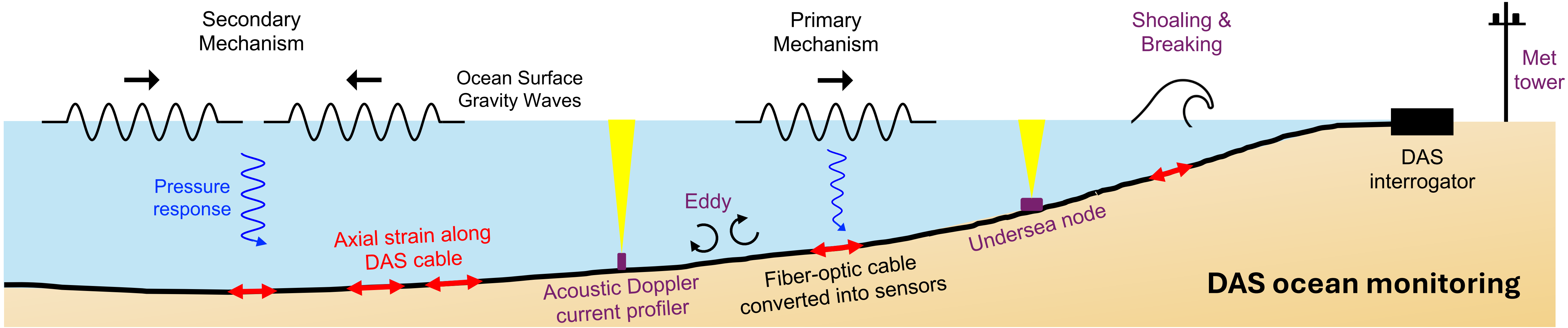
Seismic (and acoustic) sensors continuously record signal from various natural processes, beyond impulsive events such as earthquakes.

New datasets for other fields (e.g., ocean and atmospheric sciences), given advantages of seismic stations.

Station NC.JAR, UCSC Arboretum



Seismic instruments for ocean monitoring



- Continuous monitoring with high resolution

  e.g., Distributed Acoustic Sensing (DAS) with temporal and spatial resolution

- How ocean processes generate signals recorded by seismic sensors?

  e.g., strain directly caused by bottom pressure of ocean waves

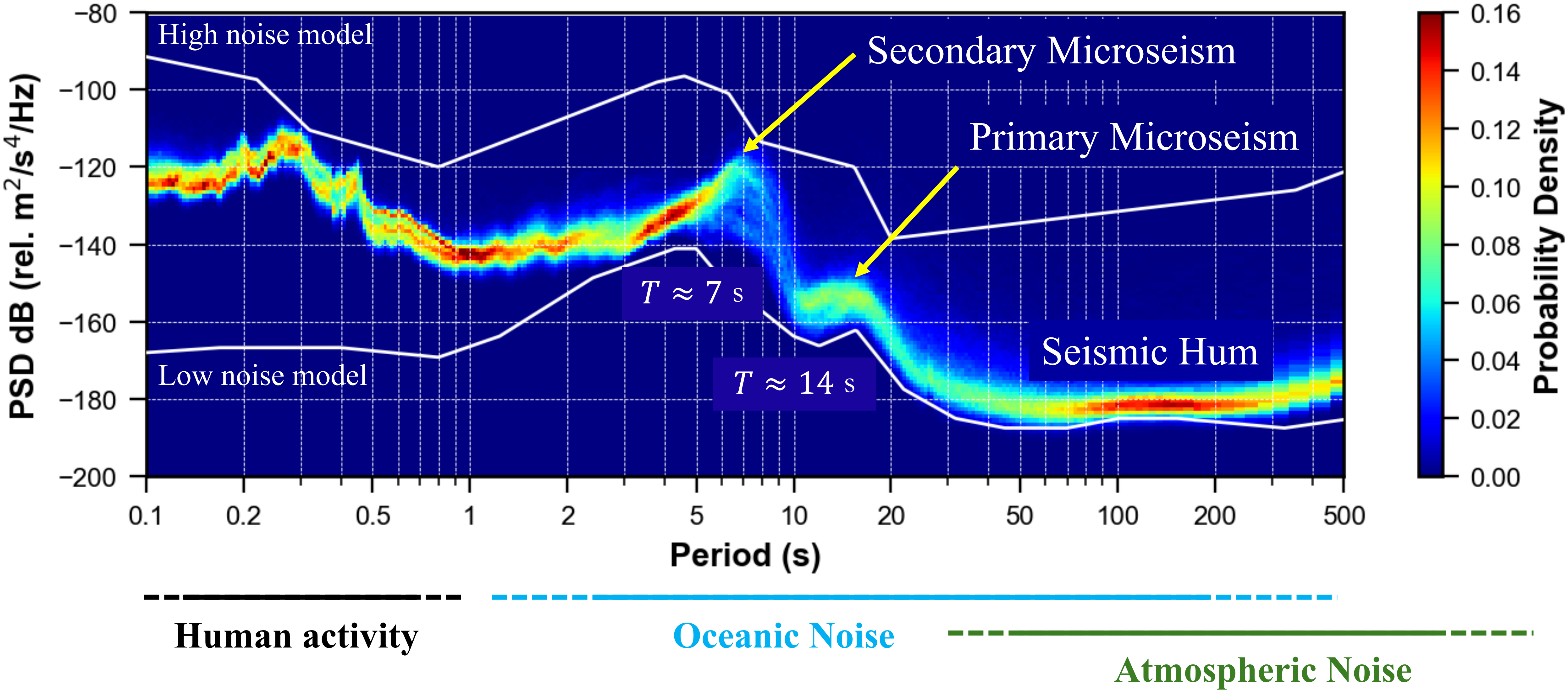
  e.g., primary microseism (period ~14 s) and secondary microseism (~7 s)

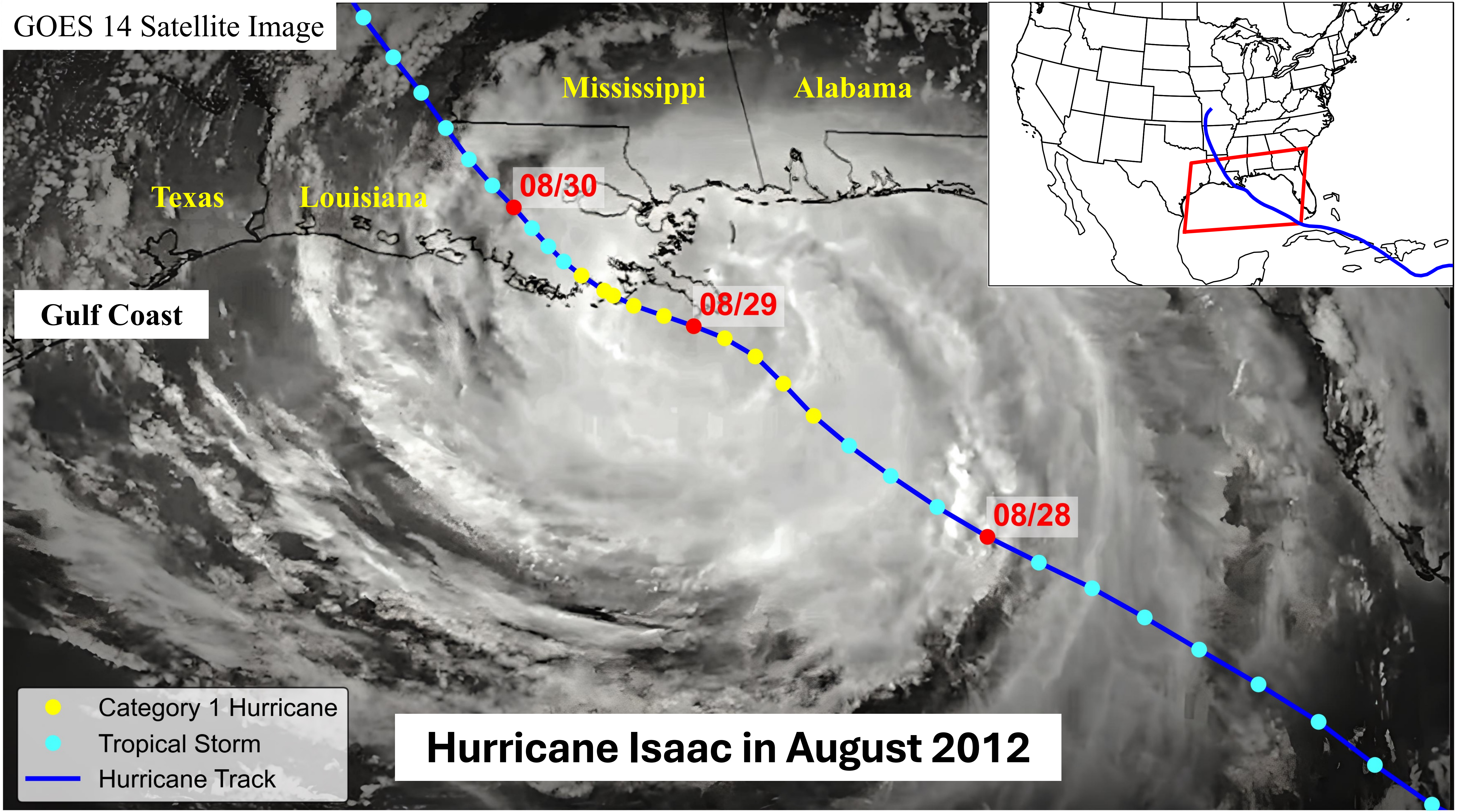
- How can seismic observations be related / converted into ocean variables?

  e.g., compare with co-located oceanographic data or ocean models

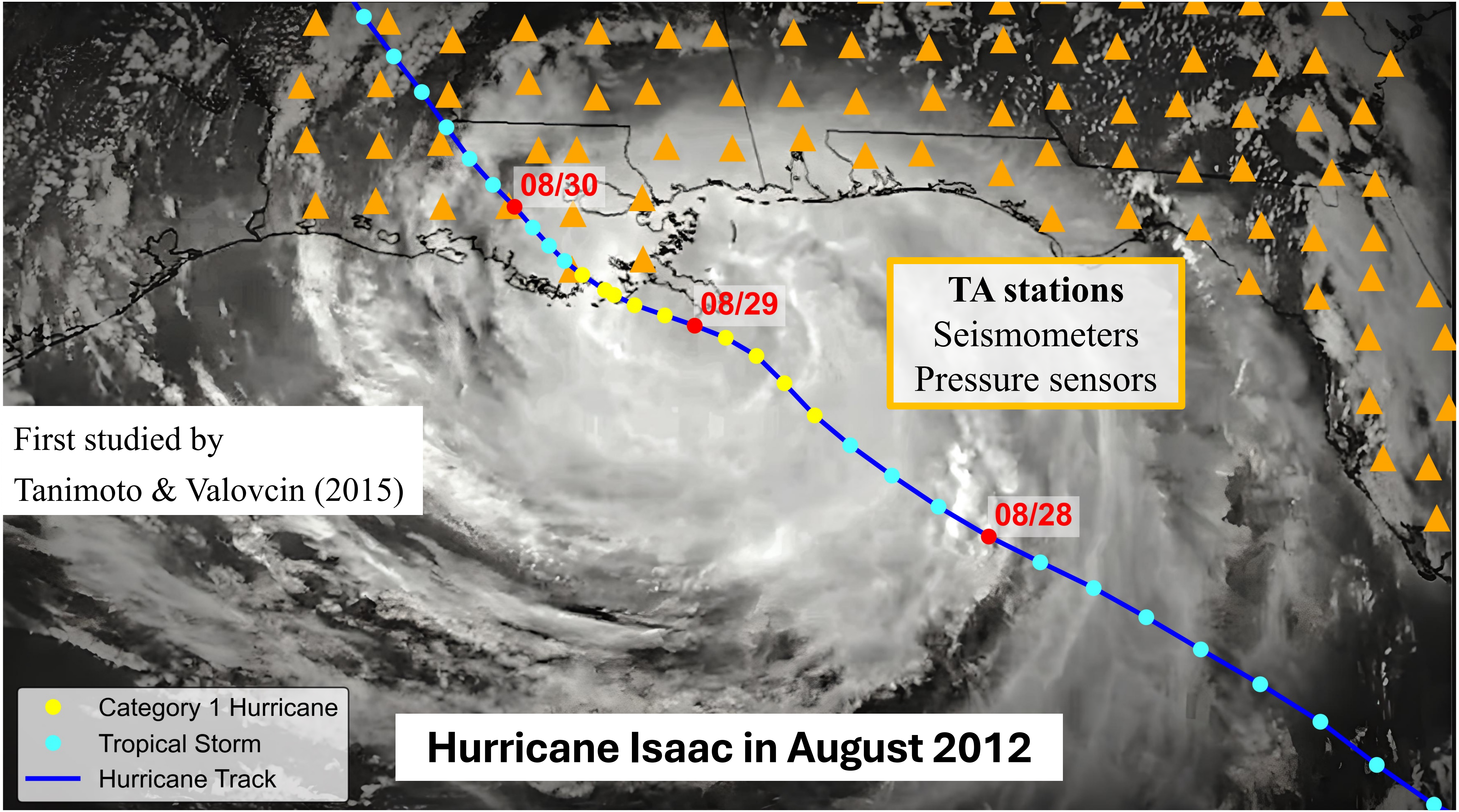
** Example: Microseism from ocean waves

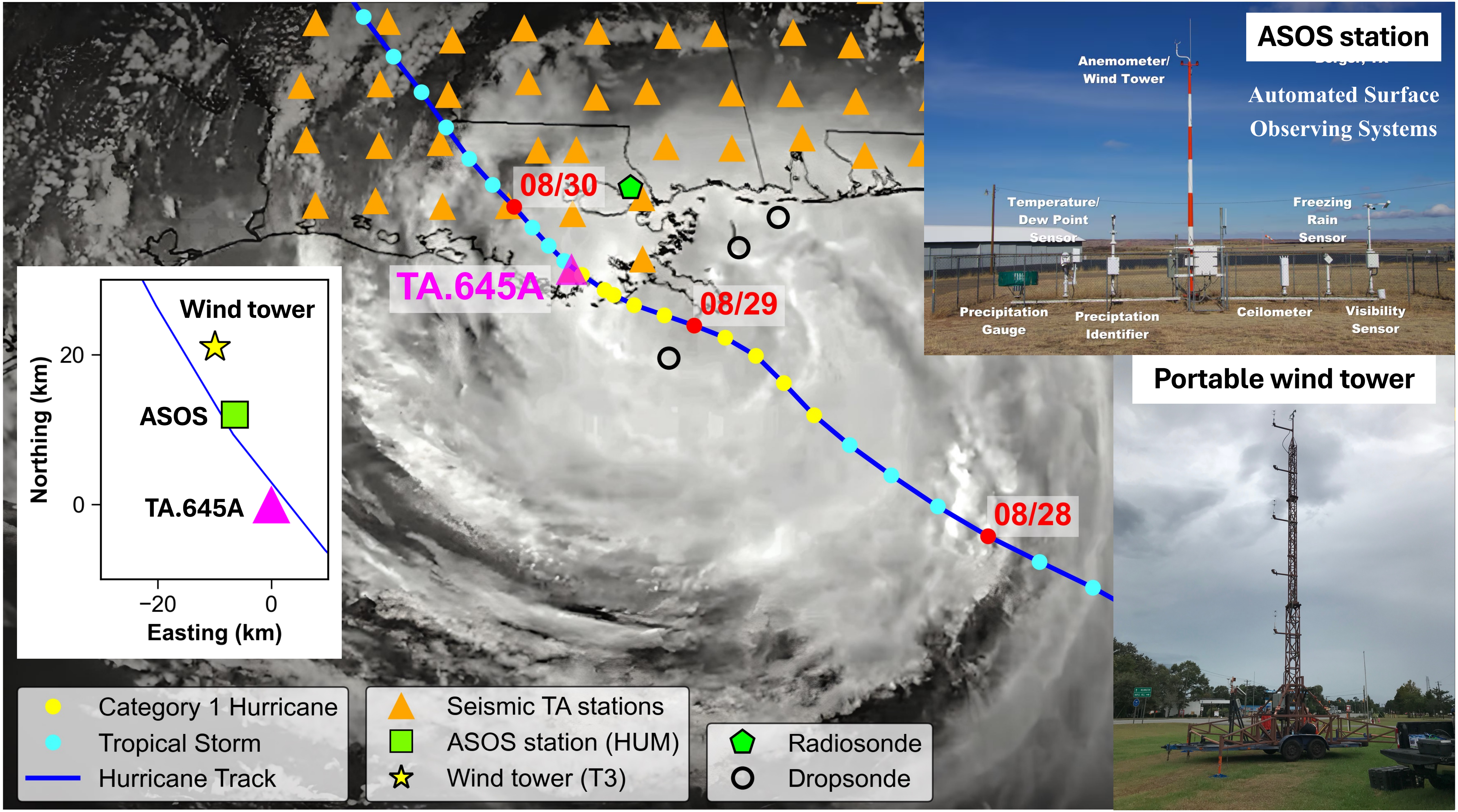
Seismic station CI.JPLS One-year data, 3-hr window for each PSD curve





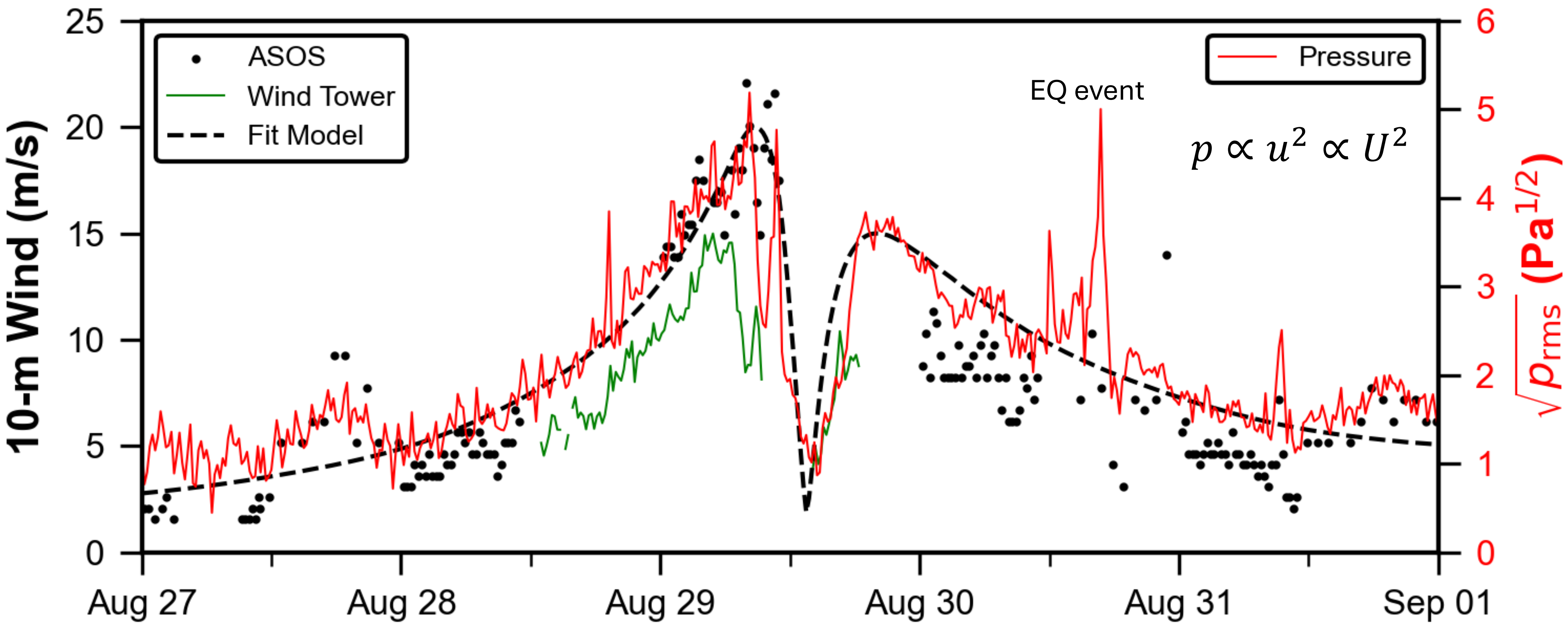
GOES 14 Satellite Image
Mississippi
Alabama
Texas
Louisiana
08/30
08/29
08/28
Gulf Coast
Category 1 Hurricane
Tropical Storm
Hurricane Track
Hurricane Isaac in August 2012


08/30
08/29
08/28
TA stations
Seismometers
Pressure sensors
First studied by
Tanimoto & Valovcin (2015)
Category 1 Hurricane
Tropical Storm
Hurricane Track
Hurricane Isaac in August 2012



08/30
08/29
08/28
TA.645A
Wind tower
ASOS
TA.645A
20
0
Northing (km)
−20
0
Easting (km)
Category 1 Hurricane
Tropical Storm
Hurricane Track
Seismic TA stations
ASOS station (HUM)
Wind tower (T3)
Radiosonde
Dropsonde
ASOS station
Automated Surface
Observing Systems
Anemometer/
Wind Tower
Temperature/
Dew Point
Sensor
Freezing
Rain
Sensor
Precipitation
Gauge
Preciptation
Identifier
Ceilometer
Visibility
Sensor
Portable wind tower

Infrasound data for hurricane study



Continuous monitoring of the evolution of atmospheric quantities (e.g., wind speed, wind turbulence)

1. Observation

Seismoacoustic imprints of Hurricane Isaac in 2012 during landfall

2. Interdisciplinary modeling

How atmospheric processes generate these observed signals?

Large-eddy simulation (LES) of turbulent surface pressure

Quasi-static seismic modeling of elastic response under turbulent pressure

3. Turbulent pressure spectrum from infrasound data

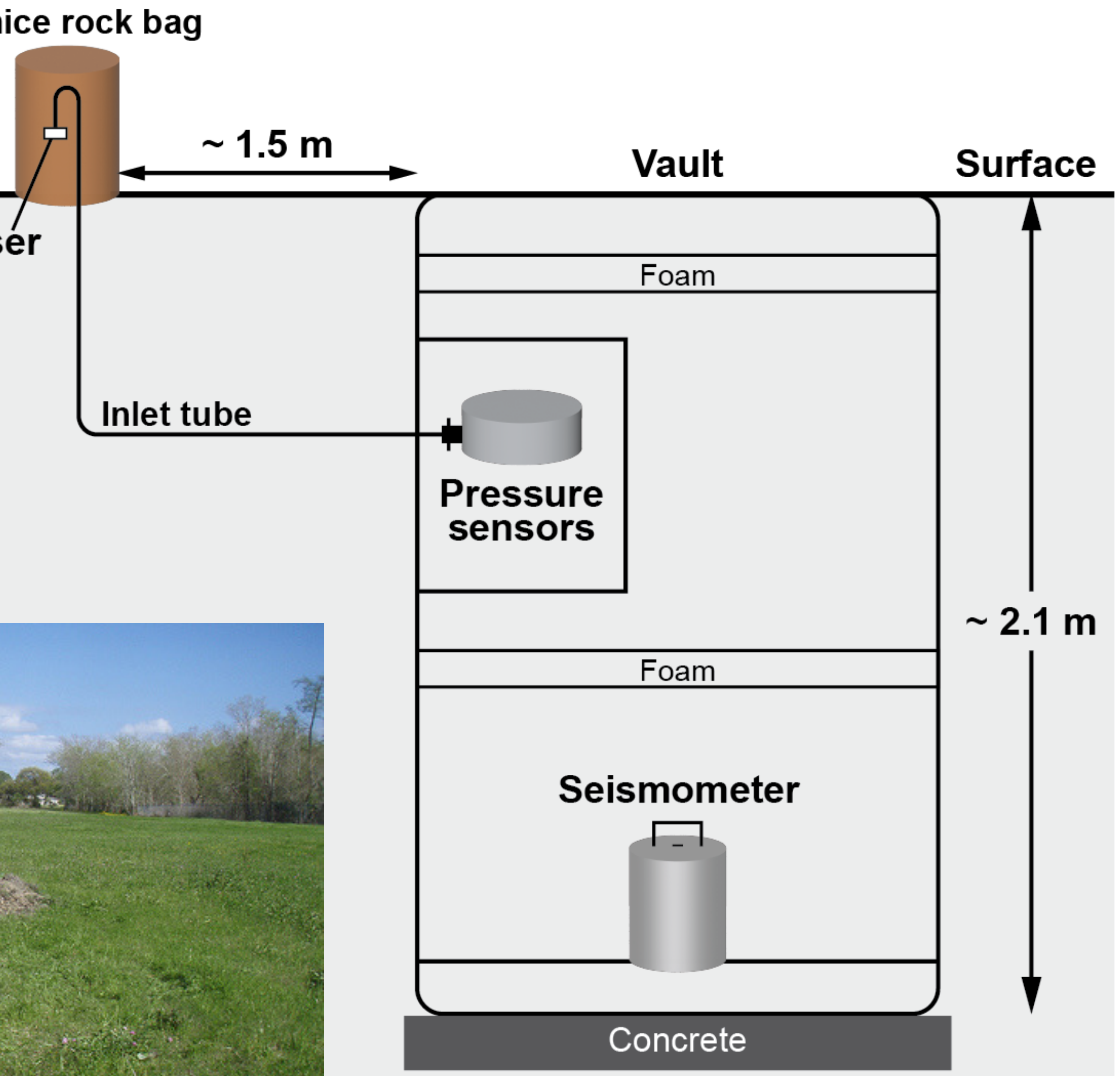
Estimate turbulent dissipation rate ε from pressure spectrum

How to relate these observations with atmospheric variables?

Seismic station with environmental sensors

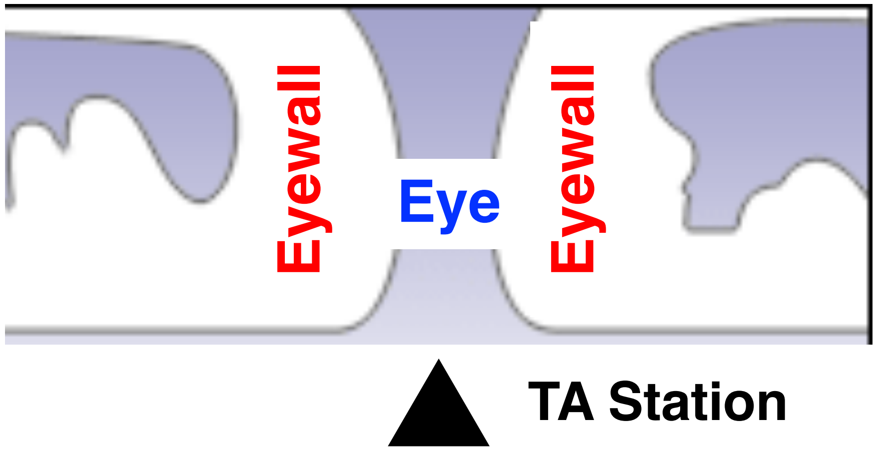
Channel	Observation
LH[ZNE]	Three-component seismic ground motion
LDO	Barometric pressure
LDF	Infrasound pressure

L: Long-period (1 Hz)   B: Broadband (40 Hz)



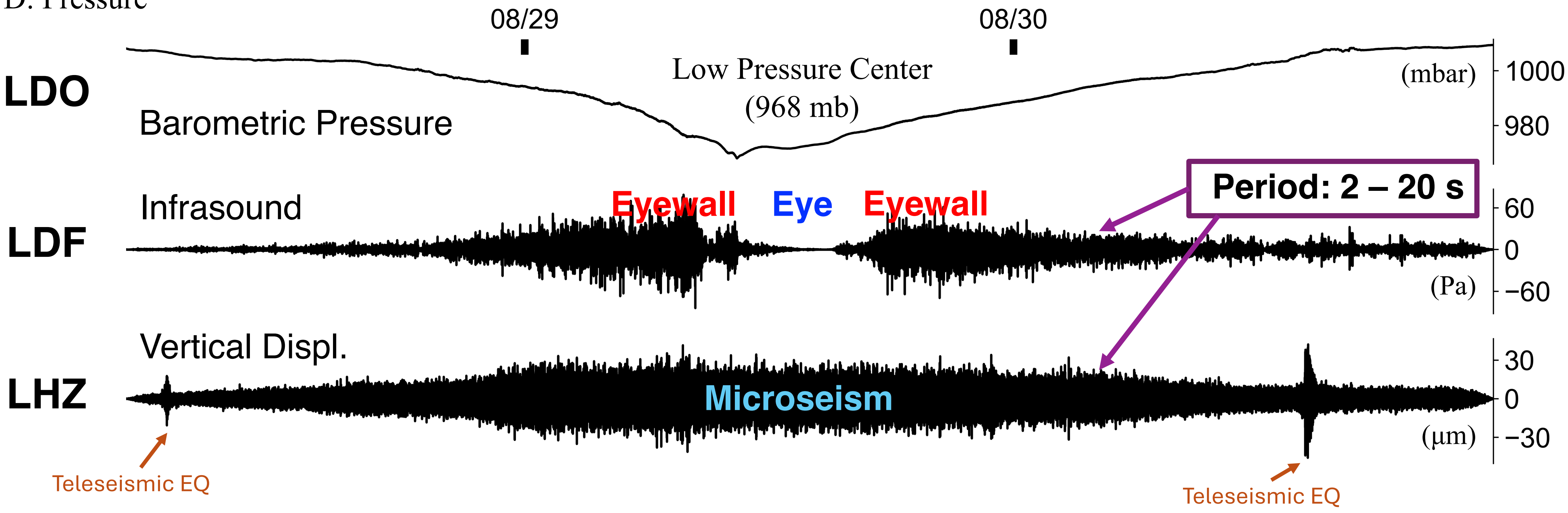
Modified from Tytell et al. (2016)

As hurricane passes the station ......

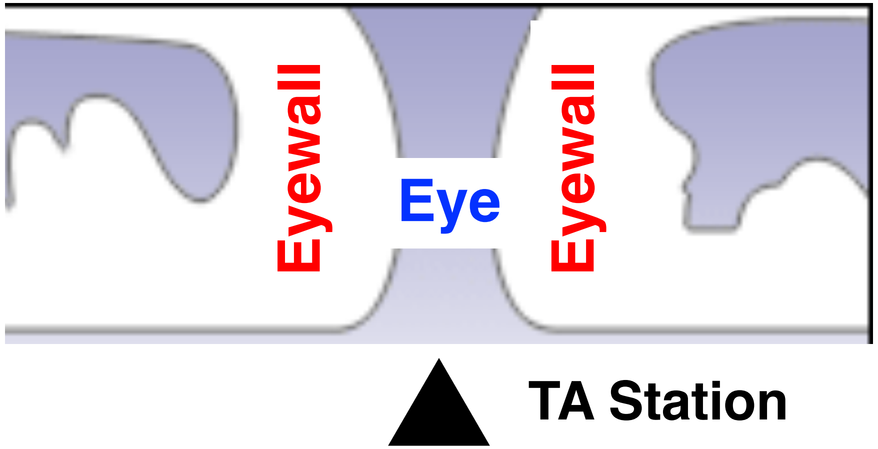


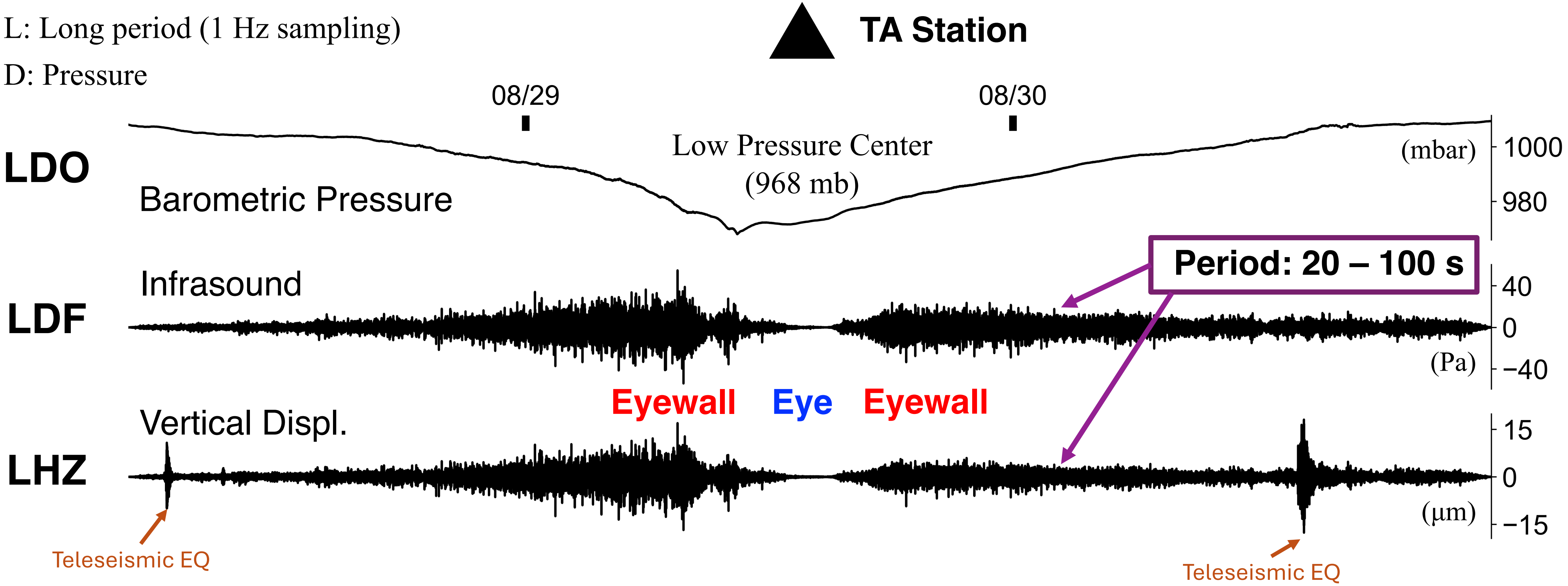
L: Long period channel

D: Pressure



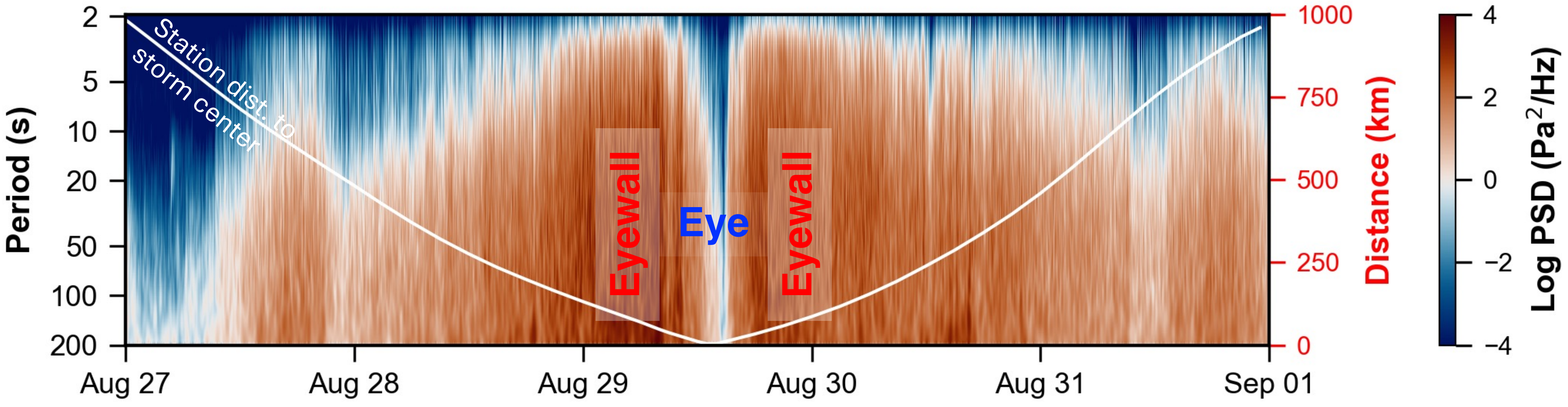
As hurricane passes the station ......



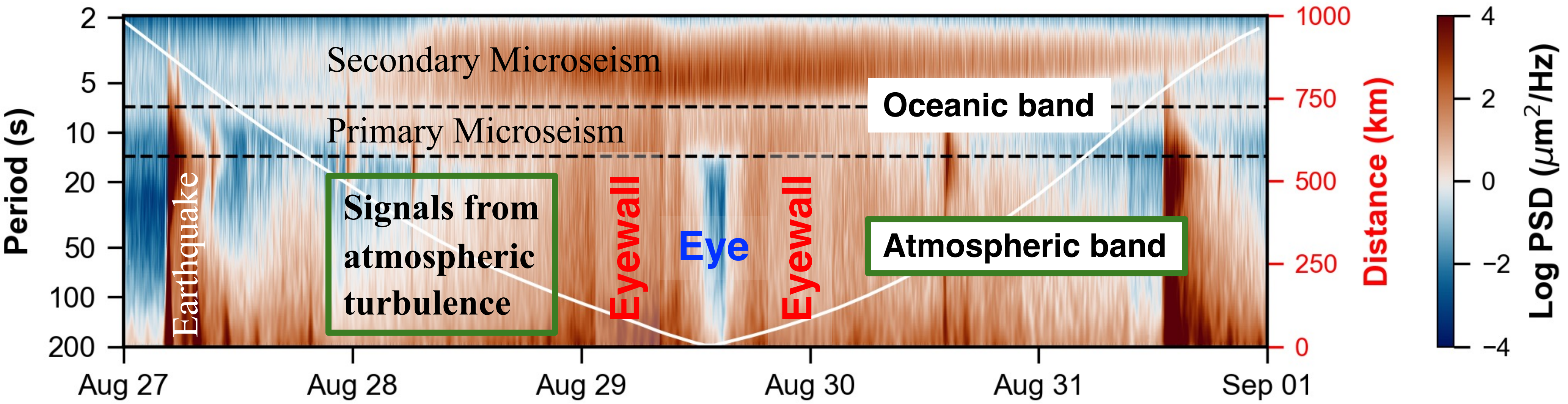


Wavelet spectrograms of infrasound & seismic data

Surface Pressure

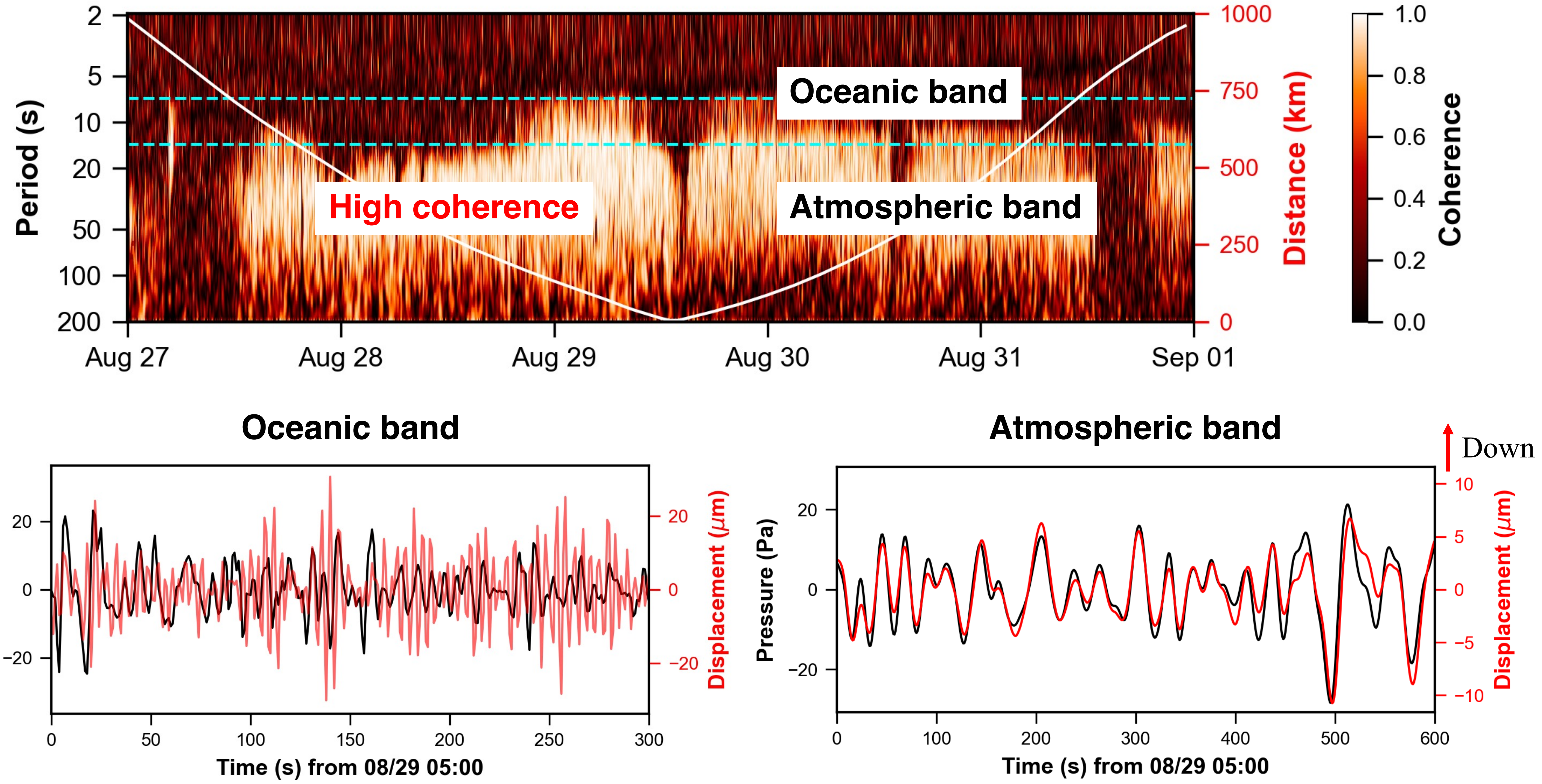


Seismic Vertical Displacement

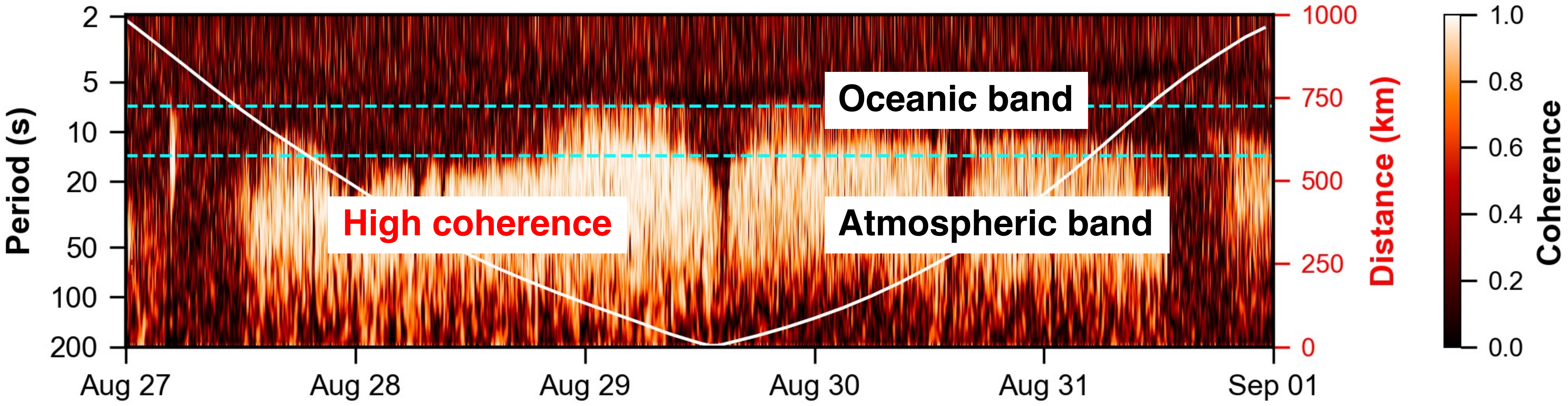


Ji & Dunham (2024)

High coherence indicates local quasi-static response



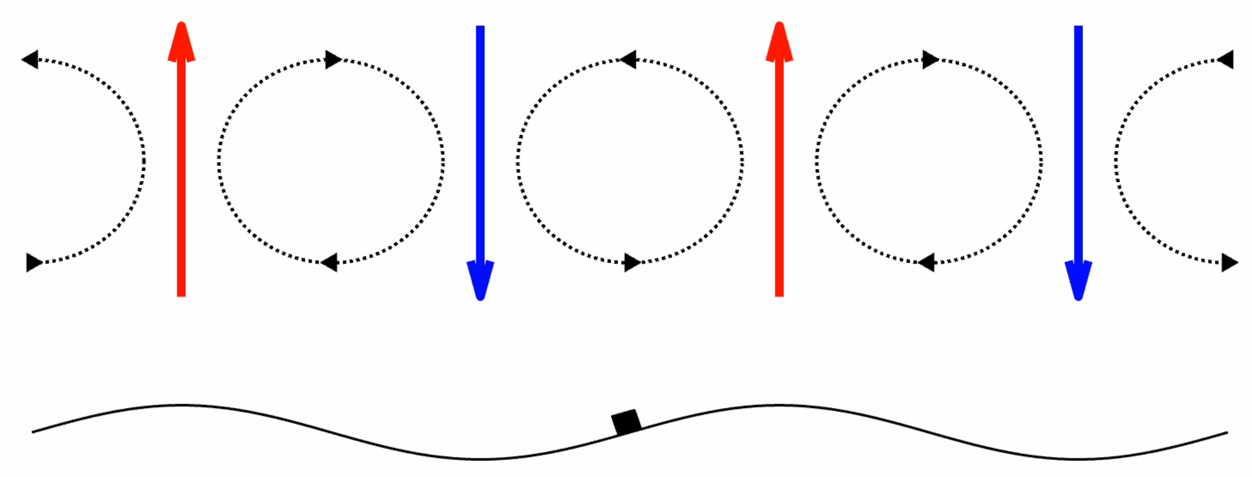
High coherence indicates local quasi-static response



Simplified illustration

Sorrells (1971) theory

Pressure wave model



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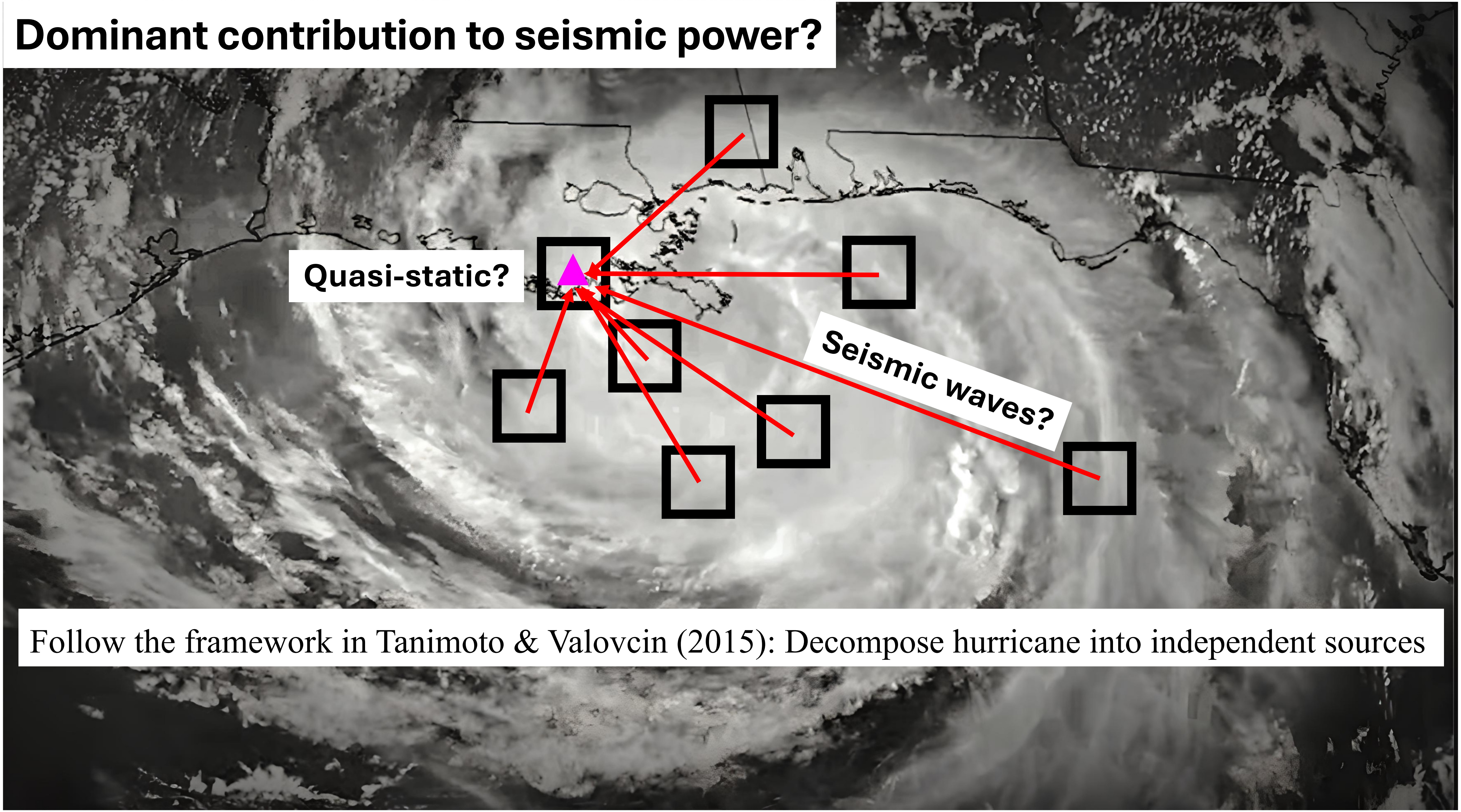
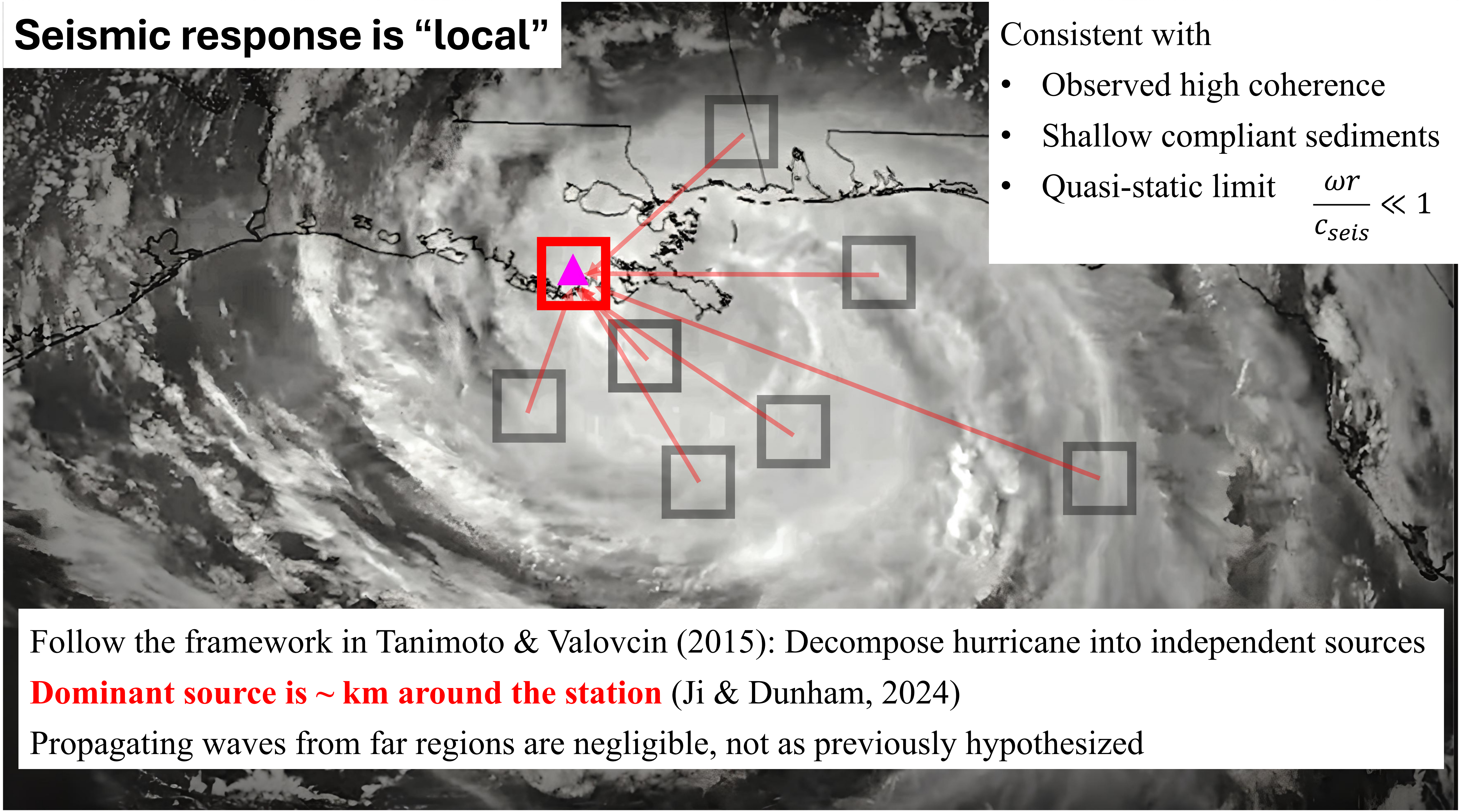
Dominant contribution to seismic power?



Follow the framework in Tanimoto & Valovcin (2015): Decompose hurricane into independent sources

Seismic response is "local"



Consistent with

- Observed high coherence
- Shallow compliant sediments
- Quasi-static limit $\frac{\omega r}{c_{seis}} \ll 1$

Follow the framework in Tanimoto & Valovcin (2015): Decompose hurricane into independent sources

Dominant source is ~ km around the station (Ji & Dunham, 2024)

Propagating waves from far regions are negligible, not as previously hypothesized

Quasi-static seismic response

Vertical displacement | Static Green's function (laterally homogeneous) | Surface pressure

Modeling (Surface field)

$$u_z(\mathbf{k},\omega) = G(|\mathbf{k}|)\; p(\mathbf{k},\omega)$$

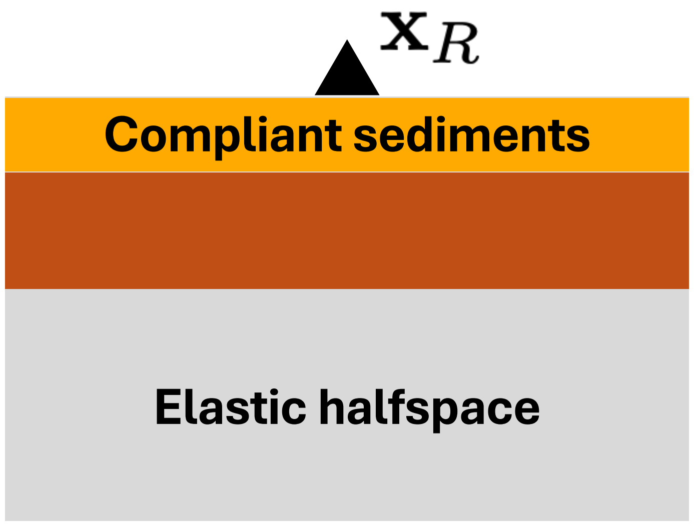
Space-time conversion

Advective velocity

Observation (Single point)

$$u_z(\mathbf{x}_R,\omega) = L(\omega)\, p(\mathbf{x}_R,\omega)$$

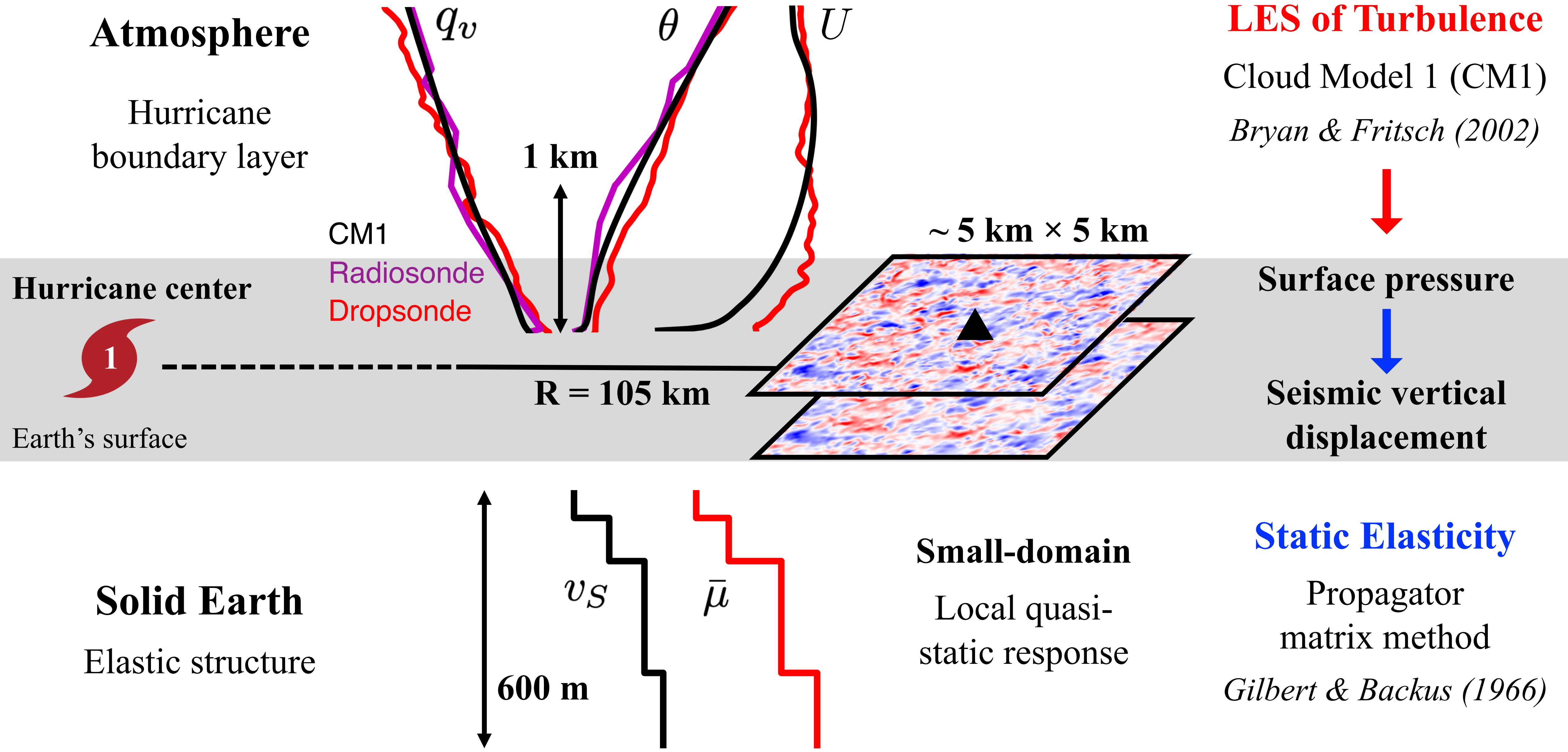
Transfer function (i.e., linear estimator)



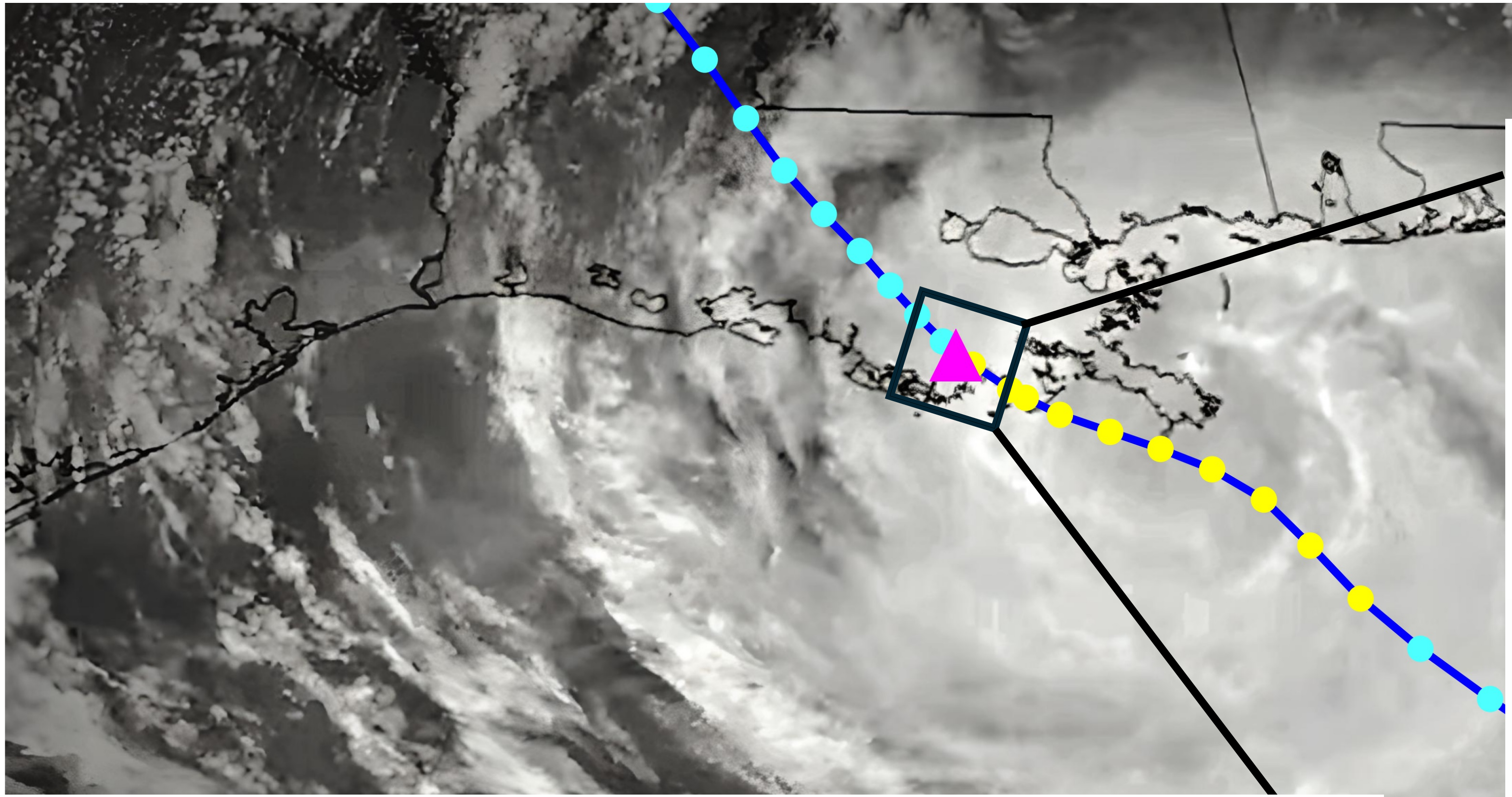
$\mathbf{k}$ Horizontal wavenumber

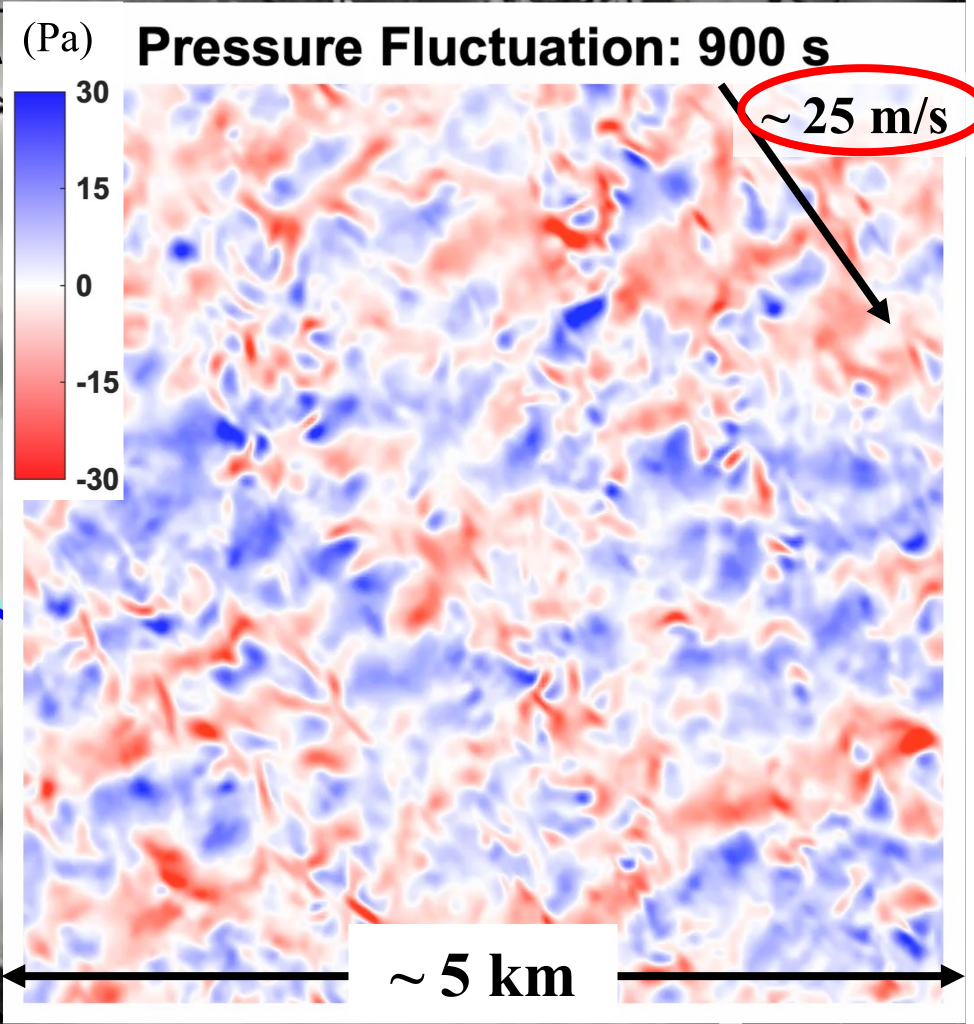
ω Angular frequency

Interdisciplinary modeling



LES of Hurricane Boundary Layer (HBL) on land





Large-Eddy Simulation (LES) of turbulent flow numerically solves the low-pass filtered Navier-Stokes equation, together with governing equations for pressure, temperature and moisture.

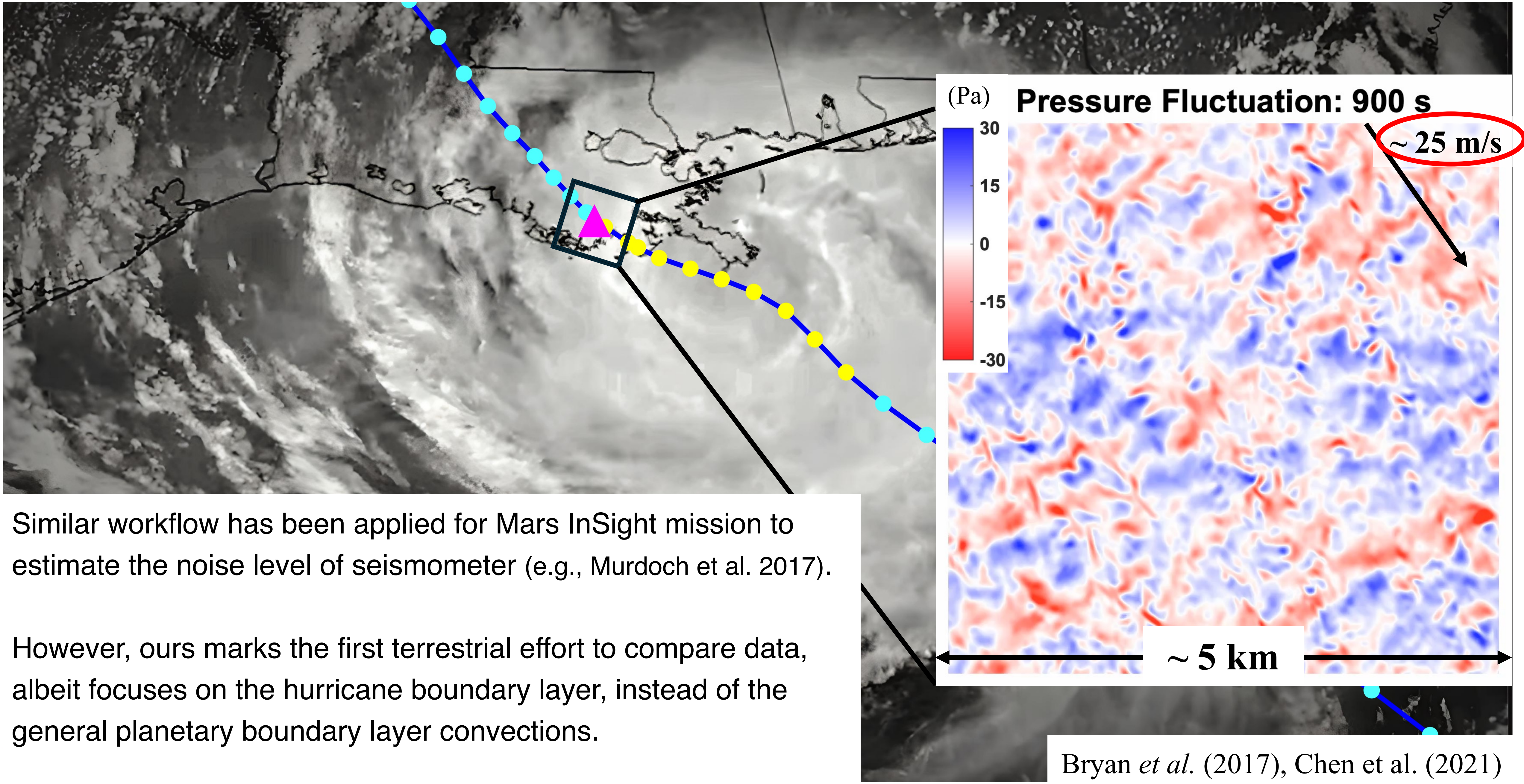
Eddy size > Grid size: Numerically resolved

Large eddy

Eddy size < Grid size: Parameterized by subgrid model

Bryan *et al.* (2017), Chen et al. (2021)

LES of Hurricane Boundary Layer (HBL) on land

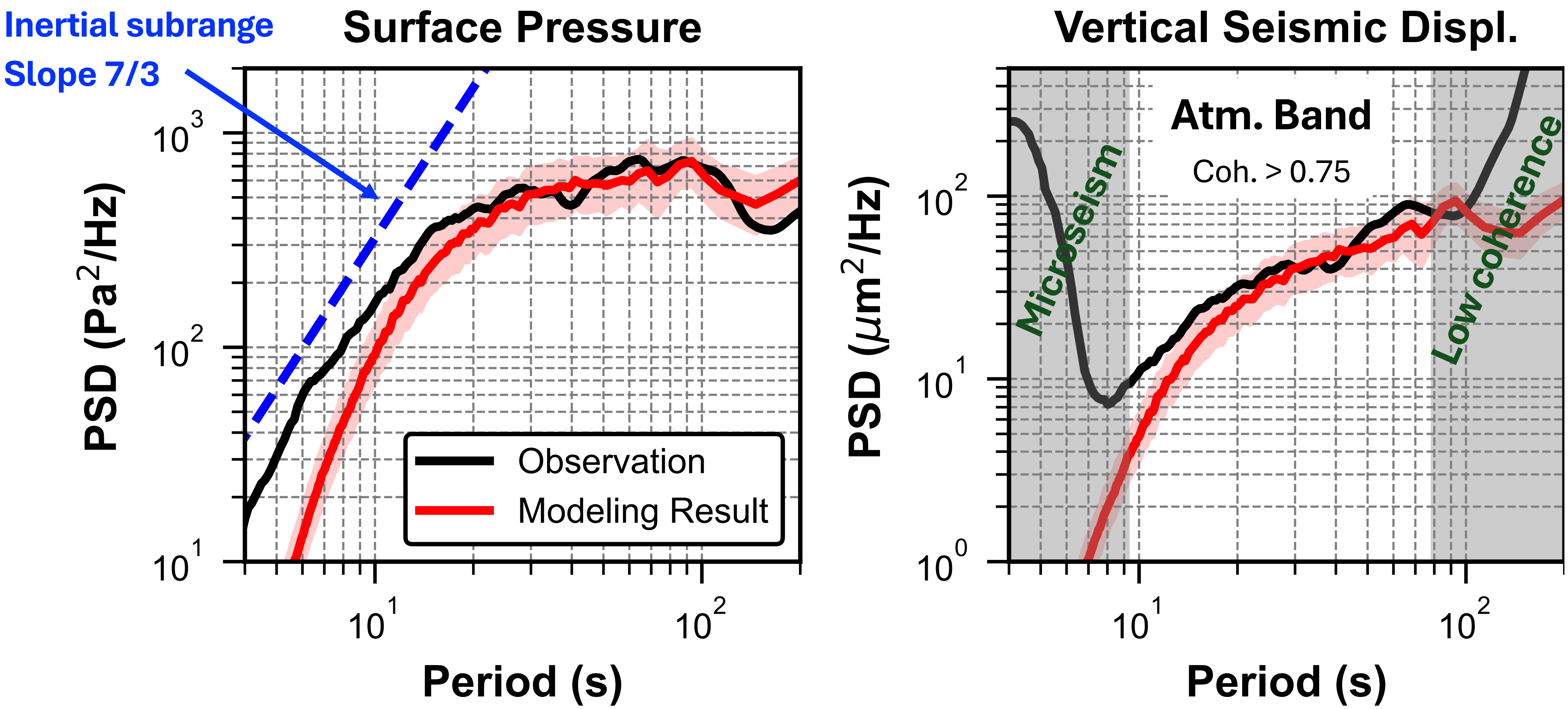


Similar workflow has been applied for Mars InSight mission to estimate the noise level of seismometer (e.g., Murdoch et al. 2017).

However, ours marks the first terrestrial effort to compare data, albeit focuses on the hurricane boundary layer, instead of the general planetary boundary layer convections.

Bryan *et al.* (2017), Chen et al. (2021)

Infrasound & seismic spectra



Infrasound data can be used for turbulent analysis.

Seismic signals originate from turbulence in the atmospheric band.

Summary: Generation mechanisms of seismic ambient noise

Fourier mode

$$e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}$$

Natural processes from ocean, atmosphere, …

↓

Seismic noise sources

(at Earth's surface)

$$p(x, y, t)$$

$c_{\text{source}} \ll c_{\text{seis}}$ ↙ ↘ $c_{\text{source}} \approx c_{\text{seis}}$

Local quasi-static response

Turbulent imprints

Ocean wave imprints on OBS …

Dynamic seismic waves

Microseism, seismic hum

Background free oscillations …

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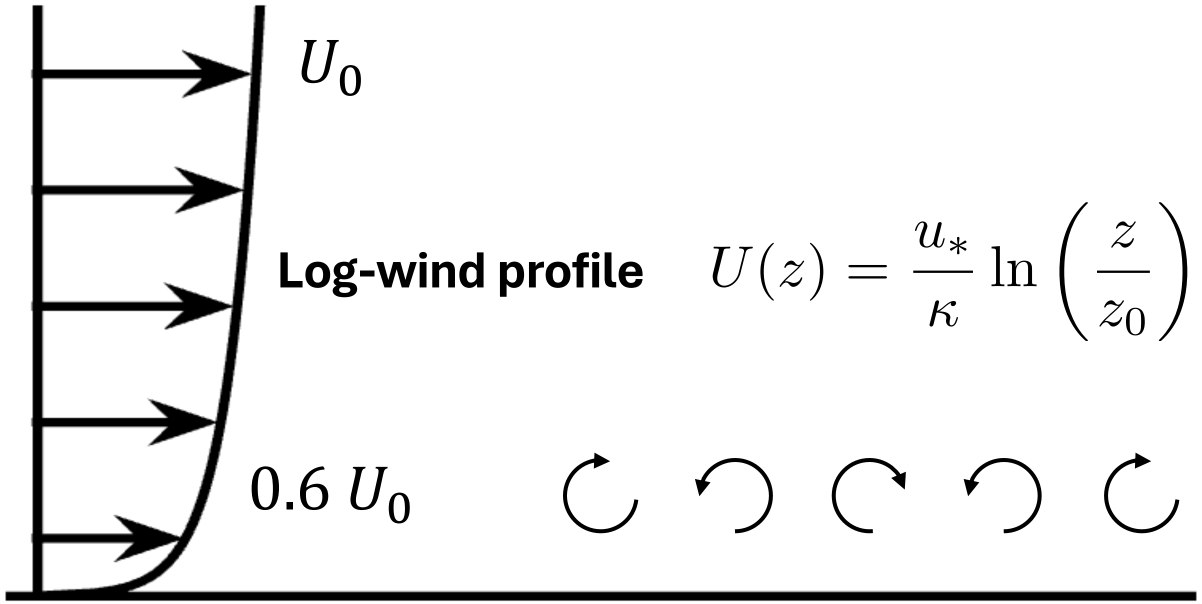
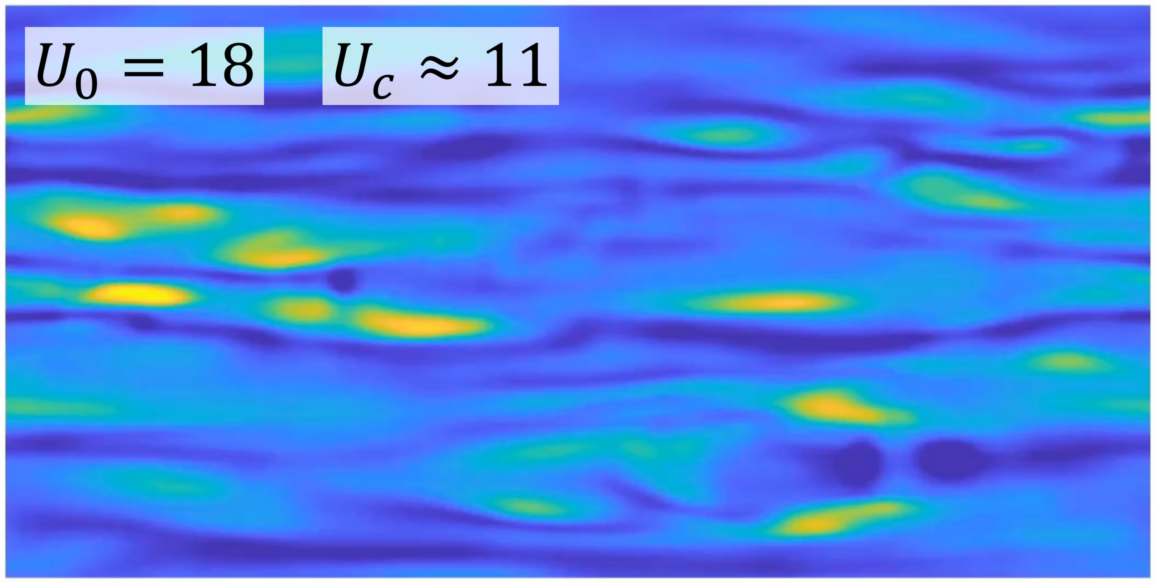
** Wall stress / pressure of turbulent boundary layers

Turbulent boundary layer



Wall shear stress of a channel flow



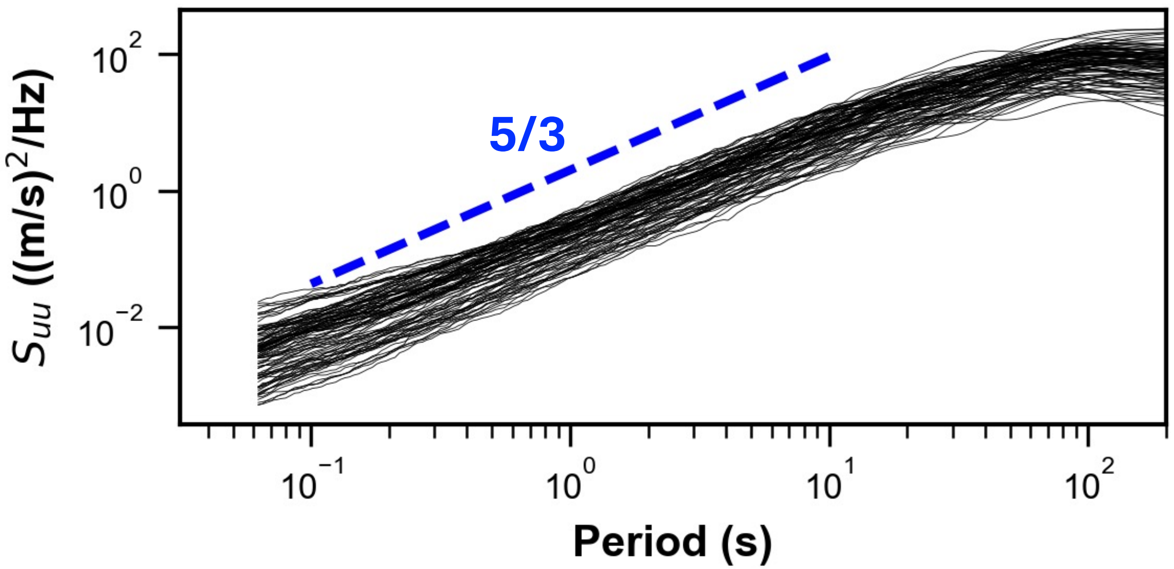
Velocity is zero at the wall, but wall stress / pressure advects with U_c (advective velocity)

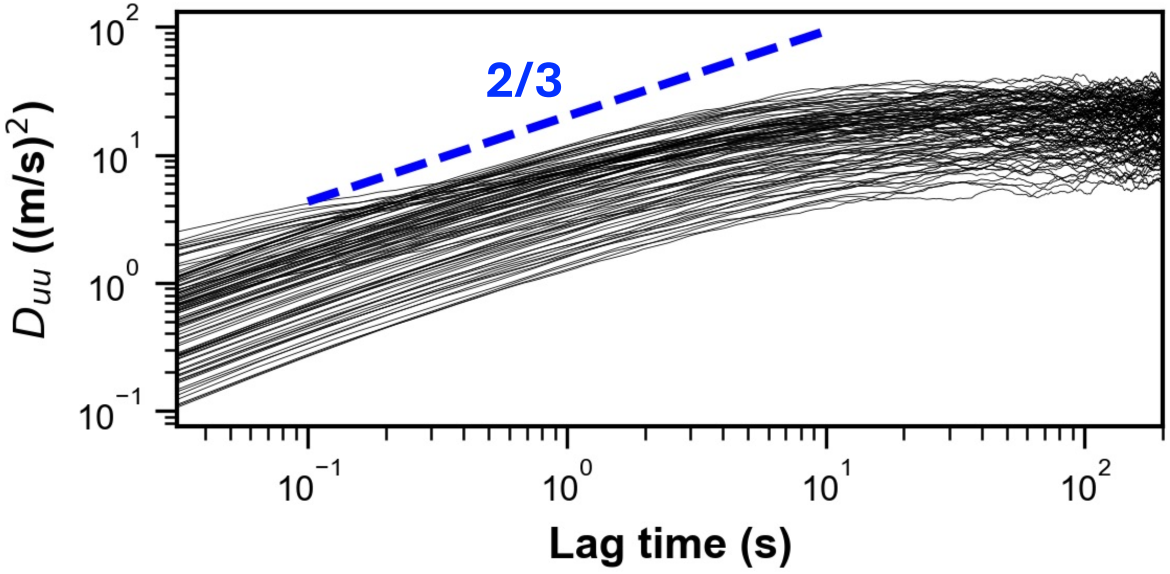
Theoretical and experimental studies show $U_c \approx 0.6\ U_0$ with free-stream velocity U_0

Assuming a log-wind profile, U_c can further be related to $U_{10\ \mathrm{m}}$ at a specific height

Turbulent wind spectrum from tower data

Inertial subrange





Streamwise velocity PSD

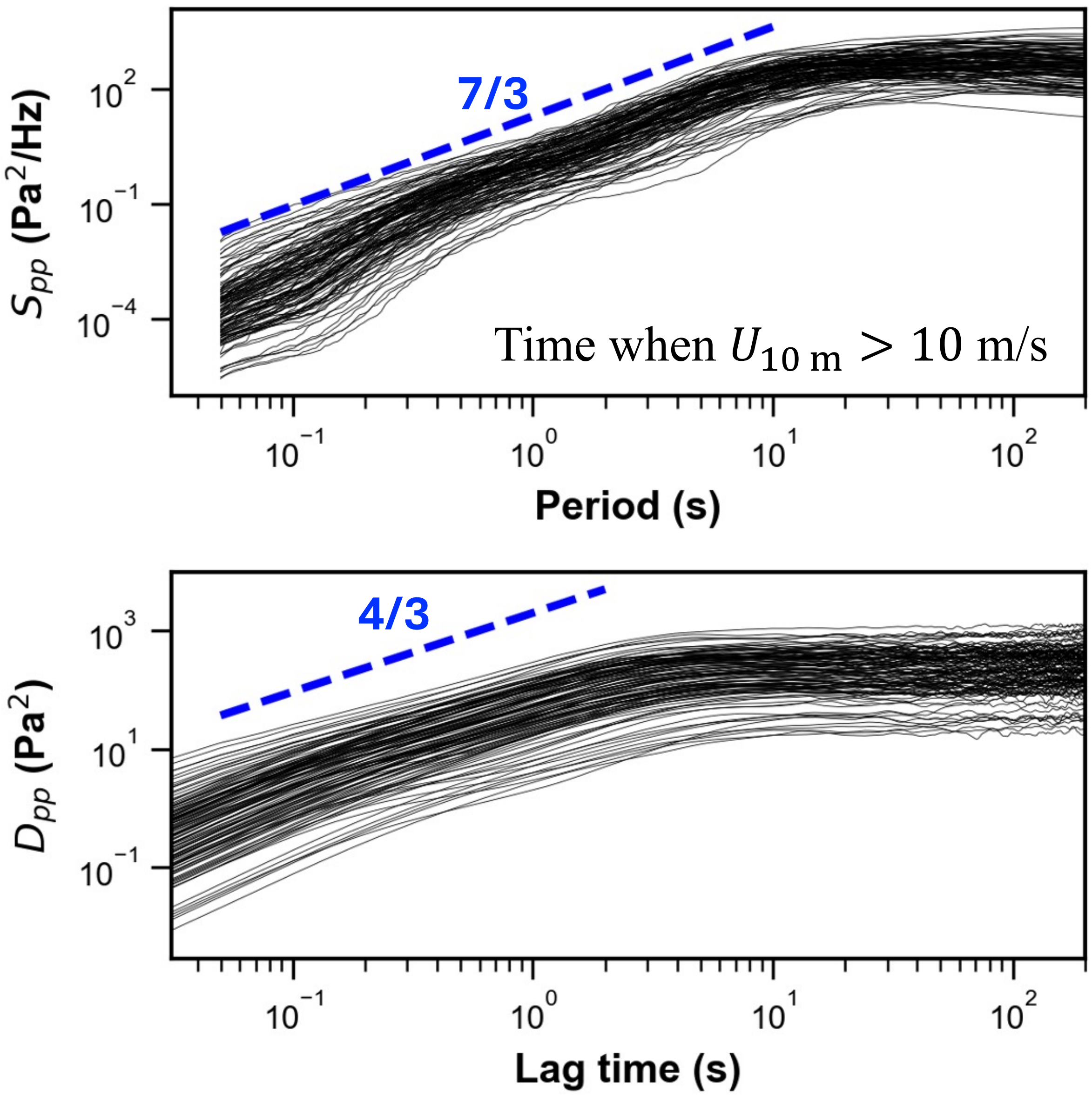
$$S_{uu}(f) = \alpha_u \left(\frac{\varepsilon U}{2\pi}\right)^{2/3} f^{-5/3}$$

Dissipation rate ε *is a key parameter describing the turbulence statistic and contributes to an important energy source for hurricanes.*

Streamwise structure function

$$D_{uu}(\tau) \equiv \overline{[u(t+\tau) - u(t)]^2} = C_u (\varepsilon U)^{2/3} \tau^{2/3}$$

Turbulent pressure spectrum from infrasound data



Pressure PSD

$$\frac{1}{\rho^2} S_{pp,\mathrm{t}}(f) = \tilde{\alpha}_p \left(\frac{\varepsilon U_c}{2\pi}\right)^{4/3} f^{-7/3}$$

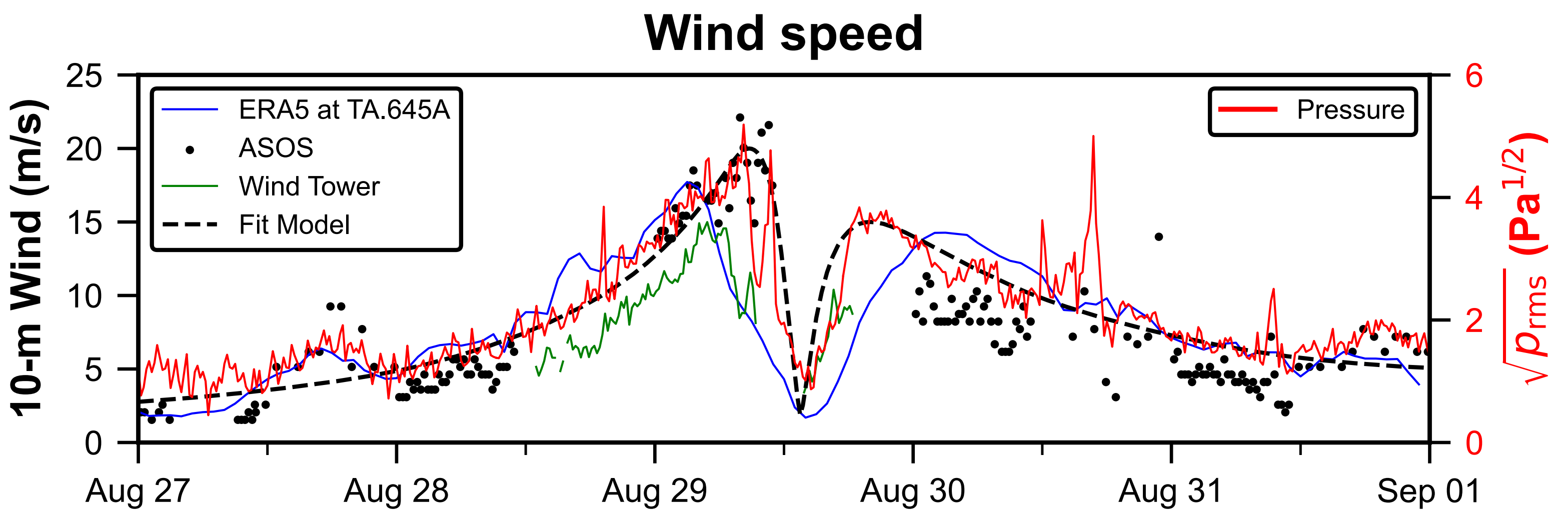
The 7/3 slope is turbulence-turbulence interaction or "slow-term" contribution (George et al. 1984)

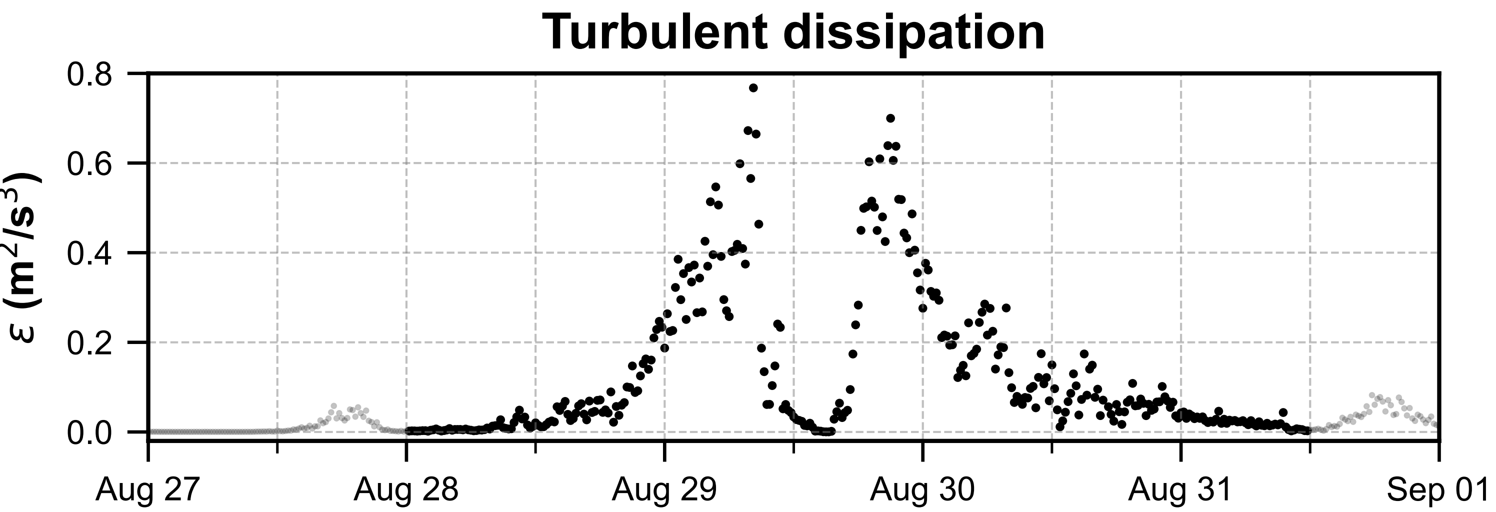
Assume $U_c \approx 1.6\, U_{10\,\mathrm{m}}$

Pressure structure function

$$\frac{1}{\rho^2} D_{pp,\mathrm{t}}(\tau) = C_p \left(\varepsilon U_c\right)^{4/3} \tau^{4/3}$$

Continuous monitoring of hurricane landfall





Fluctuation: $p_{rms} \propto u_{rms}^2$

Turbulent intensity: $u_{rms} \propto U$

Fit wind model: $U_{10\,\mathrm{m}} = U(r)$

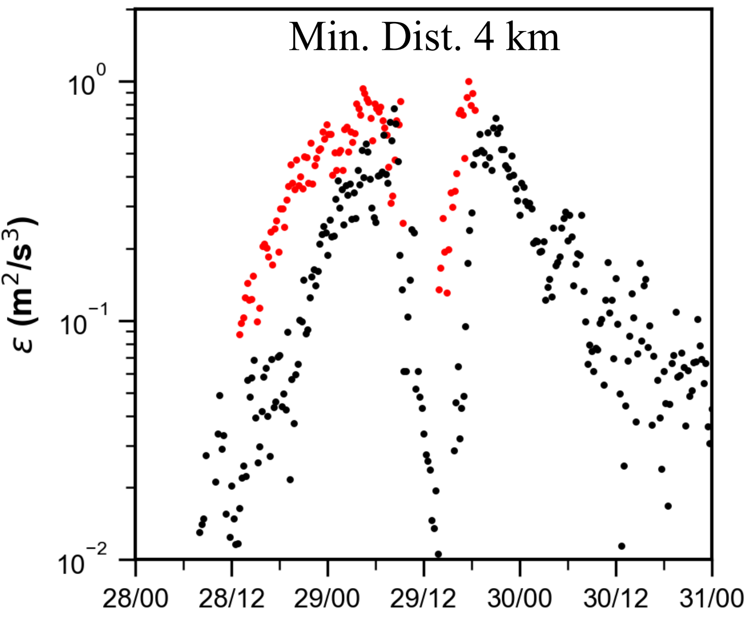
ERA5 reanalysis has a wider radius of the hurricane eye.

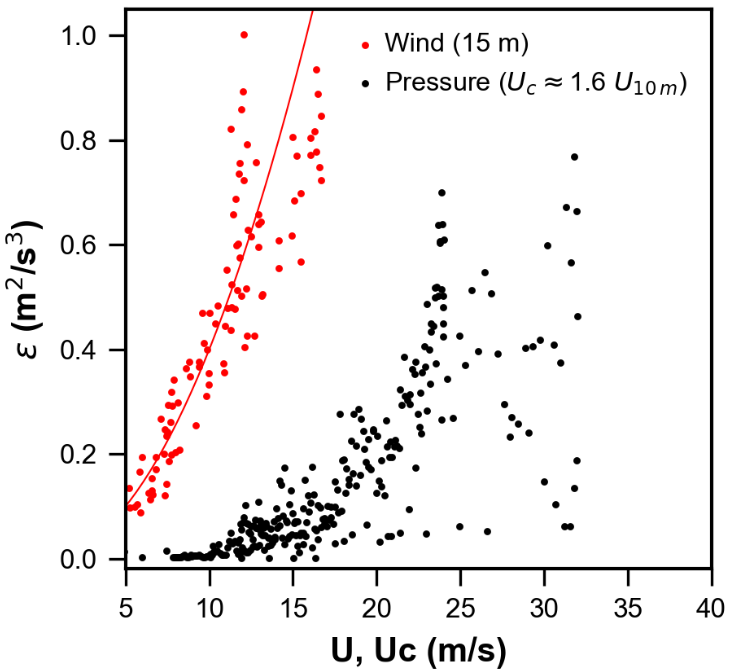
$O(0.1\ \mathrm{m}^2/\mathrm{s}^3)$ dissipation rate

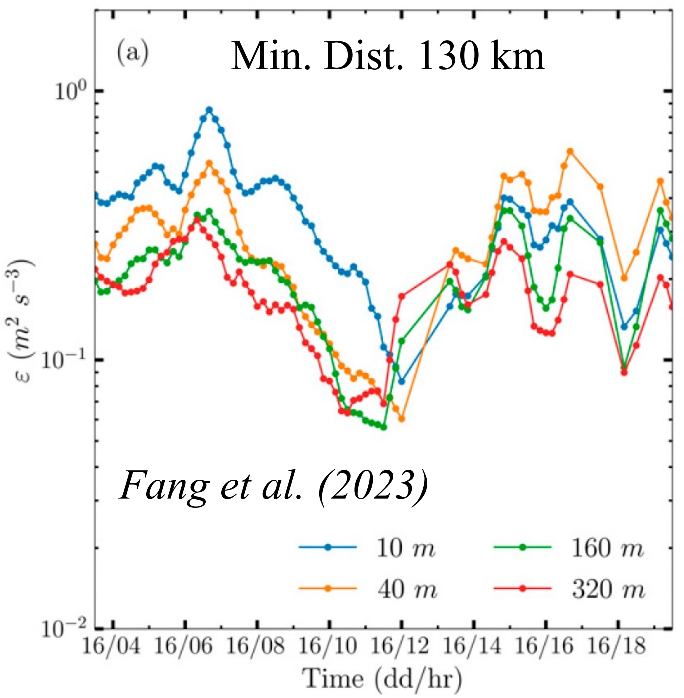
Interpreted as ε for height ~ 100 m

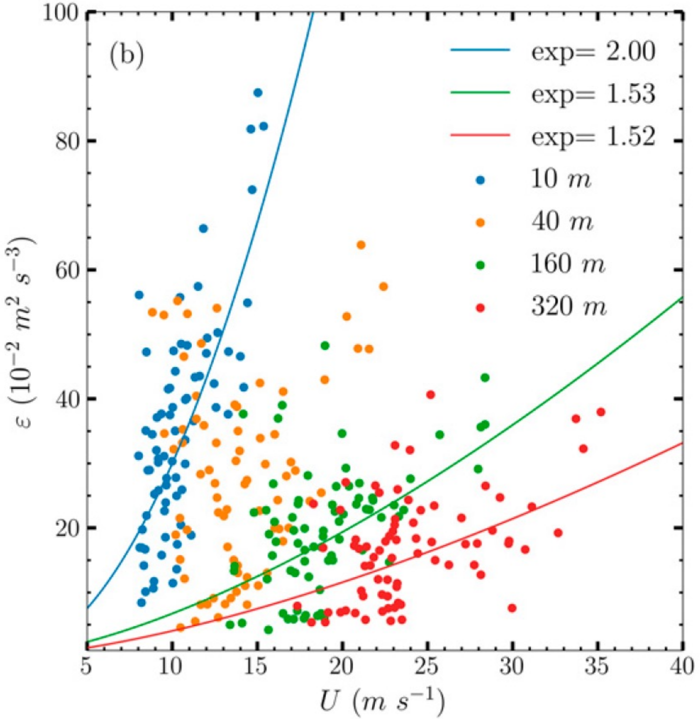
Wind model not accounted for diurnal cycles (daytime convection)

Turbulent dissipation rate during hurricane landfall







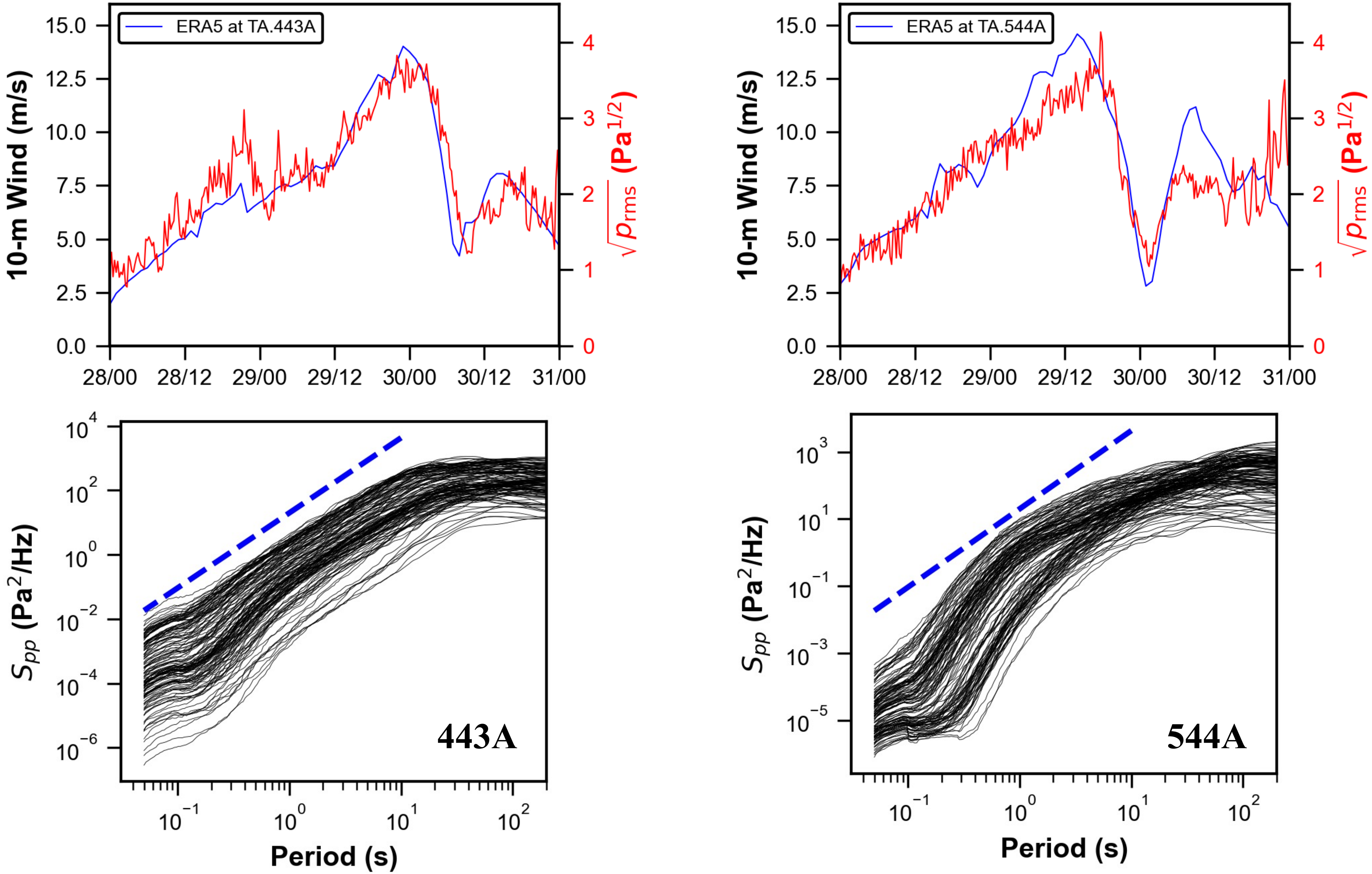


Estimation of ε from pressure uses advective velocity U_c. The result is interpreted as local ε at height where wind speed is U_c.

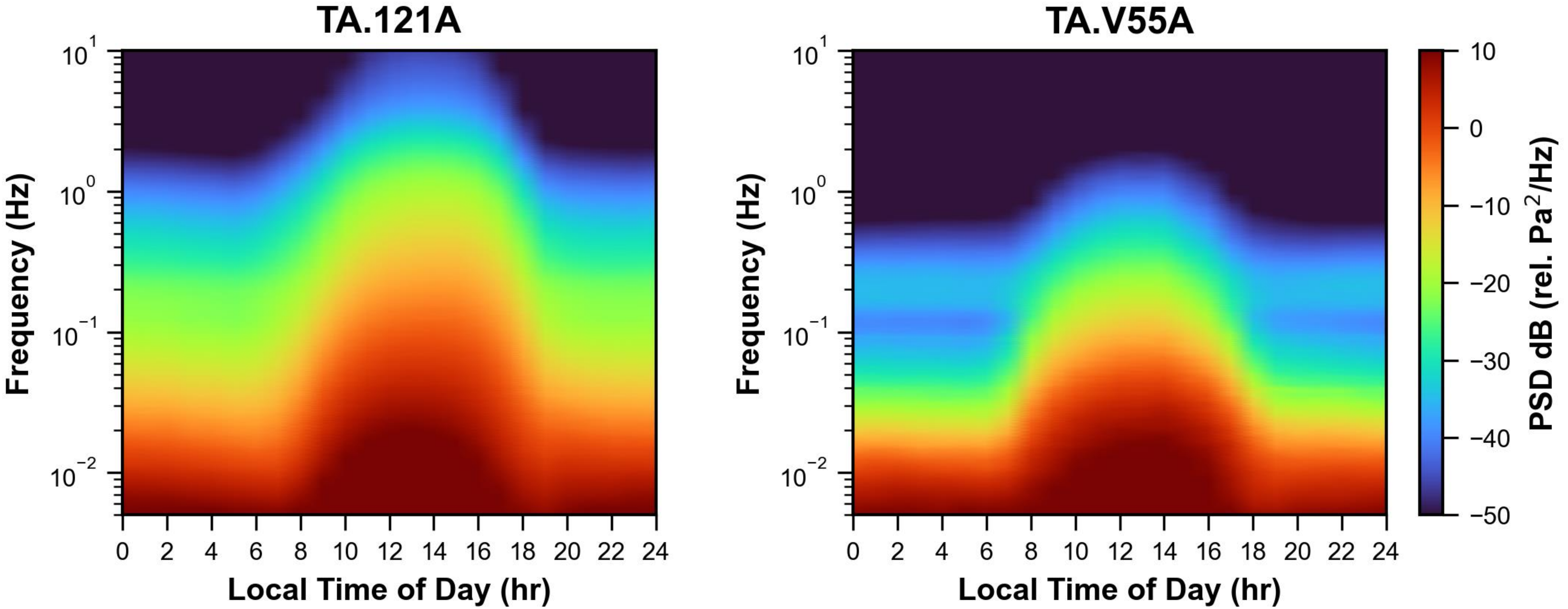
Outliers of low ε at high wind speed is due to using the fit wind model not including a transient drop in wind.

Infrasound data can provide a lower bound of ε of the surface layer.

Potential for monitoring general atmospheric conditions



Diurnal cycles shown in pressure spectral amplitude



Diurnal variation in turbulence in response to solar heating (Stull, 1988)

Surprise #1: Seismic stations record in-situ data of Hurricane Issac after landfall

Distinct seismic ground motion contributed by ocean and atmosphere

Surprise #2: Turbulence explains the seismoacoustic signatures (in the atm. band)

Interdisciplinary modeling framework to explain observations

Surprise #3: Potential of seismic stations for environmental monitoring

Station networks with years of continuous data