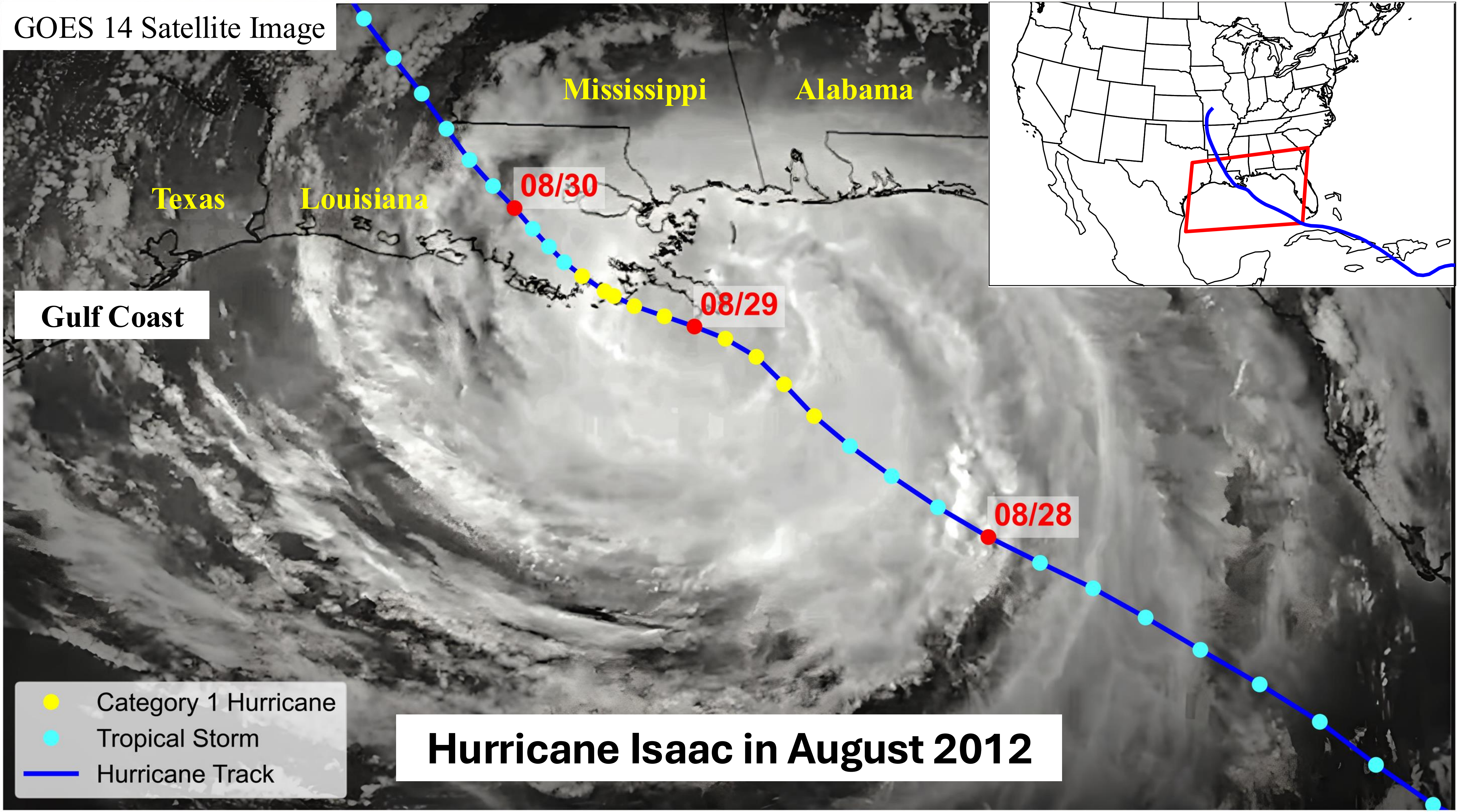
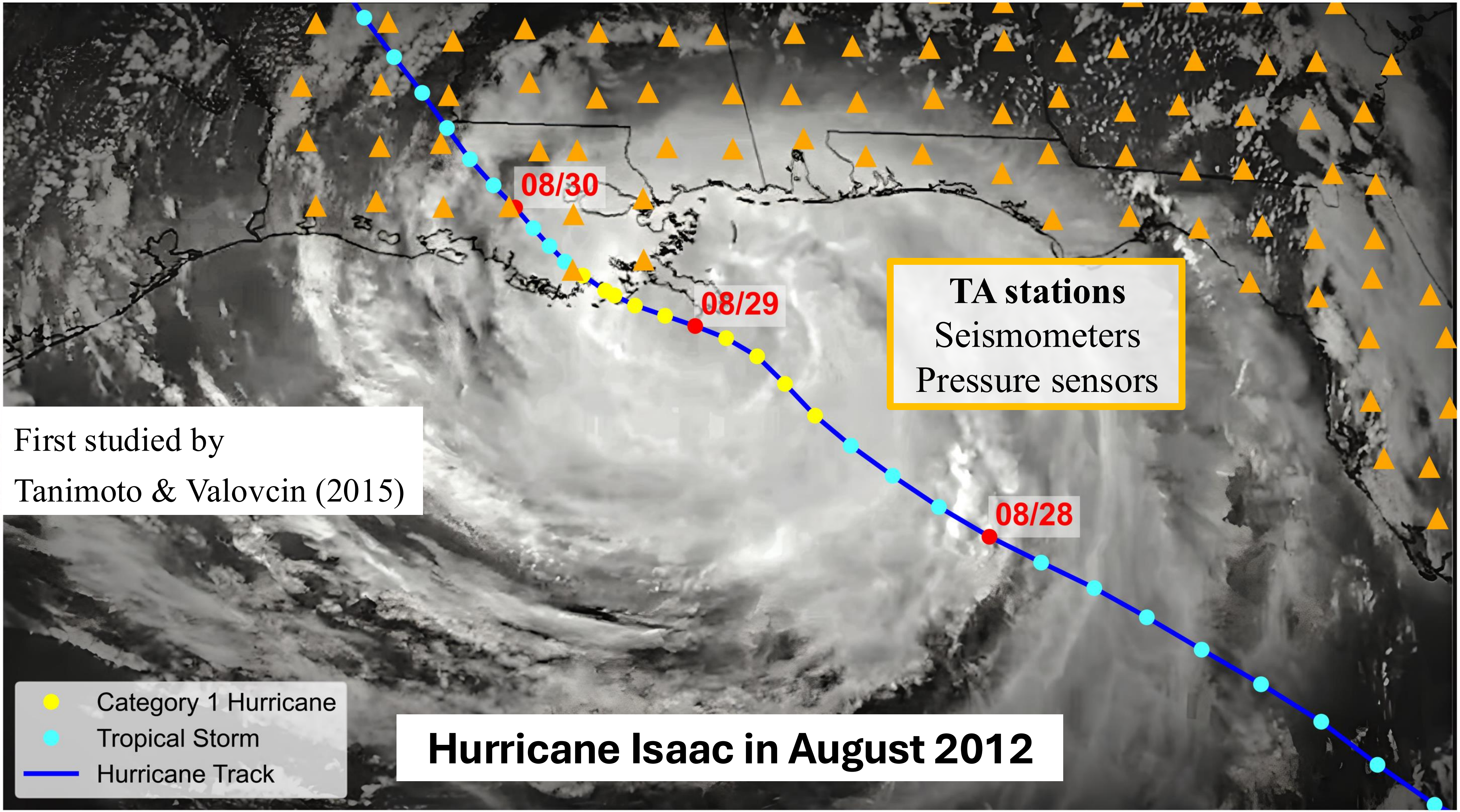
Turbulent seismoacoustic signals from a hurricane landfall

Qing Ji **Stanford University**

Brown Bag seminar at Caltech Seismo Lab, May 14


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

Valuable in-situ data from seismic stations

For atmospheric science, research aircrafts and wind towers provide data inside hurricanes

Hurricane Hunter aircraft inside the eye of Hurricane Ike (2008) *(U.S. Air Force photo)*

- Dangerous airflights, rare observations
- Hurricane boundary layer (bottom ~1 km of atmosphere) still have many open questions

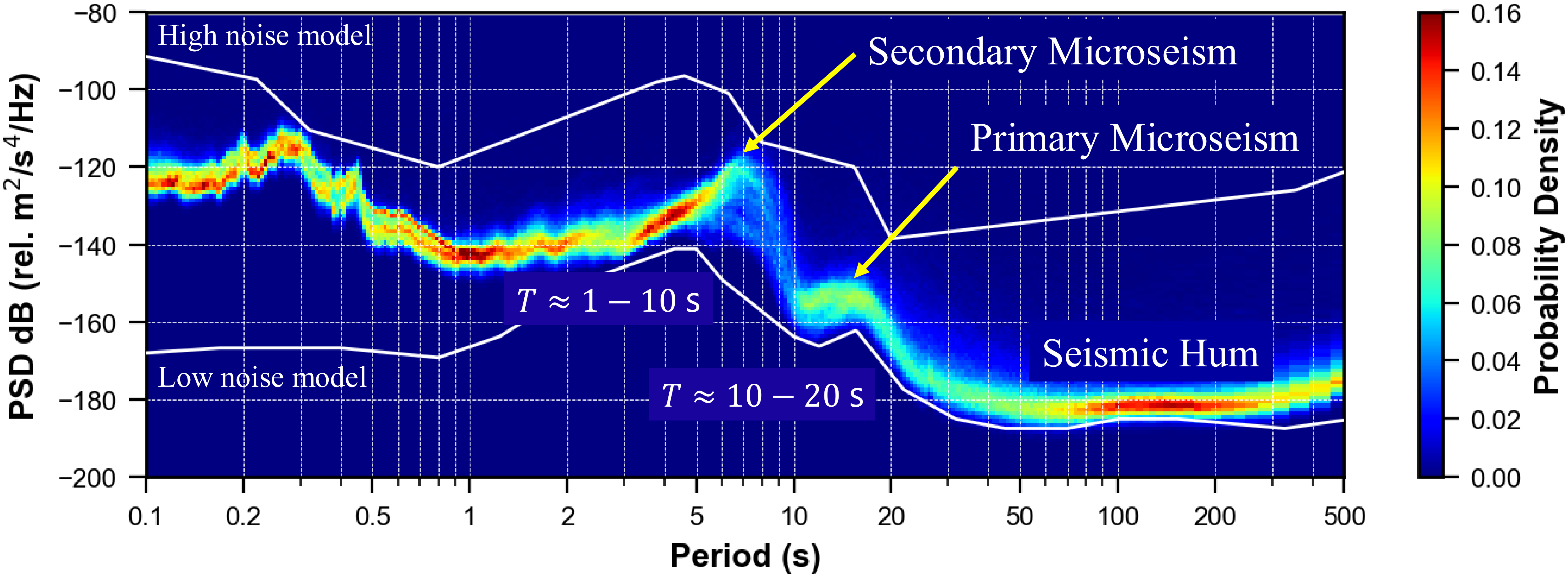
Seismic stations as surface observatory for atmospheric study

How knowledge from atmospheric sciences help understand seismic ambient noise?

How can seismic instruments contribute to the atmospheric study?

Seismic ambient noise relates to various natural processes

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



Human activity

Oceanic Noise

Atmospheric Noise

Oceanic sources of seismic ambient noise

Ocean waves

↓

Seismic noise sources

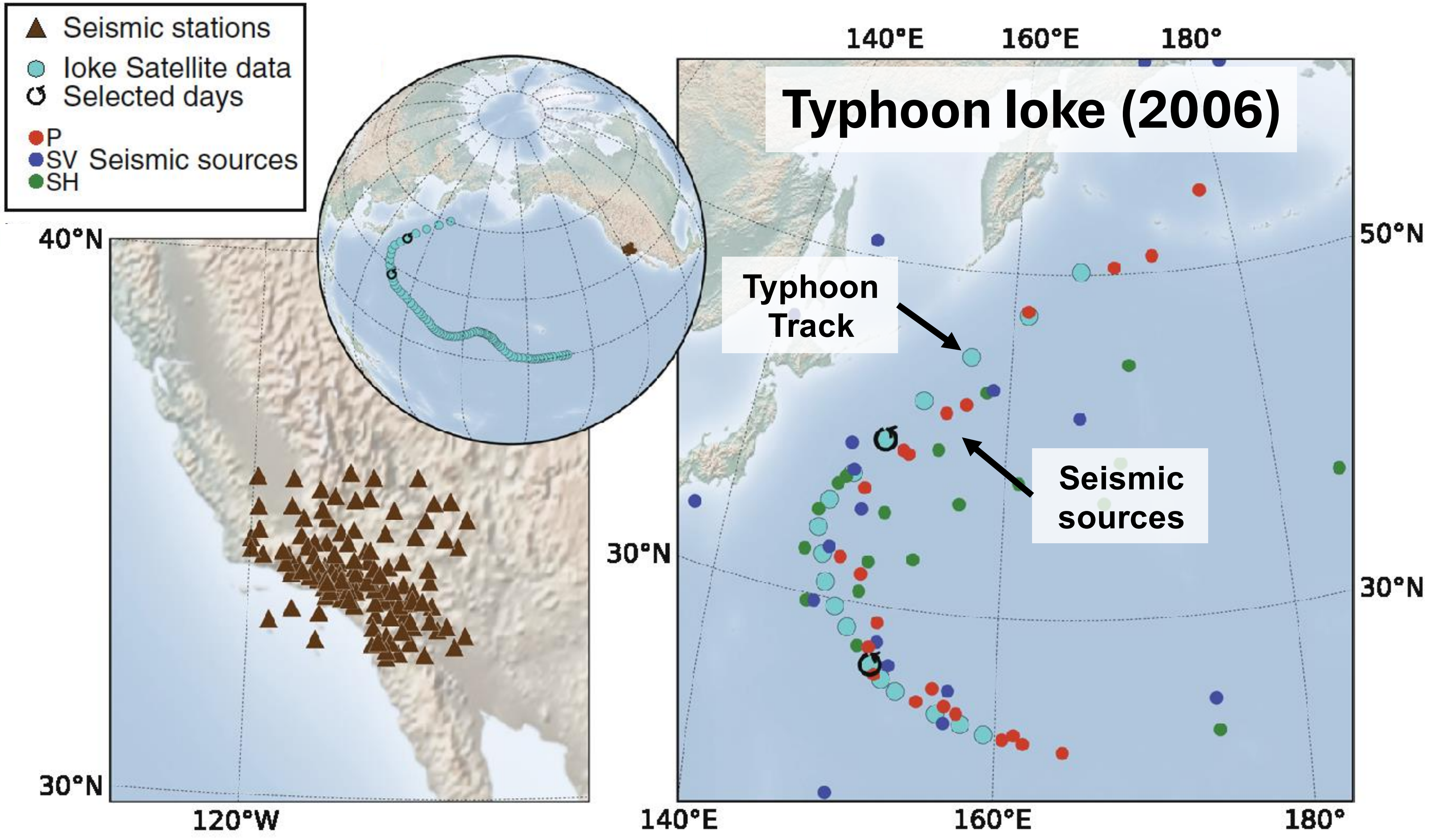
(at Earth's surface)

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

↓

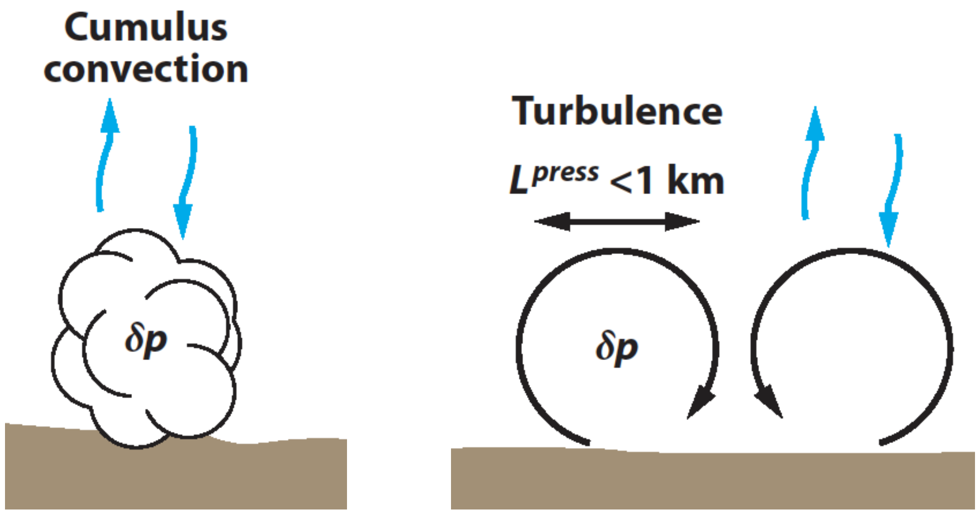
Microseism

(Seismic waves)



Retailleau & Gualtieri (2021)

Atmospheric sources of seismic ambient noise



Nishida (2013)

Atmospheric acoustic waves, internal gravity waves …

Seismic noise sources

(at Earth's surface)

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

Martian seismic noise
(e.g., Murdoch et al. 2017)

Atmospheric processes contribute to seismic signals

Seismic stations provide a new dataset for atmospheric sciences

1. Observation

Strong source, clear signals

Seismoacoustic imprints of Hurricane Isaac in 2012 during landfall

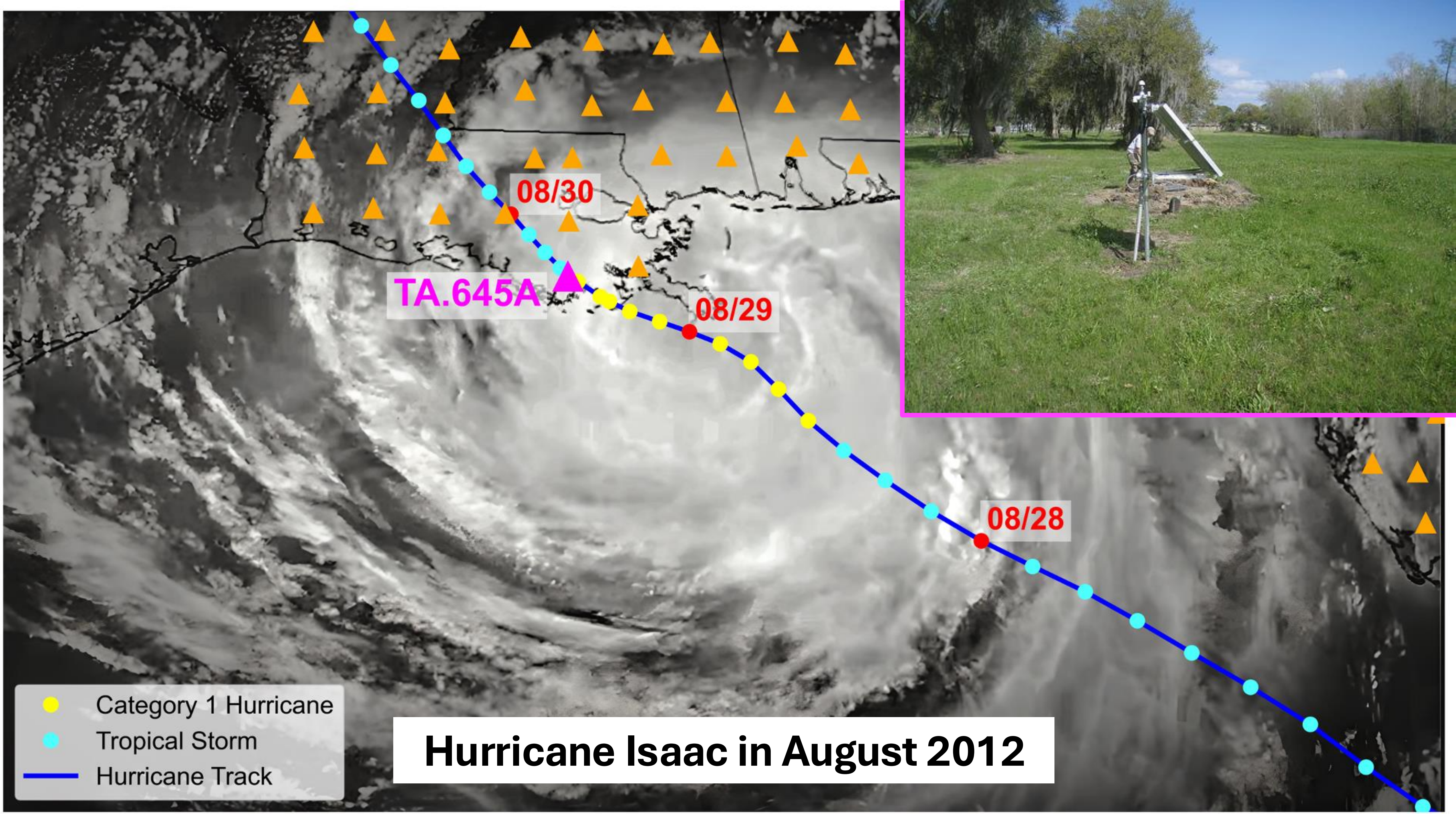
2. Interdisciplinary modeling

Large-eddy simulation (LES) of turbulent surface pressure

Quasi-static seismic modeling of elastic response under turbulent pressure

3. Prospectives

Potential of seismic station data for atmospheric sciences

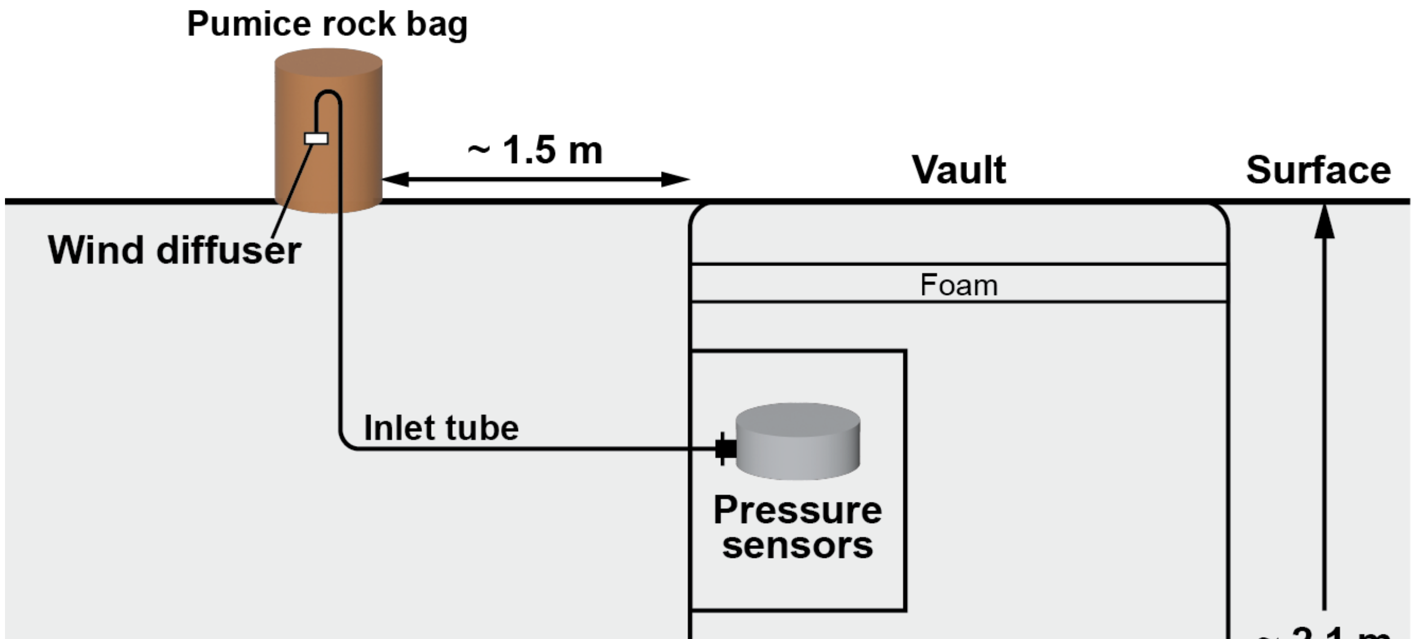


Hurricane Isaac in August 2012

Seismic station with environmental sensors

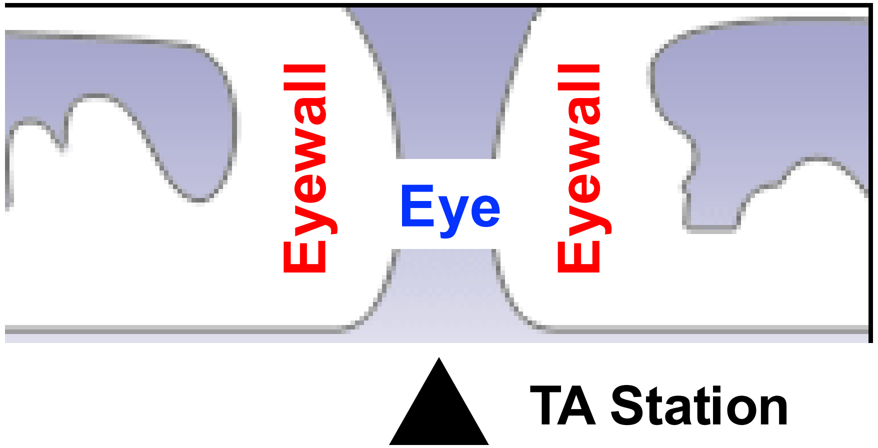
Channel	Observation
LH[ZNE]	Three-component seismic ground motion
LDO	Barometric pressure
LDF	Infrasound pressure

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



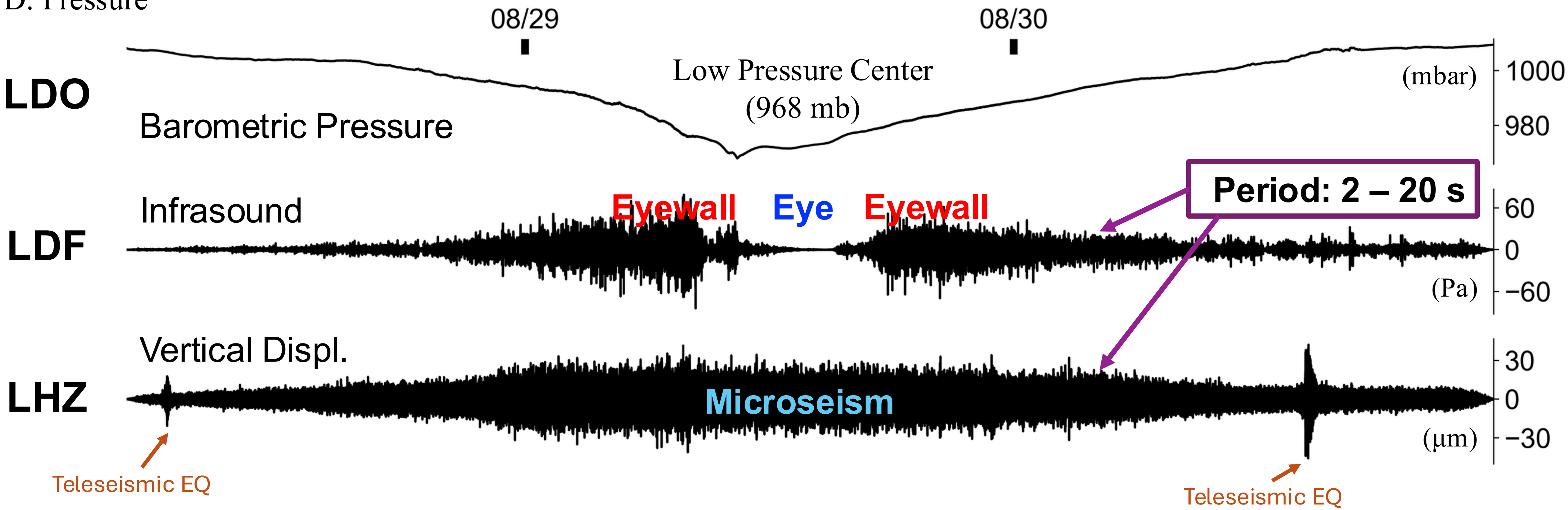
Modified from Tytell et al. (2016)

As hurricane passes the station ......

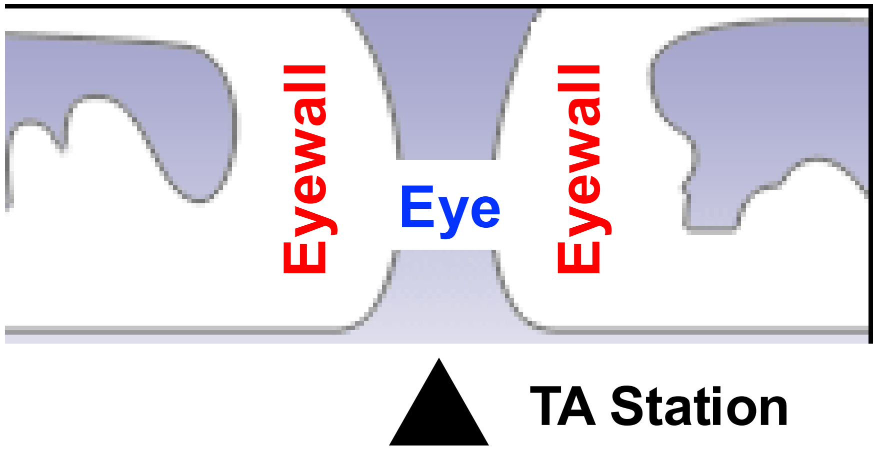


L: Long period (1 Hz sampling)

D: Pressure

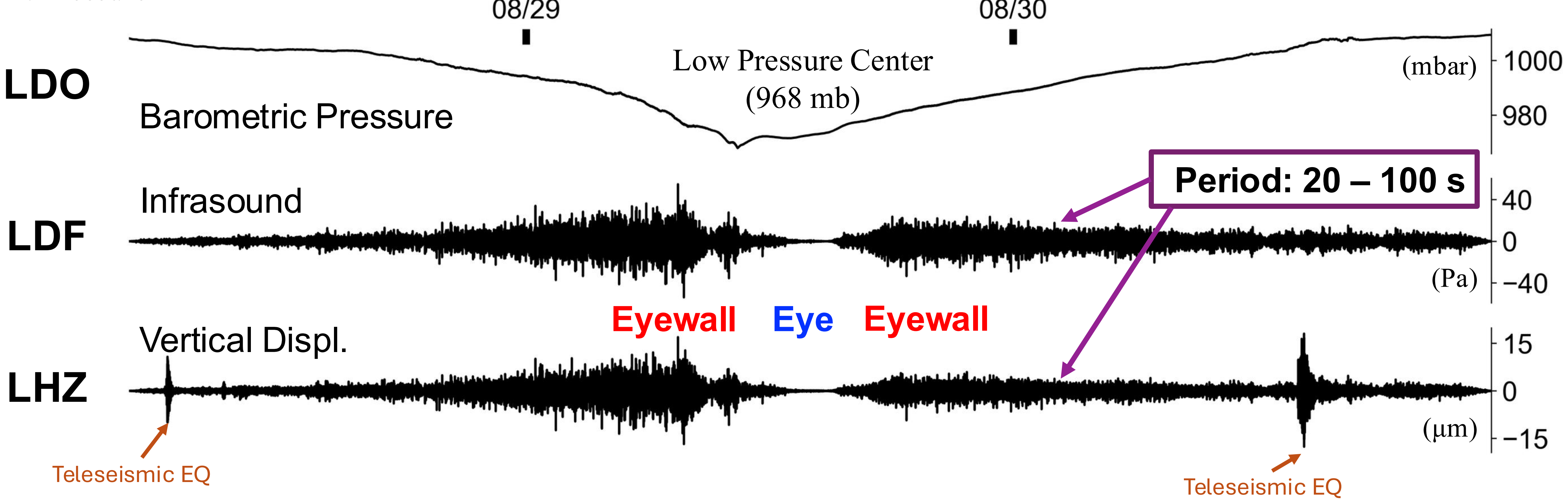


As hurricane passes the station ......



L: Long period (1 Hz sampling)

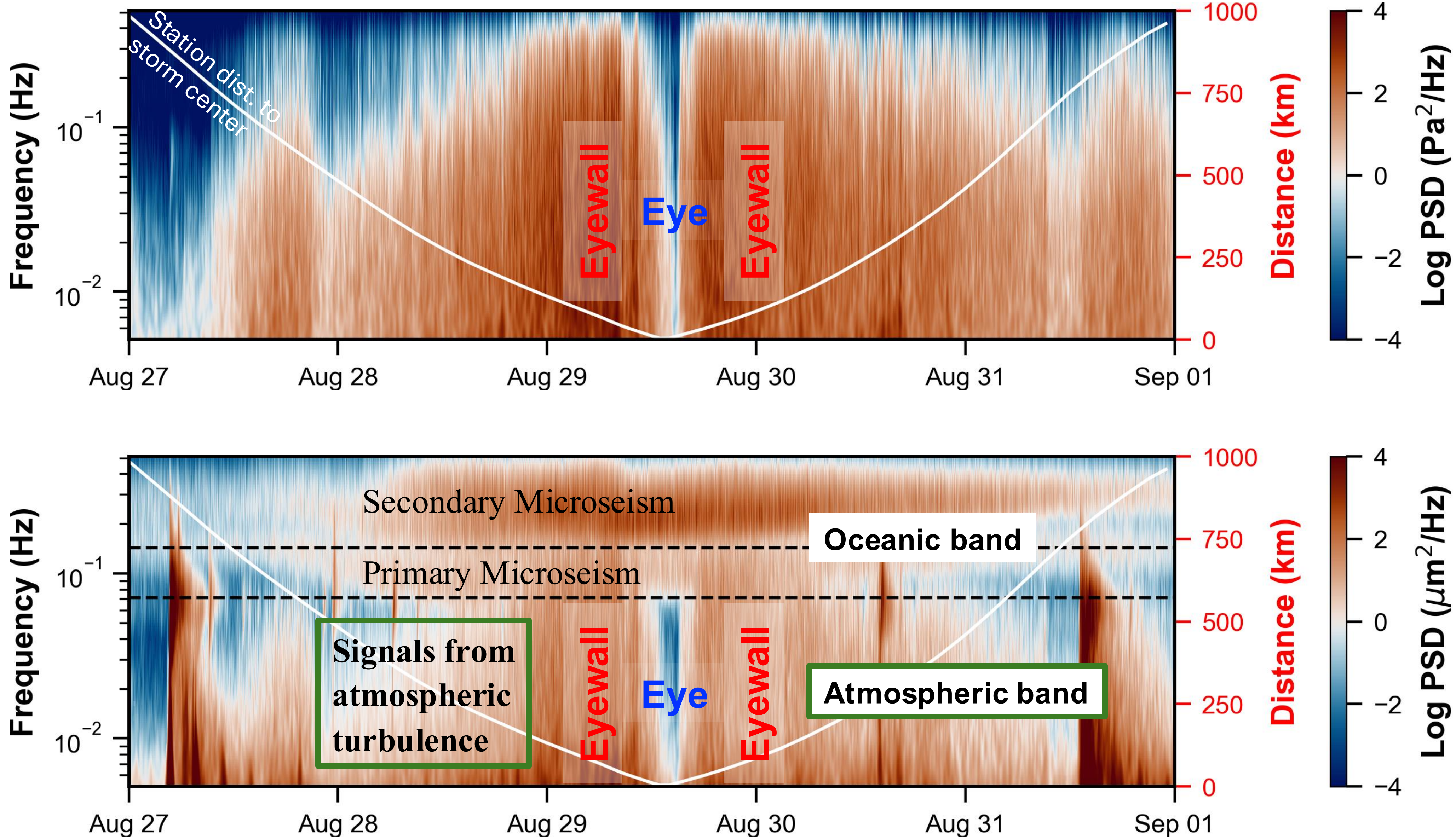
D: Pressure



Wavelet spectrograms of infrasound & seismic data

Surface Pressure

Seismic Vertical Displacement



Ji & Dunham (2024)

1. Observation

Seismic imprints of Hurricane Isaac in 2012 during landfall

2. Interdisciplinary modeling

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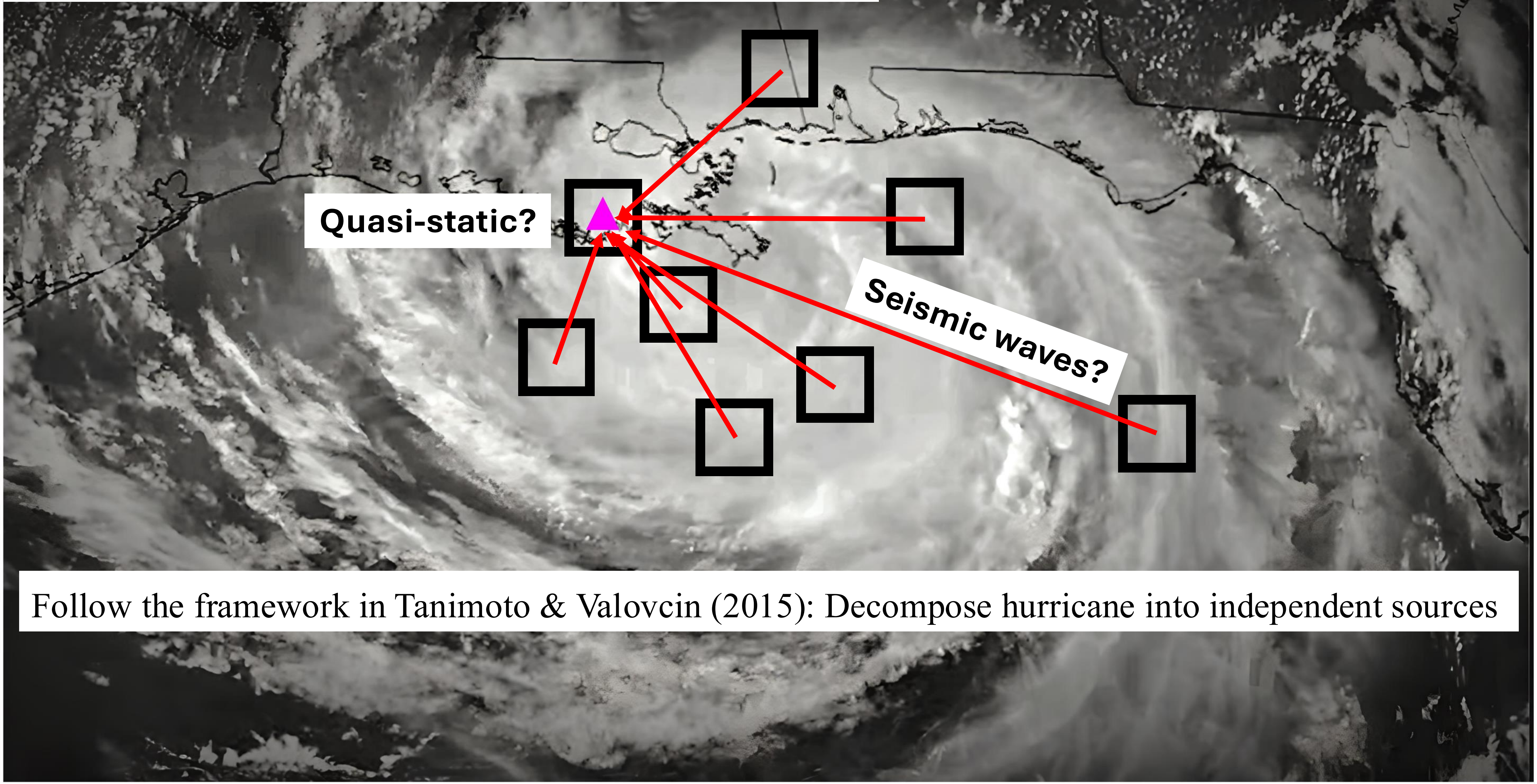
3. Prospectives

Potential of seismic station data for atmospheric sciences

Dominant contribution to seismic power?

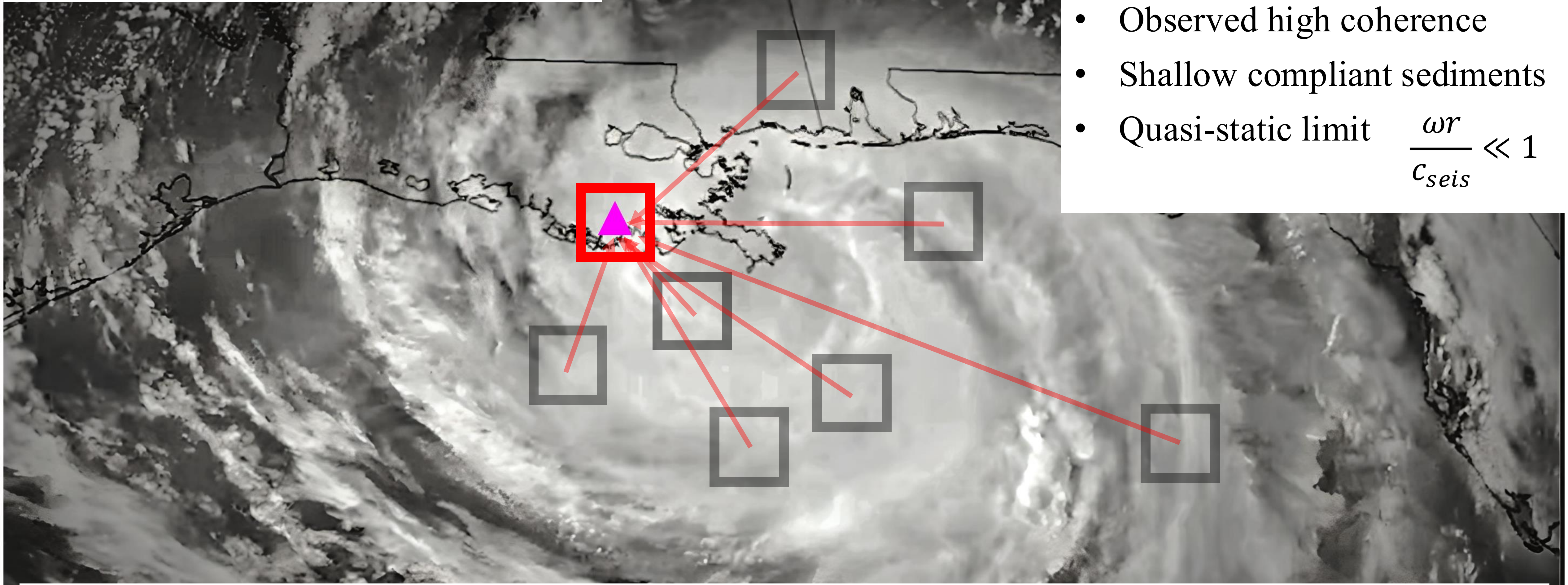


Follow the framework in Tanimoto & Valovcin (2015): Decompose hurricane into independent sources

Seismic response is “local”

Consistent with

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

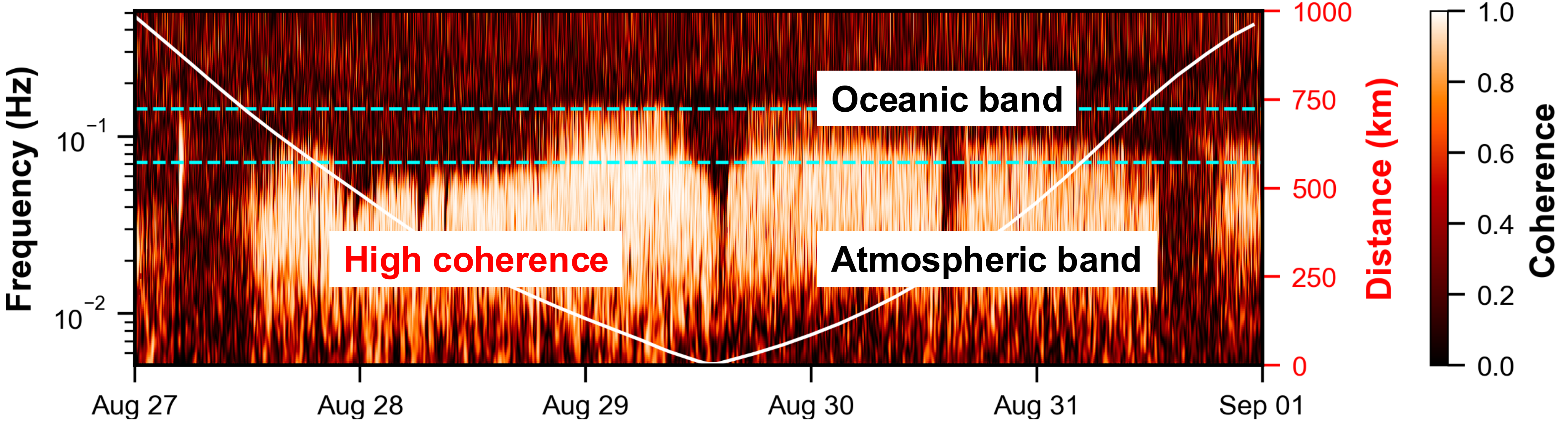


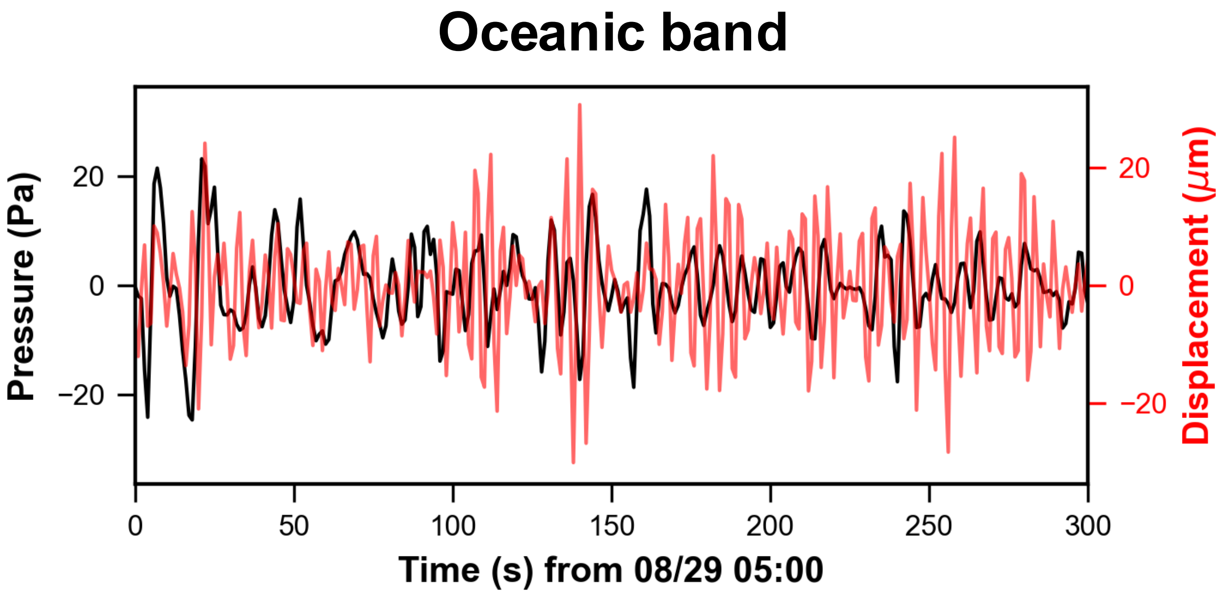
Follow the framework in Tanimoto & Valovcin (2015): Decompose hurricane into independent sources

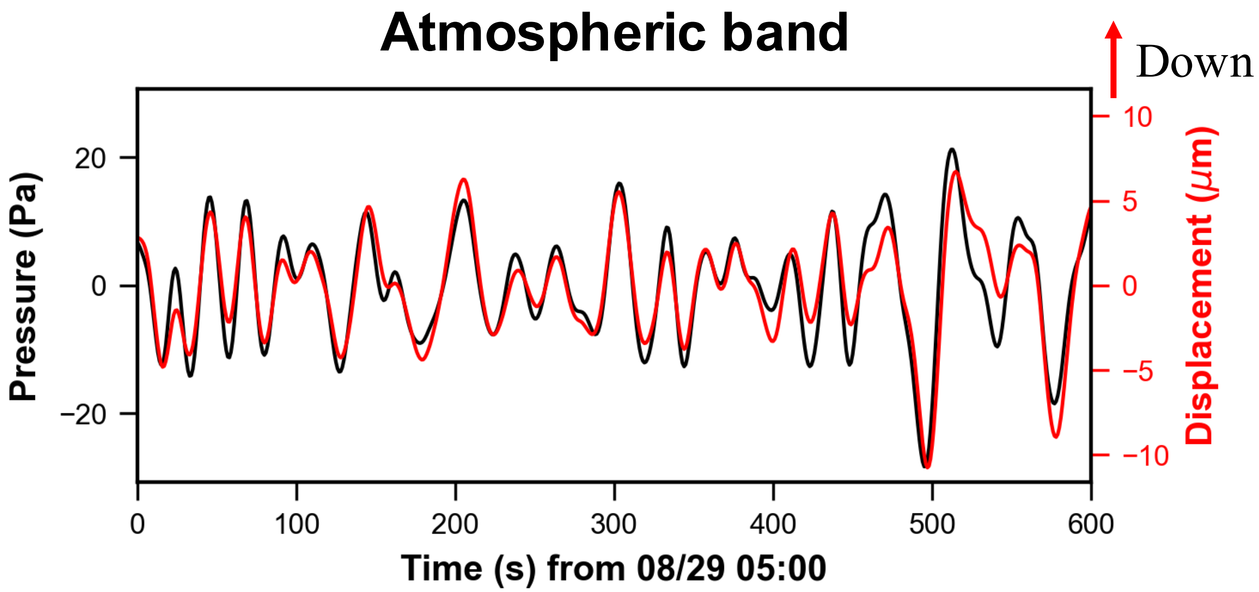
Dominant source is ~ km around the station (Ji & Dunham, 2024)

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

High coherence indicates local quasi-static response







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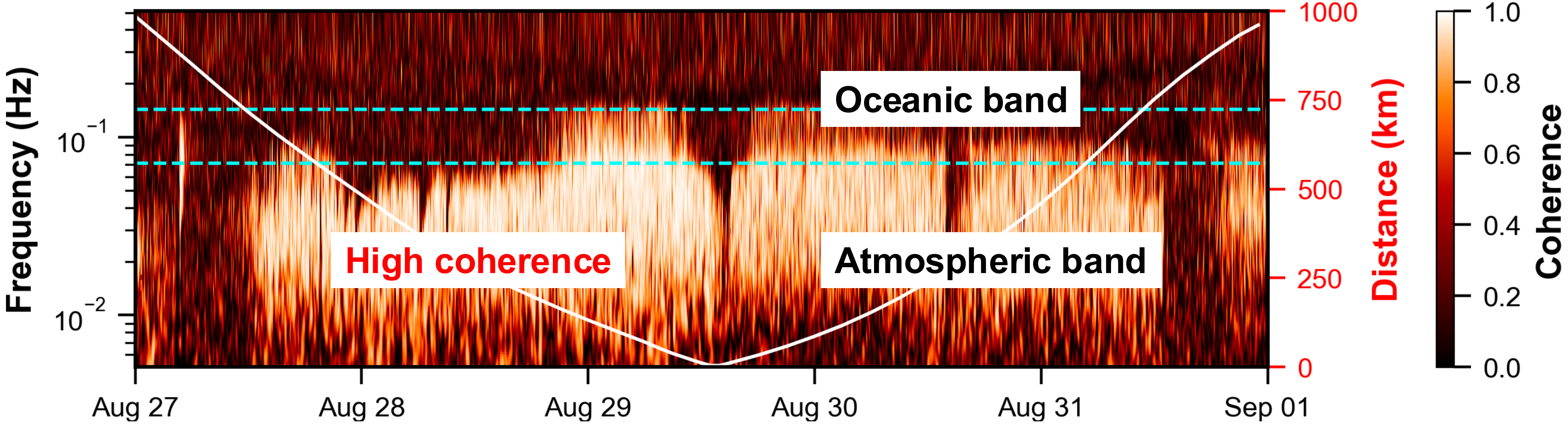
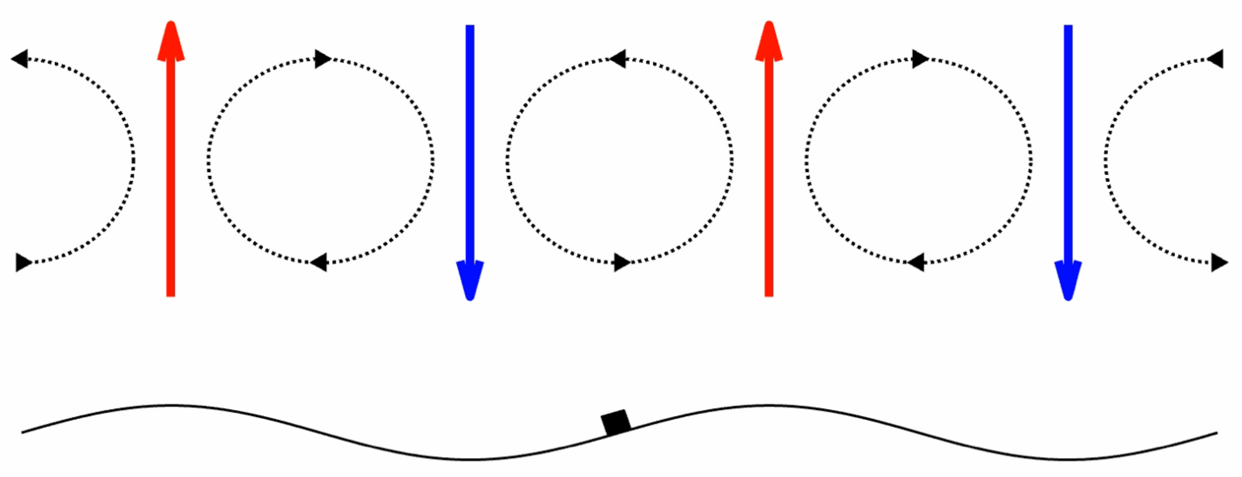


Simplified illustration

Sorrells (1971) theory

Pressure wave model



Quasi-static seismic modeling

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

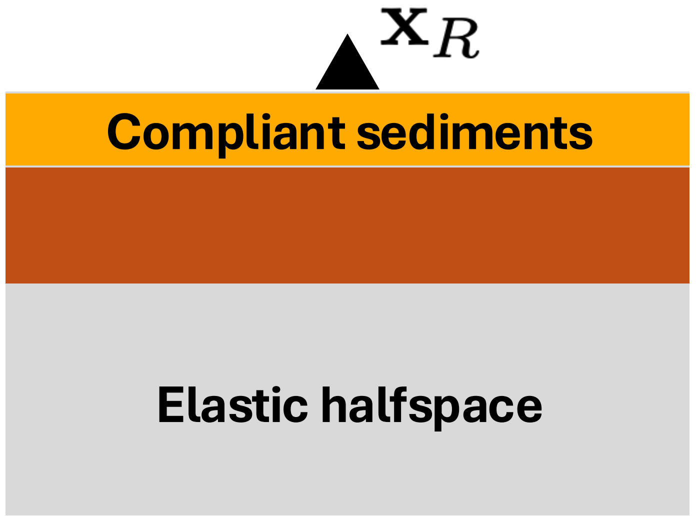
Convection velocity

Observation

(Single point)

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

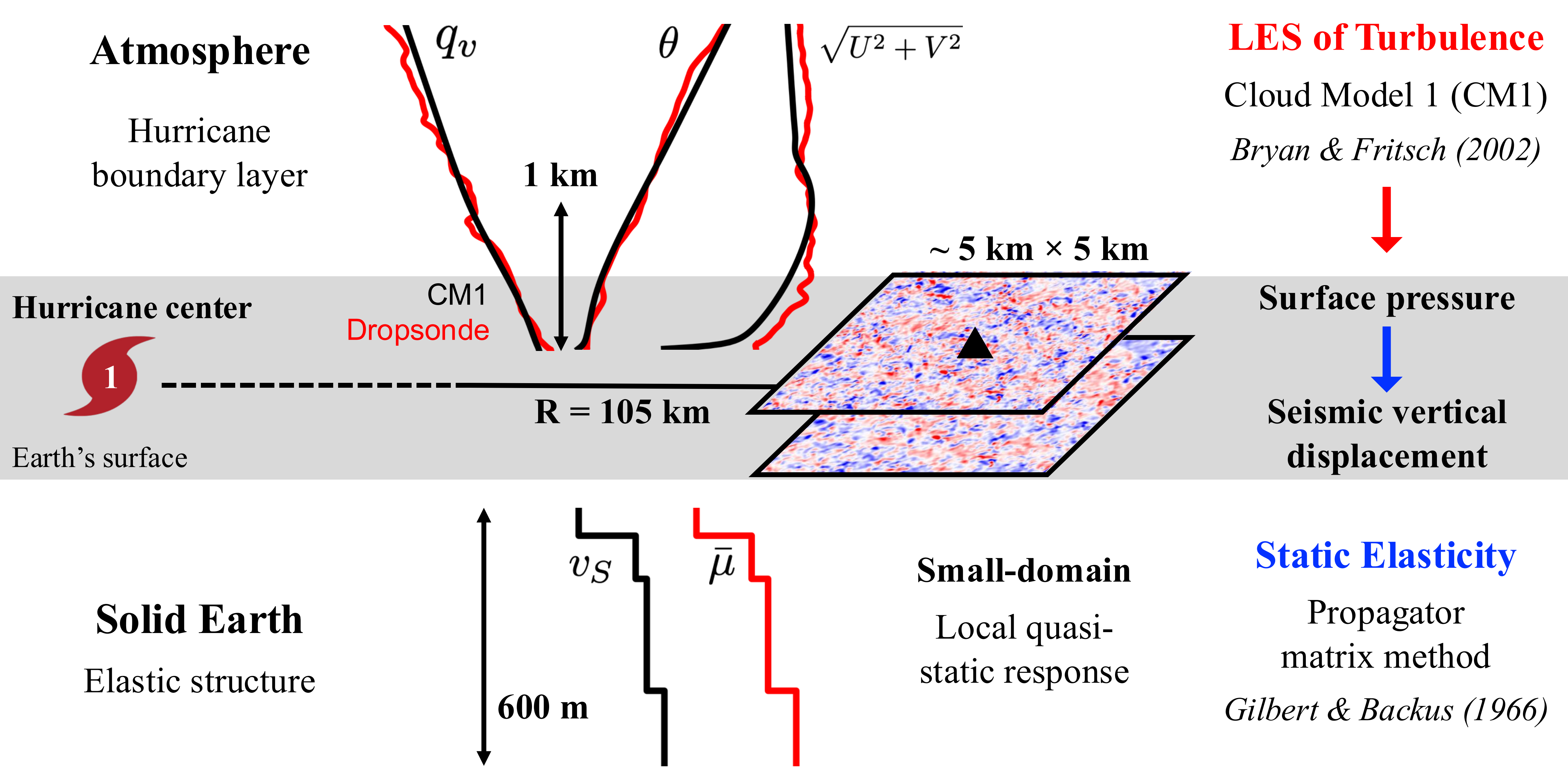
Transfer function (i.e., linear estimator)



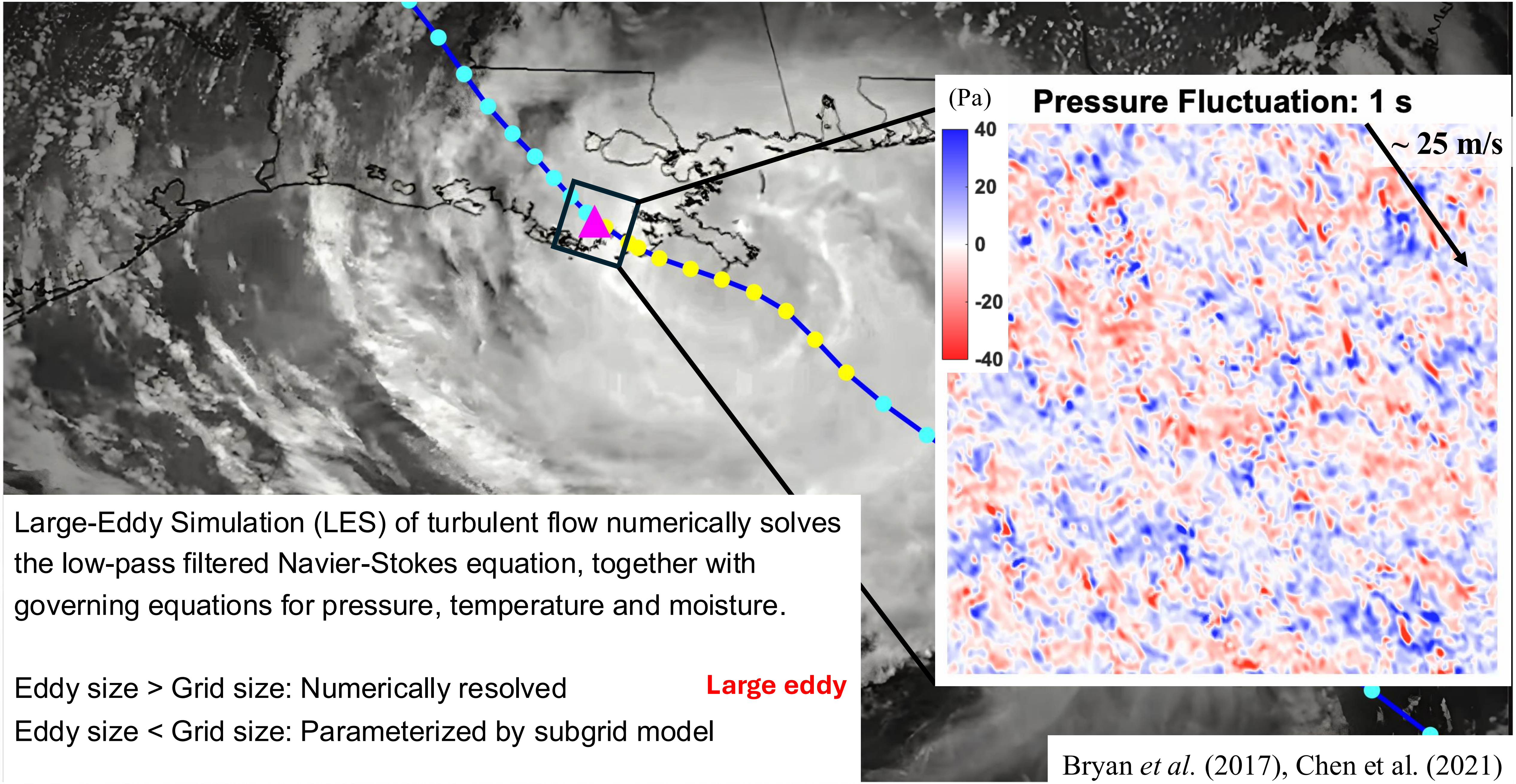
$\mathbf{k}$ Horizontal wavenumber

ω Angular frequency

Interdisciplinary modeling



CM1 LES of Hurricane Boundary Layer (HBL) over 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.

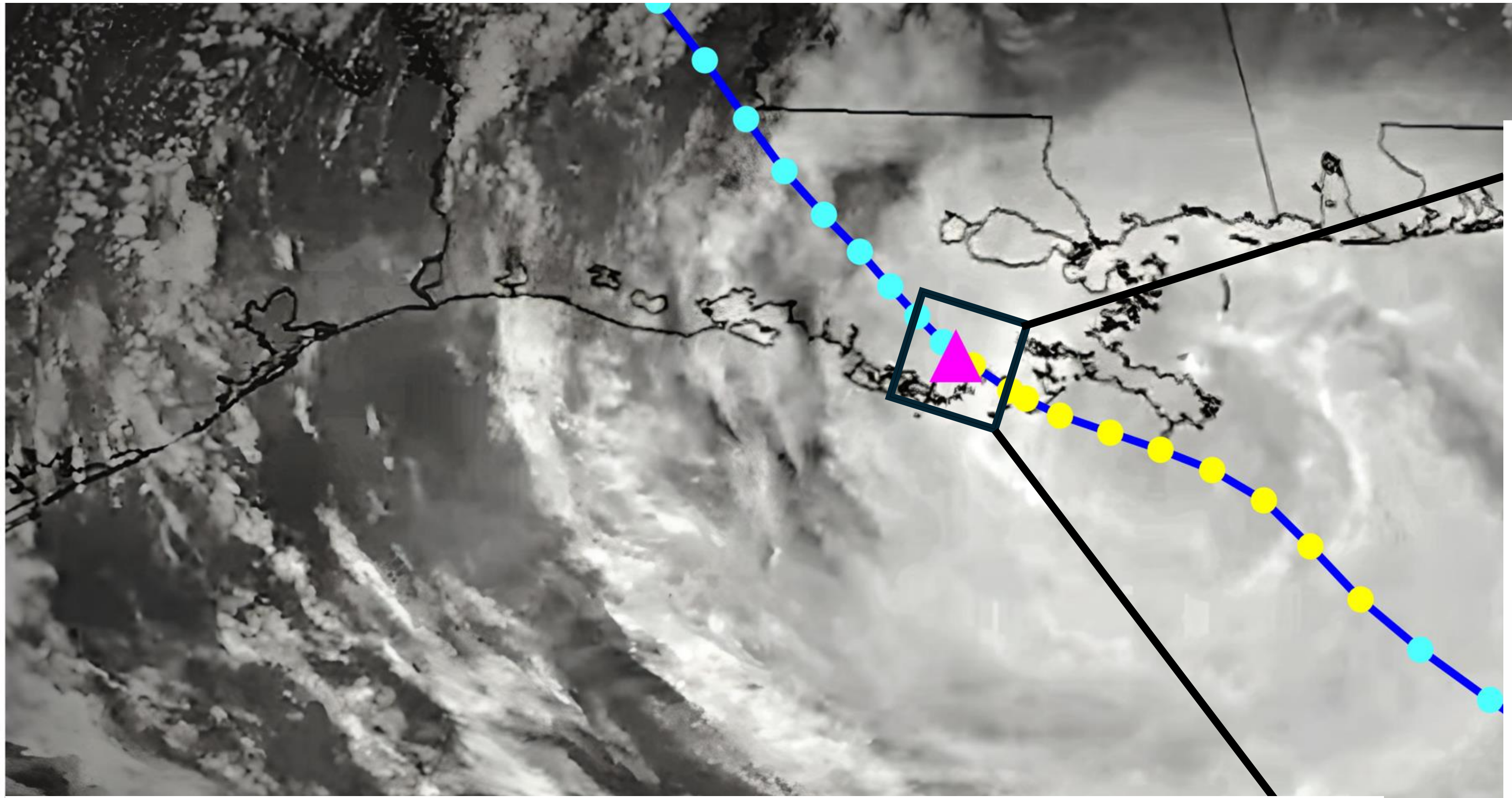
Eddy size > Grid size: Numerically resolved

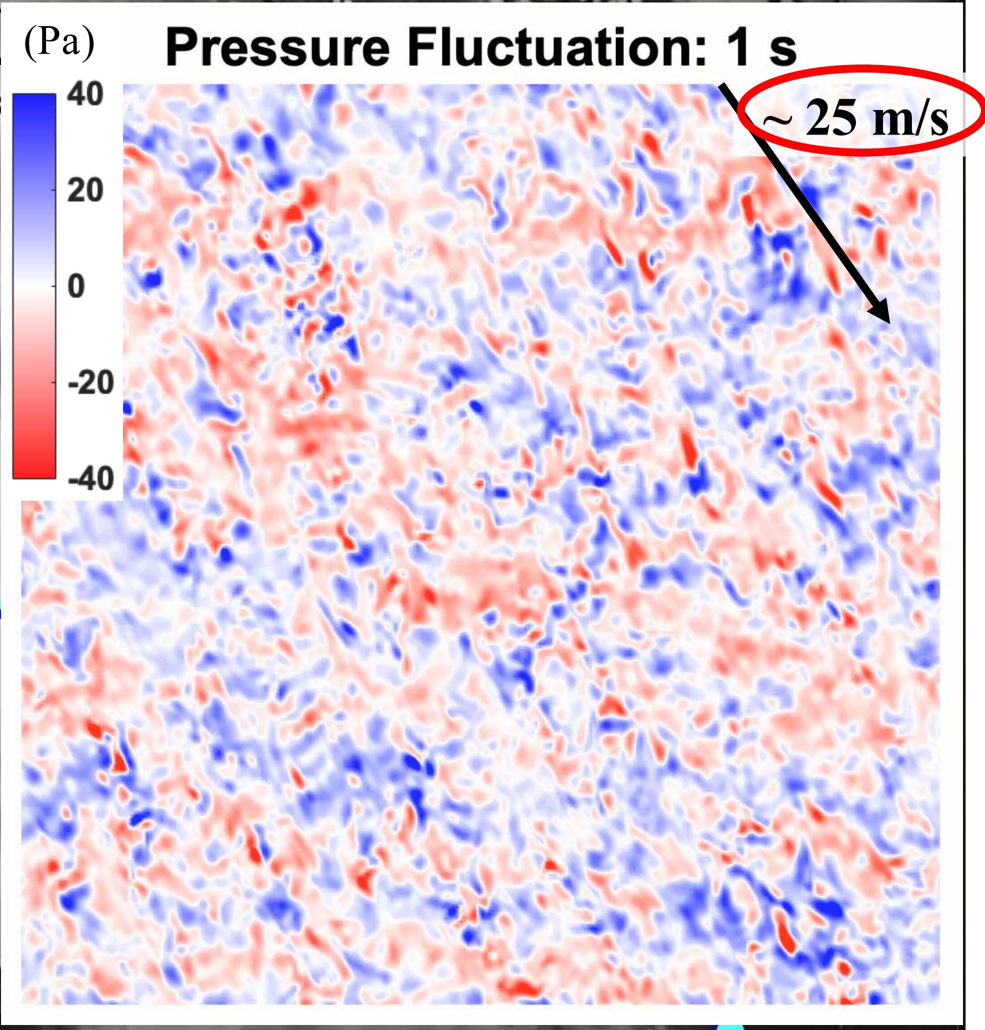
Large eddy

Eddy size < Grid size: Parameterized by subgrid model

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

CM1 LES of Hurricane Boundary Layer (HBL) over land



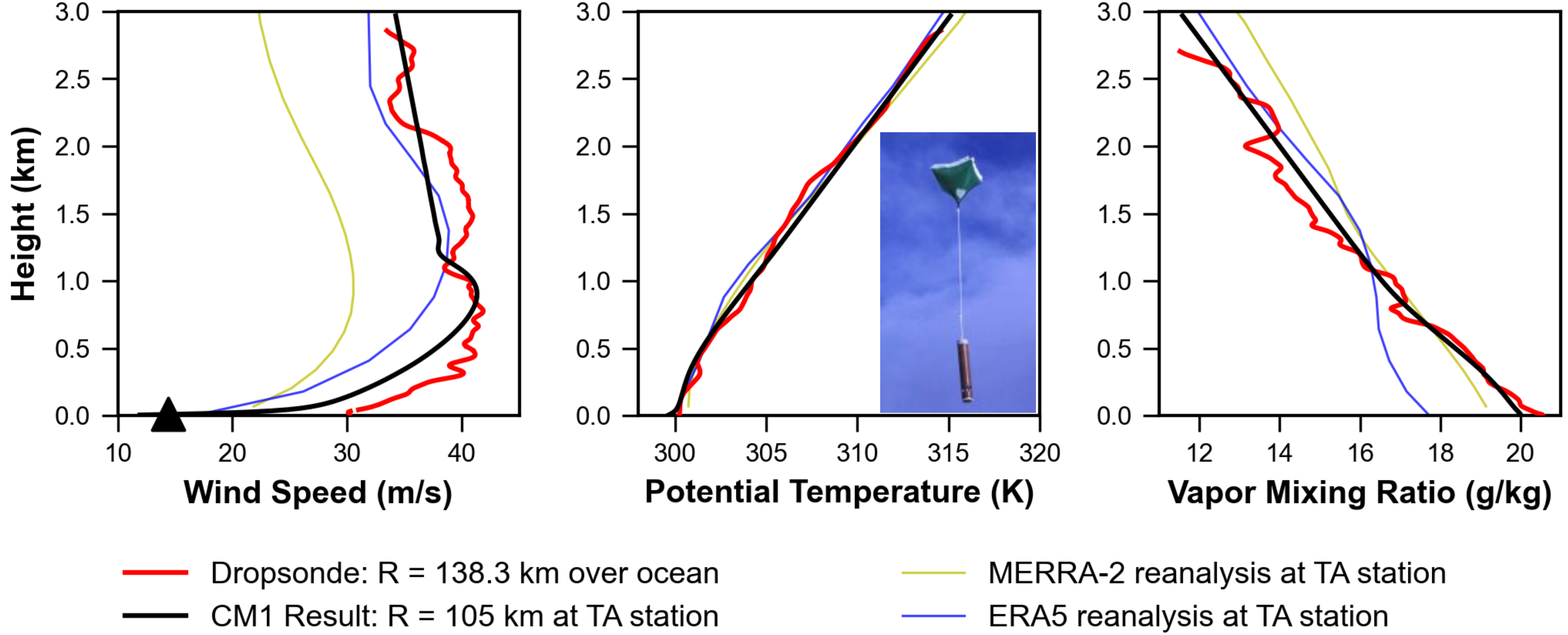


	x (radial)	y (tangential)	z (vertical)
Domain size	5.12 km	5.12 km	3 km
Grid size	20 m	20 m	10 m

Radius	10 m height wind	Roughness length
R = 105 km	U10 ≈ 14.4 m/s	z_0 = 30 cm

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

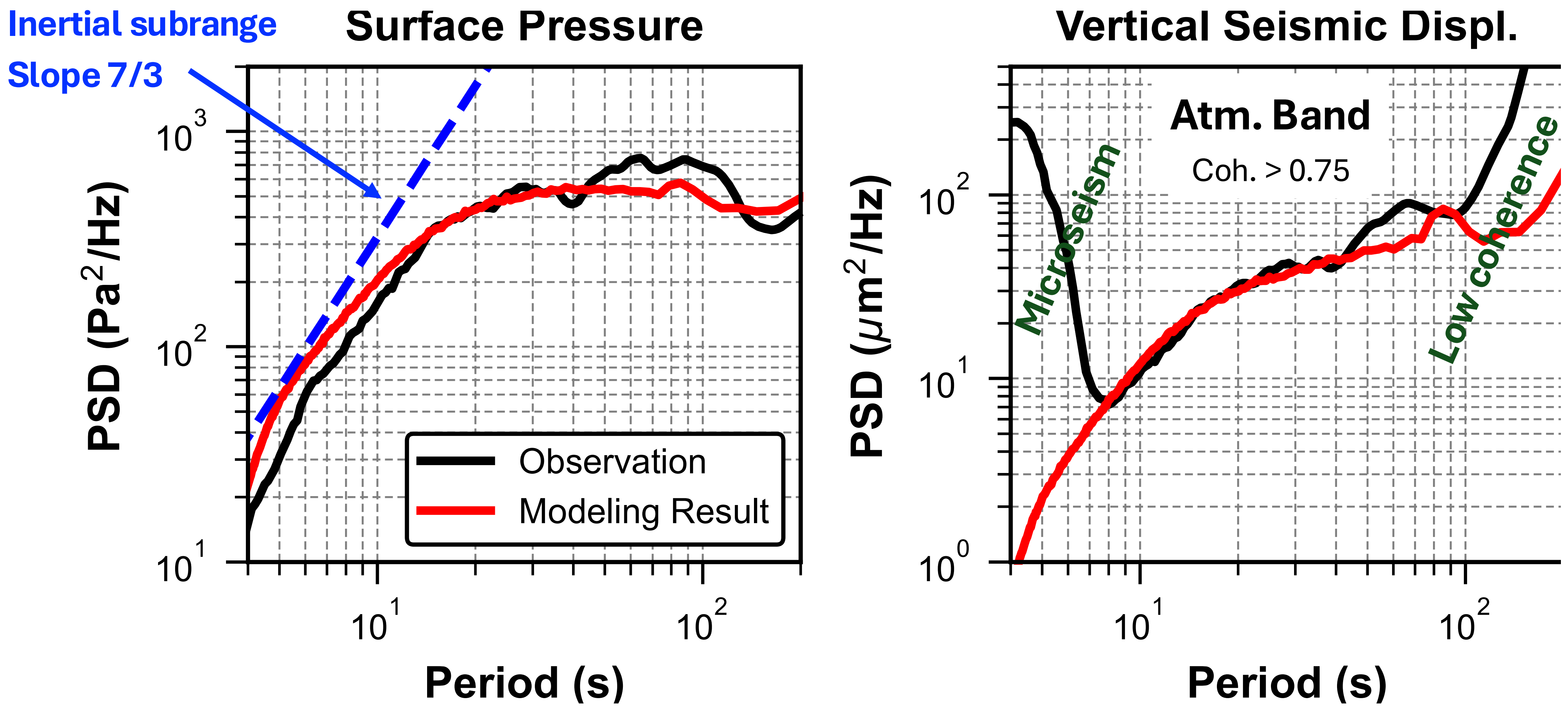
LES with constrained thermodynamic conditions



Spin up simulation for 6 hours into the **quasi-steady** state.

Then record surface pressure field for 1 hour.

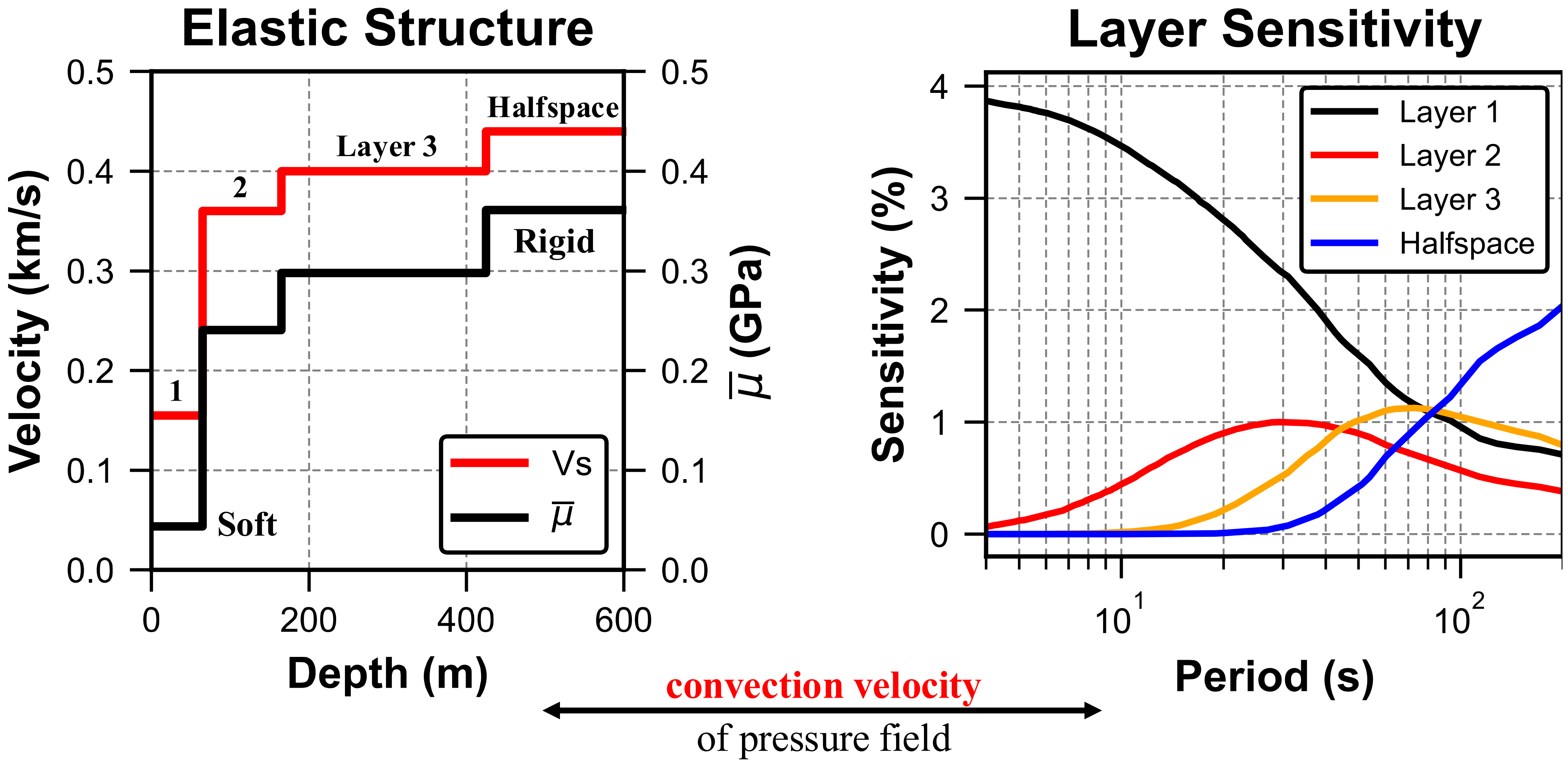
Infrasound & seismic spectra



Infrasound data can be used for turbulent spectral analysis.

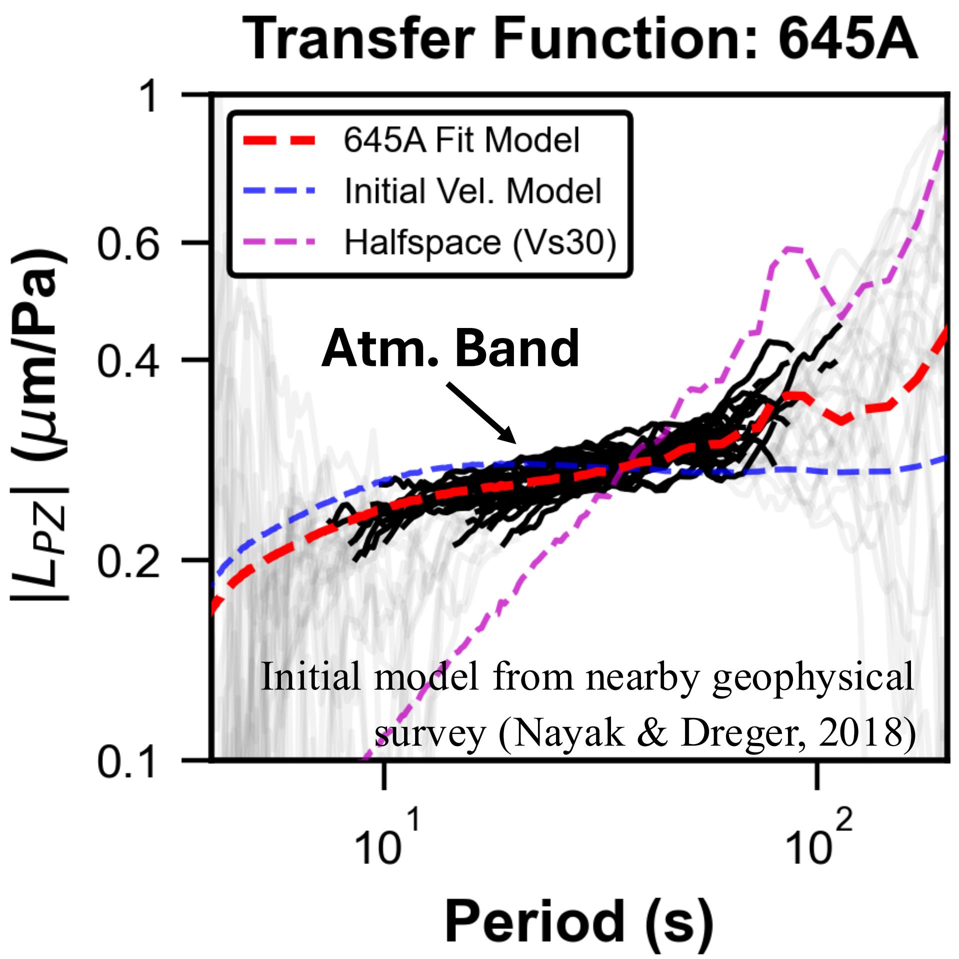
Seismic signals originate from turbulent pressure in the atmospheric band.

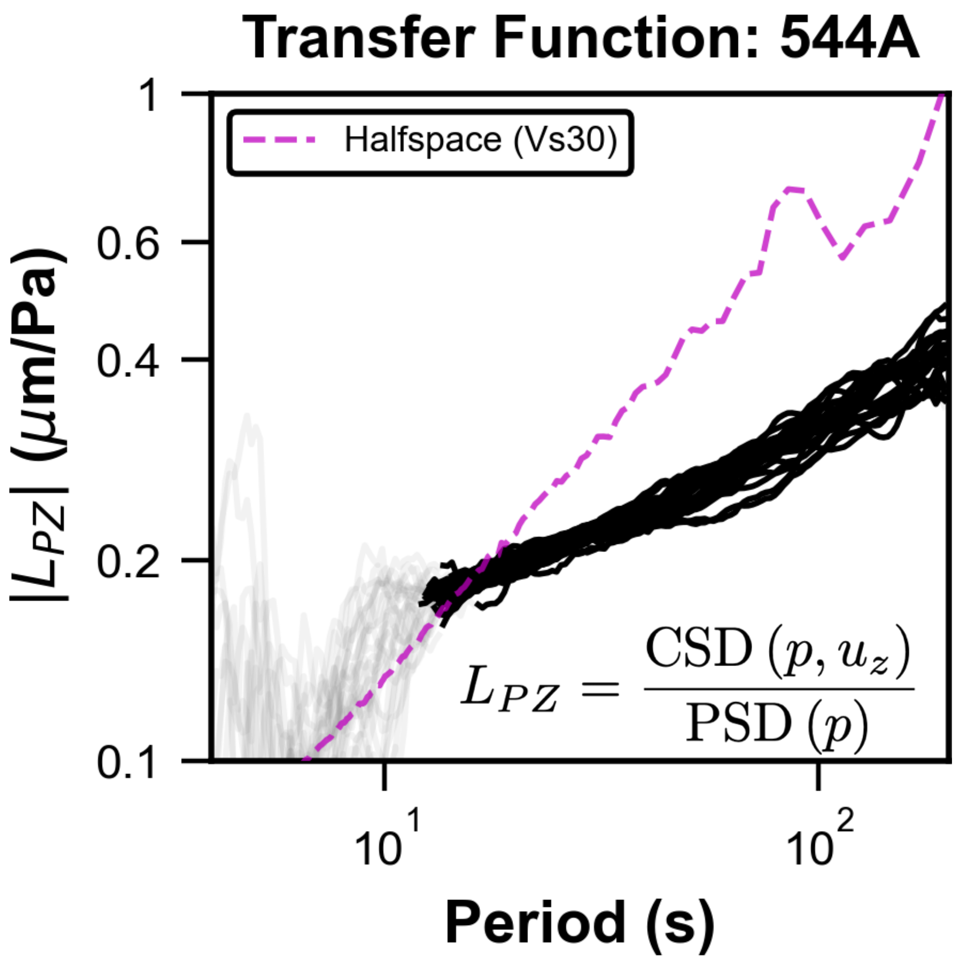
Elastic response to surface pressure



Wind speed at sensor height (~1-2 m) differs from convective velocity: 8 m/s V.S. 25 m/s

Elastic response to surface pressure





Only consider pure elastic halfspace model loses the depth resolution of the response

Summary: Generation mechanisms of seismic ambient noise

Natural processes from ocean, atmosphere, …

Fourier mode

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

Seismic noise sources

(at Earth's surface)

$p(x, y, t)$

$c_{\mathrm{source}} \ll c_{\mathrm{seis}}$

$c_{\mathrm{source}} \approx c_{\mathrm{seis}}$

Local quasi-static response

Turbulent imprints

Ocean wave imprints on OBS …

Dynamic seismic waves

Microseism, seismic hum

Background free oscillations …

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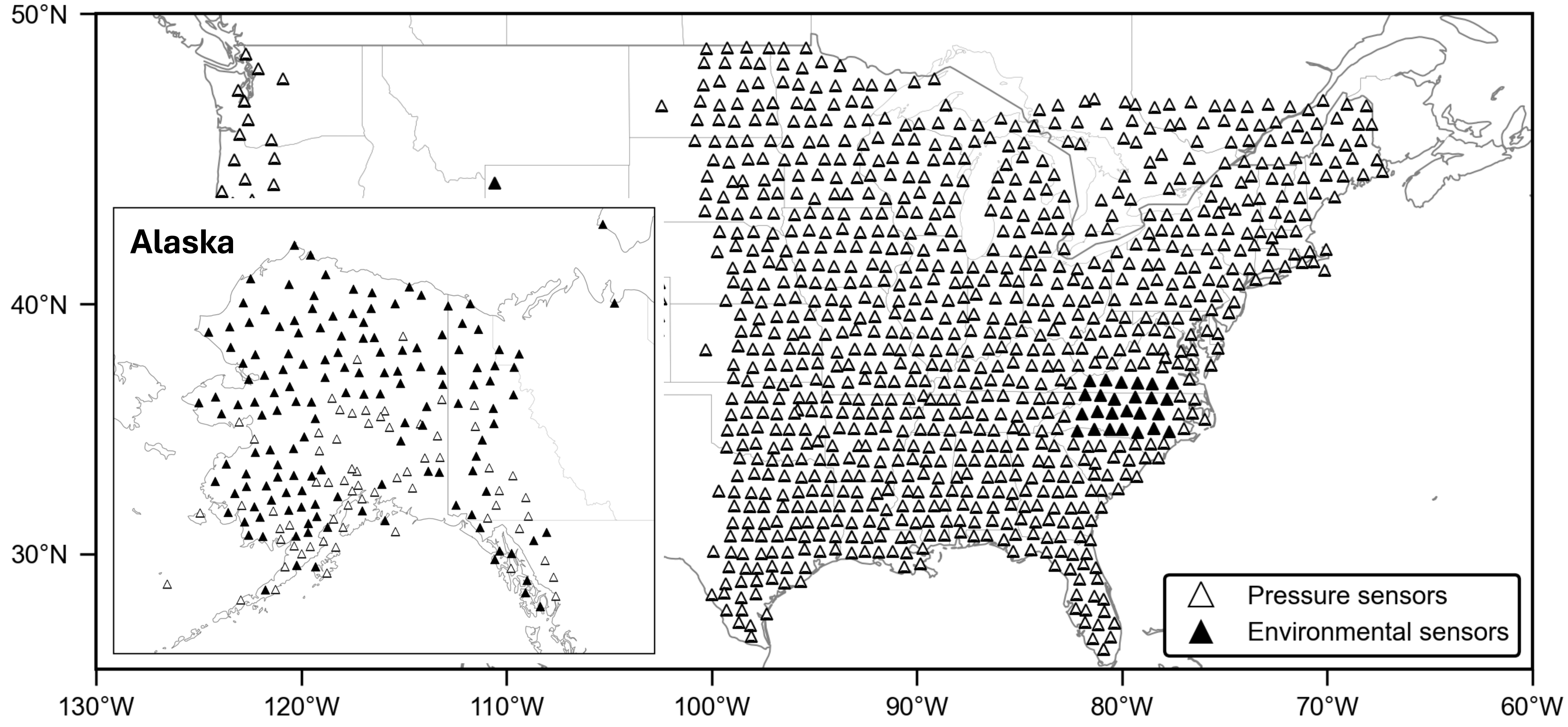
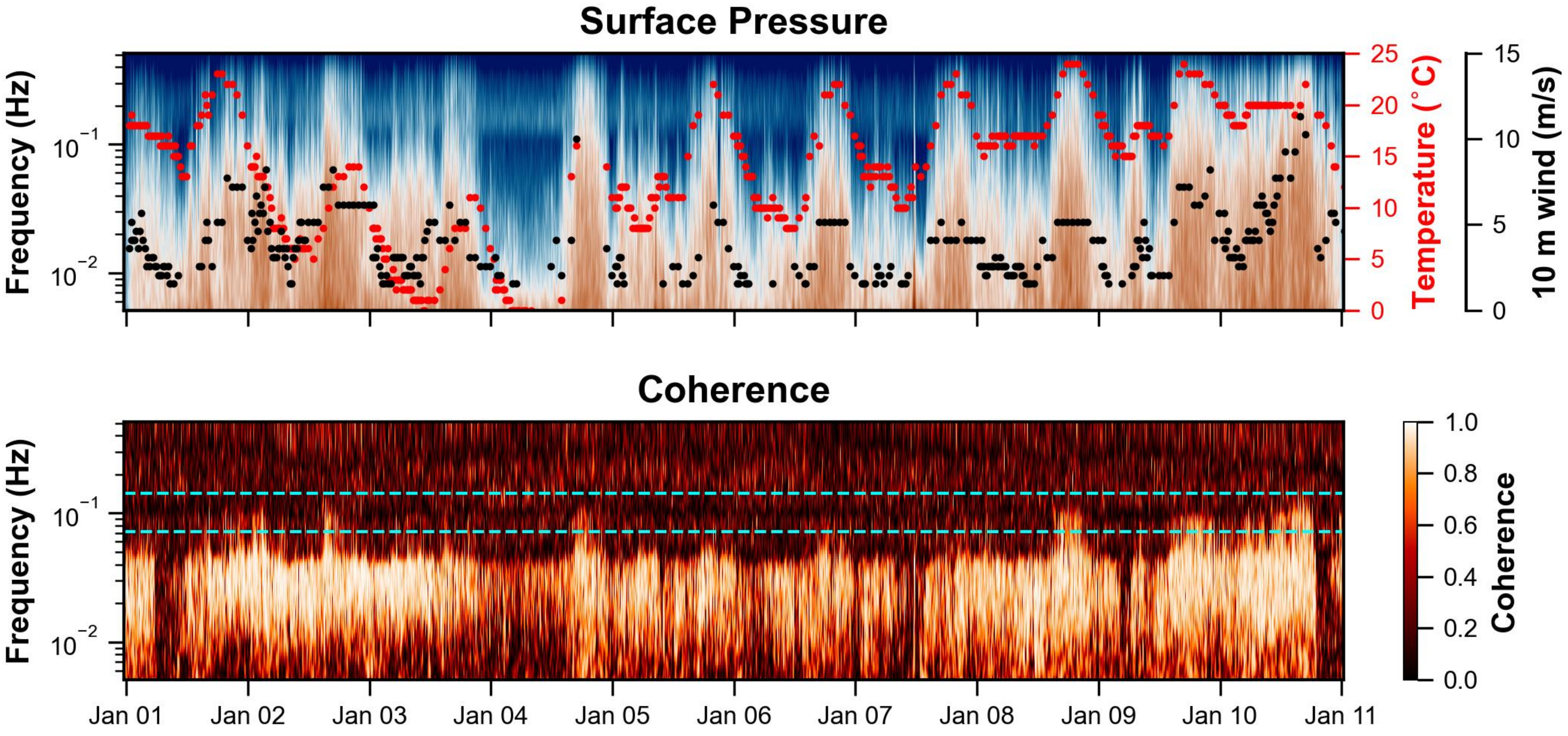
Seismic stations with environmental sensors

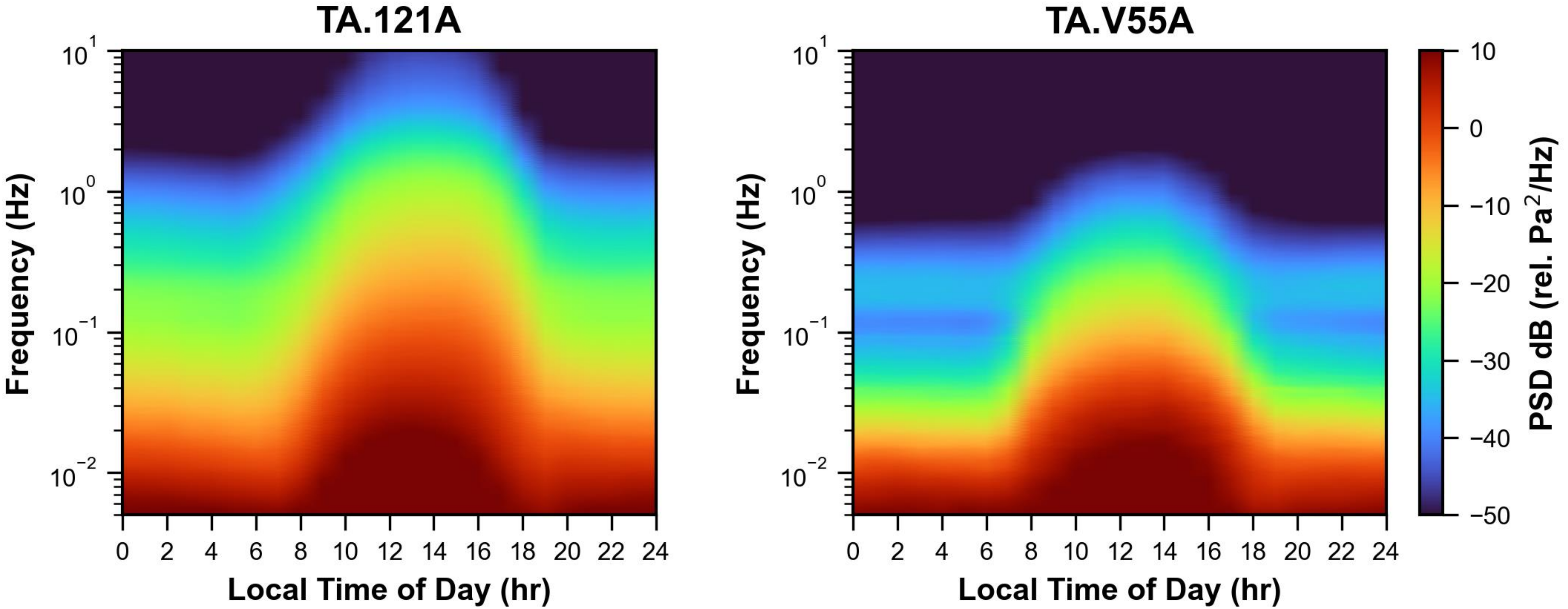


Diurnal cycles of atmospheric boundary layer (ABL)

Same station as Isaac analysis

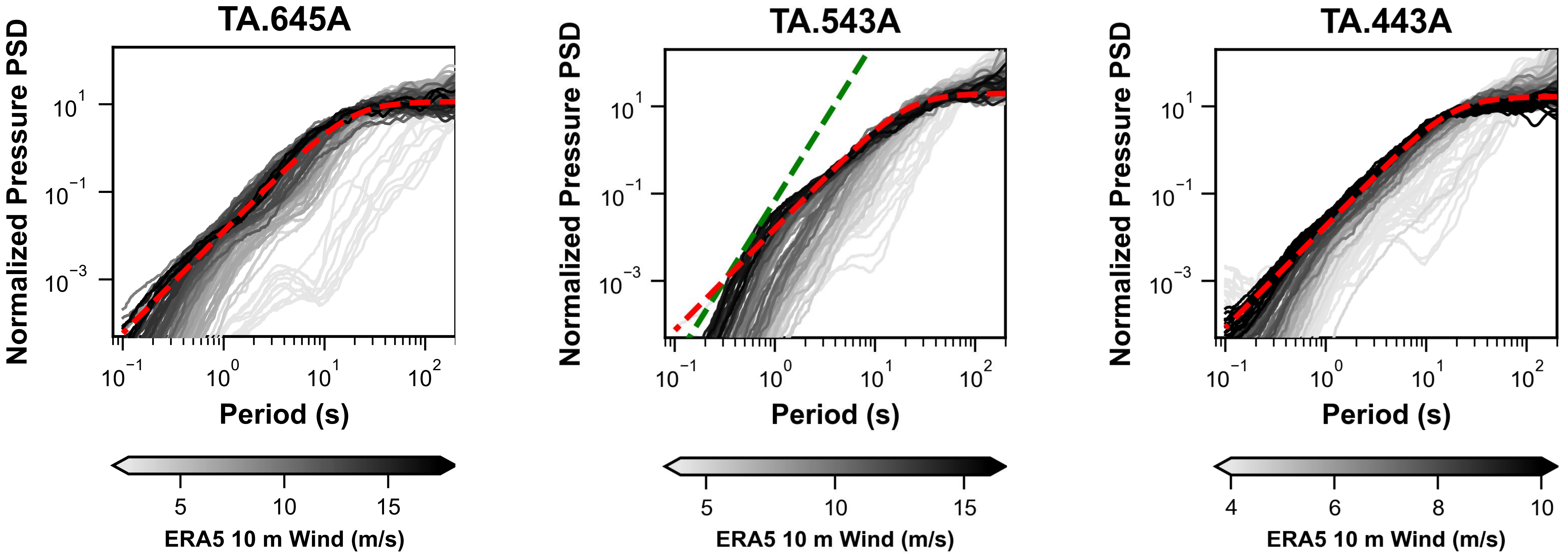


Diurnal cycles shown in pressure spectral amplitude



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

Infrasound data for turbulent pressure spectra

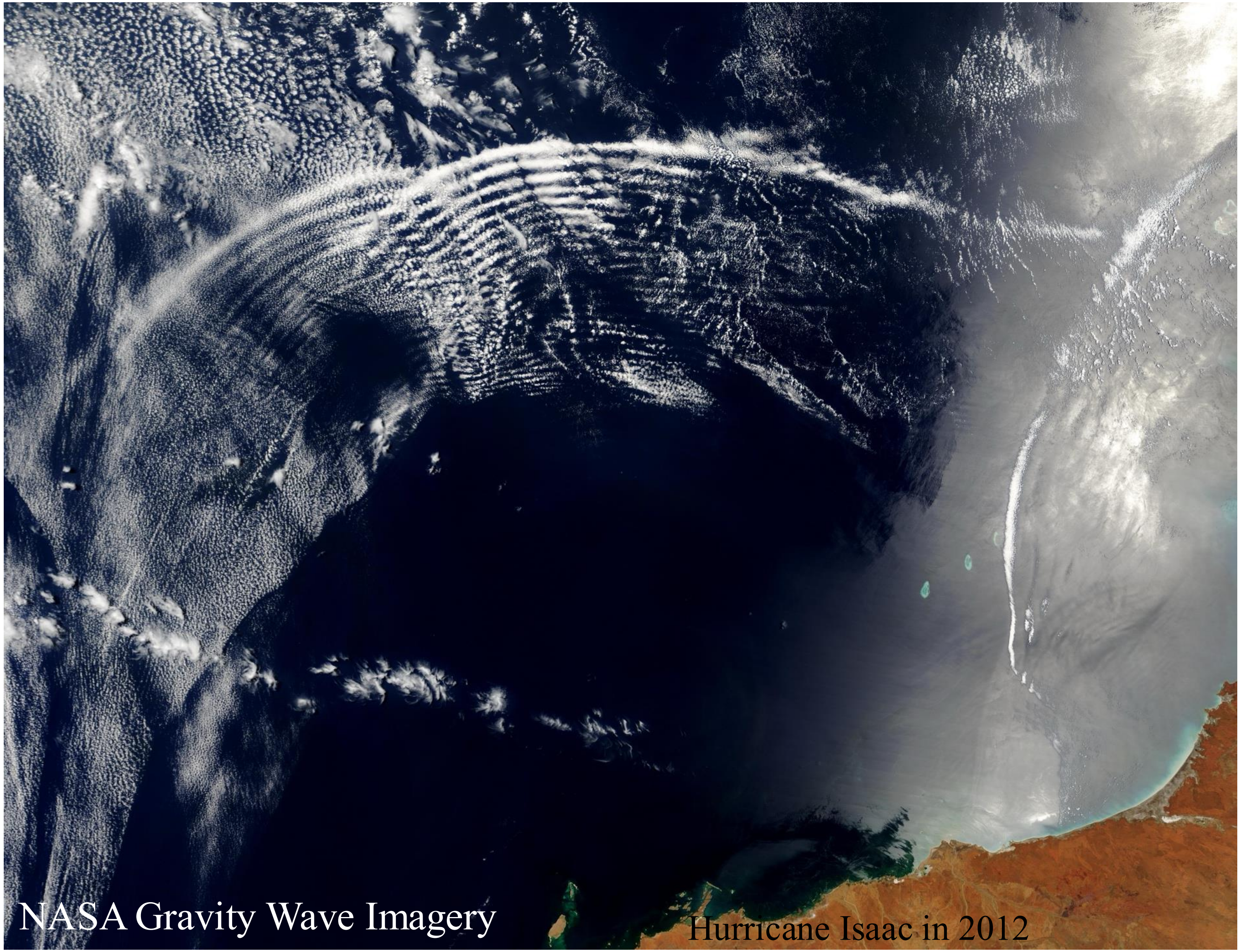


A rich dataset to investigate turbulent pressure spectra under various surface roughness, weather conditions, etc.

Mechanisms	Scaling behavior
Turbulence - turbulence interaction	Short period: $T^{7/3}$ Long period: **Flat**
Turbulence - mean shear interaction	Short period: $T^{11/3}$ Long period: $T^{-5/3}$

George et al. (1984), Tsuji & Ishihara (2003)

Atmospheric inertia-gravity waves



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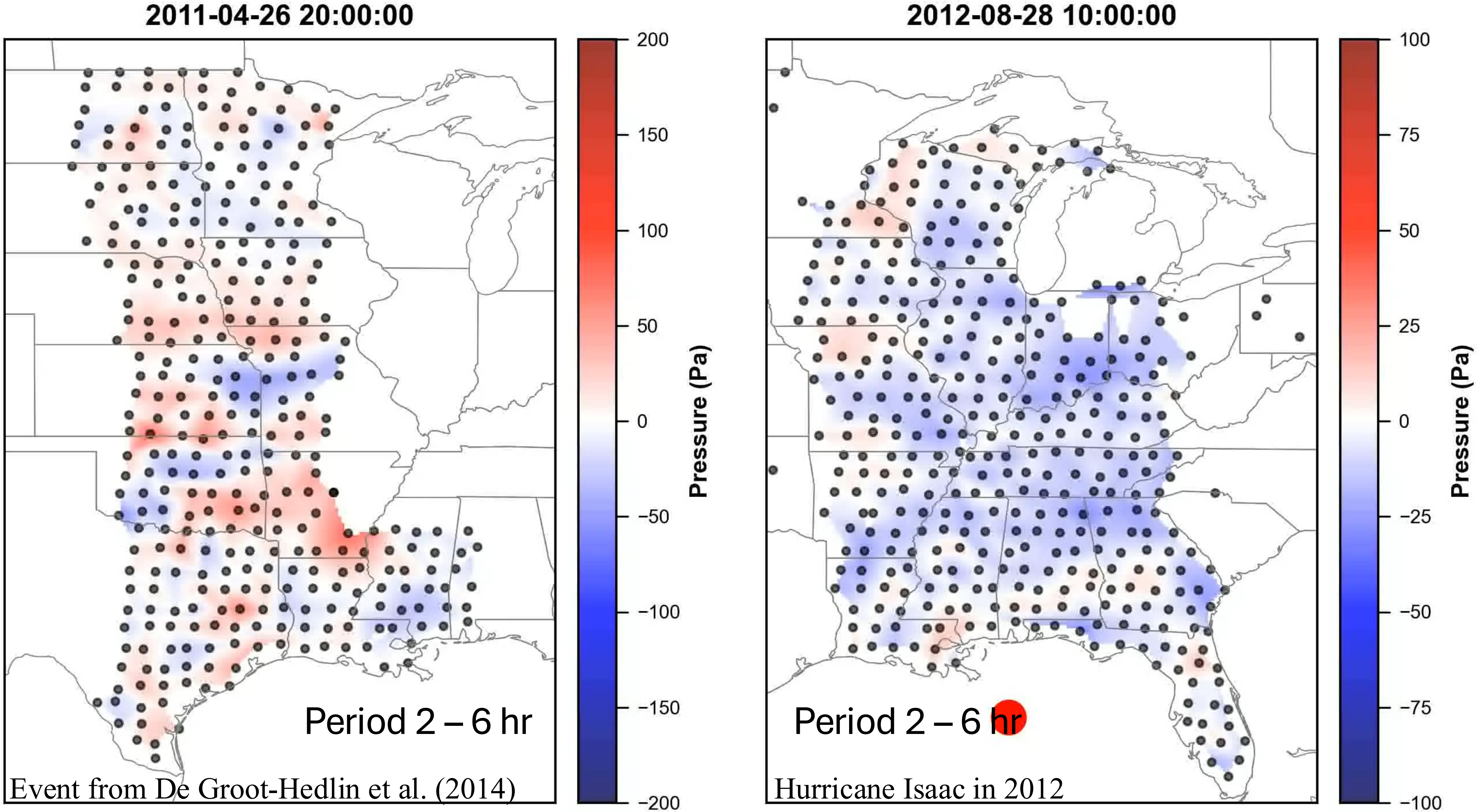
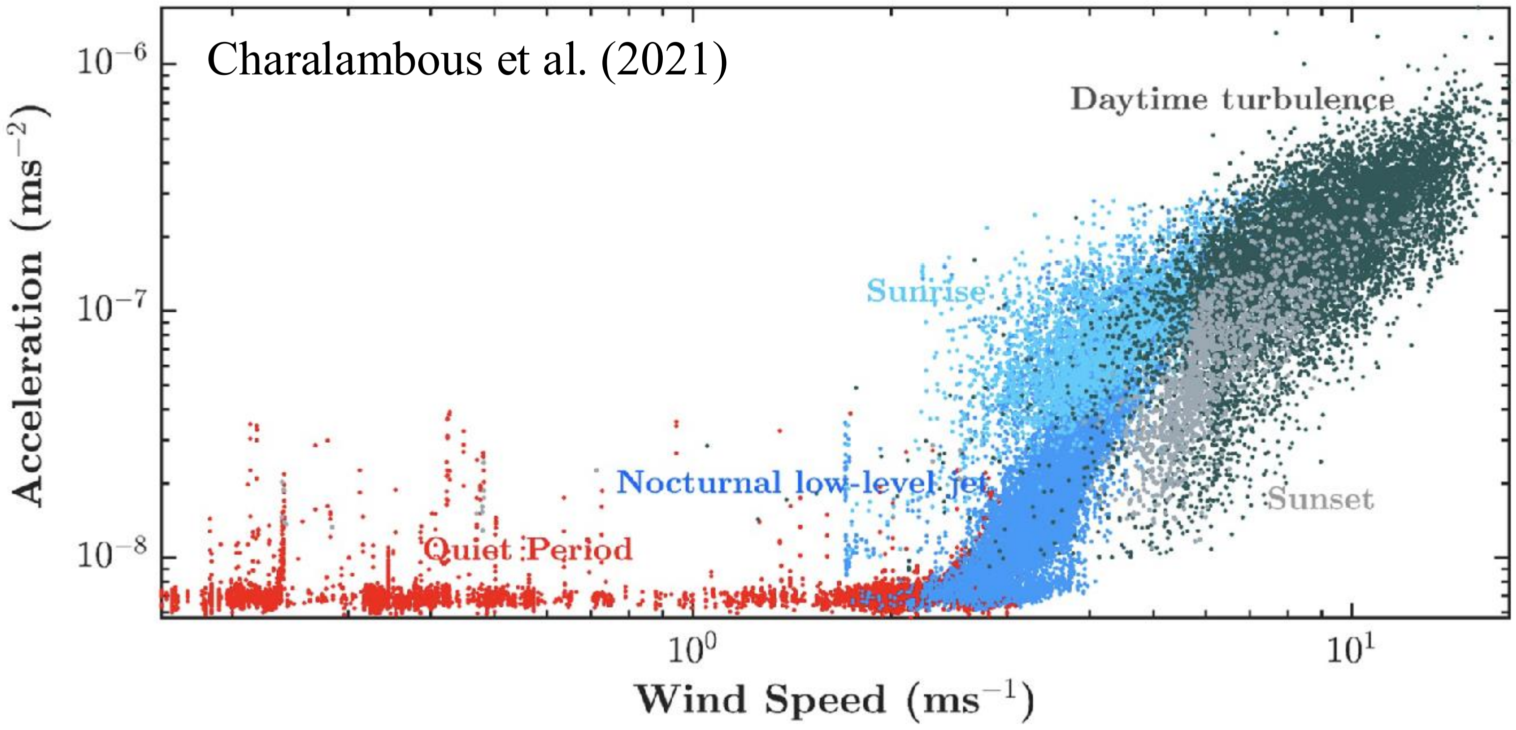


Seismic instruments on Mars

Spiga et al. (2018)



- Martian seismic ambient noise is dominated by the atmosphere
- Dust devils: Small-scale vortices with dust particles
- Estimate elastic properties of surface regolith (Kenda et al., 2017)

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 can explain the seismoacoustic signatures in the atm. band

Interdisciplinary modeling to decipher observations

Surprise #3: Much more potential to explore with seismic stations

Seismic and infrasound networks with years of continuous data