Seismic ambient noise from atmospheric turbulence

A case study of hurricane landfall

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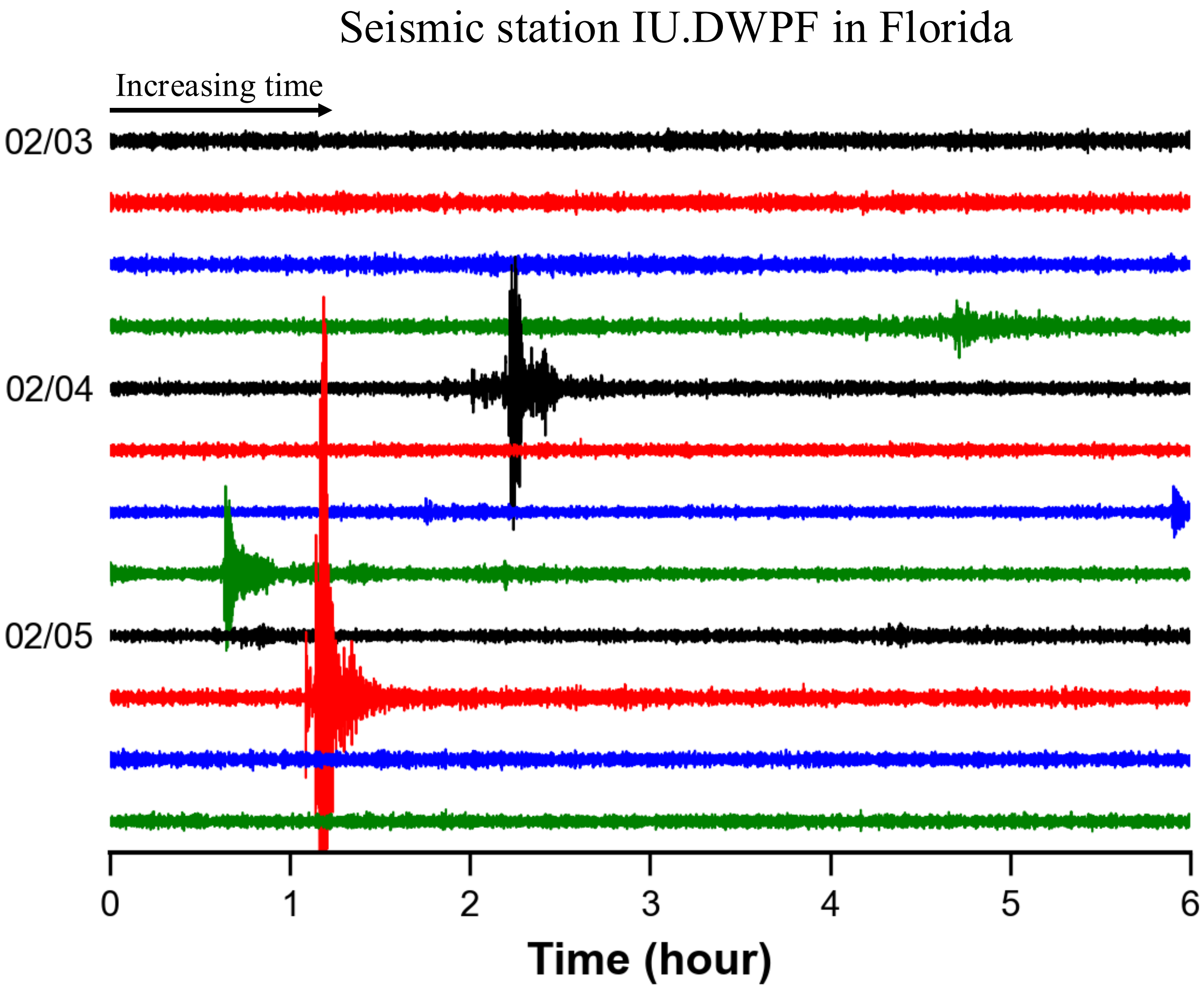
Geotopics seminar at University of Miami, Feb. 24

Seismogram

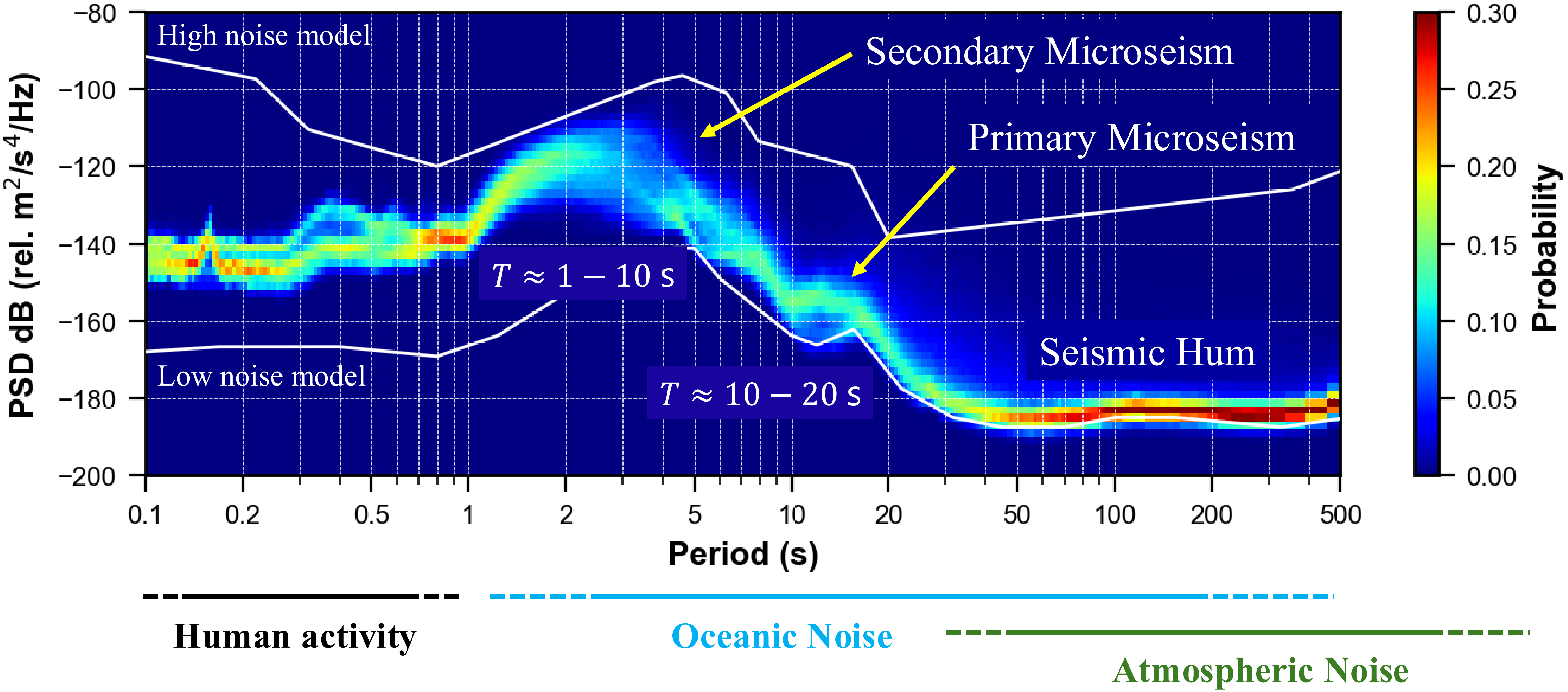
Vertical displacement record

Vast majority of seismogram is **seismic ambient noise**



Seismic ambient noise relates to various natural processes

Seismic station IU.DWPF Two-year data, 3-hr power spectral density curves



Oceanic sources of seismic ambient noise

Ocean waves

↓

Seismic noise sources

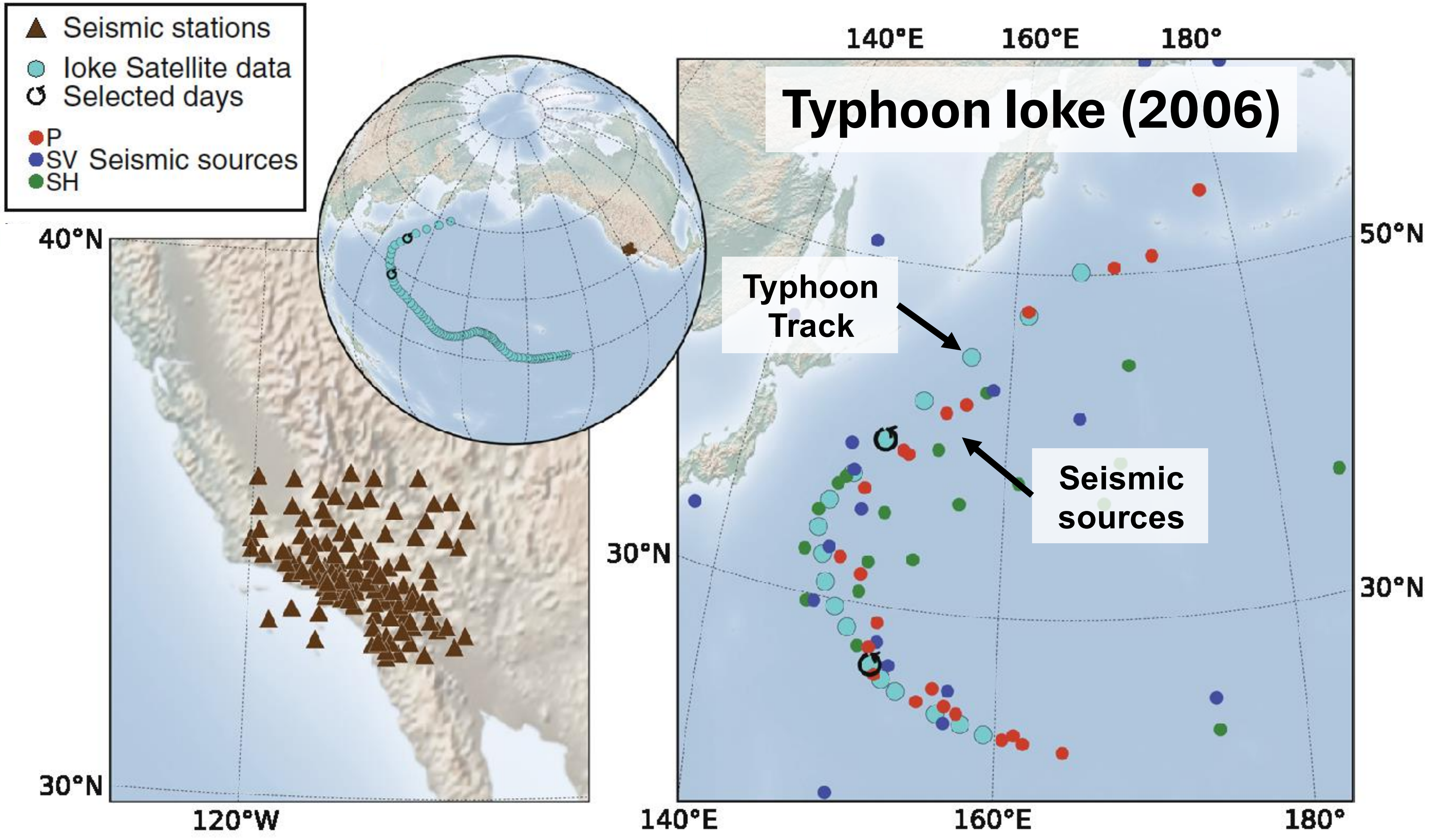
(at Earth's surface)

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

↓

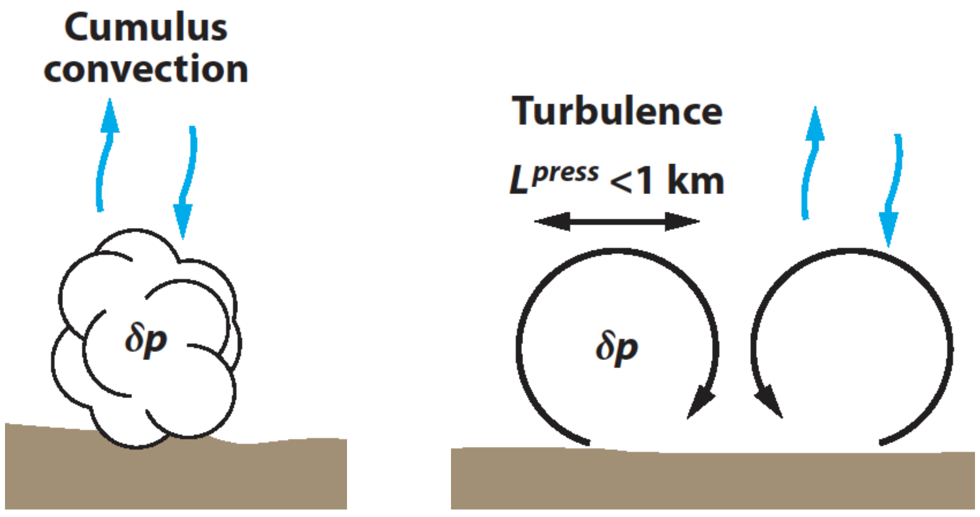
Microseism

(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)

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

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

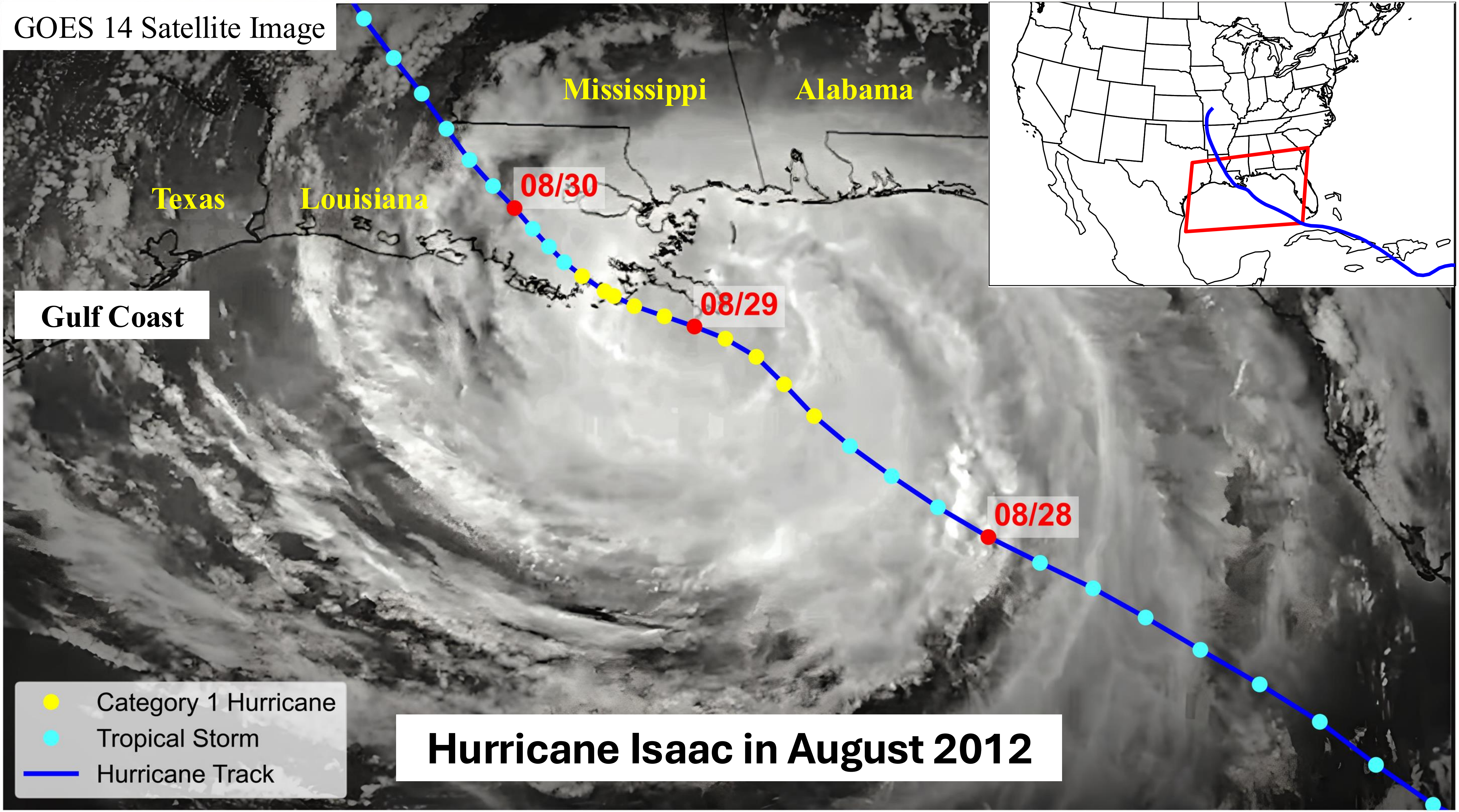
2. Interdisciplinary modeling

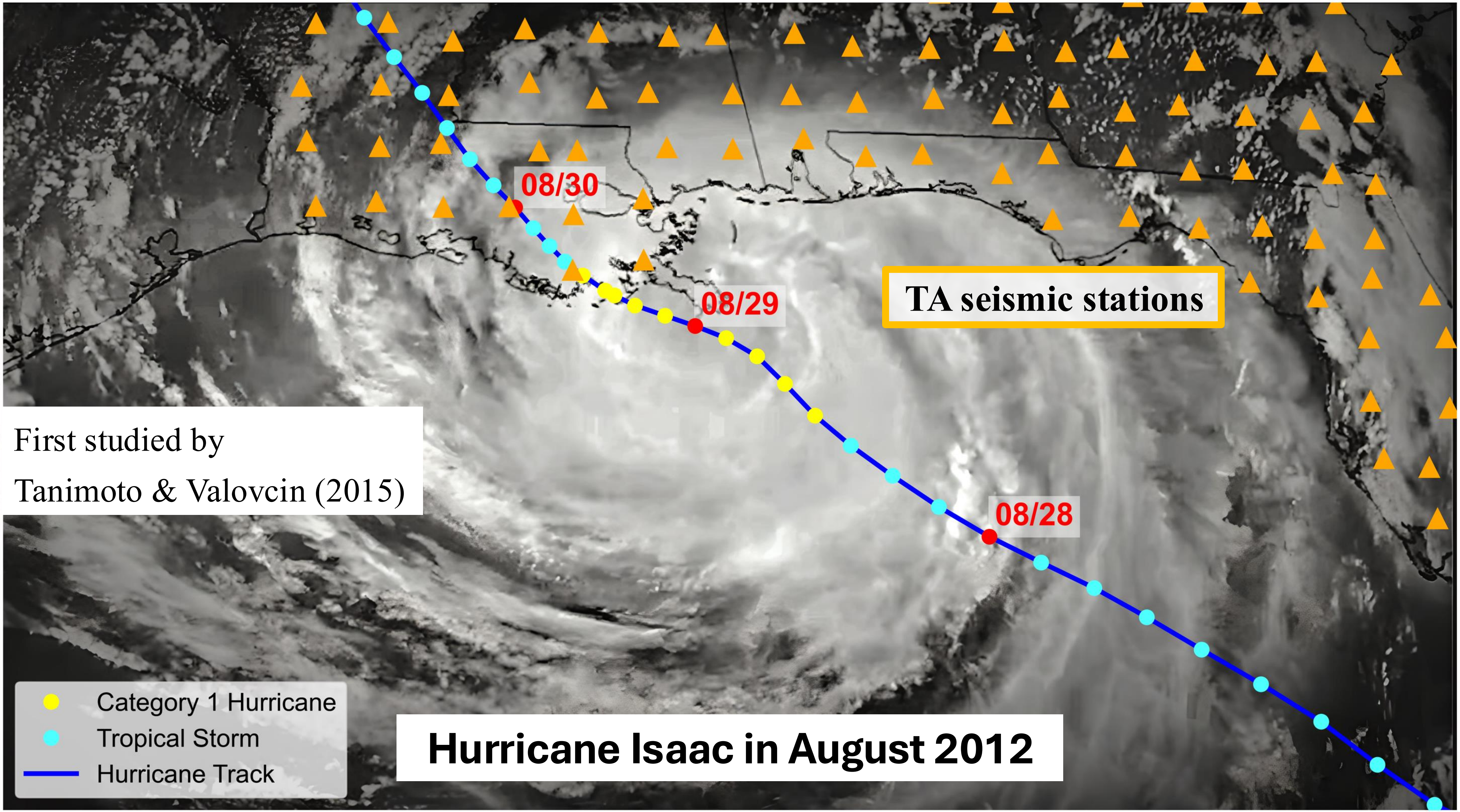
Large-eddy simulation (LES) of turbulent surface pressure

Quasi-static seismic modeling of elastic response under turbulent pressure

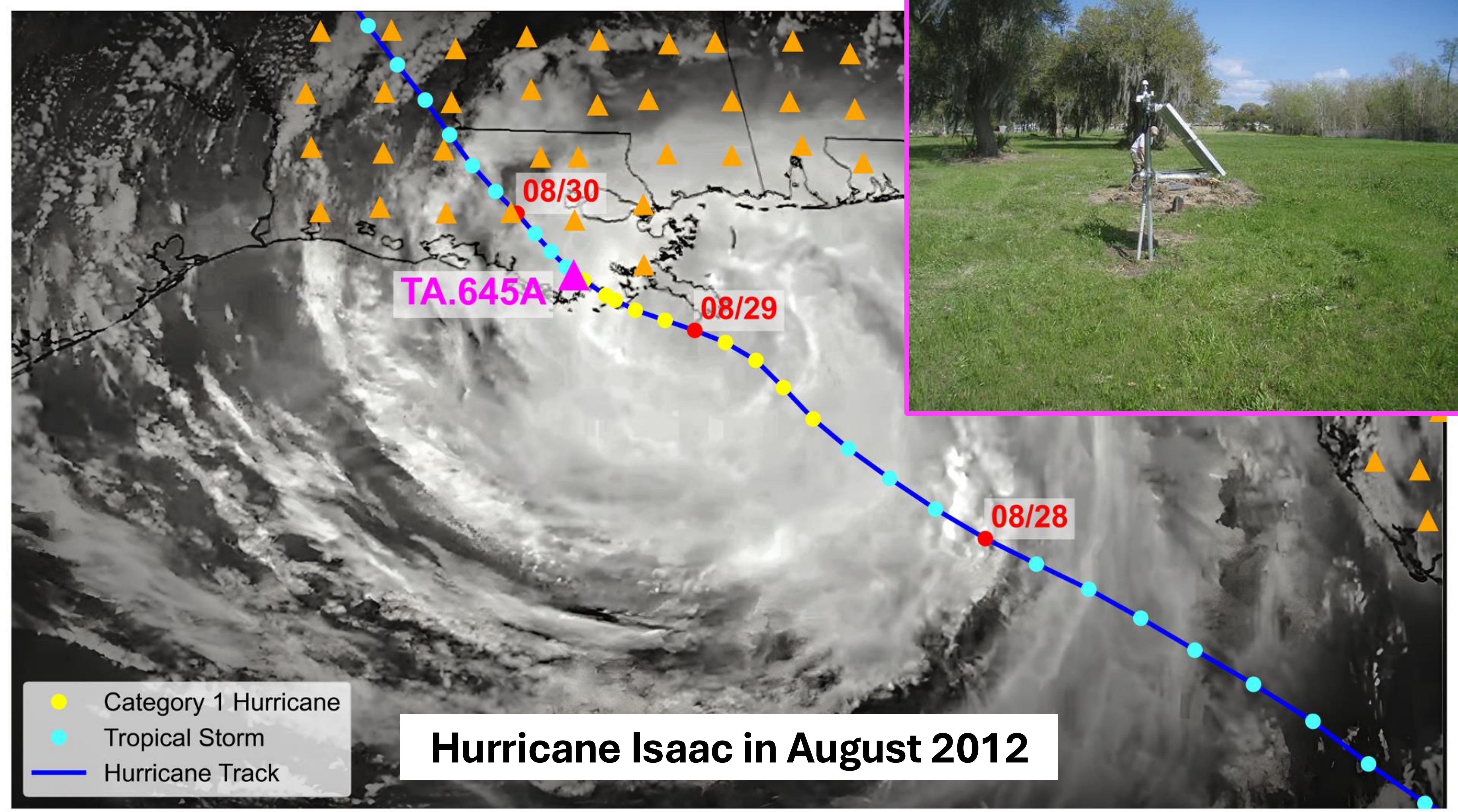
3. Prospectives

Potential of seismic station data for atmospheric sciences


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



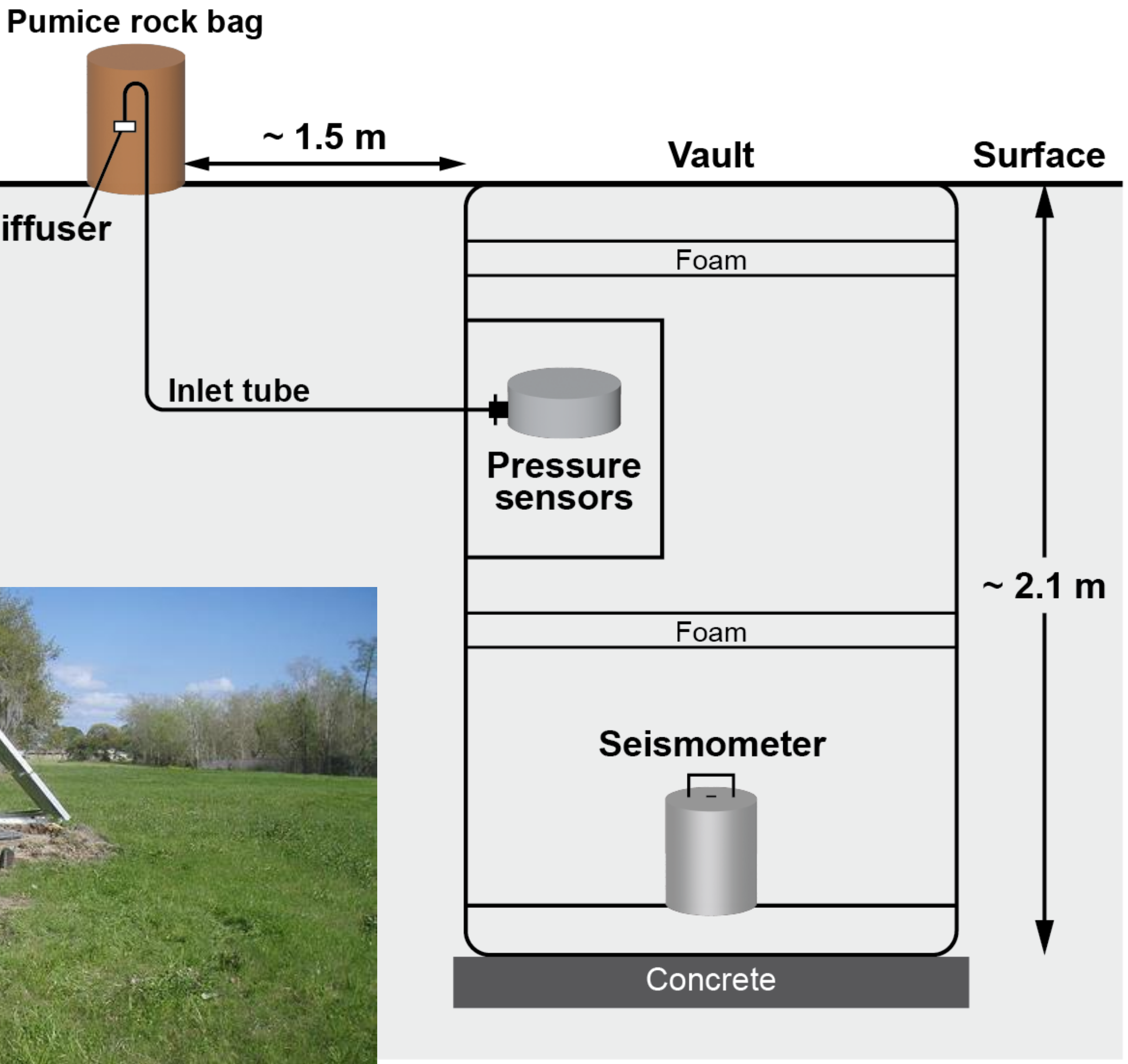
08/30
08/29
08/28
TA seismic stations
First studied by
Tanimoto & Valovcin (2015)
Category 1 Hurricane
Tropical Storm
Hurricane Track
Hurricane Isaac in August 2012


08/30
TA.645A
08/29
08/28
Category 1 Hurricane
Tropical Storm
Hurricane Track
Hurricane Isaac in August 2012

Seismic station with environmental sensors

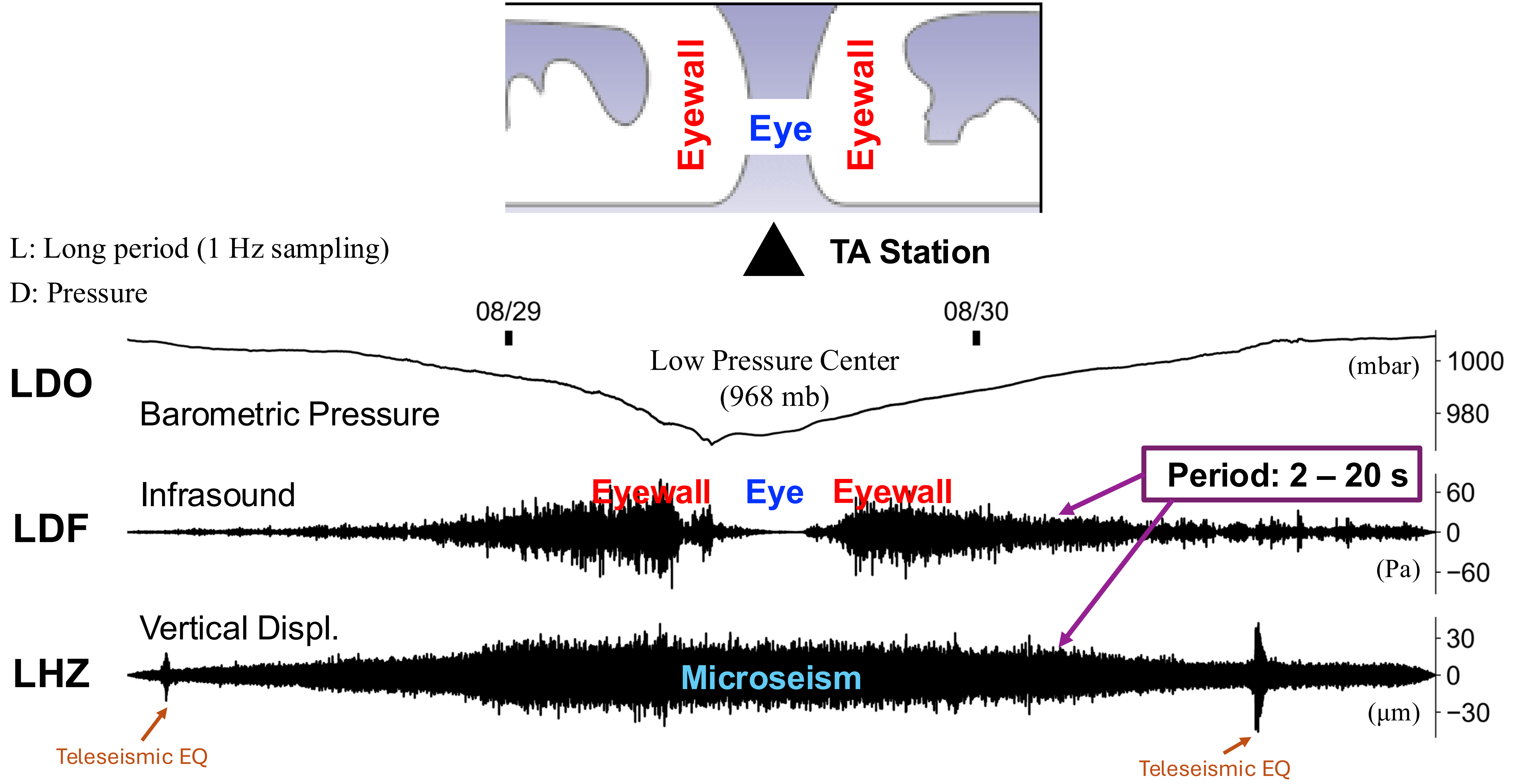
Channel	Observation
LH[ZNE]	Three-component seismic ground motion
LDO	Barometric pressure
LDF	Infrasound

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

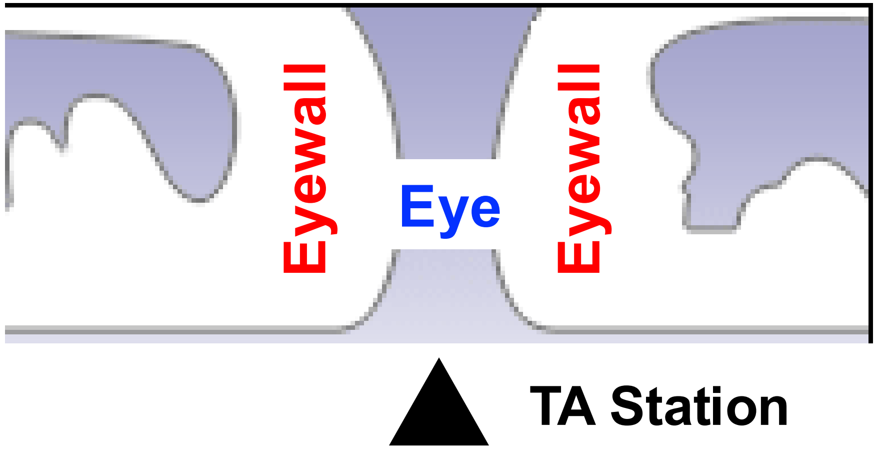


Modified from Tytell et al. (2016)

As hurricane passes the station ……

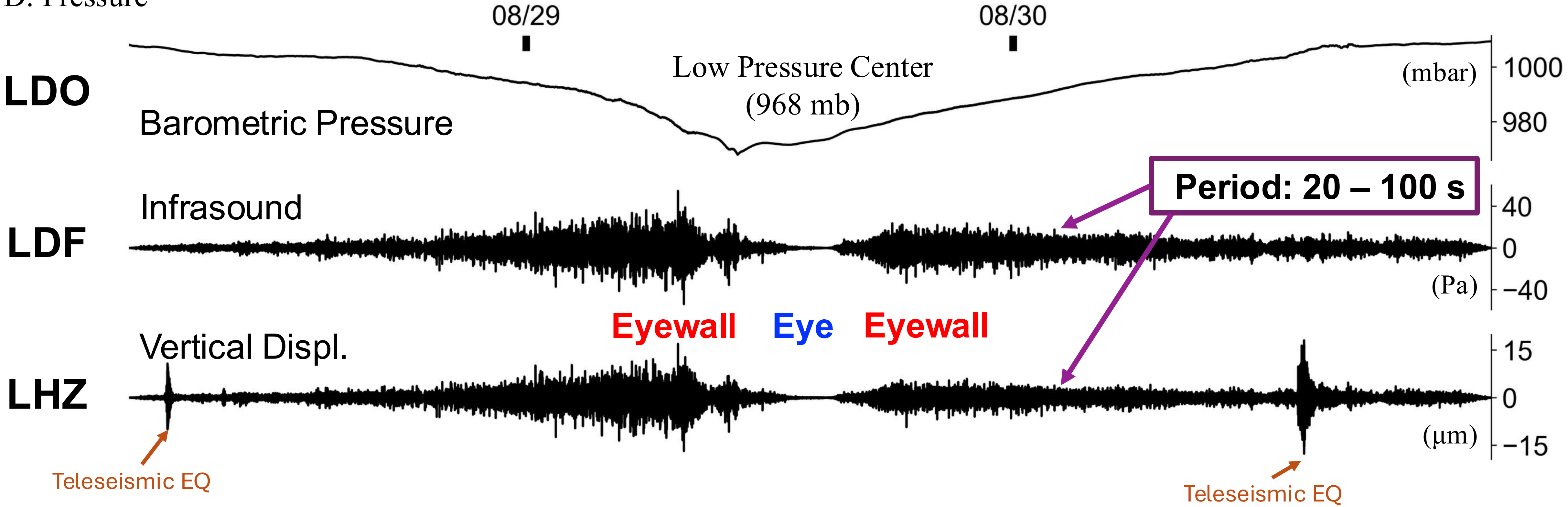


As hurricane passes the station ......

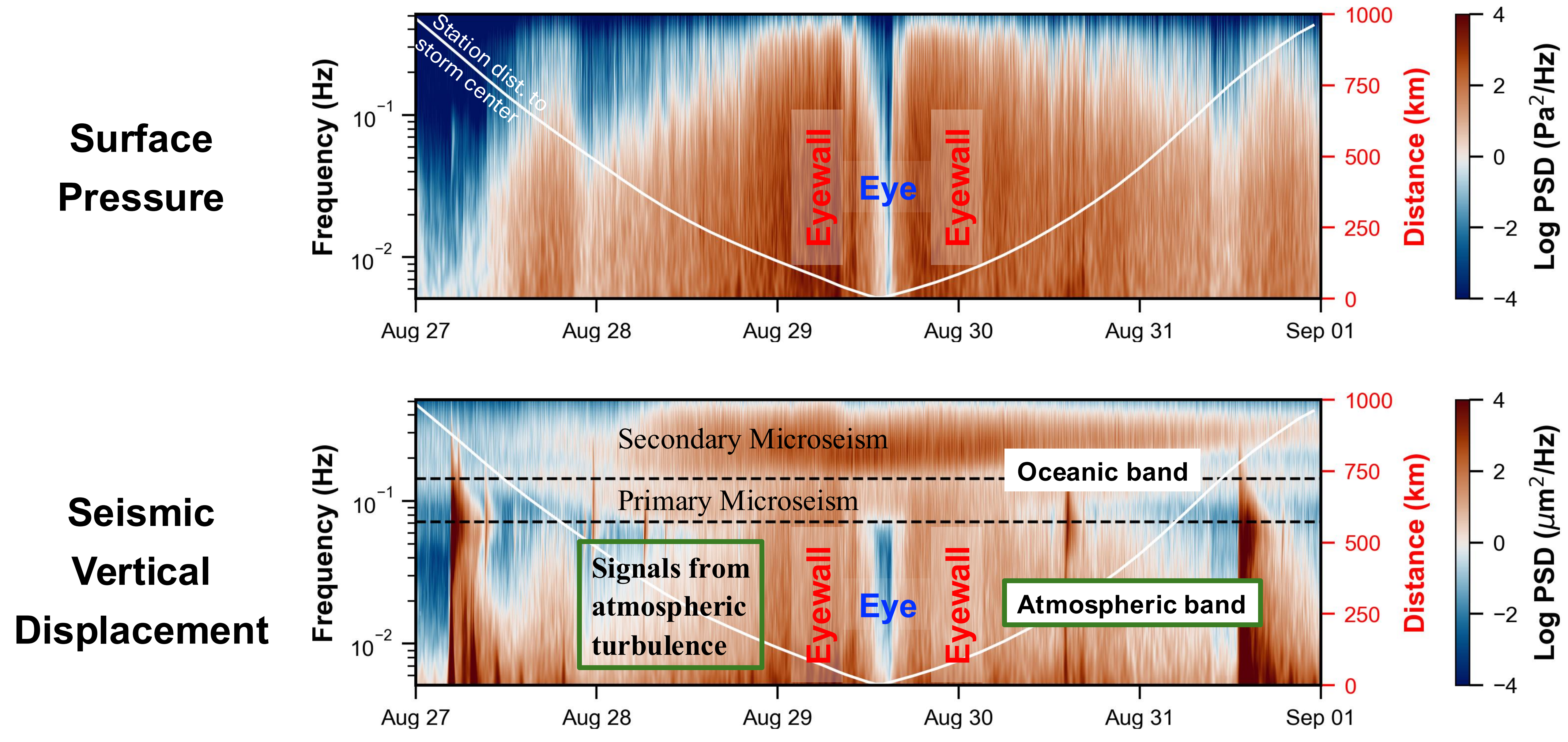


L: Long period (1 Hz sampling)

D: Pressure



Wavelet spectrograms of infrasound & seismic data



Ji & Dunham (2024)

Why are these data valuable?

For **atmospheric science**, research aircrafts and wind towers provide data within 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

For **seismology**, the strong pressure sources are suitable to

- Investigate mechanisms of pressure-seismic coupling
- Estimate elastic structure of the shallow subsurface (~ hundreds of meter), important for seismic ground motion prediction and geotechnical engineering (Wang & Tanimoto 2020)

1. Observation

Seismic imprints of Hurricane Isaac in 2012 during landfall

2. Interdisciplinary modeling

Large-eddy simulation (LES) of turbulent surface pressure

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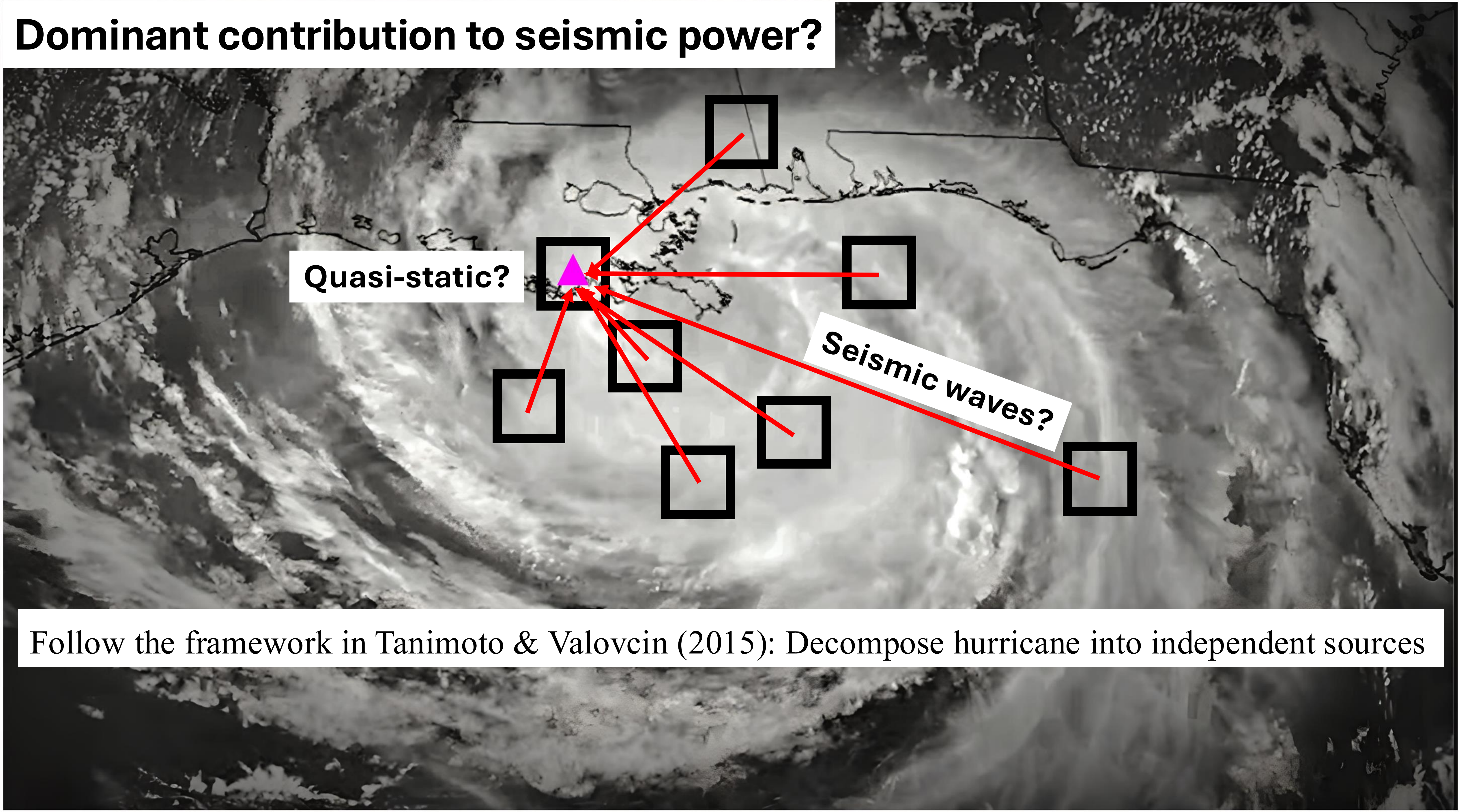
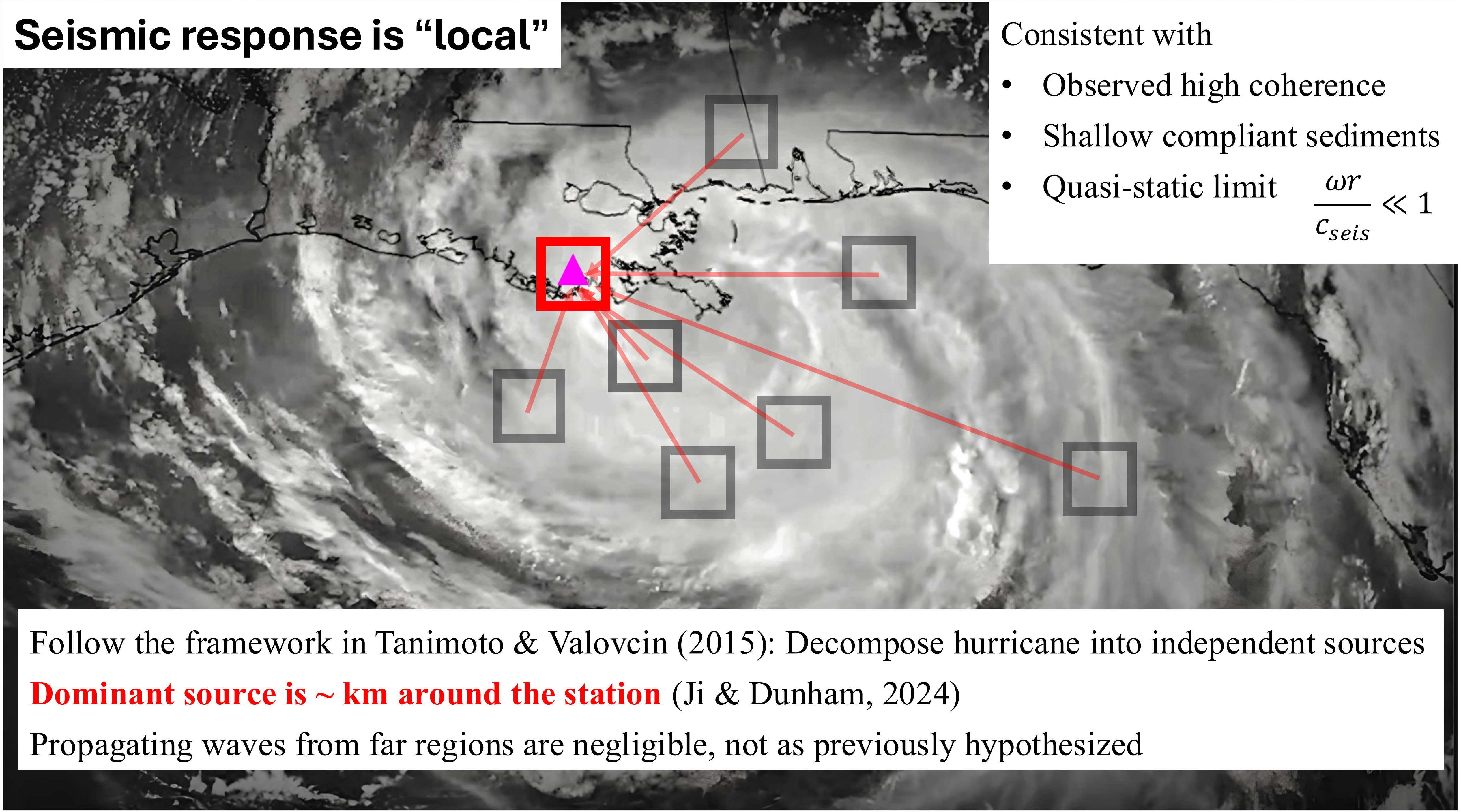
Dominant contribution to seismic power?



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

Seismic response is "local"



Consistent with

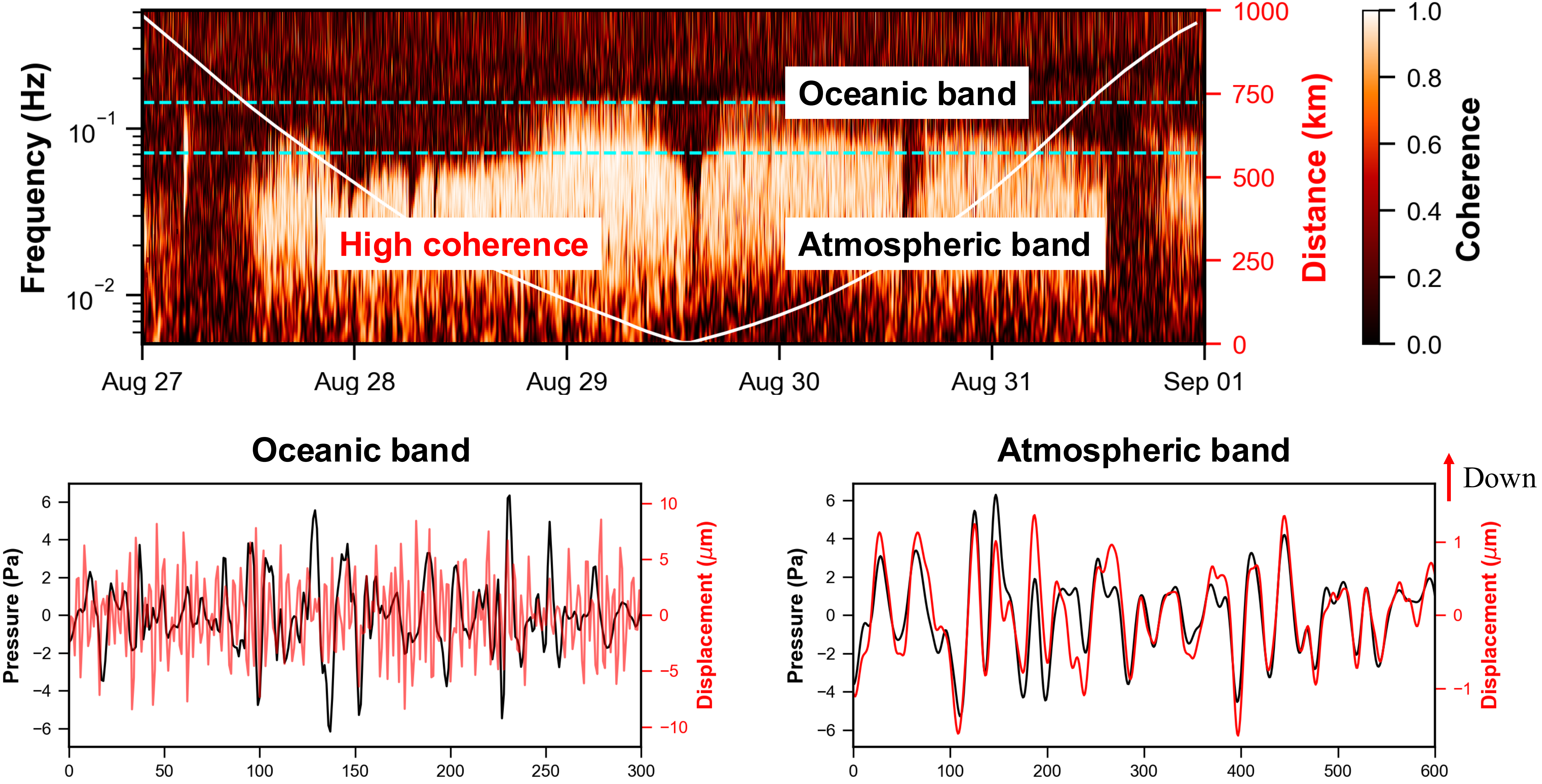
- Observed high coherence
- Shallow compliant sediments
- Quasi-static limit $\frac{\omega r}{c_{seis}} \ll 1$

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

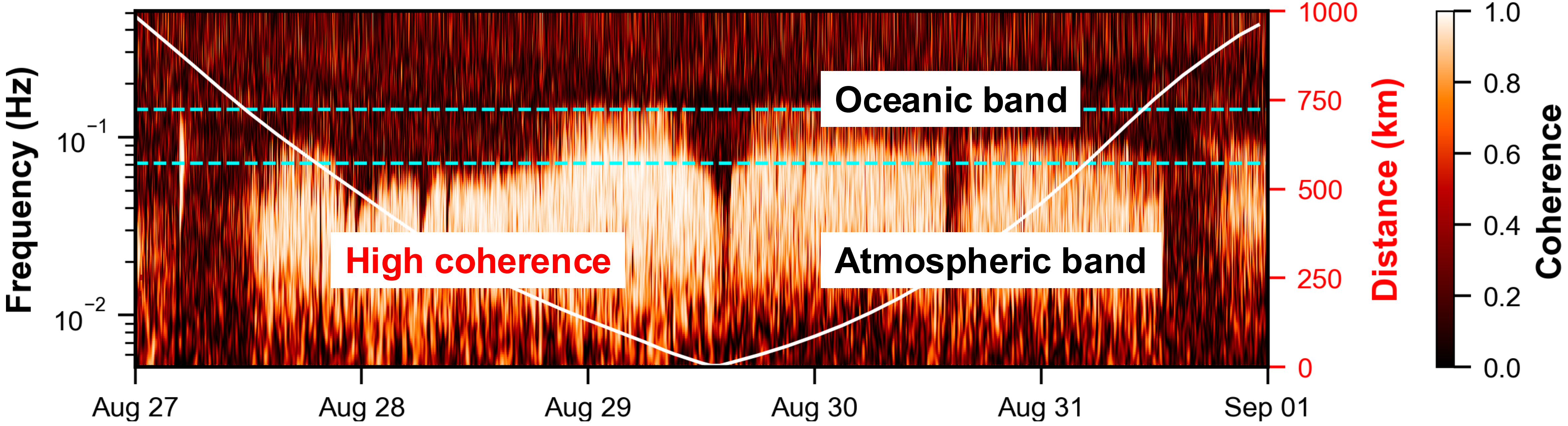
Dominant source is ~ km around the station (Ji & Dunham, 2024)

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

High coherence indicates local quasi-static response

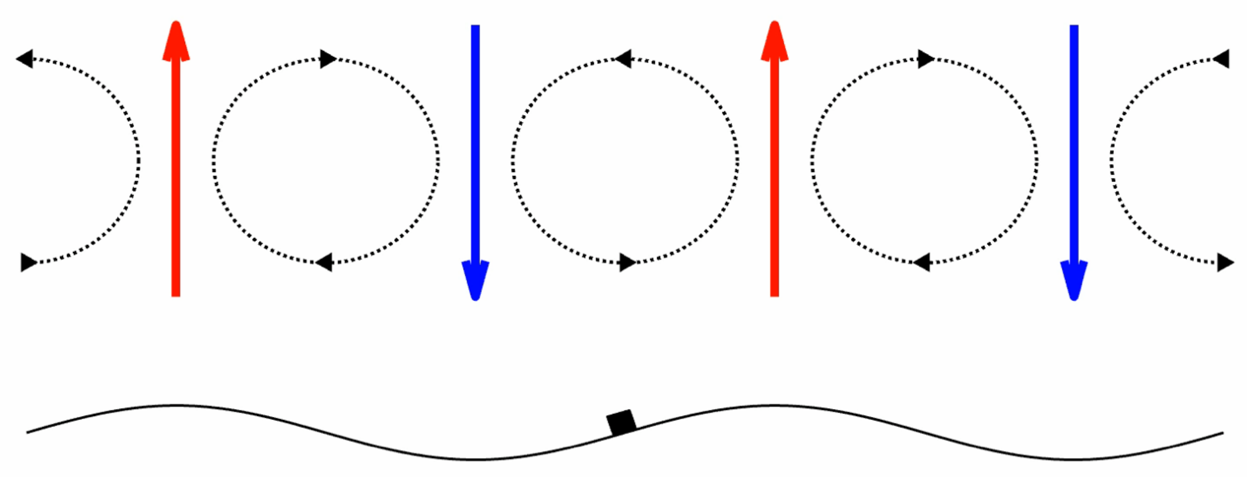


High coherence indicates local quasi-static response



Simplified illustration

Sorrells (1971) theory for wind pressure wave



Quasi-static seismic modeling

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

Modeling (Surface field)

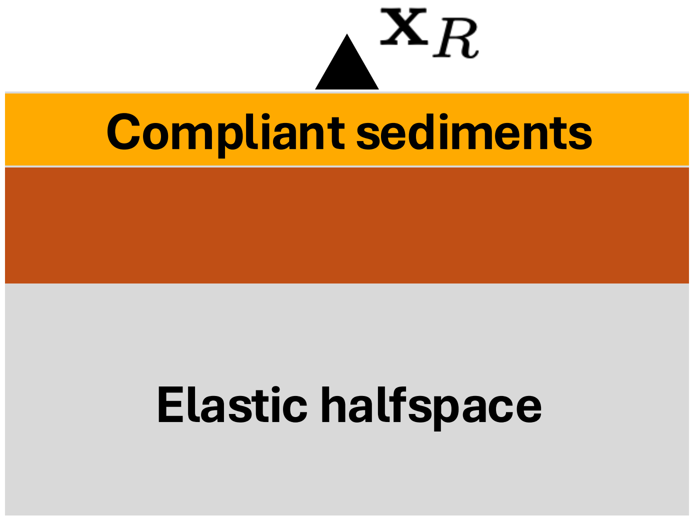
$$u_z(\mathbf{k},\omega) = G(|\mathbf{k}|)\, p(\mathbf{k},\omega)$$

Space-time conversion

Observation (Single point)

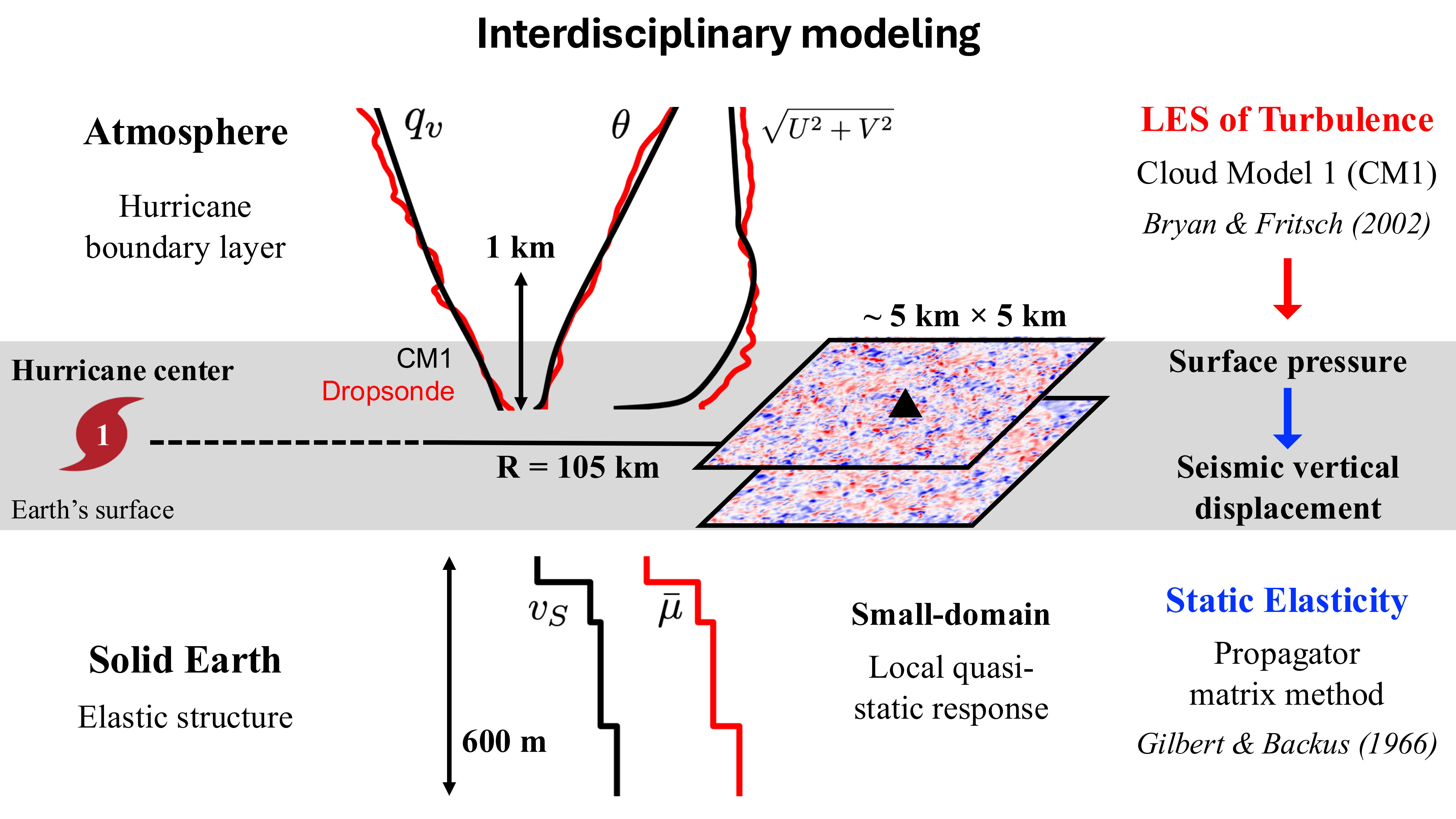
$$u_z(\mathbf{x}_R,\omega) = L(\omega)\, p(\mathbf{x}_R,\omega)$$

Transfer function (i.e., linear estimator)



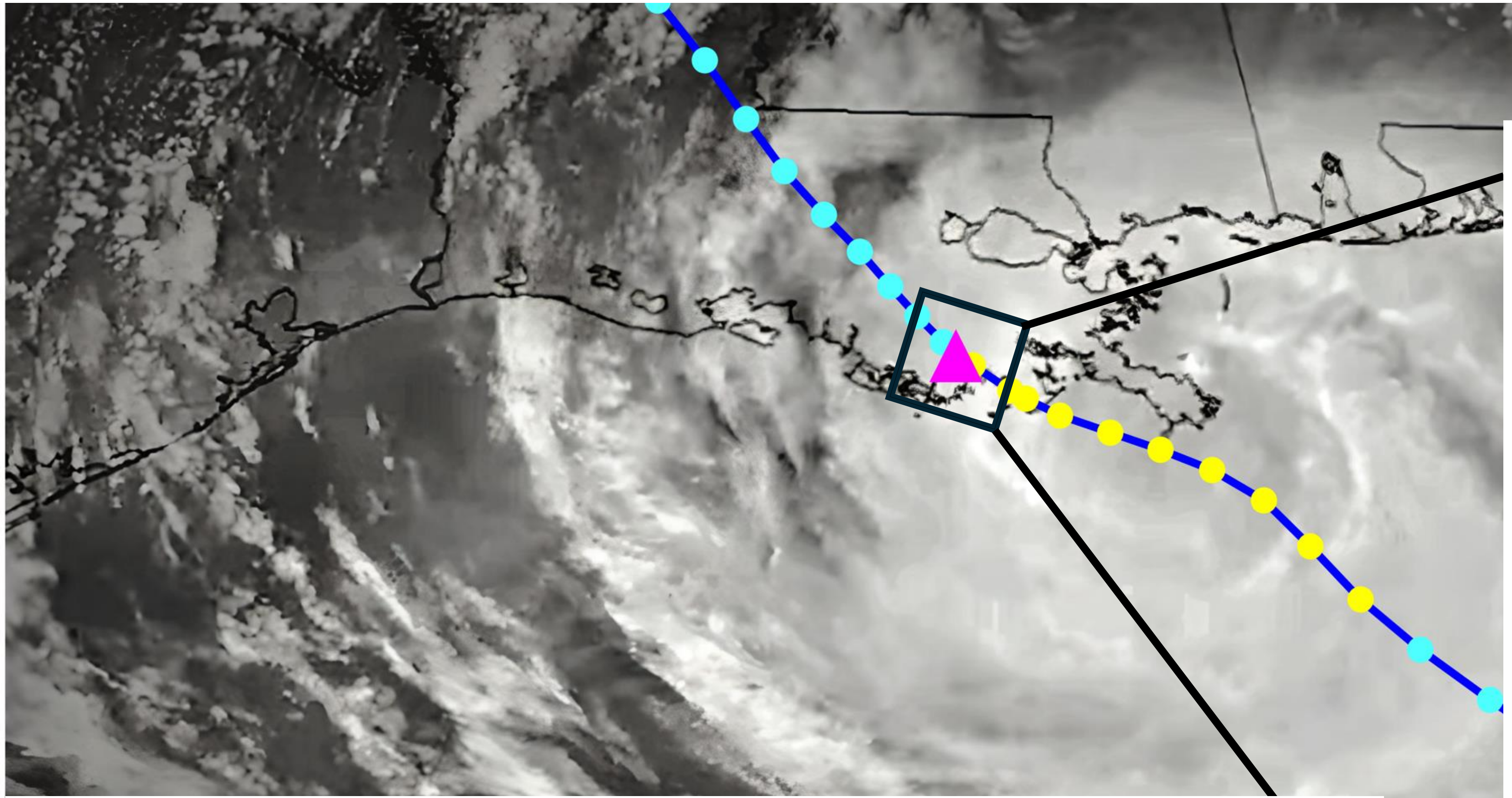
$\mathbf{k}$ Horizontal wavenumber

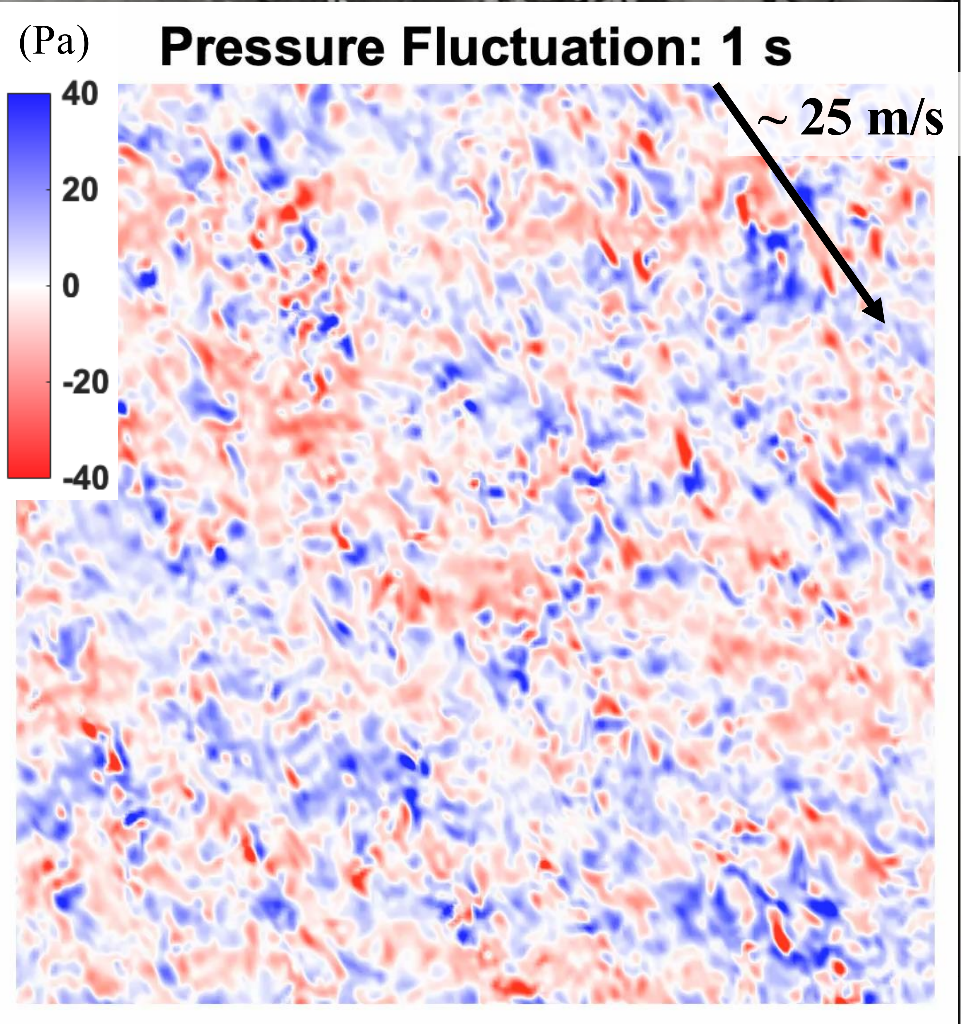
ω Angular frequency



Interdisciplinary modeling
Atmosphere
Hurricane boundary layer
q_v
θ
$\sqrt{U^2 + V^2}$
1 km
CM1
Dropsonde
LES of Turbulence
Cloud Model 1 (CM1)
Bryan & Fritsch (2002)
~ 5 km × 5 km
Hurricane center
1
R = 105 km
Earth's surface
Surface pressure
Seismic vertical displacement
Solid Earth
Elastic structure
v_S
$\bar{\mu}$
600 m
Small-domain
Local quasi-static response
Static Elasticity
Propagator matrix method
Gilbert & Backus (1966)

CM1 LES of Hurricane Boundary Layer (HBL) over land





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

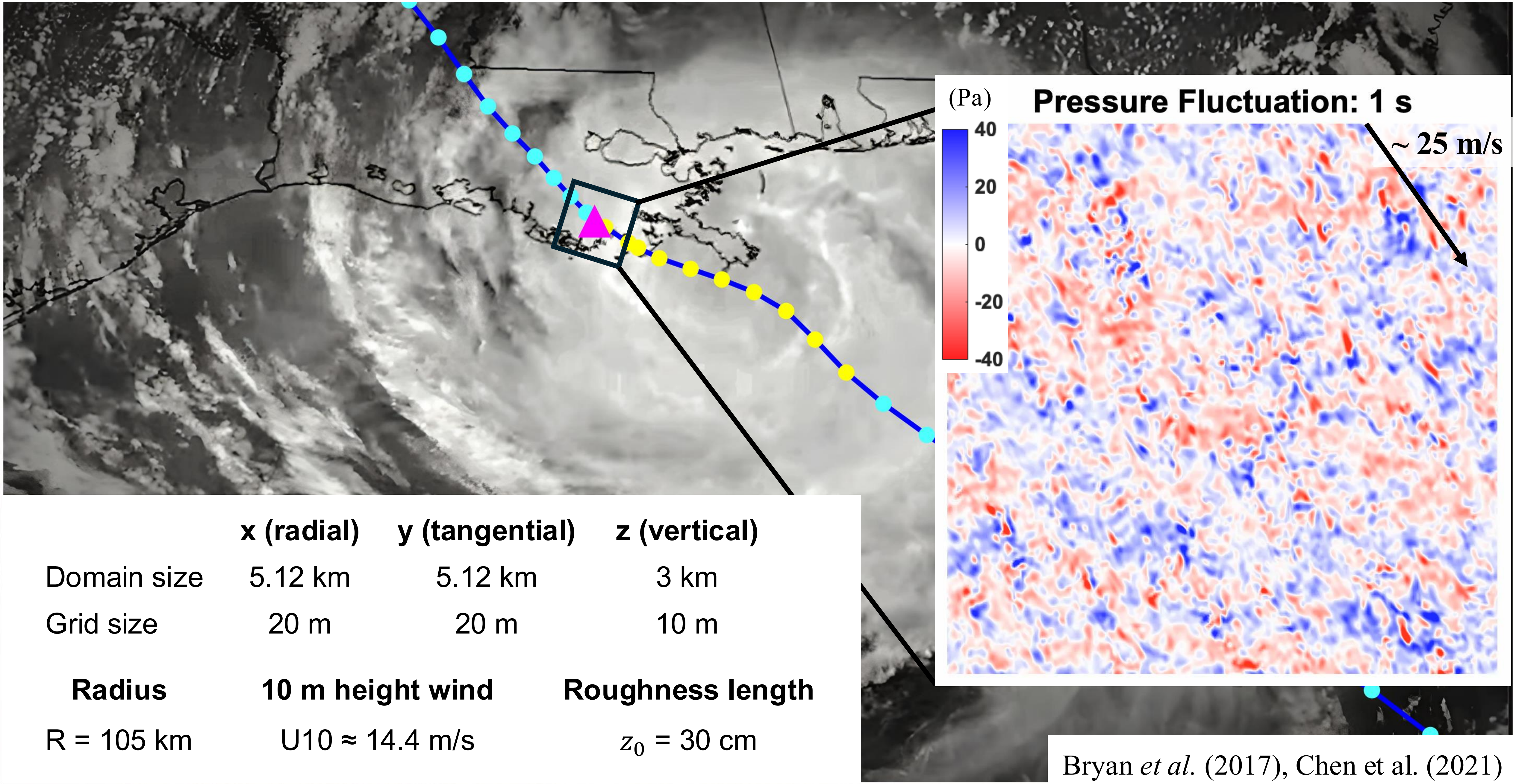
Eddy size > Grid size: Numerically resolved

Eddy size < Grid size: Parameterized by subgrid model

Large eddy

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

CM1 LES of Hurricane Boundary Layer (HBL) over land

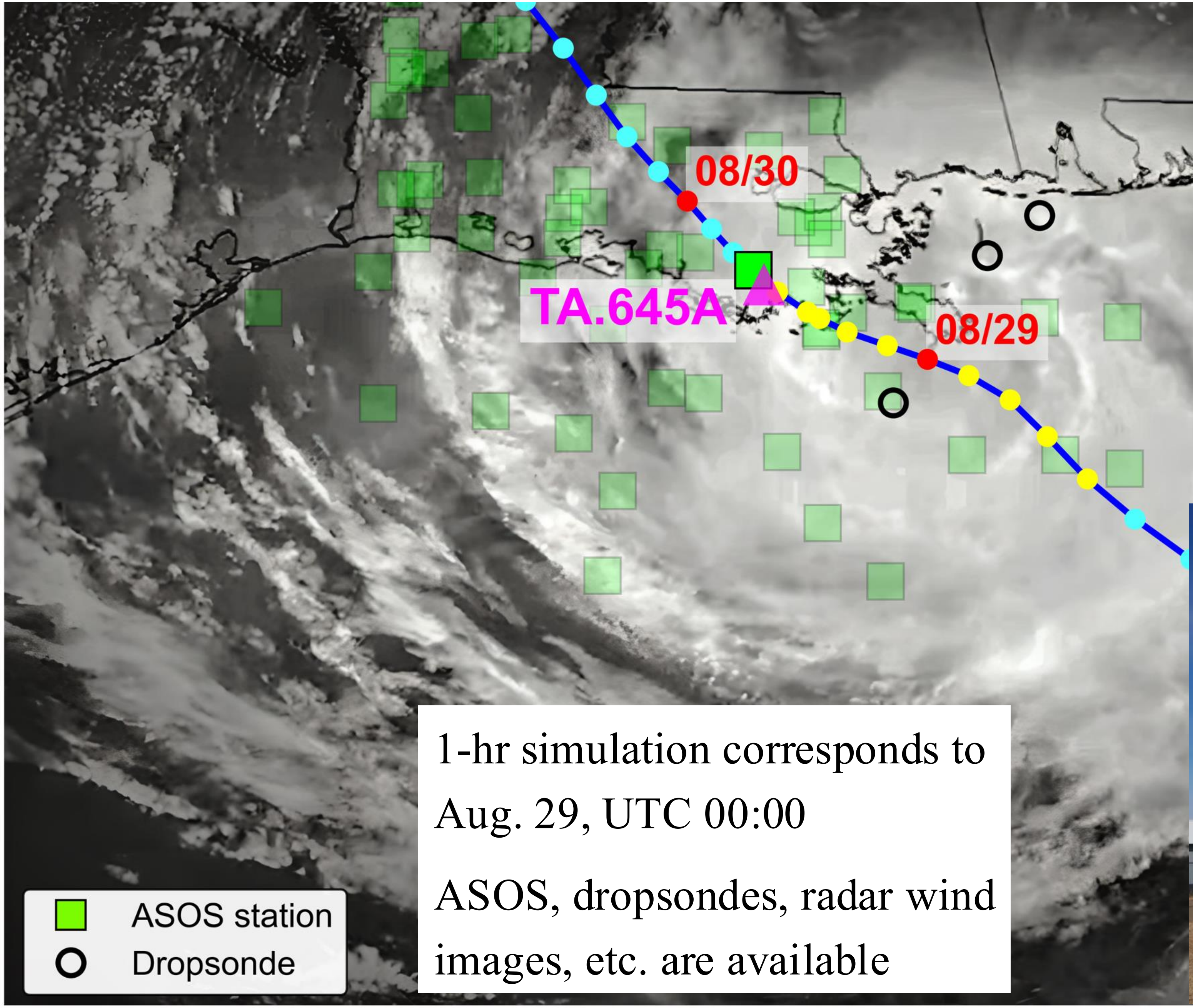


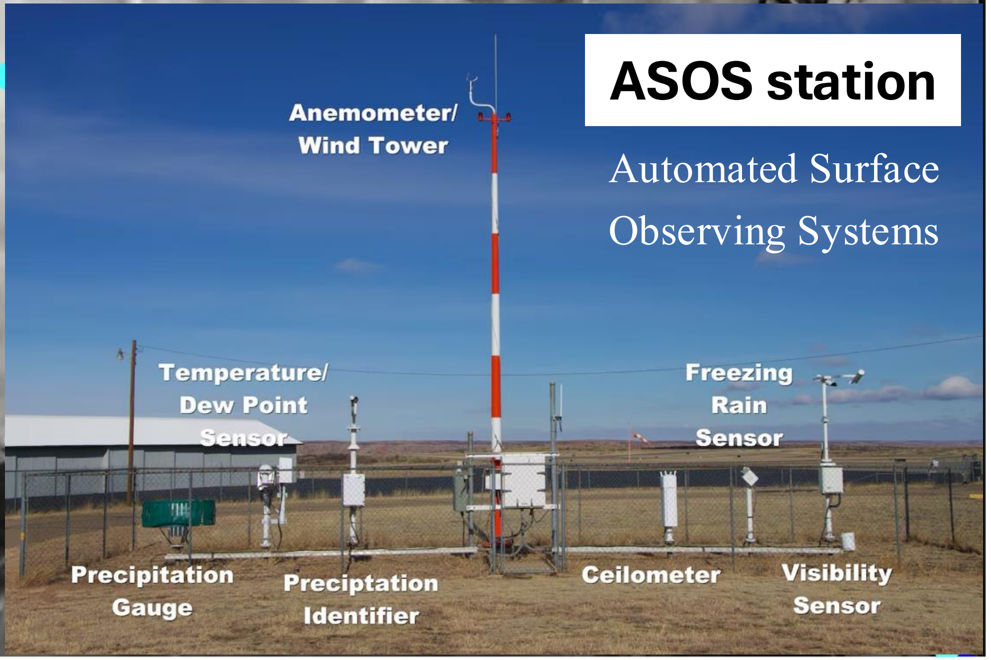
	x (radial)	y (tangential)	z (vertical)
Domain size	5.12 km	5.12 km	3 km
Grid size	20 m	20 m	10 m

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)

Integrate observations with simulations

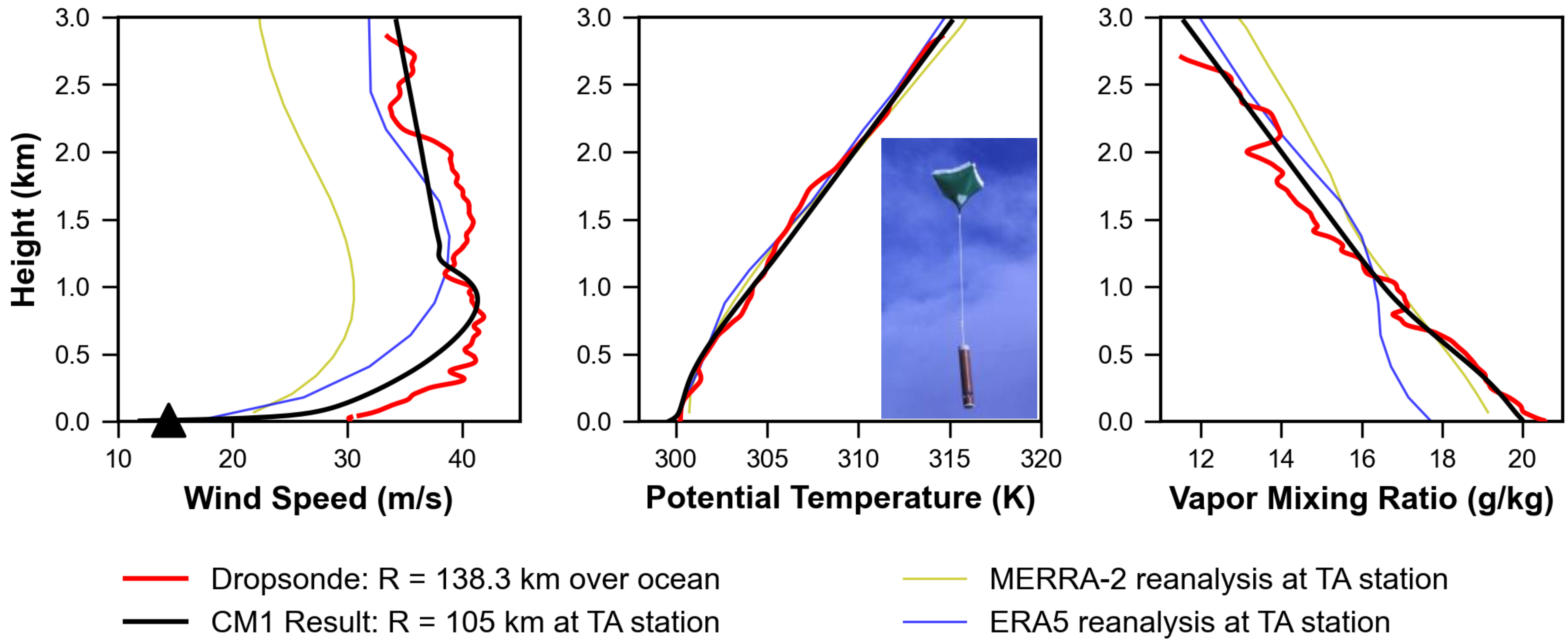




1-hr simulation corresponds to Aug. 29, UTC 00:00

ASOS, dropsondes, radar wind images, etc. are available

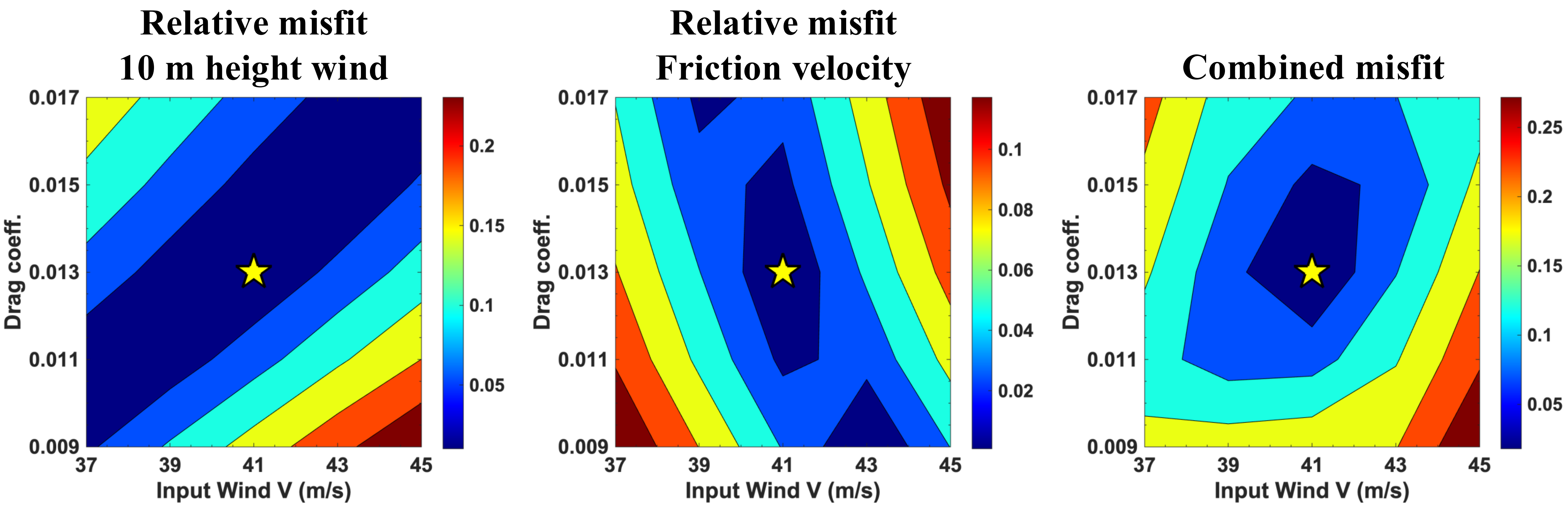
LES with constrained thermodynamic conditions



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

CM1 profiles computed from domain and time average of final 1 hour.

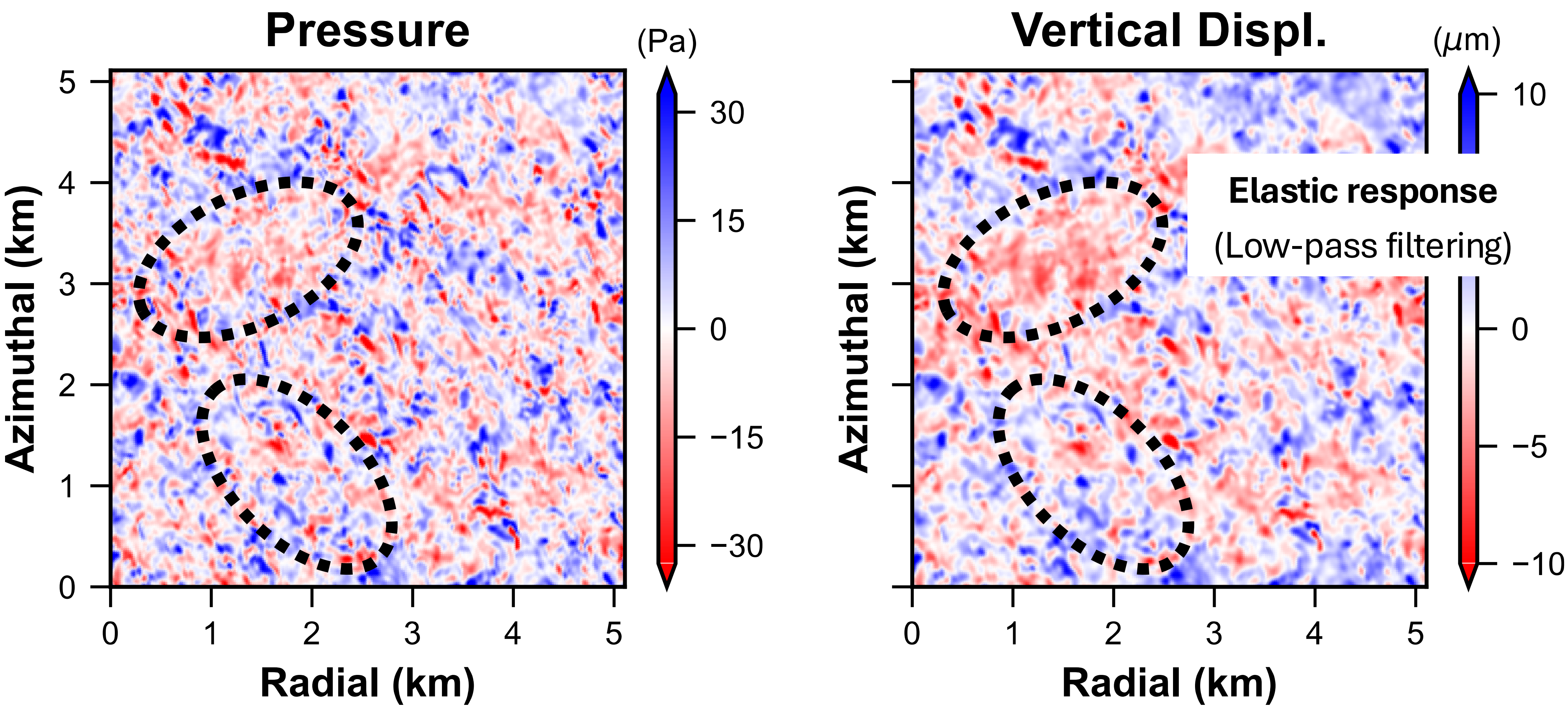
Optimize parameters by reducing misfit



Only tuning two parameters in CM1: Gradient wind V and Drag coefficient Cd

Optimized to match 10 m height horizontal wind and friction velocity (proxy of surface pressure spectral amplitude)

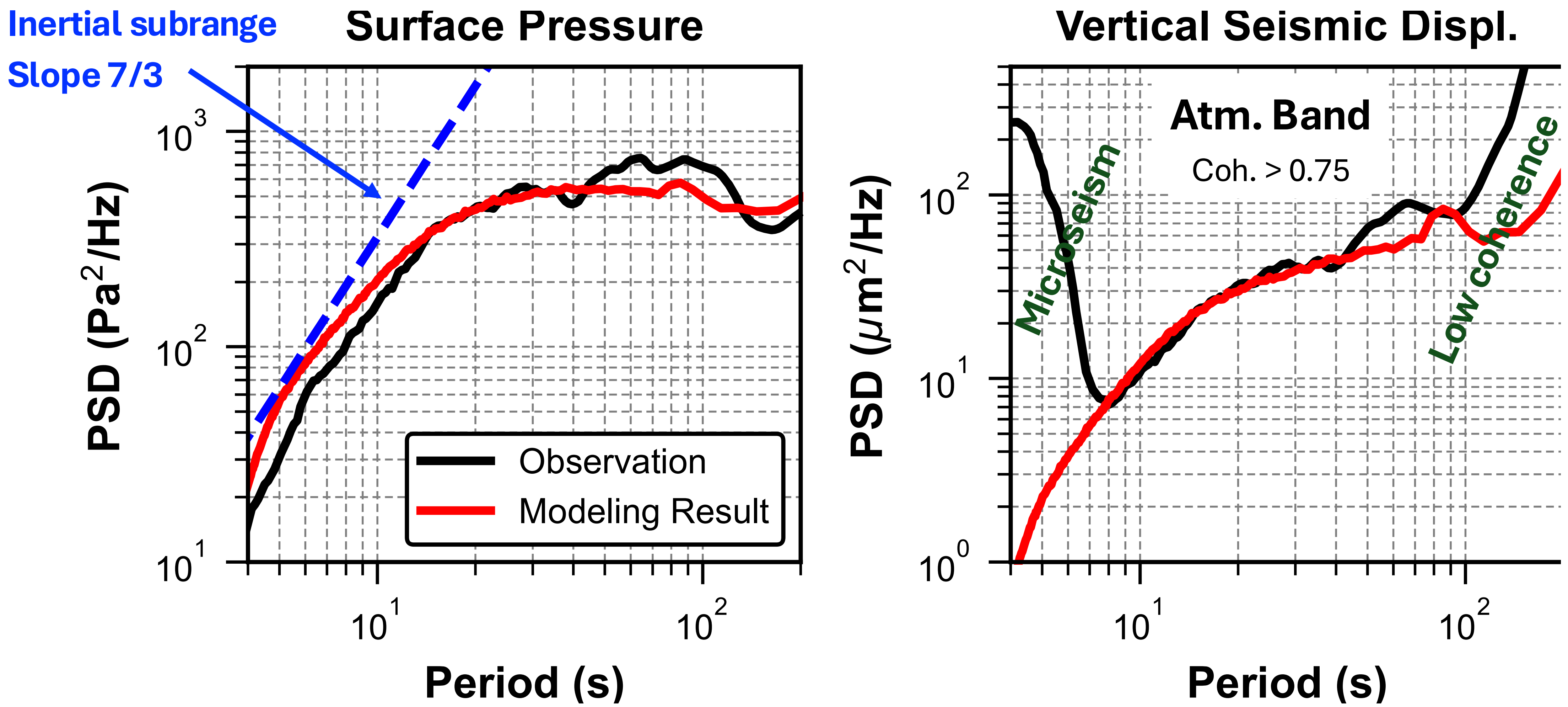
Snapshots from 1-hour modeling



Dense LES output of surface pressure for 1 hour from the final snapshot.

Quasi-static seismic modeling to obtain vertical displacement.

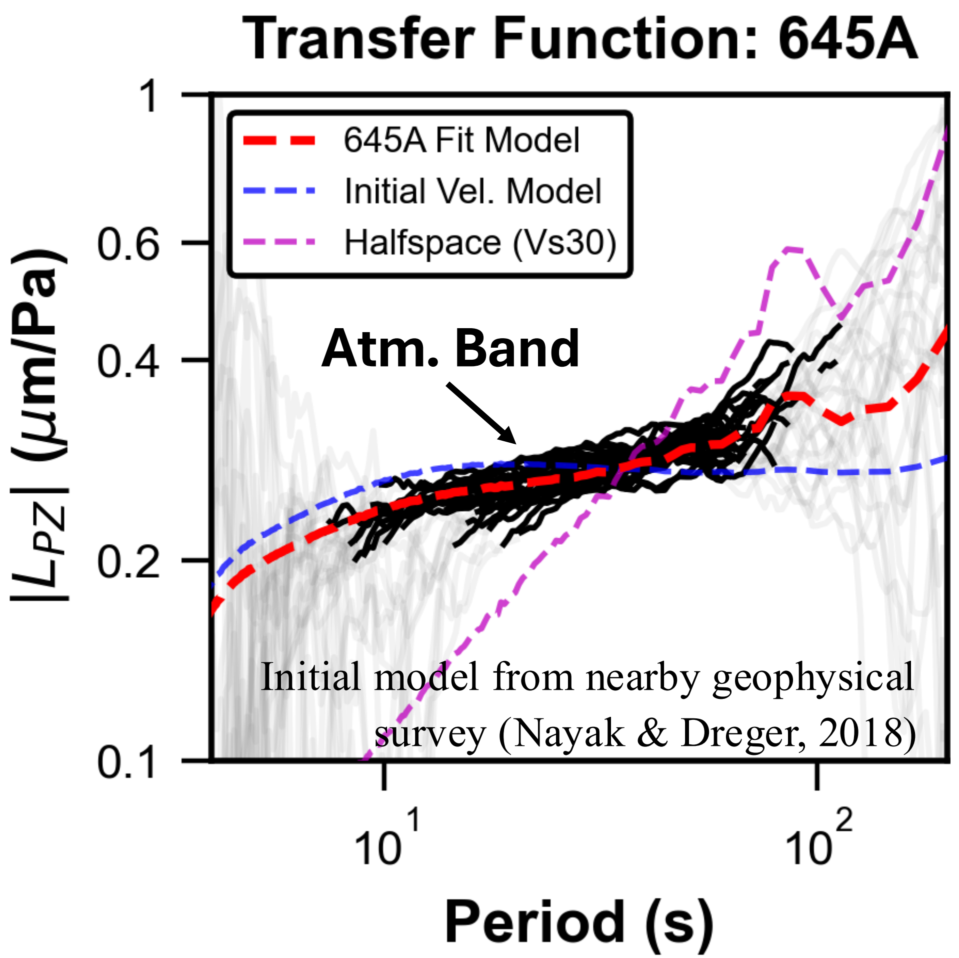
Infrasound & seismic spectra

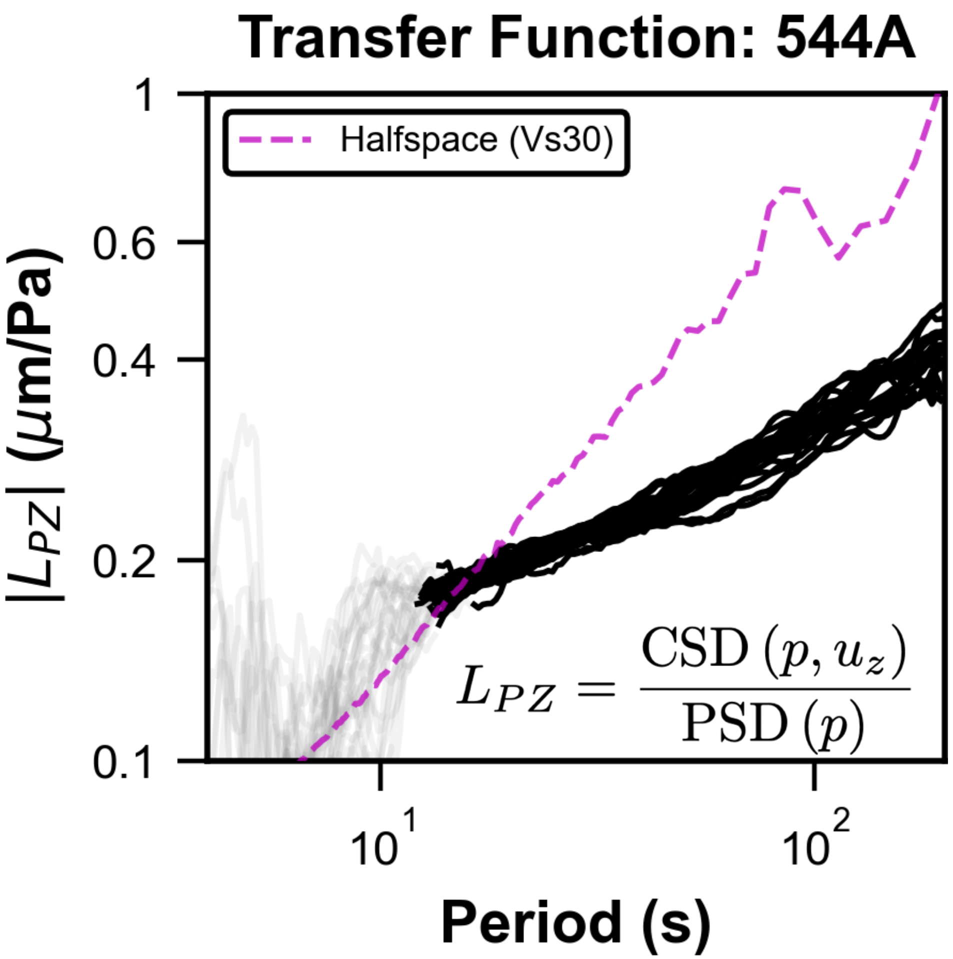


Infrasound data can be used for turbulent spectral analysis.

Seismic signals originate from turbulent pressure in the atmospheric band.

Elastic response to surface pressure





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

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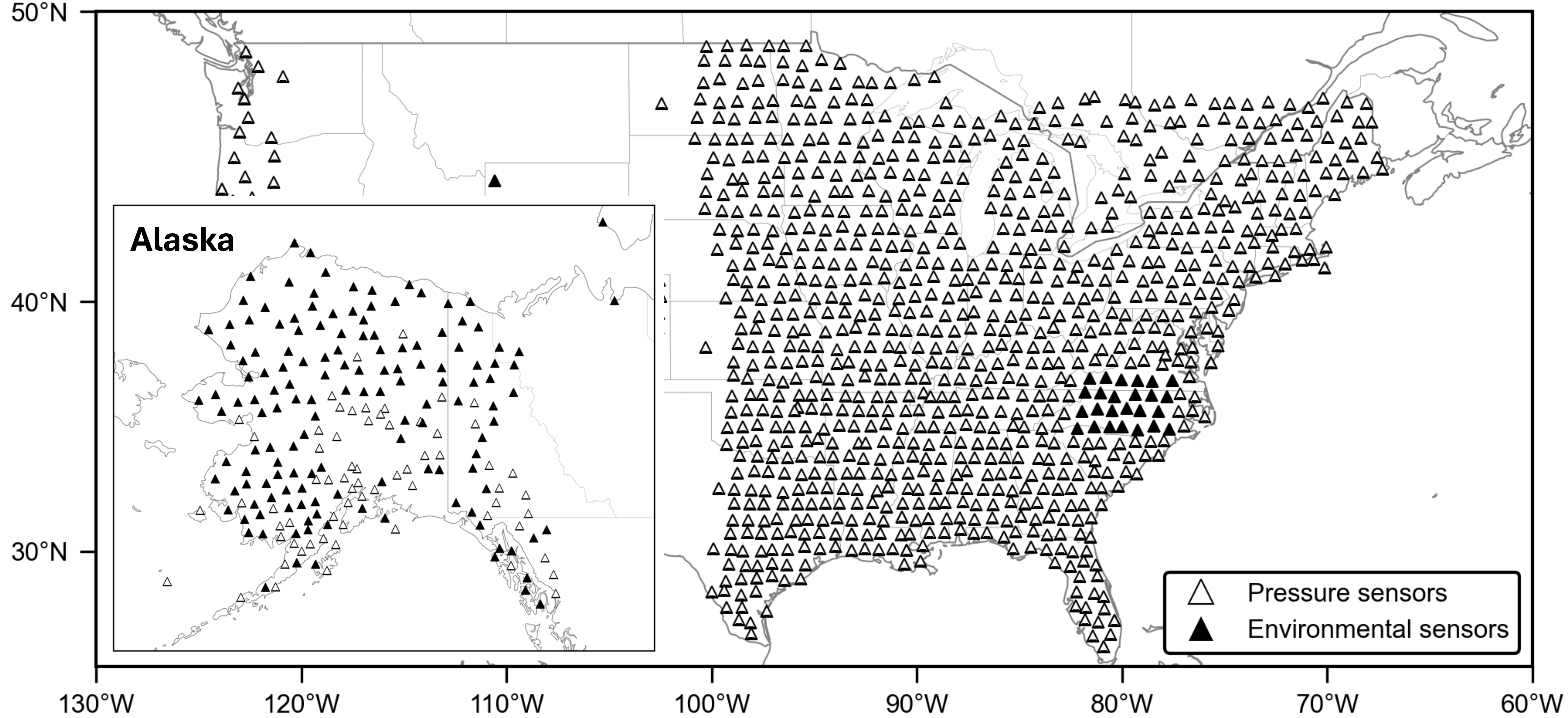
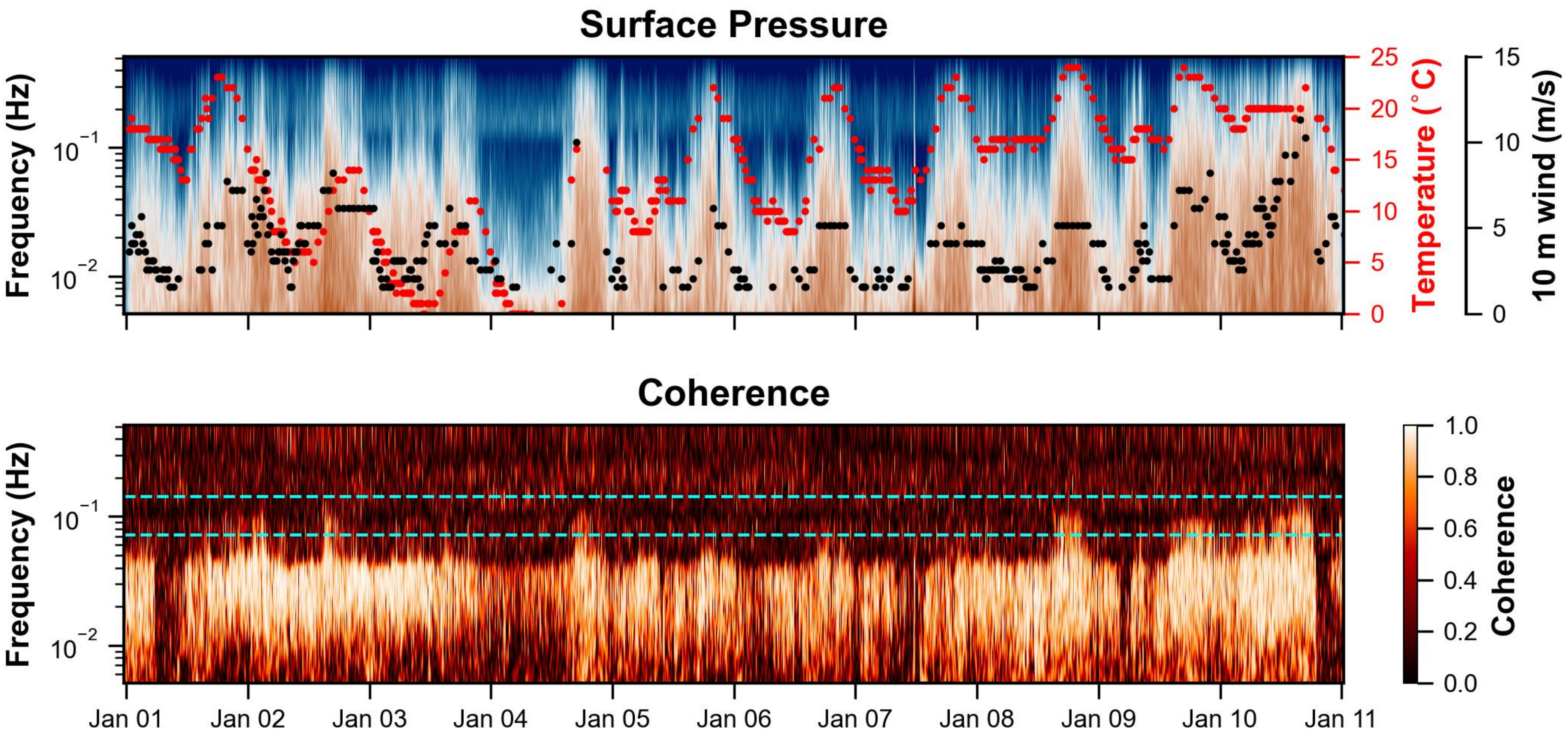
Seismic stations with environmental sensors



Modified from Tytell et al. (2016)

Diurnal cycles of atmospheric boundary layer (ABL)

Same station as Isaac analysis



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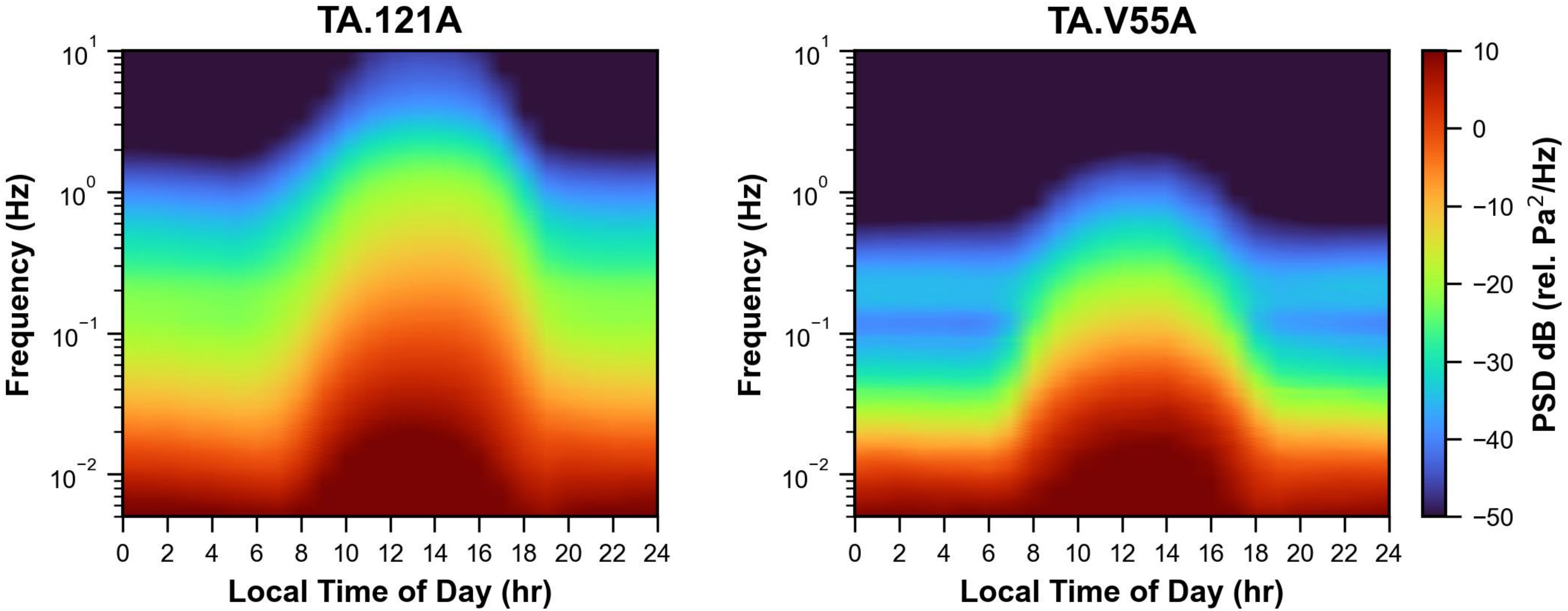
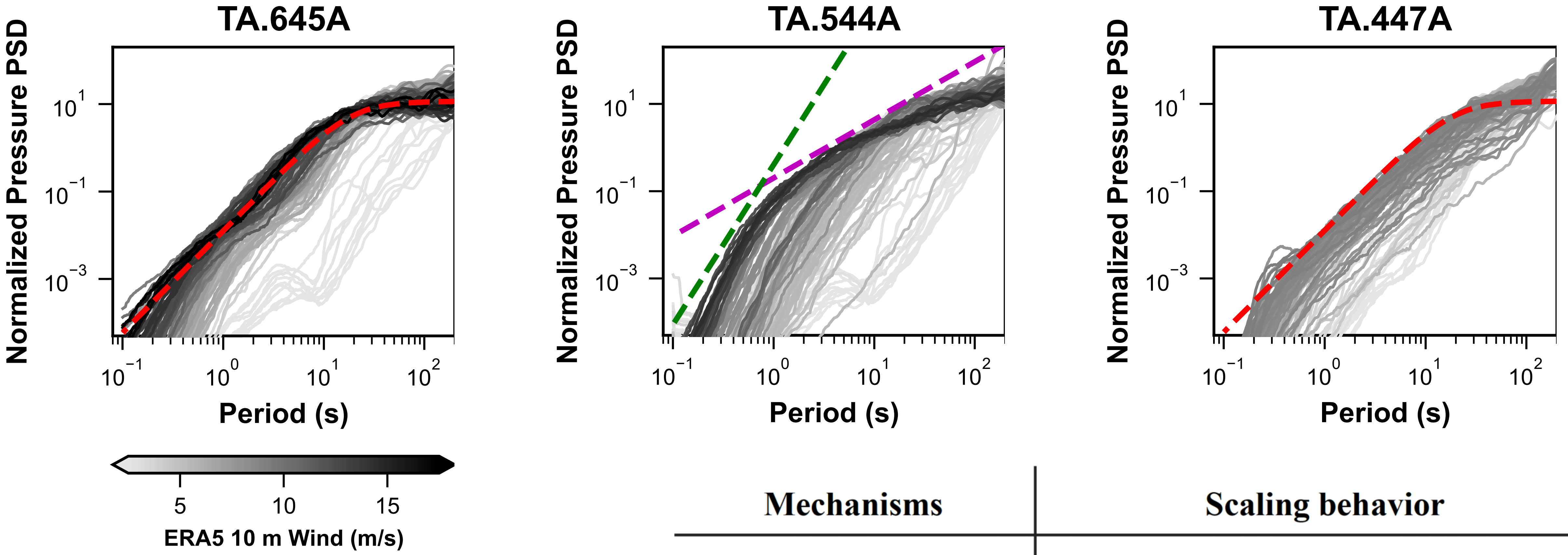


Diurnal variation in turbulence in response to solar heating (Stull, 1988)

Infrasound data for turbulent pressure spectra



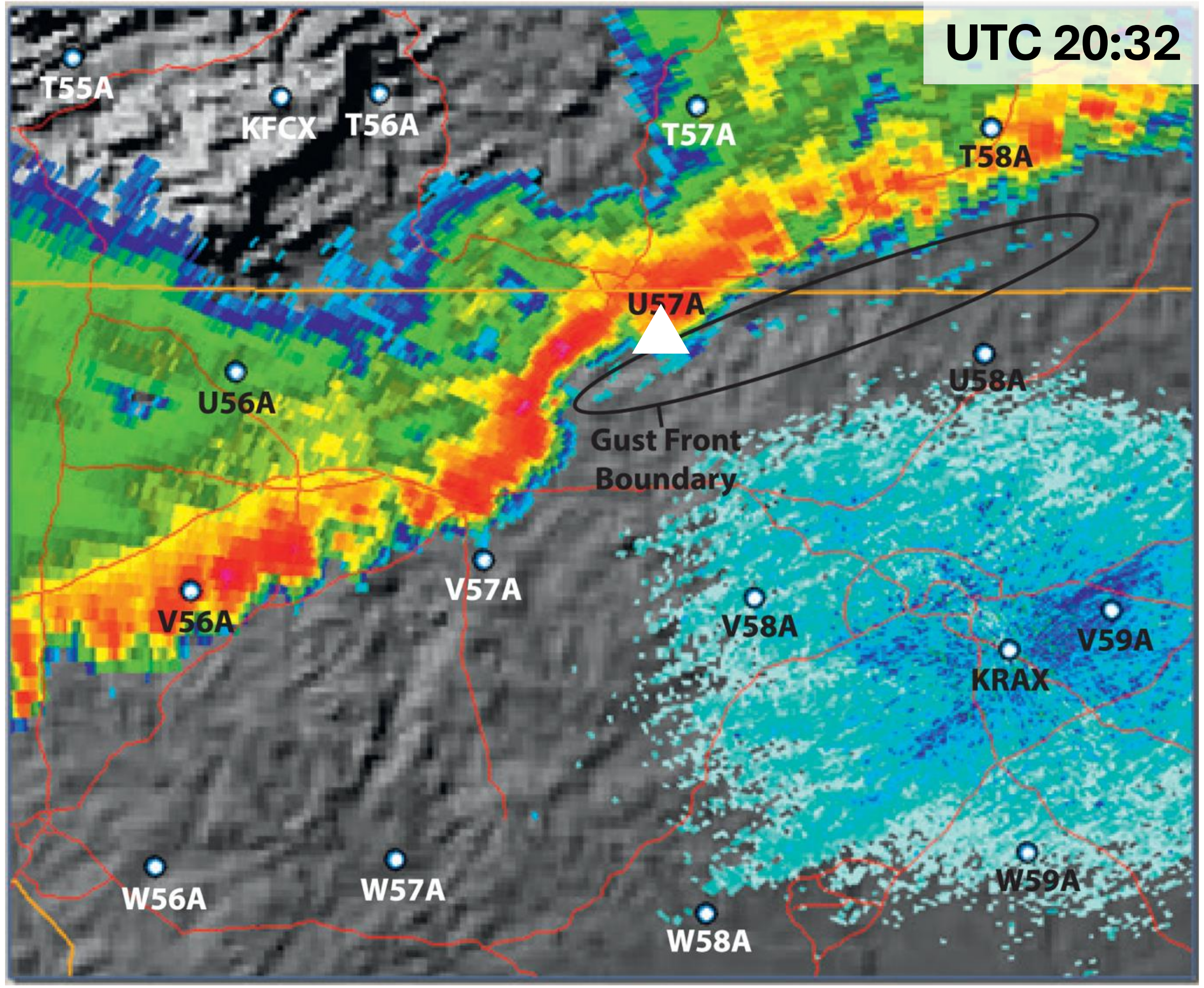
A rich dataset to investigate turbulent pressure spectra under various surface roughness, weather conditions, etc.

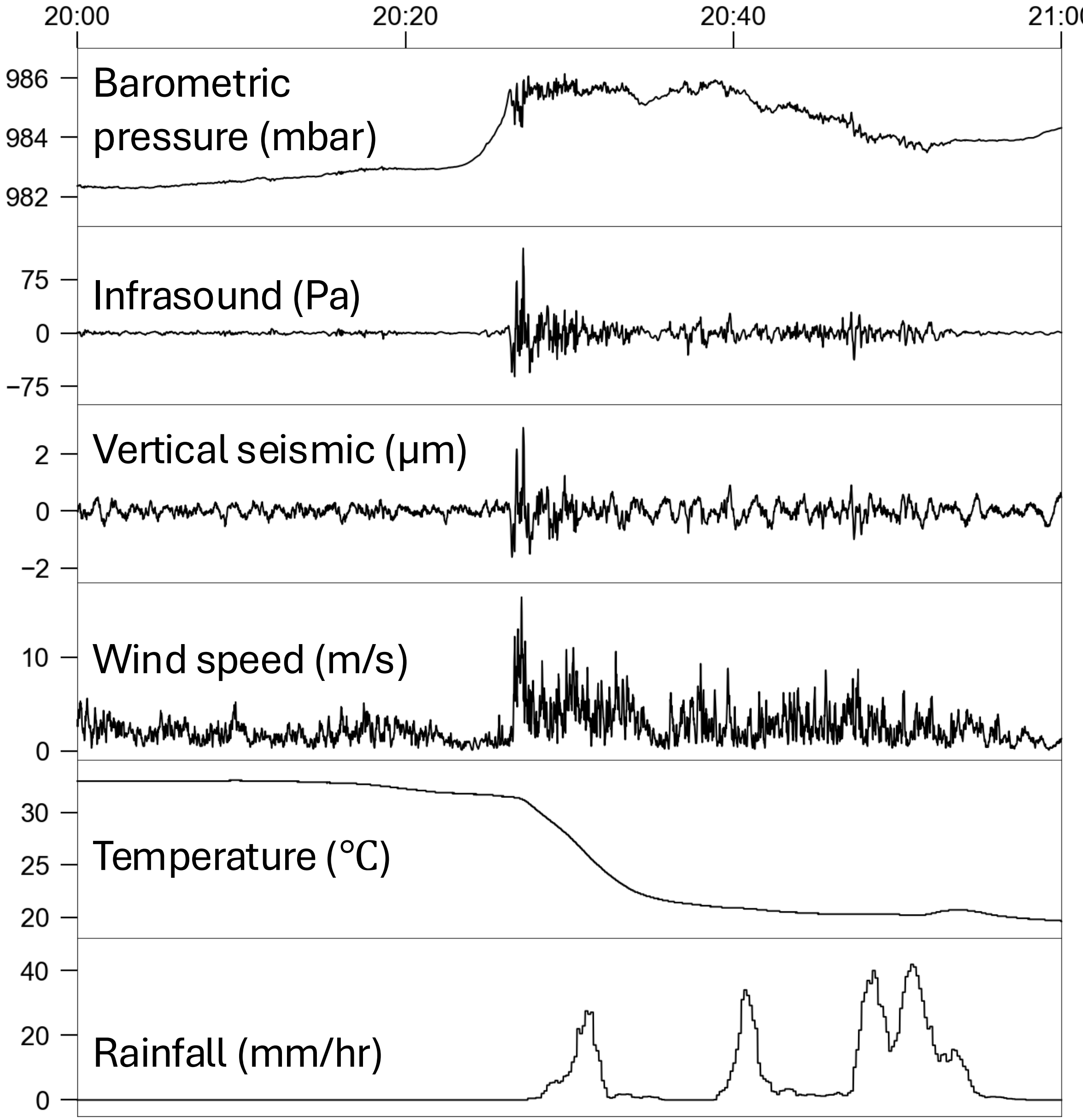
Mechanisms	Scaling behavior
Turbulence - turbulence interaction	Short period: $T^{7/3}$ Long period: **Flat**
Turbulence - mean shear interaction	Short period: $T^{11/3}$ Long period: $T^{-5/3}$
Simple vortex model	Generally close to $T^{4/3}$

George et al. (1984), Tsuji & Ishihara (2003), Hoxey et al. (2021)

Observation of gust fronts

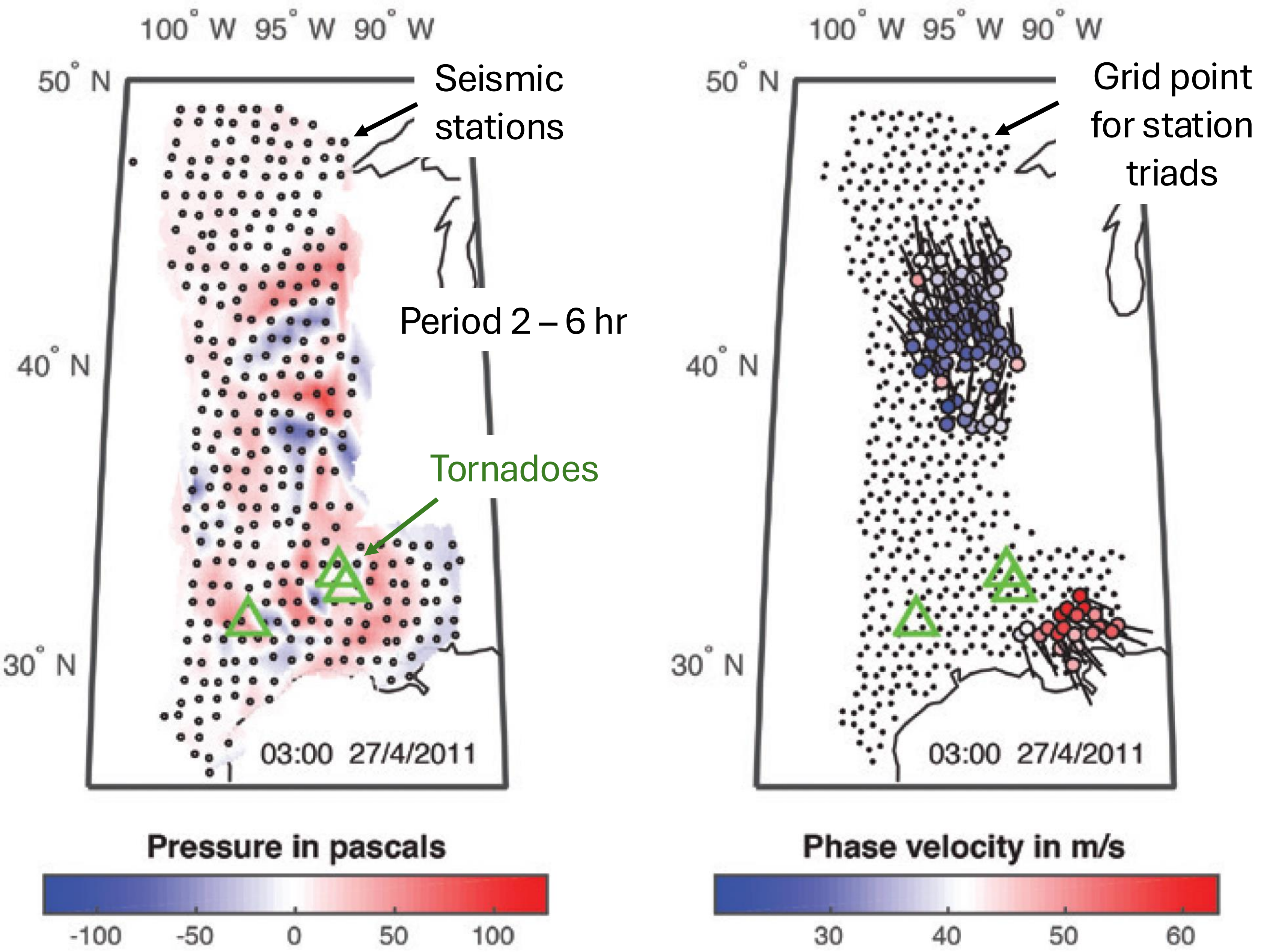
June 13, 2013 Derecho event





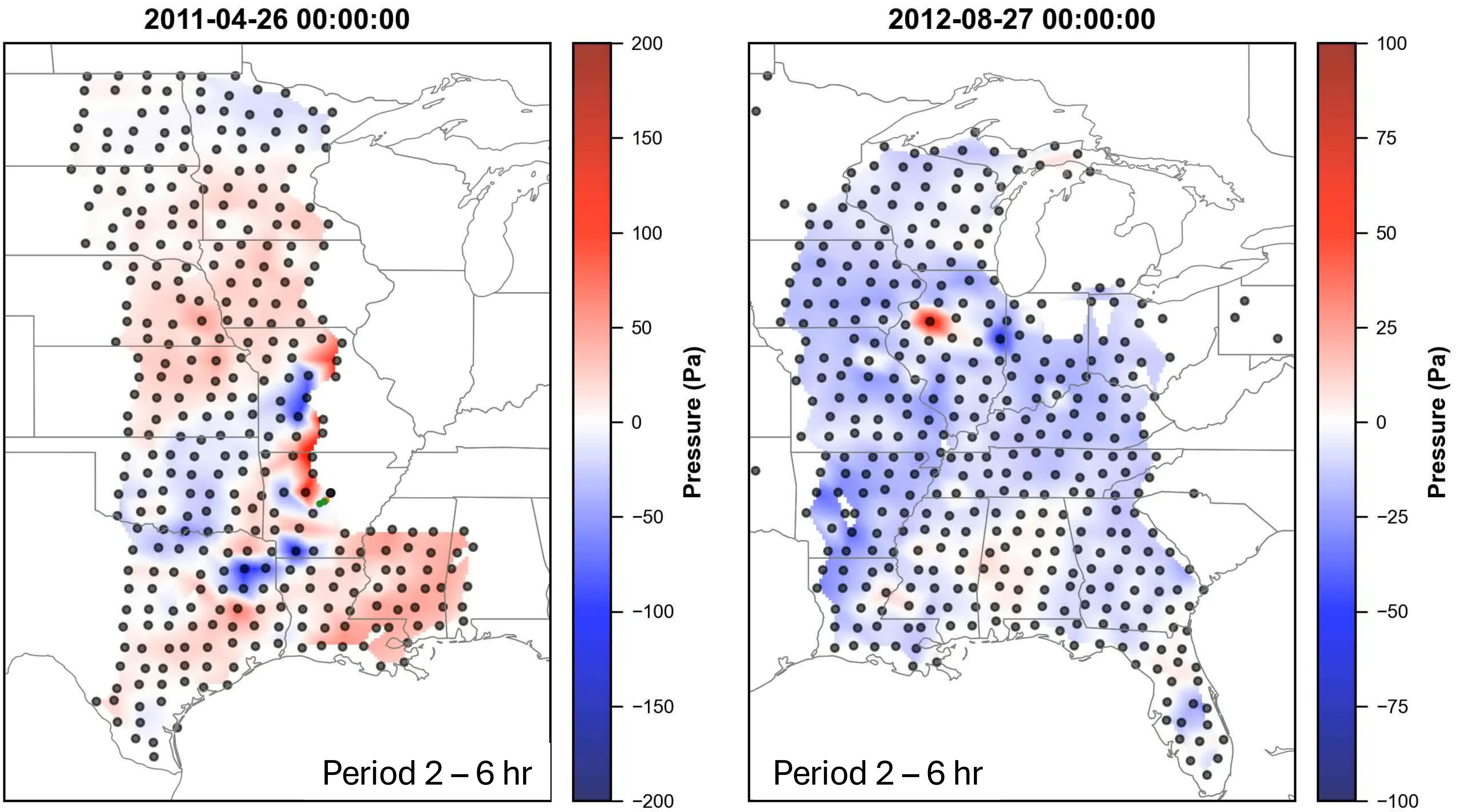
Modified from Tytell et al. (2016)

Observation of gravity waves



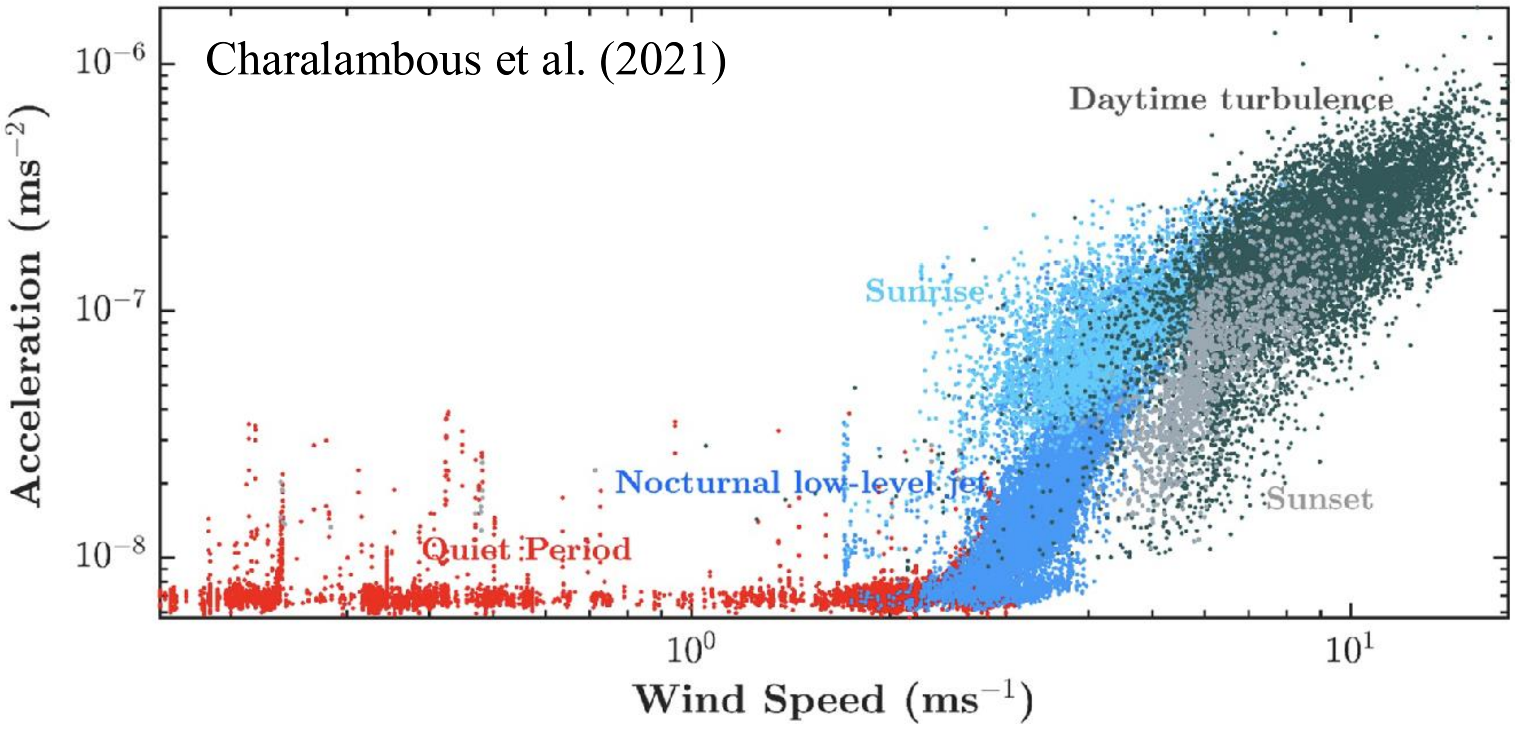
Detection and estimation of phase velocity of gravity waves using **station networks**.

Tytell et al. (2016)


2011-04-26 00:00:00
2012-08-27 00:00:00
200
150
100
50
0
−50
−100
−150
−200
Pressure (Pa)
100
75
50
25
0
−25
−50
−75
−100
Pressure (Pa)
Period 2 – 6 hr
Period 2 – 6 hr

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)

Summary

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