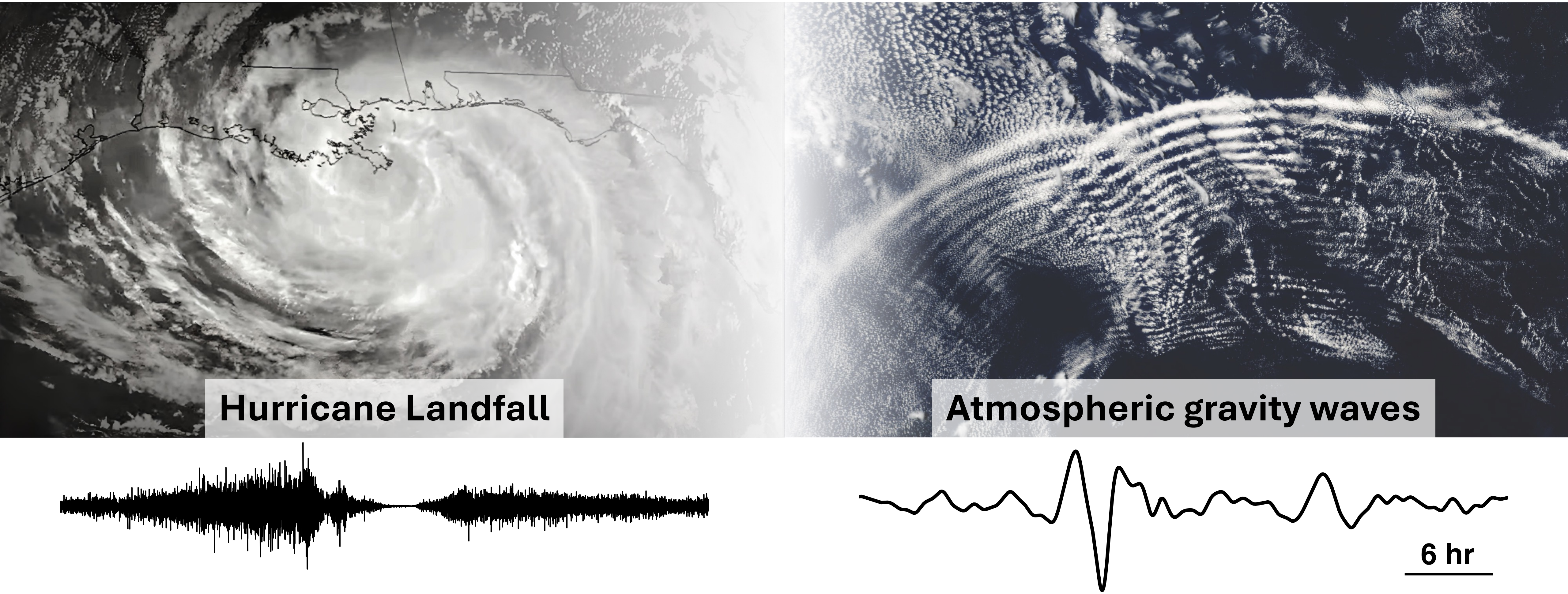
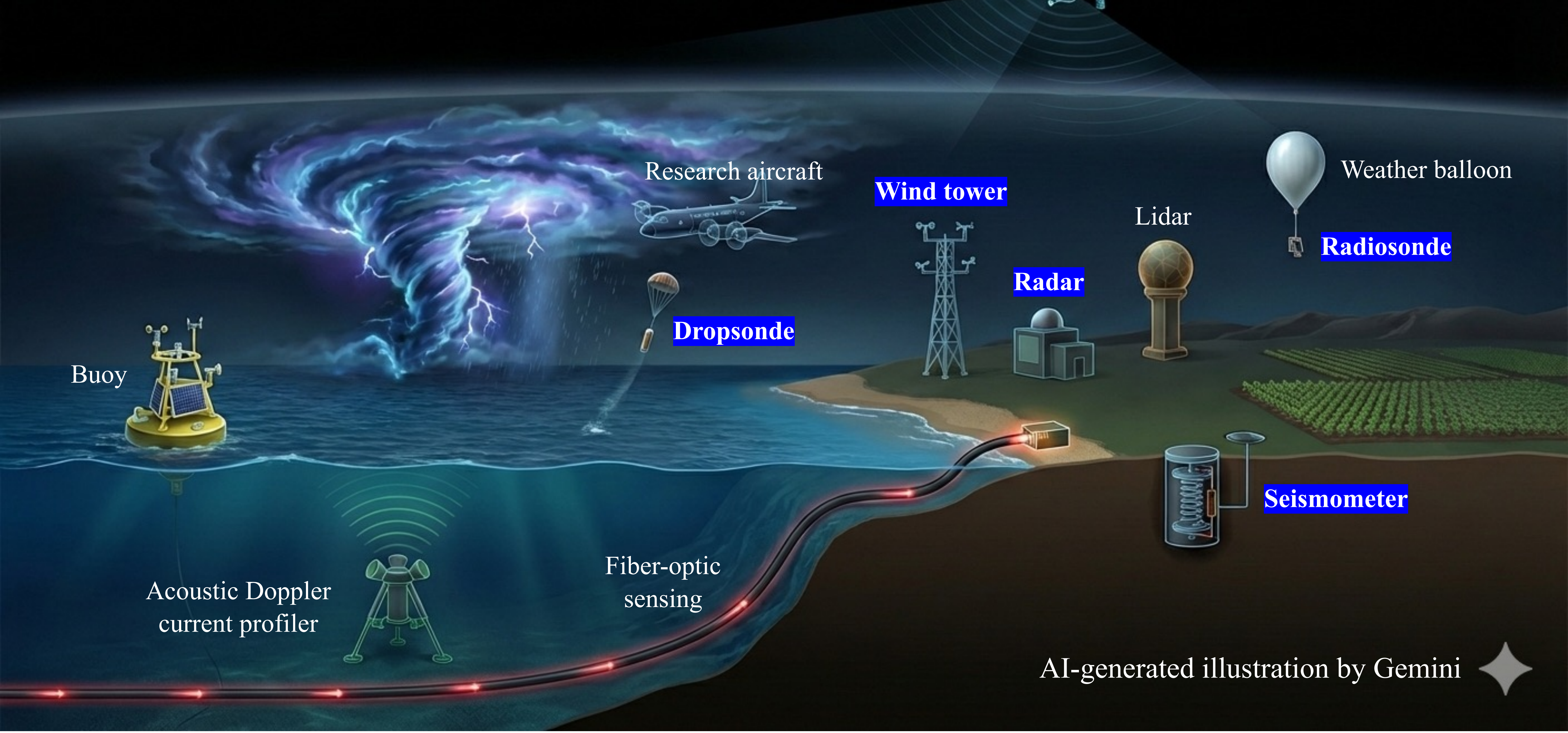
Atmospheric signatures in ambient seismoacoustic signals

Qing Ji **PhD Oral Defense**



Data are essential for understanding the complex Earth system

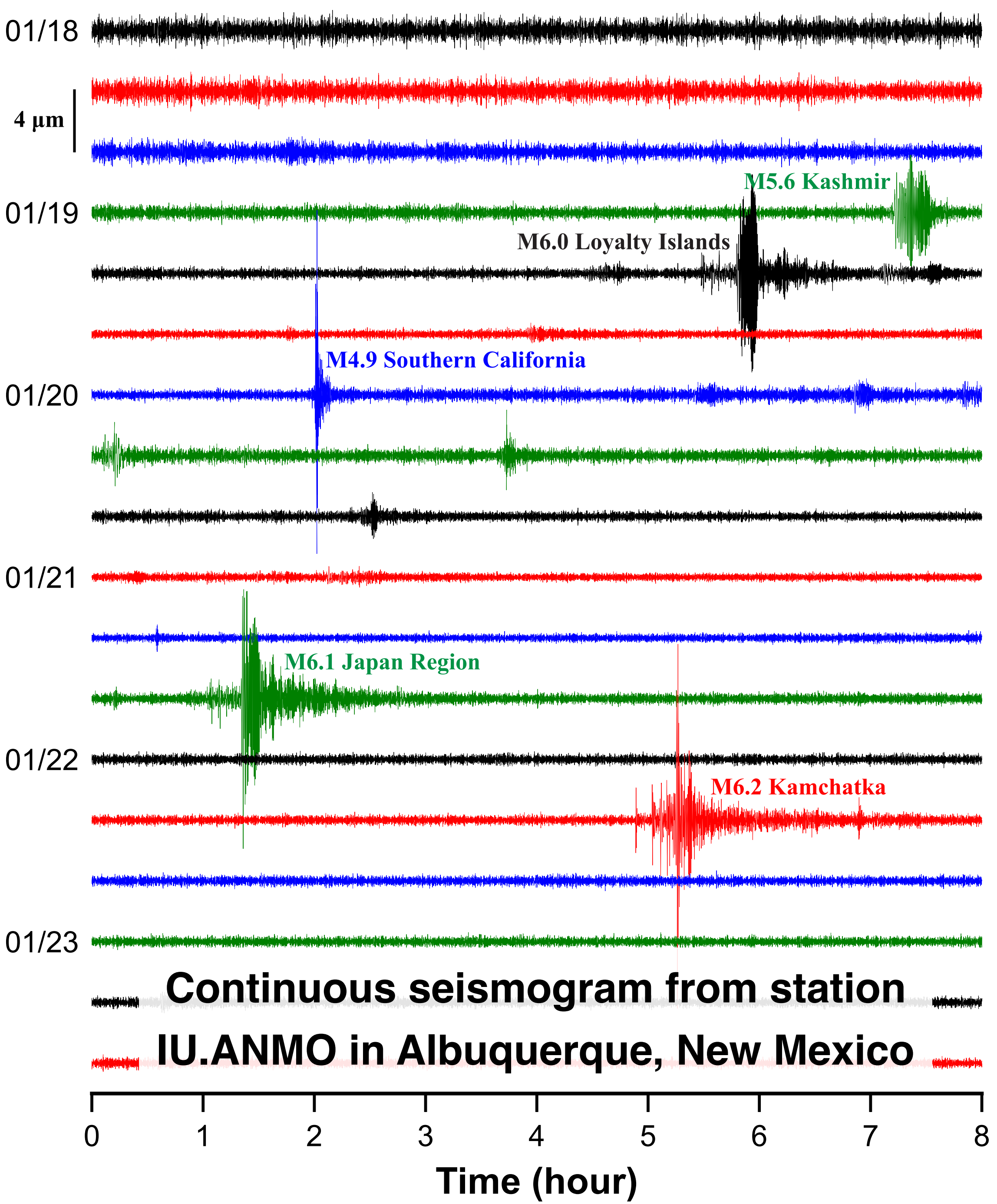


Distinct signals from earthquakes, volcanic eruptions, etc., are traditionally subjects of seismological studies.

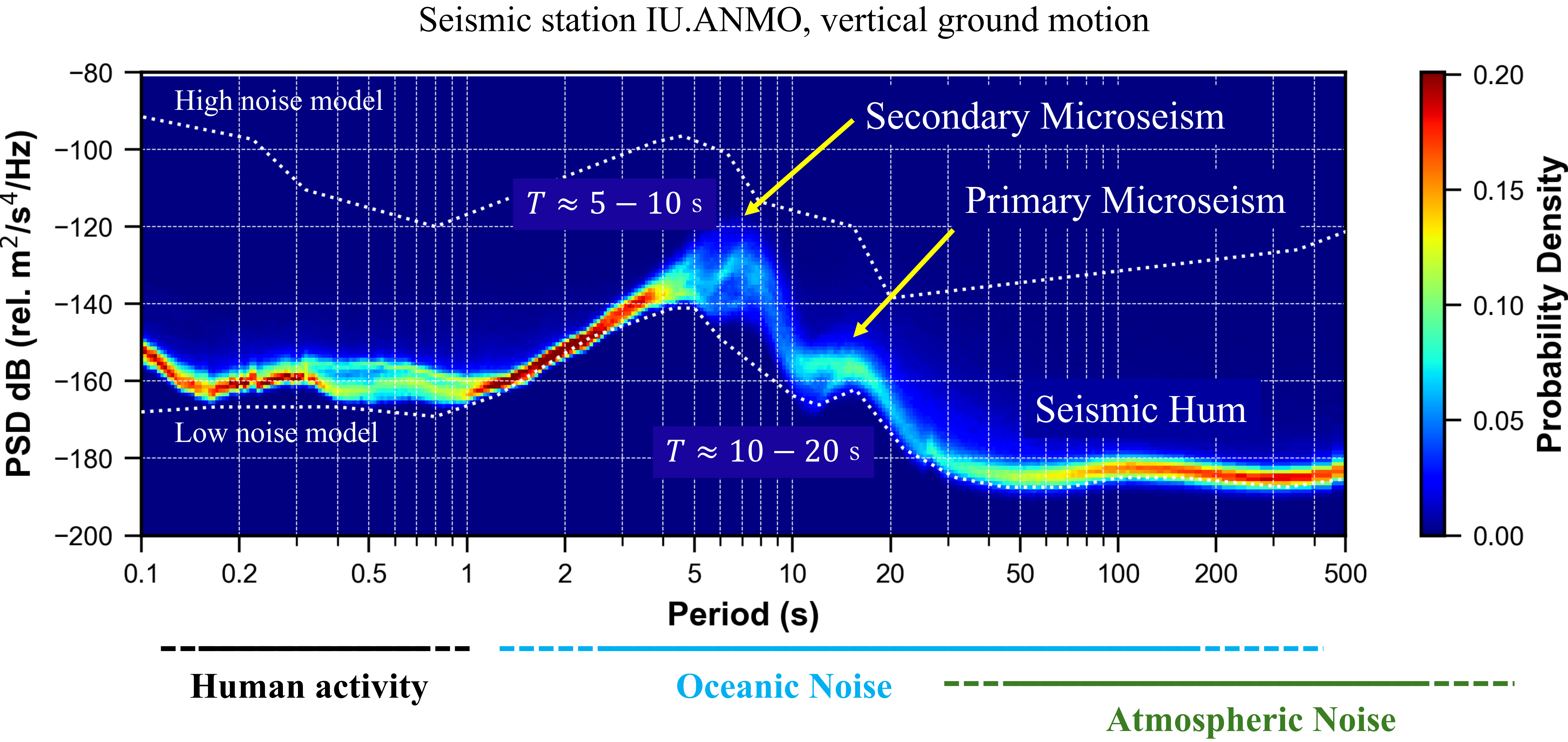
However, these signals only contribute a very small portion of seismograms.

The rest is seismic ambient noise.

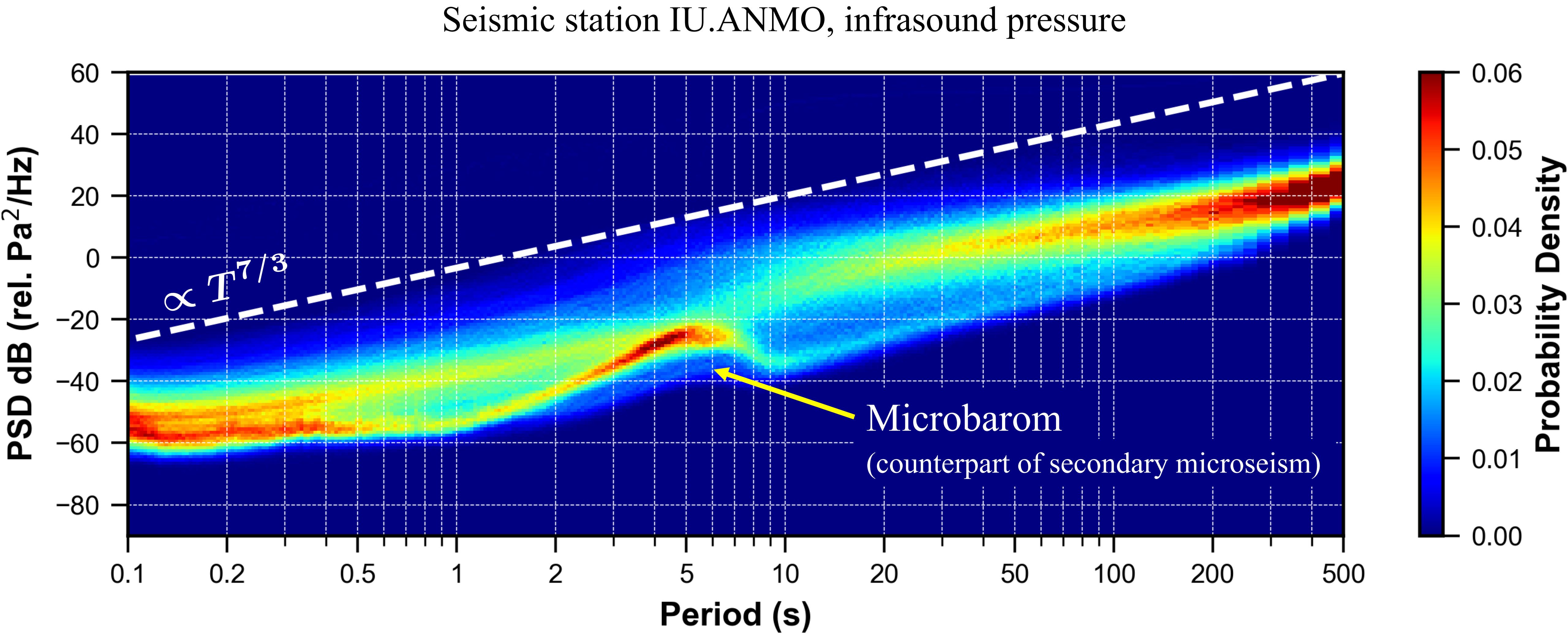
In fact, these ambient signals are linked to various natural processes and contribute to a rich dataset for environmental studies.



Seismic ambient noise comes from various natural processes



Infrasound ambient noise are less investigated



What exactly does '**wind noise**' mean? Are these signals reflective of atmospheric processes?

Tracking tropical cyclones with microseism

Ocean waves

↓

Seismic noise sources

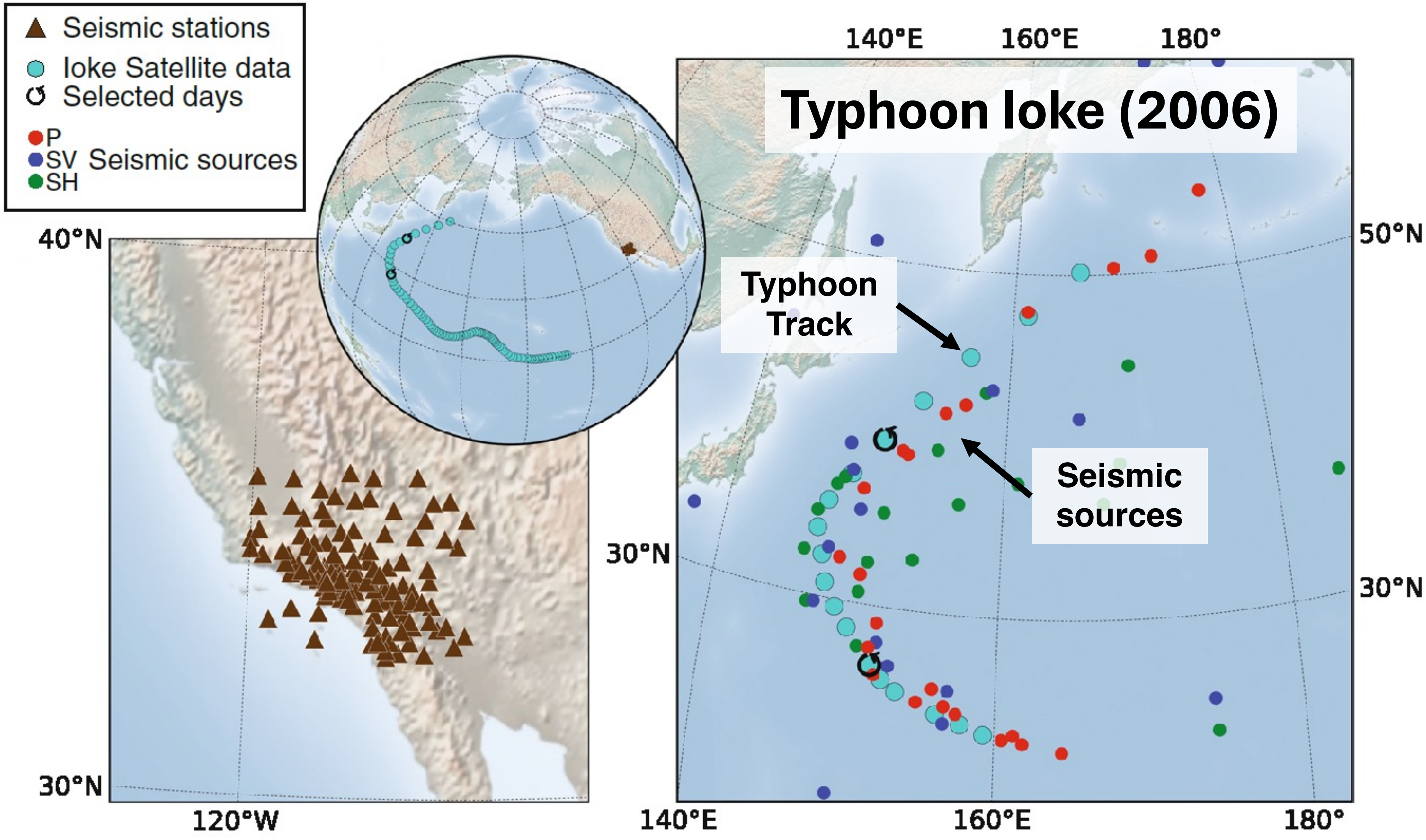
(at Earth's surface)

$p(x, y, t)$

↓

Microseism

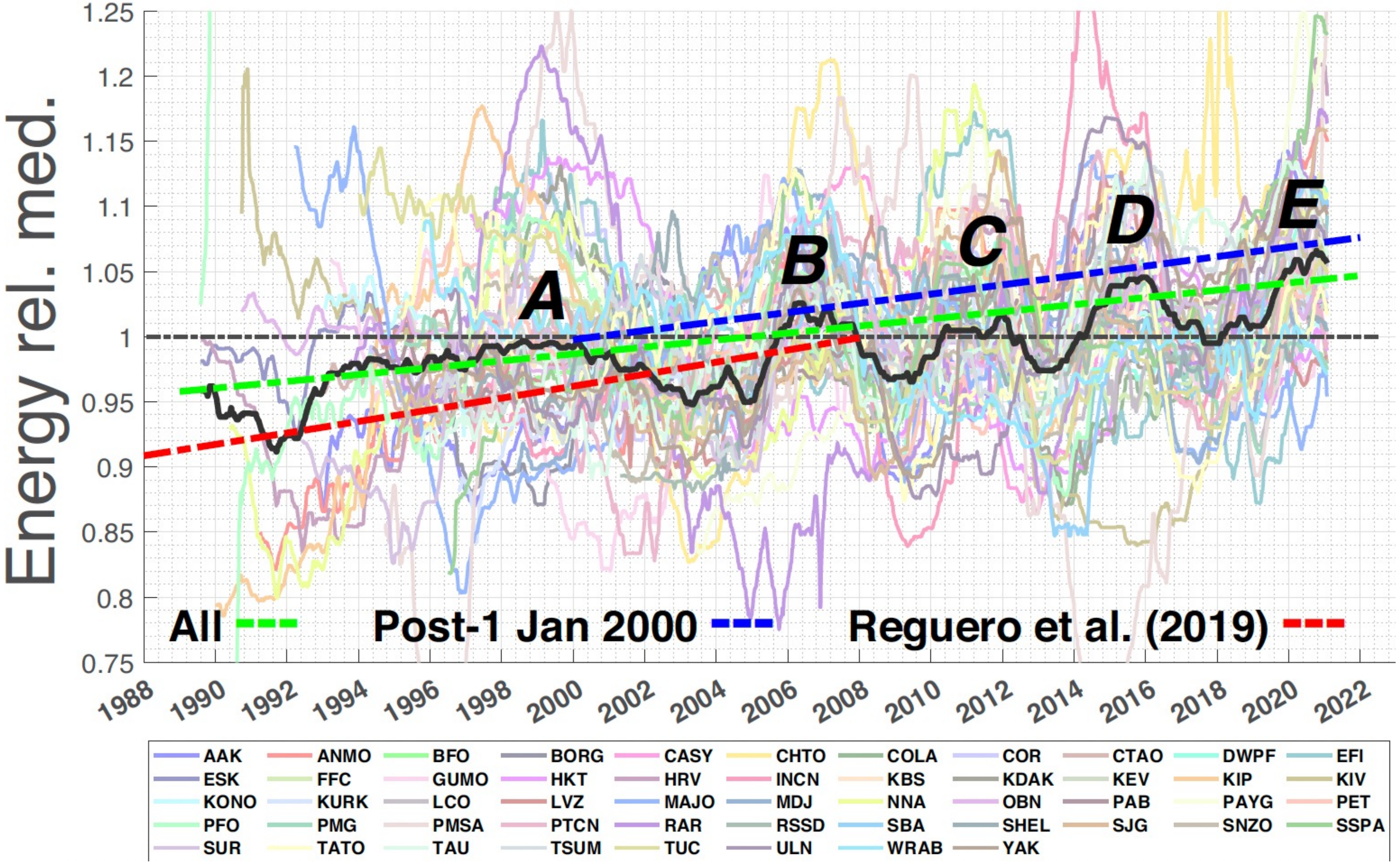
(Seismic waves)



Retailleau & Gualtieri (2021)

Microseism reflects changing ocean wave energy

Overall trend of increasing wave climate reflected by microseism energy.



Aster et al. (2023)

Dissertation Chapters

Signatures from hurricane boundary layer turbulence:

Ch 2 - Seismic ambient noise from the atmosphere: A case study of hurricane landfall

Pressure-seismic coupling mechanism (**Foundation** of modeling framework in Chapter 3): Ji & Dunham (2024)

Local quasi-static response to pressure fluctuations ~ km around the receiver.

~~Propagating seismic waves excited from sources across ~10^3 km hurricane scale~~.

Ch 3 - Turbulent seismoacoustic imprints during a hurricane landfall Ji, Dey, Dunham (under review)

Turbulent origin of pressure and seismic imprints through interdisciplinary modeling.

Convection velocity is key for estimating shallow subsurface structure from pressure-seismic coupling.

Ambient infrasound signals as an atmospheric dataset: **wind speed** and **turbulent dissipation rate**.

Signatures from atmospheric internal gravity waves:

Ch 4 - Detection of atmospheric gravity waves using barometer array Ji & Dunham (in prep.)

A novel database of **tropospheric inertia-gravity wave** parameters to study **horizontal propagation** properties.

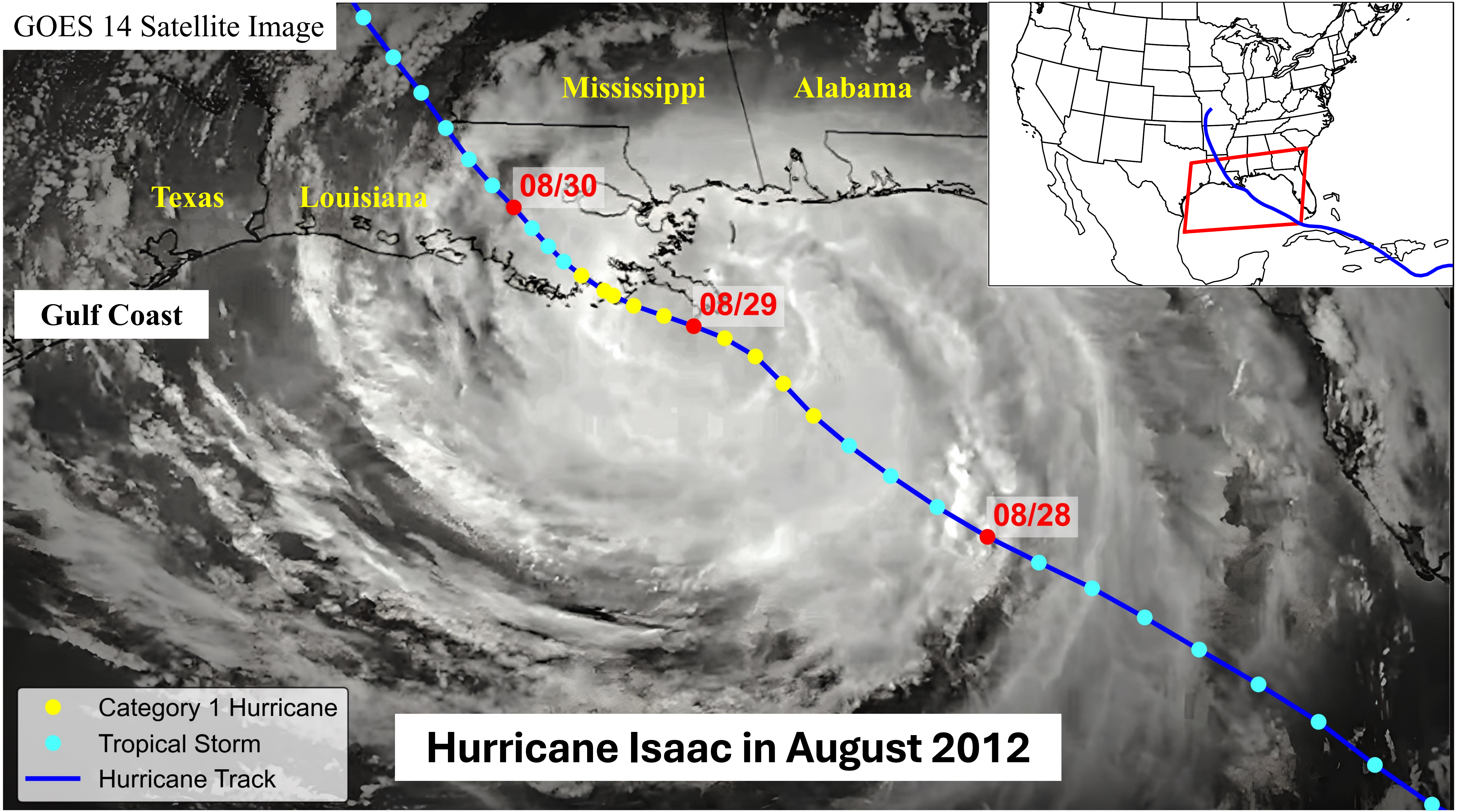
Turbulent seismoacoustic imprints during a hurricane landfall

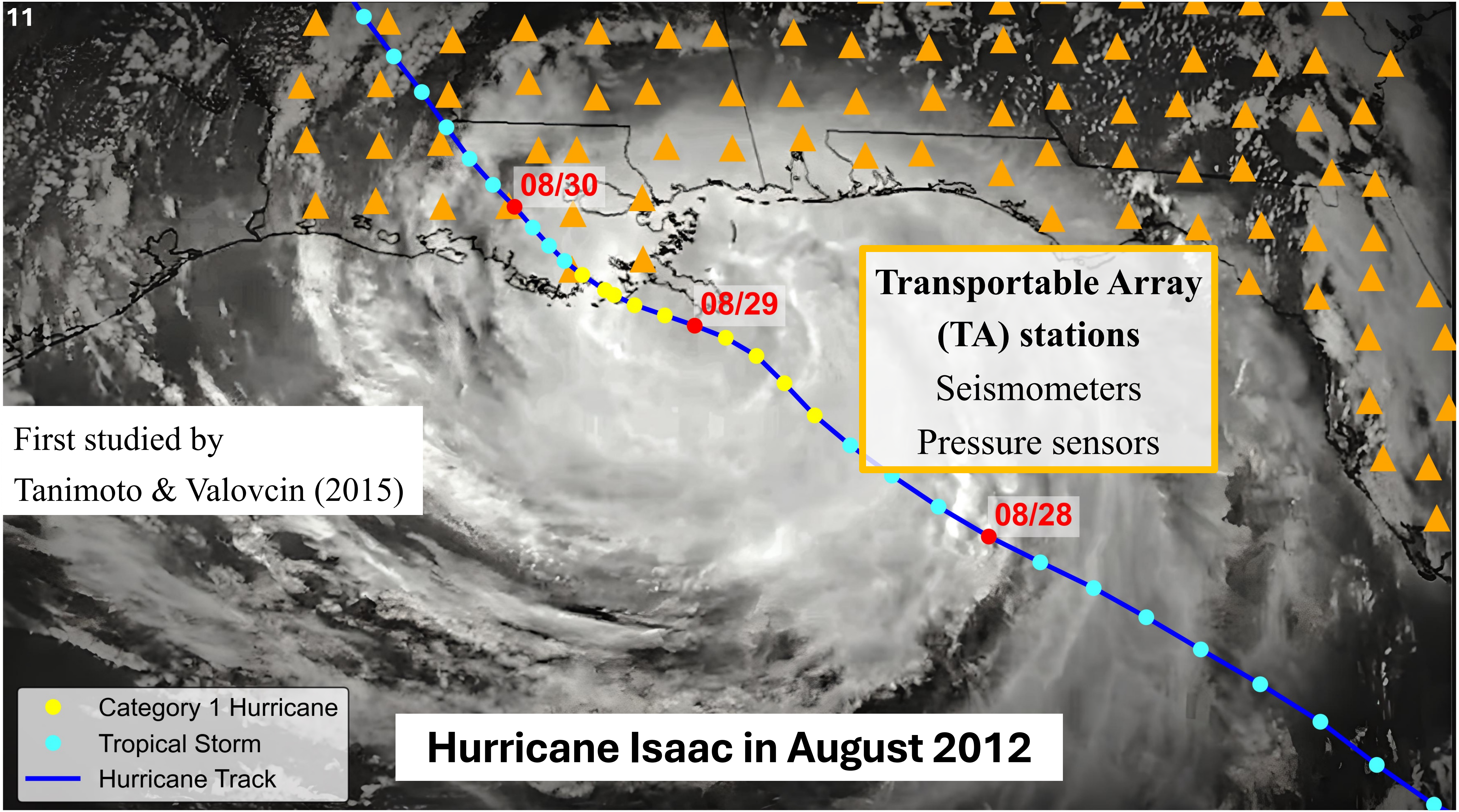
*Hurricane: “Severe tropical cyclone, a rotating **low-pressure** weather system …”*

*Turbulence: “Air motion with **chaotic** changes in flow velocity, pressure, …”*

***Seismic** imprint: **Vertical ground displacement** of O(10 μm)*

***Acoustic** imprint: **Near-surface pressure fluctuations** of O(10 Pa)*


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

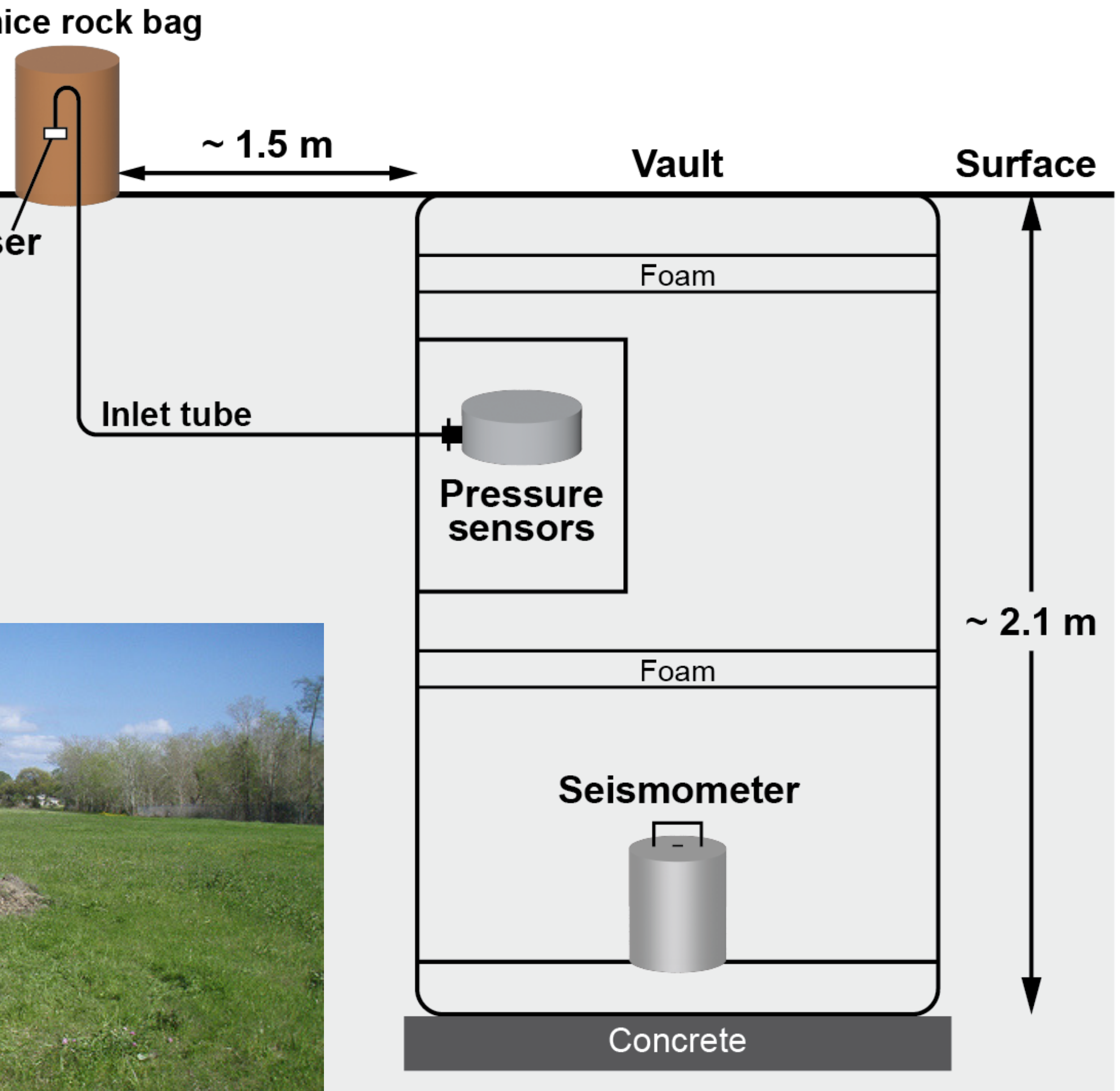

08/30
08/29
08/28
Transportable Array (TA) stations
Seismometers
Pressure sensors
First studied by
Tanimoto & Valovcin (2015)
Category 1 Hurricane
Tropical Storm
Hurricane Track
Hurricane Isaac in August 2012

Seismic station with environmental sensors

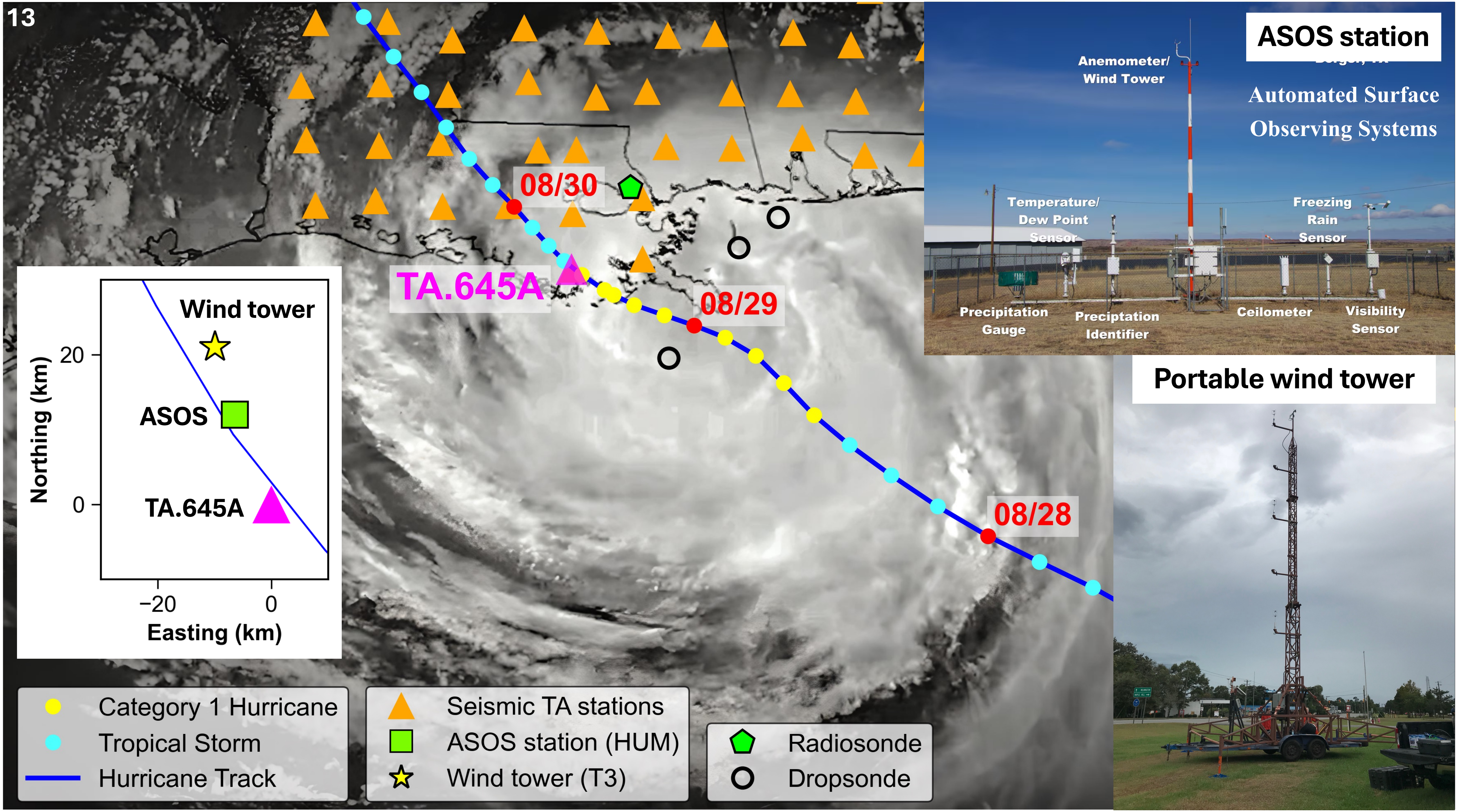
Channel	Observation
LHZ, BHZ	Vertical ground motion
LDO, BDO	Barometric pressure
LDF, BDF	Infrasound pressure

L: Long-period (1 Hz sampling rate)

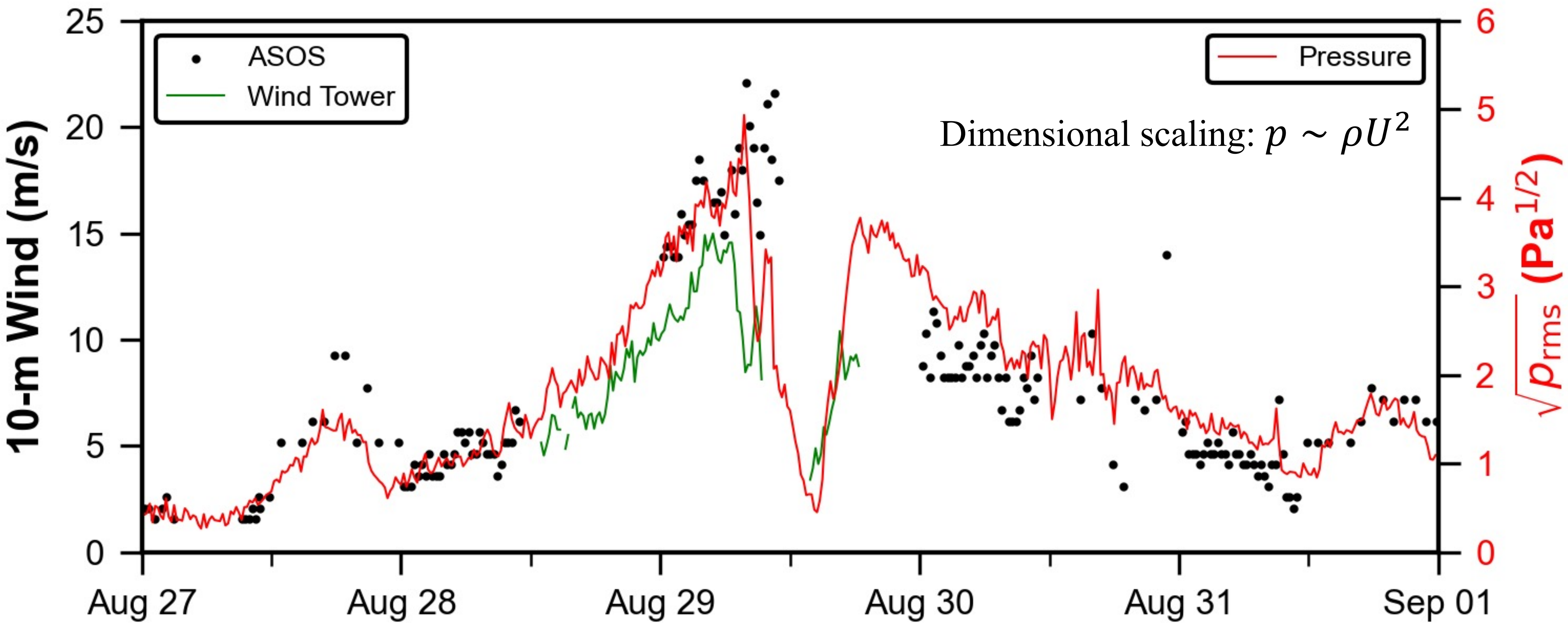
B: Broadband (40 Hz sampling rate)



Modified from Tytell et al. (2016)

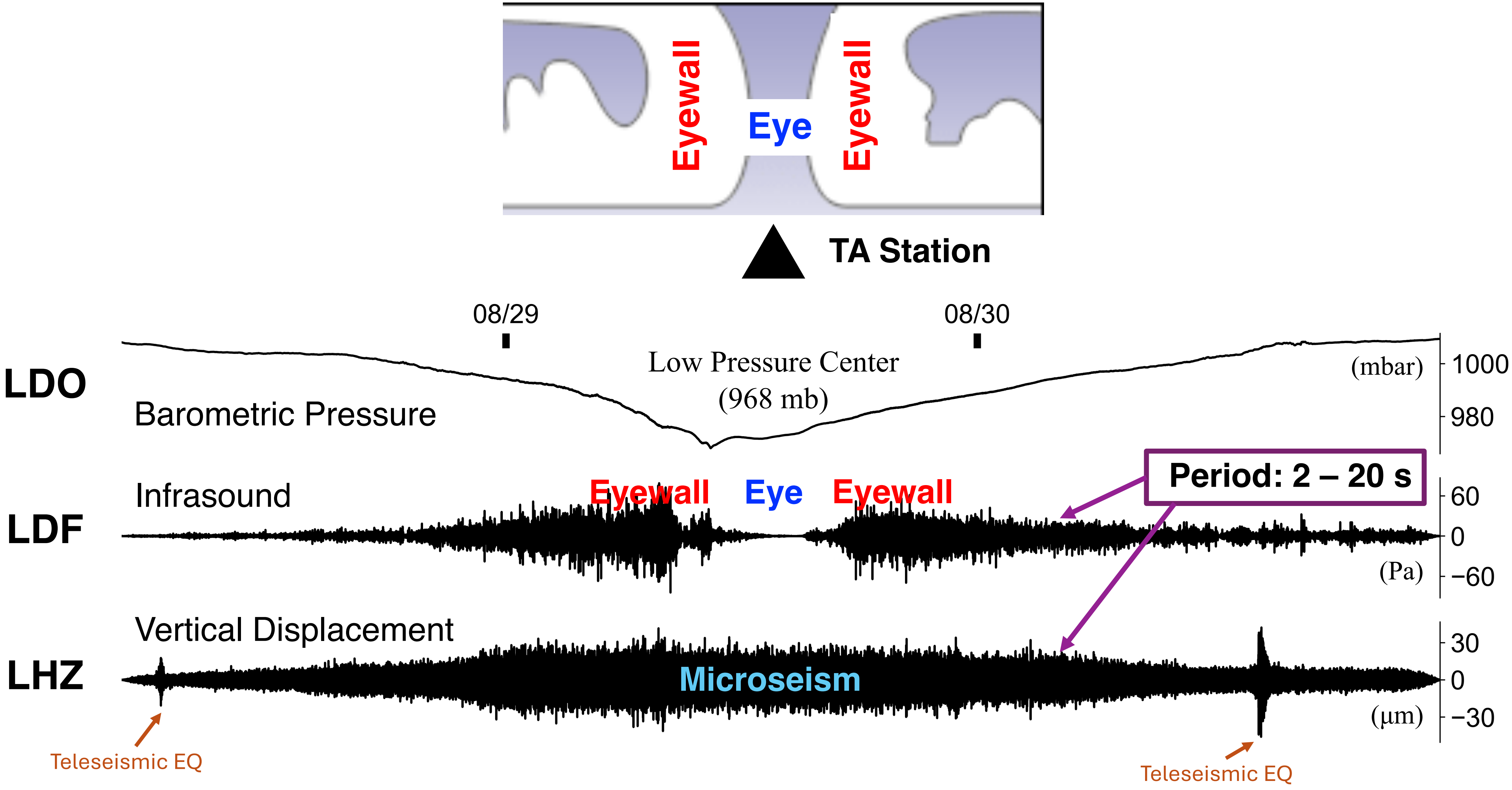

08/30
08/29
08/28
TA.645A
Wind tower
ASOS
TA.645A
Northing (km)
20
0
−20
0
Easting (km)
ASOS station
Anemometer/
Wind Tower
Automated Surface
Observing Systems
Temperature/
Dew Point
Sensor
Freezing
Rain
Sensor
Precipitation
Gauge
Preciptation
Identifier
Ceilometer
Visibility
Sensor
Portable wind tower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

Advantage of infrasound data for continuous monitoring

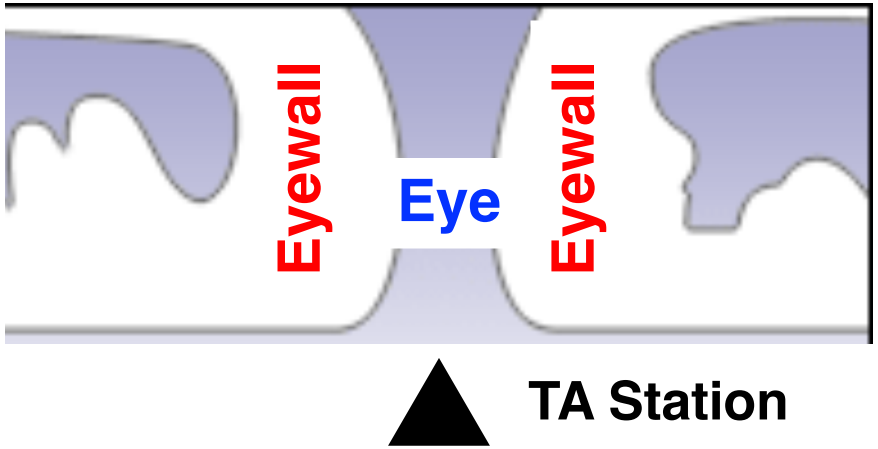


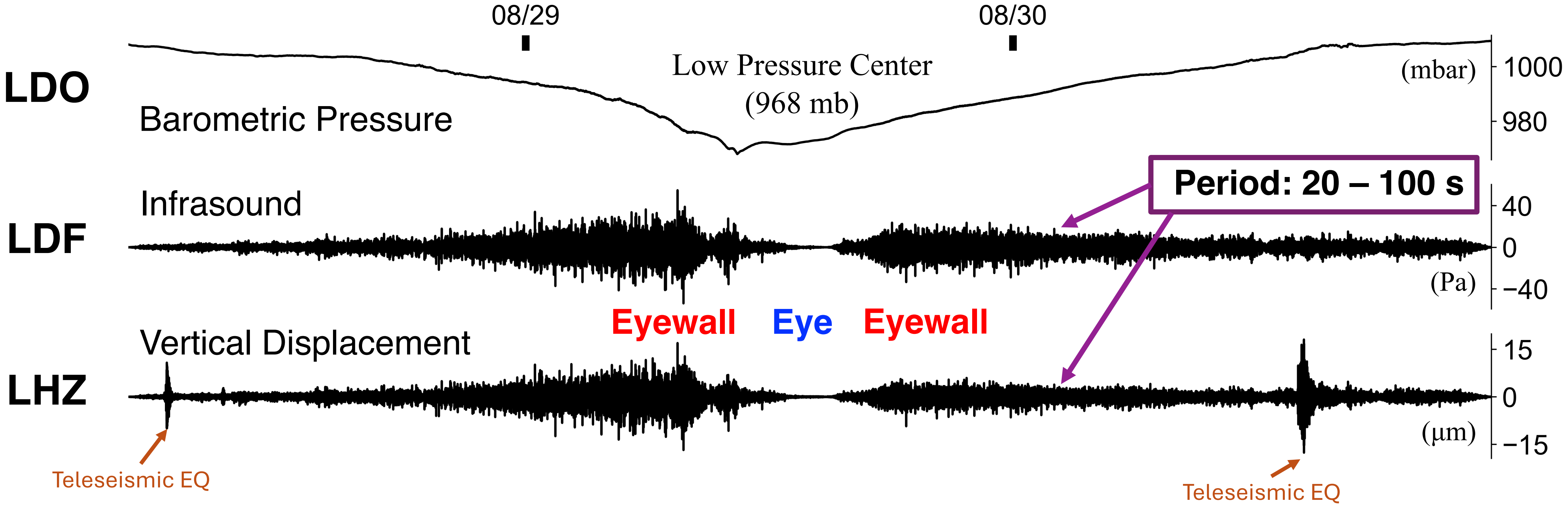
Continuous monitoring of the evolution of atmospheric quantities such as wind speed and turbulence statistics.

As hurricane passes the station ……



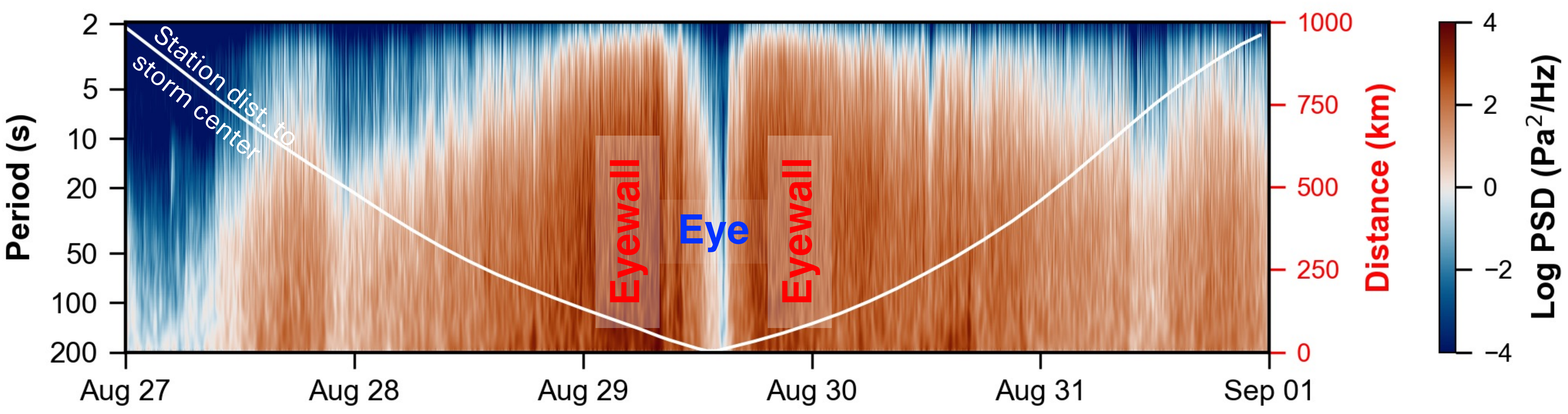
As hurricane passes the station ......



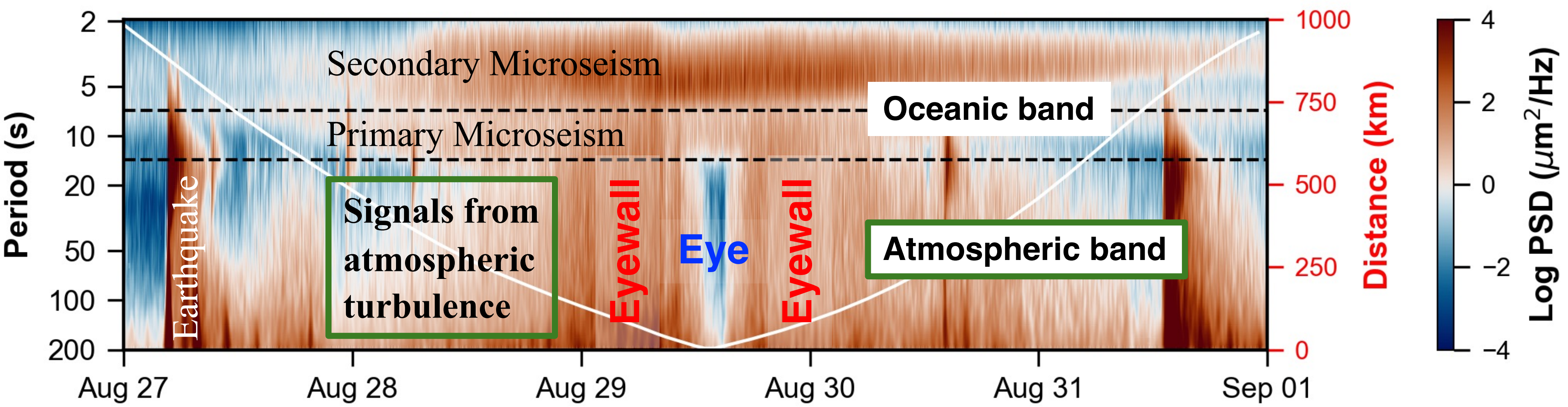


Wavelet spectrograms of pressure & seismic data

Surface Pressure

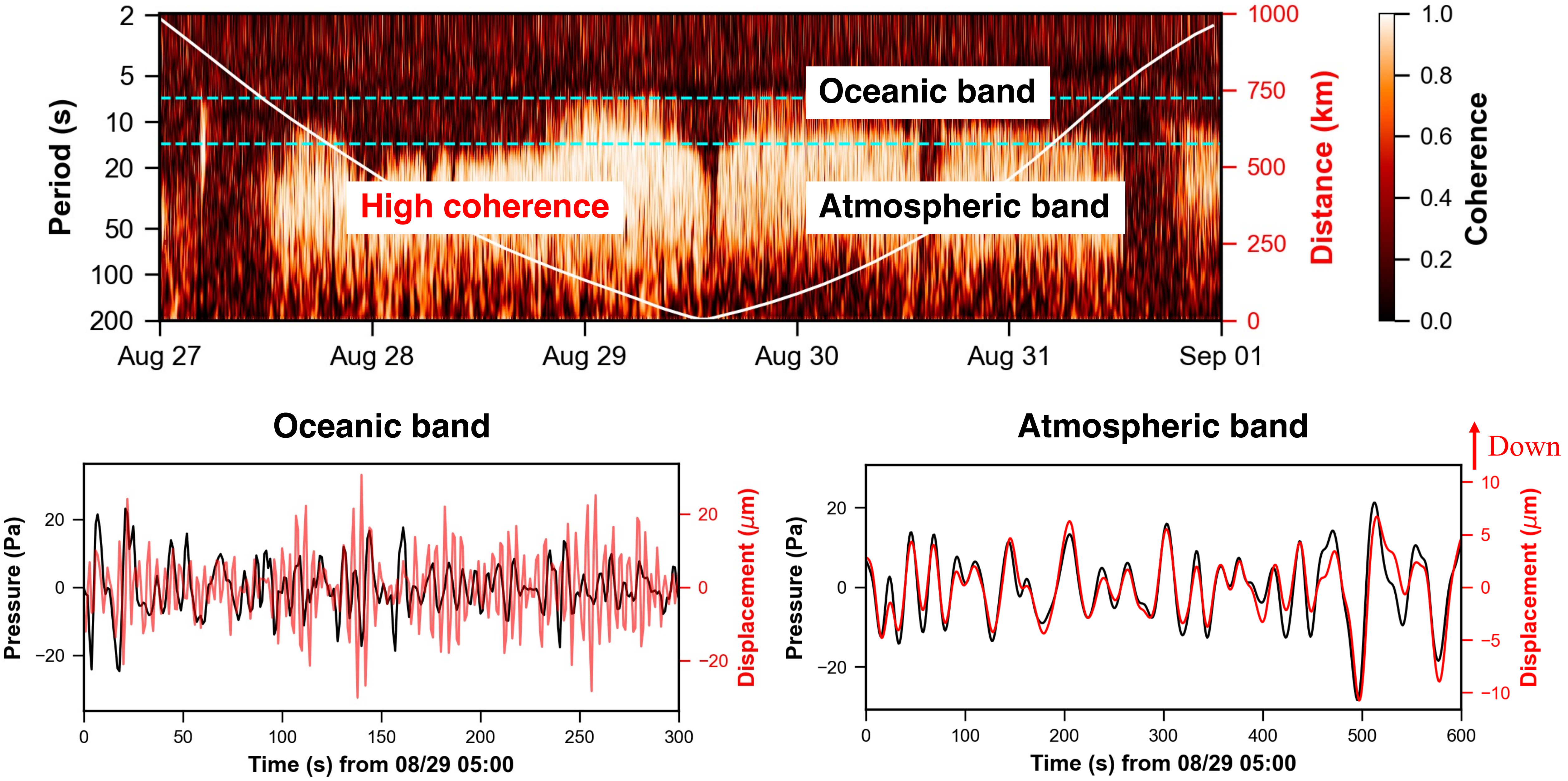


Seismic Vertical Displacement

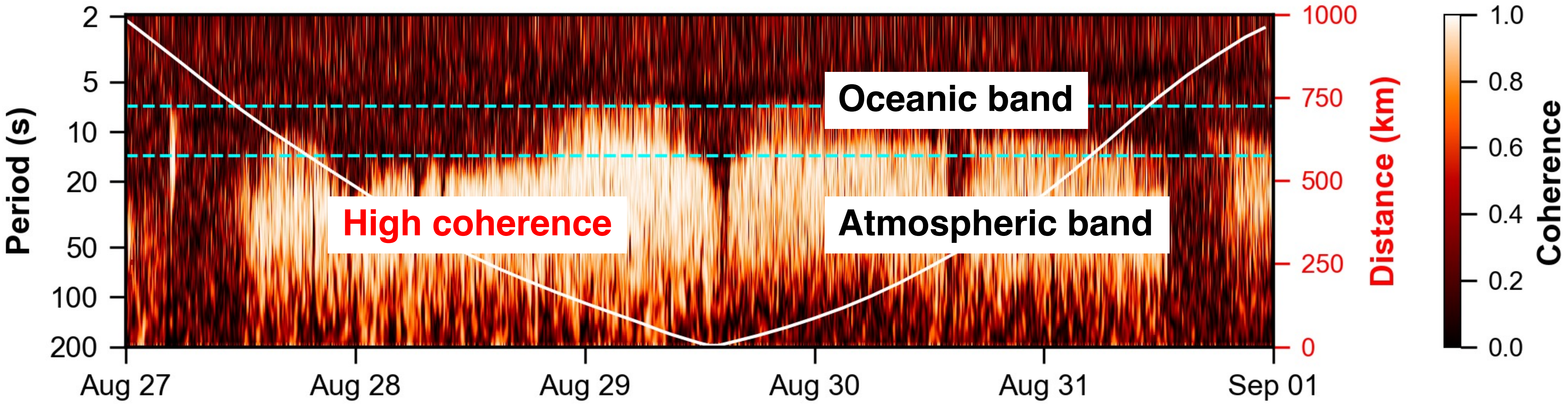


Ji & Dunham (2024)

High coherence between pressure and seismic signals



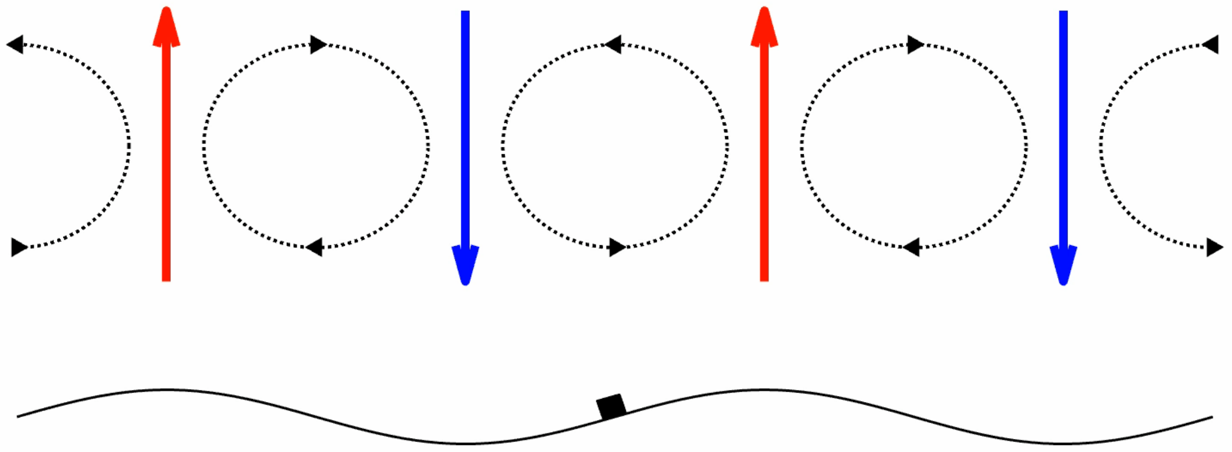
High coherence indicates local quasi-static response



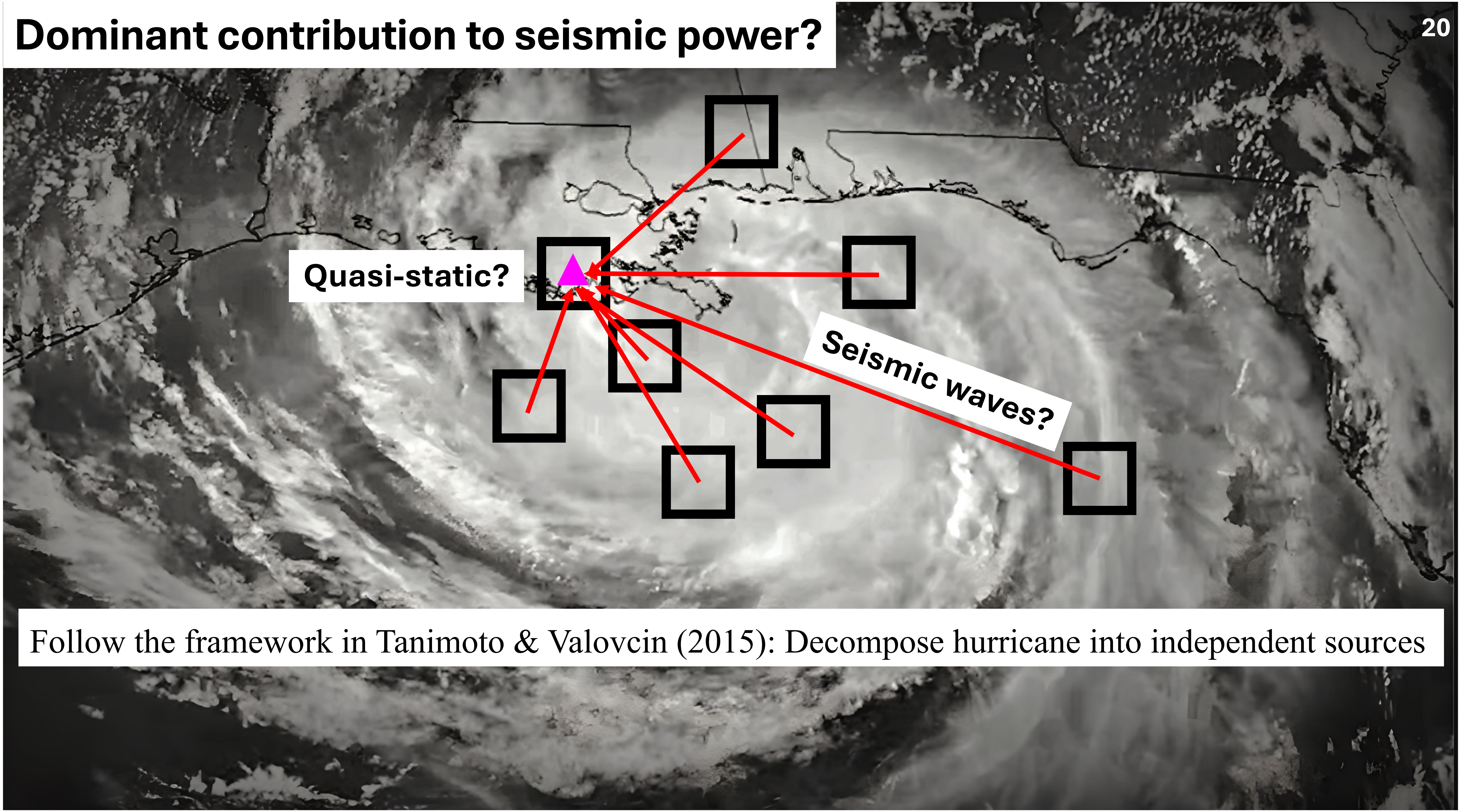
Simplified illustration

Sorrells (1971) theory

Pressure wave model

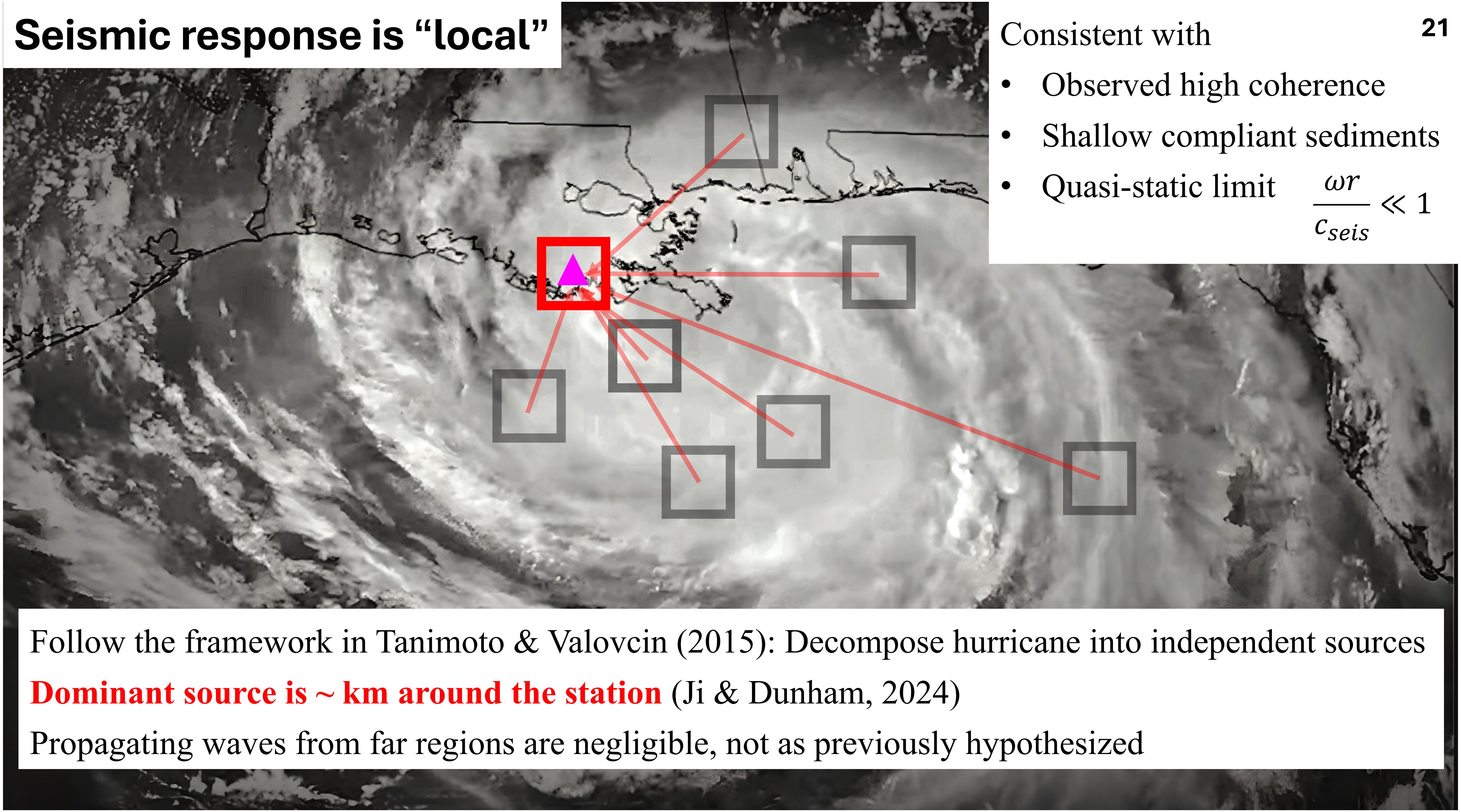


Dominant contribution to seismic power?



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

Seismic response is "local"



Consistent with

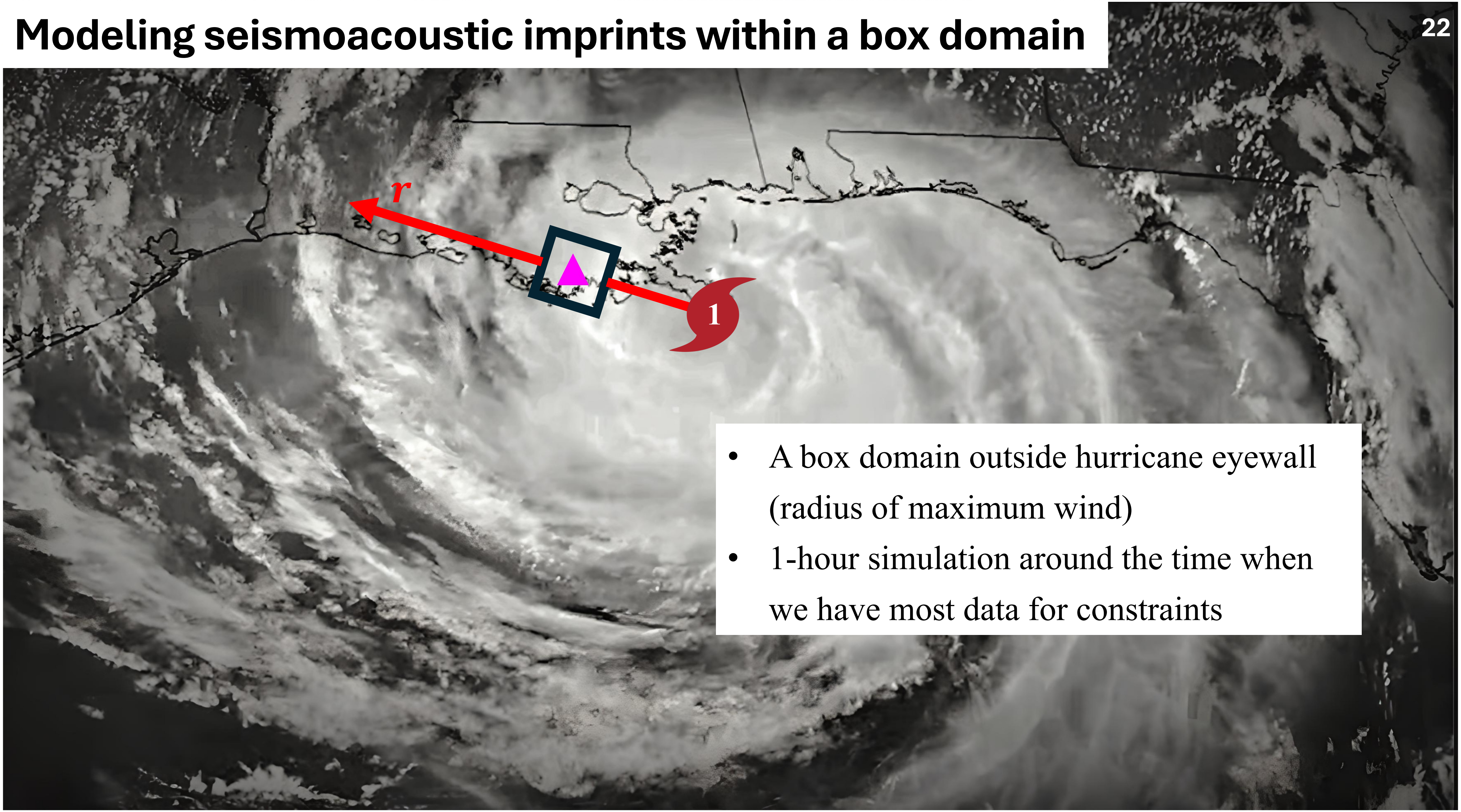
- Observed high coherence
- Shallow compliant sediments
- Quasi-static limit $\frac{\omega r}{c_{seis}} \ll 1$

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

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

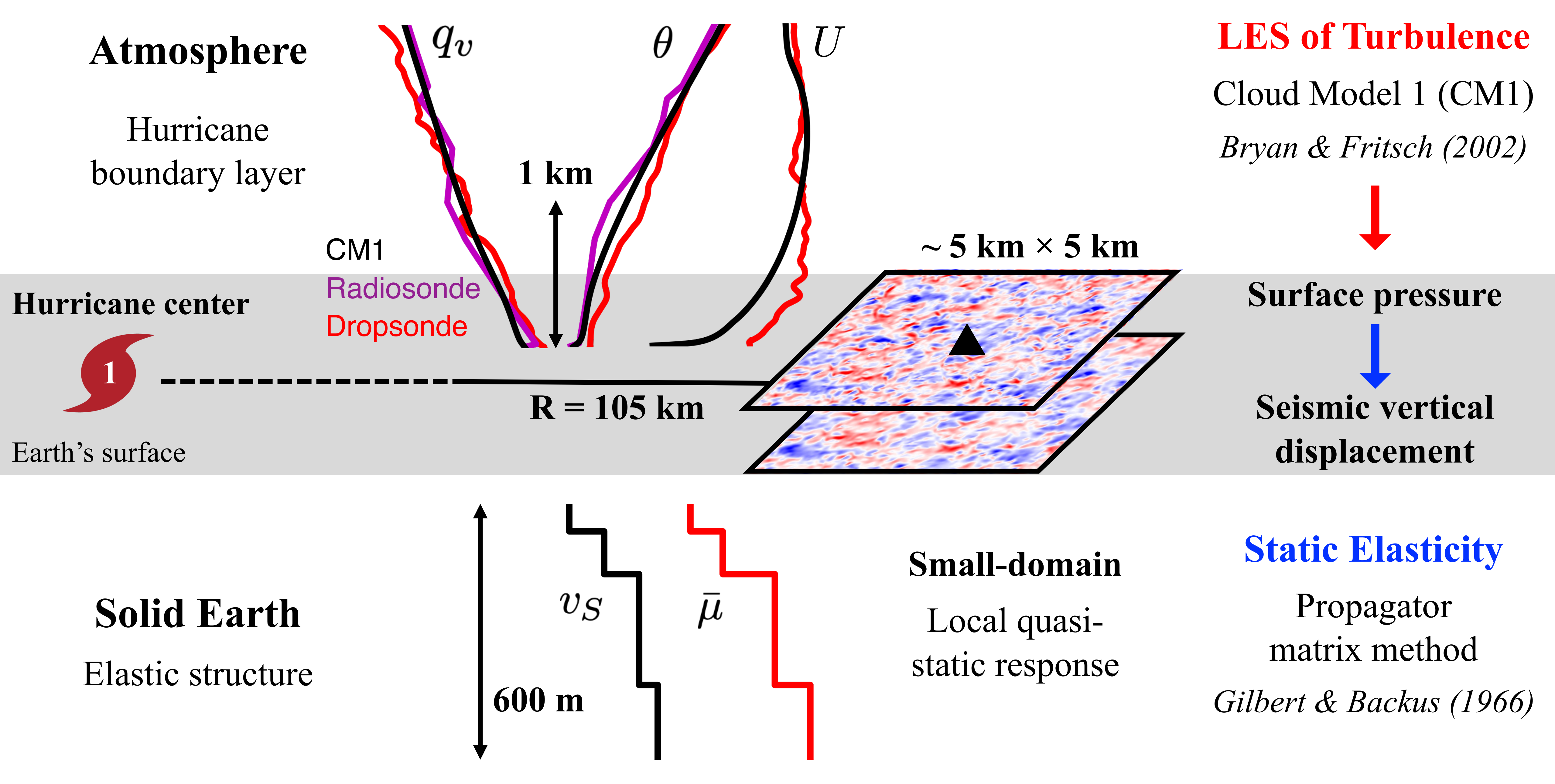
Propagating waves from far regions are negligible, not as previously hypothesized

Modeling seismoacoustic imprints within a box domain

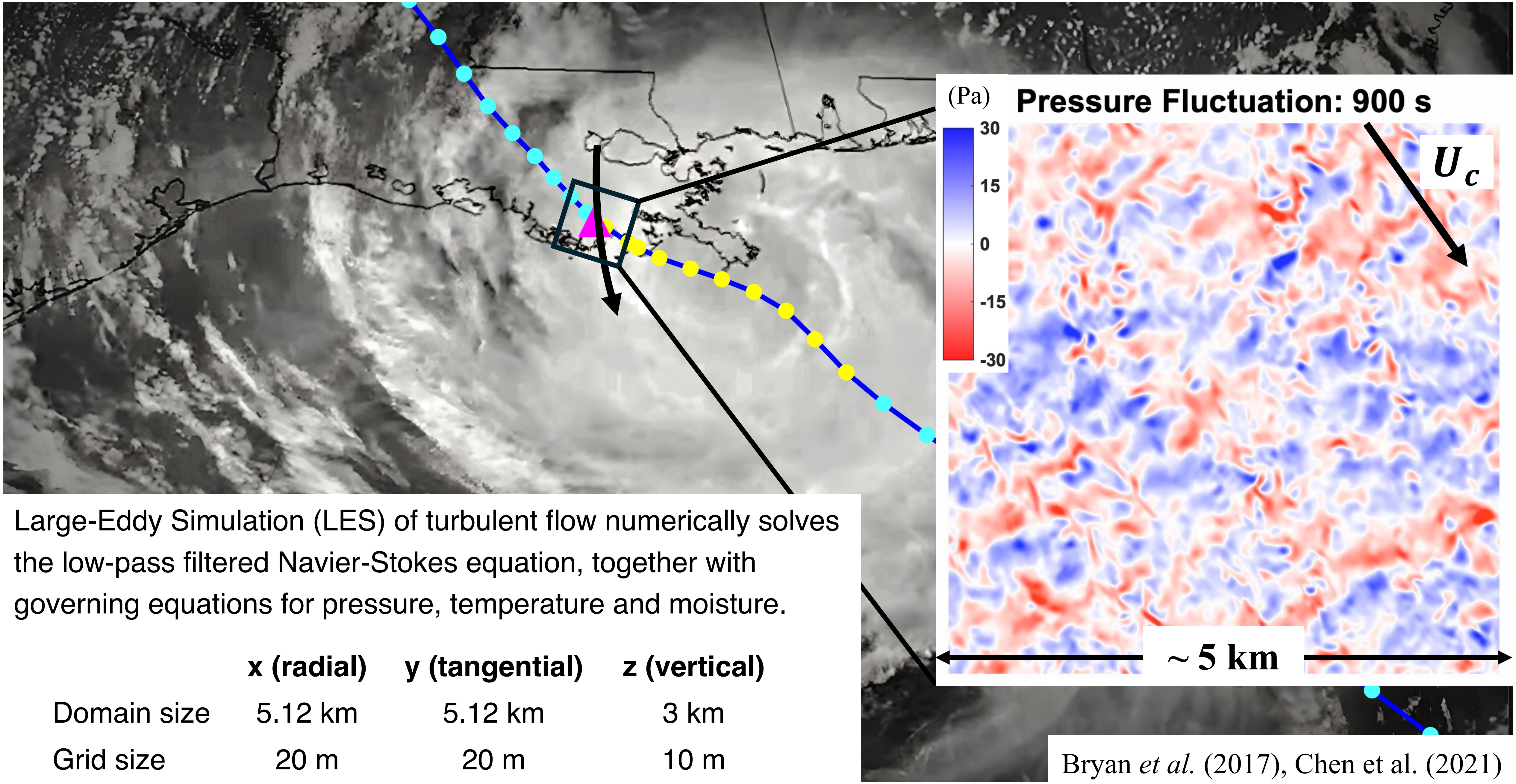


- A box domain outside hurricane eyewall (radius of maximum wind)
- 1-hour simulation around the time when we have most data for constraints

Interdisciplinary modeling



LES of Hurricane Boundary Layer (HBL) on land

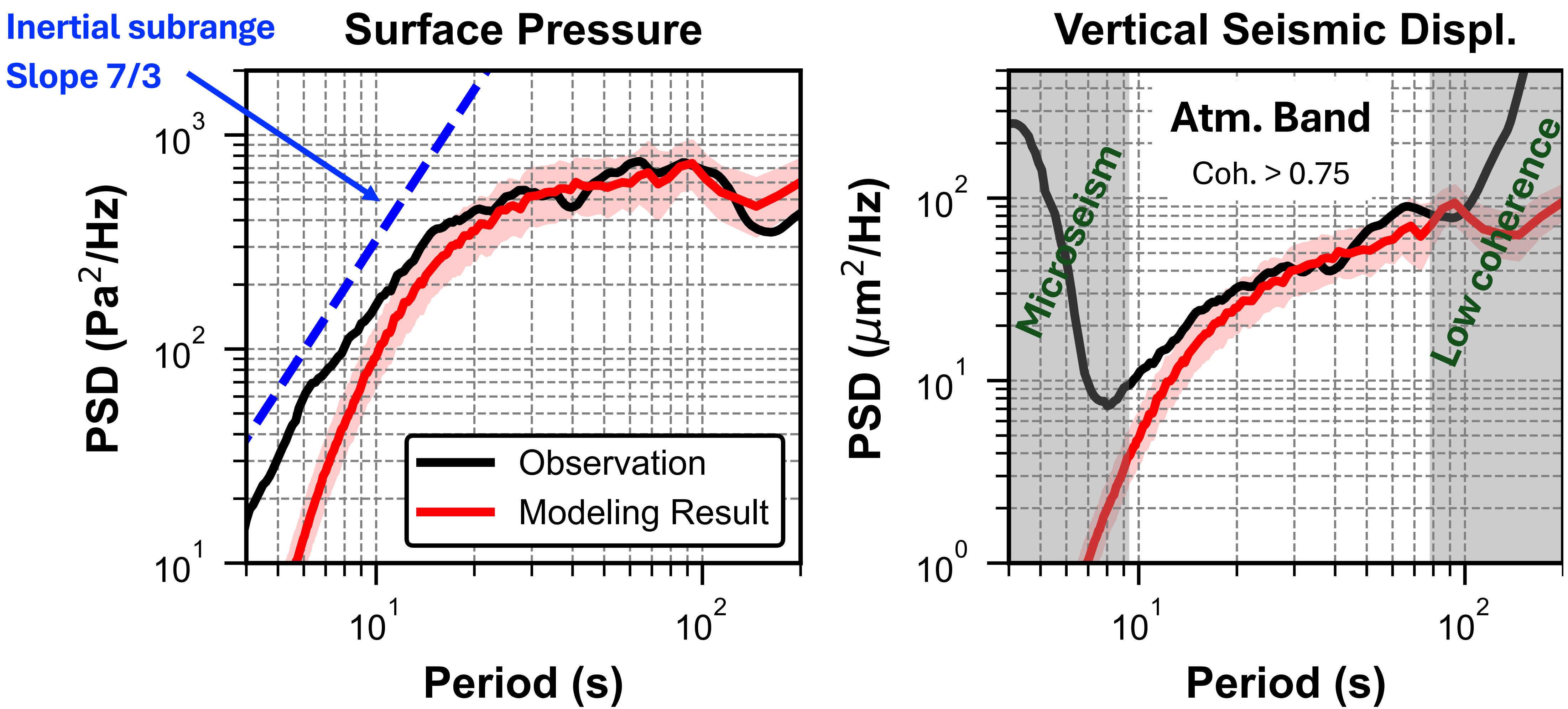


Large-Eddy Simulation (LES) of turbulent flow numerically solves the low-pass filtered Navier-Stokes equation, together with governing equations for pressure, temperature and moisture.

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

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

Modeling results explain both pressure & seismic spectra



Convection velocity plays a role in pressure-seismic coupling

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

Modeling
(Surface field)

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

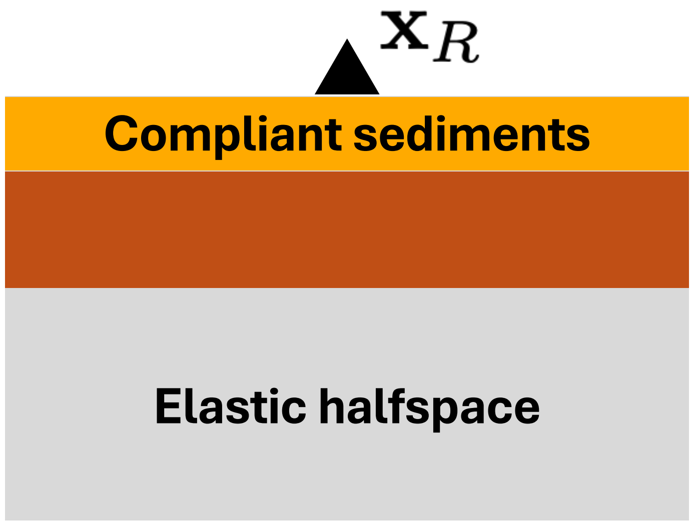
Space-time conversion

Convection velocity U_c

Observation
(Single point)

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

Transfer function
(i.e., linear estimator)

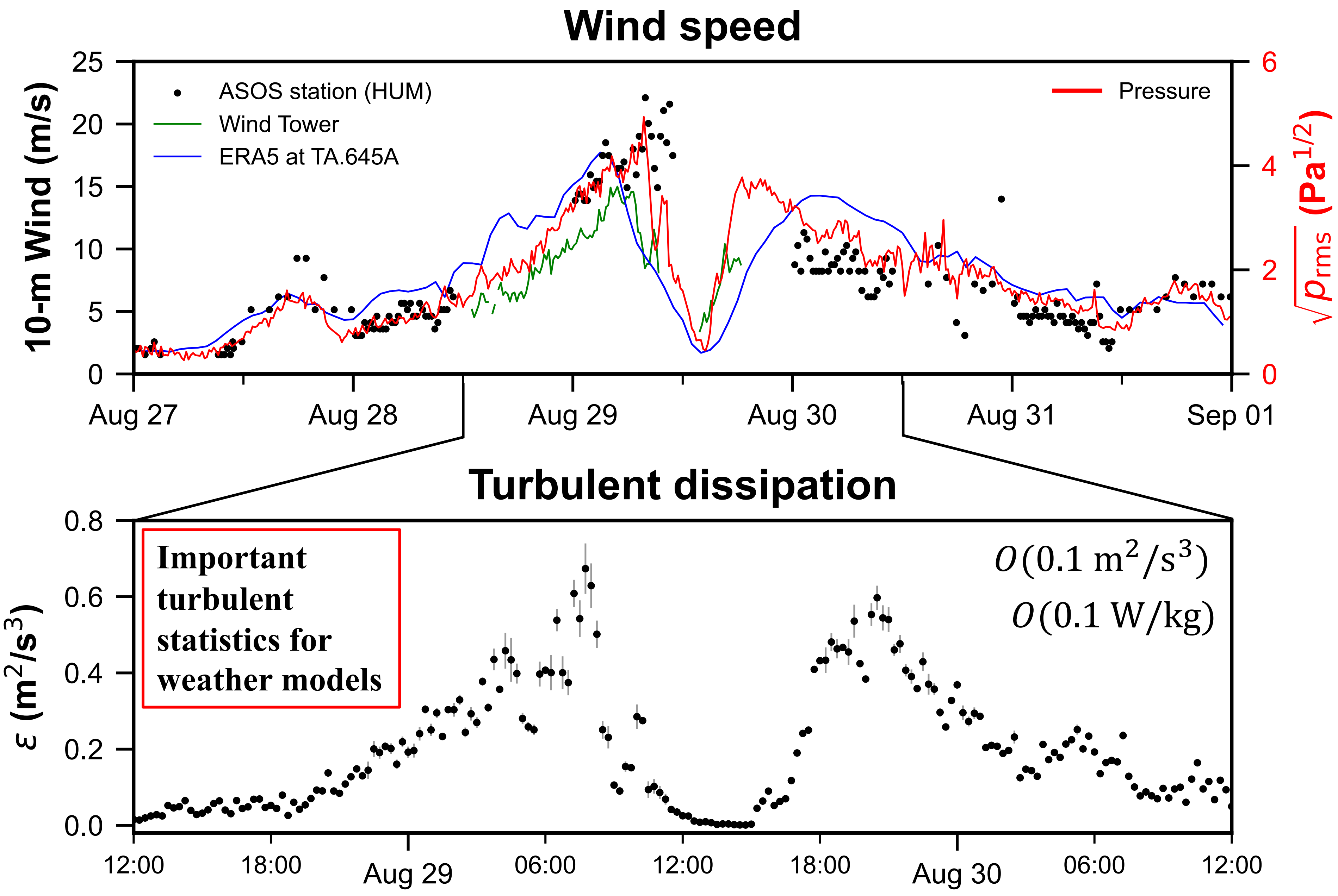


$\mathbf{k}$ Horizontal wavenumber

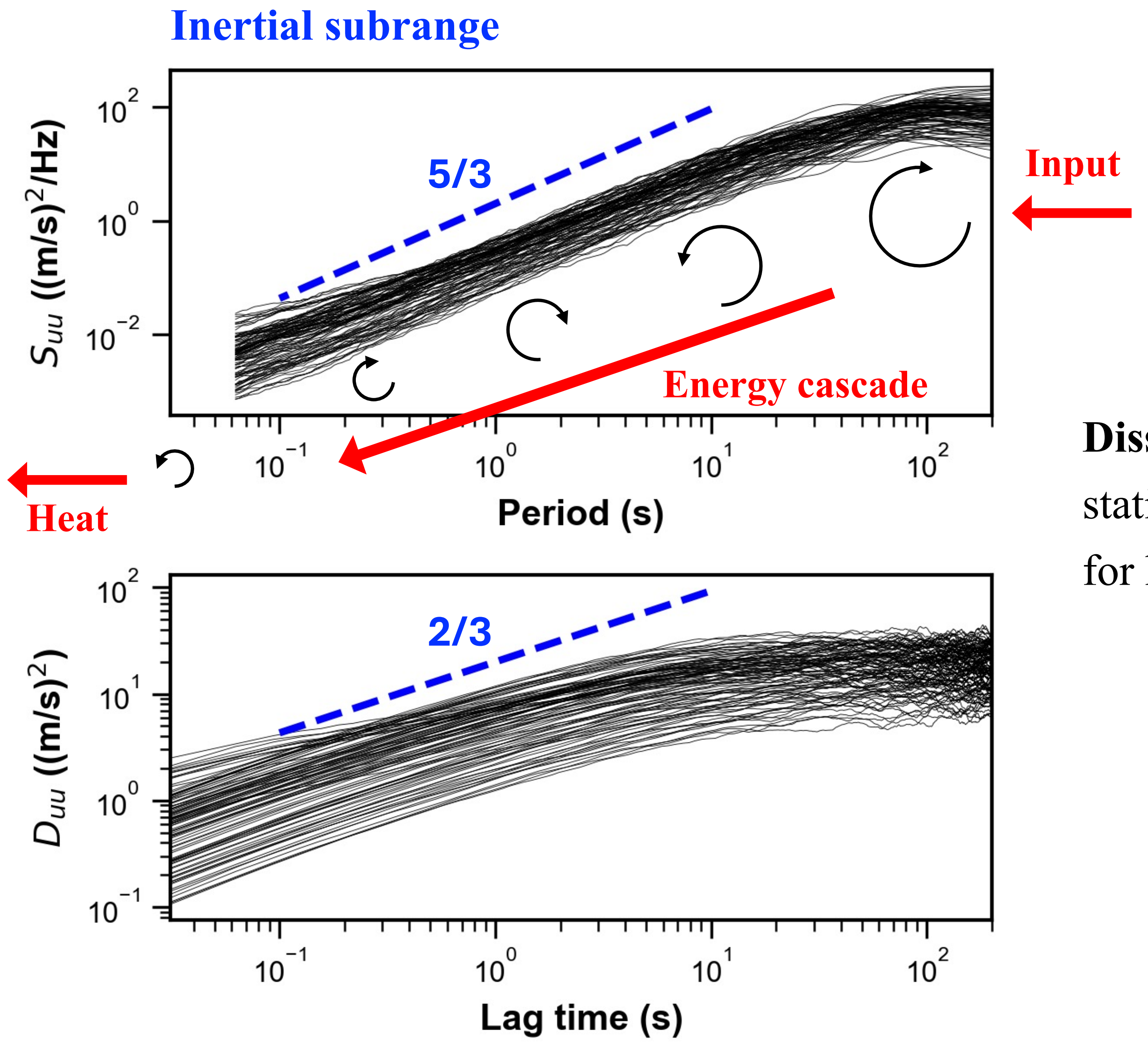
ω Angular frequency

Infrasound data for wind and turbulence analysis

Also potential to apply for general atmosphere



Turbulent spectrum from wind tower data



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 of turbulence statistic and contributes to an important energy source for hurricanes (Bister & Emanuel, 1998).

Streamwise structure function

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

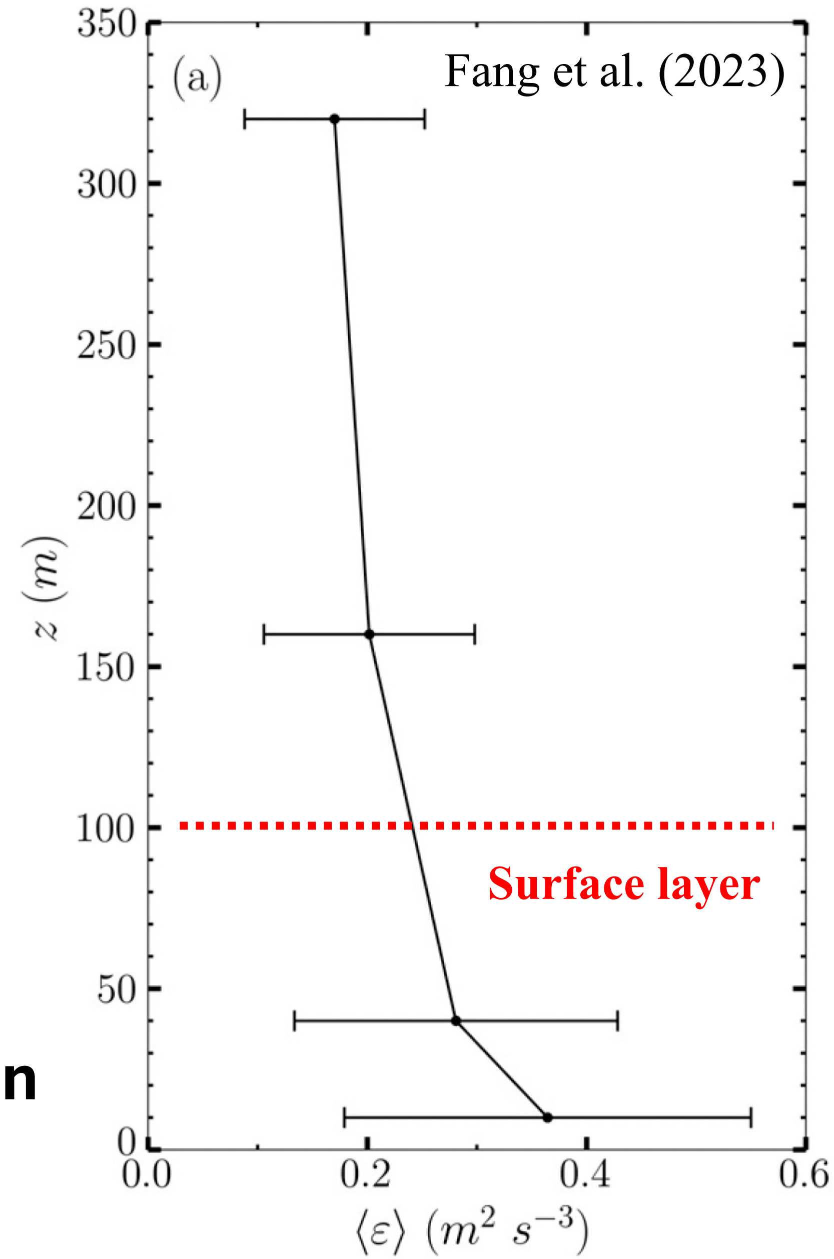
Kolmogorov (1941)

Dissipative heating — important energy source for cyclones

Integrate ε over the surface layer h_s (bottom ~10% of boundary layer)

$$\rho \int_0^{h_s} \varepsilon(z)\,\mathrm{d}z = \rho\bar{\varepsilon}h_s$$

Data gap for landfalling hurricane and its vertical extent for model evaluation



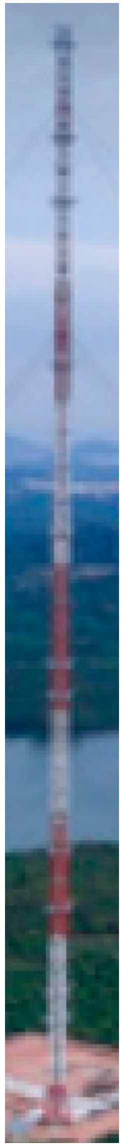
Zhang et al. (2011) +

Portable wind tower (~10 m)

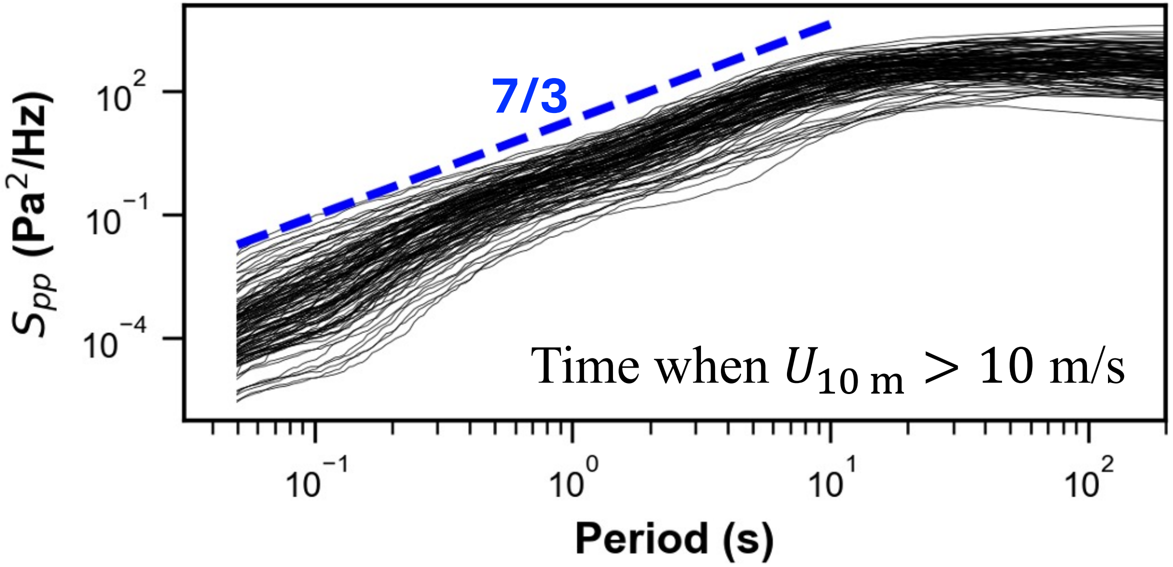
Ming & Zhang (2018) +

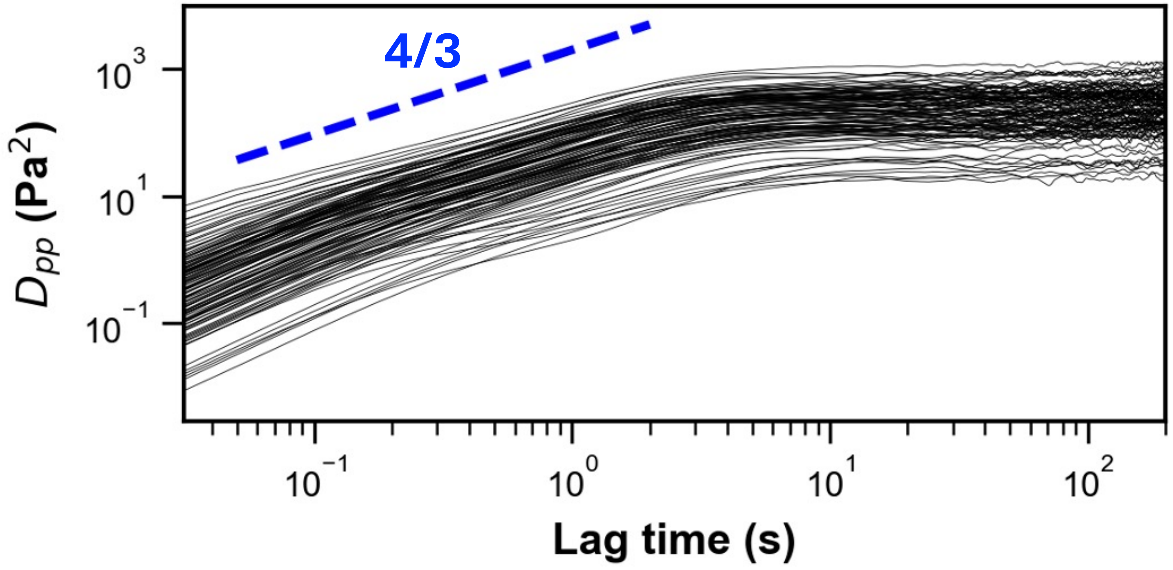
Research tower (~100 m)

Very rare wind tower (~300 m)



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.

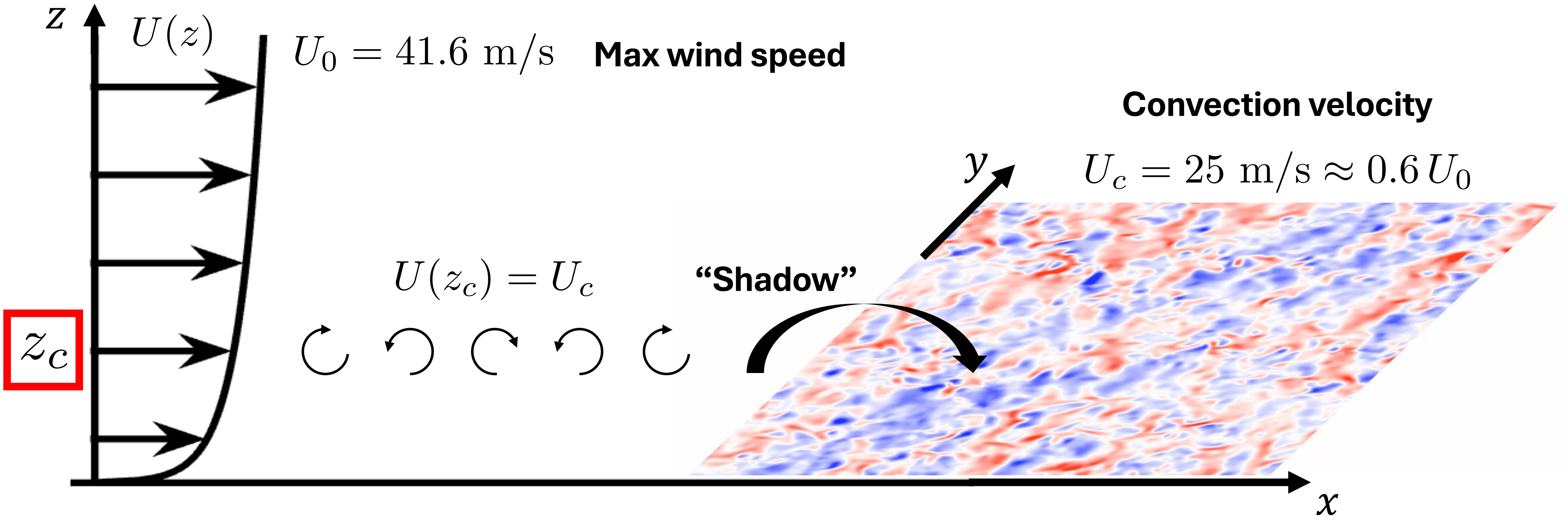
(e.g., George et al. 1984, Tsuji et al. 2007)

Pressure structure function

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

Obukhov (1949), Monin & Yaglom (1975)

Near-surface pressure of turbulent boundary layers

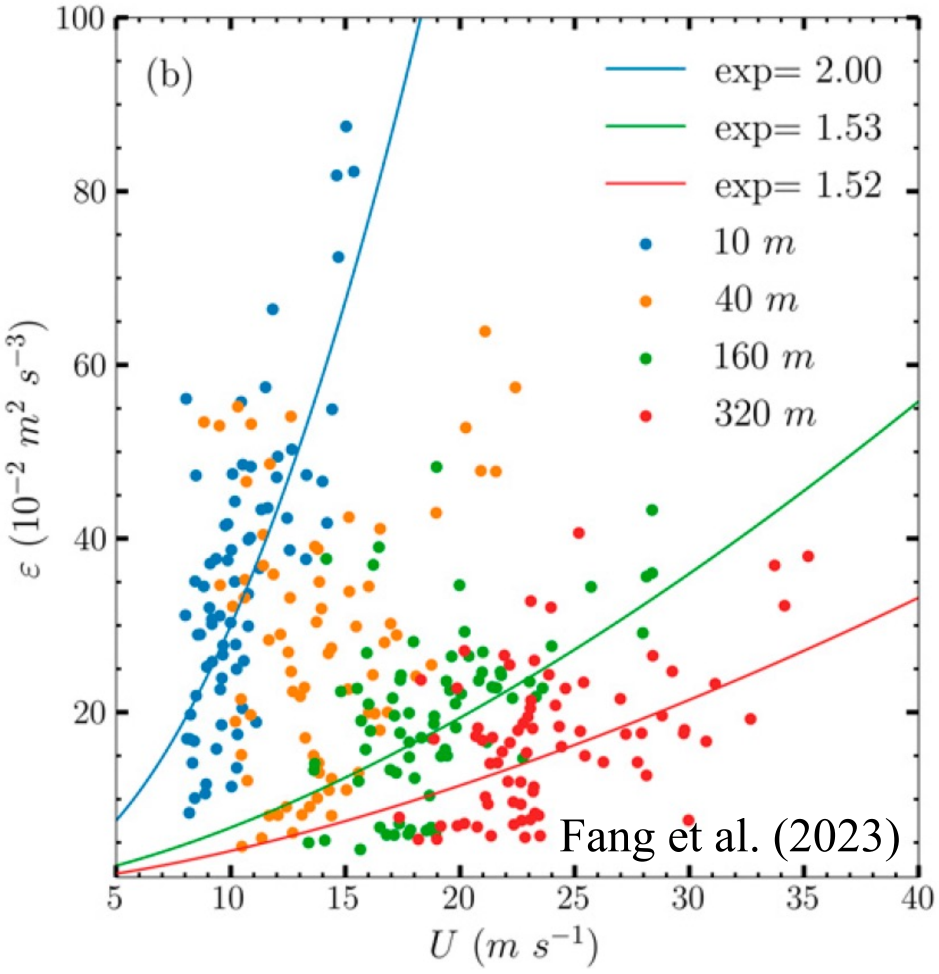


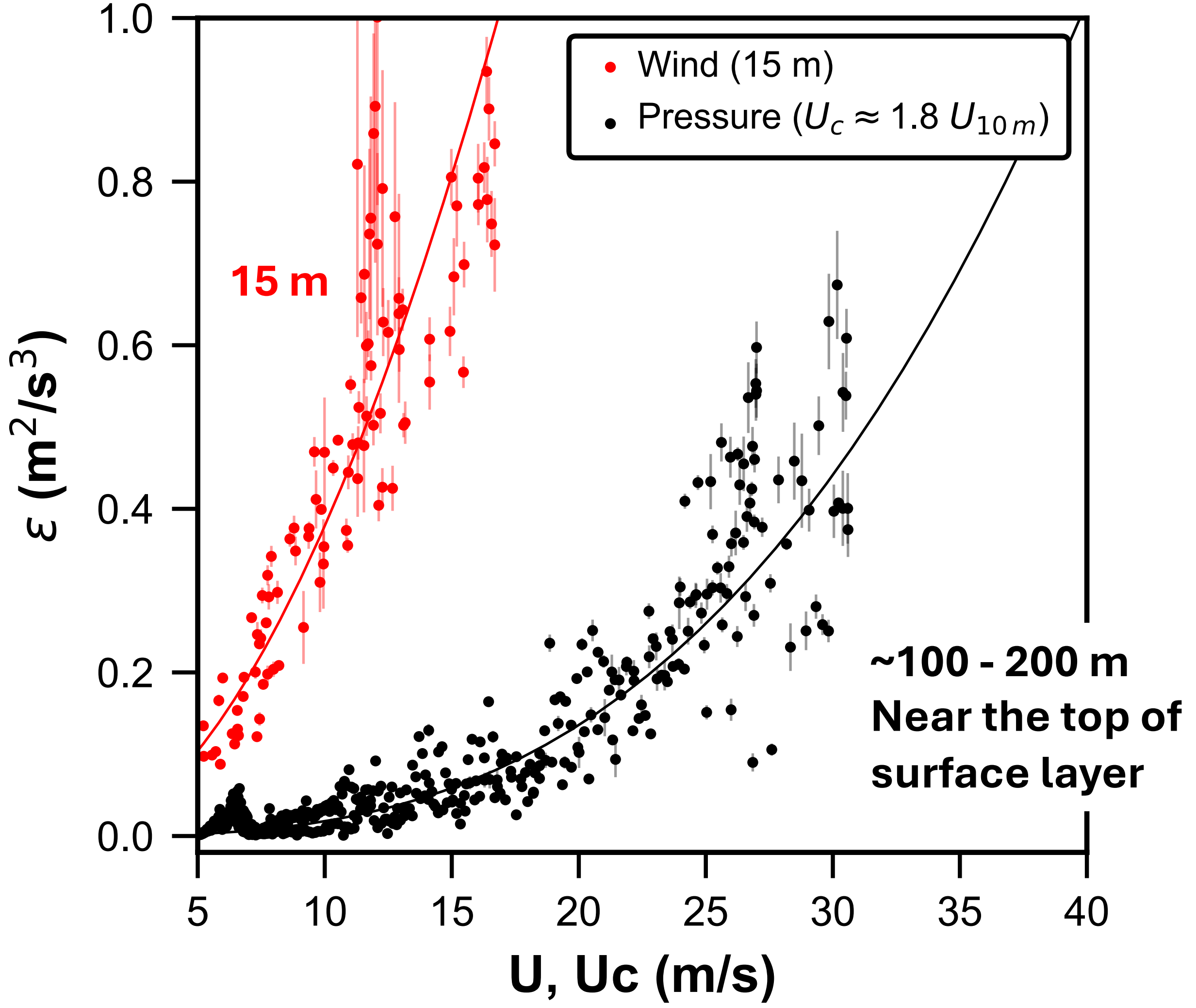
Zero velocity at surface, but pressure field is transported downstream at $\boldsymbol{U_c}$ **(convection velocity)**.

Experimental studies and simulations show $U_c \approx 0.6\, U_0$. (e.g., Lowson 1965, Choi & Moin 1990)

U_c can further be related to $\boldsymbol{U_{10\,m}}$ **(10-m wind speed)**, which is usually reported.

Pressure-derived ε complements wind tower measurements



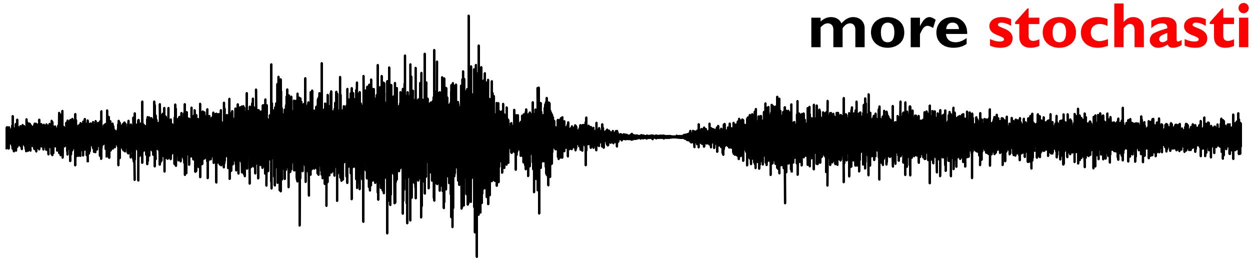


Pressure-derived turbulent dissipation rates are interpreted to correspond to height z_c near the top of surface layer. This complements typical portable wind towers for in-situ hurricane measurements.

Summary

more stochastic view

Hurricane Landfall



This trace could be both pressure and seismic imprints in atm. band

- **Local quasi-static response**
- **Reflective of hurricane structure**

Signals are turbulent

- **Turbulence affects coupling via U_c**
- **Infrasound — Turbulent pressure spectra**

Evolution of amplitude

- **Continuous in-situ monitoring**
- **Reflective of wind speed and turbulence statistics**

Detection of atmospheric gravity waves using barometer array

Atmospheric gravity wave *(AGW): Internal gravity wave in the atmosphere governed by buoyancy and Coriolis effect.*

Tropospheric inertia-gravity wave*: Long-period AGW in the troposphere, with* ***periods of several hours****.*

Barometer: Sensor to measure absolute atmospheric (barometric) pressure.

Barometers at Transportable Array (TA) stations

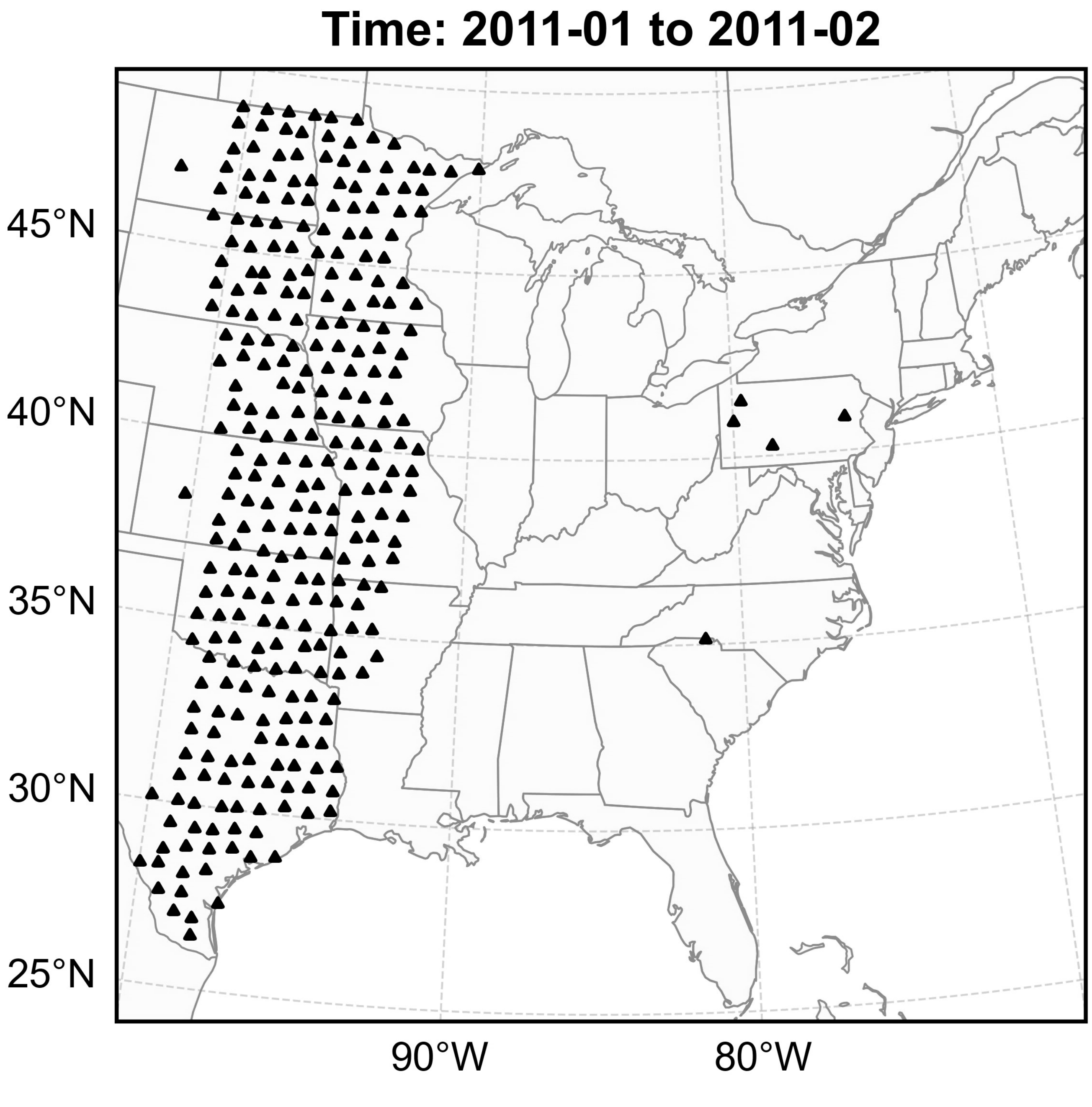
Surface pressure from 2011 – 2014

Neighboring station distance ~ 70 km

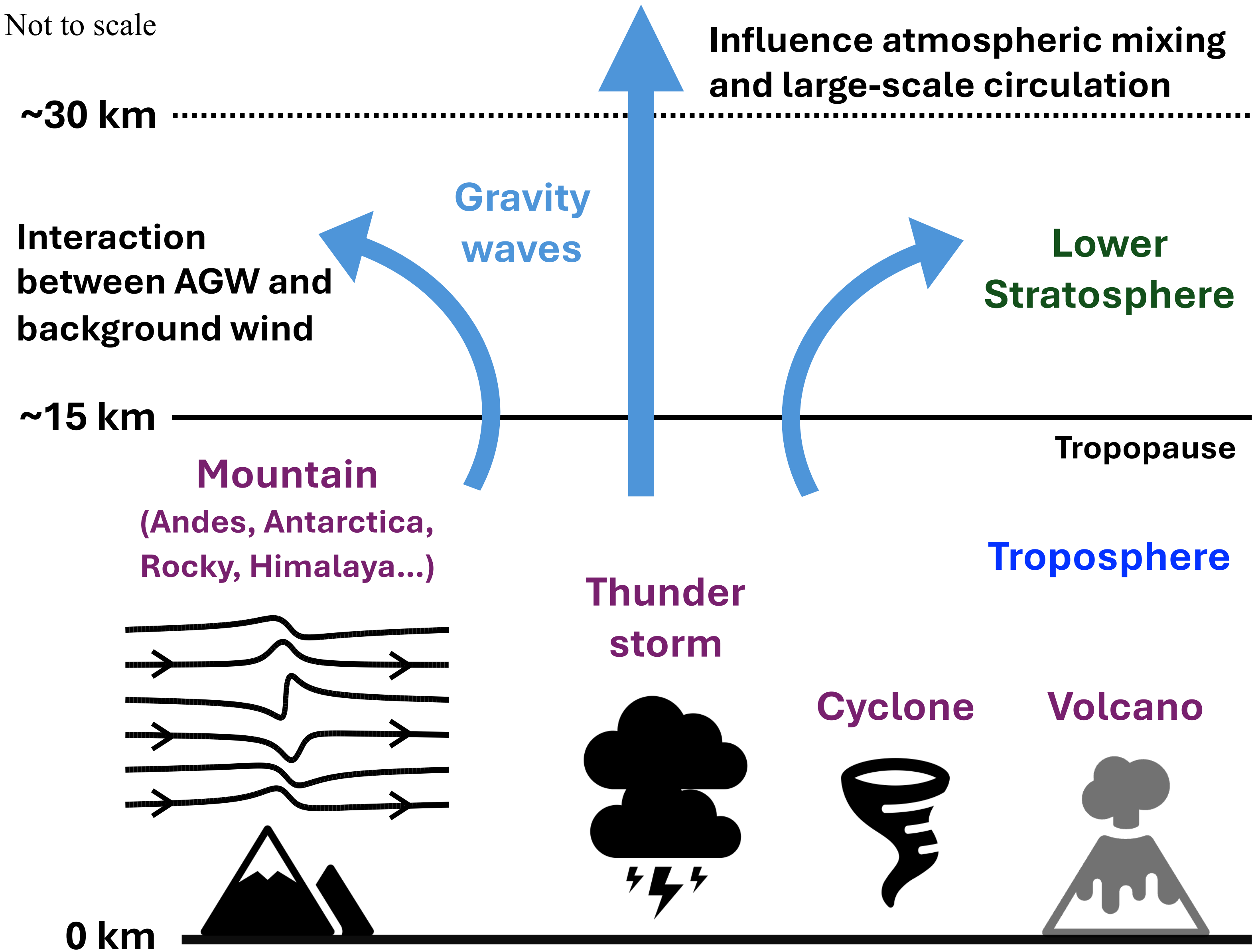
In total 900+ stations under analysis

Pressure measured by MEMS pressure sensor

Channel code LDM



Atmospheric gravity waves (AGW) are essential for climate dynamics



AGW exists for frequency range

$$f < \omega < N$$

Coriolis frequency $O(10\text{ hr})$

$$f = 2\Omega \sin(lat)$$

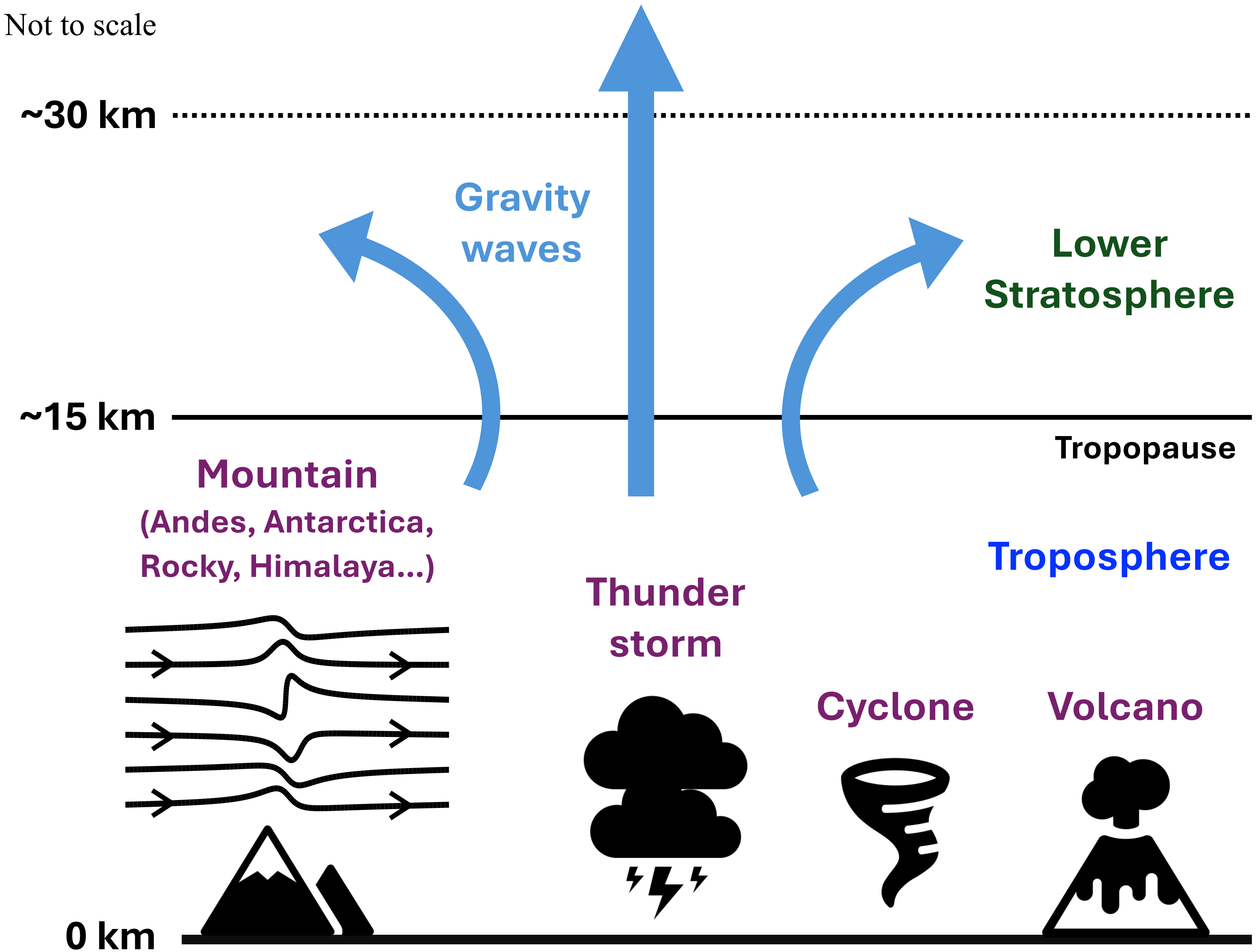
Earth's rotation → $2\pi/24\,\text{hr}$

Buoyancy frequency $O(10^2\text{ s})$

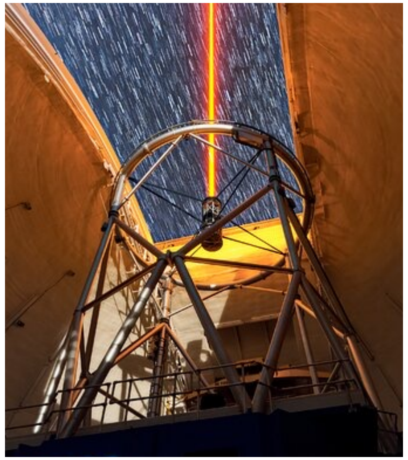
$$N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}$$

θ → Potential temperature

Challenging to obtain full-spectrum AGW observation

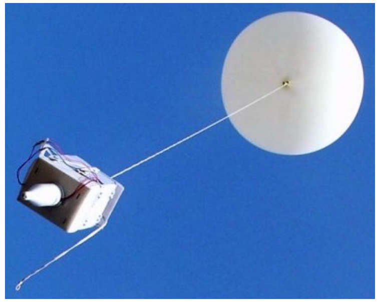


Satellite-based

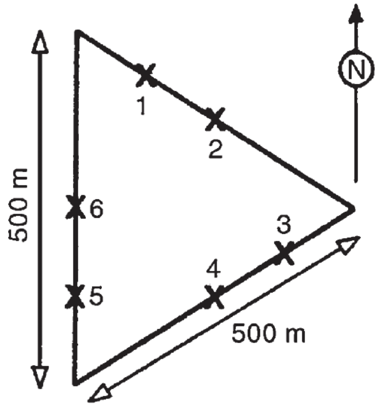


Lidar

Radar



Radiosonde

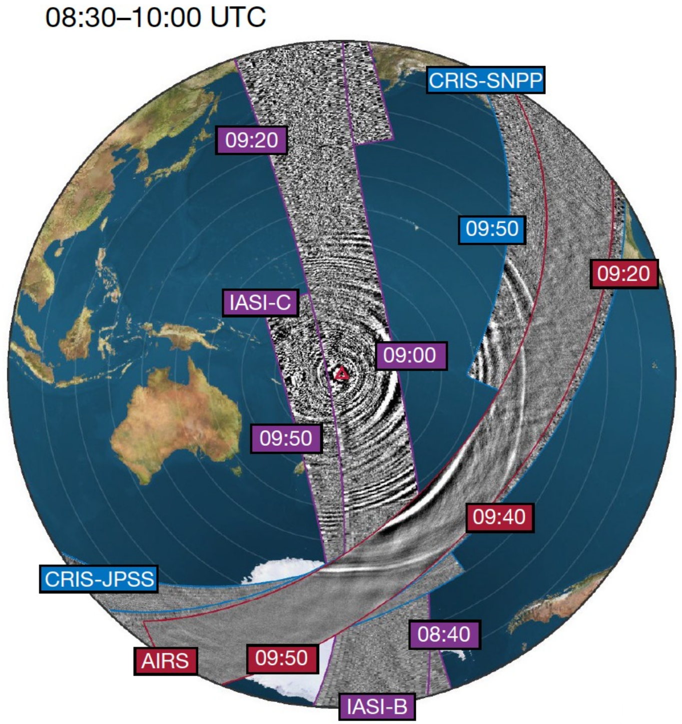


Infrasound array

How does AGW look like in other datasets?

Remote sensing from space

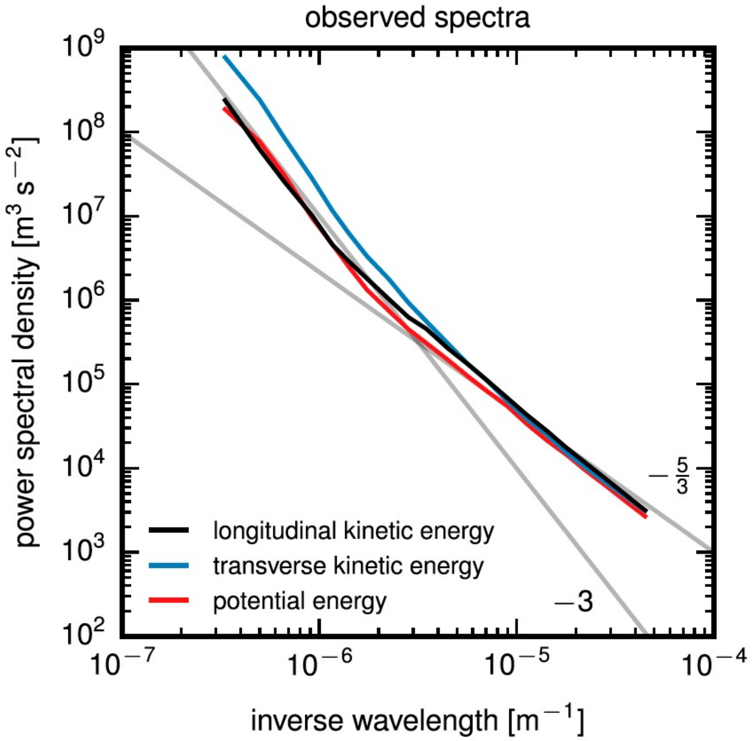
Radiation intensity



Wright et al. (2022)

Aircraft data

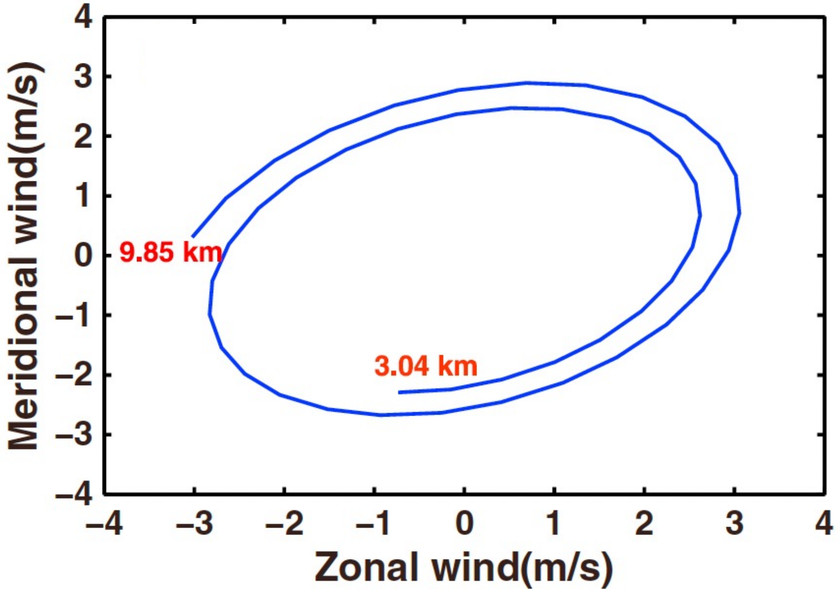
AGW spectra



Callies et al. (2014)

Radar / Radiosonde

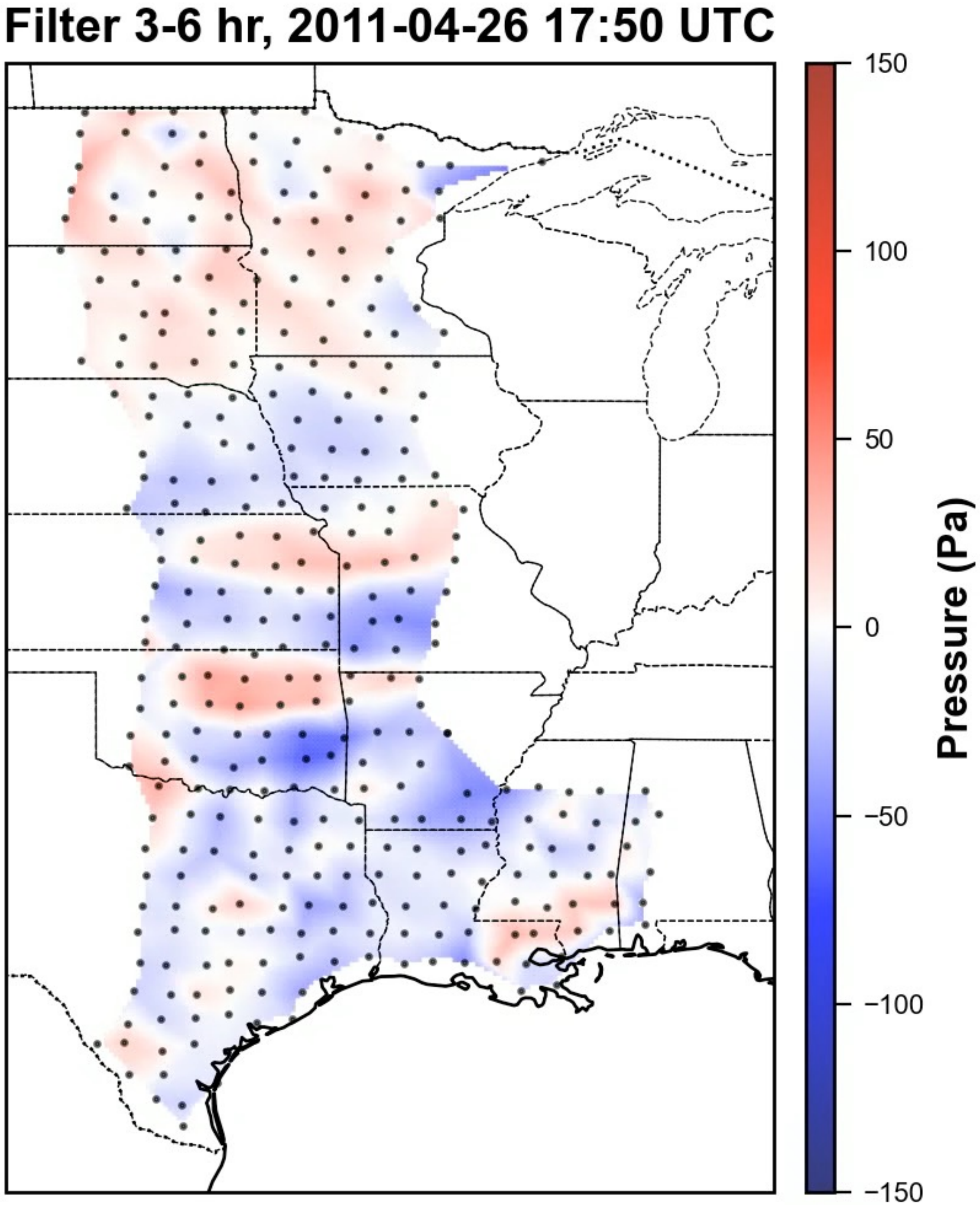
Hodograph of wind profiles



Qing et al. (2013)

In TA barometers, AGW looks like ...

Extend beyond the case study in previous work to obtain an **atmospheric gravity wave (AGW) database**



(Movie regenerated from De Groot-Hedlin et al. 2013)

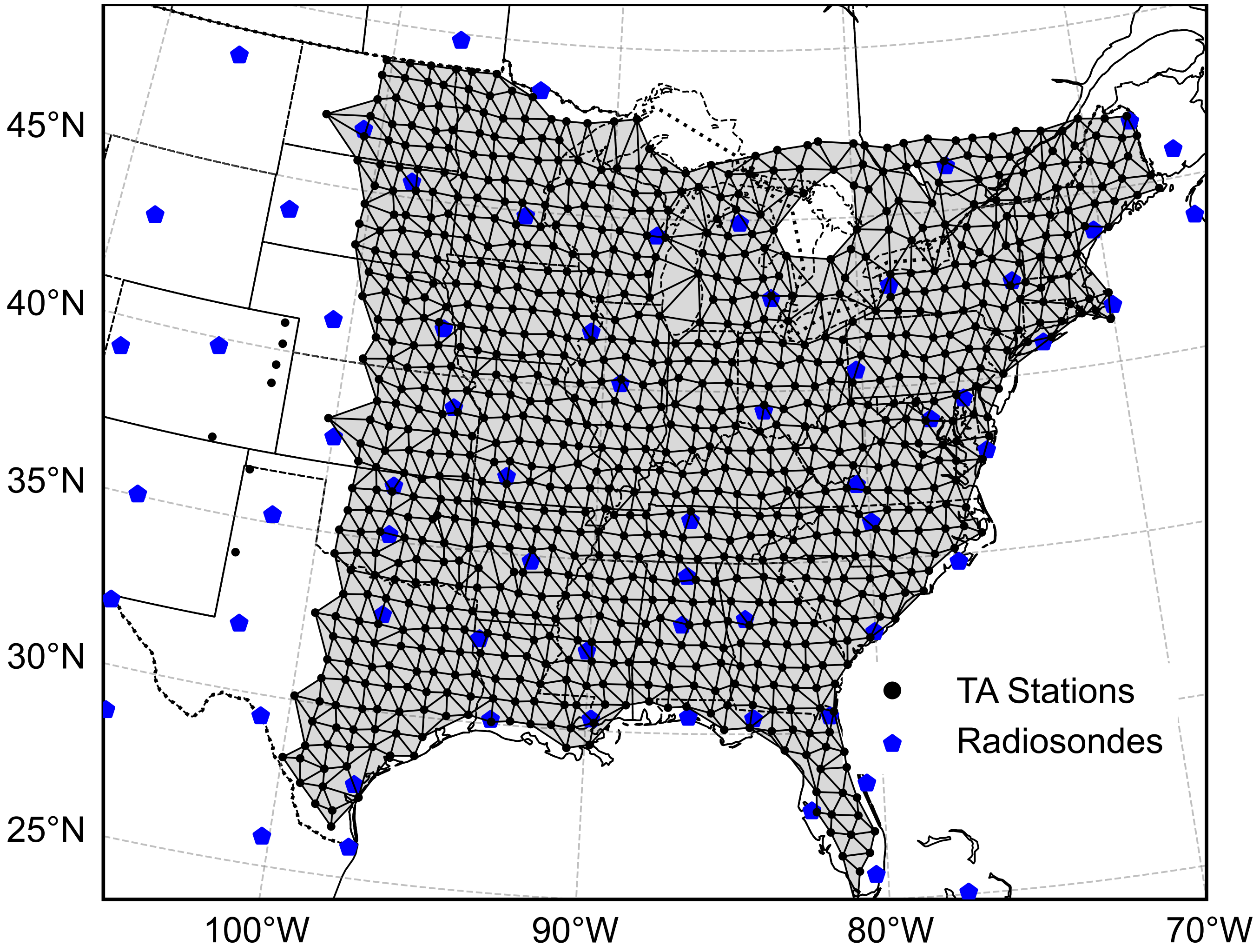
Observation of tropospheric inertia-gravity wave

Tropospheric: Height range ~2-9 km when using radiosonde data for AGW analysis

Inertia-gravity wave: Low-frequency limit. Typically suggested to have $\omega \sim 4f$ which gives period ~4-7 hr.

Radiosonde probes only twice a day at 00:00 and 12:00 UTC, obtaining vertical profiles.

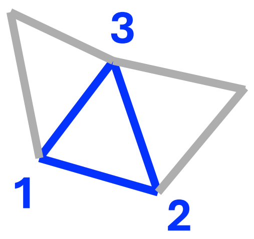
More TA barometers with higher temporal resolution, while surface pressure only.



Identify AGW from station triad

Delaunay triangulation

Total ~1700 station triads

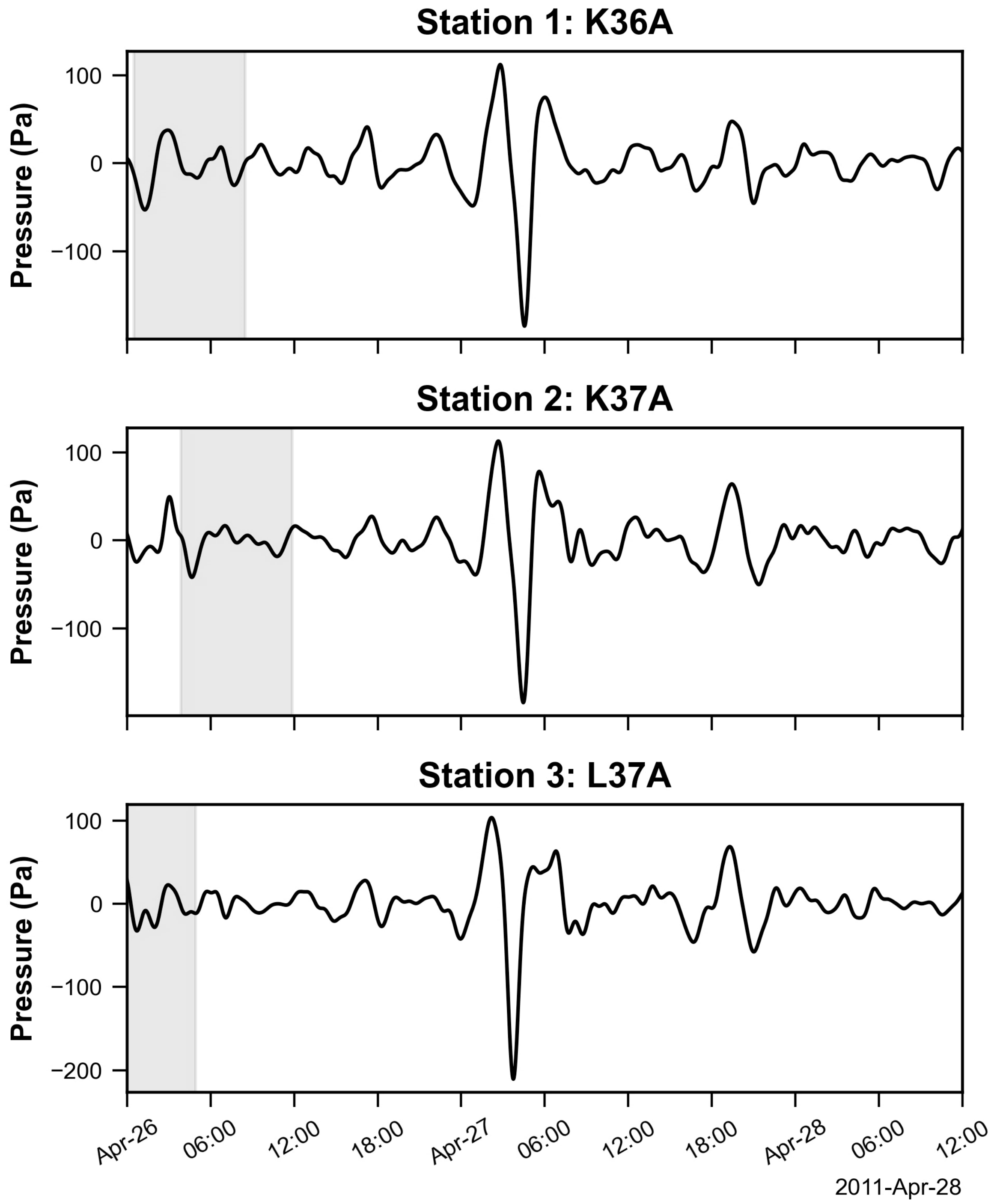


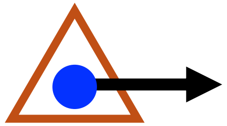
Search for AGW signals:

- Identify time windows based on similarity
- Measure cross-correlation travel time at each side of the triangle
- Fit to plane wave parameters

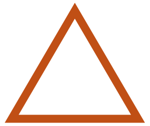
Quality control criteria:

- Correlation coefficient, pulse-like signal
- Travel time closure condition within the triad
- Misfit of plane wave fitting





~70,000 measured plane wave properties over 4 years



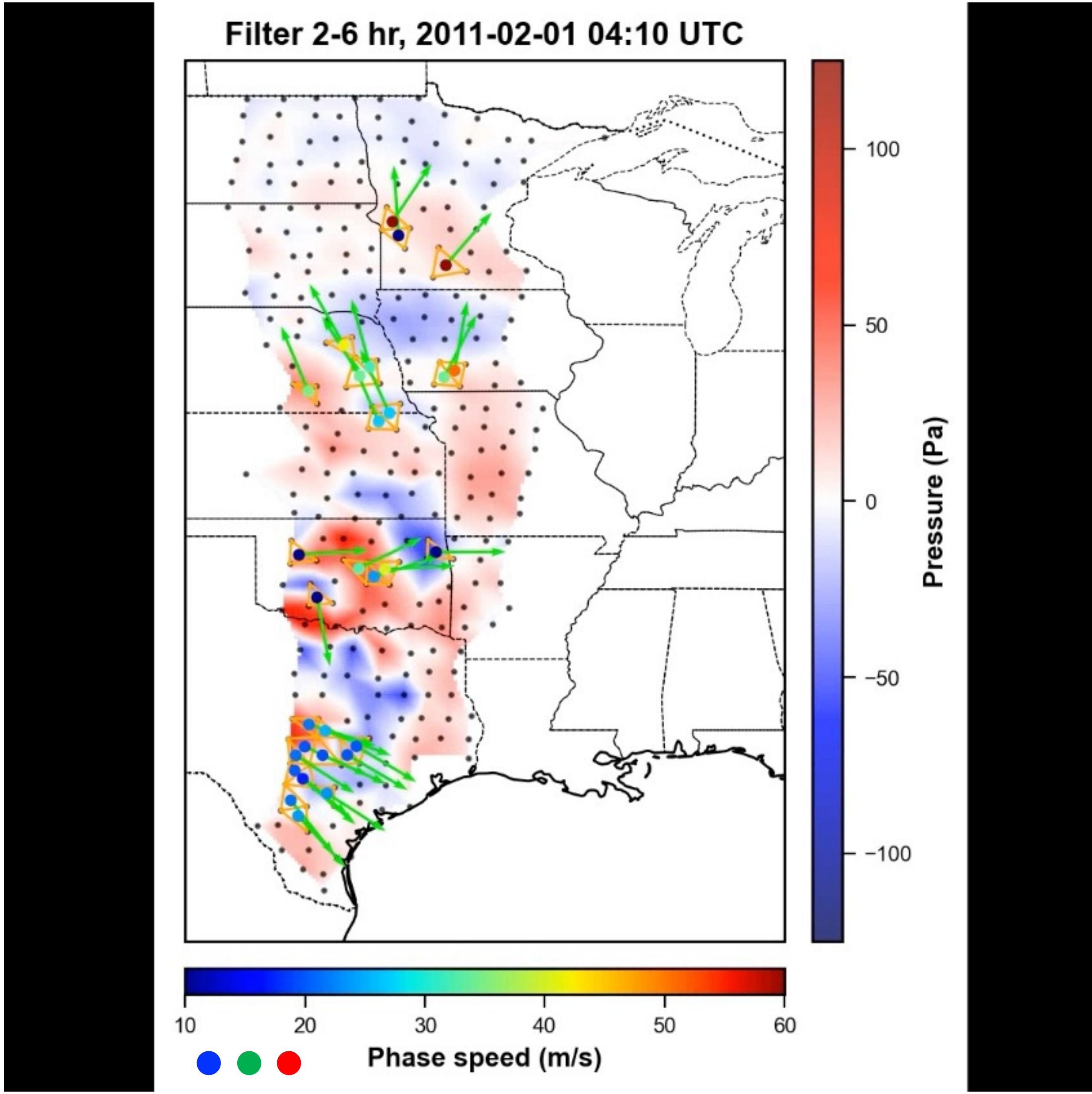
Pulse detected, but plane wave assumption may not be valid to obtain parameters

Challenges of AGW compared to earthquakes array detection …

- Point source assumption may not be valid
- Wave properties change across a large domain. Focused on each station triad

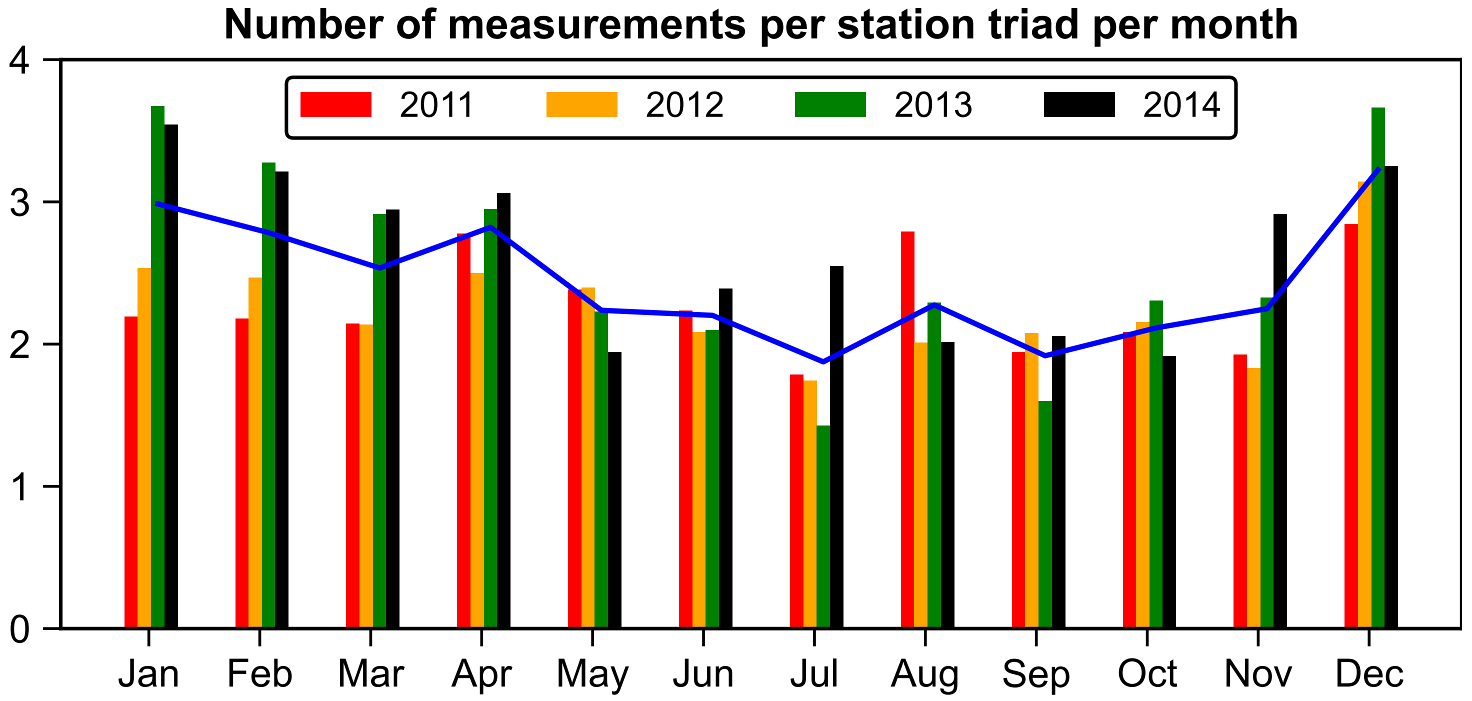
Single station triad analysis is recommended over the processing of the entire TA array

(De Groot-Hedlin et al. 2013)



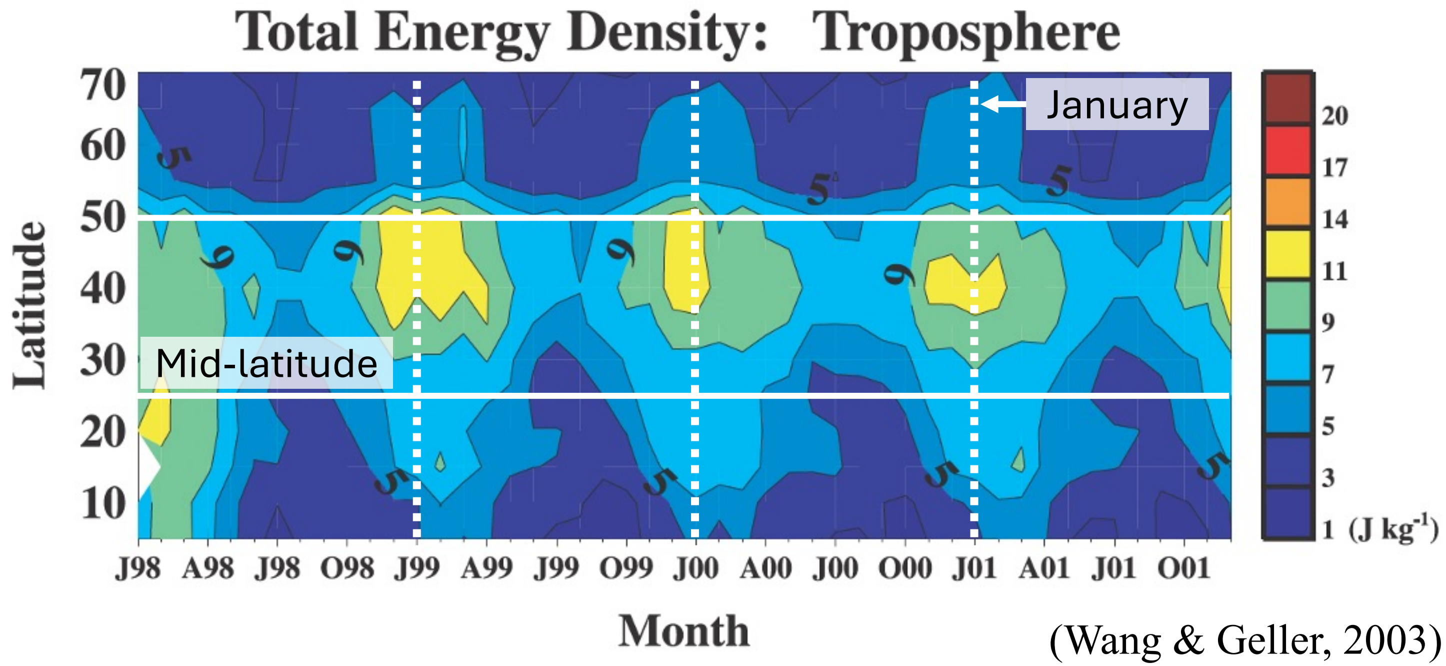
Seasonal variation of tropospheric AGW activity

- Account for TA different deployment over months.
- More detections around wintertime.



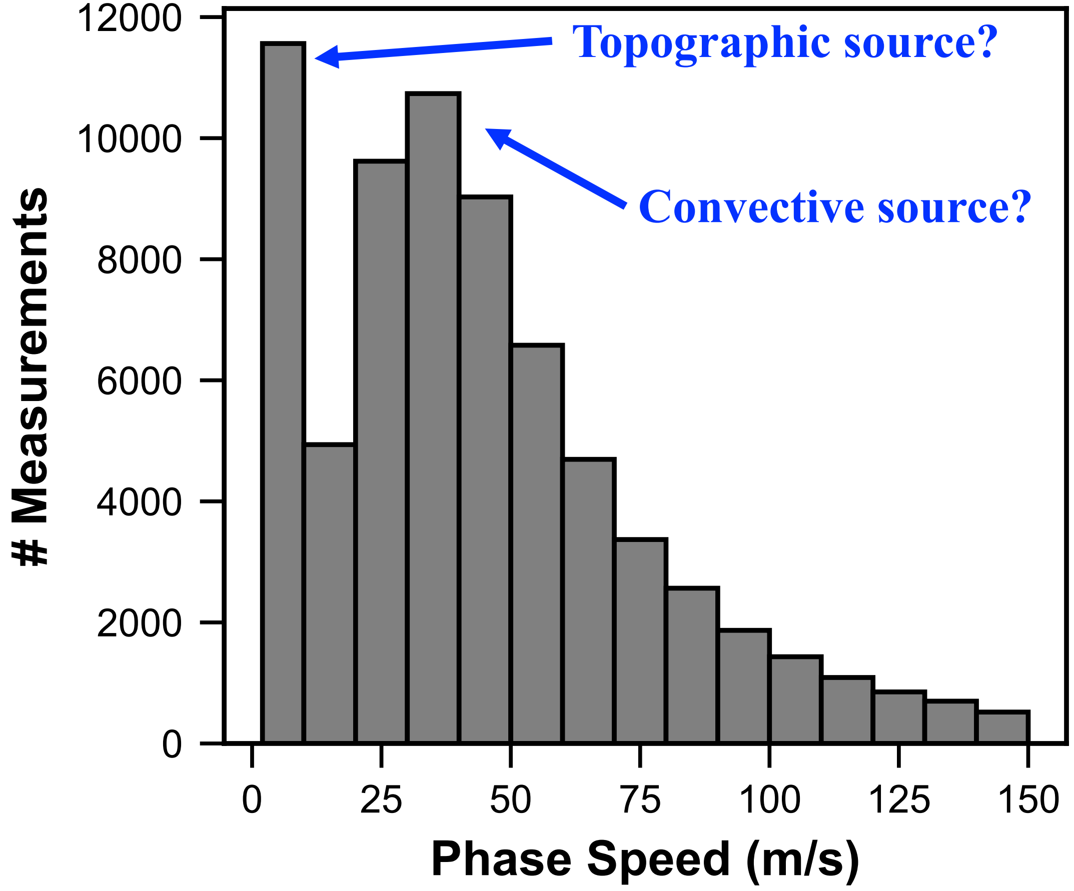
- Agree with radiosonde analysis showing stronger tropospheric AGW activity in winter.
- Strong mid-latitude tropospheric jets in winter contribute to this feature.

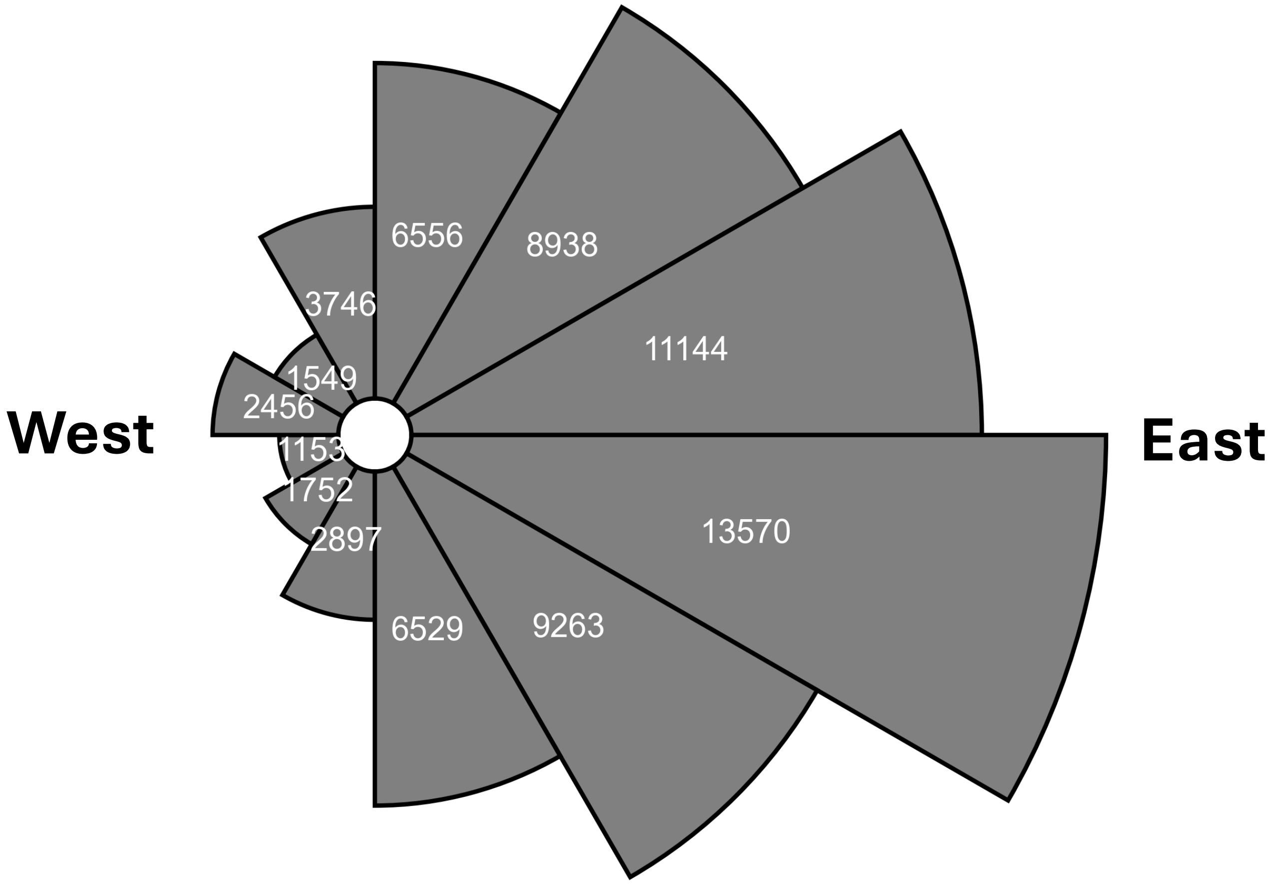
(e.g., Wang & Geller, 2003; Zhang et al. 2010)



(Wang & Geller, 2003)

Statistics of apparent AGW parameters





Two peaks of apparent phase speed could be related to **topographic** and **convective** sources.

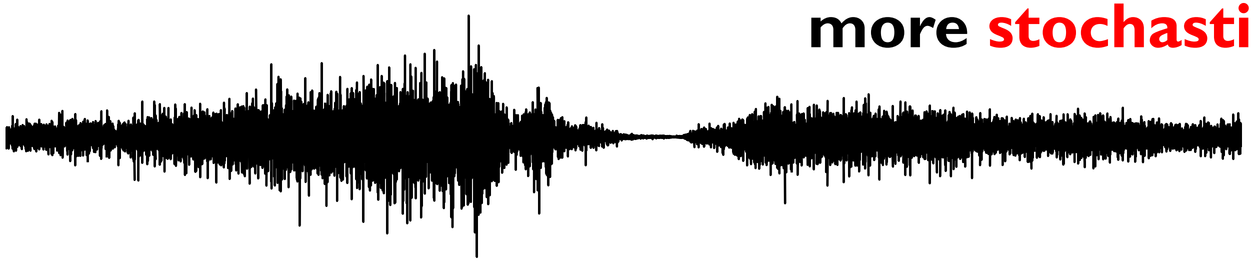
e.g., Alexander & Dunkerton (1999)

The tropospheric mid-latitude jet contributes to the observed **dominant eastward direction**.

Summary & Prospectives

more stochastic view

Hurricane Landfall



This trace can be both pressure and seismic imprints in atm. band

- **Local quasi-static response**
- **Reflective of hurricane structure**

Signals are turbulent

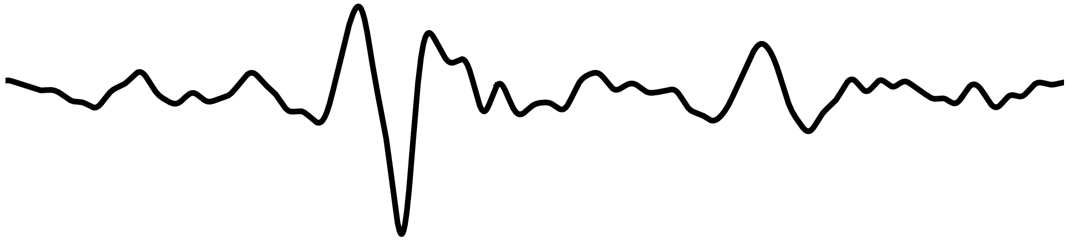
- **Turbulence affects coupling via U_c**
- **Infrasound — Turbulent pressure spectra**

Evolution of amplitude

- **Continuous in-situ monitoring**
- **Reflective of wind speed and turbulence statistics**

more deterministic view

Atmospheric gravity waves



Surface pressure imprints of tropospheric inertia-gravity waves

- **Apparent phase speed could relate to AGW sources**
- **Apparent phase direction reflects the influence of background wind (e.g. mid-latitude jet)**

Prospectives

Signatures from hurricane boundary layer turbulence:

Pressure-seismic coupling: Local quasi-static response to fluctuating pressure

Same for **ocean bottom** seismometer or DAS recordings of ocean waves.

Estimate near-surface velocity structure (e.g., Vs30 model for the top ~30 m subsurface for geoengineering).

Applied on **Mars** to estimate the compliance of Martian regolith.

Ambient infrasound signals as an atmospheric dataset for **wind and turbulence analysis**

Application of the same workflow to **general planetary boundary layers**.

The **full pressure spectrum** across different ranges.

Signatures from atmospheric internal gravity waves:

An initial AGW database from dense surface barographs

Future **comparison with radiosonde** analysis of AGWs?

Separation between **topographic** and **convective** sources?

Atmospheric signatures in ambient seismoacoustic signals