Wave–Wind Interaction Regimes in Tropical Cyclones

Revealed by Clustering of Spotter Buoy Observations

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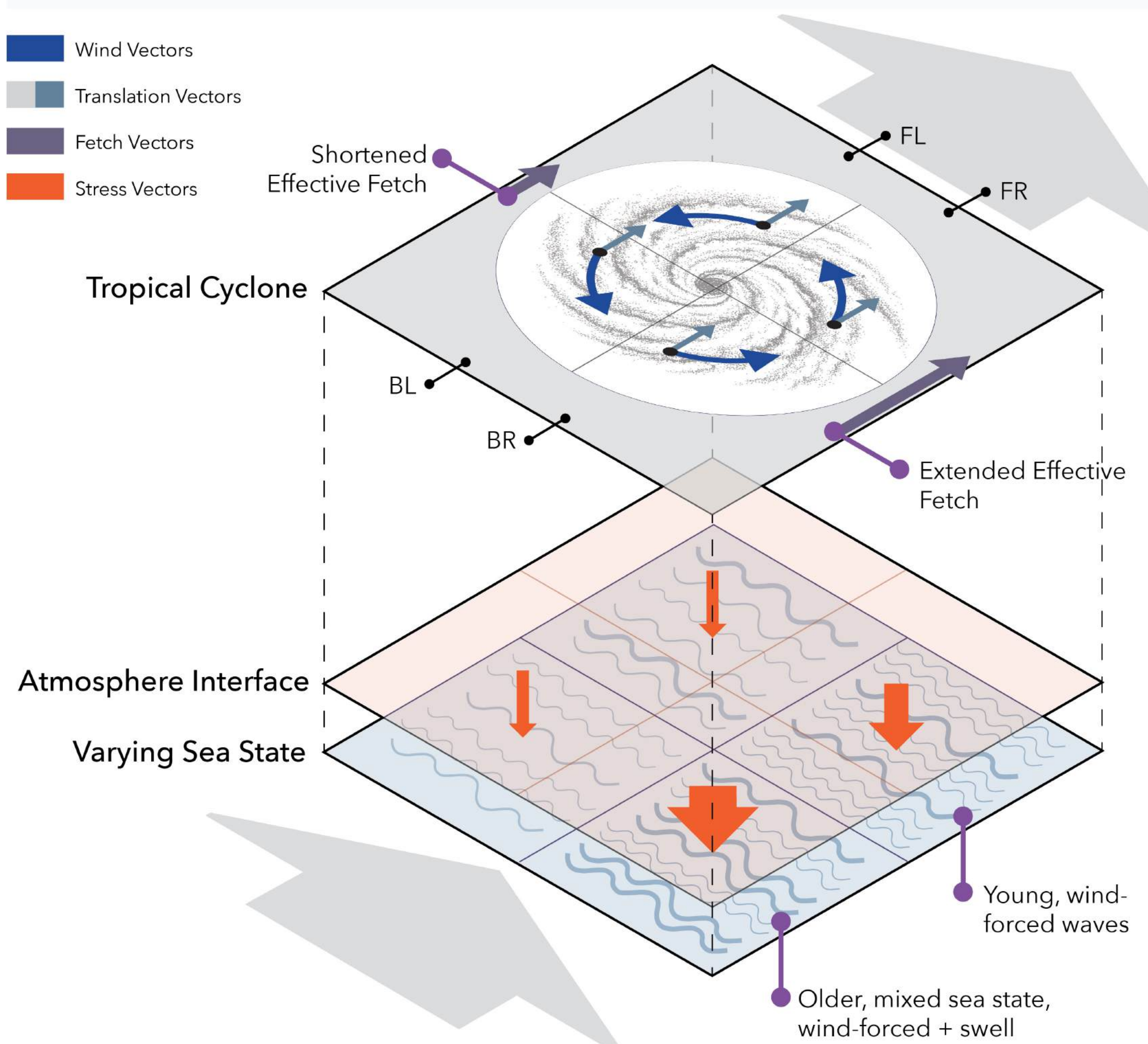
1. Introduction & Summary

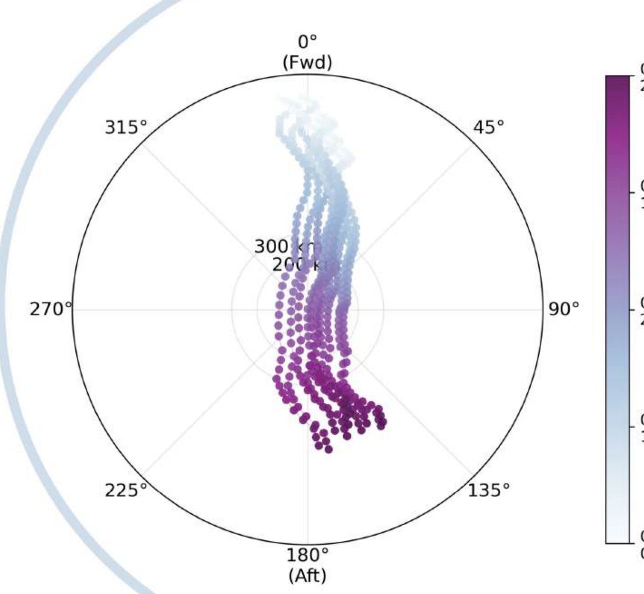
Tropical cyclones (TCs) intensify through air-sea exchanges of momentum and energy that depend strongly on near-surface winds and the evolving wave field. Because storms translate while rotating, the wind-wave system becomes highly asymmetric in a storm-relative frame.

In the Northern Hemisphere, the front-right quadrant generally exhibits the strongest winds and youngest, wind-forced waves, while other quadrants may contain more mature swell and different wind-wave alignment. These variations influence wave age, sea surface roughness, and the partitioning of surface stress between turbulent and wave-supported components. As a result, air-sea momentum flux and drag coefficients may vary systematically across the storm.

Quantifying these quadrant-dependent interactions is essential for improving parameterizations of surface drag and wave coupling in coupled atmosphere-ocean models, which remain a major source of uncertainty in forecasts of tropical cyclone intensity change.



Conceptual diagram of storm-relative asymmetries in tropical cyclone air-sea interactions. As a tropical cyclone translates, the combination of storm motion and rotational winds produces stronger winds and longer effective fetch in the front-right quadrant (NH). This region generates young, wind-forced waves and enhanced surface roughness, while rear quadrants contain more mature swell or mixed sea states. These differences influence air-sea momentum exchange and surface stress, which play a key role in regulating tropical cyclone intensity and ocean coupling.



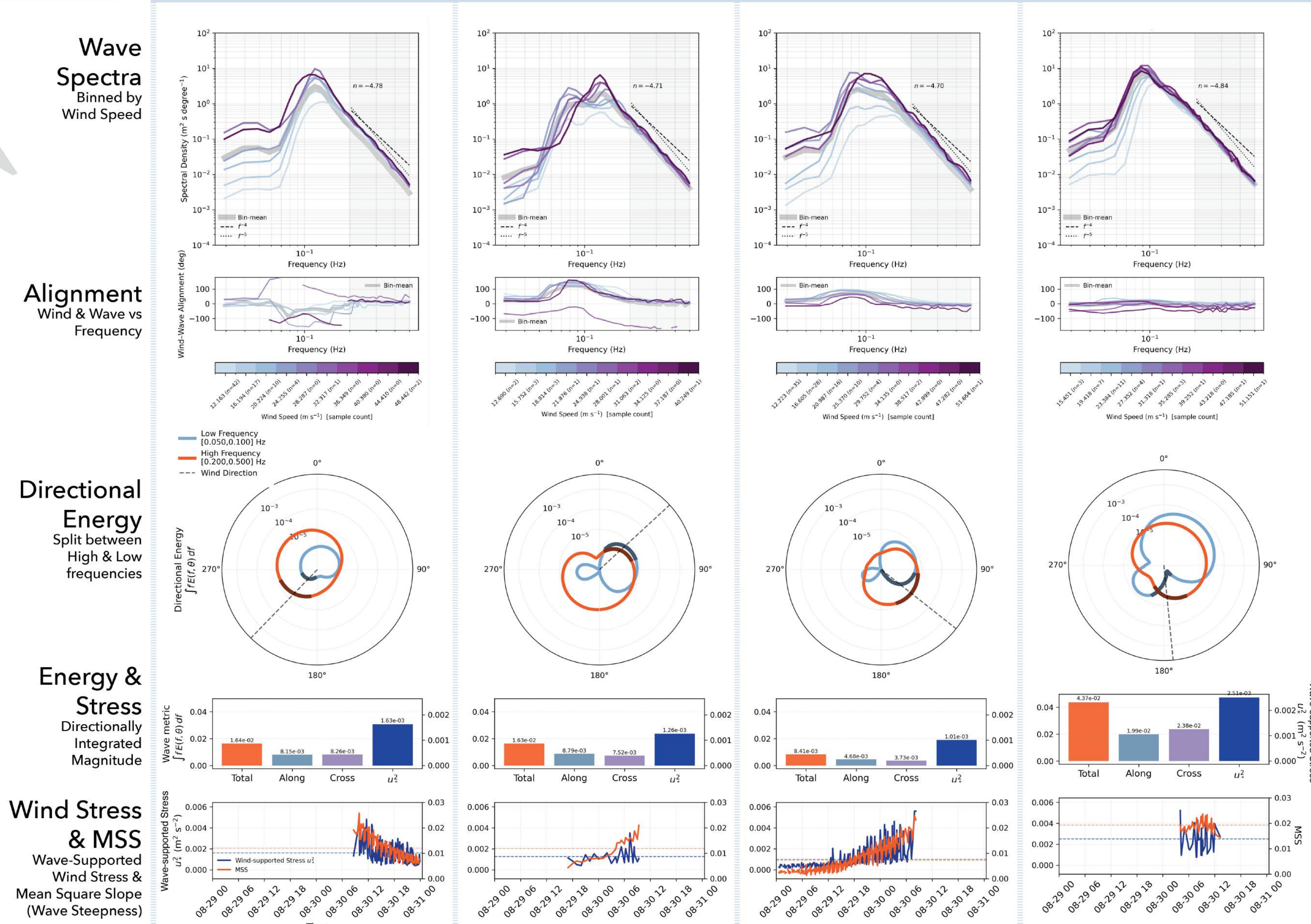
2. Spotter Buoy Data

This study uses drifting wave buoy observations collected during Hurricane Idalia. Ten buoys drifted with the ocean currents for ~2 days as the storm passed, with several instruments moving near or through the storm center.

Because the buoys drift with the ocean surface, they sample the storm in a storm-relative frame, providing rare in situ observations across multiple cyclone quadrants within a single event. These measurements capture the evolving wind and wave environment under hurricane-force winds.

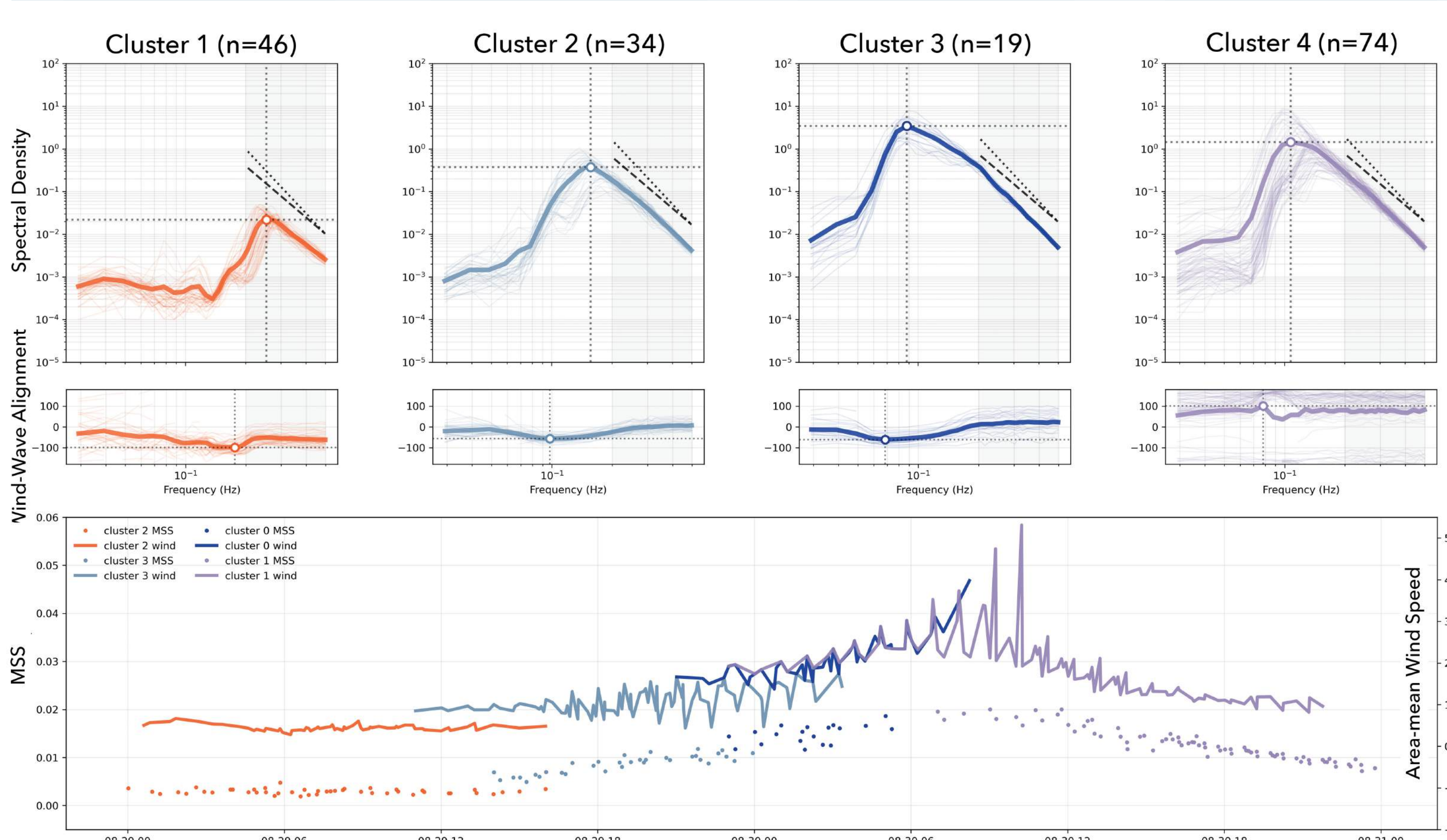
We gratefully thank Dr. Jacob Davis for sharing these observations and making this analysis possible. (Davis et al., 2023, 2025)

3. Quadrant Analysis



Davis, J. R., Thomson, J., Houghton, I. A., Doyle, J. D., Komaromi, W. A., Fairall, C. W., et al. (2023). Saturation of ocean surface wave slopes observed during hurricanes. Geophysical Research Letters, 50, e2023GL104139. https://doi. org/10.1029/2023GL104139

Davis, J. R., Thomson, J., Houghton, I. A., Fairall, C. W., Butterworth, B. J., Thompson, E. J., et al. (2025). Ocean surface wave slopes and wind-wave alignment observed in Hurricane Idalia. Journal of Geophysical Research: Oceans, 130, e2024JC021814. https://doi. org/10.1029/2024JC021814



4. Clustering (HDBSCAN)

Hierarchical Density Based Clustering for Applications with Noise

Cluster 1

Wind Speed: 4.4 m/s
Frequency Peak: 0.254 Hz
Tail Slope: -1.0
MSS: 0.003

Local wind chop, pre storm

Cluster 2

Wind Speed: 12.3 m/s
Frequency Peak: 0.156 Hz
Tail Slope:-4.1
MSS: 0.009

Classic wind sea, FR quad.

Cluster 3

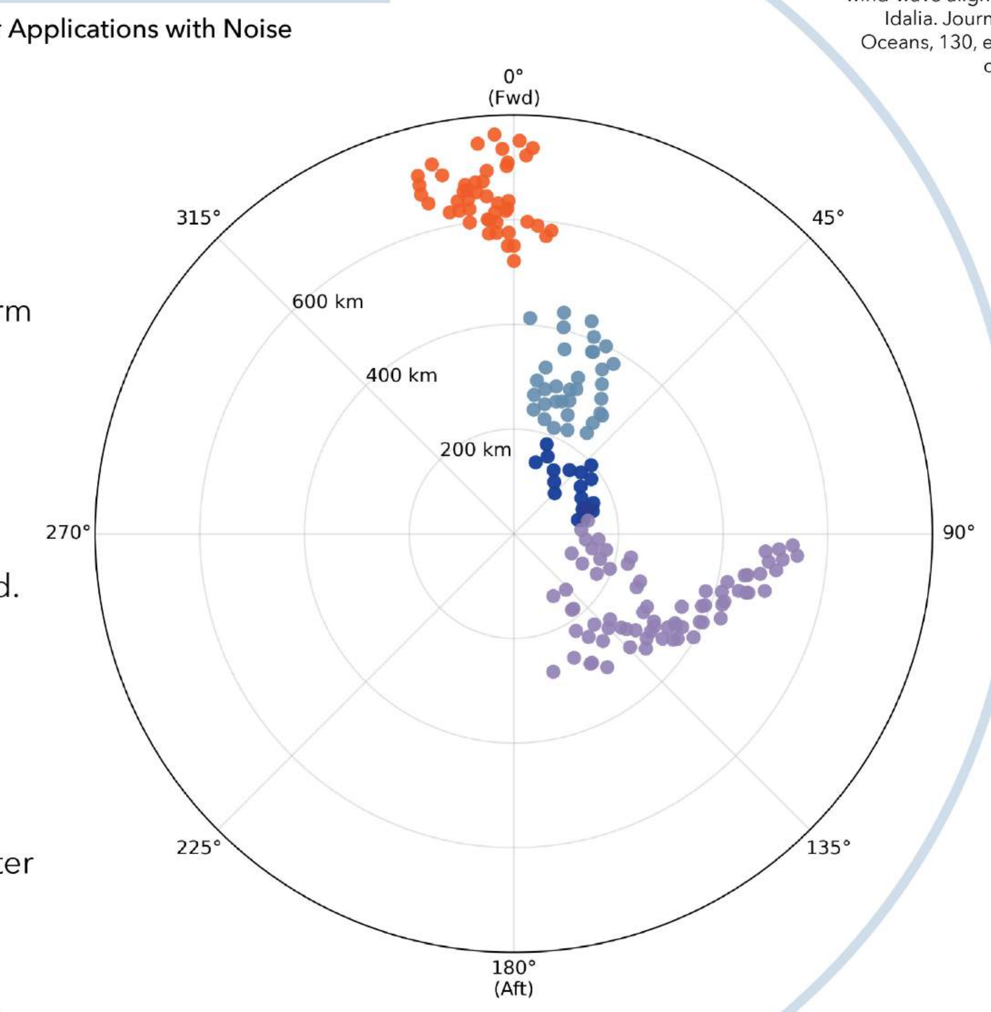
Wind Speed: 19.6 m/s
Frequency Peak: 0.088 Hz
Tail Slope:-4.7
MSS: 0.015

Mature TC wind sea, center

Cluster 4

Wind Speed: 11.3 m/s
Frequency Peak: 0.0.137 Hz
Tail Slope:-4.4
MSS: 0.012

Decaying/ mixed sea behind BR quad



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5. Key Findings

Directional wave spectra in tropical cyclones organize into distinct storm-relative wave regimes that can be objectively identified using unsupervised clustering of drifting buoy observations.

1. These regimes correspond to physically interpretable sea states, including mature hurricane wind seas, mixed swell–wind conditions, and locally forced wind chop.
2. Wave regimes vary systematically with storm-relative position, reflecting the asymmetric wind and fetch structure of the storm.
3. Differences in wave state imply spatial variability in surface roughness and air-sea momentum flux across cyclone quadrants.
4. Spotter buoys provide rare in situ observations across multiple storm regions within a single event, enabling direct observation of these storm-relative regimes.