Traveling Ionospheric Disturbances (TIDs) from GNSS TEC Observations During Hurricanes and Their Correlation with Lower-Atmosphere Gravity Waves

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1. Background & Motivations

- Hurricane-generated gravity waves can link the lower atmosphere to the ionosphere, with reported wavelengths of ~200–350 km during Hurricane Matthew.
- As gravity waves propagate upward, some wave energy reaches higher altitudes, while some is dissipated or filtered before reaching the ionosphere [Xu et al., 2019]
- The full pathway from hurricane forcing → stratospheric GWs → ionospheric TIDs remains unclear for multi-event comparisons. Specifically, **1.What are the GW features at different heights during meteorological events? 2. What are the general characteristics of TIDs induced by meteorological processes?**

2. Data and Methodology

- ECMWF IFS/HRES(1-1000)hPa: Used to examine small-scale wave structures near the hurricane source region; grid spacing ~9 km / 0.08°.
- AIRS(30-40km): Used to observe temperature perturbations and gravity-wave structures; swath width ~1650 km, nadir footprint ~13.5 km.
- GNSS TEC: Used to identify TIDs/CTIDs in the ionosphere from MIT Haystack Madrigal TEC data

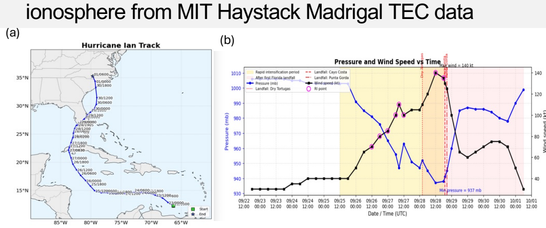

Figure 1.(a) Hurricane Ian best-track trajectory **(b)** Time evolution of minimum central pressure and maximum sustained wind speed. Blue shows pressure, black shows wind speed, red dashed lines mark Florida landfall times, yellow shading indicates the rapid-intensification period, and gold vertical lines show selected analysis times. Track and intensity data are from NOAA

- ECMWF/IFS vertical velocity was smoothed to obtain W′
- to separate perturbations, and AIRS 4µm brightness-temperature perturbation data, associated with gravity-wave activity.
- GNSS TEC data were processed to obtain TEC perturbations using 0.25° × 0.25° spatial binning and a fourth-order 20–40 min band-pass filter.
- Hurricane-centered analysis was used to calculate wave variance/RMS, dominant wavelength from FFT or crest spacing, and GNSS TEC keogram/r–t plots for estimating TID phase speed.

3. Result I: Near-source gravity-wave asymmetry analysis

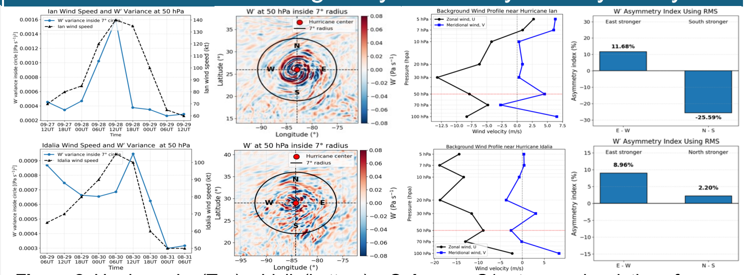

Figure 2. Hurricane Ian(Top) , Idalia(bottom) : **Columns:** C1 = temporal variation of waves in stratosphere with source, C2 Gaussian Smoothing vertical velocity W' map, C3 = Horizontal wind profile from reanalysis data , C4 = asymmetry index

- **Gravity-wave intensity will be quantified using the variance of vertical velocity perturbations, σ², with hurricane intensified.** C1(Wu et.al. 2024)
- C2: used Gaussian Smoothing for Spatial map of vertical pressure velocity(W), to look clear Gravity waves(GWs)
- Ian shows stronger south-side asymmetry, while Idalia shows stronger east-side asymmetry. Overall, near-source **gravity-wave asymmetry depends strongly on the background wind environment,** C3.
- C4: The asymmetry index quantifies the East/West(E-W) and North/South (N–S) differences in wave activity. Using AI= 2*(A-B)/(A+B)

Result II: GW Signatures from IFS/HRES and AIRS

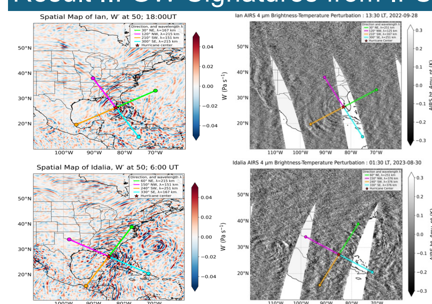

Figure 3. Vertical Pressure velocity W (left), Brightness temperature perturbation 4 µm_bt_pt (right)

- Shows Vertical coupling between different altitude using different instruments.

Event/Data	ECMWF IFS/HRES data ~22km (50hpa)	AIRS data (30 -40)km
Ian 2022/09/28	~151km (in 210∘)	~167km (in 210∘)
Idalia 2023/08/30	~215km (in 60 ∘)	~251km (in 60 ∘)

- Same propagation directions were selected where clear gravity wave patterns are visible in AIRS to compare wavelength.
- AIRS shows slightly larger dominant wavelengths than IFS/HRES by using 1D - FFT, suggesting that **wave scale changes with altitude.**

5. Acknowledgements and References

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- Wu, X., Hoffmann, L., Wright, C. J., Hindley, N. P., Alexander, M. J., Kalisch, S., ... & Lyu, D. (2024). Stratospheric gravity waves excited by Hurricane Joaquin in 2015: 3-D characteristics and the correlation with hurricane intensification. *EGUsphere*, *2024*, 1-26.

Result III: Background-wind influence in TIDs propagation

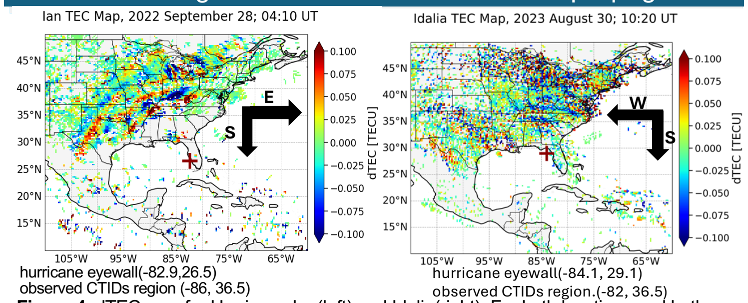
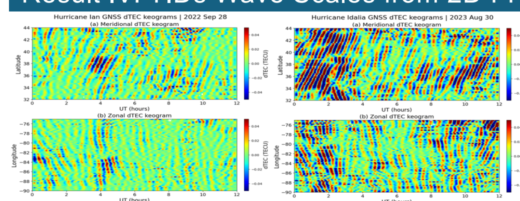


Figure 4. dTEC map for Hurricane Ian(left) and Idalia(right), For both locations and both Hurricanes, background wind direction(black perpendicular arrow), using the **HWM14** Model

- Background winds are broadly consistent with the observed TEC disturbance directions.
- Ian shows southward/southeastward background winds favoring northwestward CTID propagation.
- Idalia shows southwestward background winds consistent with northeastward TID propagation, supporting wind-controlled vertical coupling.

Result IV: TIDs Wave Scales from 2D FFT Keograms



Ian:
λh = 247.5 ± 27.2 km
ch = 123.4 ± 16.7 m/s
τ = 30.99 ± 0.86 min

Idalia:
λh = 248.4 ± 31.7 km
ch = 161.8 ± 25.3 m/s
τ = 27.41 ± 0.36 min

Figure 5. Meridional (Top) and zonal (bottom), Keogram for Ian(left) and Idalia(right)

- Horizontal wavelength, phase speed and period is consistent with previous study (Xu. et.al 2019). And we see large temporal TIDs signature in Idalia.
- Used ±1° cross-section bands: 38° latitude and −87° longitude for Ian, and 36° latitude and −87° longitude for the second case. Uncertainty was estimated from the local 50% peak-power region around the dominant 2D - FFT peak.

4. Conclusions(1)/Future Work(2)

1) a. Gravity-wave intensity will be quantified using **the variance of vertical velocity perturbations, σ², with hurricane intensified**. **b.** By comparing different data, in same wave directions, found slightly **larger dominant wavelengths in AIRS suggests wave-scale changes with altitude**. **c.** HWM14 background winds are broadly consistent with observed TEC disturbance directions. **d.** Horizontal wavelengths, phase speeds, and periods, consistent with hurricane-related TID wave scales(Xu.et.al 2019).
2) Extend the analysis to more hurricanes and altitude levels and examine GNSS viewing geometry and data coverage to explain why CTIDs vary between events.