EMBRY-RIDDLE
Aeronautical University

CEDAR GC: ITM Gravity Wave Coupling
Monday, 26 June, 2023

ITM Gravity Wave Coupling Across Scales and Systems:

Grand Challenges and Opportunities

Jonathan B. Snively, ERAU, Daytona Beach, FL.

Special thanks to coauthors and co-conveners, and folks cited,
(and apologies to the many folks not *yet* cited - please look
forward to future GC meeting sessions).

Results and examples are from the MAGIC and GEMINI models developed under prior NASA and NSF support,
and under DARPA Cooperative Agreement HR00112120003 to Embry-Riddle Aeronautical University.

ITM Gravity Wave Coupling Across Scales and Systems:

Grand Challenges and Opportunities

Workshop Purpose:

To identify, discuss, and address gaps and challenges in ITM GWs that require a coordinated approach, and to share progress, results, and timely successes in our science community.

ITM Gravity Wave Coupling Across Scales and Systems:

Grand Challenges and Opportunities

Define: *Across Scales* = Where processes have effects at distinctly separated scales, e.g., where small waves may evolve to have large-scale impacts, or where large scale motions may evolve disruptive small scale effects.

Across Systems = Interactions between ITM neutral dynamical, (photo)chemical, and electrical processes often modeled separately.

Observable Lower-ITM (MLT/Mesopause ~80-100 km)

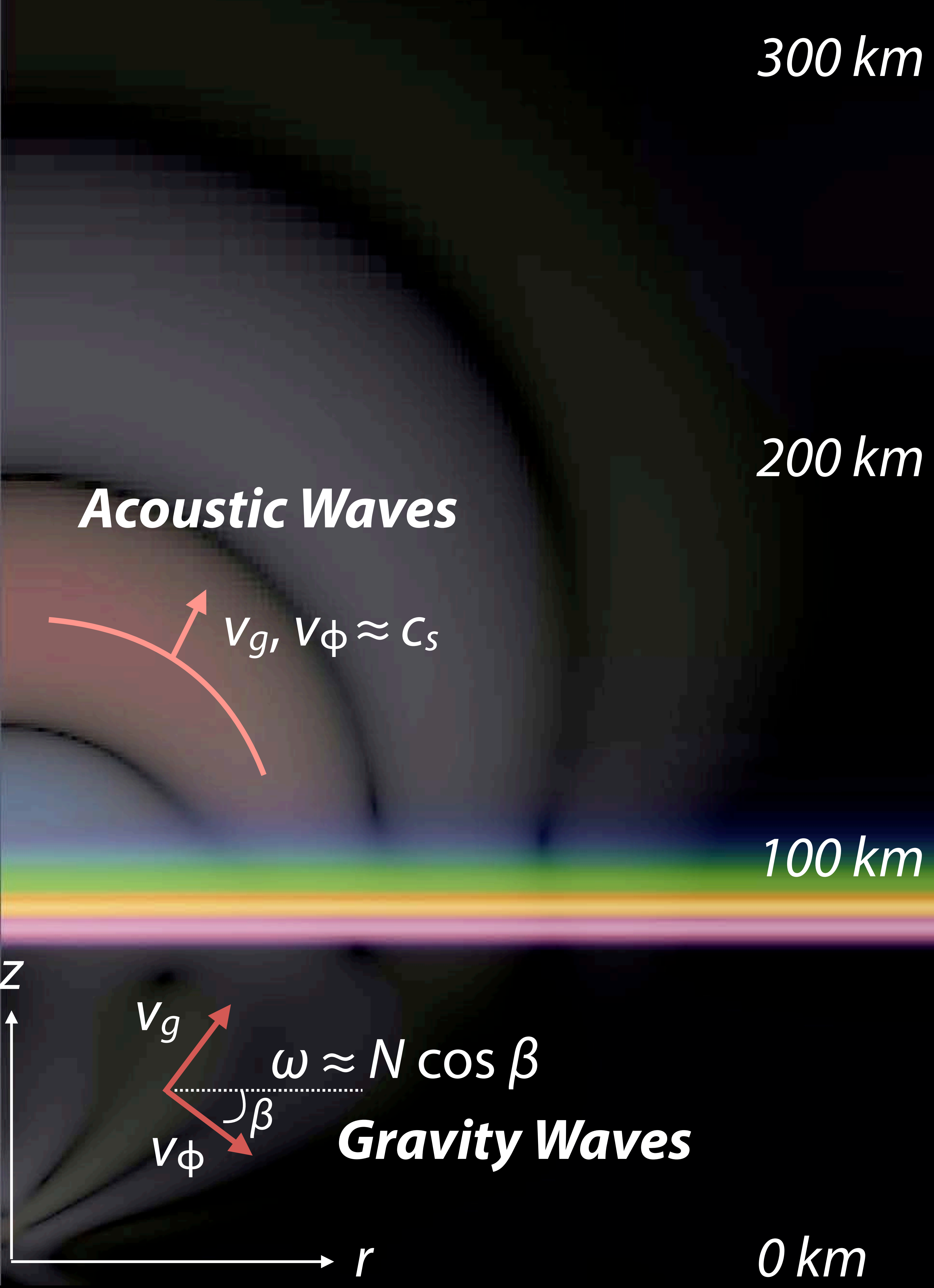
Mesopause-Region Observations Using Airglow and Trace Species:

- ~85 km **Hydroxyl (OH)** Airglow (esp. short-wave infrared);
- ~91 km **Sodium (Na)** and Other Metal Layer Sensing;
- ~95 km **Atomic Oxygen** (green-line 557.7 nm, *and emissions in ionosphere - 135.6, 630.0 nm*);
- Emissions of Molecular Oxygen (Atmospheric Bands).

Observable Middle-ITM (LT/Ionosphere >100 km)

ITM Observations Using Ionospheric Airglow and Radio Propagation:

- ≥95 km Atomic Oxygen (green-line 557.7 nm, *and* **emissions in ionosphere - *135.6, 630.0 nm***, *etc.*);
- D-Region reflections and absorption of radio signals;
- E-region modulation of MF/HF radio signals;
- F-region modulation of transionospheric microwave / GNSS signals.



The Acoustic-Gravity Wave Spectrum

Waves in a deep, stratified, compressible atmosphere:

- Long-period (infrasonic) **acoustic** waves (≤ ~3.5 min period).
- Short (intrinsic) period **gravity** waves (≥ ~5 min, < hours).
- Everything in-between (Lamb waves, external/evanescent waves, guided/ducted modes, and nominal “acoustic-gravity waves” that invoke buoyancy and compressibility to characterize).

Gravity waves may also include those at large scales where Earth’s rotation matters, at the longer-period limit: ***Inertio-Gravity Waves,*** which may nevertheless evolve nonlinearly into smaller scales.

The Acoustic-Gravity Wave Spectrum: *Example*

About this example - generating AGWs:

- A ~several-km-scale vertical force was applied at *r*=0, *z*=12 km, with a time scale of ~minutes (FWHM ~2.35 minute).
- A spectrum of acoustic and gravity waves is generated with periods from ~few-10 minutes.
- The colored layers are the direct simulations of the oxygen layer, sodium layer, and hydroxyl layer shape (product of [H] and [O_3])

The visualization of the wave field shows in grayscale the log-scale Mach number (range 0.0001-0.4), tinted by vertical velocity (range ±100 m/s, with peaks ±140 m/s in the data) in a red-blue color scheme.


300 km
200 km
Acoustic Waves
$v_g, v_\phi \approx c_s$
100 km
z
v_g
$\omega \approx N \cos \beta$
β
v_ϕ
Gravity Waves
r
0 km

Wave Evolution with Altitude

Gravity waves grow in velocity fluctuation amplitude with altitude:

- Attempt to conserve energy in exponentially decreasing density — velocity fluctuations grow with $\sqrt{\rho_0/\rho(z)}$ (until they cannot).
- May become unstable, due to environmental interactions and/or large amplitudes relative to wave phase velocities (leading to steepening, self-acceleration, instability, and/or breaking).

$$\omega \approx N \cos \beta$$

Gravity Waves

$$\omega \approx N \cos \beta$$

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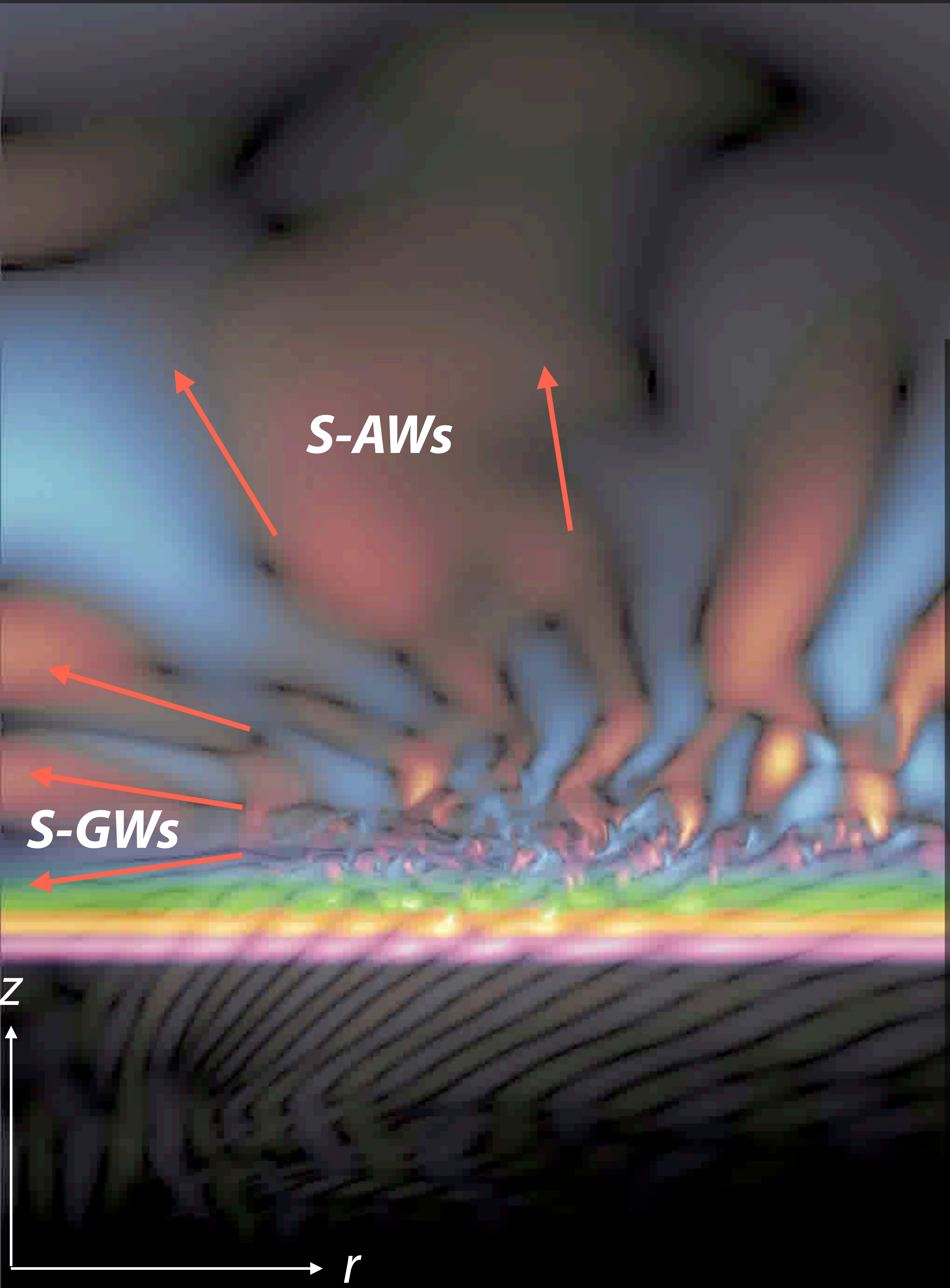
Gravity Waves

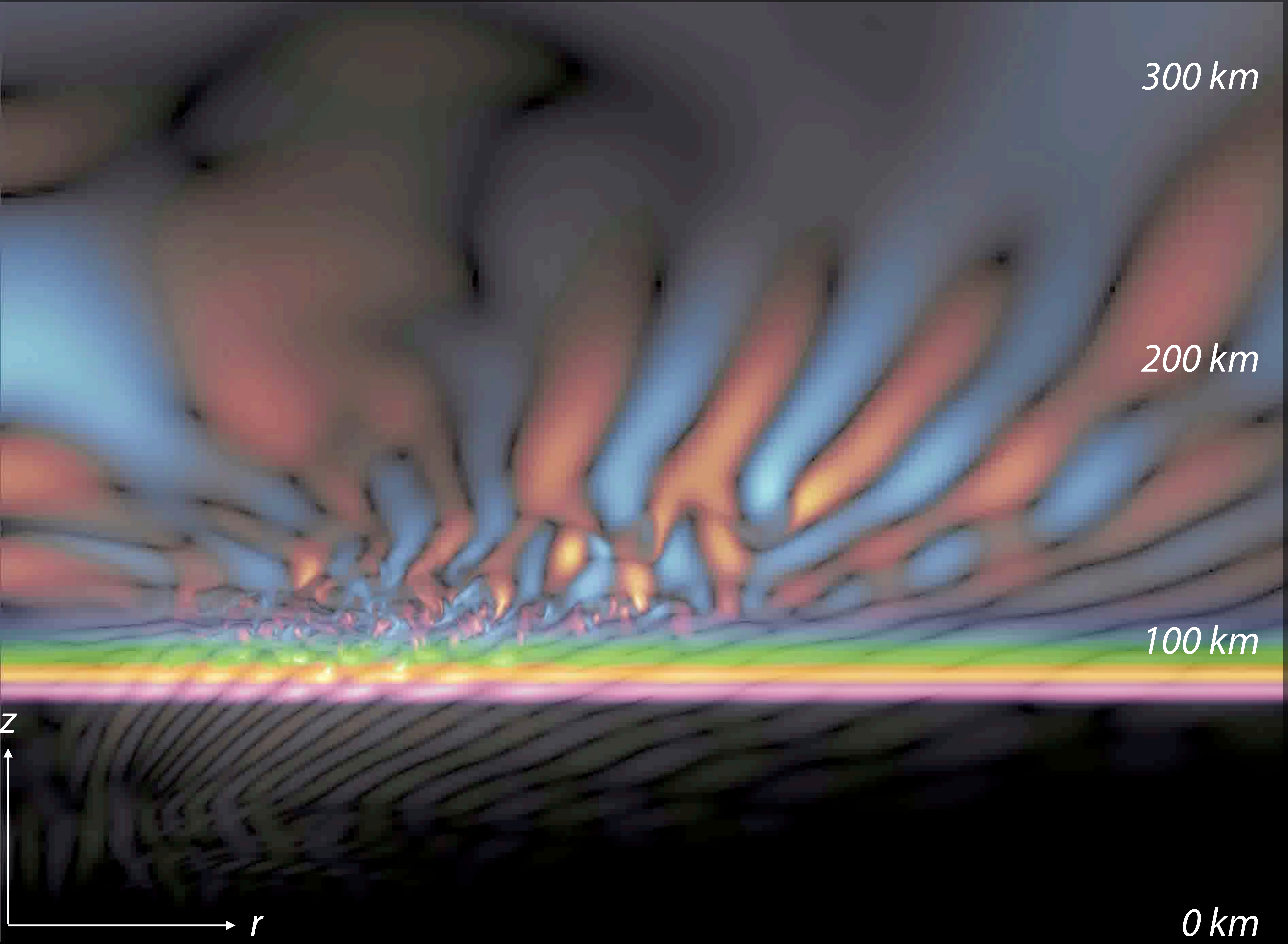


Secondary Acoustic and Gravity Waves

Gravity waves force more gravity waves in different ways…

- Net impacts of dissipating waves radiate large-scale secondary waves from packet-scale effects (e.g., *Vadas et al.*, 2003-2023).
- Nonlinear fluxes of energy and momentum that, on average, lead to radiation of other waves/modes typically at similar or smaller scales (e.g., *Snively et al.*, 2008; *Heale et al.*, 2022; *Franke and Robinson*, 1999; on small-scale secondary waves).

Primary waves may also evolve to higher intrinsic frequencies via self-acceleration, enabling them to reach high altitudes as they modulate the winds around them (e.g., *Fritts et al.*, 2015; *Dong et al.* 2020).



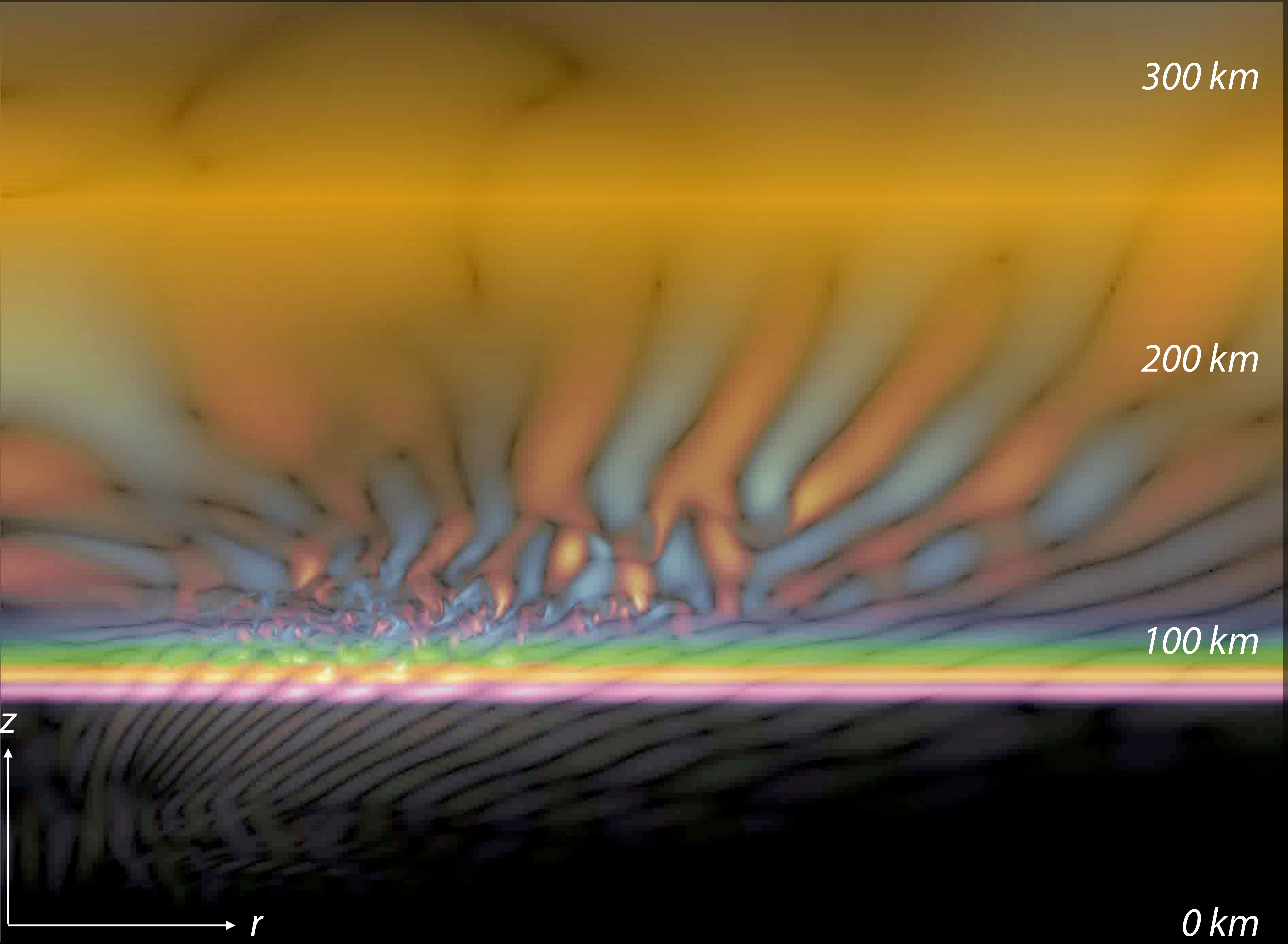
Opportunity:

Leverage Mesopause Measurements to Understand ITM Dynamics.

~80-100 km

Observable via Neutral Densities

(from ground/space)



Opportunity: Leverage Ionospheric Datasets to Measure and Understand Neutral Dynamics in ITM.

~100-180+ km
Observable via
Ionospheric Coupling

~80-100 km
Observable via
Neutral Densities
(from ground/space)

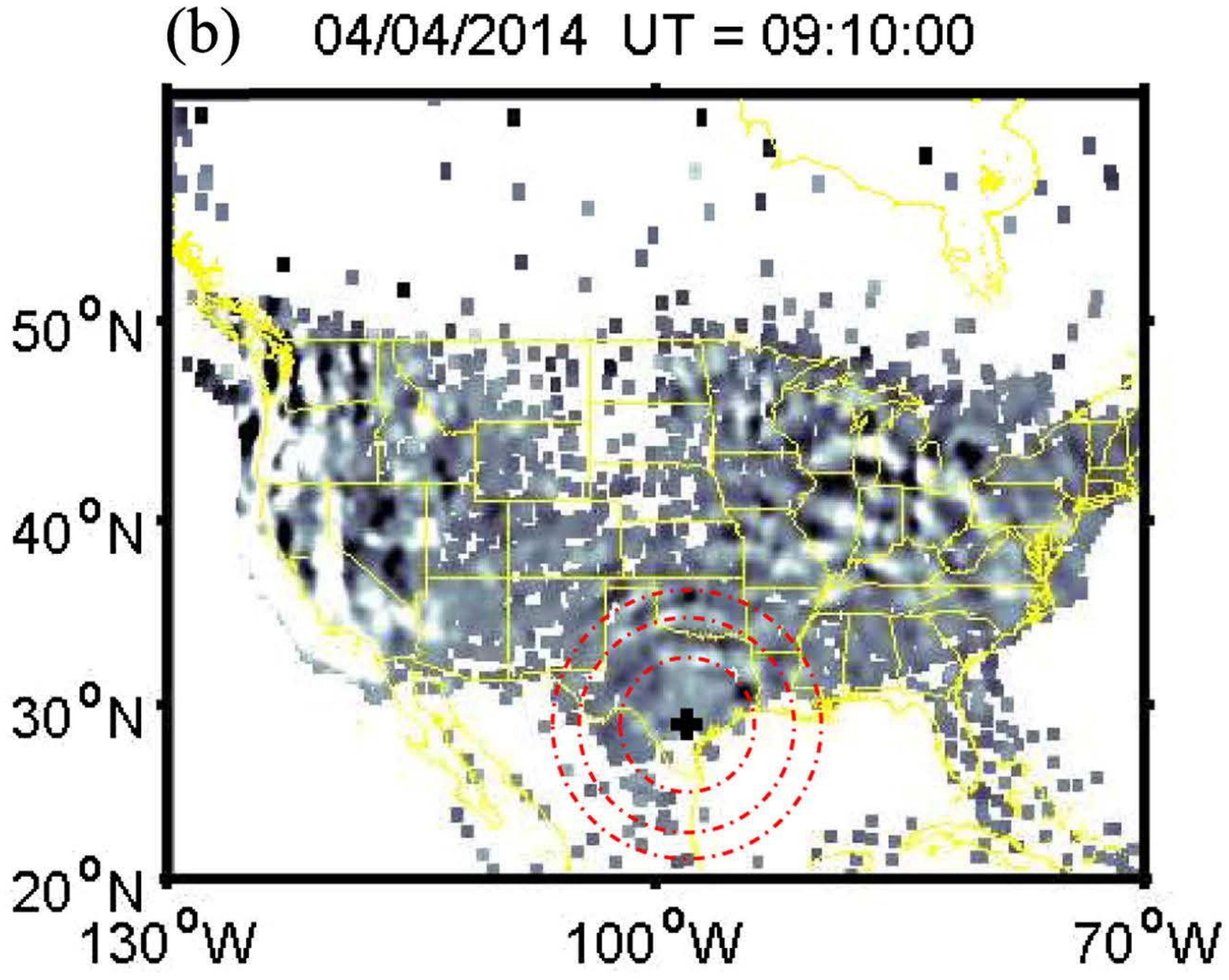
Grand Challenge → *Opportunity*

- **Mesopause measurements capture inputs to the ionosphere.**
- **Ionospheric measurements reveal neutral dynamics, too.**

Goal: *Develop a shared community understanding of the relationship between disparate but familiar measurements, to maximize the value of interpretations and quantifications of the underlying ITM systems as a whole.*

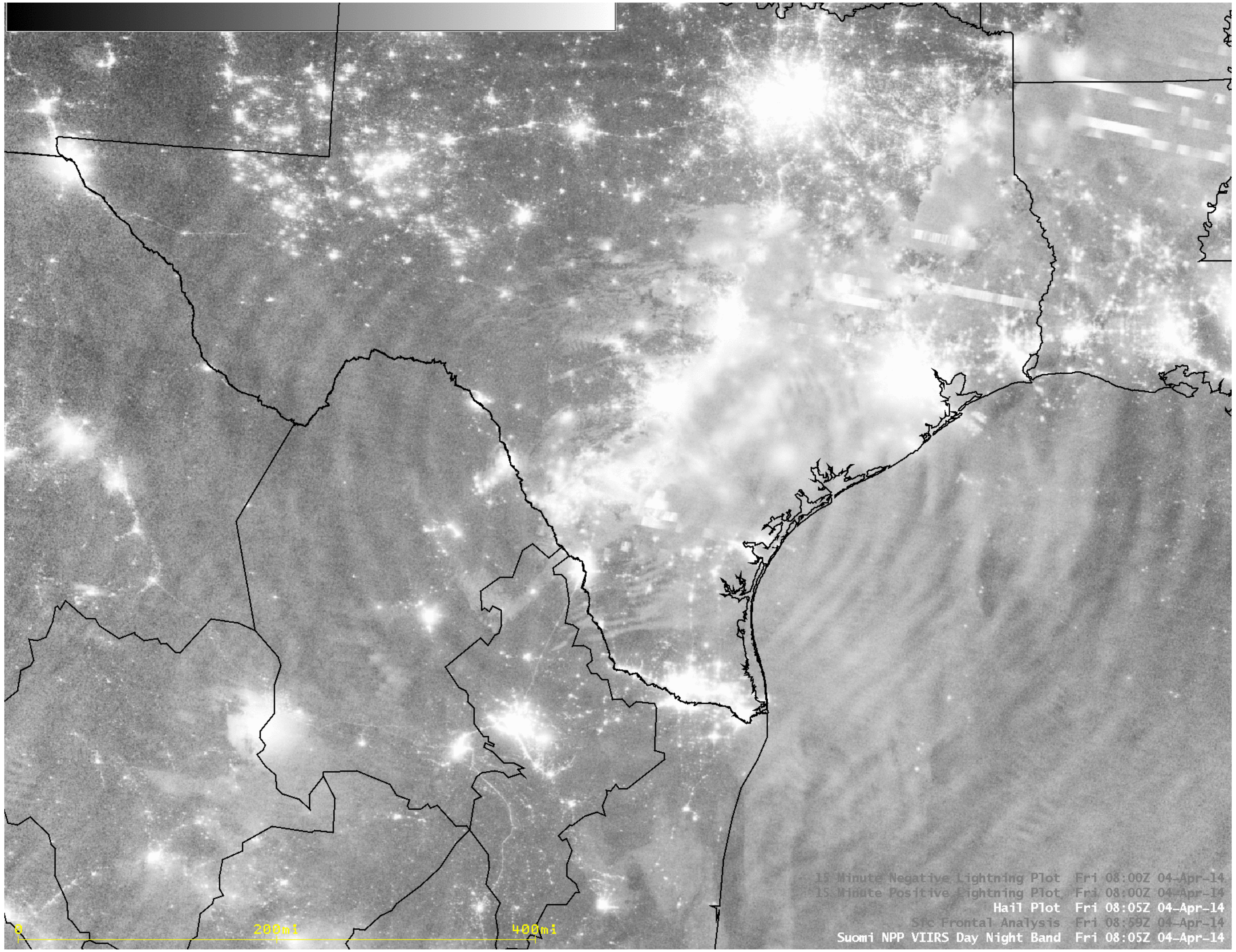
Example: Multi-Layer Optical Datasets

Miller et al., (Proc. Nat. Acad. Sci., 2015) reported meteorological satellite (Suomi's DNB) imagery of GWs in airglow over a thunderstorm in Texas, clearly corresponding with underlying meteorology; Azeem et al. (2018) later reported TEC fluctuations.



https://doi.org/10.1016/j.asr.2017.09.029

https://doi.org/10.1073/pnas.1508084112



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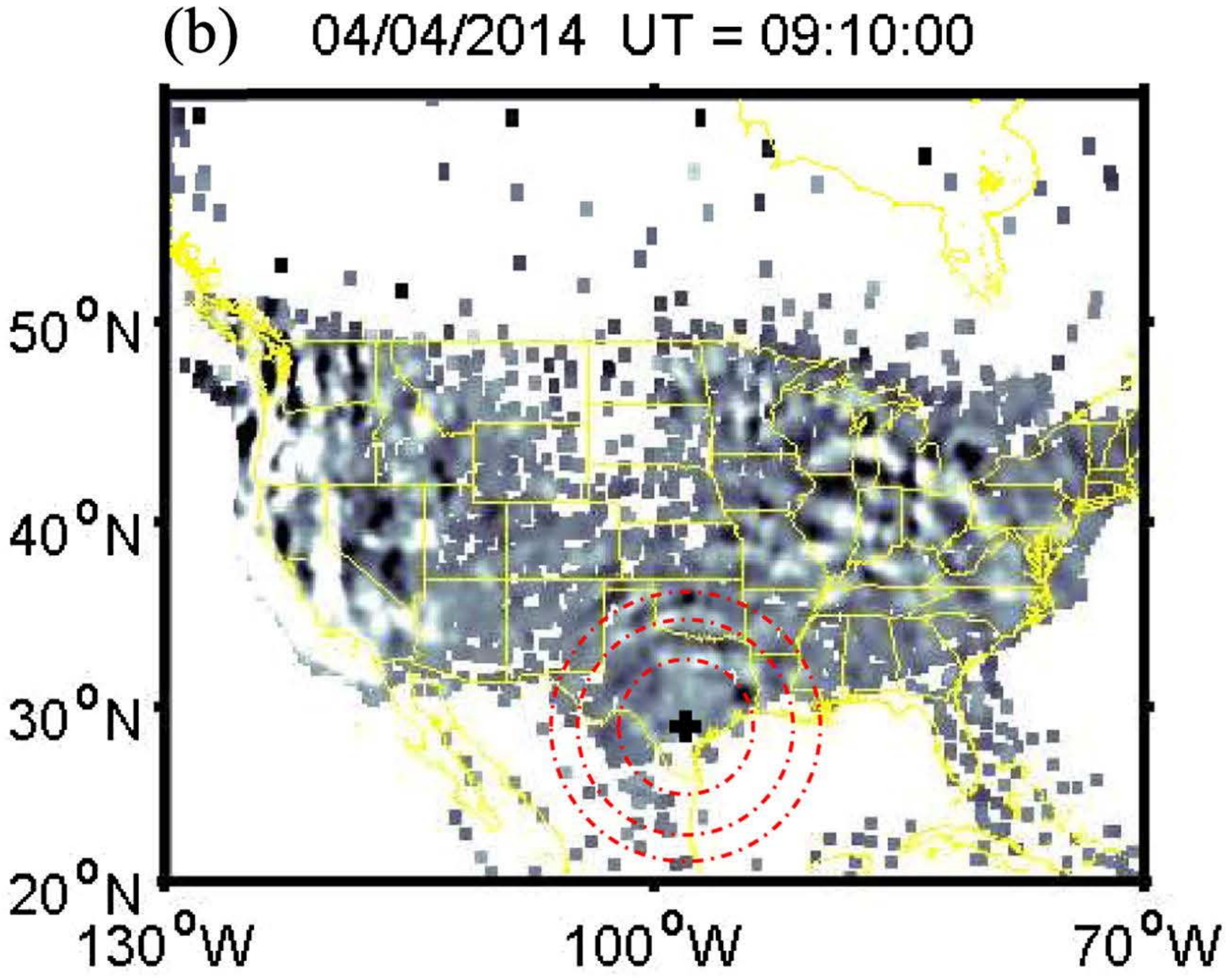
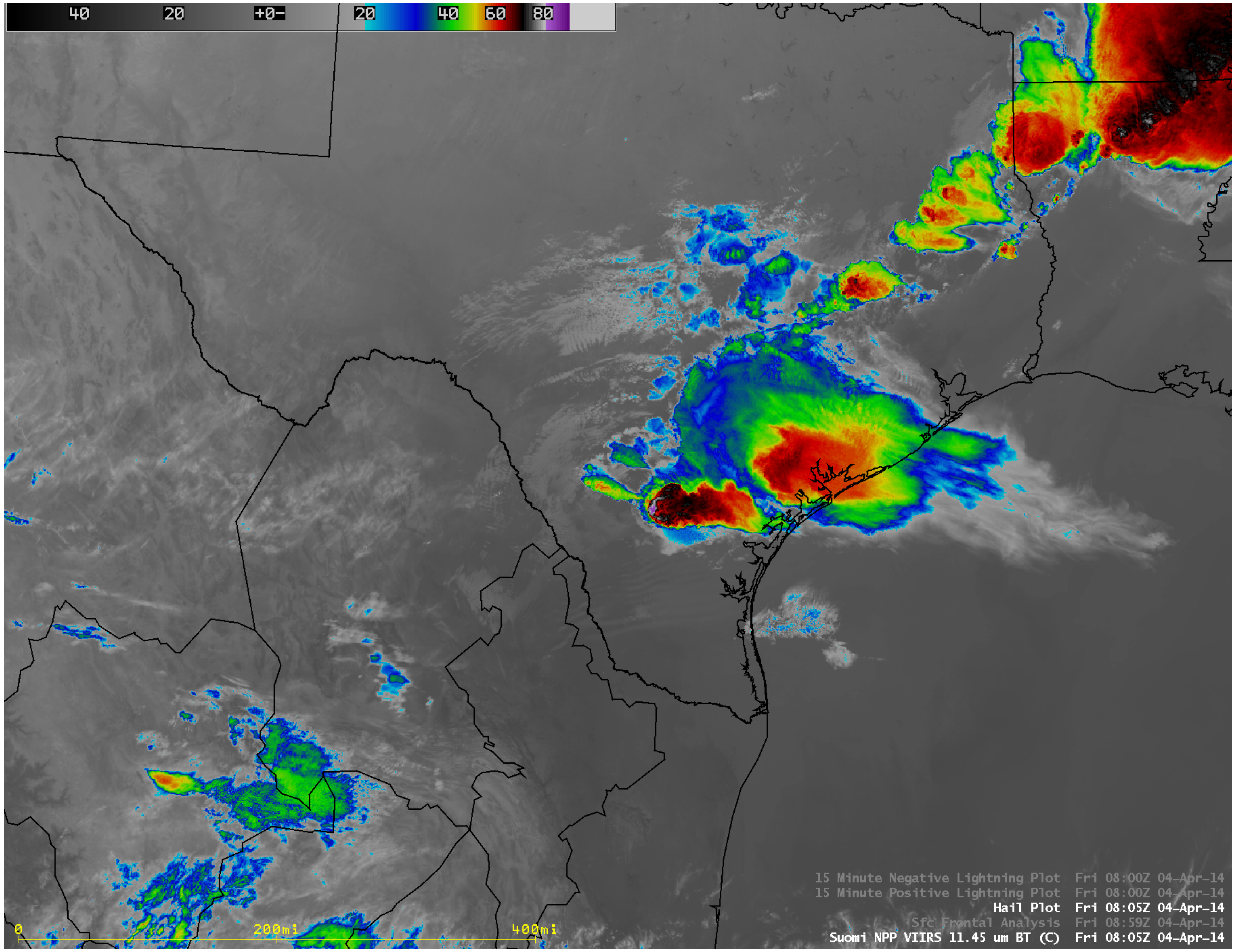


https://doi.org/10.1016/j.asr.2017.09.029

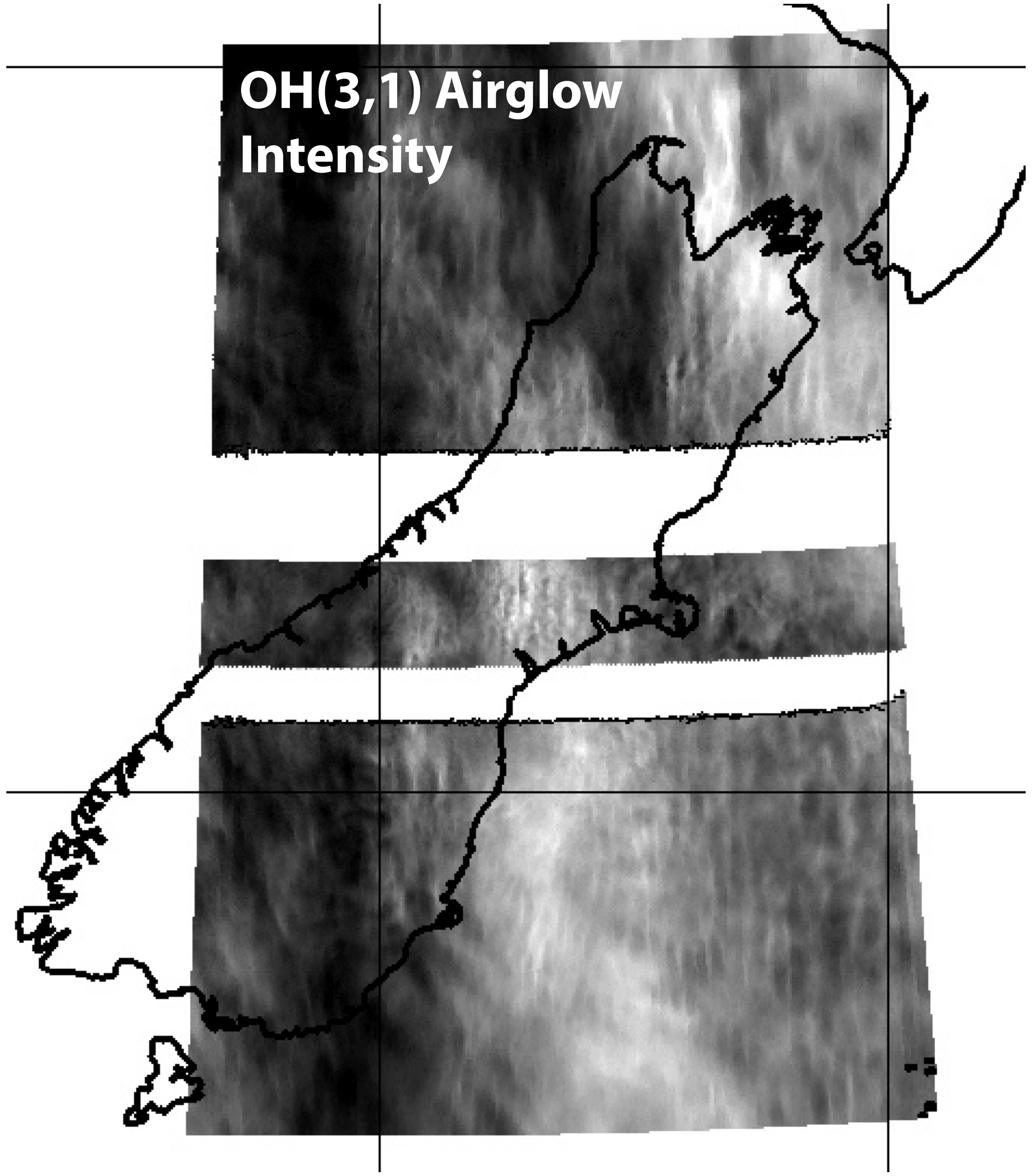
https://doi.org/10.1073/pnas.1508084112



15 Minute Negative Lightning Plot Fri 08:00Z 04-Apr-14
15 Minute Positive Lightning Plot Fri 08:00Z 04-Apr-14
Hail Plot Fri 08:05Z 04-Apr-14
Sfc Frontal Analysis Fri 08:59Z 04-Apr-14
Suomi NPP VIIRS 11.45 um BT (C) Fri 08:05Z 04-Apr-14

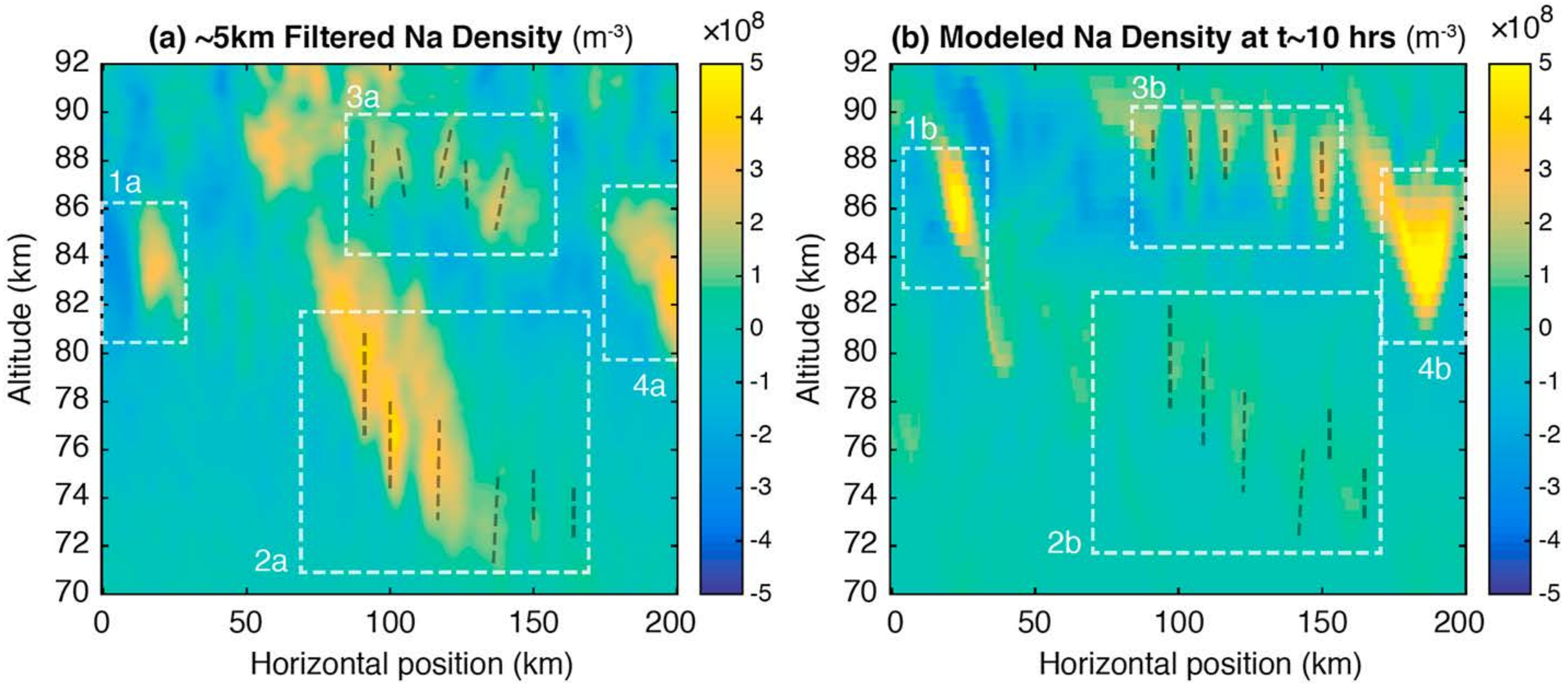
Example: Multi-Instrument, Multi-Layer Datasets and Modeling

Observations and simulations of waves from **2014 NSF DEEPWAVE Campaign**: λ_x=240 km stationary mountain gravity wave, *embedded* λ_x=20-30 km “waves” / modes…

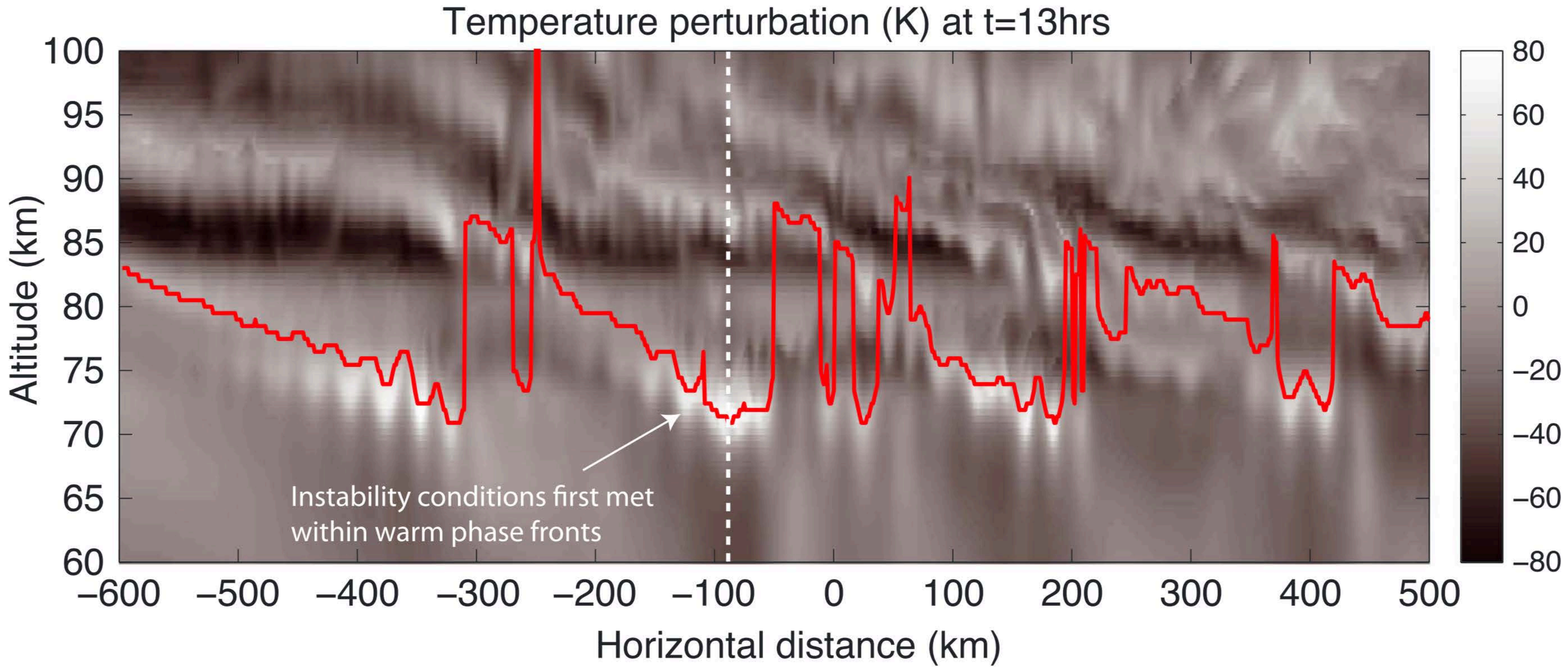


(Courtesy of P-D. Pautet and M. J. Taylor; DEEPWAVE Campaign RF22 Flight.)

Sodium Lidar Profiling, plus MAGIC Simulation



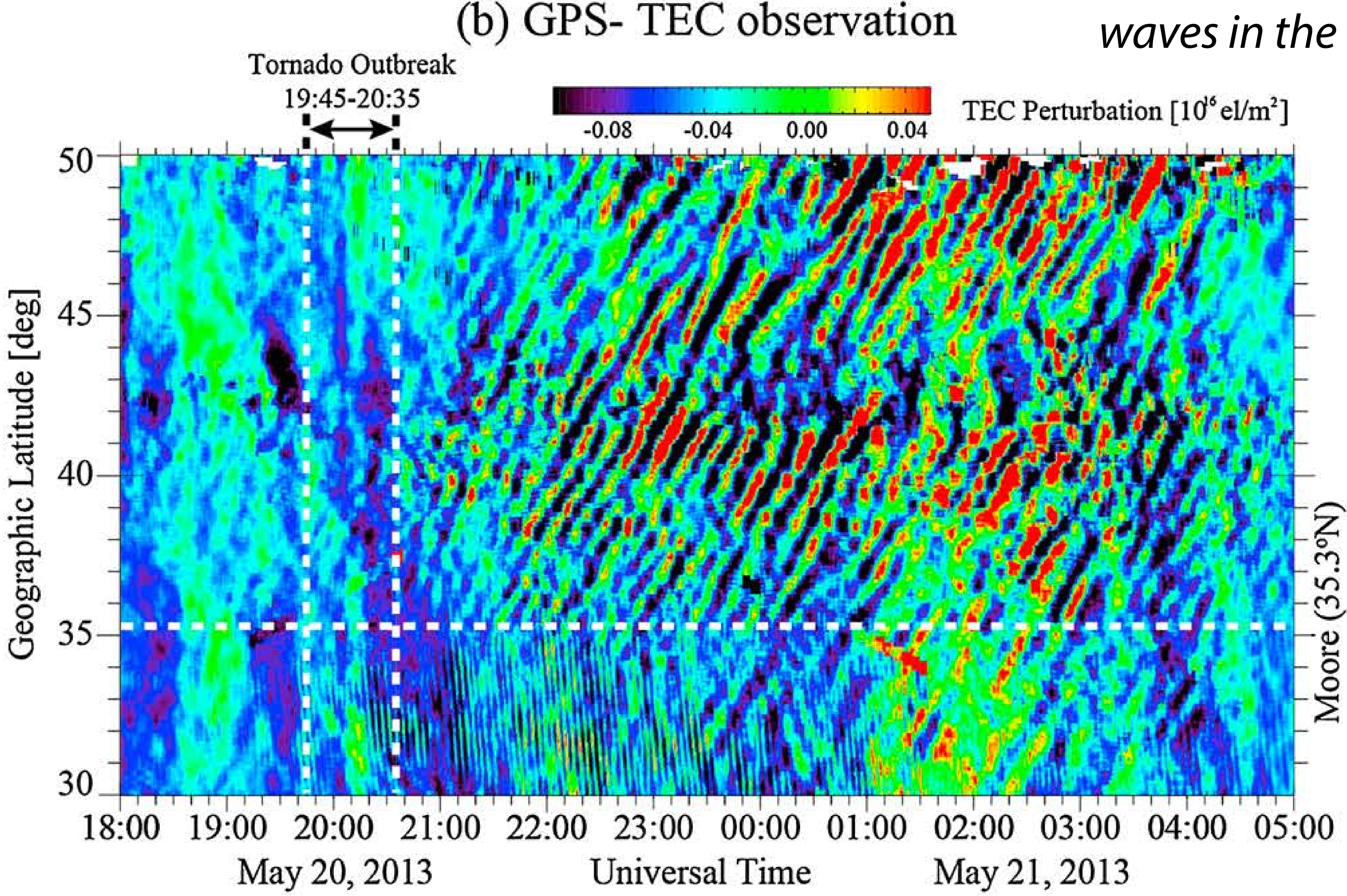
(*Bossert et al.* 2017; **http://dx.doi.org/10.1002/2016JD026079**)



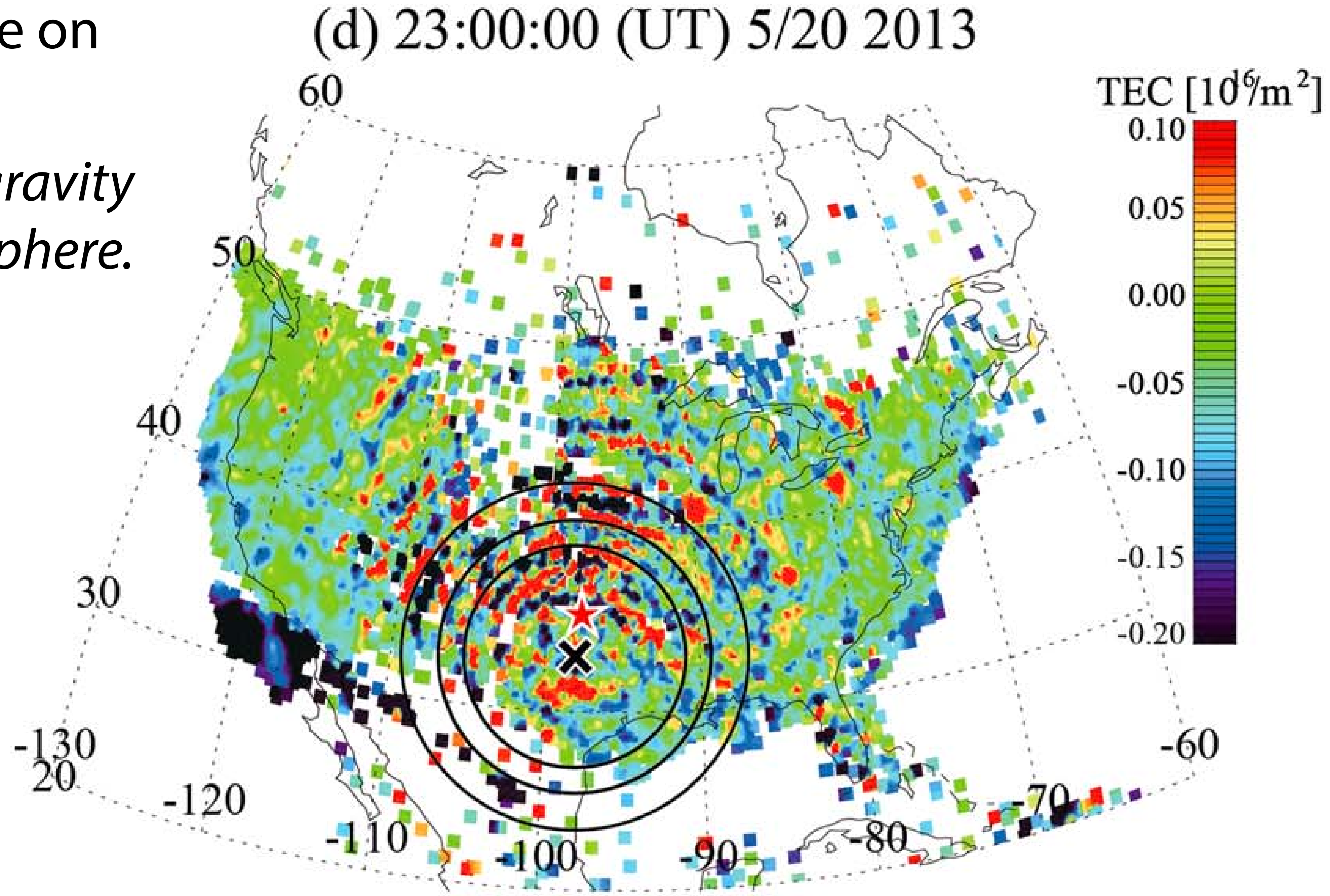
(*Heale et al.* 2017; **http://dx.doi.org/10.1002/2016JD025700**)

Example: Ionospheric Datasets Revealing AGW Fluctuations

Nishioka et al., (2013) report of Moore, OK Storm and EF5 Tornado, revealing the coupling of transiently generated acoustic-gravity waves, and pure acoustic oscillations, during severe weather. Demonstrated a 2D mapped perspective on wave fluctuations and specific dynamics.



T~13 minute period gravity waves in the ionosphere.



T~4 minute acoustic waves observed toward equator.

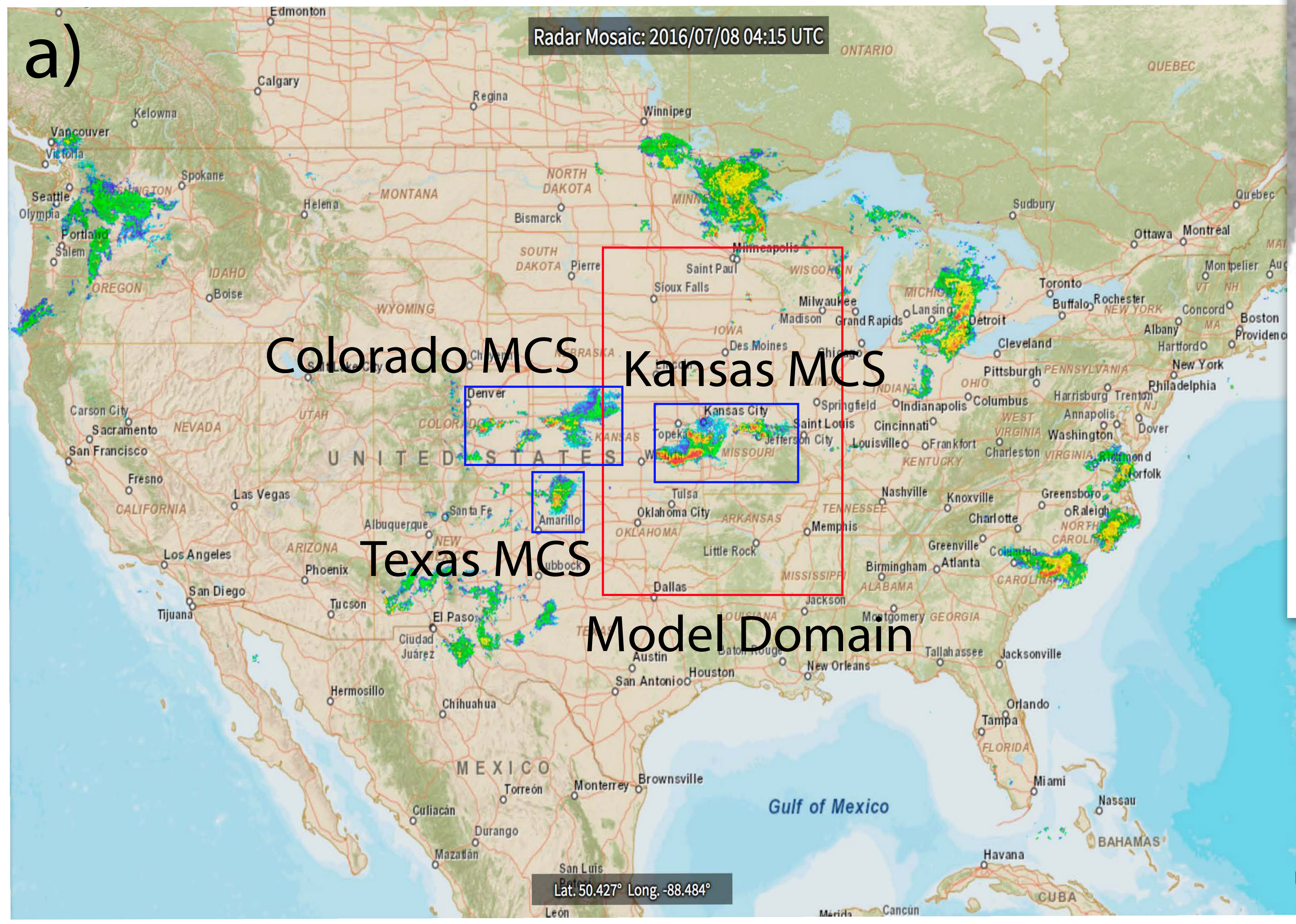
https://doi.org/10.1002/2013GL057963

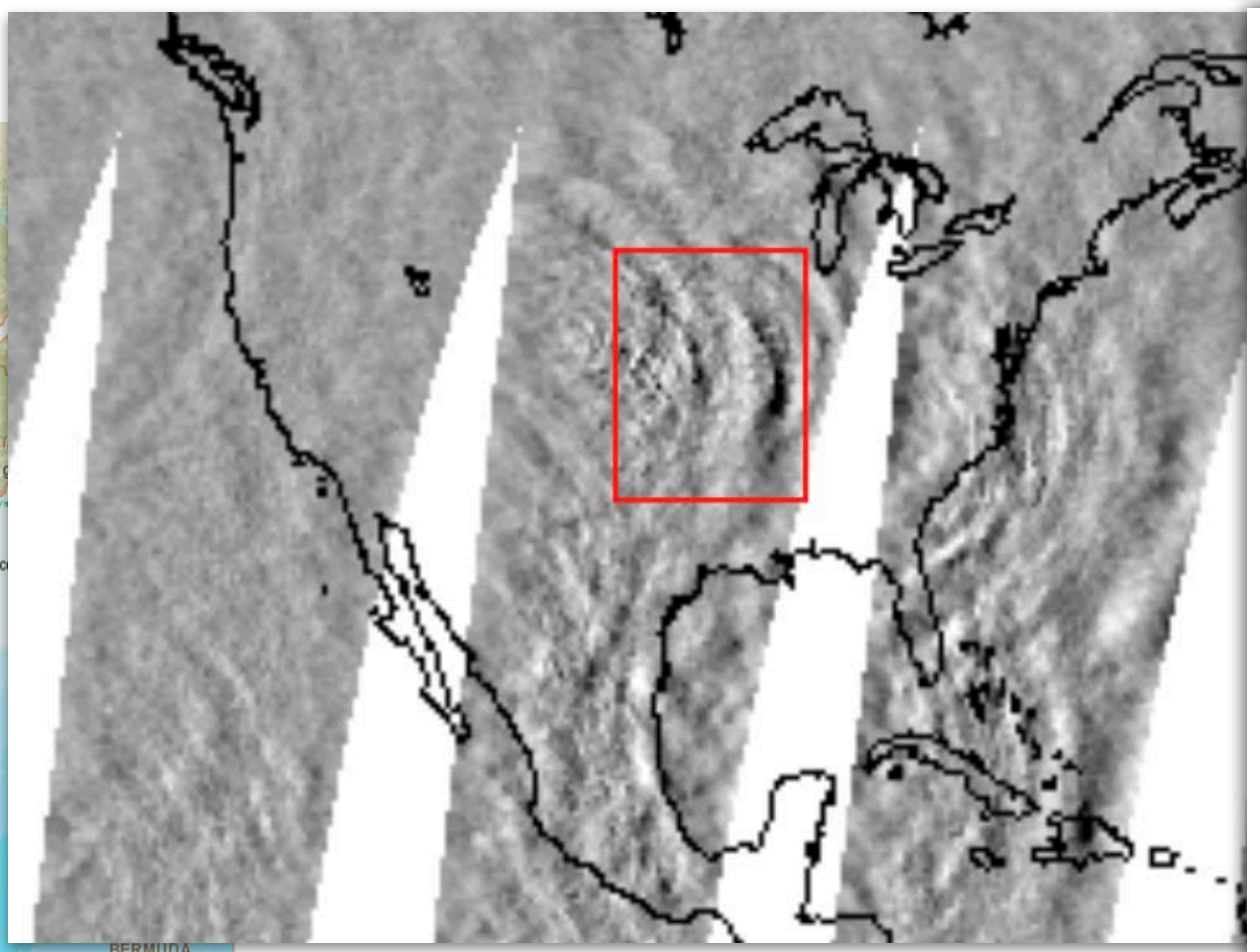
Example Case Study: Multi-Instrument, Multi-Layer Datasets and Modeling

MAGIC (and GEMINI) Convective and Mountain Acoustic-Gravity Waves,
of Detailed Mesopause-Region and Ionospheric Responses.

With coauthors ***C. J. Heale, P. A. Inchin, A. Bhatt, and M. D. Zettergren*** *…*

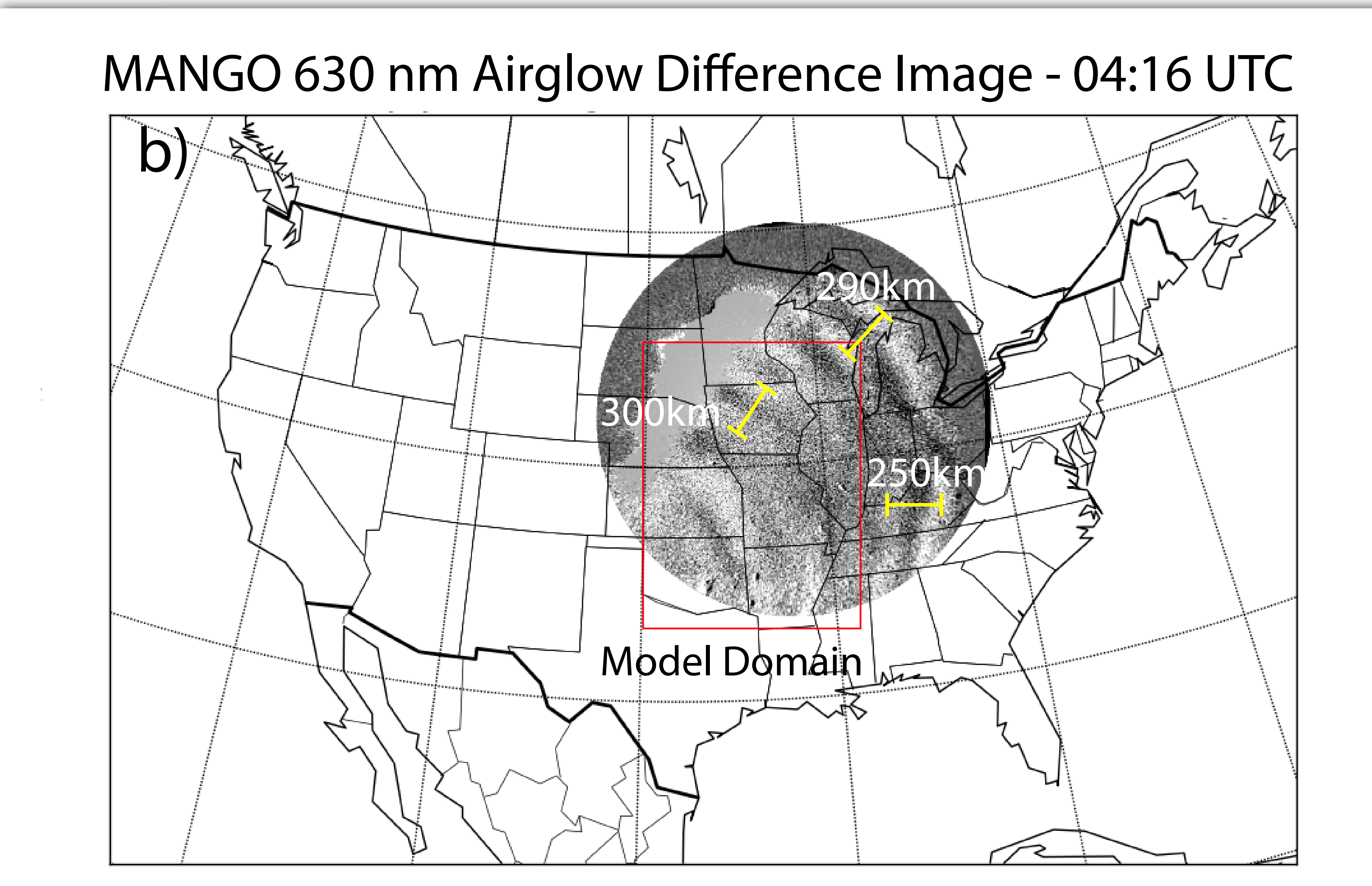
NEXRAD Reflectivity Map (dBz) - 04:15 UTC





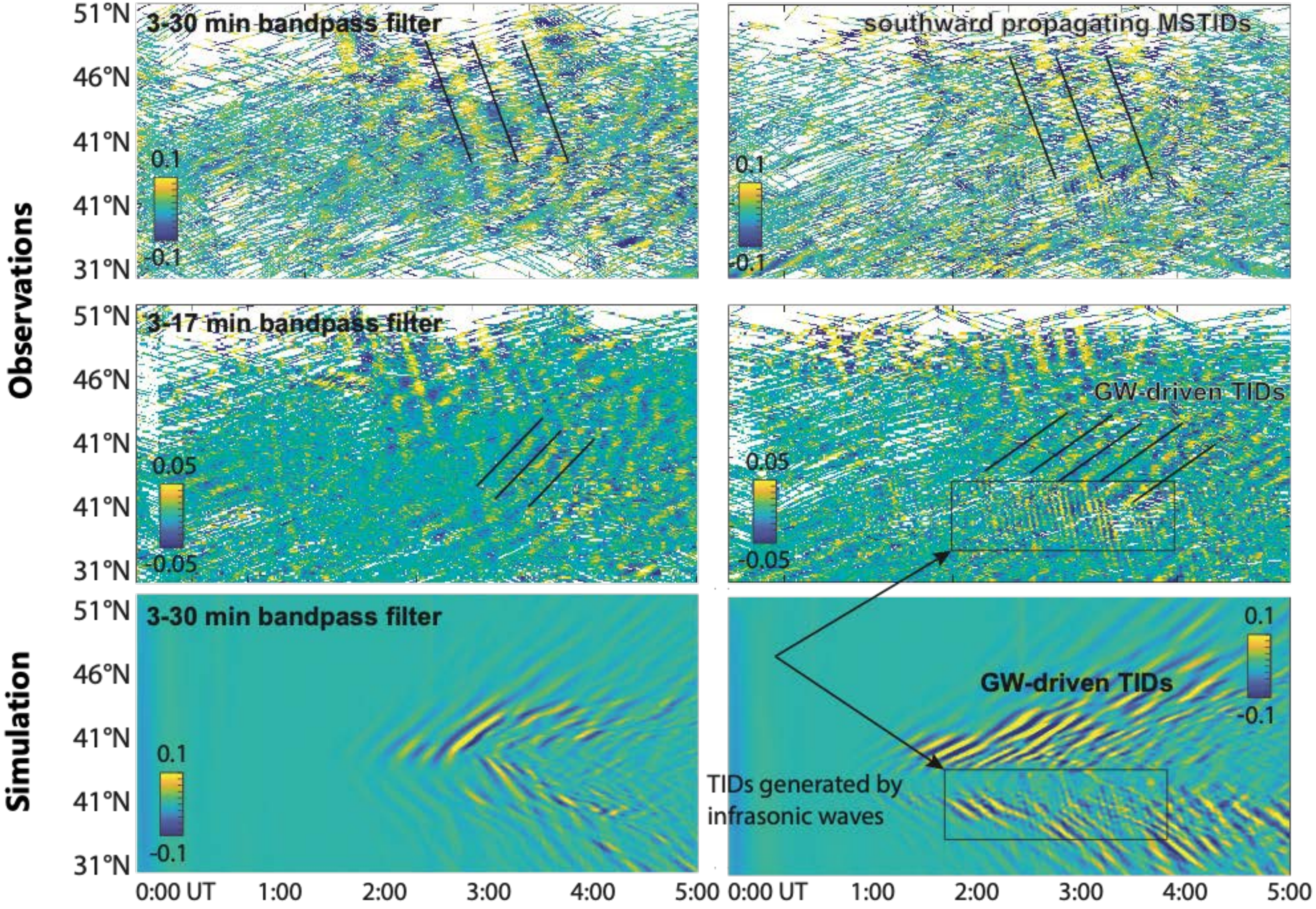
AIRS Stratospheric CO_2 Brightness Temperature.

MANGO 630 nm Airglow Difference Image - 04:16 UTC

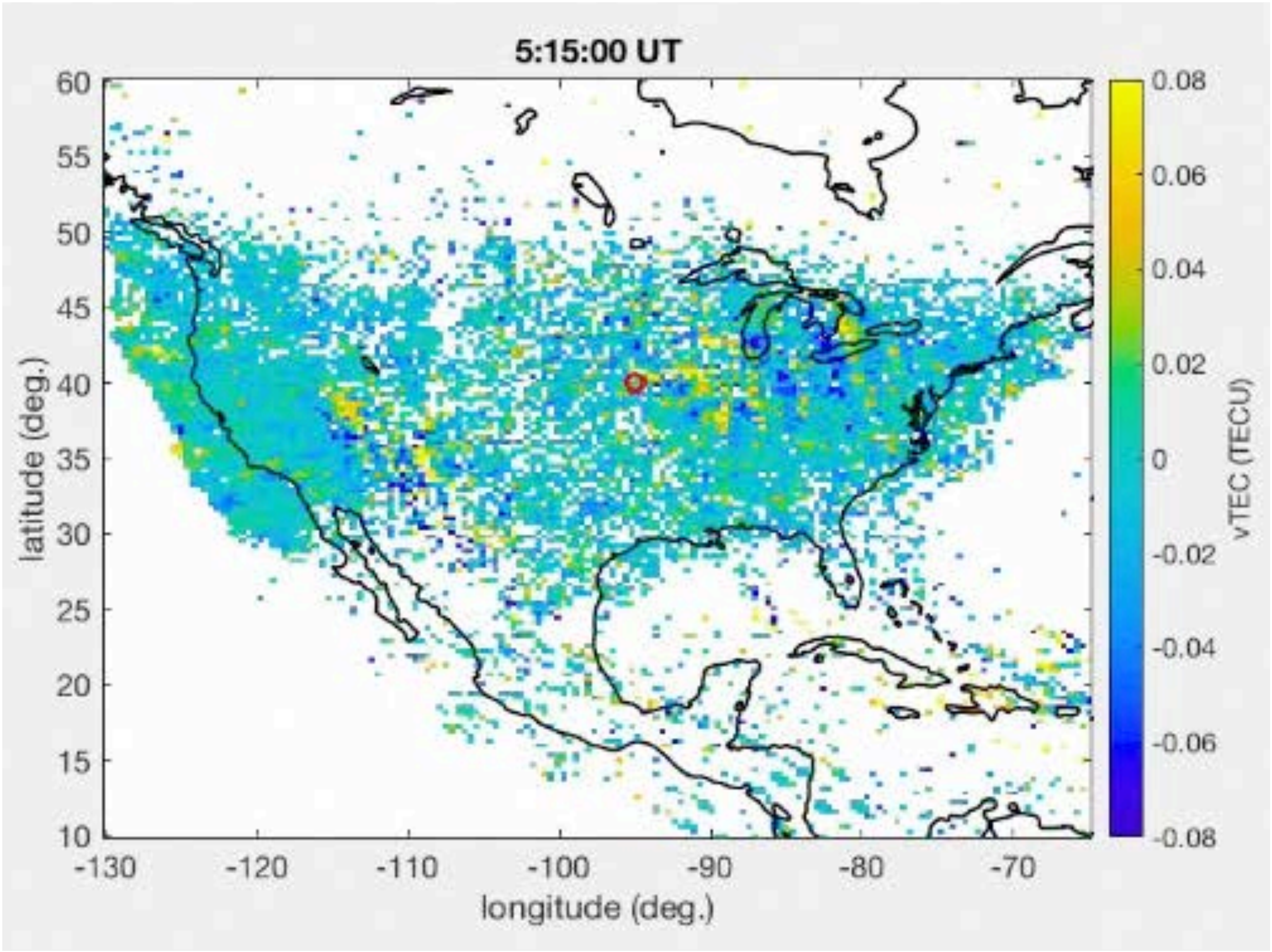


Based on an expanded, high-resolution, investigation of the event reported by *Heale et al.* (2019), https://doi.org/10.1029/2019GL085934

2016 "Iowa" (Midwestern) Thunderstorm: *Assessing GNSS TEC signals of Acoustics*



Map of gridded 30-min low-pass filtered vTEC



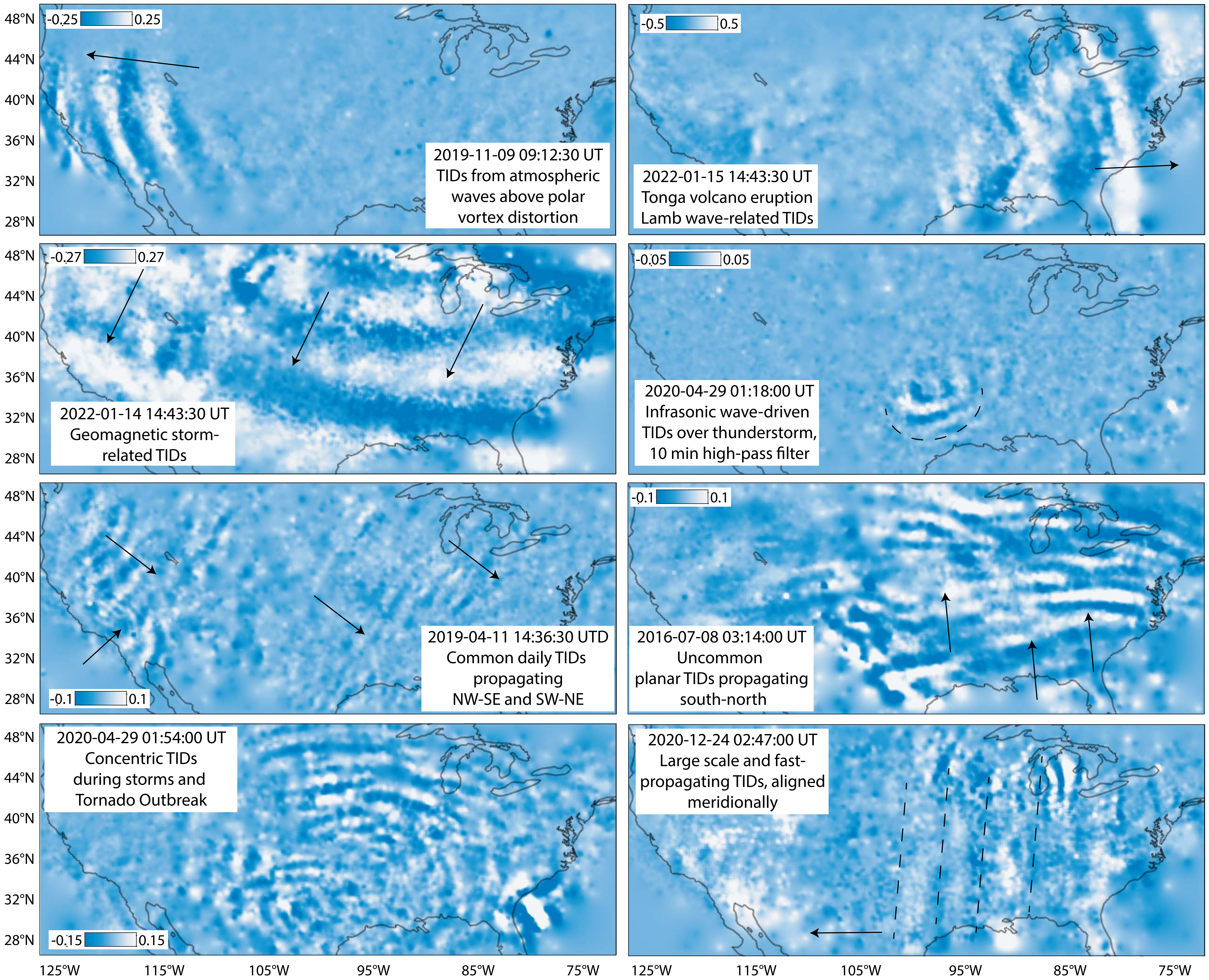
vTEC perturbations generated by AGWs from thunderstorm 90° and 95° longitude.

Example: Ionospheric Datasets Revealing AGW Fluctuations

Examples selected from the ERAU database of processed GNSS TEC data by *Inchin et al*. Daily processing includes >2700 receivers of GPS signals (>80000 Tx-Rx signals) in automatic routines on local computers and HPC, with options for multi-GNSS and high-rate processing for high resolution of AGW-TIDs.

See CEDAR presentation by Inchin in today's DASI Session.

GNSS vTEC perturbations, gridded and mapped over CONUS



2019-11-09 09:12:30 UT
TIDs from atmospheric waves above polar vortex distortion

2022-01-15 14:43:30 UT
Tonga volcano eruption
Lamb wave-related TIDs

2022-01-14 14:43:30 UT
Geomagnetic storm-related TIDs

2020-04-29 01:18:00 UT
Infrasonic wave-driven TIDs over thunderstorm,
10 min high-pass filter

2019-04-11 14:36:30 UTD
Common daily TIDs propagating
NW-SE and SW-NE

2016-07-08 03:14:00 UT
Uncommon planar TIDs propagating south-north

2020-04-29 01:54:00 UT
Concentric TIDs during storms and Tornado Outbreak

2020-12-24 02:47:00 UT
Large scale and fast-propagating TIDs, aligned meridionally

Example: Space-Based UV Measurements (GUVI) of Large-Scale Traveling Atmosphere-Ionosphere Disturbances

Bossert et al., (2022) reported 2000 km wavelength large-scale fluctuations emanating from high latitudes and seen by TIMED-GUVI, during a time of "moderate geomagnetic disturbances and a major sudden stratospheric warming (SSW)"

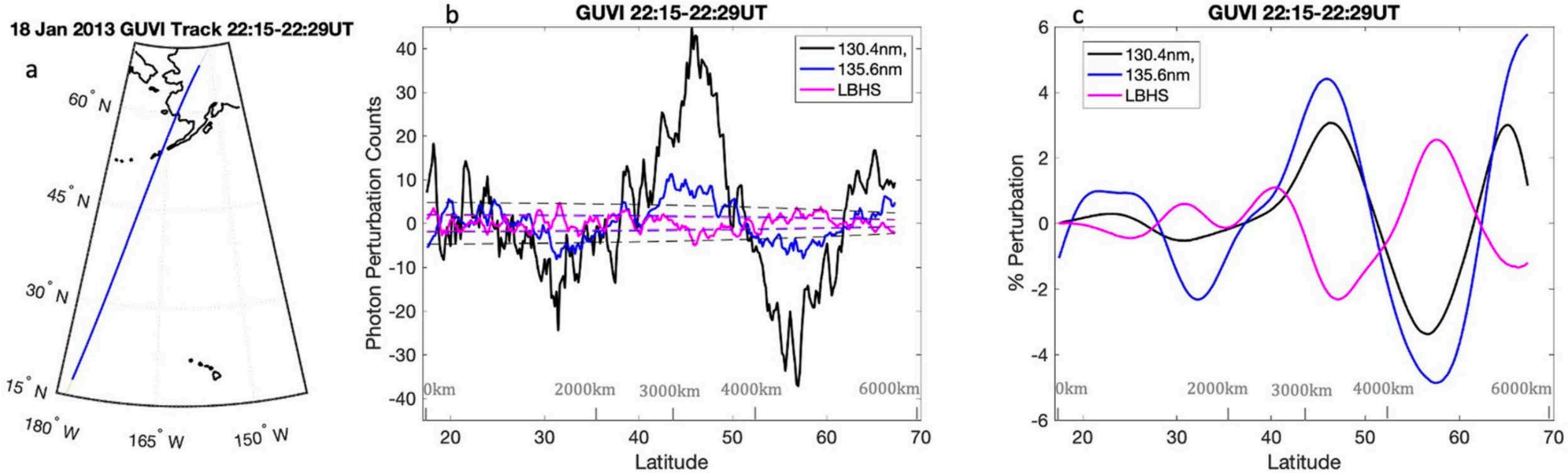


Figure 1. (a) The pierce point latitude and longitude along the Global Ultraviolet Imager (GUVI) path for emissions near 140 km. (b) The residual perturbations in photon counts after using a Savitzky–Golay filter to detrend the data (solid lines) and the noise floor determined from background photon counts (dotted lines). (c) The percent perturbation for each emission filtered for along-track wavelengths >1,600 km.

https://doi.org/10.1029/2022GL099901

Example: Untangling High Latitude GWs Associated with Neutral Dynamics

As global models reach to smaller scales, it becomes possible to investigate large-scale gravity wave evolutions in context.

Vadas et al., (2022) reported HIAMCM simulations of polar vortex generation of primary waves and evolutions to secondary waves, in contrast to adjacent mountain wave fields and effects, as seen in stratospheric and mesospheric datasets. Although the waves investigated are not likely to reach high altitudes, the results support the need to understand wave sources "from below" that are unique to high latitudes as well as at low-mid latitudes.

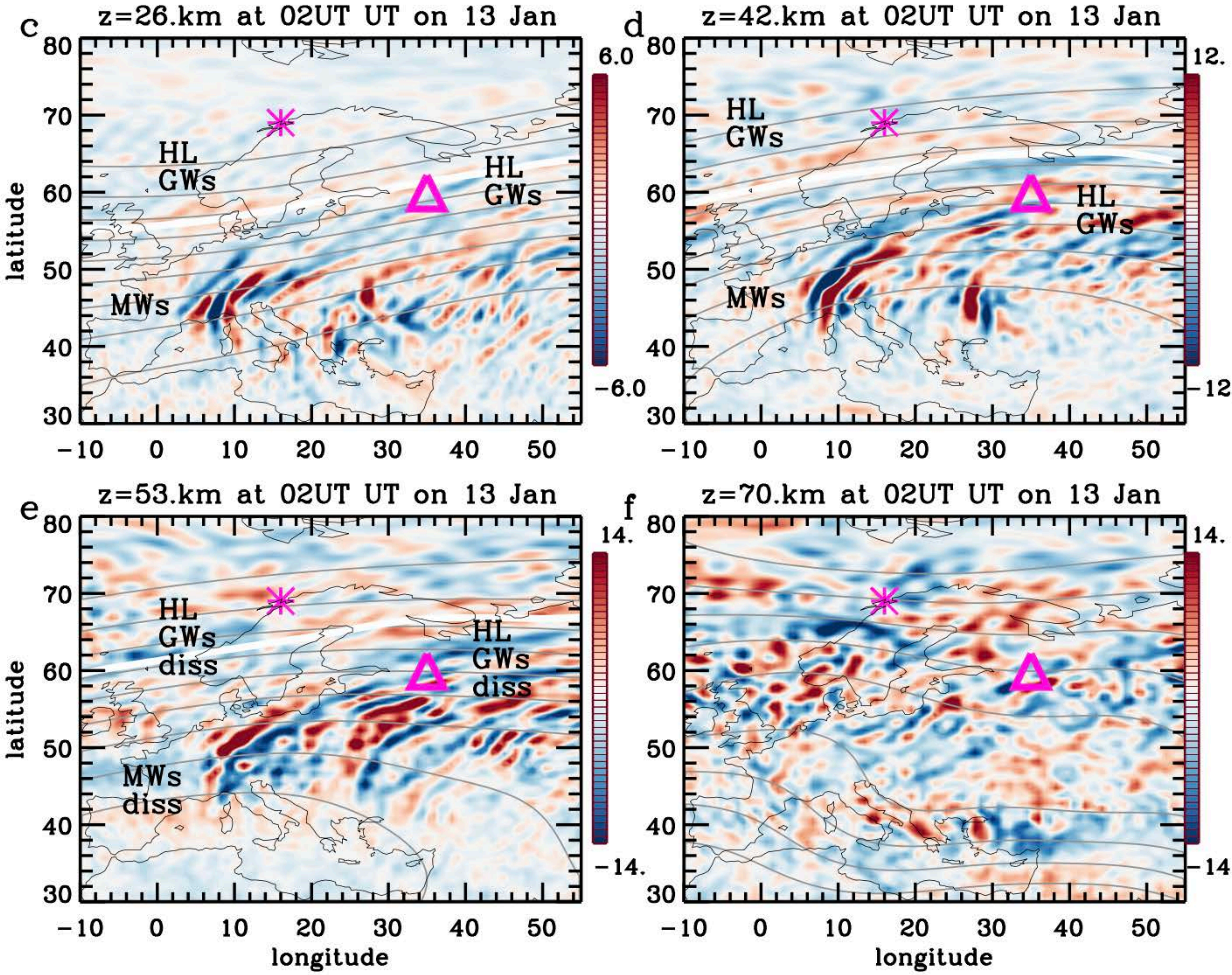


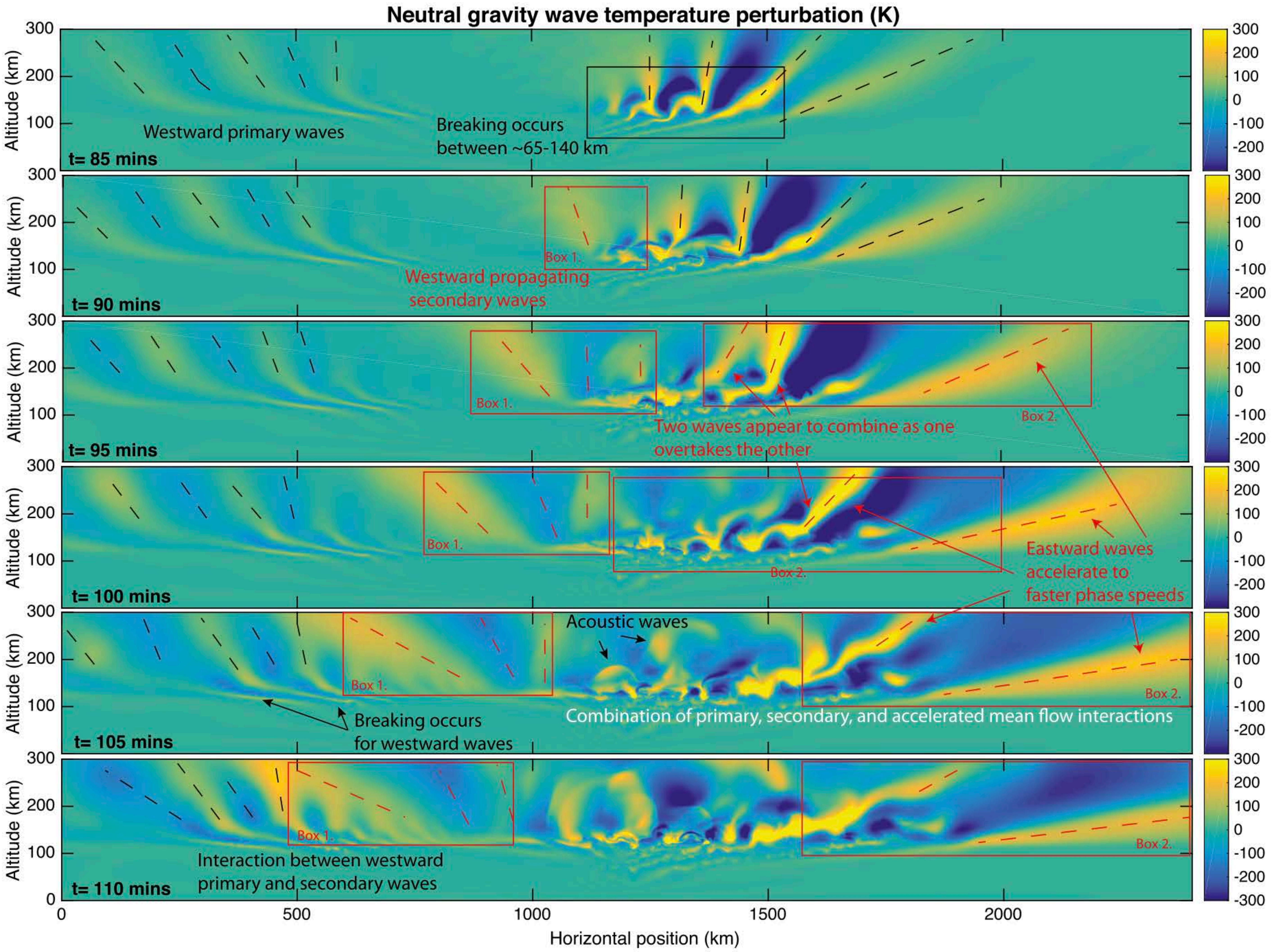
Figure 15. T' (colors, in K) and the large-scale horizontal streamfunction (gray lines) from the HIAMCM at 2 UT on 13 January 2016. (a) $z = 15$ km. (b) $z = 20$ km. (c) $z = 26$ km. (d) $z = 42$ km. (e) $z = 53$ km. (f) $z = 70$ km. The asterisks show Arctic Lidar Observatory for Middle Atmosphere Research and the triangles show the event #1 local body force at 35°E and 60°N. Labels show propagating and dissipating ("diss") mountain waves and high-latitude ("HL") gravity waves. The vortex edge is shown as white lines in (a–e).

https://doi.org/10.1029/2022JD036985

Example: Untangling Smaller-Scale Primary Wave Evolution and Secondary Generation

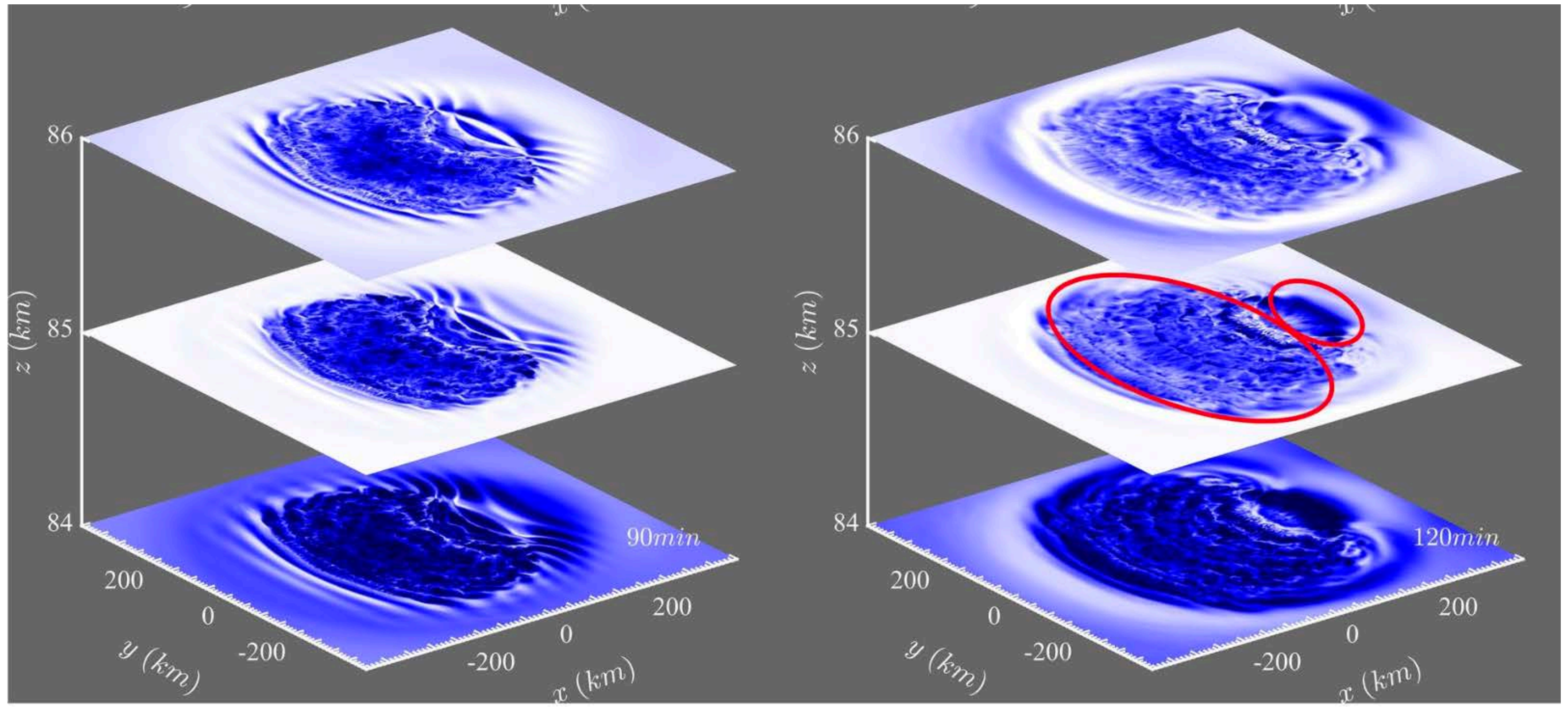
Other mechanisms require relatively high resolutions and, ultimately, full-3D treatments within realistic contexts to assess — e.g., for waves < 100s km scales.

Heale et al., (2022) reported MAGIC simulations of primary wave evolutions that lead both to nonlinear modifications to the primary wave spectrum (following self-acceleration), as well as radiation of secondary waves.



https://doi.org/10.1029/2021JA029947

Example: Self-Accelerating Primary Wave Impacts on Atmospheric Layers



Dong et al., (2021) reported CGCAM simulations of 3D primary GW self-acceleration impacts on atmospheric layers, specifically their effects on simulated polar mesospheric clouds (PMCs). The net impacts on the layers may help to quantify the effects of waves, i.e., by understanding how they facilitate "void" formation via dynamical transport.

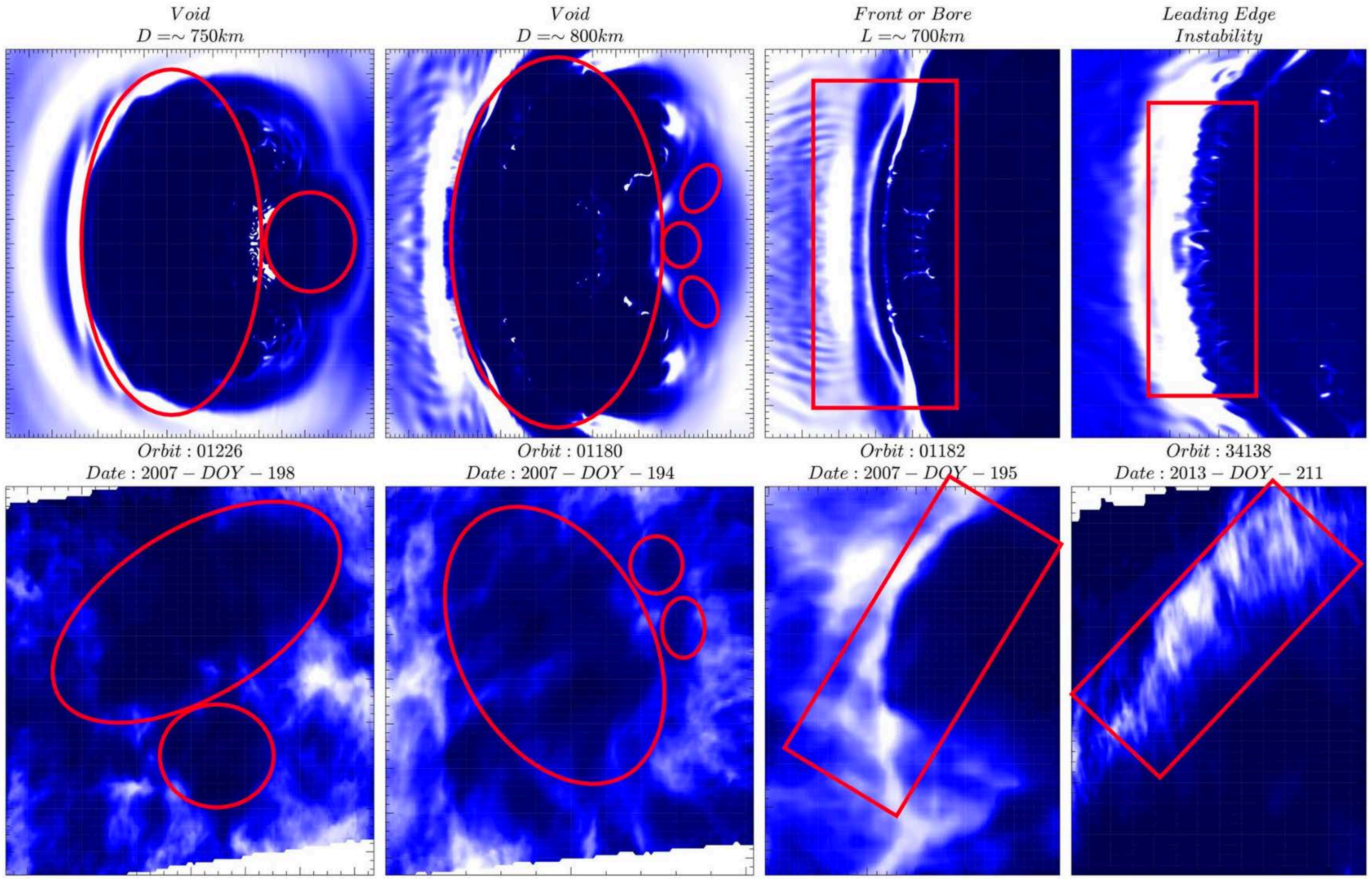
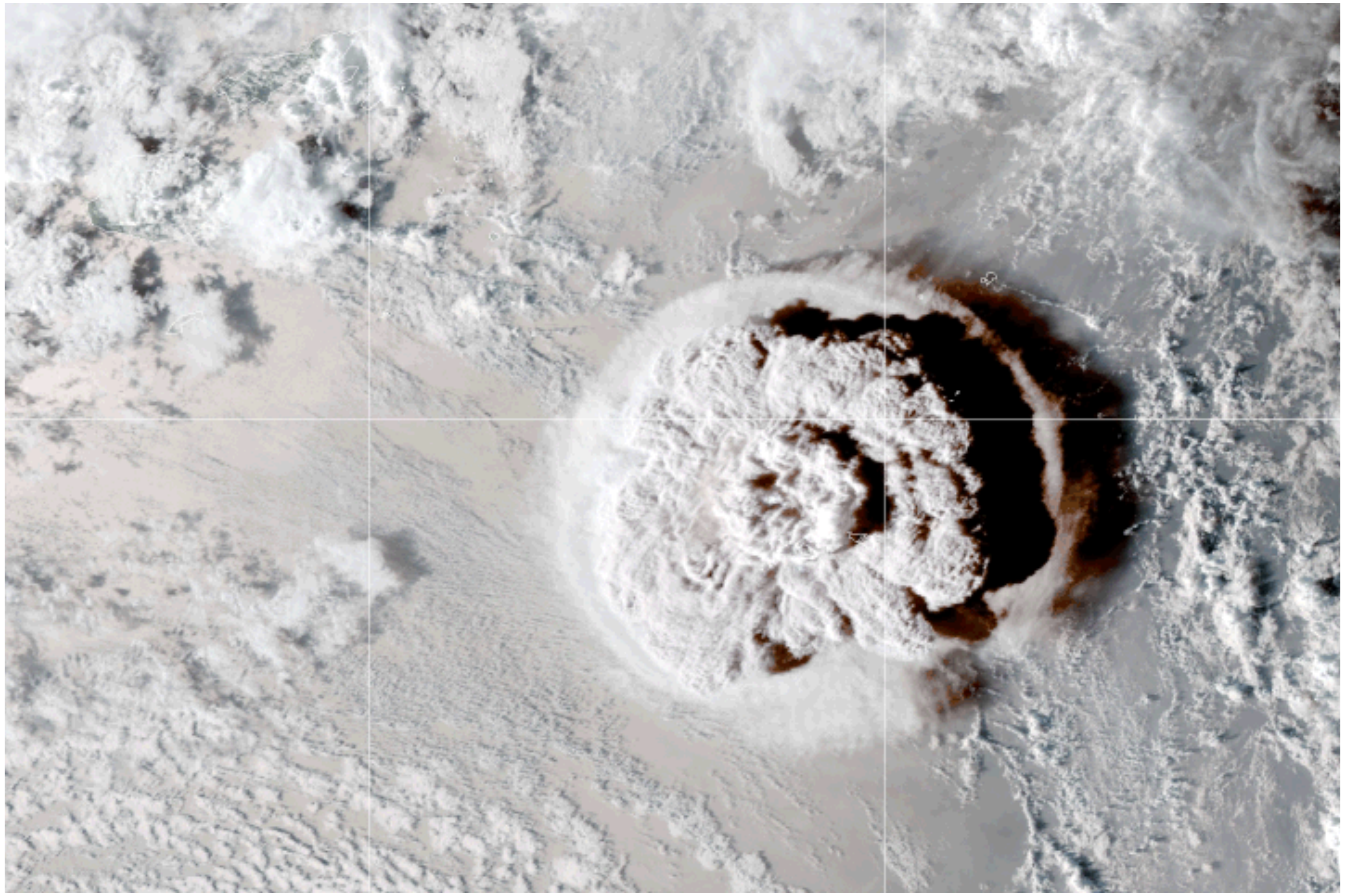


Figure 14. Modeled voids (columns 1 and 2) and leading-edge phase structures and instability dynamics (columns 3 and 4) (top, see text for details) and seen in example Cloud Imaging and Particle Size (CIPS) polar mesospheric cloud (PMC) imaging (bottom). Void diameters and front lengths are ~700–800 km. D and L denote void diameter and front length, respectively.

https://doi.org/10.1029/2021JD034643

Example: Rare Events that Raise Interdisciplinary Questions

Hunga Tonga Volcanic Eruption: Natural hazards provide science case studies for interdisciplinary science — As with Mt. St. Helens previously, the Hunga-Tonga eruption launched waves measured across the globe detected by myriad sensors.



[Animation reproduced from NASA: https://earthobservatory.nasa.gov/images/149347/hunga-tonga-hunga-haapai-erupts]

Example: Rare Events that Raise Interdisciplinary Questions

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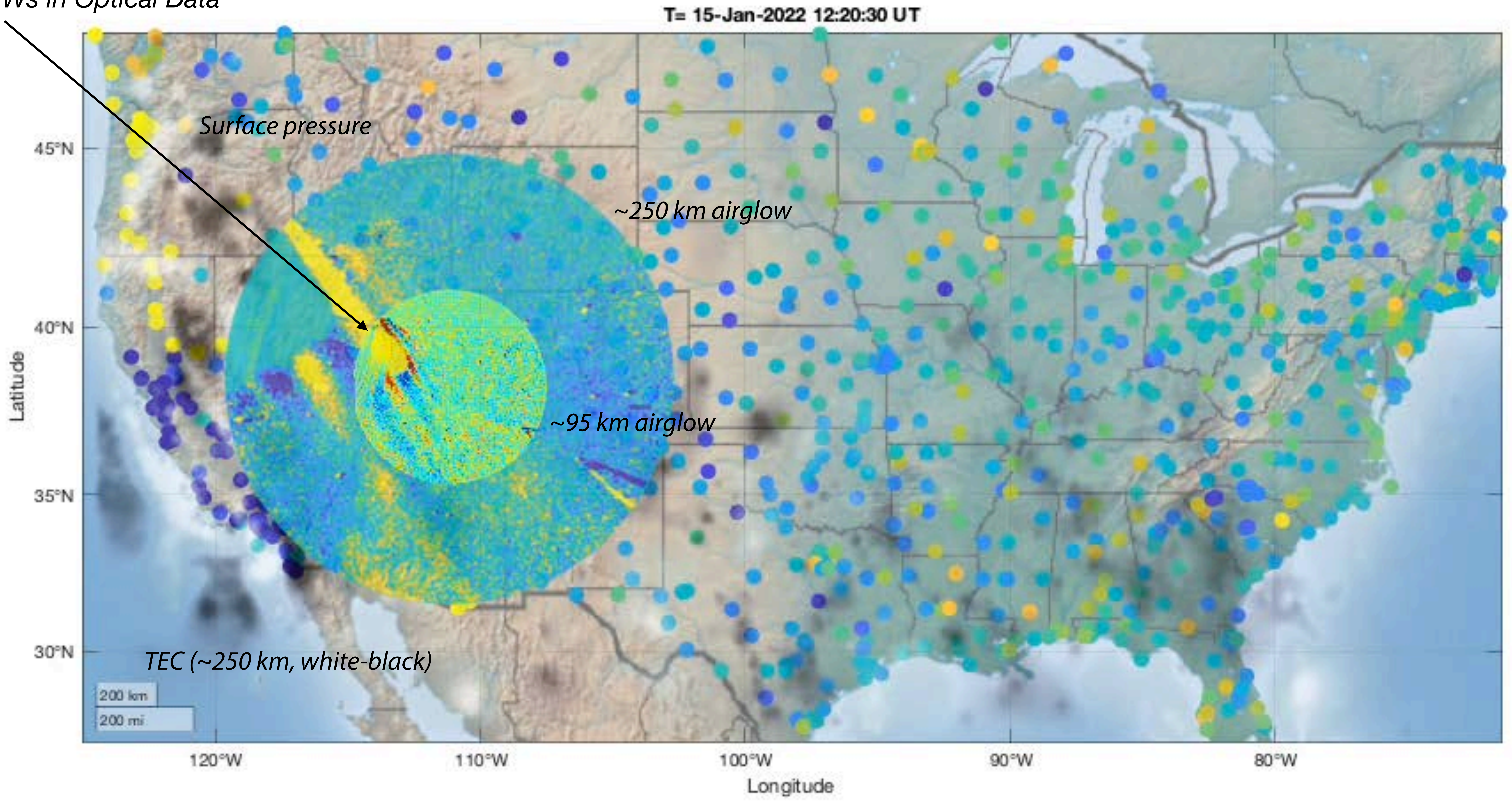
Indirect Ground-Based Detection: Observation of "faintly red" (OH band?) airglow (?) fluctuations, recorded in color nighttime imagery, with arrival times suggesting ~300+ m/s speeds following eruption.

[Animation reproduced from International Gemini Observatory/NOIRLab/NSF/AURA: https://noirlab.edu/public/videos/ann22003a/]

Tonga Analysis: CONUS Airglow, Pressure, GNSS TEC, LF Radio…

ERAU *(P. Inchin et al.)*, for GNSS TEC analysis, pressure mapping, GOES imagery,
Duke *(S. A. Cummer)*, for D-region LF, *Also: SRI (A. Bhatt)*, for MANGO airglow.

First-arriving AGWs in Optical Data



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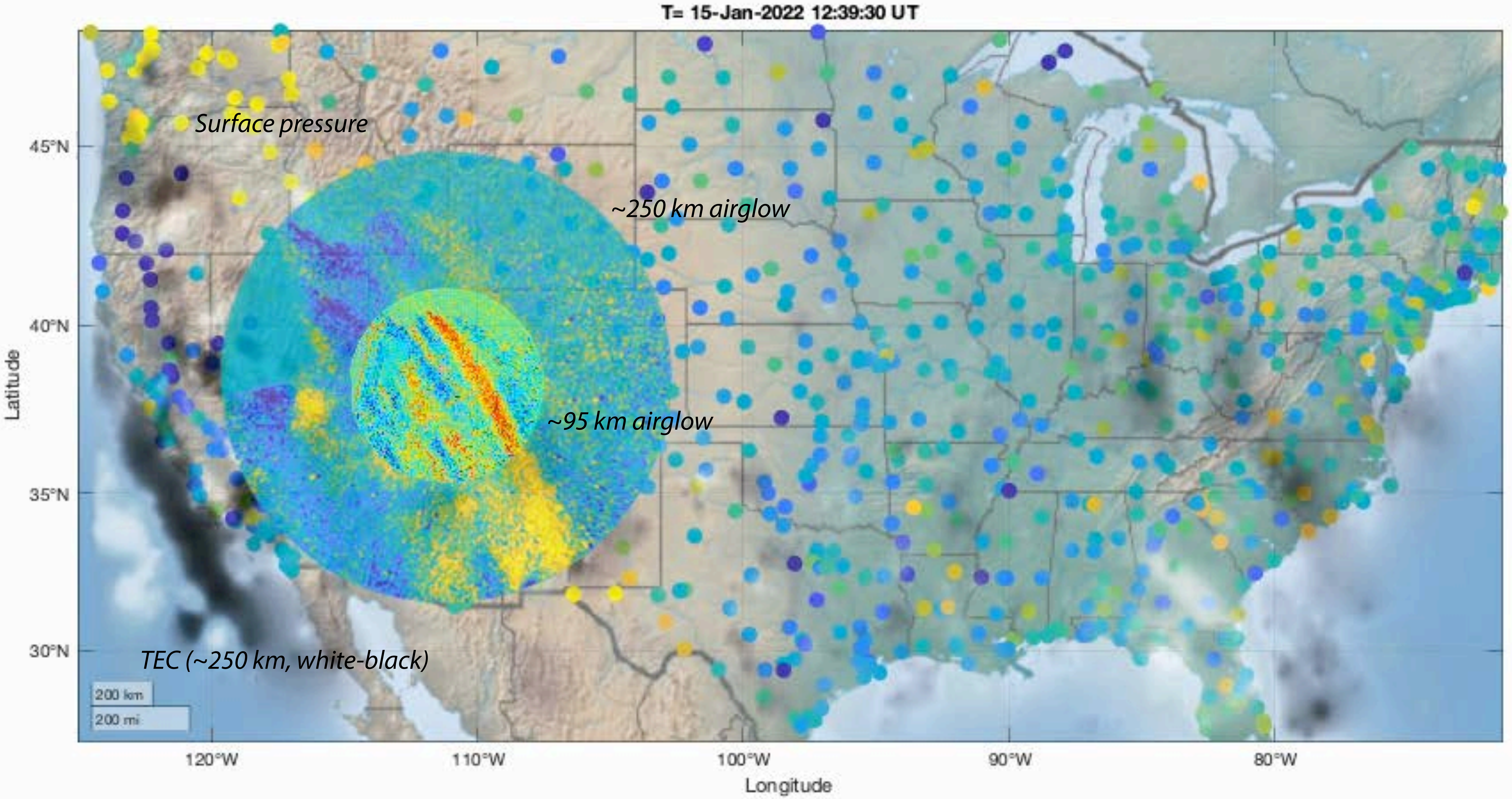

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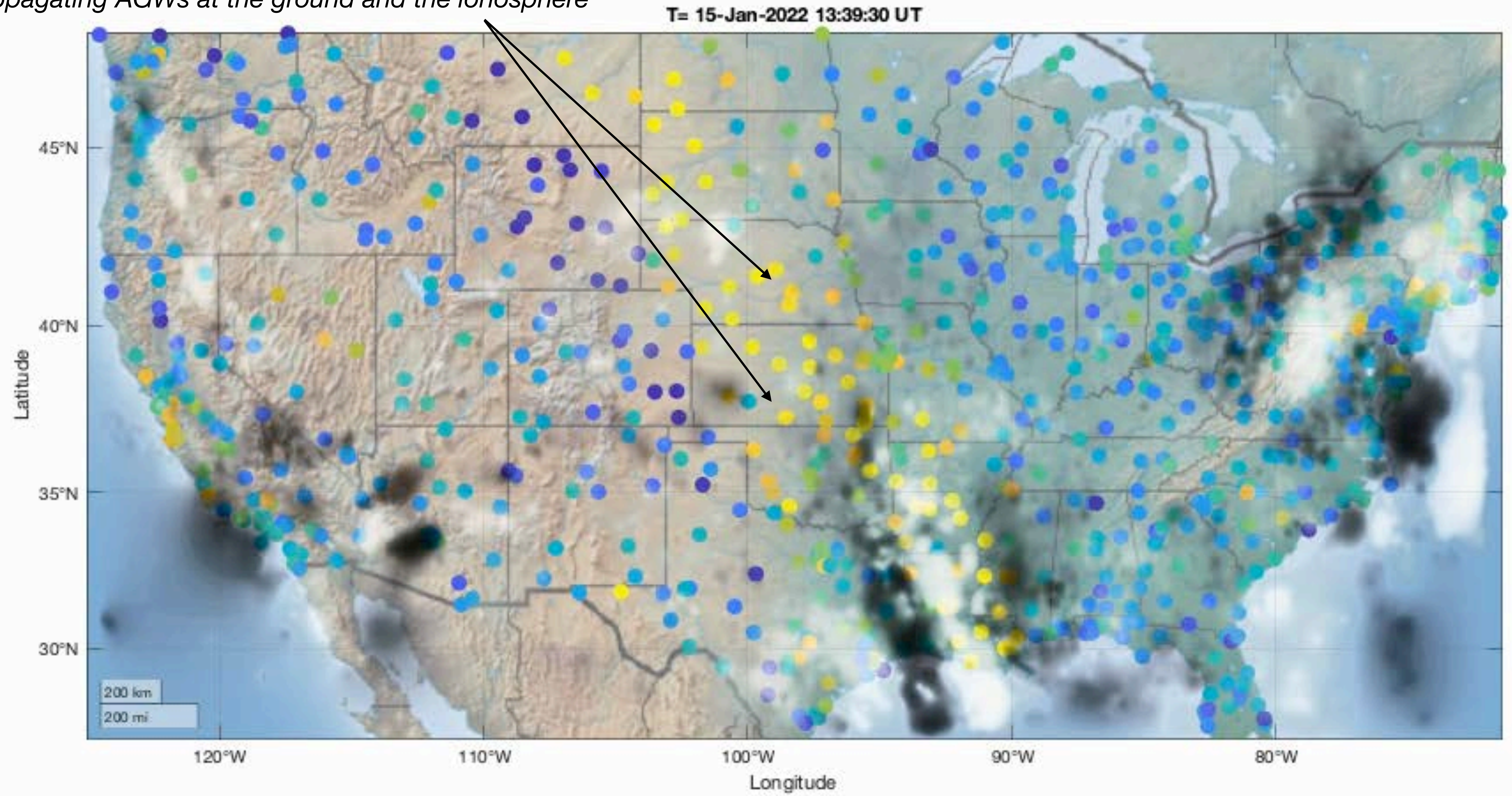
Consistently propagating AGWs at the ground and the ionosphere



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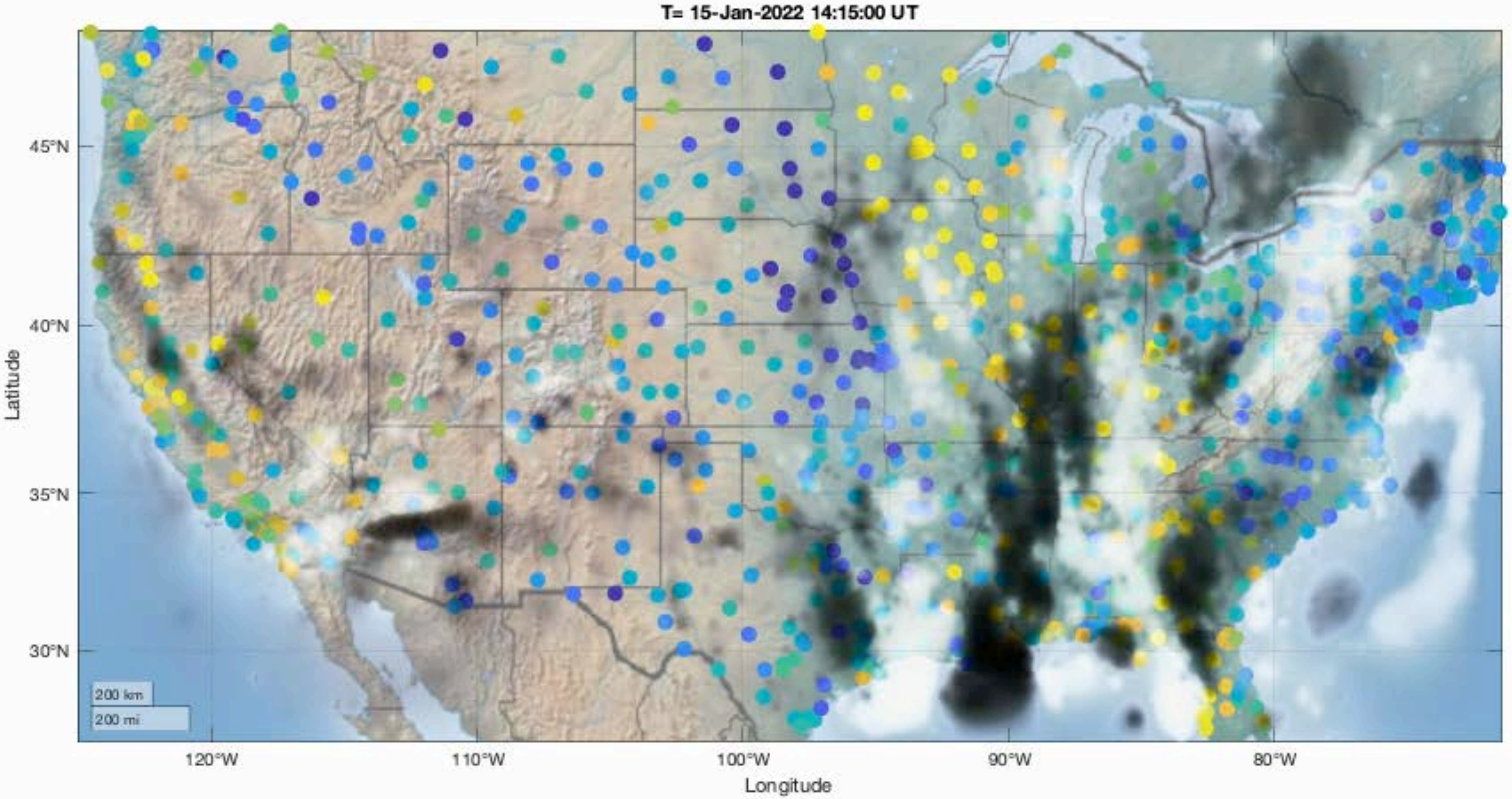
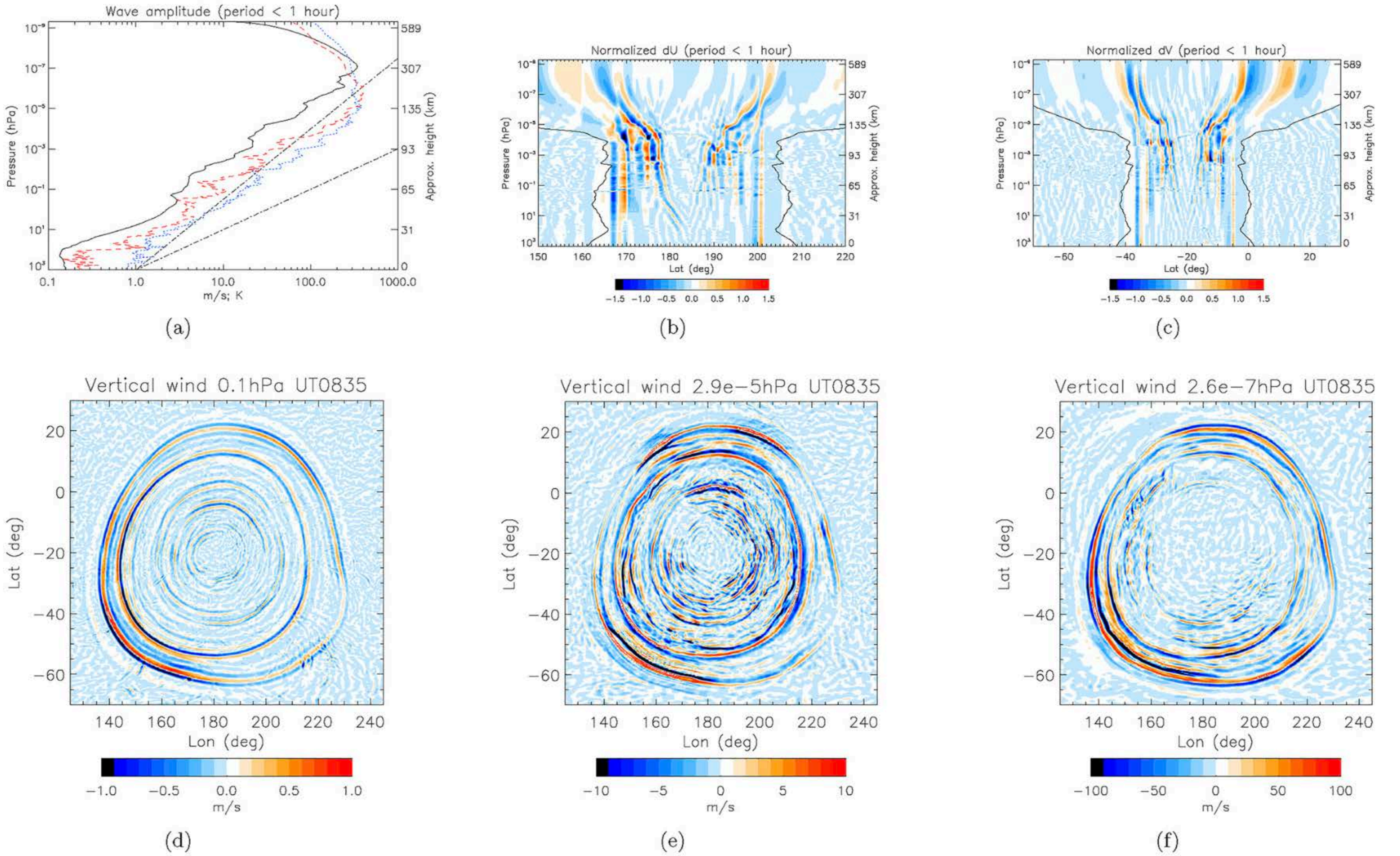


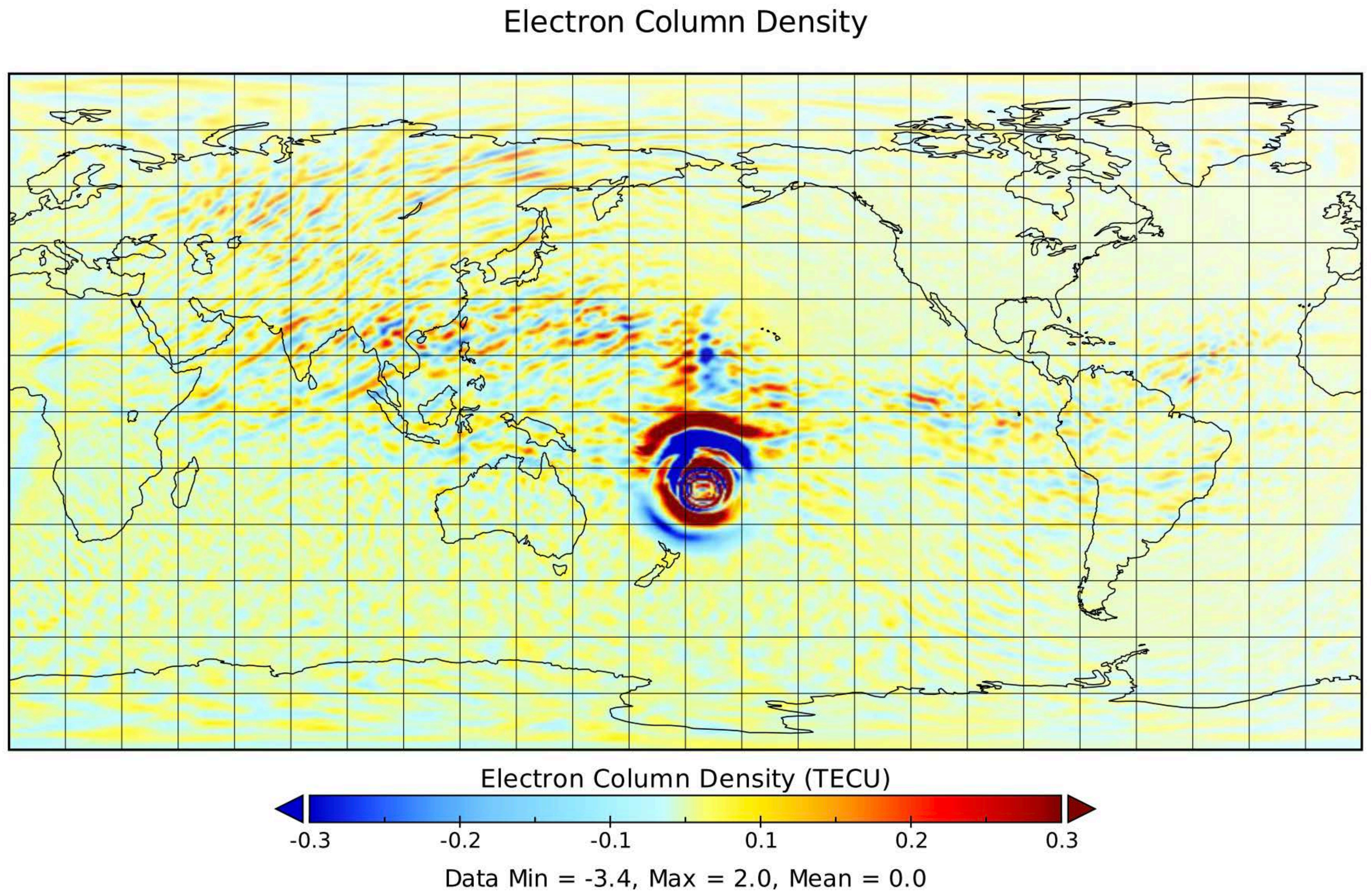
Example: Addressing the Large Scale Responses and Lamb Modes

Liu et al. (2023) demonstrated regional fluctuations and global Lamb mode propagation for long-wavelengths in WACCM-X, with coupled ionospheric responses for integrated TEC.



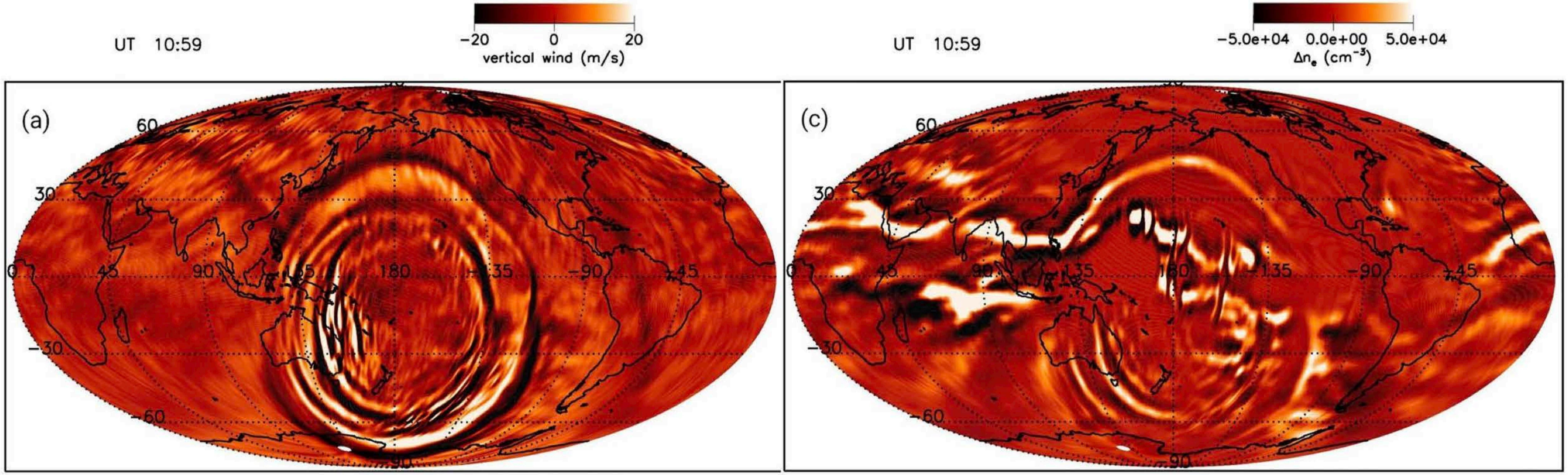
igure 2. (a) Vertical profiles of vertical wind (solid-black), zonal wind (dotted-blue), and temperature (dashed-red) amplitudes at UT 06:05 hr. The dash-dot lines ndicate the theoretical exponential growth rate for Lamb wave (upper line) and internal wave (lower line). (b, c) Zonal and meridional wind perturbations normalized by p^{κ} at 20.5°S and 175°W, respectively, at UT 06:05 hr. Vertical profiles: propagation distance from the epic center with the local acoustic speed for each altitude. (d–f) Vertical wind perturbations at 0.1, 2.9×10^{-5}, and 2.9×10^{-7} hPa at UT 08:35 hr.

https://doi.org/10.1029/2023GL103682



Example: Addressing the Secondary Waves and Ionospheric Impacts

Huba et al. (2023) demonstrated predicted secondary wave impacts (based on *Vadas et al.,* 2023), forced by the strong plume over the volcano, leading to plasma bubbles. Note that these waves are distinct from the Lamb waves reported elsewhere, and may have higher phase speeds.



https://doi.org/10.1029/2022GL101185

Past/Recent Advances in ITM-Region GW Coupling:

(Prior results in last 10 years that have advanced small-scale ITM process studies…)

1. **Radio/GNSS Measurements of AGW-TIDs —** E.g., *Nishioka et al.*, 2013; *Azeem et al.*, 2015; and others have highlighted the utility of GNSS TEC for AGWs.
2. **Campaign, Mission, and Networked Instrument Investigations —** E.g., DEEPWAVE, PMC Turbo (*Fritts et al.*), towards understanding large-amplitude GW evolutions; fortuitous space-based airglow imagery (Suomi's DNB, with by *S. D. Miller*, *J. Yue* et al.).
3. **Models that capture more physics and that can be more-easily used with or by others** — Model interoperability and higher resolutions enable continued progress.
4. **Model *and* Data Achievements of High Resolutions and Coverage —** Models and datasets are taking steps towards capturing the necessary spectrum and span/duration of events. *Instrument networks are denser, individual sensors are better and lower-cost.*
5. **Identification in Inter/Multi-disciplinary Value of Data —** e.g., for earth sciences and natural hazards diagnostics.
6. **Numerous detailed modeling & data investigations** — leveraging all of the above.

Grand Challenges (Identified in Session Proposal):

Year 1

1. **The Roles of Gravity Waves (GWs) in IT coupling:** How do various scales of GWs couple into and change the ionosphere and thermosphere's large scale neutral background?
2. **Specifics of GW Dynamics:** What are the effects of GW dissipation/deposition of energy and momentum in the upper atmosphere? What are their global distributions and seasonal variations? What are the effects of tide and planetary waves on gravity wave propagations?

Year 2

1. **The Roles of GWs in IT coupling:** How do various scales of GWs couple into and change the ionosphere and thermosphere's regional state and variable evolutions?
2. **Specifics of GW dynamics:** What is the best / most-efficient operational mode for existing local instrument clusters to address the small-scale waves effects/contributions in the GCMs?

Year 3

1. **The Roles of GWs in IT coupling:** What are the relationships between GWs and TIDs/TADs? What portion (spectrum) of the TID is induced by GWs coming from lower altitude?
2. **Specifics of GW dynamics:** How do GWs evolve from below to define the ITM wave spectrum? What are the relative roles of primary, secondary and tertiary waves and their effects on the ITM?

Grand Challenges: *Seeking Themes Clearly Identified by Participants*

Year 1, Monday
(13:30–15:30)

1. *Erich Becker*: Global scale GW simulations
2. *Sharon Vadas*: Secondary and tertiary GW simulation in thermosphere
3. *Cesar Valladares*: Studies of TIDs and GWs using TEC and GOCE data
4. *Matthew Zettergren*: IT modeling: Modeling Ionospheric Effects of TIDs Driven by AGWs
5. *Lynn Harvey*: CIPS observations of GW activity at the edge of the polar vortices and coupling to the ionosphere
6. *Jintai Li*: First Simultaneous Observation of Secondary and Tertiary GWs by lidar and investigation with HIAMCM simulation
7. *Jorge L. Chau and Miguel Urco*: Exploring MLT mesoscale dynamics with physics-informed Machine Learning approaches
8. *Nathaniel Frissell*: Multi-instrument Observations and Modeling of MSTIDs, LSTID, and Stratospheric Polar Vortex: 2018-19 Case Study and 2010-2022 Climatology

Grand Challenges: *Seeking Themes Clearly Identified by Participants*

Year 1, Tuesday
(10:00–12:00)

1. *Jeffrey Forbes:* AWE Mission Science (20-min+5 min Q&A)
2. *Hanli Liu:* WACCM GW simulations (15-min+3 min Q&A)
3. *Jonathan Makela:* Thermosphere GWs observation MANGO network. (15-min+3 min Q&A)
4. *Dominique Pautet:* Coincident neutral atmosphere and D-region gravity wave observations
5. *Fan Yang:* Statistical signatures of shear-induced KHI and their radiated GWs: insights from Numerical simulations
6. *Wenjun Dong:* A transformer-based maching learning method of simulating GW generation, propagation, breaking and secondary GW generation
7. Open Discussion

Identifying Session Themes? *(Not unique to our session — please see others, too! … and help to define!)*

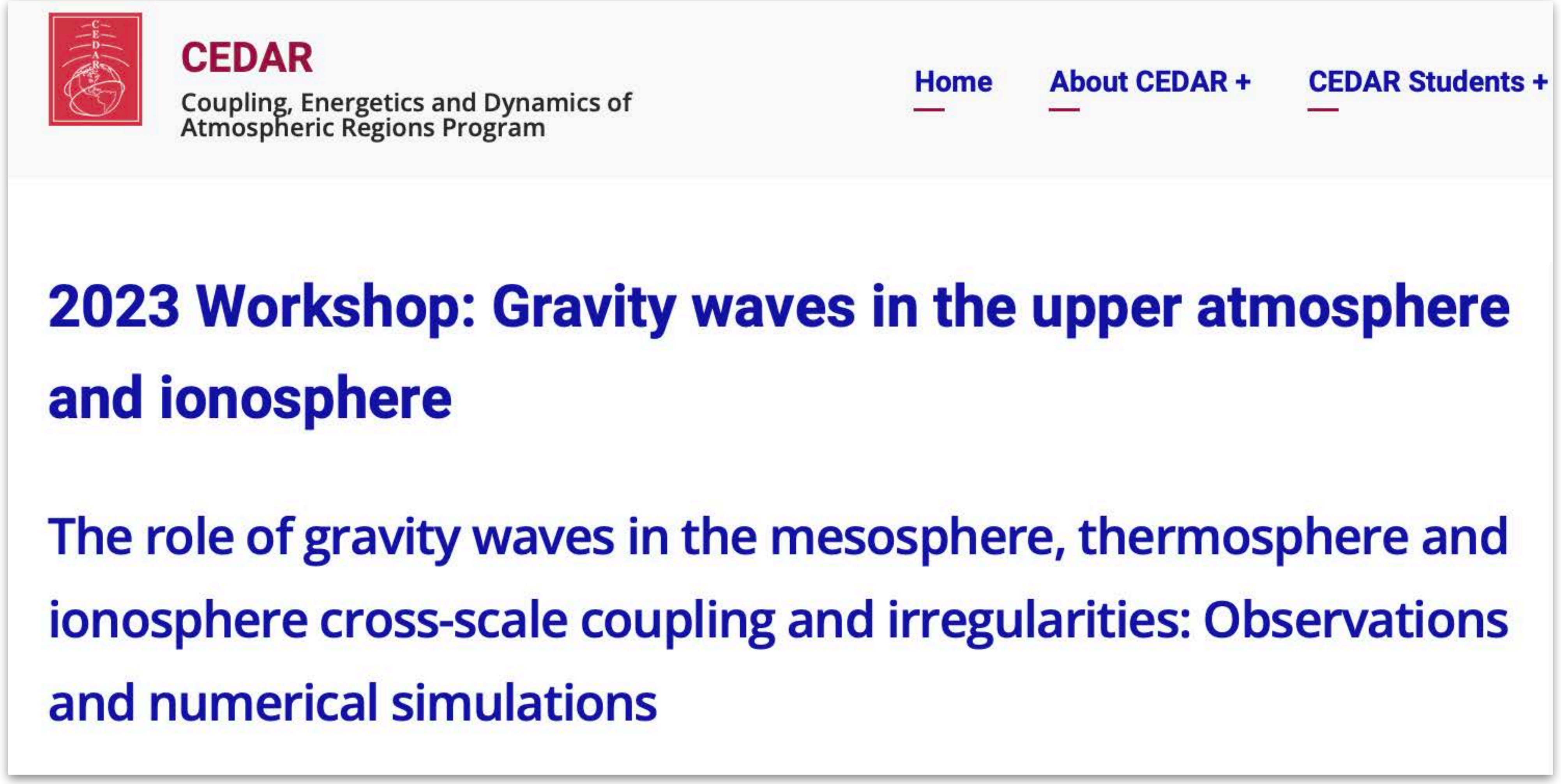
1. **Global-scale models (GC and NWP) that are beginning to resolve GWs** — HIAMCM, WACCM / SIMA here, (and others').
2. **Scalable models for AGW/TID ITM coupling** — Improvements to MAGIC+GEMINI.
3. **Simulations that enable comparisons with data on a specific basis** — i.e., high-fidelity scenario reconstructions vs. trends or means.
4. **Machine Learning applications** to accelerate models and analyses of ITM processes.
5. **Understanding evolutions of GWs** —primary, secondary, and tertiary wave evolutions; instability processes (KH) and nonlinear dissipation; as observed and simulated.
6. **High-latitude evolutions** of the atmospheric polar vortex and wave generation (and in contrast to high-latitude auroral / magnetospheric inputs of waves).
7. **Optical measurements** (from space and from ground) of the ITM — AWE (pending), MANGO, ICON, and other optical and Lidar instruments.
8. **Radio remote sensing** from GNSS (for TEC) and other Tx signals (D-, E-, F-regions).
9. **Alternative measurements of ITM dynamics** — magnetometers, accelerometers.

Please Attend to Discuss and Further-Define Session Themes, Challenges, and Opportunities!

Workshop Purpose:

To identify, discuss, and address gaps and challenges in ITM GWs that require a coordinated approach, and to share progress, results, and timely successes in our science community.

https://cedarscience.org/workshop/2023-workshop-gravity-waves-upper-atmosphere-and-ionosphere



2023 Workshop: Gravity waves in the upper atmosphere and ionosphere

The role of gravity waves in the mesosphere, thermosphere and ionosphere cross-scale coupling and irregularities: Observations and numerical simulations