Ionospheric Disturbances Generated by the 2015 Calbuco Eruption: Comparison of GITM-R Simulations with GNSS Observations

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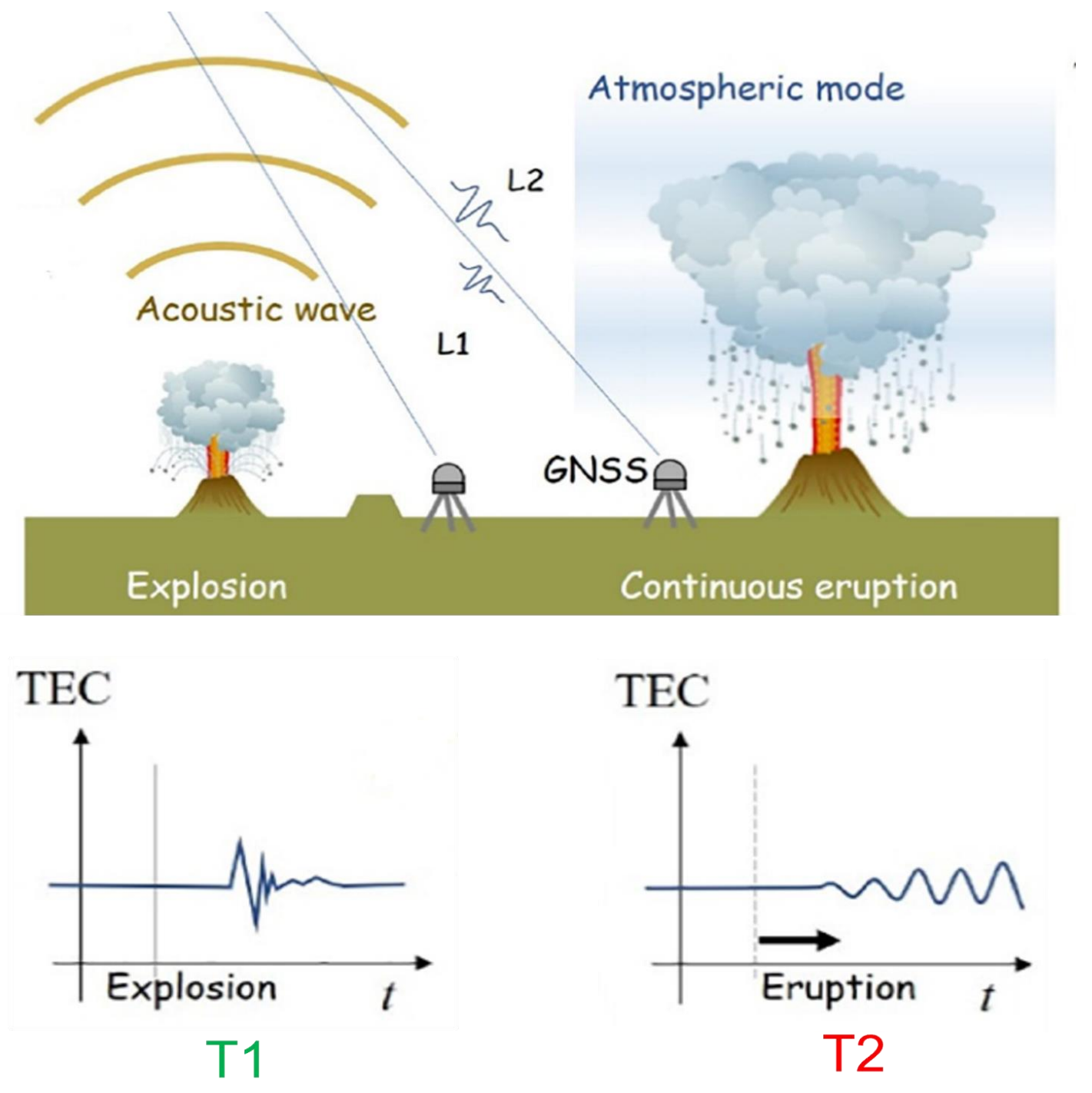
Introduction

It has been known for some time that explosive events can generate acoustic-gravity waves (AGWs) that then propagate by virtue of the background density profile to thermospheric heights and influence the ionosphere in a way detectable by dual frequency Global Navigation Satellite Systems (GNSS) through the measurement of Total electron content (TEC).



Covolcanic Ionospheric Disturbances (CVIDs) observed following main eruption phases typically follow one of two types, thought to be indicative of the eruption dynamics

Type 1 (T1)

- "N-Shaped" TEC waveforms
- Vulcanian eruption style: Sudden intense explosion
- Shock-Acoustic dominant
- 8-11 min arrival times to Ionosphere-Thermosphere (IT)

Type 2 (T2)

- Quasi-Periodic TEC waveforms
- Plinian/Sub-Plinian eruption style: Continuous/multiple explosions
- AGW/GW dominate
- 11-60 min arrival times to IT

Fig 1. Schematic of Atmospheric response to different eruption styles (re-rendered)[1]

Motivation

- There are a multitude of observational studies concerning ionospheric disturbances induced by volcanic eruptions, but little has been done to recreate such events through simulation, especially in a global circulation model (GCM).
- We believe Data-model comparisons can provide valuable in-depth analysis that can be used, not only, to access and improve the performance of models but also to better understand physical processes in complex case studies.

The focus of this study is to simulate ionospheric Total Electron Content (TEC) variations induced by the 2015 Calbuco eruption using the Global Ionosphere-Thermosphere model w/ local mesh refinement feature (GITM-R) and subsequently compare these simulations with GNSS data of the first eruption phase. Additionally, we investigate the difference in simulated TEC variations induced by different primary AGW forcing mechanisms.

Calbuco 2015 Event and GNSS data (Phase 1)

General event info [2]

Location: Southern Chile
(~41.3 S, 72.6 W)
Vent: ~2 km above sea level
Eruption Type: Plinian (continuous)
Time: April 22nd , 21:04 UT
(18:04 LT)
Volcanic Explosivity Index: 4
Plume Height: ~15 km

GNSS data [3]

Duration: 1.5 Hours

Form:

- Quasi-Periodic (T2)
- multiple wave packets (near)
- Gravity Mode (Far)

Dominant Modes:

- 4.8, 5.2 mHz (near)
- 1.0 mHz (Far)

Magnitude:

- ~0.6/0.25 TECU (max)
- ~0.45 TECU (mean)

Apparent Phase Speeds:

- 870-972 m/s (Acoustic packets)
- 200-222 m/s (Gravity packet)

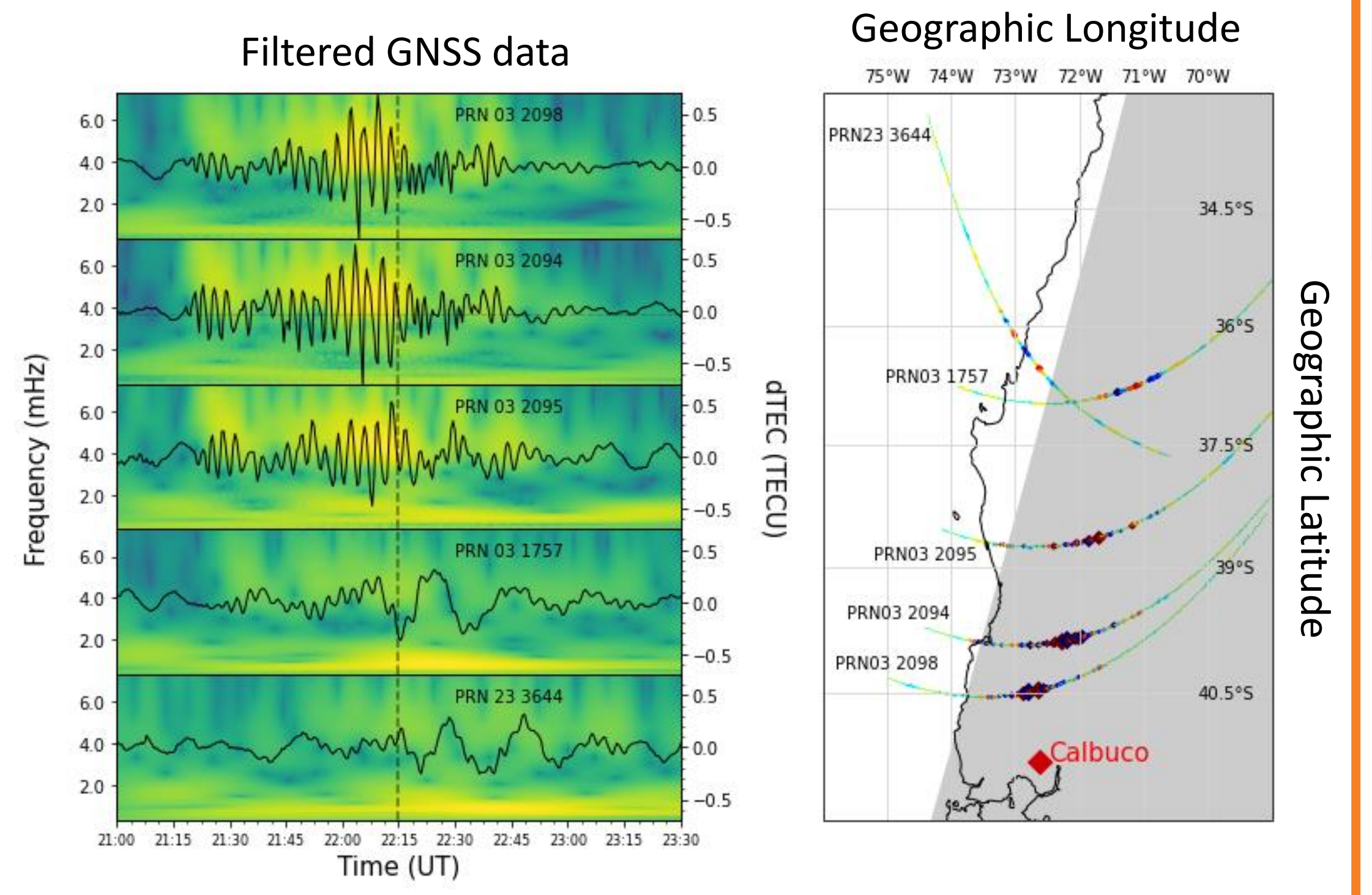


Fig2. Example of GNSS data showing TEC variations caused by Calbuco Eruption

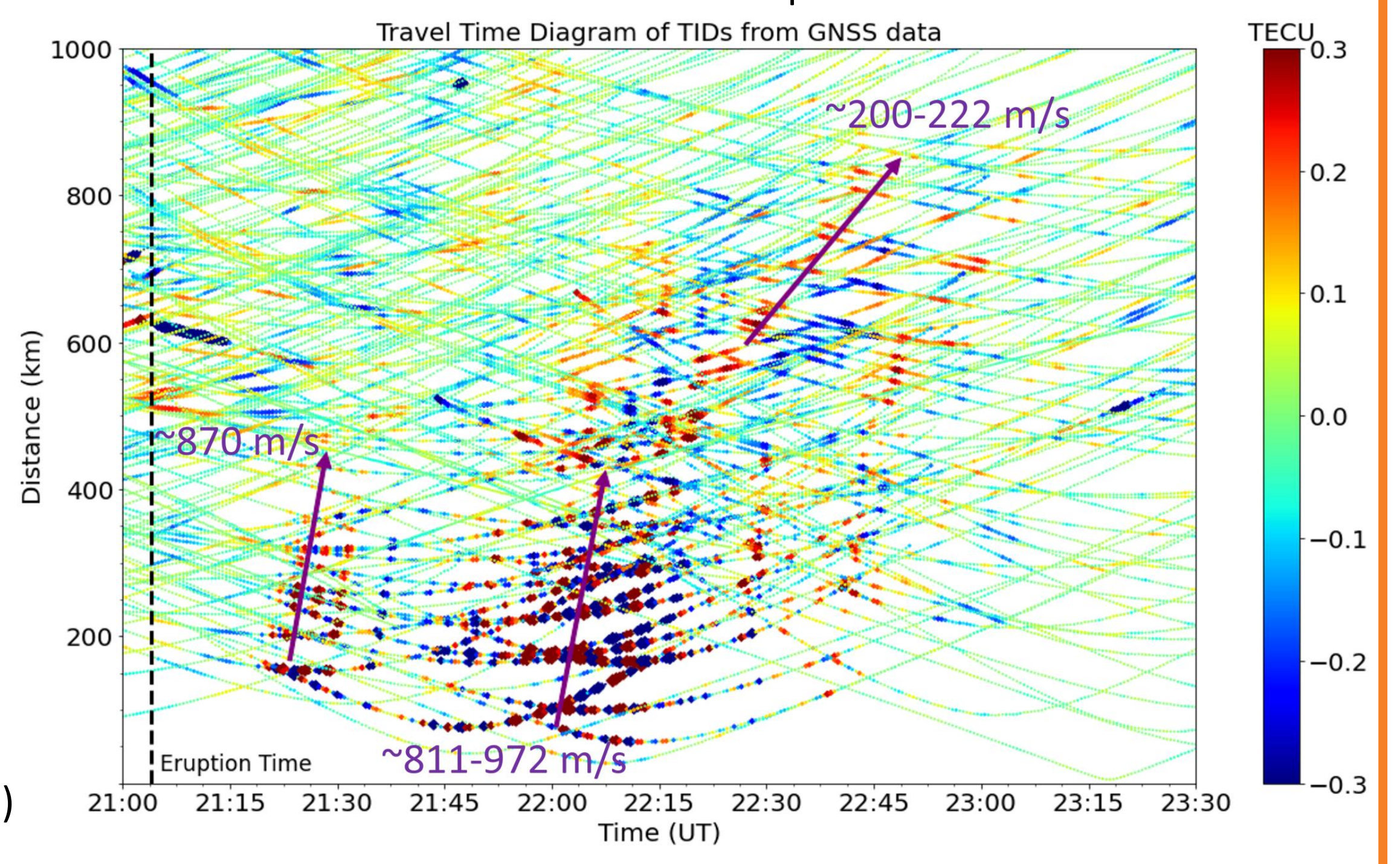


Fig 3. Travel time diagram of GNSS observations for first phase of Calbuco Event

Volcano Model and Propagation to 100 km

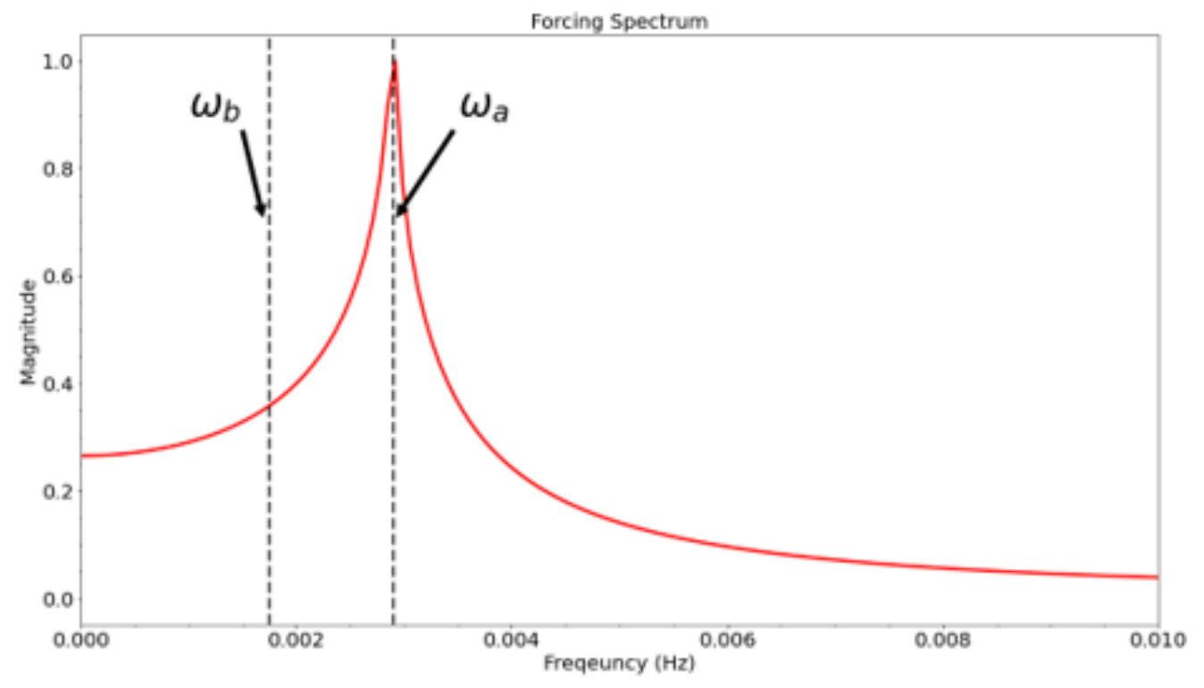
- Point source pressure oscillation at local acoustic cut-off frequency ($\omega_a \sim 2.9\ mHz,\ A = 6.0e6$) [4]

$$p'(t) = Ae^{-0.5H_\rho^{-1}}\left\{\delta(t-t_0) - \frac{\omega_a t_0 J_1\left[\omega_a (t^2 - t_0^2)^{1/2}\right]}{(t^2-t_0^2)^{1/2}} H(t-t_0)\right\}$$

- Assume a mass injection rate:

$$F_M(t) = B(t-t_0)e^{\frac{-(t-t_0)^2}{2\sigma_t^2}} \qquad B = 5000 \quad \sigma_t = 58.5$$

- Simplified Volcano Forcing Function:



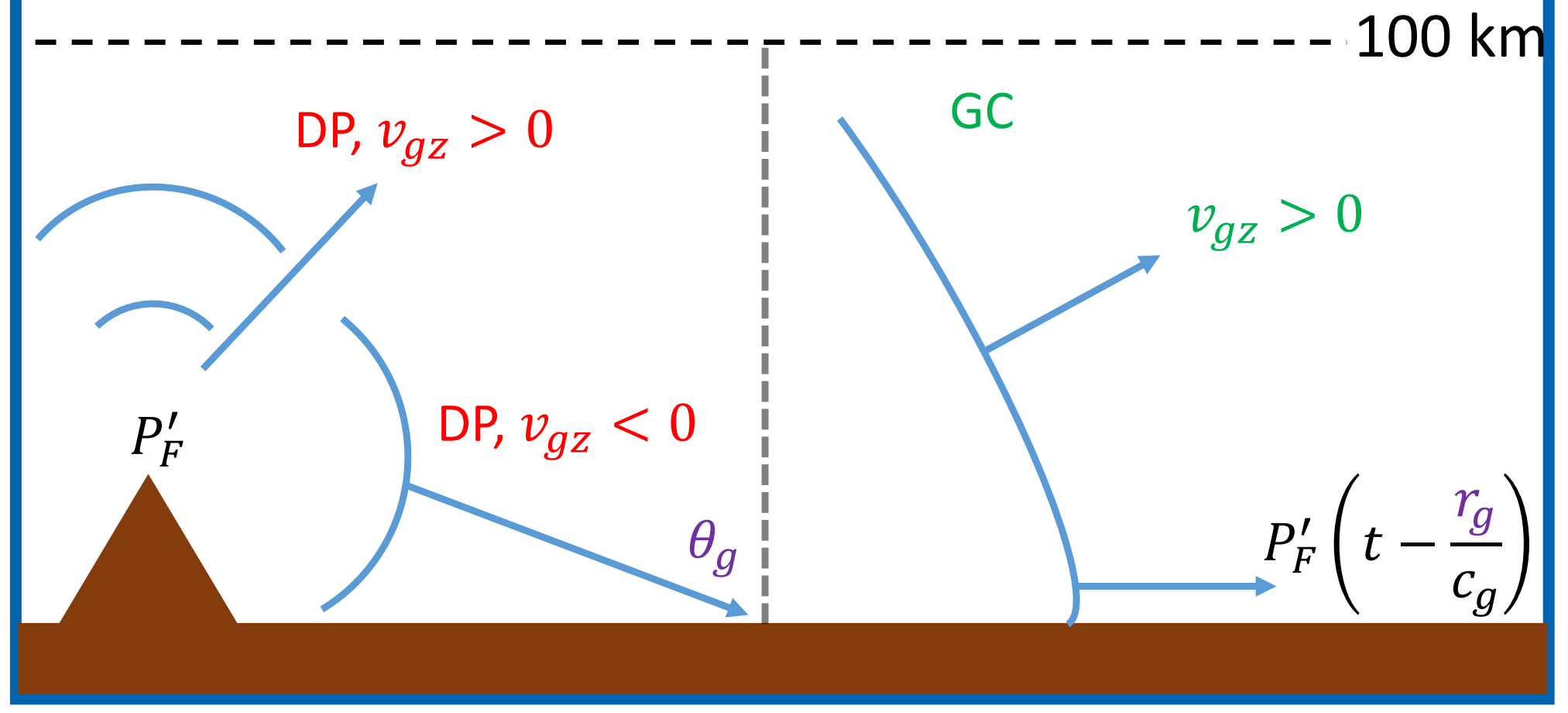
$$P_F' = F_M * p'$$

Fig 4. Normalized Forcing Function Spectrum

- Spherical Propagation to GITM-R lower boundary [5]

$$w = \left(\frac{\rho_{0km}}{\rho_{100km}}\right)^{1/2} \frac{1}{2\pi r_e} \int G_p^w \tilde{P} e^{i(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t + \varphi)} d\omega$$

Direct Propagation (DP) [5]	Ground Coupled (GC) [6]
$k^2 = m^2 tan^2\theta$	$v_s = \frac{c_g}{sin\theta_g}$
$m^2 = \frac{\omega^2 - \bar{\omega}_a^2}{\bar{c}^2} - k^2\frac{\omega^2 - \bar{\omega}_b^2}{\omega^2}$	$m^2 = \frac{\omega^2 - \bar{\omega}_a^2}{\bar{c}^2} - \frac{\omega^2 - \bar{\omega}_b^2}{v_s^2}$
$\varphi = 0$	$\varphi = (k - k)r_g - mz_s$



Data-Model Comparisons

Waveform Comparison

DP simulation

(+) Travel and onset time of CVIDs match well.
(+) The general magnitude distribution is consistent with observation.
(-) GW packet arrival time is ~15 mins off on some PRN-SITE pairs.
(-) Single AGW packet responses.

GC simulation

(+) Multiple wave packets (4 total)
(+) Arrival and relative magnitude of second wave packet are improved.
(-) Initial AW packet is offset.
(-) Dominant modes don't produce second wave packet envelope.
(-) GW packet occurs sooner than data & smaller in magnitude.

Overall the relative significance of Gravity and Acoustic dominant TEC perturbations, as a function of distance from the source, are reproduced.

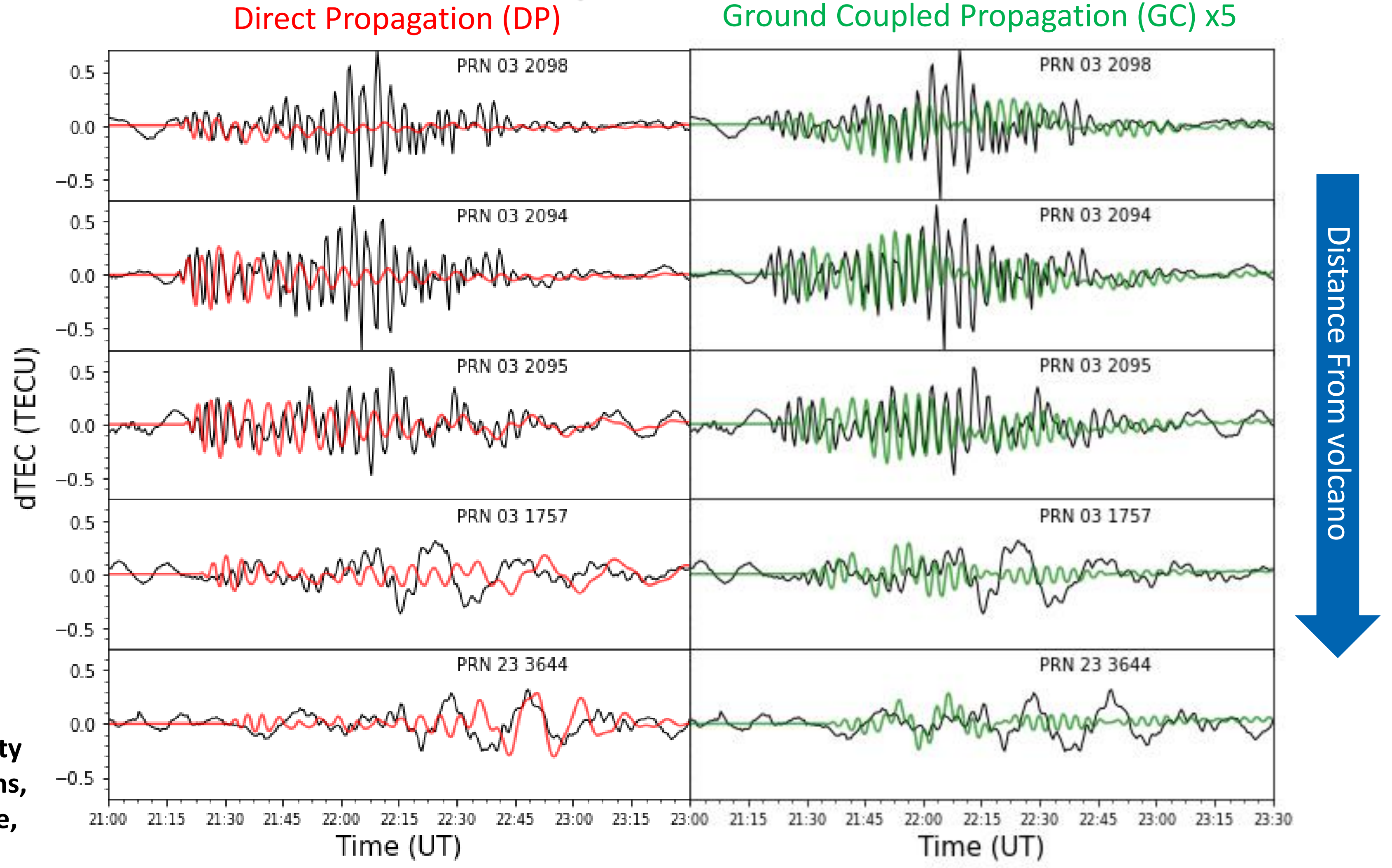


Fig 7. Direct comparison of GNSS observation and GITM-R simulation

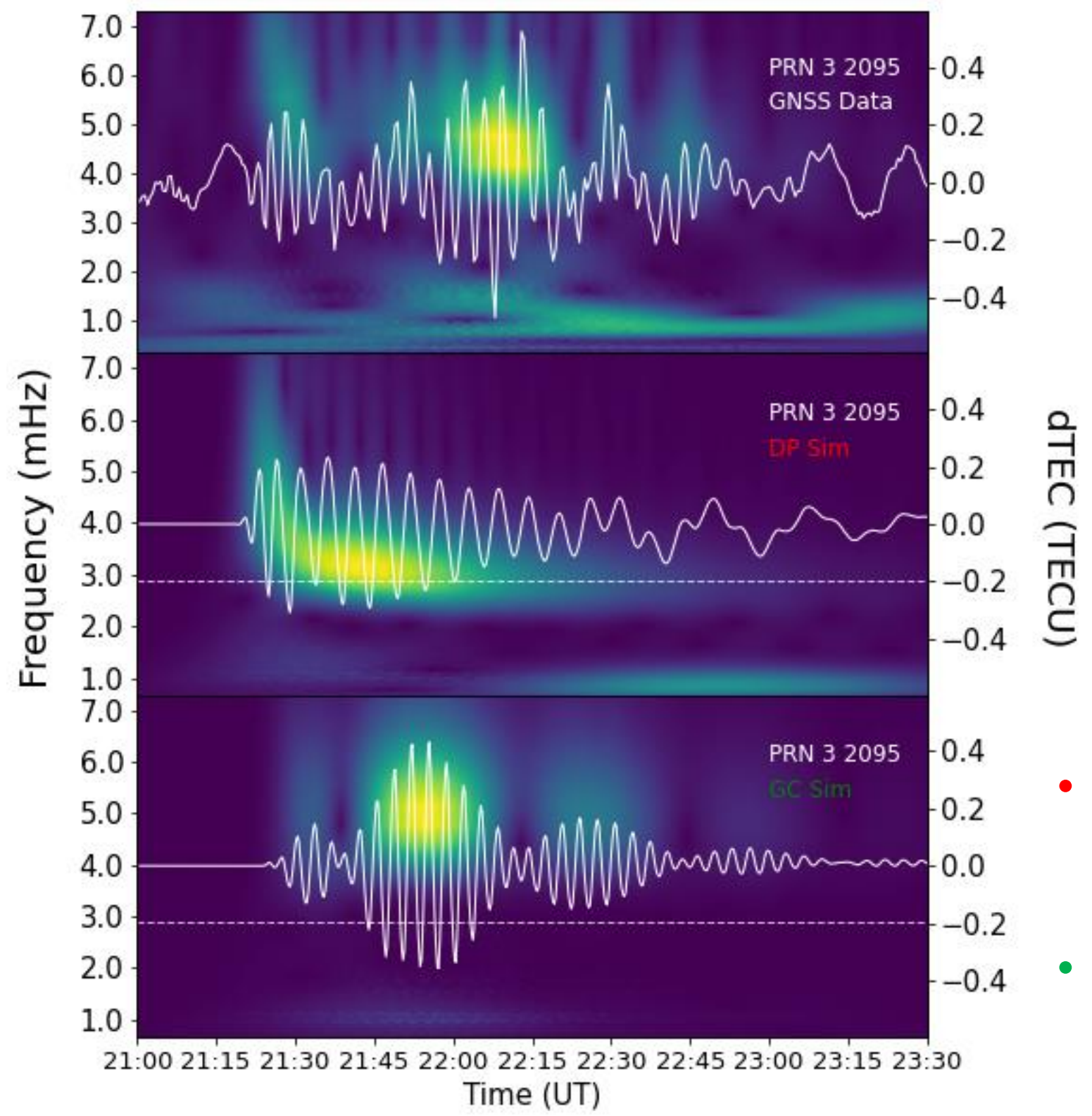


Fig 8. Comparison of spectral content via wavelet transform.

Spectral Comparison

- DP settles to near forcing frequency (dashed)
- DP GW mode has slightly larger period
- GC spectral modes match much better to data
- GC GW mode is present but small

Phase Speed Comparison

- DP AGWs have phase speed ~800 m/s while GW mode ~204-243 m/s (not shown).
- GC AWs have phase speeds ~800-842 m/s with GW mode ~263-312 m/s.

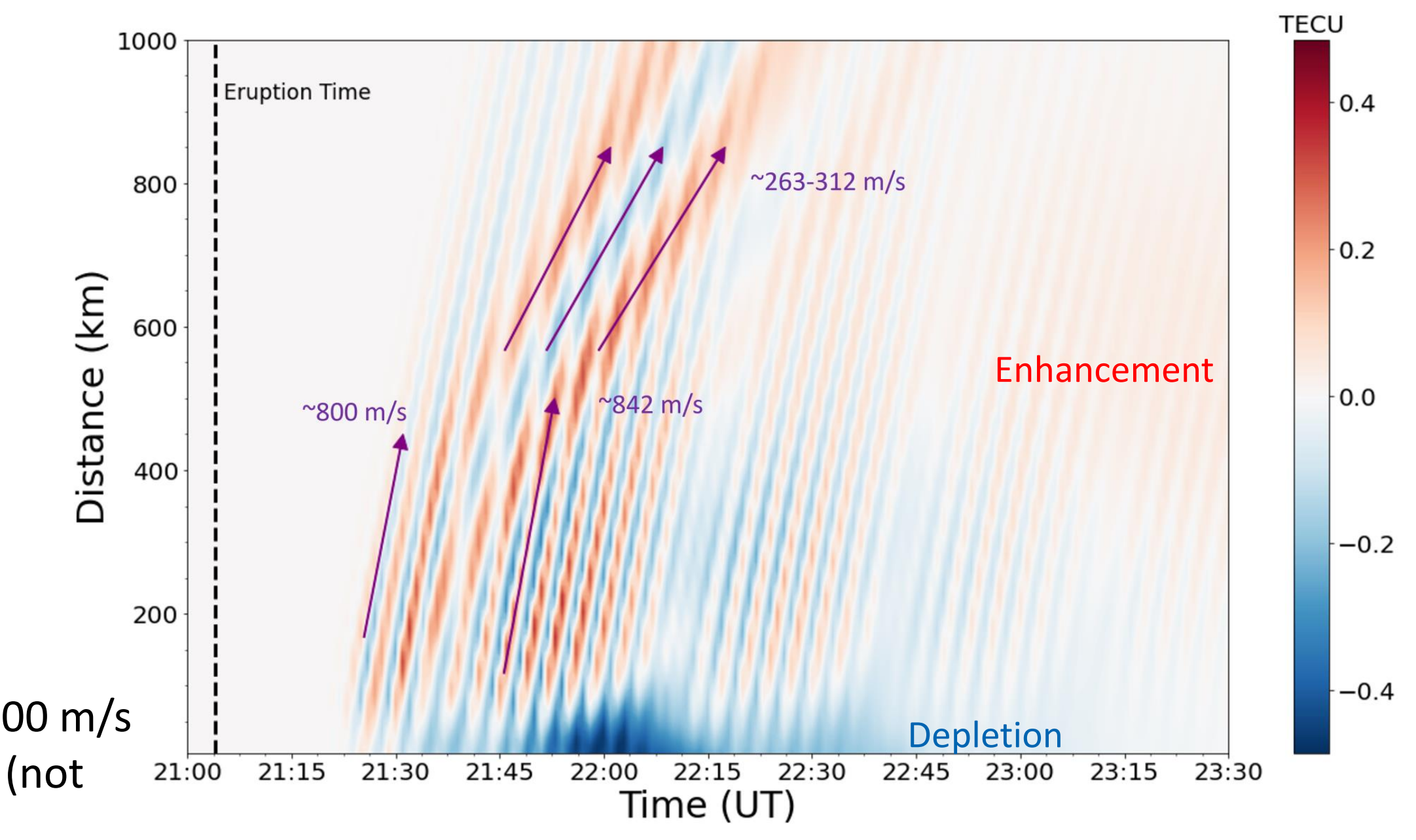


Fig 9. Latitude vs Time slice of GC dTEC at longitude of volcano.

Global Ionosphere Thermosphere Model w/ Local Mesh Refinement [7]

- GCM that models the Earth's IT system by solving Navier-Stokes for Neutrals and Simplified MHD for the plasmas
- Self consistently solves for constituent densities, temperatures, and dynamics

Why GITM-R for Meso-scale TAD-TID dynamics?

- Allows for non-hydrostatic solutions

Local Mesh Refinement feature

- Layered patches of increased resolution, imbedded and coupled together.
- realistic specification of regional boundaries

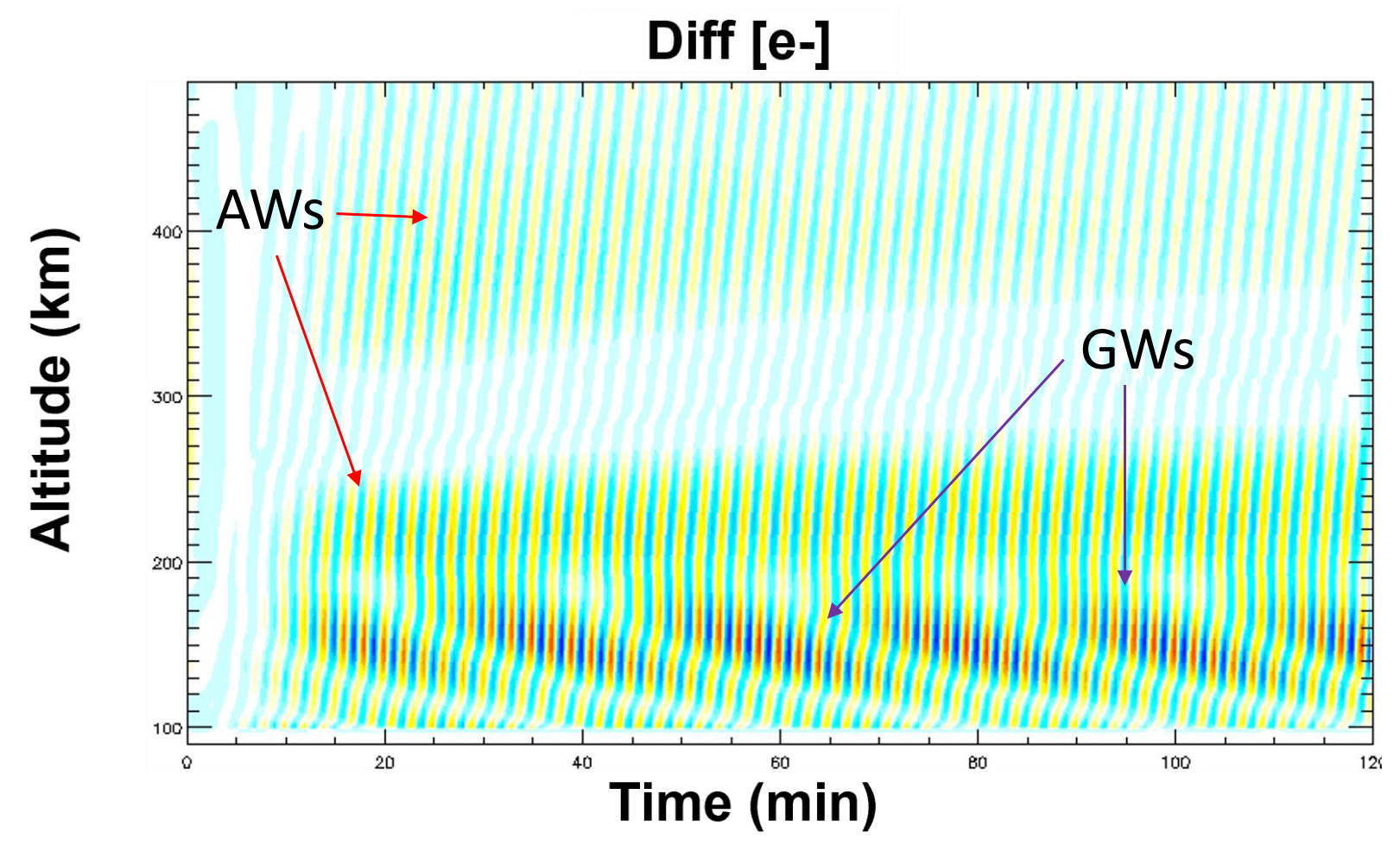


Fig 5. Example of AGWs in GITM-R simulation

Simulation Set-up

- 4 Hour Simulation time (20:30 – 24:30 UT)
- Three imbedded layers

Regional Layer 2
Lon: [55° W, 90° W]
Lat: [34° S, 59° S]
Resolution: 0.1° x 0.1°

- Specification of Ionosphere state
  - 8 hr pre-run with solar wind drivers (B, v, N_p, T)
  - F10.7 of 150

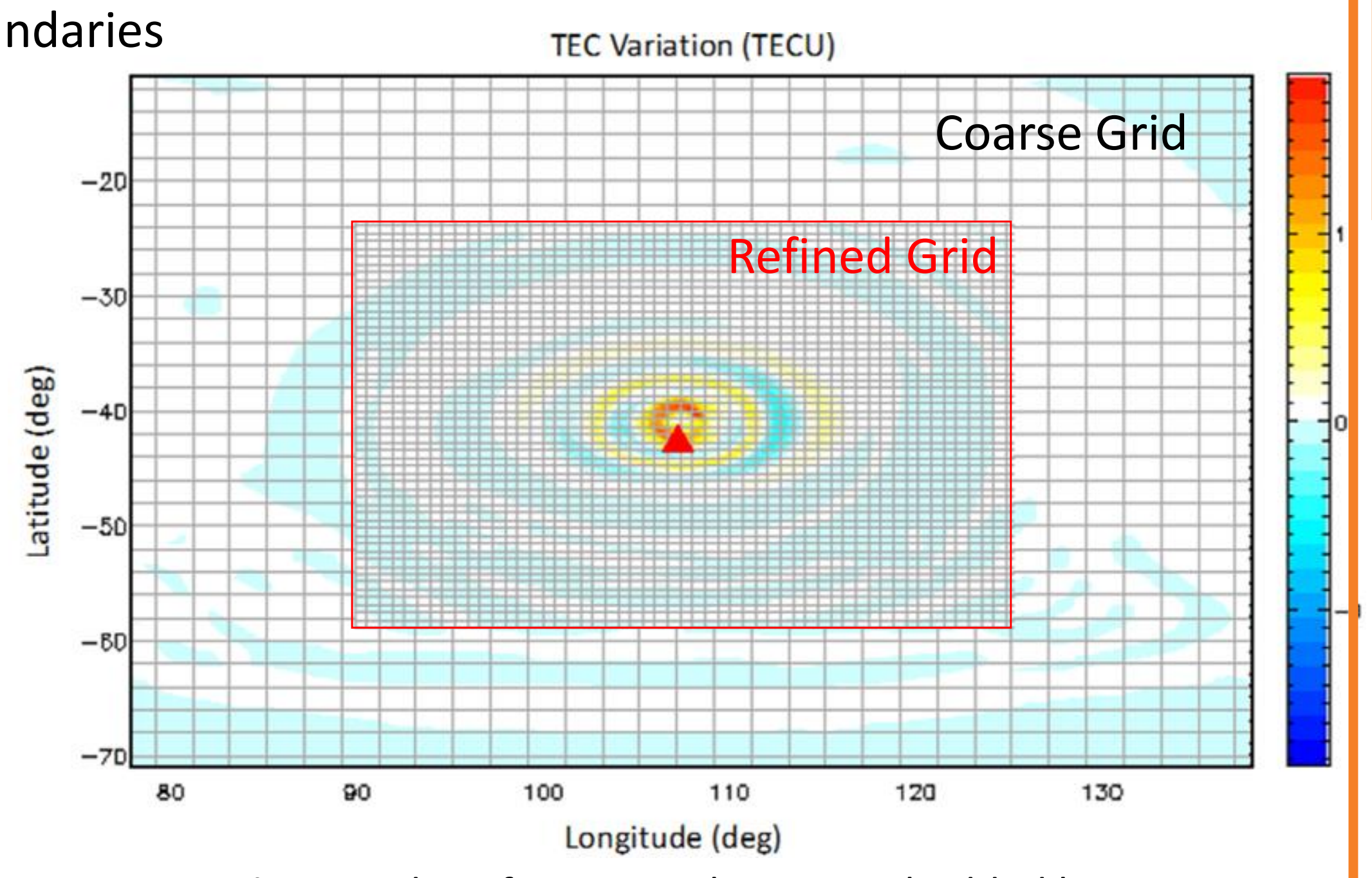


Fig 6. Grid configuration showing imbedded layers

Discussion and Conclusions

- GITM-R was able to reproduce the relative significance of gravity and acoustic dominate TEC perturbations, as a function of radial distance from the source.
- GITM-R was shown to recreate important features of the observed GNSS data such as travel/onset times, relative magnitudes, and AW/GW apparent phase speeds.
- GITM-R was able to reproduce spectral peaks of ~5.0 mHz and ~1 mHz typically seen in CVIDs.
- The simplified specification of GC propagation to force GITM-Rs lower boundary was able to improve data-model comparison of this event.
- The First wave packet is likely acoustic waves propagating from directly above the vent.
- The Second wave packet may be a localized forcing due to the passage of a ground coupled airwave
- Comparison of GW mode frequencies, temporal locations, and phase speeds between the specifications suggest they may have been launched between 2-100 km

References

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[7] Deng Y., et. Al. (2020), Global Ionosphere-Thermosphere Model with Local Mesh Refinement, J. Geophys. Res., Submitted.

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