ICON/GNSS data processing for TONGA Earthquake

Anthea Coster, Ercha Aa, Shunrong Zhang, Larisa Goncharenko, Phil Erickson, William Rideout, Andres Spicher**, Juha Vierninen**
MIT Haystack Observatory, ** The Arctic University of Norway, Tromso

Outline

Previous Storm Studies and data available to study

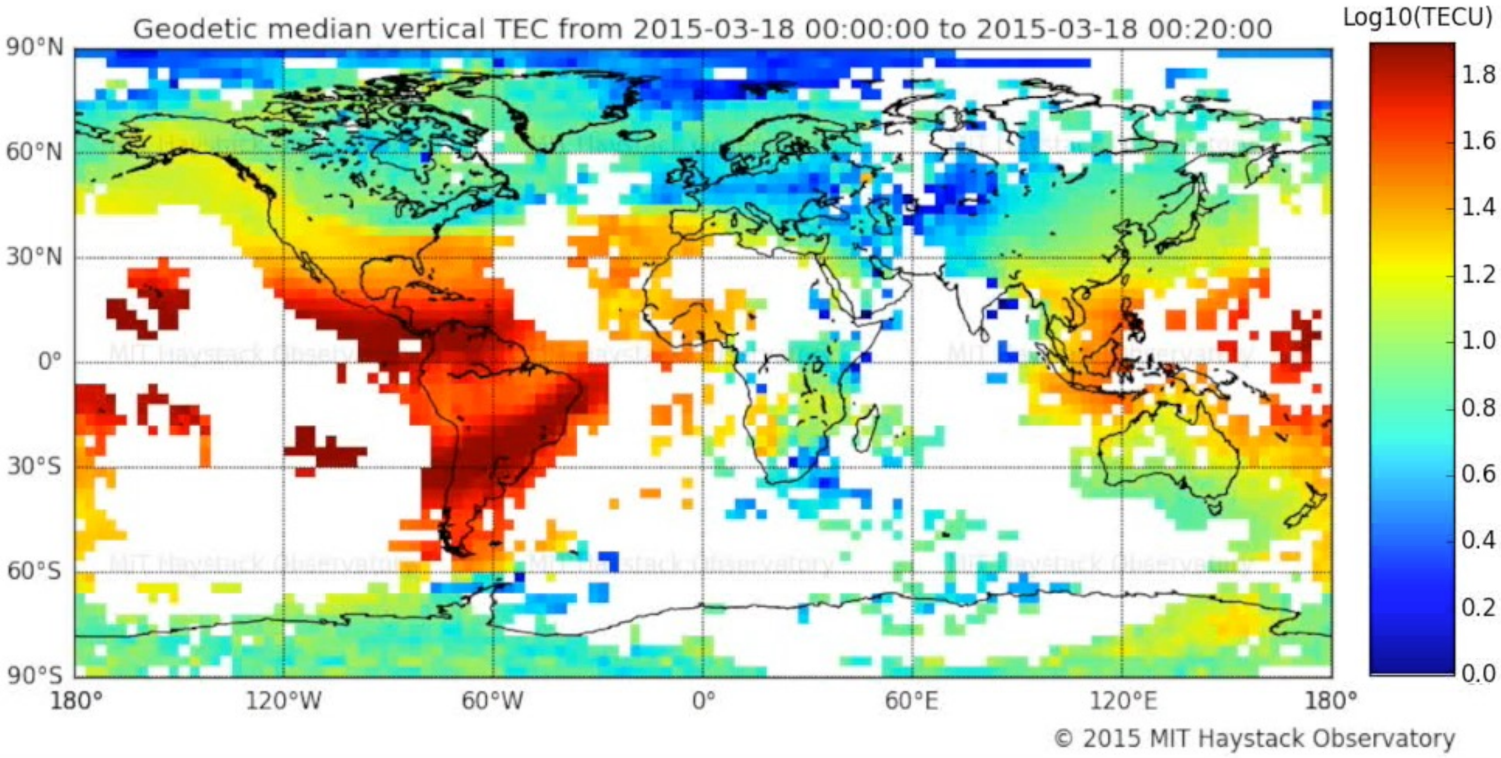
Introduction to NASA GOLD and ICON missions

Results of Tonga Explosion (Shunrong Zhang/Ercha Aa)

Haystack Papers on Tonga

- 2022 Tonga Volcanic Eruption Induced Global Propagation of Ionospheric Disturbances via Lamb Waves. *Frontiers in Astronomy and Space Sciences.* (2022). DOI: https://doi.org/10.3389/fspas.2022.871275
- 2022 Tonga Volcanic Eruption Induced Global Propagation of Ionospheric Disturbances via Lamb Waves. *Frontiers in Astronomy and Space Sciences.* (2022). DOI: https://doi.org/10.3389/fspas.2022.871275
- Significant equatorial plasma bubbles and global ionospheric disturbances after the 2022 Tonga volcano eruption. (2022). DOI: https://doi.org/10.1002/essoar.10510637.1

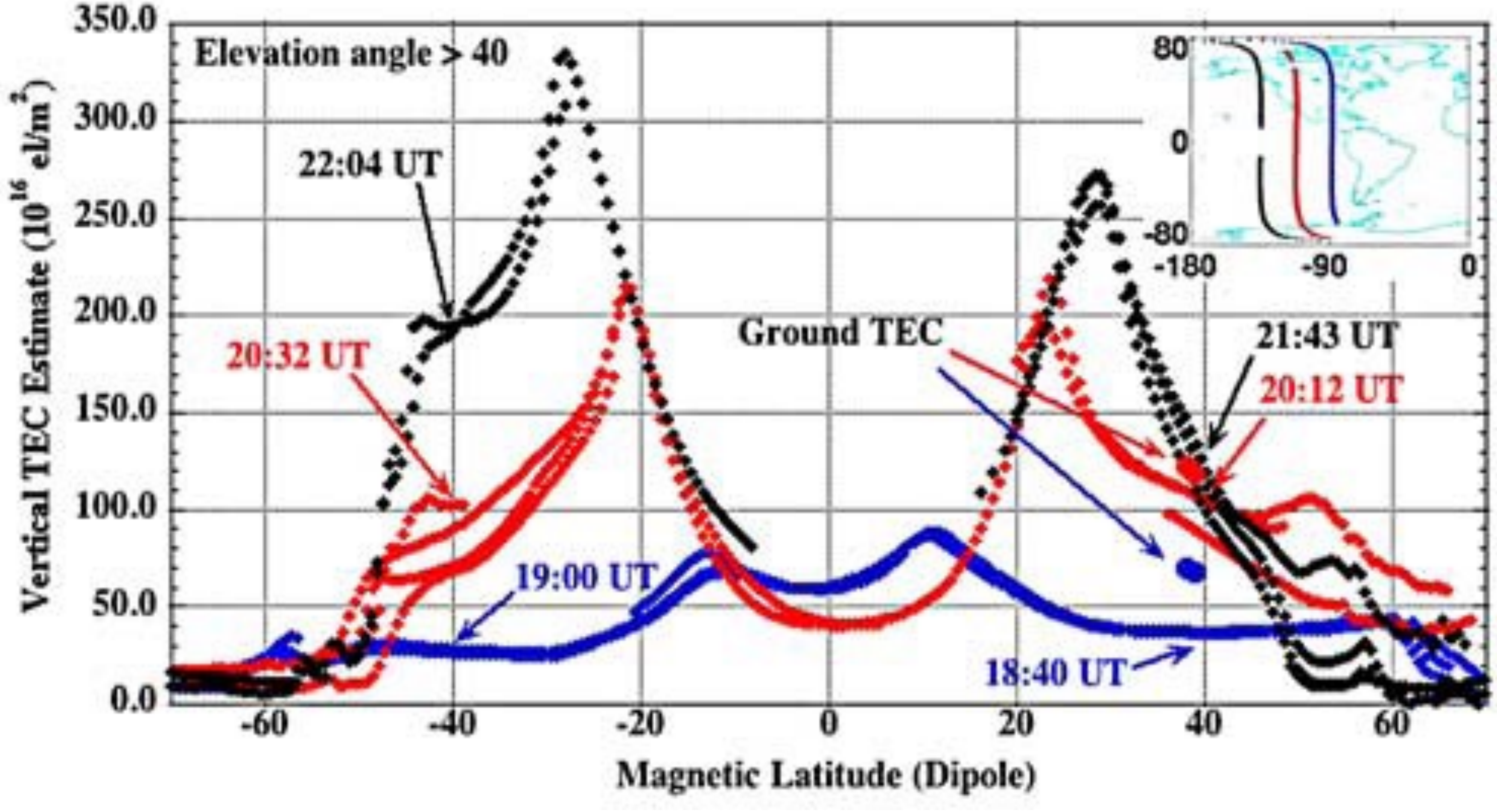
Total Electron Content from GNSS Data: Global Ionospheric Space Weather



(Coster, Rideout)

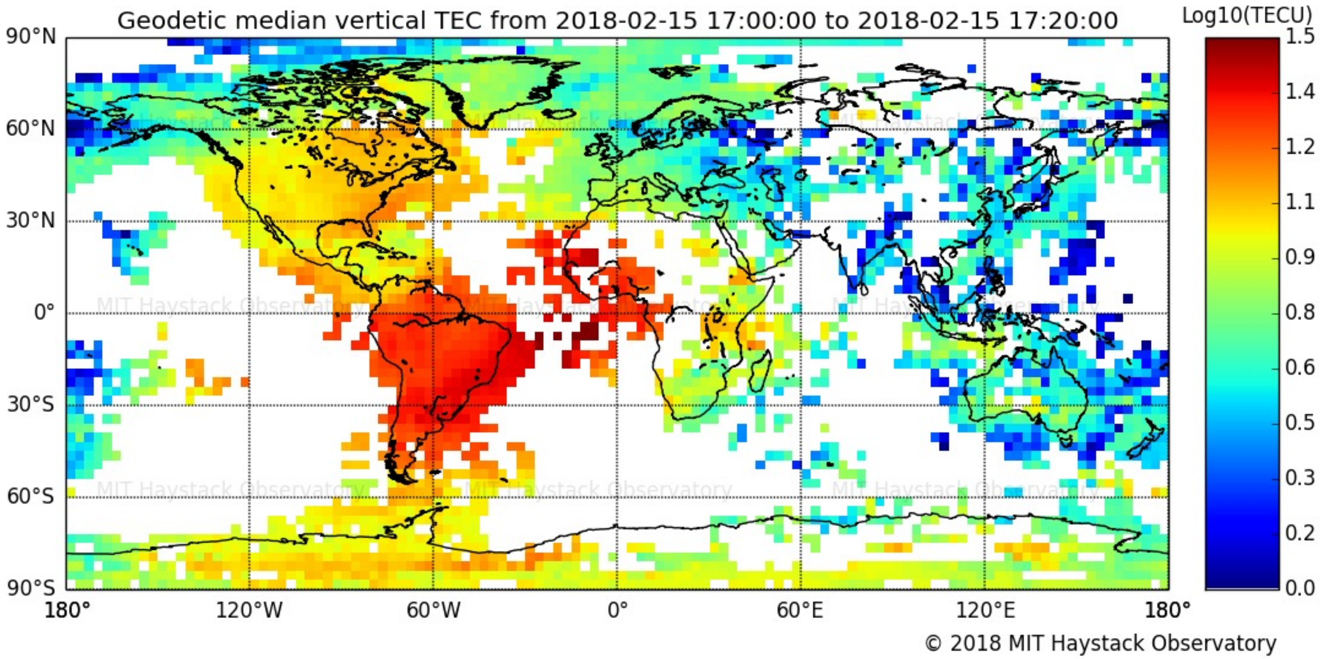
6000+ GNSS geodetic receivers from many sources (e.g. UNAVCO, Scripps Orbit and Permanent Array Center)
Processed by MIT Haystack to extract ionospheric delay information
Data provides large scale picture of global ionospheric space weather variations
Available to space science community through NSF supported Madrigal distributed database

Storm-time Appelton Anomaly



Mannucci et al., 2005, GRL

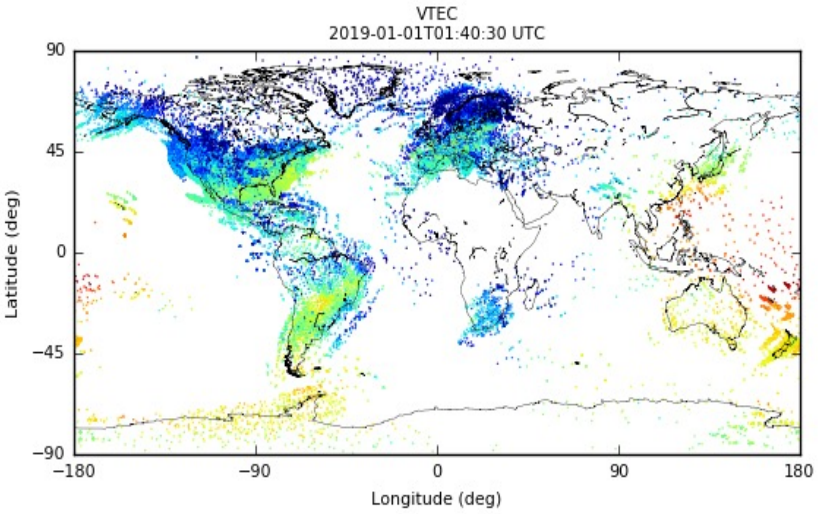
Available data : TEC



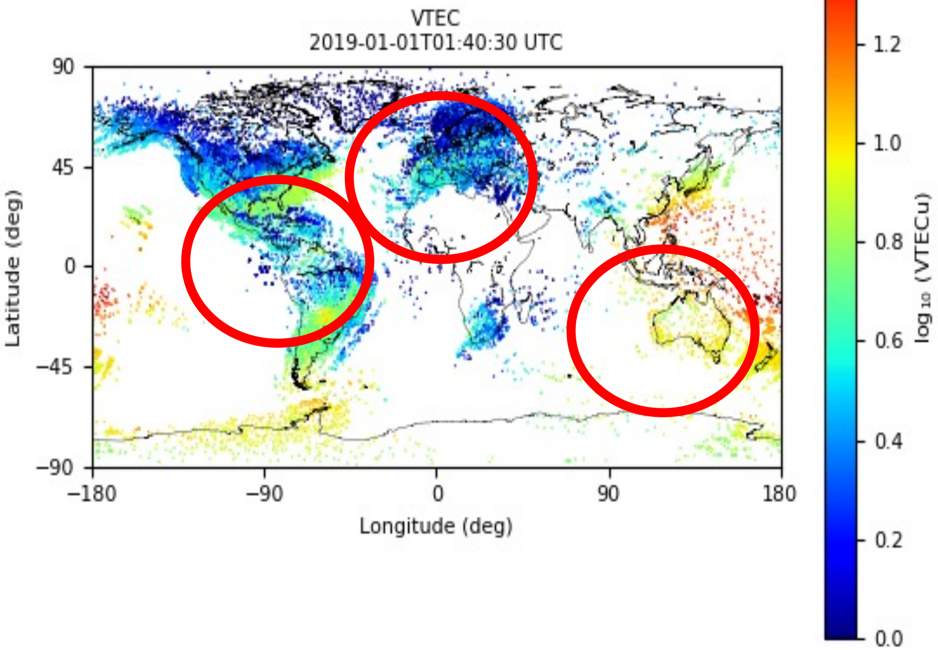
- Total Electron Content:
  - Madrigal database, Haystack Observatory
  - 2000+; > 6000 GNSS receivers,

    1 x 1 degree x 5mins resolution + Line of Sight TEC

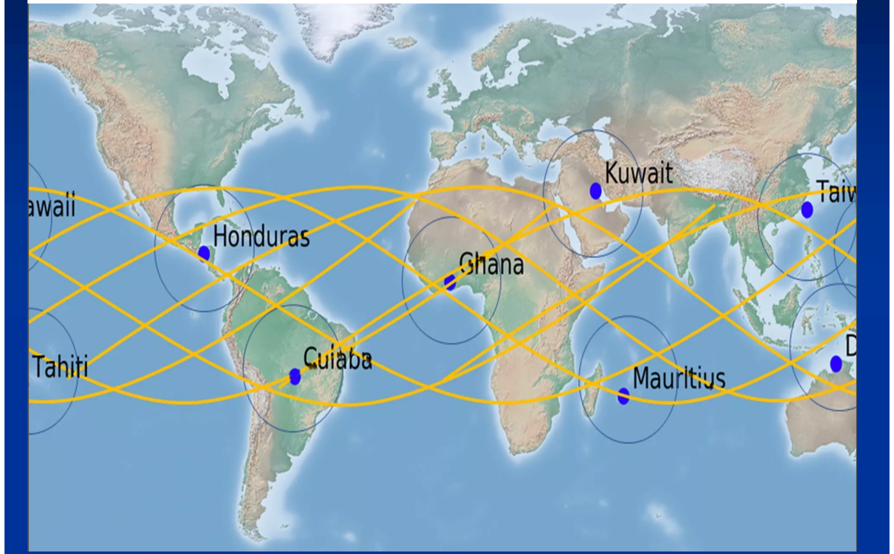
GPS Only



GPS and GLONASS



COSMIC-2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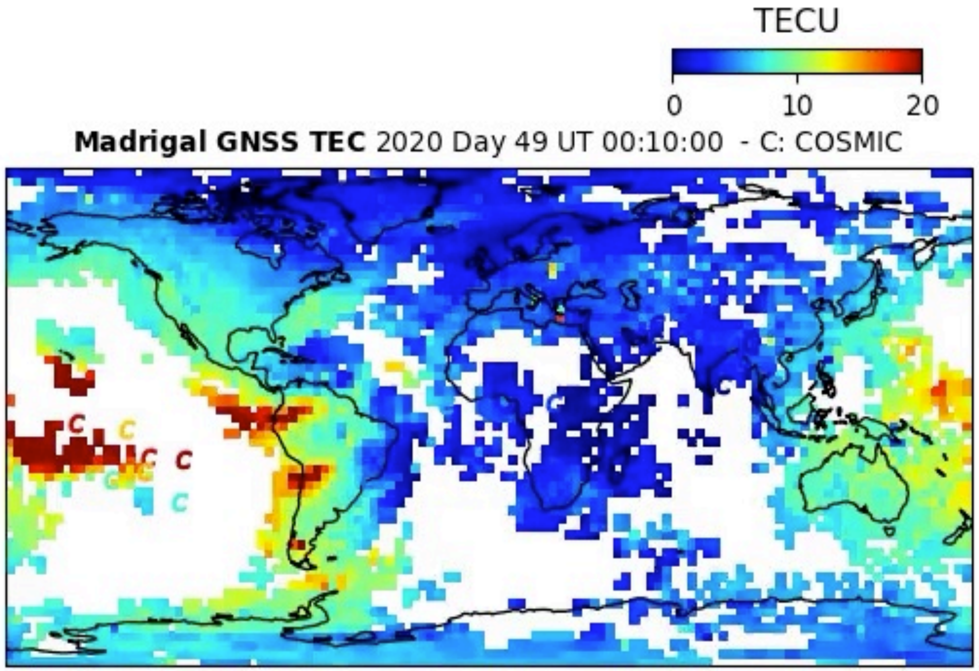
TECU
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Madrigal GNSS TEC 2020 Day 49 UT 00:10:00 - C: COSMIC
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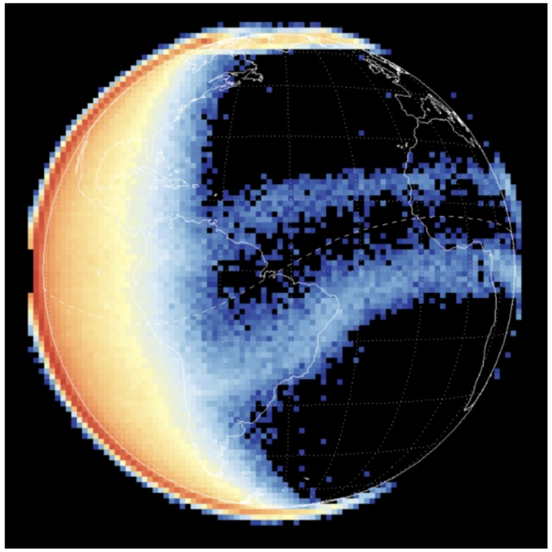
GNSS TEC | dTEC Climatology [Ongoing]

- GNSS TEC data
- dTEC derived from 30-min detrend window
  - detrending using Savitzky-Golay filter:
    - = sliding windows
      - normally assuming 0 order basis function;
      - we use 1 order (i.e., within the window, linear variation)
- Amplitude of dTEC, aTEC, is averaged in lat x lon x time bins *everyday* and *every month*
  - 4 resolutions
    - 1deg x 1deg x 5min [hig]
    - 5deg x 5 deg x 25min [med]
    - 10deg x 15 deg x 60min [reg]
    - 30deg x 45deg x 180 min [idx] We will develop a global TID index
  - same for TEC, dTEC, pTEC (aTEC/TEC)
  - so far June 2019 - June 2021; will do 2015 - now

GLOBAL-SCALE OBSERVATIONS OF THE LIMB AND DISK



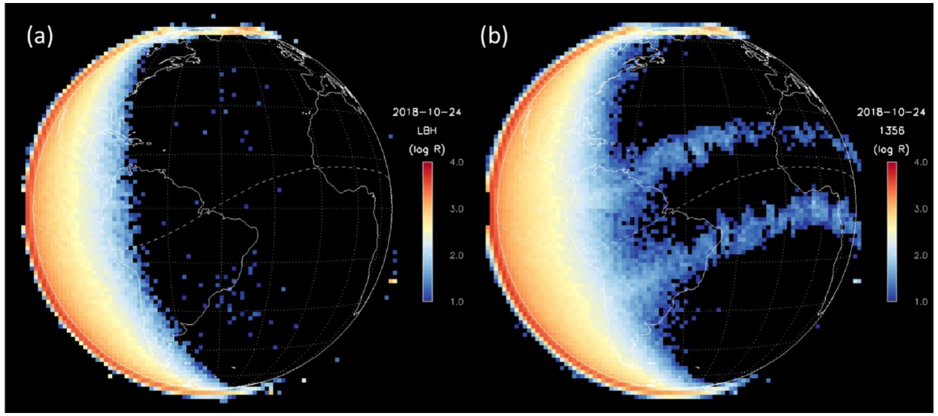
GOLD is a NASA mission of opportunity that measures densities and temperatures in Earth’s thermosphere and ionosphere.

GOLD makes these measurements, in unprecedented detail, with an ultraviolet (UV) imaging spectrograph on a geostationary satellite.

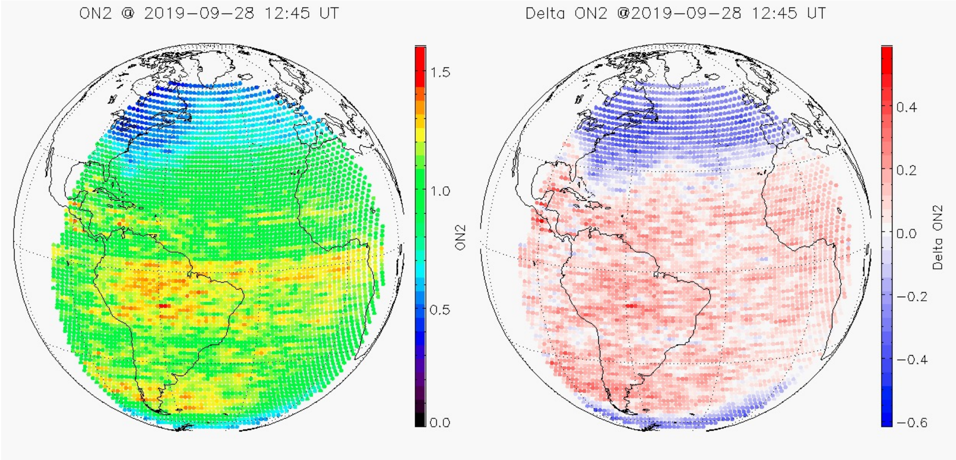
- The goal of the investigation is to provide answers to key elements of an overarching question for Heliophysics science: What is the global-scale response of the thermosphere and ionosphere to forcing in the integrated Sun-Earth system?
- The measurements from GOLD will be used, in conjunction with advanced models of the thermosphere and ionosphere, to revolutionize our understanding of the space environment.

GOLD instruments and data

Emission brightness (day + night)



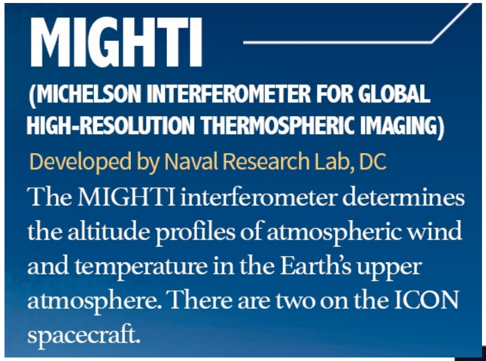
Daytime O/N_2 ratio



The Ionospheric Connection Explorer (**ICON**)

- **ICON** launched on October 10, 2019 at 9:59 p.m. EDT.
- **ICON** observes what's happening at the lowest boundary of space, from about 55 miles up to 360 miles above the surface. ICON explores the connections between the neutral atmosphere and the electrically charged ionosphere.
- It has four instruments
  - **Michelson Interferometer for Global High-Resolution Thermospheric Imaging (MIGHTI)**
  - **Ion Velocity Meter (IVM)** is an ion drift meter
  - **Extreme Ultra-Violet (EUV)**, an imager
  - **Far Ultra-Violet (FUV)**, an imager

ICON (575 km, 97 min, 27°) instruments and data

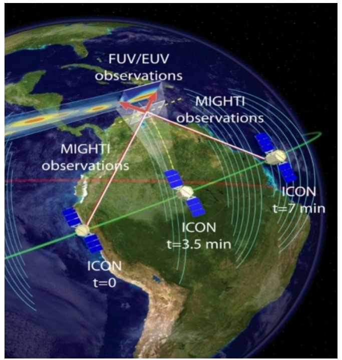


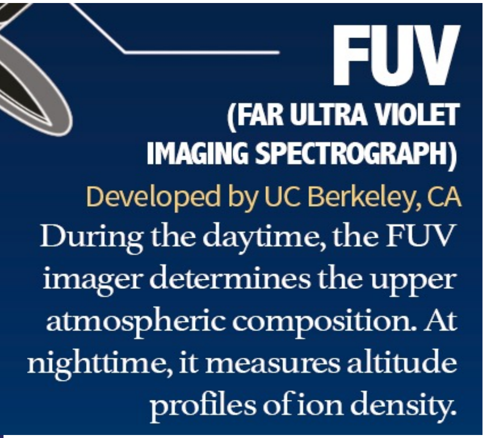
MIGHTI

(MICHELSON INTERFEROMETER FOR GLOBAL HIGH-RESOLUTION THERMOSPHERIC IMAGING)

Developed by Naval Research Lab, DC

The MIGHTI interferometer determines the altitude profiles of atmospheric wind and temperature in the Earth's upper atmosphere. There are two on the ICON spacecraft.



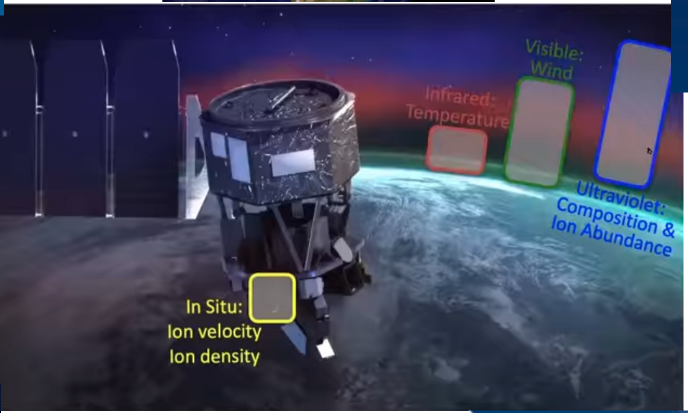


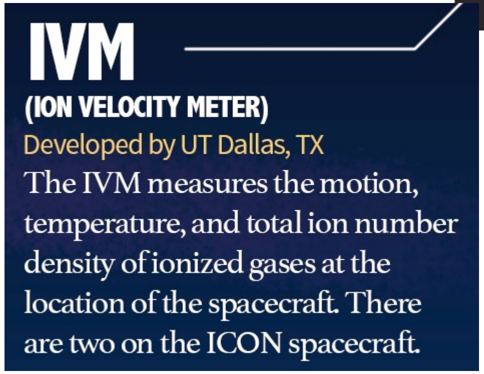
FUV

(FAR ULTRA VIOLET IMAGING SPECTROGRAPH)

Developed by UC Berkeley, CA

During the daytime, the FUV imager determines the upper atmospheric composition. At nighttime, it measures altitude profiles of ion density.



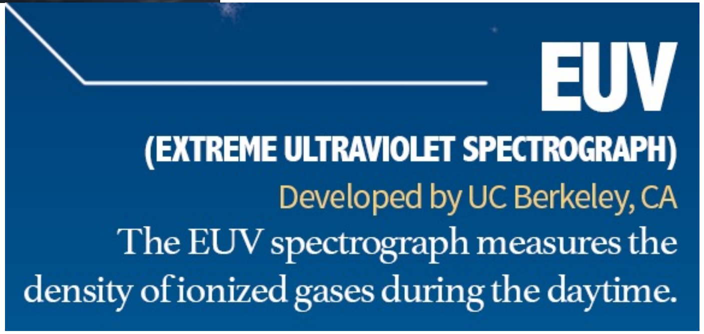


IVM

(ION VELOCITY METER)

Developed by UT Dallas, TX

The IVM measures the motion, temperature, and total ion number density of ionized gases at the location of the spacecraft. There are two on the ICON spacecraft.



EUV

(EXTREME ULTRAVIOLET SPECTROGRAPH)

Developed by UC Berkeley, CA

The EUV spectrograph measures the density of ionized gases during the daytime.

Science Objectives

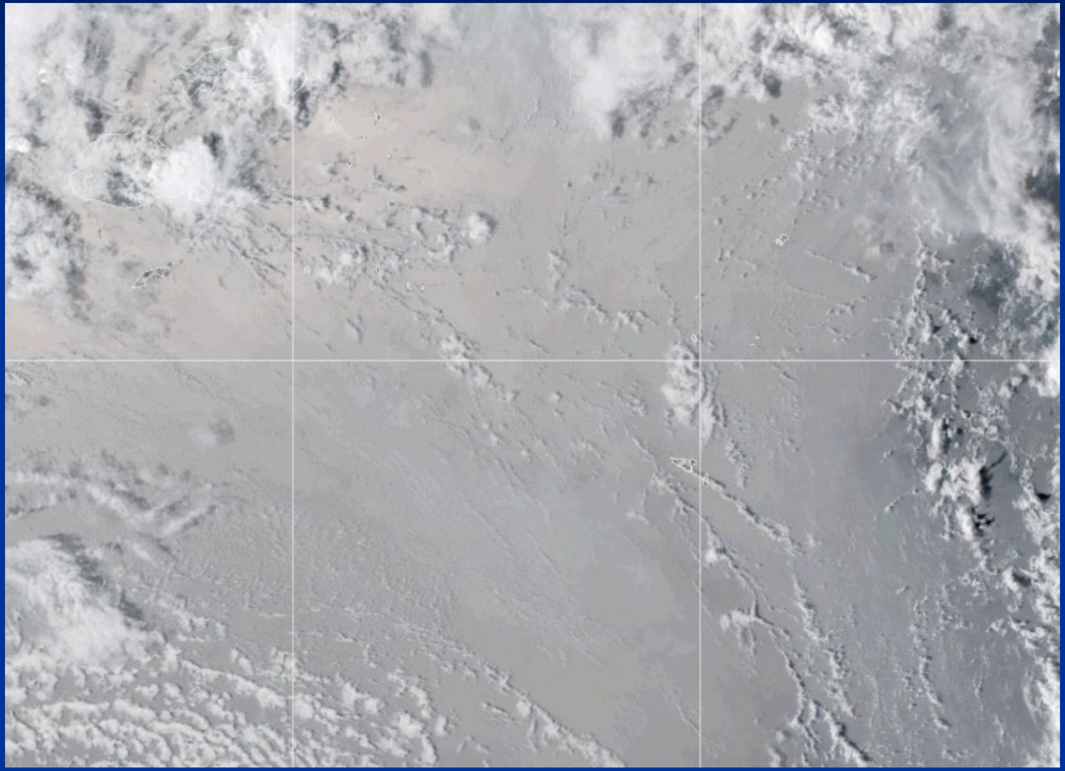
☐ ICON:

1. Understand the sources of strong ionospheric variability
2. Understand the transfer of energy and momentum from our atmosphere into space
3. Understand how do Ion-Neutral coupling processes respond to increases in solar forcing and geomagnetic Activity?

☐ GOLD:

1. Determine how geomagnetic storms alter the temperature and composition of Earth’s thermosphere
2. Analyze the global-scale response of the thermosphere to solar extreme ultraviolet variability
3. Investigate the significance of atmospheric waves and tides propagating from below on the temperature structure of the thermosphere
4. Resolve how the structure of the equatorial ionosphere influences the formation and evolution of equatorial plasma irregularities

2022 Tonga volcanic eruption induced TID global propagation

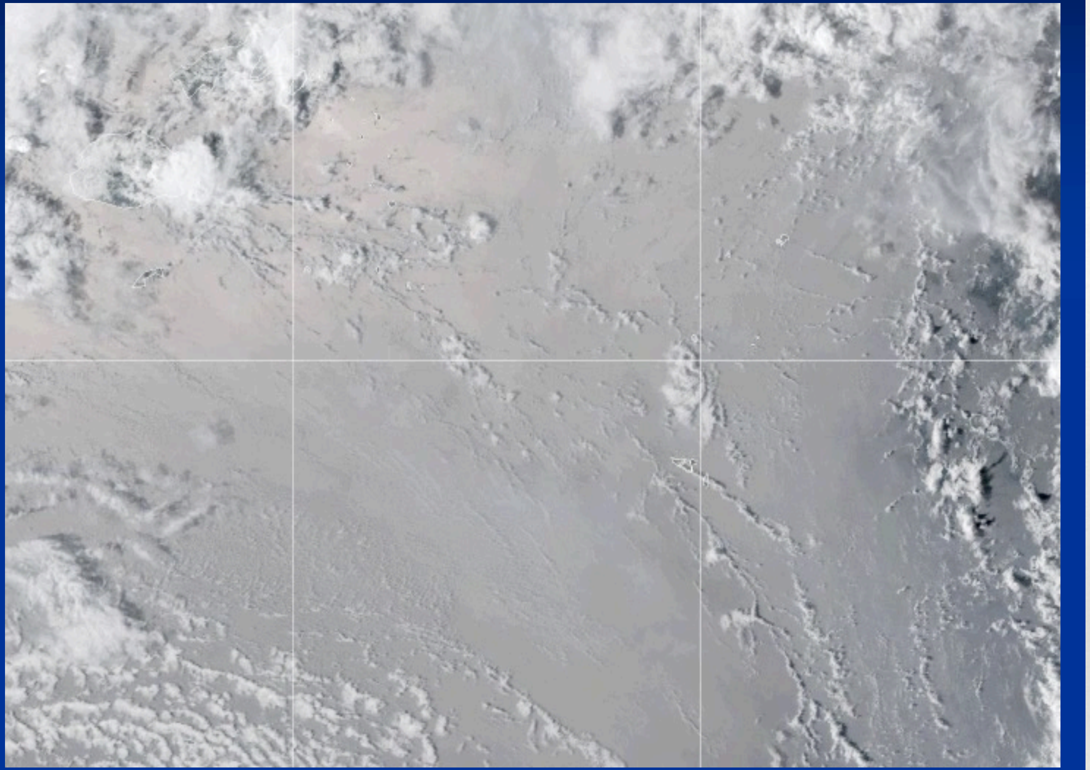


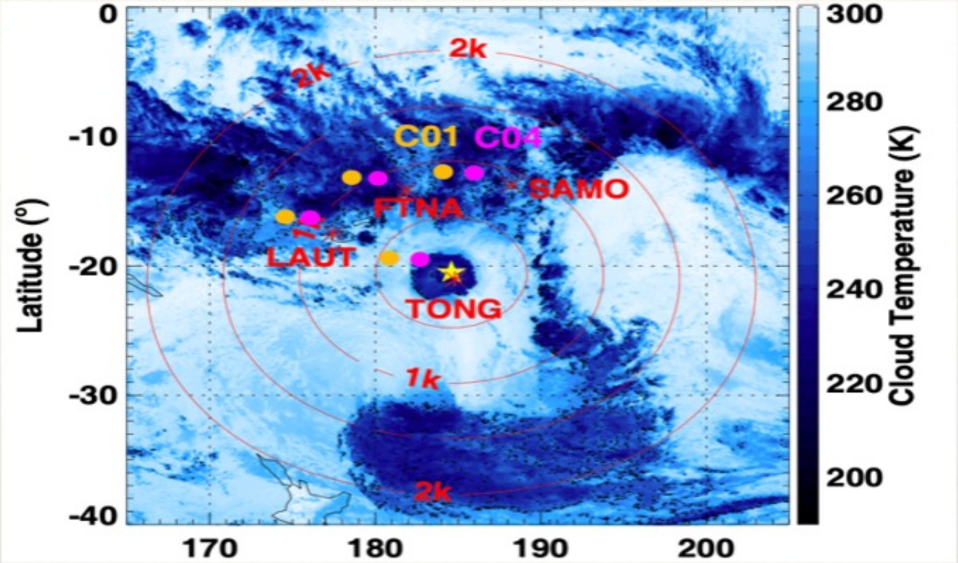
This looping video shows a series of GOES-17 satellite images that caught an umbrella cloud
generated by the underwater eruption of the Hunga Tonga-Hunga Ha'apai volcano on Jan. 15, 2022.

Crescent-shaped bow shock waves and numerous lighting strikes are also visible.

Credit: NASA Earth Observatory image by Joshua Stevens using GOES imagery courtesy of NOAA and NESDIS words from https://www.jpl.nasa.gov/news/tonga-eruption-sent-ripples-through-earths-ionosphere)

2022 Tonga volcanic eruption induced TID global propagation





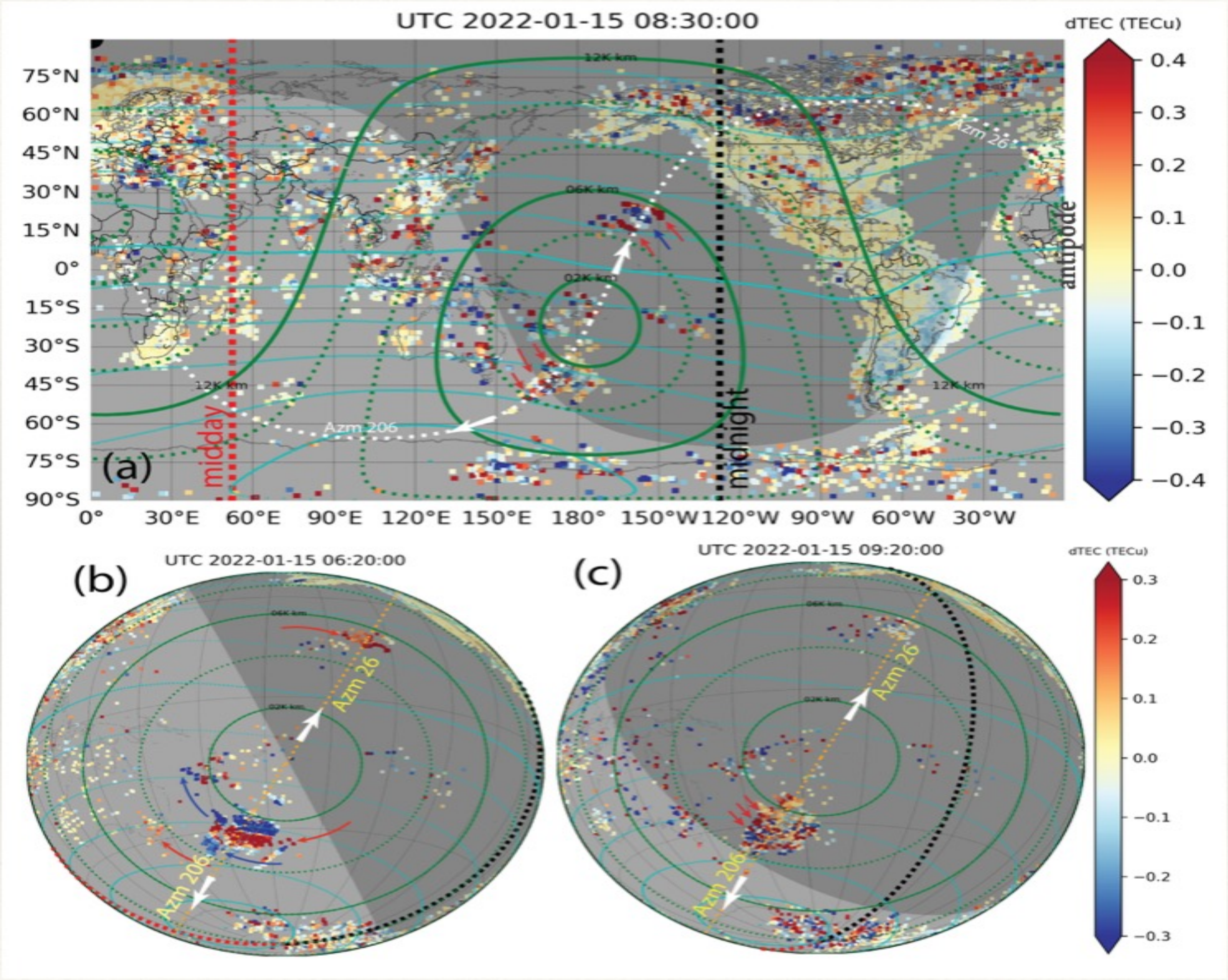
Cloud temperature dropped by ~ 80 K about 1 hour after the eruption (NASA GOES data)

Credit: NASA Earth Observatory image by Joshua Stevens u
words from https://www.jpl.nasa.gov/news/tonga-eruptio

Geometry

The eruption triggered the Mw5.8 earthquake at (-20.5N, -175.4E) at 04:14:45 UTC on Jan 15

- Distance is measured between the epicenter and the observational data point along the great circle at 300 km altitude.
- The great circle is the shortest path between the epicenter and the data point. We assume waves propagate based on this path.
- A specific great circle that passes the epicenter is identified by azimuth, the angle between the the great circle plane and the geographic meridian plane.



Data gaps over oceans but the distance from Tonga is well distributed without significant discontinuity

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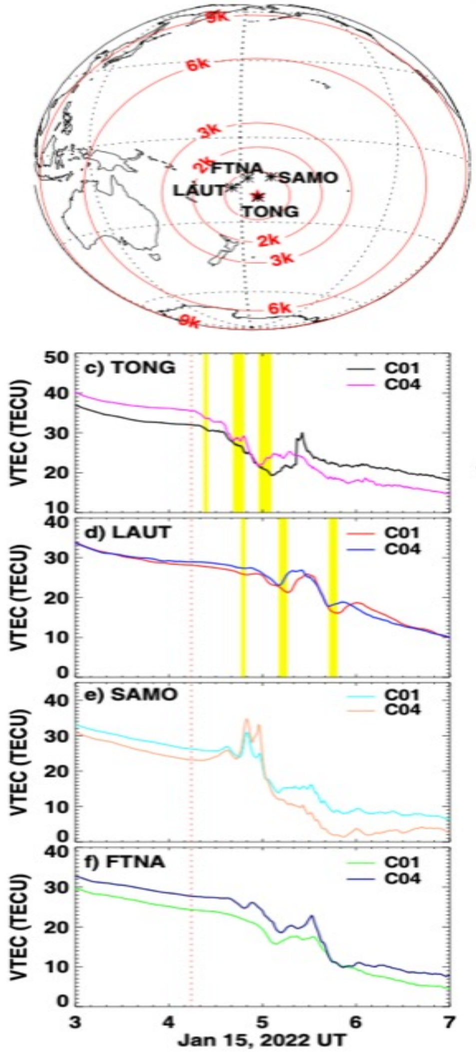
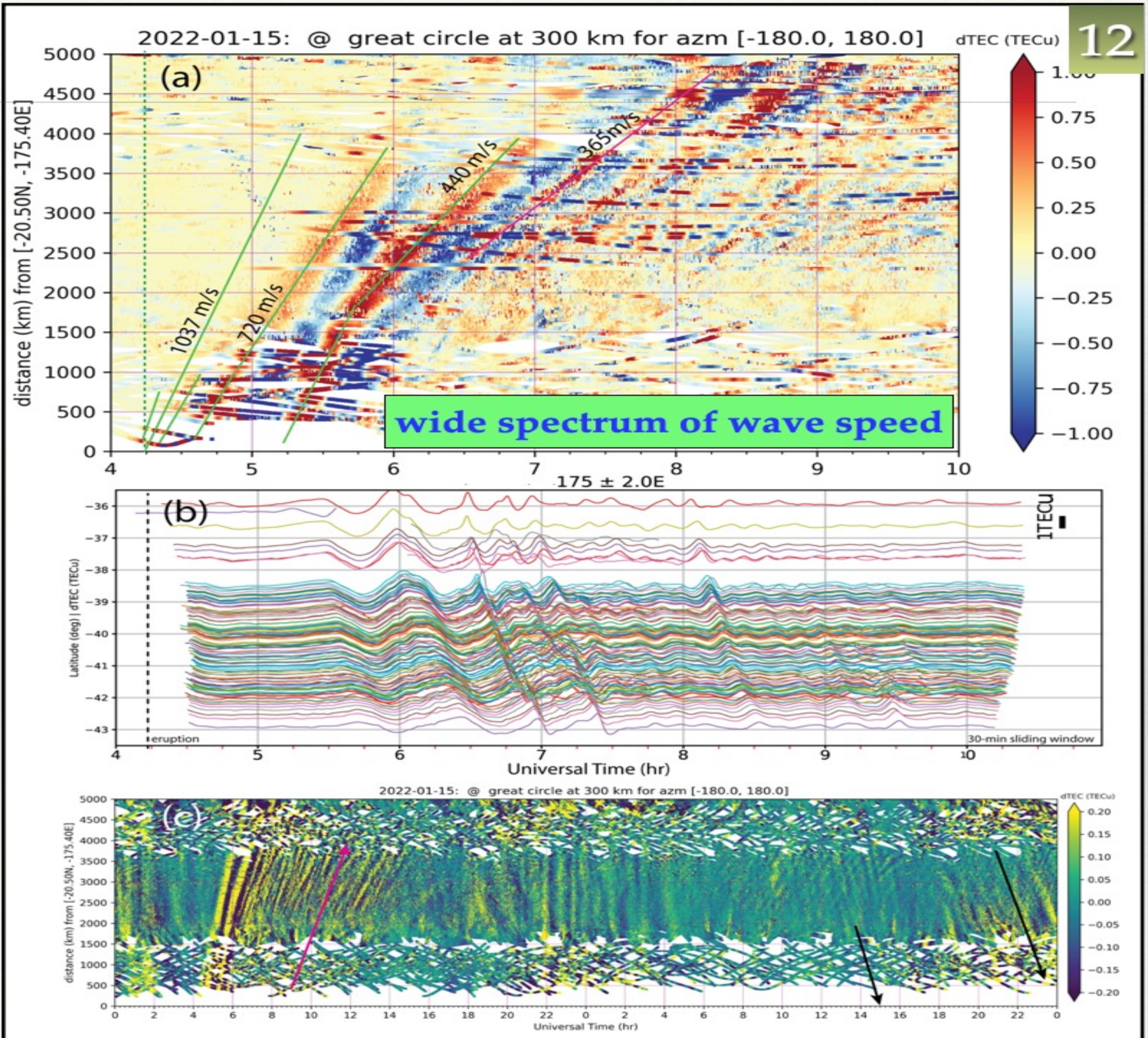
Near-field

Beidou GEO

Accurate TEC data: because of stationary ionospheric pierce point with fixed azimuth and elevation





wide spectrum of wave speed

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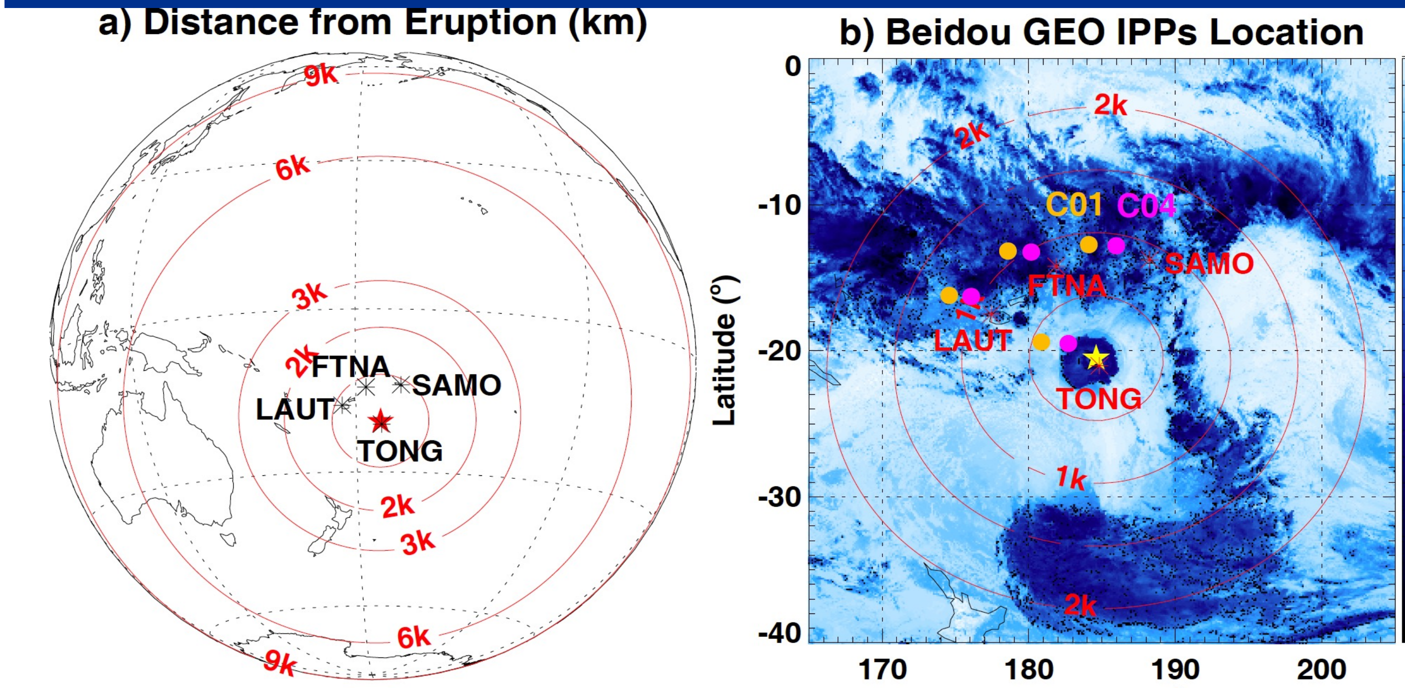
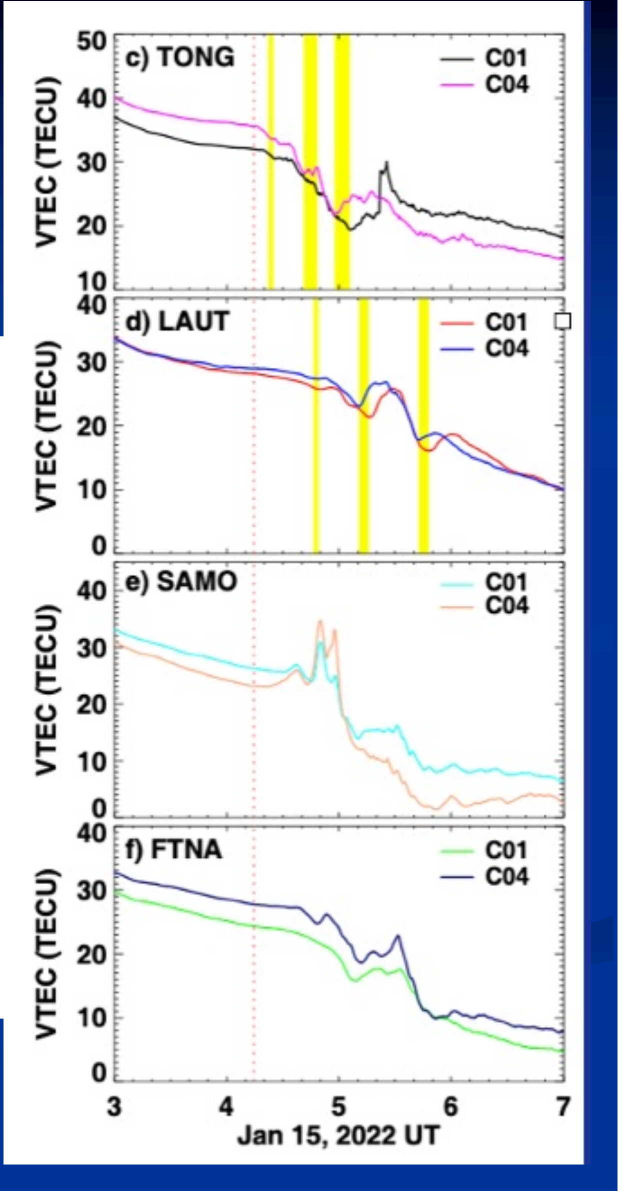
BEIDOU has 5 GEOSTATIONARY satellites and 4 MEO satellites. The GEO satellites allow for accurate TEC data because of stationary ionospheric pierce point with fixed azimuth and elevation

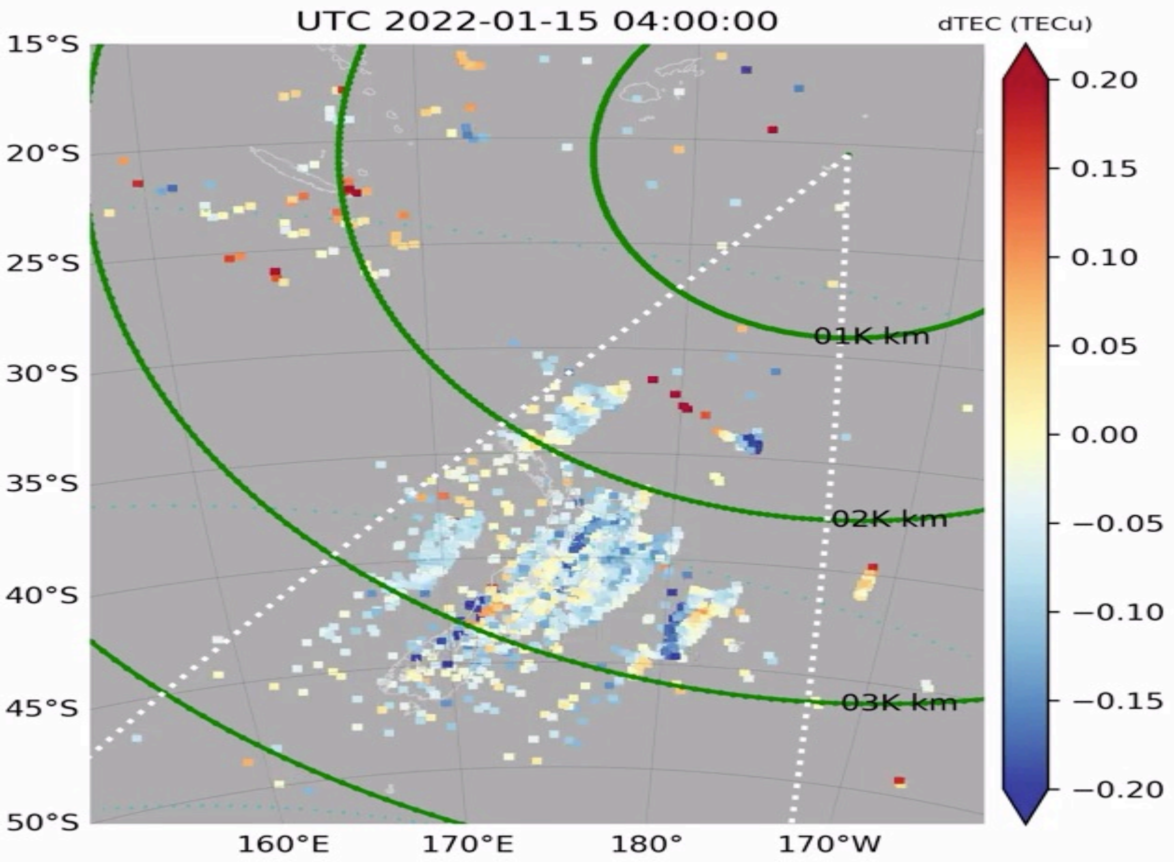




New Zealand (Animation)

Initial waves had huge amplitudes and wavelengths (~ 2K km!)

Subsequent waves had 300-500 km wavelengths



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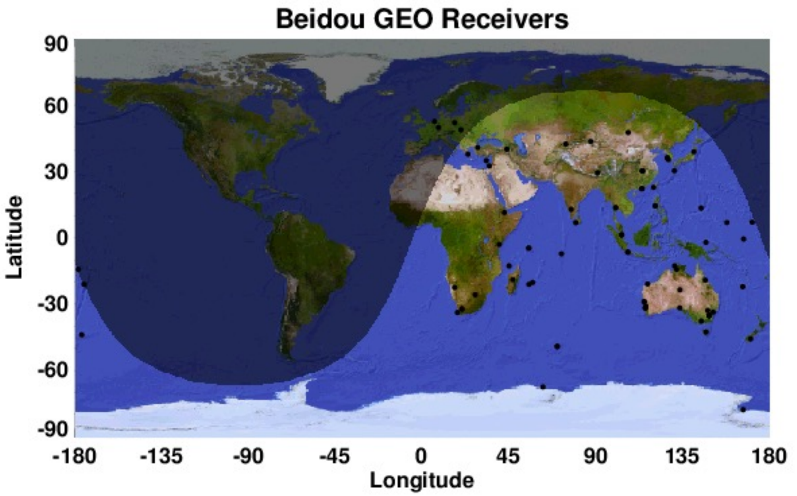

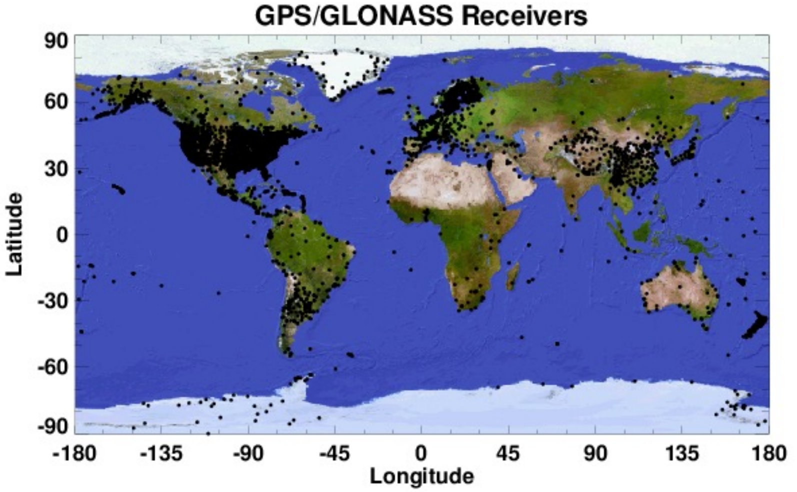

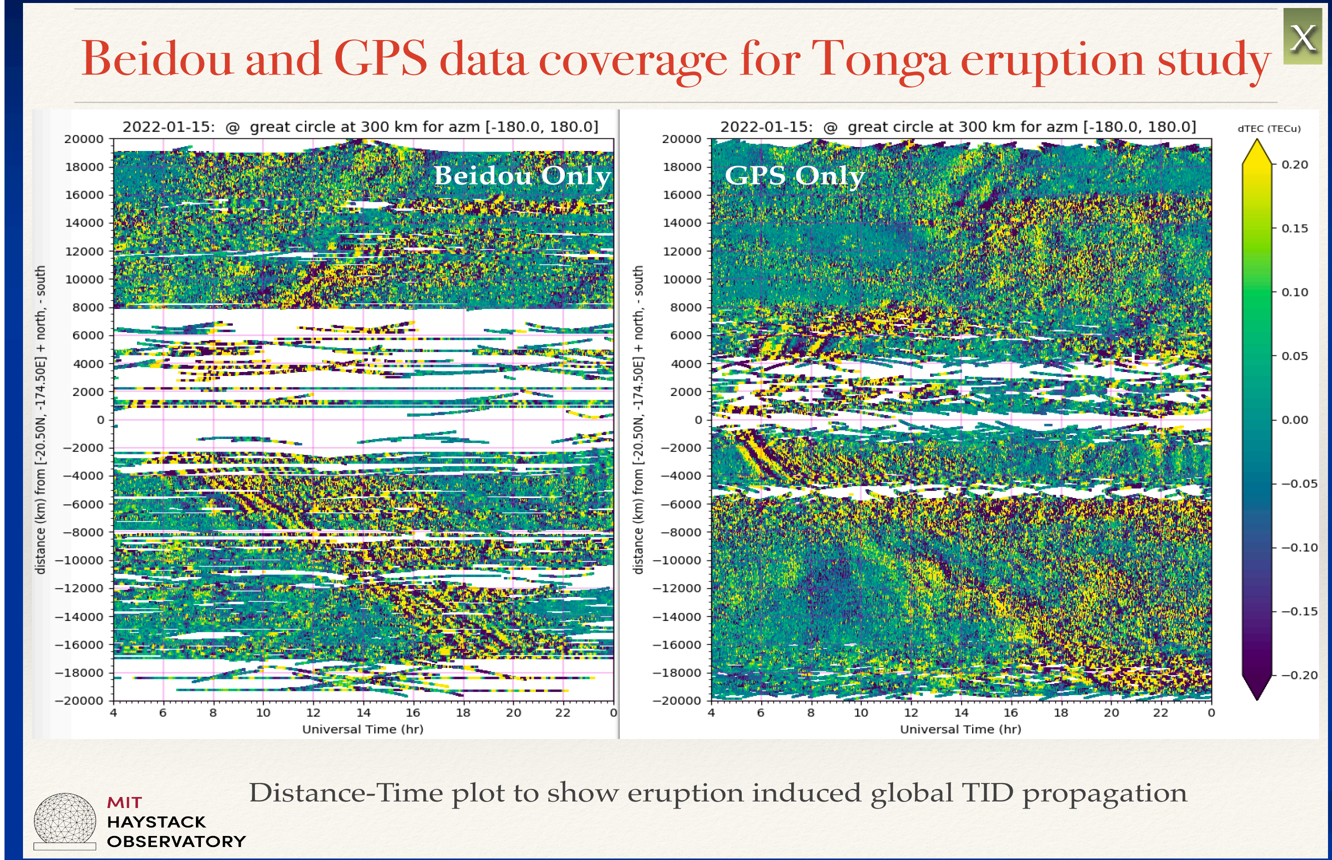

Beidou and GPS data coverage for Tonga eruption study

Distance-Time plot to show eruption induced global TID propagation

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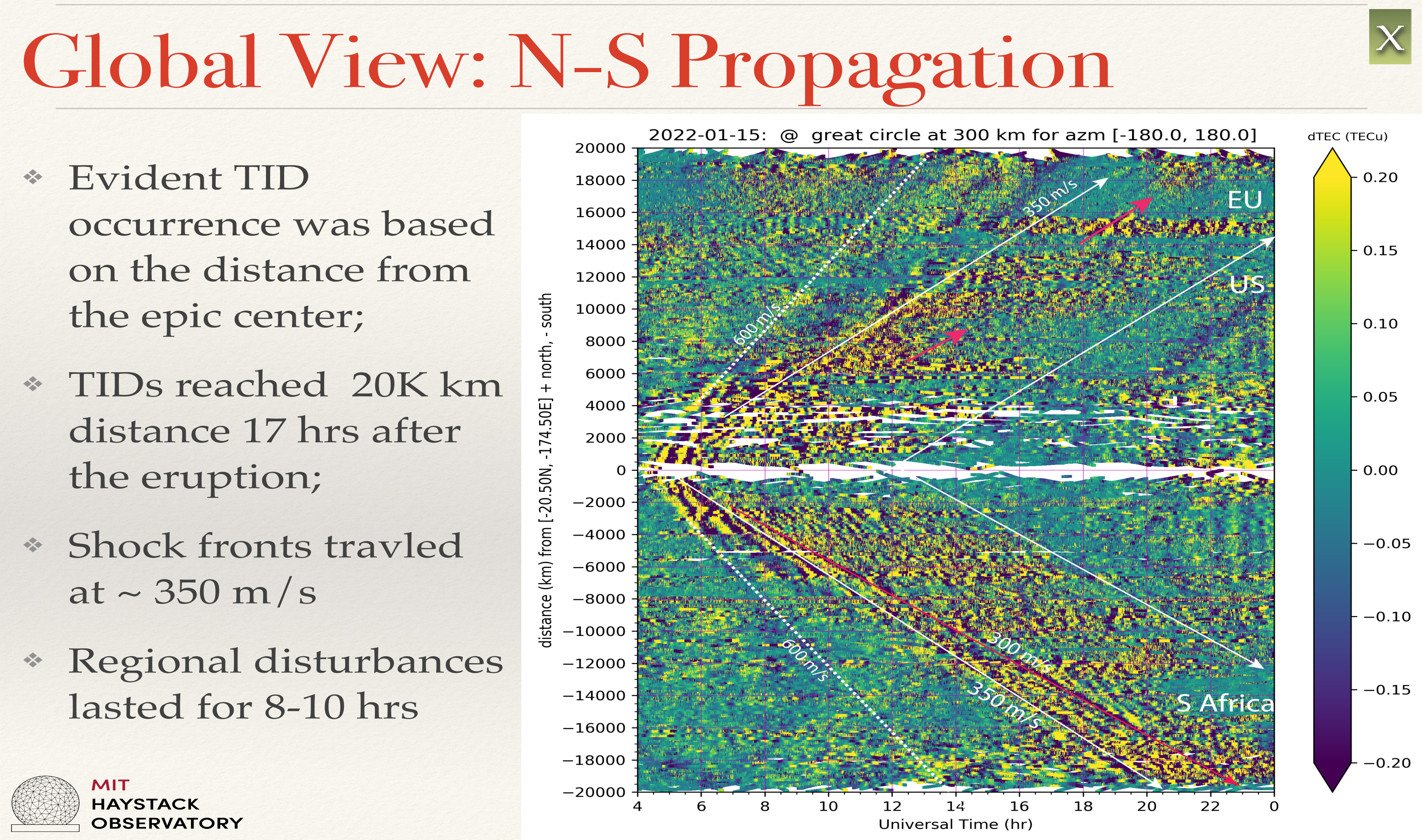
https://www.frontiersin.org/articles/10.3389/fspas.2022.871275/full



Global View: N-S Propagation

- Evident TID occurrence was based on the distance from the epic center;
- TIDs reached 20K km distance 17 hrs after the eruption;
- Shock fronts travled at ~ 350 m/s
- Regional disturbances lasted for 8-10 hrs

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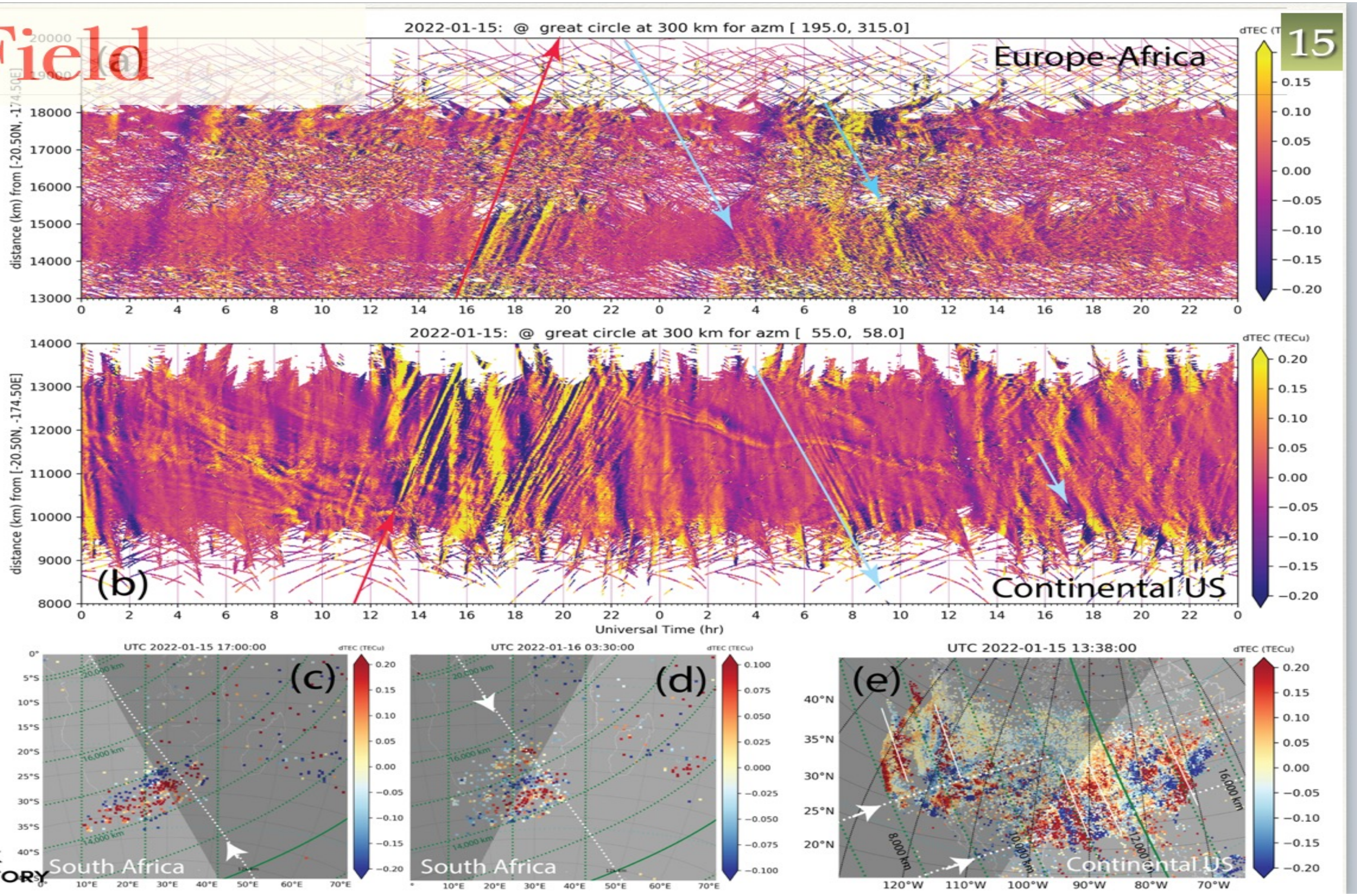
Far Field



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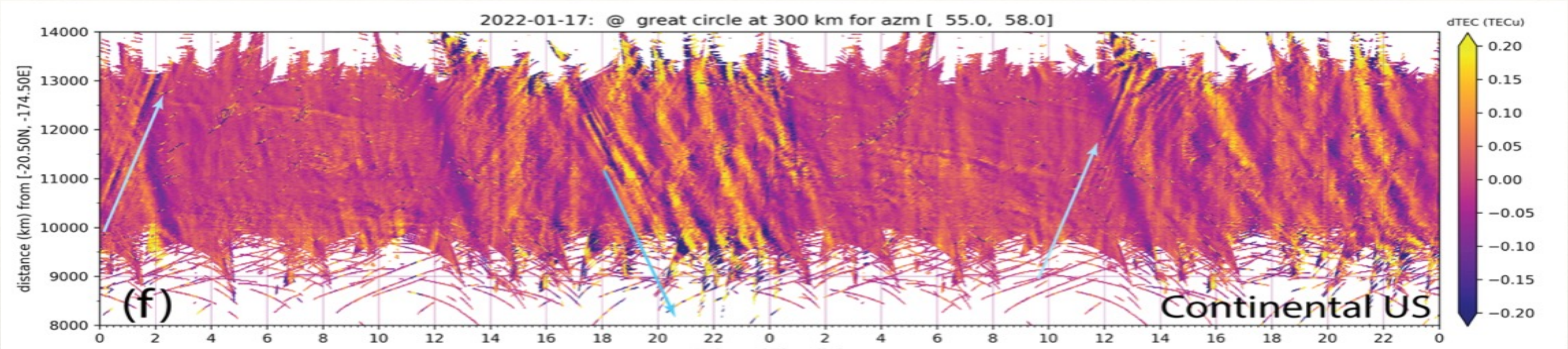
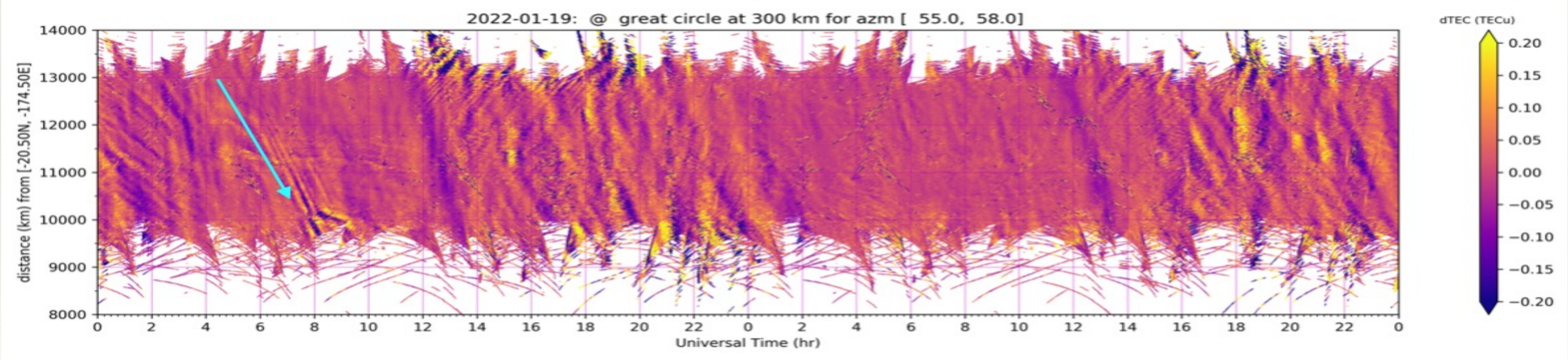
Global presence over 3 days: CONUS





Persistently at ~ 350 m/s speed, outbound or inbound
Occurrence times were consistent with global propagation at ~350 m/s speed

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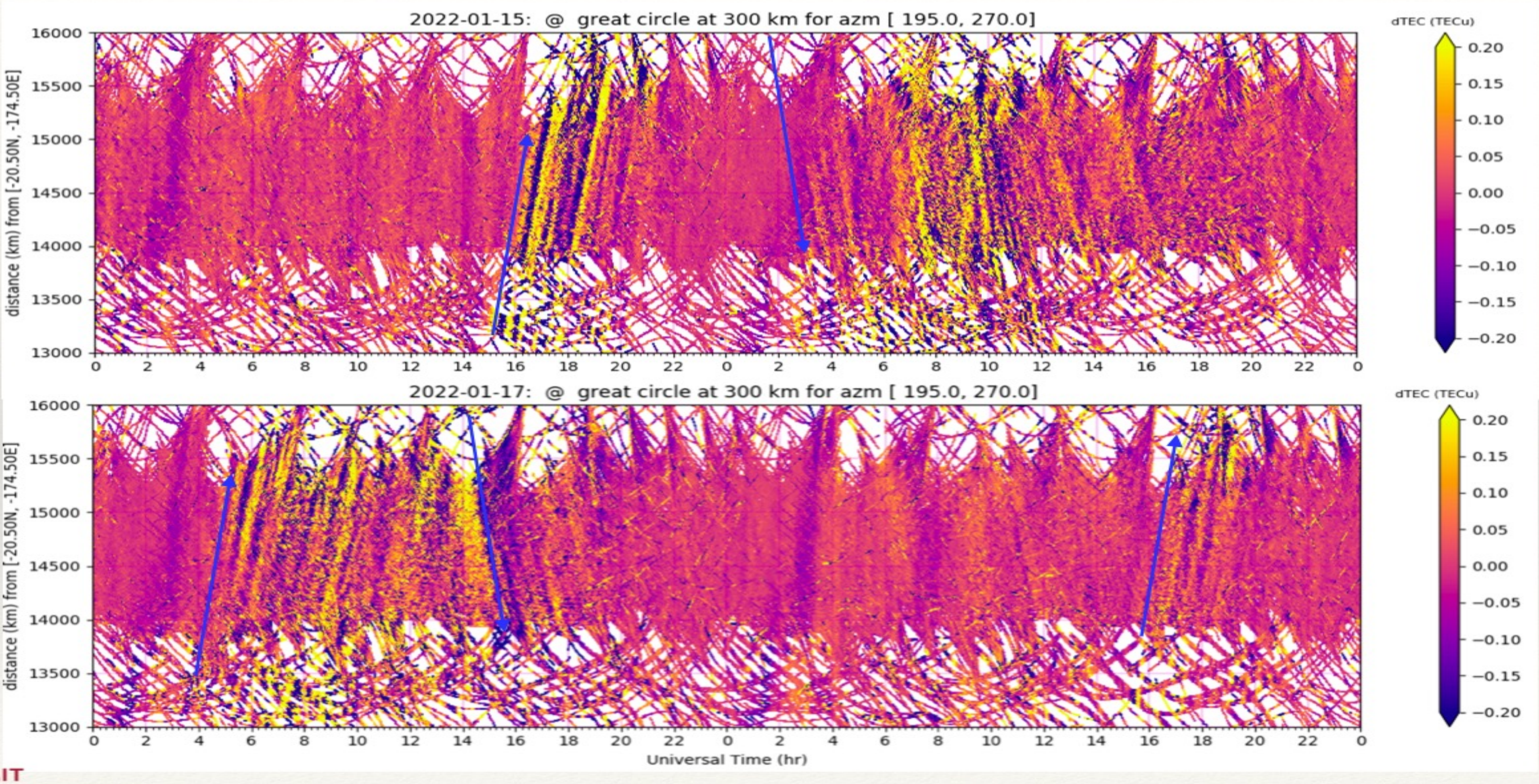
Europe-Africa sectors



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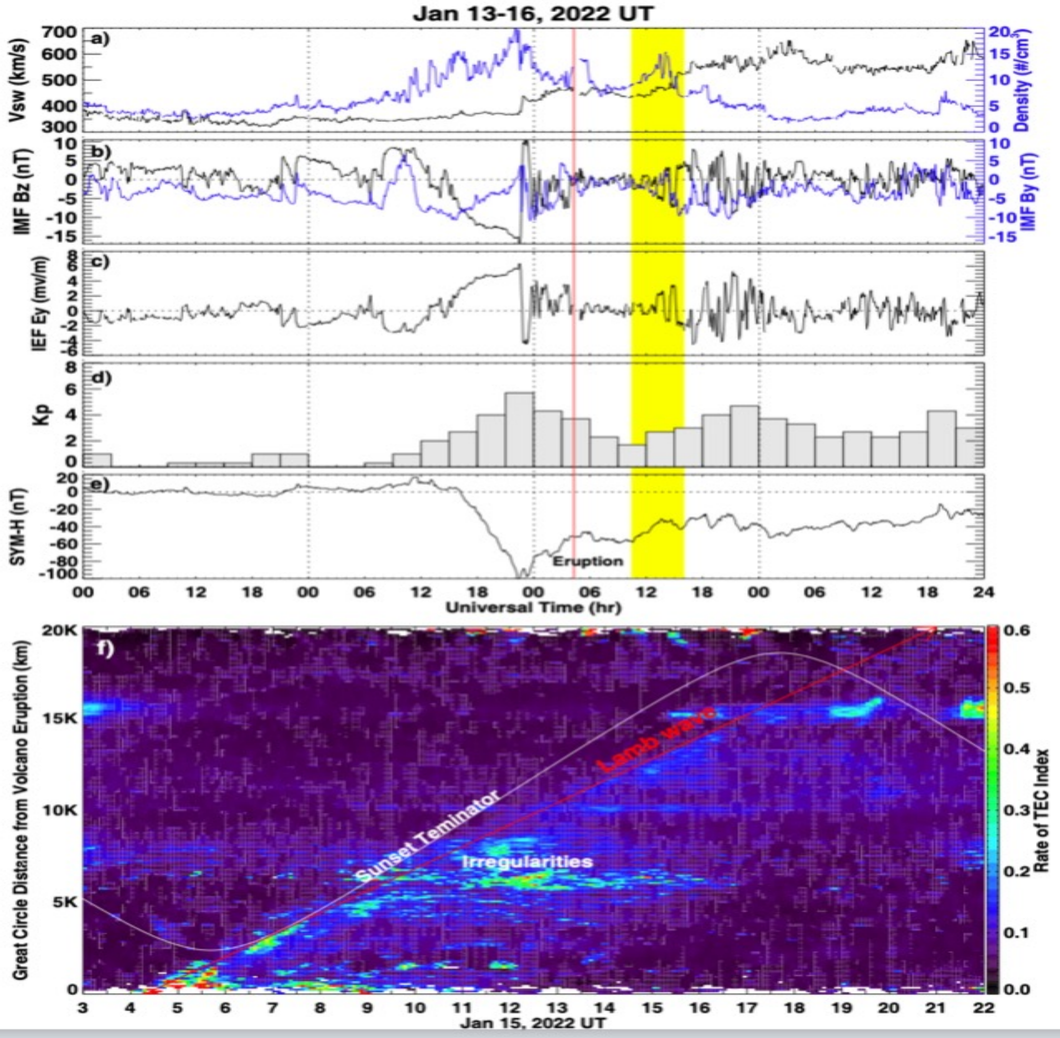
ROTI intensification

- ROTI intensification in the evening at 6-8K km distance from the epicenter, following the arrival of eruption induced TIDs/atmospheric waves
  - Lasted for several hours (11-15 UT)
- Corresponding to minor disturbances during the recovery phase of a moderate storm
- Not seen on the following day the 16th when IMF fluctuated at the same levels



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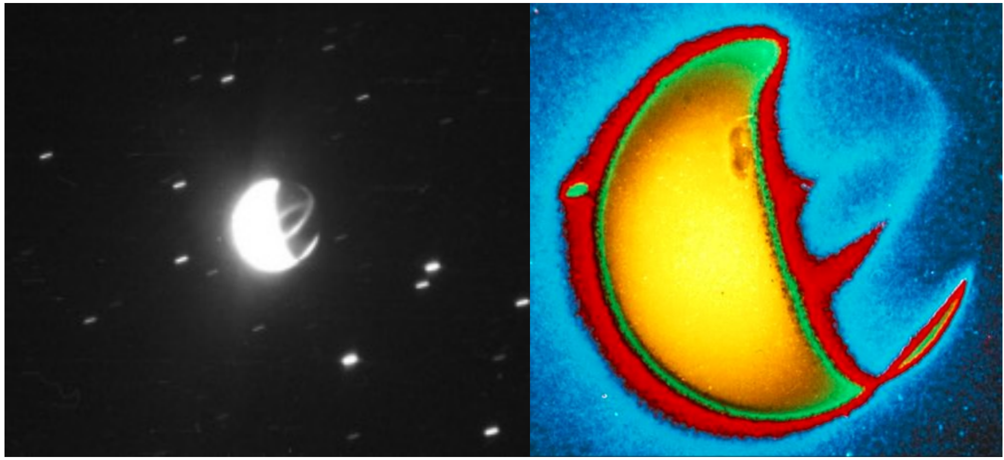
Pronounced suppression and X-pattern merging of equatorial ionization anomalies after the 2022 Tonga Volcano eruption

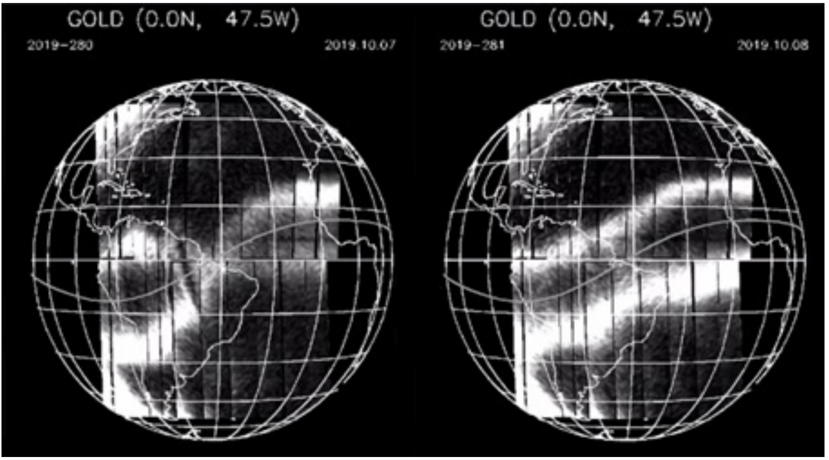
Ercha Aa[1], Anthea Coster1, Shun-Rong Zhang[1], Wenbin Wang[2], Philip J. Erickson[1], Liying Qian[2], Richard Eastes[3], Brian J. Harding[4], Thomas J. Immel[4], Deepak K. Karan[3], Robert E. Daniell[5], Larisa P. Goncharenko[1], Juha Vierinen[6], Xuguang Cai[3], and Andres Spicher[6]

[1]Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts, USA.
[2]High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA
[3]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA
[4]Space Sciences Laboratory, University of California Berkeley, Berkeley, CA, USA
[5]Ionospheric Physics, Stoughton, MA, USA
[6]Department of Physics and Technology, The Arctic University of Norway, Tromso, Norway

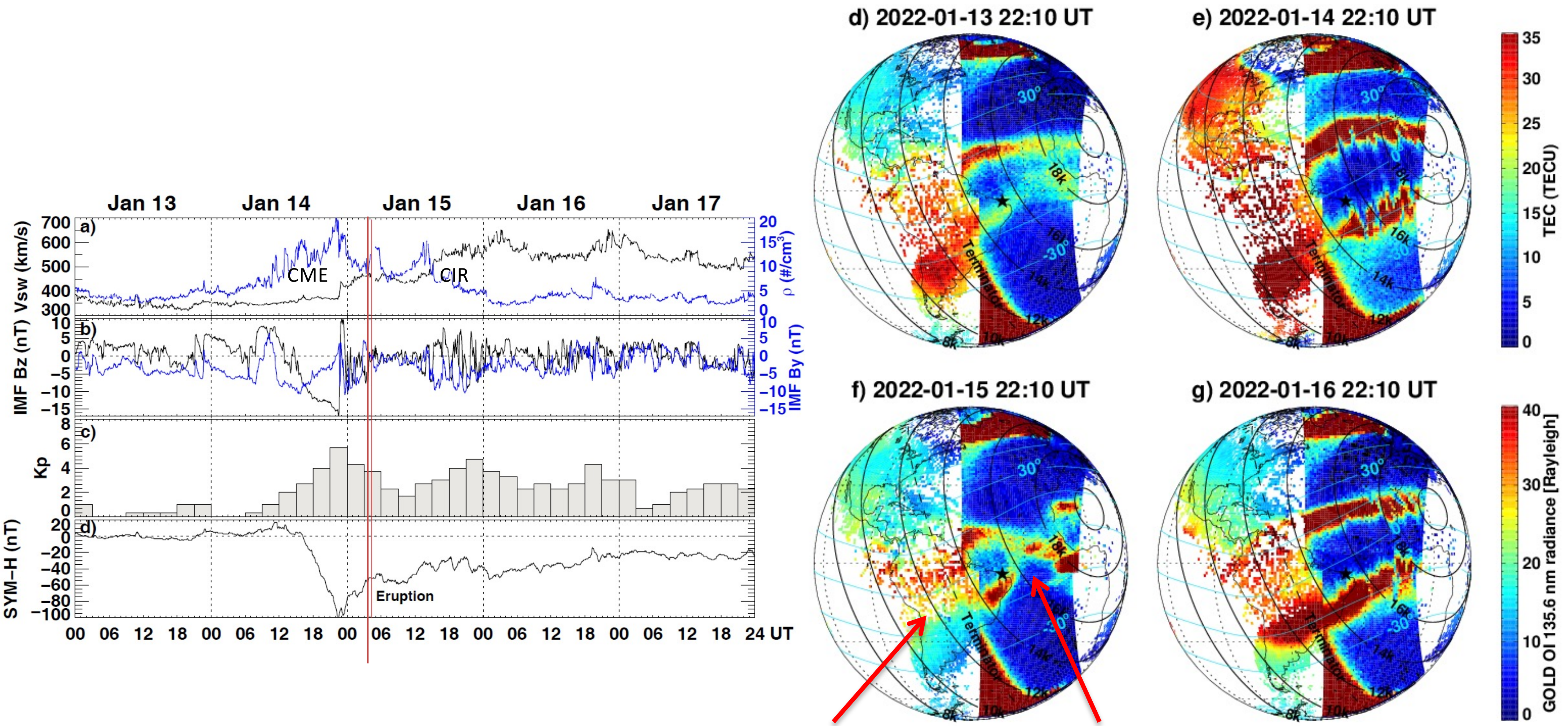
EIA X-pattern (Apollo 16)



GOLD constant LT images (Daniell et al., 2021)



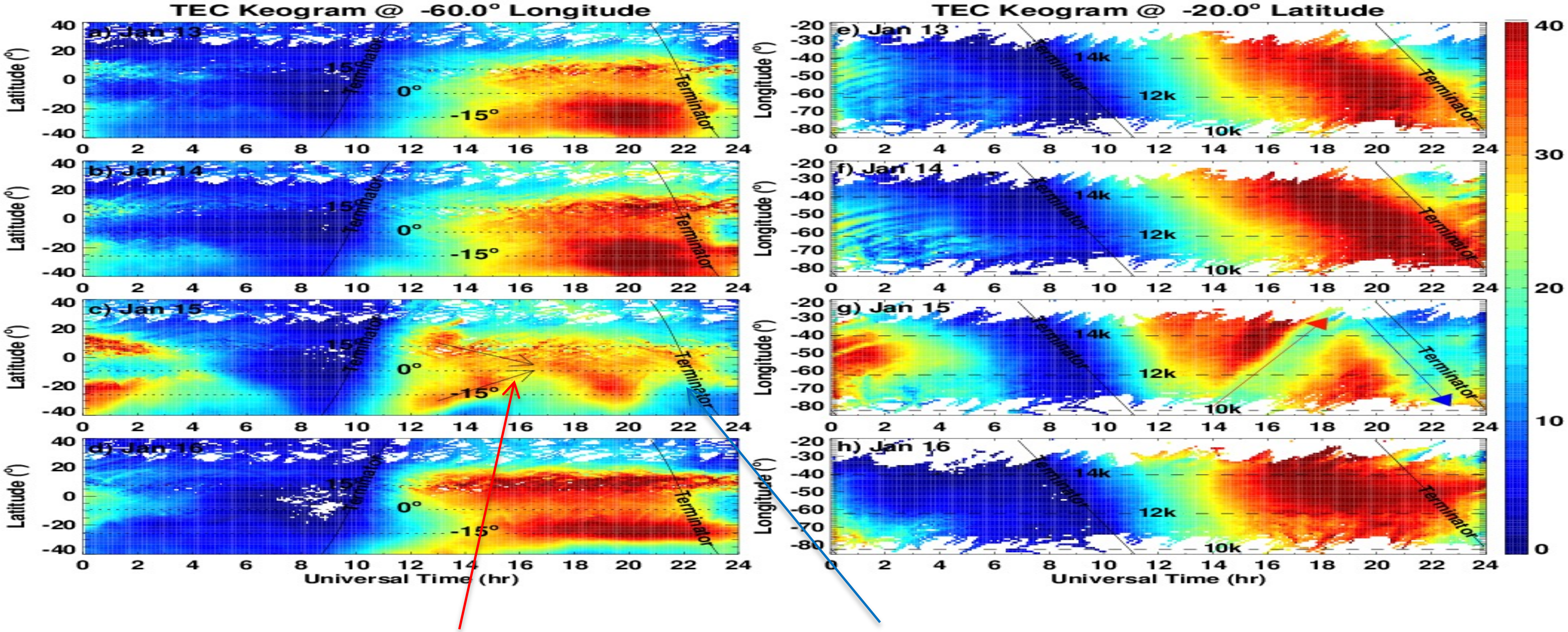
Pronounced EIA suppression and X-pattern merging after the 2022 Tonga Volcano eruption



Daytime suppression

Nighttime X-pattern merge

Pronounced EIA crests suppression and X-pattern merging



Daytime EIA crests suppression/merge

Time: 15—17 UT

Reduction: 10+ TECU

Equatorward collapse: >10°

following arrival of Lamb waves

Dusktime EIA crests suppression/merge

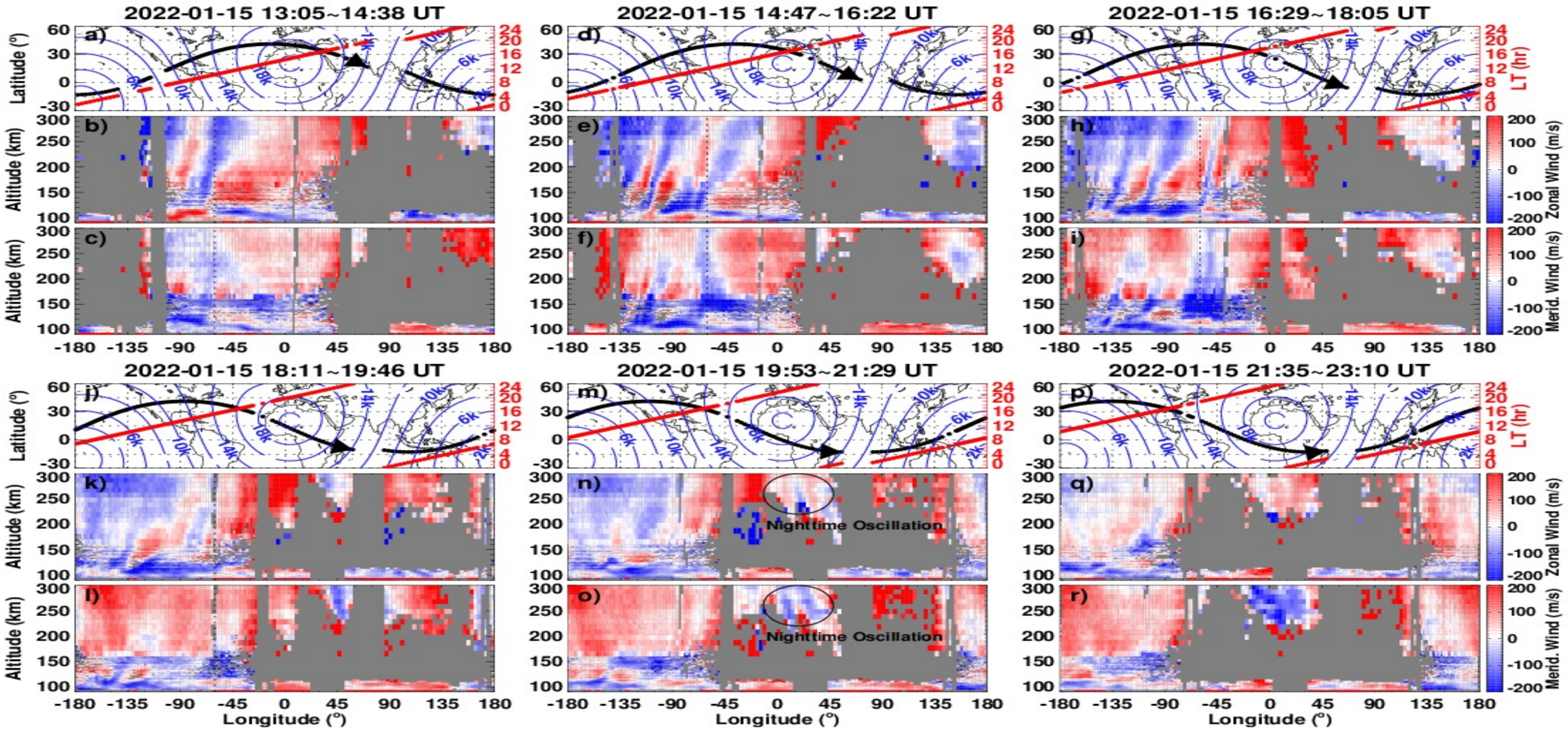
Time: 21—23 UT

Reduction: 10+ TECU

Equatorward collapse: >10°

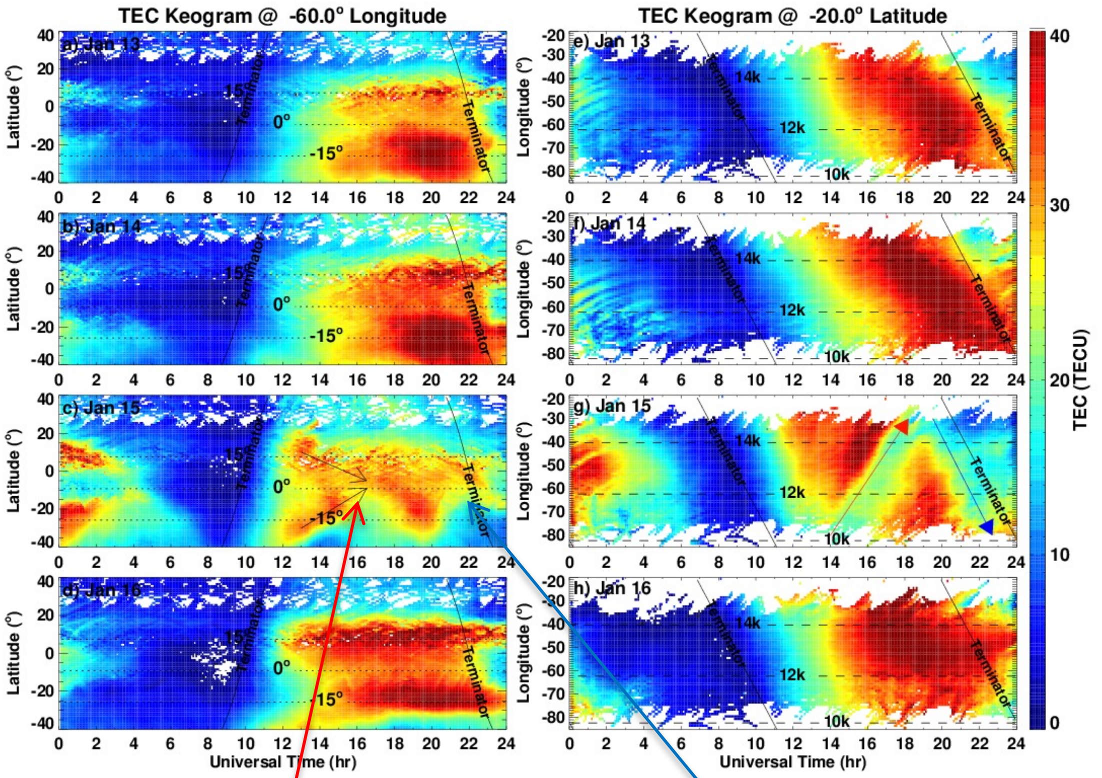
7—8 hours after waves arrival

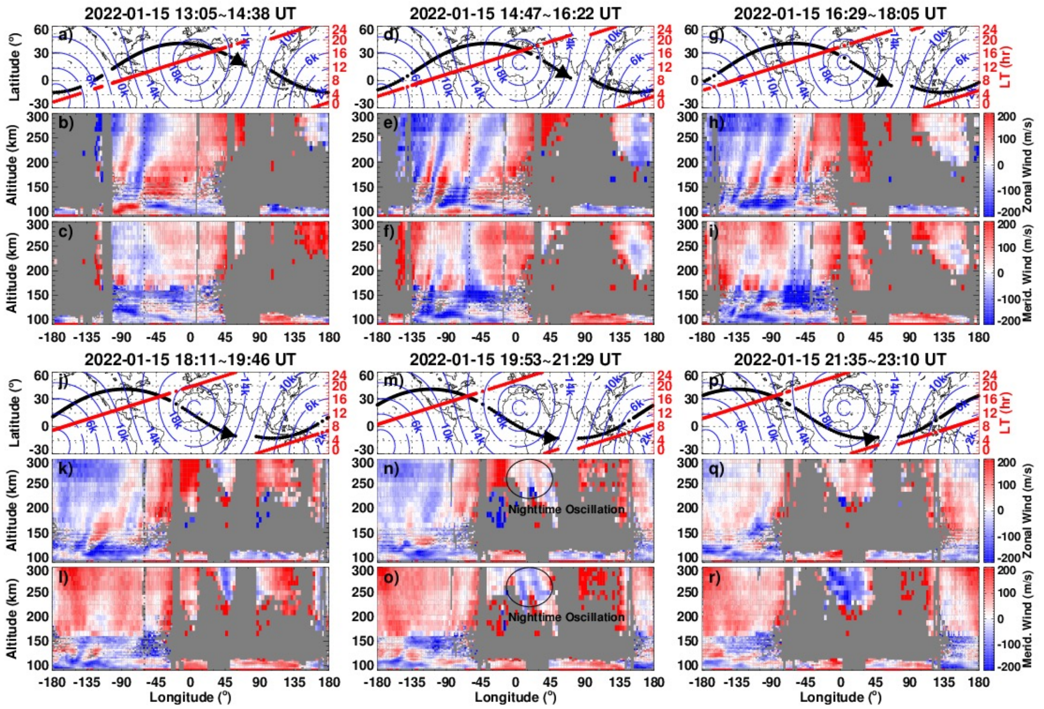
ICON MIGHTI DATA



ICON MIGHTI thermospheric horizontal winds, especially zonal winds, showed strong and prolonged post-volcanic oscillations of ±200 m/s, that are in-phase with the deformation and reformation of EIA crests shown in GNSS TEC at same longitudes

Pronounced EIA crests suppression and X-pattern merging





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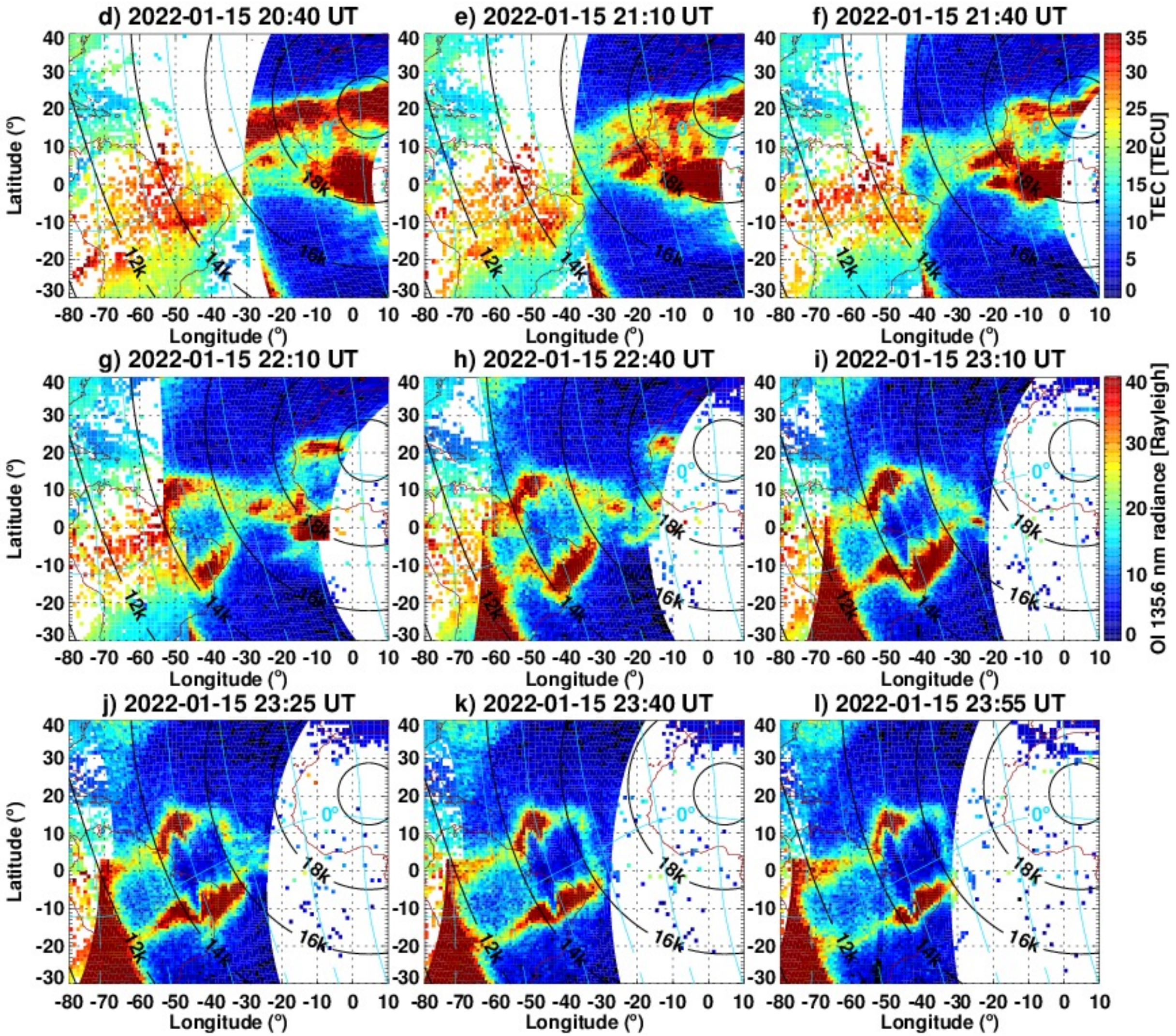
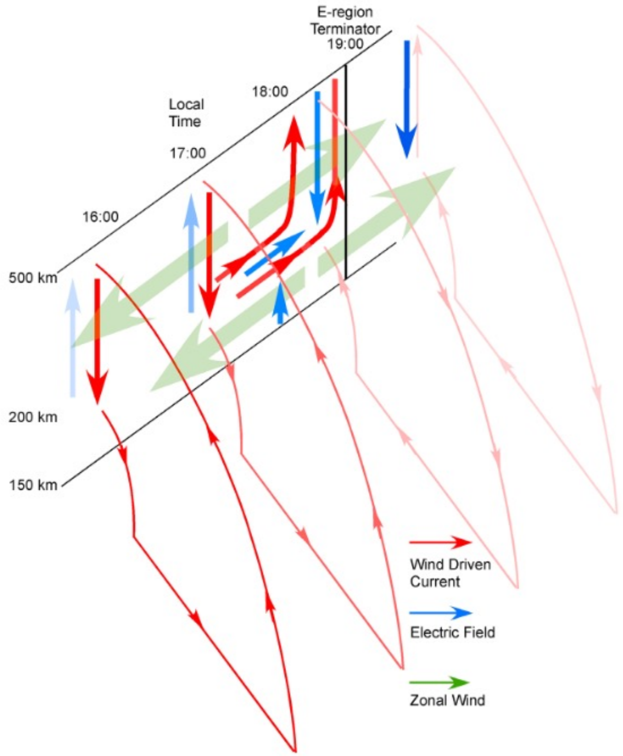


Eastward F-region zonal wind → Prereversal enhancement [edge effects, Heelis et al., (2012)]

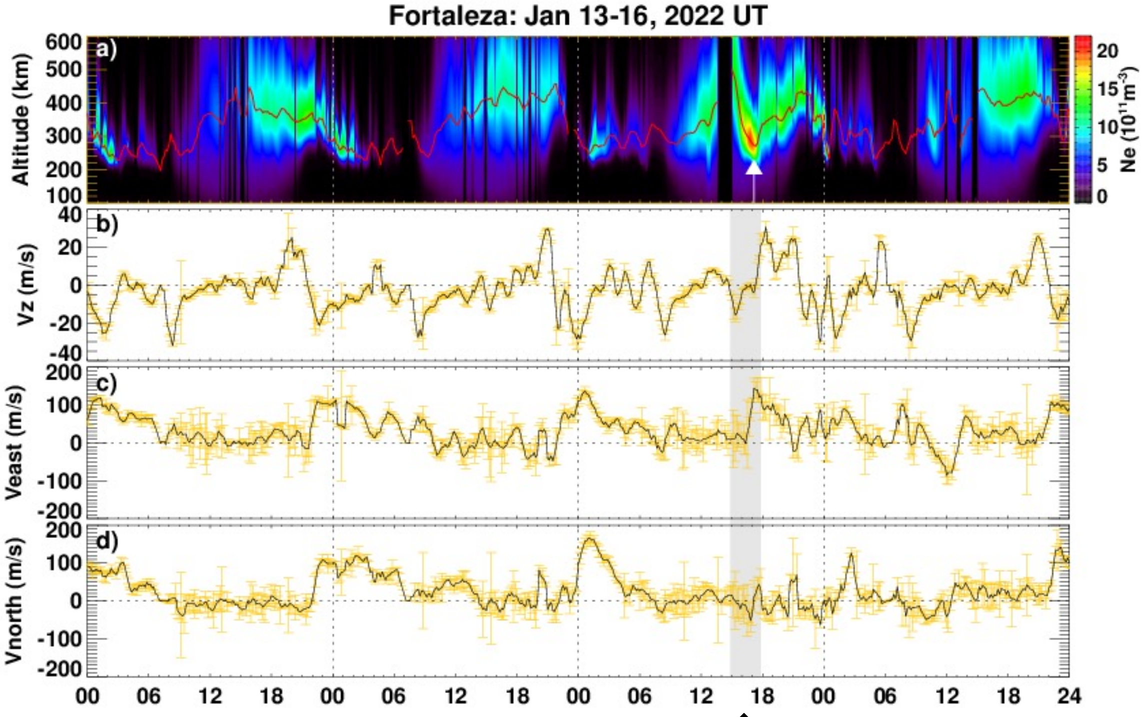


X-pattern formation

Large zonal wind oscillations with westward reversals→ Westward zonal electric field→ downward plasma drift

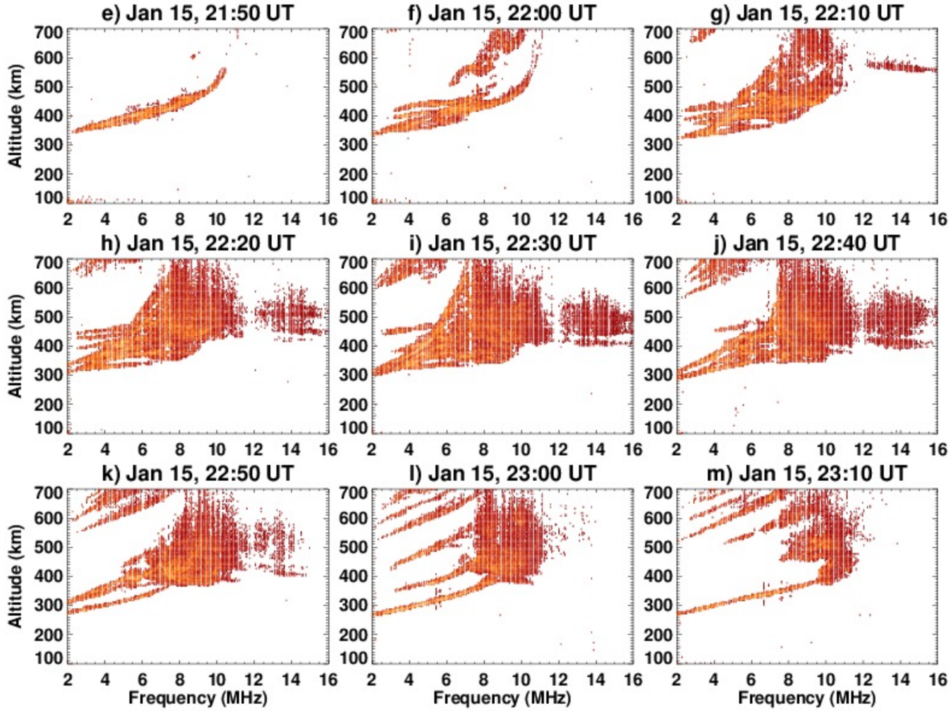
Ionosonde measurements

Drastic hmF2 decrease from 500 km to 260 km



Volcano-induced wave passage time

Strong frequency-type spread-F



Ionospheric/thermospheric modulations still exist 7—8 hours after volcano-induced wave passage

Haystack Papers on Tonga

- 2022 Tonga Volcanic Eruption Induced Global Propagation of Ionospheric Disturbances via Lamb Waves. *Frontiers in Astronomy and Space Sciences.* (2022). DOI: https://doi.org/10.3389/fspas.2022.871275

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- Significant equatorial plasma bubbles and global ionospheric disturbances after the 2022 Tonga volcano eruption. (2022). DOI: https://doi.org/10.1002/essoar.10510637.1

Main conclusions

- TIDs were radially outbound and inbound along entire Great-Circle loci at ~300-350 m/s [i.e., 34 hrs for an entire GC], **going around the globe for three times, passing six times over the continental US in 100 hours since the eruption**.
  - These TIDs have a range of periods but predominately occur at 10-30 min.
  - With the arrival of front shock, ~8 hrs continuous fluctuations followed
- TID global propagation is consistent with the effect of Lamb waves which travel at the speed of sound: first evidence of their long-duration imprints up in the global ionosphere
  - Lamb waves are normally confined in the troposphere, but some of their energy leaked to the thermosphere.
- Near-field waves and TEC depletion, consistent with known eruption/earthquake effects
  - Huge TEC depletion
- Irregularity intensification and EPBs were found in the evening hours in Asian-Oceania sector, following the arrival of eruption induced atmospheric waves/TIDs
  - unlikely an IMF effect
- EIA crests modification on both dayside and nightside with the arrival of lamb waves
  - Erosion (dayside) and X-pattern (nightside) could be caused by modifications on the E and F region dynamos due to neutral wind perturbations.