Survey of ionospheric F2 region variability from the lower atmosphere

Phil Erickson, W1PJE (Atmospheric and Geospace Sciences Group / MIT Haystack Observatory)

Carl Luetzelschwab, K9LA (ARRL)

Purpose of this Presentation

Highlight the time scales of the variations of the F2 region of the ionosphere (Part 1)

Review F2 region variations due to events at ground level and in the lower atmosphere (Part 2)

Collins, K., D. Kazdan, and N. A. Frissell (2021), Ham radio forms a planet-sized space weather sensor network, *Eos, 102,* https://doi.org/10.1029/2021EO154389. Published on 09 February 2021.

> *"Although we have a good understanding of ionospheric climate—diurnal and seasonal variations are well known, as are the rhythms of the sunspot cycle—there are new and vital areas of research to be explored. For example, it is known that the ionosphere—and near-Earth space—experiences variability (e.g., radio signals can fade in and out over periods of seconds, minutes, or hours due to changes in ionospheric electron densities along signal propagation paths), but this variability has not been sampled or studied adequately on regional and global scales."*

Agenda

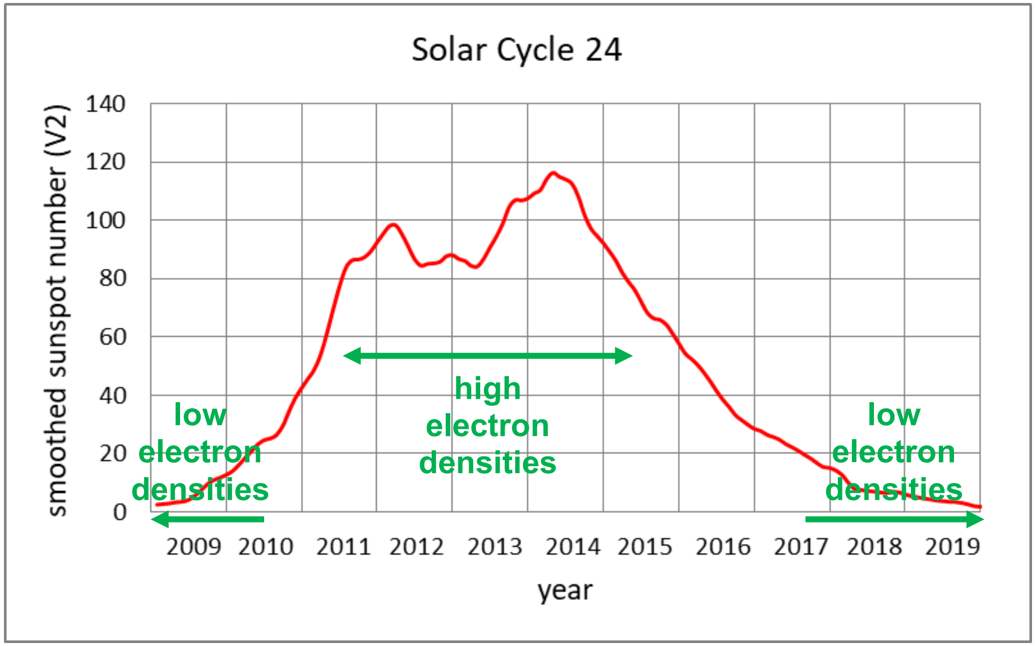
- Part 1 by Carl K9LA
  - Time scales of F2 region variation
  - Factors causing the variation
  - Preliminary look at the Tohoku earthquake of 2011
- Part 2 by Phil W1PJE
  - Types of physical processes driving F2 layer ionospheric variations “from below”
  - Numerical estimates of the various forcing terms
  - More detailed look at the Tohoku earthquake
  - Confirming results with other events

Part 1

Carl K9LA

Time Scales of F2 Variations

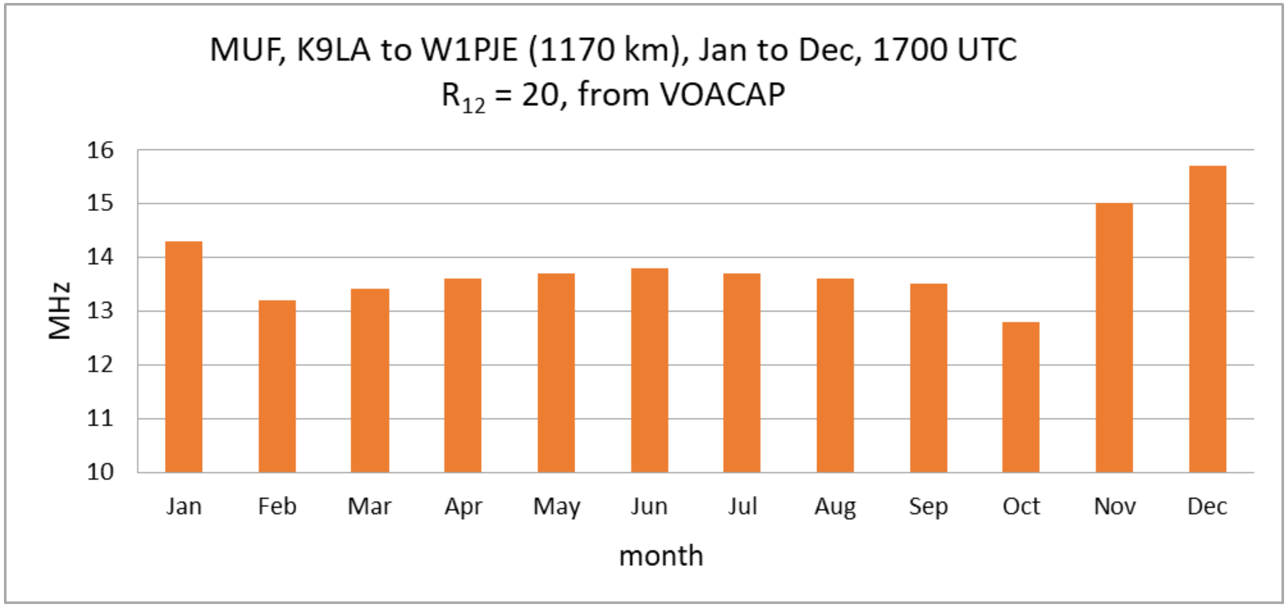
- Over an (approximate) 11-year solar cycle



The maximum F2 electron density and the height of the maximum F2 electron density are correlated to the F2 region MUF (maximum useable frequency)

Time Scales of F2 Variations

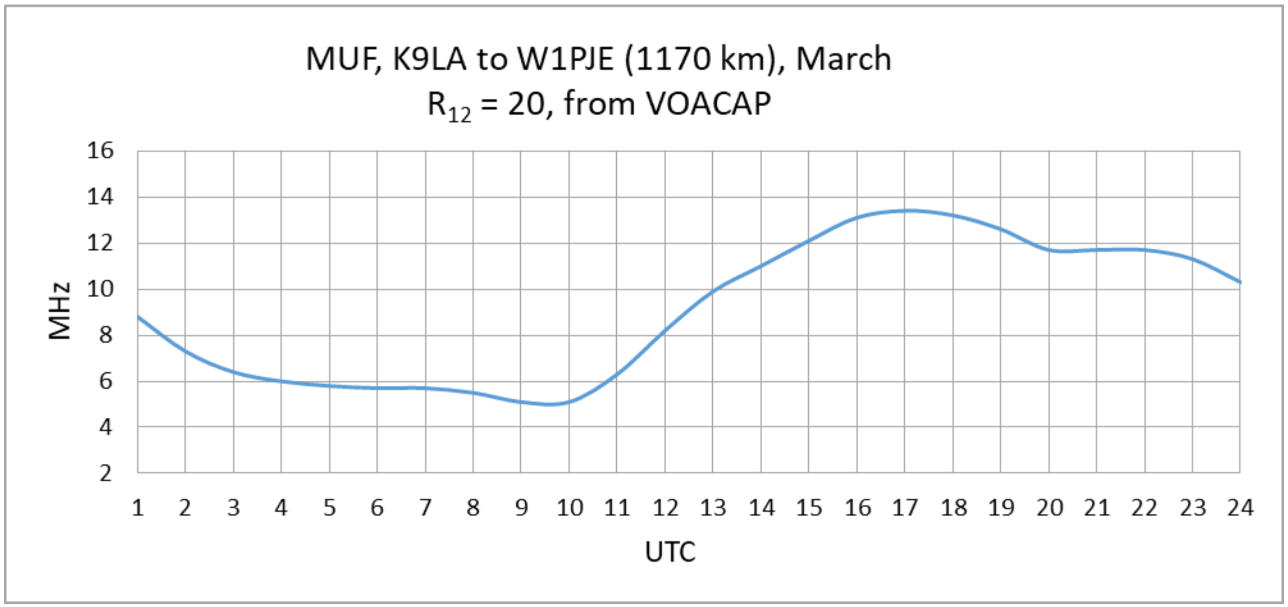
- Monthly
- Composition of the atmosphere changes on a seasonal basis



- O/N_2 ratio highest in fall and winter in northern hemisphere
- O important for electron production
- N_2 important for electron loss

Time Scales of F2 Variations

- Diurnal (daily)
- Biggest difference is night and day

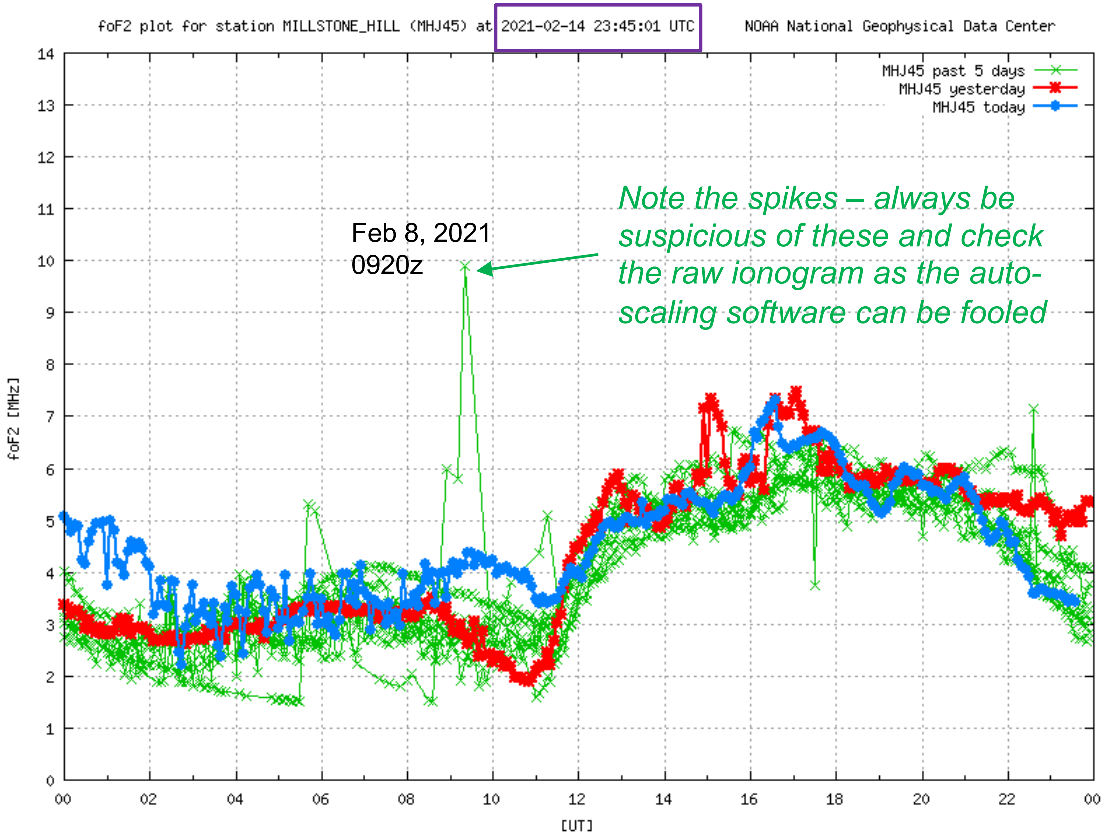


- These results are <u>monthly median</u> MUFs
- Why do we have monthly median MUFs?

median implies a 50% probability

Time Scales of F2 Variations

- Each day is <u>not</u> the same
- The day-to-day variation of the F2 region can be significant



- This is why VOACAP, W6ELProp, IRI, et al, don't give daily propagation predictions – we don't have a full understanding (yet) of these day-to-day variations
- We'll now review the factors that cause this day-to-day variation, which also tie into **even shorter F2 variations**

Factors Causing F2 Region Variation

- H. Rishbeth and M. Mendillo, *Patterns of F2-layer variability*, Journal of Atmospheric and Solar-Terrestrial Physics 63 (2001) 1661–1680
- Used data from 13 worldwide ionosondes over 34 years (1957–1990)
- They focused on the daily variation of the F2 region
- To reiterate, this study ties into very short variations of the F2 region

The Factors

1. *Solar ionizing radiation*

Solar flares
Solar rotation (27 day) variations
Formation and decay of active regions
Seasonal variation of Sun's declination
Annual variation of Sun–Earth distance
Solar cycle variations (11 and 22 years)
Longer period solar epochs

2. *Solar wind, geomagnetic activity*

Day-to-day 'low level' variability
Substorms
Magnetic storms
IMF/solar wind sector structure
Energetic particle precipitation
and Joule heating

3. *Neutral atmosphere*

Solar and lunar tides: generated within thermosphere
or coupled through mesosphere
Acoustic and gravity waves
Planetary waves and 2-day oscillations
Quasi-biennial oscillation
Lower atmosphere weather coupled through mesopause
Surface phenomena: earthquakes, volcanoes

4. *Electrodynamics*

Dynamo 'fountain effect' at low latitudes
Penetration of magnetospheric electric fields
Plasma convection at high latitudes
Field-aligned plasma flows to and from plasmasphere and
protonosphere
Electric fields from lightening and sprites

- Authors reduced all of these into three broad categories
  - solar radiation (#1 above)
  - geomagnetic activity (#2 above)
  - meteorological (#3 and #4 above)

Daytime Daily Variation

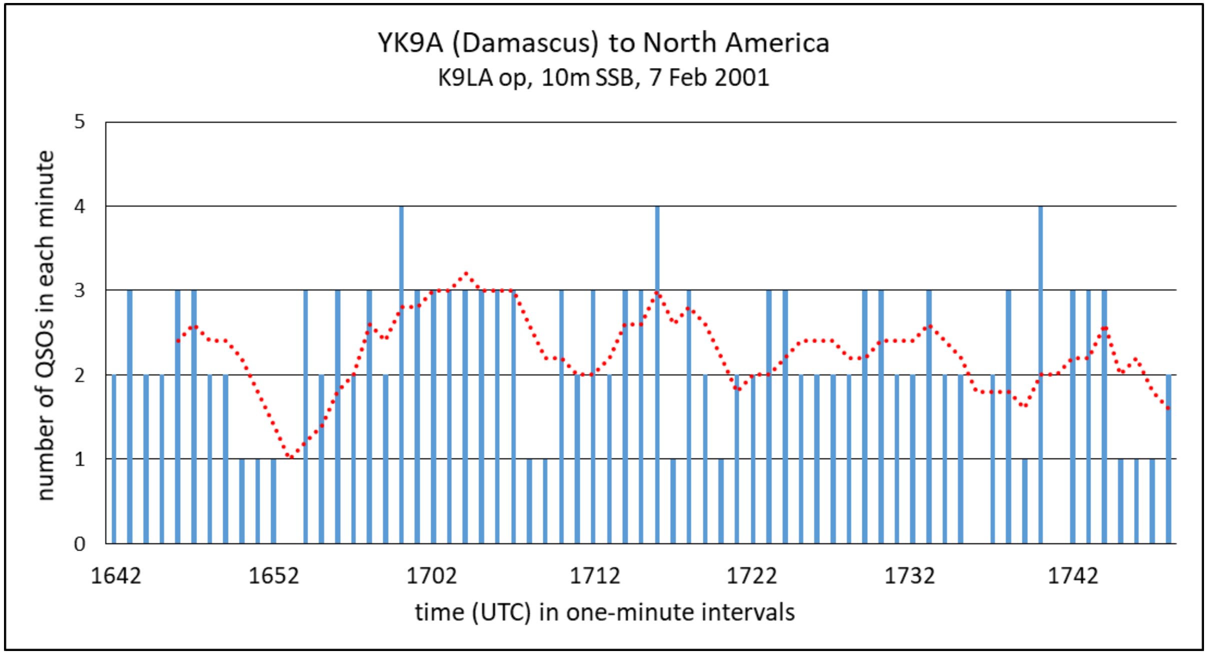
- They determined that the NmF2 std dev / NmF2 mean was, on average, 20% during the day (33% by night)
- They then determined how much each of the three factors contributed to this 20% total
  - solar radiation (std dev / mean)^2 = 3%
  - geomagnetic activity (std dev / mean)^2 = 13%
  - meteorological (std dev / mean)^2 = 15%

as a check,
$0.20^2 = 0.03^2 + 0.13^2 + 0.15^2$ ✓

- The factor that we know the most about (solar radiation) contributes the least to the daily variation
- The STORM model addresses F2 variation vs geomagnetic field activity – is it good enough?
- Lots of research on-going in the meteorology arena

On-the-Air Example of Short Variations

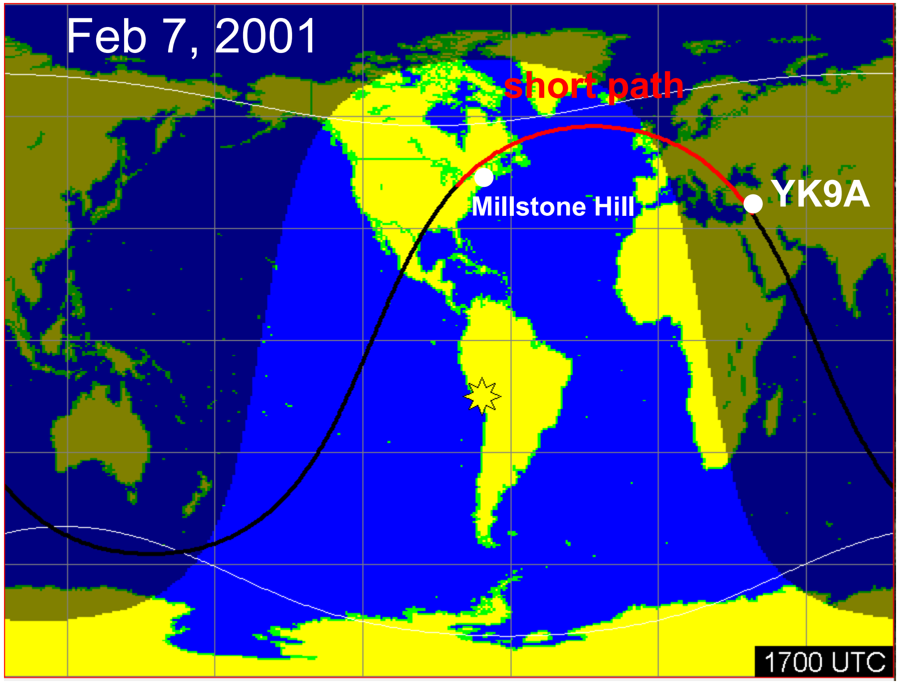
- A group of us operated from YK9A in Damascus (Syria) in February 2001 (back row - N4CFL, VE7CC, YK1AH, N7RO, YK1AO, VA7MI, W4PRO (SK), front row - K7AR, K9LA, AE9YL, W4DR)
- I was on 10m SSB in the late afternoon working NA – here's a graph from the log
  - Several minutes of many QSOs, several minutes of few (or zero) QSOs, and this would repeat



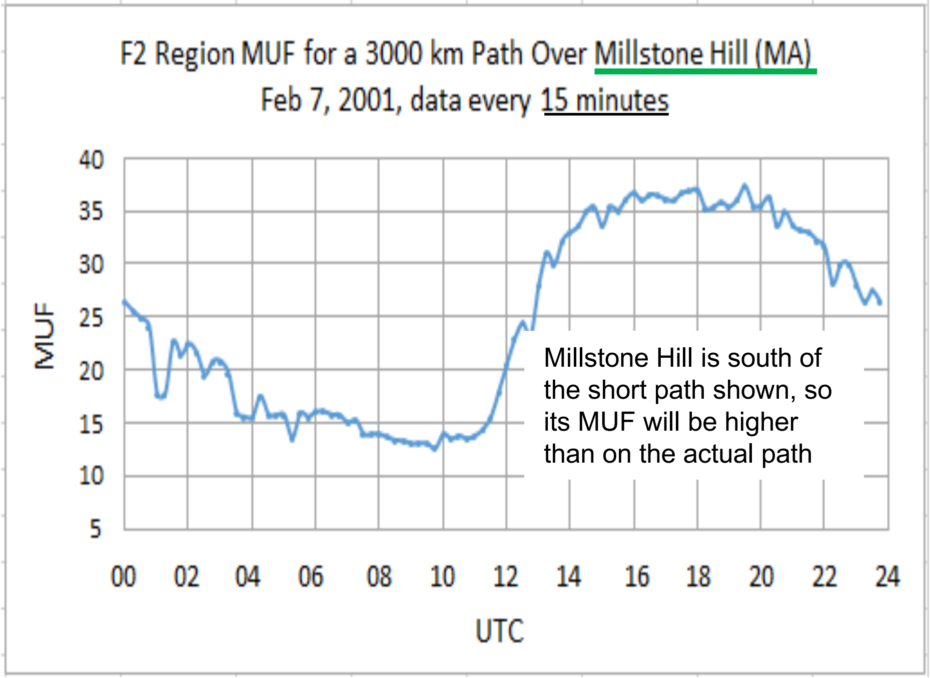
- Was this due to a TID (travelling ionospheric disturbance)?
- The MUF appeared to vary in a cyclic nature

I Tried to "See" a TID in Ionosonde Data

- Rome - 5 min, gaps in data, night
- Juliusruh (Germany) - 15 min, night
- Chilton (England) - 30 min
- Goose Bay - no data
- Narsarsuaq (southern Greenland) - no data
- Fairford (England) – no data



map from W6ELProp



- There's a hint of a TID during the day
- Would be nice to have data every 5 min

The Tohoku Earthquake of 2011

Azeem, I., S. L. Vadas, G. Crowley, and J. J. Makela (2017), Traveling ionospheric disturbances over the United States induced by gravity waves from the 2011 Tohoku tsunami and comparison with gravity wave dissipative theory, J. Geophys. Res. Space Physics, 122, 3430–3447, doi:10.1002/2016JA023659.

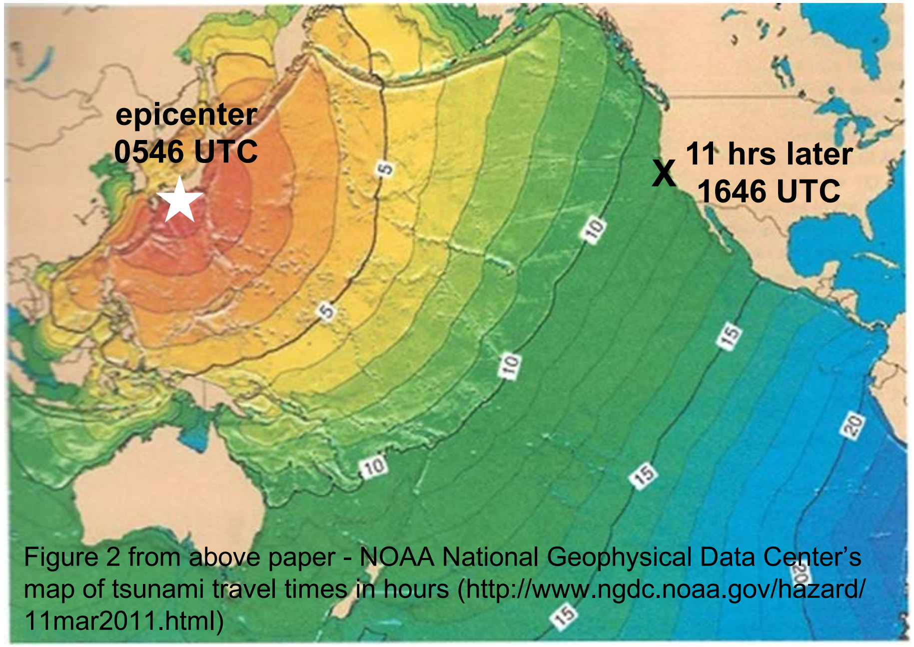


Figure 2 from above paper - NOAA National Geophysical Data Center's map of tsunami travel times in hours (http://www.ngdc.noaa.gov/hazard/11mar2011.html)

tsunami travel times

- March 11, 2011 Tohoku (Japan) earthquake (mag 9.0) at 0546 UTC
- Generated a tsunami
- Tsunami traveled across the Pacific Ocean and arrived at the US West Coast about 11 hours later

Tsunami – Effect on the Ionosphere

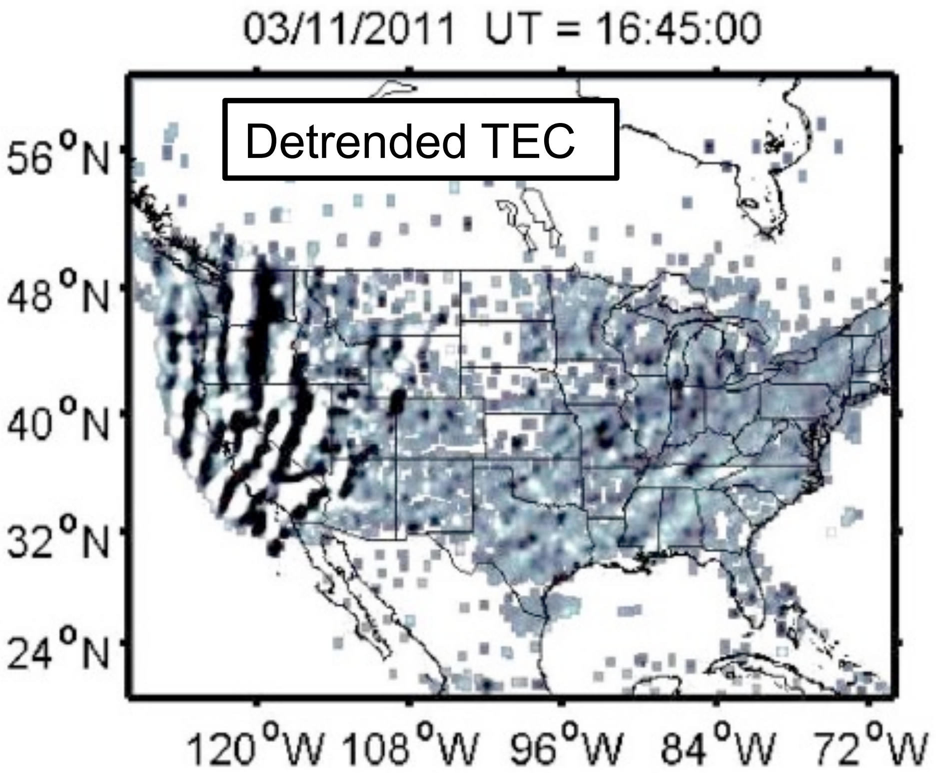


Figure 4 from same paper - Two-dimensional maps of TEC perturbations at 16:45 UT. This map show planar TID wave fronts over the West Coast of the United States.

- TEC perturbations far away from epicenter
- Pattern of TEC perturbations is similar to the pattern of the tsunami "wave front"

Now it's time for Phil with Part 2

Part 2

Phil W1PJE

Sources of Ionospheric Density Modulation

- Storm-time heating in the auroral zone, elsewhere:
  - Launches large amplitude ***acoustic gravity waves*** (AGWs)
  - Propagation in the form of ***traveling atmospheric disturbances*** (TADs)
  - Ionosphere-neutral atmosphere coupling leads to ***traveling ionospheric disturbances (TIDs)***
    - F region electron density variations – primarily relevant to this talk
    - Other parameters also vary (velocity, plasma temperature)

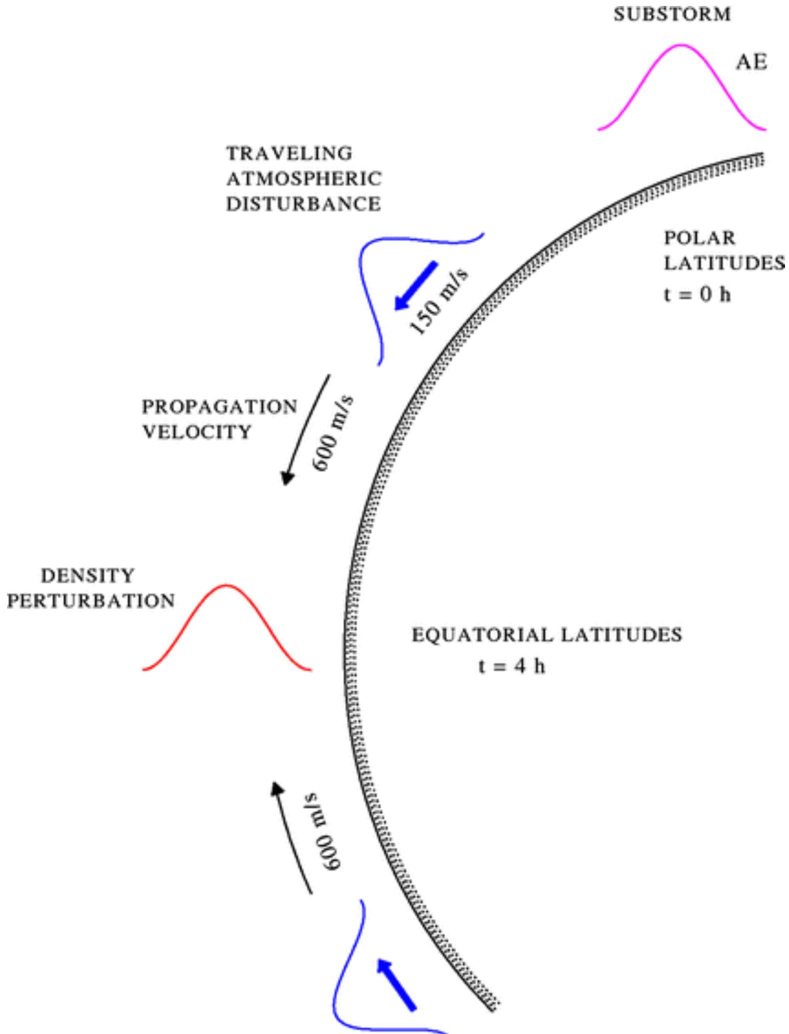
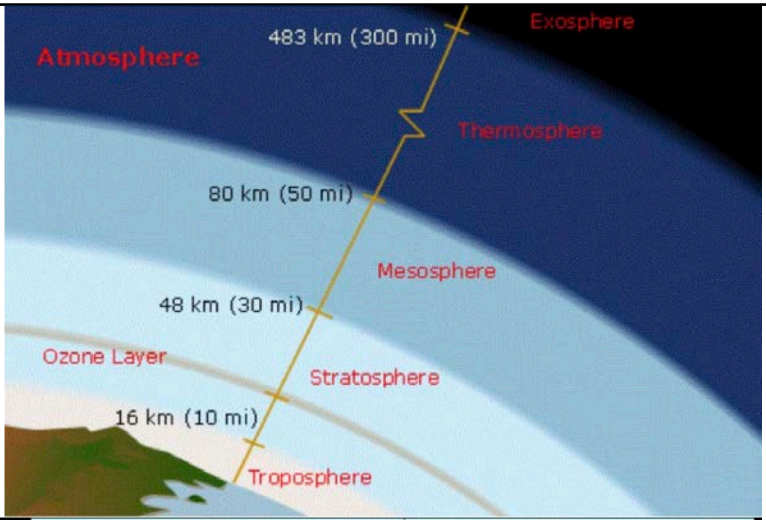
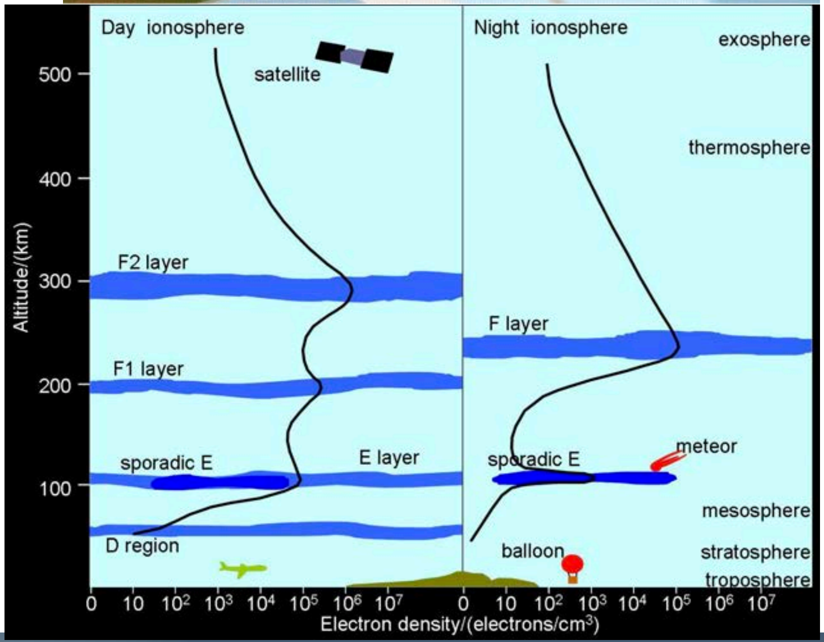


Figure from Prölss, G.W. Density Perturbations in the Upper Atmosphere Caused by the Dissipation of Solar Wind Energy. Surv Geophys 32, 101–195 (2011). https://doi.org/10.1007/s10712-010-9104-0

Sources of Ionospheric Density Modulation



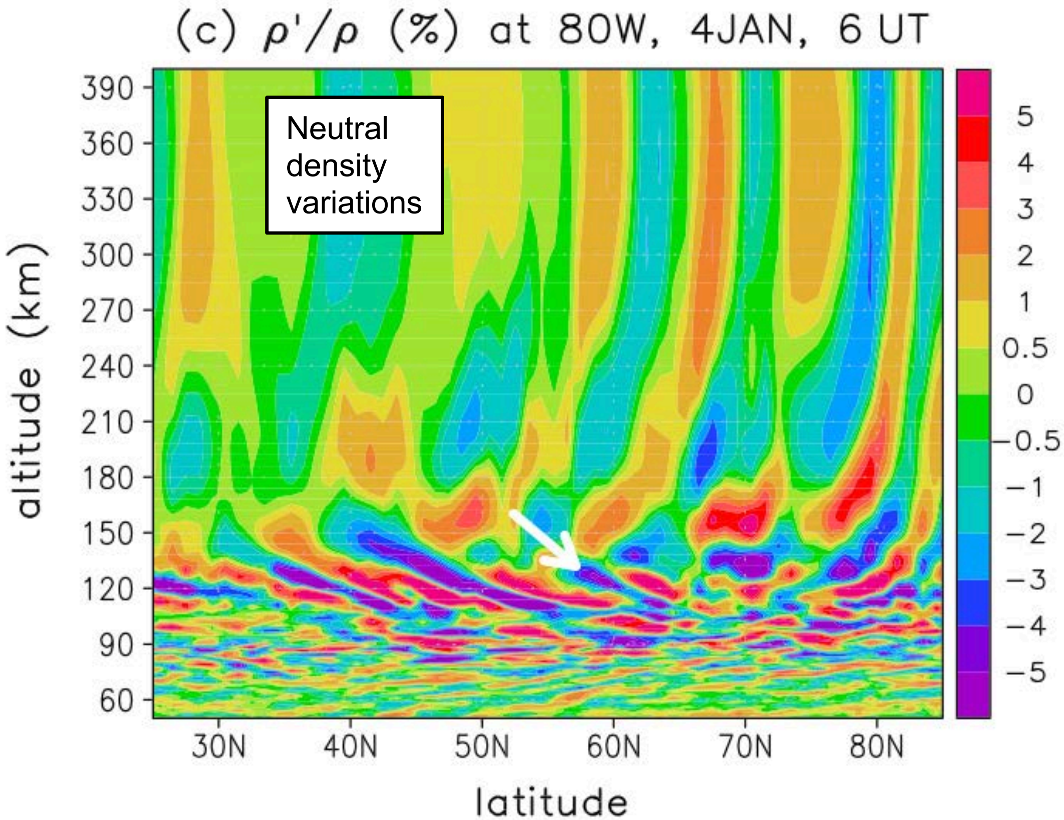


- Lower atmosphere origin AGWs also couple into TADs and TIDs during non-storm conditions
- Affected by tides, planetary waves, seasonal variations, etc.
- Driven by normal energy transitions from free oscillations in the atmosphere – atmosphere normal modes
- Forms an important part of quiet time ionospheric variability
- **We do not fully understand the coupling dynamics, but from observations we understand well the amplitude of TIDs**

http://www.sws.bom.gov.au/Educational/1/2/5

Gravity Wave Propagation: Lower Atmosphere to Thermosphere

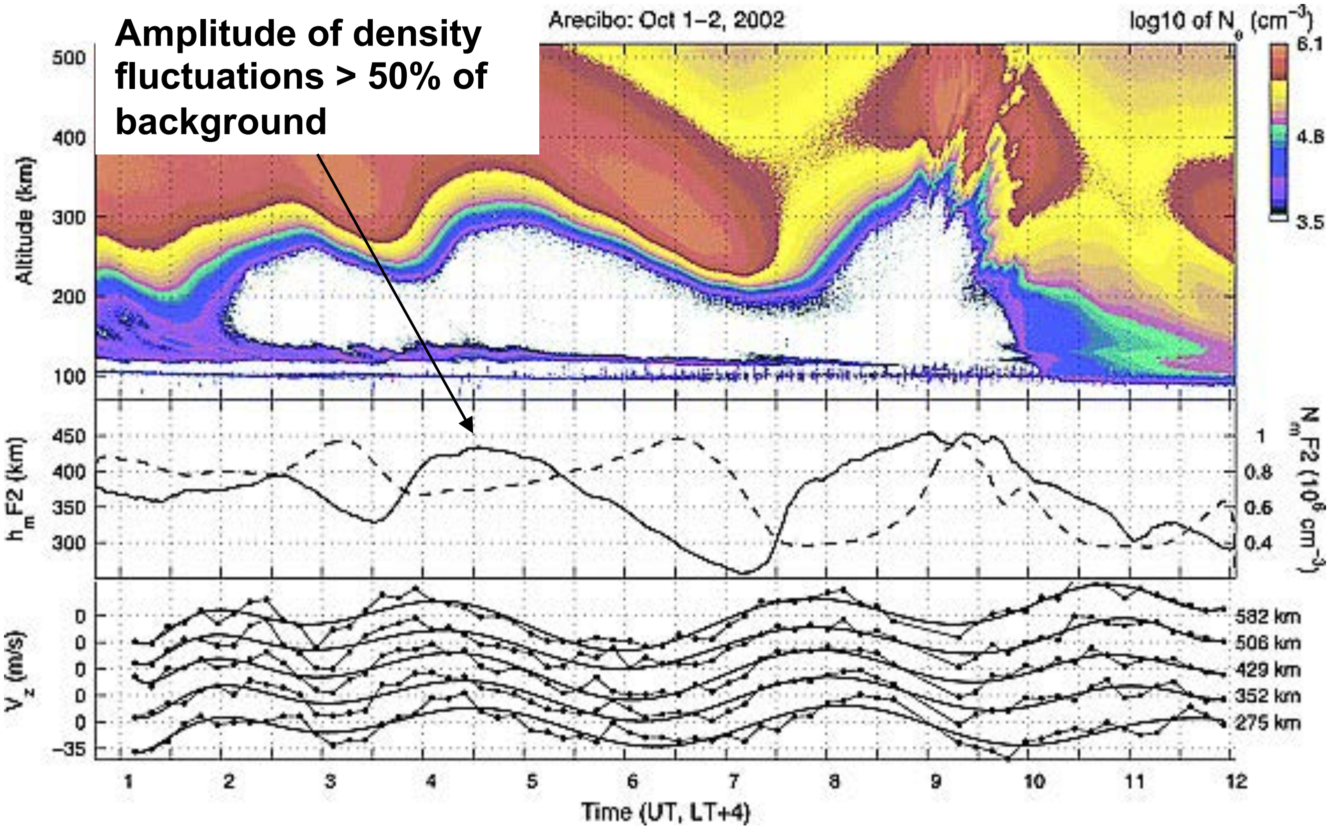
- **Primary** internal gravity waves in the troposphere
  - Flows over mountains, water
- **Secondary** gravity waves in mesosphere and stratosphere
  - Dissipation of primary waves
- **Tertiary** gravity waves in the thermosphere
  - From breaking of secondary waves
- These drive TADs and therefore TIDs in the ionosphere
- ”Waves all the way up”



Periods of 1 to 2 hr
Several hundred km wavelength
1 to several % amplitude

Becker, E., & Vadas, S. L. (2020). Explicit global simulation of gravity waves in the thermosphere. Journal of Geophysical Research: Space Physics, 125, e2020JA028034. https://doi.org/ 10.1029/2020JA028034

Large Scale TIDs at Mid-Latitudes

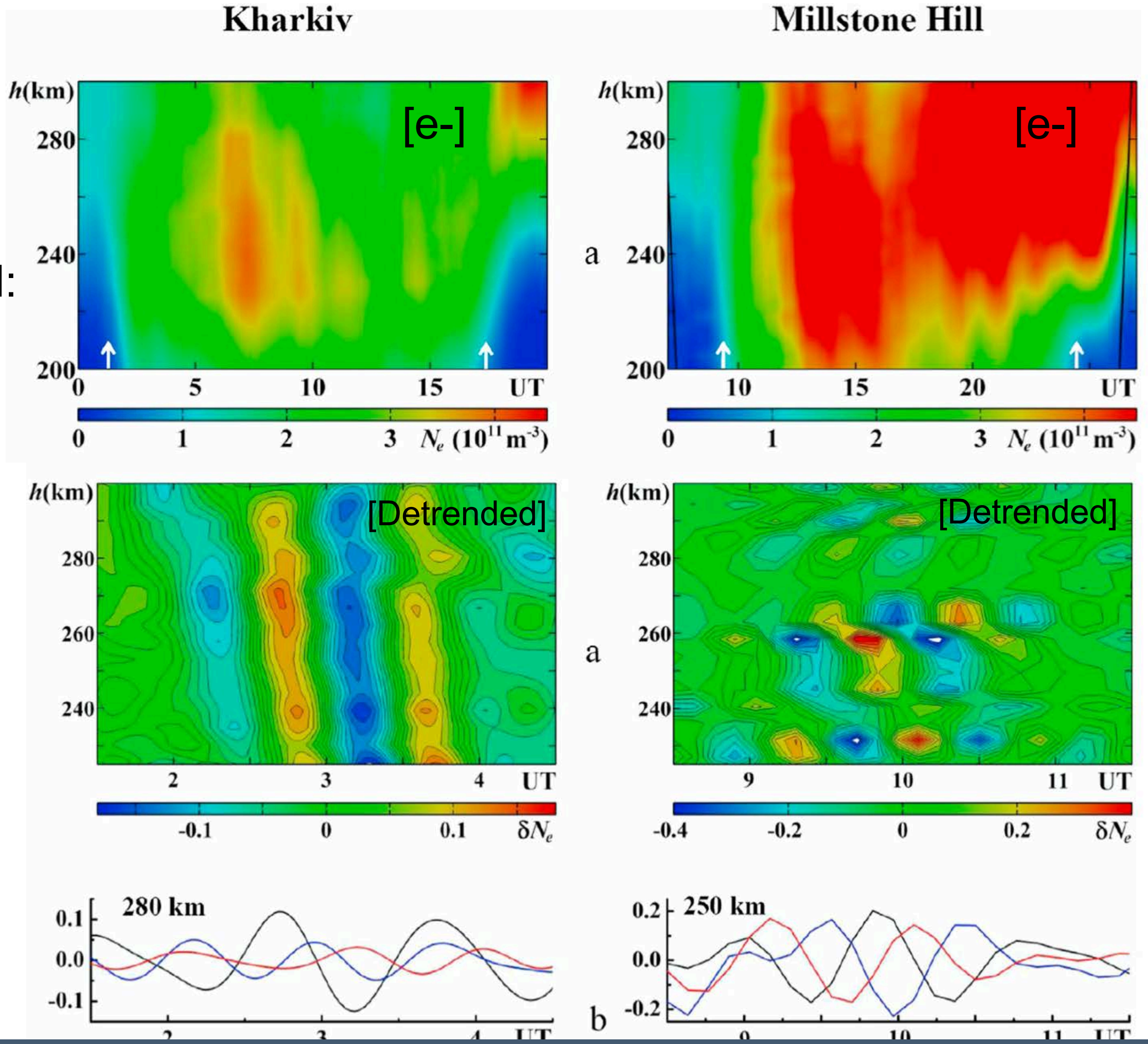


- Period of 2-3 hours
- Arecibo IS radar
- Downward phase progression (not shown) **identifies source as acoustic gravity waves from lower atmosphere**
- Confirmed by TEC maps

Nicolls, M. J., Kelley, M. C., Coster, A. J., González, S. A., and Makela, J. J. (2004), Imaging the structure of a large-scale TID using ISR and TEC data, Geophys. Res. Lett., 31, L09812, doi:10.1029/2004GL019797.

Medium Scale TIDs at Mid-Latitudes

- Mid-latitude stations
- Very geomagnetically quiet: no high latitude heating or other effects
- Lower atmosphere forced: tides, weather, etc.
- Time periods 40-80 minutes
- **Amplitudes up to 20% of background density**



Panasenko, S. V., Goncharenko, L. P., Erickson, P. J., Aksonova, K. D., & Domnin, I. F. (2018). Traveling ionospheric disturbances observed by Kharkiv and Millstone Hill incoherent scatter radars near vernal equinox and summer solstice. Journal of Atmospheric and Solar-Terrestrial Physics, 172, 10-23. doi:10.1016/j.jastp.2018.03.001

Thought Experiment

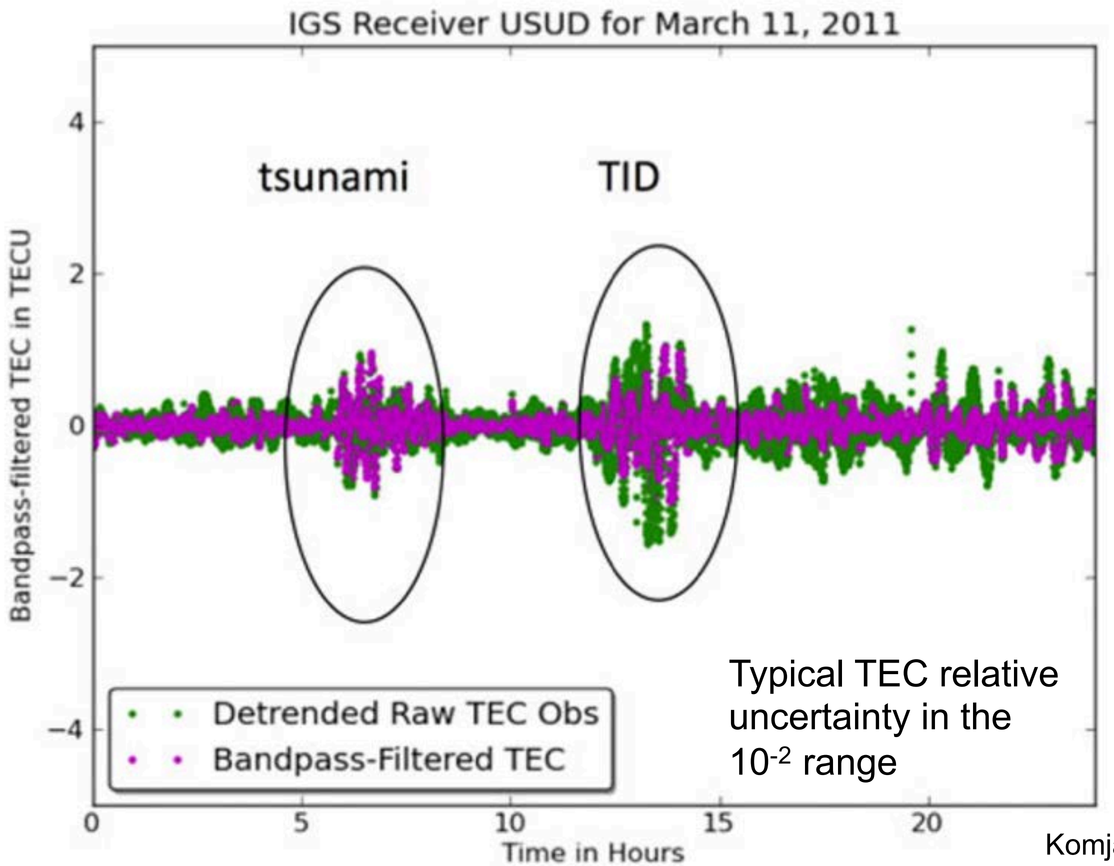
Let's work the extreme natural forcing event: Tohoku (M9.1 undersea megathrust earthquake).

- How big is the ionospheric perturbation?
- What effects might this have on HF propagation compared to other sources?

There's always enough random success to justify almost anything to someone who wants to believe.

--- John Allen Paulos, Innumeracy: Mathematical Illiteracy and its Consequences (1988; ISBN 0-679-72601-2)

Tohoku Induced Tsunami and TIDs



- Detrended TEC observations (background subtracted)
- Usuda, Japan station; 400 km from Tohoku epicenter
- Tsunami and TID signatures triggered by earthquake = +/- 1 to 1.5 TECu
- Plenty large to be detected by sensitive TEC receivers ***at L band frequencies (**)***

Komjathy, A., Galvan, D.A., Stephens, P. et al. Detecting ionospheric TEC perturbations caused by natural hazards using a global network of GPS receivers: The Tohoku case study. Earth Planet Sp 64, 24 (2012). https://doi.org/10.5047/eps.2012.08.003

Tohoku Induced Tsunami and TIDs

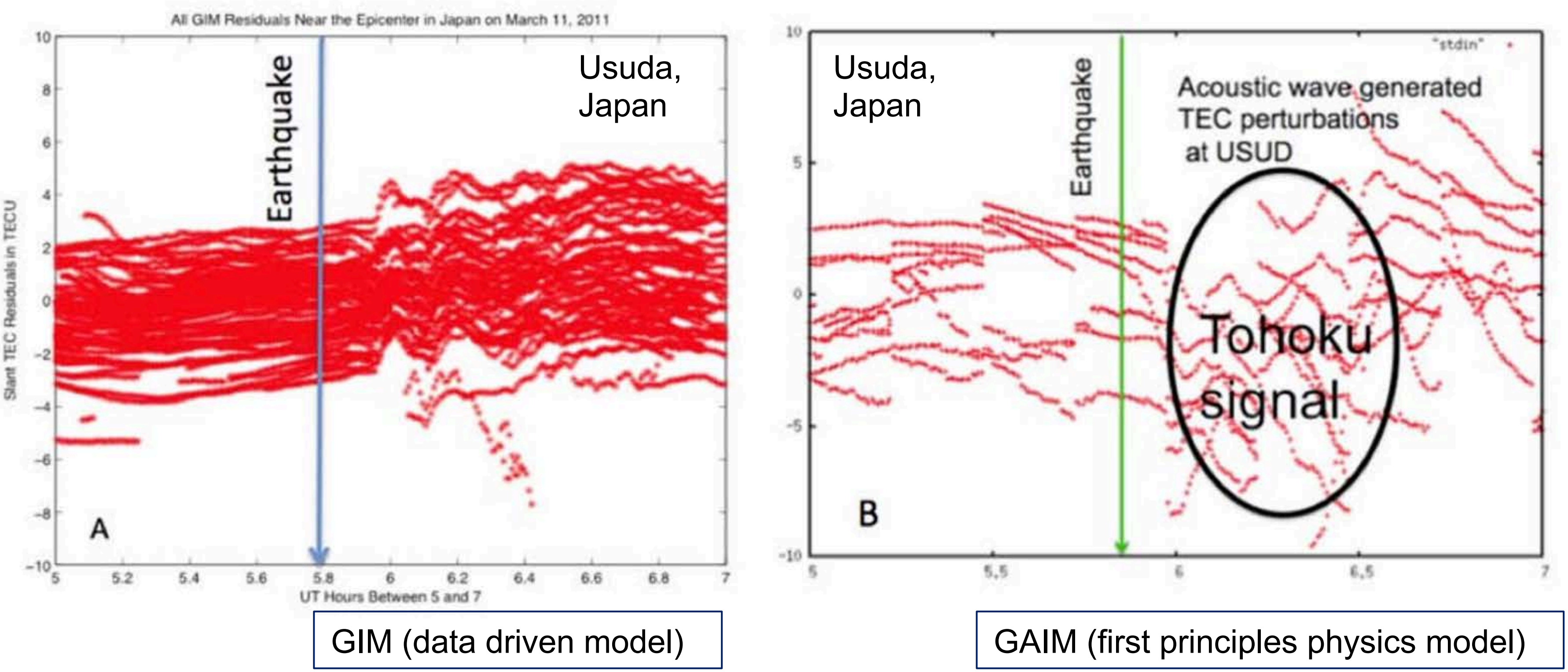
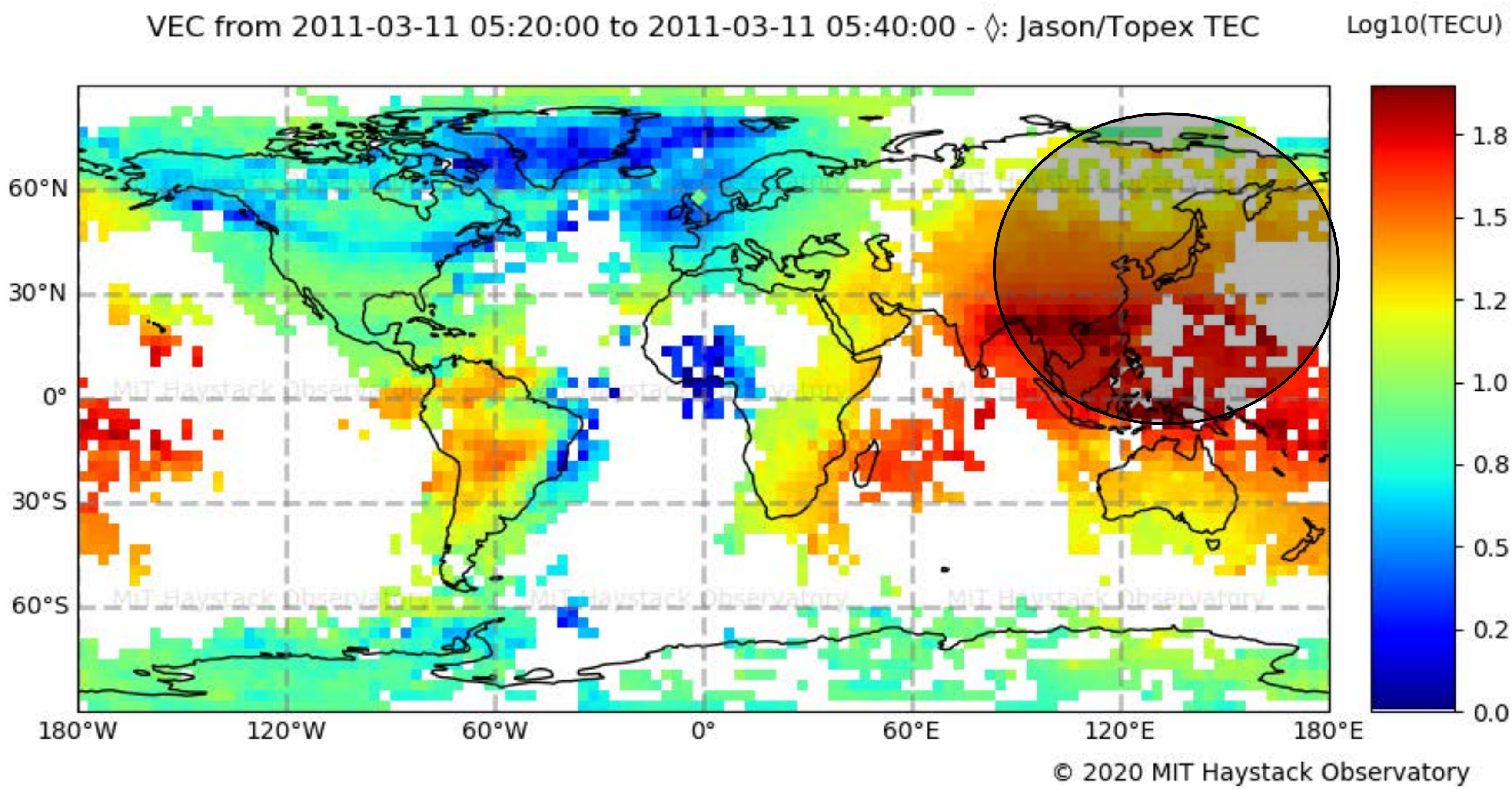


Fig. 5. (A) shows ionospheric TEC residuals using the data driven GIM model and (B) displays real-time TEC residuals using physics-based GAIM model.

Note: still 1 to 2 TEC unit perturbations..

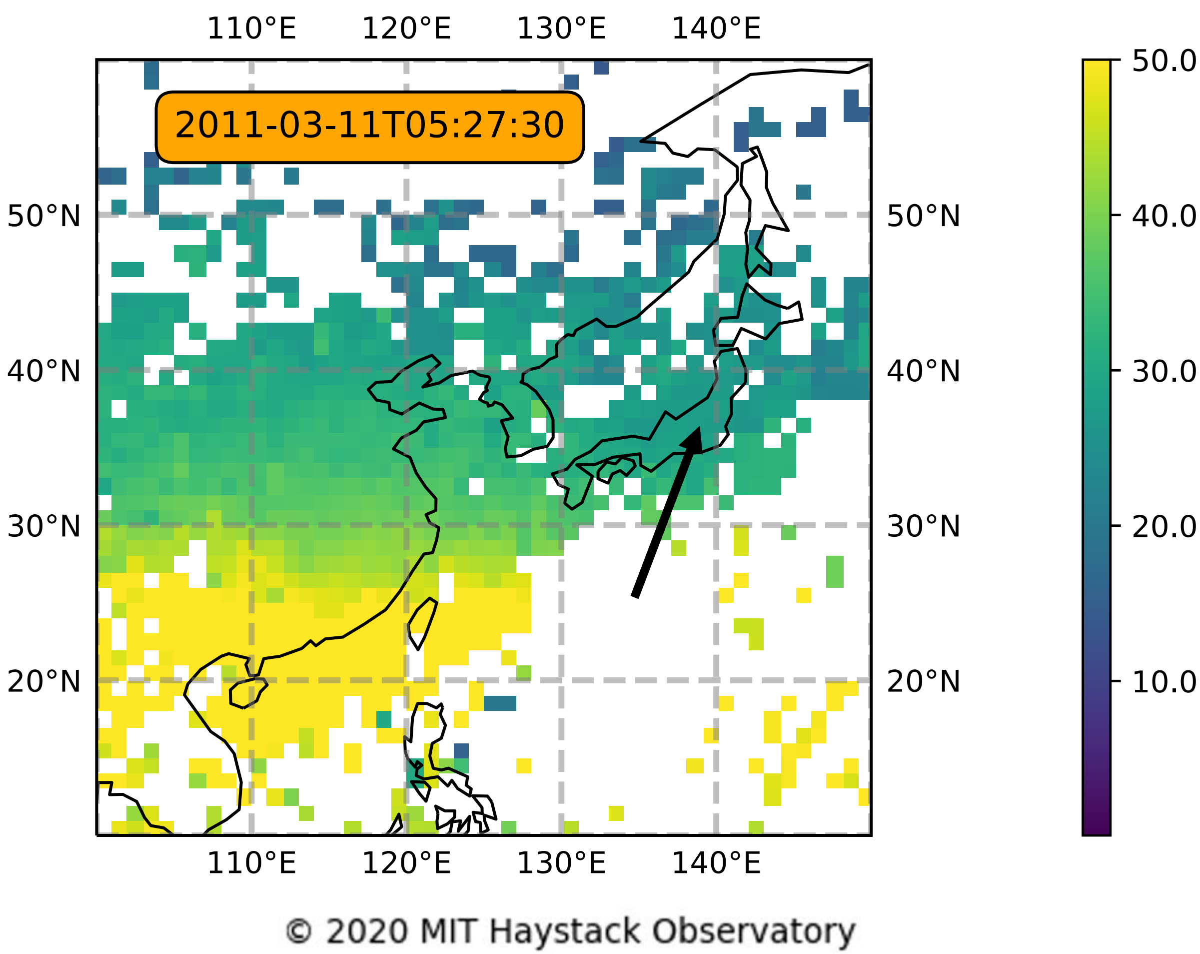
Komjathy, A., Galvan, D.A., Stephens, P. et al. Detecting ionospheric TEC perturbations caused by natural hazards using a global network of GPS receivers: The Tohoku case study. Earth Planet Sp 64, 24 (2012). https://doi.org/10.5047/eps.2012.08.003

Background TEC Pre-Earthquake



NB: 1 TECu = 10^{16} [e-]/m^2; dominated by ionosphere

Relative Ionospheric Perturbation



Before quake:
Average TEC over Japan ~ 29 TECu

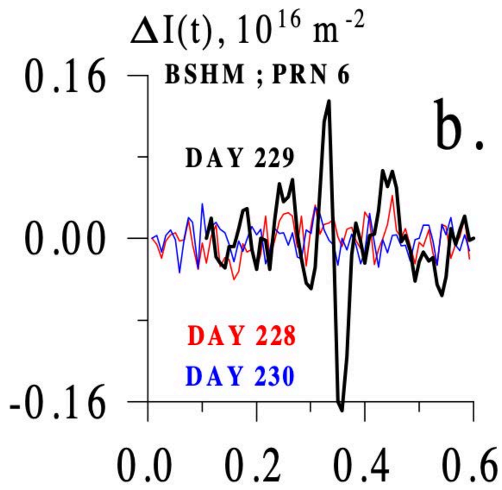
Recall perturbations seen from tsunami and subsequent TIDs were ~1.5 TECu worst case

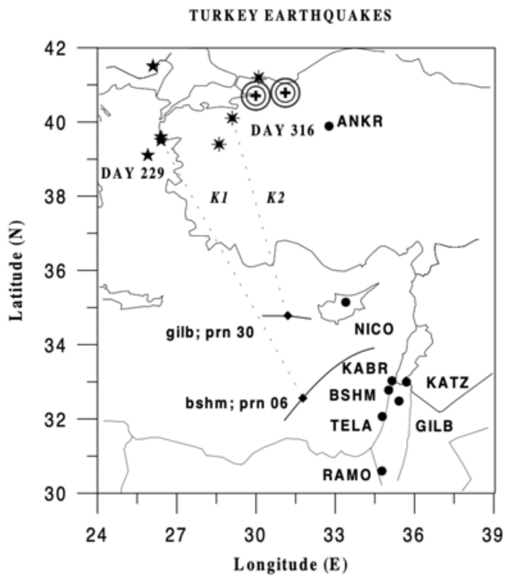
Assume TEC change reflects overall ionospheric electron density (reasonable)

Relative ionospheric density perturbation therefore is ~5.2%

Other Examples

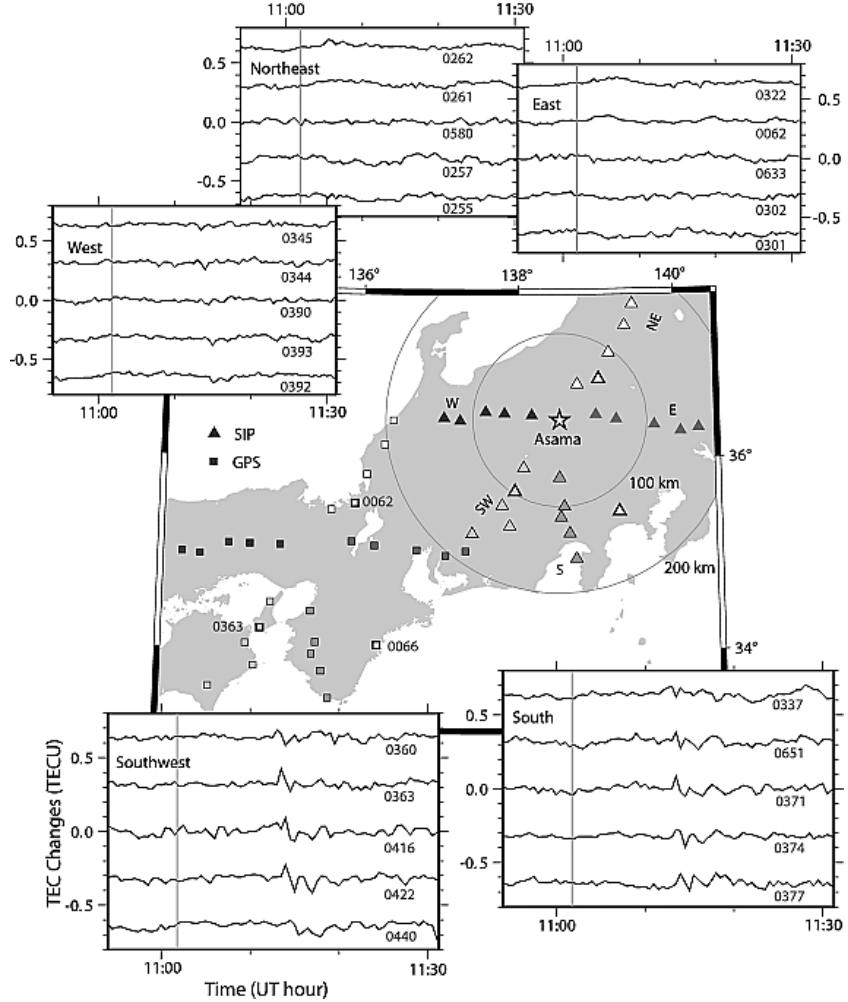
Afraimovich, Edward L., Natalia P. Perevalova, A. V. Plotnikov, and A. M. Uralov. "The shock-acoustic waves generated by earthquakes." In Annales Geophysicae, vol. 19, no. 4, pp. 395-409. Copernicus GmbH, 2001.





<1 to ~3% perturbation amplitudes

Heki, K. (2006), Explosion energy of the 2004 eruption of the Asama Volcano, central Japan, inferred from ionospheric disturbances, Geophys. Res. Lett., 33, L14303, doi:10.1029/2006GL026249.



Comparison of Mid-lat TID Strength

Tohoku M9.1 Quake	**~5.2% Amplitude**	Thankfully uncommon
Storm-time TIDs	Up to **50%** Amplitude	~10x/ year, unevenly distributed (more at solar max)
Quiet time TIDs	**5-15%** Amplitude	Every day

Conclusion: one of the largest earthquakes ever recorded **does not have** an observed electron density perturbation amplitude **larger than natural every-day ionospheric variability.**

But these extreme events are EASILY distinguishable with ***sensitive, calibrated techniques*** (e.g. GNSS at L band frequencies).

What are the implications for HF signal propagation?

Localized HF Effects: TIDs

Rays are focused near local electron density minima associated with wave passing through region

Concave electron density contours; causes local increase in HF amplitude

VERY localized fading/enhancement as wave passes by; **not a wide scale effect**

Subject of upcoming HamSCI investigations using amateur radio networks (following e.g. Frissell et al. 2014; doi:10.1002/2014JA019870.)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. A6, PAGES 7693–7709, JUNE 1, 1990

Goose Bay Radar Observations of Earth-Reflected, Atmospheric Gravity Waves in the High-Latitude Ionosphere

J. C. SAMSON[1], R. A. GREENWALD, J. M. RUOHONIEMI, A. FREY, AND K. B. BAKER
The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland

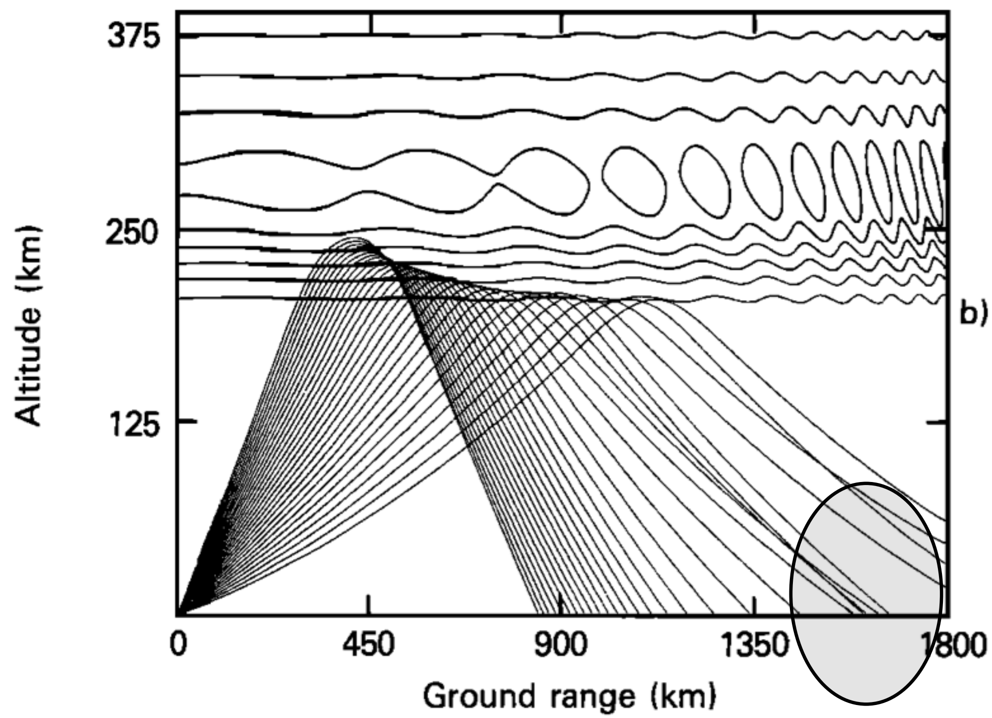
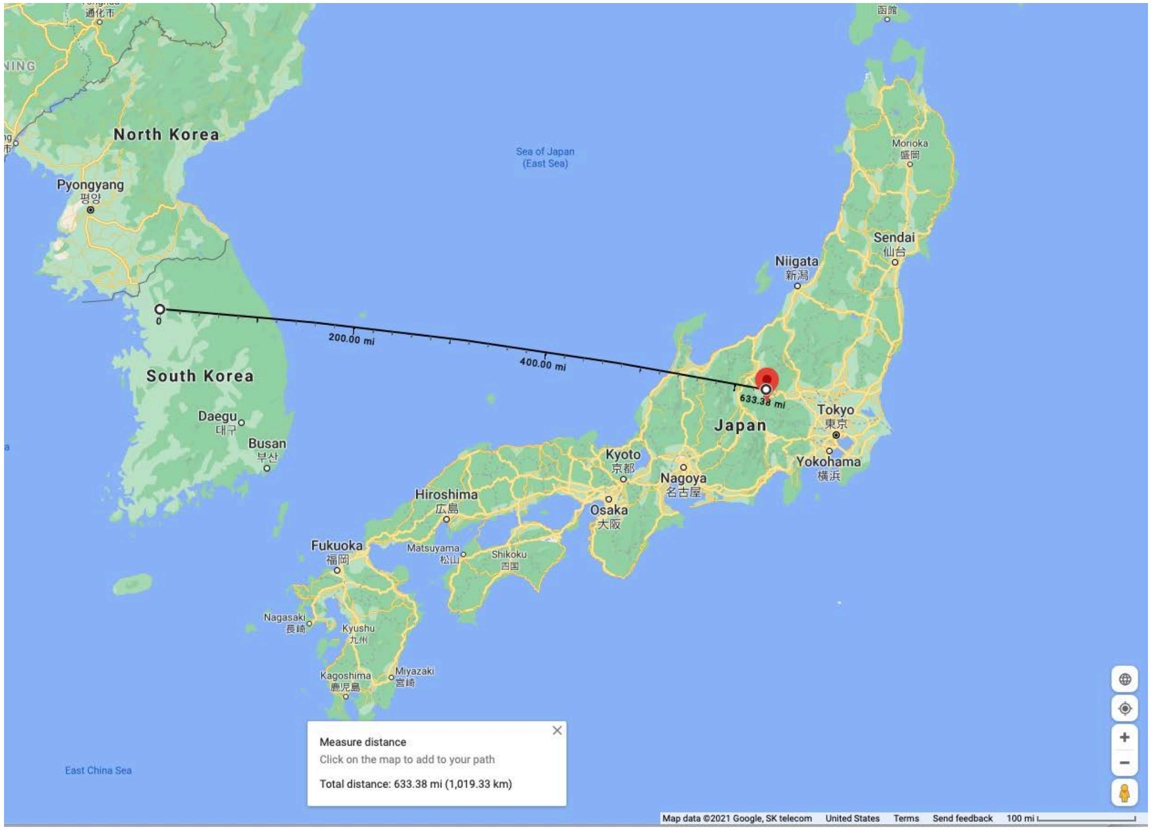


Fig. 2. Ray paths of HF radar propagation through an ionosphere modulated by an ERW. Note the focusing caused by the surfaces of the electron density minima. Top: 195 min after excitation. Bottom: 210 min after excitation.

Hypothetical HF Contact Path

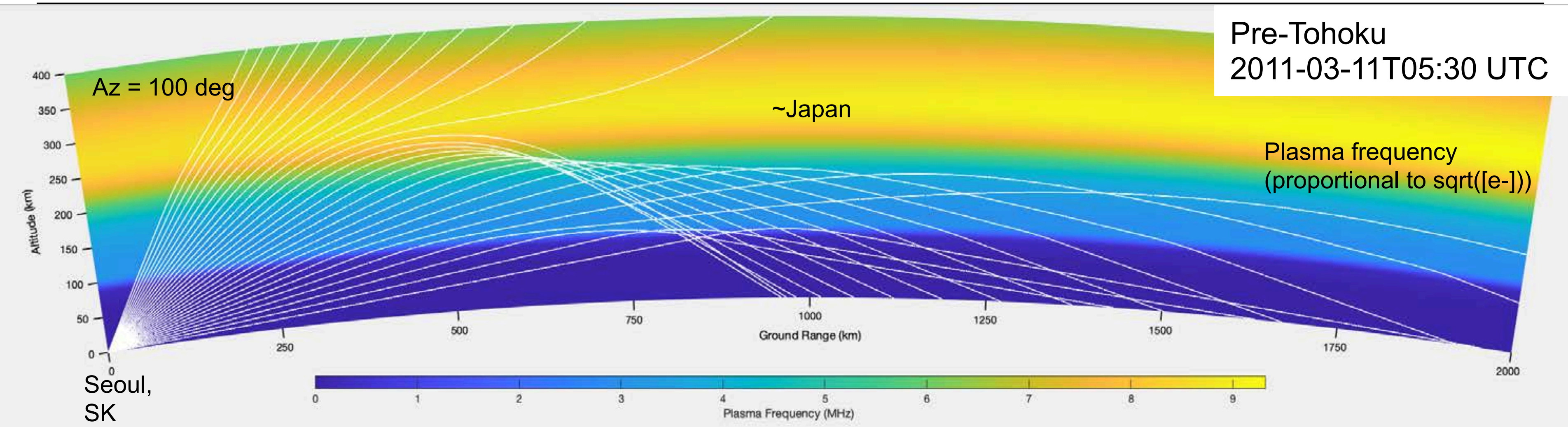


- Path shown is to control point (midpoint) of HF path originating in Seoul, SK
- Somewhere within largest perturbation zone of Tohoku event

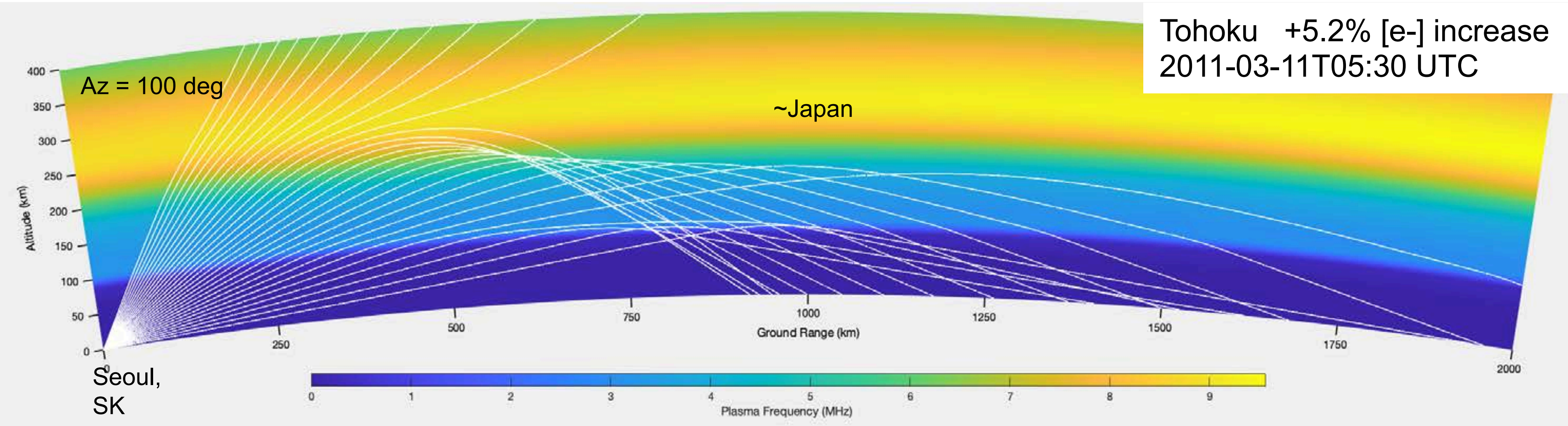
- **What alterations might happen to HF propagation on this path?**

14 MHz Propagation

Created with PhARLAP
Ray tracing engine

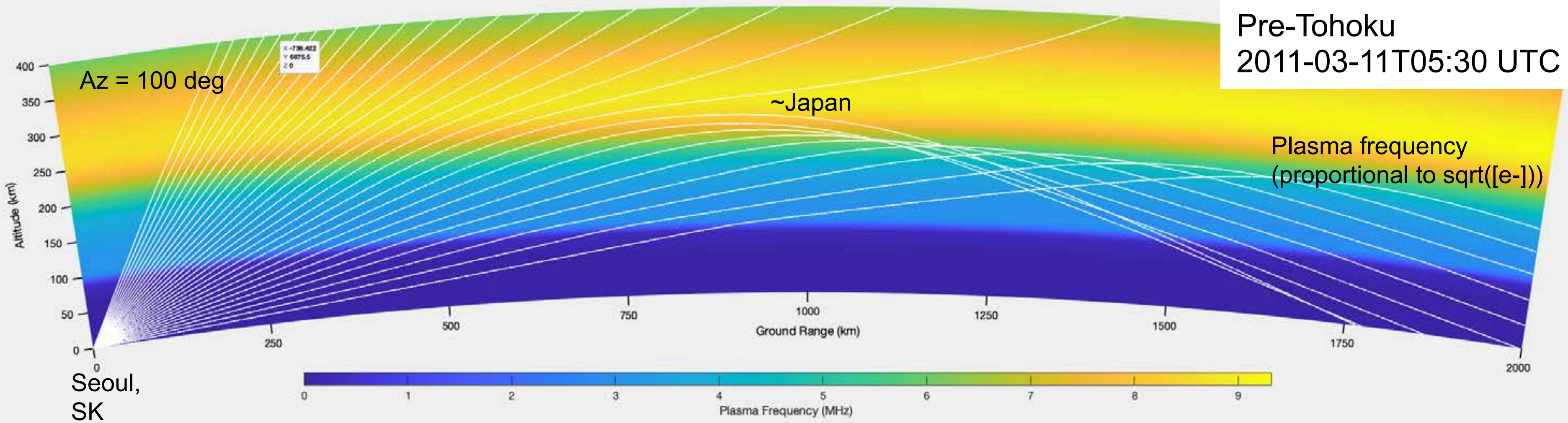


Very small wide-scale HF propagation effects

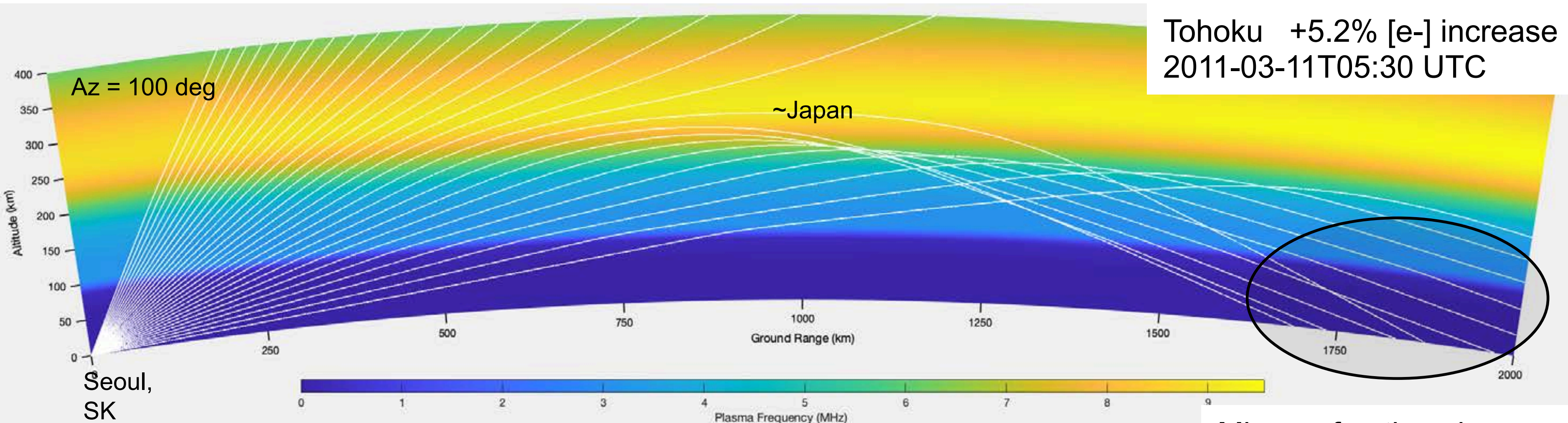


21 MHz Propagation

Created with PhARLAP
Ray tracing engine



Very small wide-scale HF propagation effects



Minor refraction changes

Summary

- Space weather ionospheric [e-] variability affects HF propagation
  - AGW forcing / TIDs – storm time, quiet time
  - Natural transients – e.g. earthquakes
- HF propagation variability includes contributions from all these sources
- Amplitude of [e-] disturbance from largest earthquakes recorded is <= natural day to day variability
- HF propagation perturbations due to average earthquakes are impossible to separate from natural variability
- Future observations will further quantify effects of “forcing from below” and “forcing from above”

K9LA and W1PJE thank you for listening

Acknowledgment

- HF ray-tracing results in this talk were obtained using the HF propagation toolbox, PHaRLAP, created by Dr Manuel Cervera, Defence Science and Technology Group, Australia (manuel.cervera@dsto.defence.gov.au). This toolbox is available by request from its author.

- Electron density model provided by the International Reference Ionosphere (2016 version). See D. Bilitza, IRI the International Standard for the Ionosphere, Adv. Radio Sci., 16, 1-11, https://doi.org/10.5194/ars-16-1-2018, 2018.

- The International Telecommunications Union Recommendation ITU-R P.372-10 (10/2009) for radio noise is used in PHaRLAP. See https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.372-14-201908-I!!PDF-E.pdf.