AGWs and TIDs related studies

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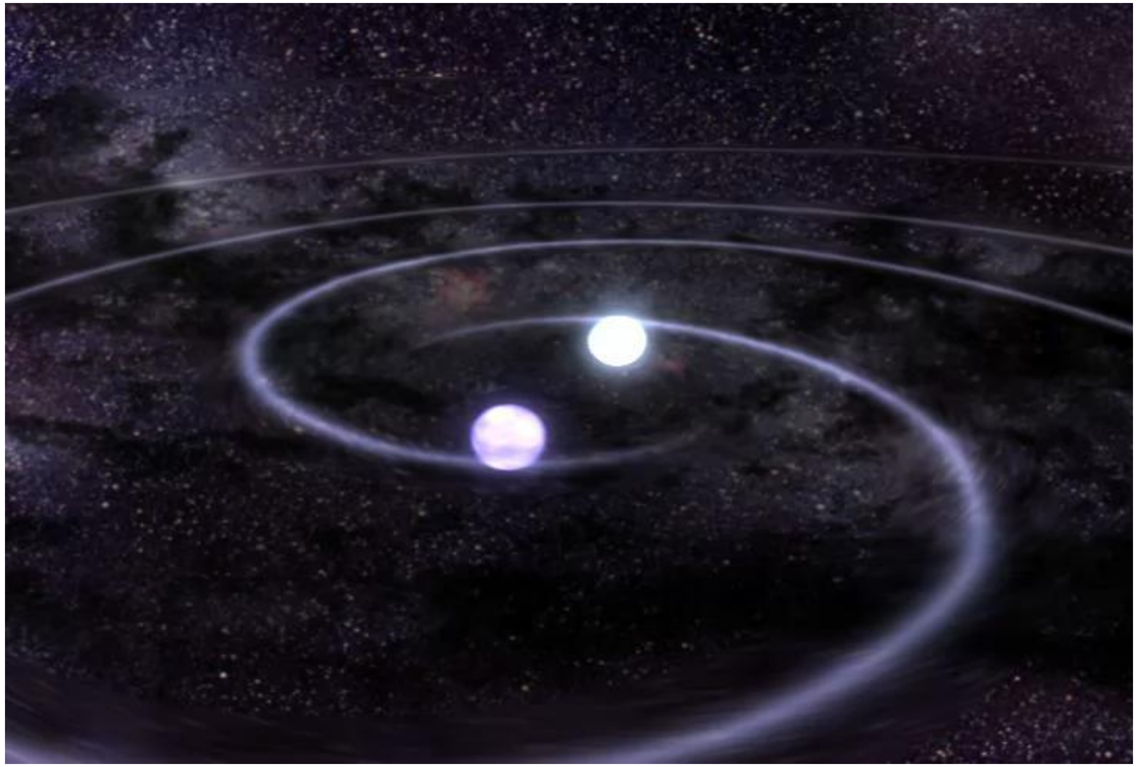
Pioneers: *Satellite Navigation Science and Technology for Africa: 2009*

Gravity Waves are not Gravitational Waves



Two neutron stars orbiting each other, later combine emitting gravitational waves: Courtesy of NASA/GSFC

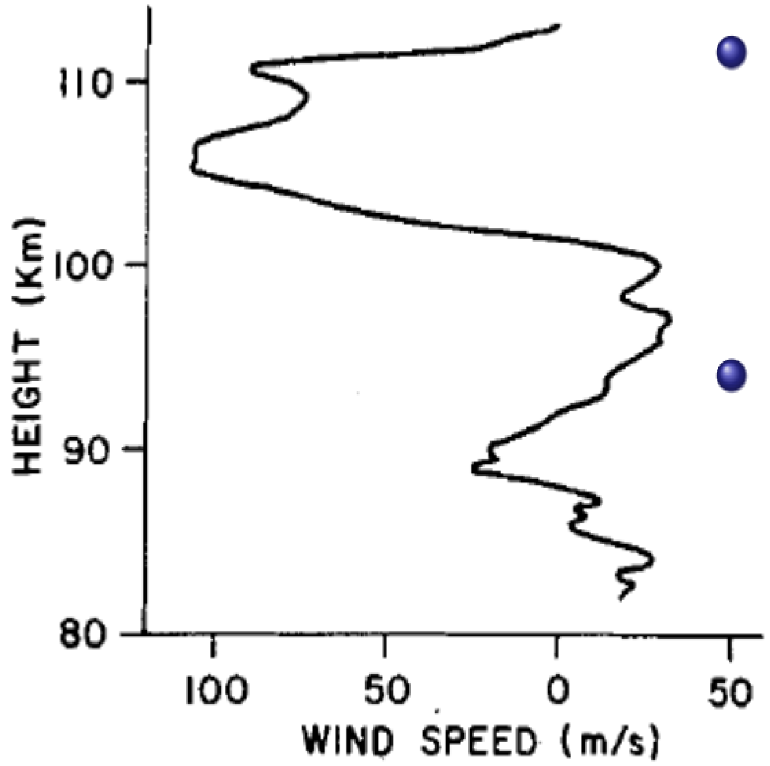
Originate from the general theory of relativity and were predicted by Einstein,(1916) as ripples in space-time because of energetic processes in the universe. Sources include

- Collision of neutron stars (such as pulsars)
- Explosion of massive stars at the end of their lifetimes === Supernovae
- Black holes collision
- Detected on Sept 14, 2015 by the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors

On the contrary, Atmospheric Gravity Waves are in our back yard! These are generated by many sources "near us" and Buoyancy acts as a restoring force

This is our focus here

Atmospheric Gravity Waves



- Commonly, gravity waves are generated in the troposphere by weather fronts or air flow over mountains.
- Their amplitudes increase as they reach higher altitudes (thin air) and later break-up thereby transfering energy and momentum from the troposphere to the stratosphere/mesosphere.

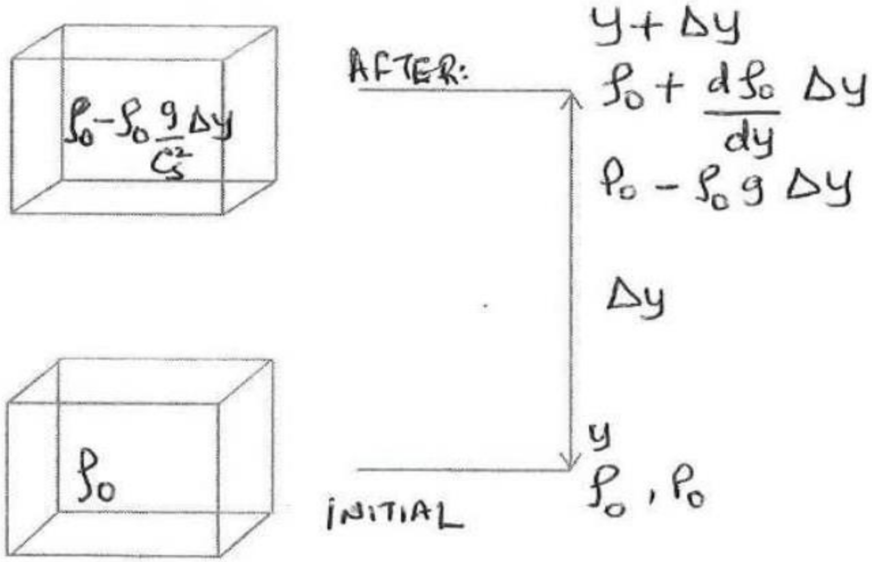
Hines (1960): Internal gravity waves at ionospheric heights, Canadian Journal of Physics, 38(11), 1441-1481: After Liller and Whipple (1954), Special Supplement to J. Atmos. and Terr. Phys., 1.

Within the Ionosphere;

- Gravity waves transfer energy between different ionospheric layers and manifest as travelling atmospheric disturbances or travelling ionospheric disturbances (TIDs)
- TIDs are mainly categorized into medium and large scale mainly based on their velocities, wavelengths and periods

TIDs: First reported by Munro (1948): Short-Period Changes In the F-region of the Ionosphere, Nature, 162, 886-887

Usually defined as signatures of Atmospheric Gravity Waves (AGWs). To understand AGWs, consider an air parcel in the lower part of the atmosphere, up to 100 km (homosphere where turbulence causes continuos mixing of atmospheric constituents) that is stable;



After: van Velthoven, (1990)

If the air parcel is displaced adiabatically, its ρ changes by $\Delta\rho = \Delta p_o / C_s^2$. For hydrostatic equilibrium, $\Delta p_o = -\rho_o g \Delta y$. After displacement, the mass density of the parcel is $\rho_o + \Delta\rho_o = \rho_o + \frac{d\rho_o}{dy}\Delta y$

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Motion of the air parcel

Due to the displacement, the equation of motion for the parcel is

$$\rho_o \frac{d^2(\Delta y)}{dt^2} = g\left(\frac{d\rho_o}{dy} + \frac{\rho_o g}{C_s^2}\right)\Delta y \qquad (1)$$

where $C_s = \sqrt{\gamma p_o/\rho_o}$ is the sound velocity and $\gamma = C_p/C_v$ is the ratio of specific heats at constant pressure p and volume v.
The air parcel will oscillate around its mean position with a frequency known as buoyancy (Brunt-Väisälä) frequency, ω_B

$$\omega_B^2 = -g\left(\frac{1}{\rho_o}\frac{d\rho_o}{dy} + \frac{g}{C_s^2}\right) \qquad (2)$$

The buoyancy force therefore acts as a restoring force

AGWs generation

Equation 1 is Newton's second law which can be considered as a differential equation for an oscillation with general solution

$$\Delta y = Ae^{j\omega_B t} \text{ where } j = \sqrt{-1},\ A \text{ is the amplitude}$$

- For a generalised perfect gas (Hines, 1960; Velthoven, 1990)

$$\omega_B^2 = \frac{(\gamma - 1)g^2}{C_s^2} + \frac{g}{C_s^2}\frac{dC_s^2}{dy} \tag{3}$$

- The quantity

$$\omega_b^2 = \frac{(\gamma - 1)g^2}{C_s^2} \tag{4}$$

is the isothermal buoyancy angular frequency.

Gravity wave generation

The considered air parcel is connected to its surroundings and therefore oscillation forcing will lead to wave propagation

Some limiting cases...

For an isothermal atmosphere over a flat Earth, the wave solution from linearised hydrodynamic equations (Hines, 1960) is

$$k_z^2 = \left(\frac{\omega_b^2 - \omega^2}{\omega^2}\right) k_x^2 - \frac{\omega_a^2 - \omega^2}{C_s^2} \quad (5)$$

$$\omega_a = \frac{\gamma g}{2C_s}$$ is the acoustic cut-off angular frequency

k_z and k_x are the vertical and horizontal components of the wave vector **k**, ω is the angular wave frequency.
Given that $\omega_a > \omega_b$ and $\omega_a \approx 1.1\omega_b$ in the atmosphere, waves arising from the above equation can be categorised into

- $\omega > \omega_a$: for limiting case $\omega >> \omega_a$, $k^2 = \frac{\omega^2}{C_s^2}$: pure acoustic wave
- $\omega_b < \omega < \omega_a$, wave equation (5) becomes a diffusion equation; evanescent waves
- $\omega < \omega_b$: limiting case $\omega << \omega_b$, the dispersion relation becomes $k_z^2 = \frac{\omega_b^2}{\omega} k_x^2 - \frac{\omega_a^2}{C_s^2}$ for pure gravity waves

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AGWs effects on the ionosphere

Continuity equation of electrons in the ionosphere is given by

$$\frac{\partial N_e}{\partial t} = q_e - L_e - \nabla.(N_e \mathbf{v_e}) \quad (6)$$

- Due to the passage of the AGW, we can split the electron density N_e into a background/stationary (N_{eo}) and perturbation (n_e) components; i.e $N_e = N_{eo} + n_e$. Assume that the velocity induced by the AGW is $\mathbf{v_{e1}}$, then $\mathbf{v_e} = \mathbf{v_{eo}} + \mathbf{v_{e1}}$
- If the perturbation in the production and loss rates (q_e and L_e) are negligible, and setting the initial velocity $\mathbf{v_{eo}}$ to zero, then for the electron density perturbation term n_e),

$$\frac{\partial n_e}{\partial t} = -\nabla.(N_{eo} \mathbf{v_{e1}}) \quad (7)$$

- The perturbed velocity component $\mathbf{v_{e1}}$ can be related to the perturbation in the velocity of the neutral gas ($\mathbf{v_n}$) through the balance between Lorentz force and ion drag

After some tiring derivation…

$$e(\mathbf{v_{e1}} \times \mathbf{B}) + \mathbf{m_e} \mathbf{v_{en}}(\mathbf{v_{e1}} - \mathbf{v_n}) = \mathbf{0} \quad (8)$$

$\mathbf{v_{en}}$ is the effective collision frequency and $\mathbf{B}$ is the Earth's magnetic field.

AGWs effects on ionosphere continued….

An exhaustive derivation leads to

The solution to the above equation is

$$\mathbf{v_{e1}} = \frac{1}{1 + \frac{\mathbf{v_{en}}}{\omega_{ce}^2}} \left(\frac{\mathbf{v_{en}^2}}{\omega_{ce}^2}\mathbf{v_n} - \frac{\mathbf{v_{en}}}{\omega_{ce}}\mathbf{v_n} \times \mathbf{b} + (\mathbf{v_n}.\mathbf{b})\mathbf{b} \right) \quad (9)$$

b is a unit vector in the direction of the geomagnetic field and $\omega_{ce} = eB/m_e$ is the electron cyclotron frequency.

In the F region, the collision frequency is negligible ($\mathbf{v_{en}} << \omega_{ce}$) and therefore

$$\mathbf{v_{e1}} \approx (\mathbf{v_n}.\mathbf{b})\mathbf{b} \quad (10)$$

The response of the electron density perturbation due to passing of the AGW is therefore

$$n_e = \frac{1}{\omega}(\mathbf{v_n}.\mathbf{b})[(\mathbf{b}.\mathbf{k}) - \mathbf{j}(\mathbf{b}.\nabla)]\mathbf{N_{eo}} \quad (11)$$

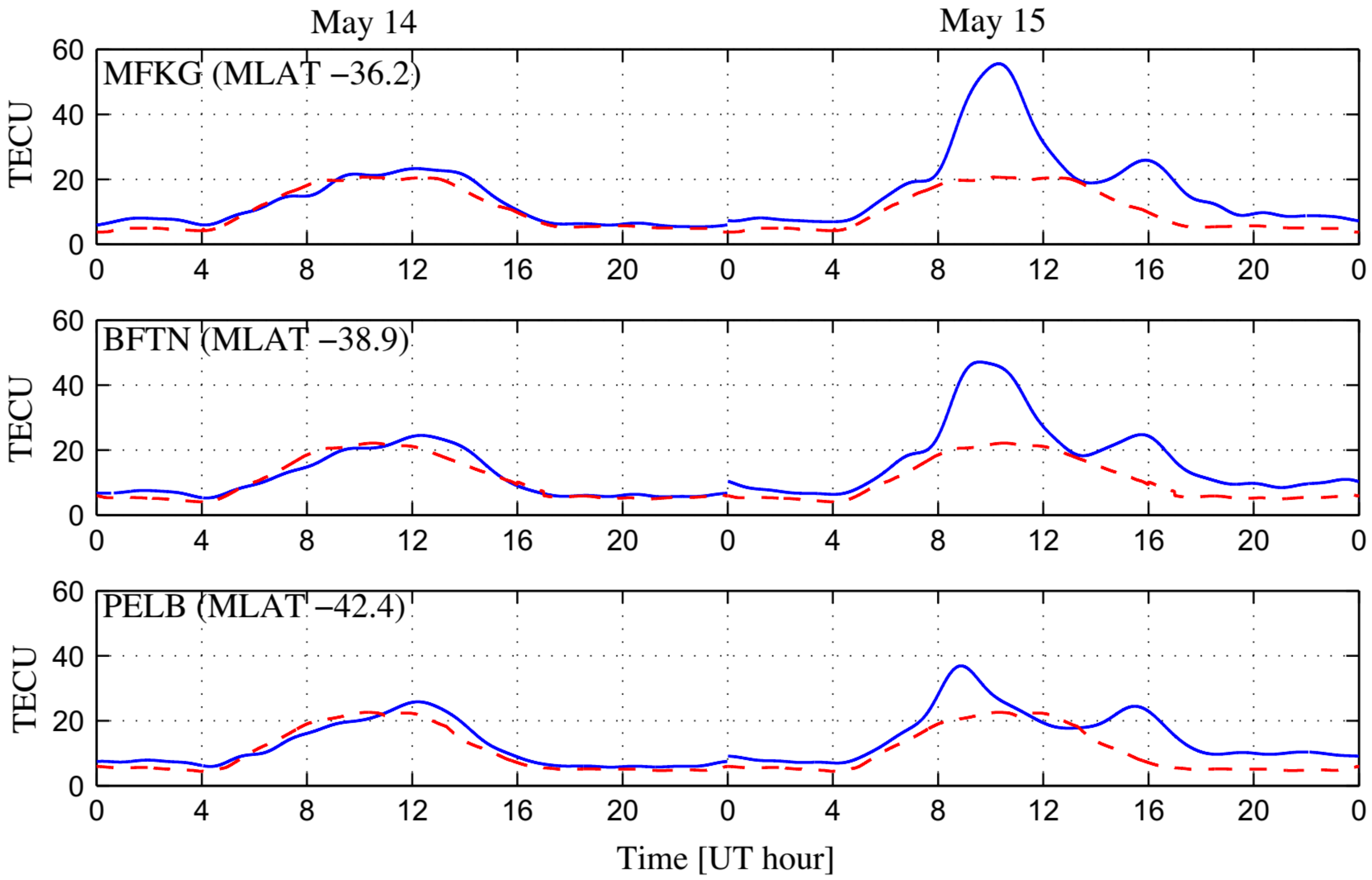
If the horizontal gradients in N_{eo} are negligible, then the scale height $H_e = -\frac{\partial ln(N_{eo})}{\partial y}$ and

$$n_e = \frac{N_{eo}}{\omega}(\mathbf{v_n}.\mathbf{b})(\mathbf{b}.\mathbf{k}) \quad (12)$$

The perturbation is proportional to the background electron density!

References: Hines (1960): Internal gravity waves at ionospheric heights, Canadian Journal of Physics, 38(11), 1441-1481; AND; van Velthoven (1990): Medium scale irregularities in the ionospheric electron content; PhD thesis, Technische Universiteit Eindhoven, doi: 10.6100/IR340464

Background determination; methods & parameterizations

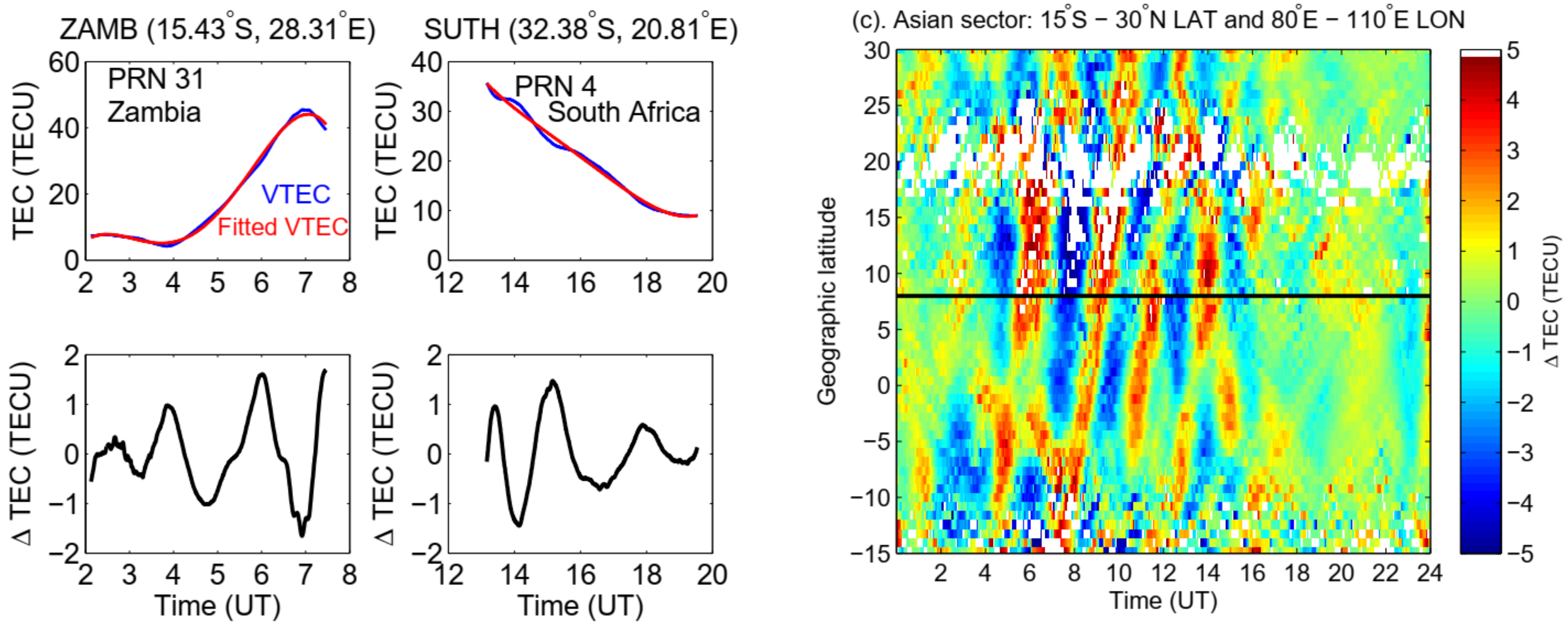


Commonly previously used method before the densification of different instruments:

Velocity values are computed based on time delay between successive peaks' appearances. These are virtual propagation values as the assumption is of 'perfectly equatorward'

Ngwira et al., (2015): *An investigation of ionospheric disturbances over South Africa during the magnetic storm on 15 May 2005*, ASR, 327-335

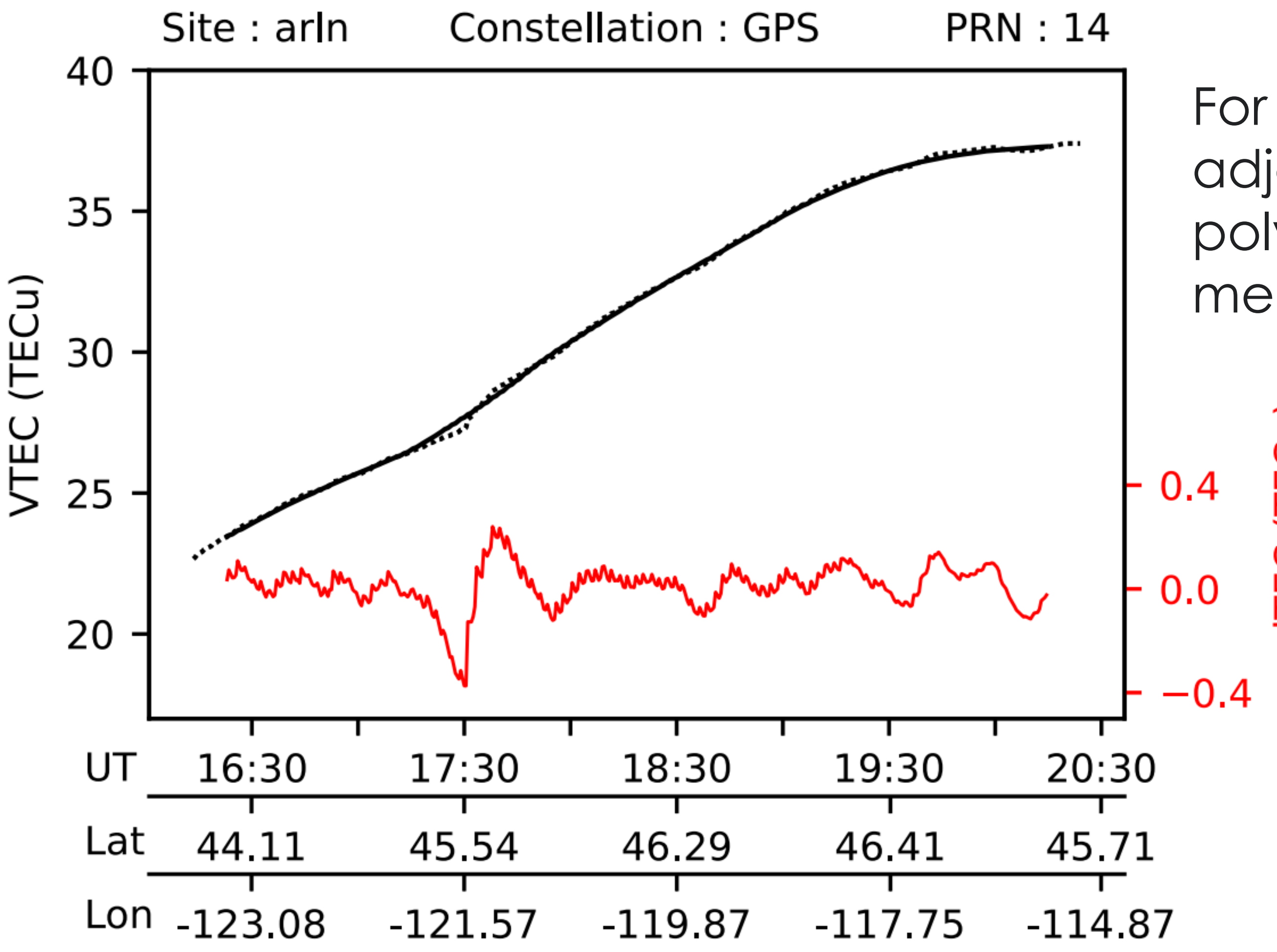
Background determination: Polynomial fitting



Some references: (1) Valladares et al., (2009), Simultaneous observation of travelling ionospheric disturbances in the Northern and Southern Hemispheres, Ann. Geophys., 27, 1501-1508

(2) Habarulema et al., (2016), Simultaneous storm time equatorward and poleward large-scale TIDs on a global scale, Geophys. Res. Lett., 43, 6678-6686

Background determination; Savitzky-Golay



For a signal, fit successive subsets of adjacent data points with a predefined polynomial through linear least squares method.

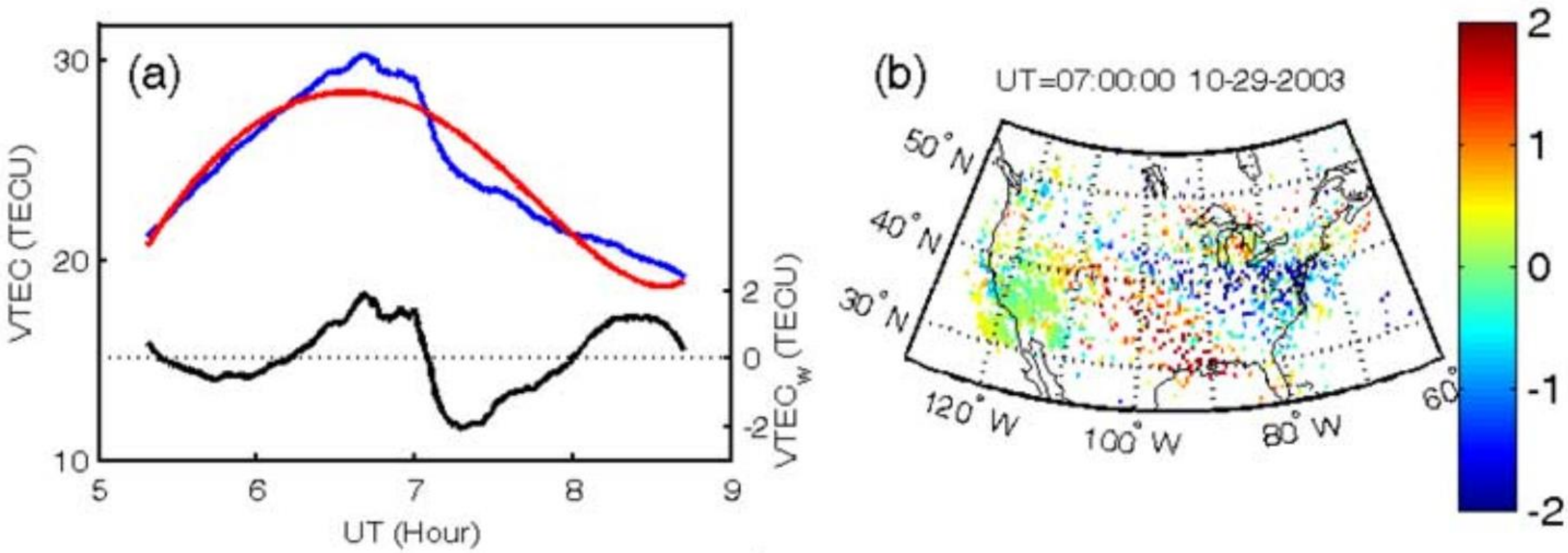
Sarp et al., (2024) applied a SG filter with a 60-step window, corresponding to a constant 30-min temporal interval. TEC perturbations are evaluated by the detrended TEC (dTEC), which is the difference between the observed VTEC values and filtered VTEC values. A half-window length is excluded from both ends of each dTEC time series to prevent extrapolation-related spurious effects .

Sarp et al., (2024). Response of the thermosphere-ionosphere system to an X-class solar flare: 30 March 2022 case study. *Space Weather*, 22, https://doi.org/10.1029/ 2024SW003938

Background determination; Dependent-independent variables

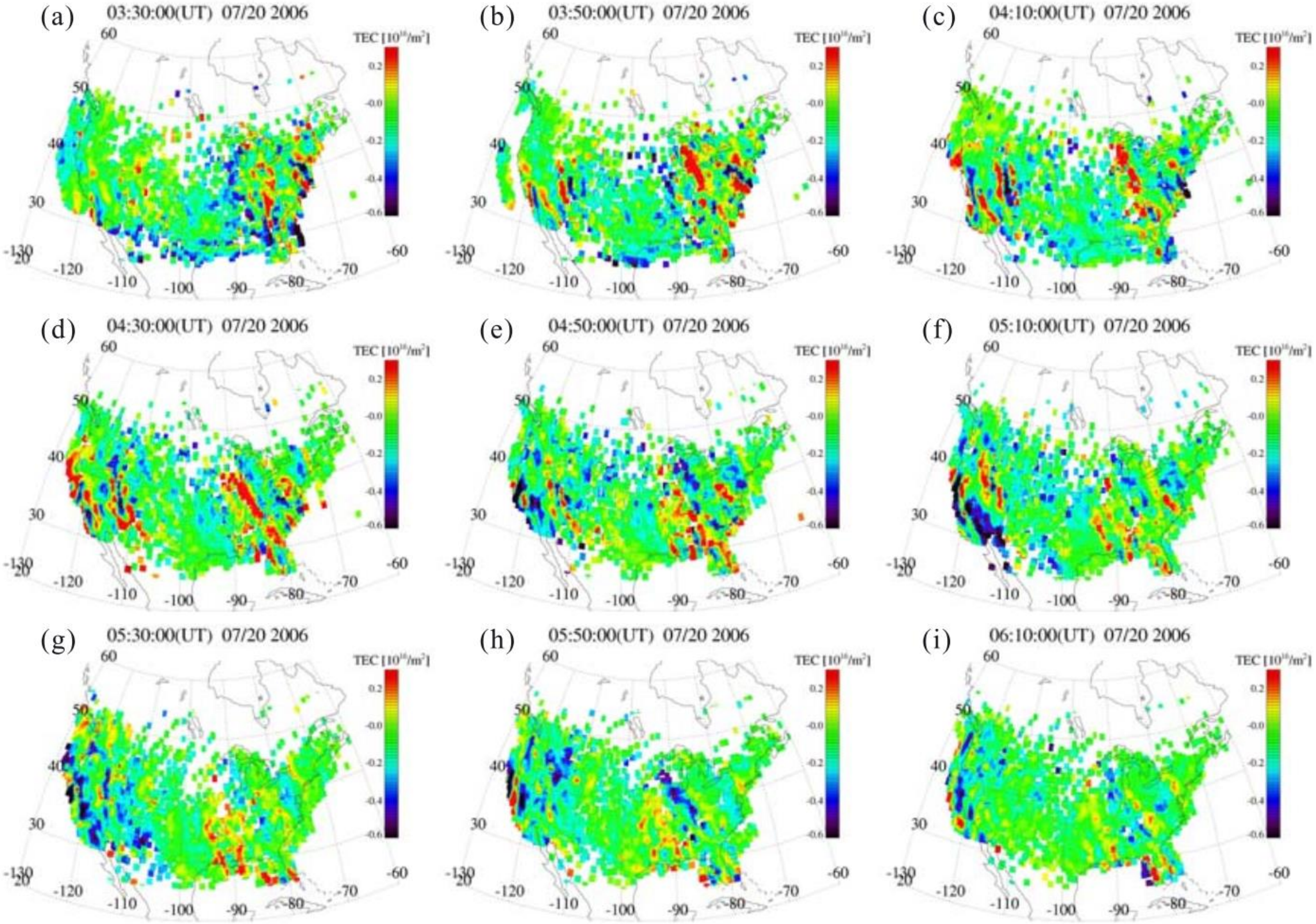
Express the parameter as a function of different factors that influence it

$$vTEC_o = a \times \mathrm{LAT} + b \times \mathrm{Time} + c, \quad \Delta TEC = vTEC - vTEC_o$$



Ding et al., (2007), Large-scale traveling ionospheric disturbances observed by GPS total electron content during the magnetic storm of 29-30 October 2003, JGR, 112, A06309, doi:10.1029/2006JA012013

Background determination



Running averages or medians

Depending on the type of the TID under consideration, different temporal resolutions are used for this purpose.

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Tsugawa et al., (2007), Medium-scale traveling ionospheric disturbances detected with dense and wide TEC maps over North America, GRL

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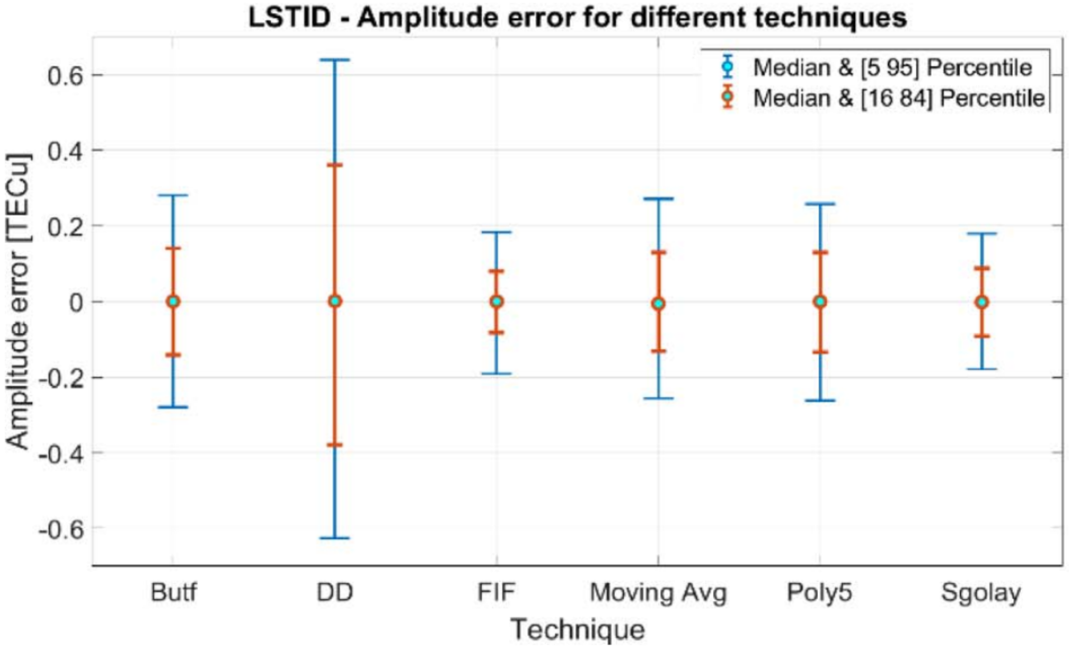
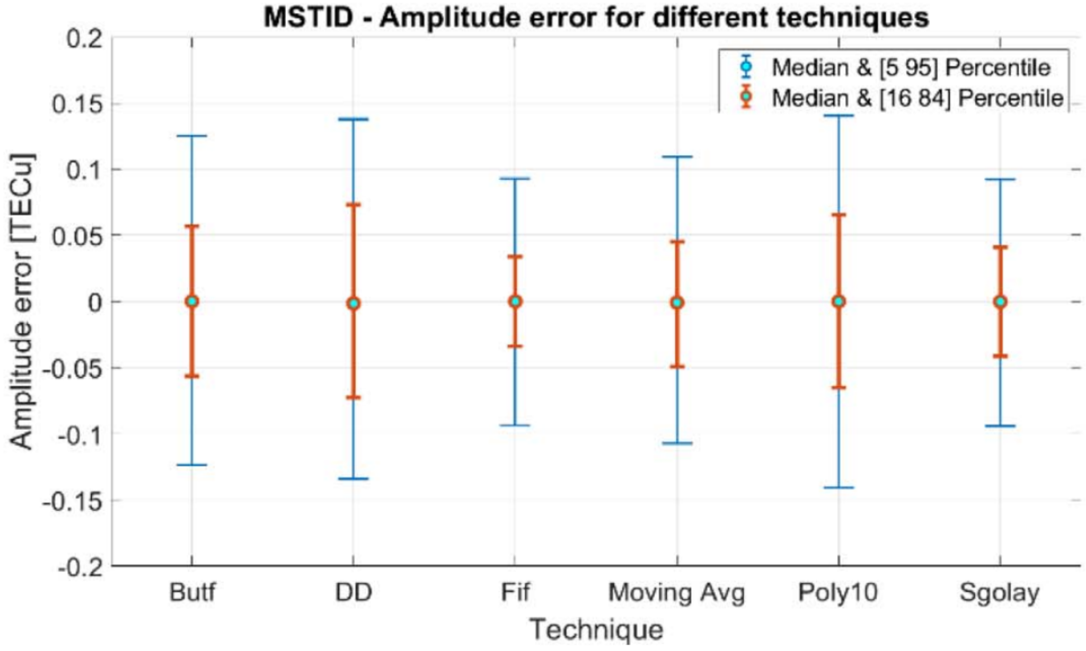
Comparison of different methodologies





- Moving average.
- The multi-order numerical difference.
- Savitzky-Golay filter.

- Finite Impulse response band-pass filter.
- Fast Iterative Filtering band-pass filter.
- Polynomial detrending.

Guerra et al., (2024) concluded that *FIF and SGOLAY proved to be the most reliable overall in estimating the wave amplitude and period*

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Guerra et al., (2024): Travelling ionospheric disturbances detection: A statistical study of detrending techniques, induced period error and near real-time observables, JSWSC

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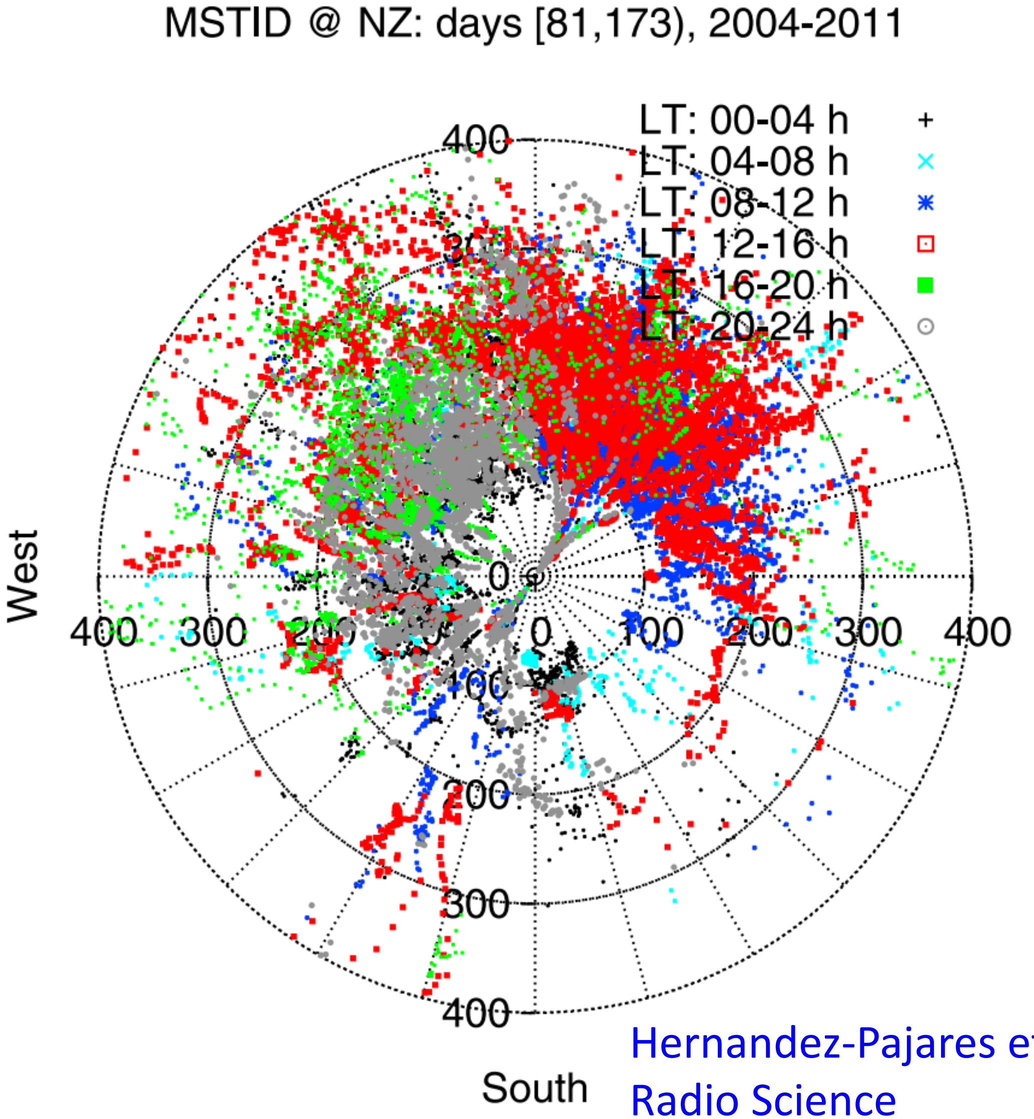
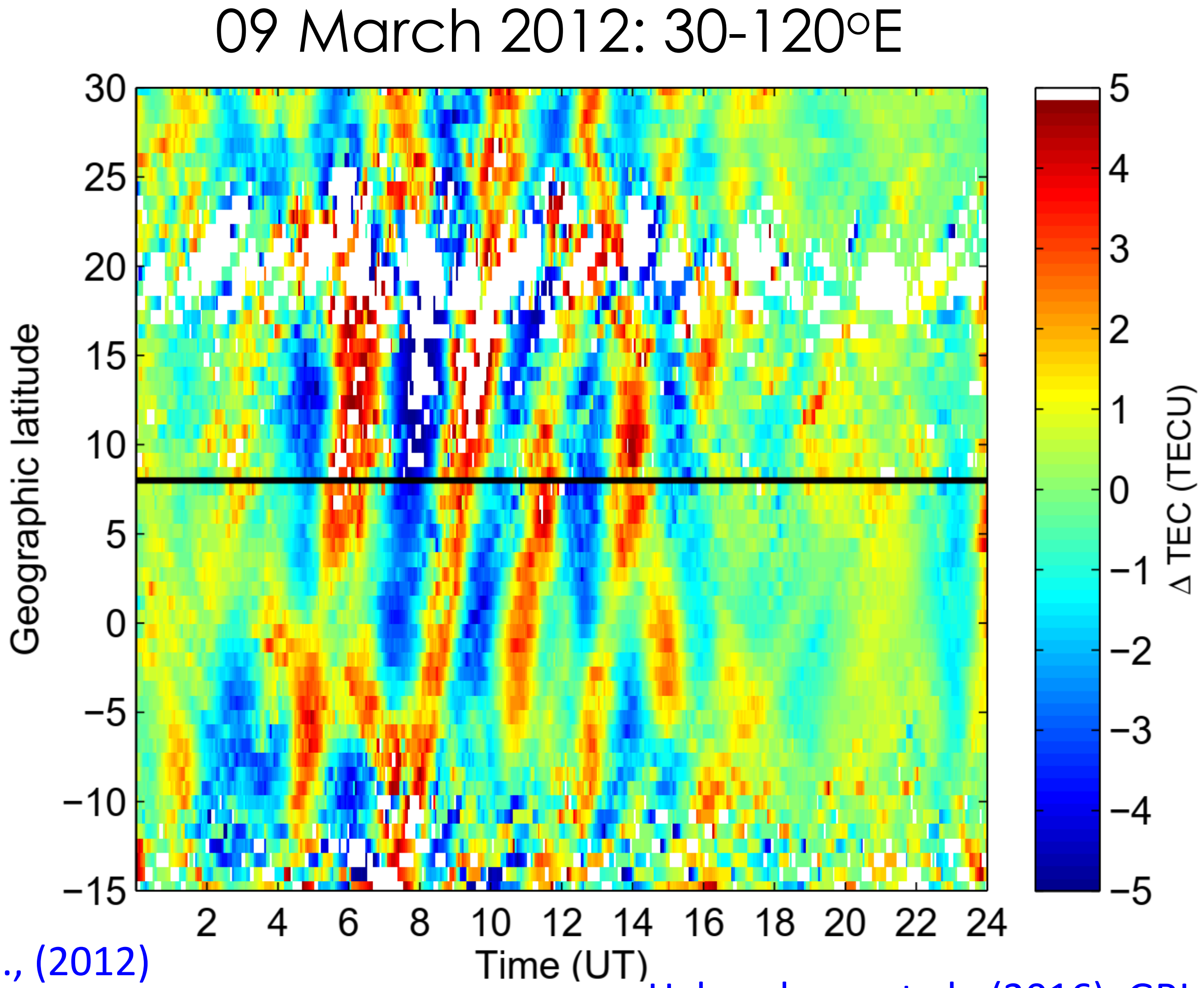
Observations of different categories



Hernandez-Pajares et al., (2012) Radio Science



Habarulema et al., (2016), GRL

MSTIDs have periods up to 1 hr and velocity values of ~ 100 - 300 m/s and occur more frequently: For LSTIDS, velocities up to 1000 m/s, periods of 1-3 hours

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TID generation mechanisms; Natural sources

Medim scale TIDs; Sources include auroral regions, changes in tropospheric systems (Valladares and Hei, 2012), Solar terminator (e.g., Somsikov, 1987; MacDougall and Jayachandran, 2011). They have seasonal dependence (e.g. Hecht et al., 2001; Shiokawa et al., 2009; Chum et al., 2012), but also propagate in any direction depending on the source and tropospheric background conditions.

Large scale TIDs; Mainly propagate equatorward from auroral regions. Main mechanisms are Joule heating, which occurs when the magnetospheric electric fields drive a large scale current, the auroral electrojet, through the high-latitude ionosphere (e.g. Hines 1960, Hunsucker 1982, van Velthoven 1990, Hocke and Schlgel 1996); Lorentz force that follows from the interaction between the electrojet current and the geomagnetic field; and precipitation of energetic particles into the atmosphere near the poles, which causes local heating of the auroral atmosphere.

Different mechanisms have different effective rates...

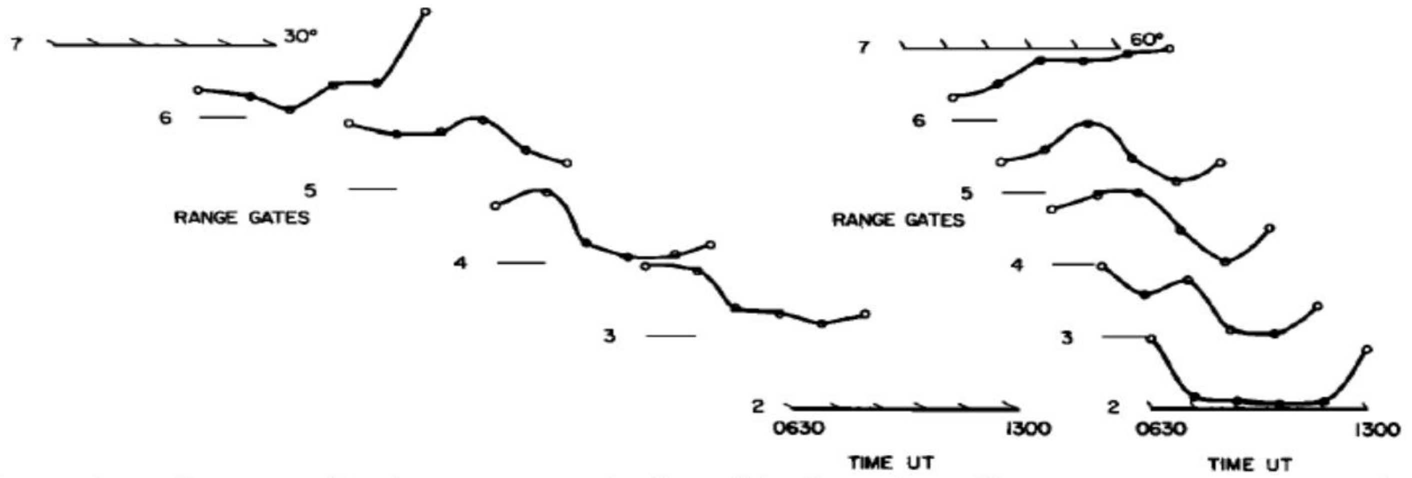
During geomagnetic storms, there are two dominant mechanisms in both low and auroral regions.

- Direct heating of the atmosphere (Joule/particle-particle heating)
- Force $\mathbf{J} \times \mathbf{B_o}$ which is transfered from the ionized component to the neutrals through collisions (Lorentz coupling).

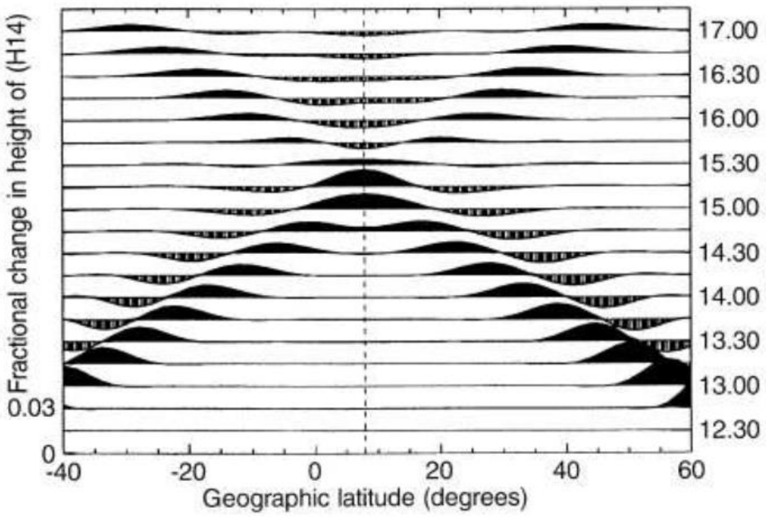
Differences

- For direct heating of the atmosphere (Joule/particle-particle heating; $\mathbf{J}.\mathbf{E} = \mathbf{J}^2/\sigma_\mathbf{c}$). For a given current distribution, the difference is due to the cowling conductivity
- Lorentz coupling: In auroral latitudes, geomagnetic field is almost vertical and Lorentz coupling just transfers momentum horizontally to the neutral gas, while $\mathbf{J} \times \mathbf{B_o}$ at the equator is vertical

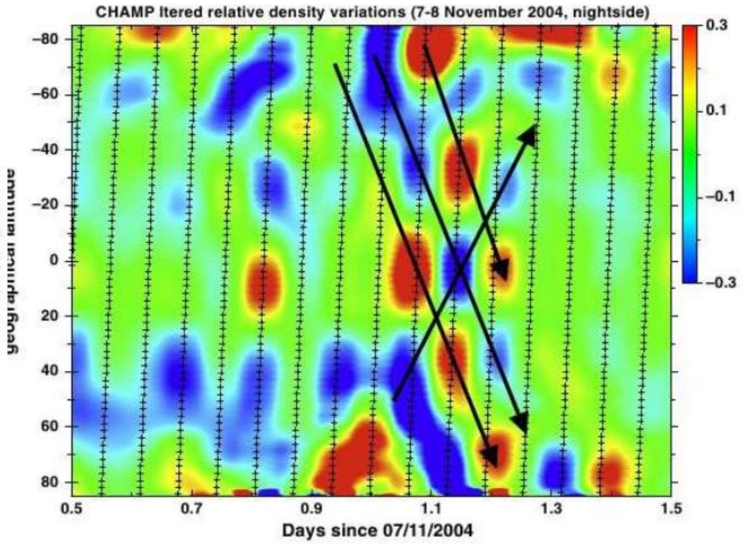
Numerical simulation and observational studies



Chatanaka radar normalised wave power in four altitude regions. Two separate antennas pointing 60 and 30 degrees elevation angle in the magnetic meridian looking south (Pinger, 1979)

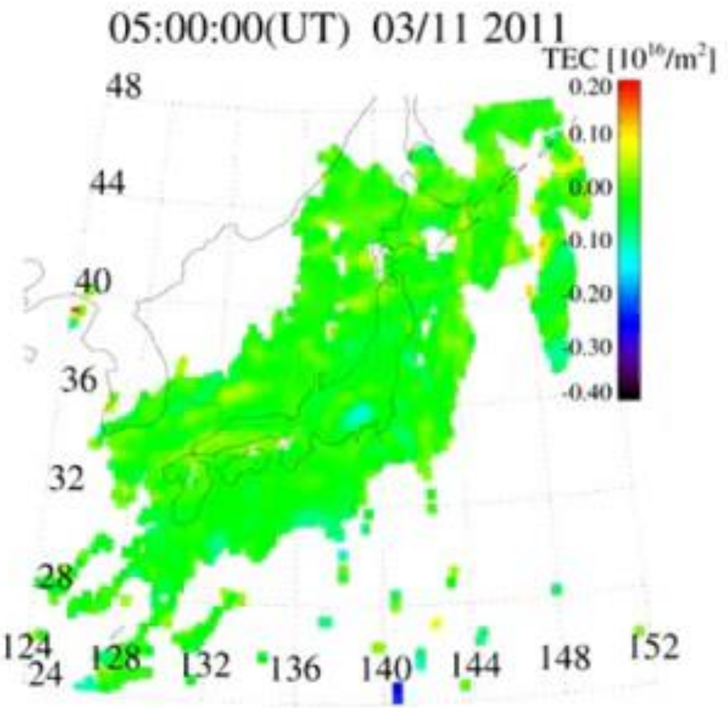


Coupled thermosphere-ionosphere-plasmasphere model simulations at fixed pressure surface, approximate altitude of 380 km (Balthazor and Moffet, 1997)

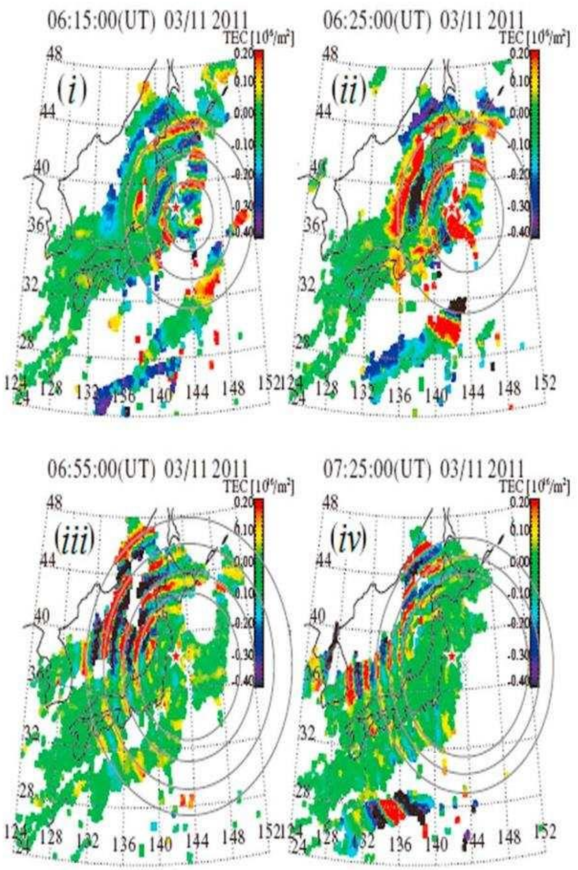


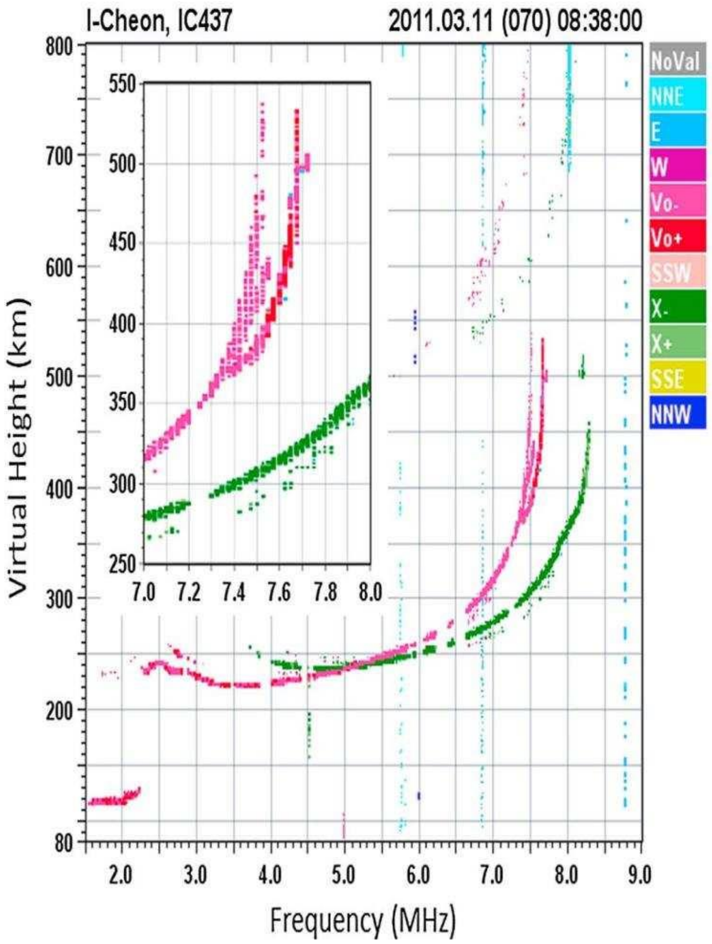
Densities from CHAMP accelerometer measurements (about 400 km altitude) (Bruinsma and Forbes, 2008)

Earthquake generated TIDs



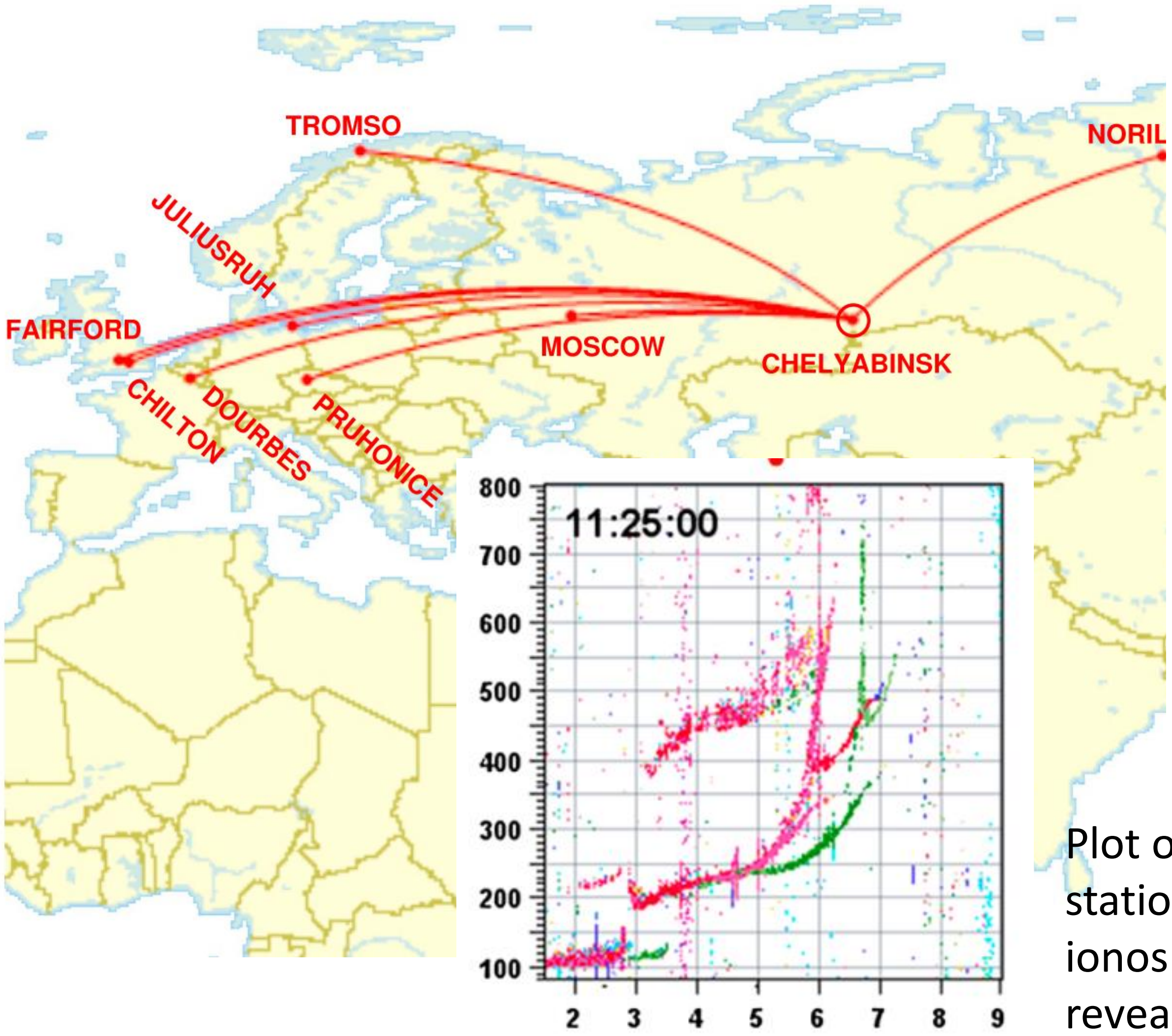
Total electron content (TEC) variation derived using GEONET

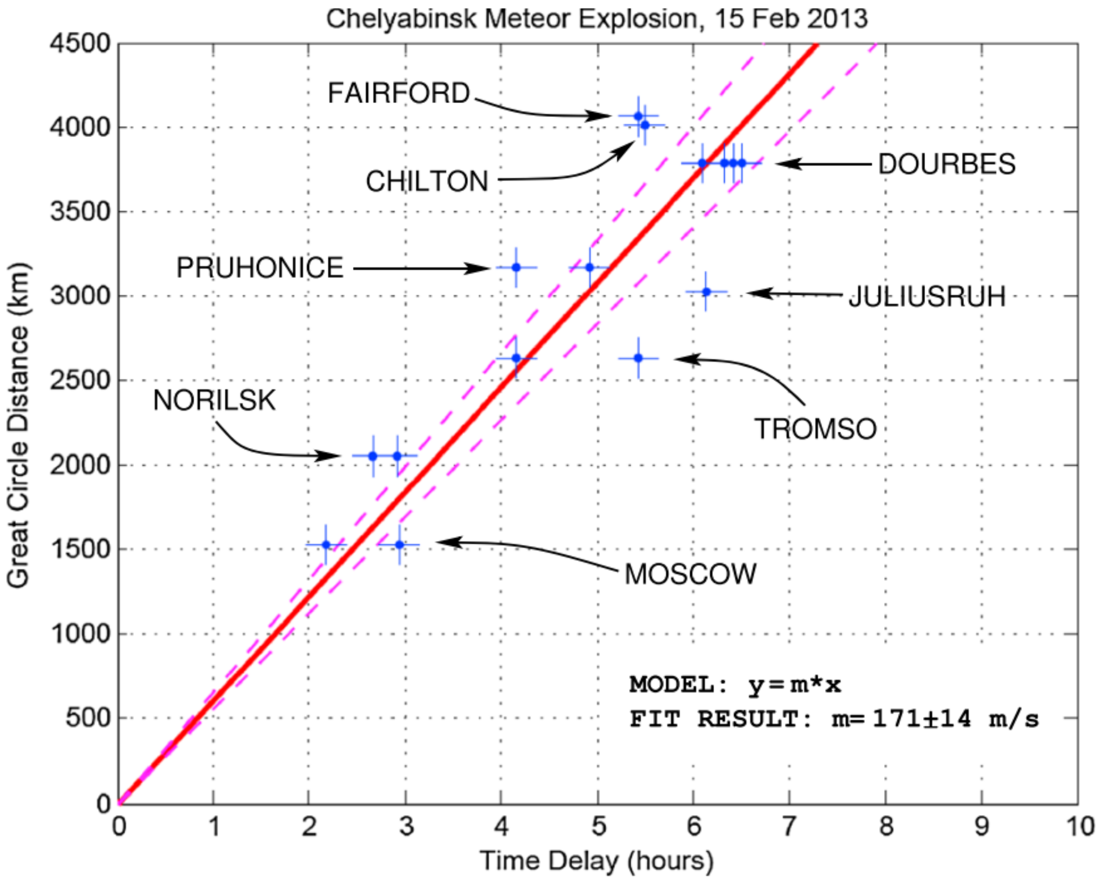




Concentric wave fronts reconstructed from GPS TEC data over Japan after 11 March 2011 earthquake; and ionosonde data showing signatures of TIDs. References: Pradipta et al., (2015), Ionosonde observations of ionospheric disturbances due to the 15 February 2013 Chelyabinsk meteor explosion, JGR Tsugawa et al., (2011), Ionospheric disturbances detected by GPS total electron content observation after the 2011 off the Pacific coast of Tohoku Earthquake, EPS

TIDs generated by meteor explosion





Plot of the great circle distance from Chelyabinsk to each ionosonde stations versus the corresponding time delay for the traveling ionospheric disturbances to arrive. The solid red line is a linear fit, revealing a propagation speed of roughly 171 m/s. The dashed magenta lines indicate the 95% confidence interval bounds

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Pradipta et al., (2015); JGR

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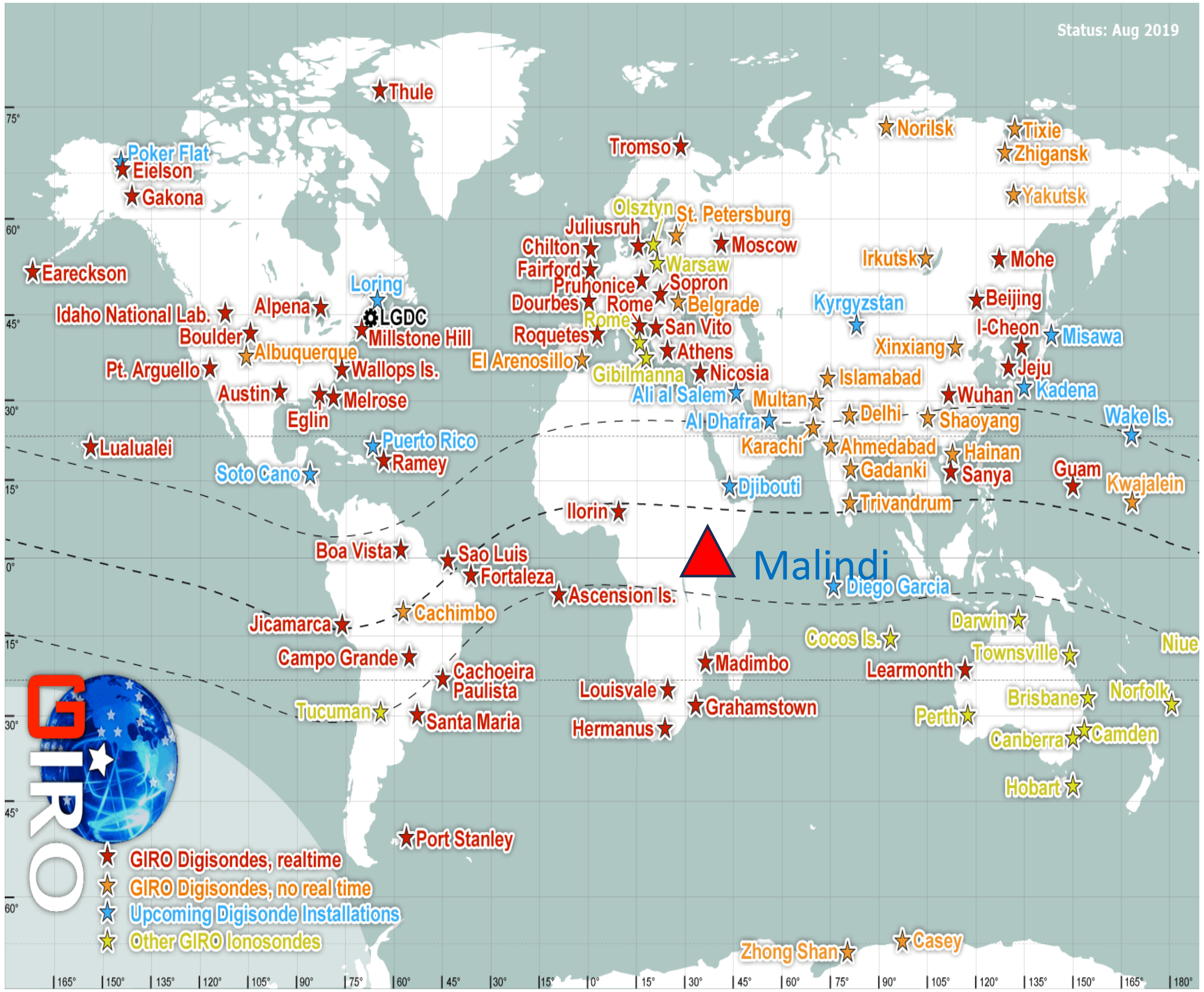
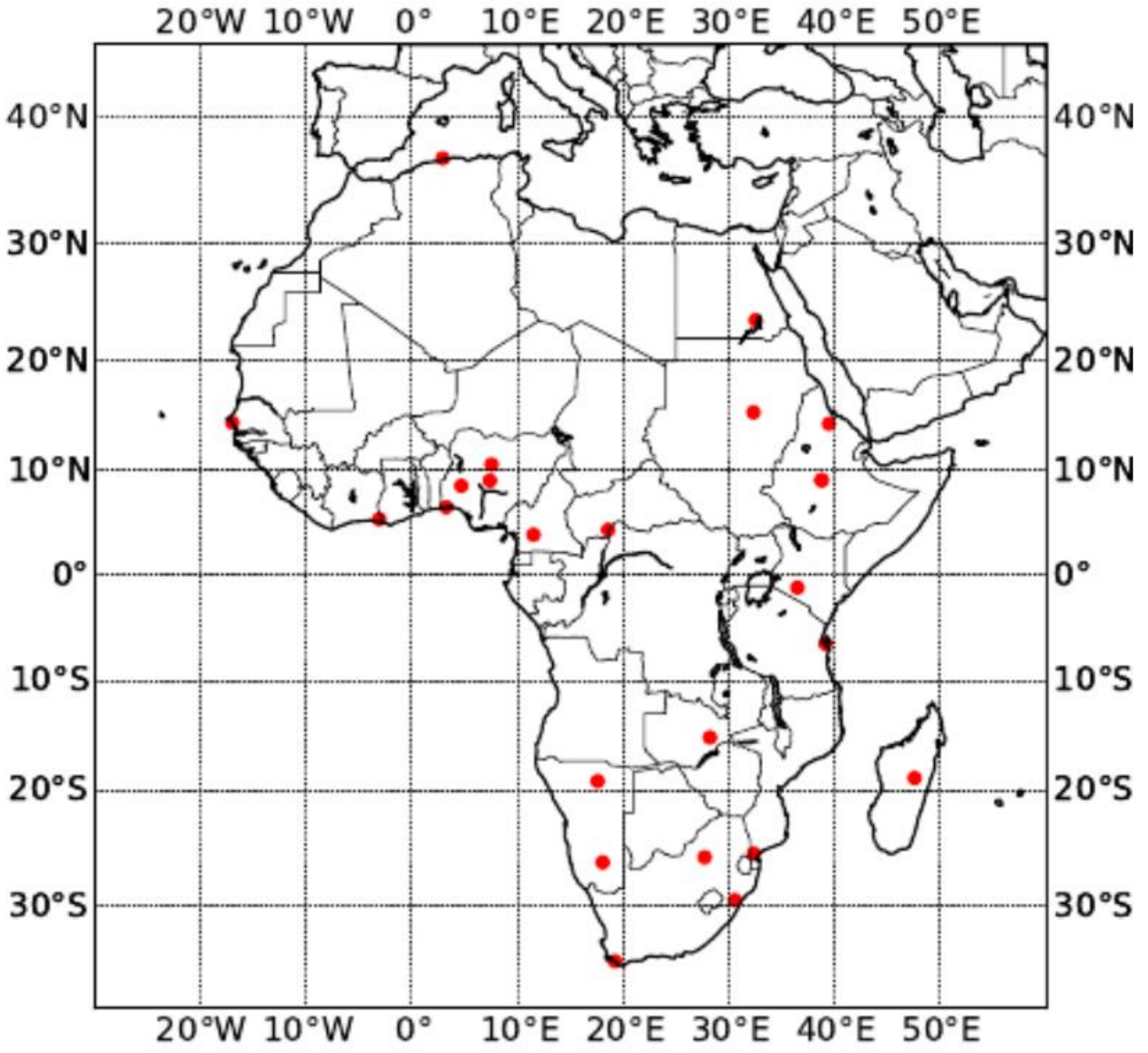
Challenges? Ionosondes (biased) and magnetometers





https://giro.uml.edu/

Magnetometer networks: INTERMAGNET, MAGDAS, AMBER, SANSA

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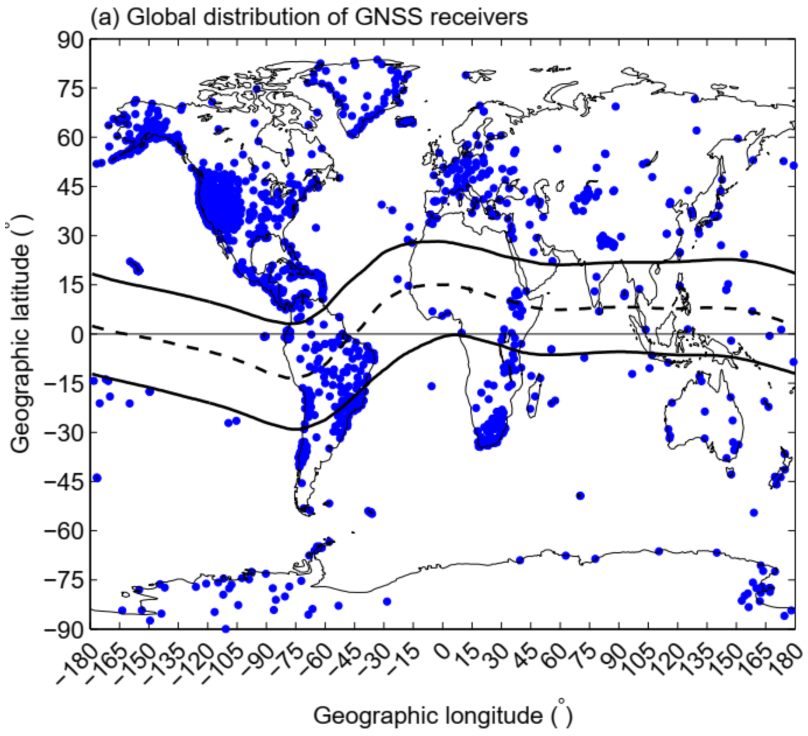
Some regions are constrained by research infrastructure



YES and NO,
For Different Reasons

We are trying to answer scientific questions

- YES, if the scientific question can only be answered in specific latitude regions; such as study of low latitude electrodynamics; specific to low latitudes and using specific datasets (e.g., vertical drifts)
- NO, if the question is not region specific. There are many sources of data and there is no restricting reason to remain within the African continent. It is possible to search for data elsewhere and you go ahead to answer scientific questions as we continue sorting out our African backyards.

Should instrumentation challenges continue to limit us?

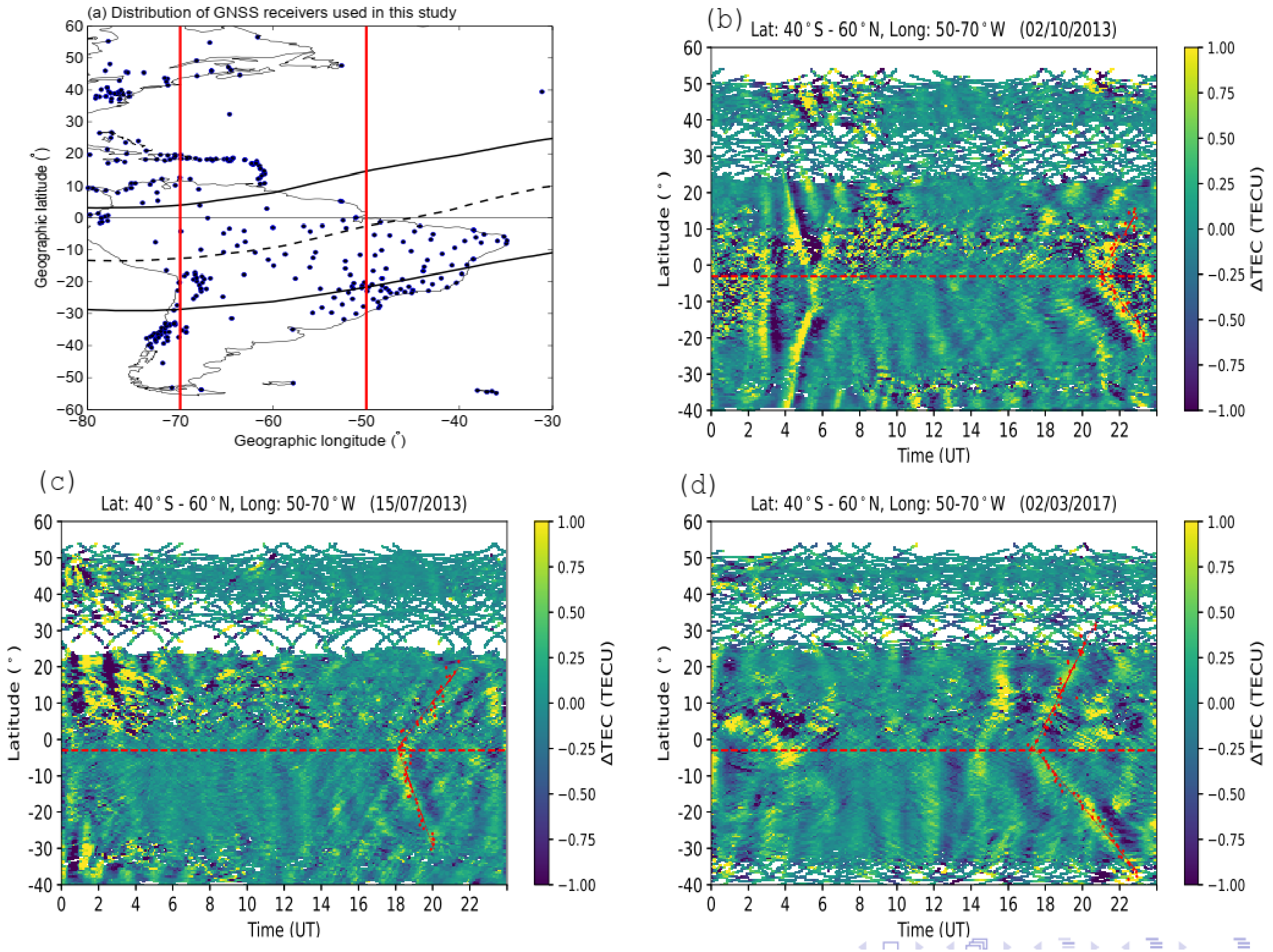
Statistical study of TIDs: Geomagnetic equator origin

- Analysed TEC changes during geomagnetic storms which occurred from 2010-2018 within latitude range of 40°S-60°N and longitude ranges of $20 - 40°$E (African sector) and $50 - 70°$W (American sector).
- Geomagnetic storm criterion of Kp>4 and Dst≤-50 nT was used
- Background TEC estimation performed through polynomial fitting
- ΔTEC is binned in 5 minutes and 0.5° latitude grids
- Propagation characteristics such as velocity, periods and wavelengths are estimated

Details on estimation of characteristics can be found in:

Thaganyana G. P., Habarulema J. B, Ngwira C. and Azeem I. (2022): Equatorward medium to large scale travelling ionospheric disturbances of high latitude origin during quiet conditions, Journal of Geophysical Research, Space Physics, 127, https://doi.org/10.1029/2021JA029558.

Examples of TIDs originating from Equator: American sector



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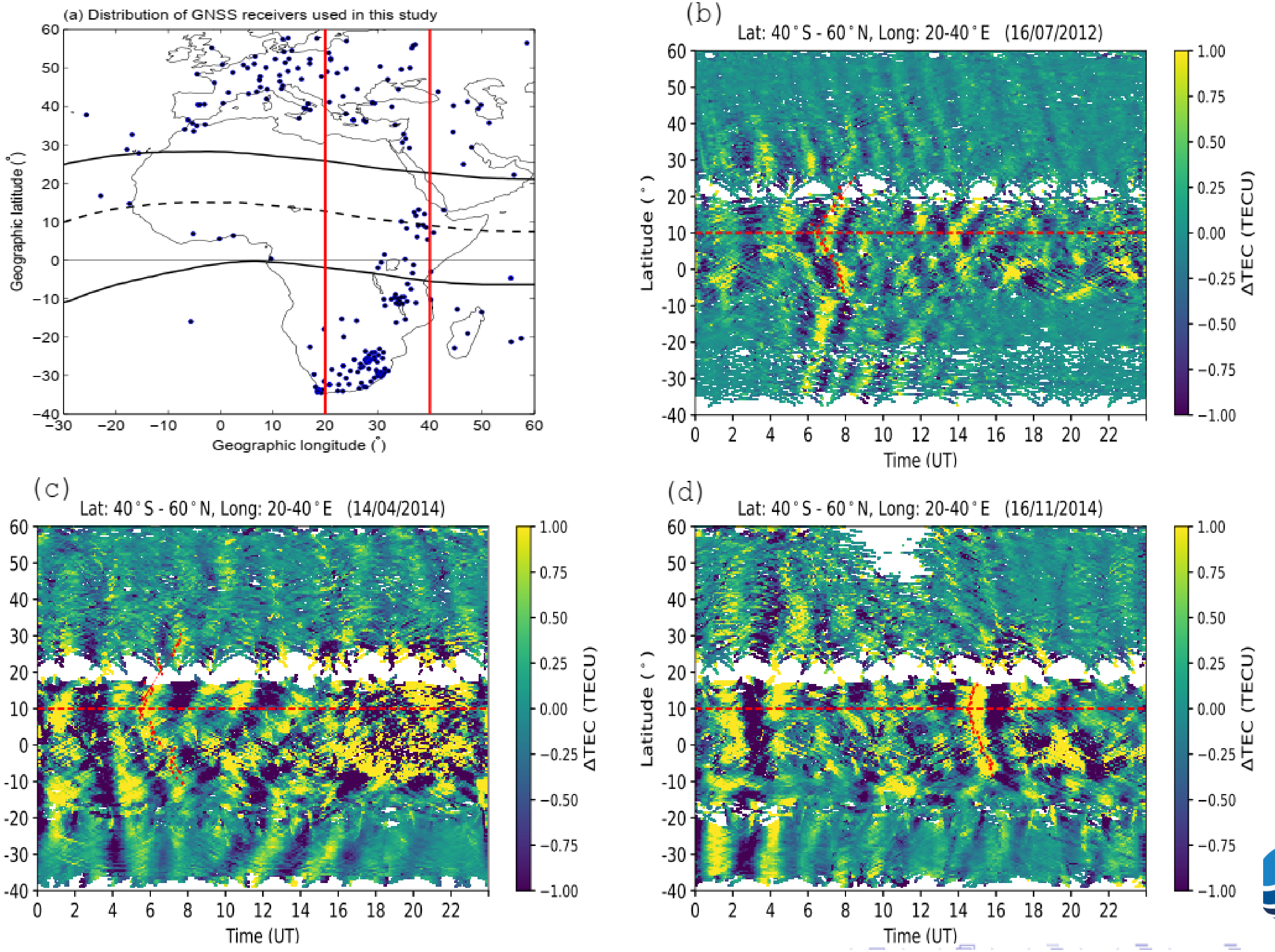
Examples of TIDs originating from Equator: African sector



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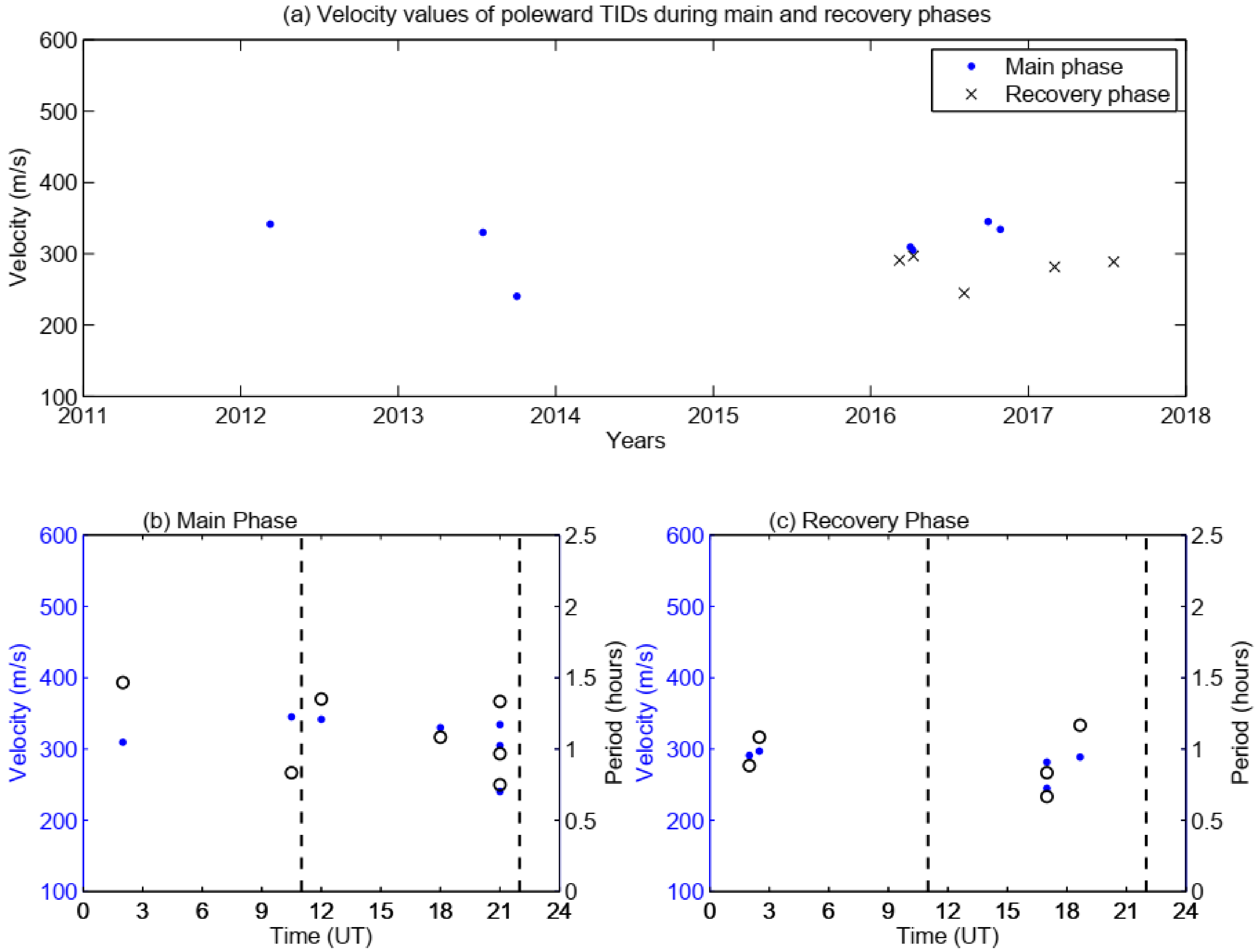
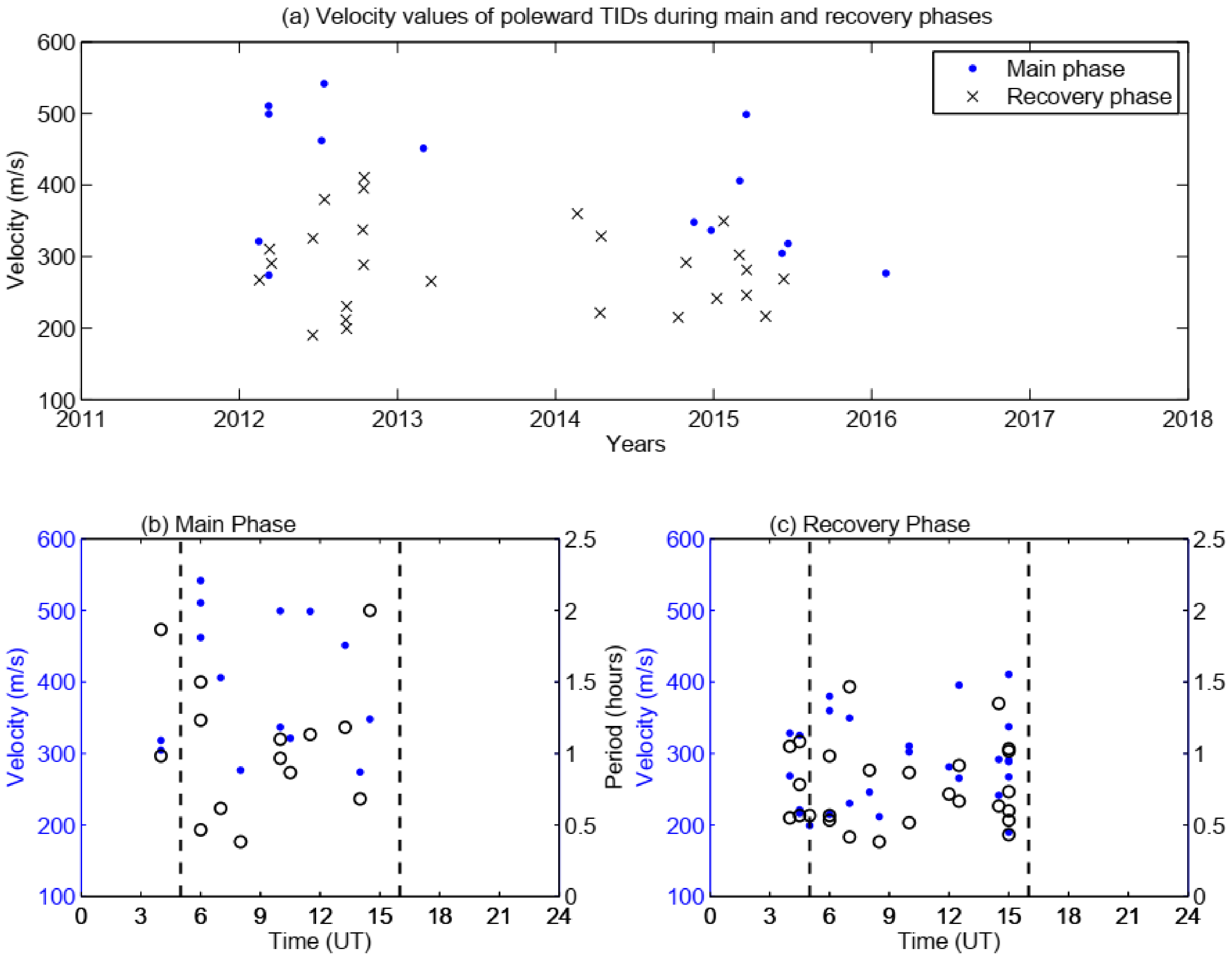
Statistical Results; American sector



Statistical Results; African sector



Over the African sector, almost all observed poleward TIDs during main phase are LS with velocity values of 300-550 m/s

During the recovery phase, 63% and 37% of the poleward TIDs accounted for medium and large scale TIDs with period (velocity) ranges of 23-50 minutes (190-290 m/s) and 0.5-1.5 hours (300-410 m/s) respectively; over the African sector.

Statistically, results over the American sector are similar to those over the African sector

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Habarulema et al.,. (2022). A statistical study of poleward traveling ionospheric disturbances over the African and American sectors during geomagnetic storms, JGR, https://doi.org/10.1029/2021JA030162

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Relationship between ΔH and vertical ExB drift

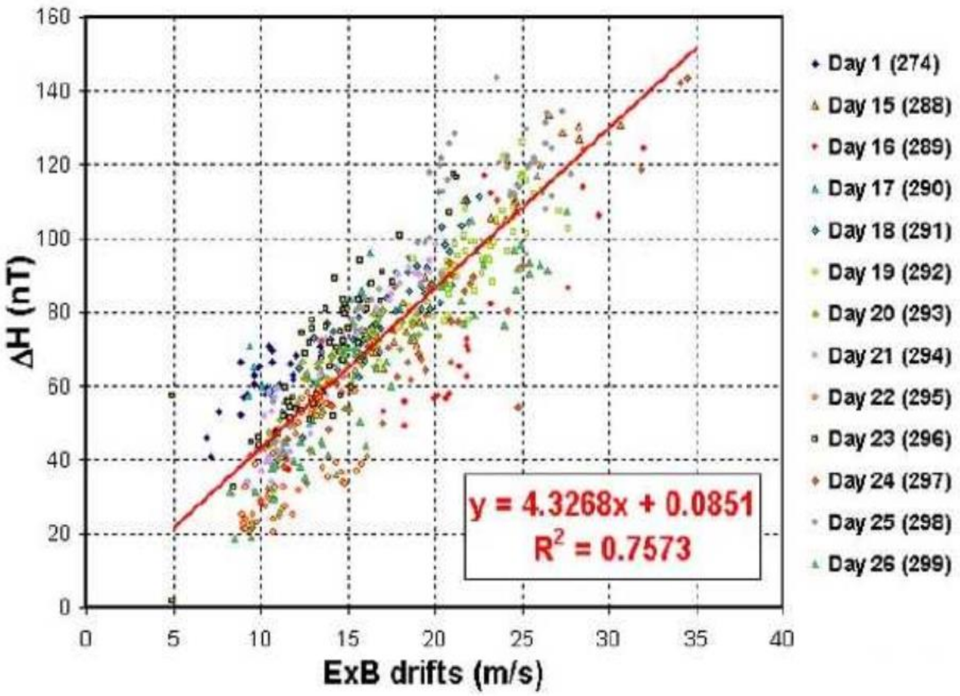
Requirement: Equatorial magnetometer and the one displaced $6^\circ - 9^\circ$ away (Rastogi and Klobuchar, 1990; Anderson et al., 2004)

$$B_{\text{off}} = \sum_{i=1}^{5} B_i \qquad \text{Observed B off the equator} \qquad (14)$$

$$B_{\text{equ}} = \sum_{i=1}^{6} B_i \qquad \text{Observed B at the equator} \qquad (15)$$

1. B_1: Main field==Earth core contribution
2. B_2: Long-term changes, Secular Variation
3. B_3: Field Aligned currents contribution
4. B_4: Ring Current contribution
5. B_5: Others such as Magnetospheric particle precipitation or magnetopause currents?
6. B_6: Equatorial Electrojet (EEJ), Only affects the equatorial station

$\Delta H = H_{\text{equator}} - H_{\text{off-equator}}$ is the EEJ contribution which is directly proportional to $\mathbf{E} \times \mathbf{B}$ drift



Correlation of 0.87 during local daytime:

Anderson et al., (2004), Daytime vertical $\mathbf{E} \times \mathbf{B}$ drift velocities inferred from ground-based magnetometer observations at low latitudes, Space Weather, 2, S11001. doi:10.1029/2004SW000095

ΔH is a proxy of EEJ which in turn is directly proportional to vertical ExB drift. Differential magnetometer approach has shown this in different longitude sectors

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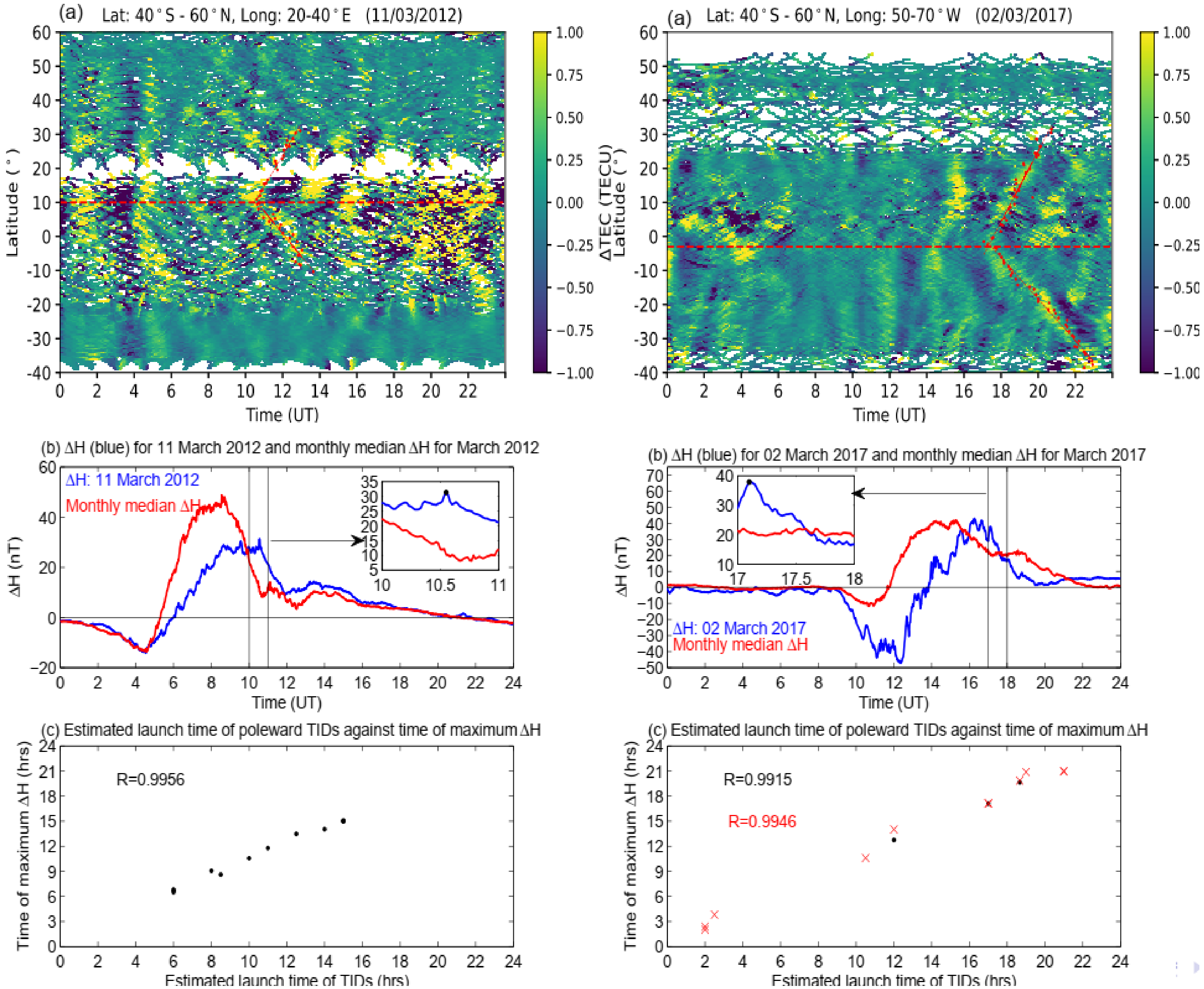
Link between electrodynamics and resulting TIDs?



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Difficult to detect and amplitude comments

It has been suggested and numerically shown that changes in EEJ can have influence in contributing to TIDs during disturbed conditions.

- Chimonas (1969): *The upper atmosphere in motion: The equatorial electrojet as a source of long period traveling ionospheric disturbances*, Geophysical Monograph Series, 18, 698-709.

- Knudsen (1969), *Neutral Atmosphere Wave Generation by the Equatorial Electrojet*, J. Geophys. Res. 74(16), 4191-4192.

In their analysis of properties of traveling atmospheric disturbances (TADs) during storms of 2001–2007, Bruinsma and Forbes (2009) stated that few cases of poleward TADs were observed but did not propagate far from their source and were difficult to be tracked

1. Despite their possible existence having been suggested and numerically shown about 50 years ago (Chimonas, 1969; Knudsen, 1969), literature about their observations is nearly nonexistent. This is because AGWs generated through EEJ dynamics and electrodynamics are difficult to observe and track due to their small amplitudes compared to the ones that originate from auroral regions (Knudsen, 1969). Made possible by relatively dense network of GNSS receivers
2. Specification of amplitudes depends on the parameterisation used in analyses and the methodology used to determine the background conditions

First suggested by Knudsen (1969) and numerically shown by Chimonas (1969)

THE EQUATORIAL ELECTROJET AS A SOURCE OF LONG PERIOD TRAVELLING IONOSPHERIC DISTURBANCES

G. CHIMONAS
Department of Physics, University of Toronto, Toronto 5, Canada

(*Received* 11 *November* 1969)

2. QUANTITATIVE ANALYSIS

The general mathematical development of this problem has been made in paper A; here we will just quote the results needed for the special geometry of a horizontal magnetic field. Let (x, y, z) form a right handed set of co-ordinates set up at the Earth's equator such that **g**, the gravitational acceleration, acts in the negative z direction and $\mathbf{B}_0$, the geomagnetic field, defines the negative x direction. The equatorial electrojet is taken to flow from $-\infty$ to $+\infty$ along the y direction. The atmosphere is taken to be isothermal with scale height H. Then we define

$$\mathbf{J} = \hat{y}j(x, z)T(t) \tag{1}$$

as the current density flowing in the atmosphere,

$$D(t) = \frac{d}{dt}T(t), \qquad \omega_g^2 = \frac{(\gamma-1)g}{\gamma H}, \qquad B_0 = |\mathbf{B}_0|, \qquad 24.$$

γ = usual ratio of specific heats, $C_L^2 = \gamma g H(\gamma - 1)4/\gamma^2$, $\rho_0(z)$ = mass density of the atmosphere.

Use of Equations (25) and earlier of 'A', with a further integration by parts, provides the low frequency part of the fractional pressure perturbation at the point (x, z) at time t

$$p_L(x, z, t) = \frac{-B_0}{4\pi g H \omega_g}\iint dx'\, dz' \int_0^\infty ds\, \frac{j(x', z')}{\rho_0(z')} \times \exp\left[(z-z')/2H\right]\left\{\frac{(2-\gamma)}{\gamma H} + 2\frac{\partial}{\partial z'}\right\}\frac{D(t-\sqrt{s^2+R^2/C_L^2})\cos\omega_e s}{\sqrt{s^2+R^2/C_L^2}} \qquad (2)*$$

where $R^2 = (x-x')^2 + (z-z')^2$, $\omega_e = \omega_g(z-z')/R$.

The geometry of this system is shown in Fig. 1. Because of the form chosen for **J** the system is uniform in y and the problem is worked entirely in the two dimensions (x, z). We may choose reasonable forms for the functions $j(x, z)$ and $T(t)$ so that the larger part of the numerical work may be performed with approximations and analytic steps. Such forms

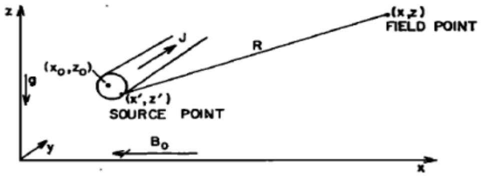

Fig. 1. The geometry used in the calculation of equatorially launched TID's.

Resultant TIDs are confined within latitude ranges of +/-30 degrees. Why?

- The orientation of the Lorentz force driving the ion-neutral collisions at equatorial and auroral regions. Due to nearly vertical nature of the magnetic field in auroral regions, Lorentz coupling involves a direct transfer of energy to the neutrals in a horizontal way (e.g., Chimonas, 1969; Knudsen, 1969).
- Lorentz force in equatorial regions is vertical due to the eastward electric field and the magnetic field is almost horizontal.

- An additional consideration is the strength of the magnetic field in auroral and equatorial regions. The magnetic field strength in auroral regions is approximately double that of the strength in the equatorial region, and given that the current density magnitude in EEJ about 1/3 that of the auroral electrojet (AEJ) during geomagnetic storms (Akasofu et al., 1965; Knudsen, 1969), the resulting force ($J \times B$) in EEJ is smaller than that in the auroral region by a factor of 1/5 (Knudsen, 1969; Yizengaw et al., 2018).

- The orientation of the Lorentz force, integrated current density in EEJ and AEJ, and magnetic field strength influences the resultant energy transferred from ions to neutrals; and hence distinguishes the characteristics of the launched AGWs in auroral and equatorial regions.

More ways of studying TIDs…. And different considerations

- Theoretical studies of TIDs which would require solving the hydrodynamic equations (continuity, energy and momentum) from first principles
- Models: Theoretical and/or empirical/semi empirical models of TIDs; including data assimilation approaches

Resources available for AGWs/TIDs studies

- Ground based instrumentation e.g. ionosondes, incoherent scatter radars, optical instruments, etc
- Space-based instrumentation.. satellite data e.g. GNSS, LEO satellites (CHAMP, COSMIC, GRACE, C/NOFS, SWARM, etc)

Knowledge of different latitude regions required

In addition to understanding the different datasets required,

- Knowledge of drivers for AGWs require understanding of different physical mechanisms in different latitude region
- The interpretation of AGWs/TIDs require 'reference point' and therefore one region may not necessarily be studied in isolation
- Multiple data sources from variety of instrumentation provide complete and comprehensive understanding of the phenomena under investigation.

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