Atmospheric Gravity Waves, TIDs and their monitoring techniques

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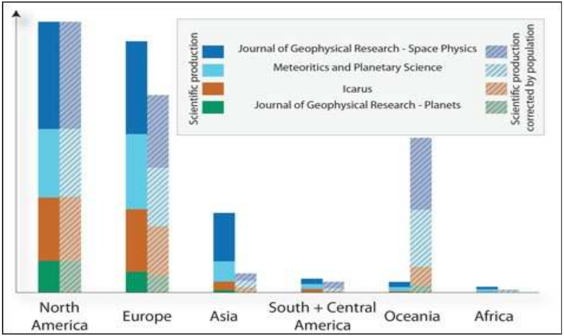
The idea stemmed from a panel discussion during the planetary science sessions of the 35th International Geological Congress (IGC) in Cape Town, South Africa, in 2016.

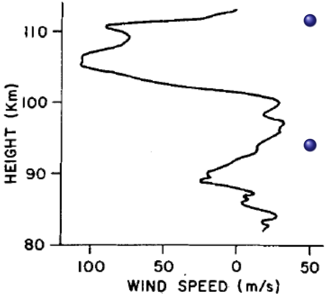


Scientific productivity expressed by the number of articles (solid colors) between 2000-2015 in four of the most representative PSS journals that publish exclusively in the field of planetary and/or space sciences

Baratoux et al. (2017), Africa initiative for planetary and space sciences, Eos, 98, `https://doi.org/10.1029/2017EO075935`.

Please visit `https://africapss.org` and consider getting involved!

Lets now focus on AGWs/TIDs ...



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.

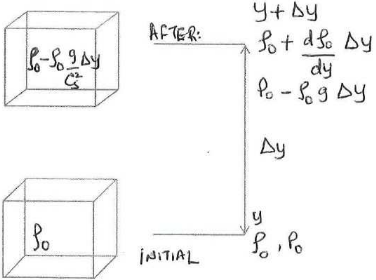
- Commonly, gravity waves are generated in the troposphere by weather fronts or air flow over mountains.
- Their amplitudes increase as they reach higher altitudes (thin air) and later break-up thereby transfering energy and momentum from the troposphere to the stratosphere/mesosphere.

Within the IONOSPHERE

- Gravity waves transfer energy between different ionospheric layers and manifest as travelling atmospheric disturbances or travelling ionospheric disturbances (TIDs)⇒⇒ Our interest in this discussion
- TIDs are mainly categorised as medium and large scale mainly based on their velocities, wavelengths and periods

TIDs: Discovered 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 $\rho_o + \Delta\rho_o = \rho_o + \frac{d\rho_o}{dy}\Delta y$

Description of the air parcel motion

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 continued

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

AGWs continued

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

How do AGWs affect the ionosphere

Continuity equation of electrons in the ionosphere is given by

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

- 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),

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

- 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

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

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

AGWs effects on ionosphere continued

The solution to the above equation is

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

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 ($\mathbf{v_{en}} << \omega_{\mathbf{ce}}$) and therefore

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

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

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

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

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

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

Classification of TIDs

Class	Velocity (m/s)	Period	Wavelength	Possible sources	Remarks
Large scale	400-1000	30 min- 3 hrs	$\gtrsim$ 1000 km	Polar regions during storms	Propagate equatorward
Medium scale	1000-250	15 min-$\approx$ 1hr	100s of km	Auroral sources play a crucial role	dominant direction is from winter polar regions
Small Scale	300-3000	2-5 min		severe convective activity	seasonal occurrence peak in the summer

Hunsucker (1982): Atmospheric Gravity Waves Generated in the High-Latitude Ionosphere: A Review; Reviews of Geophysics and Space Physics, 20 (2), 293-315

Current Understanding

- Large Scale: Largely manifest during storm conditions and propagate equatorward: New observations show poleward propagating TIDs with origin from around the geomagnetic equator (Habarulema et al., 2016)
- Medium Scale: Can propagate in any direction and sources are associated with tropospheric systems, energy dissipation of large scale TIDs, solar terminator etc
- Man-made sources such as nuclear explosions can give rise to both medium and large scale TIDs
- Other natural sources such as Earthquakes and tsunamis

Various mechanisms in different latitude regions

Dominant mechanisms are;

Auroral regions

Gravity waves are generated through

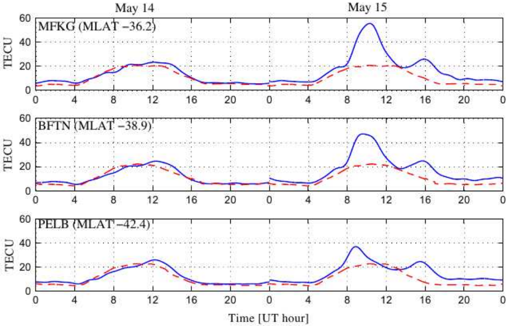
- Direct heating of the atmosphere (Joule/particle-particle heating)
- Force $\mathbf{J} \times \mathbf{B_o}$ which is transfered from the ionized component to the neutrals through collisions (Lorentz coupling). Geomagnetic field is almost vertical and Lorentz coupling just transfers momentum horizontally to the neutral gas
- Particle precipitation

Equatorial regions

- Joule coupling: Direct heating of the atmosphere (Joule/particle-particle heating).
- Lorentz force $\mathbf{J} \times \mathbf{B_o}$ at the geomagnetic equator is vertical

Other proposed sources especially for medium scale TIDs include unstable wind shears, solar terminator, tropospheric systems, etc

Background determination(1) ⇒⇒Comparison with quiet periods

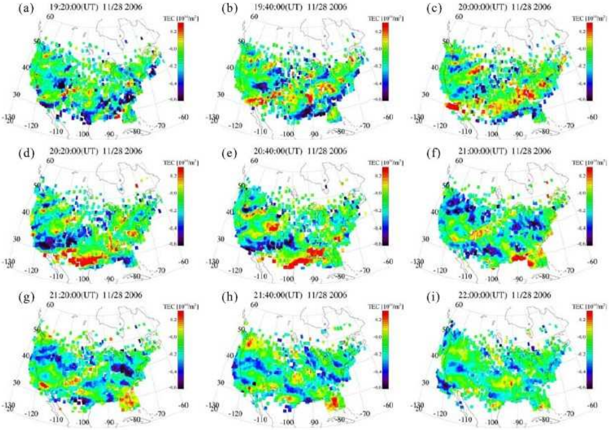


Temporal TEC variations during May 14–15, 2005 at three GPS reference stations approximately along the same longitude, but separated in latitude. The monthly median TEC values (red dashed lines) are used as quiet day reference. At the three locations shown, standard time = UT+2 hr. The data is sampled at 30-second intervals and the jump in the TEC at the end of the first day is a consequence of the data processing method.
Reference: Ngwira et al., (2012): An investigation of ionospheric disturbances over South Africa during the magnetic storm on 15 May 2005, Advances in Space Research, 49, 327-335

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'

Background determination (2)

⇒⇒Running averages

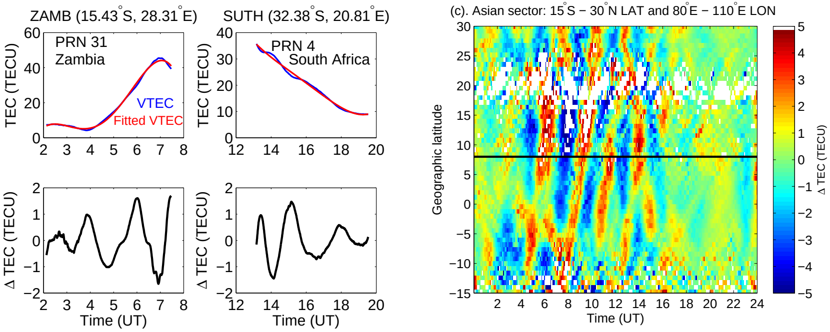


Tsugawa et al. (2007), Medium-scale traveling ionospheric disturbances detected with dense and wide TEC maps over North America, Geophys. Res. Lett., 34, L22101, doi:10.1029/2007GL031663.

Options ranging from 10, 20 up to 60 minutes running windows have been used

Background determination (3)

⇒⇒Polynomial fitting



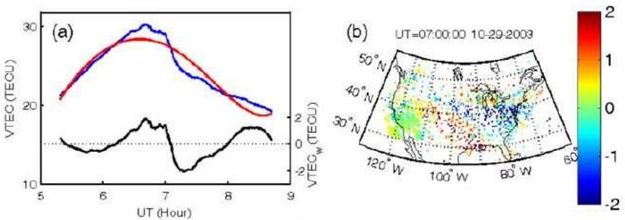
Some references: (1) Valladares et al., (2009), Simultaneous observation of travelling ionospheric disturbances in the Northern and Southern Hemispheres, Ann. Geophys., 27, 1501-1508

(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 (4)

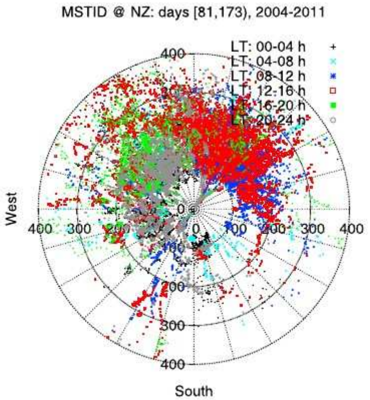
⇒⇒Expression of the parameter as a function of different quantities which influence it

$$vTEC_o = a \times \mathrm{LAT} + b \times \mathrm{Time} + c, \quad \Delta TEC = vTEC - vTEC_o \quad (13)$$

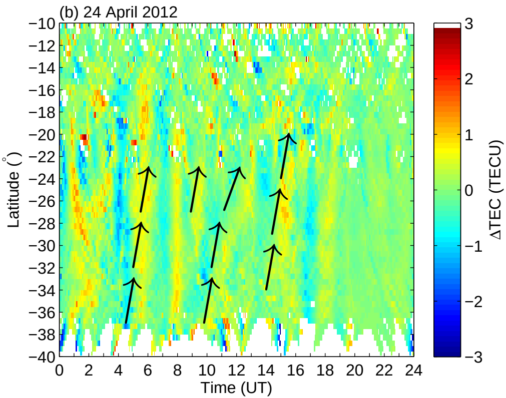


Ding et al (2007): Large-scale traveling ionospheric disturbances observed by GPS total electron content during the magnetic storm of 29 –-30 October 2003, J. Geophys. Res., 112, A06309, doi:10.1029/2006JA012013.

Observations of different categories of TIDs



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



Habarulema et al., (2017), JGR

MSTIDs have periods up to 1 hr and velocity values of $\sim 100 - 300$ m/s and occur more frequently: LSTIDS. Velocites up to 1000 m/s, periods of 1-3 hours.

Examples of instruments for TIDs' studies

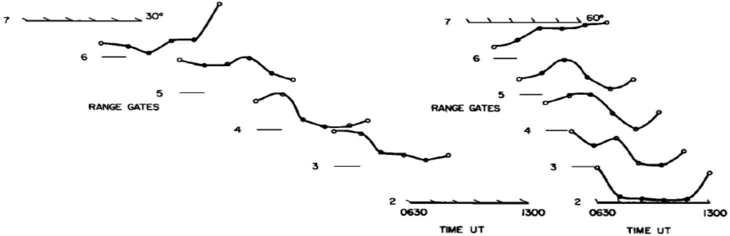
All times?

- Satellites (various types): Afraimovich et al., (1998): GPS radio interferometry of travelling ionospheric disturbances, Journal of Atmospheric and Solar Terrestrial Physics 60, 1205-1223, Valladares et al., (2012): Measurement of the characteristics of TIDs using Small and Regional Networks of GPS Receivers during the Campaign of 17-30 July of 2008, International Journal Geophysics.
- Ionosondes: Morgan et al., (1978): Techniques for the study of TID's with multi-station rapid-run ionosondes, Radio Science, 13(4), 729-741, Klausner et al., (2009): Observations of GW/TID oscillations in the F2 layer at low latitude during high and low solar activity, geomagnetic quiet and disturbed conditions, JGR, 114, doi:10.1029/2008JA013448
- High Frequency Doppler Radars: Wan et al., (1998): Traveling ionospheric disturbances associated with the tropospheric vortexes around Qinghai-Tibet Plateau, GRL, 25 (20), 3775-3778, Chum et al., (2010): Horizontal velocities and propagation directions of gravity waves in the ionosphere over the Czech Republic, JGR, 115 (A11322), doi:10.1029/2010JA015821.
- Incoherent Scatter Radars: Pinger, 1979: Detection of traveling ionospheric disturbances with auroral zone incoherent scatter radar, Radio Science, 14 (1), 75-84, Nicolls et al., (2004): Imaging the structure of a large-scale TID using ISR and TEC data, GRL, 31, L09812, https://doi.org/10.1029/2004GL019797, Van de Kamp et al., (2014): TID characterised using joint effort of incoherent scatter radar and GPS, Ann. Geophys., 32, 1511-1532, Galushko et al., (2003): Frequency-and-angular HF sounding and ISR diagnostics of TIDs, Radio Science, 38 (6), doi:10.1029/2002RS002861

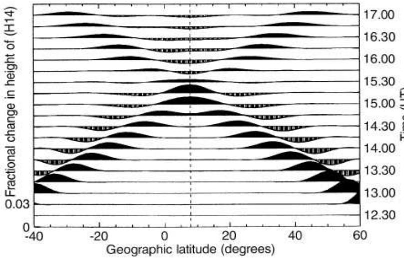
Night time ground based observations?

- Air glow Imagers: Taylor and Hapgood, (1988): Identification of a thunderstorm as a source of short period gravity waves in the upper atmospheric nightglow emissions, Planet Space Sci., 36 (10), 975-985, Makela et al., (2010): Nighttime medium-scale traveling ionospheric disturbances at low geomagnetic latitudes, GRL, 37 (L24104), doi:10.1029/2010GL045922
- Fabry Perot Interferometers: Shiokawa et al., (2003): Thermospheric wind during a storm-time large-scale travelling ionospheric disturbance, JGR, 108 (A12), doi:10.1029/2003JA010001, Ford et al., (2006): Thermospheric gravity waves in Fabry-Perot Interferometer measurements of the 630.0nm OI line, Ann Geophys, 24, 555-566.

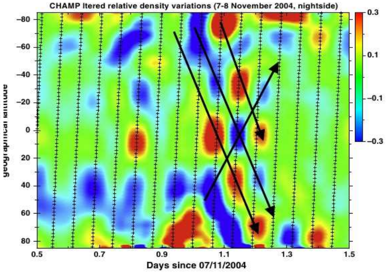
Observation and simulation studies



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)

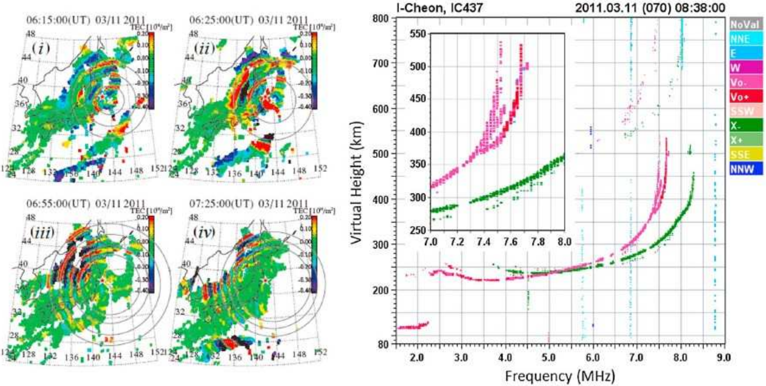


Coupled thermosphere-ionosphere-plasmasphere model simulations at fixed pressure surface, approximate altitude of 380 km (Balthazor and Moffet, 1997)



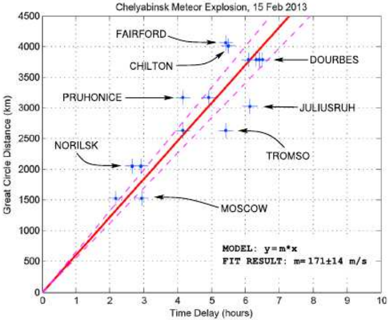
Densities from CHAMP accelerometer measurements (about 400 km altitude) (Bruinsma and Forbes, 2008)

Earthquake generated TIDs



Tsugawa et al., (2011), Ionospheric disturbances detected by GPS total electron content observation after the 2011 off the Pacific coast of Tohoku Earthquake, Earth Planets Space, 63, 875–879.

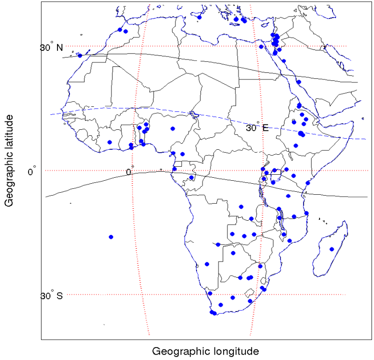
TIDs as a result of meteor explosion



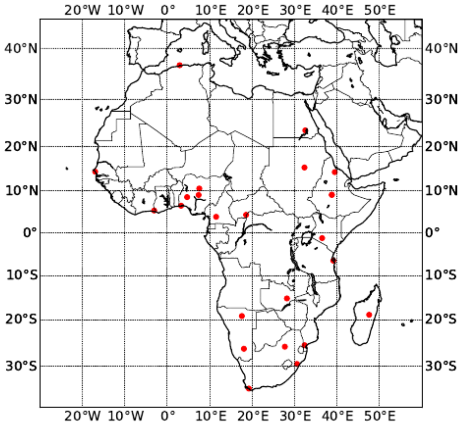
Location of the meteor explosion and a plot of the great circle distance from Chelyabinsk to each ionosonde stations versus the corresponding time delay for the traveling ionospheric disturbances to arrive. The result of a linear fit to the data points is also overlaid on he graph (solid red line), revealing a propagation speed of roughly 171 m/s. The dashed magenta lines indicate the 95% confidence interval bounds.

Reference: Pradipta et al., (2015), Ionosonde observations of ionospheric disturbances due to the 15 February 2013 Chelyabinsk meteor explosion, J. Geophys. Res. Space Physics, 120, 9988–9997, doi:10.1002/2015JA021767.

Constrained by infrastructure!

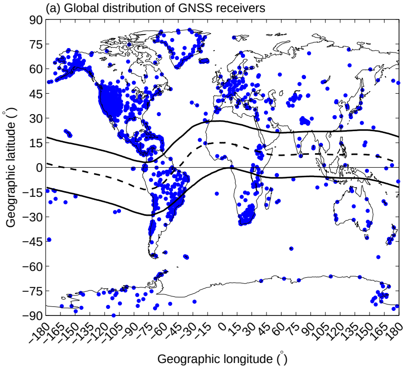


IGS, AFREF, UNAVCO and South African networks. There are currently about 60 GPS receiver stations in South Africa



Magnetometer stations for INTERMAGNET, MAGDAS, AMBER, SANSA; Credit to Stefan Lotz

SUMMARY: Limited ionosondes, GNSS receivers, Doppler Radars, Airglow Imagers: [No Incoherent Scatter Radar] ETC



YES and NO,
For Different Reasons

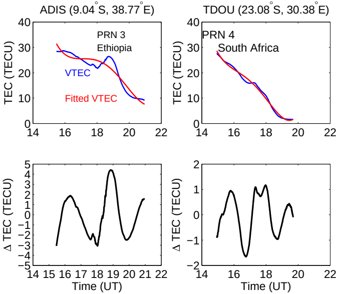
We are trying to answer scientific questions

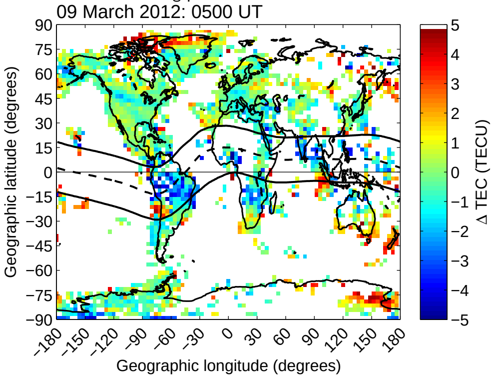
- YES, if the scientific question can only be answered in specific latitude regions; such as study of low latitude electrodynamics; specific to low latitudes and using specific datasets (e.g., vertical drifts)
- NO, if the question is not region specific. There are many sources of data and there is no 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.

Let's go ahead with research using existing infrastructure and we shall fill in the knowledge gaps when sufficient instrumentation becomes available

$$\begin{cases} vT^f(t)_{i,j} = at_{i,j}^4 + bt_{i,j}^3 + ct_{i,j}^2 + dt_{i,j} + \varepsilon, & \text{for } j = 1, 2, ..., 31 \\ \Delta\text{TEC}(t)_{i,j} = \text{TEC}(t)_{i,j} - vT^f(t)_{i,j}, & \forall i, j \end{cases}$$

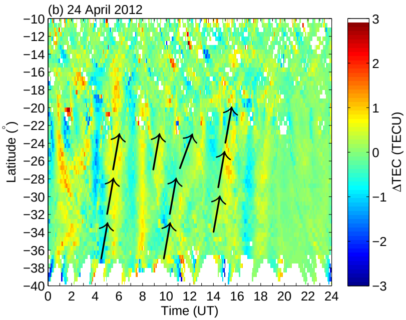
where $i = 1, 2, \ldots, 2500^+$ is the number of considered receiver stations, $j = 1, 2, \ldots, 31$ is the number of satellites, $vT^f(t)$ and $\text{TEC}(t)$ represent fitted and actual vertical TEC at time t; and the coefficients a, b, c, d are obtained through the least-squares method, ε is the residual error of the fitting process.



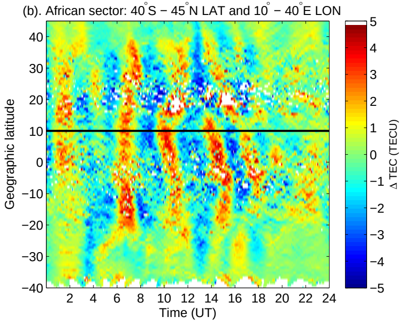


Habarulema et al., (2016); Geophysical Research Letters

Different propagation directions



Habarulema et al., (2017), JGR

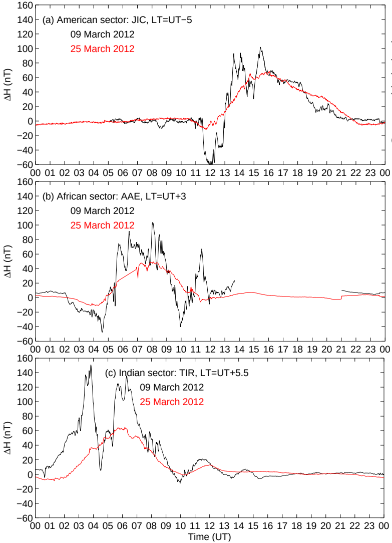


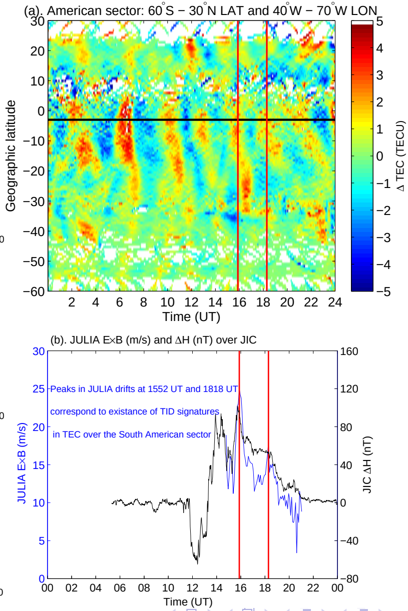
Habarulema et al., (2016), GRL

Different driving mechanisms

- Equatorward TIDs understood to originate from the auroral regions
- Poleward TIDs originating from the geomagnetic equator believed to be due to enhanced EEJ and hence increased Lorentz force. First suggested by Knudsen, (1969) and shown numerically by Chimonas, (1969), this is the first direct observational evidence globally.

Physical mechanism confirmation?





Low Latitude Physics

- Increase in $\mathbf{E} \times \mathbf{B}$ lifts ionospheric plasma to higher altitudes (stays there longer because recombination rate is slower)
- Pressure gradients and gravitational forces move plasma along the geomagnetic field lines on both sides of the equator

$$V_d = \frac{1}{n_e q} \frac{\nabla \mathbf{P} \times \mathbf{B}}{B^2} \qquad \text{Electron diamagnetic drift velocity}$$

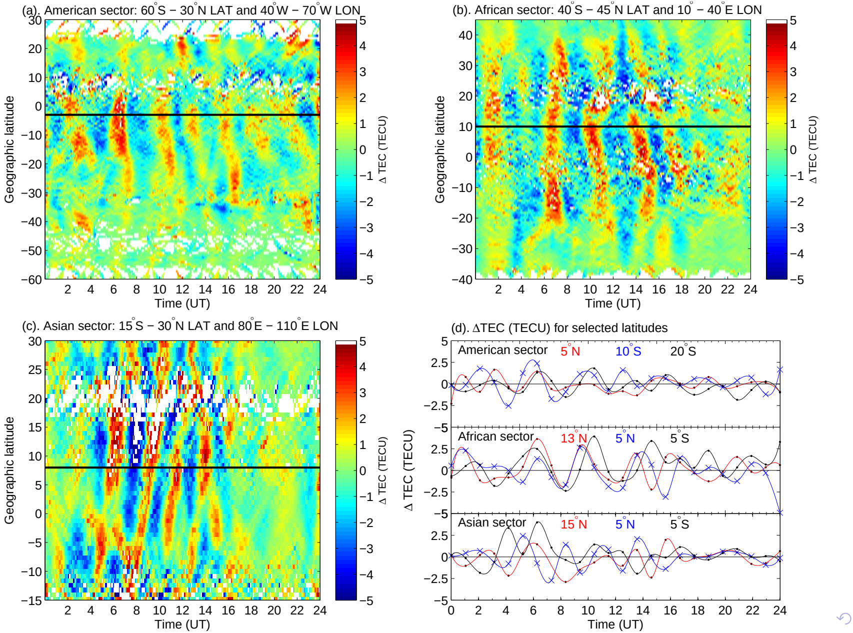
$$V_g = \frac{m}{e} \frac{\mathbf{g} \times \mathbf{B}}{B^2} \qquad \text{Gravitational drift velocity}$$

Possible explanation

- Lorentz coupling transfers energy and momentum from ionized/charged to neutral particles through collisions thereby launching atmospheric gravity waves that result into TIDs
- TID related waves (density/pressure imbalance) move with plasma along the geomagnetic field lines. Since $\mathbf{E} \times \mathbf{B}$ is responsible for the formation of the EIA, then it could also act as a modulator of the generated TIDs

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

Different sectors



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.

Not covered in this Talk

- 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

Thank You!

⊕ ⊕ ⊕ Your Questions may introduce more Problems and Opportunities!
⊙ ⊙ ⊙
Let's continue the discussion (Email: jhabarulema@sansa.org.za)