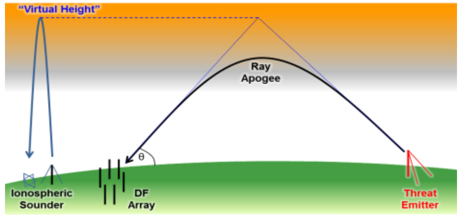
Ionosphere Measurements Gaps

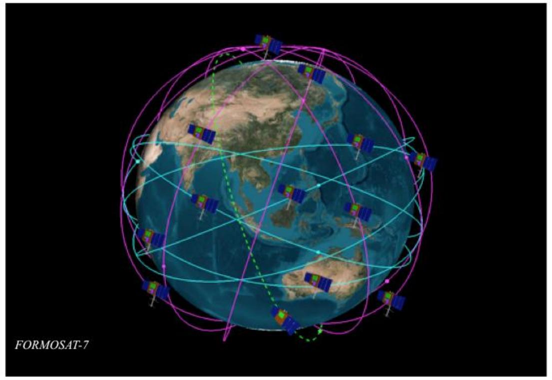
Space Weather Operations and Research Infrastructure Workshop
NAS

Tim Fuller-Rowell
CIRES, University of Colorado
(based at NOAA Space Weather Prediction Center)
June 16-17, 2020

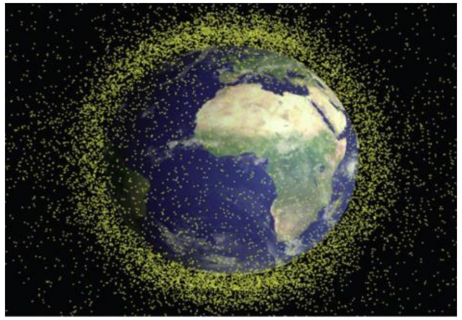
Context: Upper Atmosphere Space Weather Impacts on Operational Systems

- Ionosphere – impacts radio wave propagation
  - HF *communications* 3 – 30 MHz: D-region absorbs; structure, gradients, undulations, and tilts scatter signals
  - GNSS PNT precise point *positioning*, satellite *navigation*, and *timing*: line of sight total electron content (TEC) delays and refracts signals; plasma irregularities, structure and gradients diffract signals, causing amplitude and phase scintillations and sometime complete loss of signal
  - Satellite *communications*: plasma irregularities and structure cause scintillations and loss of signal

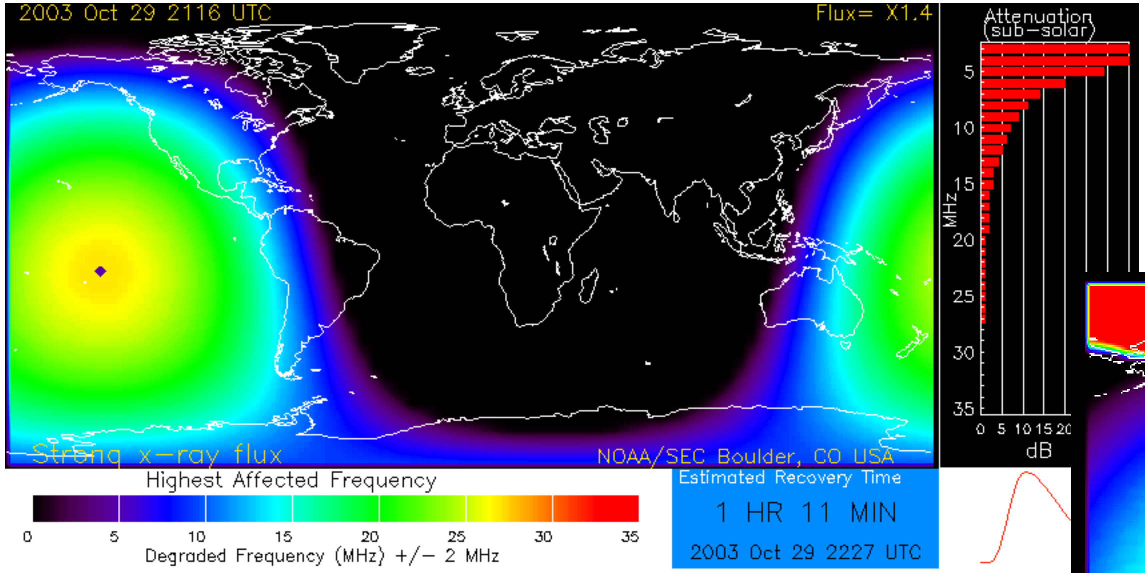




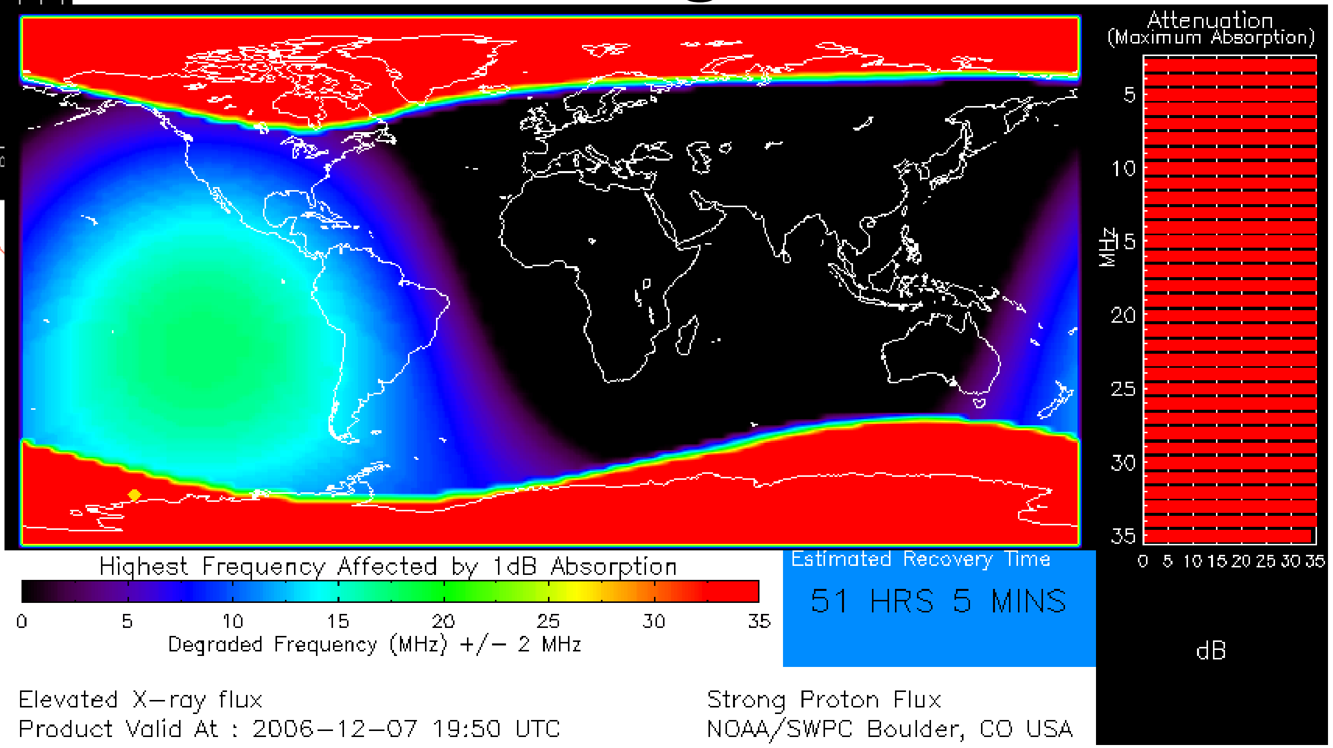
- Neutral density
  - Satellite drag in low-Earth orbit (LEO): space traffic management, orbit prediction, conjunction prediction, collision avoidance, re-entry (neutral mass density, winds, structure, waves)



D-RAP Product for D-region absorption for HF comms.



High Latitude:
driven by observations of GOES Solar Energetic Particles



Mid and Low Latitude:
driven by GOES X-rays Solar Flare Observations

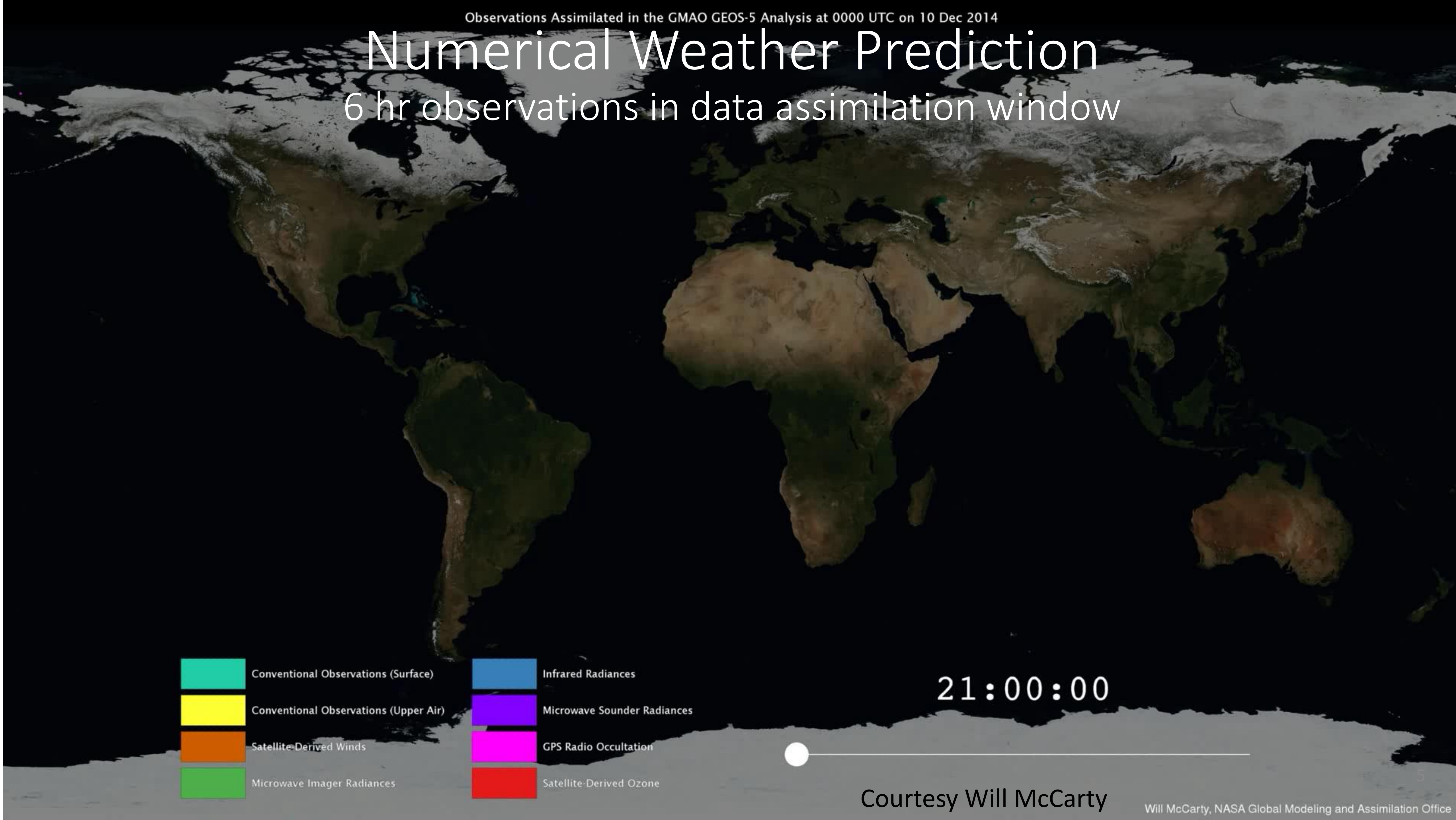
Forecast relies on predicting solar flares and solar proton event

Ionosphere-Thermosphere Observation Gaps - Rationale

- Pragmatically, if you want to specify or forecast a space weather parameter that impacts an operational system (e.g., plasma density, ionospheric irregularities, neutral density):
    - first ***measure it***,
    - then ***model it*** with a physical model (to fill observation gaps)
    - then ***measure and model what drives it*** (for short-term forecast).

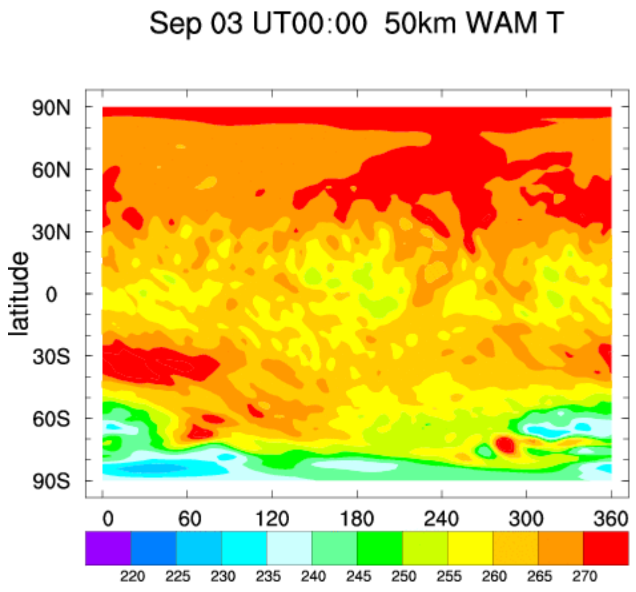
Numerical Weather Prediction

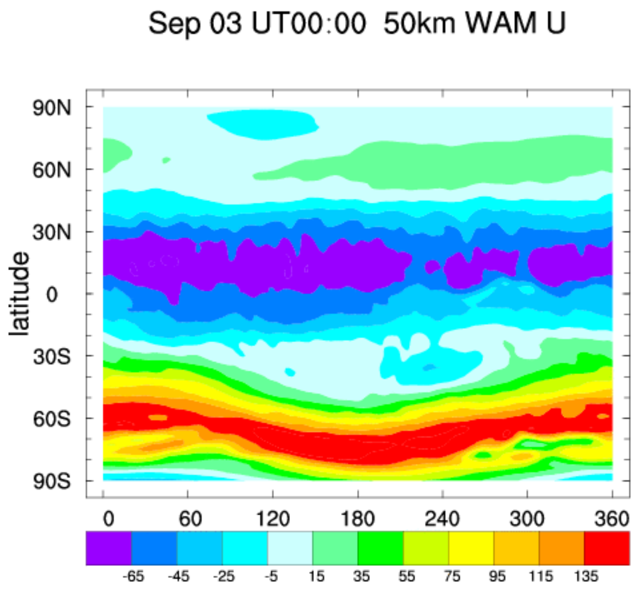
6 hr observations in data assimilation window



Courtesy Will McCarty

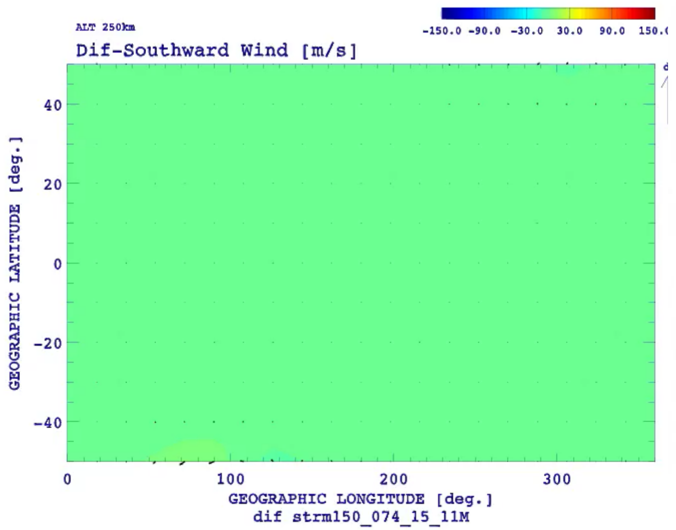
Data Sparse Compared with Tropospheric Numerical Weather Prediction

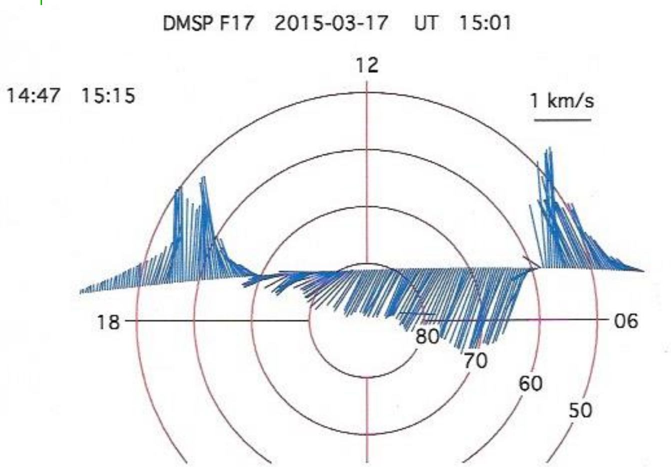




Troposphere:

- Relatively slowly varying system, max winds ~70 m/s
- Parameters: pressure, winds, temperature, water vapor
- 6-hour data assimilation window for update cycle





CTIPe F-region mid and low latitude neutral dynamics during impulsive storm
neutral wind vector plus meridional wind color contours at 300 km altitude

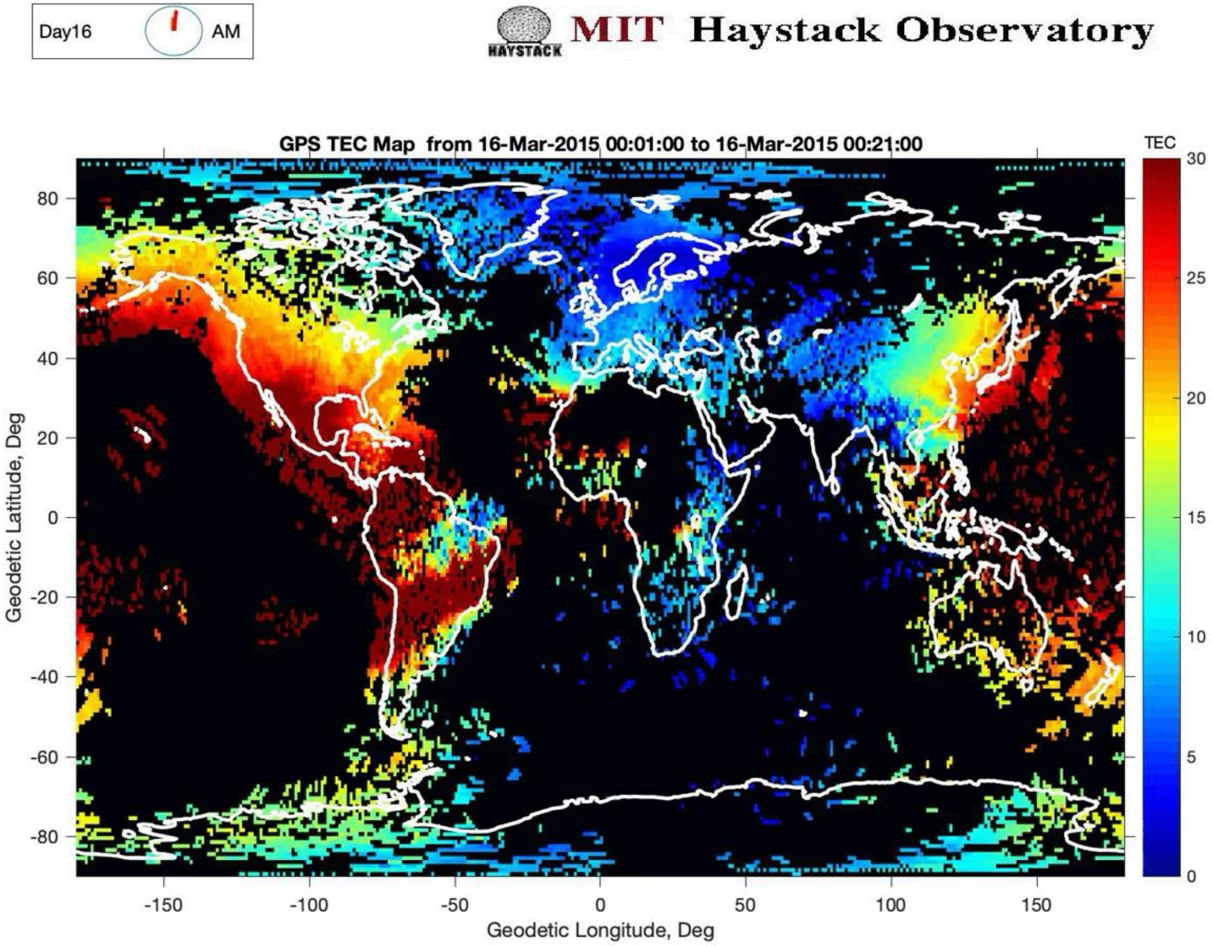
Thermosphere/Ionosphere:

- Rapidly varying system, max winds ~1000 m/s, plasma drifts 2-4 km/s
- Parameters: neutral winds, temperature, composition (e.g., O/N_2), density, plasma density, plasma transport
- Typically 5 to 15 minute data assimilation window for update cycle

Ionosphere-Thermosphere Observation Needs

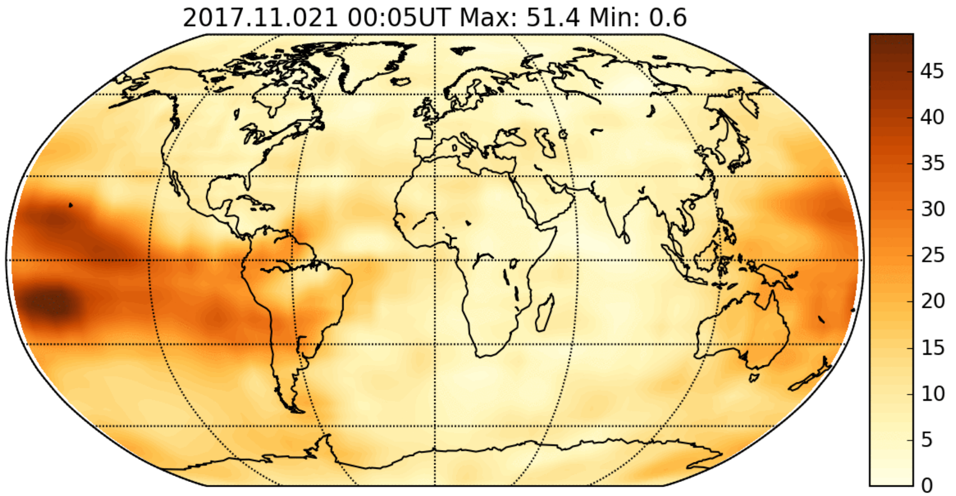
- Plasma density: N_e, line-of-sight total electron content (TEC) from GNSS ground-based and space-based radio occultation (RO) observations, and ability to assimilate and combine ground-based and satellite data.
- Measure of ionospheric structure or irregularities (S_4, σ_ϕ, rate-of-TEC index ROTI), and ability to combine different metrics from ground-based and satellite.
- For satellite drag and orbital prediction, need measurements of neutral density ρ in LEO (e.g., access to tracking data, accelerometer CHAMP, SWARM, or in-situ neutral species densities), and to a lesser extent neutral wind and composition. [Eric Sutton]
- For the "drivers": solar EUV spectrum (GOES), magnetosphere energy input (Poynting flux), plasma drifts V_i (DMSP, COSMIC-II IVM, ISR), neutral composition O/N_2 (GUVI/SSULI, GOLD), dynamics V_n and forcing from the lower atmosphere.

Retrospective ~5000 GNSS receivers

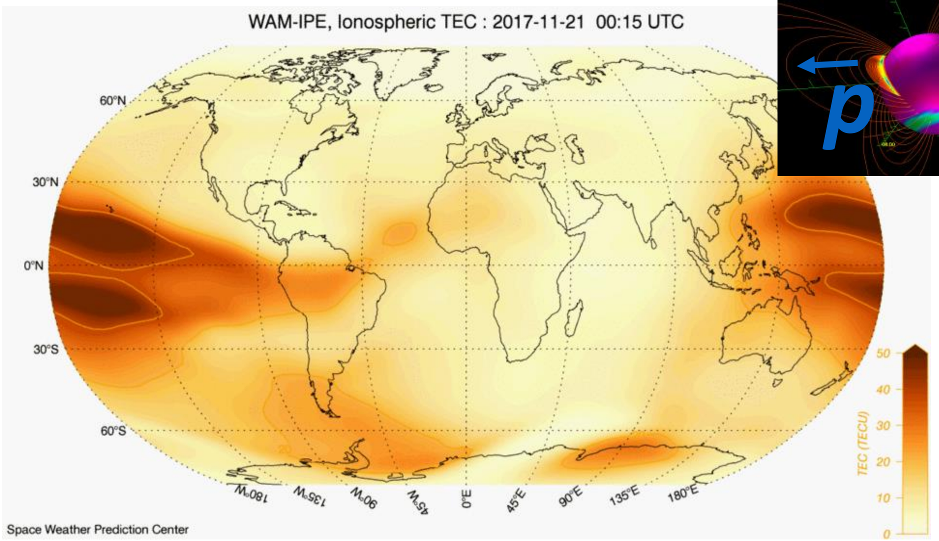


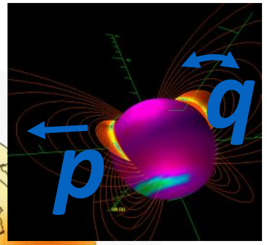
Courtesy Anthea Coster

Real-Time ~500 GNSS receivers



Glo-TEC NOAA Operational Product 2019
Kalman Filter DA System

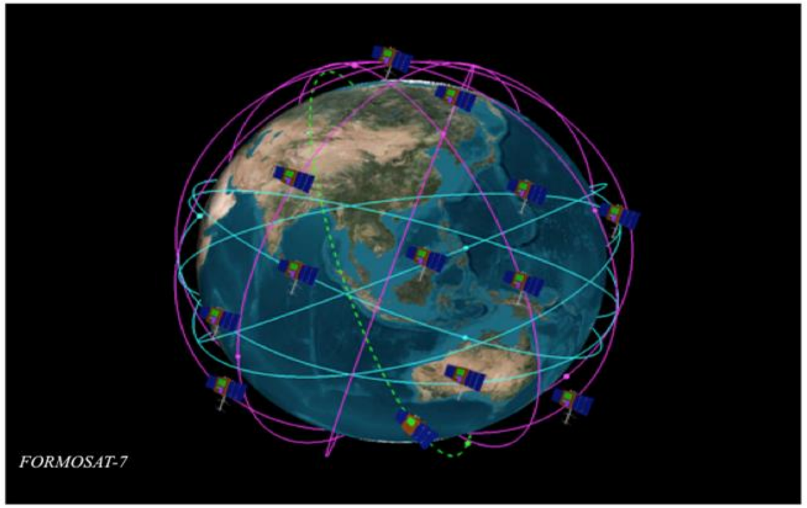


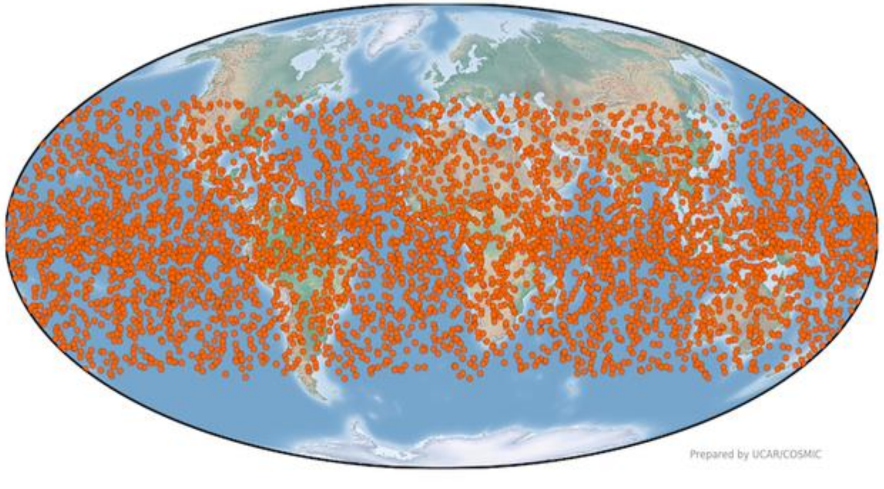


WAM-IPE NOAA Operational Product 2020
Whole Atmosphere-Ionosphere Physical Model

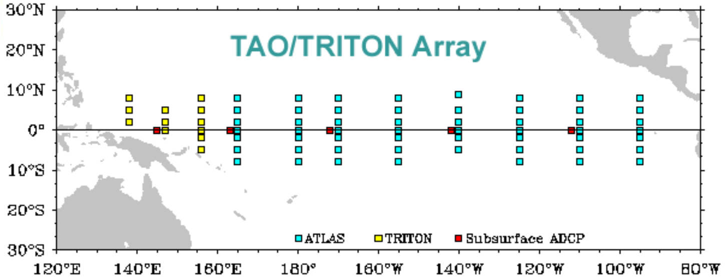
Satellite based radio occultation and buoy data for improved coverage

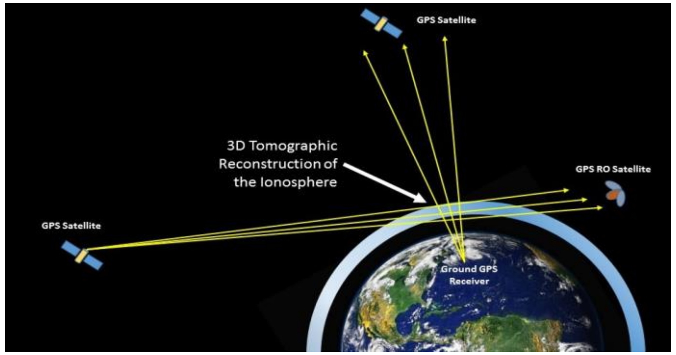
e.g., low-latitude COSMIC-II constellation plus commercial data



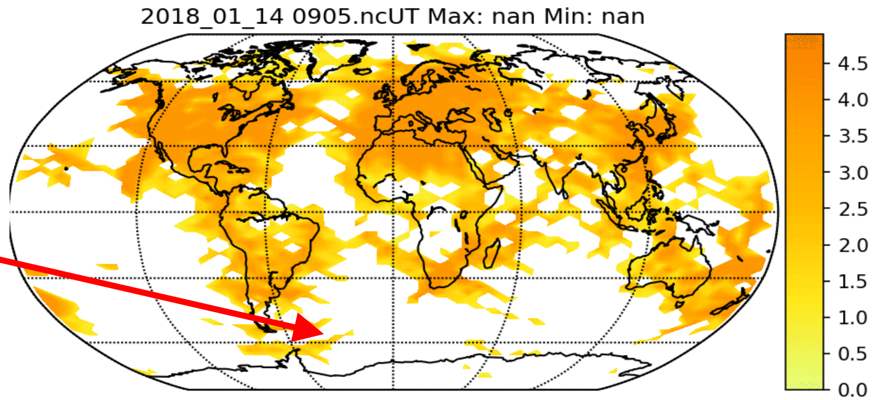


Plus: Commercial Weather and Buoy Data



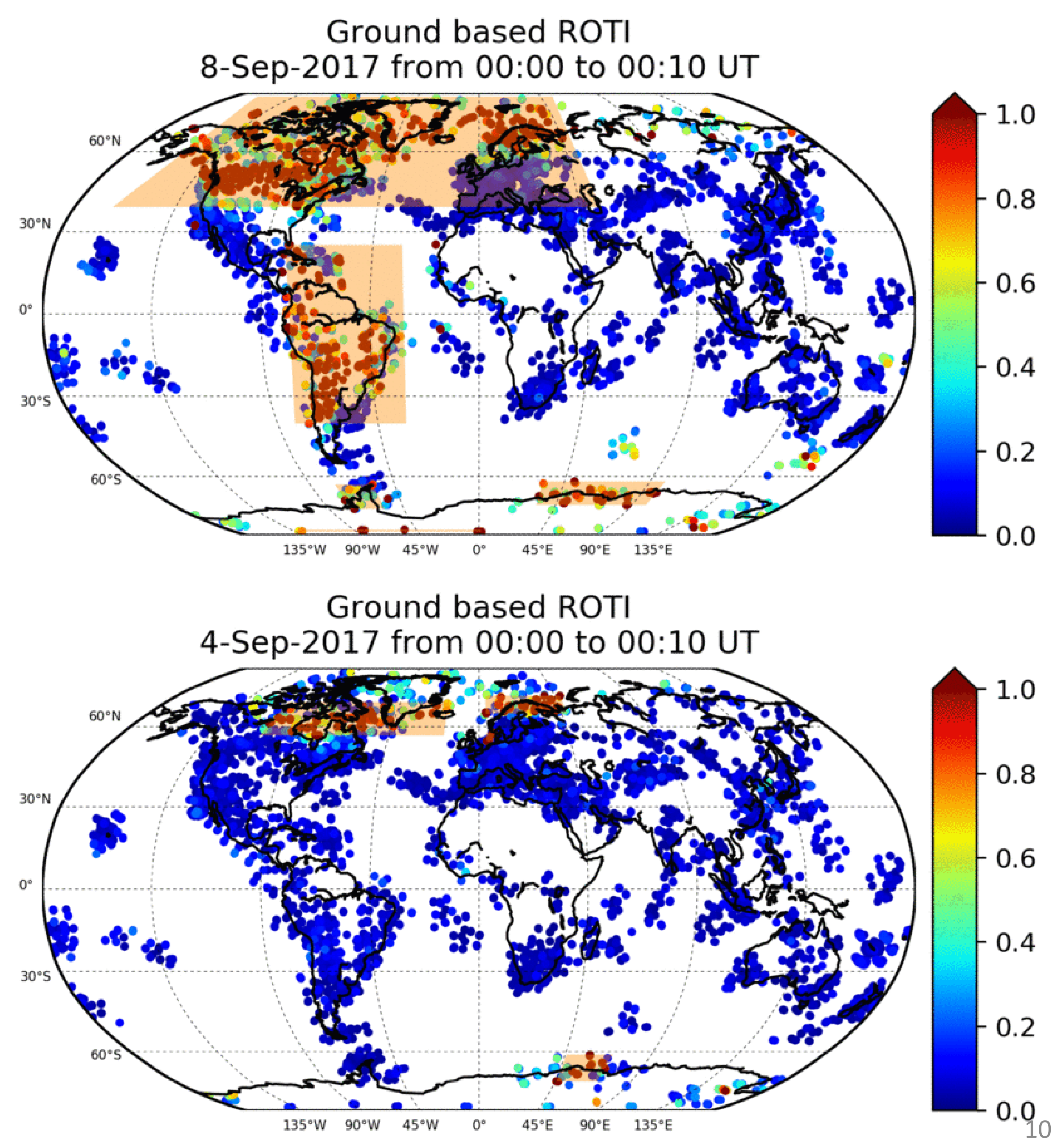


Observational contribution from a single radio occultation satellite

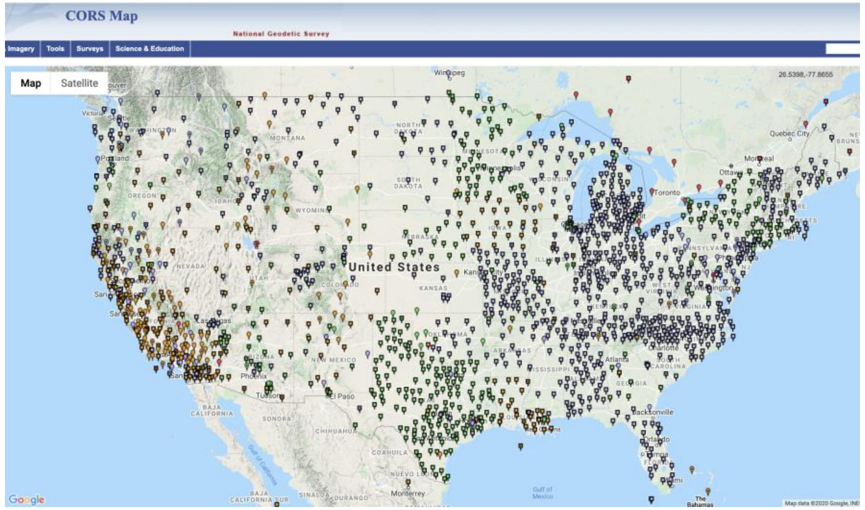


$$ROTI^2(\delta t) \equiv \left\langle \frac{|TEC(t+\delta t) - TEC(\delta t)|^2}{\delta t^2} \right\rangle$$

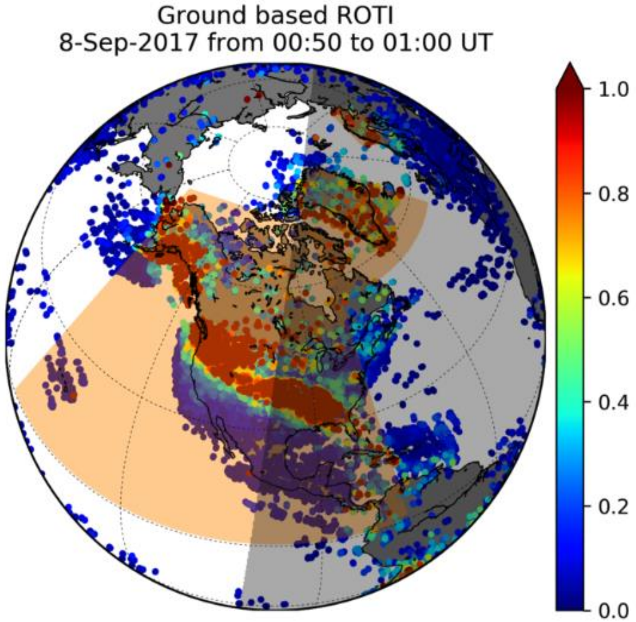
- Same ground based GNSS observation data as GloTEC
- ROTI - Rate of TEC Index
    - STD of detrended TEC
    - Elevation angle dependence sTEC-> vTEC
- Proxy for amplitude and phase scintillation (S_4 and σ_φ)
- Automatically draw advisory boxes
    - DBSCAN machine learning algorithm
    - Tuned to ignore "noise" (anomalous ROTI observations)
- ROTI and GloTEC to be used by forecast office to issue ICAO advisories
- Space based S_4
    - Geolocating irregularities (with Keith Groves and Charlie Carrano)



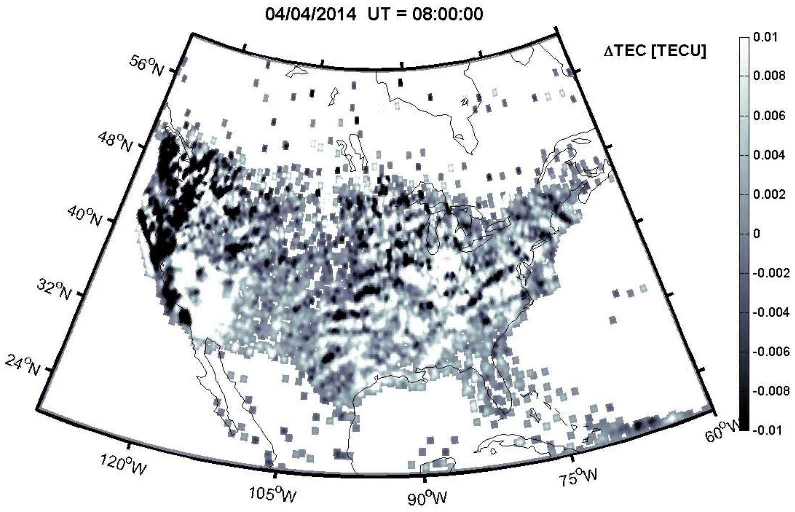
Potential for high-resolution GNSS mapping



CORS Network

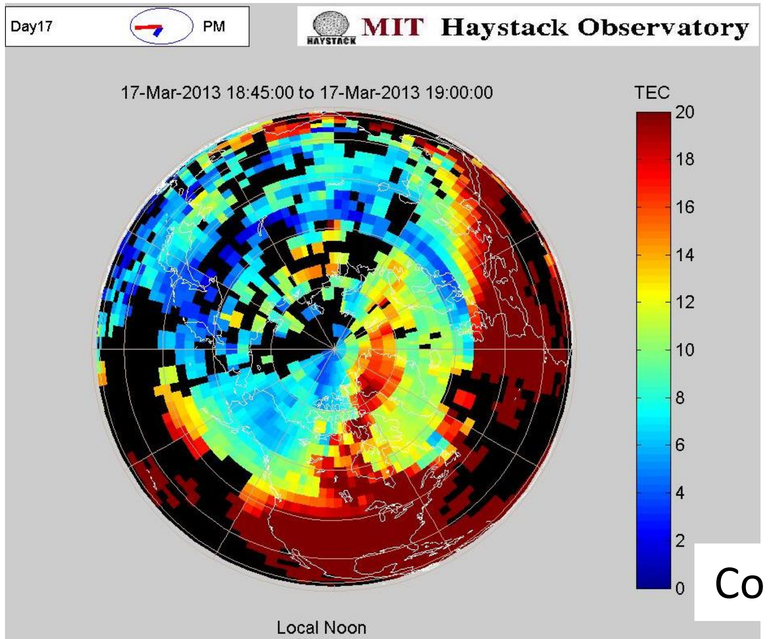


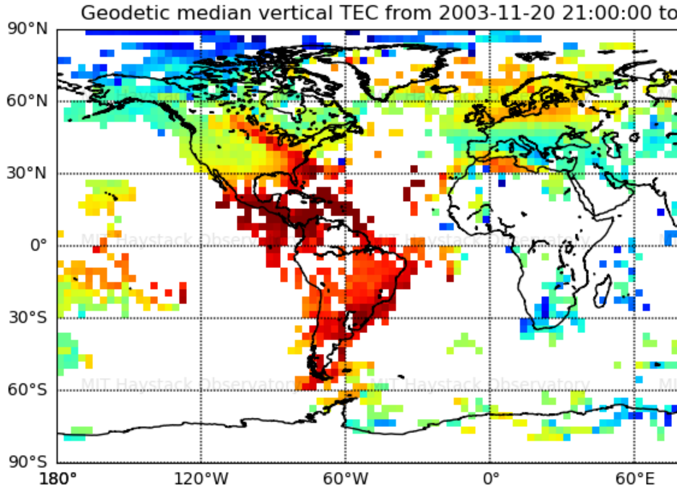
Courtesy Dominic Fuller-Rowell



iazeem@astraspace.net 14-Apr-2015 3:27 PM

Courtesy Irfan Azeem



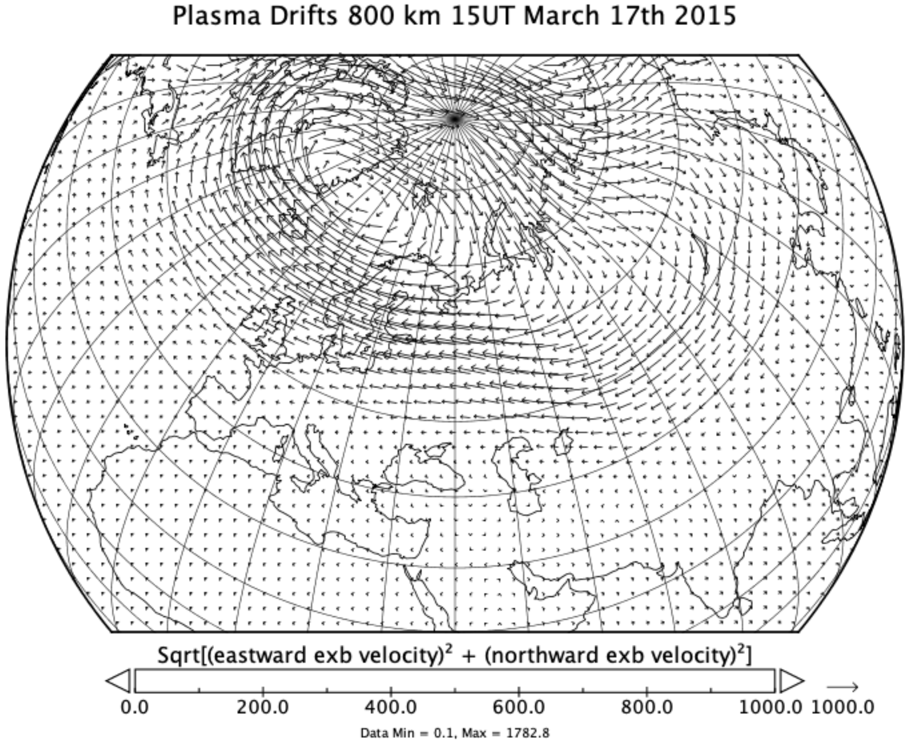


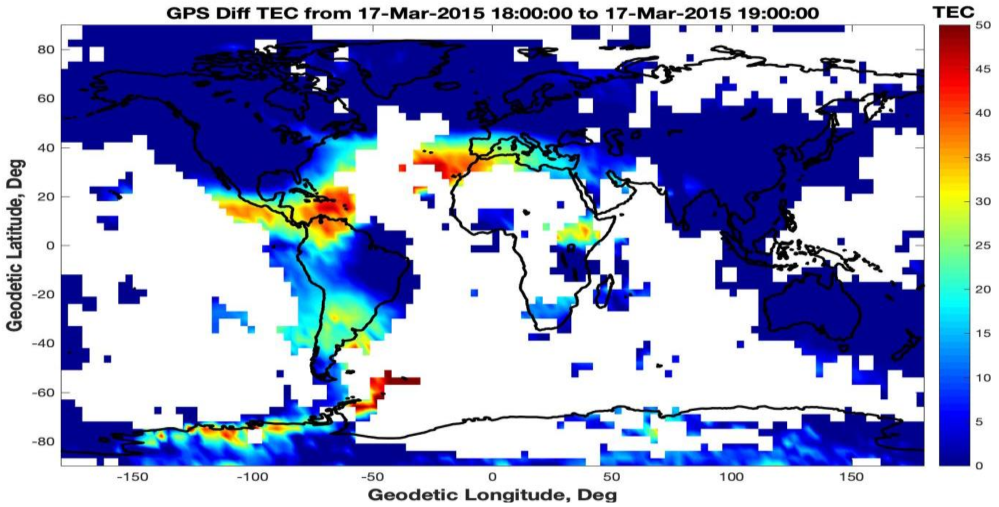
Courtesy Anthea Coster

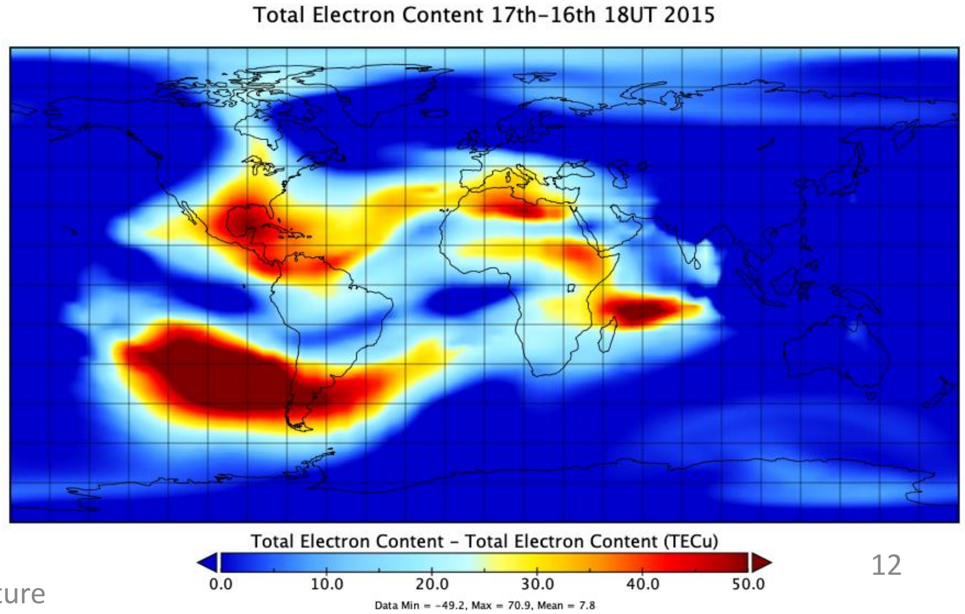
Plasma Drifts (COSMIC II IVM, DMSP)

A significant of driver storm-time TEC enhancement at mid-latitude

Needed to interpret irregularity metrics: ROTI, S4, and σ_φ





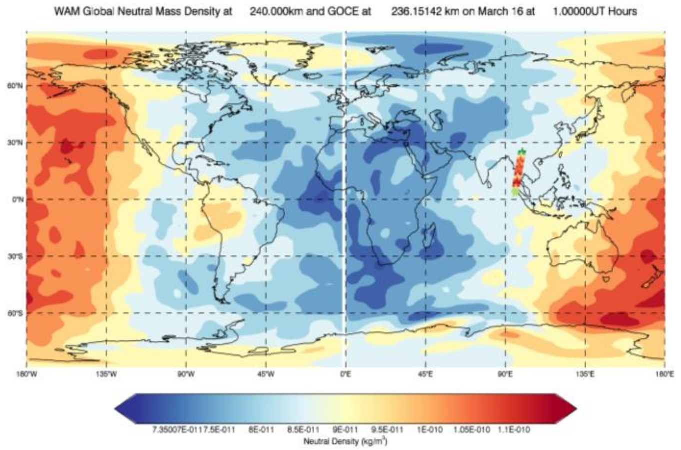


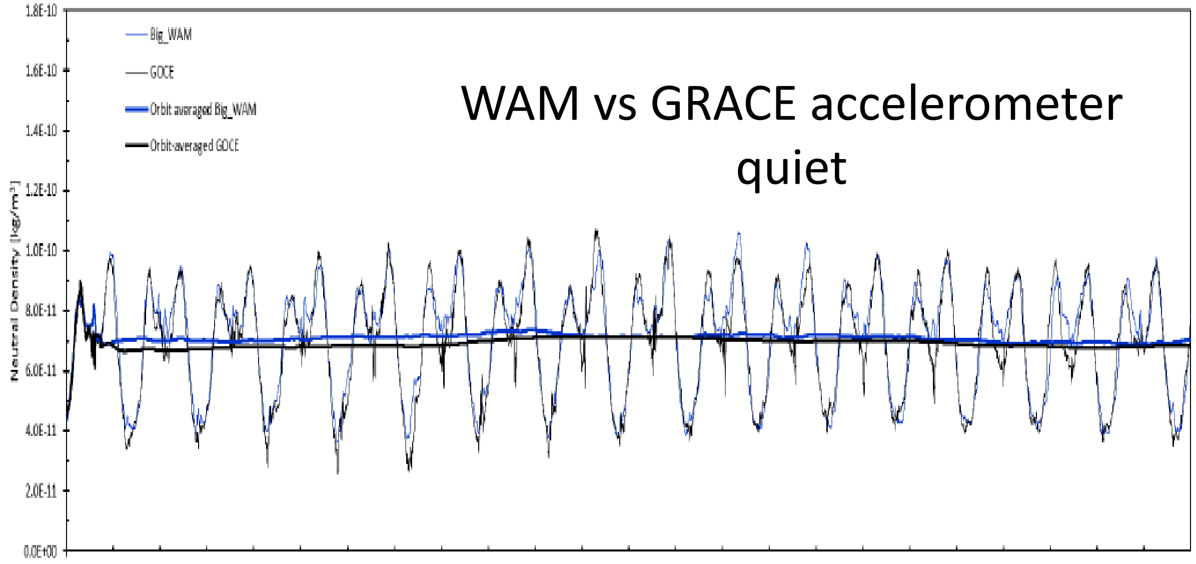
$$ROTI^2(\delta t) \sim \frac{c^2}{\delta t^2} C_p G \left[\frac{1}{2\pi} \frac{2\Gamma(3/2-\nu)}{\Gamma(\nu+1/2)(2\nu-1)2^{2\nu-1}} \right] \cdot \left| V_{eff}\,\delta t \right|^{2\nu-1}, \quad \tfrac{1}{2} < \nu < \tfrac{3}{2}$$

- Phase metrics (ROTI, σ_φ) depend on effective scan velocity to relate to intensity metric S_4 (Charlie Carrano and Keith Groves)

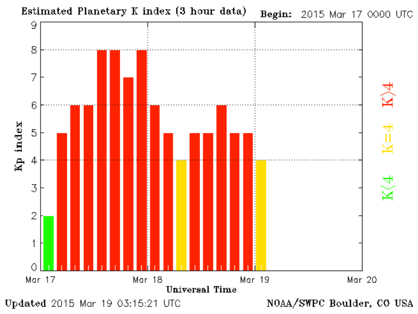
Poynting Flux, Neutral Density, and Global Circulation

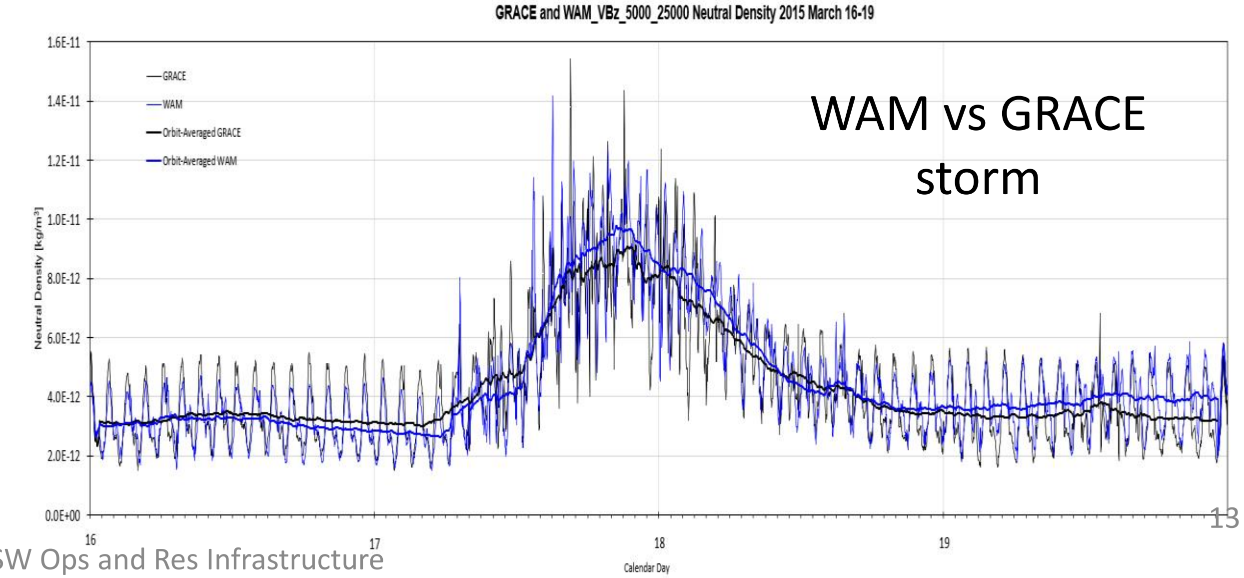
- Whole atmosphere model (WAM): extension of the US weather model (Global Forecast System spectral model) to 600 km altitude, 150 layers, follows response to real weather events and solar and geomagnetic activity



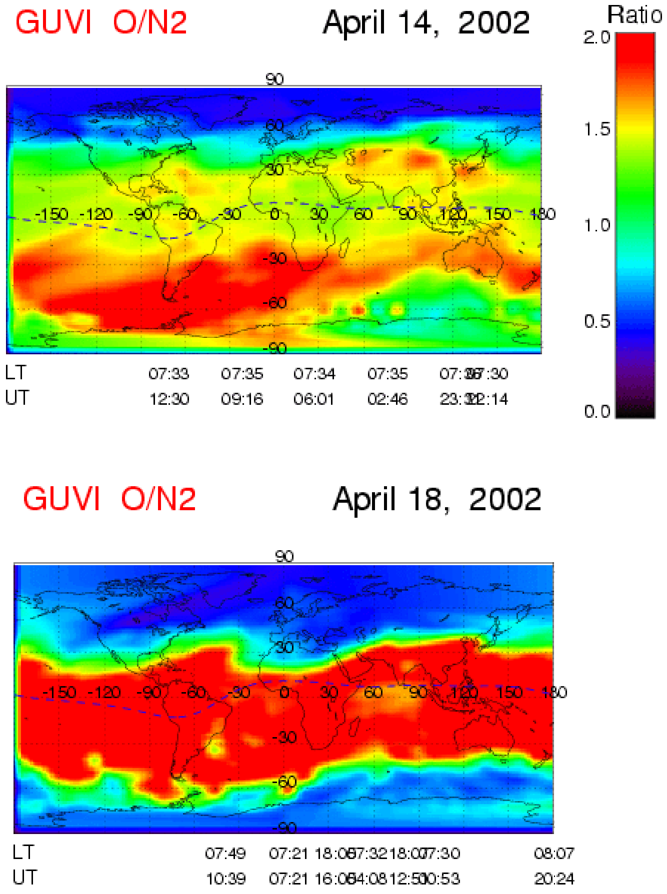


- WAM: Neutral density for satellite drag, orbit prediction, and collision avoidance



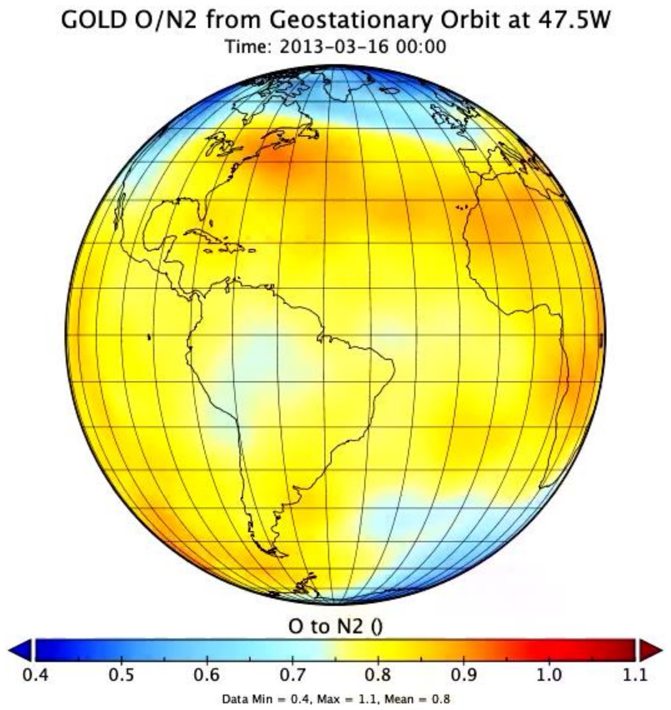


O/N_2 Neutral Composition – for plasma loss rates

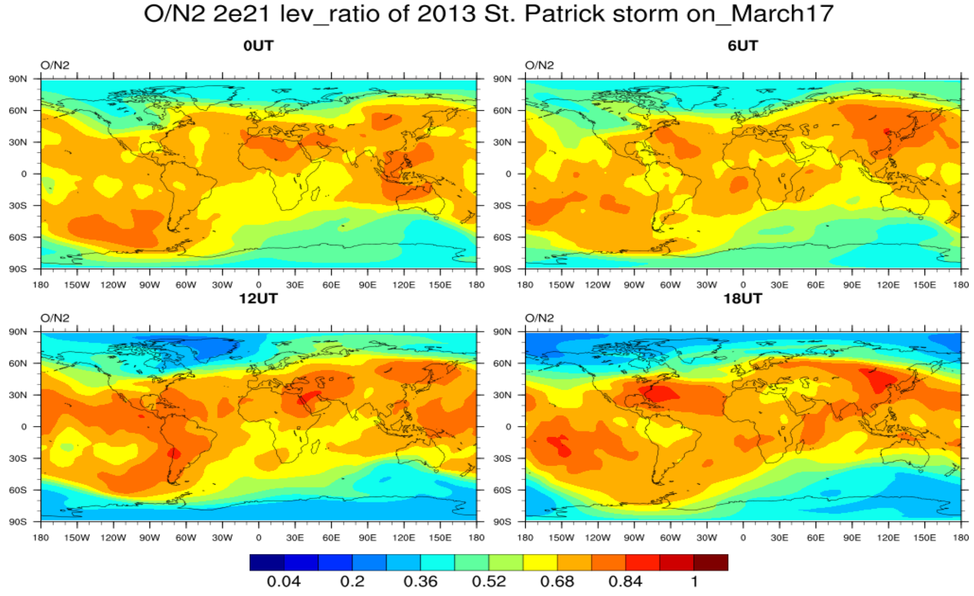


GUVI scanning at LEO

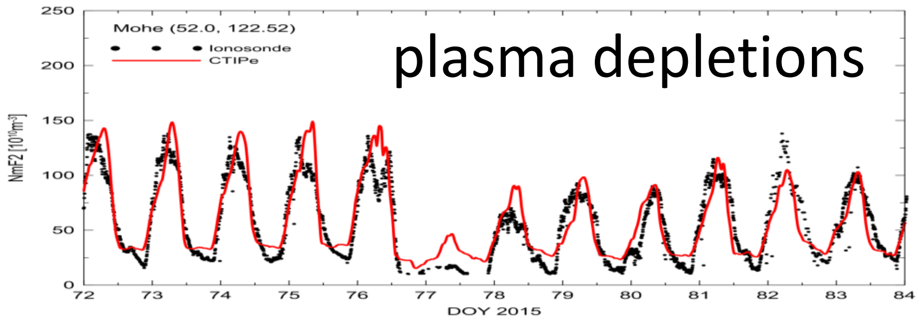
Paxton



Geostationary imaging
e.g., GOLD Eastes



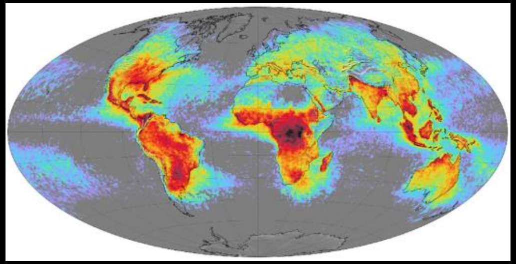
WAM-IPE NOAA Operational Model

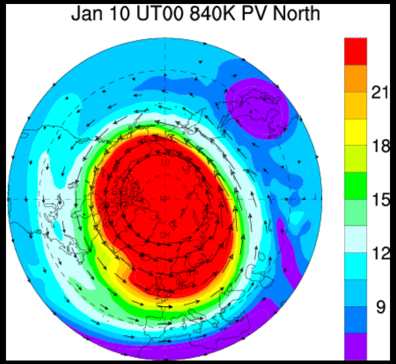


plasma depletions

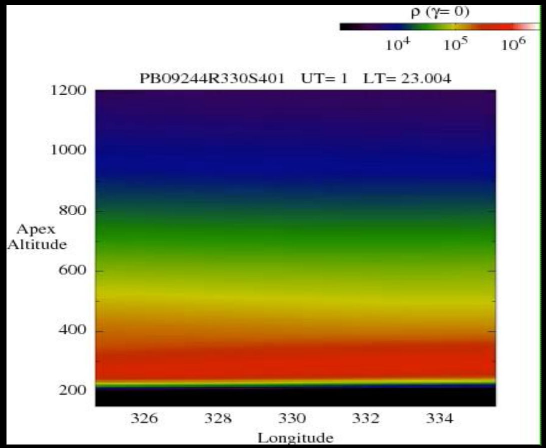
Neutral Dynamics and Sources from the Lower Atmosphere

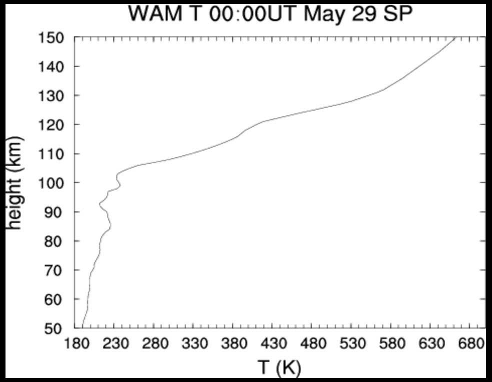
- Longitude structure of tropical convection modulates non-migrating tidal modes (DE3, DE2), which drive winds and electrodynamics in lower thermosphere dynamo region



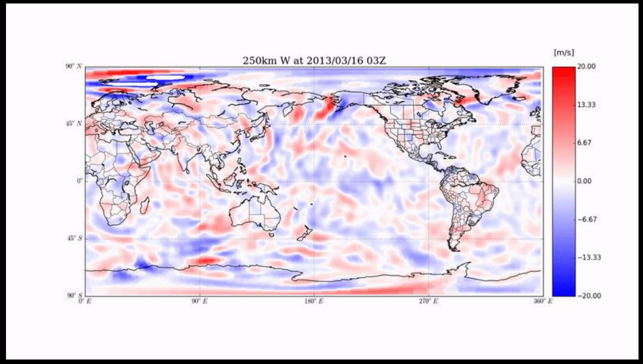


- Changes in stratospheric circulation (e.g., sudden stratospheric warmings) modulating semi-diurnal migrating tidal modes, which also drive electrodynamics





- Spectrum of waves from lower atmosphere driving wind, temperature, and composition variability directly impacts the ionosphere and electrodynamics, including possible triggering of ionospheric irregularities



Ionosphere-Thermosphere Priorities

- Expand real-time ground-based GNSS network
- Explore GNSS buoy and ship deployment
- Increase space-based GNSS coverage and reduce latency (e.g., COSMIC-II)
- Global distribution of plasma drift (e.g., COSMIC-II IVM, DMSP)
- Global distribution of neutral composition (O/N_2) (e.g., GUVI, GOLD)
- Neutral dynamics/winds (lower atmosphere from NWP data assimilation, dynamo region (100-200km), F-region)
- The need to re-invigorate the LEO capability including constellations (e.g., COSMIC-II)
- Observations and physical modeling go hand-in-hand to fill gaps in observations and provide forecast
- Enhance thermosphere-ionosphere physical model data assimilation capability (bias correction, driver estimation, ensemble Kalman filter

New Theories for Phase and Intensity Metrics

- Rino's power law (weak) scintillation theory implies, in scale-free limit $q_0 \to 0$:

$$ROTI^2(\delta t) \sim \frac{c^2}{\delta t^2} C_p G \left[\frac{1}{2\pi} \frac{2\Gamma(3/2-\nu)}{\Gamma(\nu+1/2)(2\nu-1)2^{2\nu-1}} \right] \cdot \left| V_{eff}\, \delta t \right|^{2\nu-1}, \quad \tfrac{1}{2} < \nu < \tfrac{3}{2}$$ (Carrano et al., 2019)

$$\sigma_\varphi^2(\tau_c) = \frac{2}{2\nu-1} C_p G \frac{\sqrt{\pi}\,\Gamma(\nu)}{(2\pi)^{2\nu+1}\Gamma(\nu+1/2)} \cdot \left| \tau_c V_{eff} \right|^{2\nu-1}, \quad \tfrac{1}{2} < \nu$$ (Carrano et al., 2016)

$$S_4^2 = C_p\, \wp(\nu) \frac{\Gamma[(5/2-\nu)/2]}{2^{\nu+1/2}\sqrt{\pi}\,\Gamma[\nu/2+1/4](\nu-1/2)} \rho_F^{2\nu-1}, \quad \tfrac{1}{2} < \nu < \tfrac{5}{2}$$ (Rino, 1979)

where

C_p – phase spectral strength

$\wp(\nu)$ –geometry and propagation factor

ν - related to irregularity spectral index as $p(3)=2\nu+1$

G – phase enhancement factor due to geometry

ρ_F – Fresnel scale $\quad \rho_F = \sqrt{\lambda z_R \sec\theta / (2\pi)}$

Γ – gamma function

- Phase metrics (ROTI, σ_φ) depend on effective scan velocity to the power 2ν+1.
- Intensity metric (S_4) depends on Fresnel scale to the power 2ν+1.
- All three metrics depend on irregularity strength in the same way.