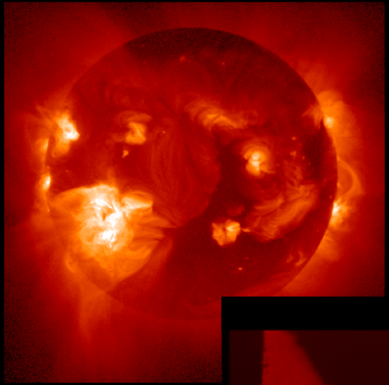
Space Weather in the Upper Atmosphere

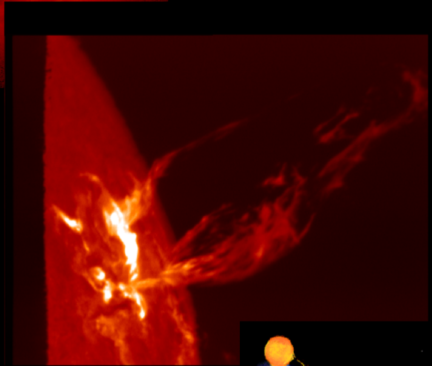
Tim Fuller-Rowell
CIRES, University of Colorado and
Space Weather Prediction Center, NOAA

University of Colorado Boulder

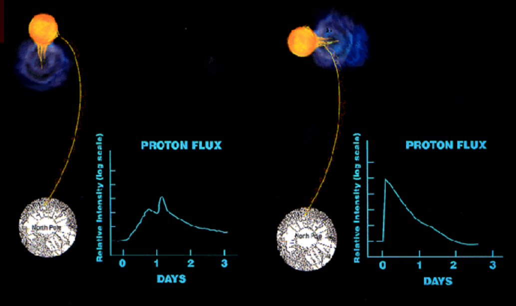
So what is (traditional) Space Weather?



Solar Flares (increased X-ray flux)
Arrives: 8 mins; Duration: 1-2 hrs
Impacts: D-region ionization, High Frequency (HF) radio absorption, geolocation, low-frequency navigation, GPS navigation



Coronal Mass Ejections (plasma)
Arrives: 1-3 days; Duration: 1-2 days
Impacts: Drives a geomagnetic storm, satellite charging, drag, communication, navigation (e.g., GPS), HF communication, ground induced currents (power outages)



Solar Proton Events (energetic particles)
Arrives: 15 mins to a few hours; Duration: days
Impacts: Polar HF absorption, satellite anomalies, radiation hazard

NOAA Scales R, S, and G

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	<u>HF Radio:</u> Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. <u>Navigation:</u> Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	<u>HF Radio:</u> HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. <u>Navigation:</u> Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	<u>HF Radio:</u> Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. <u>Navigation:</u> Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	<u>HF Radio:</u> Limited blackout of HF radio communication on sunlit side of the Earth, loss of radio contact for tens of minutes. <u>Navigation:</u> Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	<u>HF Radio:</u> Weak or minor degradation of HF radio communication on sunlit side of the Earth, occasional loss of radio contact. <u>Navigation:</u> Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

URL: *www.swpc.noaa.gov/NOAAscales* April 7, 2011

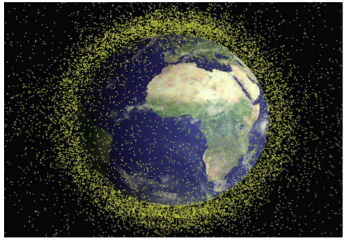
Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	<u>Biological</u>: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** <u>Satellite operations</u>: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. <u>Other systems</u>: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	<u>Biological</u>: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** <u>Satellite operations</u>: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. <u>Other systems</u>: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	<u>Biological</u>: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** <u>Satellite operations</u>: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. <u>Other systems</u>: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	<u>Biological</u>: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** <u>Satellite operations</u>: infrequent single-event upsets possible. <u>Other systems</u>: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	<u>Biological</u>: none. <u>Satellite operations</u>: none. <u>Other systems:</u> minor impacts on HF radio in the polar regions.	10	50 per cycle

Drivers of Space Weather in the Upper Atmosphere

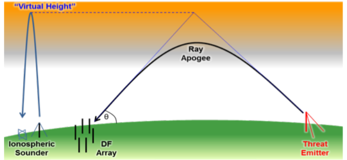
- Solar flares
- Solar Proton Events
- Solar Radio Bursts
- Geomagnetic storms driven by coronal mass ejections or corotating interaction regions
- Waves propagating from the lower atmosphere

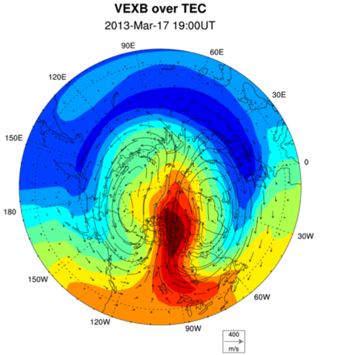
Upper Atmosphere Space Weather Impacts on Operational Systems

- 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)



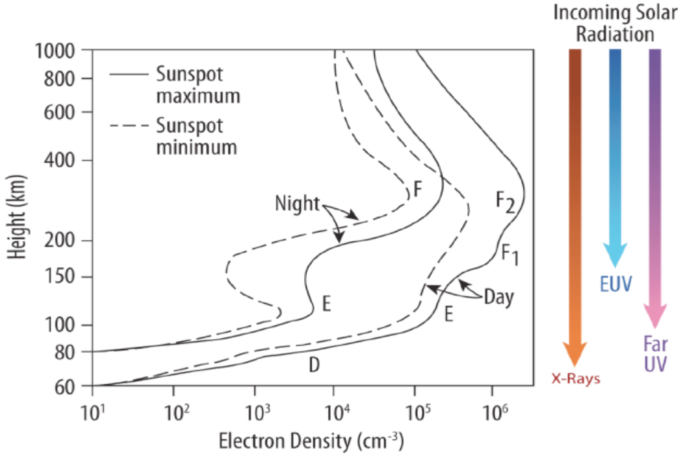
- Ionosphere – impacts radio wave propagation
    - HF *communications* 3 – 30 MHz: D-region absorbs signal; F-layer reflects/ refracts signal; structure, gradients, undulations, and tilts scatter signals
    - GNSS precise point *positioning*, satellite *navigation*, and *timing* (PNT; GPS 1575 and 1228 MHz): line of sight total electron content 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 cause scintillations and loss of signal





Ionospheric parameters affecting radio wave propagation users

- D-region flare and polar cap enhancements - HF absorption
- F-region peak density and bottom-side waves and undulations - HF propagation, geo-location
- Negative phase geomagnetic storms - MUFs
- Positive phase geomagnetic storms – GNSS range delay and MUF
- Ionospheric gradients and irregularities – diffraction and scintillations

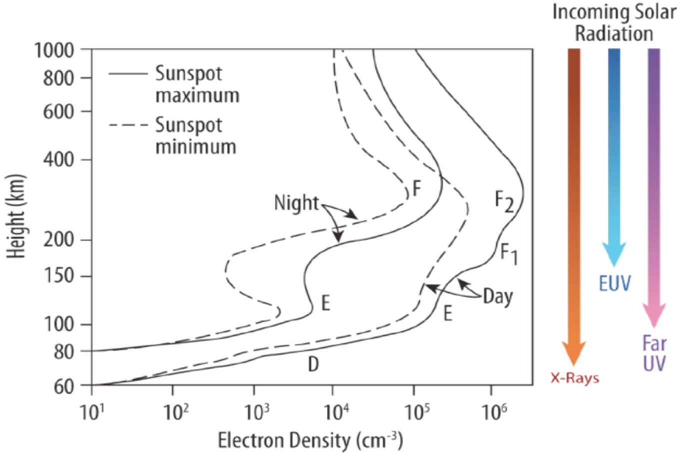


Drivers of Space Weather in the Upper Atmosphere

- Solar flares
- Solar Proton Events
- Solar Radio Bursts
- Geomagnetic storms driven by coronal mass ejections or corotating interaction regions
- Waves propagating from the lower atmosphere

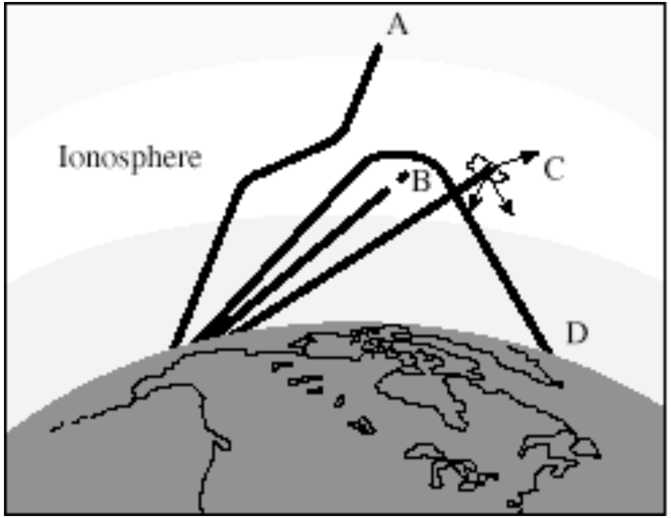
Solar Flares

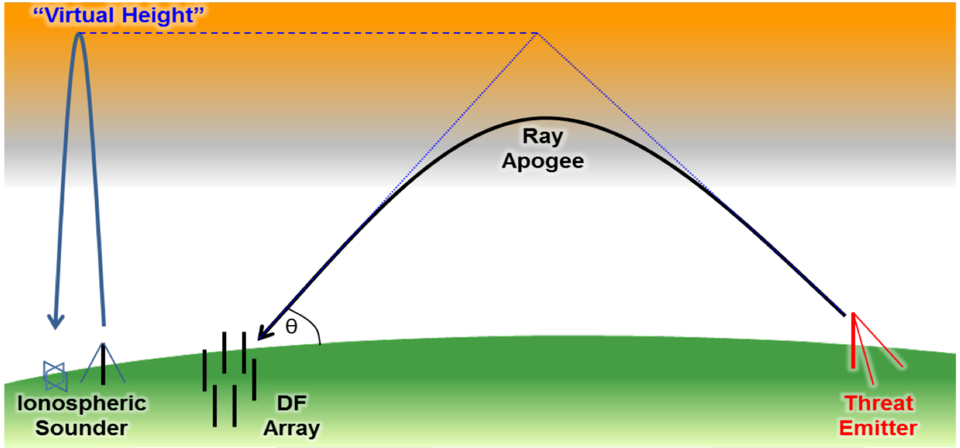
- Increase in X-ray flux
- GOES geostationary satellite measures X-ray flux in 0.1 – 0.8 nm
- Neutral atmosphere has small cross-section for X-ray photons
- Penetrate deep into the atmosphere, below 100 km altitude
- Ionize the D-region and absorbs HF radio waves
- Flares arrive in 8-minutes
- Flare duration 1-2 hours
- Users: disaster response (FEMA),
  commercial aviation, coast guard,
  mariners, HF frequency manages,
  military



HF Radio Wave Communication

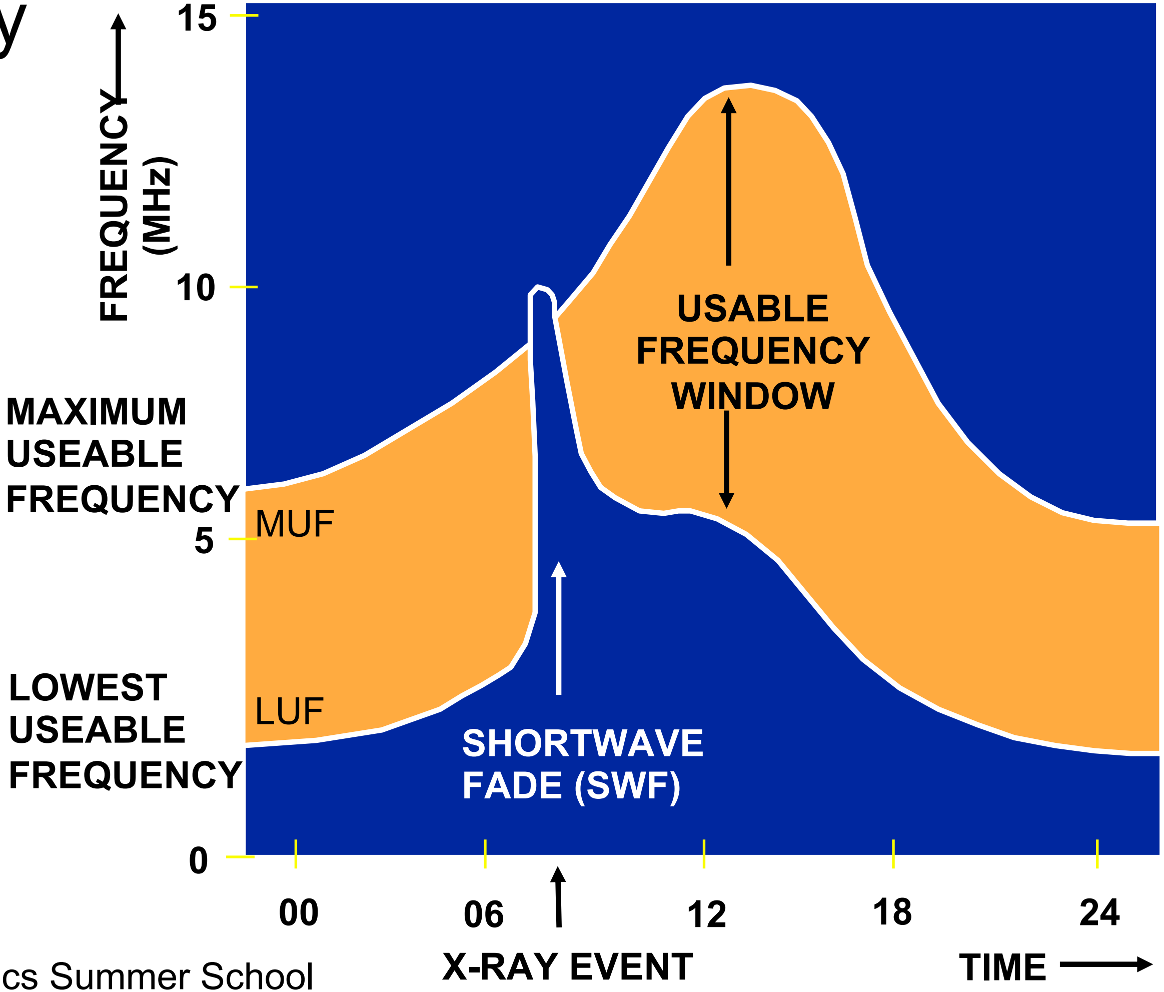
- For vertical propagation, the radio wave will reflect when plasma density matches the radio wave frequency
- The peak plasma density (usually NmF2) determines the maximum frequency for reflection
- NmF2 (m-3) = 1.24 x 10^{10} x foF2 (MHz)
- At an oblique angle, the radio wave refracts (changws direction) as the waves encounters denser plasma enabling higher frequencies and communication to greater distances (e.g., M3000)
- Apparent reflection usually from F2 layer
- Maximum usable frequency (MUF) for a given angle (skip distance) and NmF2
- Higher frequencies suffer less absorption
- A radio wave blackout only refers to HF





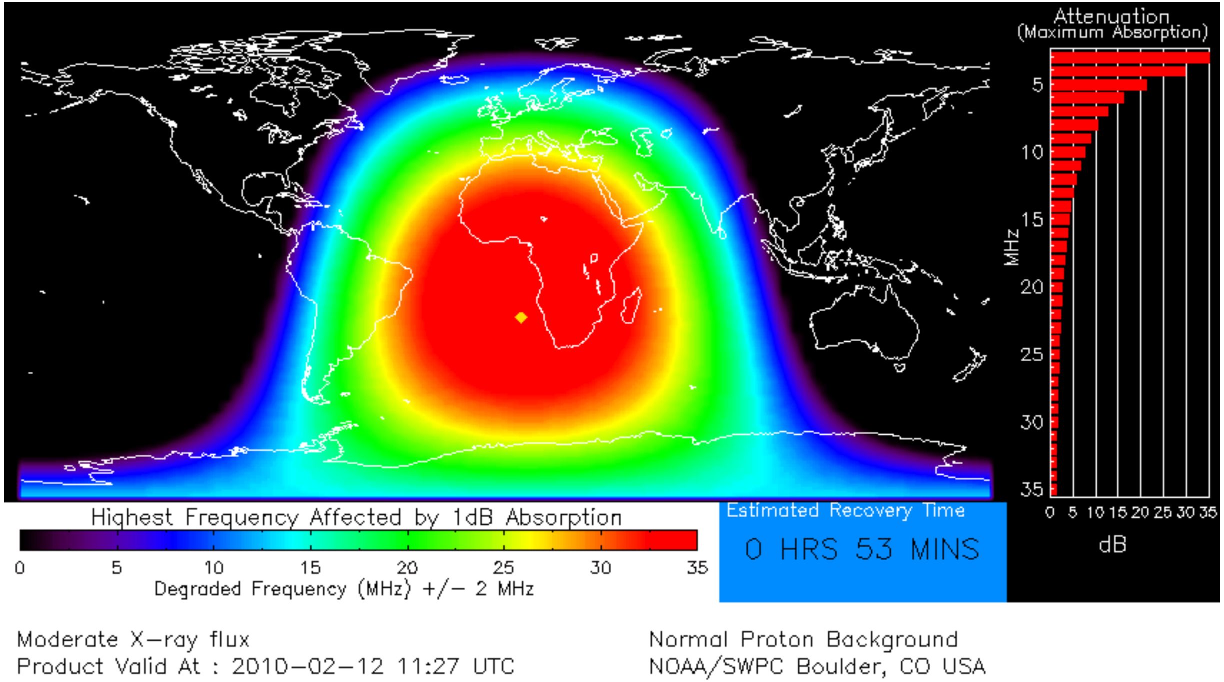
Usable Frequency Window

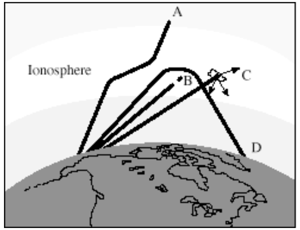
- MUF controlled by F2 region peak density and angle of propagation
- LUF controlled by degree of absorption in the D-region
- Lower frequencies are more susceptible to absorption
- Large flares can cause a shortwave fade, and can wipe out useable frequency window

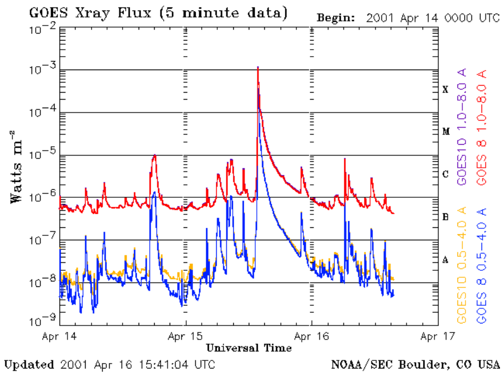


SWPC D-region absorption product

D-region responds to X-rays in less than a minute
HF absorption follows time history of source and requires high cadence

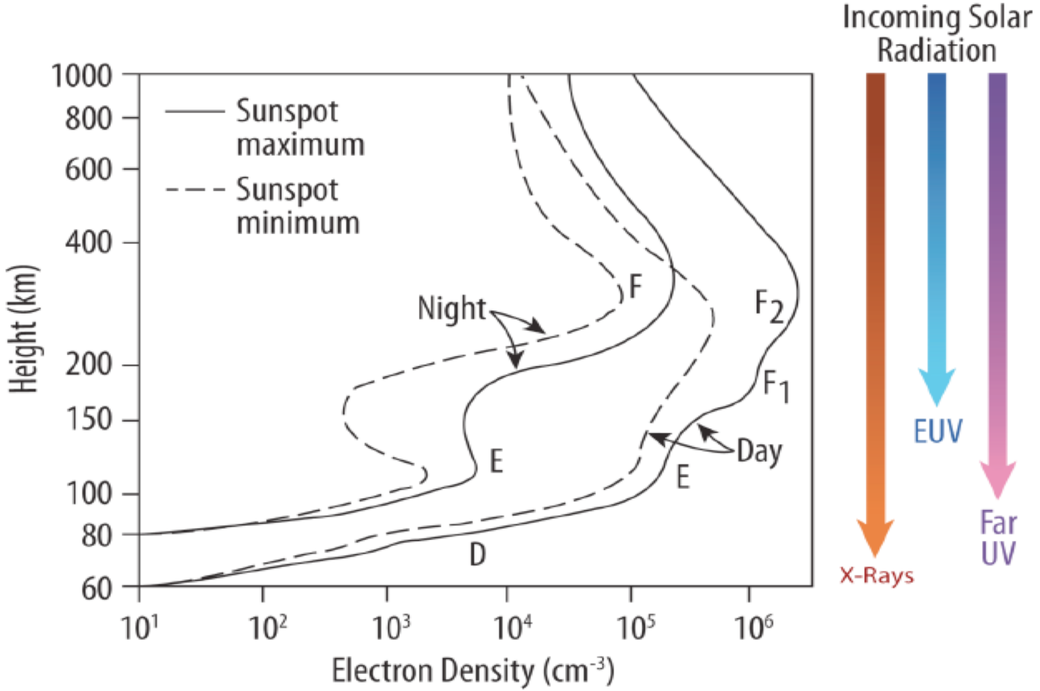






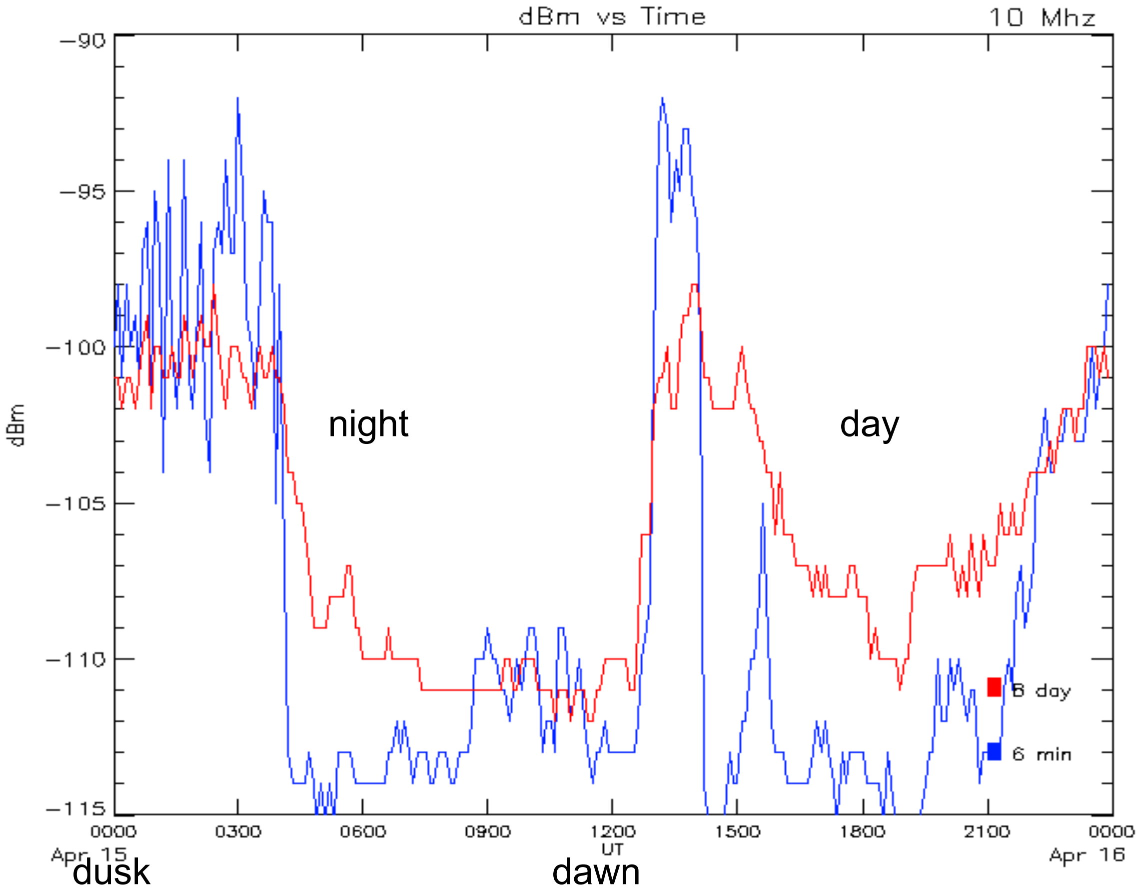
Driven by GOES X-ray observations in geostationary orbit

Quiz: Why does D-region absorb the radio wave when it has the lowest density of the ionospheric layers, compared to the F-region ?



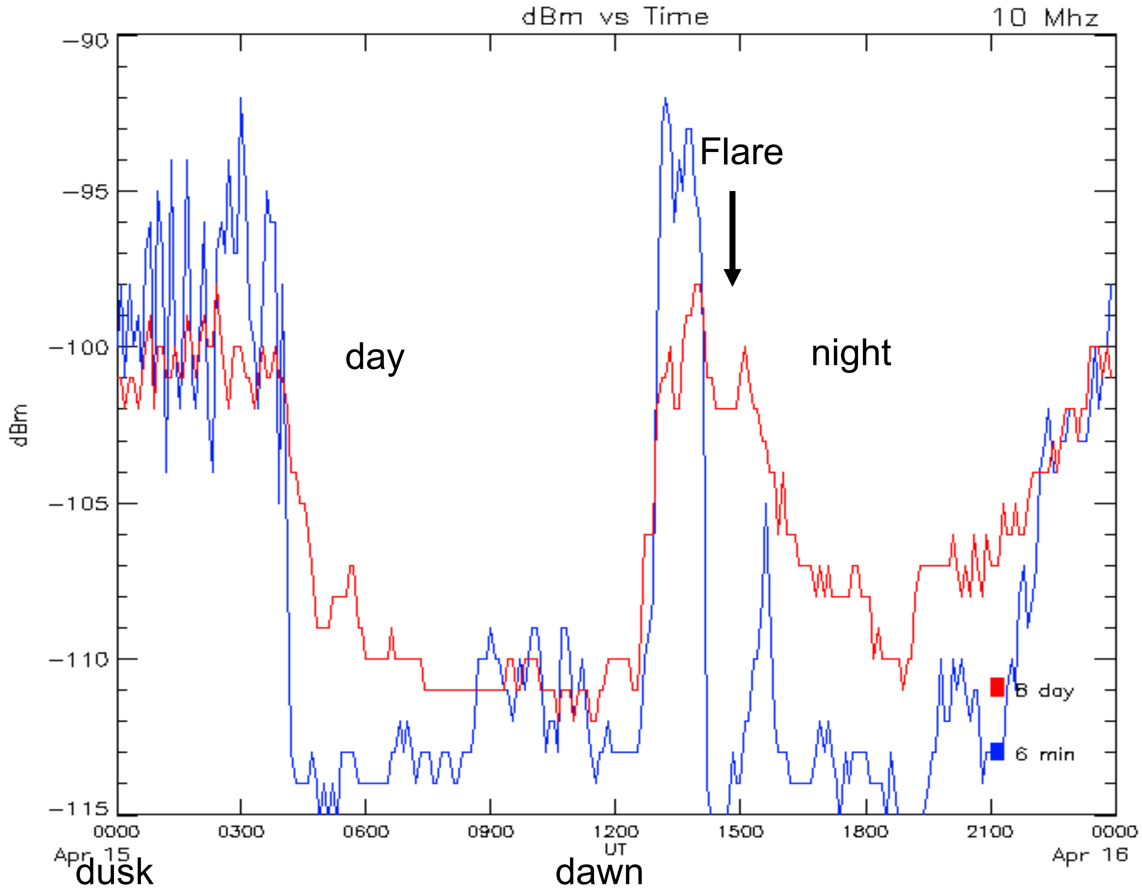
Operator view

- Signal Strength at 10 MHz
- Red - 5-day average
- Blue – every 6 minute data
- Where is the flare?



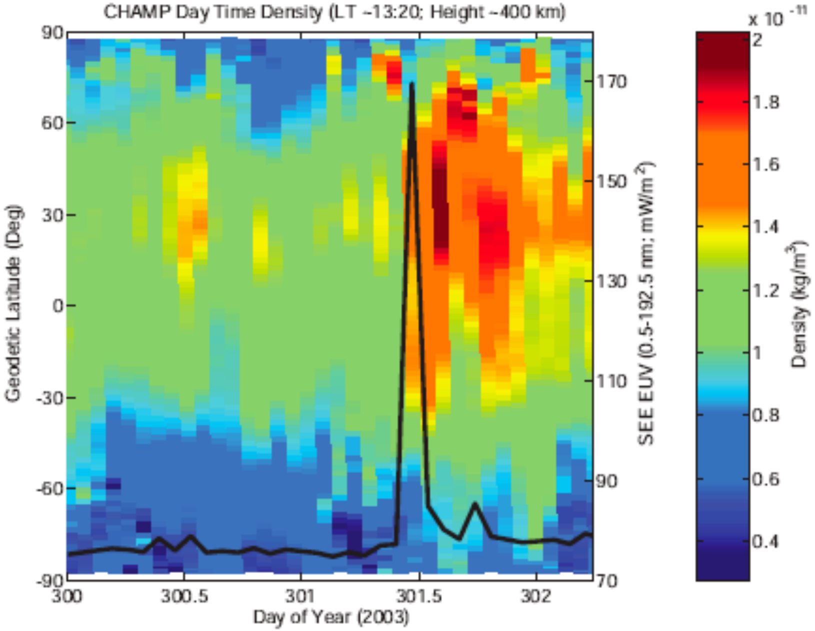
Operator view

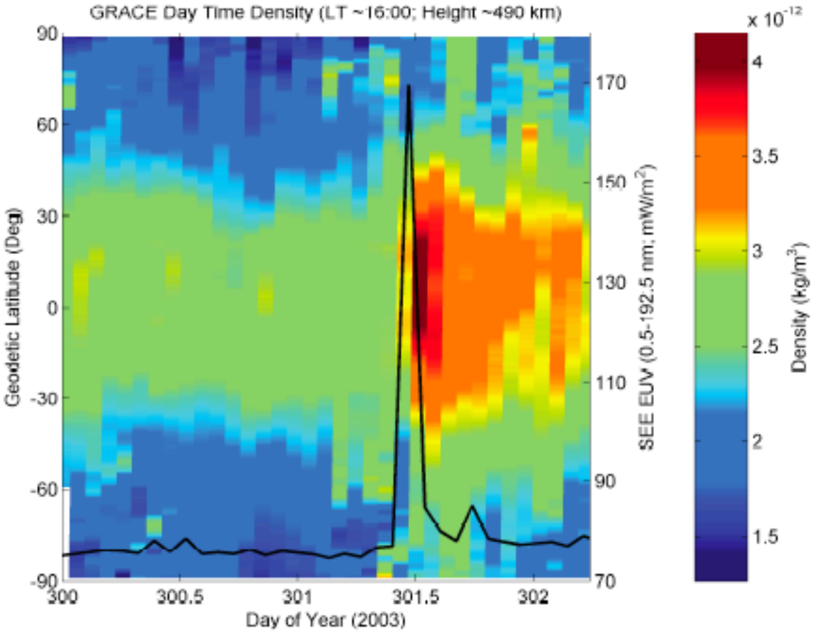
- Signal Strength at 10 MHz
- Red - 5-day average
- Blue – every 6 minute data
-



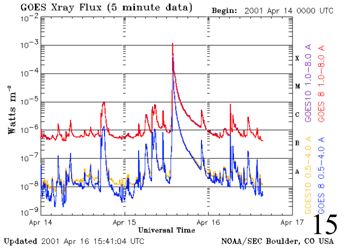
Response to Extreme Ultraviolet (EUV) flare component

Sutton and Forbes





- EUV heats and ionizes the upper atmosphere (improves HF comms)
- Heating expands atmosphere increasing neutral density in low Earth orbit (LEO) up to ~50% increase in satellite drag
- Neutral density has longer response and recovery time to EUV flare



Drivers of Space Weather in the Upper Atmosphere

- Solar flares
- Solar Proton Events
- Solar Radio Bursts
- Geomagnetic storms driven by coronal mass ejections or corotating interaction regions
- Waves propagating from the lower atmosphere

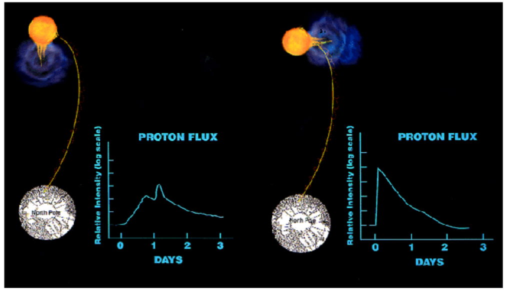
Solar Proton Event

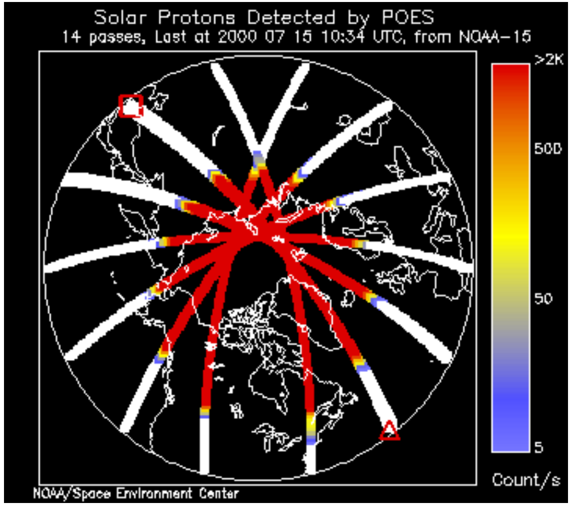
- Increase in high energy solar protons directed to polar and high latitude region by Earth's magnetic field (open magnetic field)
- GOES geostationary satellite measures particle flux in 10 to 100 MeV (energy range)
- Neutral atmosphere has small cross-section for energetic protons
- Penetrate deep into the atmosphere <100 km
- Ionizes the D-region and causes HF radio waves absorption at high latitudes (same as X-rays)
- Solar protons arrive in 15 minutes to a few hours (depending on the interplanetary magnetic field
- Duration several days
- Users: disaster response (FEMA), commercial aviation, coast guard, mariners, HF frequency manages, military

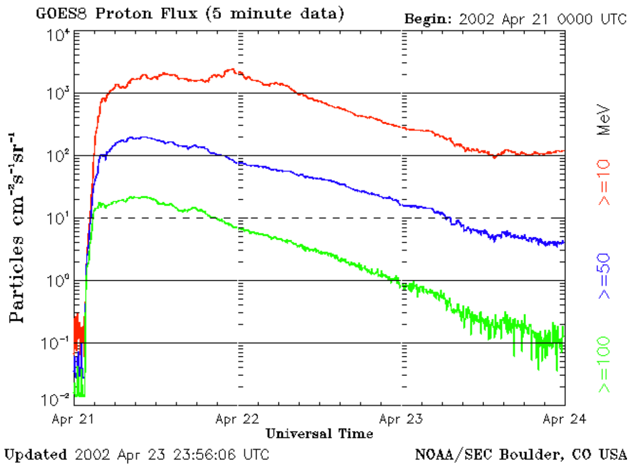
Polar Cap Absorption

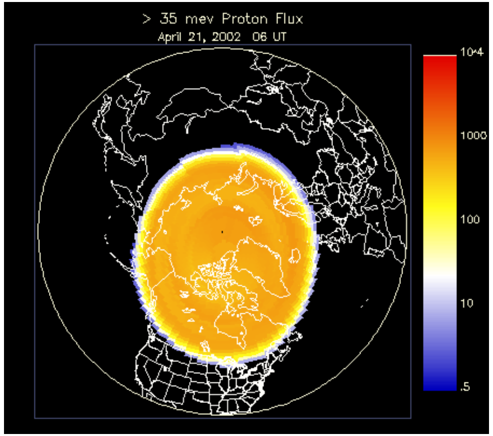
high latitude proton flux

cut-off latitudes controlled by Earth's magnetic field

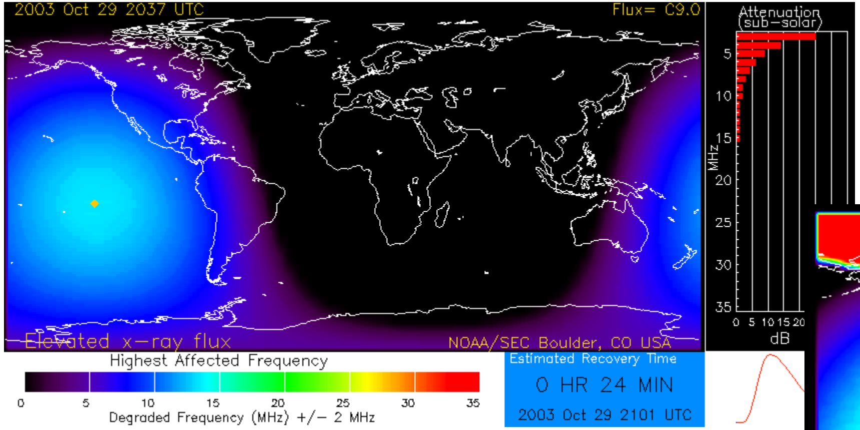




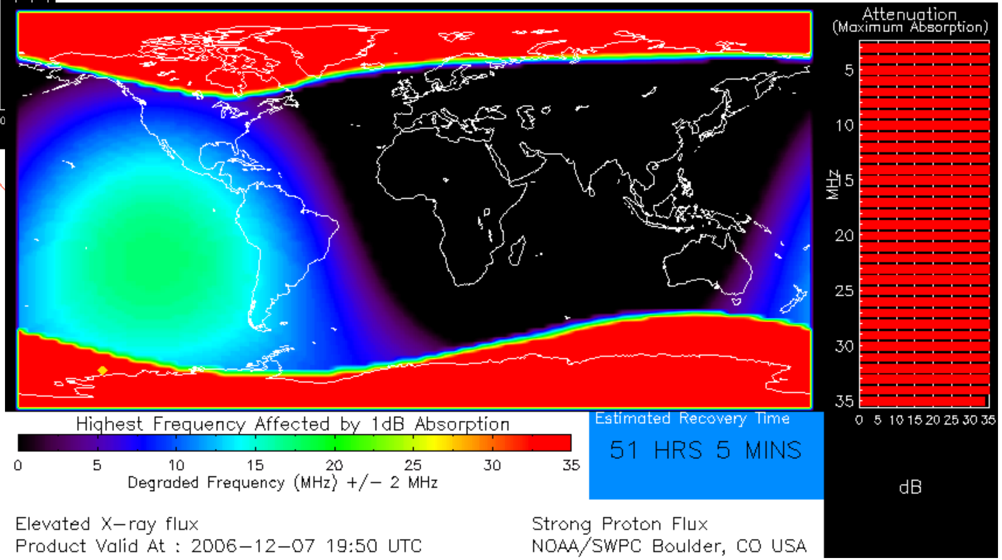




D-RAP Product for D-region absorption for HF comms.



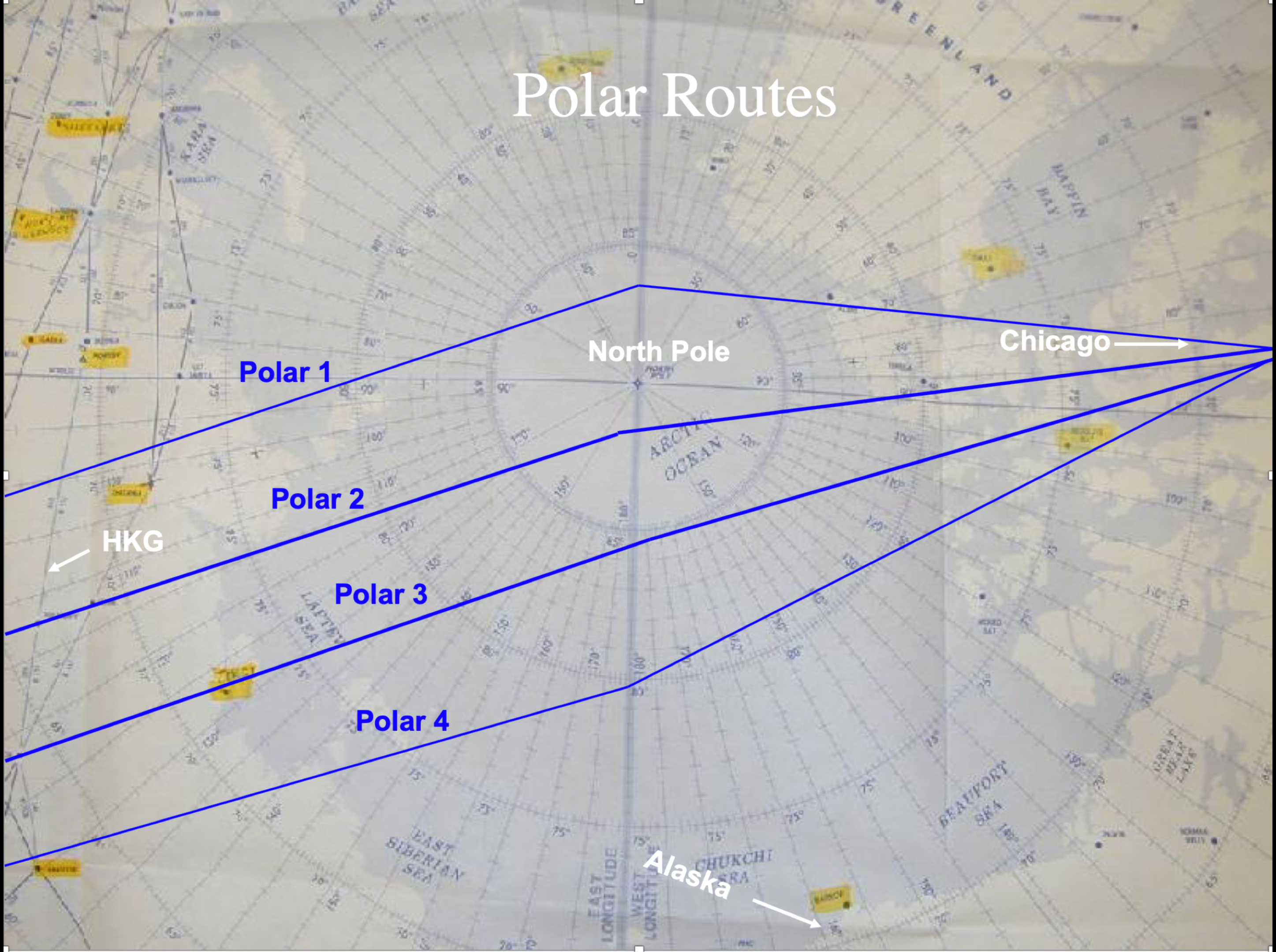
High Latitude:
driven by observations of GOES Solar Energetic Particles



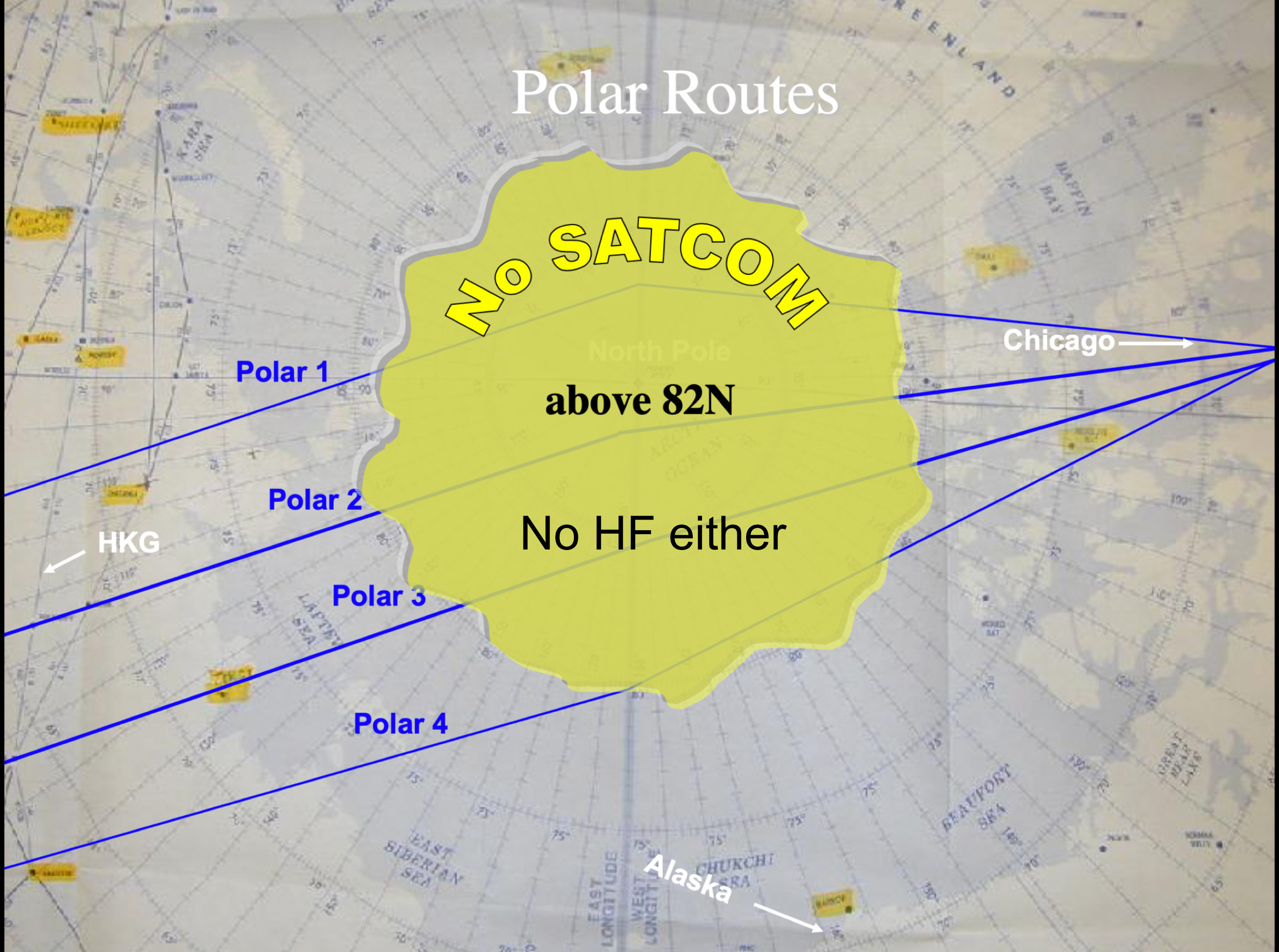
Mid and Low Latitude:
driven by GOES X-rays Solar Flare Observations

Forecast relies on predicting solar flares and solar proton event

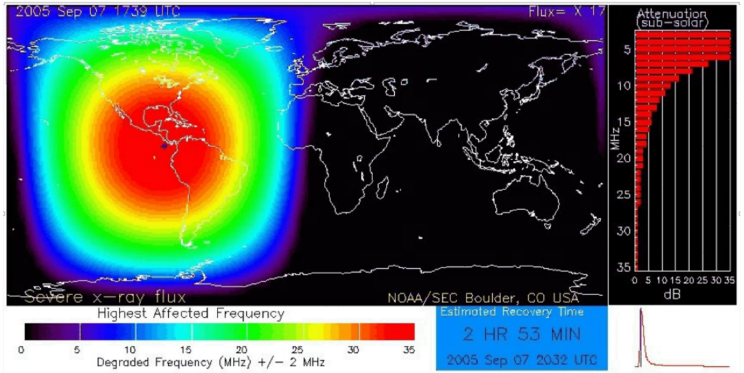
Polar Routes



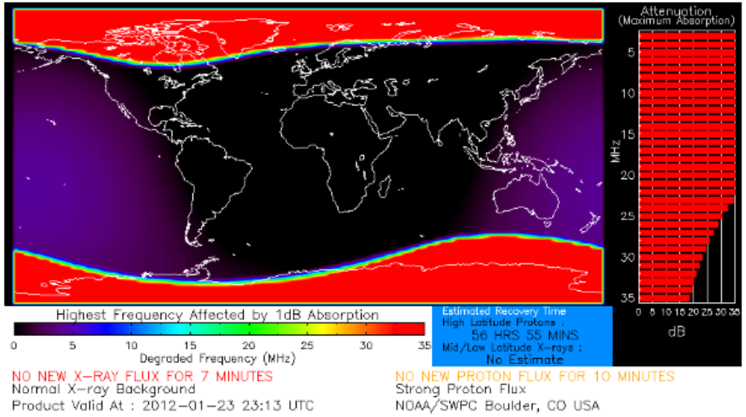
Polar Routes



D-region absorption product (DRAP) for HF communication

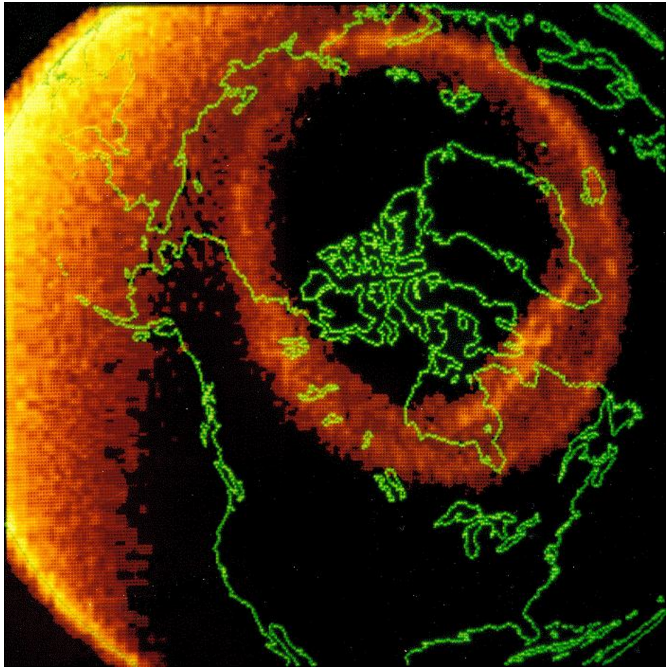


Solar flare: GOES solar X-Ray flux



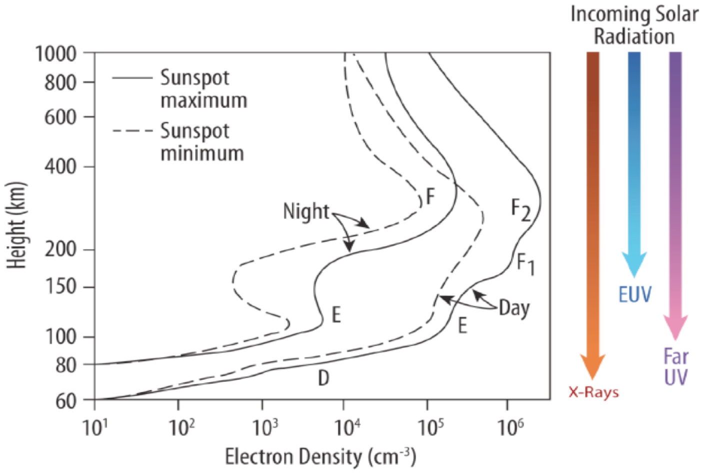
Solar proton event: GOES solar proton flux

Auroral absorption:
currently missing



Why does D-region absorb the radio wave when it has the lowest density of the ionospheric layers, compared to the F-region ?

- As the radio wave propagates through the medium the free electrons are oscillate with the wave as it passes through.
- In the E and F region the electron collision frequency is low so the energy stays in the wave
- In the D-region below 100 km altitude the dense atmosphere increases the electron-neutral collision frequency, so as the wave passes through some of the wave energy is lost through electron-neutral collisions



Drivers of Space Weather in the Upper Atmosphere

- Solar flares
- Solar Proton Events
- Solar Radio Bursts
- Geomagnetic storms driven by coronal mass ejections or corotating interaction regions
- Waves propagating from the lower atmosphere

Coronal Mass Ejection Striking Earth

- Drives a geomagnetic storm at Earth if the interplanetary magnetic field (IMF) is southward
- Arrival time 1-3 days
- Duration 1-2 days
- Effects:

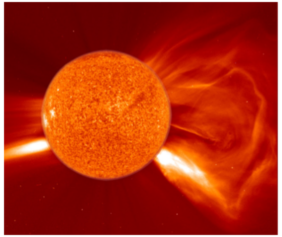
  Atmospheric heating, expansion and increased satellite drag

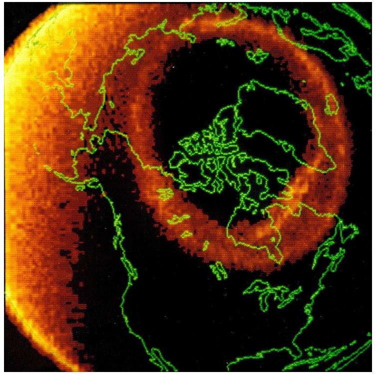
  Disruption of HF Communications

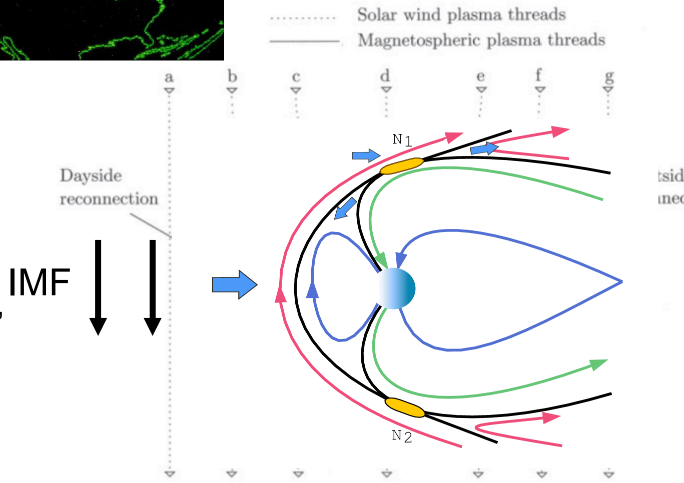
  Compromised GNSS Positioning, Navigation, and Timing

  Induced currents/power outages

  Satellite anomalies
- Users: power companies, satellite operators, HF operators, satelite communication, PNT, ……….

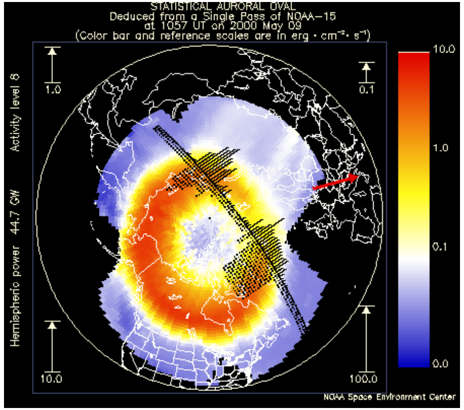




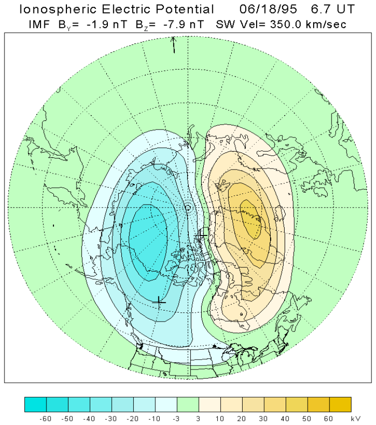


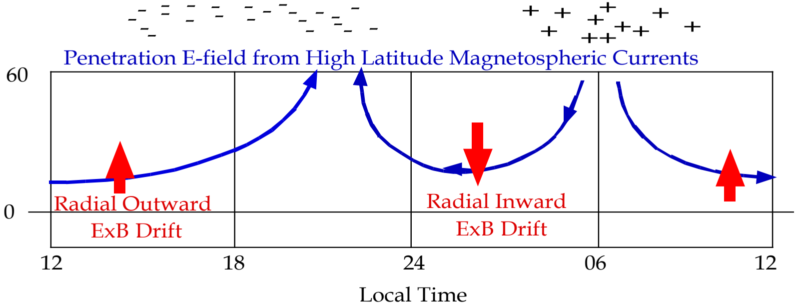
Increase in Magnetospheric Forcing

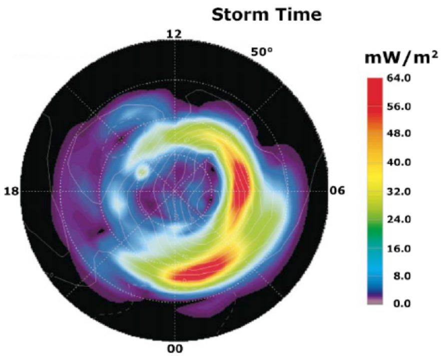
TIROS/NOAA auroral precipitation patterns driven by power index:



Weimer electric field patterns driven by solar wind data:







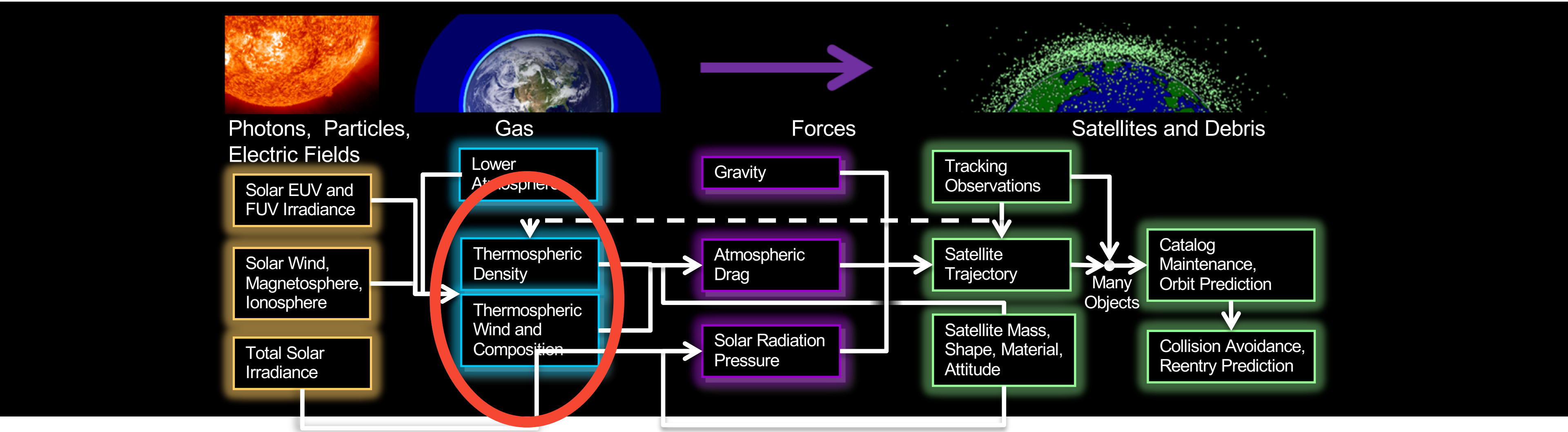
Joule heating

Thermosphere-Ionosphere Responses to Magnetospheric Sources

- Auroral precipitation and magnetospheric convection expanded enhancing conductivity and plasma transport at high latitudes (scintillations, absorption)
- Magnetospheric “penetration electric fields” imposed globally in less than a second (plasma reconfiguration at mid and low latitudes, HF comms., plasma gradients, irregularities, satellite communications, navigation)
- Ion drag drives high latitude wind system up to ~ 1 km/s (drag)
- Joule and particle energy heats atmosphere, thermal expansion, neutral density increase, winds (drag)
- Horizontal pressure gradients, equatorward wind surges, changes in global circulation, neutral composition changes (HF comms.)
- Disturbance dynamo electric fields (plasma reconfiguration)
- Positive and negative ionospheric storm phases

Upper Atmosphere Expansion and Satellite Drag

Effects of the Environment

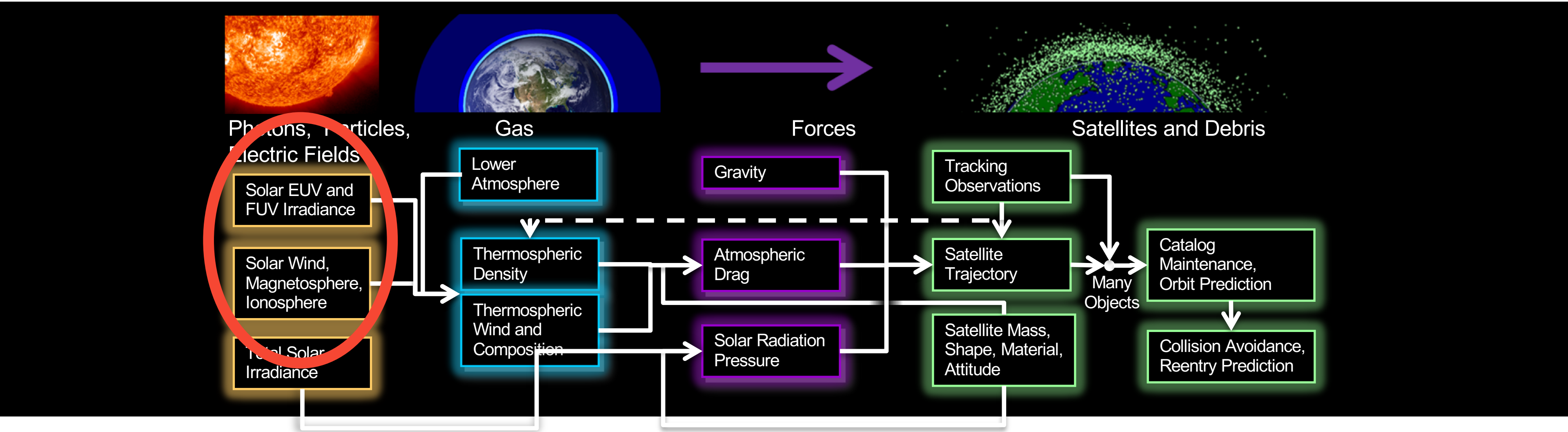


Neutral density and wind risks to operational spacecraft:

- Direct: drag, changing orbit, orbit uncertainty, decreased orbit lifetime
- Indirect: inability to monitor/predict debris trajectories for collision avoidance

Upper Atmosphere Expansion and Satellite Drag

Effects of the Environment



Main causes of Upper Atmospheric Expansion:

1. Solar UV radiation increase
2. Coronal mass ejections (CMEs) (geomagnetic transient events)

Atmospheric expansion, satellite drag risks

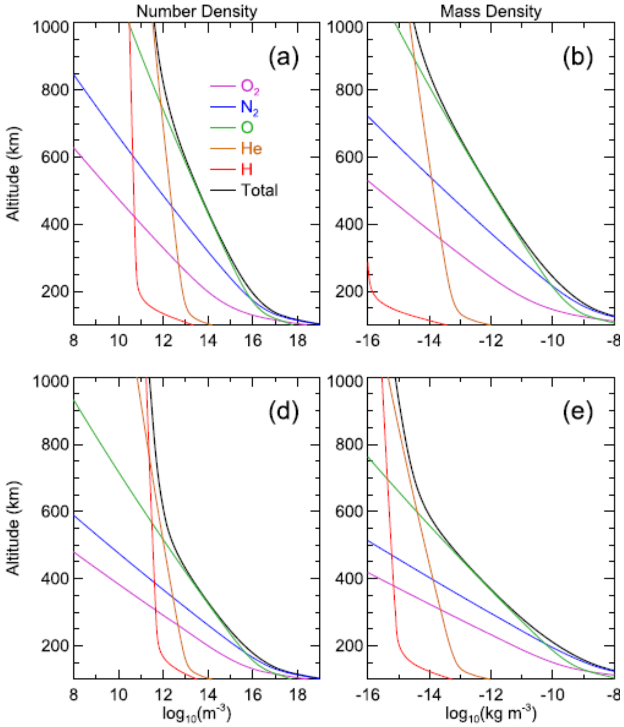
Atmospheric expansion poses two distinct risks to operational spacecraft:

1. Direct effect of enhanced drag on the spacecraft, changing its orbit, increases the uncertainty of its position, and reducing the orbital lifetime.

2. Indirect effect of atmospheric expansion on the ability to monitor the trajectories of debris, including objects with high area-to-mass ratio, for collision avoidance.

Neutral density responds to thermospheric heating, density and temperature are considered synonymous. Density response depends on atmospheric composition.

Small-scale structure – important for debris with high area-to-mass ratio and collision avoidance



Global mean neutral composition and density profiles at solar min (lower panels) and solar maximum (upper panels) Emmert (2015)

Useful Terminology for Orbital Debris

Courtesy Joe Carroll
Tether Applications, Inc

Cars
(~3000)

<u>Intact objects</u>, mostly ton-class; **<u><1%</u>** of all lethal LEO objects

98% of target area & **99%** of mass for debris-creating impacts!

Easy to track & avoid, but the source of hubcaps & shrapnel

Hubcaps
(~9,000)

<u>Tracked fragments</u>, mostly **>**10 cm, **<**1kg: **~ 2%** of lethal objects

Hubcaps dominate tracking costs; most are too light to shred cars

<u>44%</u> are from just 2 collisions: Fengyun/A-sat **+** *Cosmos/Iridium*

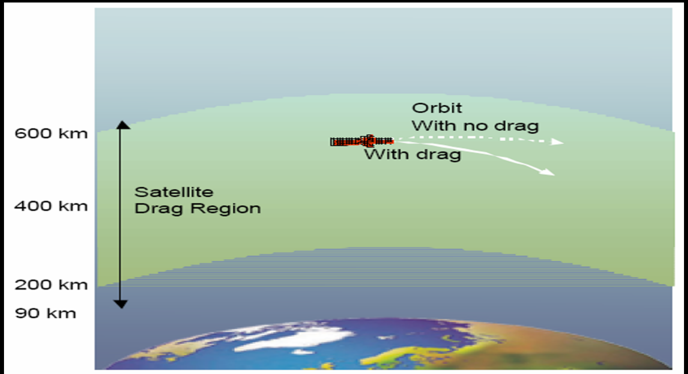
Shrapnel
(~500,000?)

<u>Lethal untracked fragments</u>, ~1 gm: **>97%** of all lethal objects?

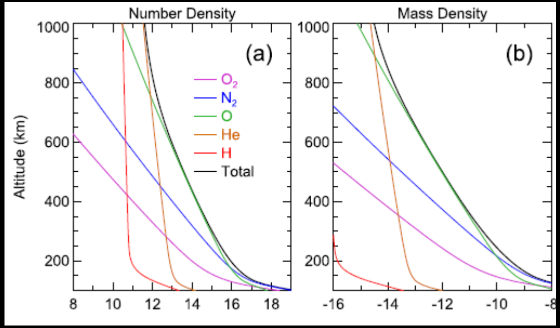
Too small to track & avoid (now), but too heavy to shield against

This is the <u>expensive</u> (but invisible) direct threat to assets!

We worry mostly about a cascade of hubcap/car collisions in low earth orbit making more & more hubcaps (Kessler Syndrome). We should perhaps worry <u>mostly</u> about lethal shrapnel, and the accidental car/car collisions that will create most of it!

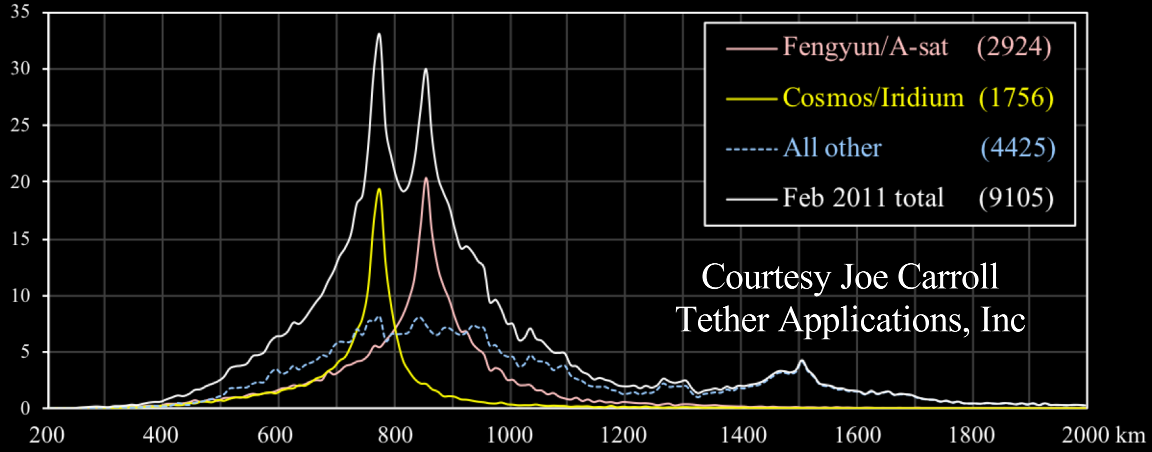


Hotter more expanded atmosphere – drag significant up to 1000 km altitude



Tracked fragments (<1 kg) from two recent collisions are half of all tracked fragments

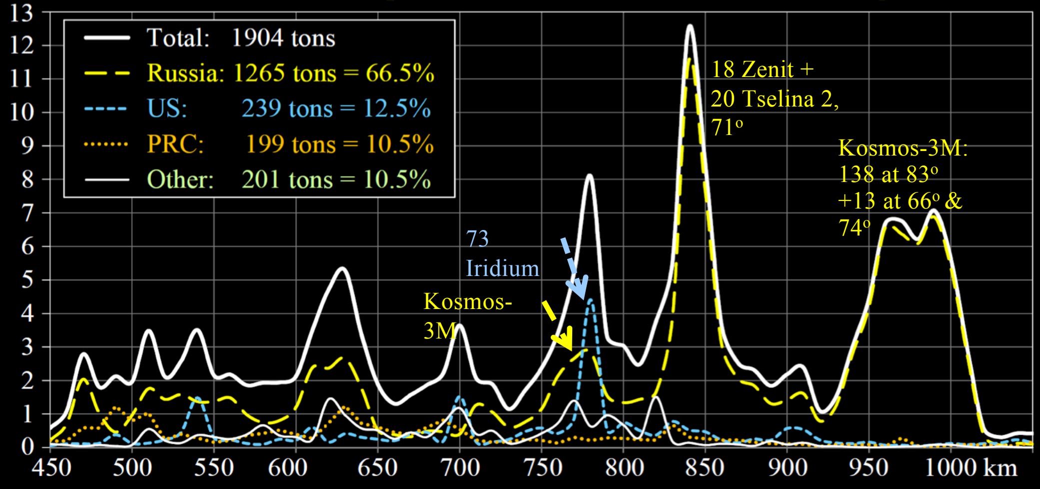
Tracked <1 kg LEO "Hubcap" Population per Km Altitude, in February 2011



Cars and Owners at Congested Altitudes in LEO

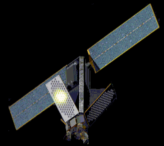
1. Larger objects have higher collision risk, and their high mass raises collision yield.
2. Tight altitude clustering of massive large objects further raises their collision risk.
3. Most Iridium satellites can (& will?) maneuver, & may deboost when replaced.
4. Russian rocket bodies are most of the mass in most of the crowded altitude bands.
5. They aren't the only issue, but they will be the source of most collisional shrapnel.

Tons/Km Mass at 450-1050 km in April 2016 (93% of future shrapnel!)



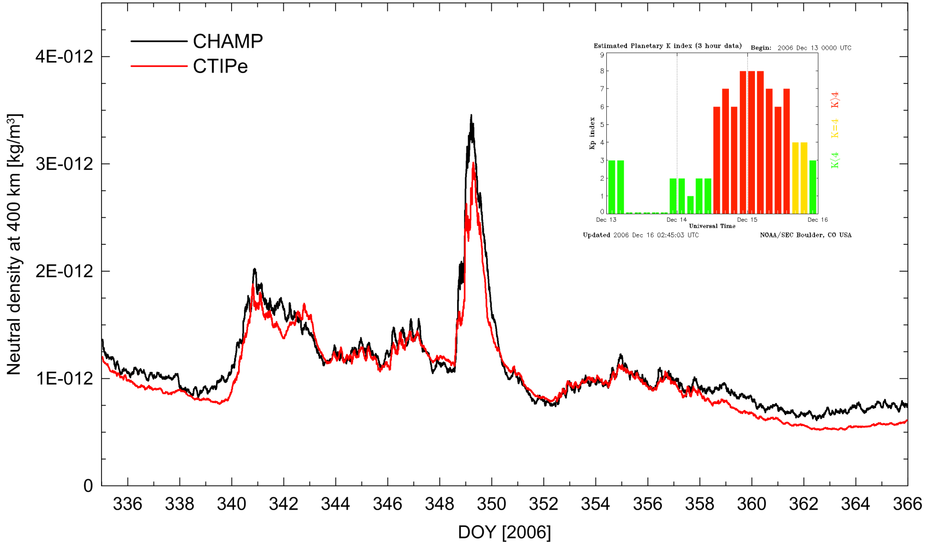
Kosmos-3M
2.4x6m, 1434 kg;
282 at 600-1600 km

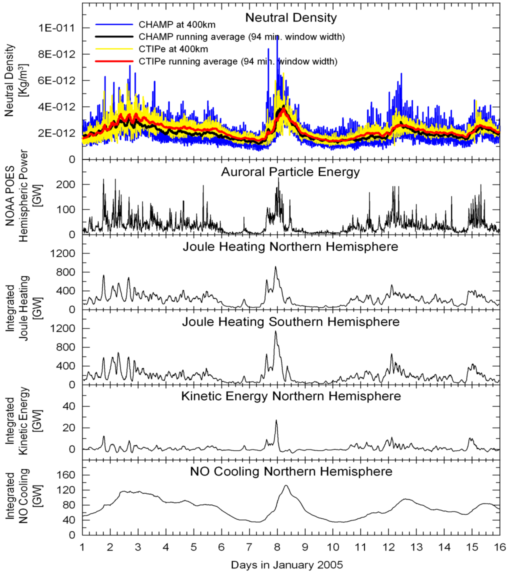
Zenit
3.9 x 11 m
8300 kg,
71º

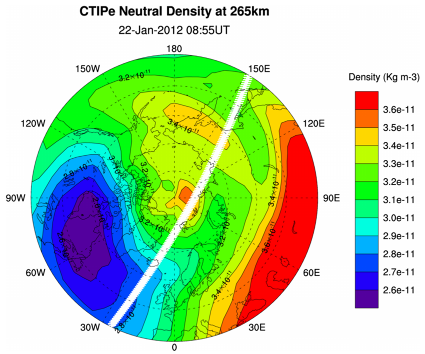


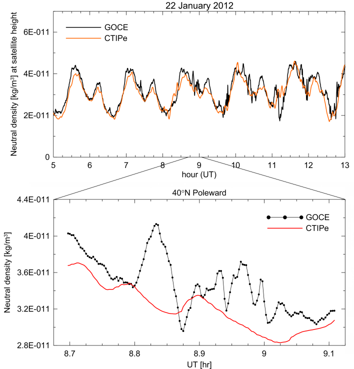
Iridium
~2 x 4 x 8 m,
550 kg, 86º

CTIPe vs CHAMP or GOCE



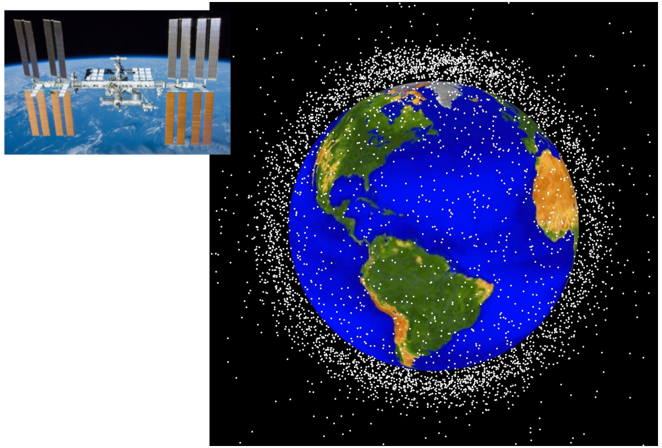




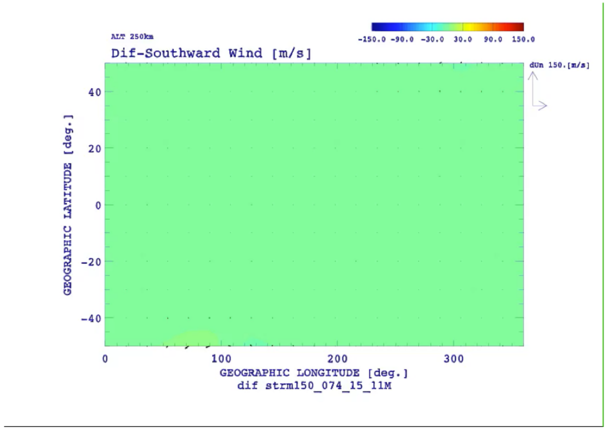


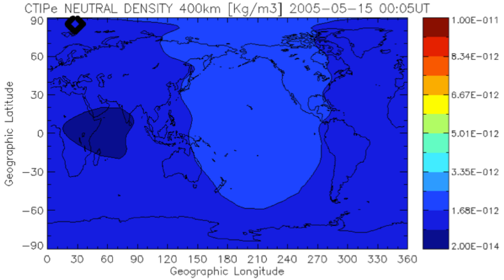
What would this density response look like during a Carrington event?

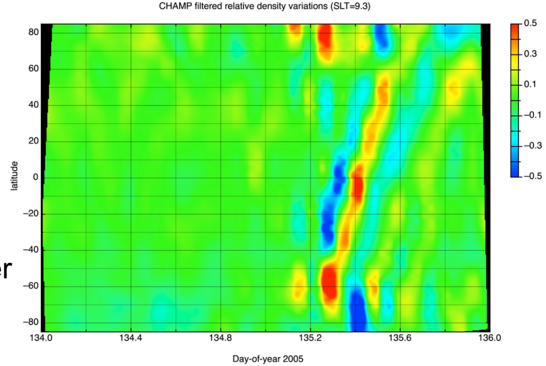
Time dependent response: wind surges, temperature, and density

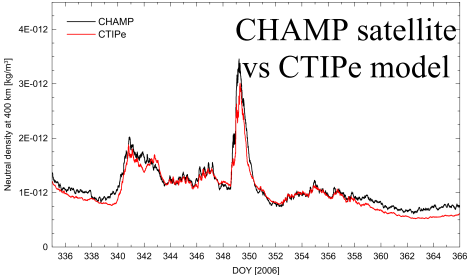


~20,000 pieces of debris > 5 cm are tracked







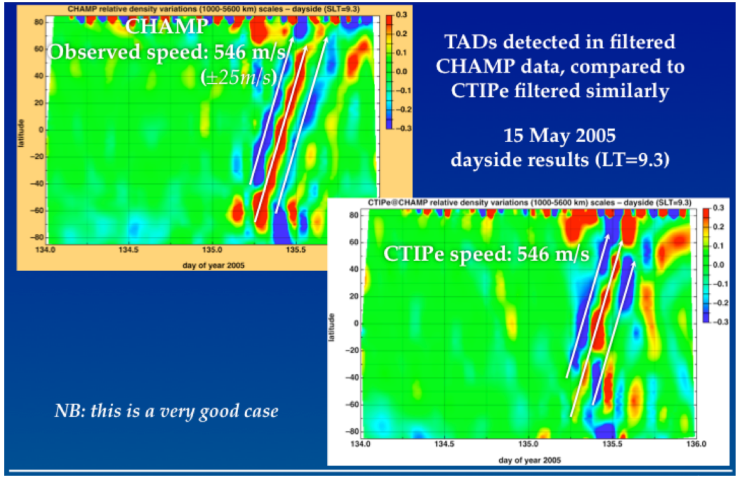


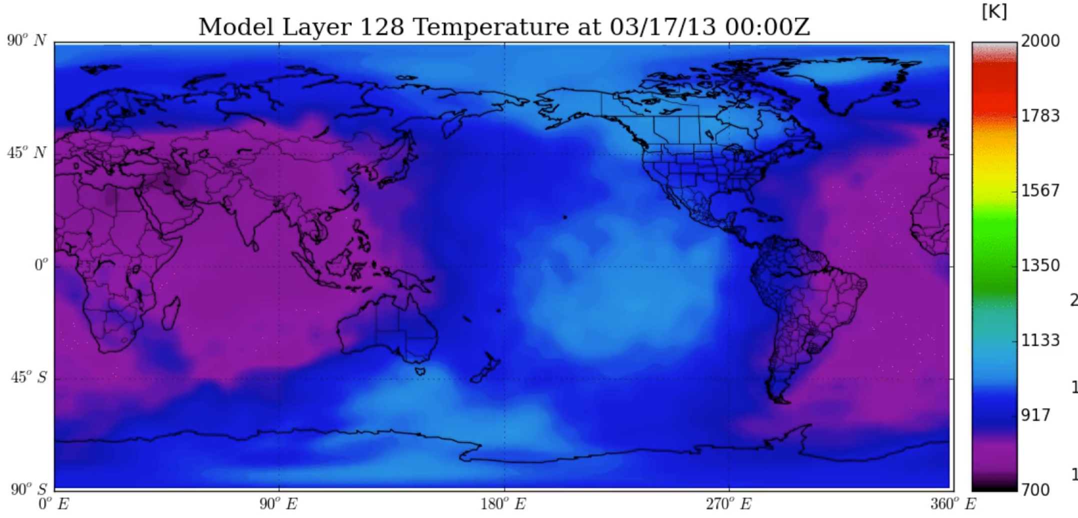
Heliophysics Summer School

July 15th, 2020

Impulse Joule heating: launches large-scale TIDs, temperature and density increase

LSTIDs

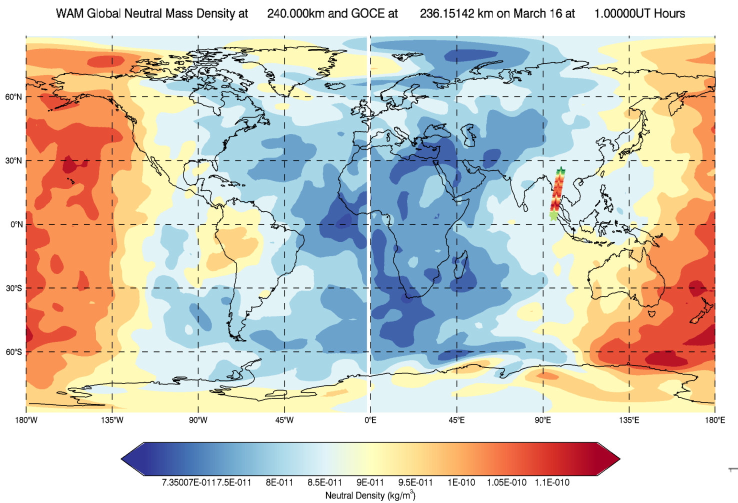


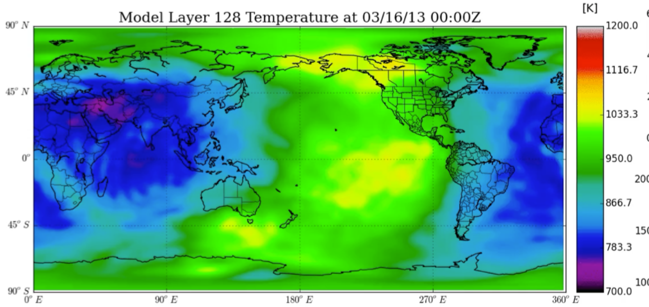


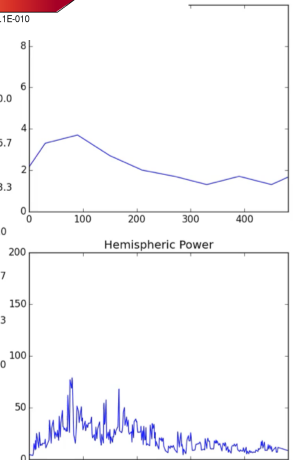
WAM Whole Atmosphere Model Neutral Atmosphere Component

- Whole atmosphere model (WAM): an extension of the US weather model (Global Forecast System GFS spectral model) to 600 km altitude, 150 layers, variable g
- WAM runs at ~180 km horizontal resolution, T62, compared to operational weather model of ~12 km, T1534
- Includes all the lower atmosphere weather and dynamics processes, as well as all the additional T-I physics
- Provides the 3D neutral winds, temperature, density, major species composition O, O_2, N_2
- WAM coupled to the IPE ionospheric module using ESMF (3-D re-gridding)

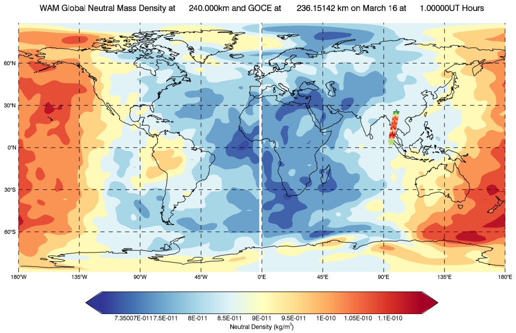
Examples: neutral density and 1-day temperature animation at 240 km



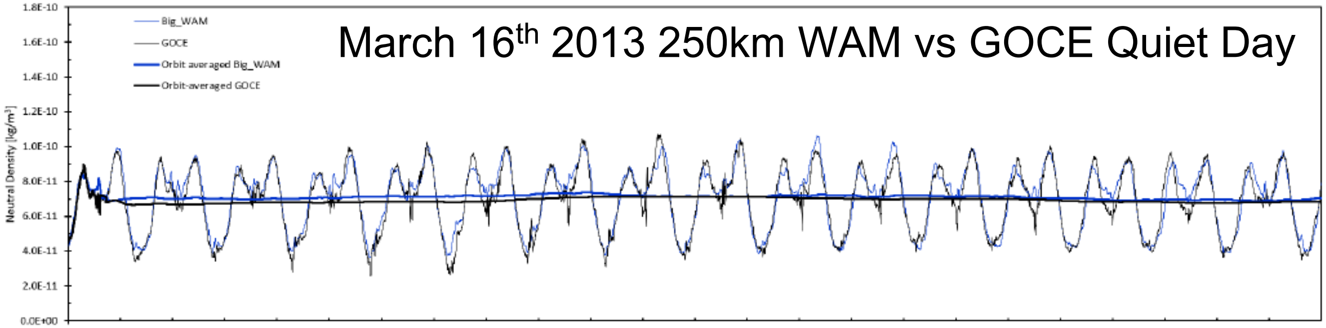


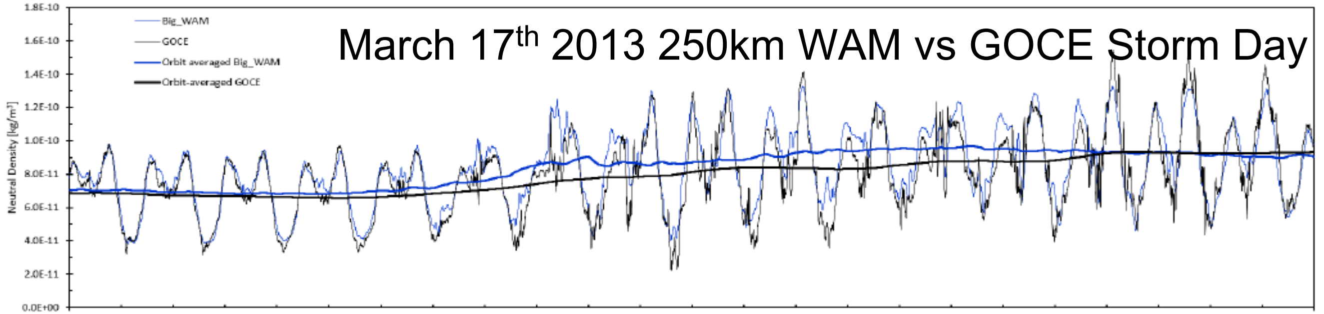


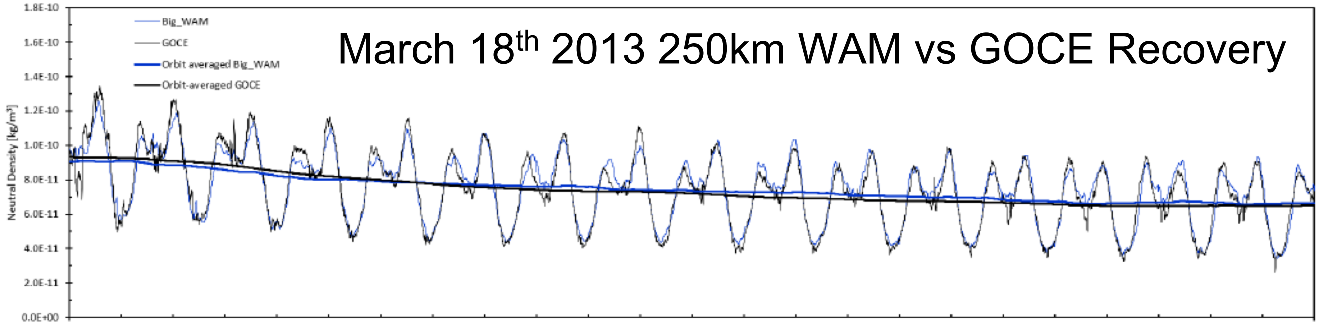
WAM Validation Neutral Density



- Comparison of WAM with GOCE satellite neutral density along-orbit accelerometer observation at ~250 km altitude
- Diurnal/latitude structure and storm response captured







WAM vs GOCE St. Patrick's Day 2013

RMSE: 4.5% orbit average, 9.8% along track

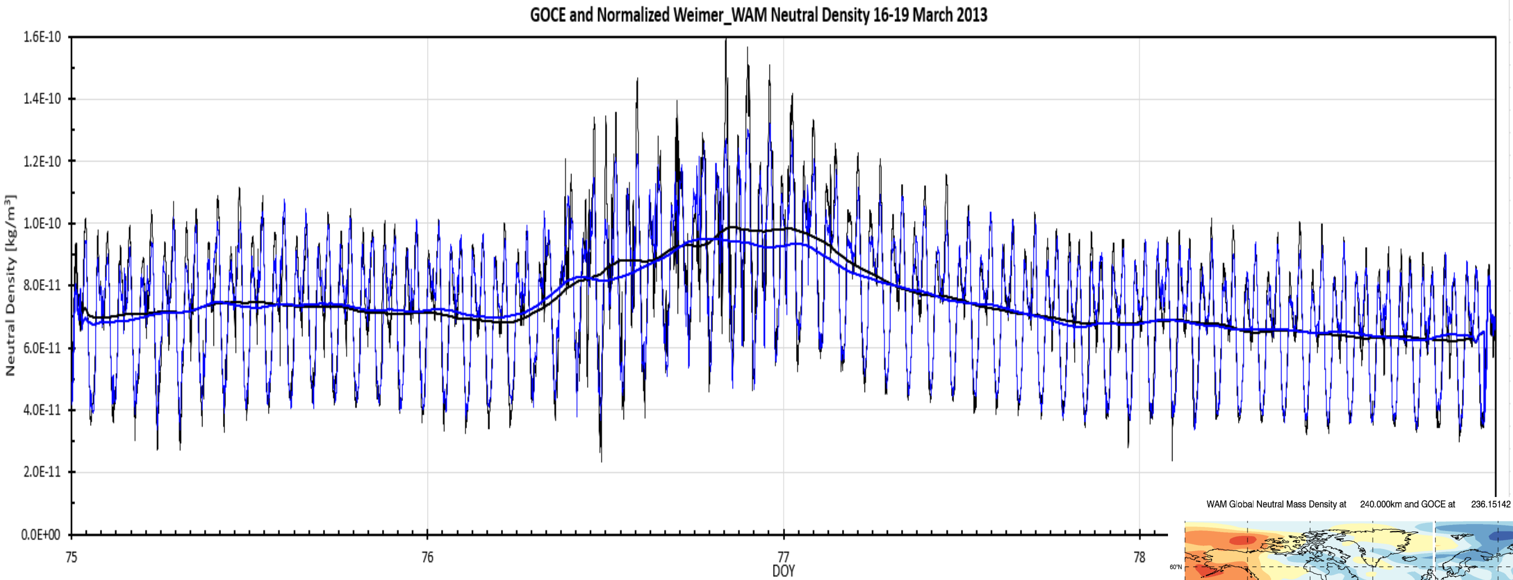
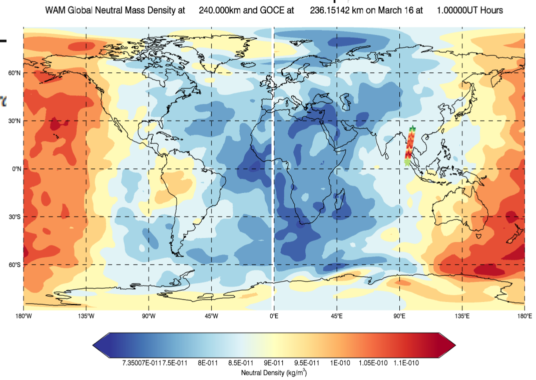


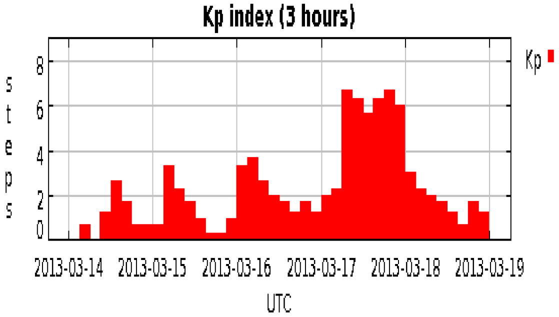
Table 1. *16-19 March 2013 ...nsphys1_del8.nc (nonBIG_WAM) for point-to-point (along-orbit) and smooth (orbit-avera*

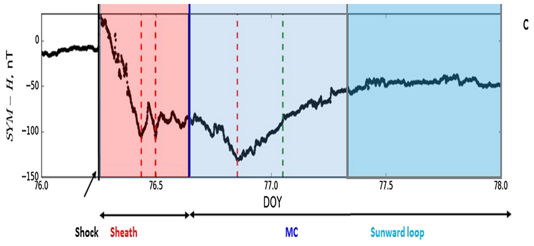
Log space metrics	Along-Orbit	Orbit-Averaged
R	0.9488	0.95789
RMSE	0.09781	0.045426
$RMSE^2$	0.009567	0.0020635
BIAS	1.035	1.0297
Standard Deviation	0.09173	0.034758



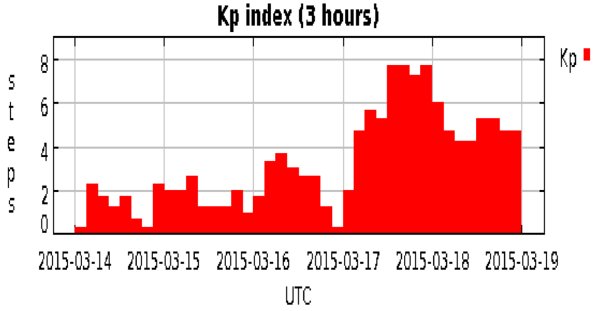
Solar and Geomagnetic Activity Validation
Simulate response to increasing levels of IMF/SW drivers

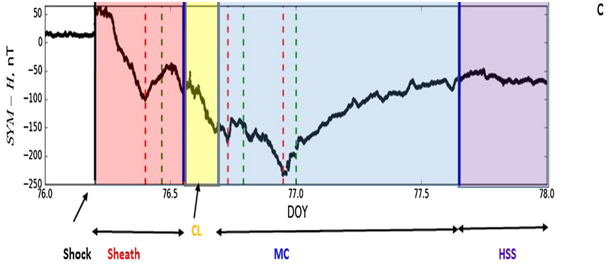
Moderate: D_{st} -132
St. Patrick's Day
March 17th, 2013



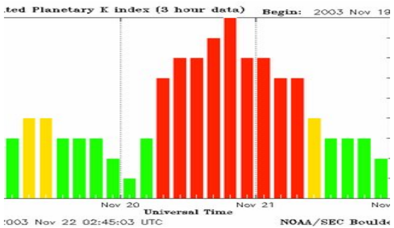


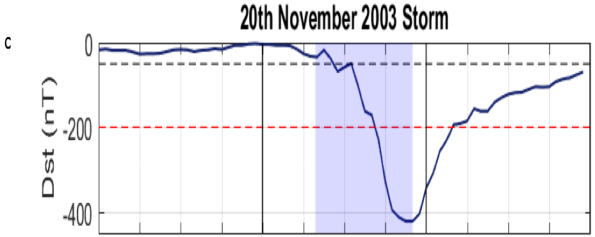
Strong: D_{st} - 234
St. Patrick's Day
March 17th, 2015



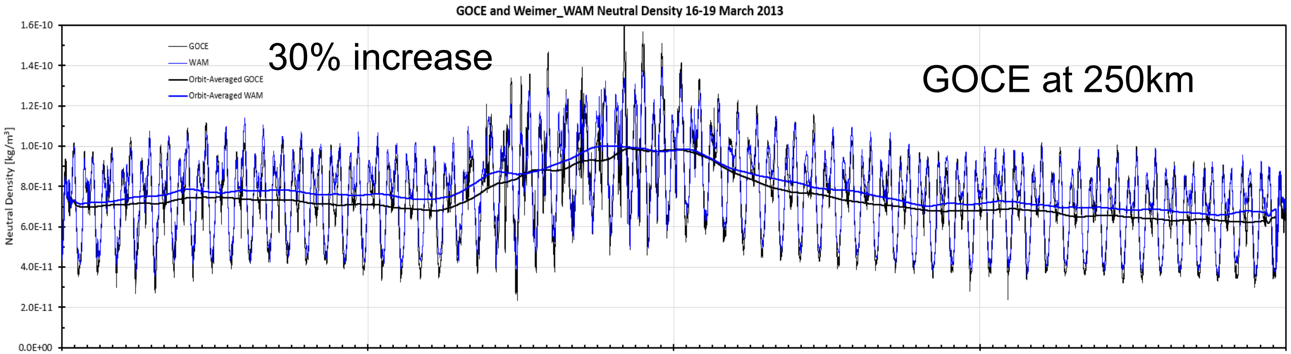


Major: D_{st} -472
Nov 20th, 2003

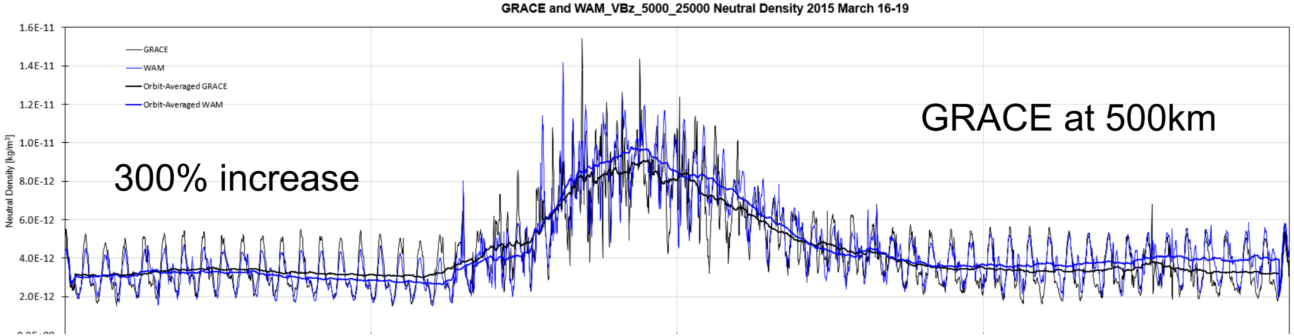




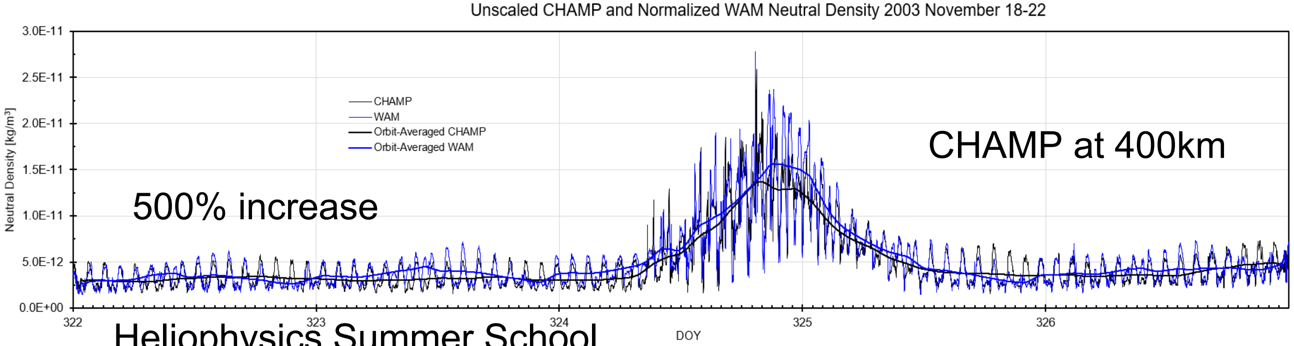
Moderate storm
St. Patrick's Day
March 2013
Dst - 132



Strong storm
St. Patrick's Day
March 2015
Dst - 234



Major storm
November 2003
Dst - 472



Satellite Drag Take-Aways

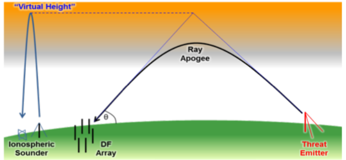
- Thermal expansion by EUV and geomagnetic storms are the most likely drivers of thermal expansion and increased drag, flare EUV is likely to be smaller
- The increased drag reduces lifetime of satellites, reduces accuracy of orbit prediction increasing risk of collisions, but also cleans out some debris
- The storm response is more uncertain and dynamic because the Joule heating in structured and changes rapidly is response of the magnetosphere
- The magnetosphere modulates the energy flow into the upper atmosphere from a CME striking Earth
- The structure produced during a storm will make tracking objects with high area to mass ratio uncertain, which again increases risk of collisions
- The increase in nitric oxide from auroral production and temperature changes during a geomagnetic storm is uncertain and will modulate the temperature and density response
- The drag at higher altitudes 800-1000 km becomes more relevant with a big storm, and is a well populated area of LEO objects, including debris
- Ion density (e.g., O^+) may contribute to drag at the higher altitudes during storms because the ion scale heights are greater, and vertical ion distribution is more extended
- Geomagnetic storms can occur at the same time as elevated EUV flux so the effects would be additive, which could be a factor 10 increase in drag at 400 km altitude

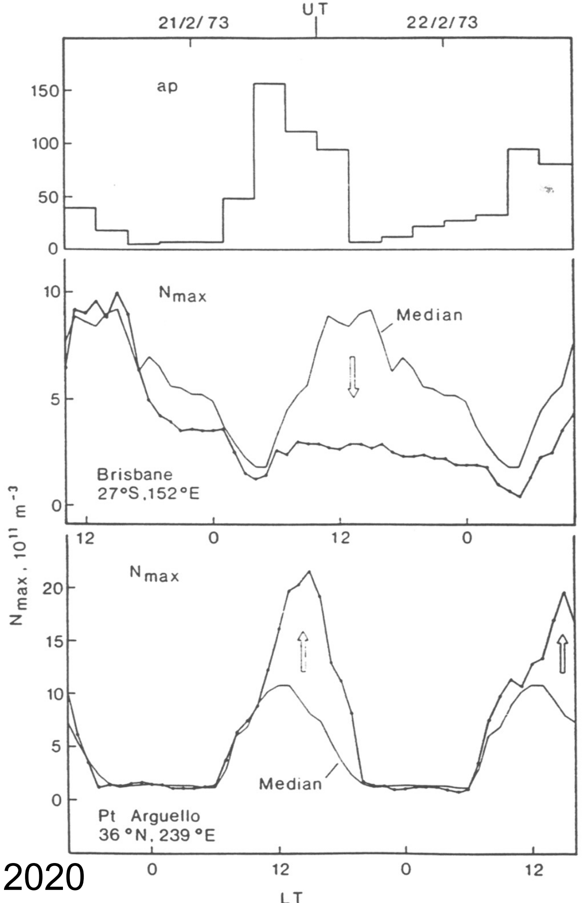
Break

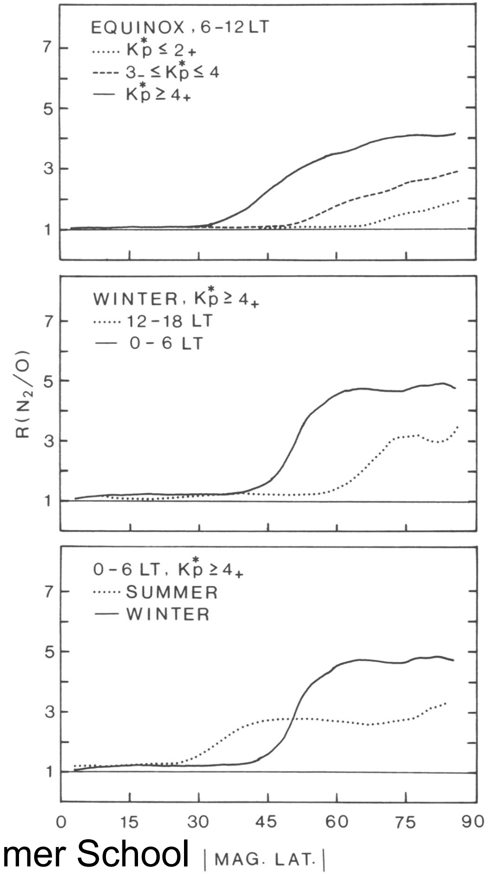
Thermosphere-Ionosphere Responses to Magnetospheric Sources

- Auroral precipitation and magnetospheric convection expanded enhancing conductivity and plasma transport at high latitudes (scintillations, absorption)
- Magnetospheric "penetration electric fields" imposed globally in less than a second (plasma reconfiguration at mid and low latitudes, HF comms., plasma gradients, irregularities, satellite communications, navigation)
- Ion drag drives high latitude wind system up to ~ 1 km/s (drag)
- Joule and particle energy heats atmosphere, thermal expansion, neutral density increase, winds (drag)
- Horizontal pressure gradients, equatorward wind surges, changes in global circulation, neutral composition changes (HF comms.)
- Disturbance dynamo electric fields (plasma reconfiguration)
- Positive and negative ionospheric storm phases

Neutral composition and positive and negative ionospheric phases

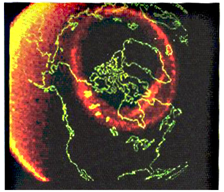


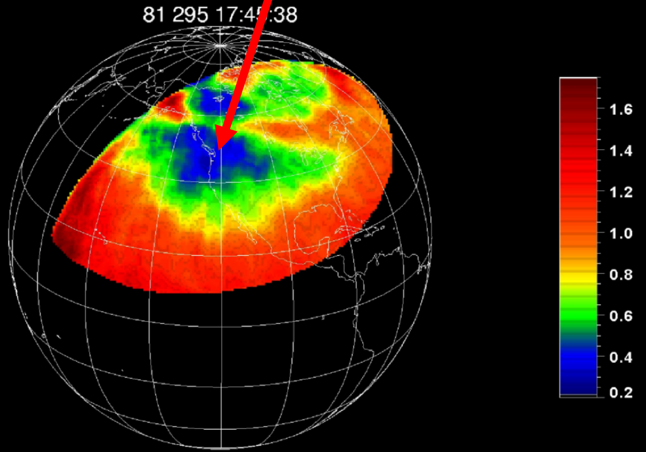


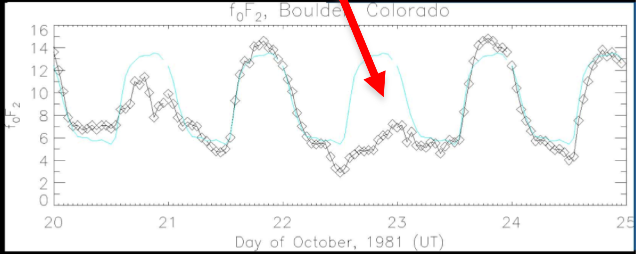


Prölss 1997

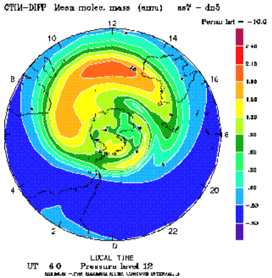
Oxygen Depletions Imaged from Space – drives ionospheric depletions

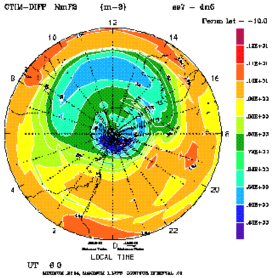


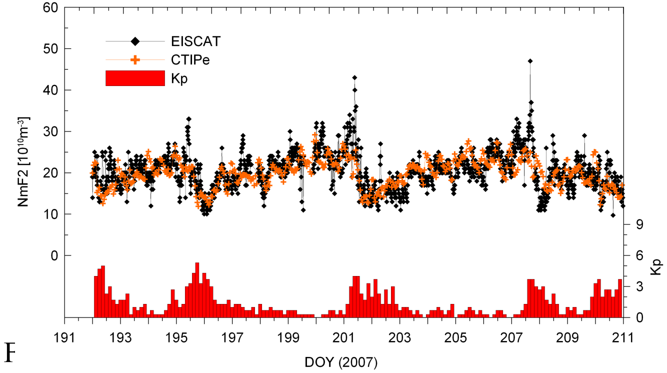




Strong correlation between O/N_2 and ionospheric depletions





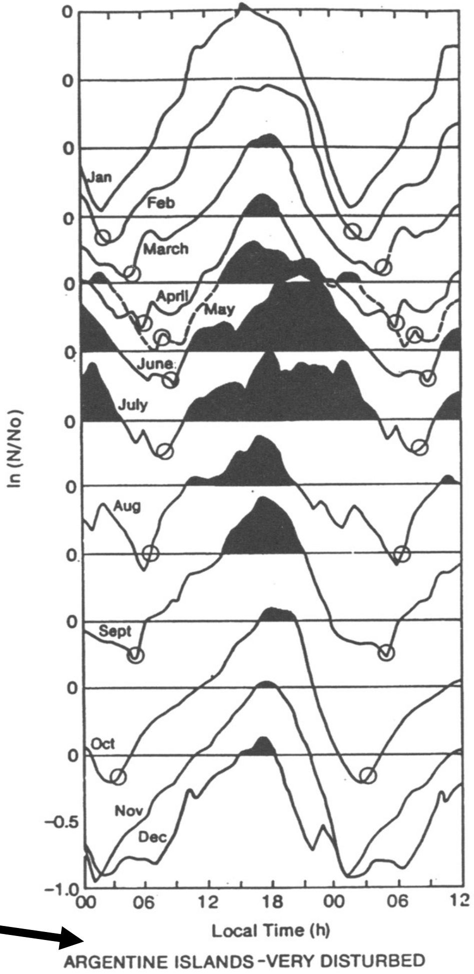


F

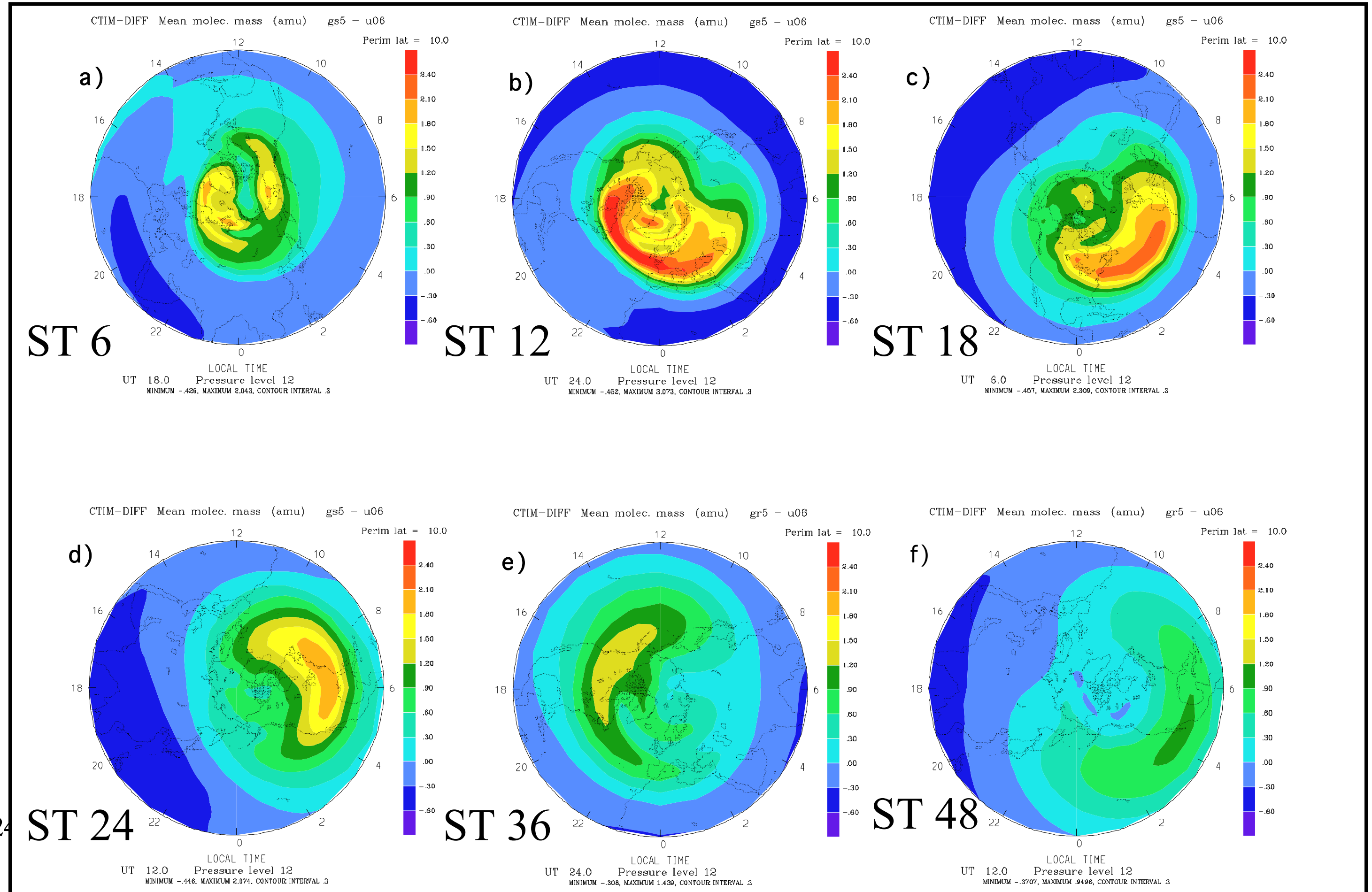
Seasonal/local time variation in ionospheric response at mid-latitudes
Rodger et al. 1989

- Negative phase peaks in summer
- Positive phase peaks in winter
- Negative phase peaks at dawn
- Positive phase peaks at dusk
- Response to summer/winter seasonal circulation and poleward/equatorward diurnal wind variation

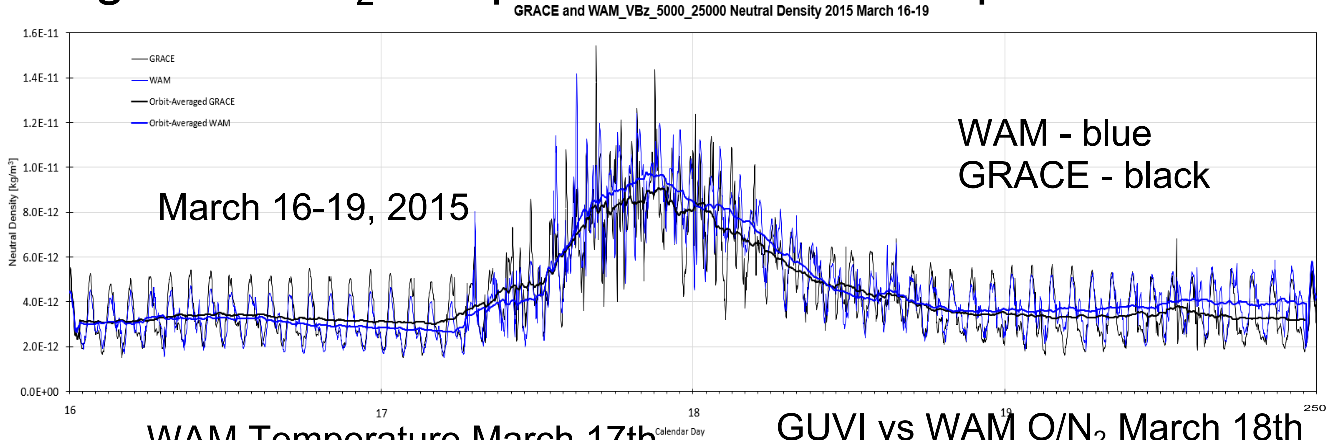
(southern hemisphere mid-latitude station)

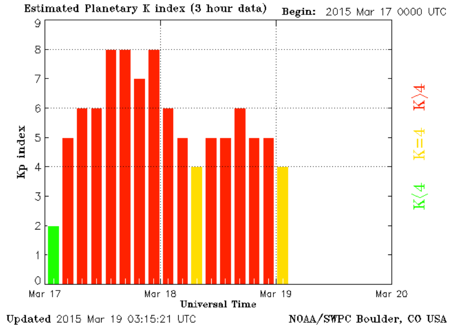


Composition transport at solstice

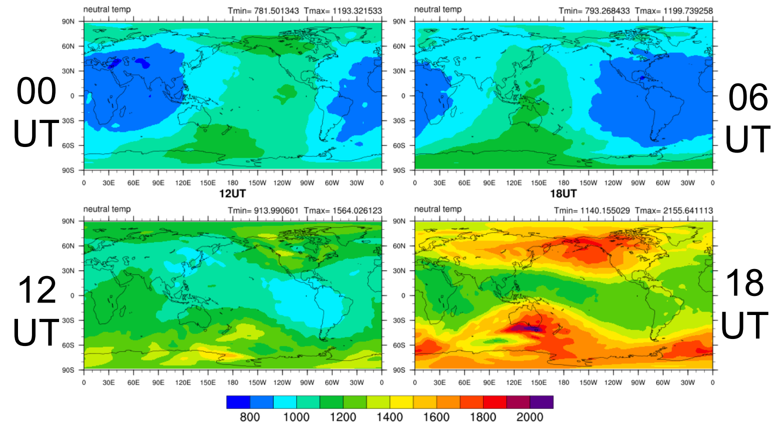


WAM neutral density compared to GRACE at 450 km, temperature and height-integrated O/N_2 compared to GUVI in response to St. Patrick's Day 2015 storm

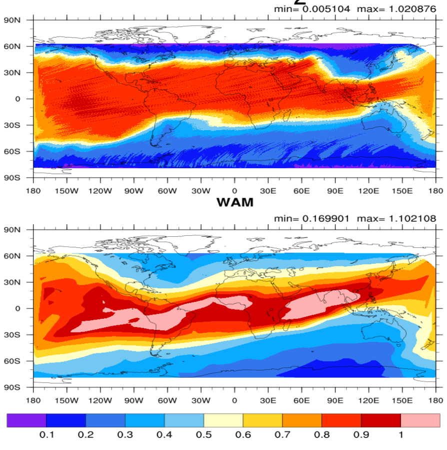


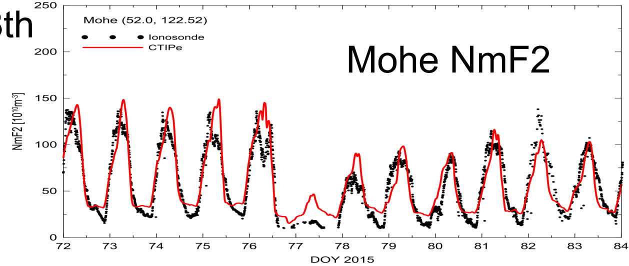


WAM Temperature March 17th



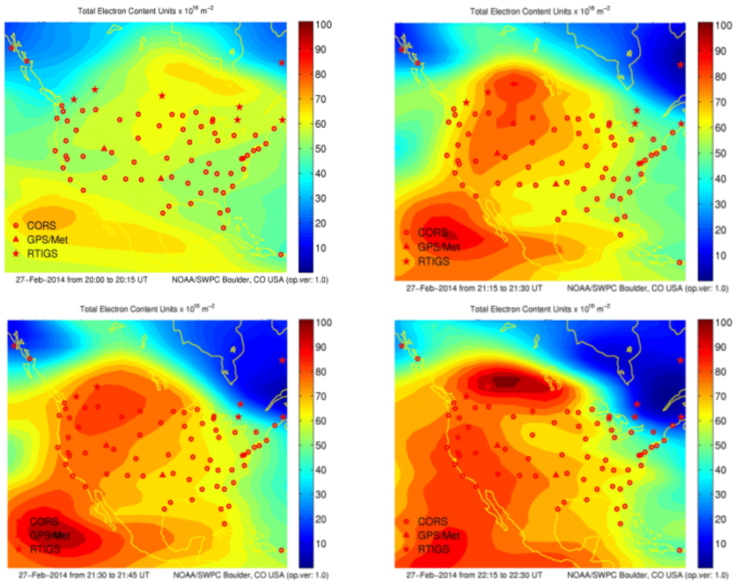
GUVI vs WAM O/N_2 March 18th



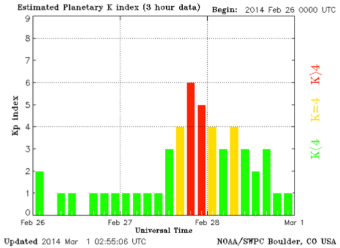


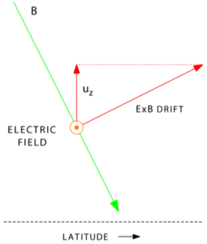
Upwelling → increased N_2 and faster loss rates at mid and high latitudes negative phase, Downwelling → decreased N_2 slower loss rates at low latitudes positive phase

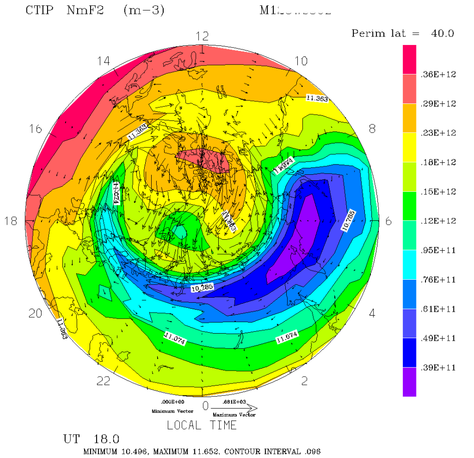
Positive phase -TEC response to expansion of magnetosphere convection (Rod Heelis)



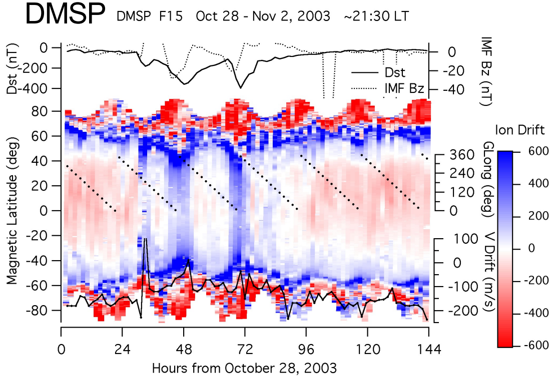
Response of SWPC US-TEC product to modest storm on Feb 27th 2014

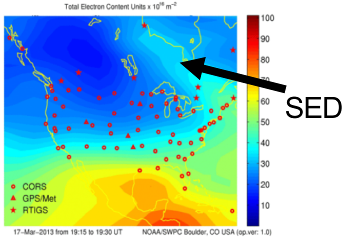






DMSP

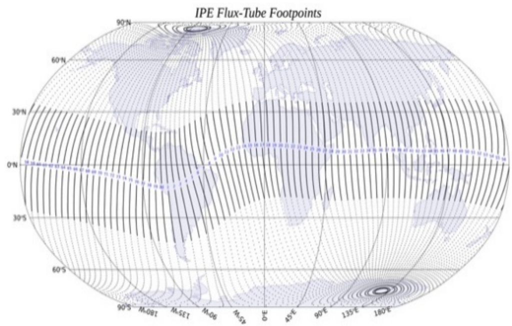


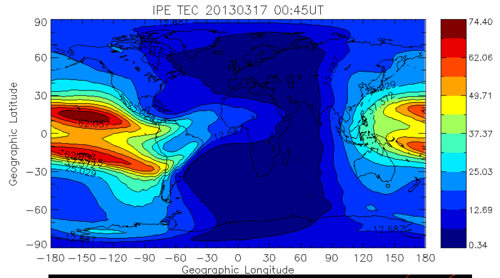


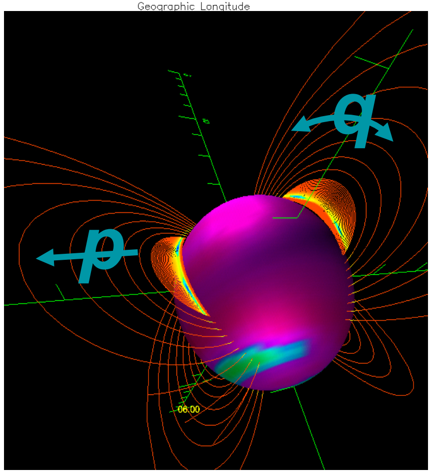
Walls of TEC:
compromises integrity of WAAS aviation navigation, 130 TEC units over 50 km, causes 20 meters of delay of GPS signals

Ionosphere-Plasmasphere-Electrodynamics Component

- Based on FLIP flux-tube model, Phil Richards (GMU), validated for > 20 years
  - Solves for ion species (O^+, H^+, He^+, NO^+, N_2^+, O_2^+, N^+), electron and ion temperature
  - Solve for photoelectron production, transport, and loss – source of secondary ionization, plasma heating, conjugate effects
  - Comprehensive photochemistry
  - Stable flux-preserving numerical scheme
  - Comprehensive neutral gas heating rates – when fed back to WAM
- Global Ionosphere-Plasmasphere-Electrodynamics configuration
  - Global seamless distribution of flux-tubes (see grid)
  - Perpendicular semi-Lagrangian ExB transport
  - Flexible resolution to match WAM T62
  - International Geomagnetic Reference Atmosphere and APEX coordinate system
  - Variable time-dependent polar cap boundary for plasma outflow and refilling
- Self-consistent global dynamo electrodynamics, Richmond/Maute
- ESMF 3-D re-gridding: information exchange between WAM and IPE
- MPI parallel processing

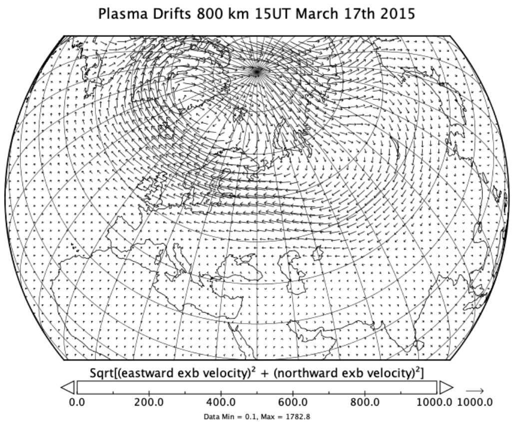


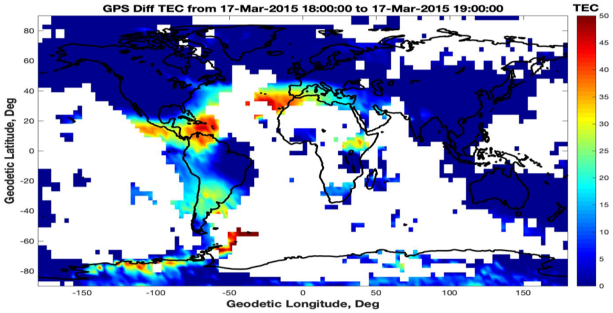


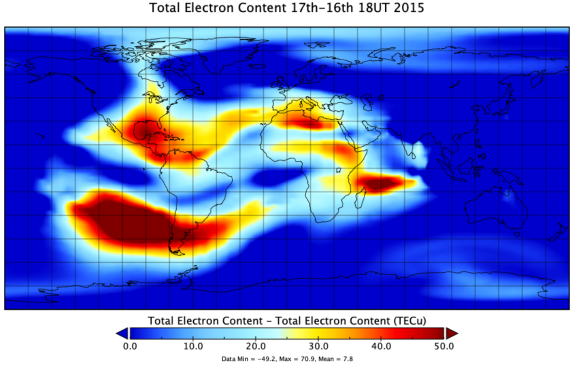


Plasma Drifts (COSMIC II IVM, DMSP)

A significant of driver storm-time TEC enhancement at mid-latitude
Needed to interpret irregularity metrics: ROTI, S4, and σ_φ



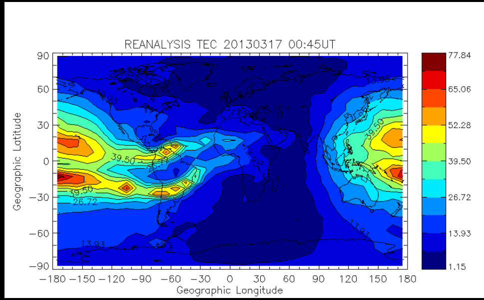


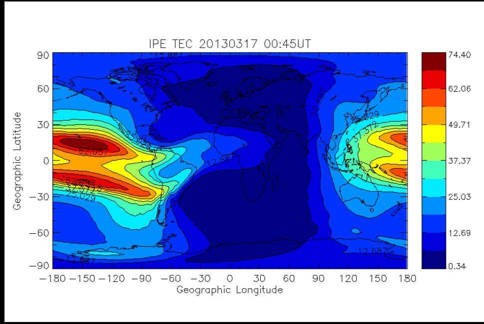


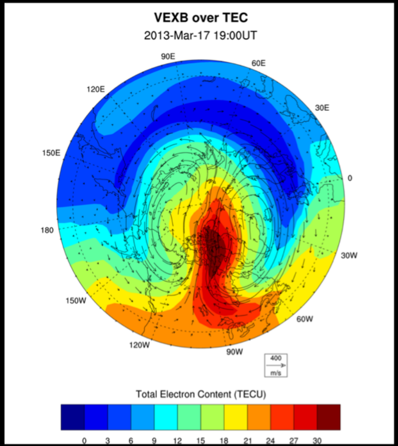
$$ROTI^2(\delta t) \sim \frac{c^2}{\delta t^2} C_p G \left[\frac{1}{2\pi} \frac{2\Gamma(3/2-\nu)}{\Gamma(\nu+1/2)(2\nu-1)2^{2\nu-1}} \right] \cdot \left| V_{eff}\, \delta t \right|^{2\nu-1}, \quad \tfrac{1}{2} < \nu < \tfrac{3}{2}$$

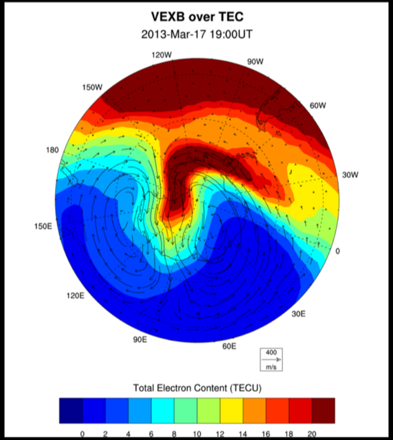
- Phase metrics (ROTI, σ_φ) depend on effective scan velocity to relate to intensity metric S_4 (Charlie Carrano and Keith Groves)

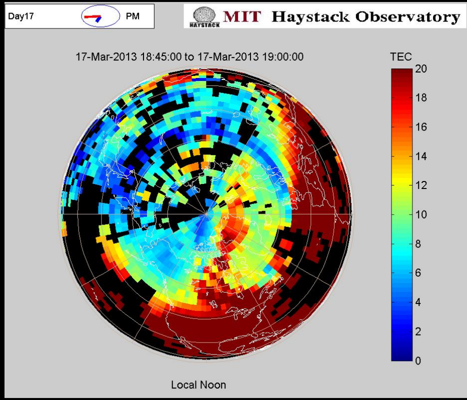
19UT March 17, 2013 North and South Hemisphere

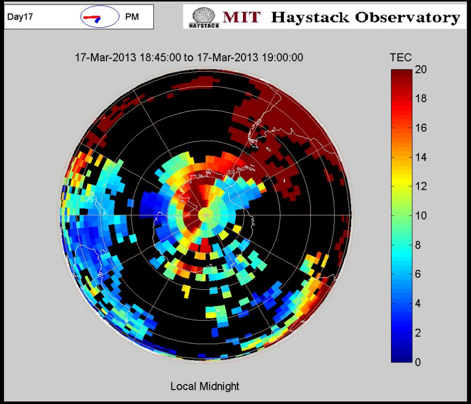






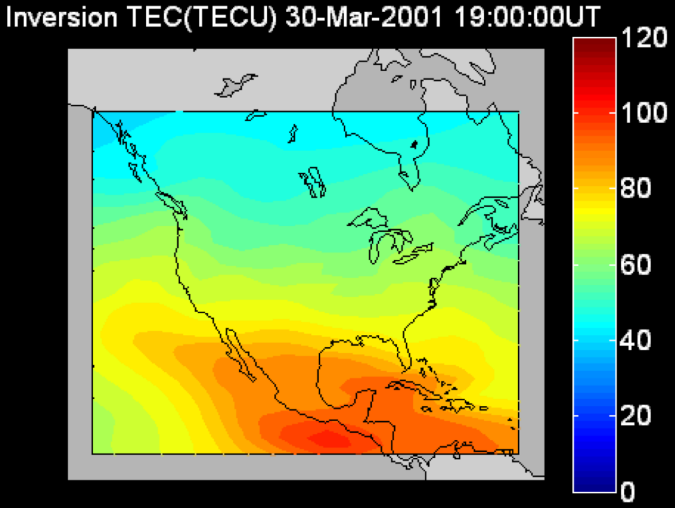




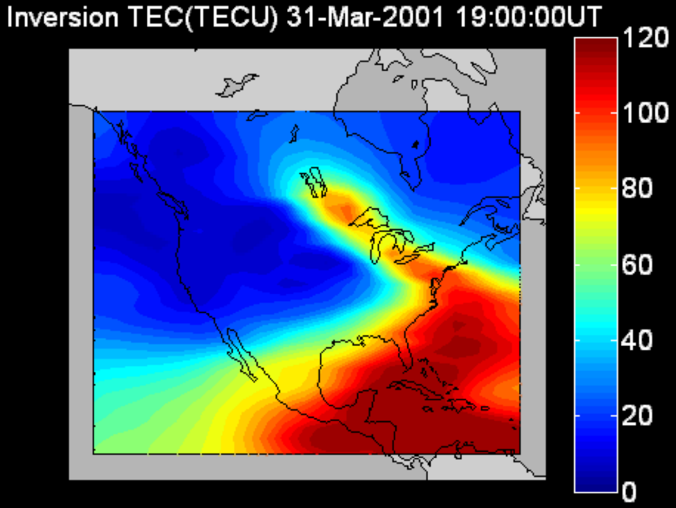


quiet initial conditions
Re-analysis vs IPE

Anthea Coster
TEC maps MIT



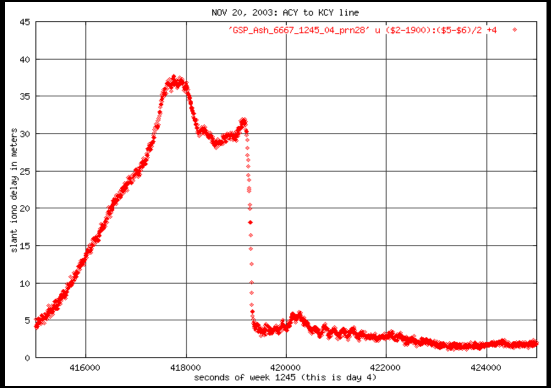
Quiet



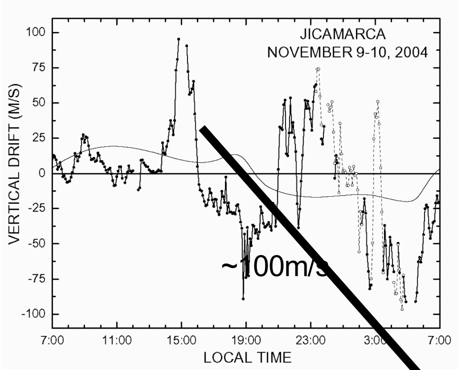
Disturbed

Storm Enhanced Density (SED)

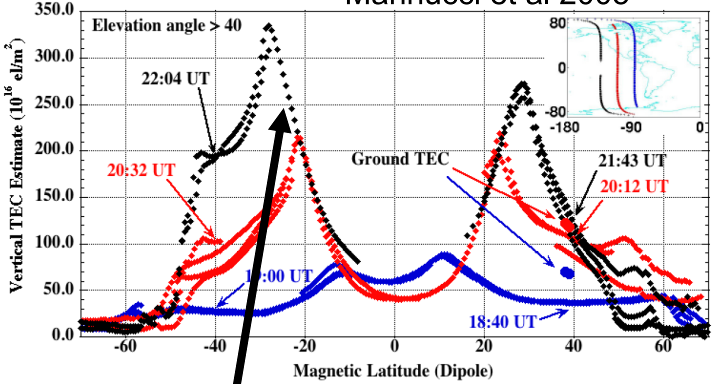
Impact on commercial aviation
Steep gradient at the “wall” of TEC
compromise integrity of navigation signals,
130 TEC units over 50 km, 20 m of GPS delay.
Outages of Wide Area Augmentation System (WAAS)



Ionospheric positive storms: Combination of poleward movement of Equatorial Ionospheric Anomalies (EIA) due to penetration electric field and build-up of mid-lat plasma by the Heelis effect



Mannucci et al 2005



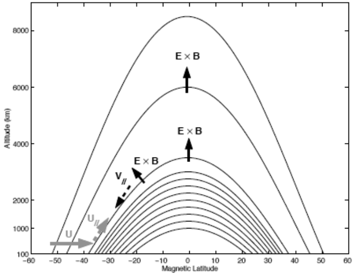


Figure 6. Schematic of the competing effect of the downward field-aligned diffusion and the upward movement of the plasma produced by an equatorward neutral wind at mid latitudes.

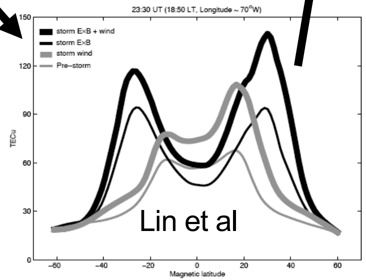
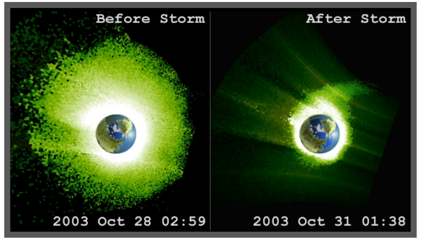
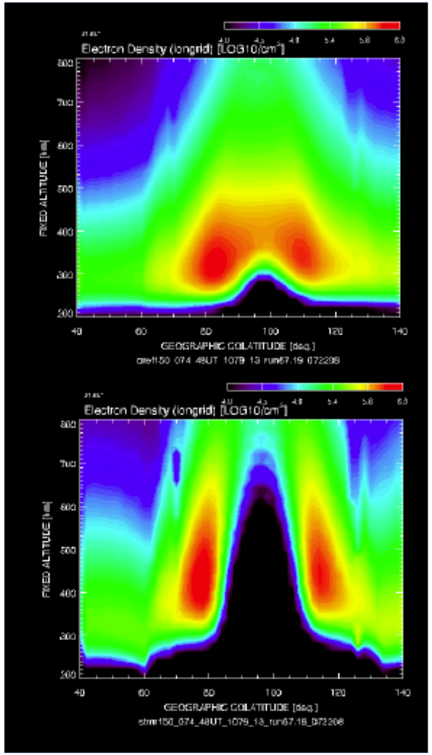


Figure 10. The total electron content (TEC) between altitudes 100 and 2000 km from the SUPIM results at 23:30 UT (18:50 LT) at -70° geographic longitude on the pre-storm day (thin gray line), case 1 (bold gray line), case 2 (thin black line), and the case 3 (bold black line).

Penetration electric field and vertical plasma drift at the magnetic equator



Plasma erosion



Storm-Time Electrodynamics: disturbance dynamo

Blanc and Richmond (1980) theory:

$$\mathbf{J} = \sigma (\mathbf{E} + \mathbf{V_n} \times \mathbf{B})$$

$$\nabla \cdot \mathbf{J} = 0 \qquad E = - \nabla \Phi$$

- Equatorward winds drive zonal winds at mid-latitude through the action of the Coriolis force
- Zonal winds → equatorward Pedersen current
- Equatorward wind → equatorward Hall current
- Positive charge builds up at the equator producing a poleward directed electric field which balance the wind driven equatorward current
- Eastward Hall current causes +ve charge build up at the dusk terminator and -ve charge build-up at dawn
- Reverse S_q

$$J_{\vartheta u} = -\frac{\sigma_1}{\sin I} u_\phi B + \sigma_2 u_\theta B$$

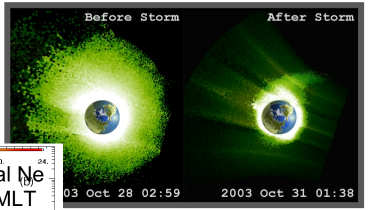
$$J_{\phi u} = \sigma_1 \sin I u_\theta B + \sigma_2 u_\phi B$$

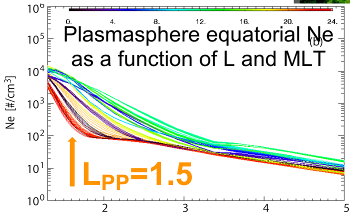
$$J_{\theta E} = \frac{\sigma_1}{\sin I} E_\varepsilon + \frac{\sigma_2}{\sin I} E_\phi$$

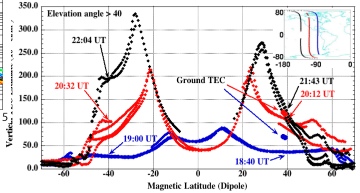
$$J_{\phi E} = -\sigma_2 E_\varepsilon + \sigma_1 E_\phi$$

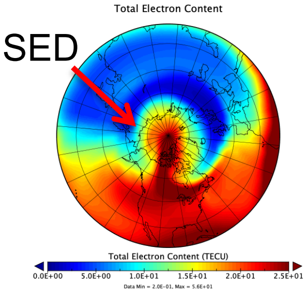
Ionospheric Storm Response

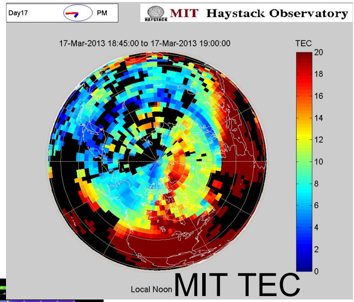
- The erosion of plasma from the expanded convection and movement of the polar cap (open/closed) boundary equatorward
- A build up of plasma can occur at mid-latitude, possibly with storage in the topside ionosphere and plasmasphere and aided by equatorward neutral winds
- The plasma build up is associated with the development of the SED feature, characterized by the tongues of ionization transported towards the magnetic poles
- “Negative phases” from the change in thermospheric neutral composition
- Poleward movement of equatorial ionization anomaly by low latitude penetration and dynamo electric fields



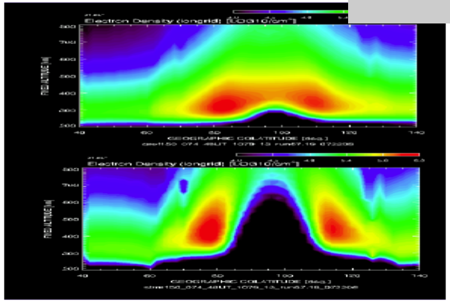








Anthea Coster

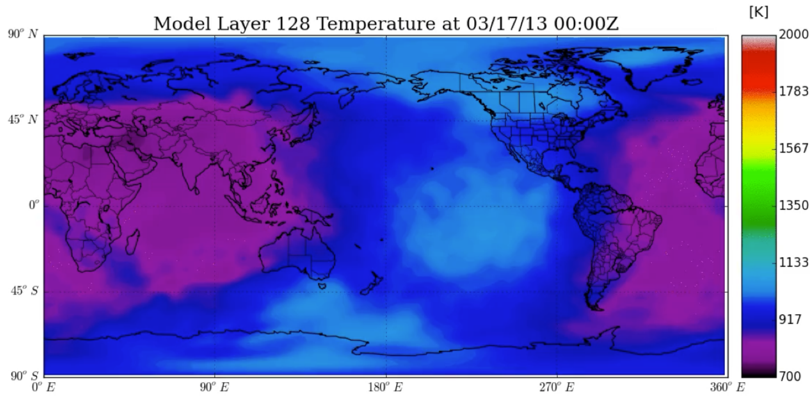


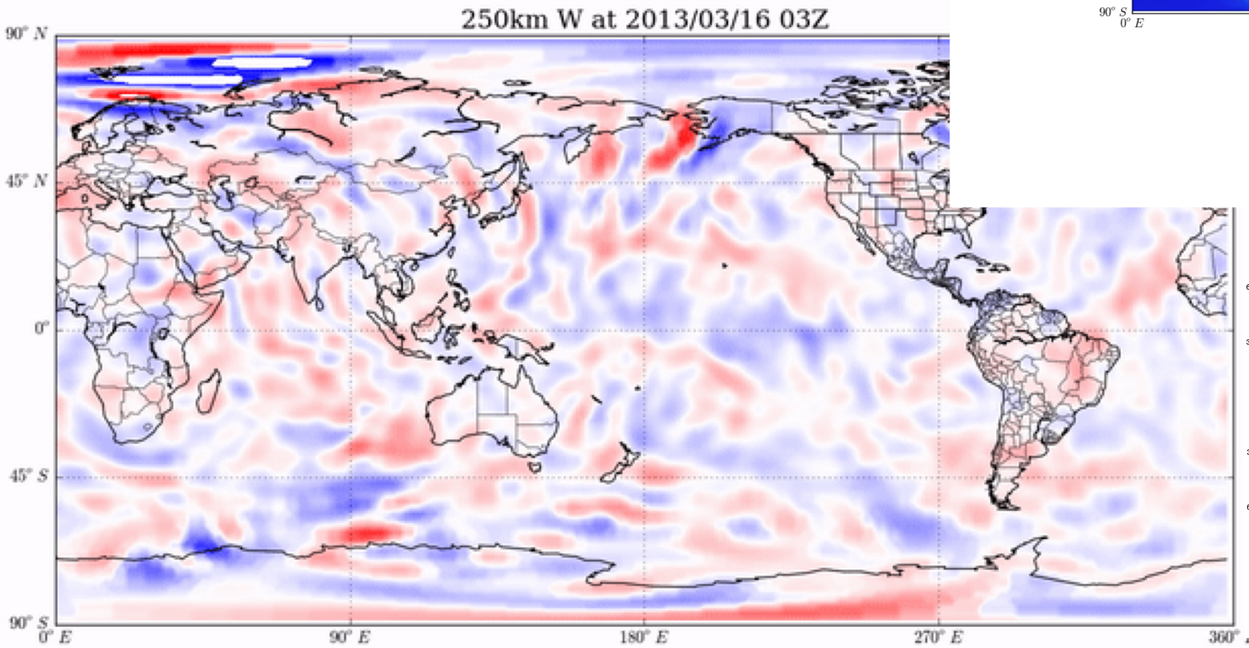
EIA

Drivers of Space Weather in the Upper Atmosphere

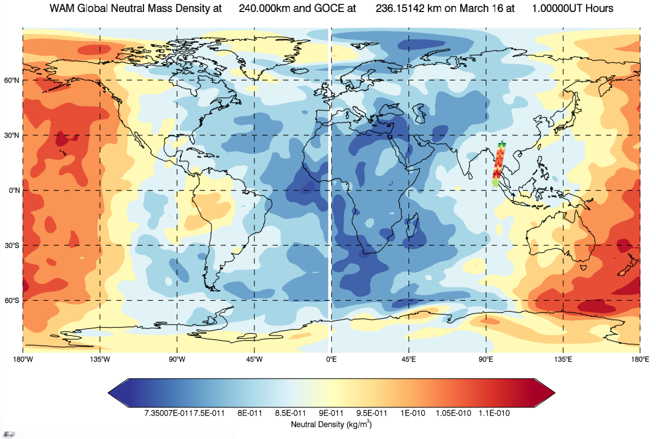
- Solar flares
- Solar Proton Events
- Solar Radio Bursts
- Geomagnetic storms driven by coronal mass ejections or corotating interaction regions
- Waves propagating from the lower atmosphere

Structure and variability of vertical wind, temperature, and density at 250 km altitude in response to waves from lower atmosphere





Neutral temperature (above)
neutral density (below)
250km altitude



Four peak longitude structures in the ionosphere

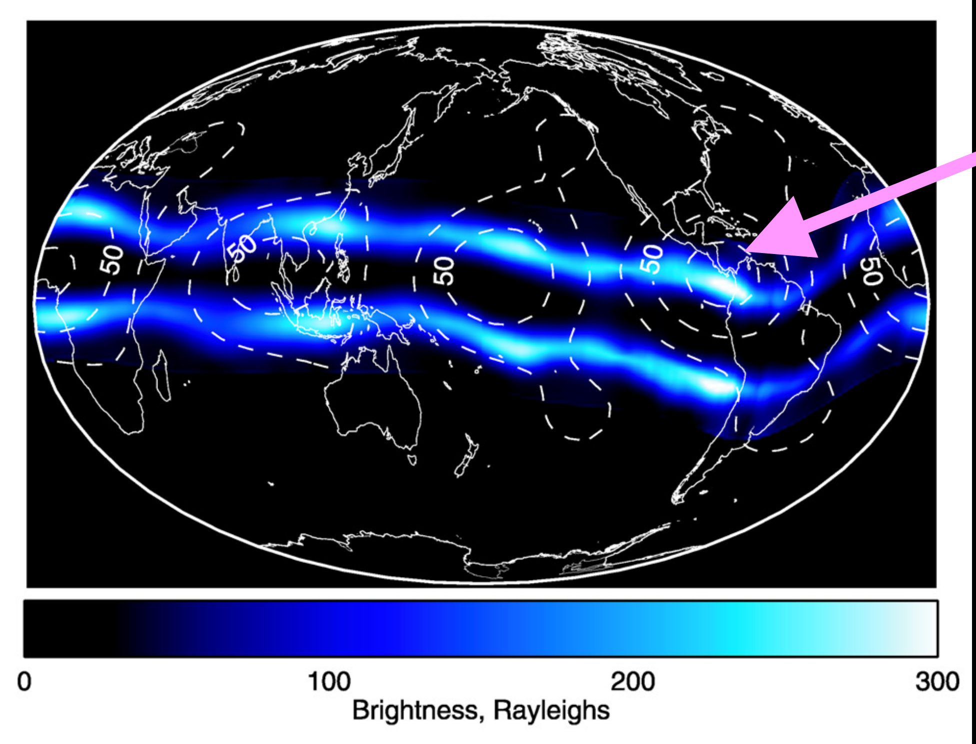
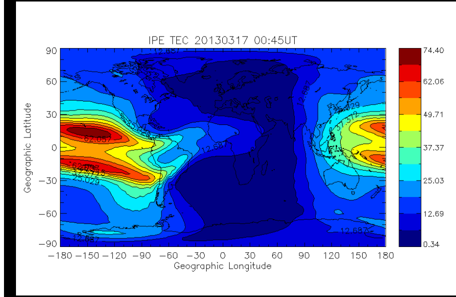
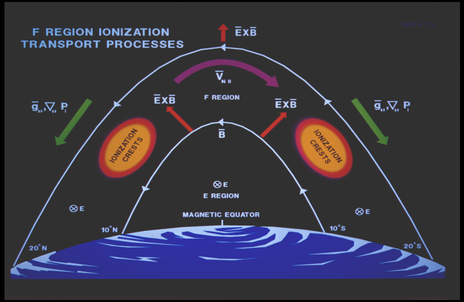


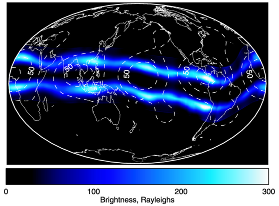
IMAGE composite of 135.6-nm O airglow (350–400 km) in March–April 2002 for 20:00 LT and amplitude of modeled diurnal temperature oscillation @ 115 km (Immel et al., 2006).

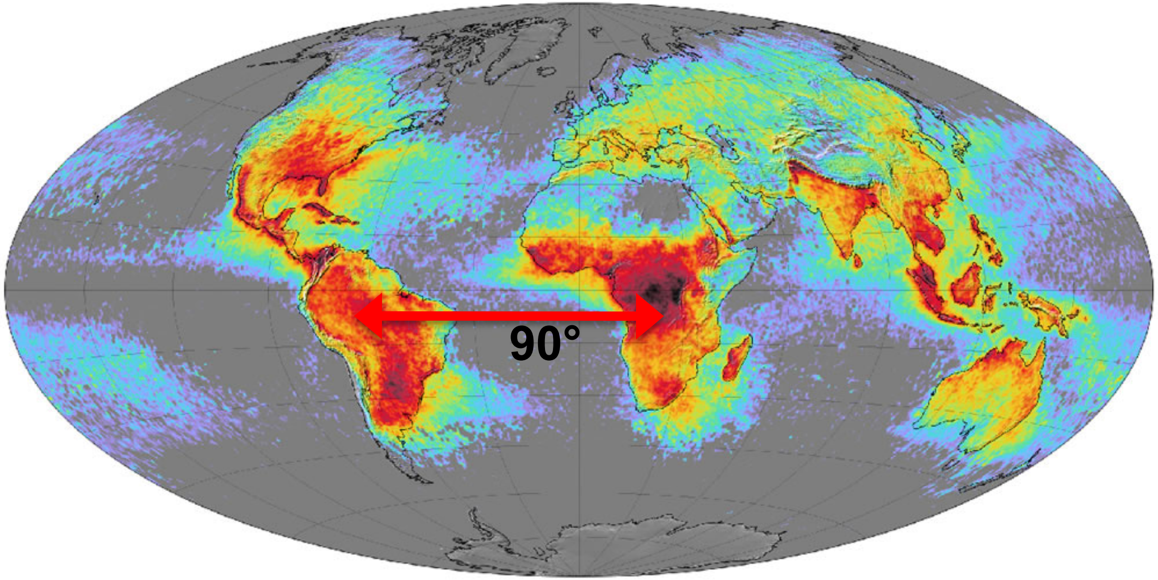
The four peaks driven by nonmigrating eastward propagating tidal mode with zonal wavenumber 3 (DE3) in dynamo region.





Driver of the Immel longitude structure





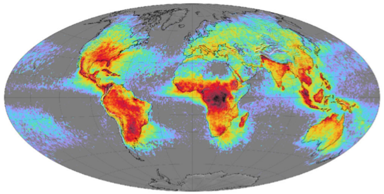
Lightning strikes from convective storms, signature of latent heat release:
Either three or four peaks in longitude: wave 3 or 4
Illuminated by the Sun every 24 hours: diurnal

$$\cos(\Omega t + \lambda)\cos 4\lambda \quad \text{--->} \quad \cos(\Omega t + 5\lambda) + \cos(\Omega t - 3\lambda)$$

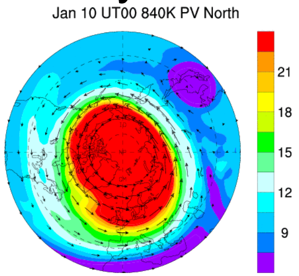
$$\cos(\Omega t + \lambda)\cos 3\lambda \quad \text{--->} \quad \cos(\Omega t + 4\lambda) + \cos(\Omega t - 2\lambda)$$

Can create a diurnal eastward propagating W2 or W3 DE2 and DE3

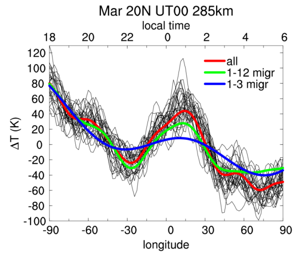
Sources from the Lower Atmosphere



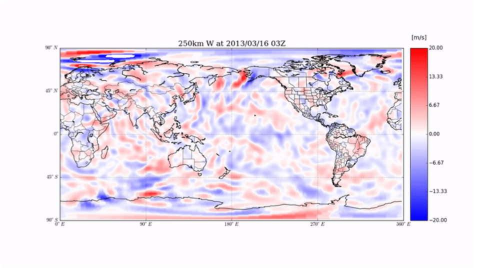
- Longitude structure of tropical convection modulates non-migating tidal modes (DE3, DE2), which drive winds and electrodynamics in lower thermosphere dynamo region



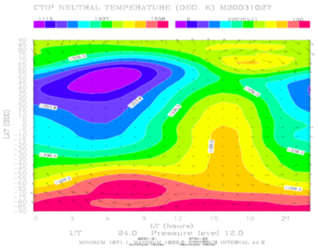
- Changes in stratospheric circulation (e.g., sudden stratospheric warmings) modulating semi-diurnal migrating tidal modes, which also drive electrodynamics



- Midnight temperature and density maxima (MTM, MDM) modulates temperature and density structure, wind reversals, and direct impact on F-region ionosphere



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

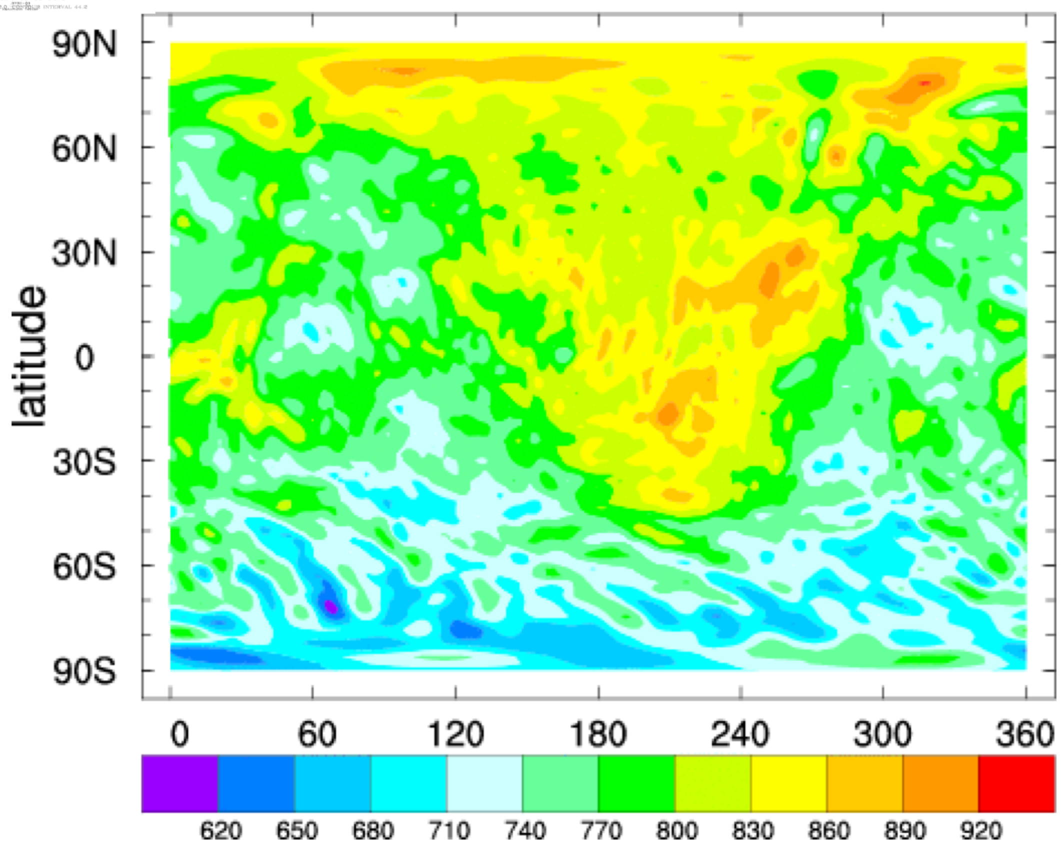


…is this reality?

Sep 03 UT00:00 200km WAM T

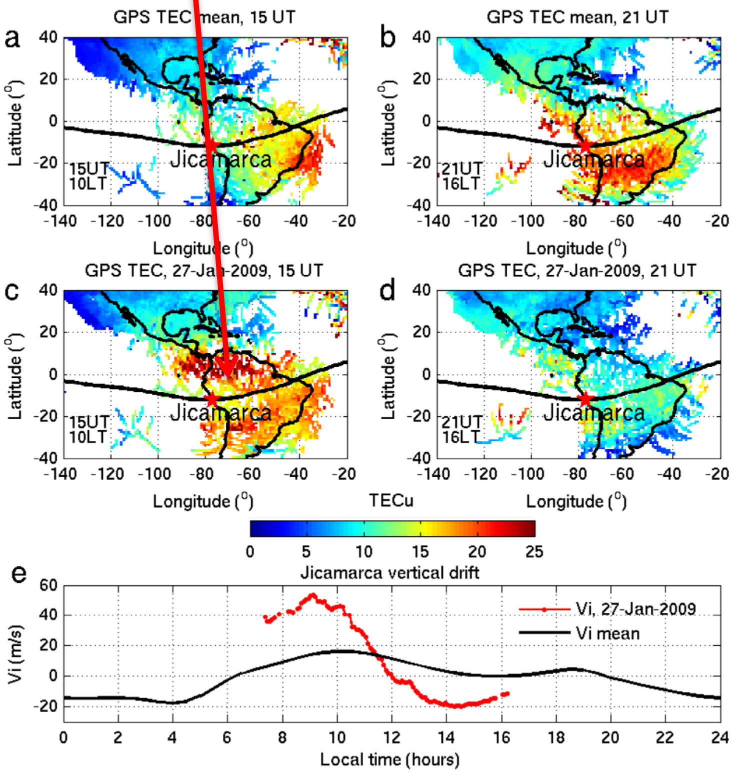
Temperature 200 km altitude

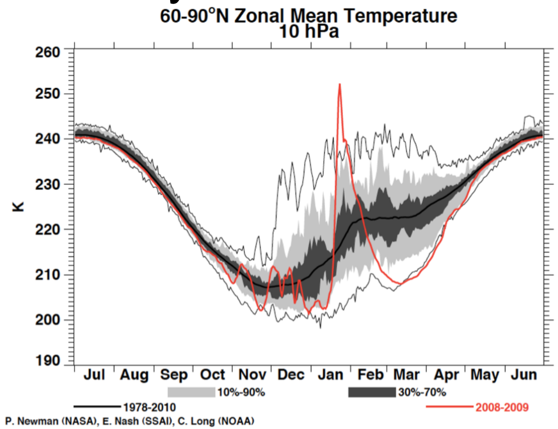
…or is it this ?

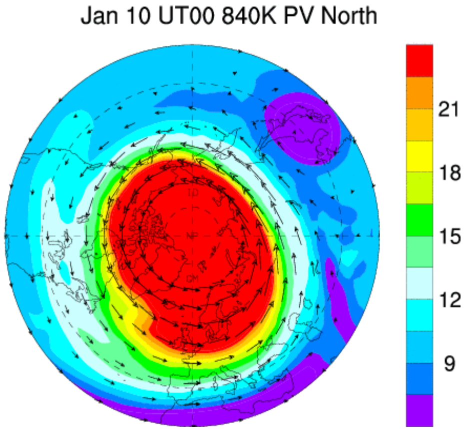


50% increase in TEC in January 2009 when solar and geomagnetic activity were very low

Goncharenko et al. 2010







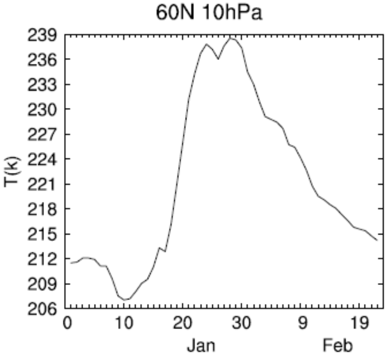
Is this also a response to changing tidal amplitudes?

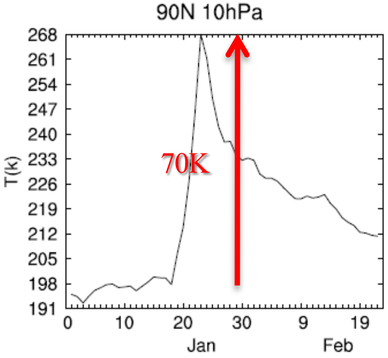
Sudden stratospheric warming

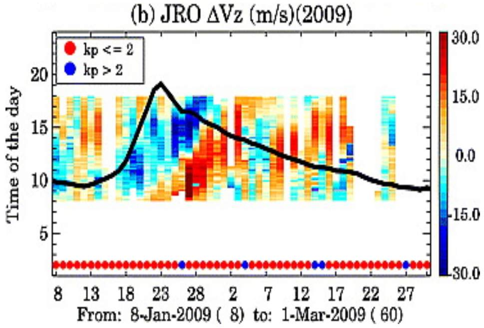
Benefits of WAM

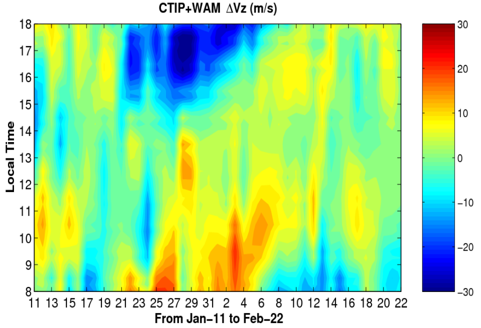
- Compatible with the US weather model already running operationally
- Can implement the operational Gridpoint Statistical Interpolation (GSI) data assimilation system, utilizing the lower atmosphere data
- Able to follow real lower atmosphere weather events and their impact on the upper atmosphere and ionosphere (such as hurricanes, tornados, planetary waves, sudden stratospheric warming, tropical convection, longitude structure in migrating and non-migrating tides)

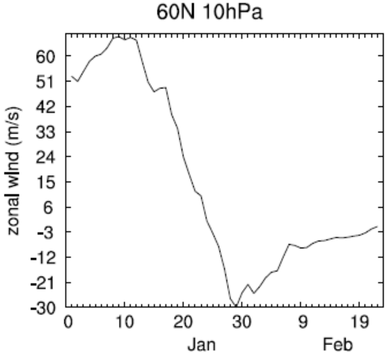
WAM simulations of the January 2009 sudden stratospheric warming

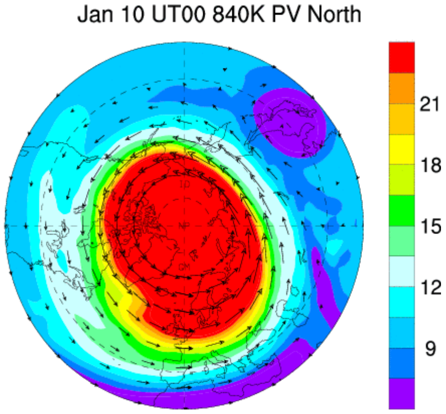


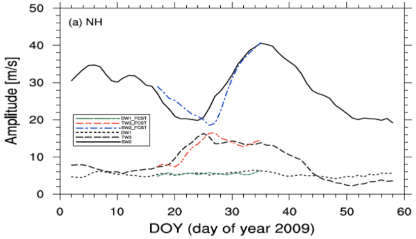






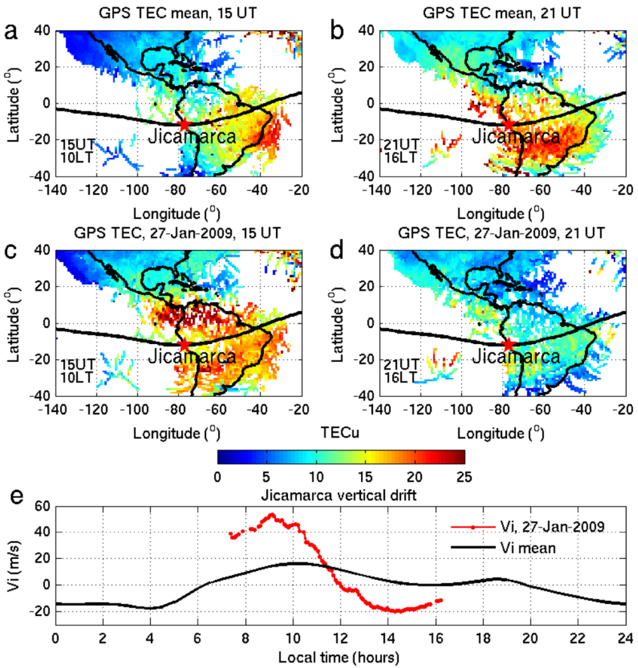






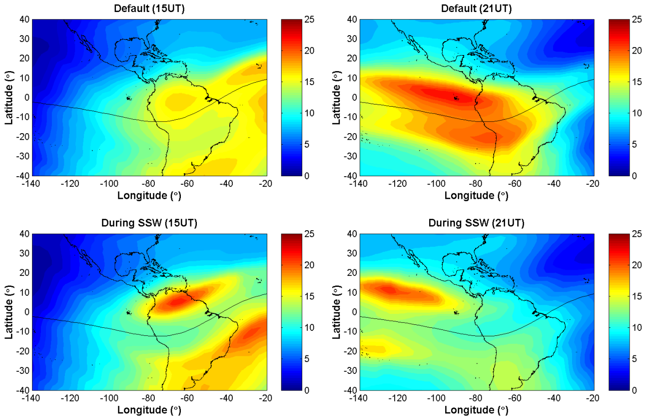
January 2009 Stratospheric Warming impact on EIA

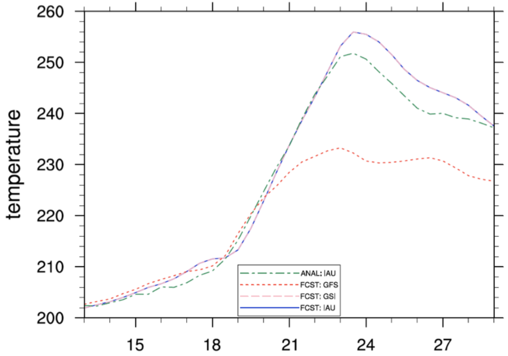
GPS-TEC observation
before and after SSW
Goncharenko et al. (2010)



SSW vertical plasma drift
Jicamarca (Chau et al., 2010)

WAM-GIP
before and after SSW



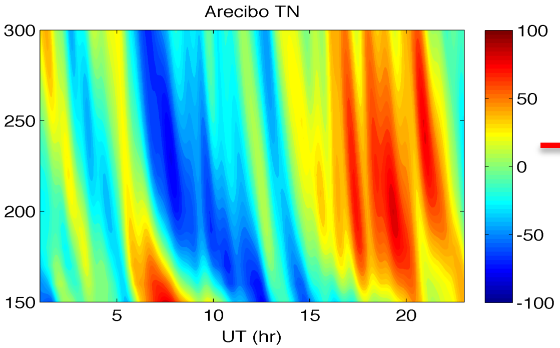


Can be forecast more than a week ahead

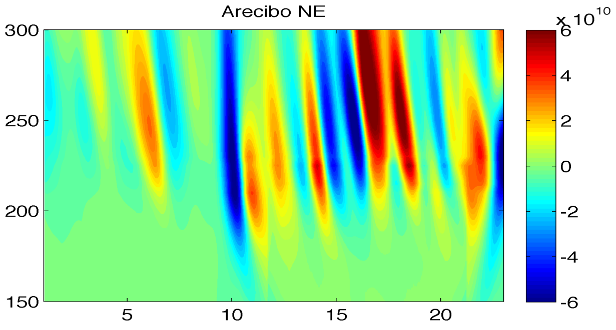
Use WAM winds, composition, density to drive GIP plasma density

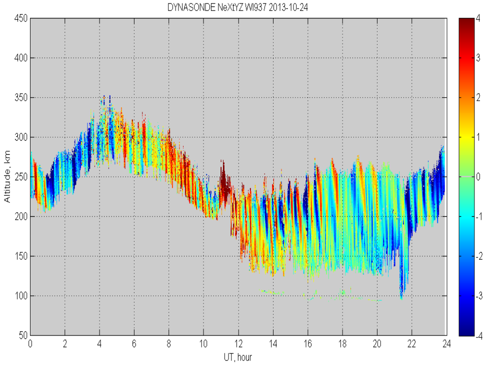
- agrees well with Arecibo ISR observations by Djuth et al. -

WAM temperature perturbations at Arecibo

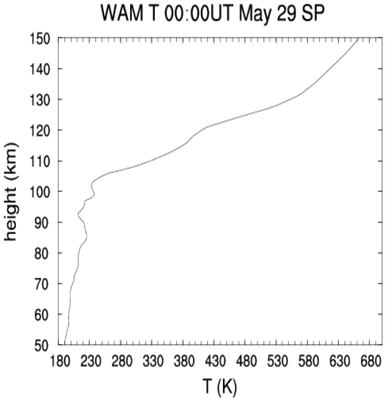


WAM-GIP ~20% plasma density perturbations at Arecibo

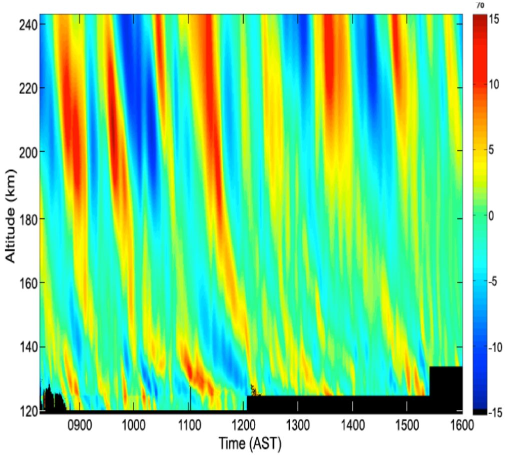




Dynasonde - vertical velocity and tilts, Nikolay Zabotin

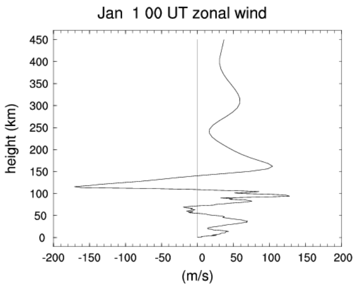


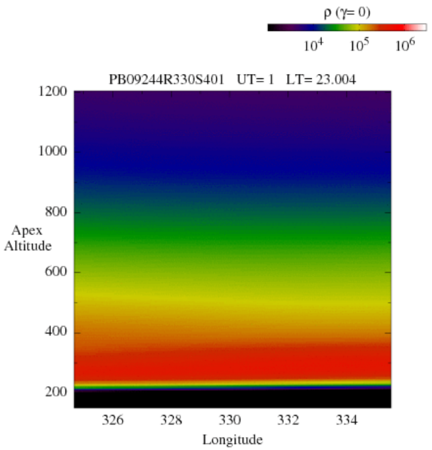
WAM temperature

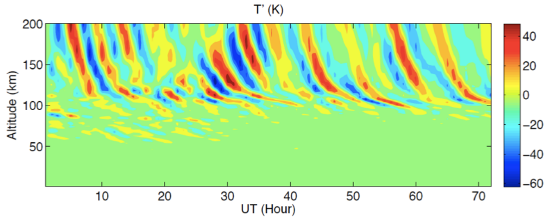


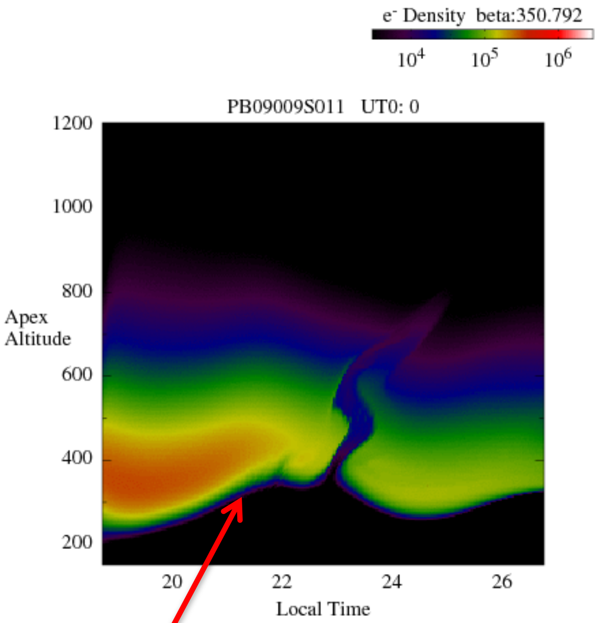
De-trended ISR observations of N_e perturbations, Djuth et al.

Bubble development in physics-based irregularity model (PBMOD) with WAM fields (180 km horizontal. resolution, ¼ scale-height vertical, ~2-5km) with no additional seeding Retterer et al.

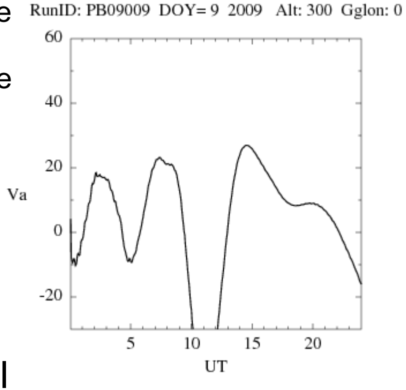




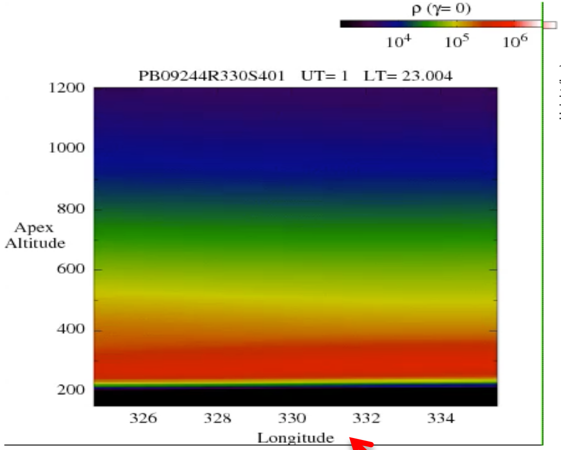




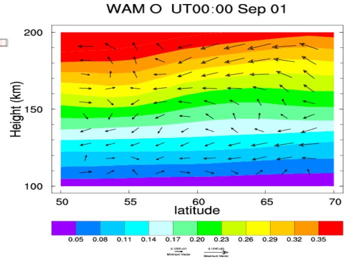
forecasting large scale wave structure, (LSWS) on bottomside

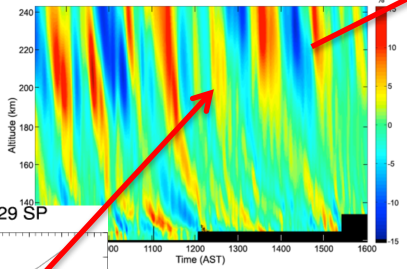


Waves propagate from tropospheric sources through the atmosphere

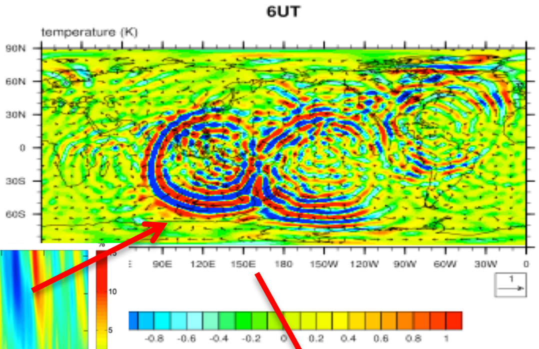


WAM fields spawn ionospheric irregularities with no additional seeding Retterer, Boston College

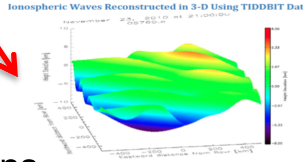


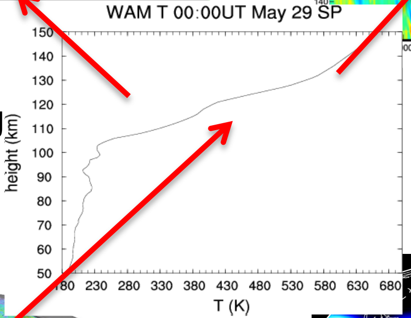


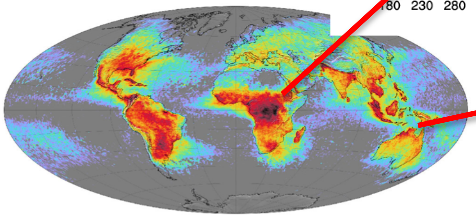
Arecibo Ne perturbations Djuth et al.

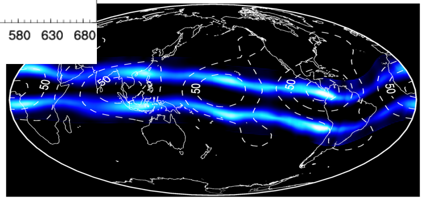


Tropospheric sources drive concentric circle waves in neutral winds, temperature and plasma density



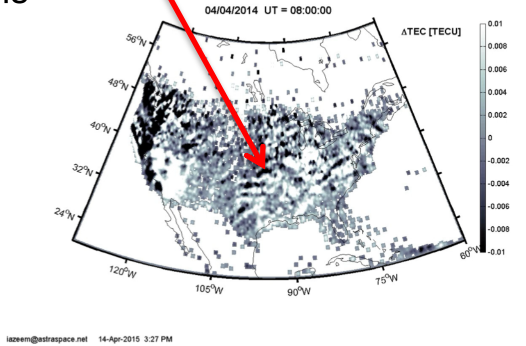






Tropical convection drives plasma longitude structure

Observations: TEC Perturbations undulations in plasma



Azeem et al. 2015

New Theories for Phase and Intensity Metrics

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

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

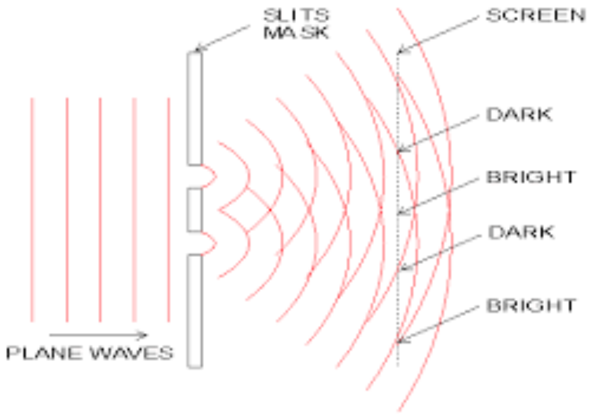
(Carrano et al., 2019)

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

(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 $\rho_F = \sqrt{\lambda z_R \sec\theta / (2\pi)}$
- Γ – gamma function

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

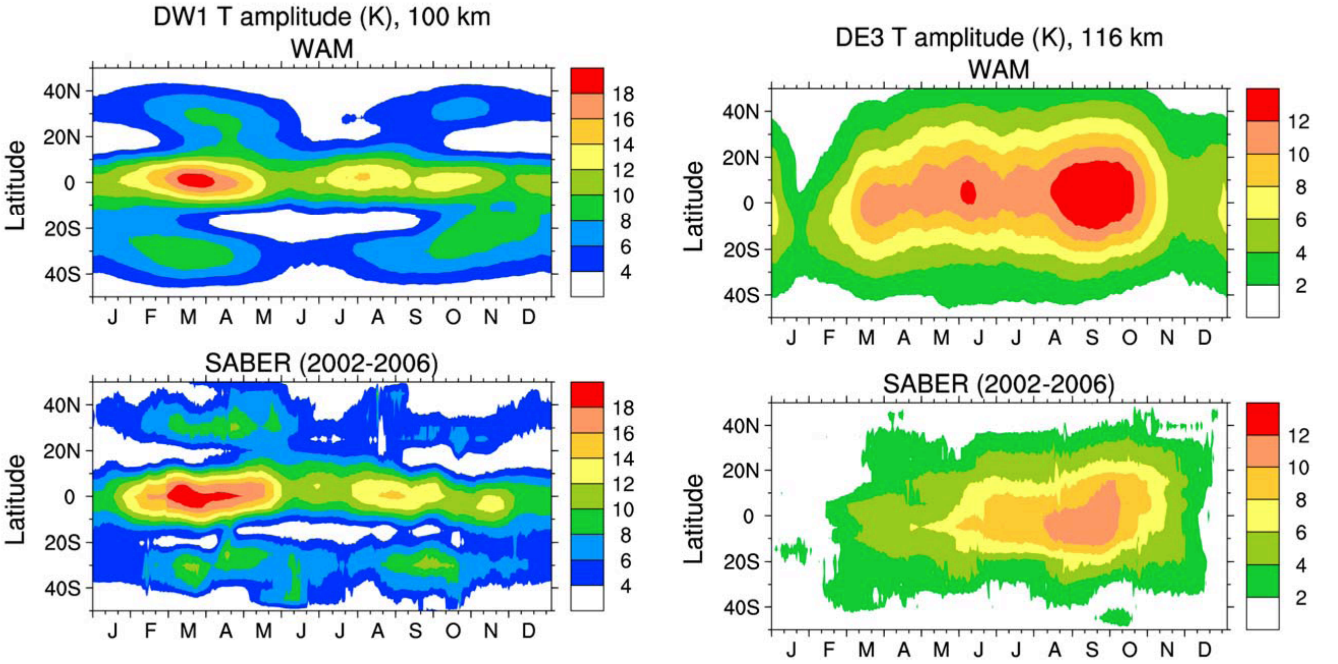
Summary and Conclusion

- The thermosphere and ionosphere is end point of much of the solar and magnetospheric forcing of space weather, and the host of many of the impacts on operational systems (e.g., HF propagation, satellite drag, satellite communication and navigation)
- Space weather can also be driven from the chaotic lower atmosphere – a new paradigm in space weather

- Questions?
- Email tim.fuller-rowell@noaa.gov

WAM agrees well with the diurnal migrating tide DW1 and the famous DE3

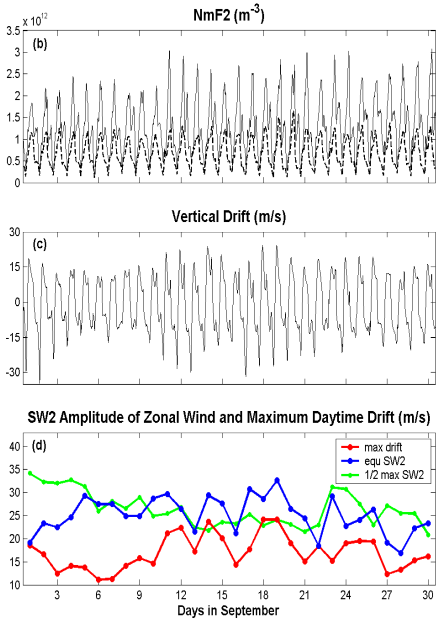
WAM model top: Akmaev et al. 2008

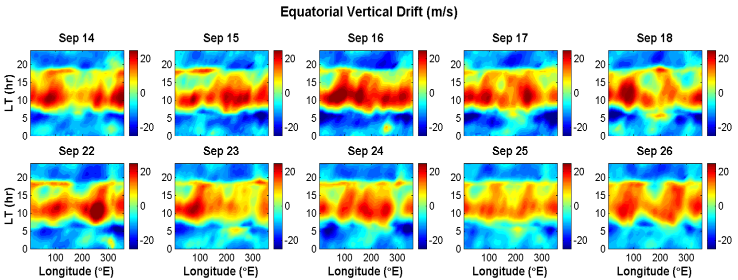


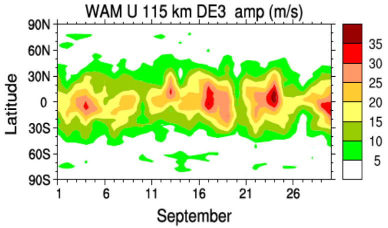
DW1 SABER observations below: Forbes et al. 2008 DE3

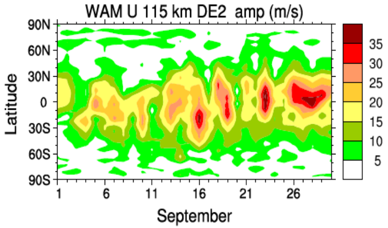
Example of impact of tidal variability

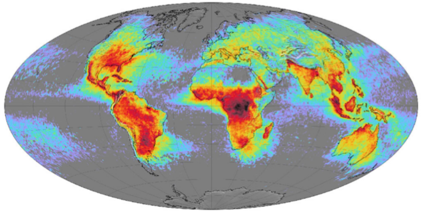
Tzu-Wei Fang et al. 2013 from WAM-GIP model simulation

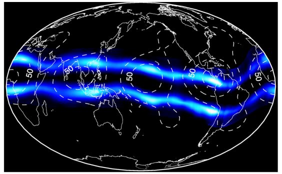










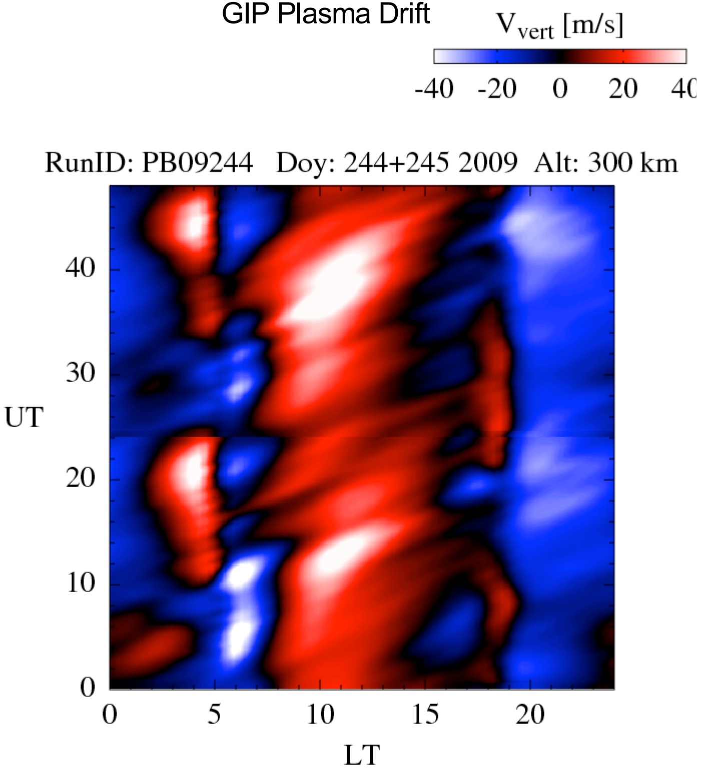


Modulation of semi-diurnal tide SW2 correlates with increases in peak vertical plasma drift and N_mF2

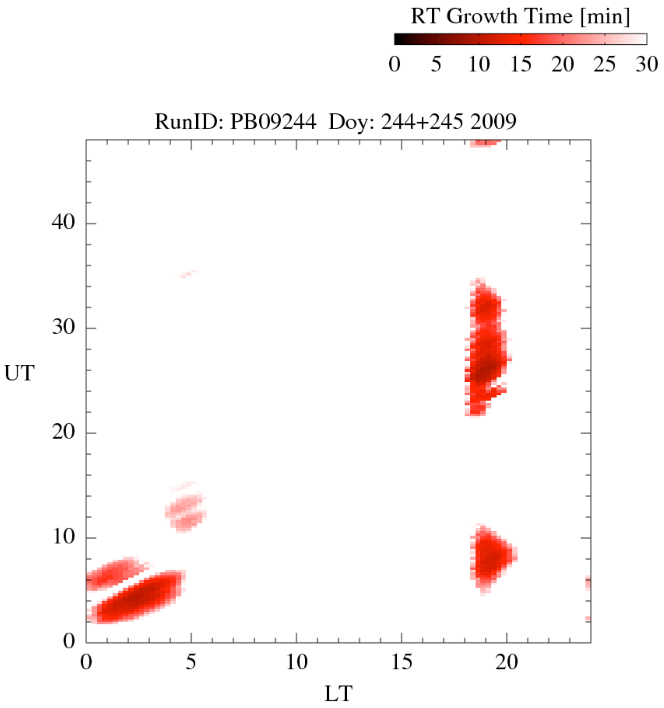
Modulation of DE3 and DE2 tidal amplitudes correlates with number of peaks in longitude structure of vertical plasma drift

Variability of Electrodynamics

GIP Plasma Drift



RT Growth Timescale



Days 244 and 245