Upper Atmosphere and Ionosphere Forecast

Tzu-Wei Fang

NOAA Space Weather Prediction Center

Space Weather

Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-based and ground-based technological systems, as well as endanger life or health. Just like weather on Earth, space weather has its seasons, with solar activity rising and falling over an approximate 11 year cycle.

Sunspots

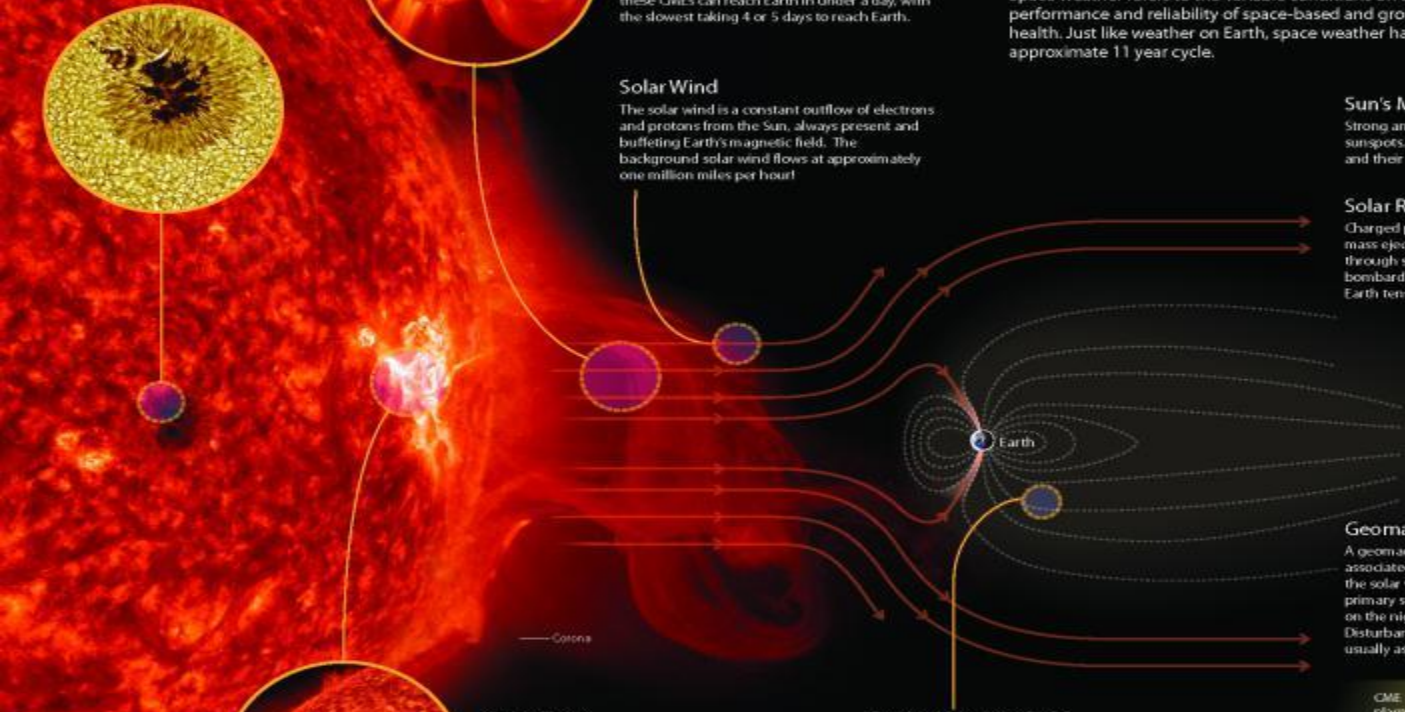
Sunspots are comparatively cool areas at up to 7,700° F and show the location of strong magnetic fields protruding through what we would see as the Sun's surface. Large, complex sunspot groups are generally the source of significant space weather.

Coronal Mass Ejections (CMEs)

Large portions of the corona, or outer atmosphere of the Sun, can be explosively blown into space, sending billions of tons of plasma, or superheated gas, Earth's direction. These CMEs have their own magnetic field and can slam into and interact with Earth's magnetic field, resulting in geomagnetic storms. The fastest of these CMEs can reach Earth in under a day, with the slowest taking 4 or 5 days to reach Earth.

Solar Wind

The solar wind is a constant outflow of electrons and protons from the Sun, always present and buffeting Earth's magnetic field. The background solar wind flows at approximately one million miles per hour!



Sun's Magnetic Field

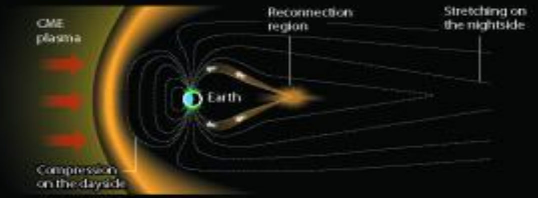
Strong and ever-changing magnetic fields drive the life of the Sun and underlie sunspots. These strong magnetic fields are the energy source for space weather and their twisting, shearing, and reconnection lead to solar flares.

Solar Radiation Storms

Charged particles, including electrons and protons, can be accelerated by coronal mass ejections and solar flares. These particles bounce and gyrate their way through space, roughly following the magnetic field lines and ultimately bombarding Earth from every direction. The fastest of these particles can affect Earth tens of minutes after a solar flare.

Geomagnetic Storms

A geomagnetic storm is a temporary disturbance of Earth's magnetic field typically associated with enhancements in the solar wind. These storms are created when the solar wind and its magnetic field interacts with Earth's magnetic field. The primary source of geomagnetic storms is CMEs which stretch the magnetosphere on the nightside causing it to release energy through magnetic reconnection. Disturbances in the ionosphere (a region of Earth's upper atomosphere) are usually associated with geomagnetic storms.



Solar Flares

Reconnection of the magnetic fields on the surface of the Sun drive the biggest explosions in our solar system. These solar flares release immense amounts of energy and result in electromagnetic emissions spanning the spectrum from gamma rays to radio waves. Traveling at the speed of light, these emissions make the 93 million mile trip to Earth in just 8 minutes.

Earth's Magnetic Field

Earth's magnetic field, largely like that of a bar magnet, gives the Earth some protection from the effects of the Sun. Earth's magnetic field is constantly compressed on the day side and stretched on the night side by the ever-present solar wind. During geomagnetic storms, the disturbances to Earth's magnetic field can become extreme. In addition to some buffering by the atmosphere, this field also offers some shielding from the charged particles of a radiation storm.

NOAA Space Weather Prediction Center – www.spaceweather.gov

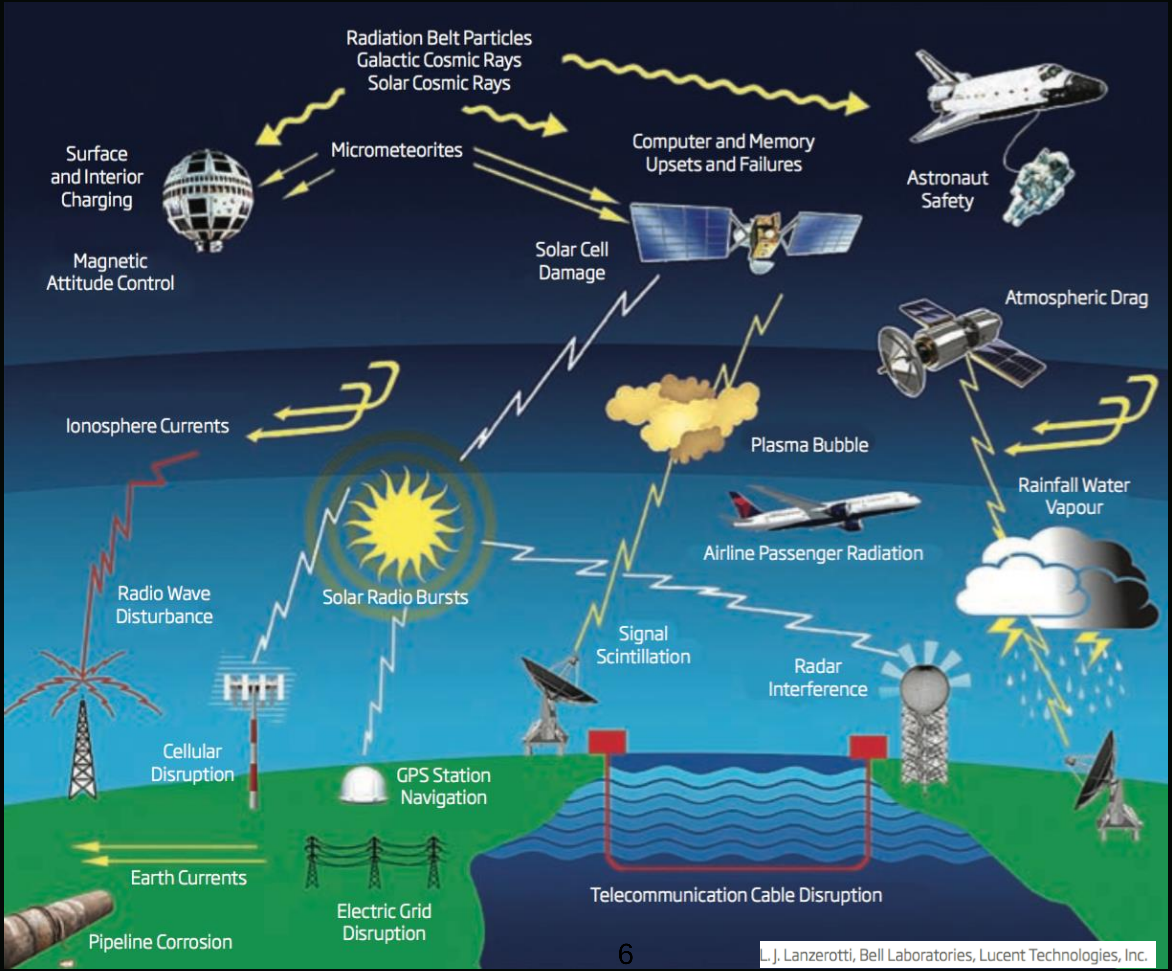
Source images: NASA, NOAA.

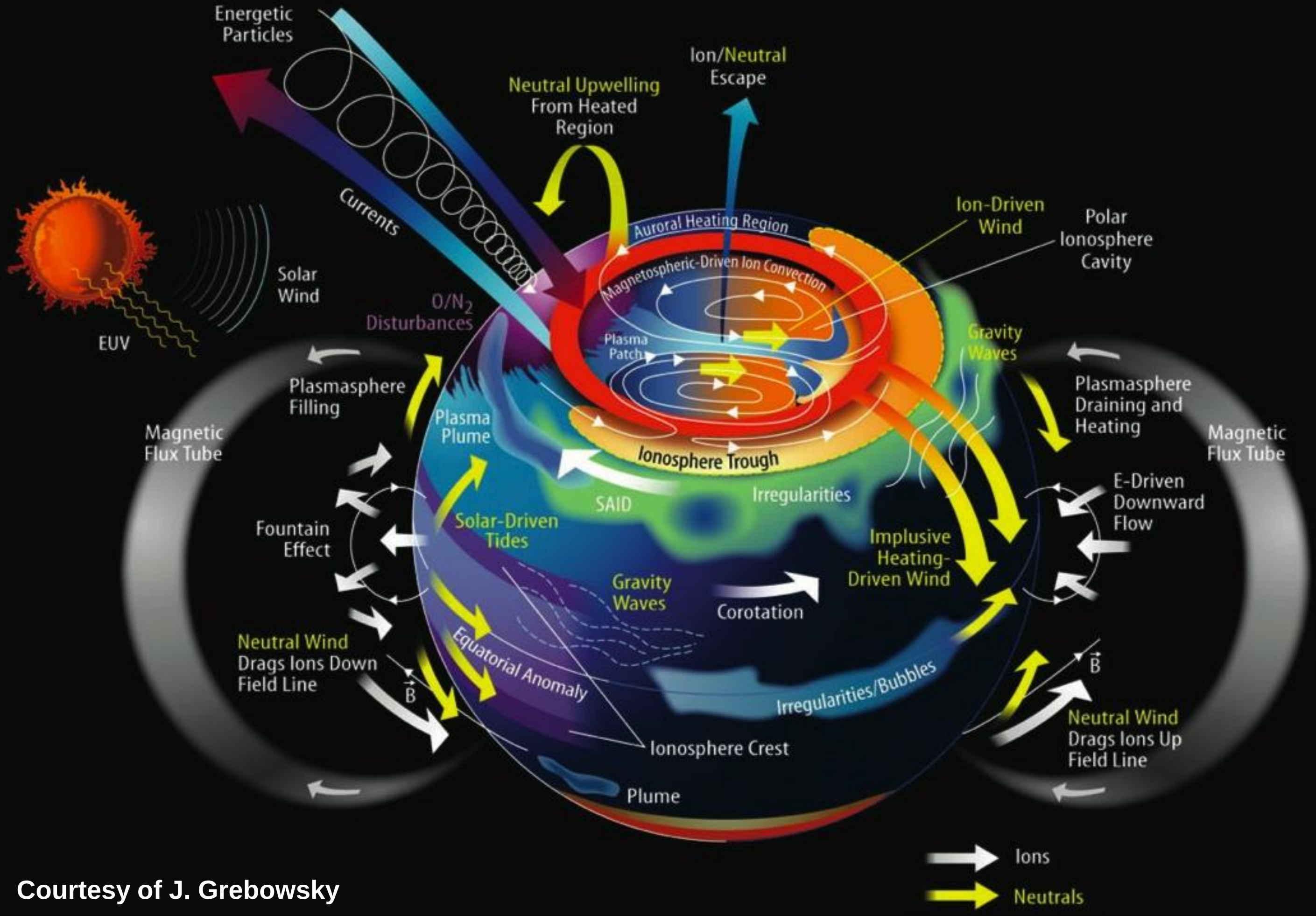
Space Weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.

The Only Way to See Space Weather

Colors of the Aurora

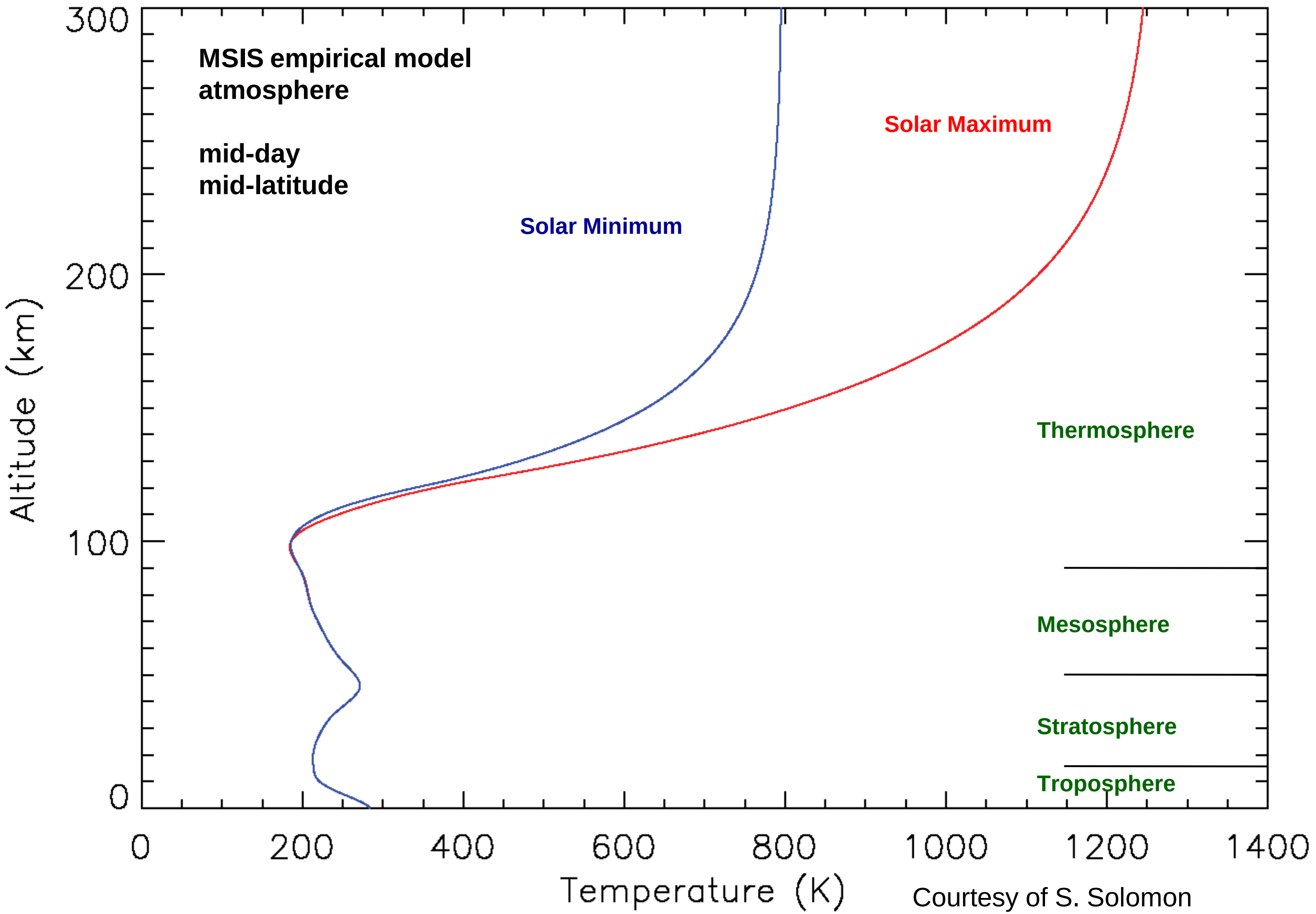
Impact of Space Weather





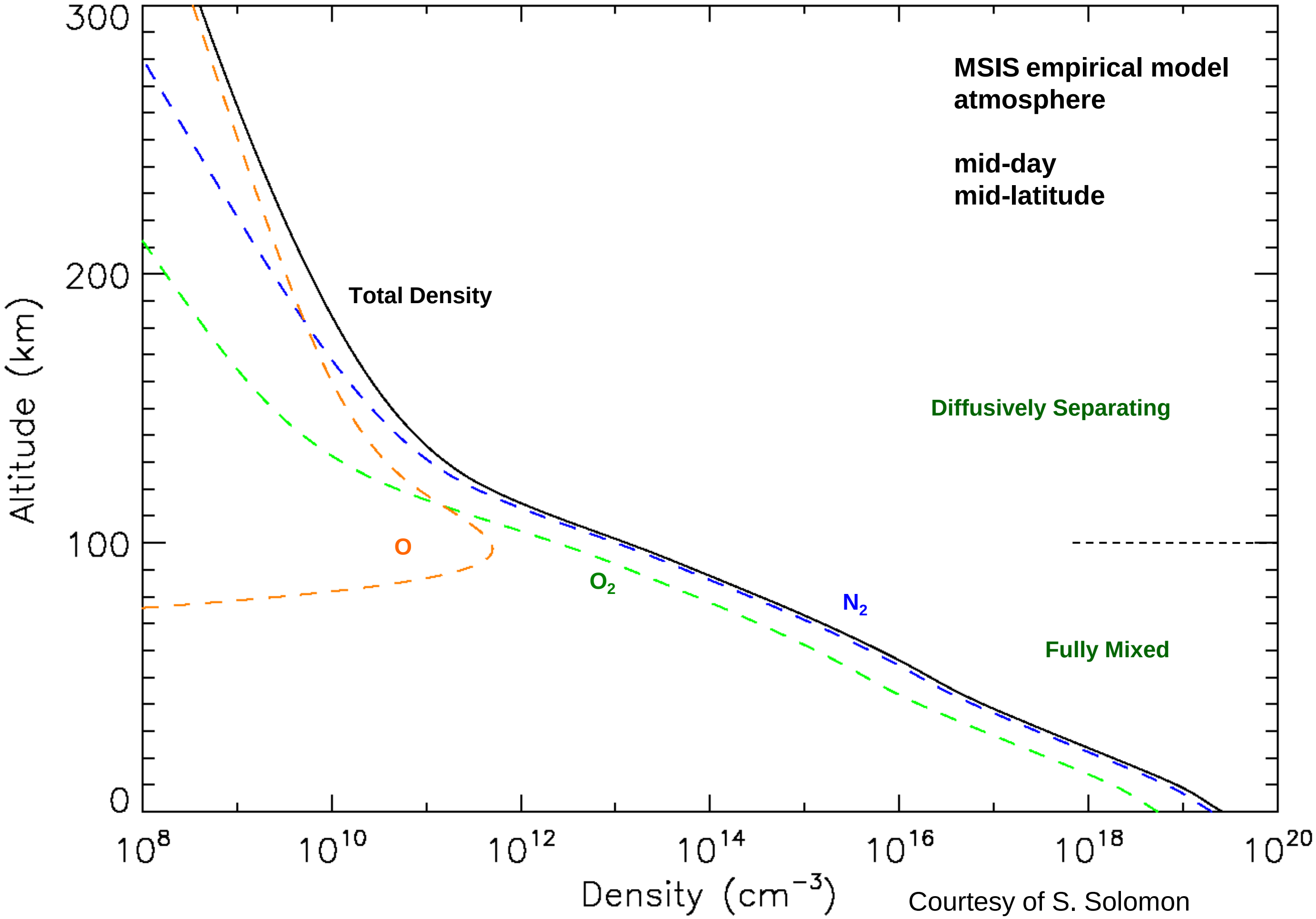
Courtesy of J. Grebowsky

Temperature Structure of the Atmosphere



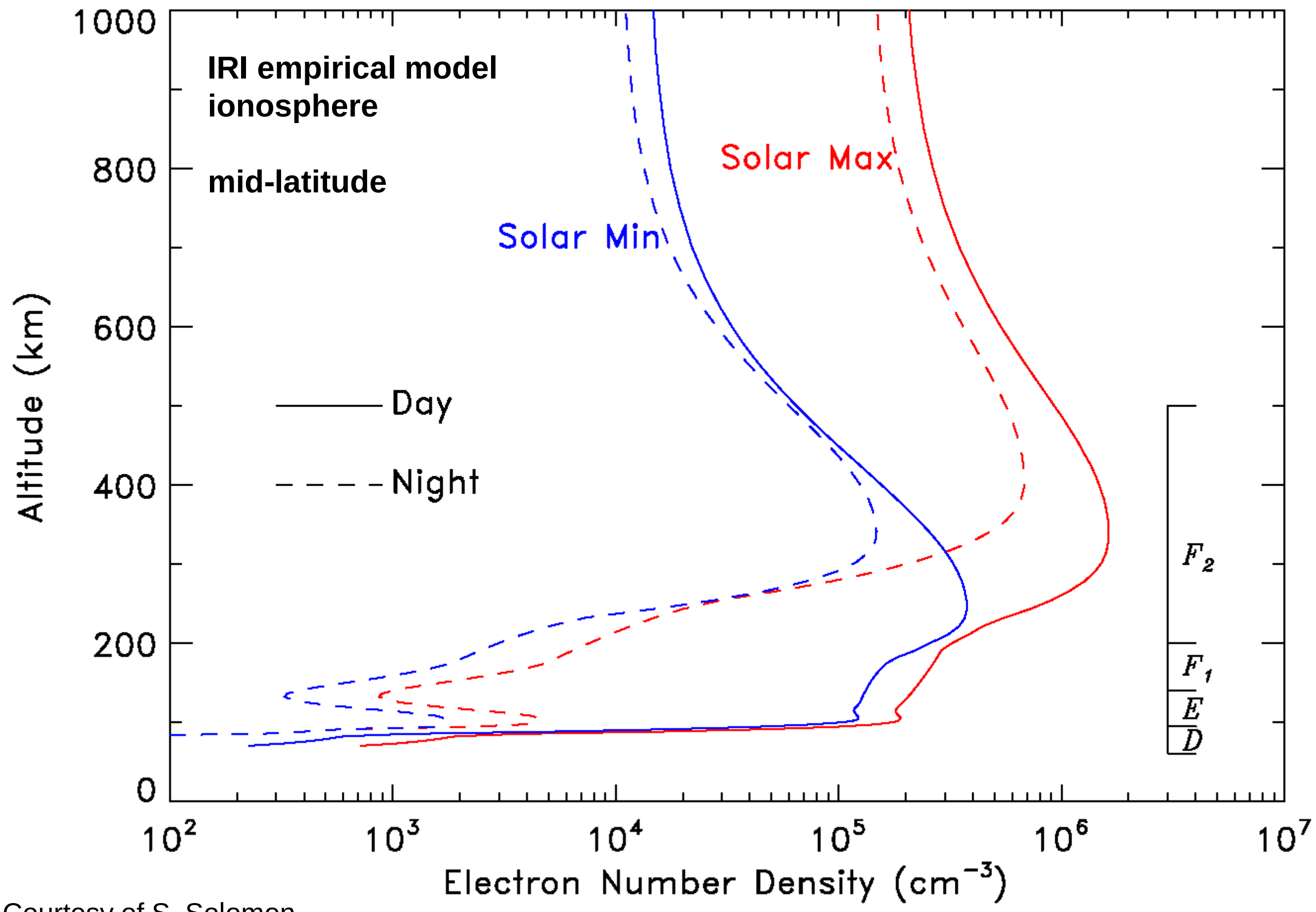
Courtesy of S. Solomon

Major Species Density Structure of the Atmosphere



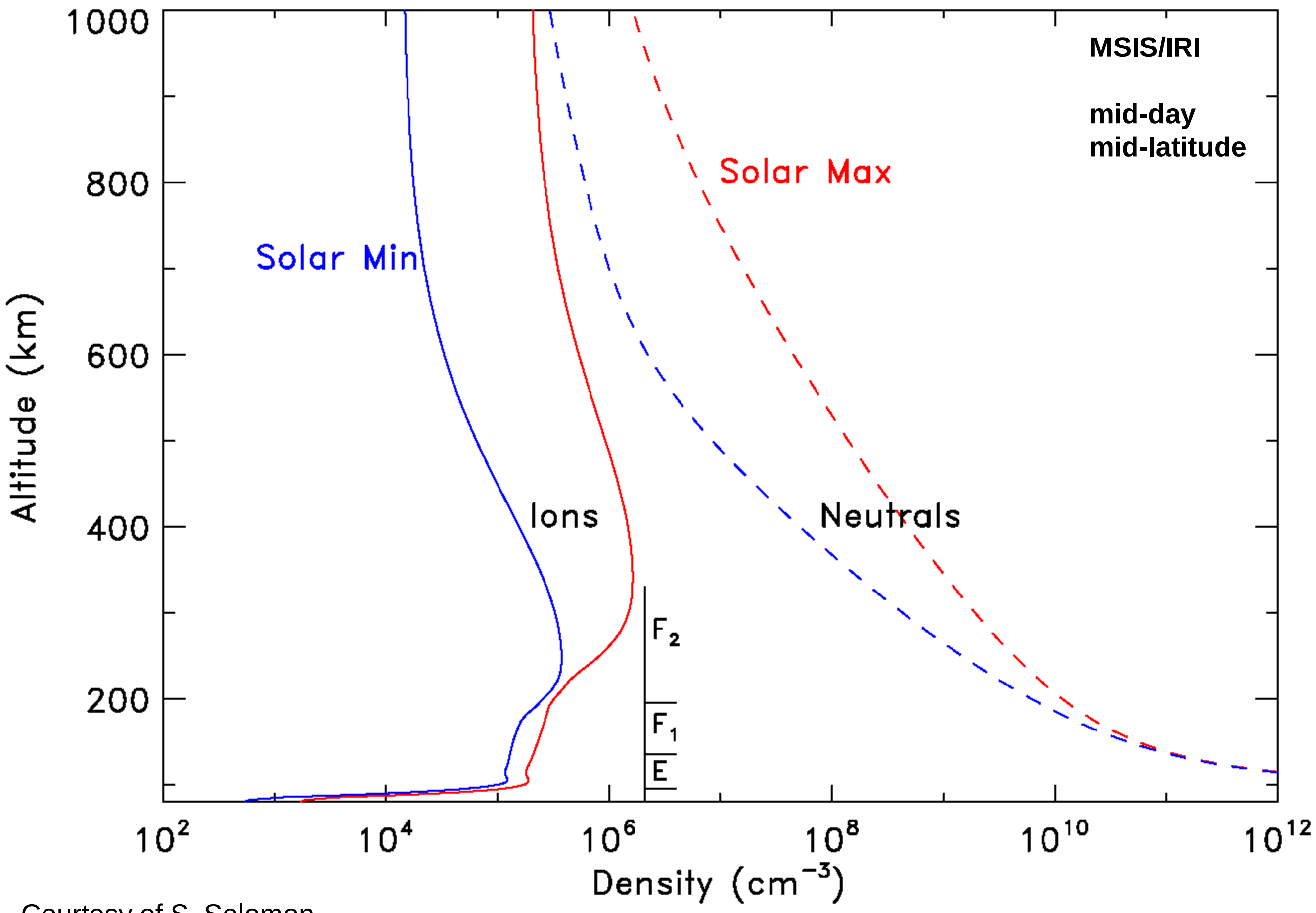
Courtesy of S. Solomon

Ionosphere Basic Altitude Structure

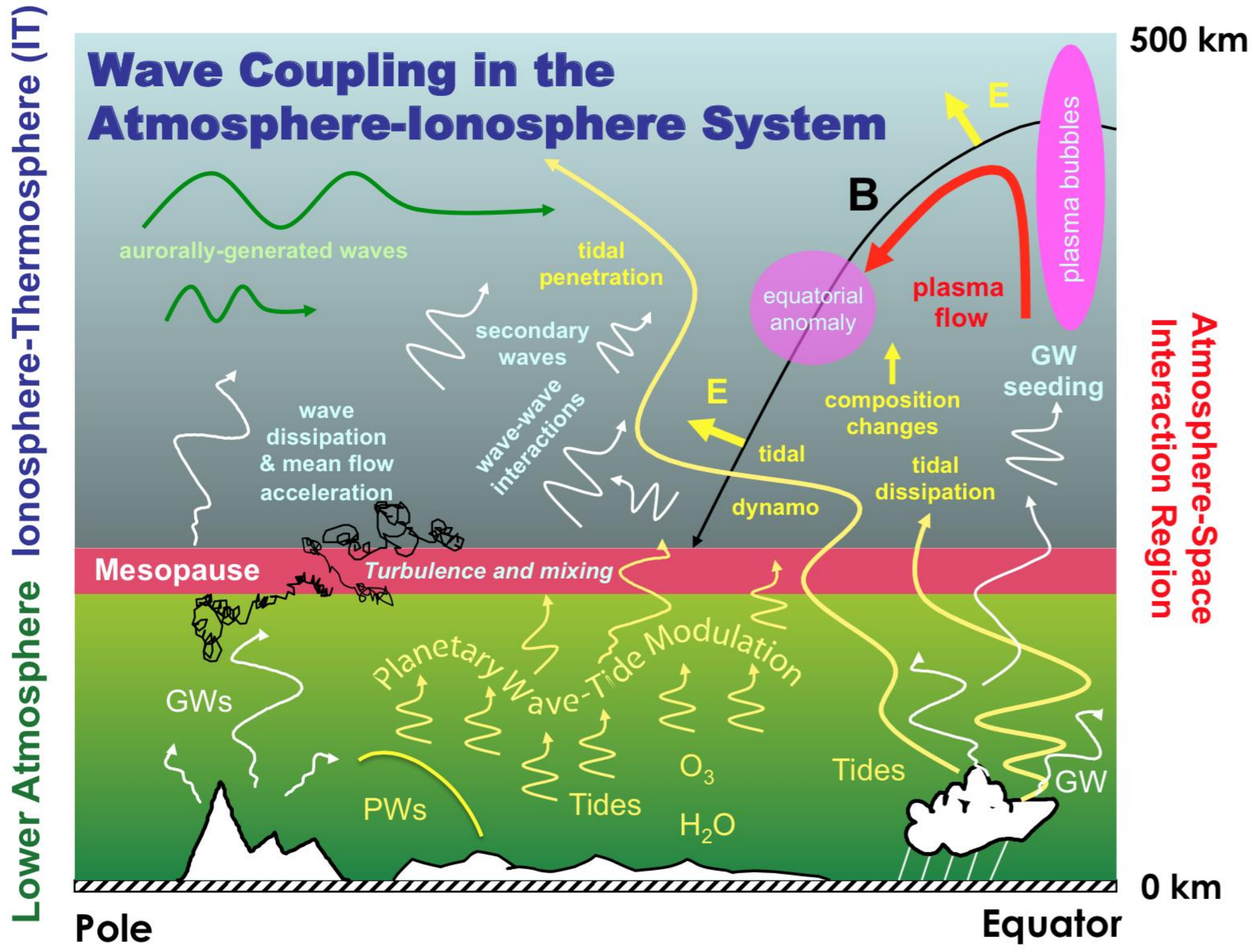


Courtesy of S. Solomon

Thermosphere-Ionosphere Variability



Courtesy of S. Solomon

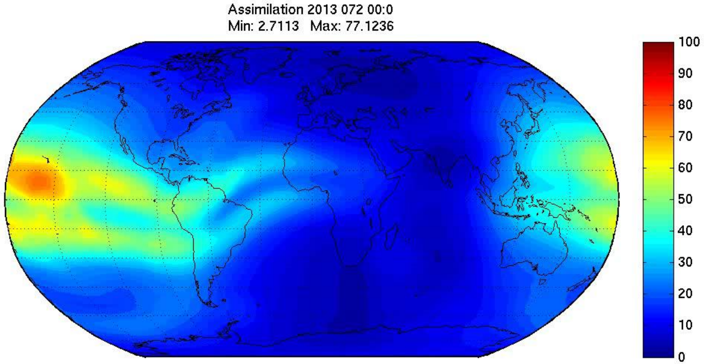


Curtsey of J. Forbes

Ionosphere and Thermosphere Weather

Solar and Geomagnetic Activities

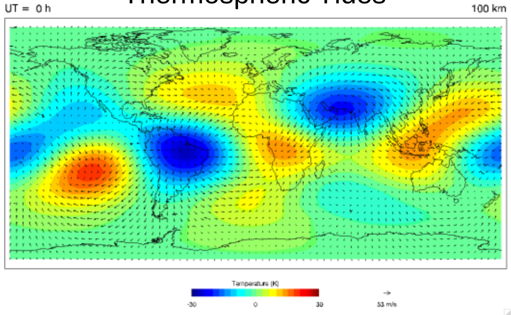
(solar radiation, high-latitude ***E***, *aurora, joule heating)*

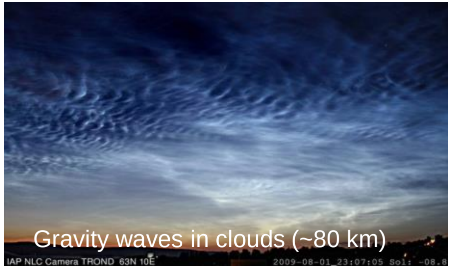


Lower Atmospheric Perturbations

(thermospheric tides, planetary waves, gravity waves)

Thermospheric Tides

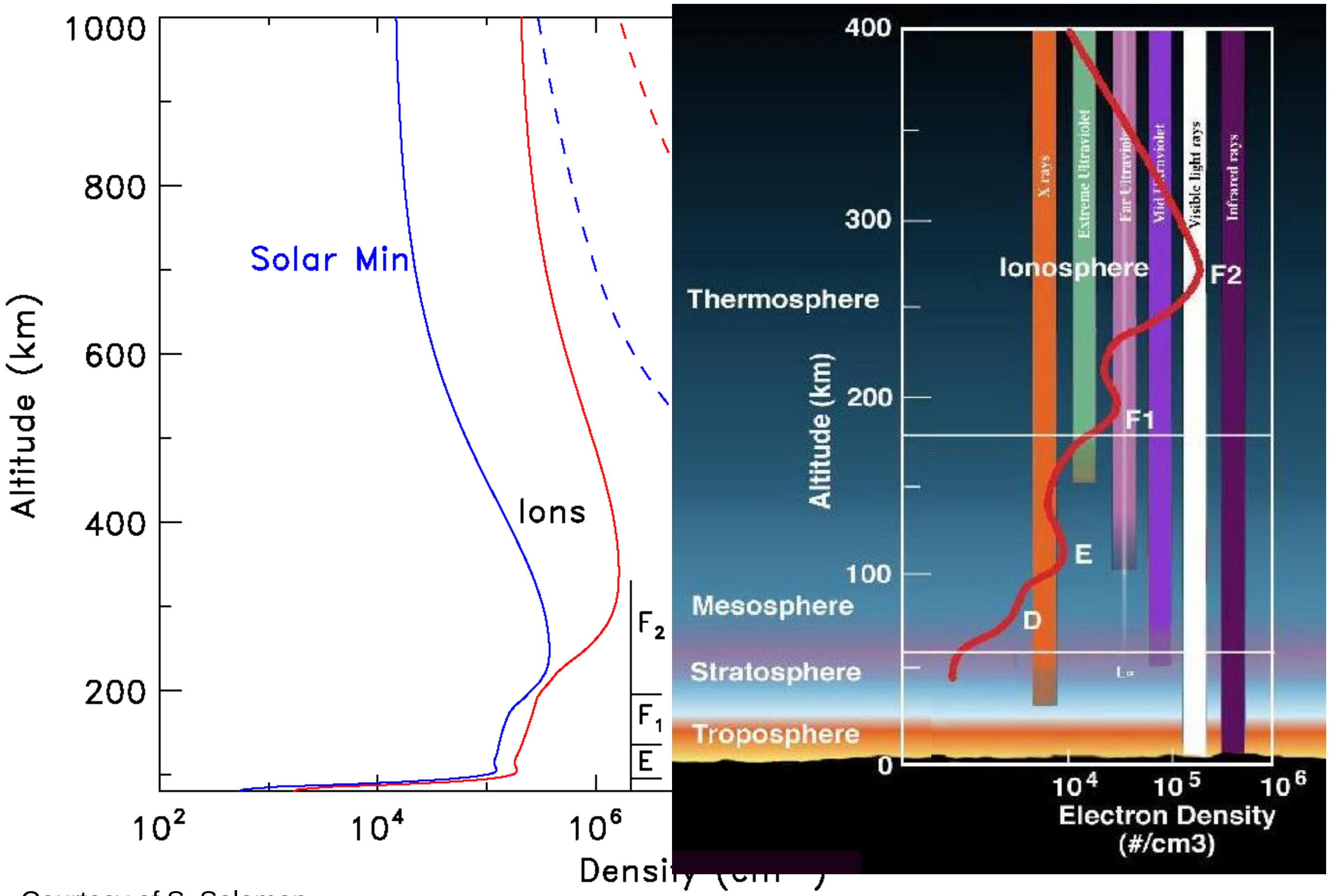




Gravity waves in clouds (~80 km)

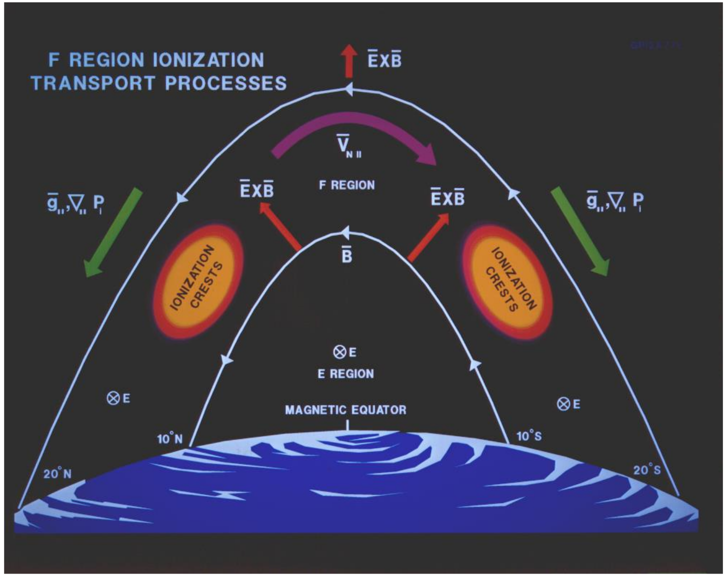
Gravity waves in clouds (~10 km)

Thermosphere-Ionosphere Variability



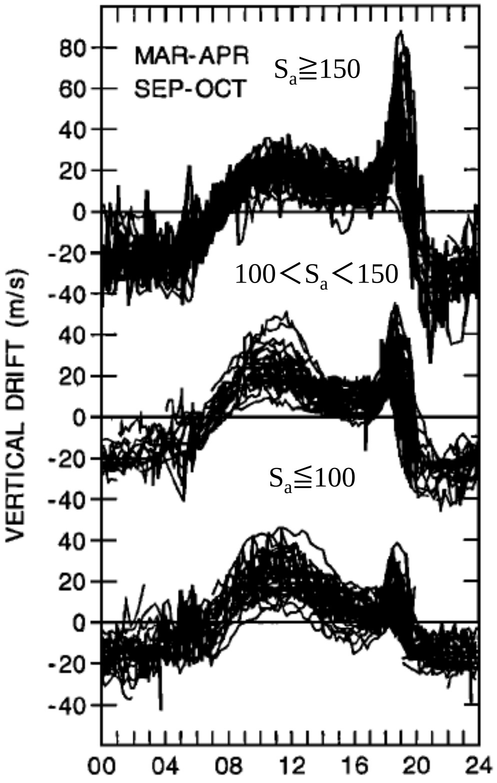
Courtesy of S. Solomon

Transport Processes in the Equatorial Ionosphere



$$\frac{\partial N}{\partial t} = \underbrace{q}_{\text{Prod.}} - \underbrace{\beta(N)}_{\text{Loss}} - \underbrace{div(N\mathbf{V})}_{\text{Transport}}$$

Jicamarca Drifts

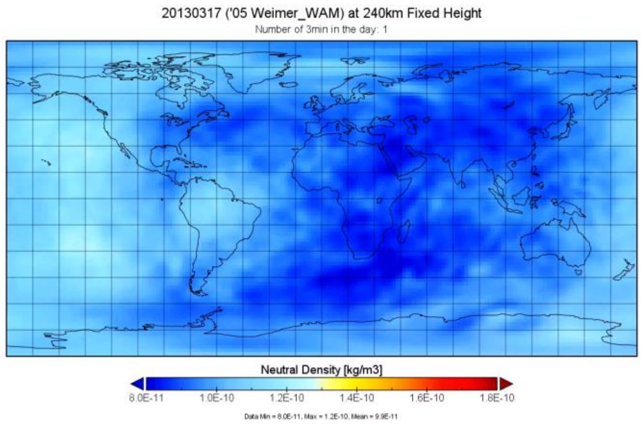


[Scherliess & Fejer, 1999]

- Perpendicular transport ($V_\perp$)
  - E×B drift
- Zonal transport
- Parallel transport ($V_\parallel$)
  - Neutral wind effect
  - Plasma diffusion
  - Thermo expansion/contraction

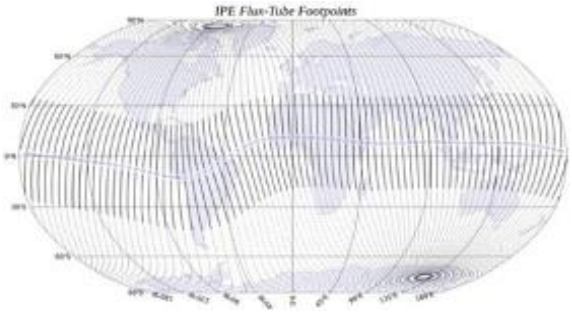
Whole Atmosphere Model (WAM)

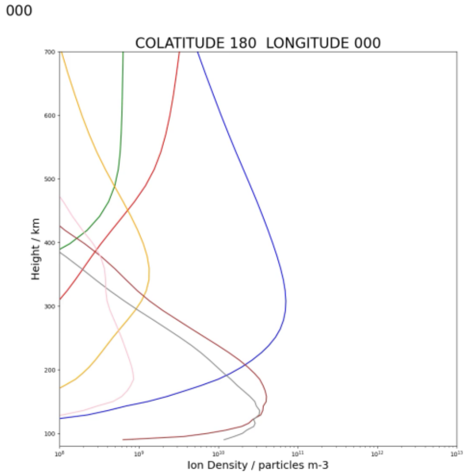
- An extension of the US weather model (Global Forecast System spectral hydrostatic dynamical core) to 600 km altitude, 150 layers, variable g
- *5 species* dynamical core of O, O_2, O_3, N_2, H_2O enthalpy thermodynamics
- WAM runs at ~180 km horizontal resolution, T62, compared to operational weather model of ~12 km, T1534
- Includes all the lower atmosphere weather and dynamics processes, as well as all the additional T-I physics (including electrodynamics and plasma processes)
- Provides the 3D fields for neutral winds, temperature, density, major species composition O, O_2, N_2
- WAM coupling to IPE based on time-dependent 3D re-gridding in SW mediator (ESMF/NUOPC)



Ionosphere Plasmasphere Electrodynamics (IPE)

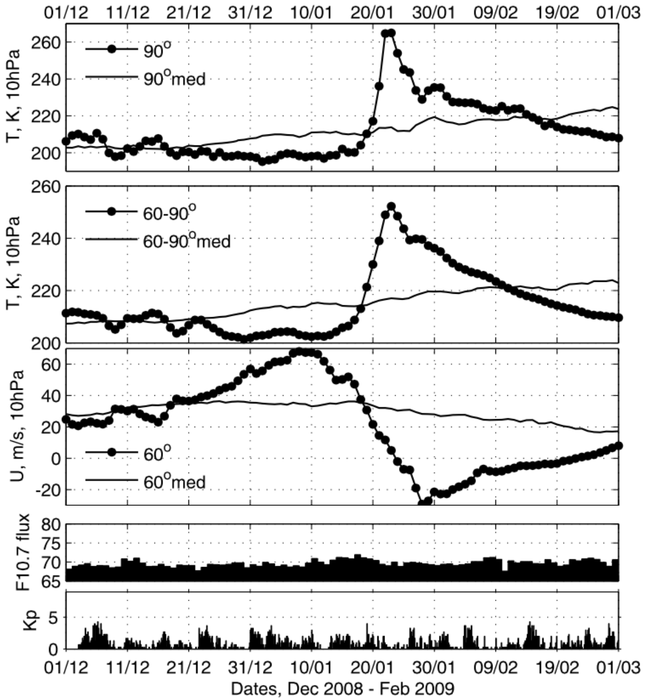
- Space weather *plasma* component of the atmosphere
- Time-dependent, global 3D model of the ionosphere and plasmasphere 90 km to ~10,000 km
- Flux-tube solver based on the Field Line Interhemispheric Plasma (FLIP) model
- Seamless perpendicular plasma transport pole-to-pole
- Weimer/Heelis empirical ion convection model driven by solar wind data, TIROS auroral empirical model
- Provides: plasma densities and velocities (9 ion species), thermal electron and ion temperatures in the ionosphere and plasmasphere

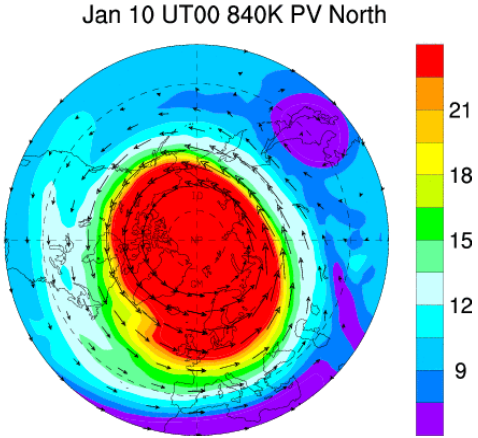




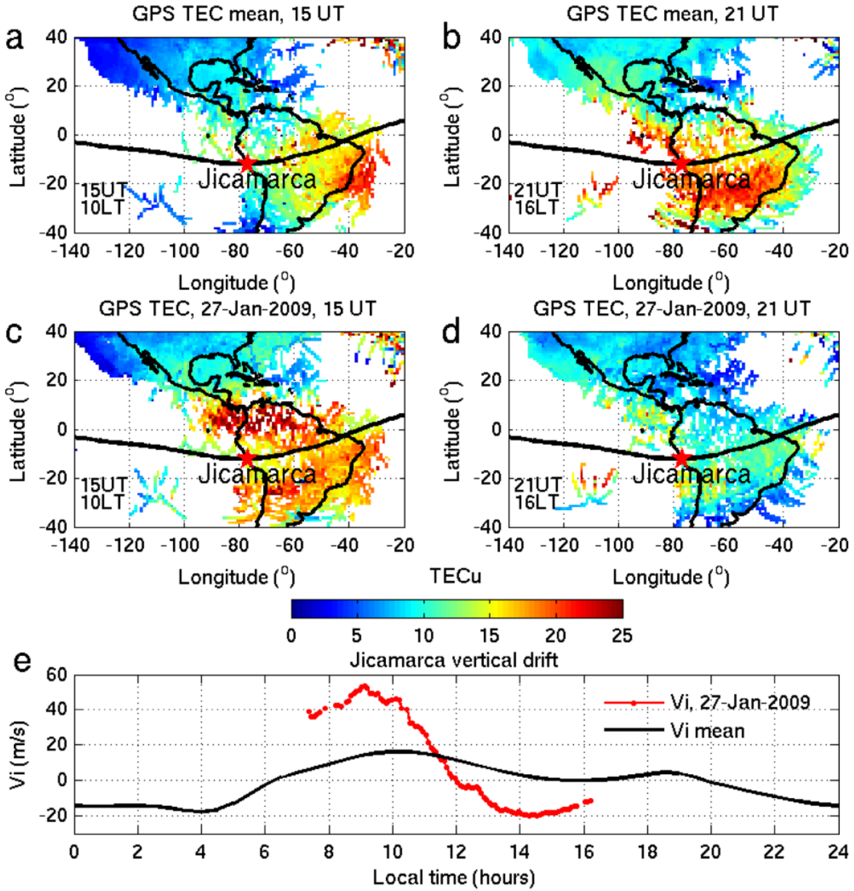
2009 January Sudden Stratospheric Warming

NOAA NCEP Dataset





Ionospheric Responses to Sudden Stratospheric Warming Events



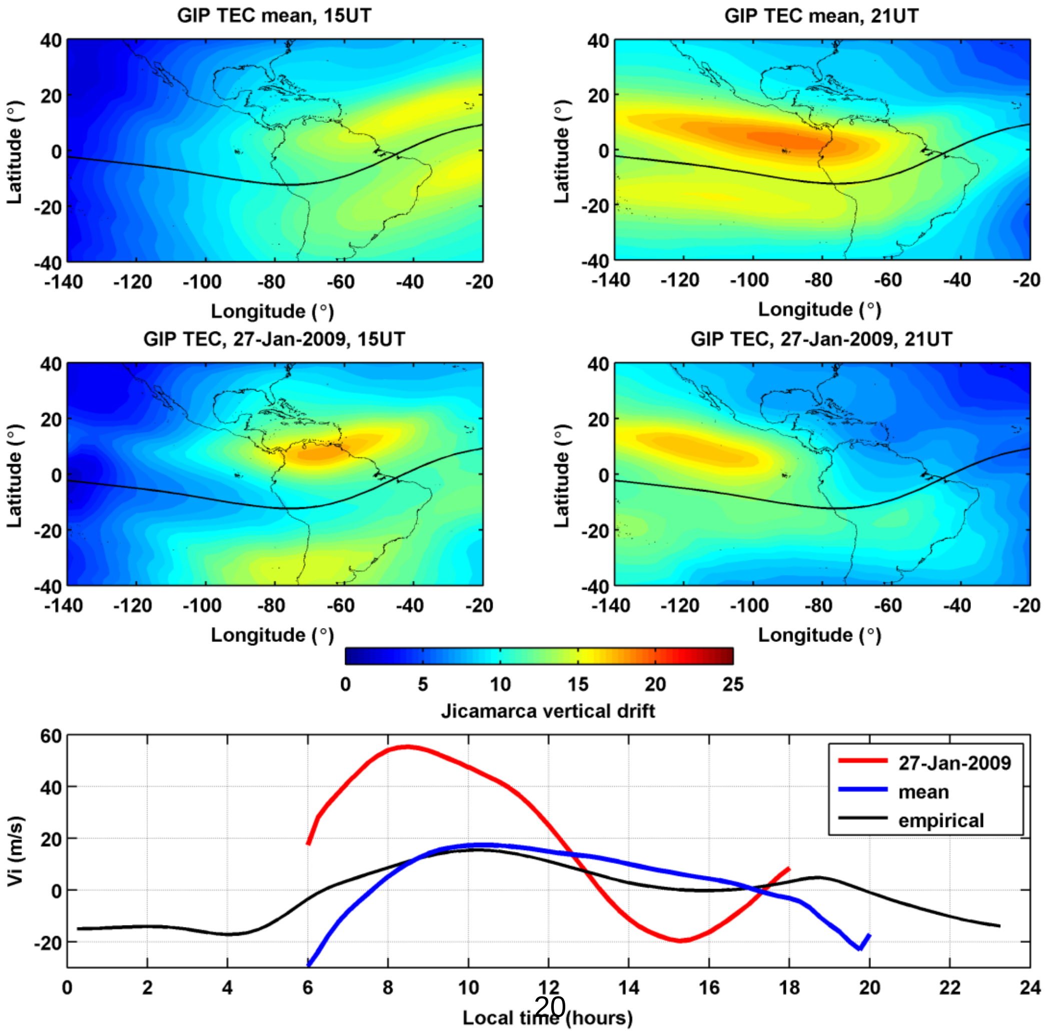
Goncharenko et al. (2010):

Climatological TEC at 10 and 16 LT from ground GPS observations.

Same on January 27, after the peak of the warming.

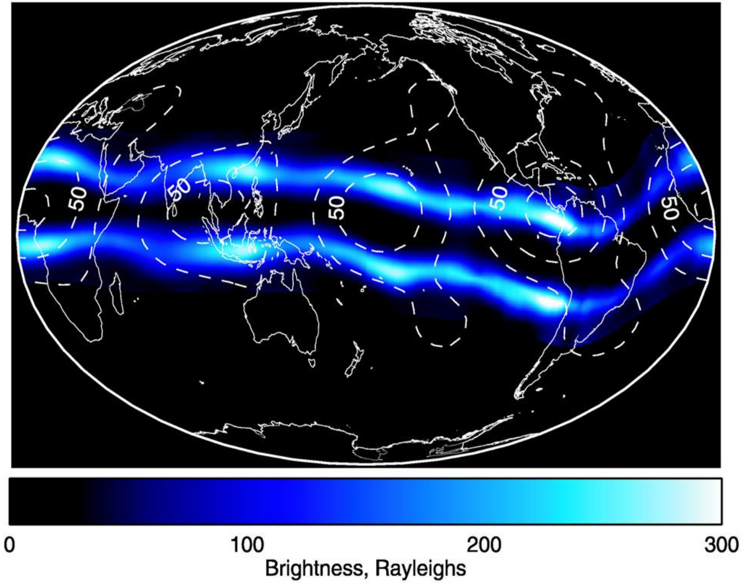
Comparison of plasma drift climatology with observations at Jicamarca on Jan. 27.

Simulation Results

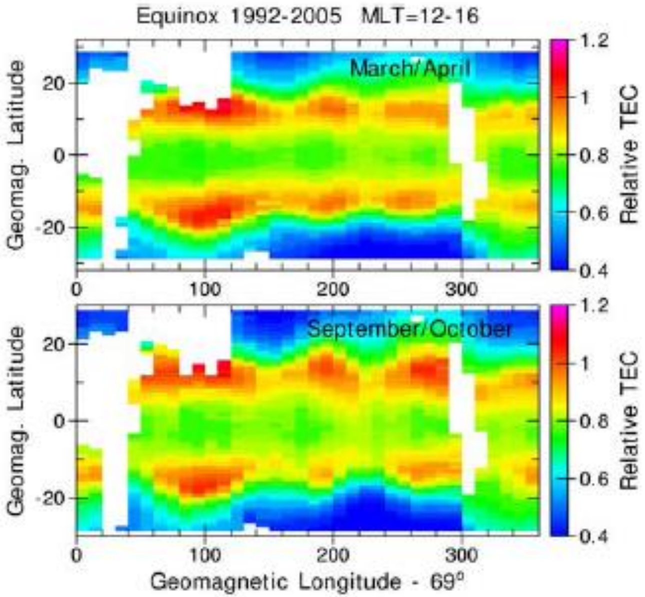


Impact of the Lower Atmosphere on the Upper Atmosphere

Longitudinal and Day-to-day Variability in the Ionosphere

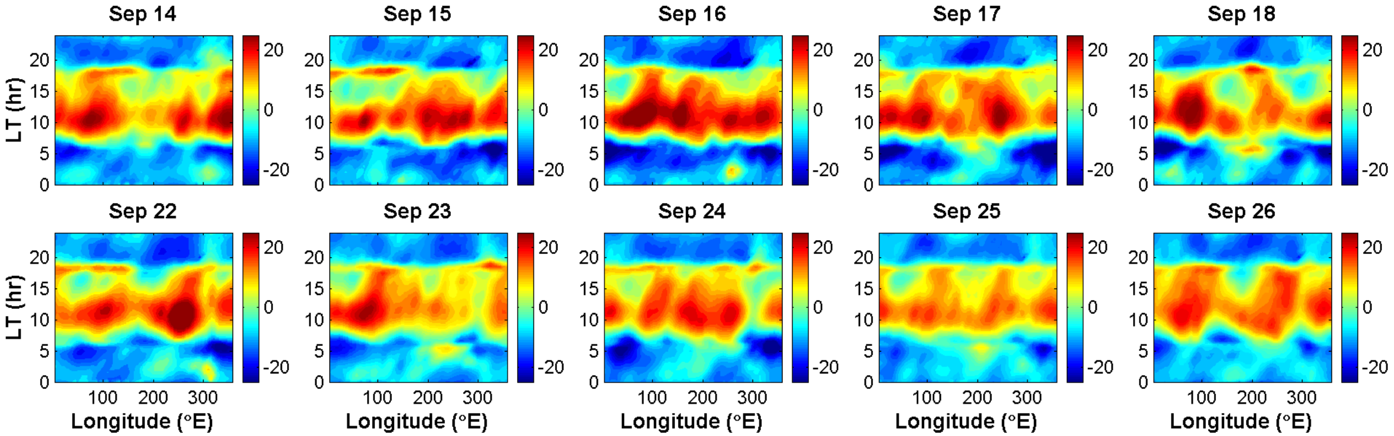


Nighttime ionospheric emission from IMAGE-FUV imager. (Immel et al., 2006)

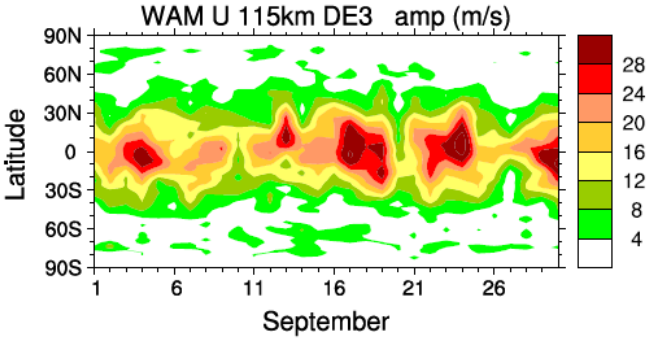


Normalize TOPEX Total Electron Content (TEC) maps during equinox conditions. (Scherliess et al., 2008)

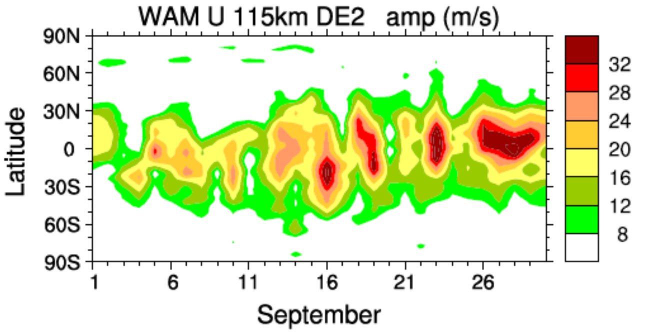
Equatorial Vertical Drift (m/s)



4-Peak Structure



3-Peak Structure

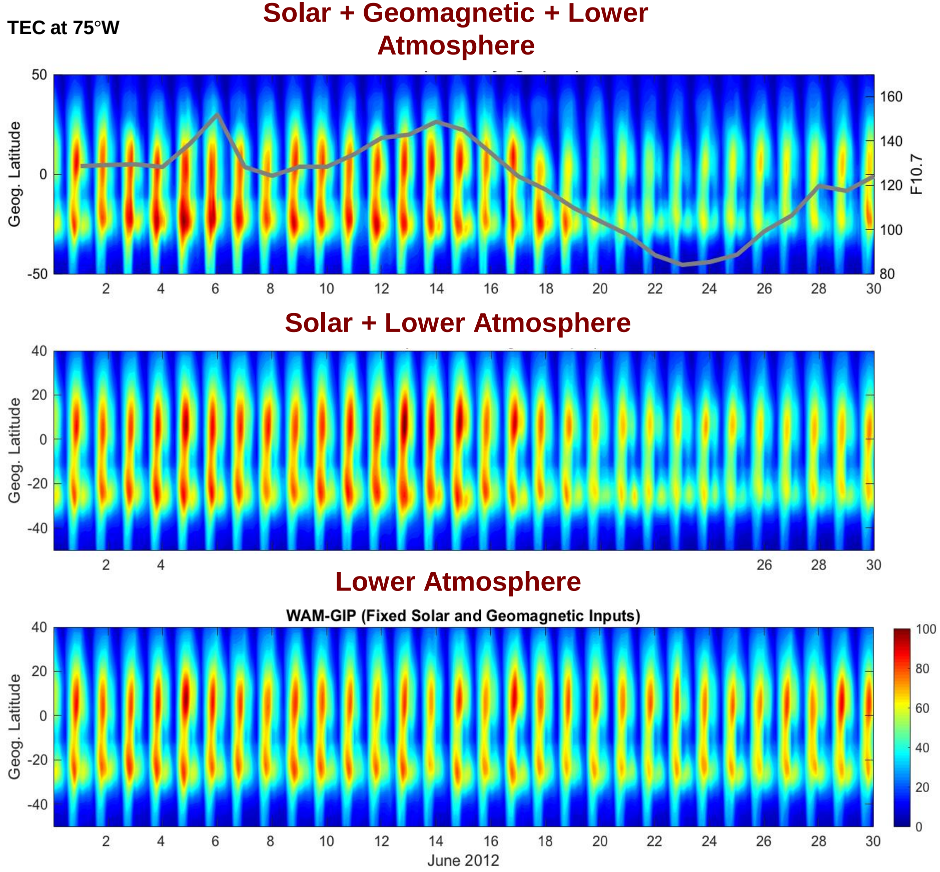


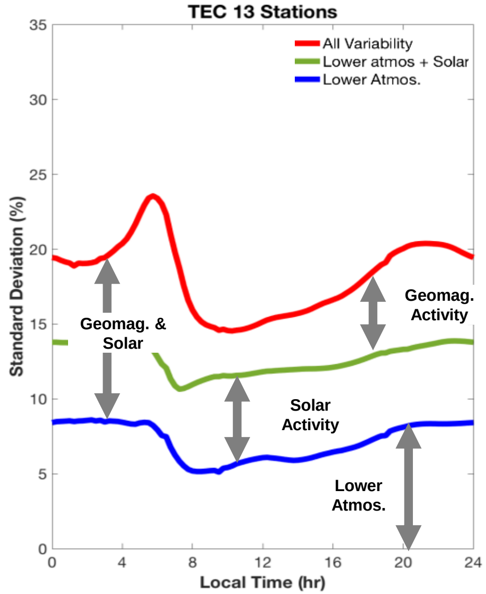
Modulation of DE3 and DE2 tidal amplitudes correlates with number of peaks in longitude structure of vertical plasma drift

Ionospheric Day-to-day Variability

Fang et al., JGR, 2018

(13 stations that were used in *Rishbeth and Mendillo*, 2001)





- Averaging over 13 locations that are mostly located in mid and high latitudes, our results show that relative TEC variability is largely driven by the geomagnetic followed by solar activity, then lower atmosphere perturbation.

WAM-IPE Workflows

CONOPS I — Include tropospheric weather into upper atmosphere forecast

- Low-frequency (atmospheric data driven, hours)
- Based on NWS global workflow (6-hour cycles) with WAM data assimilation
- WAM Data Assimilation Scheme (WDAS): modified Gridpoint Statistical Interpolation (GSI) 3D-VAR with Incremental Analysis Update (IAU)
- Observed and predicted space weather drivers for external forcing

CONOPS II — Capture the impact of near real-time solar wind conditions

- High-frequency (solar data driven, minutes)
- Extension of global workflow (CONOPS I) with online solar data polling
- Initialize at end of IAU “corrector” segment from CONOPS I with available solar wind drivers
- Advance as soon as observed solar wind data are available

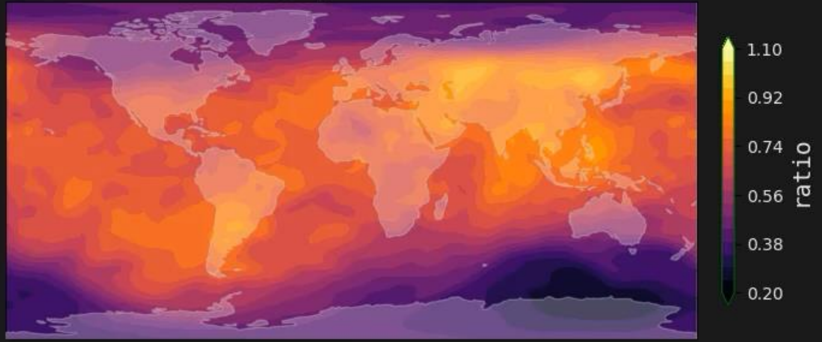
Valid at: Mar 17 2015 00:00 UTC

Neutral Atmosphere

Model: WAM-IPE Init: Mar 17 2015 00 UTC

400km Neutral Density

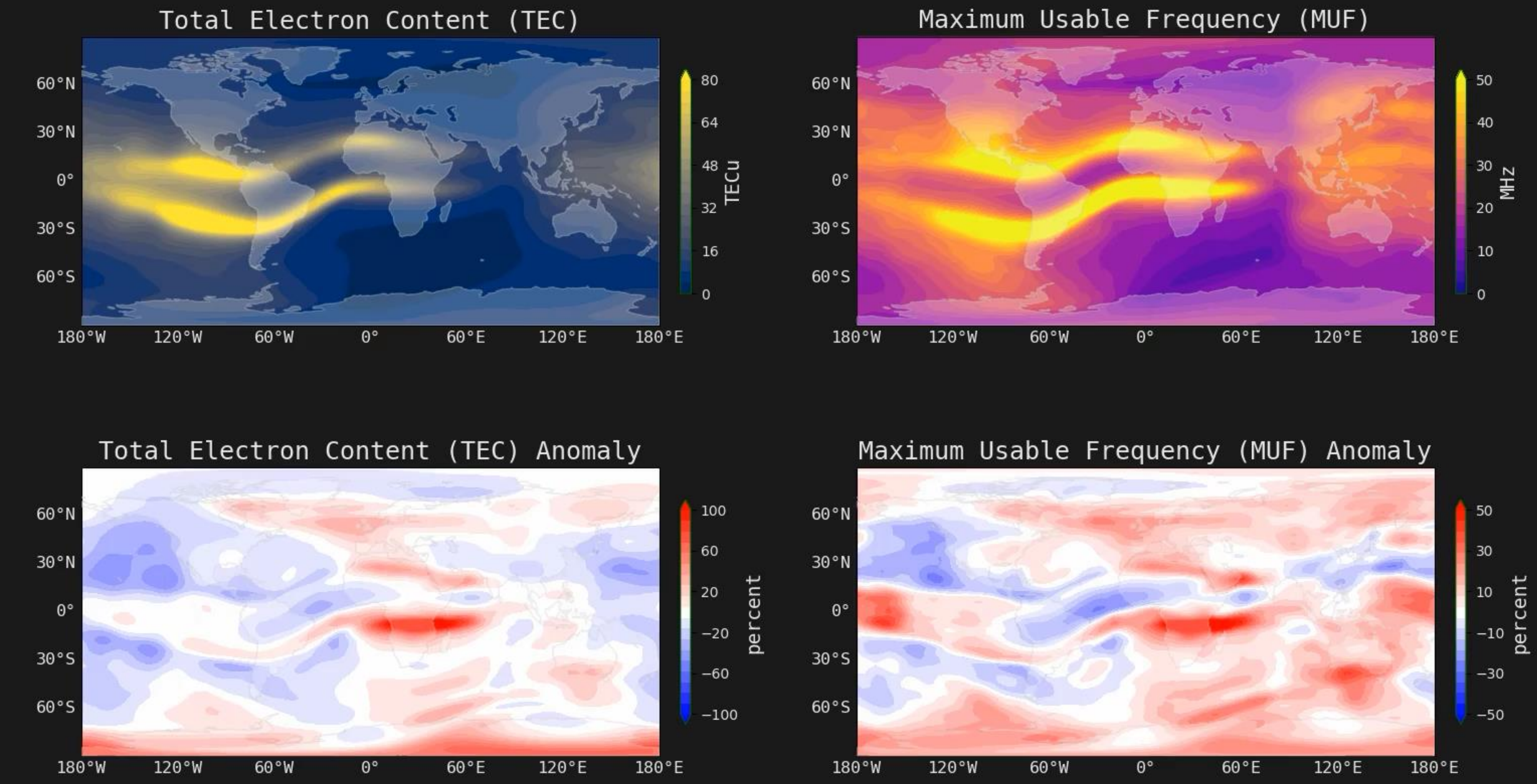
O/N_2 Ratio



400km Neutral Density Anomaly

Space Weather Prediction Center

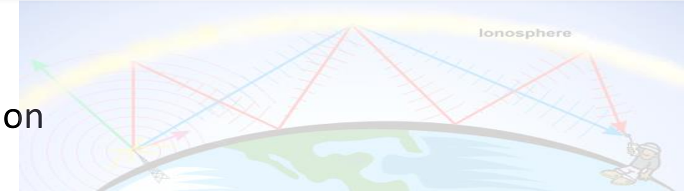
Global Ionosphere Valid at: Mar 17 2015 00:00 UTC



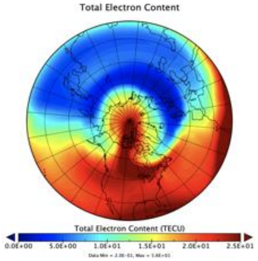
Space Weather Prediction Center

What operators care about

what WAM-IPE contributes marked in red



- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) due to the peak plasma density (NmF2) and height of peak (hmF2)
  - Undulations in bottom-side F-region

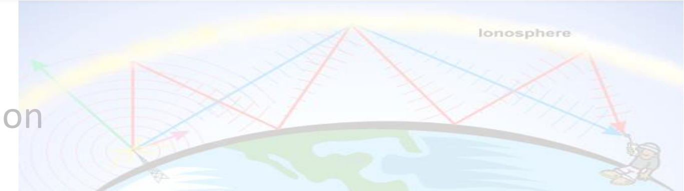


- **For satellite positioning, navigation, timing, and communication:**
  - Mesoscale structure and gradients in plasma density (diffract radio signals and cause amplitude or phase fluctuation in GNSS signals)
  - Delay in navigation signal due to line of sight electron content (position error)
  - Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal

- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning)

What operators care about

what WAM-IPE contributes marked in red



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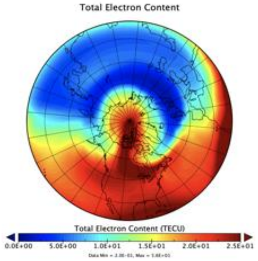

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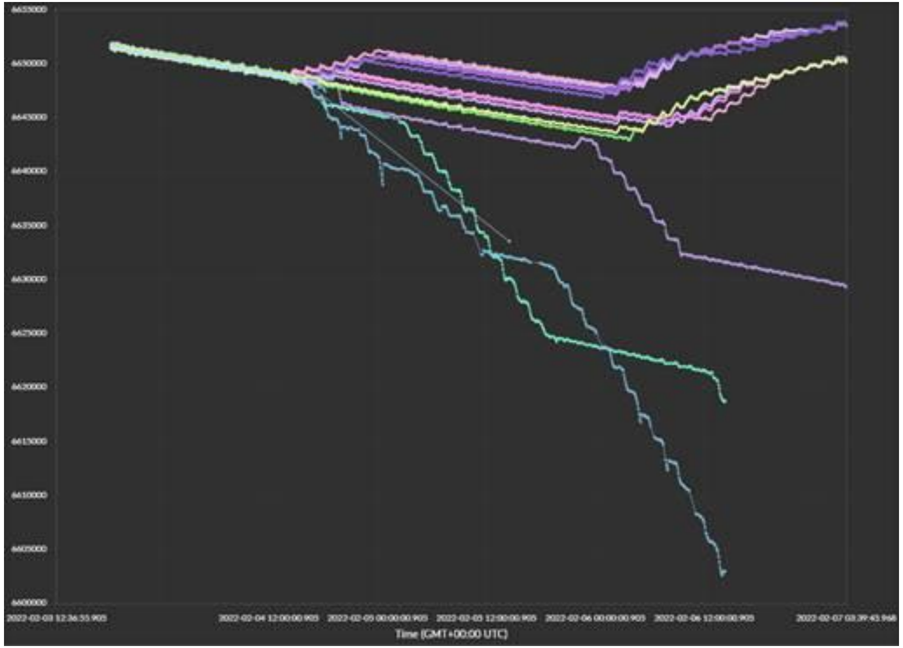
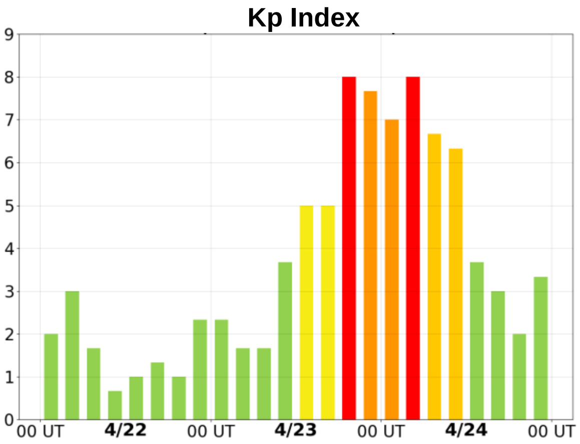
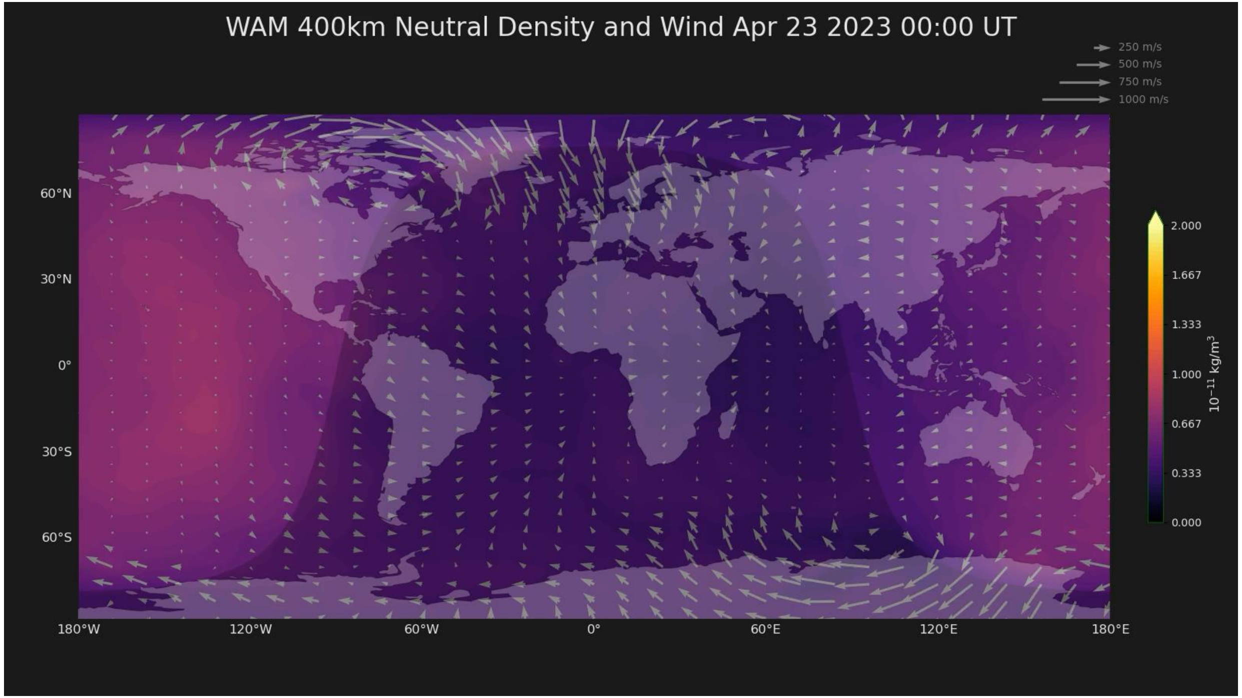
The Starlink Incident on Feb 4th, 2022



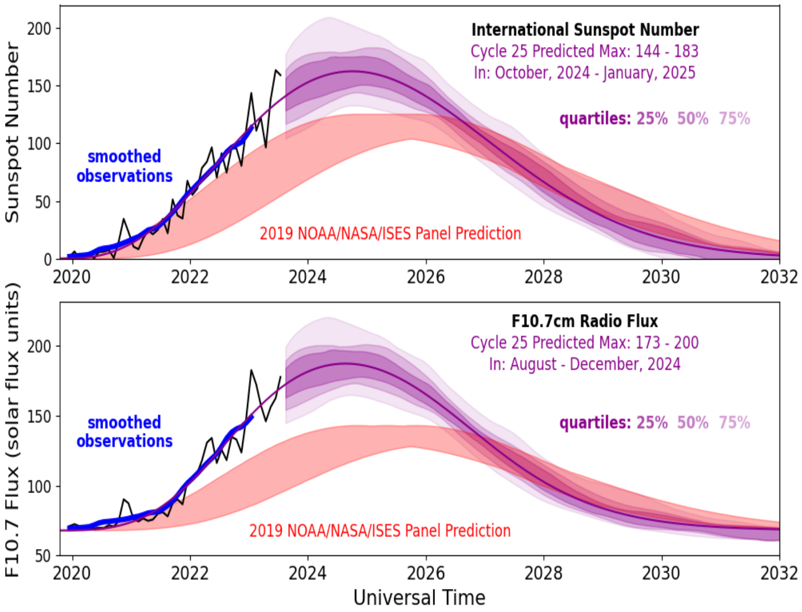
On 3rd February at 1:13 pm EST (18:13 UTC), a SpaceX Falcon 9 launched 49 Starlink satellites to low Earth orbit (350 x 210 km, 53°) from the Kennedy Space Center in Florida. SpaceX reported the loss of up to 38 of the 49 satellites when they encountered increased atmospheric drag due to a geomagnetic storm while they were in orbit-raising maneuvers. https://www.spacex.com/updates/ (8th Feb 2022).

Geomagnetic Storm 23-24 April 2023

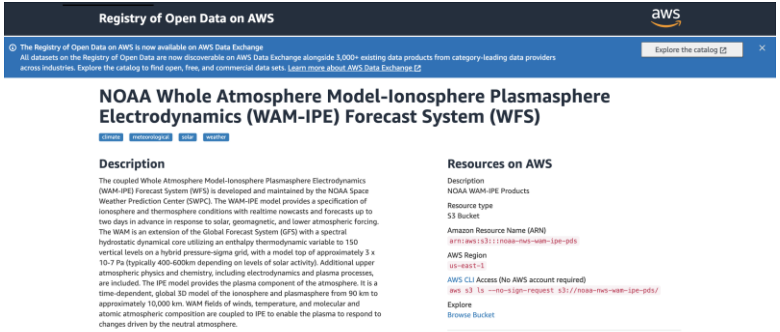




SWPC's Customer Engagement



https://registry.opendata.aws/noaa-nws-wam-ipe/


Registry of Open Data on AWS

The Registry of Open Data on AWS is now available on AWS Data Exchange
All datasets on the Registry of Open Data are now discoverable on AWS Data Exchange alongside 3,000+ existing data products from category-leading data providers across industries. Explore the catalog to find open, free, and commercial data sets. Learn more about AWS Data Exchange

Explore the catalog

NOAA Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics (WAM-IPE) Forecast System (WFS)

climate meteorological solar weather

Description

The coupled Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics (WAM-IPE) Forecast System (WFS) is developed and maintained by the NOAA Space Weather Prediction Center (SWPC). The WAM-IPE model provides a specification of ionosphere and thermosphere conditions with realtime nowcasts and forecasts up to two days in advance in response to solar, geomagnetic, and lower atmospheric forcing. The WAM is an extension of the Global Forecast System (GFS) with a spectral hydrostatic dynamical core utilizing an enthalpy thermodynamic variable to 150 vertical levels on a hybrid pressure-sigma grid, with a model top of approximately 3 x 10-7 Pa (typically 400-600km depending on levels of solar activity). Additional upper atmospheric physics and chemistry, including electrodynamics and plasma processes, are included. The IPE model provides the plasma component of the atmosphere. It is a time-dependent, global 3D model of the ionosphere and plasmasphere from 90 km to approximately 10,000 km. WAM fields of winds, temperature, and molecular and atomic atmospheric composition are coupled to IPE to enable the plasma to respond to changes driven by the neutral atmosphere.

Resources on AWS

Description
NOAA WAM-IPE Products

Resource type
S3 Bucket

Amazon Resource Name (ARN)
arn:aws:s3:::noaa-nws-wam-ipe-pds

AWS Region
us-east-1

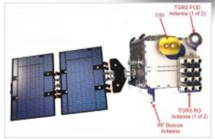
AWS CLI Access (No AWS account required)
aws s3 ls --no-sign-request s3://noaa-nws-wam-ipe-pds/

Explore
Browse Bucket

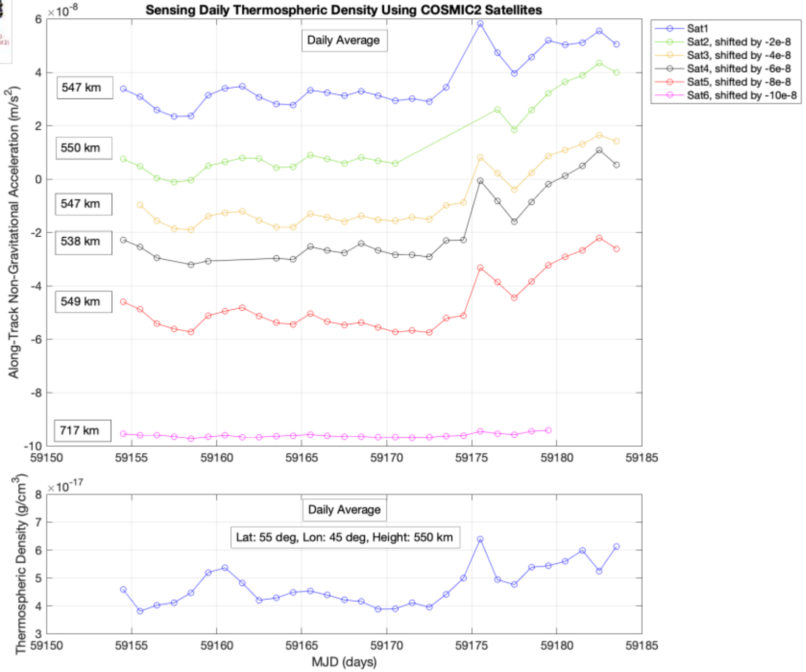
SPACEX
AGI An Ansys Company
amazon | project kuiper
COMSPOC
LEO LABS
SLINGSHOT AEROSPACE
CELESTRAK SINCE 1985
AEROSPACE
PRIVATEER
kayhan. space
SPACENAV
ensemble
planet.
Blue Eye Soft
MIT Aeronautics and Astronautics
XVIII
NASA
SWx TREC Boulder
Office of Space Commerce U.S. Department of Commerce
MIT LINCOLN LABORATORY

Space Weather Testbed Exercise with Satellite Industry

Neutral Density Estimation

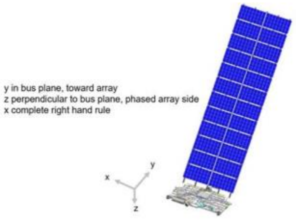


COSMIC-2 Mission

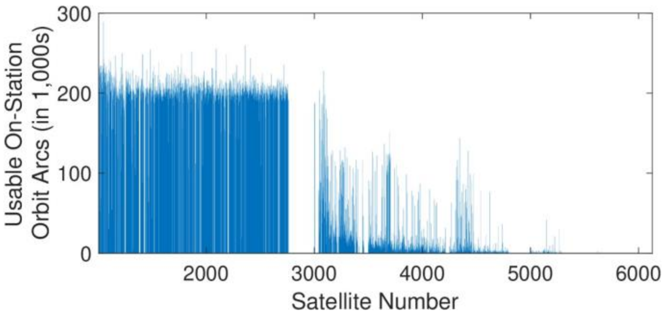


Courtesy of Jian Yao and COSMIC Team

SpaceX Starlink



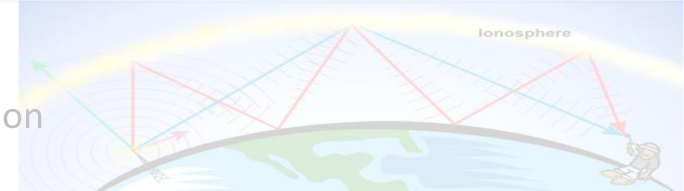
- Position & velocity ephemeris
- Attitude & panel articulation
- Estimated non-conservative accelerations
- Initial satellite geometry
- Time period: April 2022—April 2023
- ~3,900 satellites (v1.0, v1.5, v2-mini)
- ~1 minute cadence
- ~250 GB



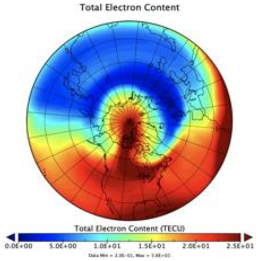
Courtesy of Eric Sutton and the Starlink Team

What operators care about

what WAM-IPE contributes marked in red



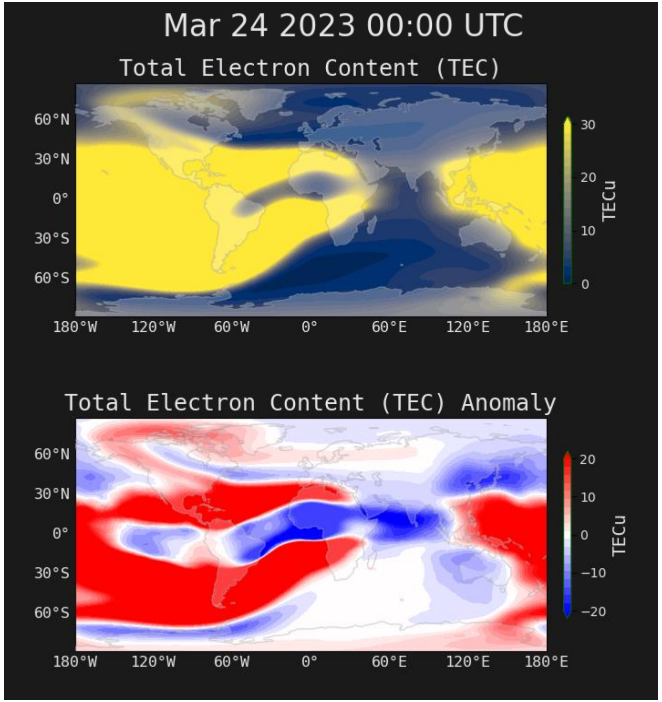
- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) due to the peak plasma density (NmF2) and height of peak (hmF2)
  - Undulations in bottom-side F-region



- **For satellite positioning, navigation, timing, and communication:**
  - Mesoscale structure and gradients in plasma density (diffract radio signals and cause amplitude or phase fluctuation in GNSS signals)
  - Delay in navigation signal due to line of sight electron content (position error)
  - Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal

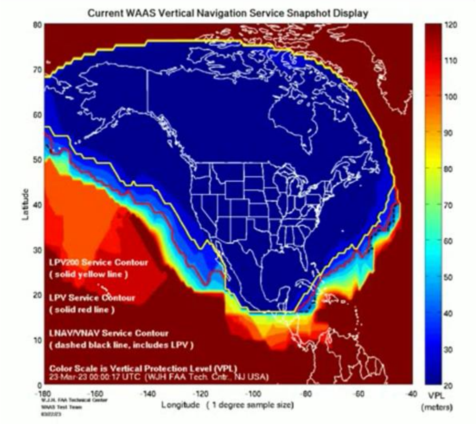
- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning)

WAM-IPE captures the storm enhanced densities (SED) as it develops over the CONUS. At 00UT on March 24th the SED feature was well developed stretching from north west to south east across CONUS, which coincided with the outage of the WAAS commercial aviation navigation system, and reports of interference in airline satellite communication.



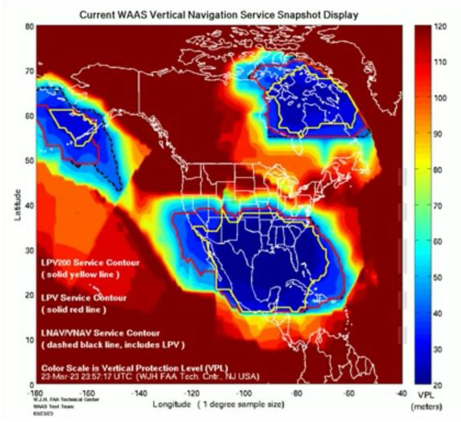
FAA Wide Area Augmentation System

WAAS 23 MAR/0017 UTC



Quiet day before the storm: full WAAS coverage

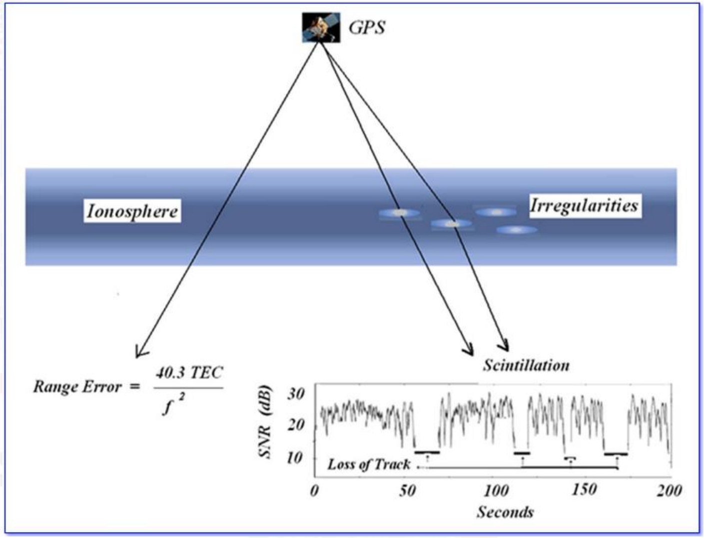
WAAS 23 Mar/2357UTC

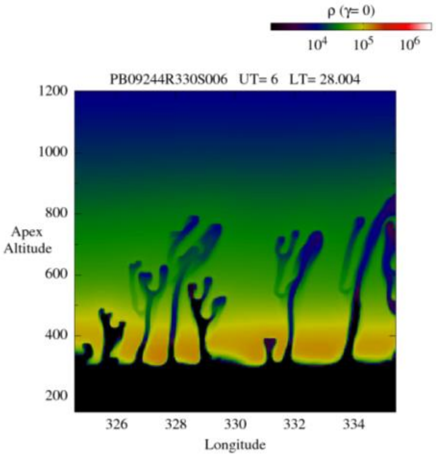


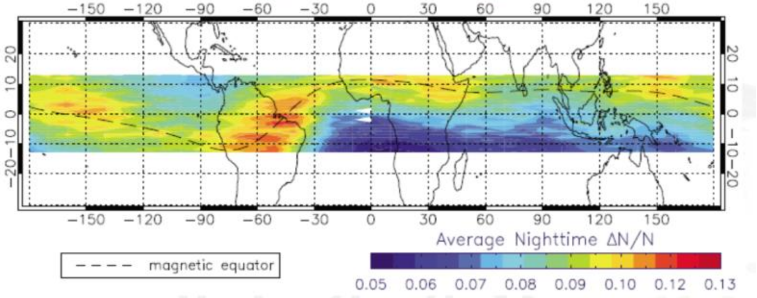
Vertical error limits exceeded over large part of continent due to geomagnetic storm.

Small-scale Plasma Irregularities

- Plasma irregularities can cause scintillation in GNSS signals or pose a hazard for critical communication, navigation, and imaging systems
- Signals propagate through regions of quickly varying density resulting in diffraction and/or refraction and signal intensity drops and phase shifts.



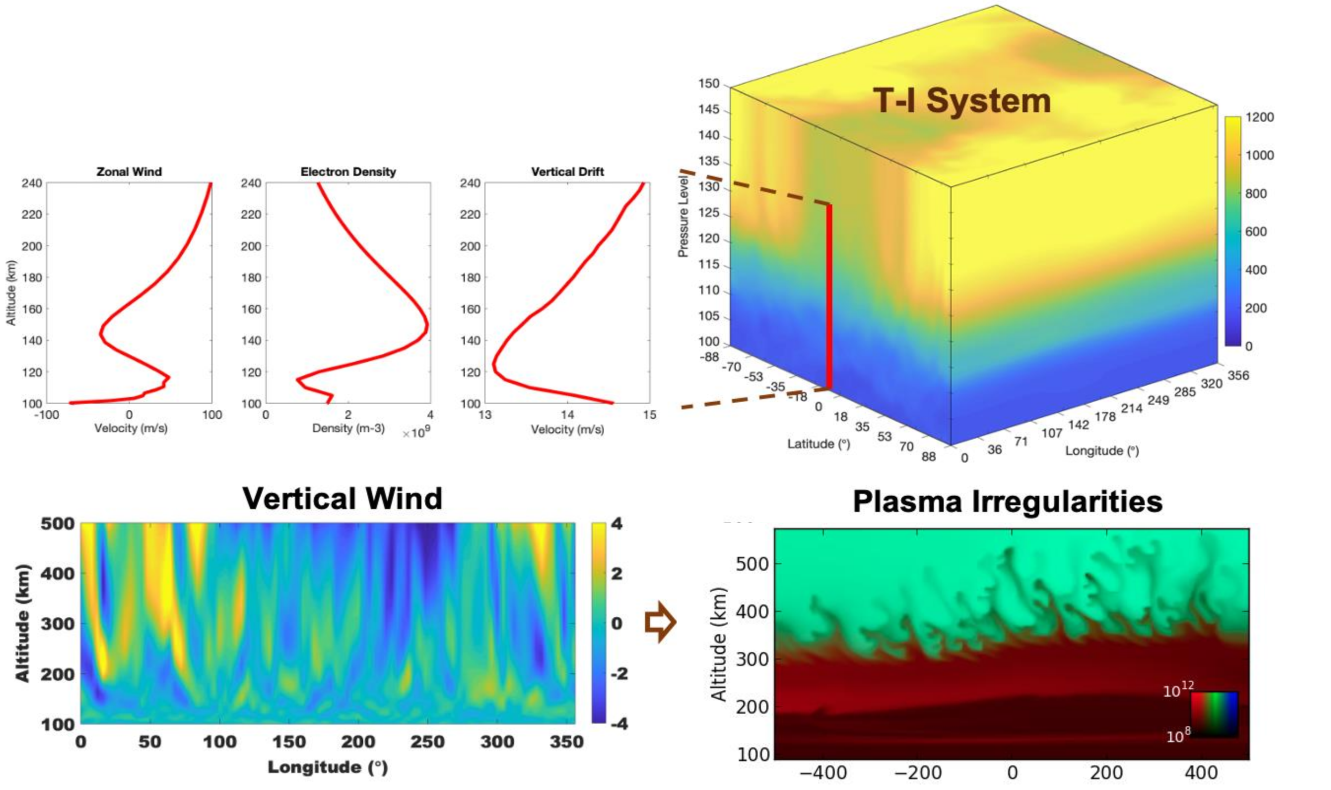




Dao et al, 2011

Data from May 2008 to March 2010

Forecasting the Small-scale Plasma Irregularities



Funded by NSF SWQU AGS 2028032

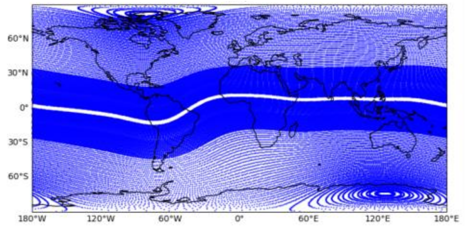
Upgrade WAM neutral atmosphere resolution from T62 to T254 spectral truncation

- Approximate resolution increase from ~200 km horizontal to ~50 km, still with 150 layer at ~1/4 scale height in upper levels
- Simulation without lower atmosphere data assimilation, so there will be biases below 50 km in topics and midlatitude, and MLT zonal mean and wind reversals will not be perfect
- Therefore wave sources in the troposphere and stratosphere propagating upward, and filtering of the wave spectrum by MLT winds not perfect

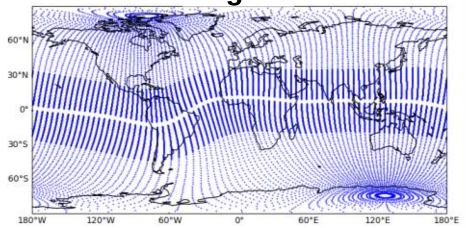
Upgrade IPE ionosphere/plasmasphere resolution

- Original – 80 longitude grid, 170 latitudinal tubes, 44515 pts in each longitude slice
- New – 320 longitude grid, 170 latitude tubes, 44515 pts in each longitude slice
- Increase the resolution of dynamo solver to make the new grid
- The mediator between WAM and IPE has not been modified

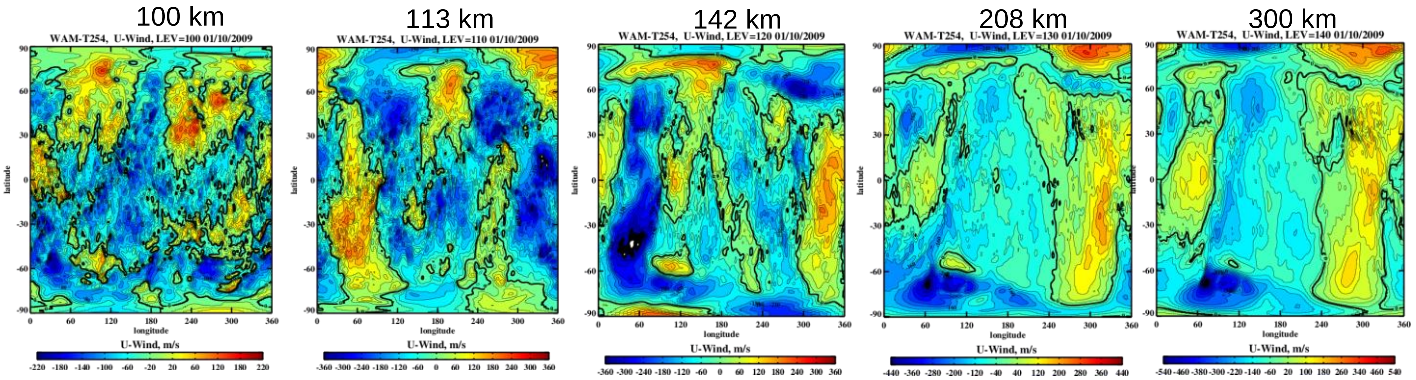
New



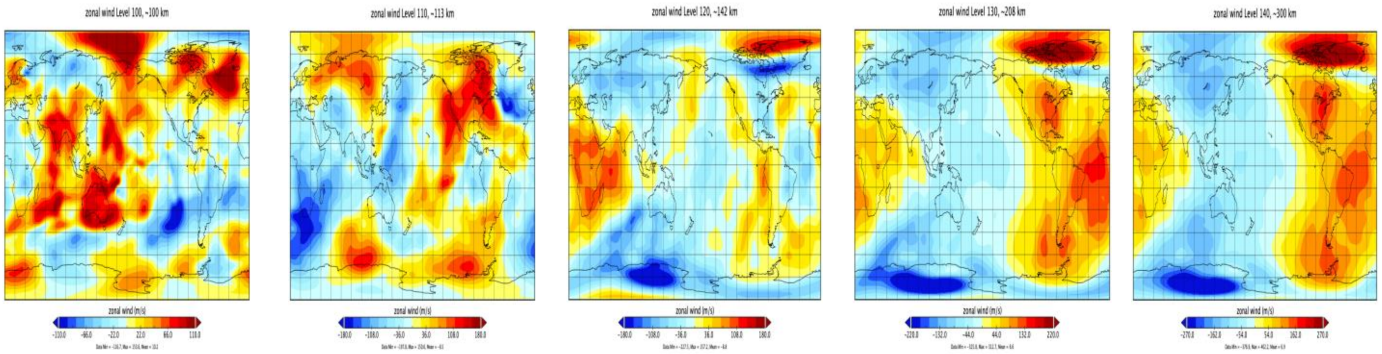
Original



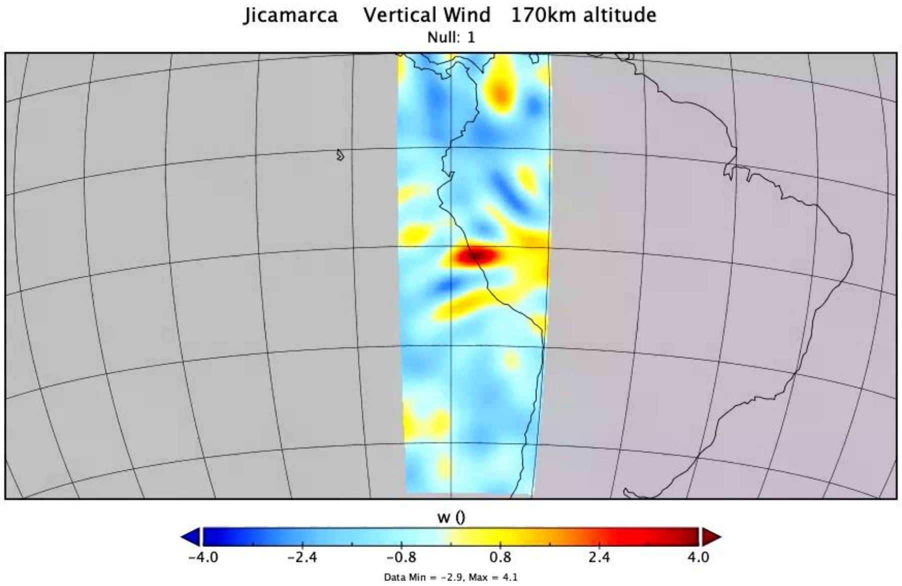
Zonal Wind: T254 ~70km

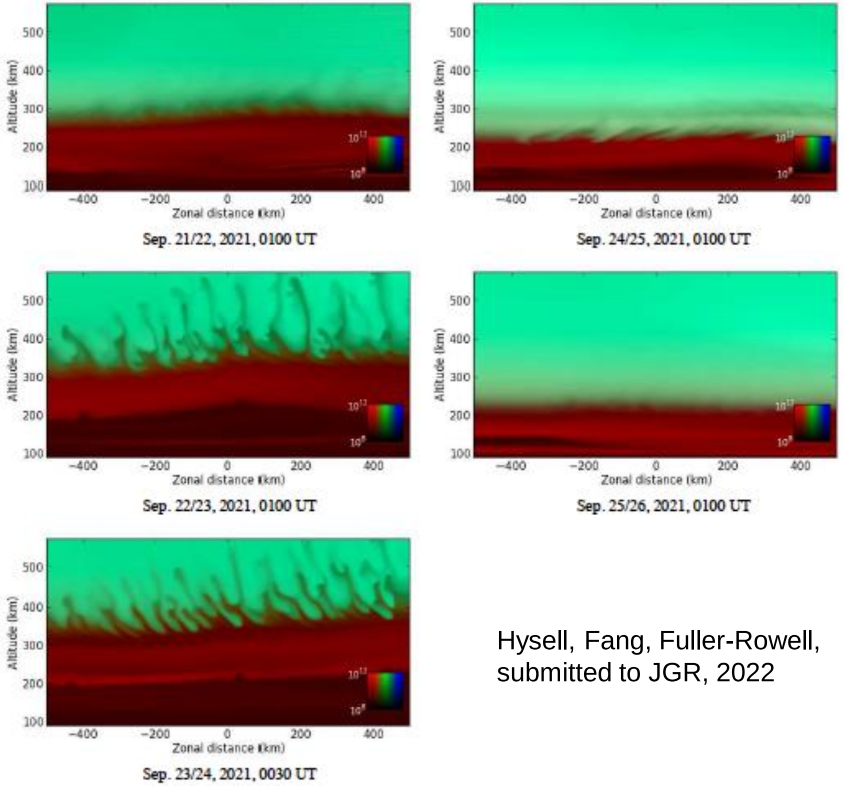


T62 ~200km



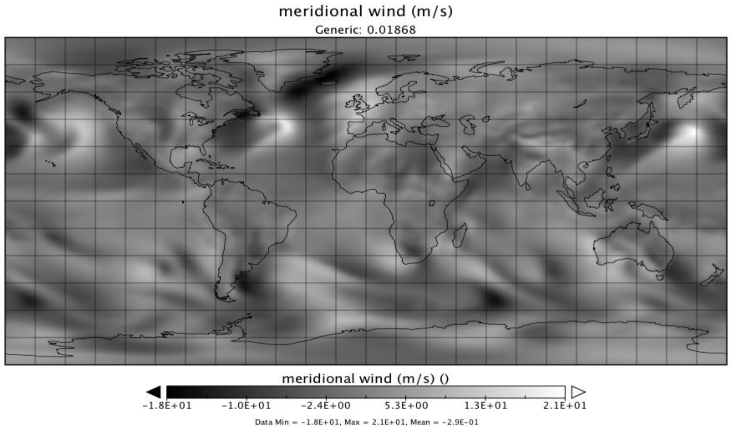
Forecasting the Small-scale Plasma Irregularities



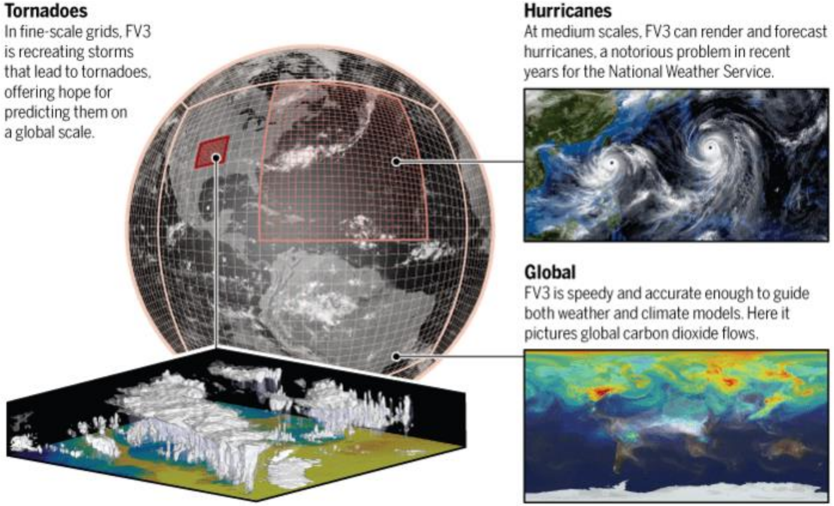


Hysell, Fang, Fuller-Rowell, submitted to JGR, 2022

High-Resolution WAM and FV3-WAM



- WAM at T254, ~50 km resolution, Hydrostatic
- Extend WDAS-GSI data assimilation to 100 km
- Improved gravity wave parameterization
- Thermosphere – Ionosphere data assimilation will be included in the future.



- Finite-Volume Cubed-Sphere Dynamical Core (FV3)
- Non-hydrostatic
- Extending to ~600 km with all the necessary physics

Summary and Next Steps

- The WAM-IPE has been in operation and provide products continuously since July 2021 (https://www.swpc.noaa.gov/products/wam-ipe). The products include ionosphere TEC, MUF, and thermosphere neutral density that are used at the NOAA Space Weather Forecast Office for issuing alerts and warnings.
- Future development of the WAM-IPE
  - Engaging the user community to improve product designs.
  - Implement the DA systems for WAM-IPE operation.
  - High-resolution model for capturing small-scale plasma irregularities (funded by NSF SWQU).
  - New WAM based on the Finite-Volume Cubed-Sphere Dynamical Core FV3 model for the US global forecast system.