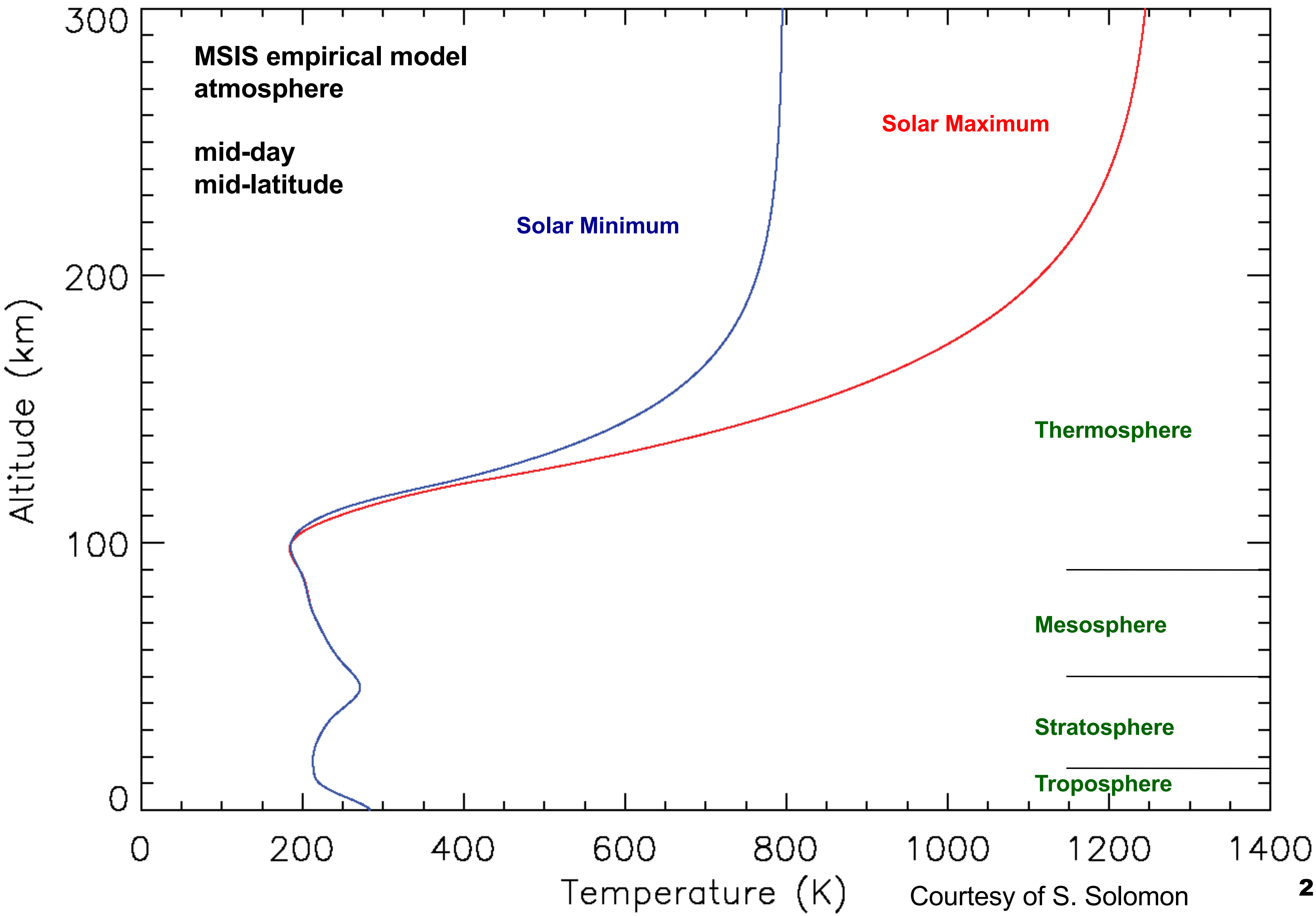
Model Simulation of the Coupled Whole Atmosphere-Ionosphere System

Tzu-Wei Fang

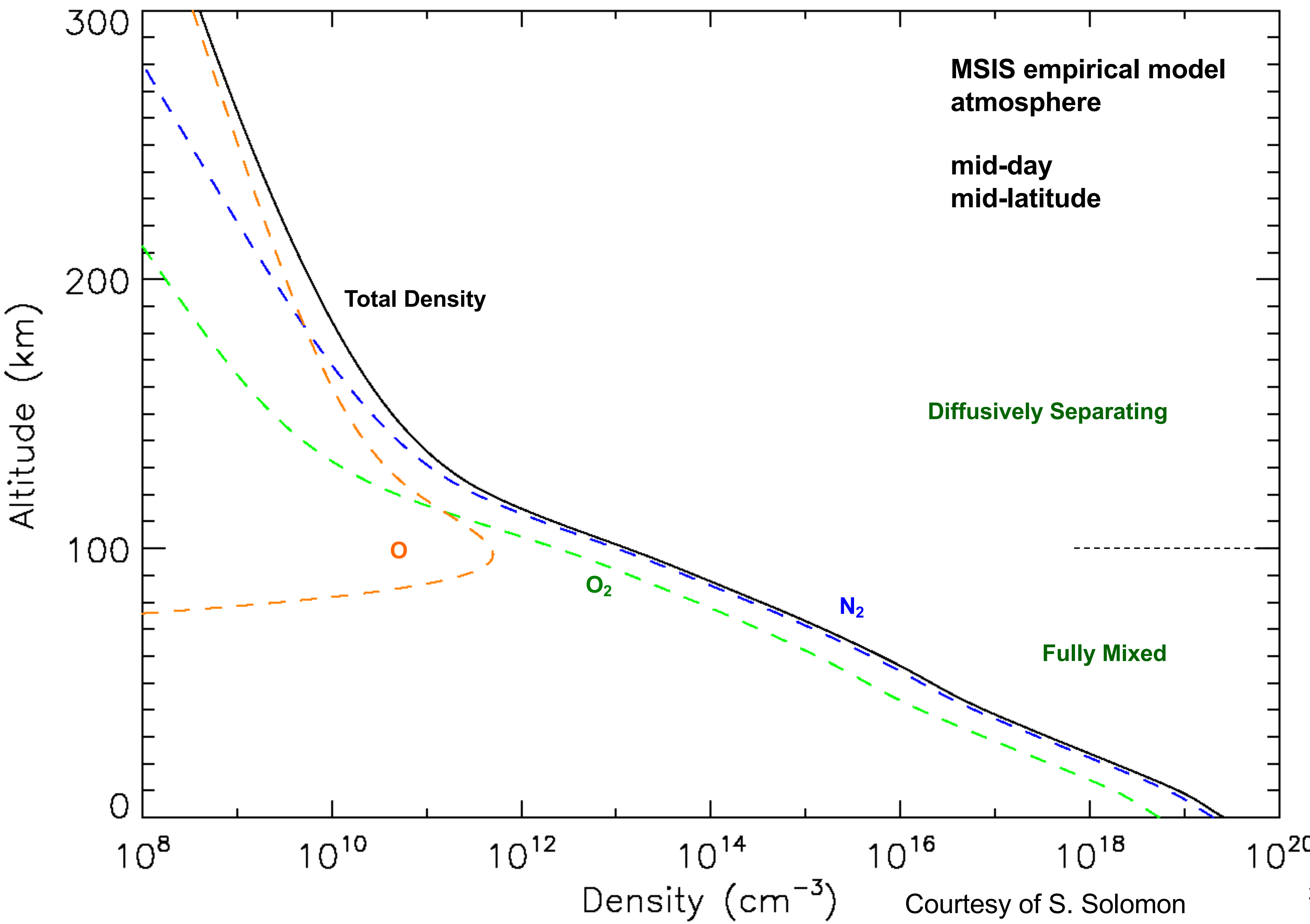
NOAA Space Weather Prediction Center

Temperature Structure of the Atmosphere



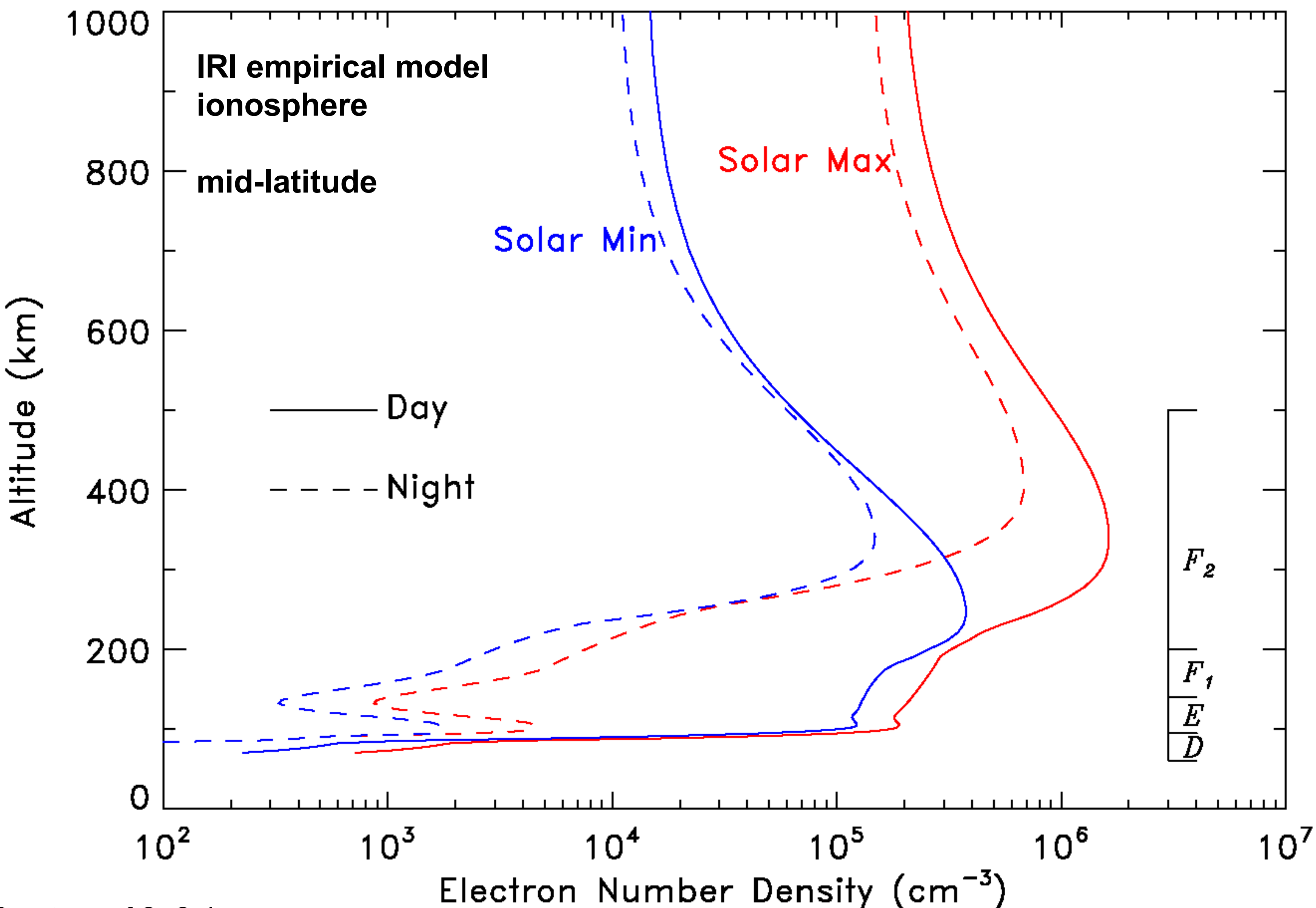
Courtesy of S. Solomon

Major Species Density Structure of the Atmosphere



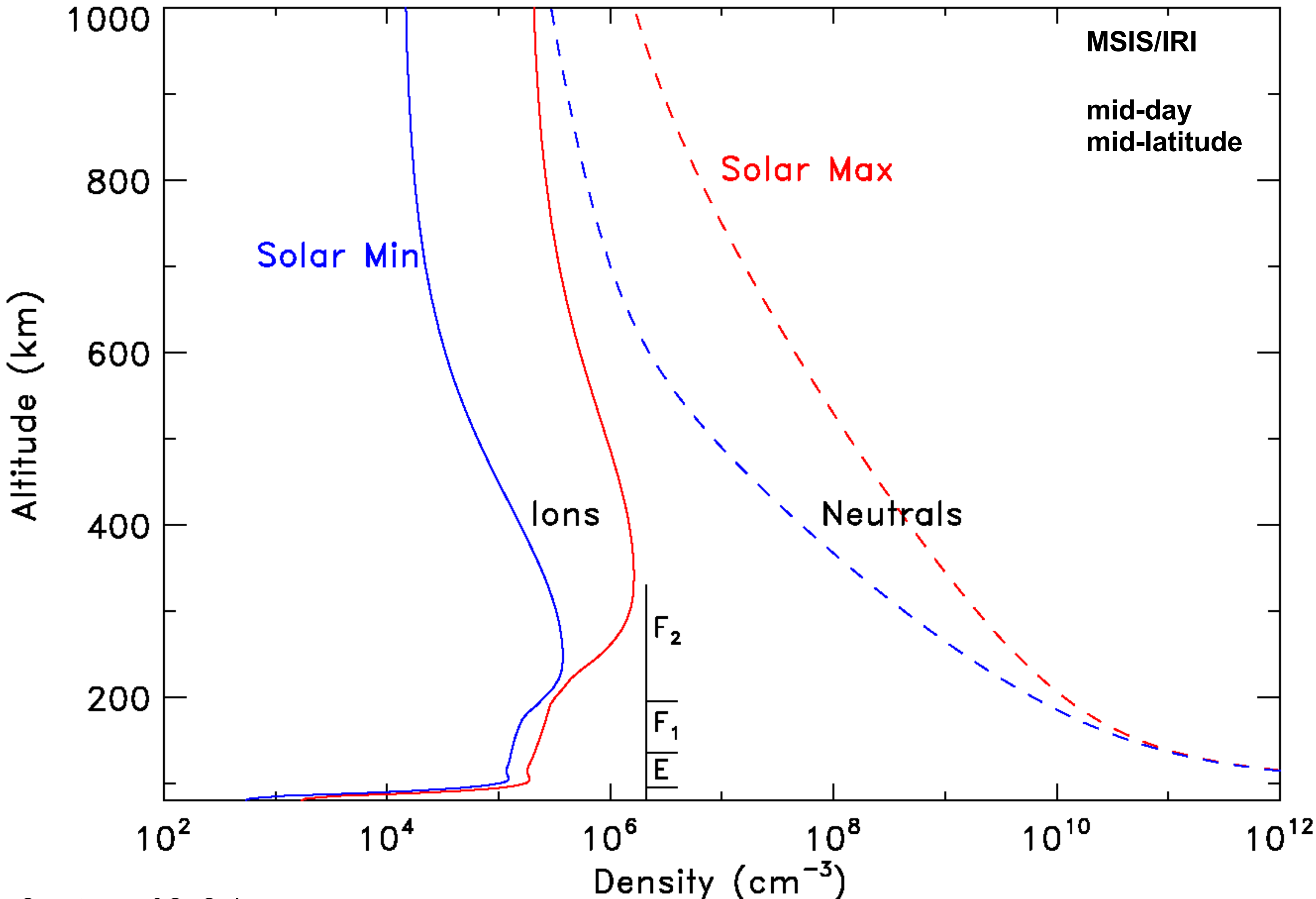
Courtesy of S. Solomon

Ionosphere Basic Altitude Structure



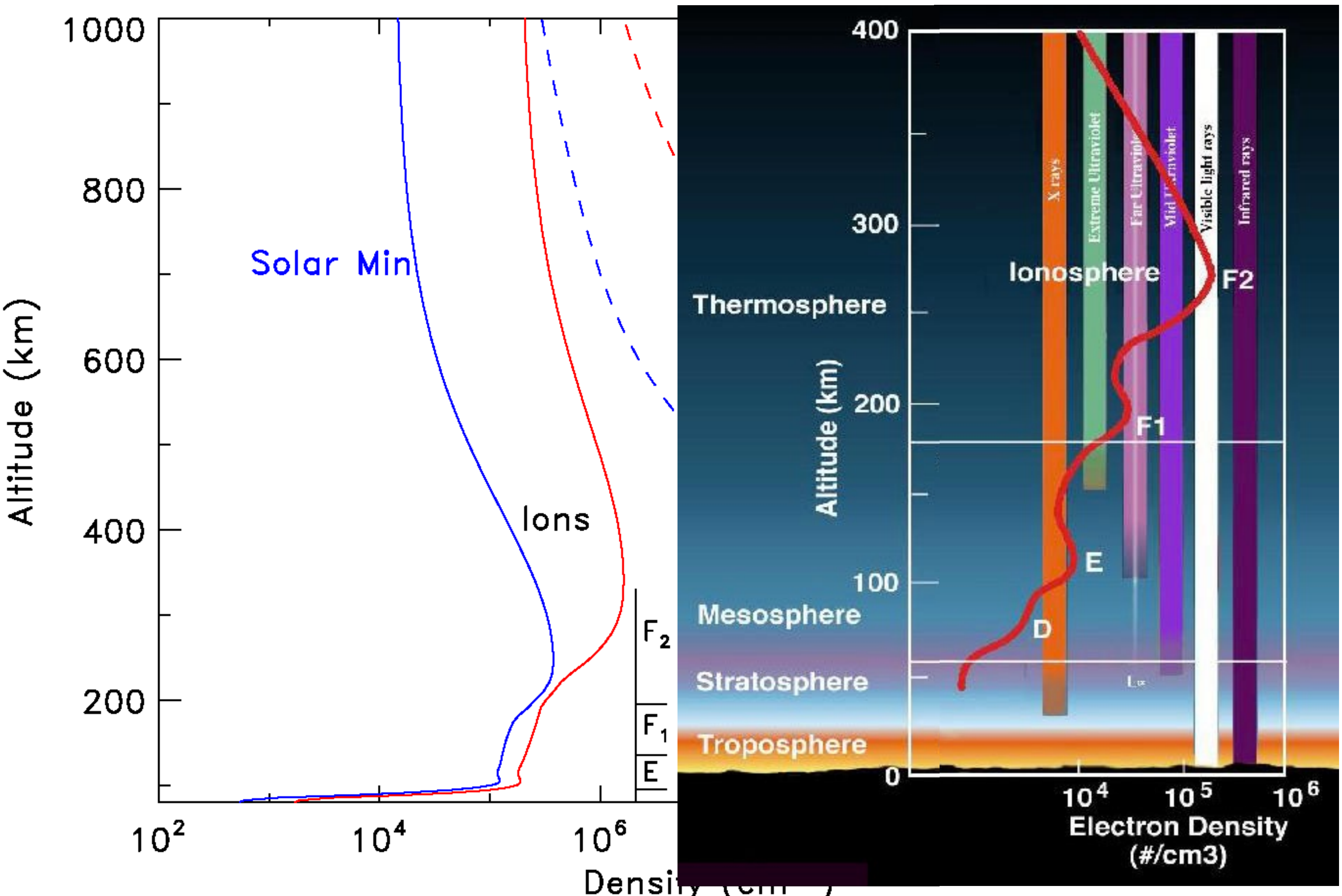
Courtesy of S. Solomon

Thermosphere-Ionosphere Variability



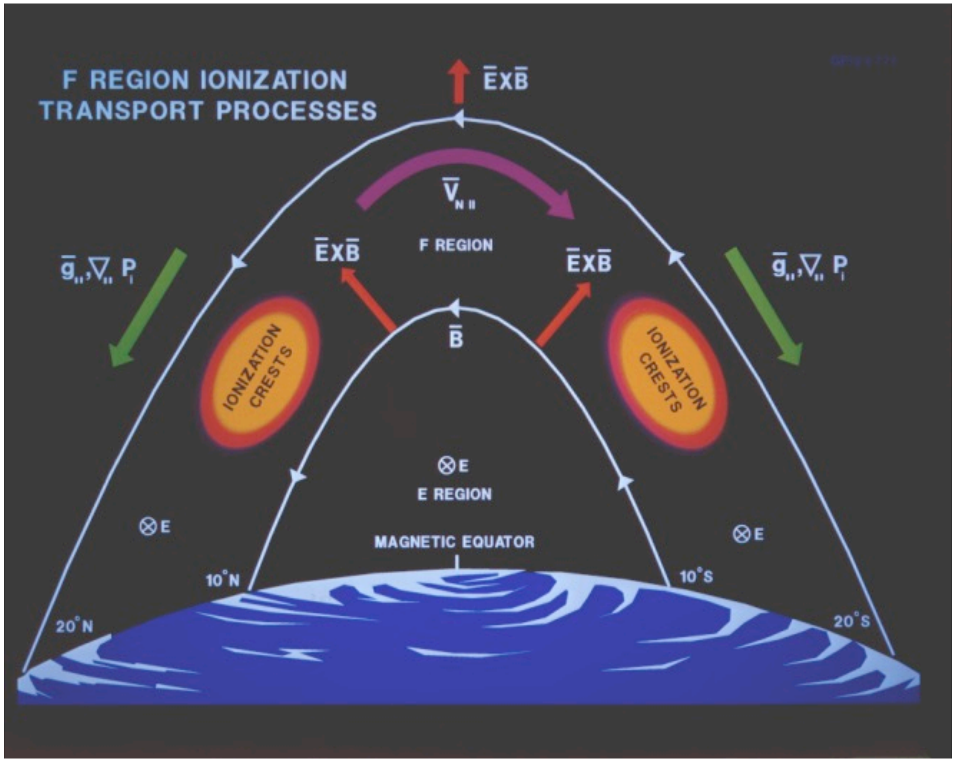
Courtesy of S. Solomon

Thermosphere-Ionosphere Variability



Courtesy of S. Solomon

Transport Processes in the Equatorial Ionosphere

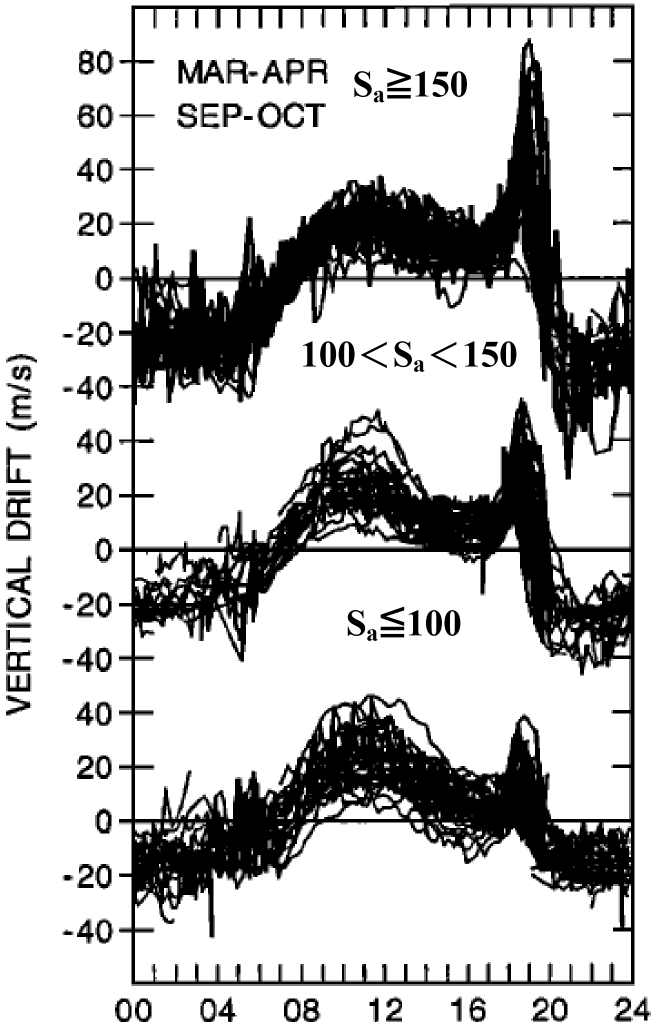


$$\frac{\partial N}{\partial t} = \underbrace{q}_{\text{Prod.}} - \underbrace{\beta(N)}_{\text{Loss}} - \underbrace{div(N\mathbf{V})}_{\text{Transport}}$$

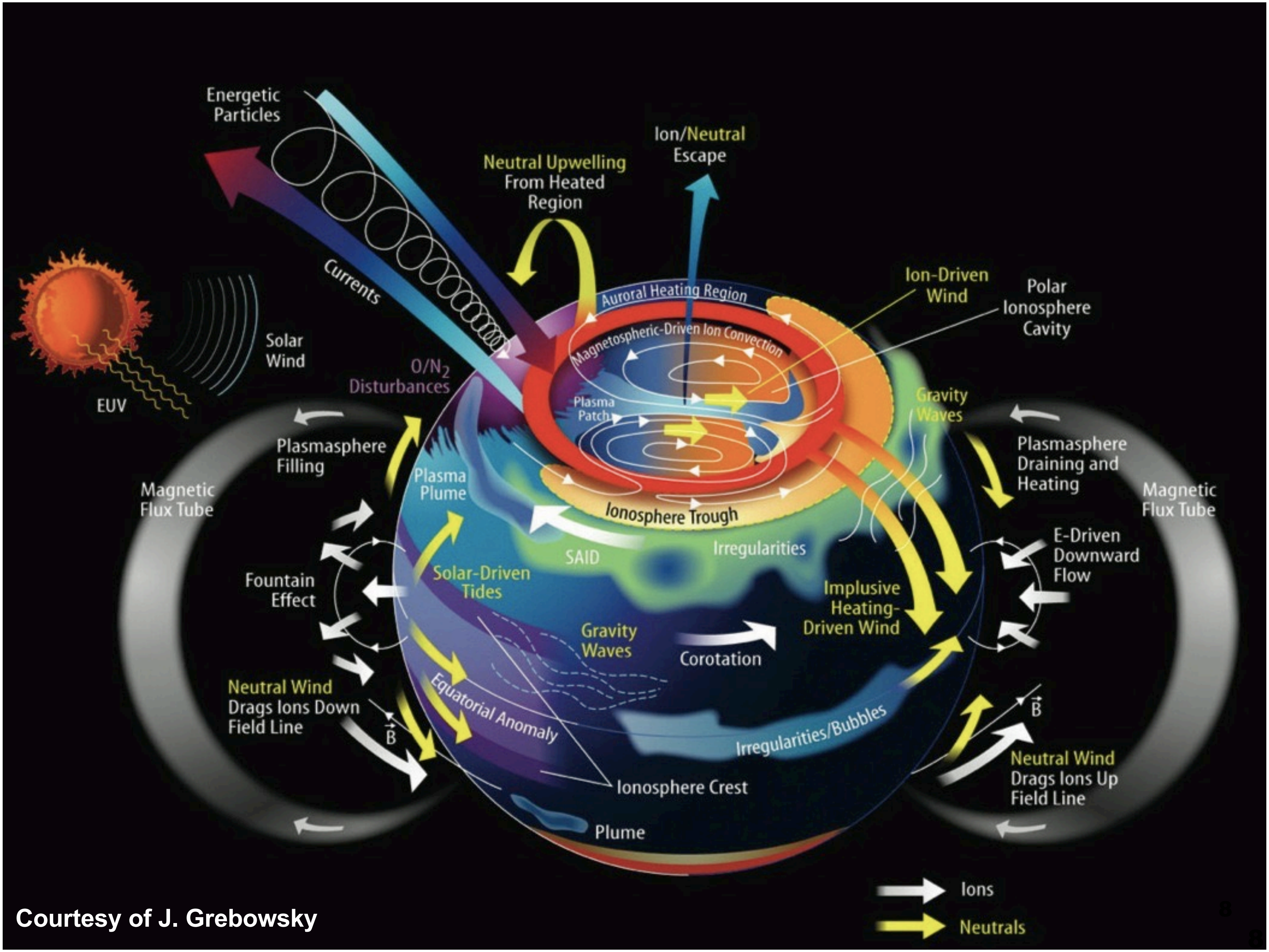
- Perpendicular transport ($V_\perp$)
  - E×B drift
- Zonal transport

- Parallel transport ($V_{\|}$)
  - Neutral wind effect
  - Plasma diffusion
  - Thermo expansion/contraction

Jicamarca Drifts



[Scherliess & Fejer, 1999]

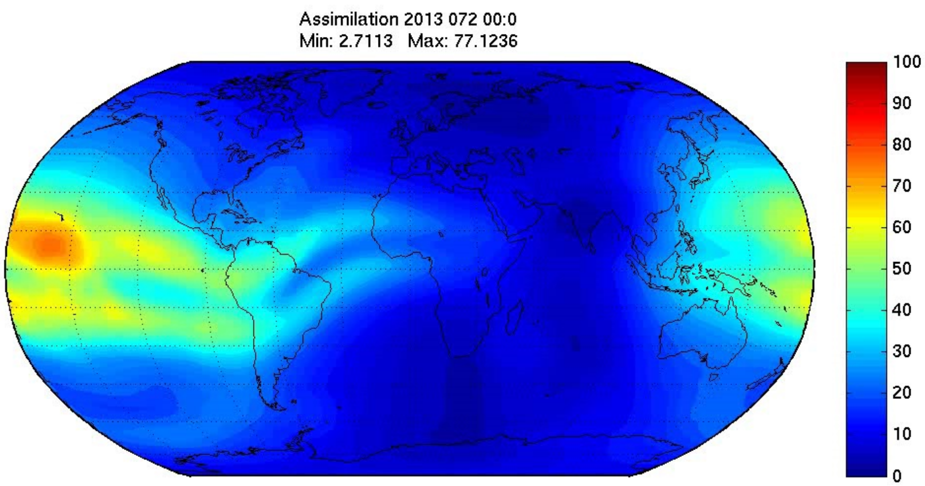


Courtesy of J. Grebowsky

Ionosphere and Thermosphere Weather

Solar and Geomagnetic Activities

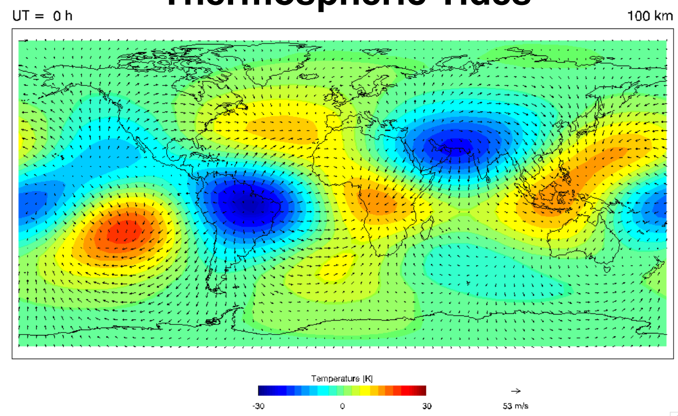
(solar radiation, high-latitude *E*, *aurora, joule heating*)

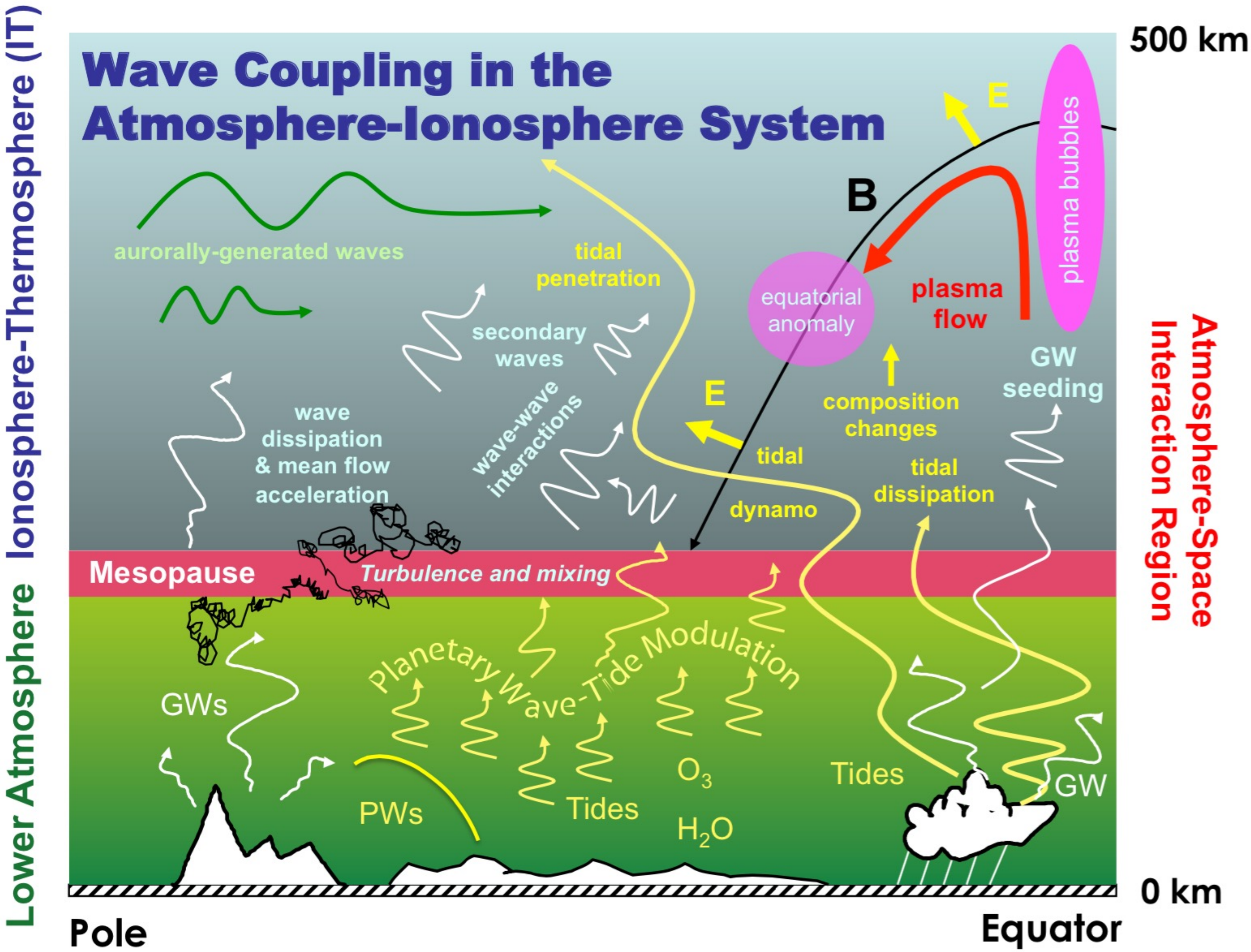


Lower Atmospheric Perturbations

(thermospheric tides, planetary waves, gravity waves)

Thermospheric Tides

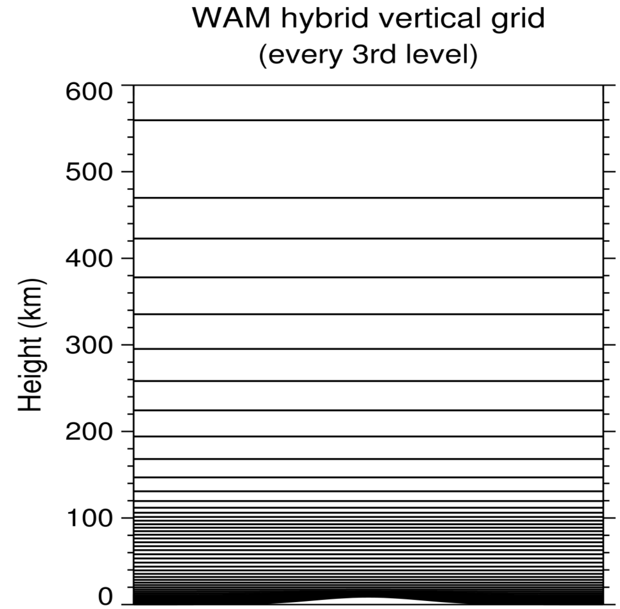


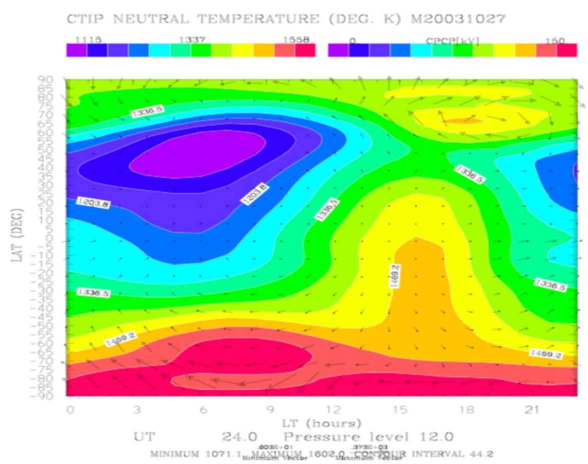


Curtsey of J. Forbes

Whole Atmosphere Model (WAM)

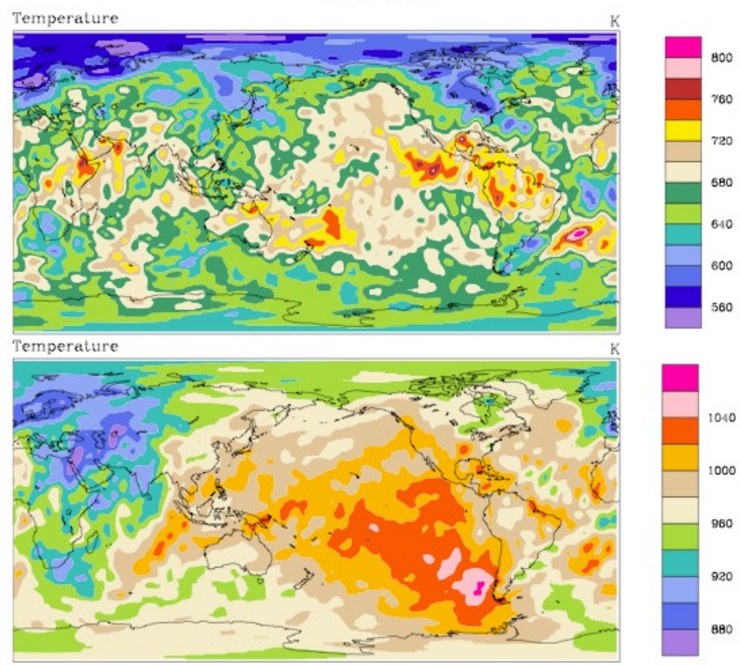
- Global seamless whole atmosphere model (WAM) 0-600 km, 0.25 scale height, $2^{\circ} \times 2^{\circ}$ lat/long, T62, hydrostatic, 150 levels, 10-fold extension of Global Forecasting System (GFS) US weather model.
- O_3 chemistry and transport
- Radiative heating and cooling
- Cloud physics and hydrology
- Sea surface temperature field and surface exchange processes
- Orographic and non orographic gravity waves parameterization
- Diffusive separation, ion drag, Joule heating, etc.





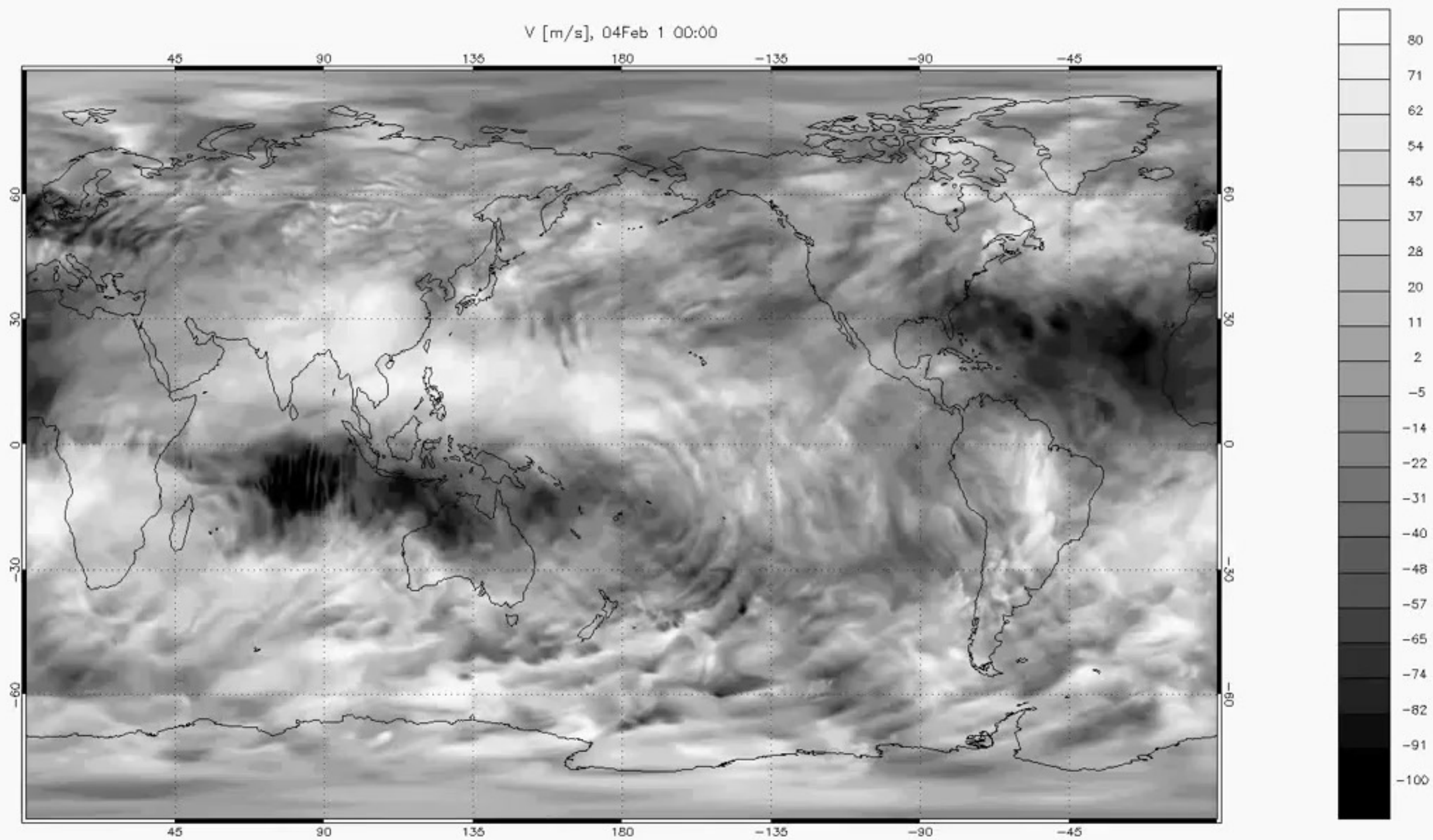
CTIPe thermospheric temperature (like MSIS)

WAM
150 and 300 km altitude



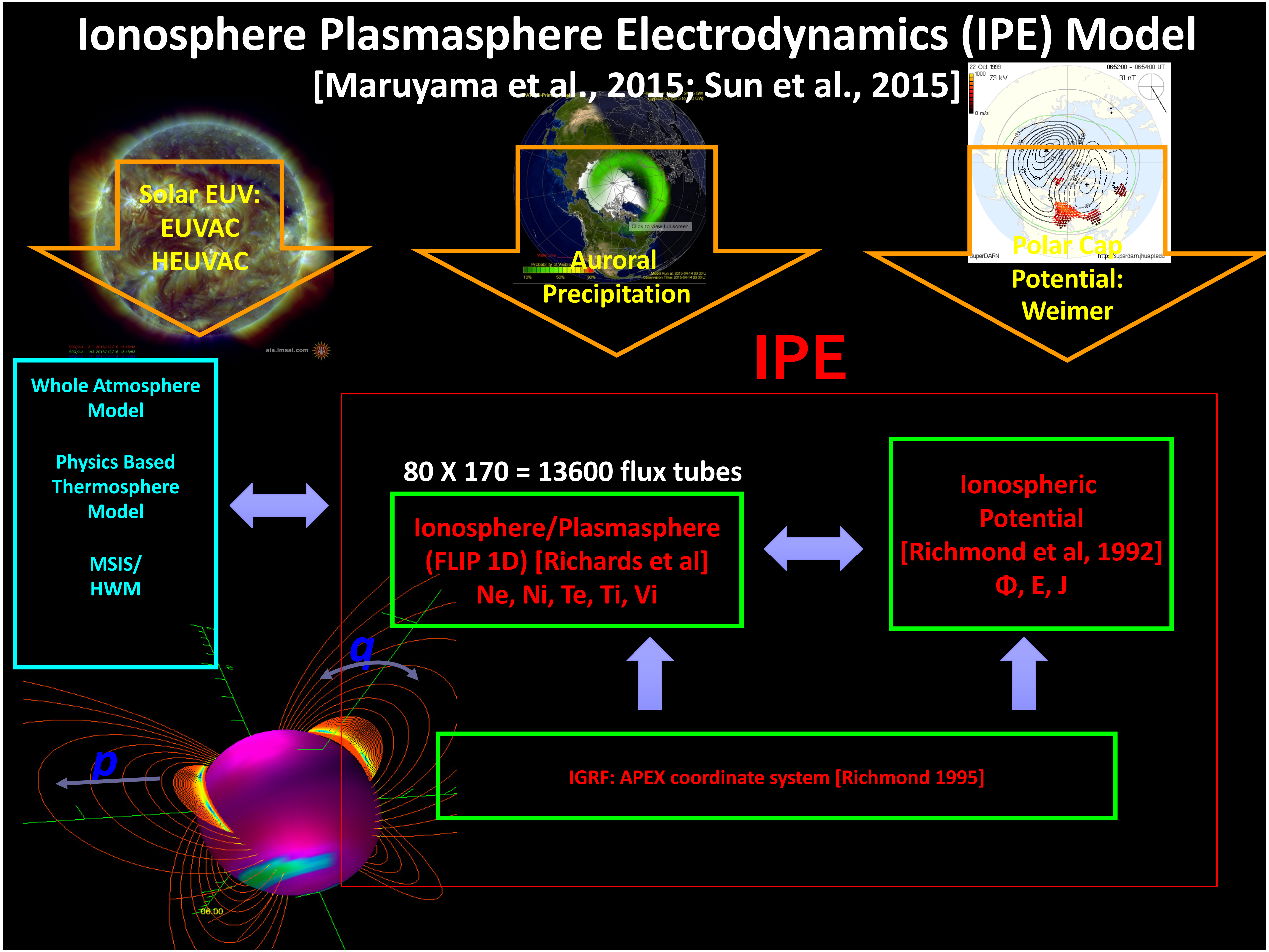
WAM global temperature

NCAR Whole Atmosphere Community Climate Model (WACCM)



Courtesy of Hanli Liu (NCAR/HAO)

https://www2.hao.ucar.edu/news/2015-jan/linking-terrestrial-and-space-weather-using-high-resolution-waccm


Ionosphere Plasmasphere Electrodynamics (IPE) Model
[Maruyama et al., 2015; Sun et al., 2015]
Solar EUV:
EUVAC
HEUVAC
Auroral
Precipitation
Polar Cap
Potential:
Weimer
aia.lmsal.com
22 Oct 1999
73 kV
31 nT
SuperDARN
IPE
Whole Atmosphere
Model
Physics Based
Thermosphere
Model
MSIS/
HWM
80 X 170 = 13600 flux tubes
Ionosphere/Plasmasphere
(FLIP 1D) [Richards et al]
Ne, Ni, Te, Ti, Vi
Ionospheric
Potential
[Richmond et al, 1992]
Φ, E, J
IGRF: APEX coordinate system [Richmond 1995]
q
p
06:00

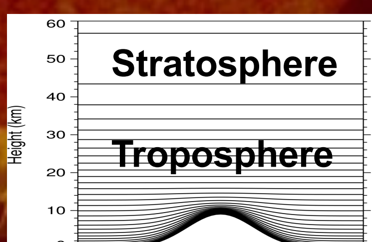
Integrated Dynamics in Earth's Atmosphere (IDEA)

Whole Atmosphere Model (WAM = Extended GFS)
Ionosphere Plasmasphere Electrodynamics (IPE)
Integrated Dynamics in Earth's Atmosphere (IDEA = WAM+IPE)

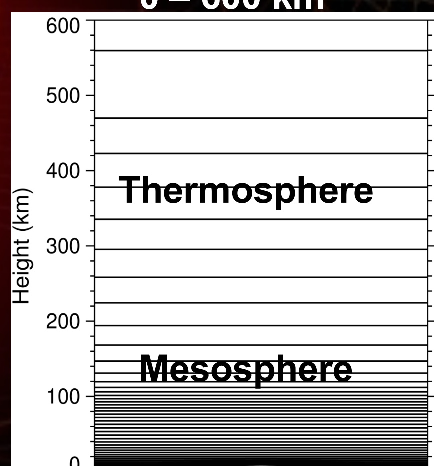
- **History:**
  - Research development started in 2004 with NASA, NSF, DOD funding
  - Focus shifts to operational implementation in 2011
- **Execute Real-time run of WAM-IPE on NOAA WCOSS since 2017**

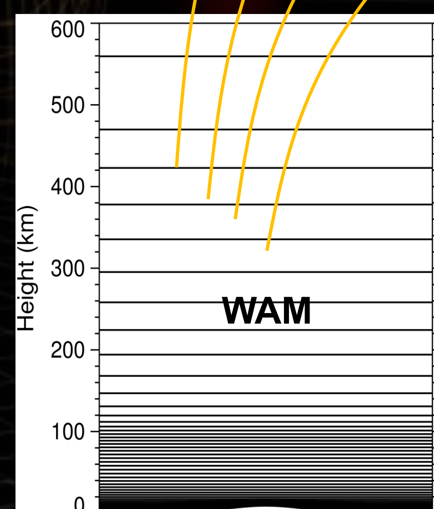
Ionosphere/Plasmasphere Model

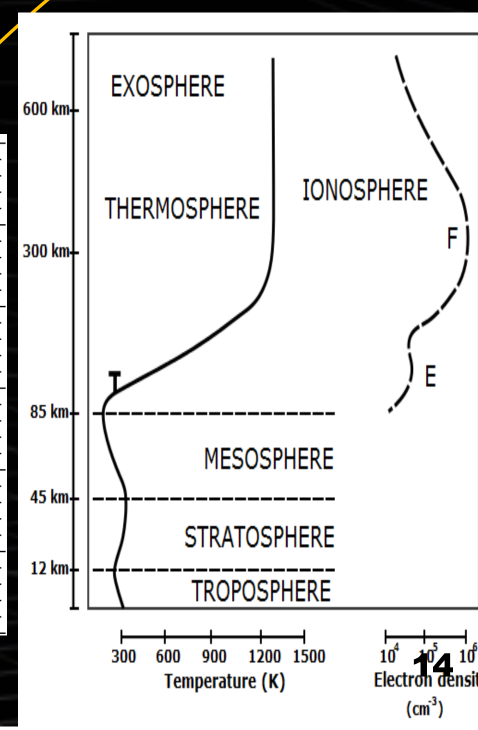
GFS
0 – 60 km



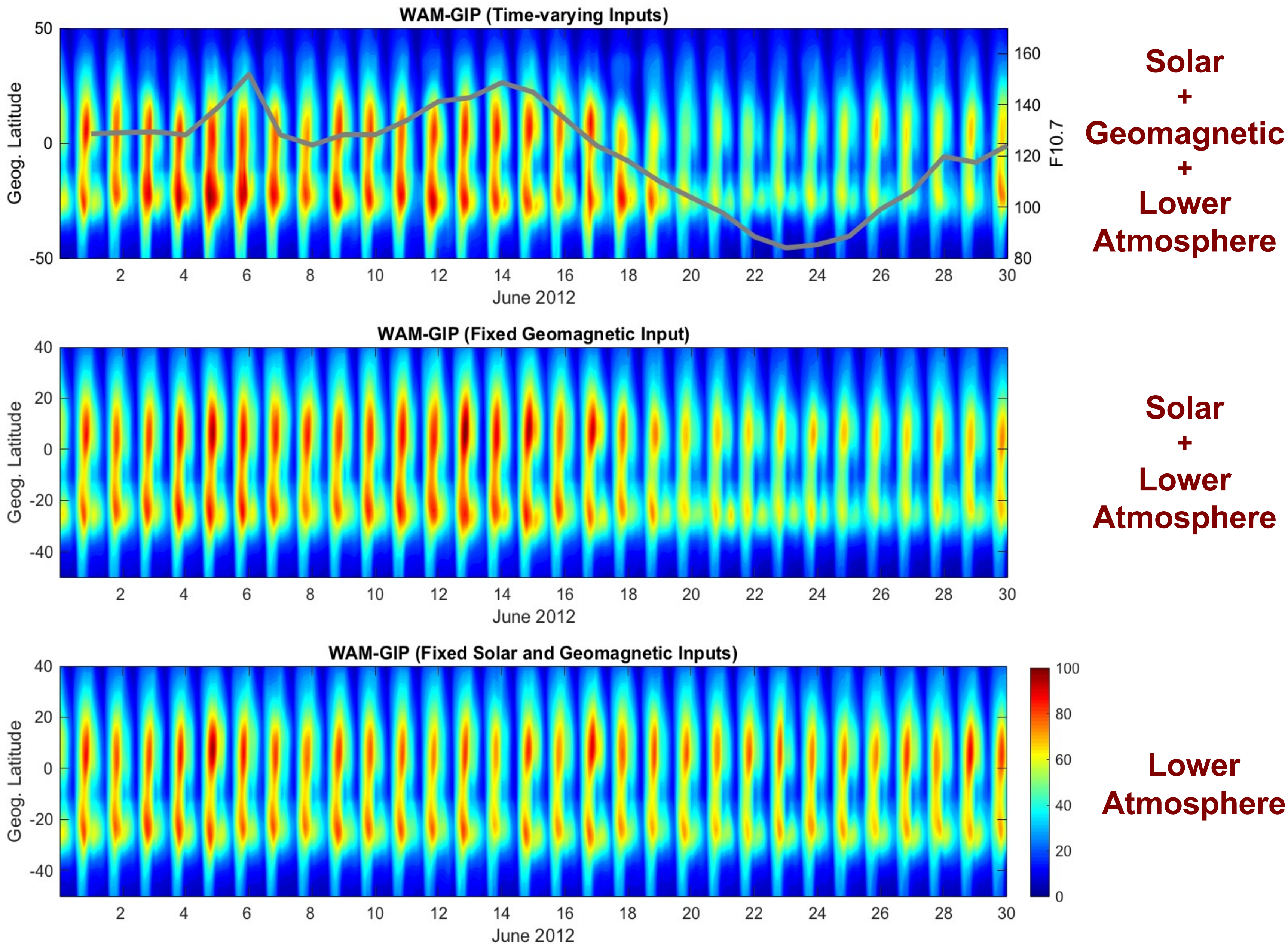
WAM
Neutral Atmosphere
0 – 600 km





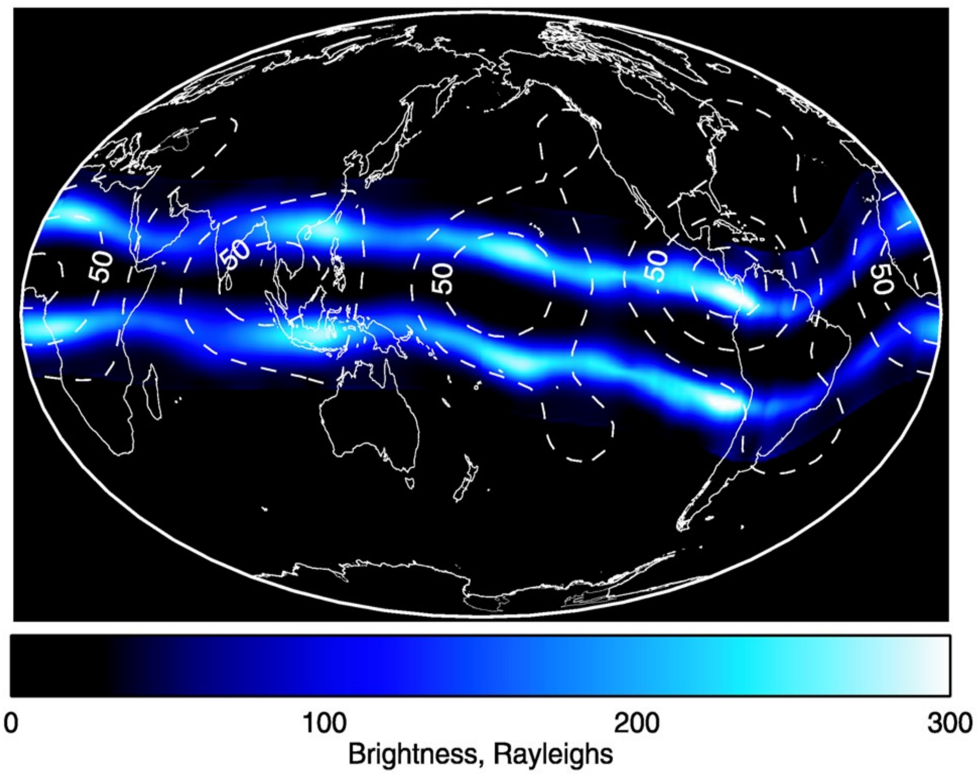


TEC at 75°W

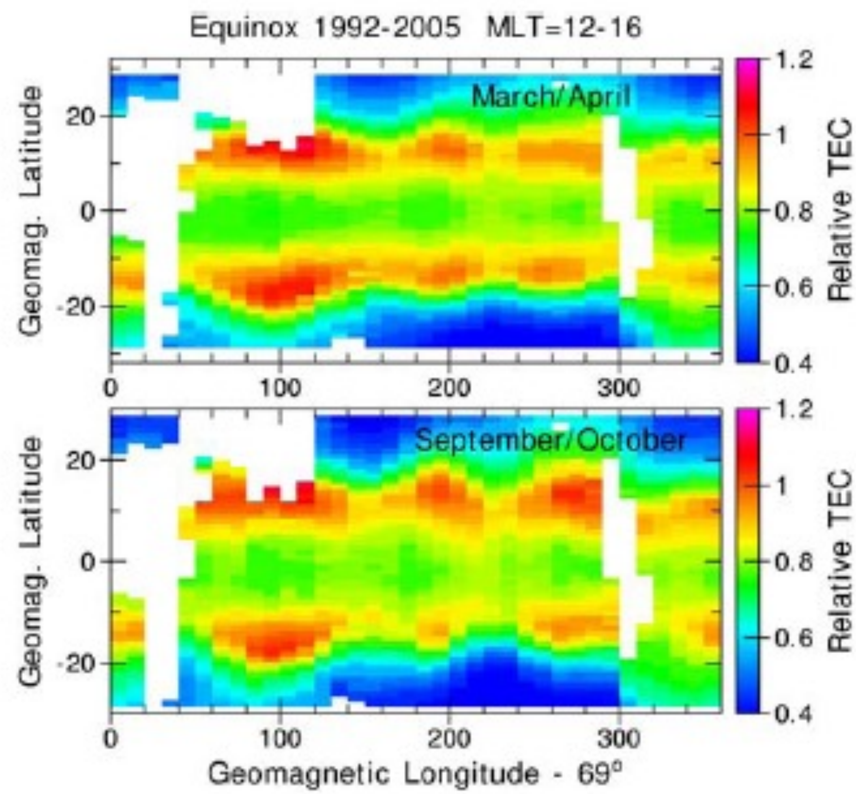

WAM-GIP (Time-varying Inputs)
Geog. Latitude
F10.7
June 2012
WAM-GIP (Fixed Geomagnetic Input)
Geog. Latitude
June 2012
WAM-GIP (Fixed Solar and Geomagnetic Inputs)
Geog. Latitude
June 2012
Solar + Geomagnetic + Lower Atmosphere
Solar + Lower Atmosphere
Lower Atmosphere

Impact of the Lower Atmosphere on the Upper Atmosphere

Longitudinal and Day-to-day Variability in the Ionosphere

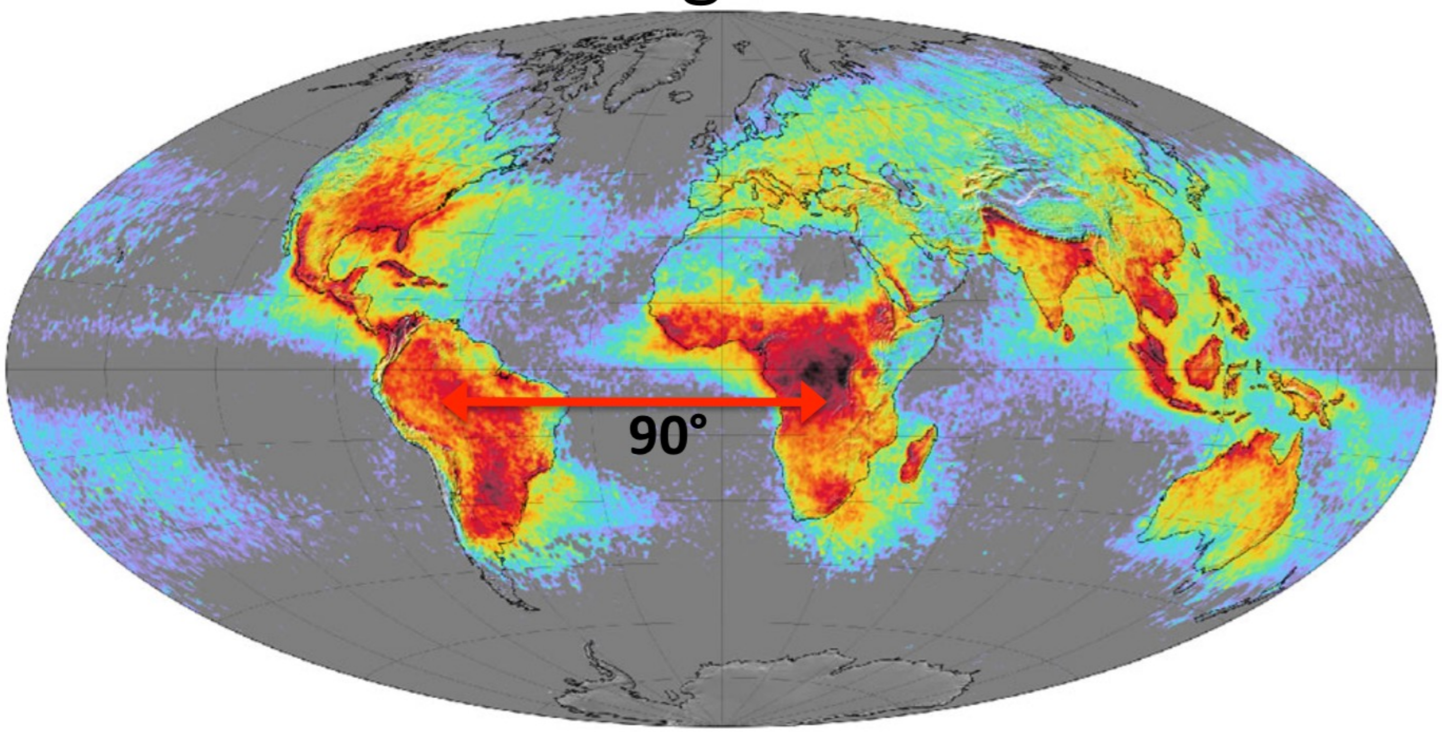


Nighttime ionospheric emission from IMAGE-FUV imager. (Immel et al., 2006)



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

Drivers of longitude structure



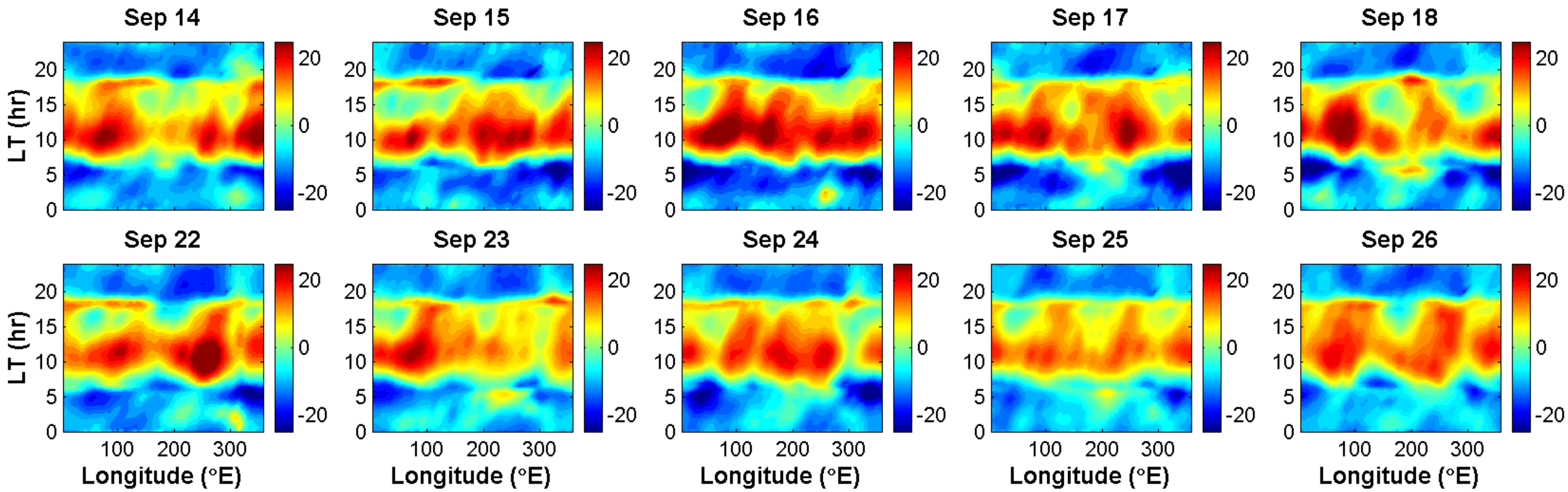
Lightning strikes from convective storms, signature of latent heat release:
Either three or four peaks in longitude: wave 3 or 4
Illuminated by the Sun every 24 hours: diurnal

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

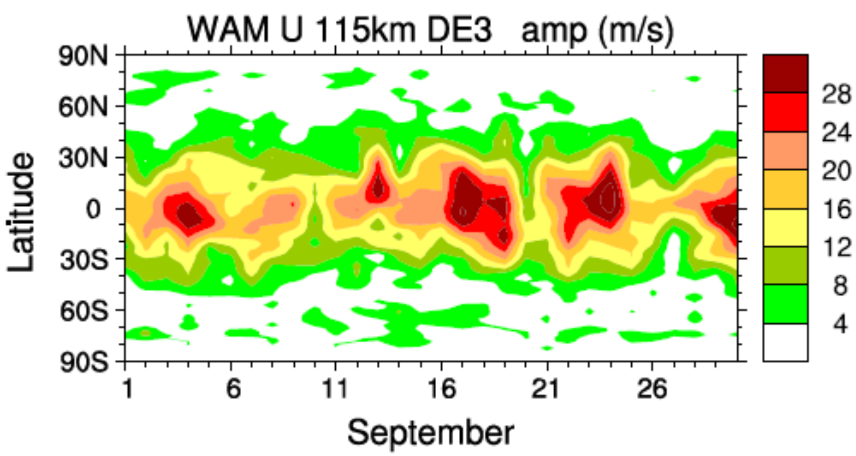
$$\cos(\Omega t + \lambda)\cos 3\lambda \quad \text{--->} \quad \cos(\Omega t + 4\lambda) + \cos(\Omega t - 2\lambda)$$

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

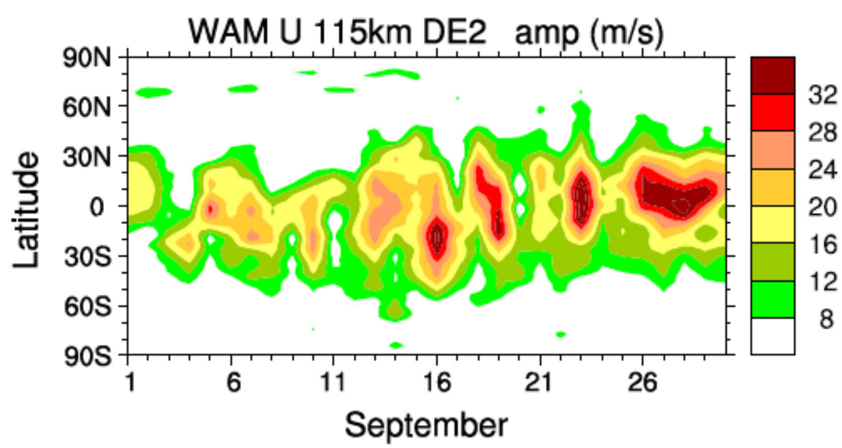
Equatorial Vertical Drift (m/s)



4-Peak Structure



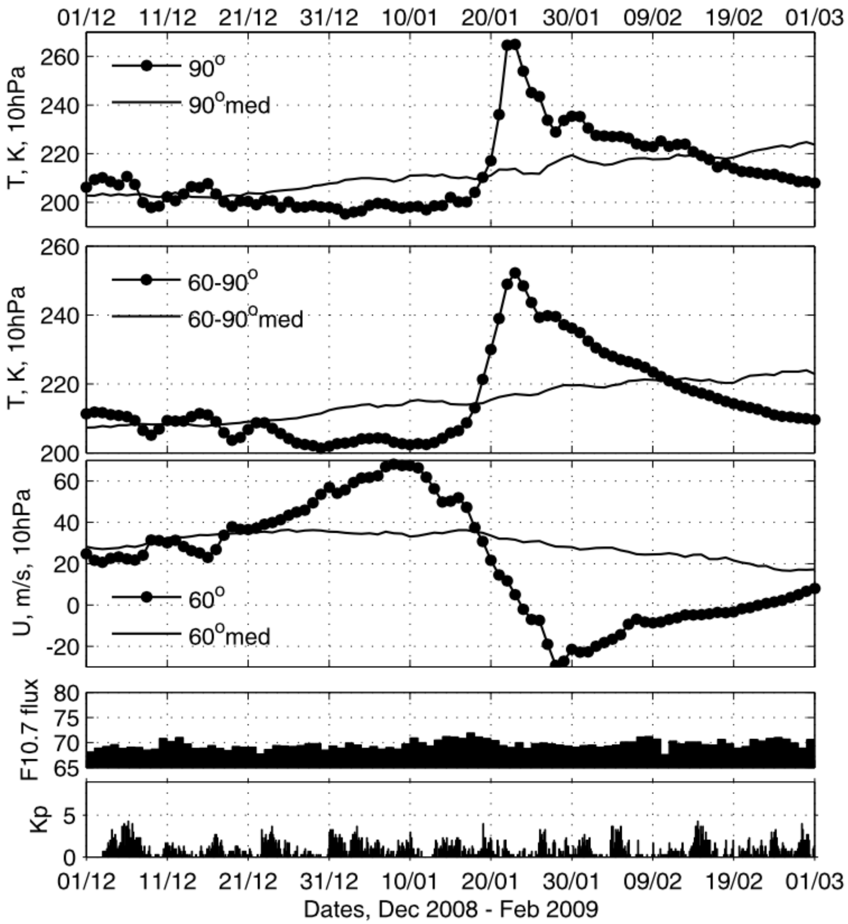
3-Peak Structure

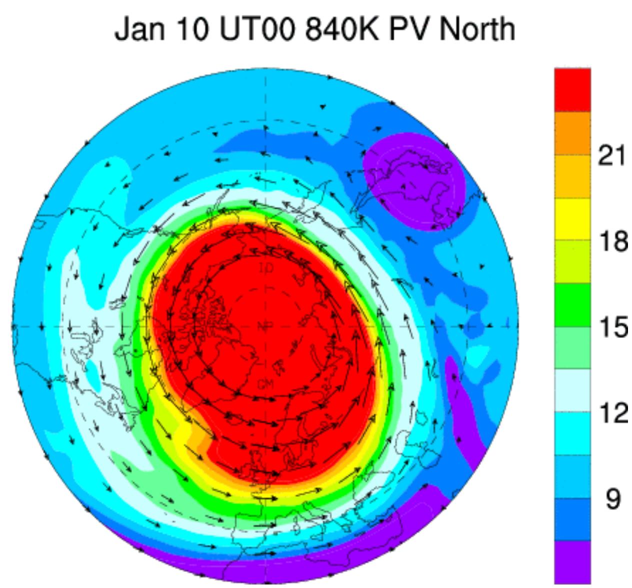


Modulation of DE3 and DE2 tidal amplitudes correlates with number of peaks in longitude structure of vertical plasma drift

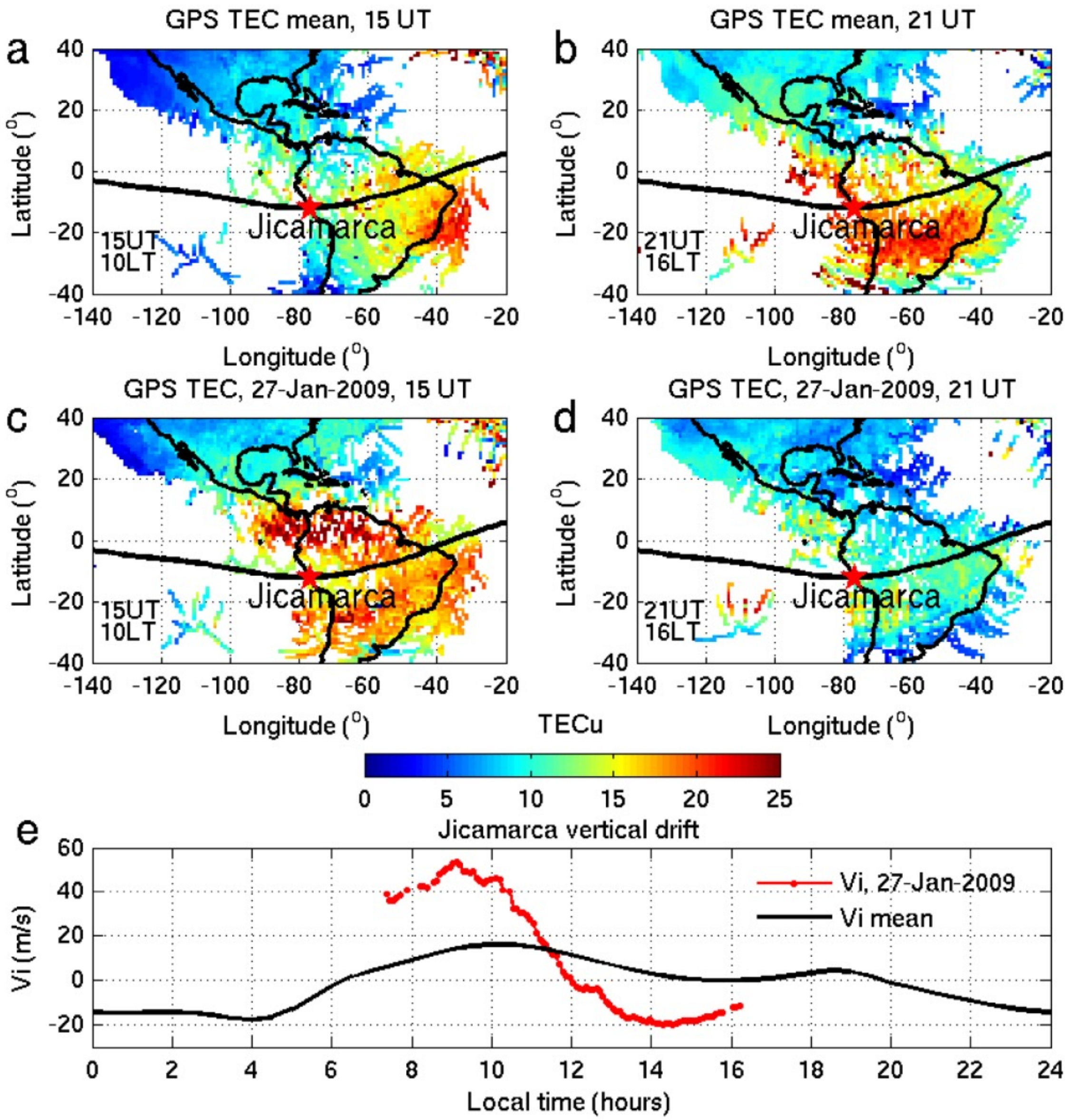
2009 January Sudden Stratospheric Warming

NOAA NCEP Dataset





Ionospheric Responses to Sudden Stratospheric Warming Events



Goncharenko et al. (2010):

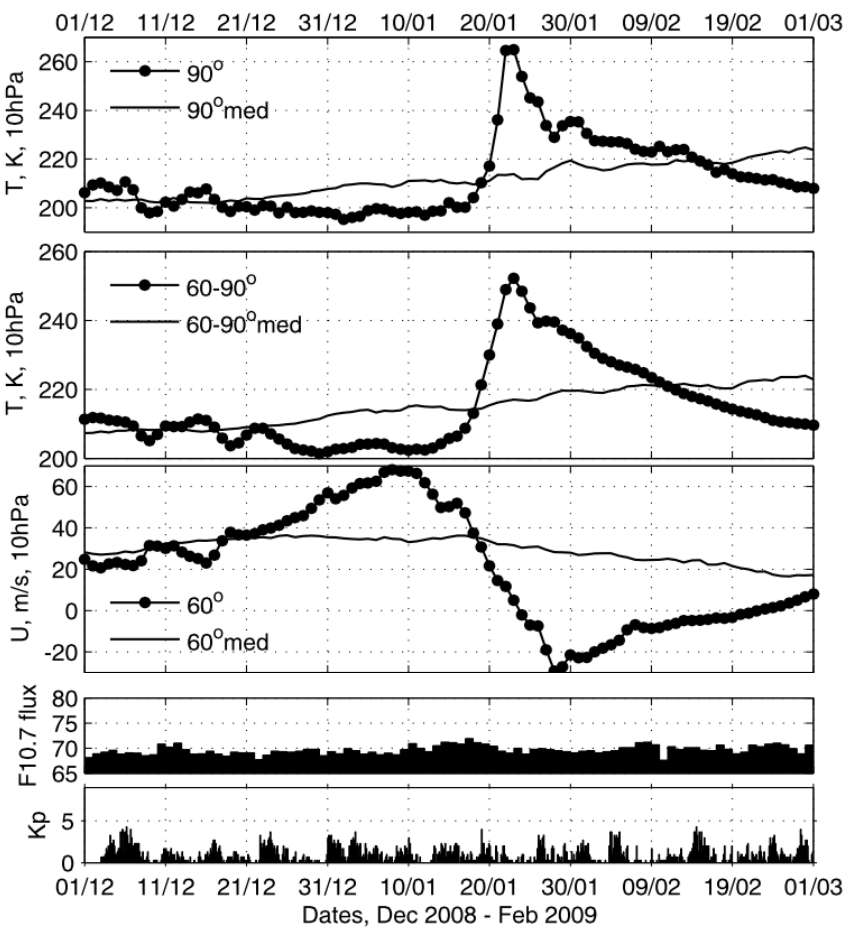
Climatological TEC at 10 and 16 LT from ground GPS observations.

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

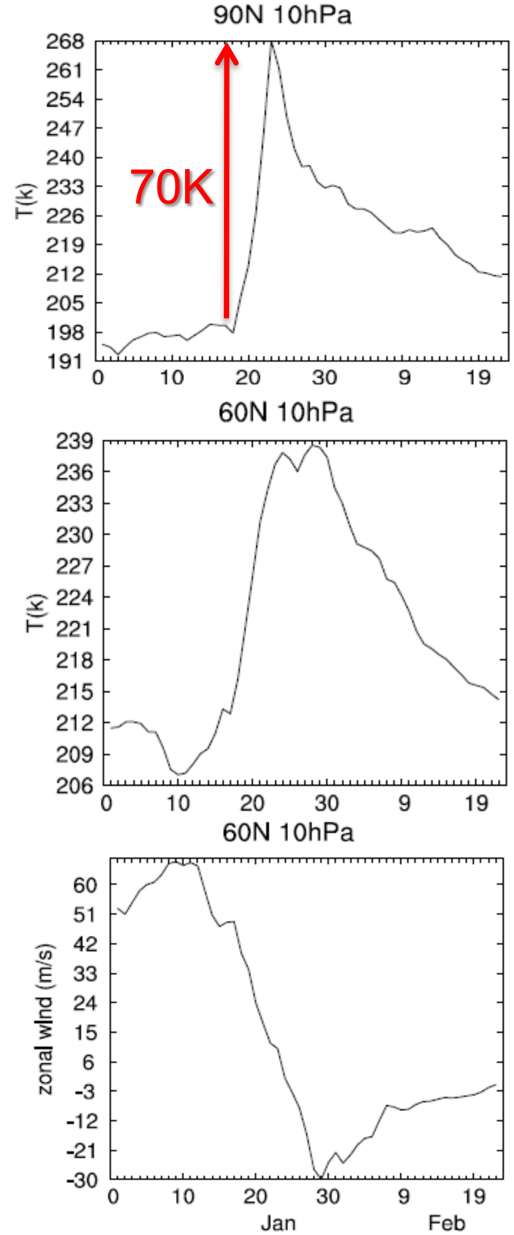
Comparison of plasma drift climatology with observations at Jicamarca on Jan. 27.

2009 January Sudden Stratospheric Warming

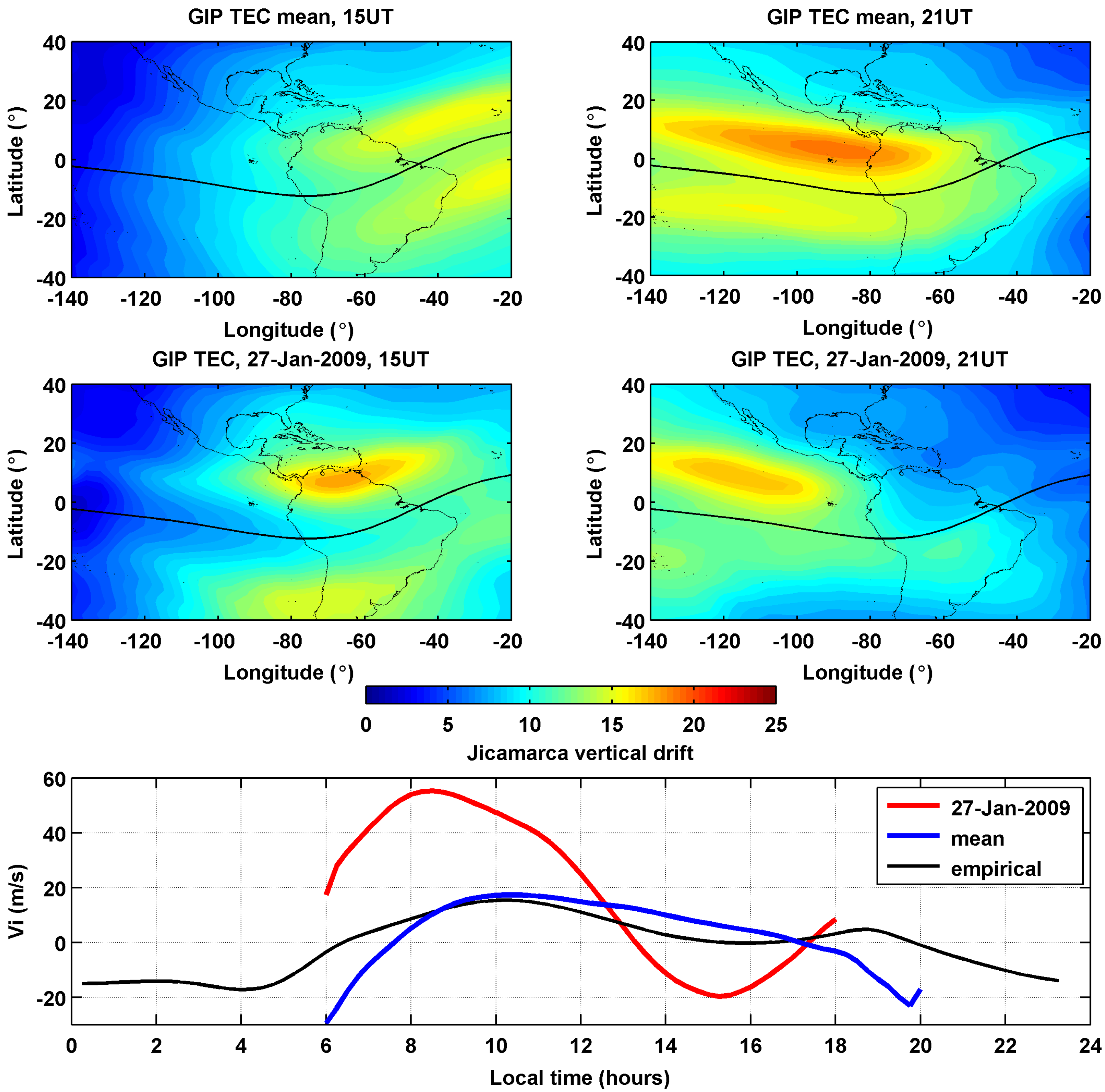
NOAA NCEP Dataset



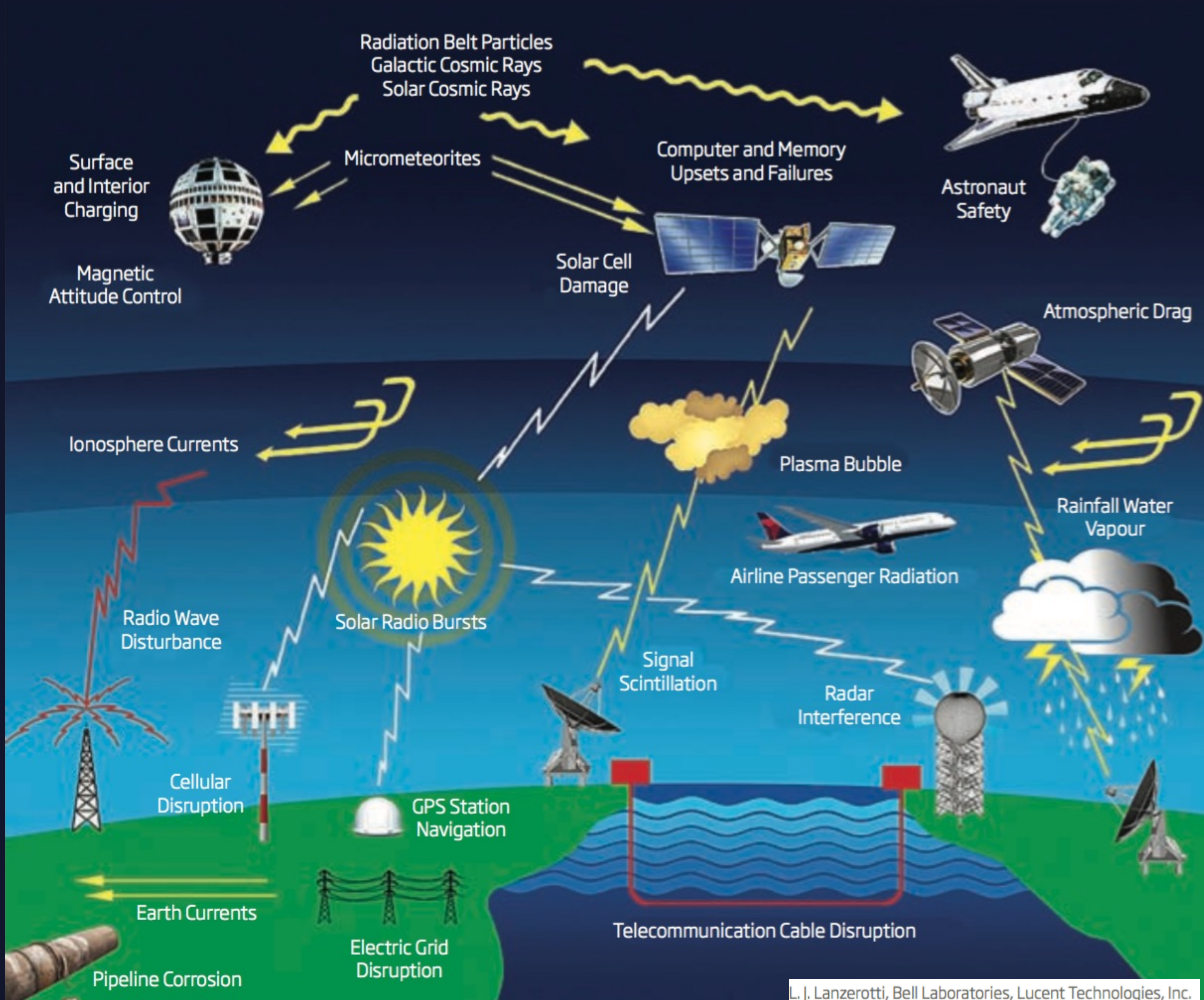
WAM Data Assimilation and Forecast System

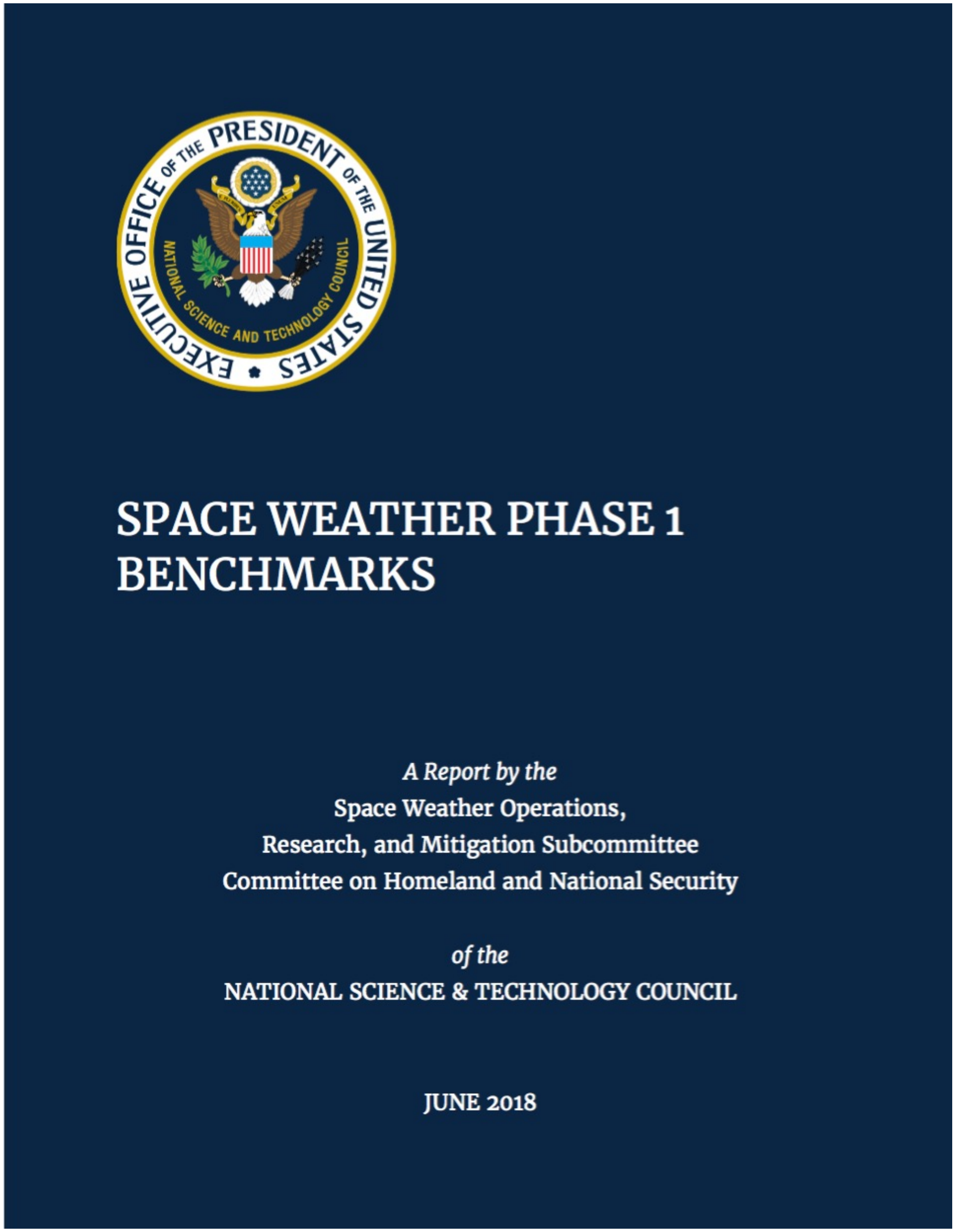


Simulation Results



Impact of Space Weather





SPACE WEATHER PHASE 1 BENCHMARKS

A Report by the
Space Weather Operations,
Research, and Mitigation Subcommittee
Committee on Homeland and National Security

of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

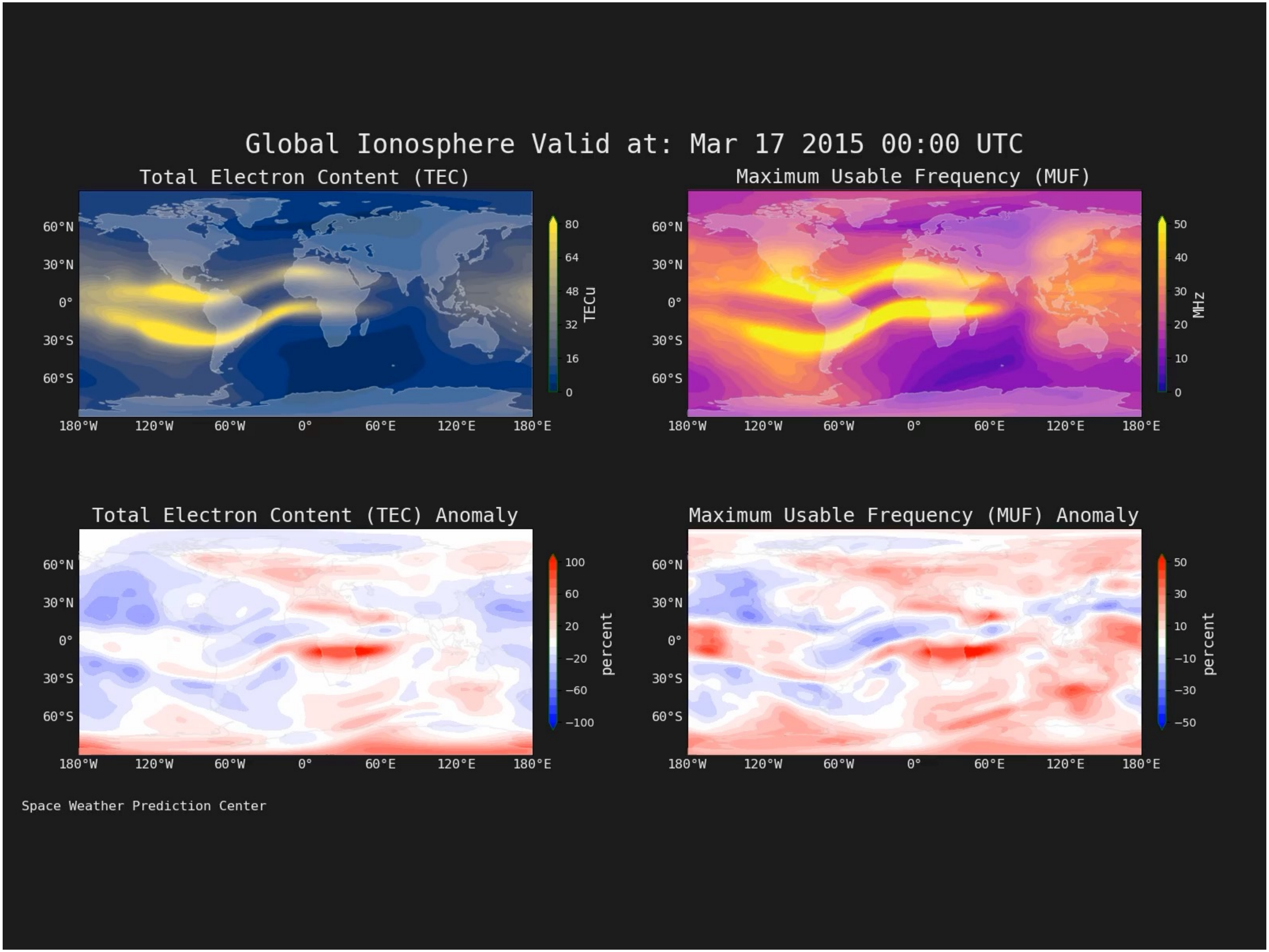
JUNE 2018

Executive Order -- Coordinating Efforts to Prepare the Nation for Space Weather Events

Space Weather Operations, Research, and Mitigation (SWORM) Subcommittee -- to coordinate Federal Government departments and agencies to enhance national preparedness by achieving the goals and objectives identified in National Space Weather Strategy.

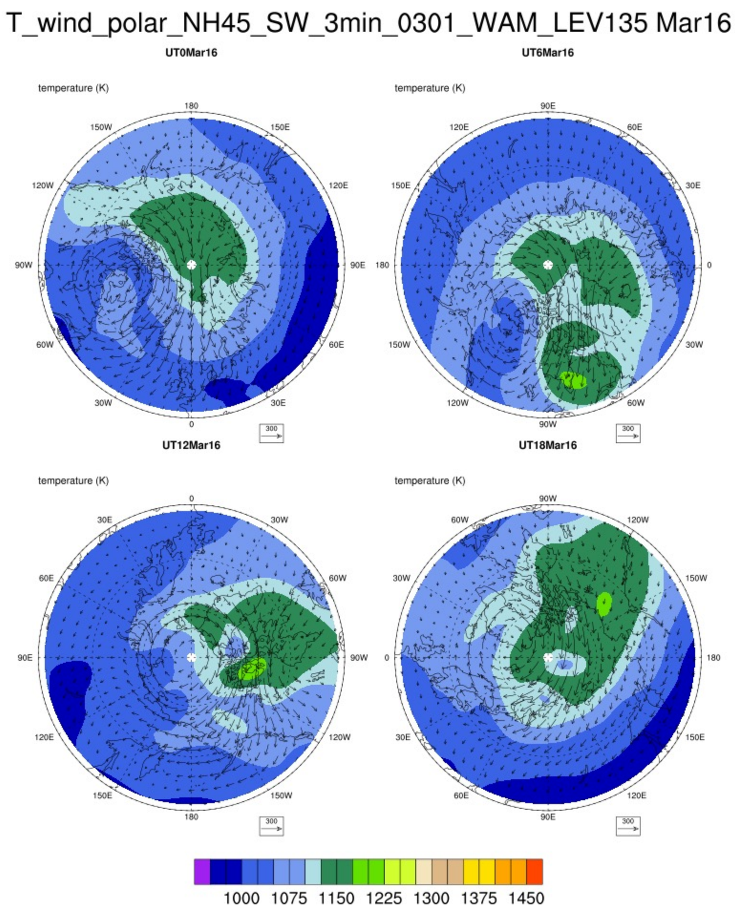
Initial benchmarks for five phenomena associated with space weather events identified in the **National Space Weather Action Plan**:

1. Induced geo-electric fields
2. Ionizing radiation
3. Ionospheric disturbances
4. Solar radio bursts
5. Upper atmospheric expansion

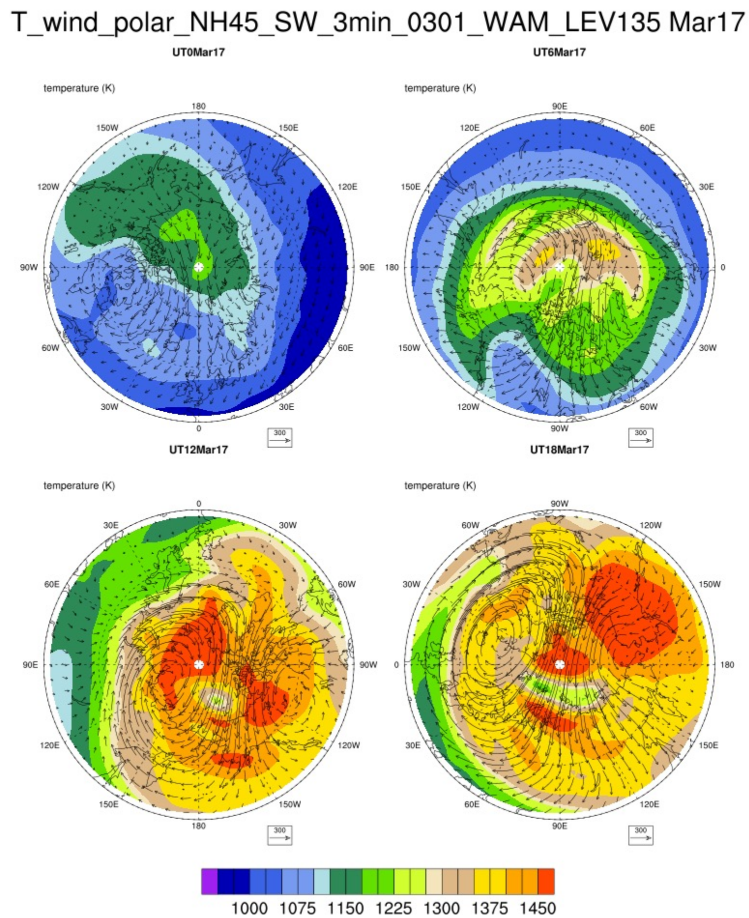

Global Ionosphere Valid at: Mar 17 2015 00:00 UTC
Total Electron Content (TEC)
Maximum Usable Frequency (MUF)
Total Electron Content (TEC) Anomaly
Maximum Usable Frequency (MUF) Anomaly
60°N
30°N
0°
30°S
60°S
180°W
120°W
60°W
0°
60°E
120°E
180°E
TECu
0
16
32
48
64
80
MHz
0
10
20
30
40
50
percent
−100
−60
−20
20
60
100
percent
−50
−30
−10
10
30
50
Space Weather Prediction Center

2013 St. Patrick's Day Storm

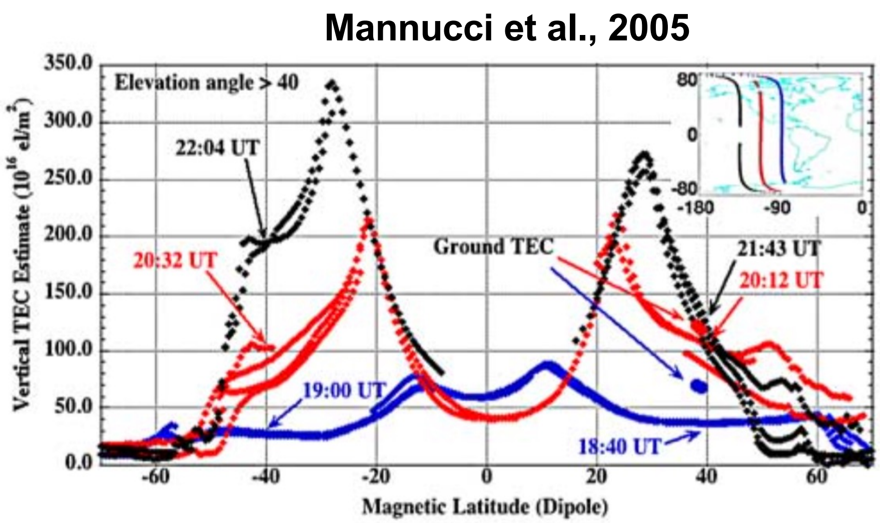
Quiet Day

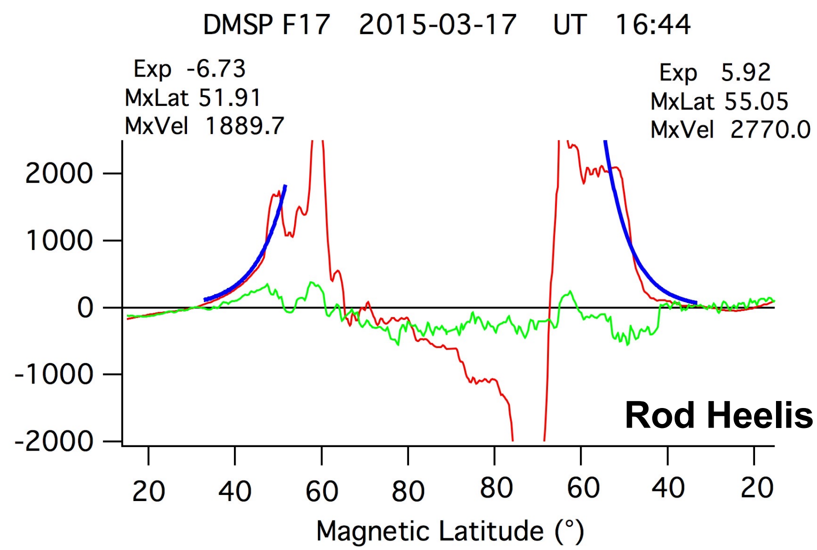


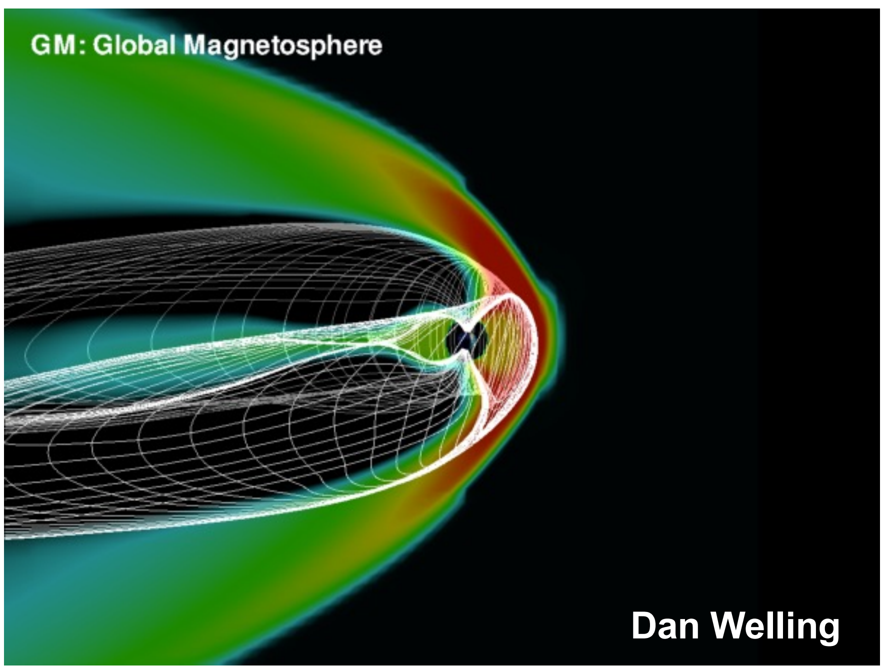
Storm Day

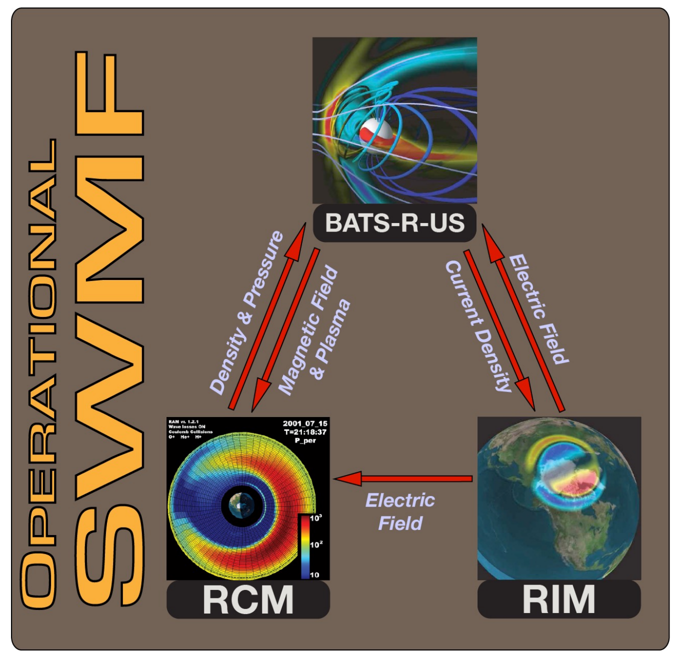


Michigan Geospace Model for M-I Coupling

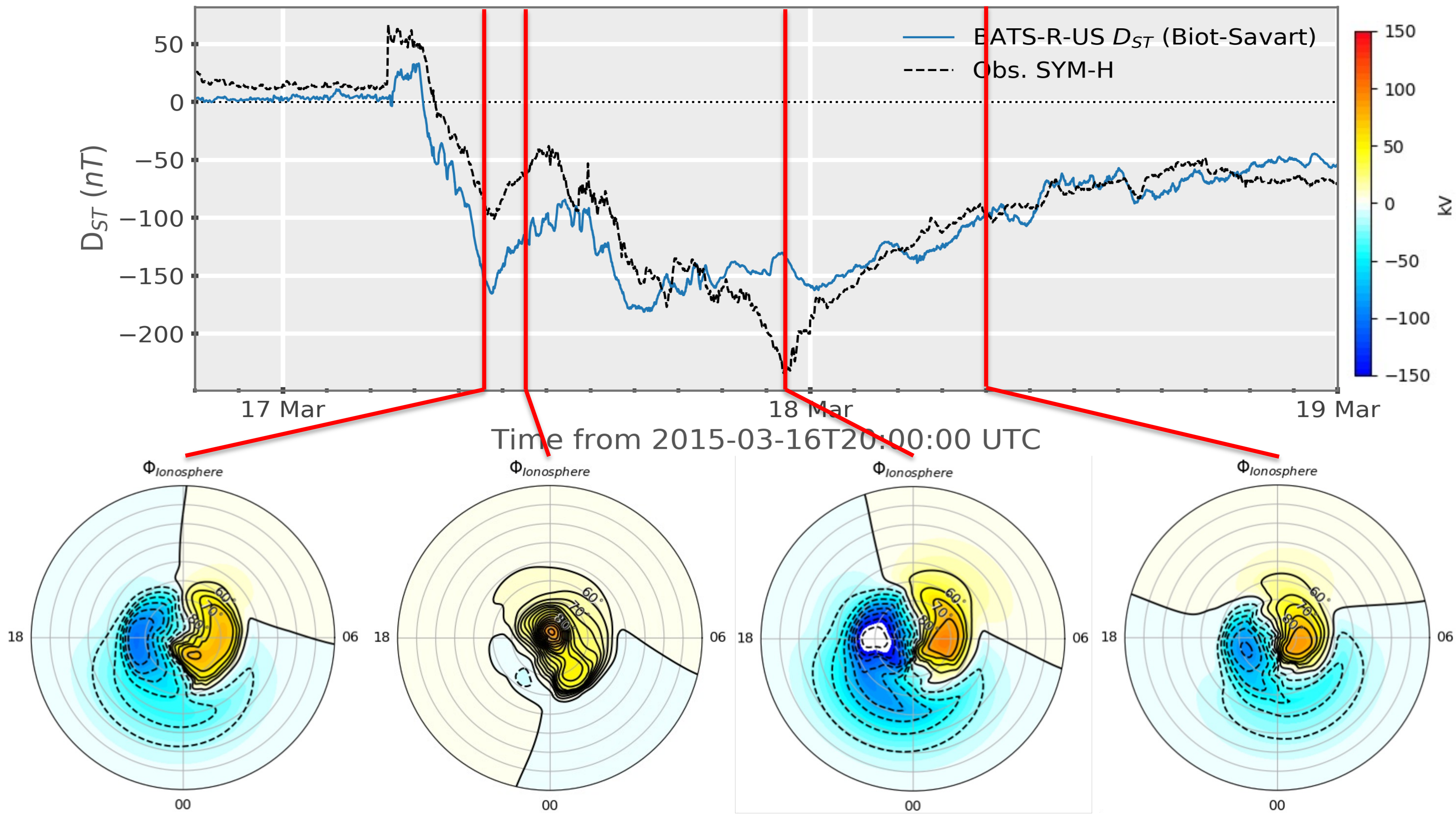




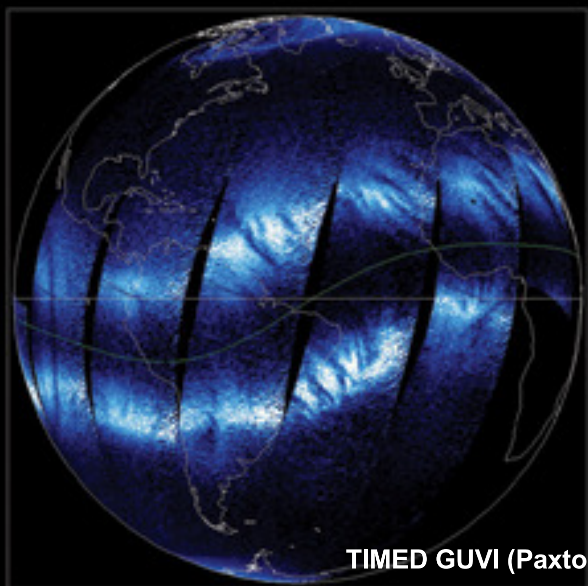




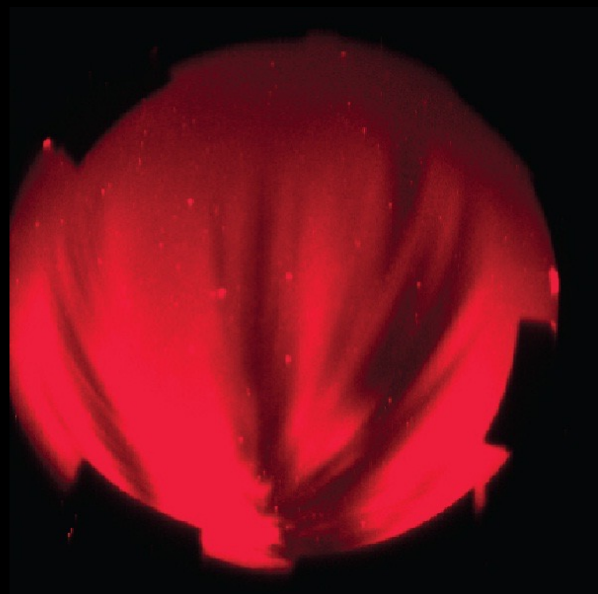
Michigan Geospace Model for M-I Coupling



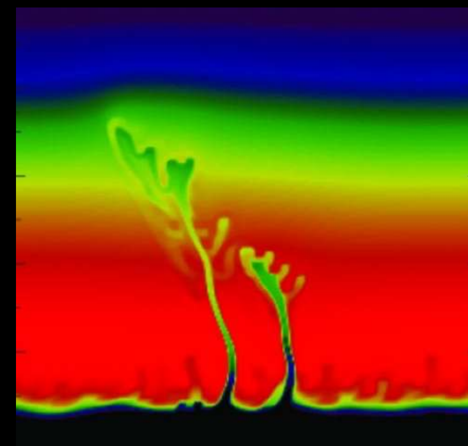
Forecasting the Conditions that Lead to Plasma Bubbles and Irregularity



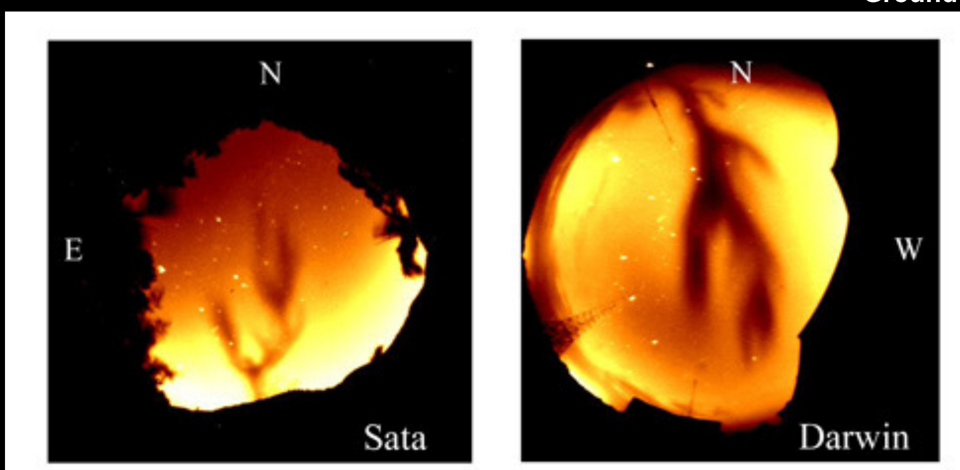
TIMED GUVI (Paxton)

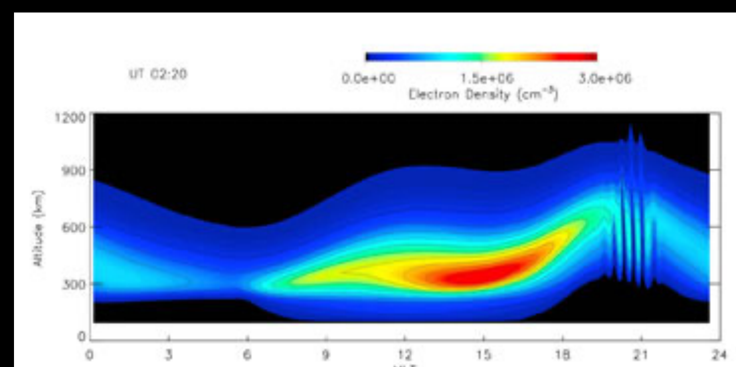


Ground-Based Imager (Taylor)



Plasma Bubble Model (Retterer)

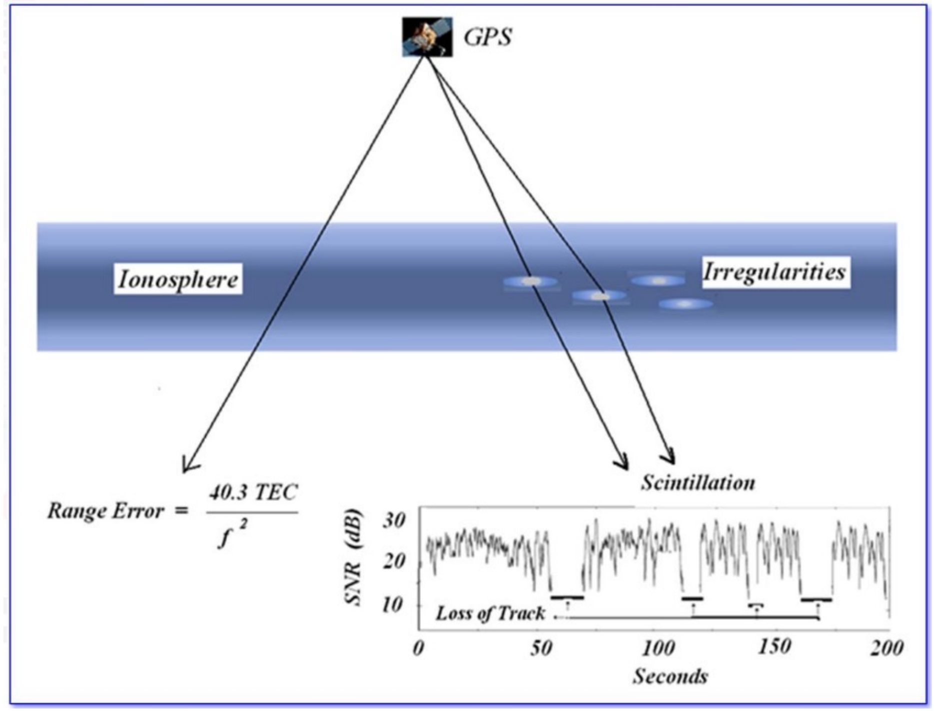


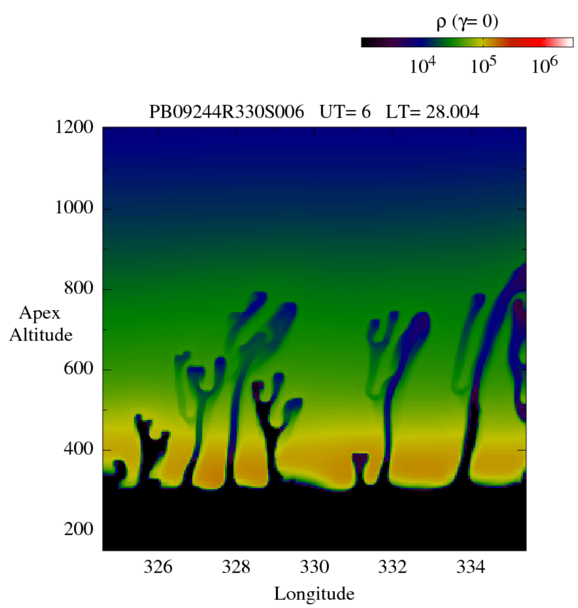


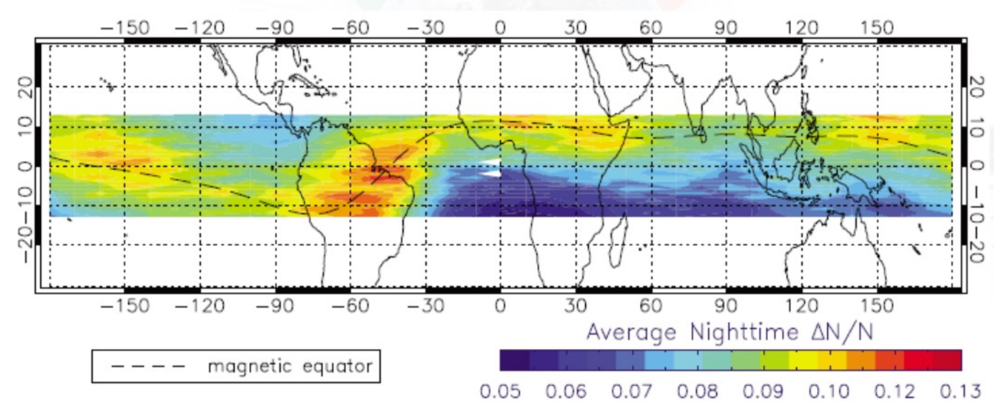
Ionospheric Model (Huba)

Equatorial Plasma Irregularities

- Plasma irregularities can cause scintillation of GPS or other signals which propagate through the upper atmosphere
- Signals propagate through regions of quickly varying density resulting in diffraction and/or refraction and signal intensity drops and phase shifts



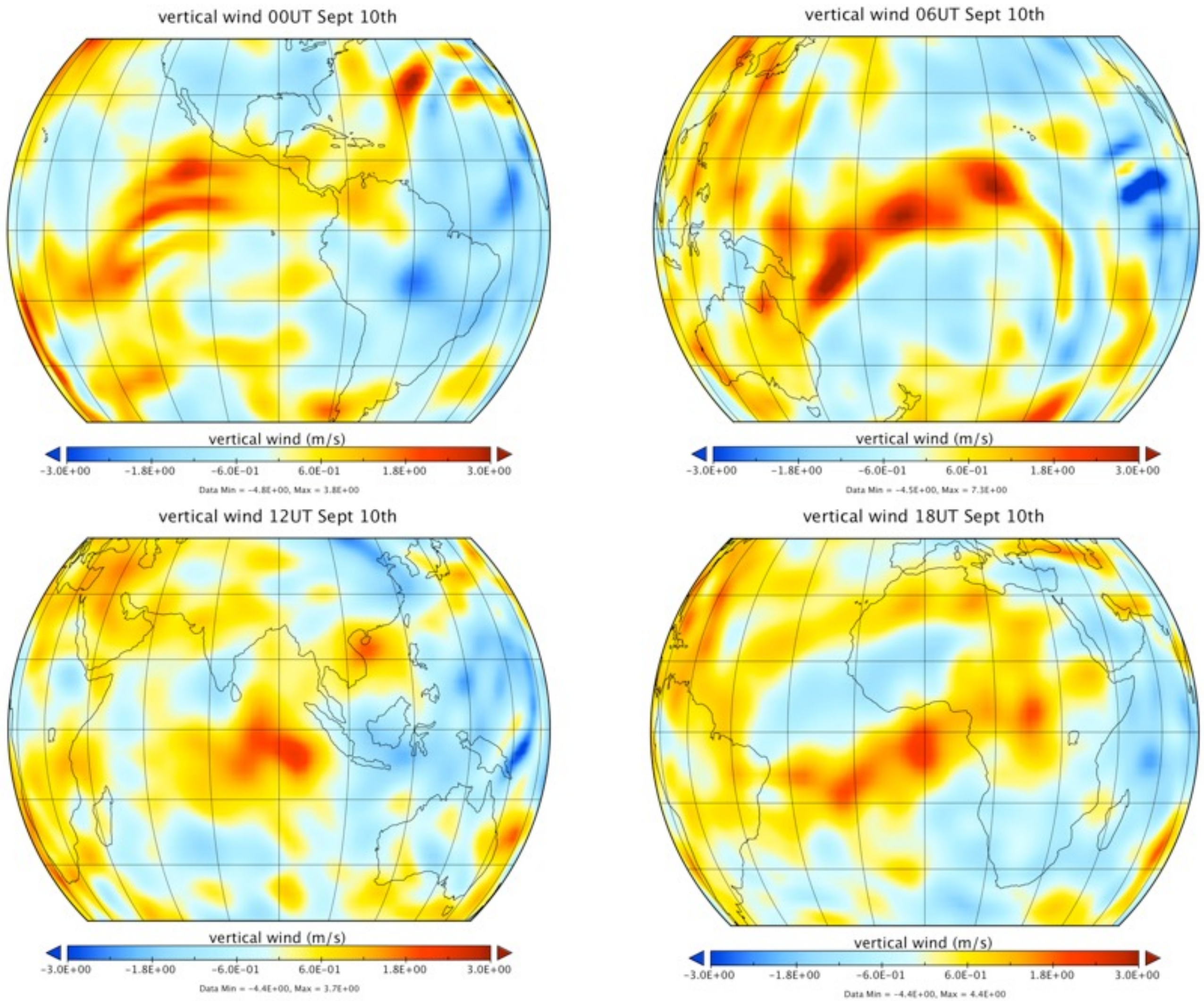




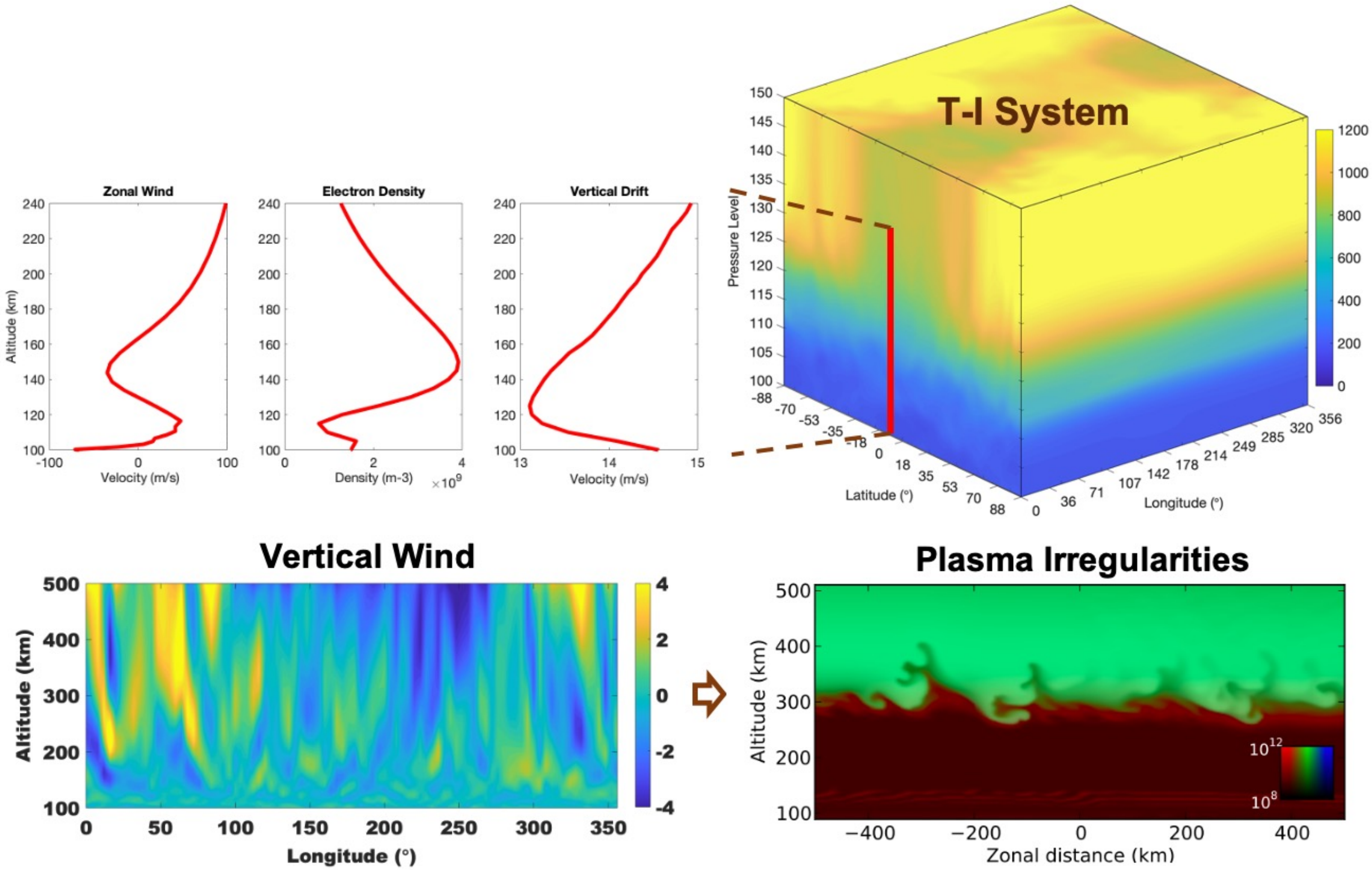
Dao et al, 2011

Data from May 2008 to March 2010

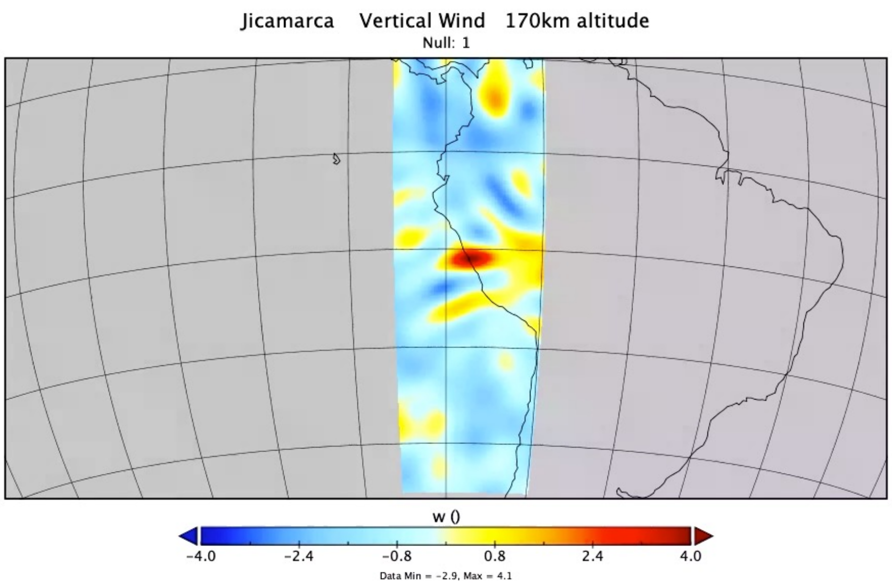
Bottom-side neutral vertical wind variability

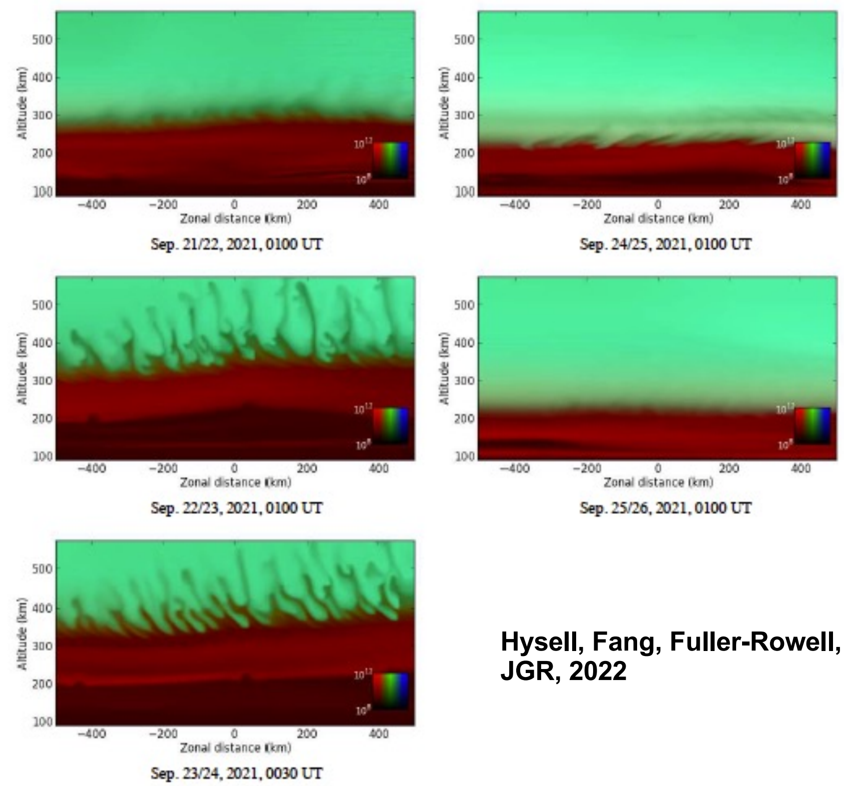


The vertical wind at about 200 km altitude at 00, 06, 12, and 18UT on September 10th, in the dusk sector at 18 LT. The vertical wind variability is illustrative of the variability that is present in all the dynamical and electrodynamical fields that are passed to the Retterer ionospheric irregularity model


Zonal Wind
Velocity (m/s)
Altitude (km)
Electron Density
Density (m-3)
×10^9
Vertical Drift
Velocity (m/s)
T-I System
Pressure Level
Latitude (°)
Longitude (°)
Vertical Wind
Altitude (km)
Longitude (°)
Plasma Irregularities
Altitude (km)
Zonal distance (km)

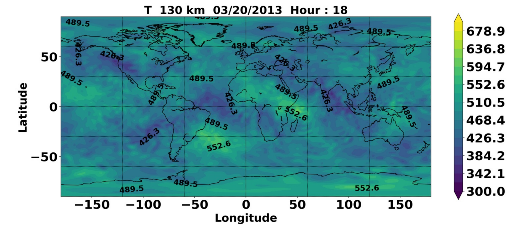
Forecasting the Small-scale Plasma Irregularities





Hysell, Fang, Fuller-Rowell, JGR, 2022

Upgrade WAM neutral atmosphere resolution from T62 to T254 spectral truncation

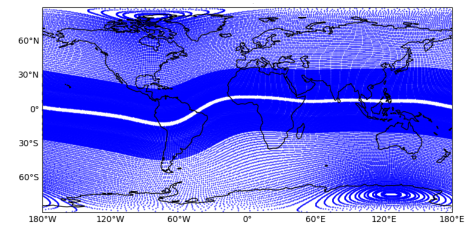


- Approximate resolution increase from ~200 km horizontal to ~50 km, still with 150 layer at ~1/4 scale height in upper levels
- Simulation without lower atmosphere data assimilation, so there will be biases below 50 km in topics and midlatitude, and MLT zonal mean and wind reversals will not be perfect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

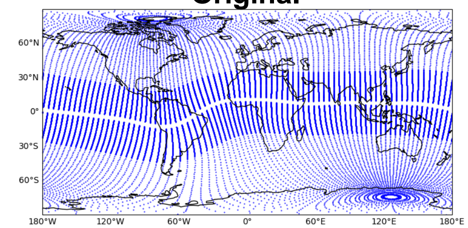
Upgrade IPE ionosphere/plasmasphere resolution

- 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

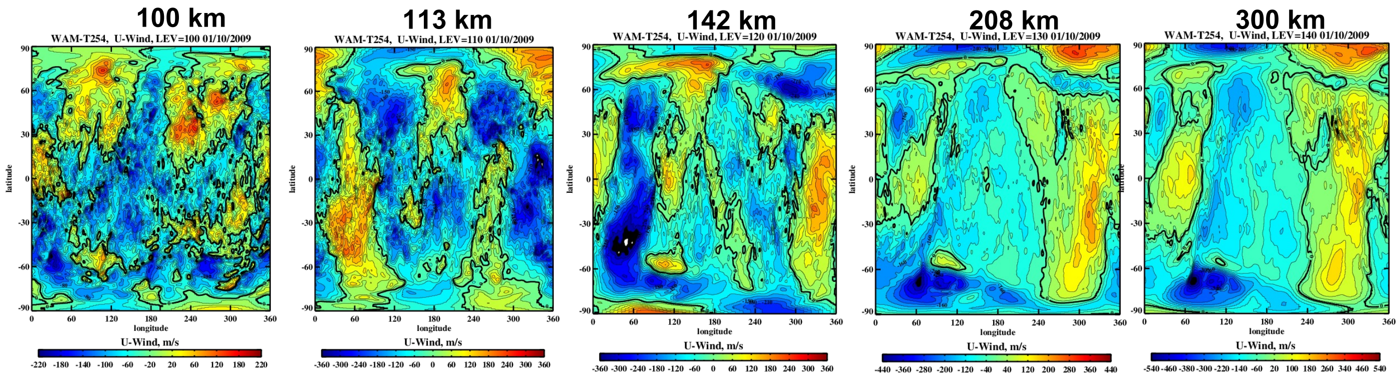
New



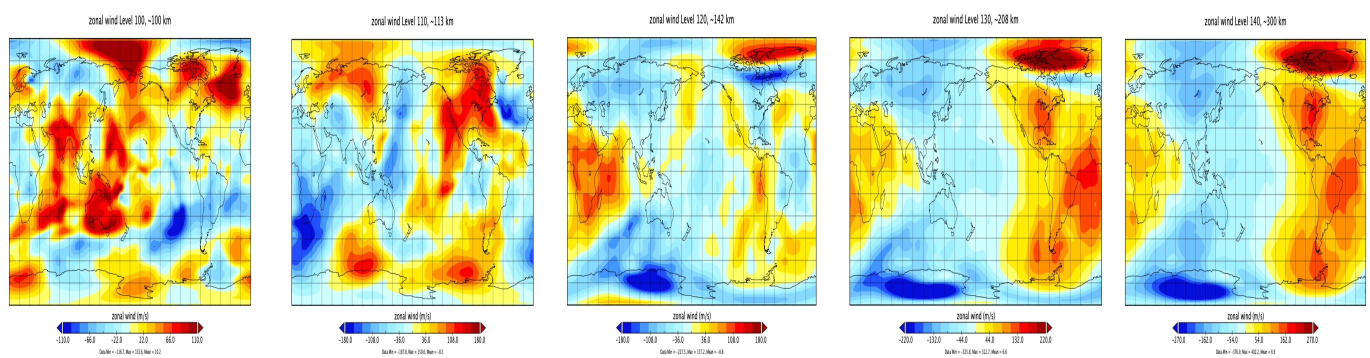
Original



Zonal Wind: T254 ~70km

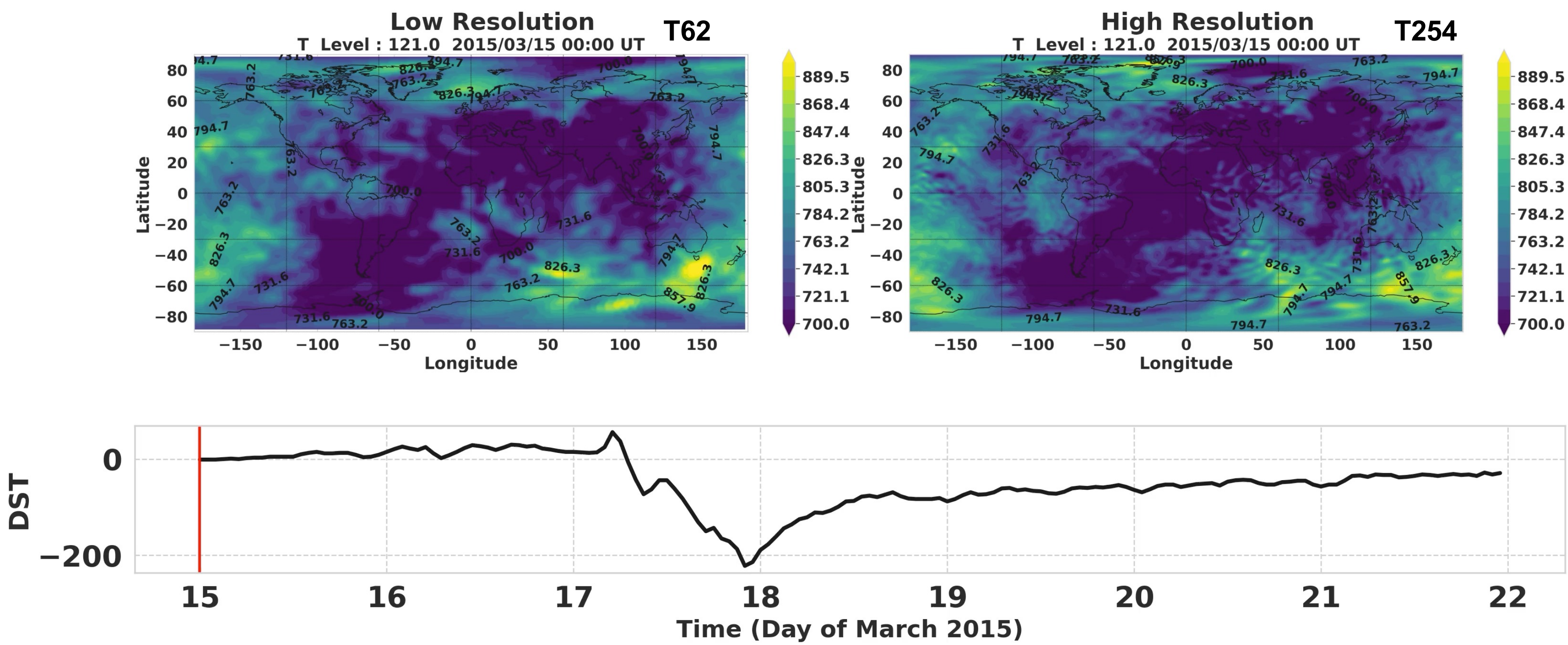


T62 ~200km



Forecasting the Small-scale Plasma Irregularities

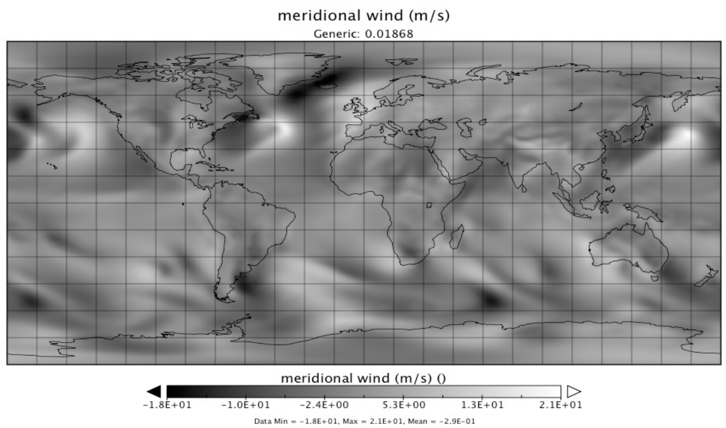
WAM-IPE



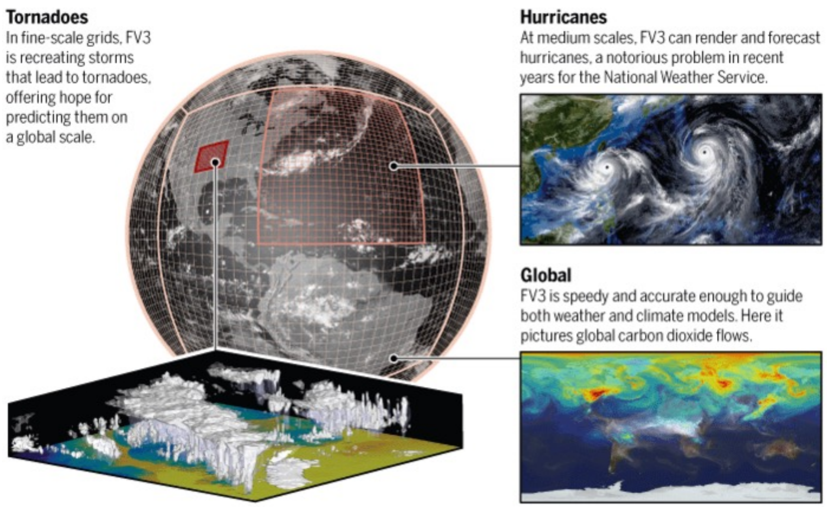
Funded by NSF SWQU AGS 2028032

Courtesy of Garima Malhotra

High-Resolution WAM and FV3-WAM



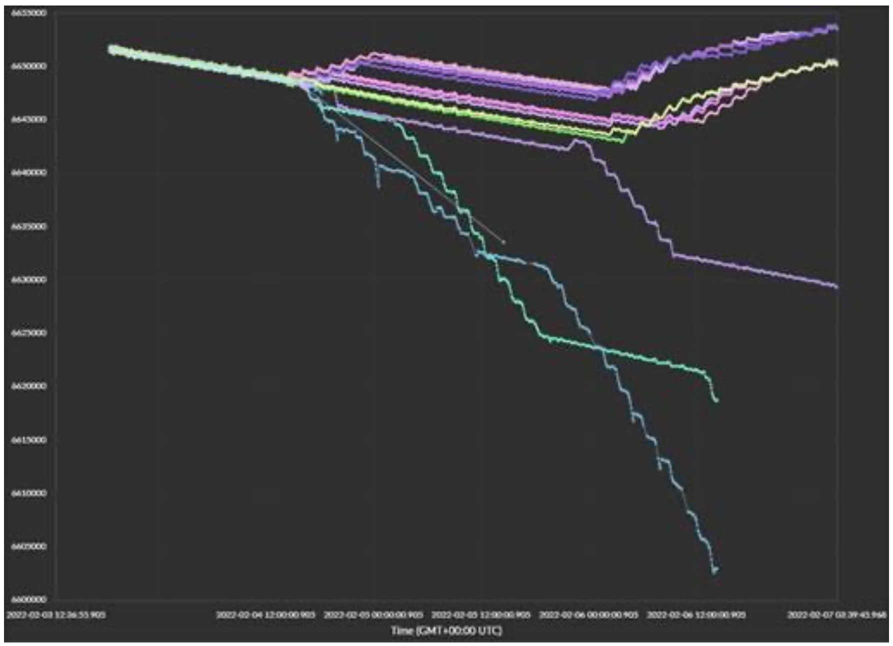
- WAM at T254, ~50 km resolution, Hydrostatic
- Extend WDAS-GSI data assimilation to 100 km
- Improved gravity wave parameterization
- Thermosphere – Ionosphere data assimilation will be included in the future.



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

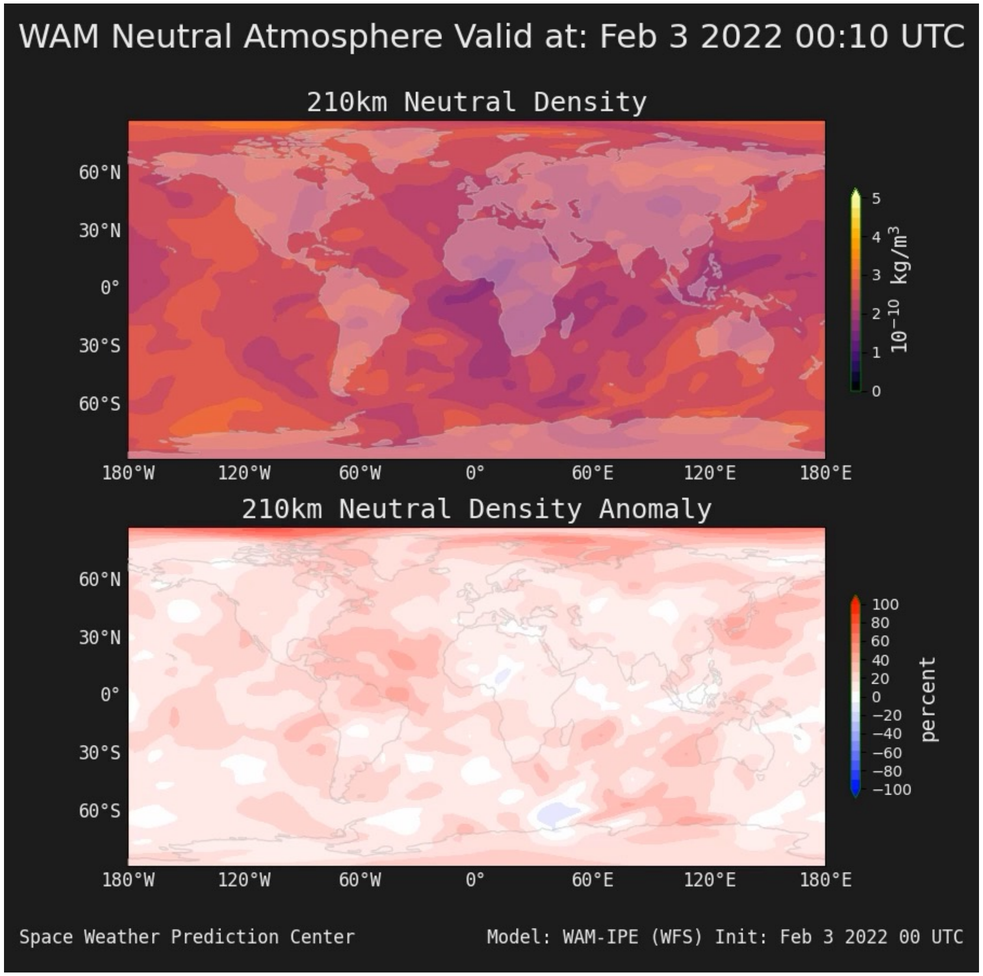
Satellite Drag Environment

Starlink Satellite Loss Event



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).

Space Weather Conditions on Feb 3-4, 2022



- SWPC's operational model, the coupled Whole Atmosphere Model - Ionosphere Plasmasphere Electrodynamics (WAM-IPE), was able to capture the enhanced neutral density globally. The model currently provides 2-day forecasts every 6 hours.
- WAM-IPE calculates the atmospheric conditions from the ground all the way to ~600 km follows the US Weather Forecast System to provides upper atmosphere weather.
- Solar radiation (F10.7) and solar wind parameters (Bz, velocity, density) are used in our model.

Space Weather

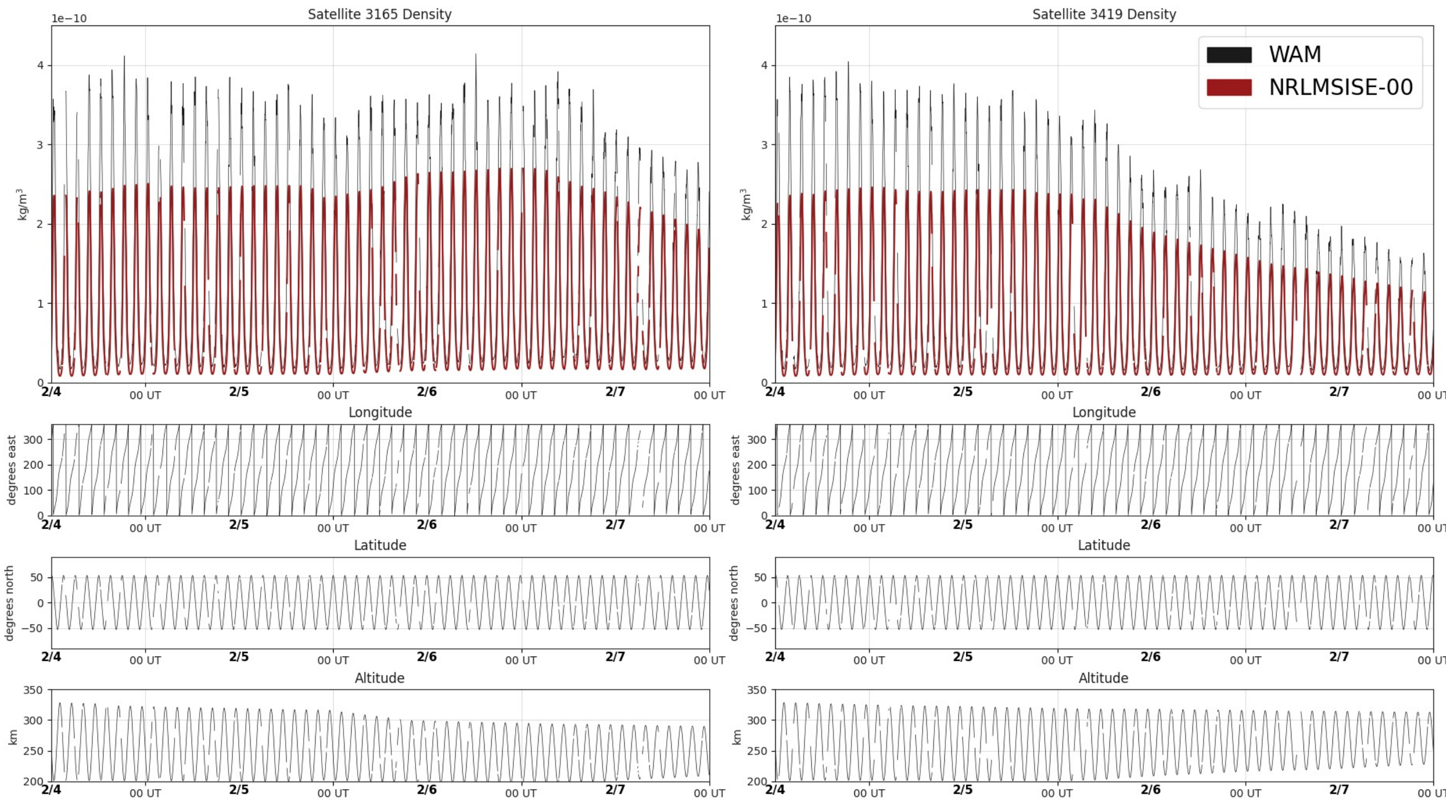
RESEARCH ARTICLE
10.1029/2022SW003193

Key Points:
- Geomagnetic storms lead to thermosphere expansion and increase satellite drag
- National Oceanic and Atmospheric Administration's coupled Whole Atmosphere Model and Ionosphere

Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022

Tzu-Wei Fang[1], Adam Kubaryk[1,2], David Goldstein[3], Zhuxiao Li[1,2], Tim Fuller-Rowell[1,2], George Millward[1,2], Howard J. Singer[1], Robert Steenburgh[1], Solomon Westerman[3], and Erik Babcock[3]

[1]NOAA Space Weather Prediction Center, Boulder, CO, USA, [2]CIRES, University of Colorado Boulder, Boulder, CO, USA, [3]SpaceX Starlink, Hawthorne, CA, USA



Neutral density sampled along orbits of survived Starlink satellites based on WAM-IPE (black) and MSIS (brown) global densities. WAM have shown a much higher density environment compared to MSIS and captures more pronounced storm responses.