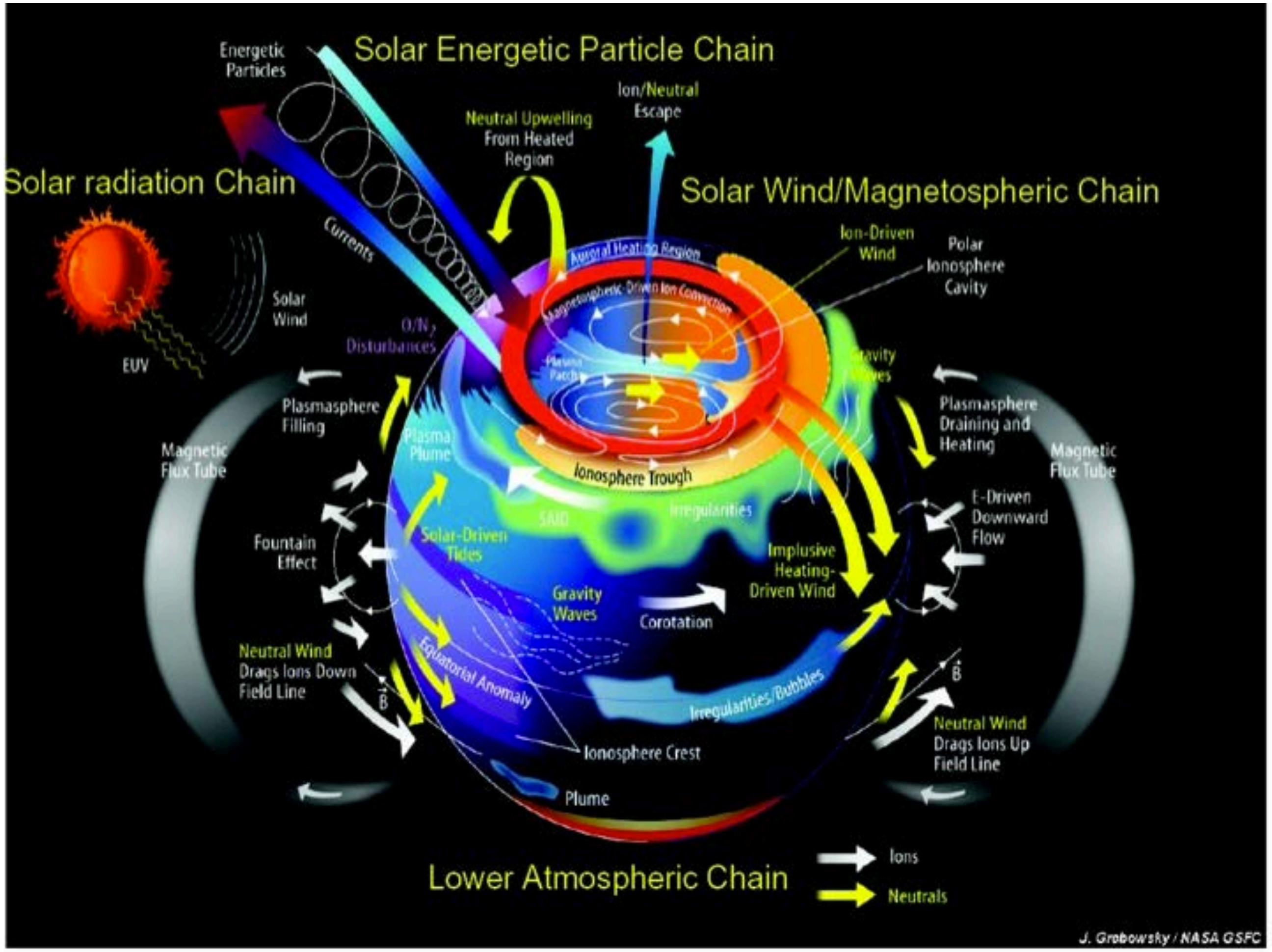
Space Science for Ham Radio Operators

Larisa Goncharenko, MIT Haystack Observatory

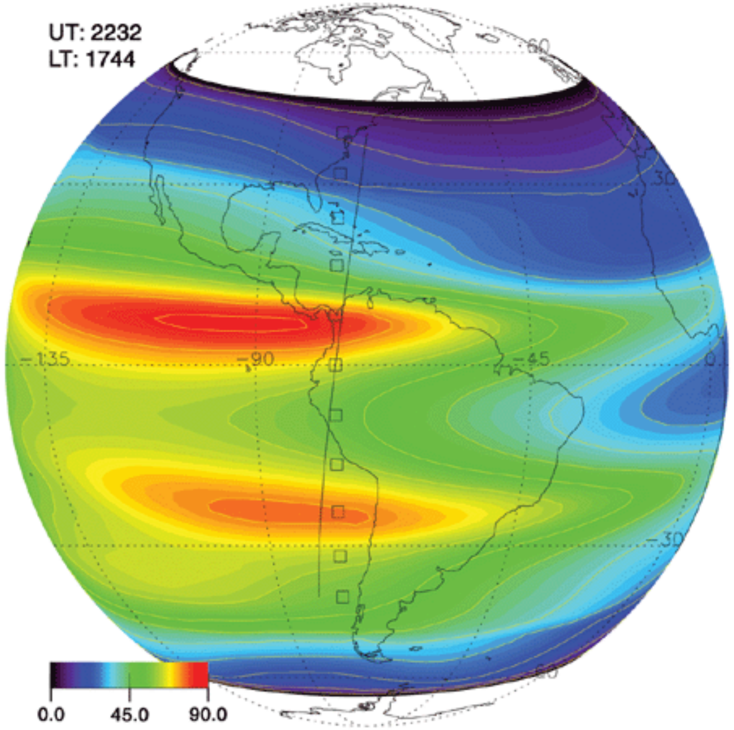
HamSci meeting, Mar 22-23, 2019

Atmosphere-ionosphere-magnetosphere system



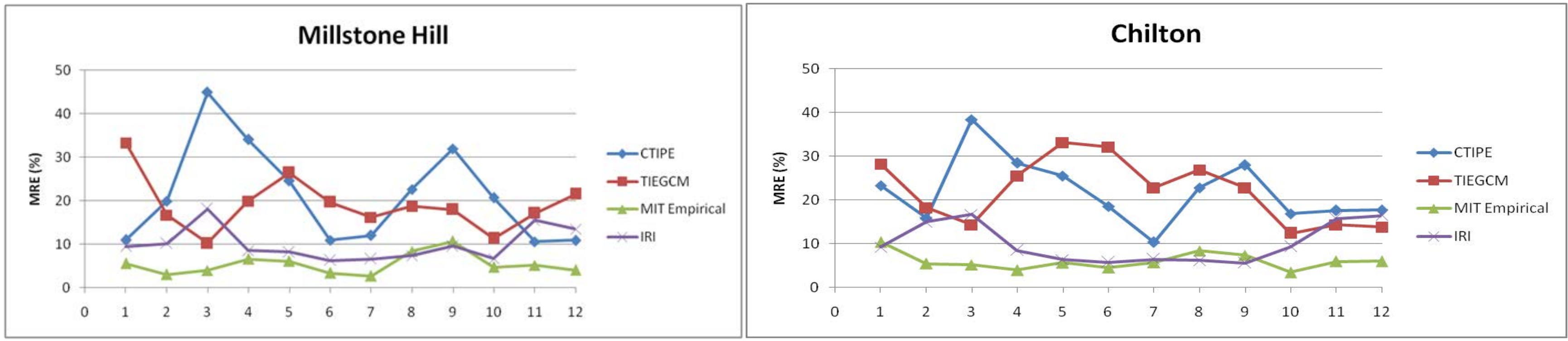
- Strongly driven by solar and magnetospheric processes
- Primary example: strong geomagnetic storm
- Studies of geomagnetic storms enable understanding of energy transfer from Sun to the near-Earth space
- Studies of lower atmospheric phenomena enable understanding of energy transfer from the troposphere/stratosphere upwards

What we know well: average ionospheric behavior



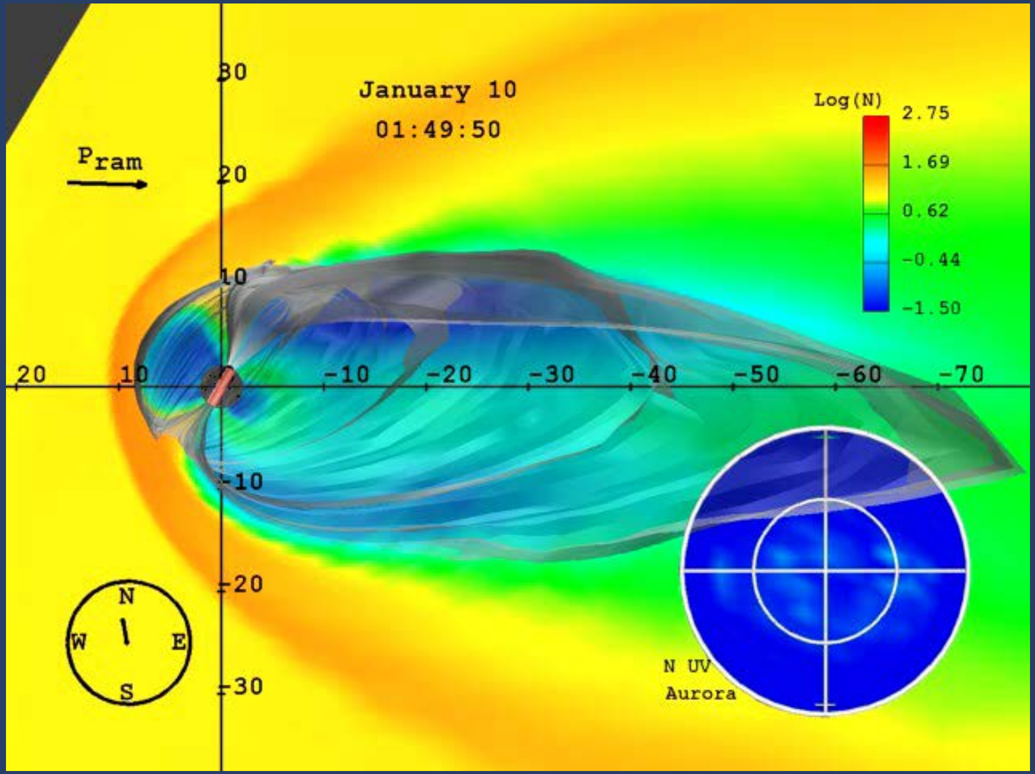
SAMI3 simulations, J. Huba, NRL

- Strong correlation with solar activity
- Strong diurnal variation
- Strong seasonal variation
- Peaks of equatorial ionization anomaly at +/-15MLAT
- Monthly mean behavior is well described by IRI model (International Reference Ionosphere)
- IRI model still performs better than first-principle model

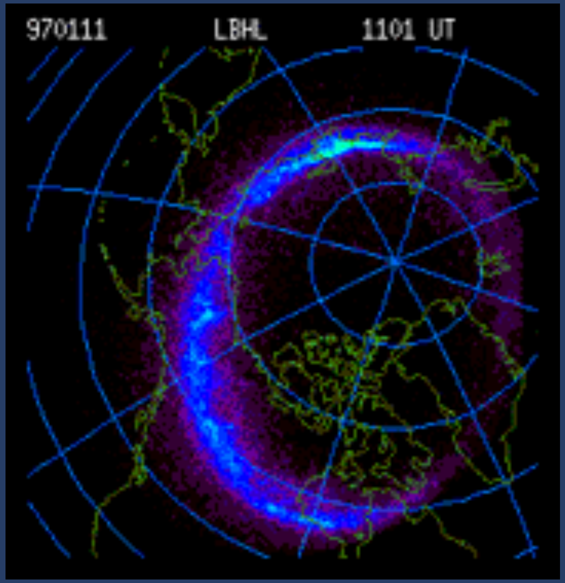


Tsagouri et al., 2018

Geomagnetic Storms

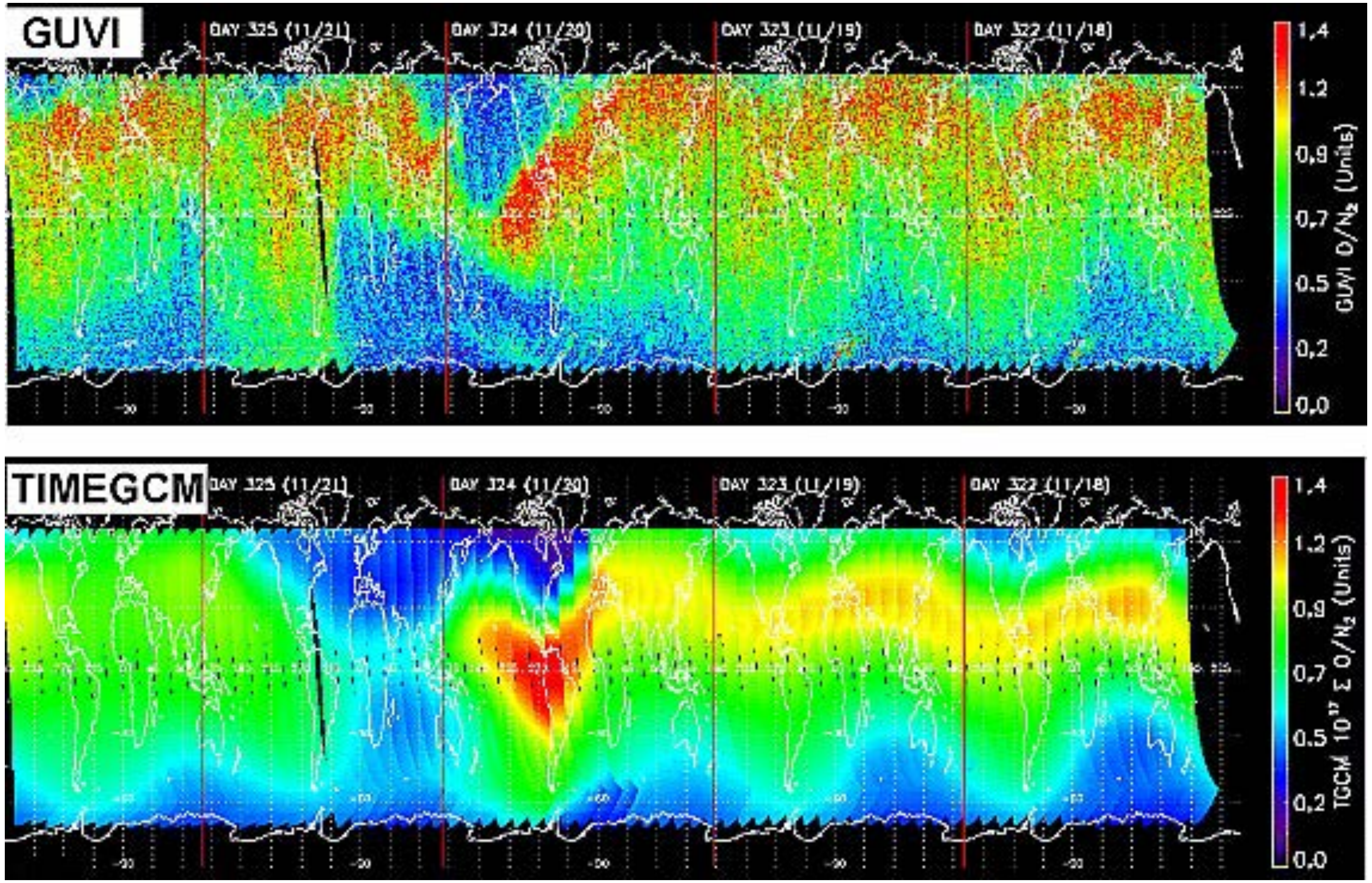


Magnetospheric Response



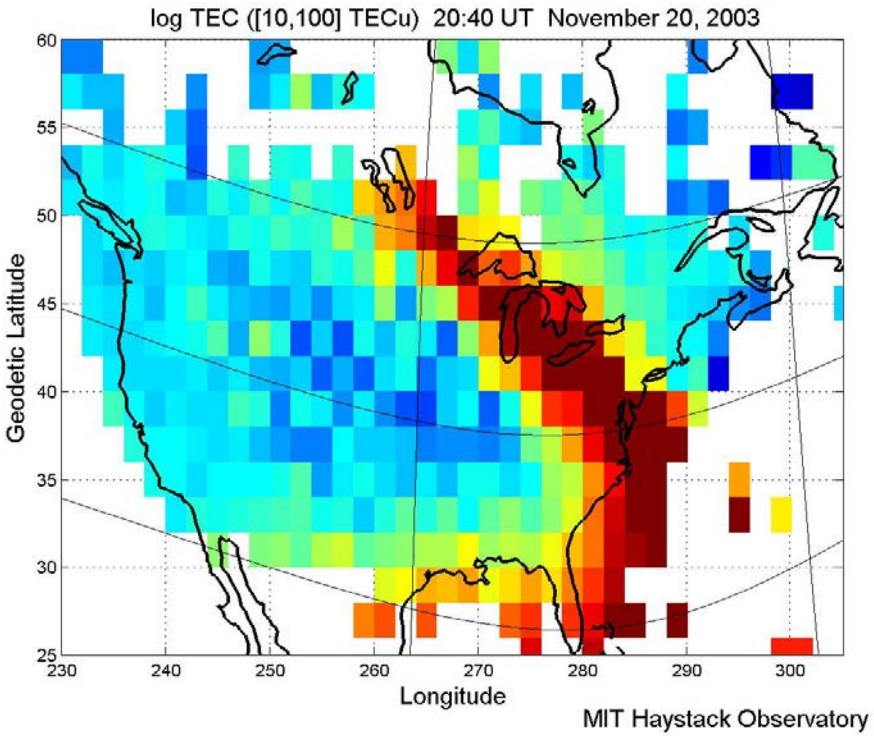
Atmospheric Response

What we don’t know very well:
ionospheric disturbances during geomagnetic storm



Mejer et al., 2005

Thermospheric O/N2 behavior: good data/model agreement prior to the storm of 20 Nov 2003; model overestimates increase in O/N2 at low latitudes and underestimates recovery phaze



Foster et al., 2005

Storm Enhanced Density plume: narrow region of large increase in TEC

Empirical model of ionospheric disturbances

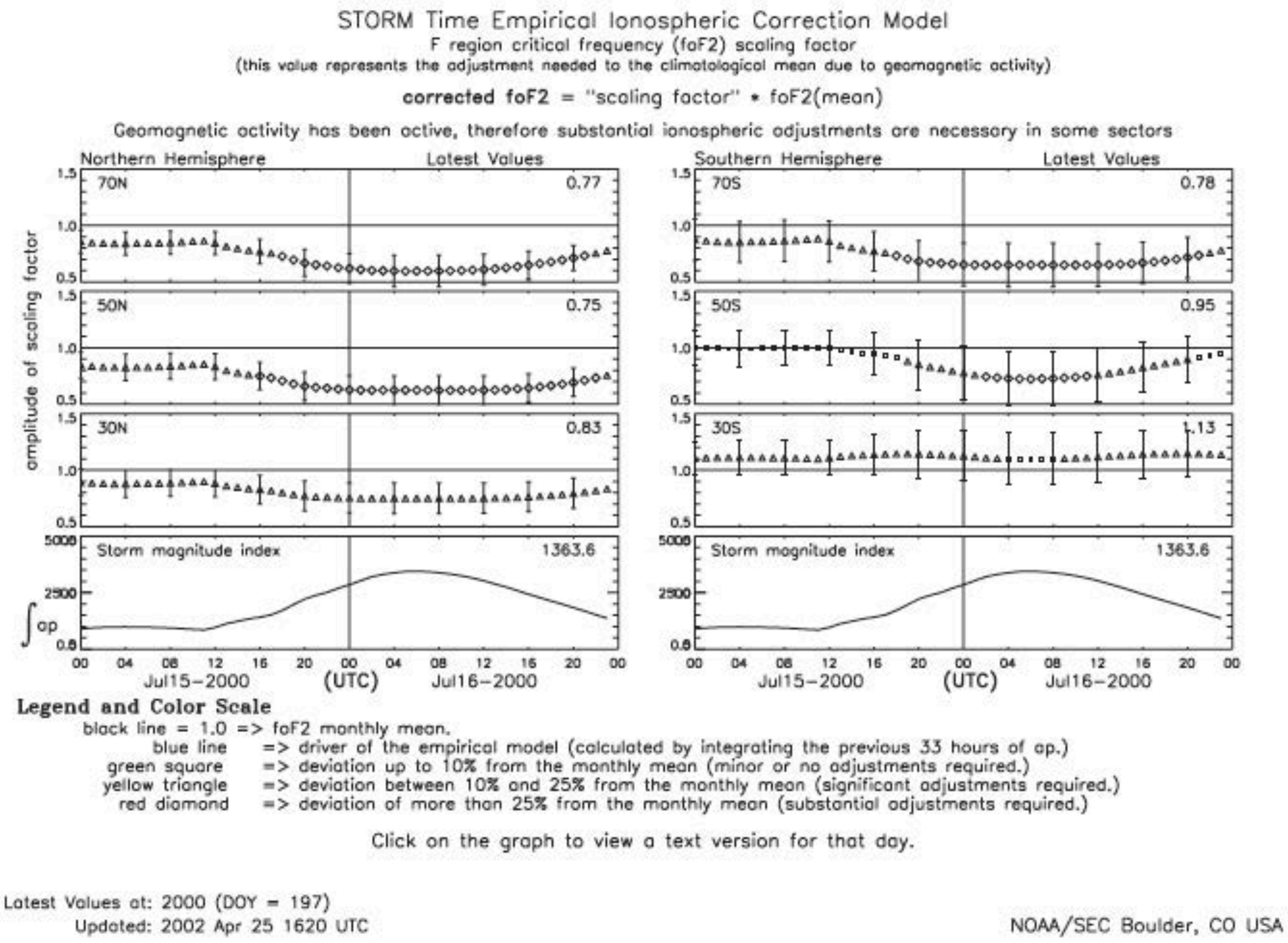


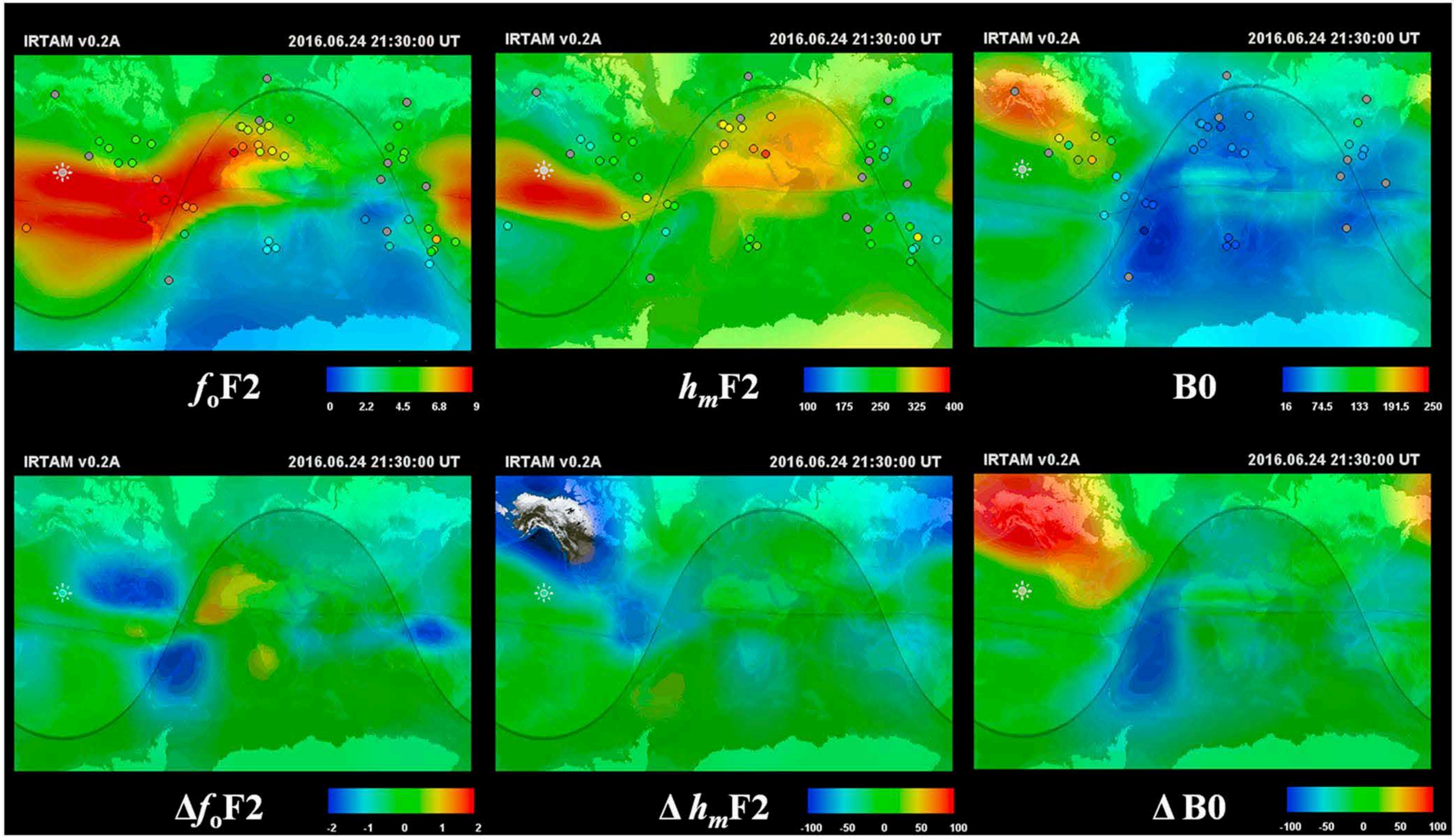
Figure 6. Output of the STORM model for the Bastille Day storm (July 15 and 16, 2000). The full line represents the input of the model (integral of a_p), and the symbols the different levels of the model output. The color-coded page can be seen at http://sec.noaa.gov/storm/.

Araujo-Pradere et al., 2002

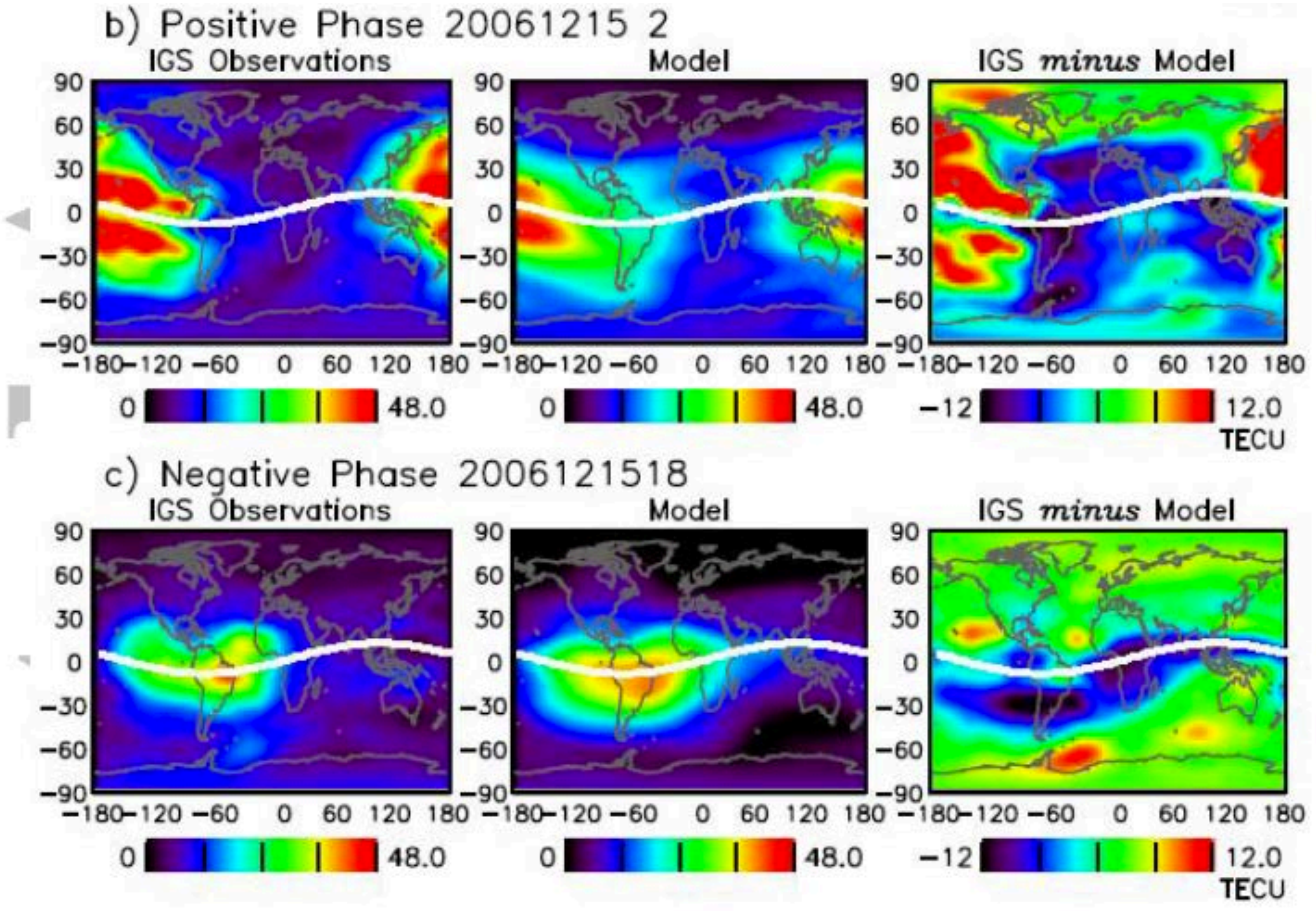
- Empirical model of ionospheric correction is based on **75 ionospheric stations** and **43 geomagnetic storms**
- Output provides correction to quiet time foF2
- This model is included in IRI model (International Reference Ionosphere)
- Improves predicted foF2 in equinox and summer; performs worse in winter.

Just imagine how understanding could be advanced with data from 500 citizen scientists…or 5000…

Other effort: real-time IRI



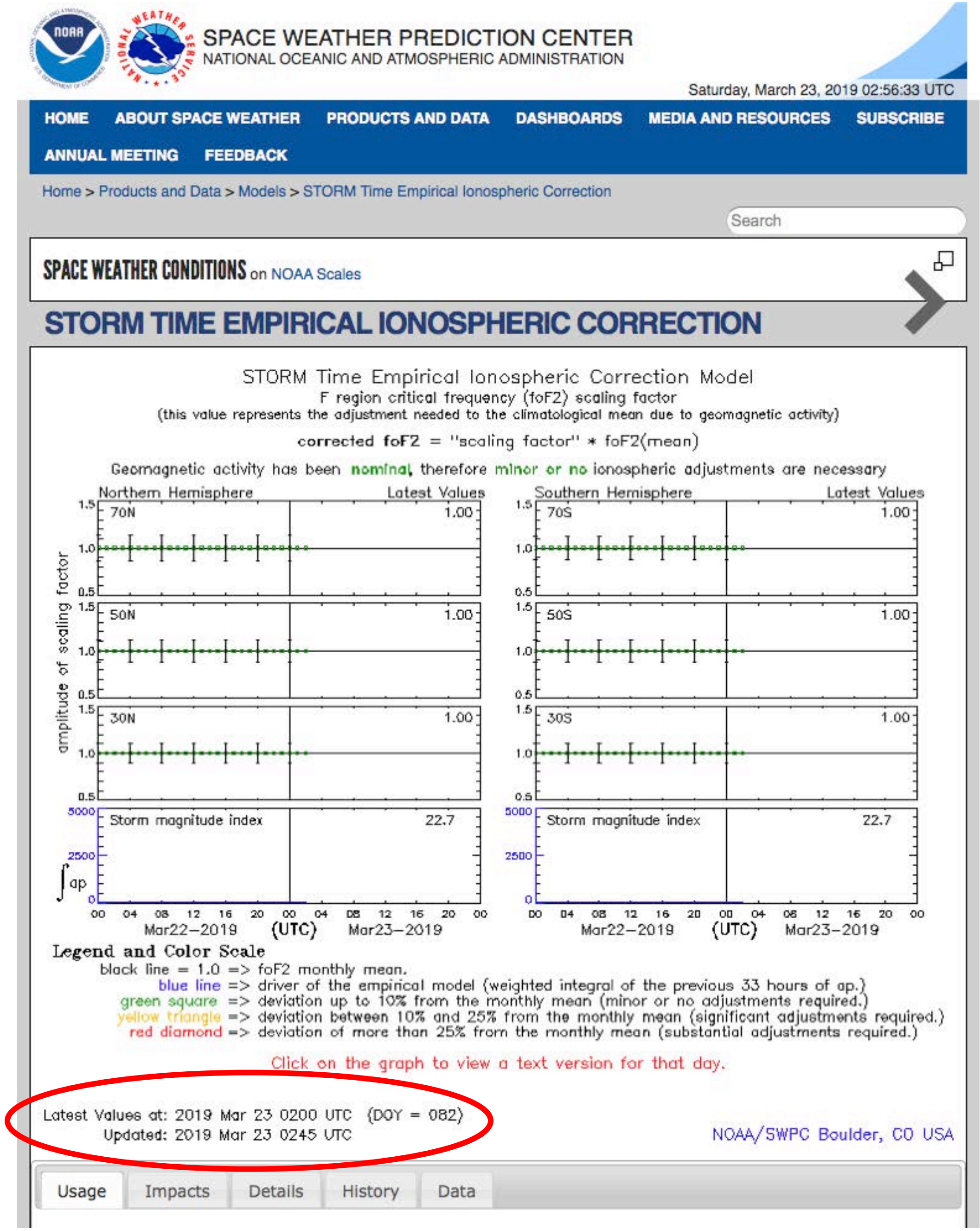
Yet another model: GIM TEC



- Empirical model based on GIM TEC 2-hour maps (1998-2015)
- Forecast for 1,2,3,5,8 and 10 days
- Geomagnetic inputs are not forecasted

Lean, 2019, Space Weather

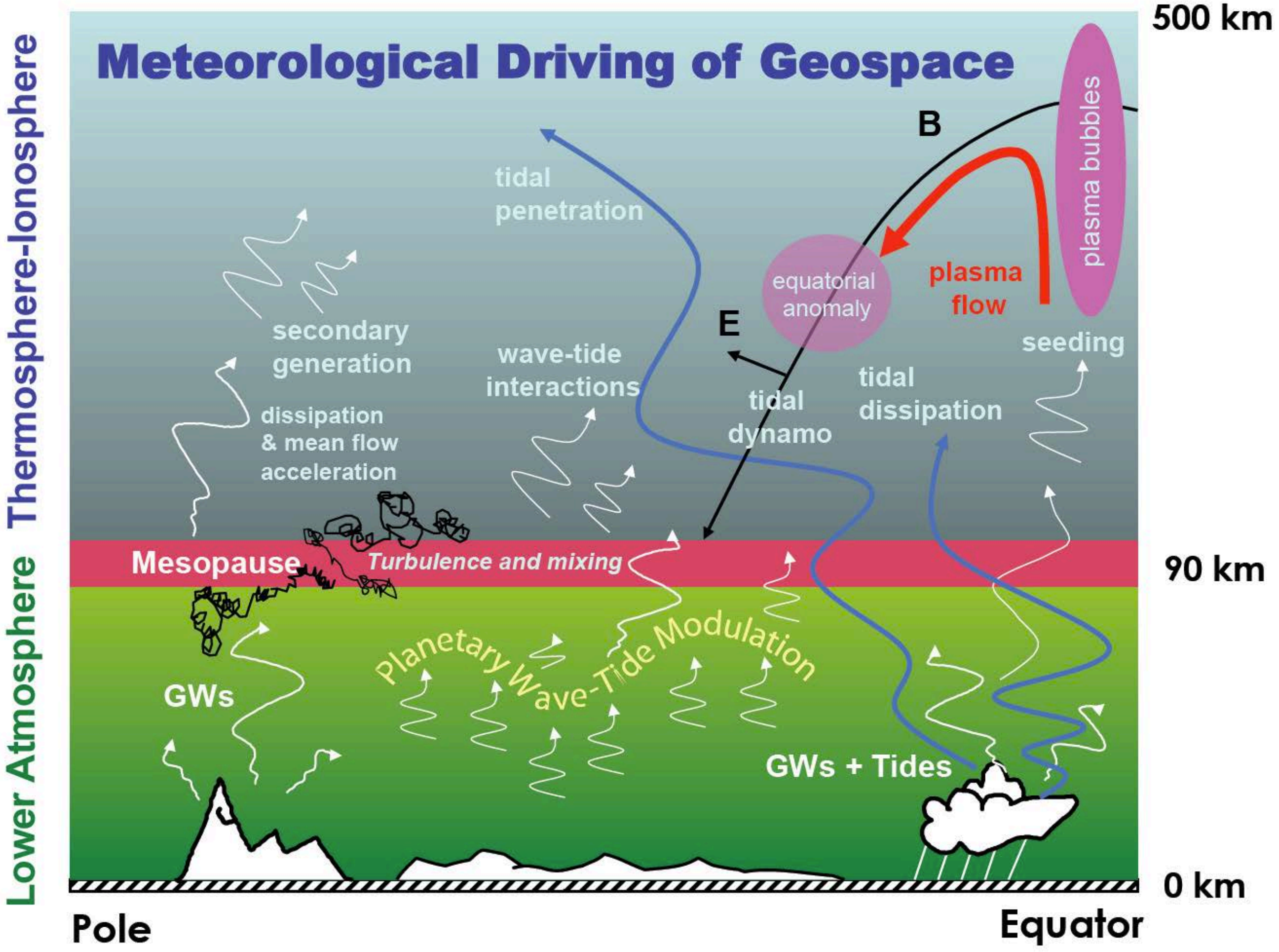
NOAA Storm Time Empirical Ionospheric Correction



- Is expected to be of benefit to HF users
- No prediction even for several hours in advance
- Expected variations are ~10% from monthly mean
- Any feedback on the model from ham radio operators?

1. What drives ionosopheric weather during geomagnetically quiet time?
2. 95% of the time geomagnetic activity is < Kp=4

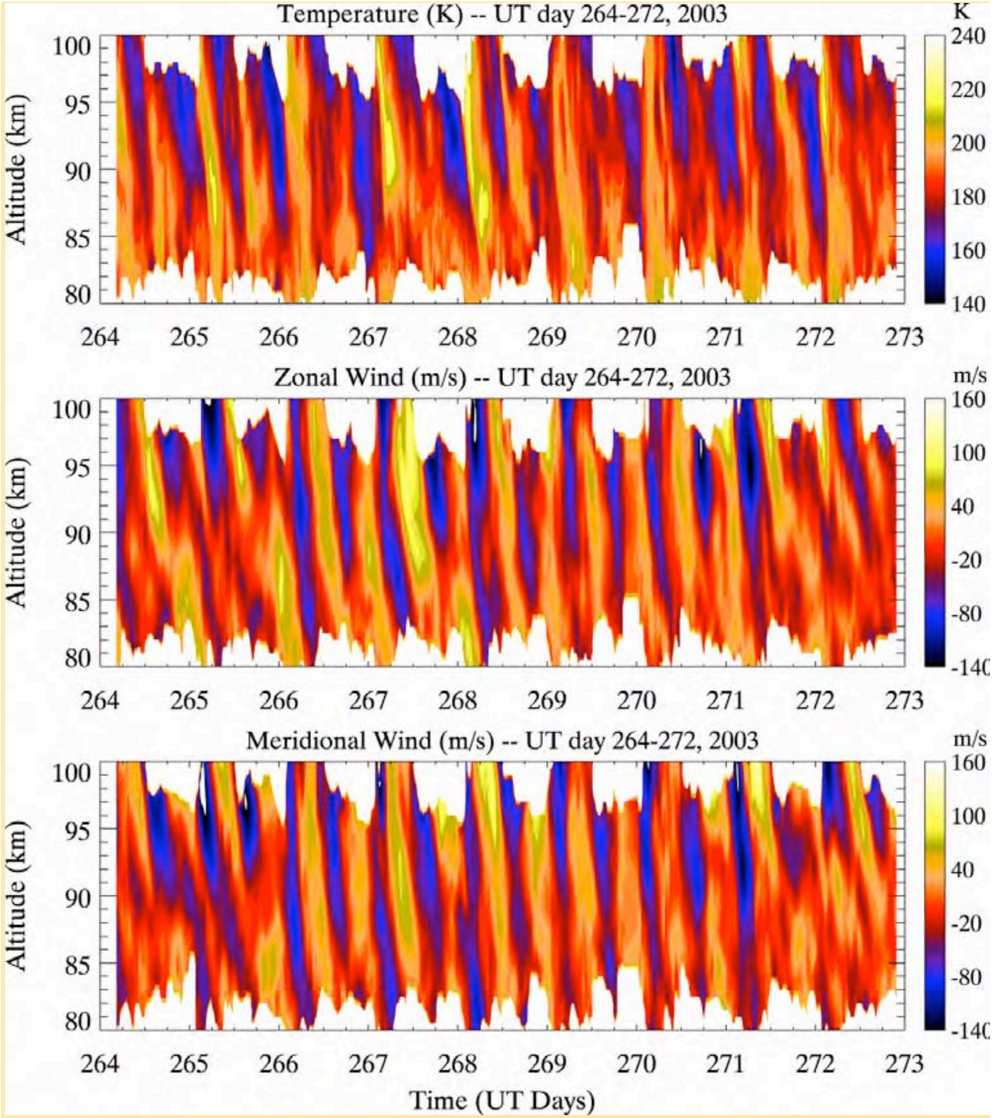
Last decade+: impact of tropospheric weather



- Ionospheric electron density can strongly vary on a day-by-day basis
- Effects of waves generated in the lower atmosphere
    - Planetary waves – 10-16 day, 5-6 day, 3-4 days Kelvin waves, 2-day
    - Tidal waves – 24-hrs, 12-hrs, 8-hrs
    - Gravity waves – variations with periods ~5mins – 6-8 hrs
    - Generated in the lower atmosphere and propagate upward

Waves carry momentum and energy to ionosphere

- Amplitudes strongly increase with altitude
- By lower thermosphere, waves become dominant features
- Waves reach max amplitudes at 100-120 km
- Strong impact on E-region and bottomside ionosphere
- We have very little observational data in this region

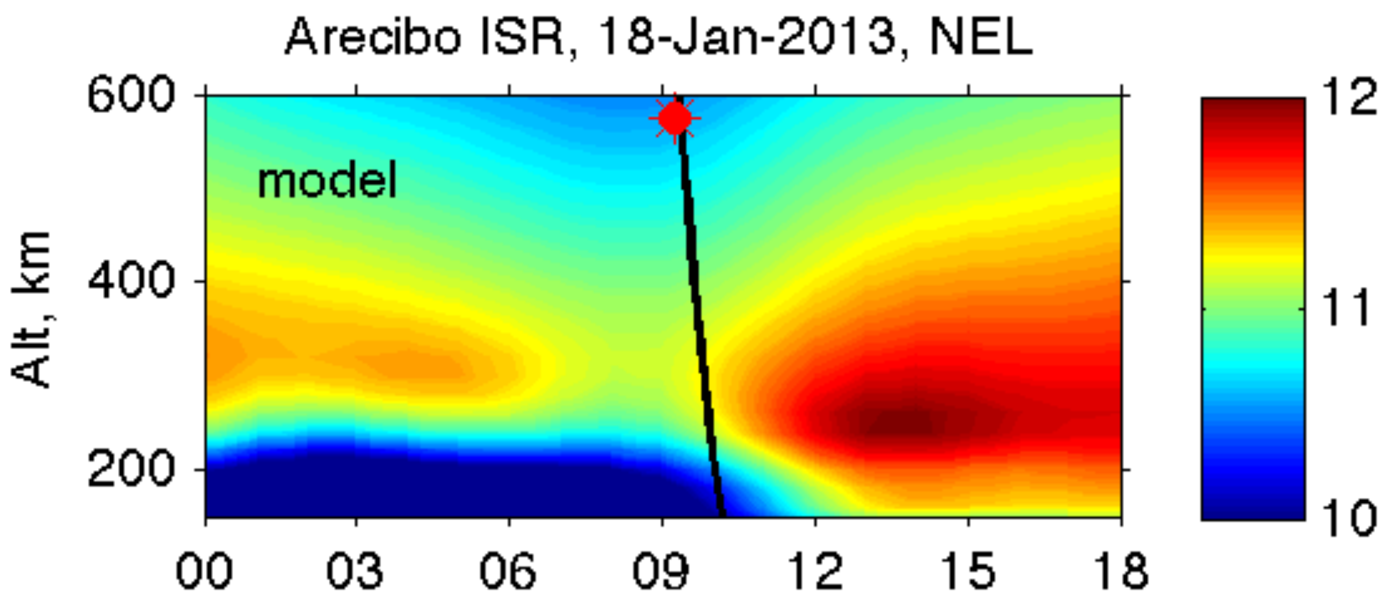


She et al., 2004,
Colorado State University lidar

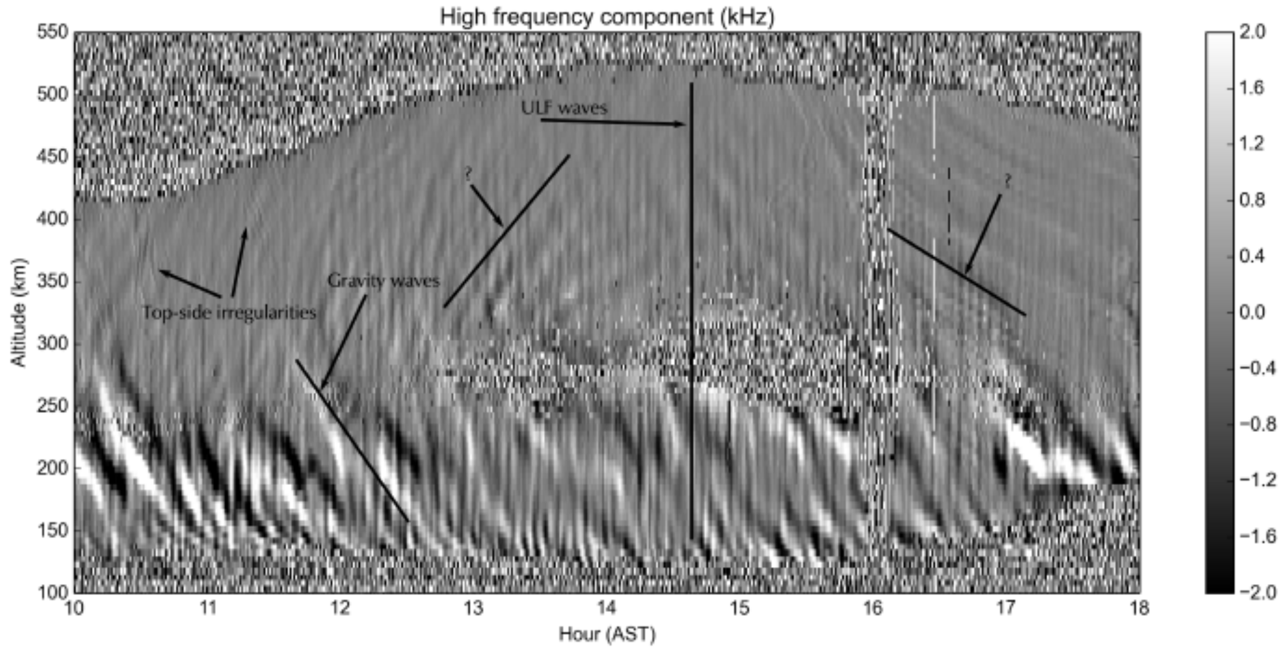
What we know about waves

- There are many, many sources of waves:
  - Planetary waves – land/sea temperature differences, air flow over the mountain ranges
  - Tidal waves – heating of water vapor in the troposphere (clouds); heating of ozone in the stratosphere (~30-40 km)
  - Gravity waves – weather systems, mountains, tropospheric convection, solar terminator…but also earthquakes, tsunamis
- Wave propagation strongly depends on the temperature and wind between the source and upper atmosphere
- Waves interact with each other and create secondary waves
- Varying sources of waves + varying propagation conditions => highly variable energy flux entering ionosphere from below

It's a zoo of waves out there!



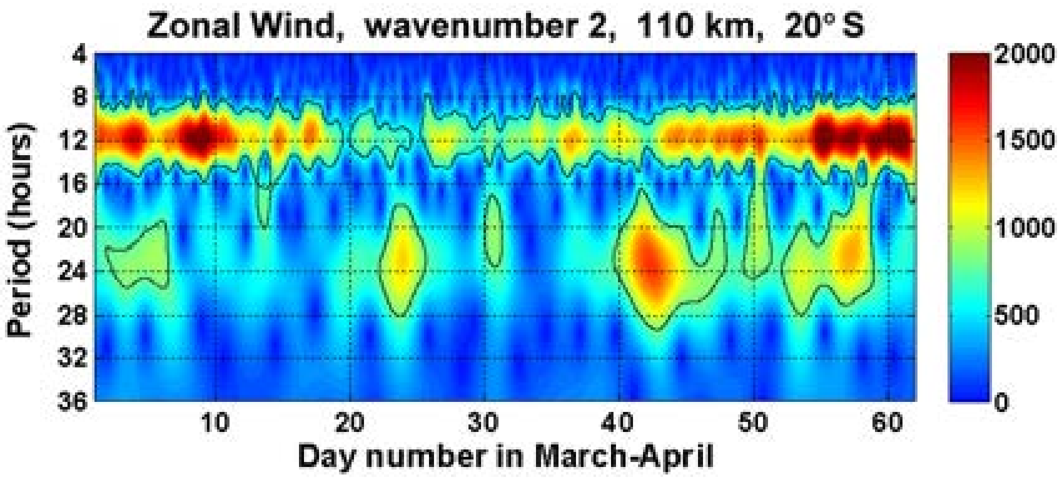
This is what we expect to see from empirical model….



…and this is what we actually observe…
Plasma line experiment, Arecibo ISR.
Image from Juha Vierinen.

Effects of planetary waves: periodic variations

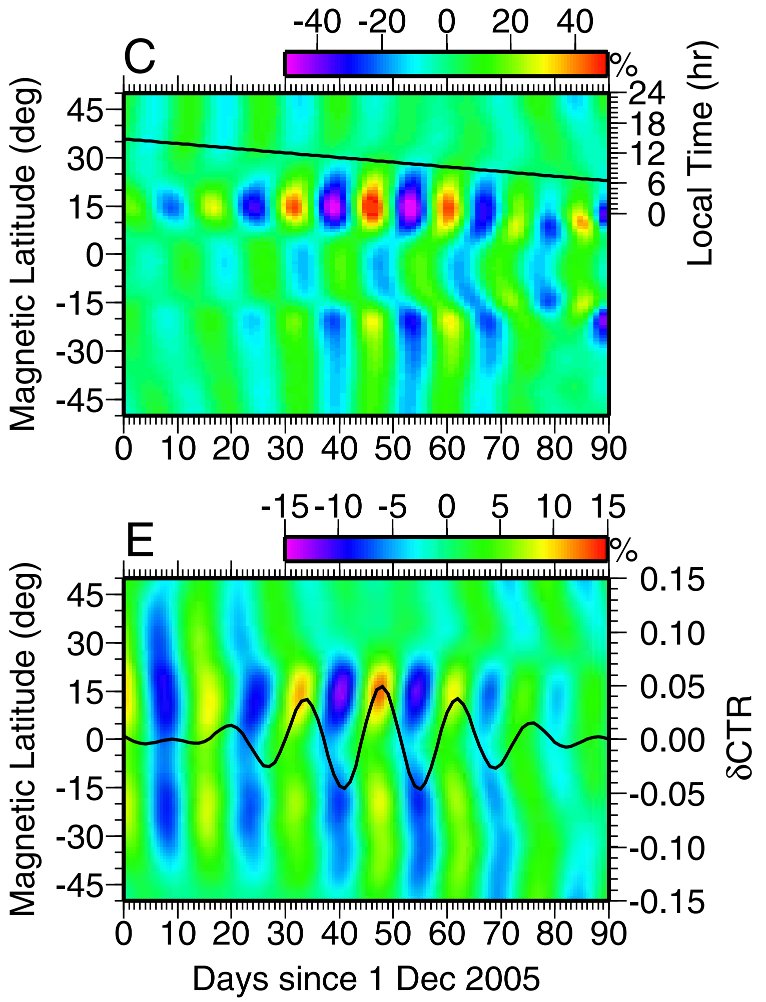
Model: WAM



PW modulate E-region tides
(*Fuller-Rowell*, 2008)

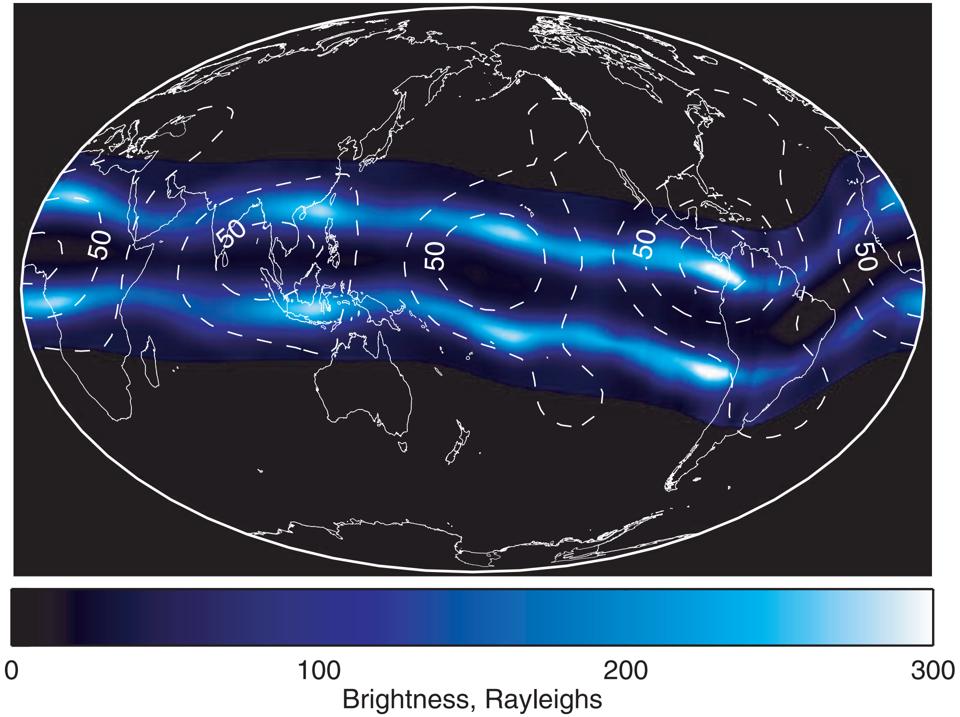
- PW often do not propagate to ionospheric heights; PW signatures are carried by tidal modes
- Non-linear interaction of stationary PW with migrating tides generates non-migrating tides

Data: CHAMP, IGS TEC



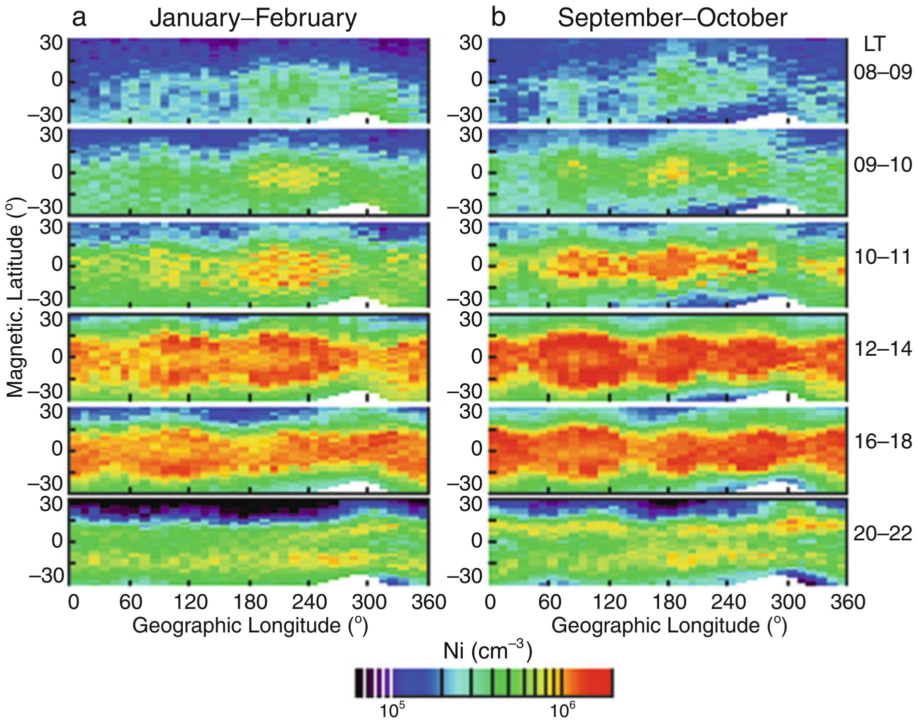
~40% variations in Ne at 350 km
(*Pedatella and Forbes*, 2009)

Effect of non-migrating diurnal tides: longitudinal variation in ionospheric parameters



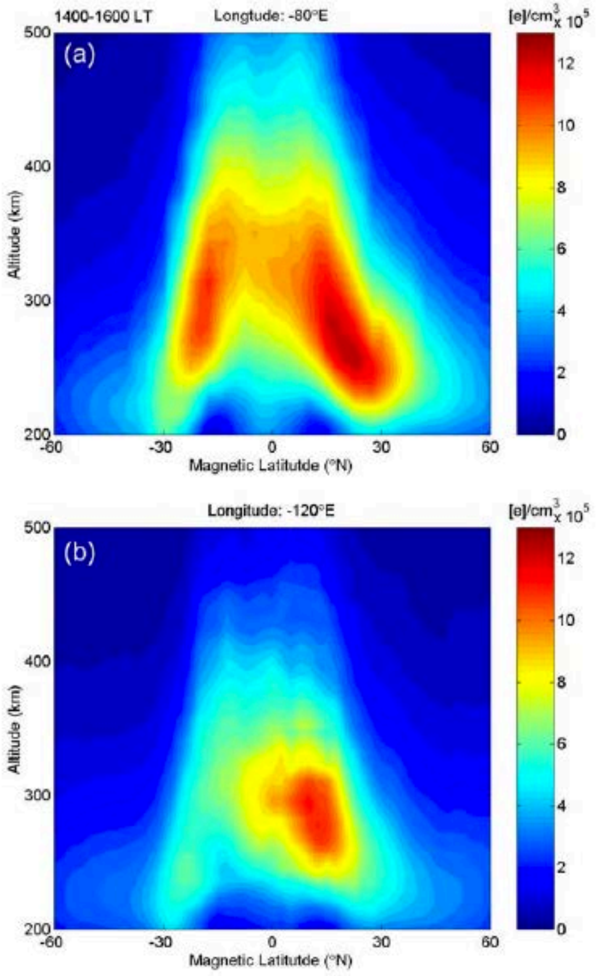
Immel et al., 2006

Variations in airglow brightness and location related to DE3 tide – NASA TIMED satellite



Kil et al., 2008

Ion density from ROCSAT satellite

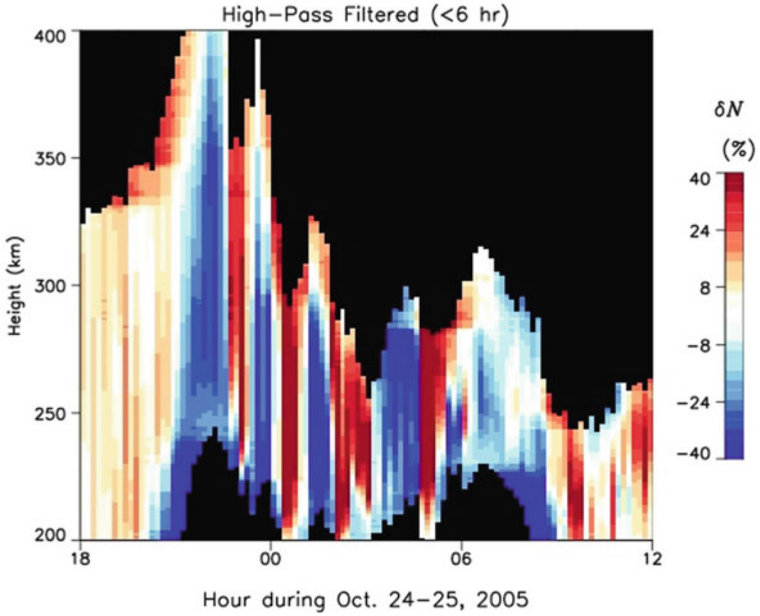


Lin et al., 2007
COSMIC data

Variations in electron density due to non-migrating diurnal tide reach 20-50%

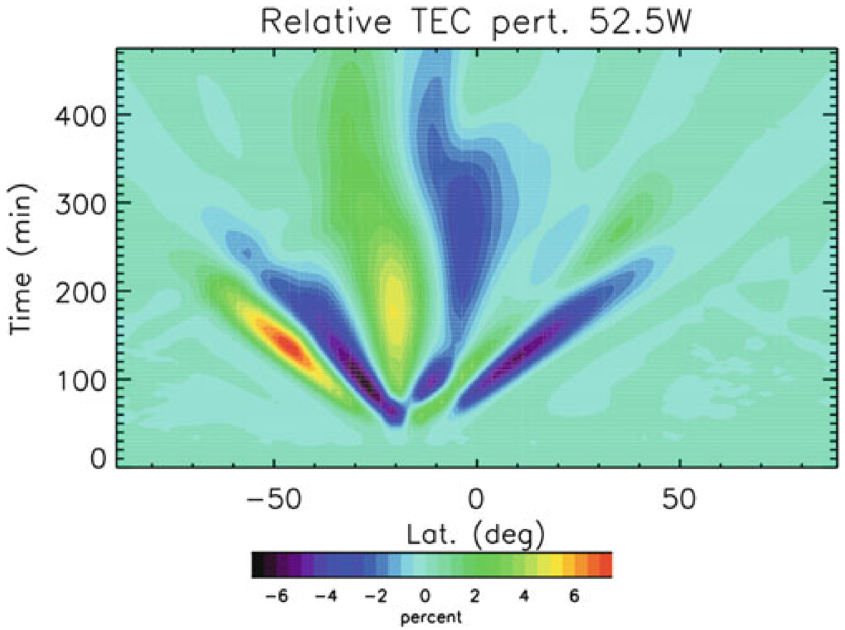
Gravity wave effects in the ionosphere

Data: digisonde, Fortaleza, Brazil



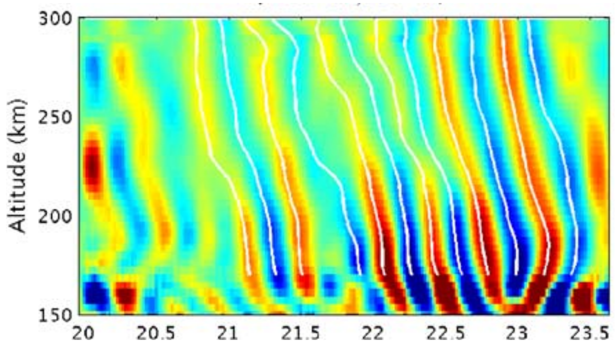
40% variation in *Ne*, *Fritts et al.*, 2008

Model: TIMEGCM



~8% in TEC, *Vadas and Liu, 2009*

Data: PFISR, Alaska



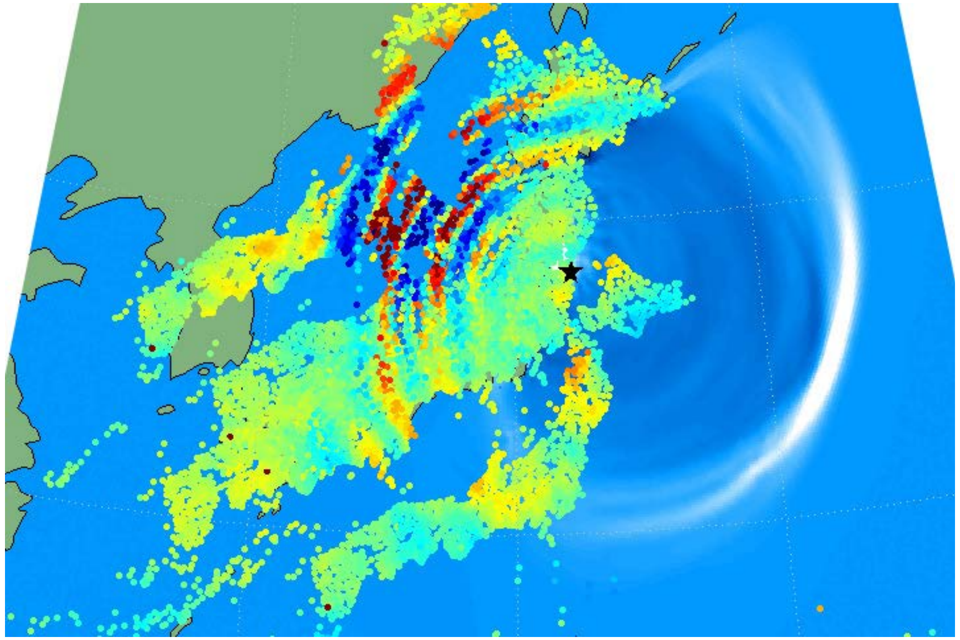
20% in *Ne*, *Vadas and Nicolls*, 2009

- GW can produce secondary GW and TID
- Propagates globally (*Gardner and Schunk*, 2011)
- Nonlinear spectral GW parameterization in GCM leads to ~200K cooling (*Yigit and Medvedev*, 2009)

Reviews: *Fritts and Alexander*, 2003, *Fritts and Lund*, 2011

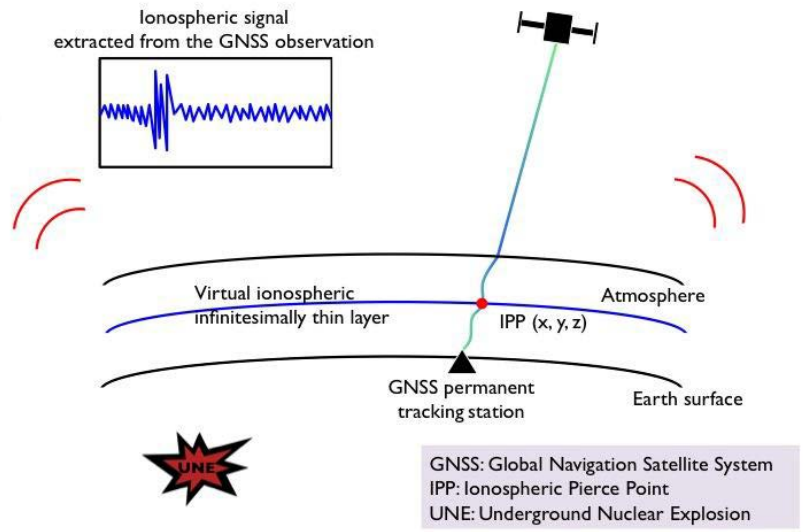
Special cases of GW effects:
earthquakes, tsunami, underground nuclear tests

2011 Tohoku-Oki earthquake in Japan



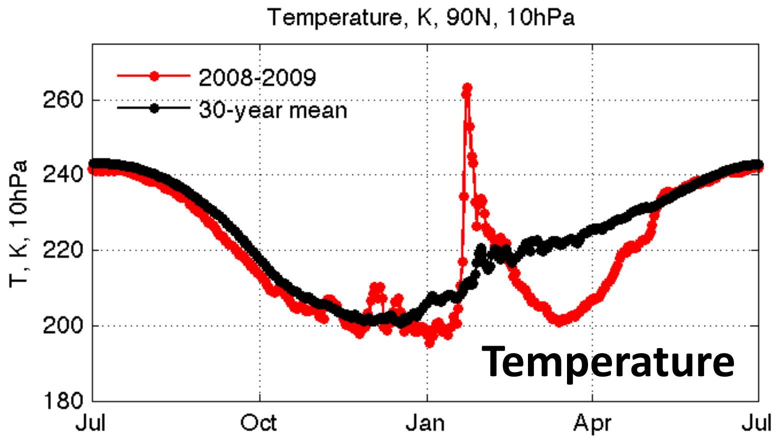
- The earthquake created acoustic and Raylegh waves that moved up into the ionosphere within 10 minutes after the quake.
- The motion of the tsunami also disturbed the atmosphere, creating gravity waves that took 30 to 40 minutes to reach the ionosphere.

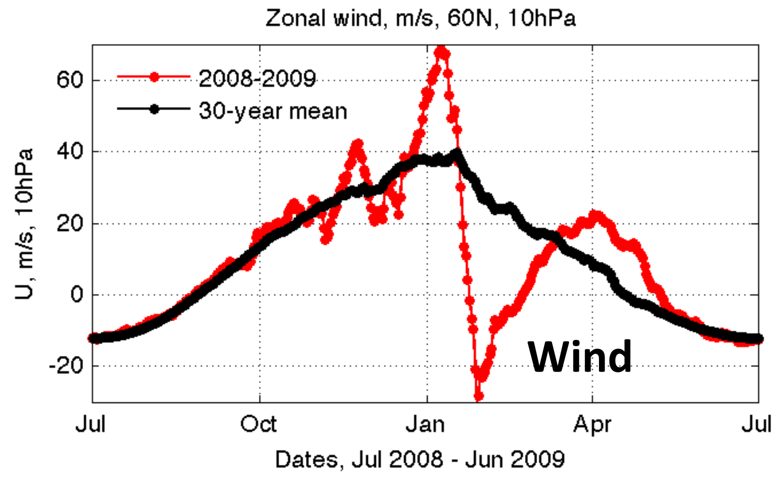
Traveling ionospheric disturbance excited by UNE



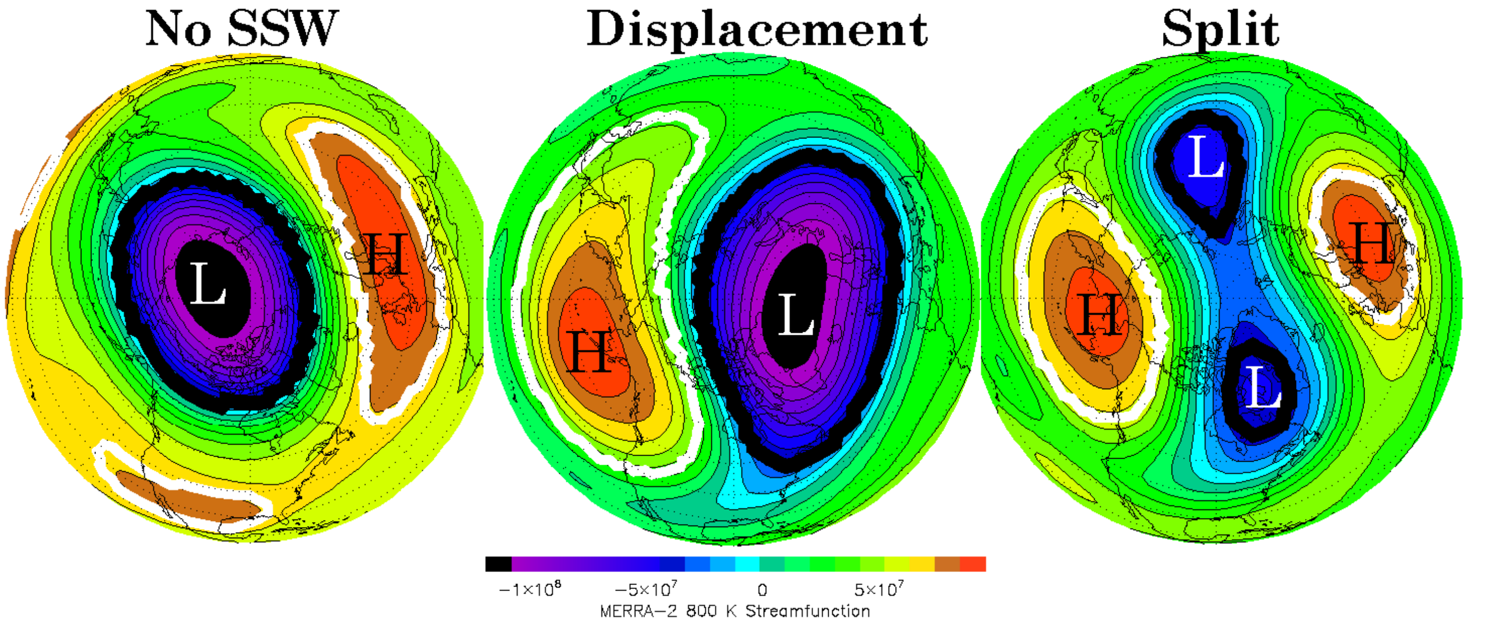
- Underground nuclear test by North Korea in Feb 2013 detected through GPS satellites signals
- Independent analysis by South Korea, UK, USA

Special type of event: sudden stratospheric warming





- Large disruption of the polar vortex
- Largest known meteorological disturbance
- Rapid increase in temperature in the **high-latitude** stratosphere (25K+); from winter-time to summer-time
- Accompanied by a change in the zonal mean wind
- **Anomalies last for a long time in the stratosphere (2 weeks +)**
- SSW events occur 1-3 times per winter



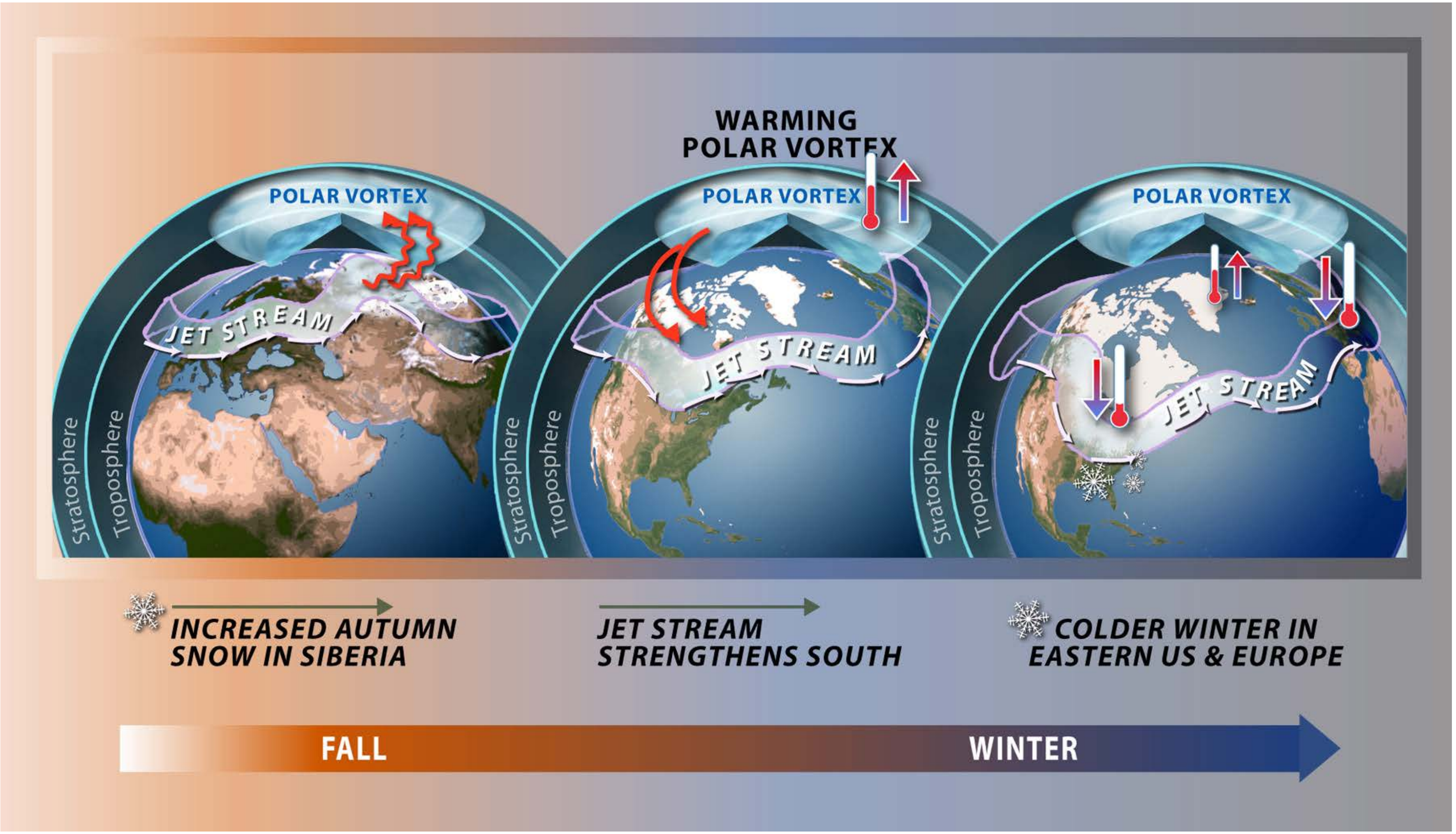
"Normal" polar vortex is small, round, centered on the North Pole

Disturbed vortex is broken into 2 cells

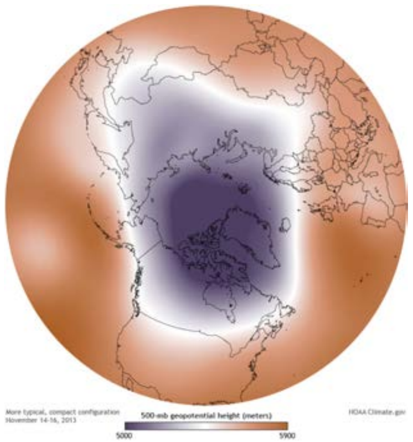
Disturbed vortex is broken into 4 cells

Polar vortex and weather impacts due to stratospheric warming

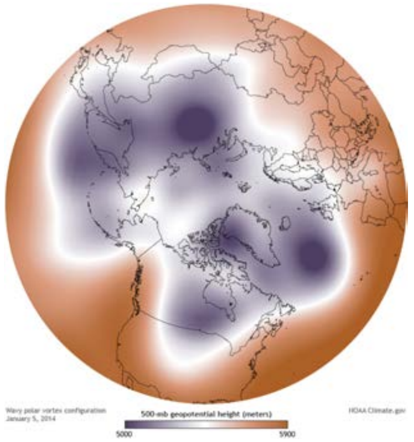
- Snow cover in Siberia in October is linked to US winter temperature
- If in doubt, check your utility bills!



Early 2014 North American cold wave



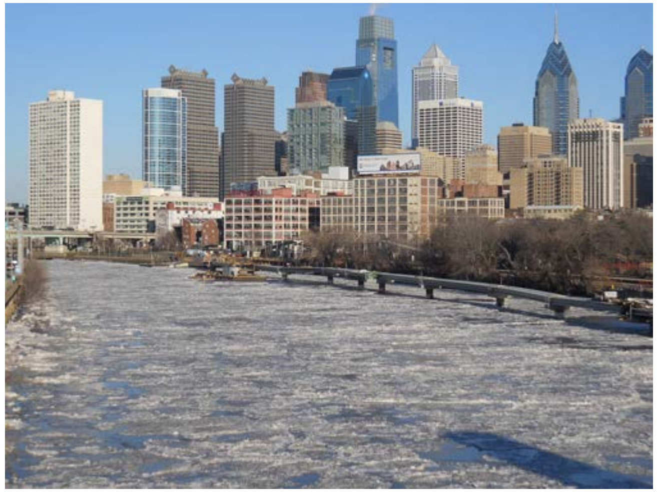
Typical polar vortex:
Nov 15, 2013



Abnormal polar vortex:
Jan 5, 2014

Ongoing blizzard across Ohio River Valley and Northeastern US as cold air from Canada moves across warm air from the Gulf of Mexico.
A GOES-13 image on January 2, 2014

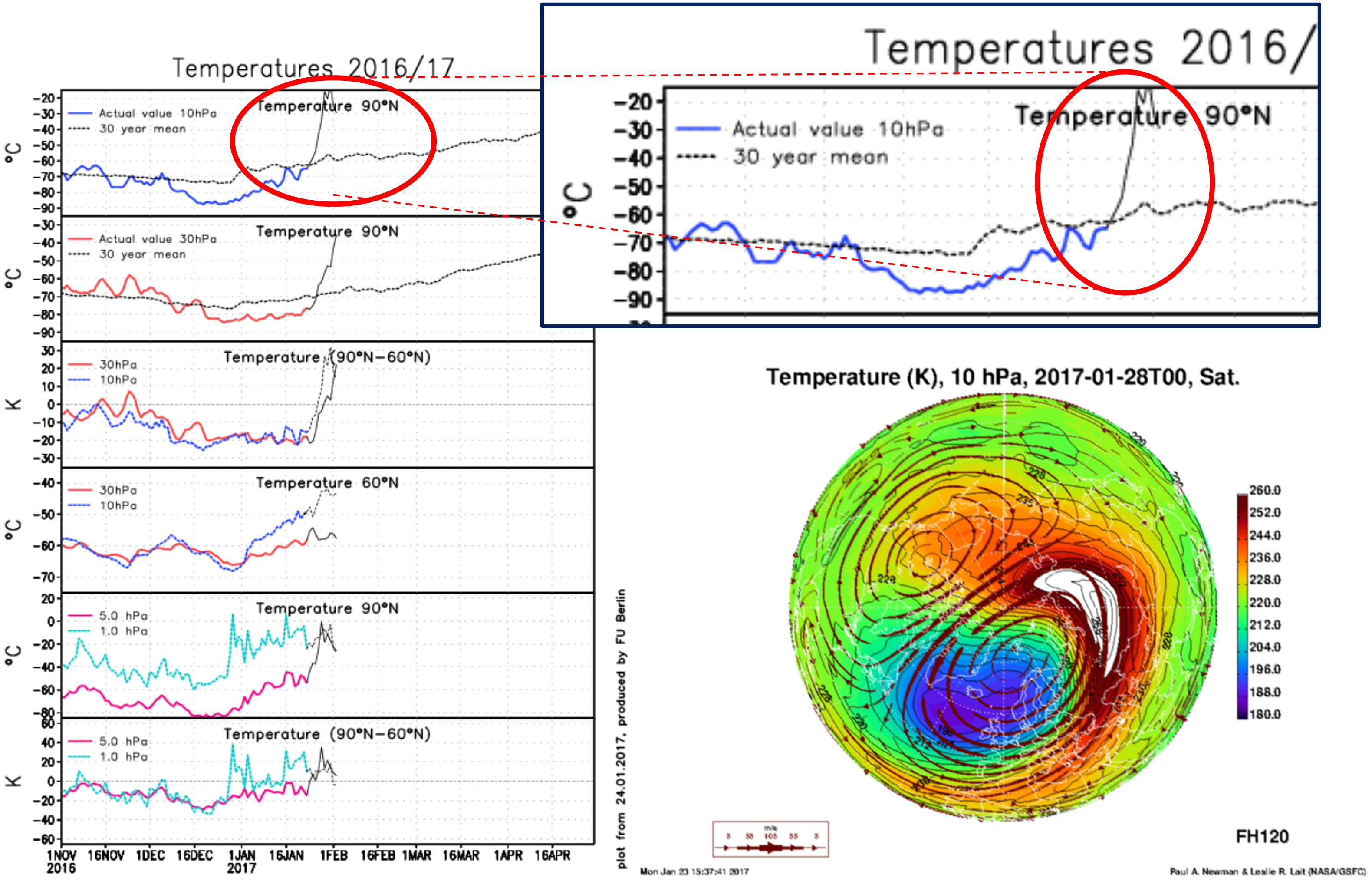
- Record (or near record) temperatures:
  - -37°F in Babbit, Minnesota
  - -9°F in Marstons Mills, MA
  - 21°F in Huston, 31°F in Tampa, FL
- 49 record lows for the day across the country on January 7
- Heavy snowfall or rainfall + strong winds
- 23.8 inches of snow in Boxford, MA
- $5 billion in damage, 21 fatalities



Ice formations on the Schuylkill River in Philadelphia

… and in Massachusetts …

Meteorological forecast: 8-10 days in advance



University of Berlin

NASA/GSFC

Forecast on Jan 24, 2017: by Jan 28, North Pole temperature at ~30 km will increase by 50°C; stratospheric polar vortex strongly disturbed

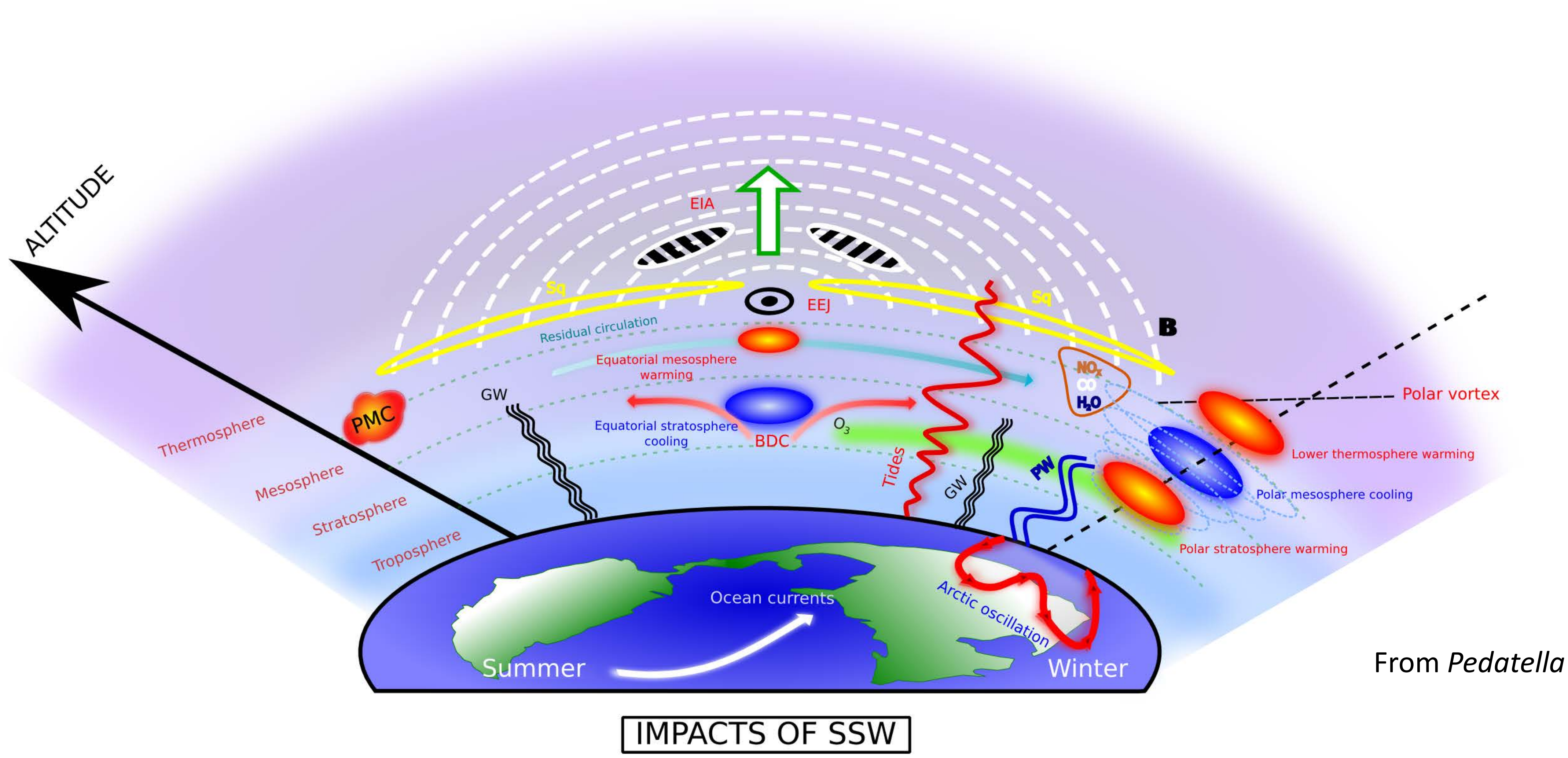
- Continuous global observations of major parameters since 1979
- **Well-developed global assimilation models provide dozens of atmospheric parameters with high resolution in time and space**
- **Current status: reliable forecast up to 8-10 days in advance**
- Tropospheric weather forecast is improved with increased SSW predictability [Baldwin et al., 2003; Sigmond et al., 2013]
- **Current research effort: meteorological forecasts 2-3 months in advance**

Things are different for the ionosphere-thermosphere system…

- Smaller research community, fewer resources, bigger area to study
- Observations are scarce
- Many important parameters are not observed at all (temperature and wind profiles)
- Data assimilation is in its infancy
- 24-hr forecast is work in progress
- We are missing major pieces of puzzle
- 30-50 years behind meteorology

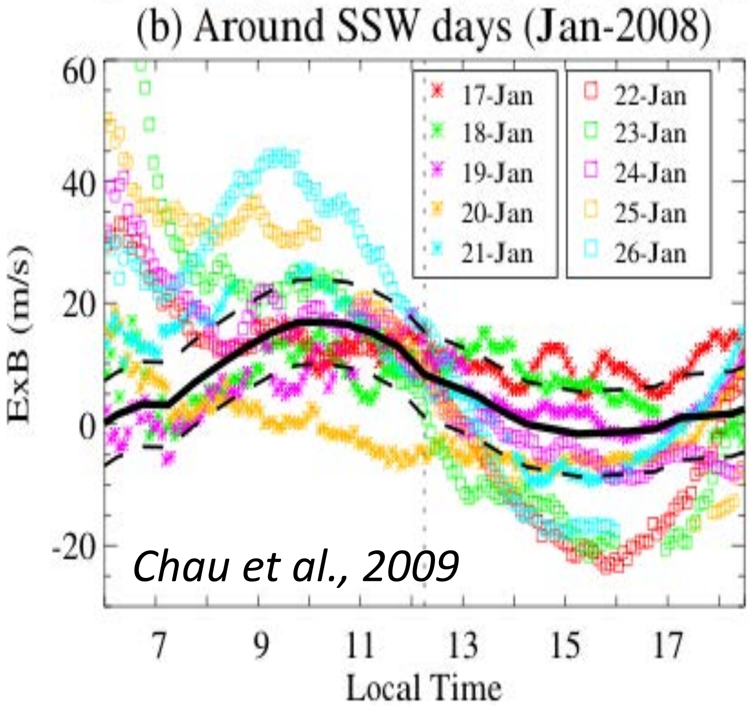
- Plenty of room for innovation in research instrumentation
- Opportunities for major discoveries
- Leveraging advances in meteorology holds a promise of multi-day ionospheric forecast
- **Enormous need for more observational data – plenty of room for citizen science**

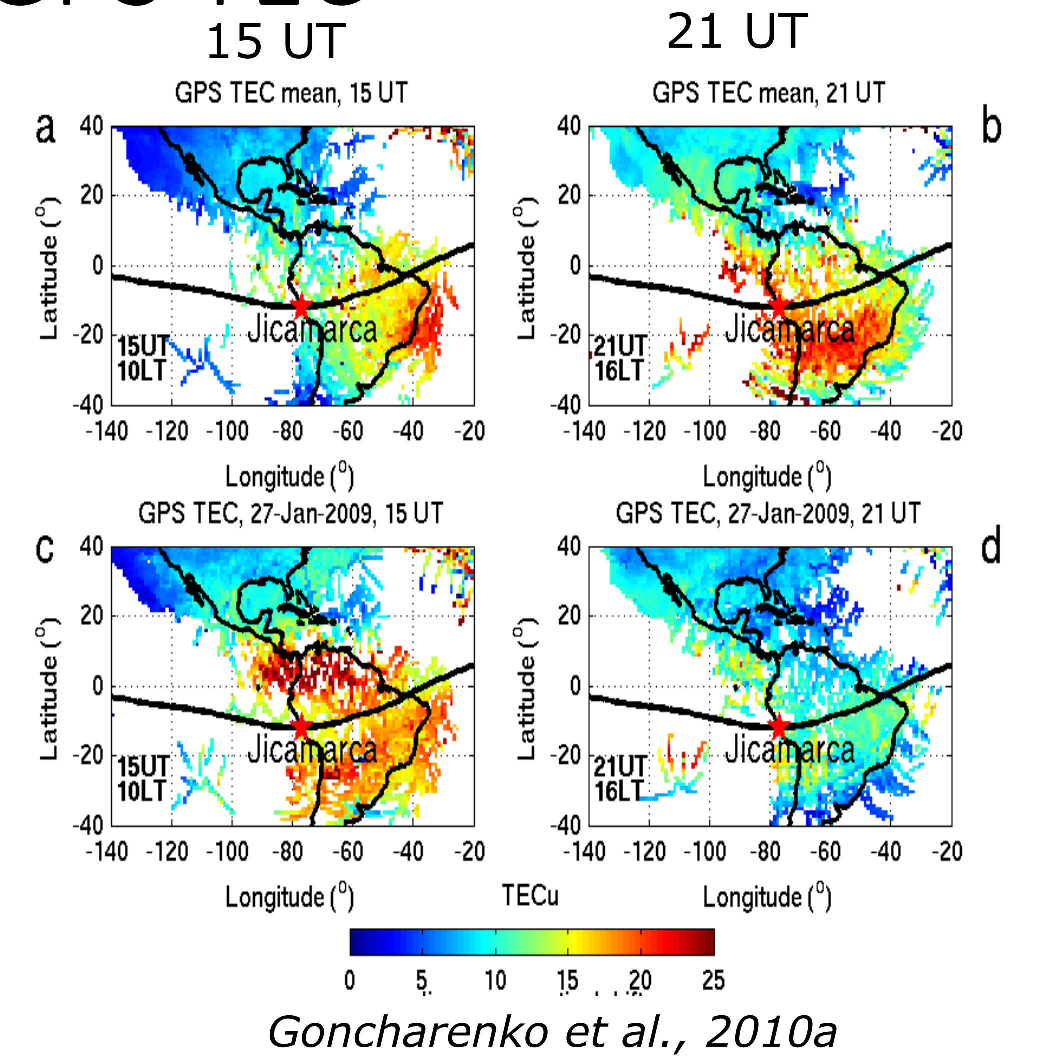
Variety of effects during SSW: from Arctic stratosphere to ionosphere over Antarctica



From *Pedatella et al., 2018*

Ionospheric response to January 2009 SSW: plasma motion and GPS TEC



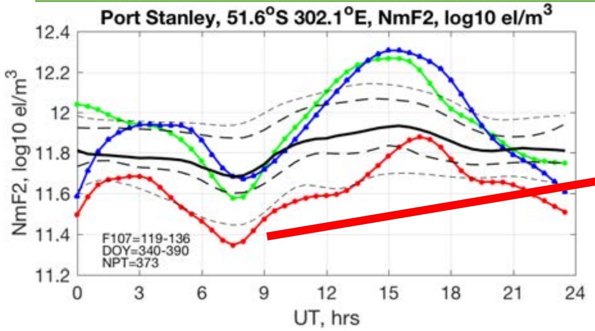


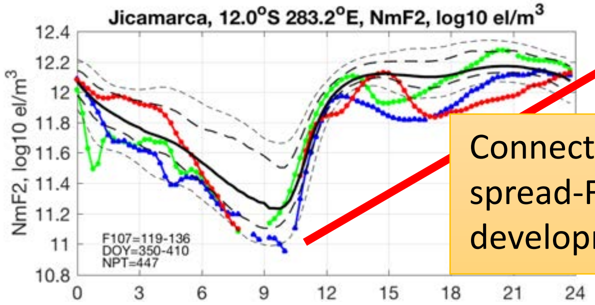
- Upward drift in the morning, downward in the afternoon -12-h wave
- Interpreted as evidence of enhanced 12-tide
- Related increase and decrease in electron density

Entire daytime low to mid-latitude ionosphere is affected during stratwarming; Total Electron Content change 50-150%

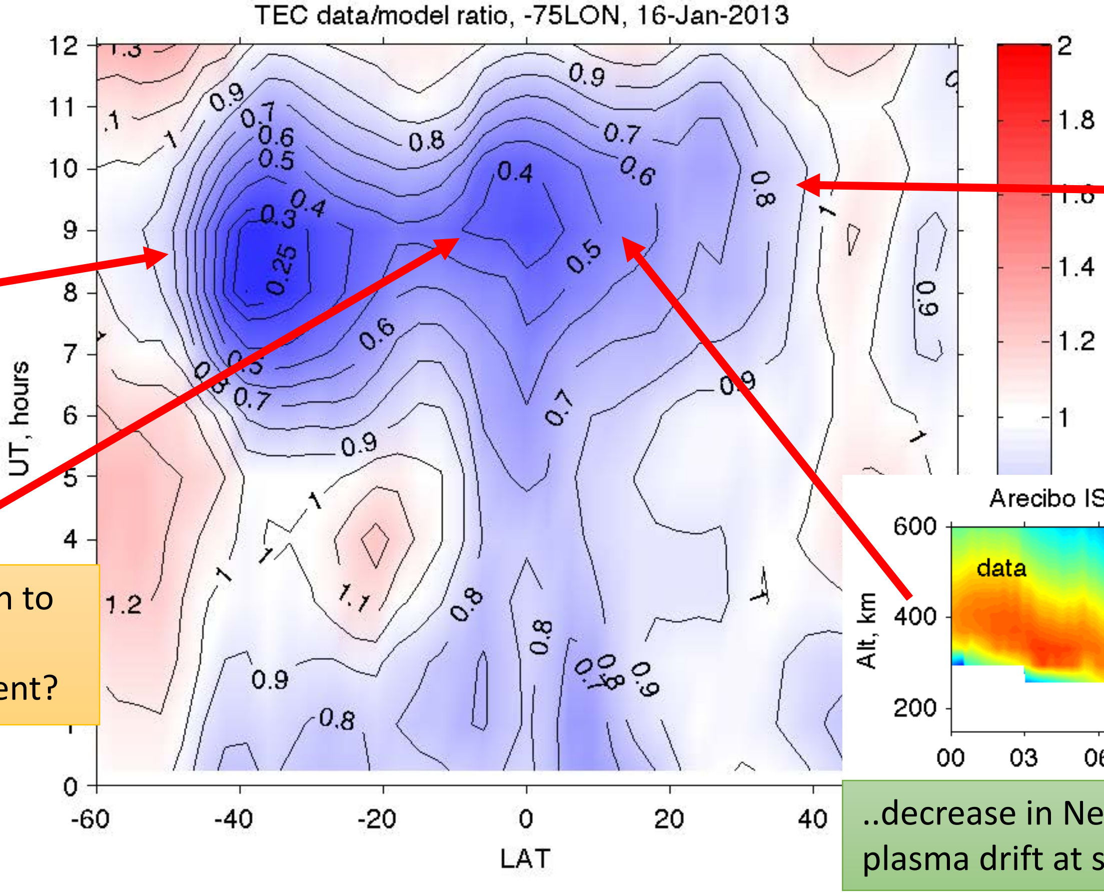
Nighttime effects of SSW: deep depletion in electron density from ~50ºS to 40ºN in multi-diagnostics study

..decrease in Nmf2 in the Southern Hemisphere midlle latitude…

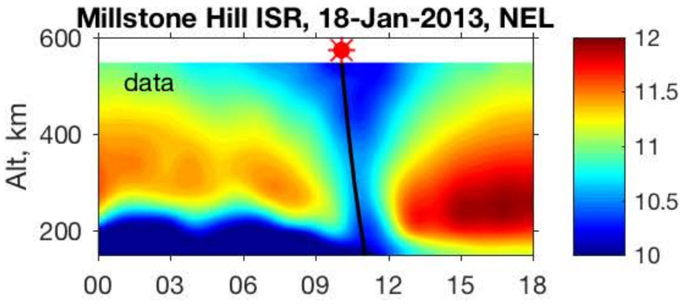




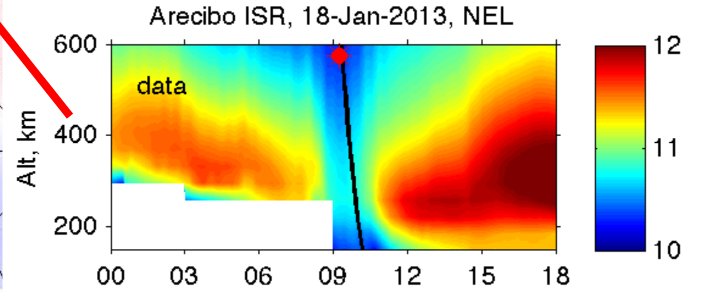
…spread-F development at the magnetic equator…



Connection to spread-F development?



..decrease in Ne, cooling, and large downward plasma drift at NH middle latitude..



..decrease in Ne and large downward plasma drift at subtropical latitude..

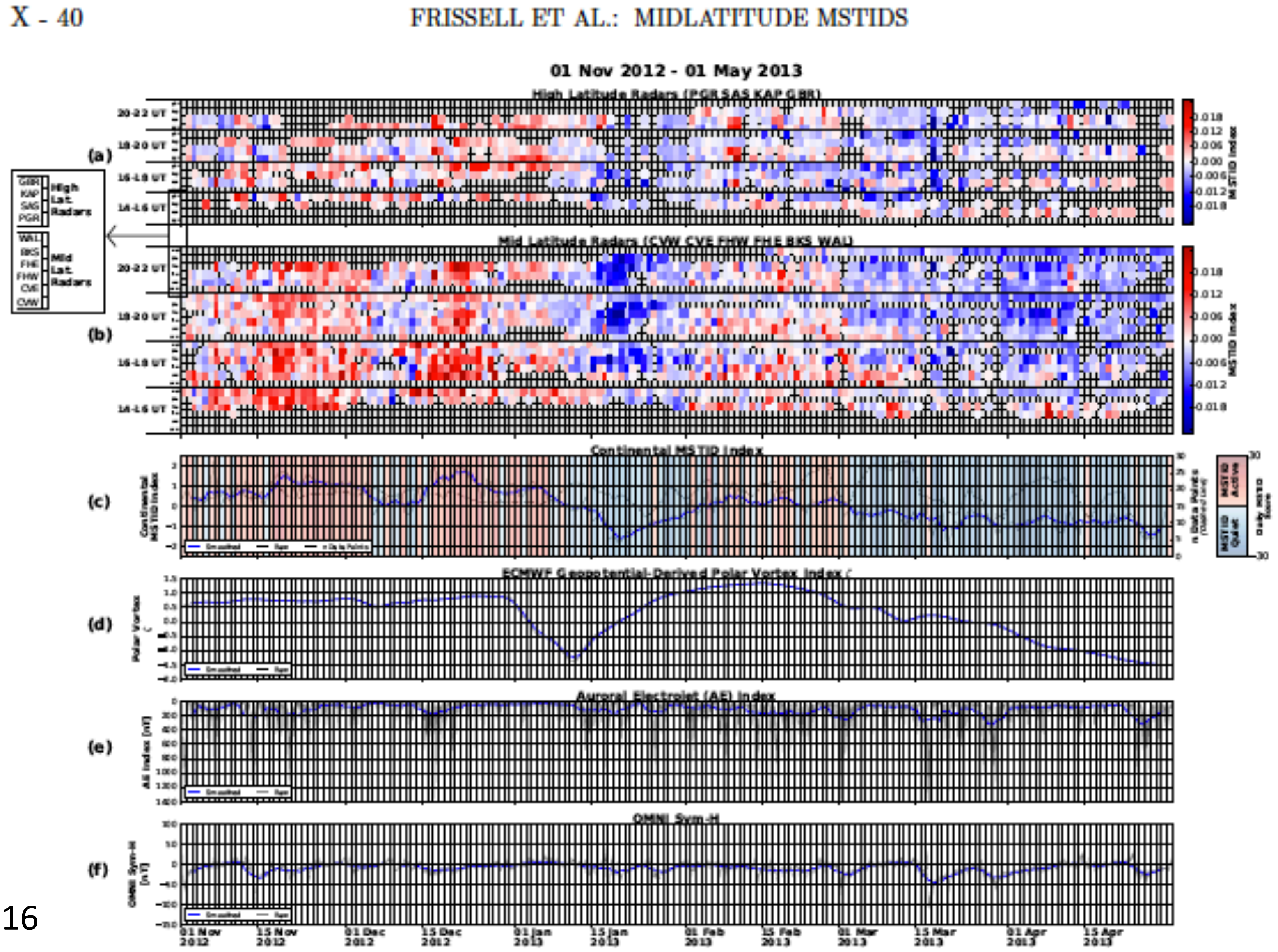
- SSWs affect the nighttime electron density, decreasing it by a factor of 2-4 in a large range of latitudes – 50ºS to ~40ºN
- These effects are likely to be related to changes in thermospheric zonal wind
- Effects of tidal dynamics on electric field are understood better than on thermospheric wind
- Likely related to lunar tide; lunar tides are amplified during SSW, but significant throughout Nov-Mar

Goncharenko et al., 2018, JGR-Space physics

Observational evidence: MSTIDs are weaker after polar vortex weakening

- Medium-scale traveling ionospheric disturbances from SuperDARN data have a strong correlation with polar vortex dynamics, but no correlation with space weather activity

- Possible explanation: Filtering of gravity waves by stratospheric wind system



Frissel et al., 2016

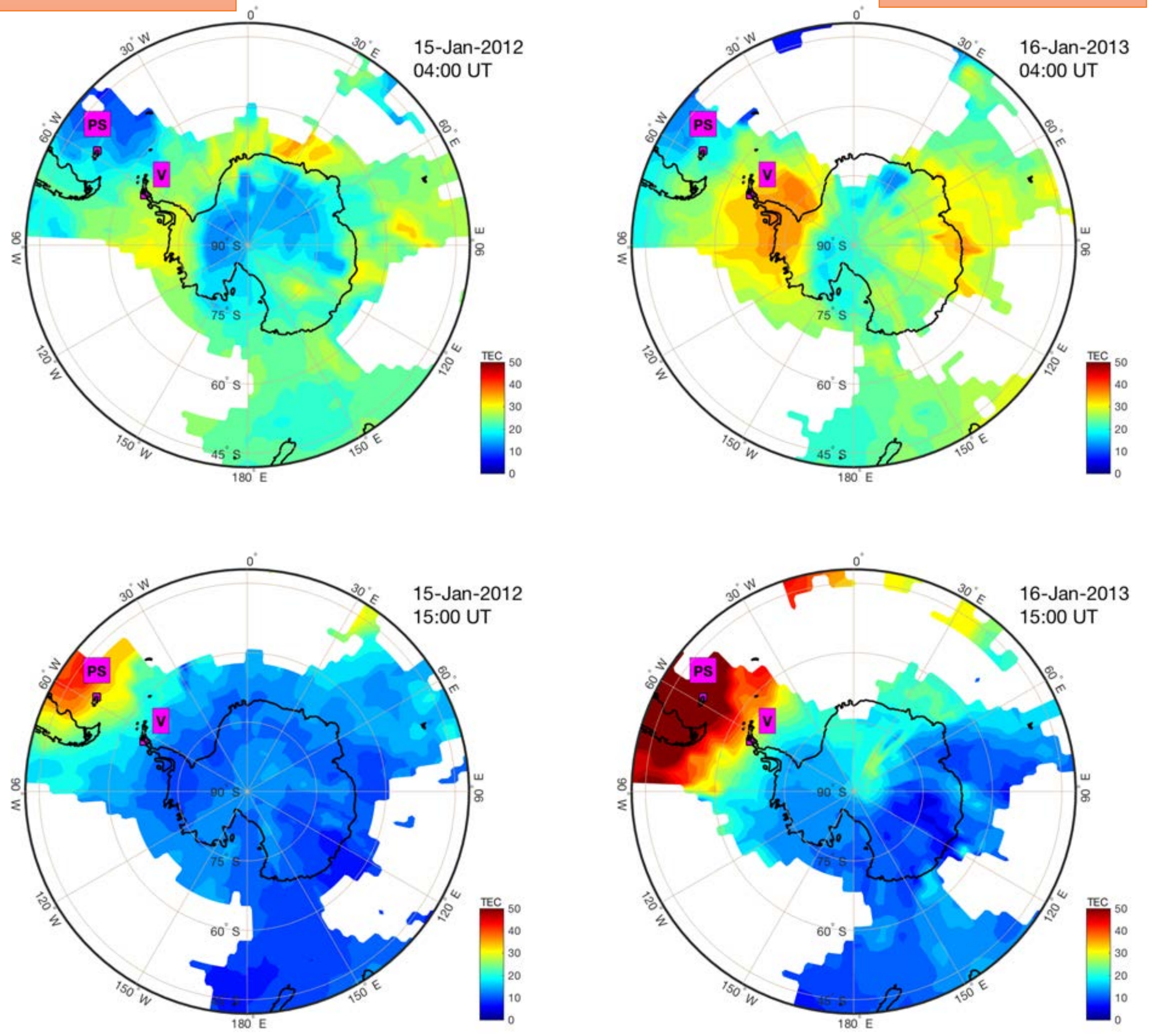
Yet another piece: SSW disturbances in the ionosphere over Antarctica

- Variations in total electron content follow familiar semidiurnal pattern
- Independent observations from ionosondes confirm the level of disturbances

SSW disturbances are truly global, from Arctic stratosphere to ionosphere over Antarctica…

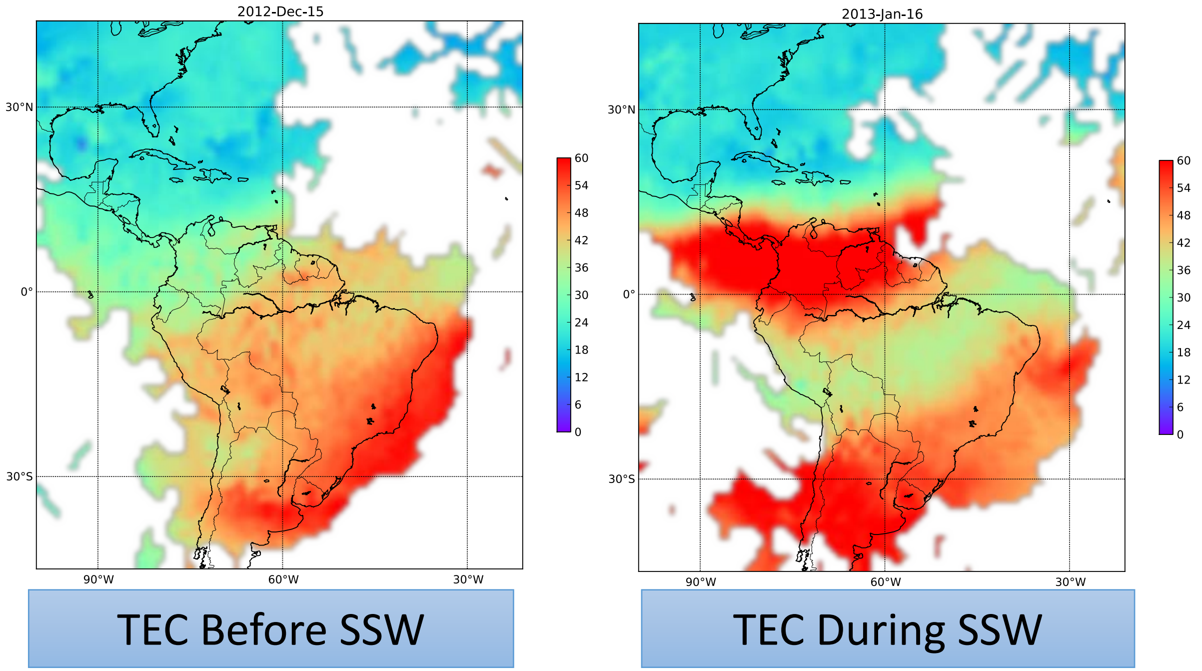
Before SSW

During SSW



Implications for ionospheric research

- **SSW studies highlights importance of lower atmospheric drivers in ionospheric variability**
  - Need solar EUV + geomagnetic drivers + meteorological forcing
  - Impact will increase in the future
    - Mild current & future solar cycles
    - 78% decrease in number of storms
- **Provides direct pathway to multi-day ionospheric forecast**
  - Stratospheric parameters can be predicted 8-10 days in advance

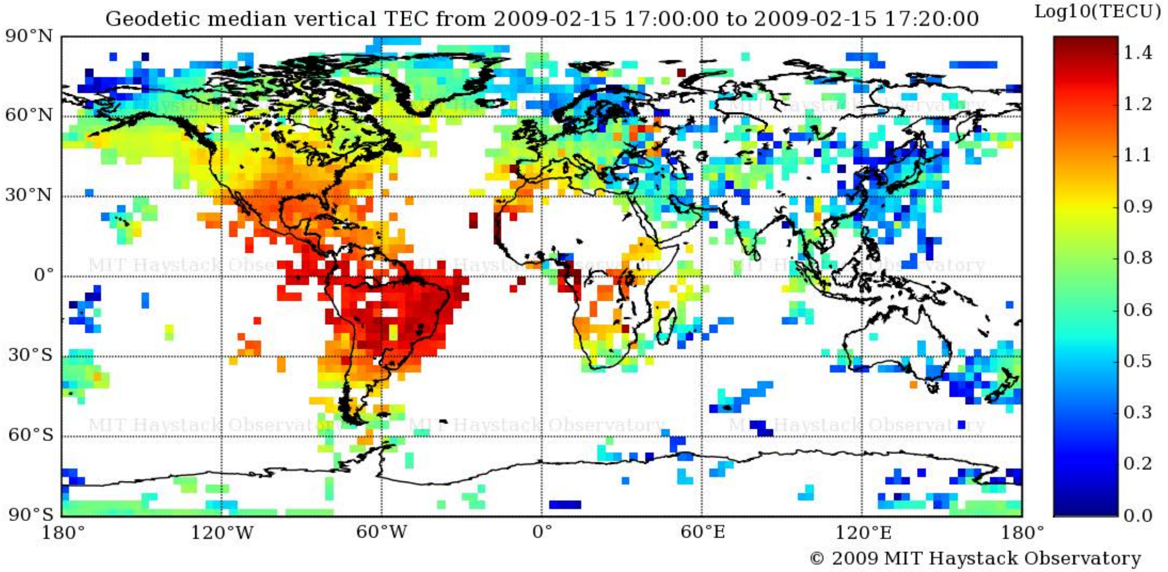


After Goncharenko et al., 2019

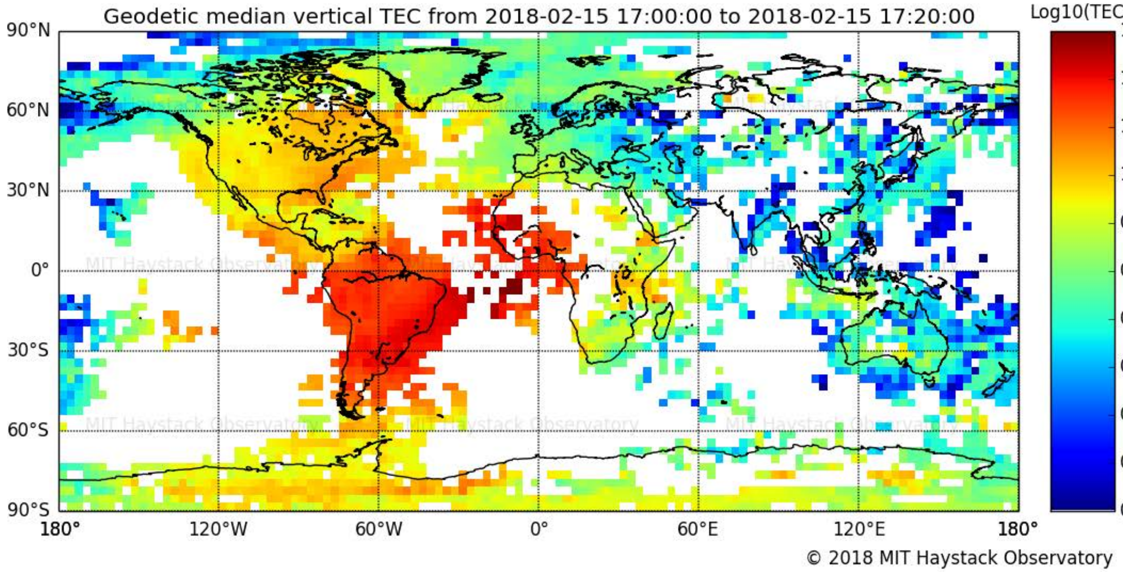
Power of distributed instrumentation

- Data: GNSS TEC, Madrigal database, 1 x 1 degree, 6000+ receivers
- Enables huge variety of studies
- Still major gaps over the oceans, Africa, Russia, China

February 15, 2009



February 15, 2018



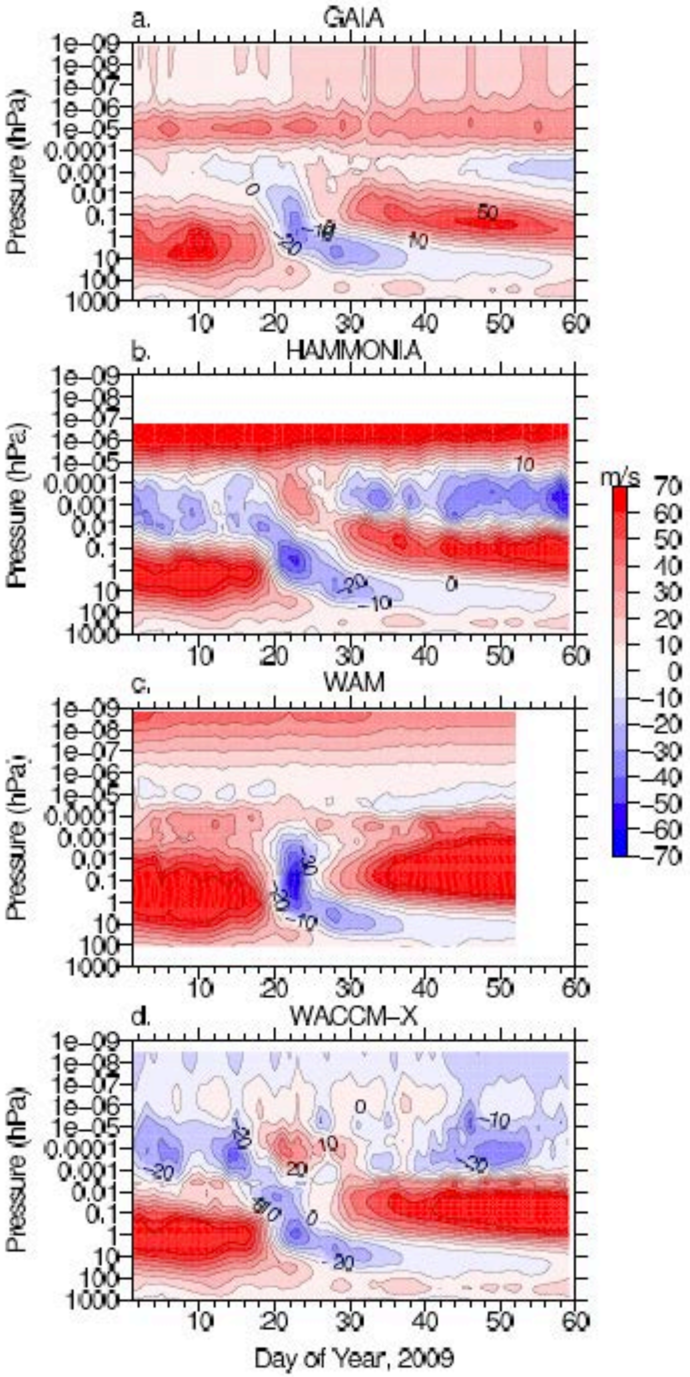
Improved GNSS TEC coverage enables more detailed studies of ionospheric disturbances

Concluding remarks

- Space physics is making good progress towards physics based ionospheric forecasting
  - Empirical models are still better than first principles – some physics is missing
- Ionospheric system remains strongly undersampled by available research instruments
- There is a particularly strong need for observations in the bottomside ionosphere
  - HF radiowaves are well suited to address this need
  - Operational information from existing HF systems is not publicly available for research
  - TIDs from TEC, incoherent scatter radars and ionosondes have different characteristics
- Networks developed by amateur radio operators can provide critical information with a potential to advance physical understanding of near-Earth space environment.

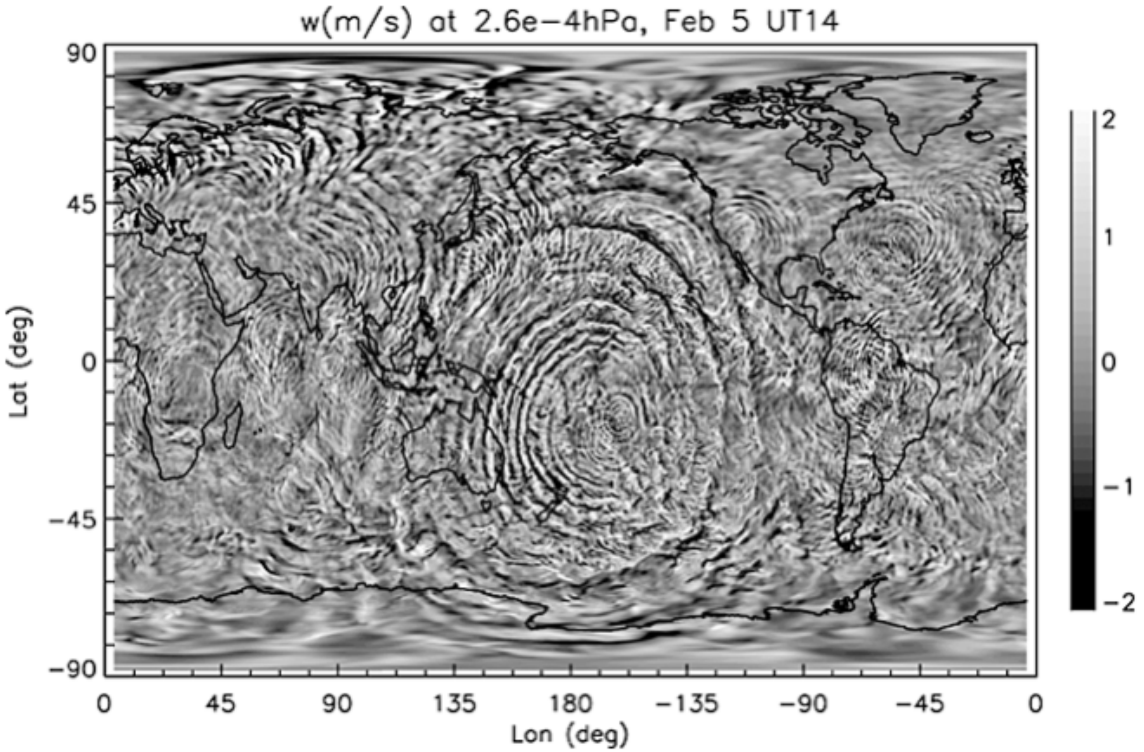
Our vision: In years from now, we will look at the weather forecast on the ground to predict what happens in space.

Can you help us to make it happen?



Can models simulate atmospheric processes during SSW?

- Comparison of four Whole Atmosphere Models for SSW 2009 case:
  - GAIA, Japan,
  - HAMMONIA, Germany,
  - WAM, USA, NOAA,
  - WACCM-X, USA, NCAR
- Variations are similar in the stratosphere where models are restricted by reanalysis data (below 0.1hPa level)
- Large disagreements are seen in the mesosphere-lower thermosphere region (0.001-1e-06hPa) that is critical for ionospheric coupling
- Limitations in gravity wave specifications are thought to be the main reason for these differences



w(m/s) at 2.6e−4hPa, Feb 5 UT14
90
45
0
−45
−90
Lat (deg)
0
45
90
135
180
−135
−90
−45
0
Lon (deg)
2
1
0
−1
−2

The Science Behind the Polar Vortex

The polar vortex is a large area of low pressure and cold air surrounding the Earth's North and South poles. The term vortex refers to the counter-clockwise flow of air that helps keep the colder air close to the poles (left globe). Often during winter in the Northern Hemisphere, the polar vortex will become less stable and expand, sending cold Arctic air southward over the United States with the jet stream (right globe). The polar vortex is nothing new — in fact, it's thought that the term first appeared in an 1853 issue of E. Littell's *Living Age*.