Ionosphere and Thermosphere Panel

Key questions:

- What are the advances in modeling and observations needed to improve the understanding of the Sun-Earth system that generates space weather?
- What are the biggest challenges in ITM science in the coming decades?
- What observations are needed to test our understanding and our ability to nowcast/forecast the system?
- To what extent is space weather in the Ionosphere/Thermosphere driven from below?

Moderator:	***Larry Paxton, Committee***
Bill Lotko	*Dartmouth/HAO*
Naomi Maruyama	*University of Colorado*
Larisa Goncharenko	*MIT/Haystack*
Matt Zettergren	*ERAU*
Hanli Liu	*NCAR/HAO*
Katrina Bossert	*University of Arizona*

Space Weather Operations and Research Infrastructure Workshop: Phase II, Monday April 11, 2022, 1300 ET

Big Challenges in ITM Science for Space Weather *Prediction*

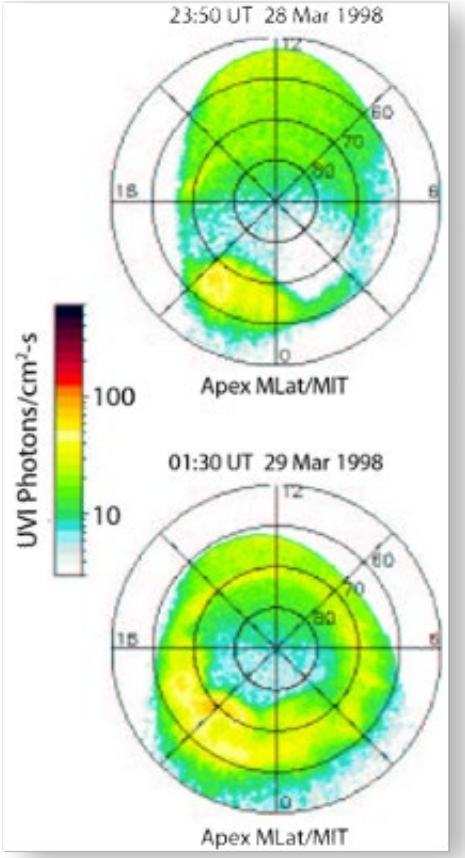
Perspectives on what's needed to improve the fidelity of magnetosphere-ionosphere(-thermosphere) coupling in predictive global geospace models

Bill Lotko | HAO/NCAR and Dartmouth College

- *Global distribution of ionospheric conductivity*
- *Global distribution of ionospheric ion outflows into geospace*
- *Formation and evolution of polar cap patches*

Global specification of dynamic ionospheric conductivity at mesoscales (10-100 km), esp. precipitation-induced conductivity

- ***Geospace impacts:*** Distributions of convection, currents, auroral electrojets, EM energy deposition; thermospheric heating, upwelling, winds; field-aligned current draw from magnetospheric dynamos
- ***SW impacts:*** AE, GICs, S/C orbit prediction
- ***Observational needs:*** Global multispectral imaging complemented with mesoscale imaging down to 10 km resolution | last global imagers: POLAR (2007), IMAGE (2005)
- ***Techniques/models:***
  - Improvements in image *inversion* to determine precipitating electron energy and energy flux, constrained by complementary ISR and GDC data, among other assets
  - Improved precipitation models. Advances in knowledge of how EM energy is converted to particle energy (where, when, how, how much?)

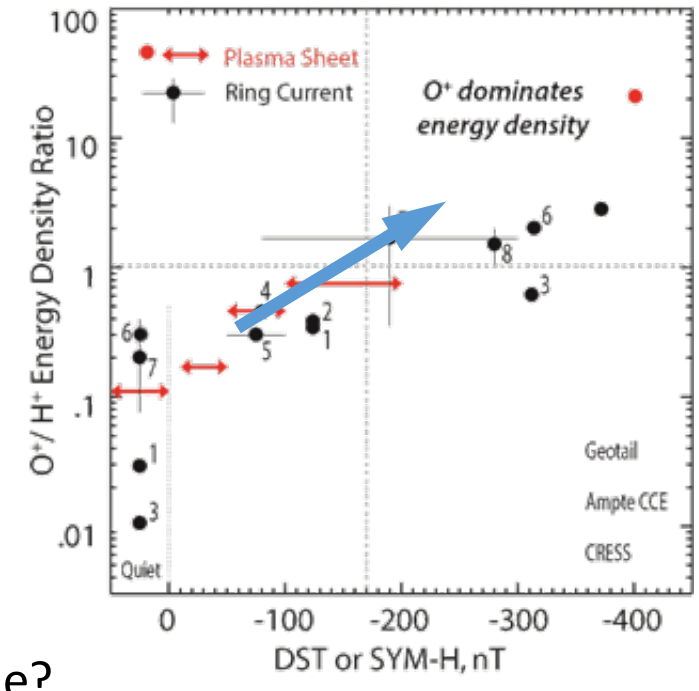


Palmroth et al. 2006

Global specification of dynamic ionospheric ion outflows, esp. nonthermal *heavy* ions during storm conditions

- ***Geospace impacts:*** Magnetic Rx rate, global dynamics, tail and substorm dynamics, ring current intensification; feedback to iono-thermosphere
- ***SW impacts:*** Dst, radiation belts
- ***Observational needs:***
  - Global UV imaging would facilitate knowledge of outflow sources and fluxes
  - Measurements during initial energization (GDC?), dedicated low-altitude S/C missions (Explorers?); measurements of energization profile and processes vs altitude, from initiation upward
  - *Super Grand Challenge*: Is direct global imaging of ion outflow possible?
    "Every time we explore a new region of phase space, we discover something new." – Bob Lin

Ring current / P.S. ion composition vs Dst

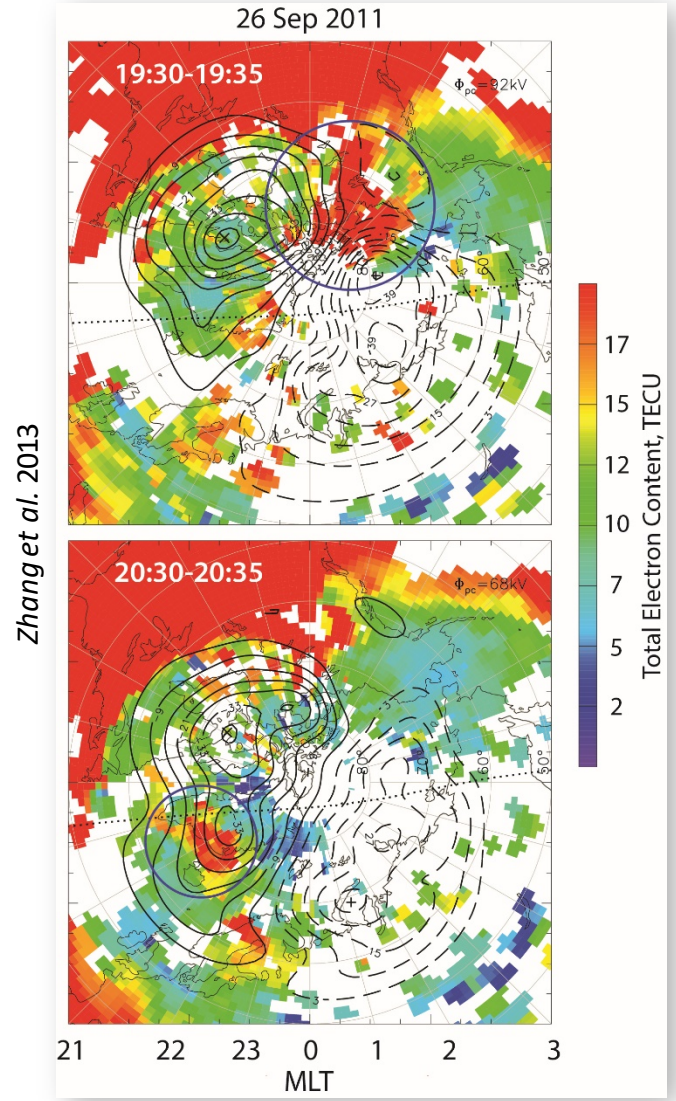


Nosé et al. 2005

- ***Model needs:*** Improved ionospheric ion energization and outflow models in a global context (where, when, how, how much?). Determine accessibility, transport and fate of outflows.

Prediction of the formation, characteristics and evolution of polar cap patches

- ***Geospace impacts:*** Ionospheric variability; development of ionospheric irregularities; enhanced outflows over polar cap; coupling to nightside processes upon entering nightside auroral zone
- ***SW impacts:*** RF scintillations; communications; navigation
- ***Observational needs:***
  - Track across PC with GB, S/C measurements.
  - Determine the magnetospheric/SW regulators
- ***Model needs:***
  - Poorly represented in current global geospace models
  - Improved geospace models that relate magnetospheric sources of precipitation and convection transients to patch formation and evolution



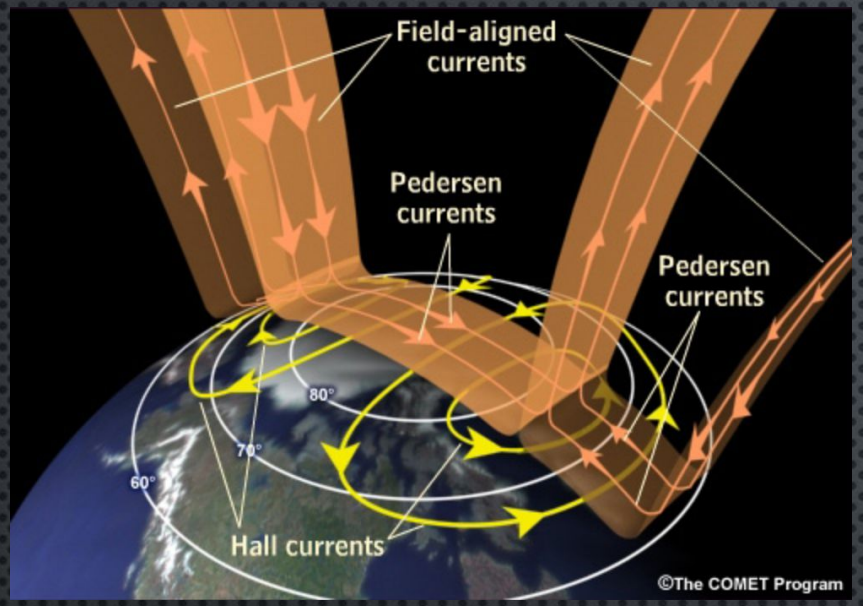
CHALLENGES IN UNDERSTANDING VARIABILITY IN THE IONOSPHERIC ELECTRIC FIELDS AND CURRENTS: THEIR ROLES IN CONNECTING GEOSPACE AND EARTH'S ATMOSPHERE

Naomi Maruyama

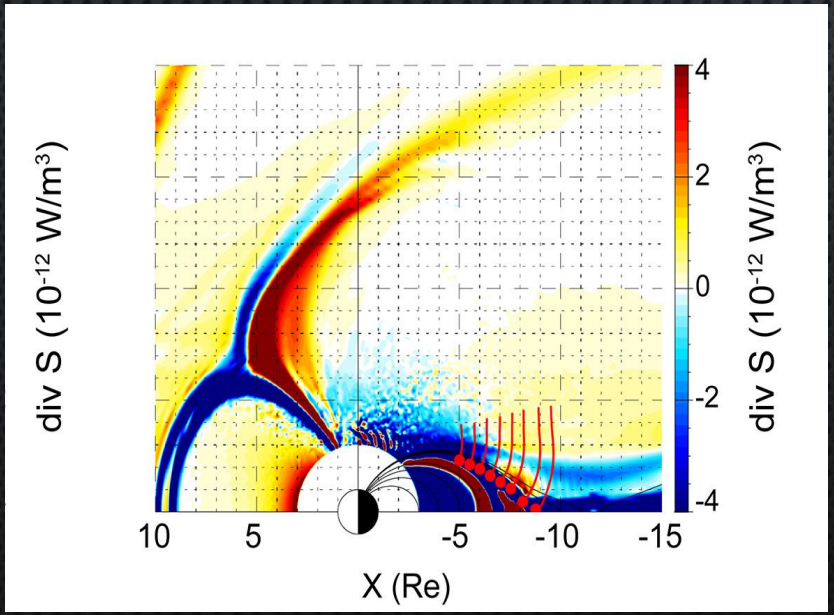
University of Colorado Boulder

Acknowledgements:
Art Richmond, Ludger Scherliess, Tony Mannucci, Fabrizio Sassi, Mei-Ching Fok, Cristian Ferradas

(1)HOW ARE MAGNETOSPHERIC ELECTRIC CURRENTS CONNECTED TO THE IONOSPHERE (REGION I VS. II FACS) WITH VARIOUS TEMPORAL AND SPATIAL SCALE SIZES?

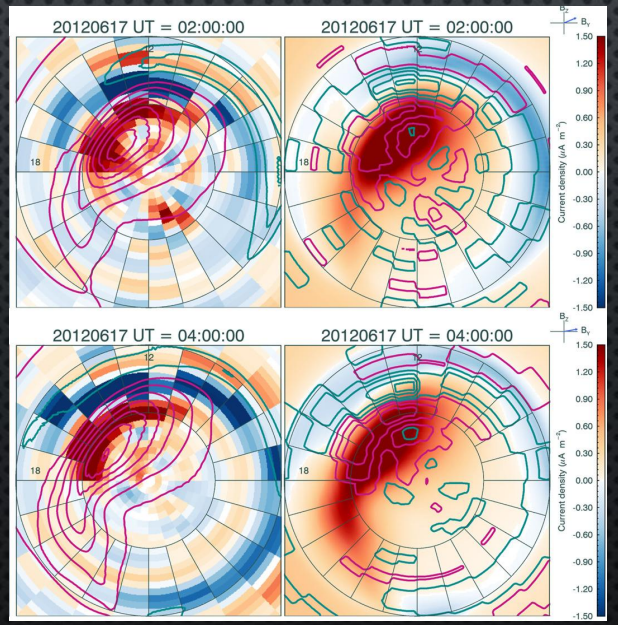


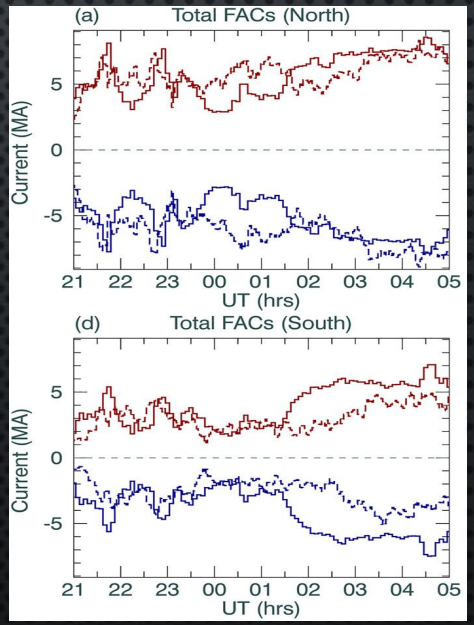
(courtesy: COMET & HAO/NCAR)



(Ebihara&Tanaka, 2017)

AMPERE SWMF



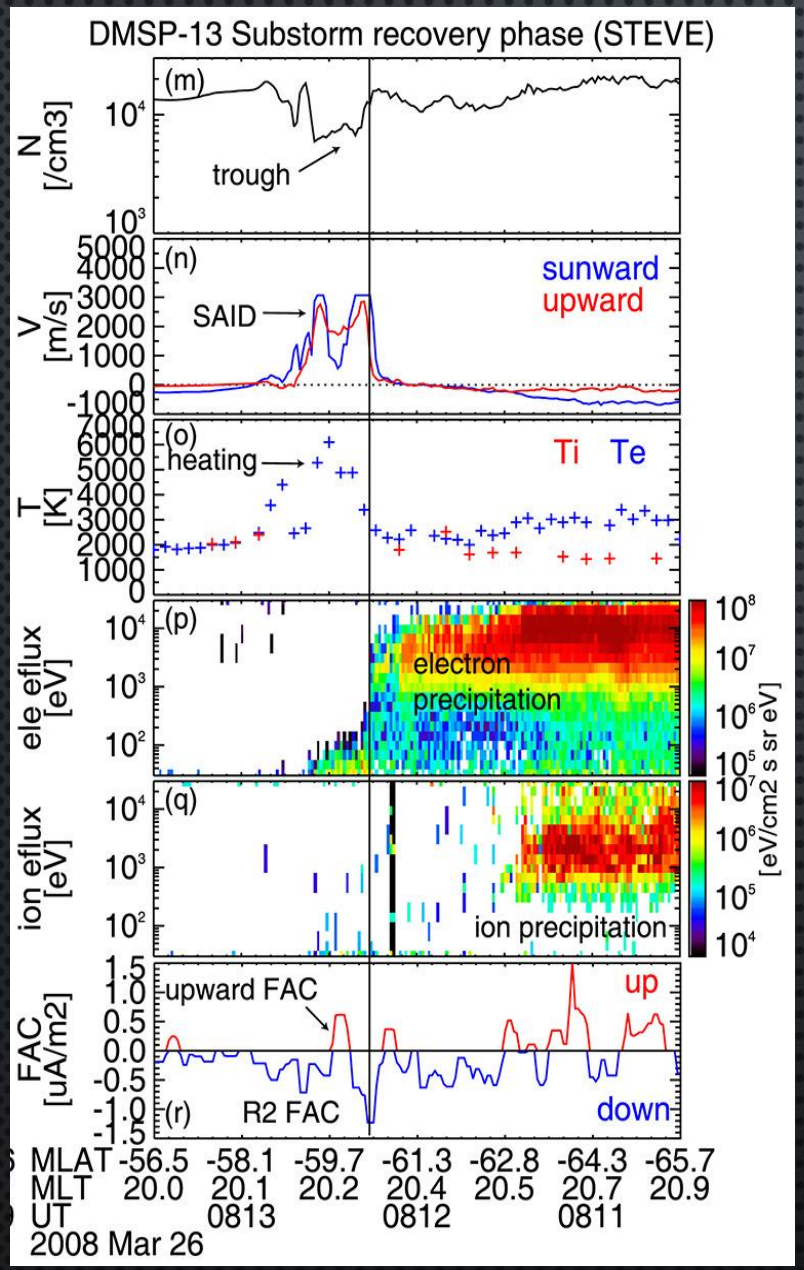


AMPERE:

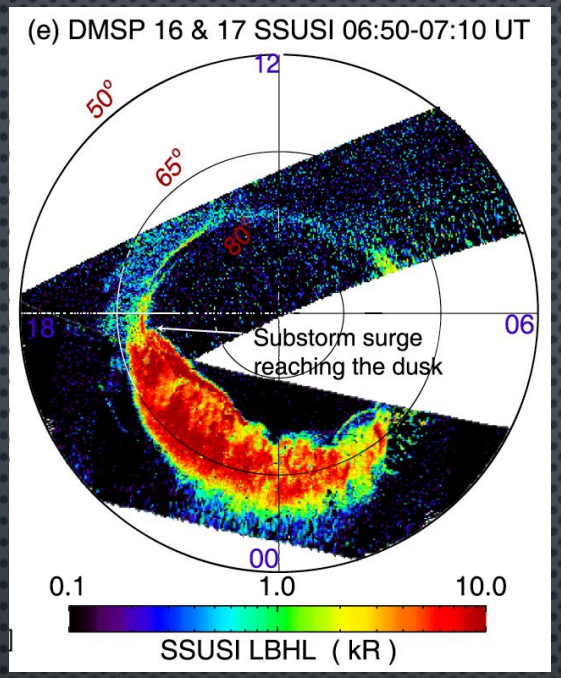
SWMF:

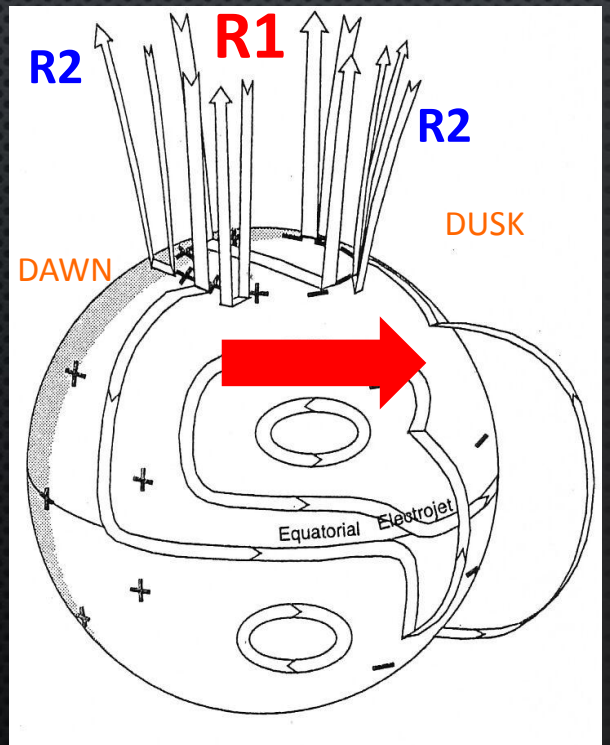
(Carter+, 2021)

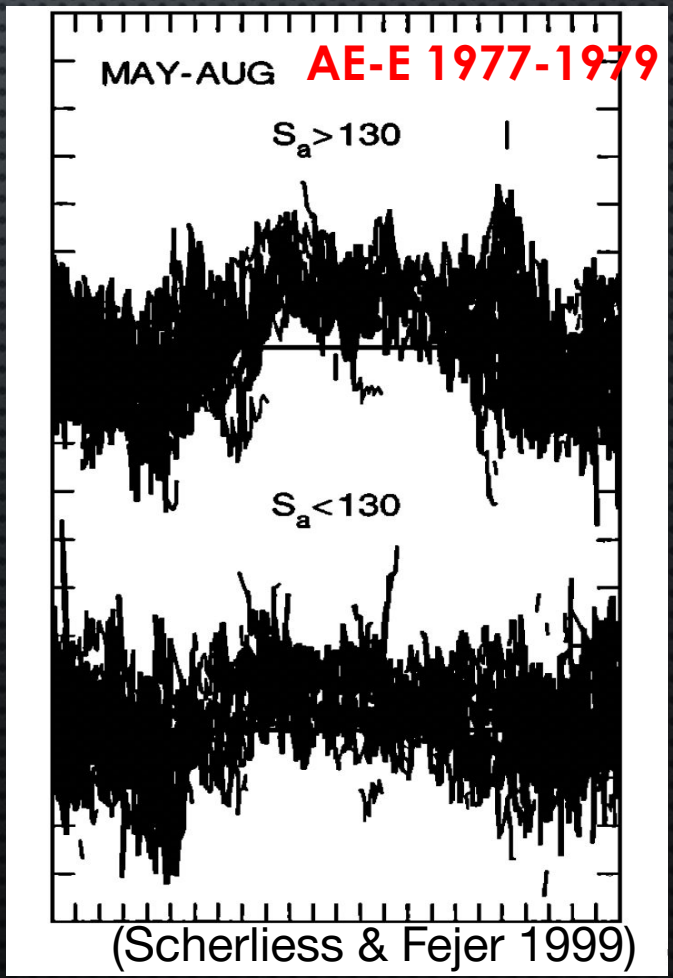
(2)HOW DOES NONLINEAR MAGNETOSPHERIC VARIABILITY IMPACT THE IONOSPHERIC ELECTRIC CURRENTS AND FIELDS?



(Nishimura+, 2020)

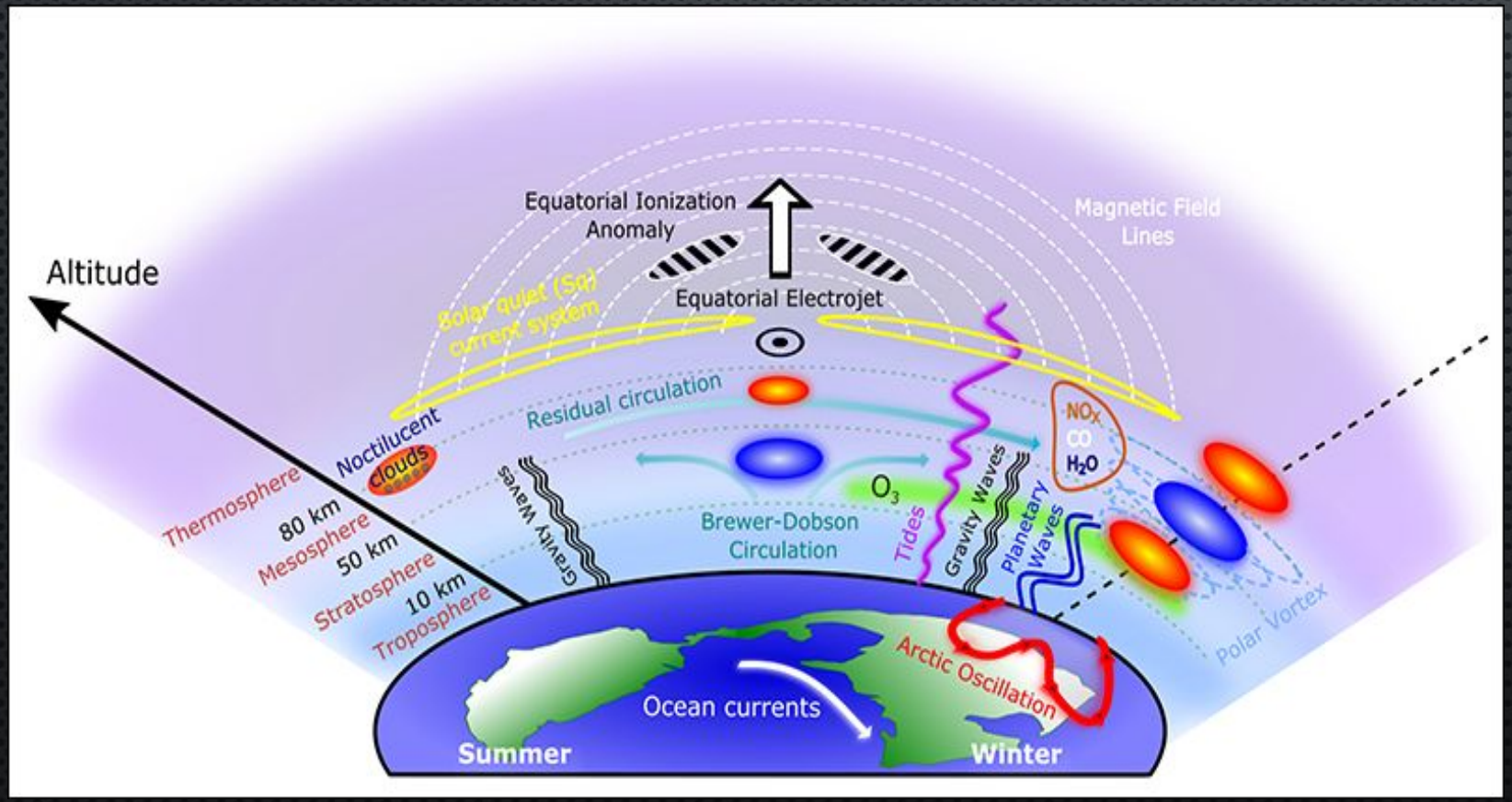




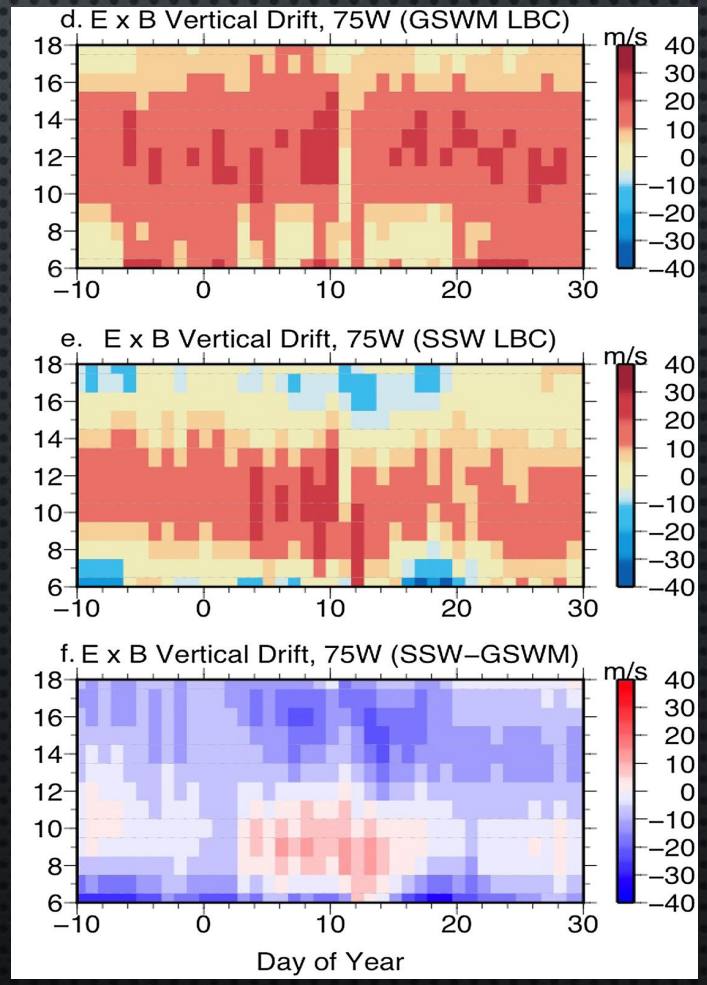


(Scherliess & Fejer 1999)

(3) HOW DOES THE PRECONDITIONING OF THE UPPER ATMOSPHERE IMPACT GEO-EFFECTIVENESS OF EXTERNAL FORCING VIA ELECTRIC CURRENTS AND FIELDS?

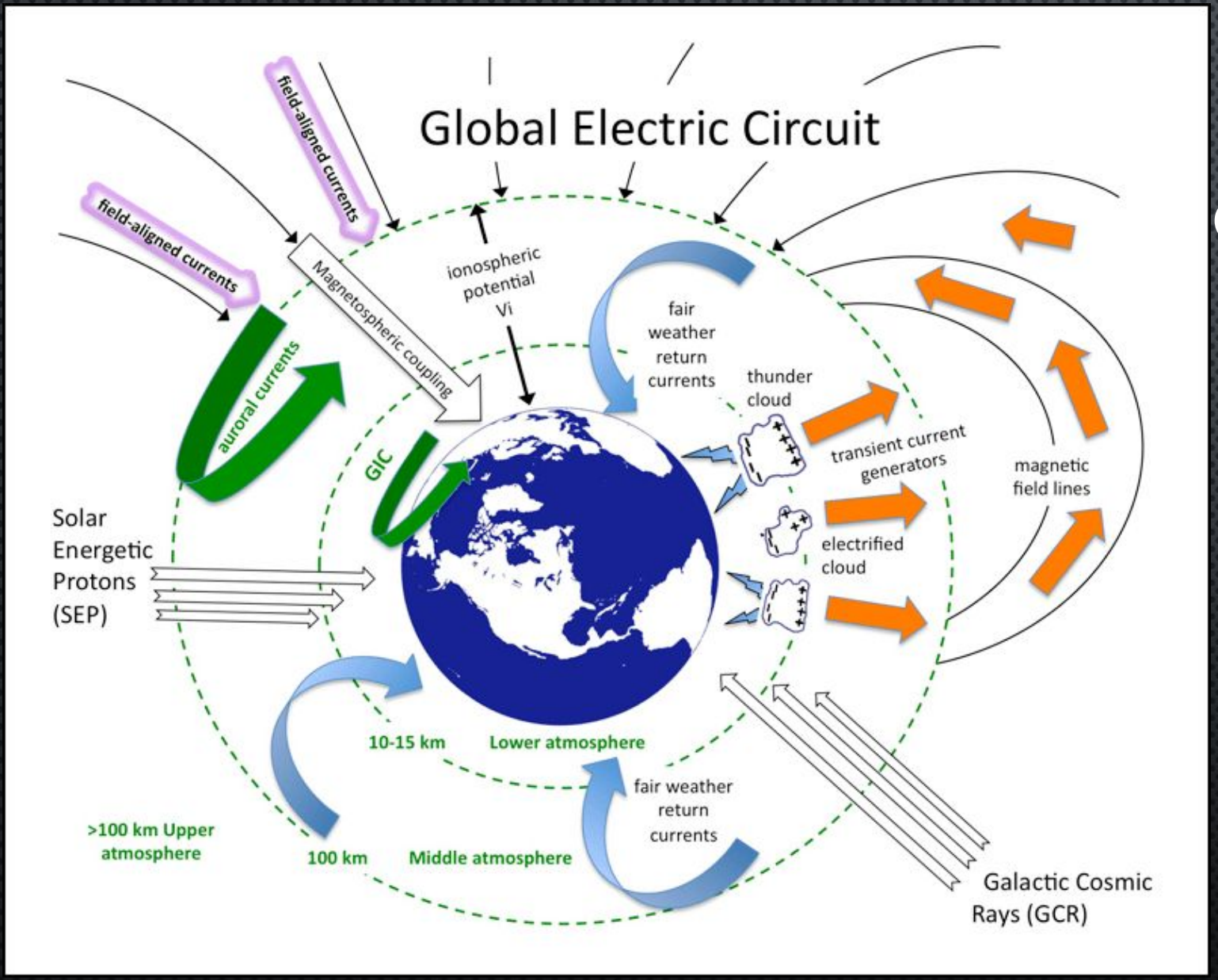


(Pedatella+ 2018)



(Pedatella, 2016)

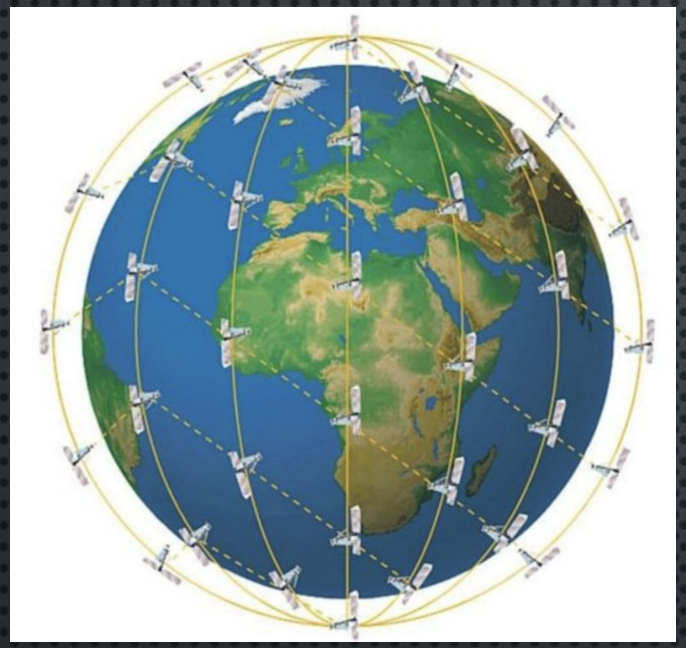
(4) HOW DOES CLIMATE CHANGE IMPACT THE WAY THE IONOSPHERE IS CONNECTED TO THE EARTH'S GLOBAL ELECTRIC CIRCUIT?



(Forbes+ 2006)

"Blue jet" from ISS propagating upward from thundercloud

NSF AMPERE IRIDIUM® constellation



CONCLUSION

- IONOSPHERE CURRENTS AND FIELDS PLAY AN IMPORTANT ROLE IN CONNECTING GEOSPACE AND EARTH'S ATMOSPHERE.
- WE NEED TO CONTINUE MONITORING THE ELECTRIC CURRENTS BY AMPERE AND SWARM, WITH MORE S/C TO IMPROVE MORE SPATIAL AND TEMPORAL COVERAGE.

ESA SWARM constellation

Big challenges in ITM science: thermospheric parameters

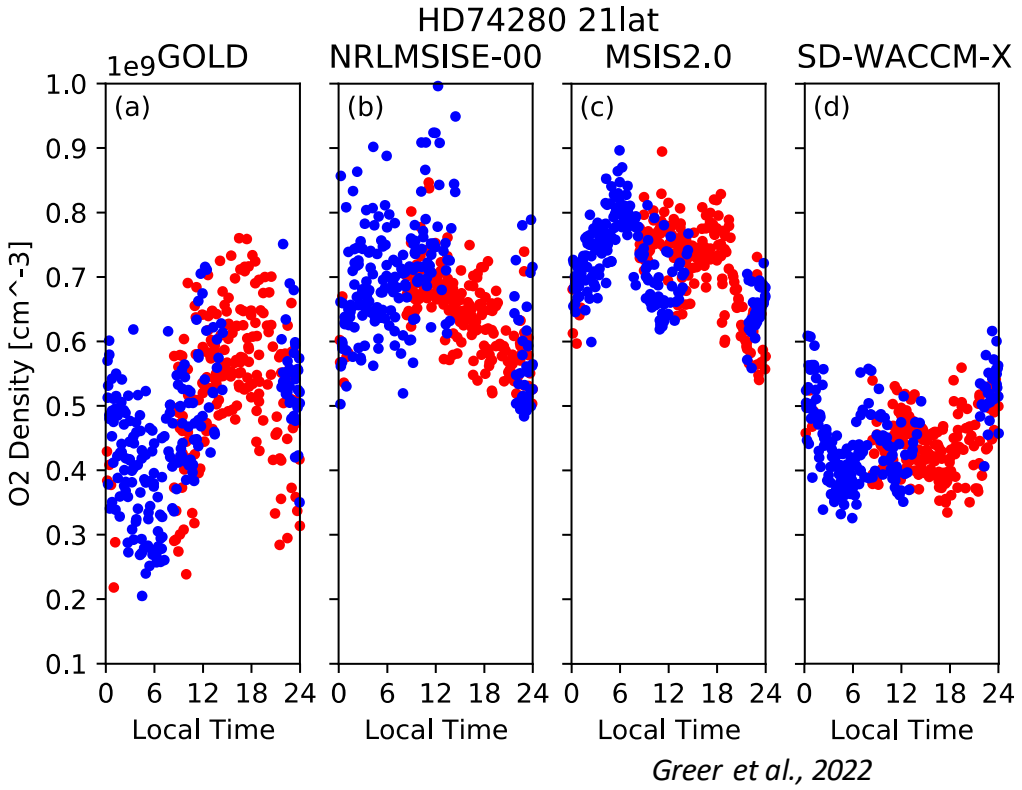
Larisa Goncharenko,

MIT Haystack Observatory

Knowledge & data gaps: observations of thermospheric parameters

What do we need:

- global, high spatial resolution and self-consistent specification of ***modern era*** altitude profiles of thermospheric parameters (temperature, O, N_2, O_2 density, winds).
- Combination of different techniques (space-based and ground-based) to measure temperature and wind profiles
- Designated effort to reconcile systematic biases between historic and new observations and between different techniques (also need for data assimilation)
- Multi-satellite observations to resolve evolution of different waves in the IT system and understand their impacts (DYNAMIC+; DYNAMIC++)

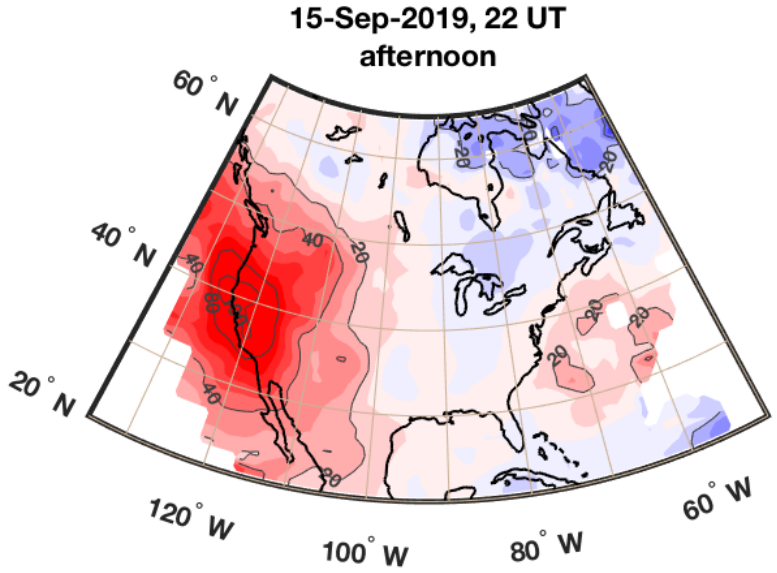


Greer et al., 2022

O2 density observed by GOLD is significantly different from empirical and theoretical models: diurnal structures in GOLD, semidiurnal structures in MSIS and SD-WACCMX. It is not known if discrepancies are related to a long-term change or biases between different datasets.

Why do we need high-accuracy data on thermospheric parameters?

- The state of the thermosphere affects numerous science topics: the state of ionosphere, cross-scale coupling, conductivity, ion outflow, electrodynamics, ITM structures
- Entire ITM is highly sensitive to thermospheric parameters:
  - A 10m/s change in meridional wind can lead to a 50-80% change in electron density
    - Thermospheric winds + orientation of magnetic field lines → strong regional variations in electron density
  - Change in the residual circulation in MLT (95-110km) can drive ~18% change in O/N2 and ~50%+ change in NmF2; strongly affects annual and semiannual variations in the thermosphere and ionosphere
  - Lower thermosphere temperature profile is linked to thermospheric density at ~400km
    - A 30 K decrease in temperature above 120 km produces an ~25% decrease in mass density at 400 km)
- Our current knowledge heavily relies on modeling, but we do not even have sufficient observations to understand the strengths and weaknesses of different models
- **Space weather impacts and relevance:**
  - Accurate predictions of Ne, TEC, thermospheric density and satellite drag & orbits
  - Development of predictive capability of SW models: 'short memory' of ionospheric state vs 'long memory' for thermospheric state

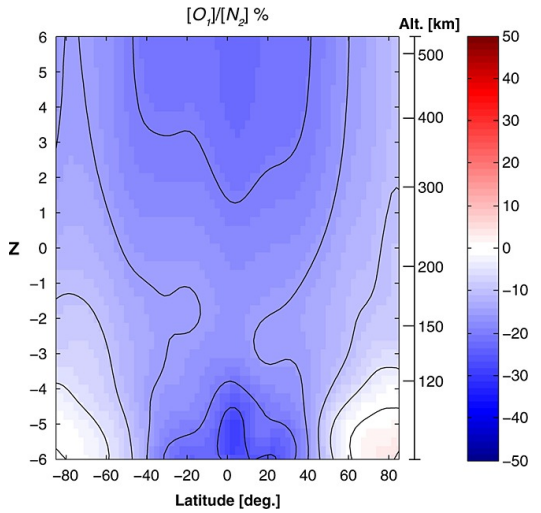


Goncharenko et al., 2021

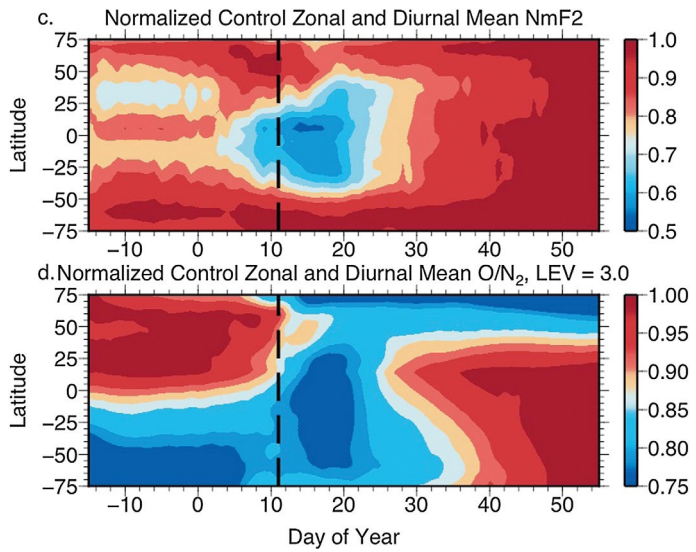
Regional perturbations in TEC reach 80-100% over western US during disturbances in the Antarctic stratosphere. It is hypothesized that this anomaly is caused by a combination of disturbances in the zonal thermospheric wind and high magnetic declination angle.

Importance of links between lower and upper atmosphere

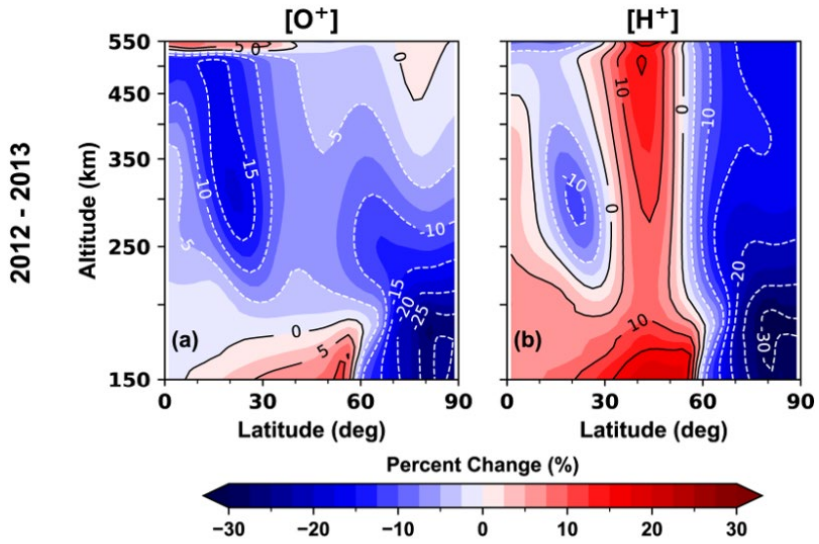
- Paradigm change (~2006+): variability of the lower atmosphere can drive large (up to 100%+) and persistent variations in the IT system on a variety of temporal and spatial scales - from minutes (traveling ionospheric disturbances) to days, months or years (Madden-Julian Oscillation, quasi-biennial oscillation)
- Large variety of mechanisms; varying roles of each mechanism
- Wave dissipation can lead to changes in residual circulation with large scale effects in the thermospheric composition, winds, and ionospheric electron density
- Effects can potentially extend to the plasmasphere and magnetosphere



Yamazaki and Richmond, 2013



Pedatella et al., 2016



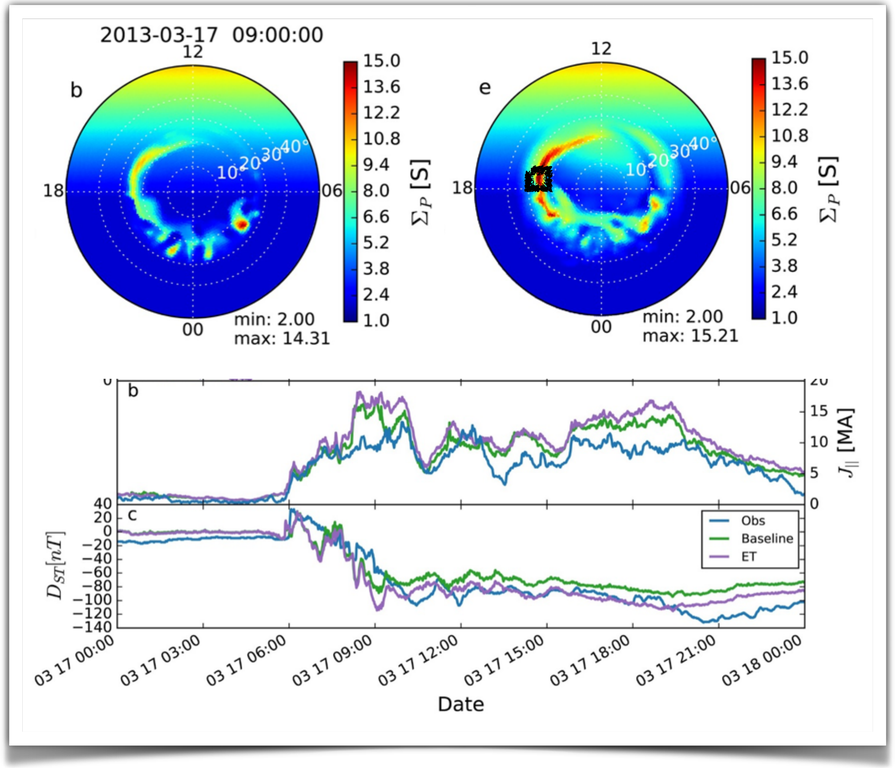
Jones et al, 2020

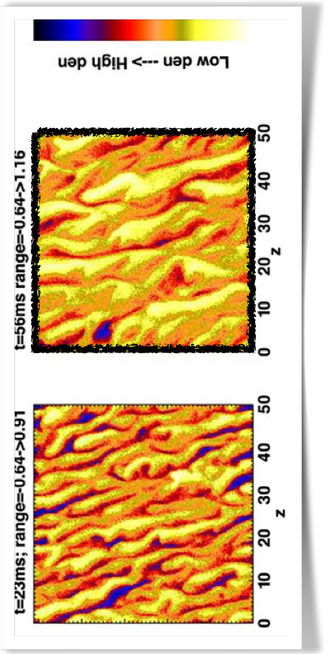
Simulations: dissipation of tides, gravity waves, or planetary waves leads to large-scale changes in composition and electron density

Modeling Needs (part I)

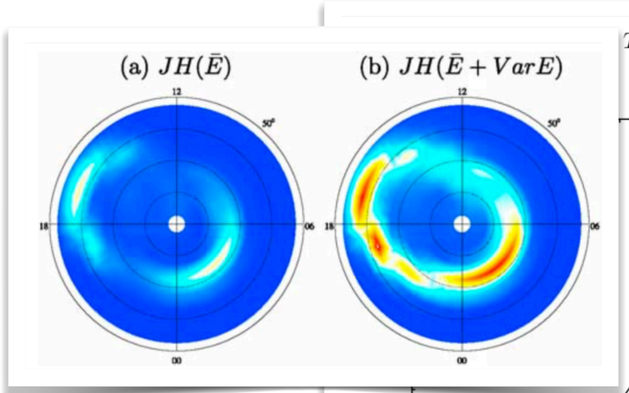
- **Develop new approaches to multi-scale physics describing coupling and feedback across scales** (coupling and parameterization strategies)
  - Plasma instabilities associated with radio disruptions depend on background state
  - Kinetic turbulence alters conductance which can have global consequences *(Wiltberger et al, 2017)*
  - Small-scale electrodynamics of MI coupling: joule heating and momentum inflow *(Deng et al, 2009)*
- **Improve predictive capability of models:** physics
  - It is challenging to predict simple day-to-day variability in IT —> smaller scale studies may be “biased” by lack of knowledge of “mean state”
  - In many cases we know physical processes are not being accounted for properly (e.g. GW dynamics in LT; Alfvenic processes mediating MI coupling)

Wiltberger et al (2017)

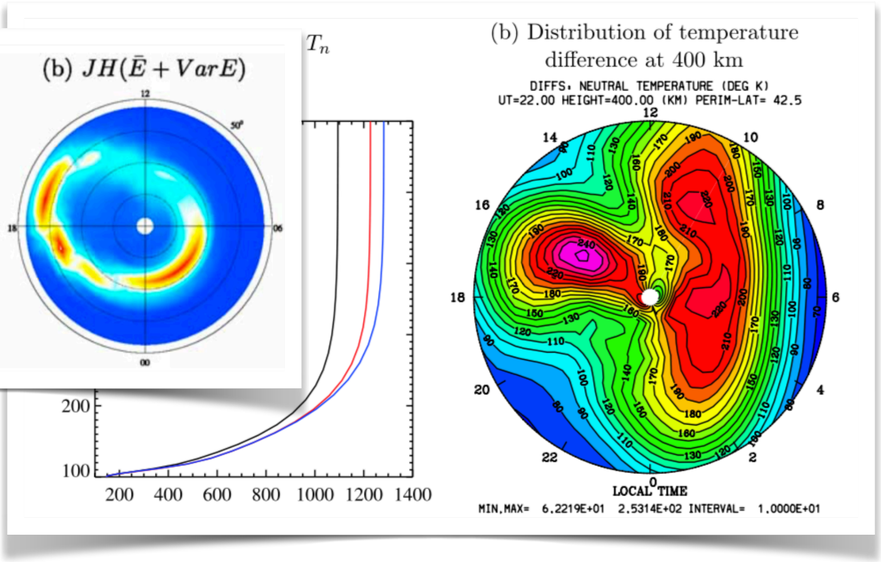




Oppenheim and Dimant, (2013)

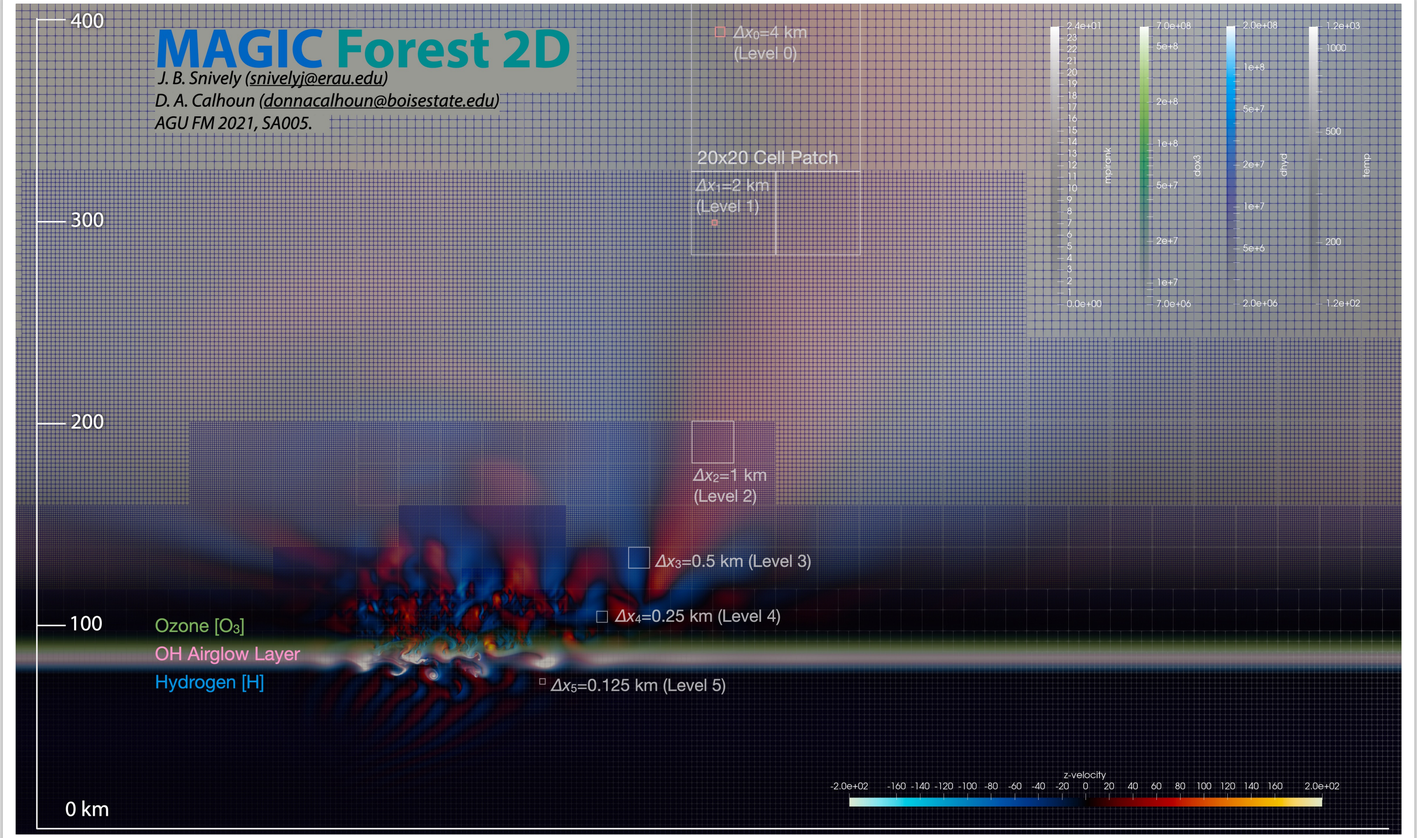


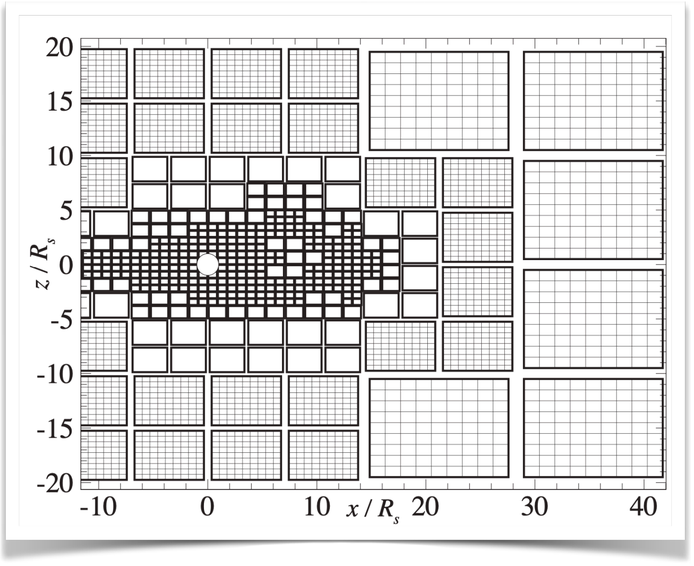
Deng et al. (2009)



Modeling Needs (part II)

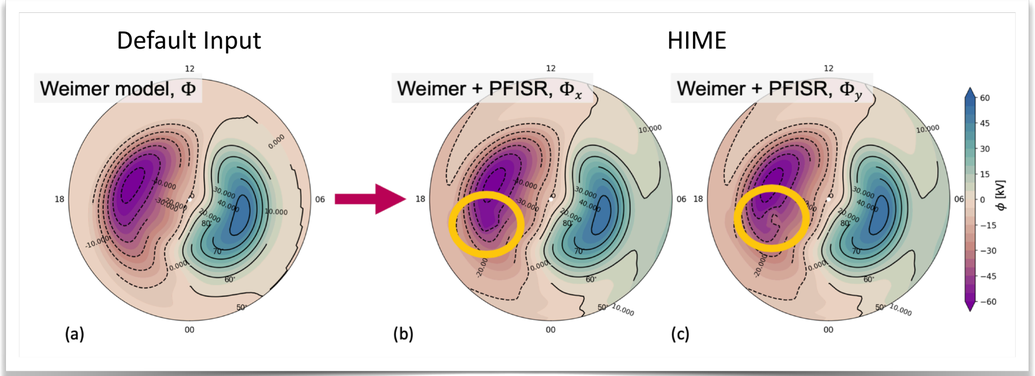
- **Improve predictive capability of models:** resolution
  - Require *<u>both</u>* global and local general-purpose models.
  - Leverage techniques to efficiently deal with localized processes in a global context; i.e. adaptive mesh refinement (AMR)
- **Sustain investment in general purpose codes** — can reduces time to science/application and “cost”.
  - Continue ground-up development of bespoke models tailored to specific problems.
  - Modest software engineering investments to improve and promote accessibility (build/run, post processing and visualization, verification)
- **Accessibility challenges** — Computational infrastructure/resources and licensing practices.
- **Explore collaborations benefitting both science and industry**, e.g. commercial space.



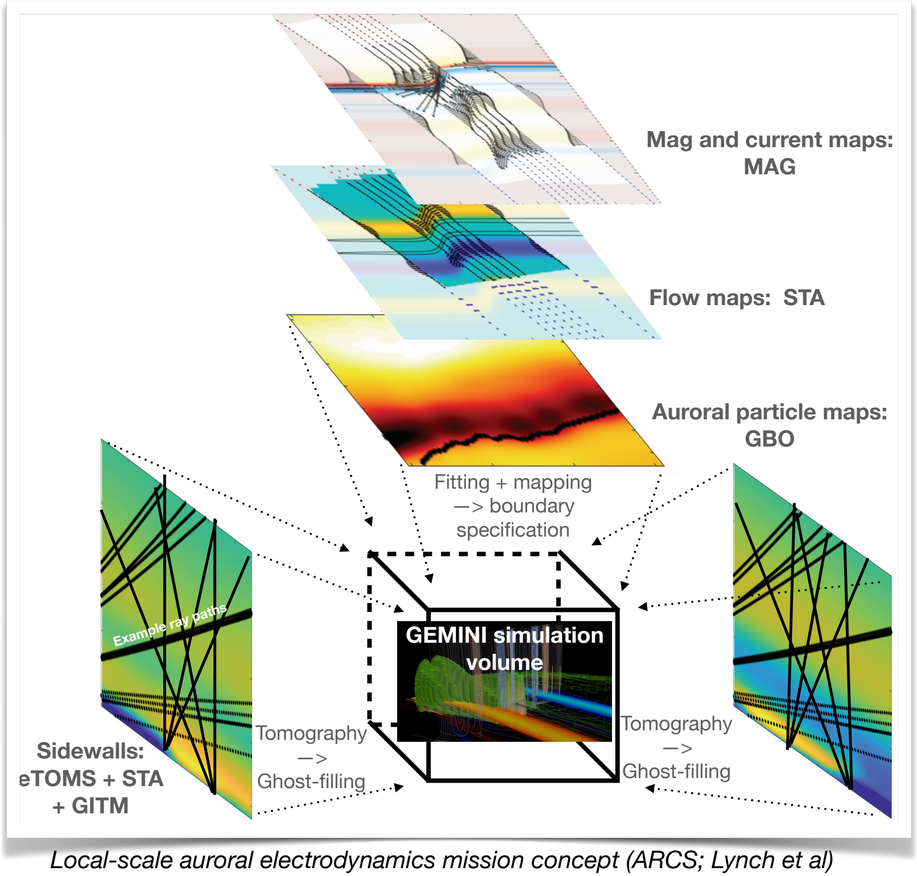


Gombosi et al (2001)

Two AMR codes: (Top) MAGIC-Forest compressible model simulation of breaking GWs. (Left) BATSRUS MHD model mesh configuration



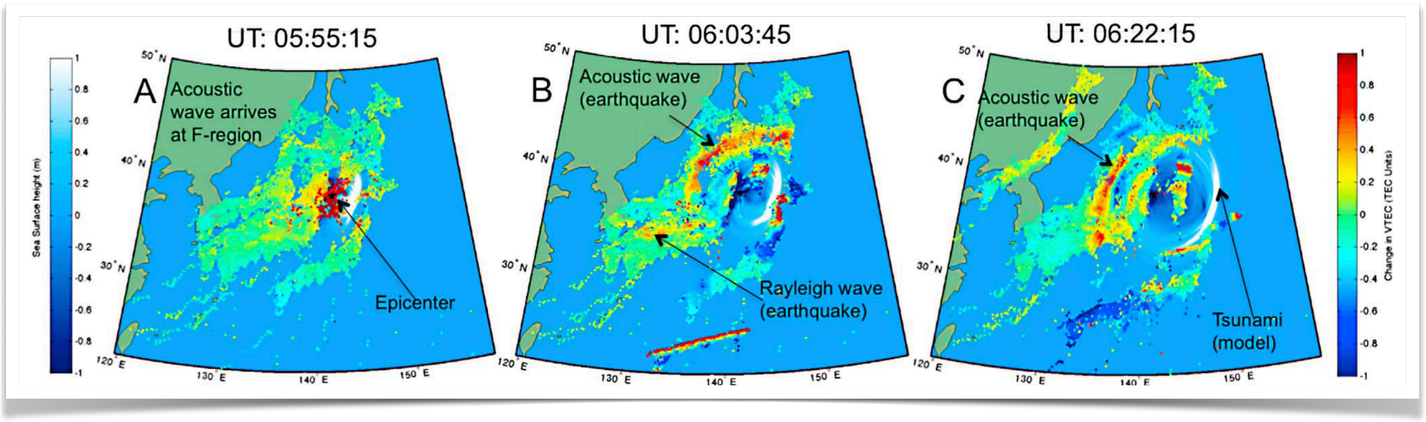
Incorporation of local measurements into global modeling (HIME Ozturk et al 2020)



Local-scale auroral electrodynamics mission concept (ARCS; Lynch et al)

Data constraints for models

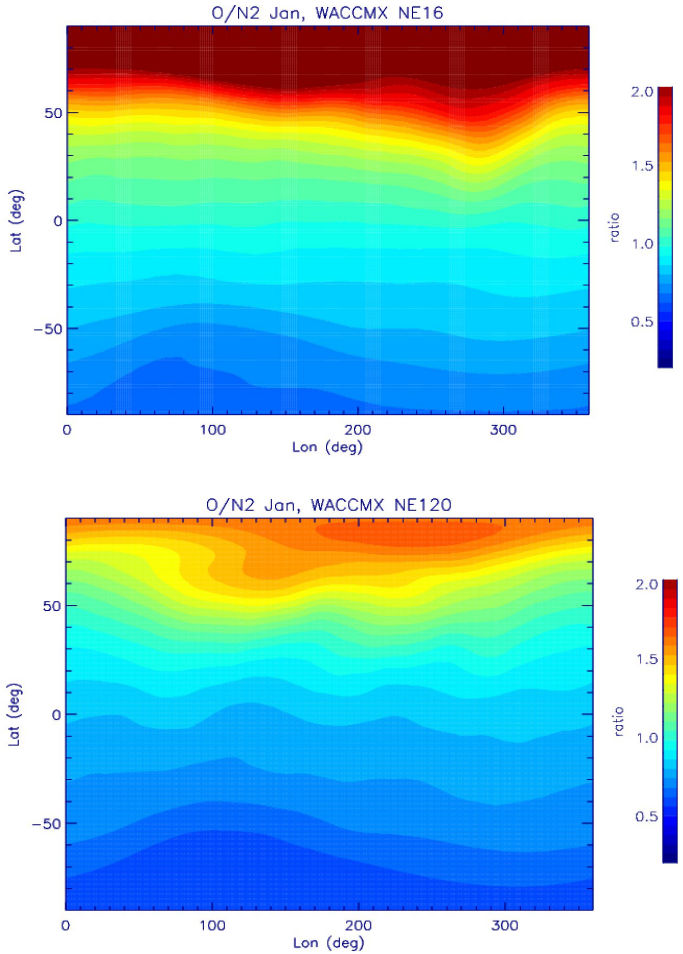
- **Model applications (as opposed to purely theoretical studies) suffer from relatively poor data constraints.**
  - High latitude ionosphere modeling - potentials, initial density, precipitating particles/conductance. Auroras, plasma patches.
  - Ground-level transient disturbances - diagnosing lower atmospheric dynamics, e.g. from seismic sources, from IT data.
  - Ionospheric plasma sources to magnetoshere - spatial distribution of energy sources affects ionospheric mass provided to the magnetosphere.
- **Tools for direct comparisons with data are needed to bring simulation outputs closer to quantities that can be compared to data.**
  - Improves quality of and realism in conclusions — improves the value of both the simulations and data products. Space mission and ground-based instrument design; planning of operations



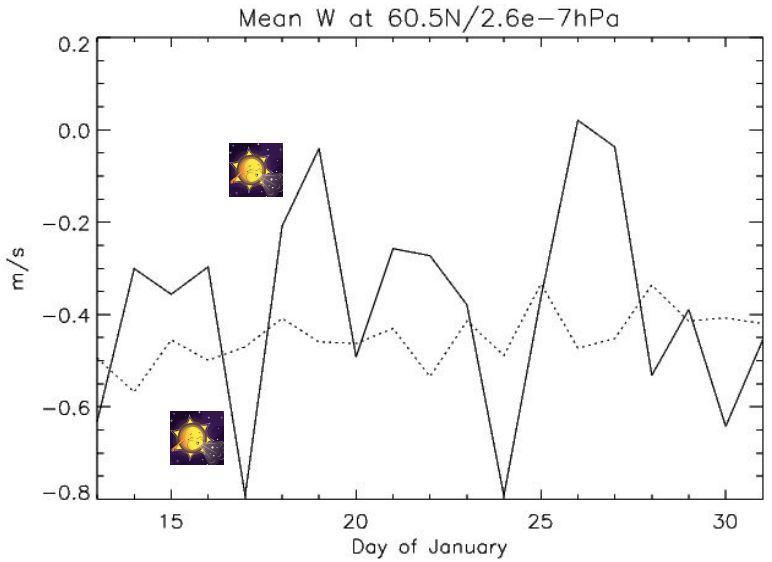
Connections with Lower Atmosphere and Small Scales:

Thermospheric Circulation and Composition, Ion-Neutral Coupling, System Predictability

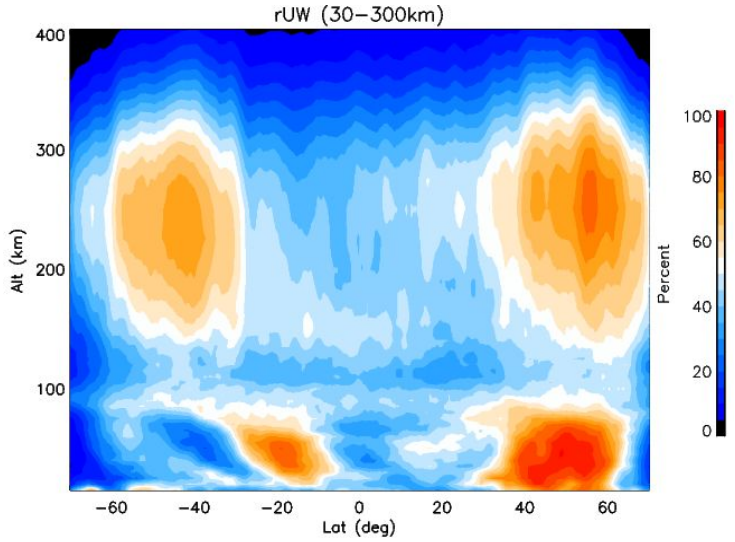
- How do gravity waves impact the circulation and compositional structures in the thermosphere?



- How much does the thermosphere, including its circulation and compositional structures, change from day-to-day? What are the roles of wave forcing? What is the implication for storm time response?



- How much do small-scale waves contribute to the thermospheric structure and its variability?

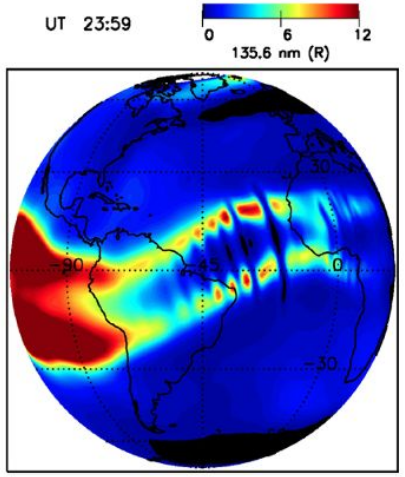


Momentum flux from small scale gravity waves

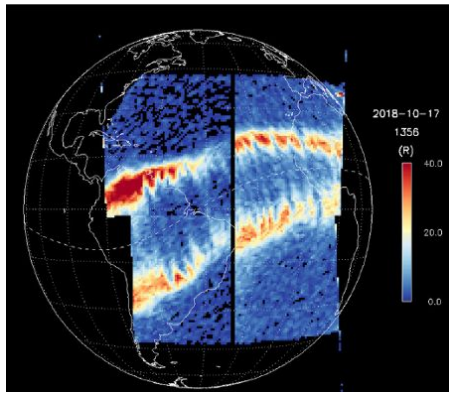
Connections with Lower Atmosphere and Small Scales:

Thermospheric Circulation and Composition, Ion-Neutral Coupling, System Predictability

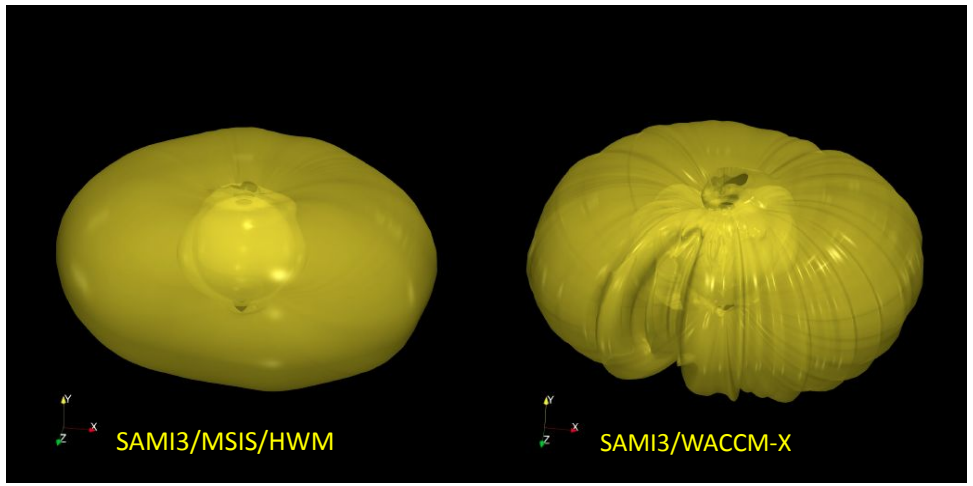
- How do atmospheric waves affect the variability of the geospace environment?



Huba & Liu, 2020



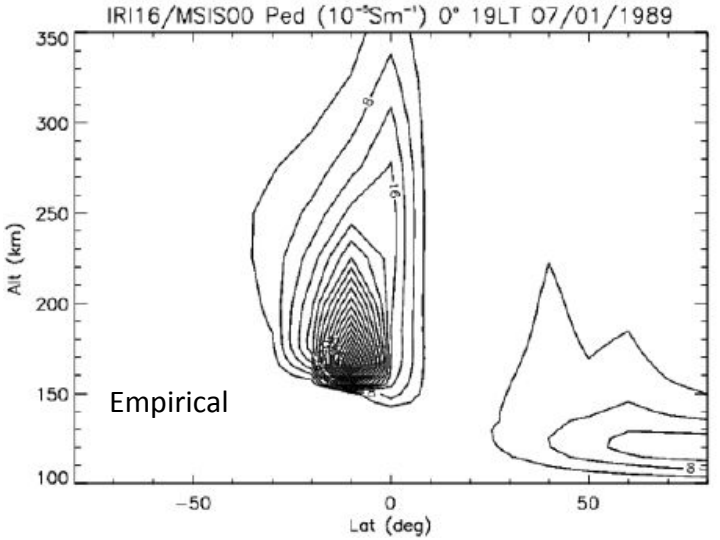
Eastes et al., 2019

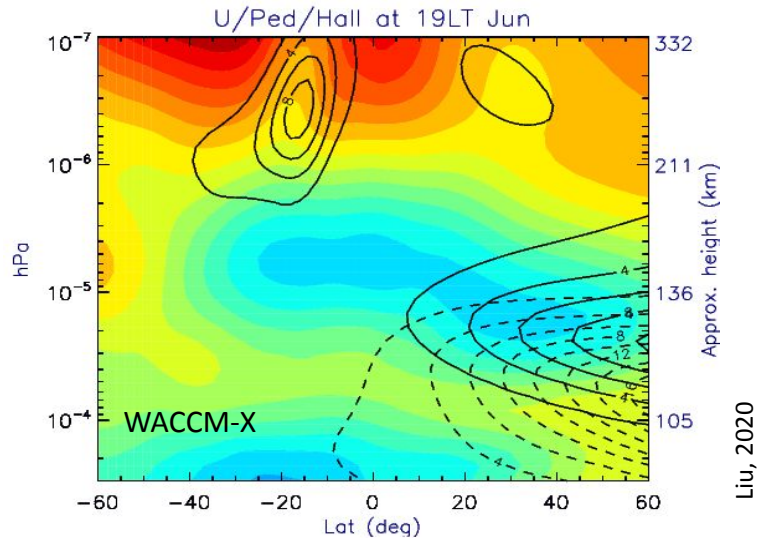


Huba et al. (URSI, 2021)

- What are the ionospheric conductivities in E and F regions?

Ionospheric conductivities: Large Gap



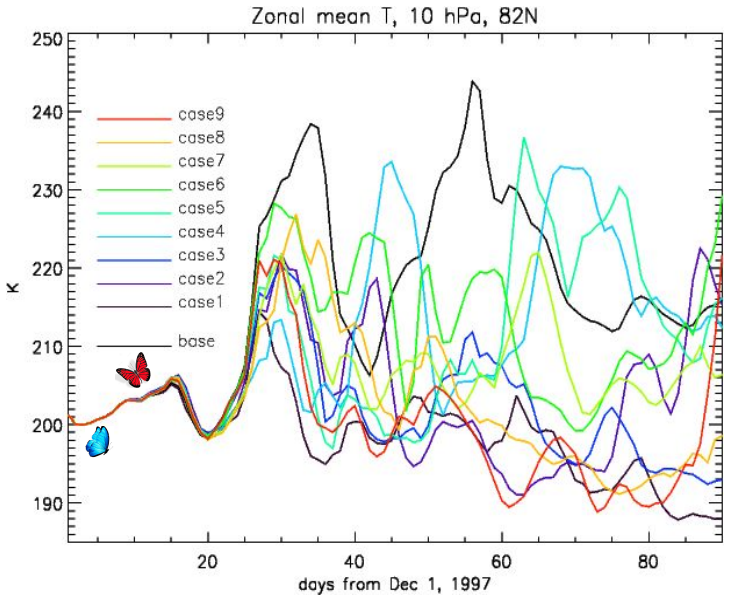


Liu, 2020

Connections with Lower Atmosphere and Small Scales:

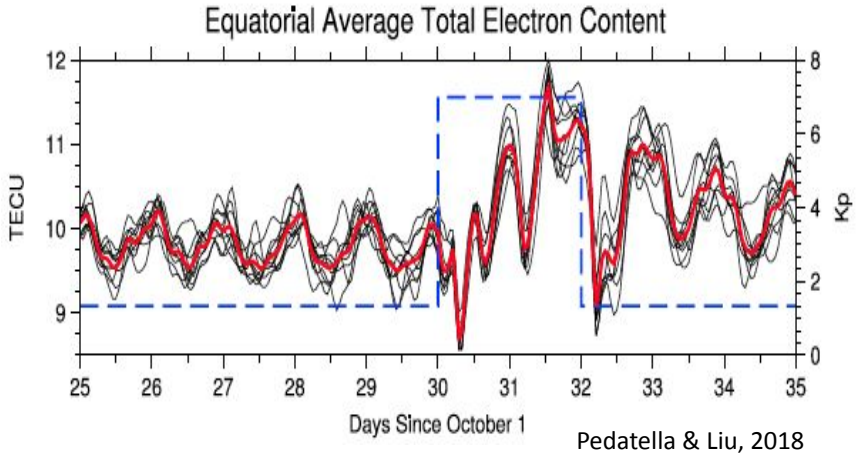
Thermospheric Circulation and Composition, Ion-Neutral Coupling, System Predictability

- What determines the predictability of the thermosphere and ionosphere?



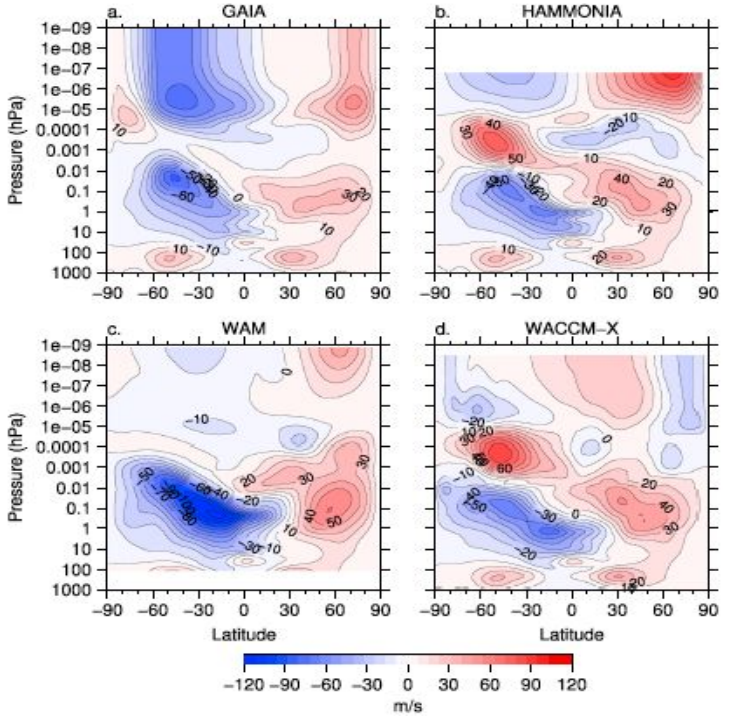
Liu et al., 2009

- Does system predictability change during geomagnetic storms?



Pedatella & Liu, 2018

- How does the lower atmosphere processes affect the whole atmosphere model fidelity?



Pedatella et al. (2014)

Major cause of whole atmosphere model bias and loss of predictability: Uncertain gravity wave forcing.

- Observations: Mesoscale and day-to-day variability; ionospheric conductivities.
- Numerical Modeling: Exascale computing to capture the full mesoscale range.
- Integration and forecast: Whole atmosphere data assimilation.

Challenges: Waves in the thermosphere/ionosphere

Gravity wave forcing from below

- What implications do gravity waves (GWs) have on the thermosphere ionosphere system?
- What are the most common sources of GWs in the thermosphere?
- Are there seasonal and spatial dependencies on GW activity in the IT system?

Observational Needs: Thermosphere wind/temperature/density measurements, especially with resolutions to capture gravity wave perturbations

Multi-scale interactions in the I-T system

- What implications do tides and tidal filtering have on the IT system?
- What role does tidal filtering play on GWs, especially with regards to propagation into the thermosphere?
- How do GWs affect tides in the thermosphere?

Observational Needs: Thermosphere climatological measurements, tidal measurements in the thermosphere, seasonal wind variations in the thermosphere

Intersection of forcing from below and above

- Are there differences in waves and wave filtering from below during geomagnetically quiet vs. active times?
- What is the interaction between GWs generated from below and LSTIDs/LSTADs generated from auroral regions?
- How do changes in waves due to solar activity impact wave propagation and filtering from below?

Observational Needs: Global scale thermosphere measurements, including auroral regions