Whole Atmosphere Community Climate Model-eXtended (WACCM-X): Development, Validation and Capabilities

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NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

CEDAR Prize Lecture, NSF CEDAR Workshop, June 28, 2018, Santa Fe, NM

NSF

Outline

- WACCM-X Development Background.
- Recent Development and Validation.
- Model Capabilities for Research.
- Ongoing and Future Efforts.

Genesis—It goes back in TIME (GCM):

Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model

- Developed by Ray Roble and colleagues since the 1970s.
- Validated and widely used by the CEDAR community.

1) 1989, Arthur Richmond (HAO/NCAR) - Assimilative Mapping of Ionospheric Electrodynamics

2) 1990, Michael Mendillo (Boston U) - The Discovery of a Sodium Magneto-Nebula Around Jupiter

3) 1991, Craig Heinselmann (SRI International) - Sondrestrom MUSCOX

4) 1992, Colin Hines (Arecibo Obs) - The Doppler Spreading Theory of Gravity Wave Spectra

5) 1993, John Cho (Arecibo Obs), Radar Scattering from the Coldest Place in our Atmosphere: Polar Mesosphere Summer Echoes

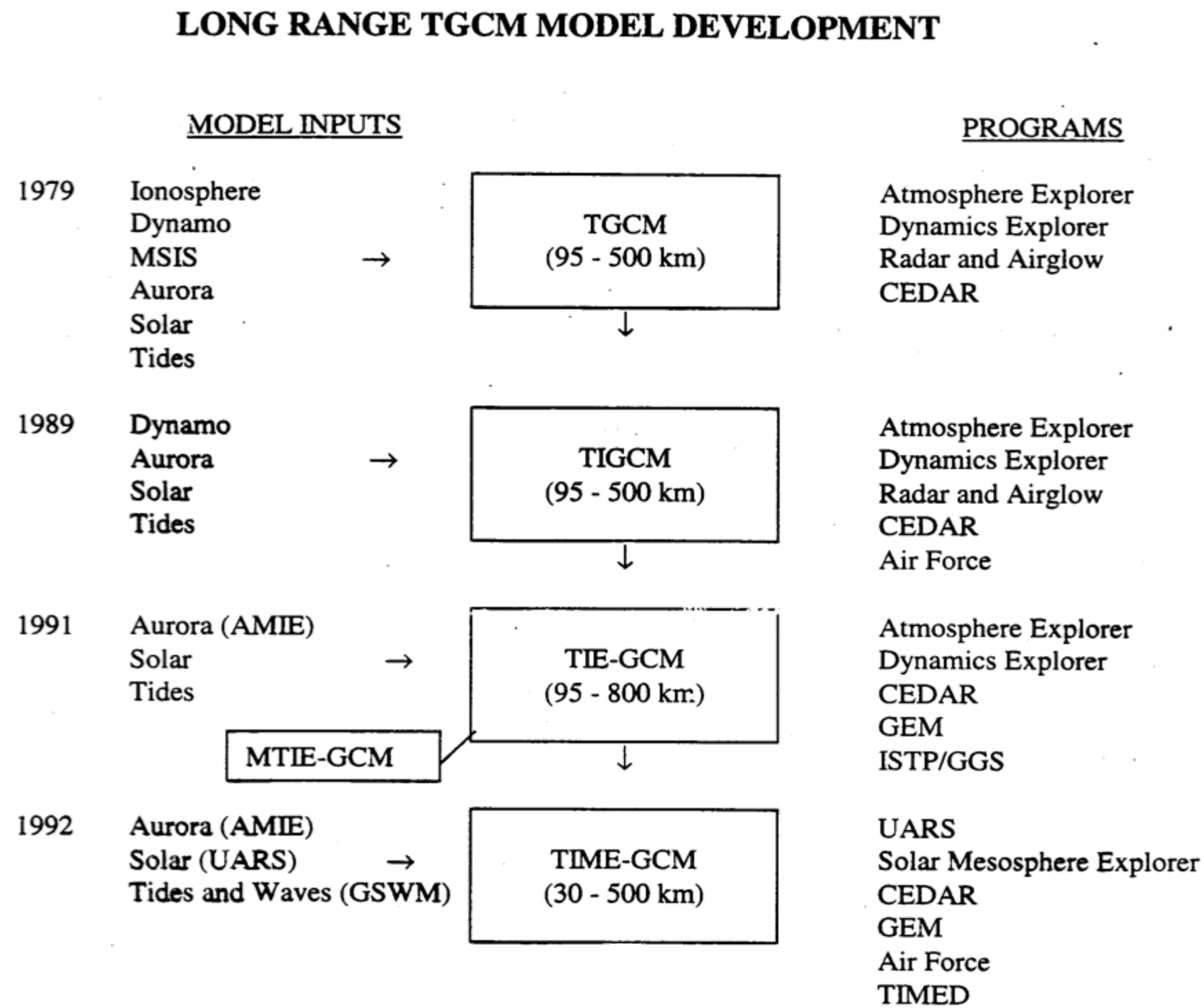
6) 1994, Raymond Roble (HAO/NCAR), Modelling the Circulation, Temperature and Compositional Structure of the Upper Atmosphere (30-500km)

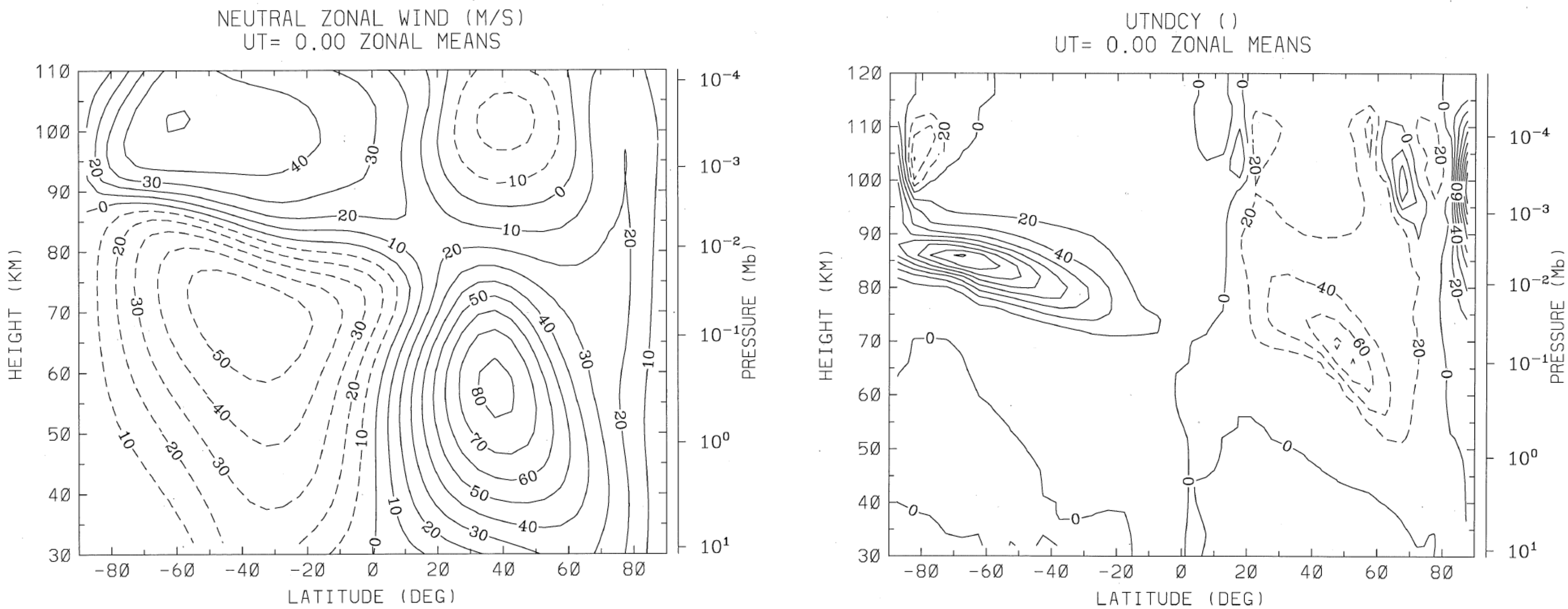
7)1995, David Fritts (U of Colorado) - Modeling of Gravity Wave and Instability Processes in the Middle Atmosphere

8) 1996, Chester Gardner (U of Illinois) - The ALOHA/ANLC-93 Campaigns

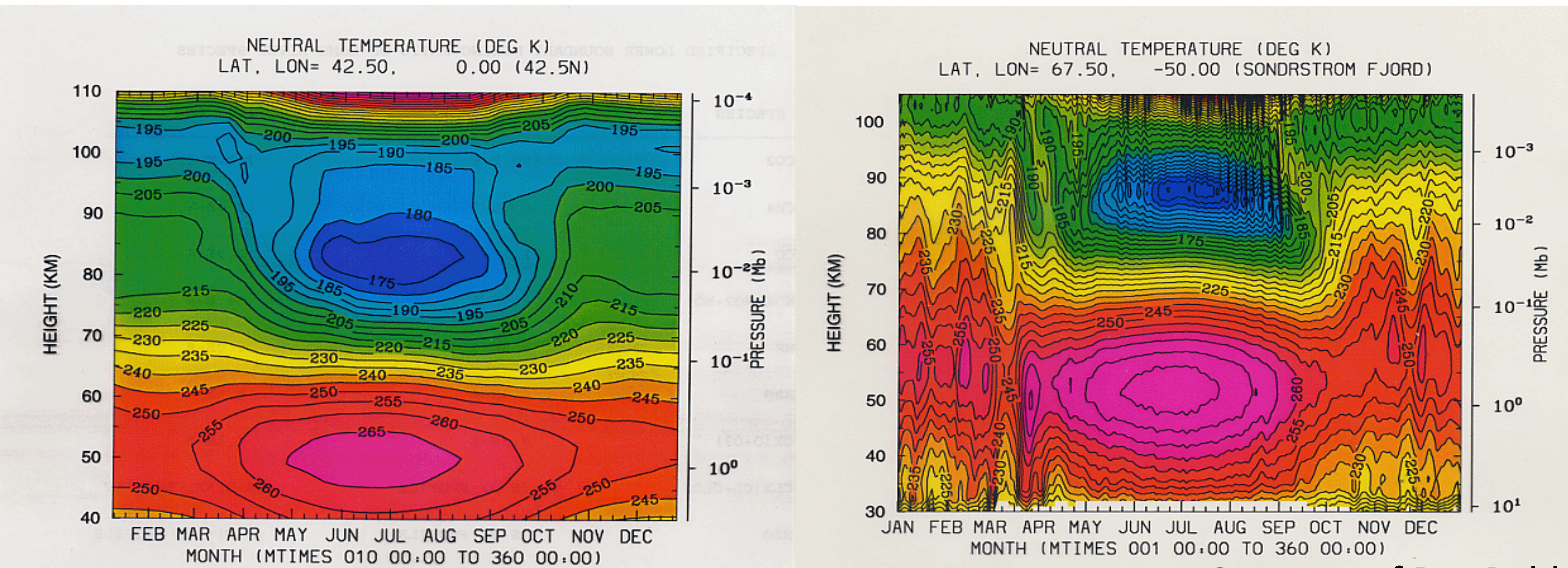
9) 1997, Bela Fejer (Utah State U) - Multi-Instrument Studies of Ionospheric Electrodynamics

From Ray's Prize Lecture in 1994





My first TIME-GCM project: Gravity wave drag parameterization—got MLT climatological wind/temperature.



Courtesy of Ray Roble

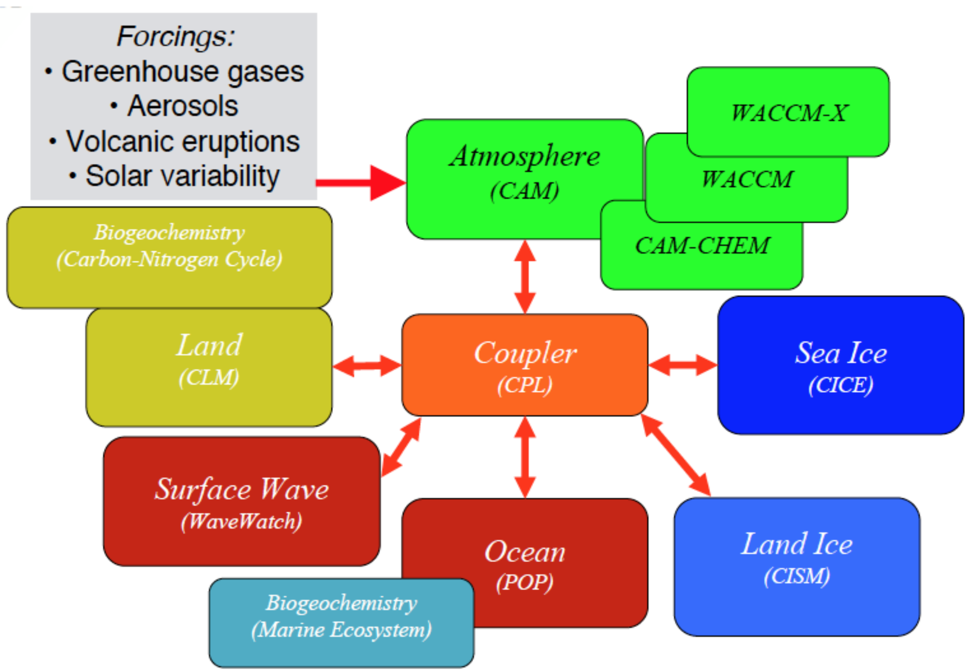
Further Development to Better Represent the Lower Atmosphere

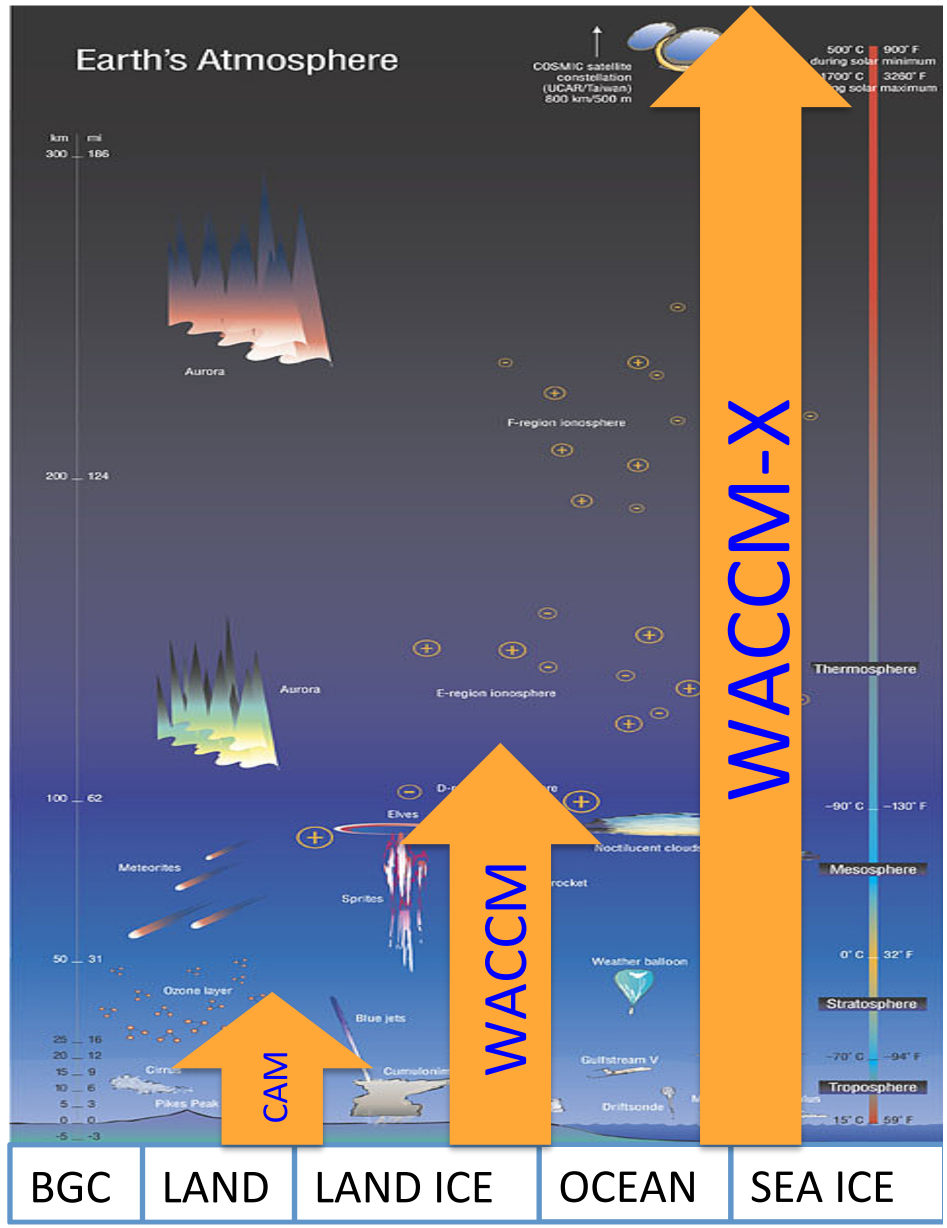
- From climatology to climate/weather variability:
  - Atmospheric tidal climatology, specified by the Global Scale Wave Model (GSWM).
  - Gravity wave drag parameterization.
  - Lower atmosphere by NCEP or ECMWF data.
- Self-consistent representation of the whole atmosphere system
  - Coupled TIME-GCM/CCM3.
  - WACCM/WACCM-X.

Scientific Objectives of Whole Atmosphere Community Climate Model and its extended version (WACCM/WACCM-X)

- Solar impacts on the Earth System.
- Understand and quantify couplings between atmospheric layers through chemical, physical and dynamical processes.
- Implications of the couplings to climate (downward coupling) and to space environment (upward coupling).

NCAR Community Earth System Model (CESM)





Major CESM WACCM/WACCM-X Components

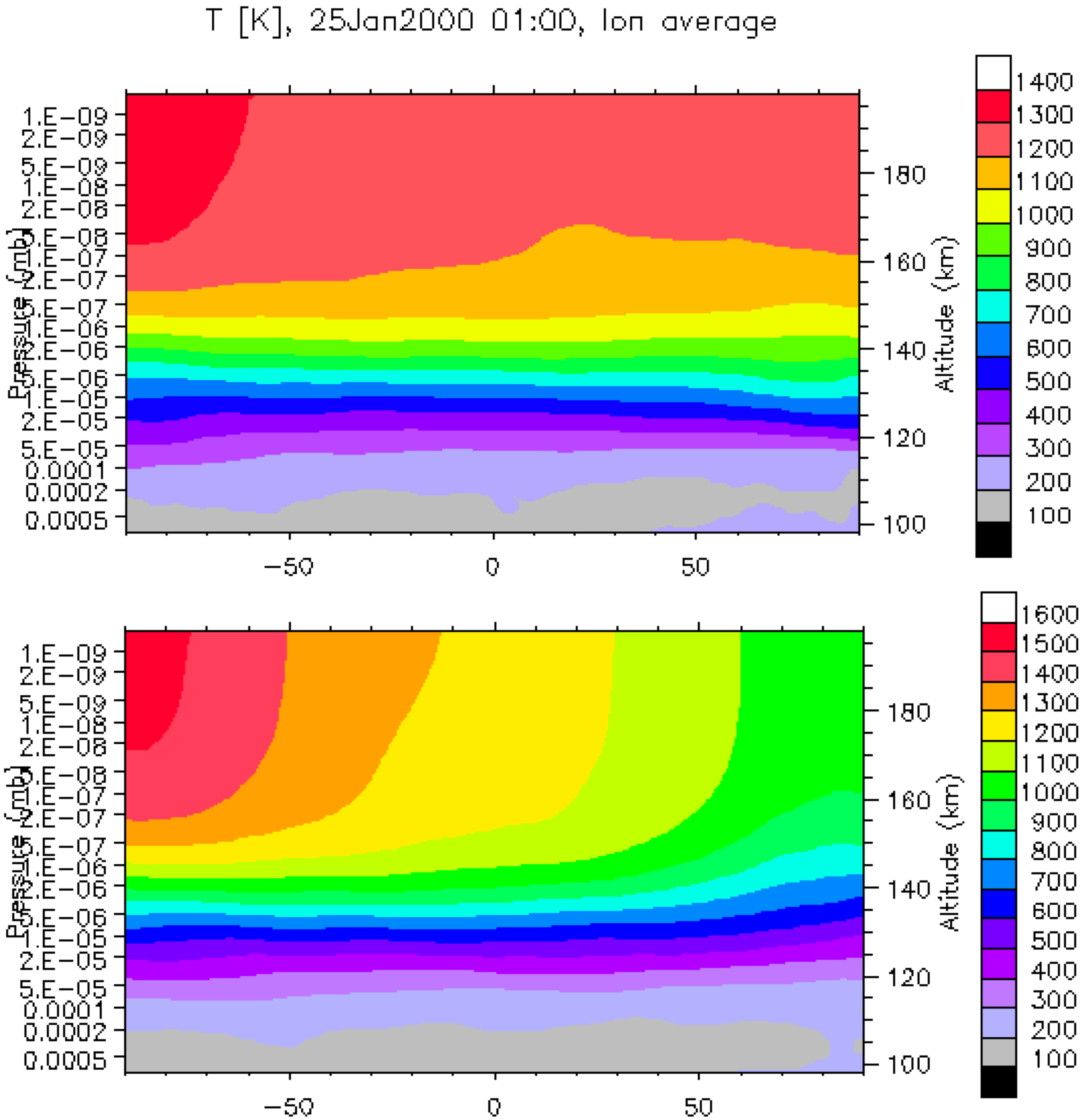
Model Framework	Chemistry	Physics	Physics	Resolution
Atmosphere component of NCAR Community Earth System Model (CESM)	MOZART+ Ion Chemistry (~60+ species)	Long wave/short wave/EUV	Parameterized electric field at high, mid, low latitudes. IGRF geomagnetic field.	Horizontal: 1.9° x 2.5° (lat x lon configurable as needed)
Extension of the NCAR Community Atmosphere Model (CAM)	Fully-interactive with dynamics.	RRTMG	Auroral processes, ion drag and Joule heating	Vertical: 66 levels (0-140km) 81/126 levels 0-~600km
Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m)		IR cooling (LTE/non-LTE)	Ion/electron energy equations	Mesoscale-resolving version: 0.25 deg/0.1 scale height.
Spectral Element Dynamical Core		Modal Aerosal	Ambipolar diffusion	
		CARMA	Ion/electron transport	
		Convection, precip., and cloud param.	Ionospheric dynamo	
		Parameterized GW	Coupling with plasmasphere/ magnetosphere	
		Major/minor species diffusion (+UBC)		
		Molecular viscosity and thermal conductivity (+UBC)		
		Species dependent Cp, R, m.		

Important Physical Properties of Whole Atmosphere

- Deep: 10% of Earth radius, ~29 scale-heights, 10^{13} change in density from Earth surface to exobase.
- Diffusive separation above the homopause.
- Ion-neutral coupling
  - Different transport processes of neutral species and ionospheric plasma (oriented along magnetic field lines).
- Coupling between dynamics and photochemistry.
- Short temporal and spatial scales in the upper atmosphere
  - Increasing significance of gravity waves and tides.
  - Large wind (~300m/s) and acoustic speed (~800m/s).
  - Geomagnetic storms and fine ionospheric structures.
  - Ionospheric irregularities.
  - Large molecular viscosity and diffusion (both vertically and horizontally).

Implications for Mathematical and Numerical Formulation (1)

- Diffusive separation above the homopause:
  - Specific heats and mean molecular weight (thus gas "constant" of dry air) are dependent on major species (O, O_2, N_2, He, H), thus vary spatially and temporally.
  - Potential temperature becomes an ill-posed quantity: the mixing ratios of the major species are different from those at reference levels.
  - Variable gravity affects the scale height (thus the vertical distribution) of individual species.



p^{κ} used as vertical coordinate (standard FV dycore)

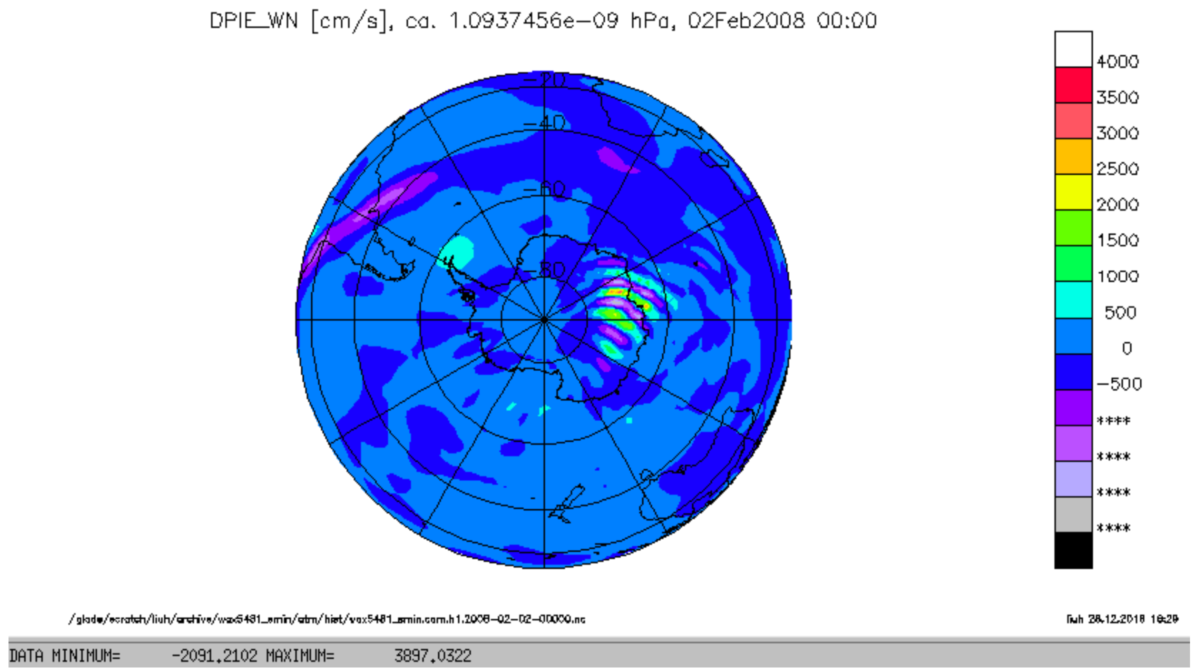
Tmax = 1372 K

ln(p) used as vertical coordinate (modified FV dycore)

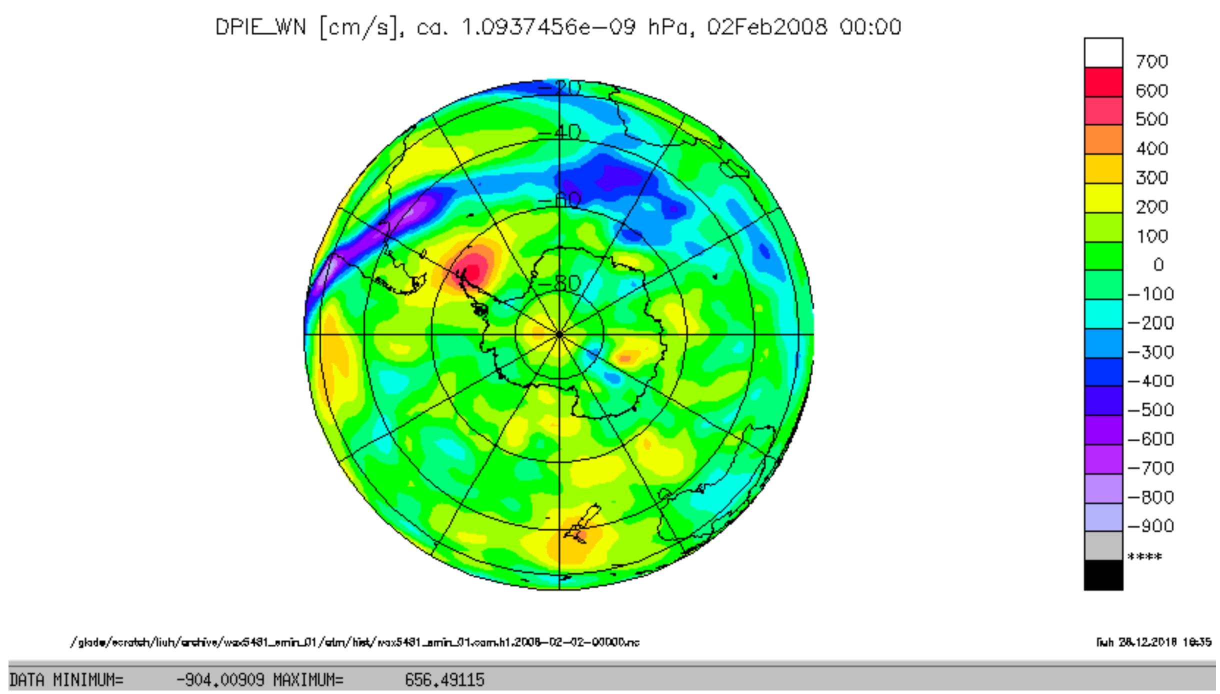
Tmax = 1523 K

Horizontal winds and divergence are solved incorrectly (and often become too strong) with the standard formulation. Causes excessive upwelling in the summer and downwelling in the winter.

Without advecting κ



With κ advection



Implications for Mathematical and Numerical Formulation (2)

- Coupling between dynamics and photochemistry.
  - Conservative and efficient computation of advective transport of large number of chemical species.
- Ion-neutral coupling:
  - Frequent mapping between dycore grid and geomagnetic grid.
  - Transport routines that can handle different advective velocities (neutral winds and ion velocities).

Implications for Mathematical and Numerical Formulation (3)

- Short temporal/spatial scales of physical processes:
  - Parameterization schemes that can accommodate short time steps (5 minutes or less).
  - Code design that is capable of subcycling and super-cycling.
  - Mesh refinement capability.
  - Non-hydrostatic dynamics.
  - Horizontal diffusion should be included with increasing spatial resolution.
  - Efficient scaling for high-resolution simulations.

Ionospheric Electric Dynamo

Ionospheric electrostatic potential is solved by using Ohm's Law and current continuity condition (Richmond, 1983)

$$\nabla \bullet (\sigma : \nabla \Phi) = \nabla \bullet (\sigma : (\vec{V} \times \vec{B}))$$ + **Highlatitude electric potential**

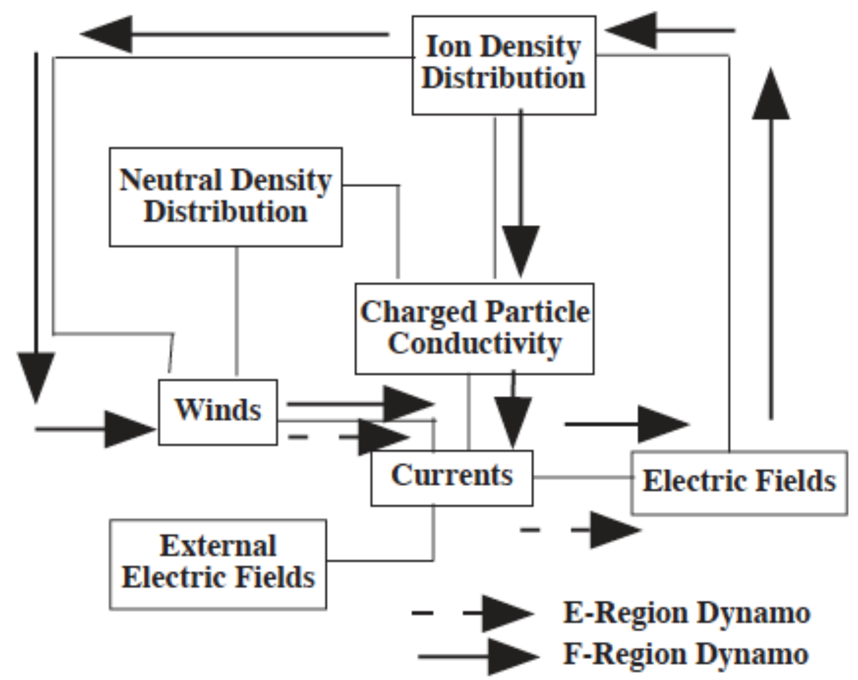


Fig. 6. Block diagram connecting the physical attributes at work in the E- and F-region dynamos.

Heelis, 2004 (CEDAR Tutorial)

F-region O^+ Transport and Electron/Ion Temperatures

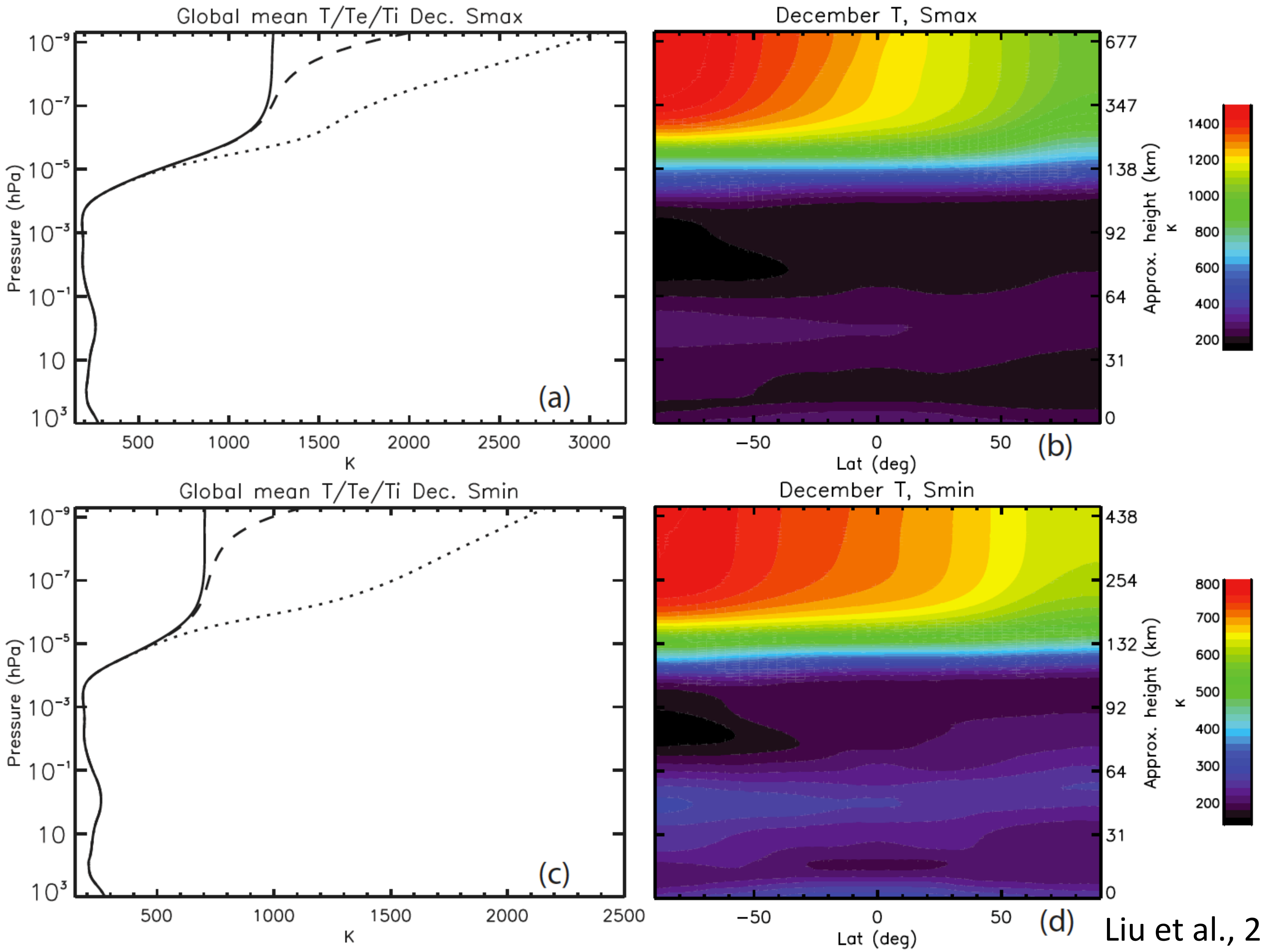
- O+ transport determined by field aligned ambipolar diffusion and ExB drifts.
- Ambipolar diffusion depends on electron and ion temperatures.
- Te tendency considered: vertical component of electron heat conduction along field-line and heating/cooling.
- Heating of neutrals by thermal electrons and ions are now included in the model.

Key WACCM-X Capabilities

- Physics-based whole atmosphere general circulation model (0-700km)
- Solves dynamics, radiative transfer, photolysis and energetics
- Fully interactive chemistry, including ion chemistry.
- Ionospheric electrodynamics using fully interactive dynamo.
- Ion transport in the *F*-region.
- Magnetospheric inputs using empirical or specifications, including AMIE.
- Coupling with a plasmasphere model (partnership with NRL).
- Meteorology can be constrained by reanalysis data (MERRA).
- Whole atmosphere data assimilation for specification and forecast.

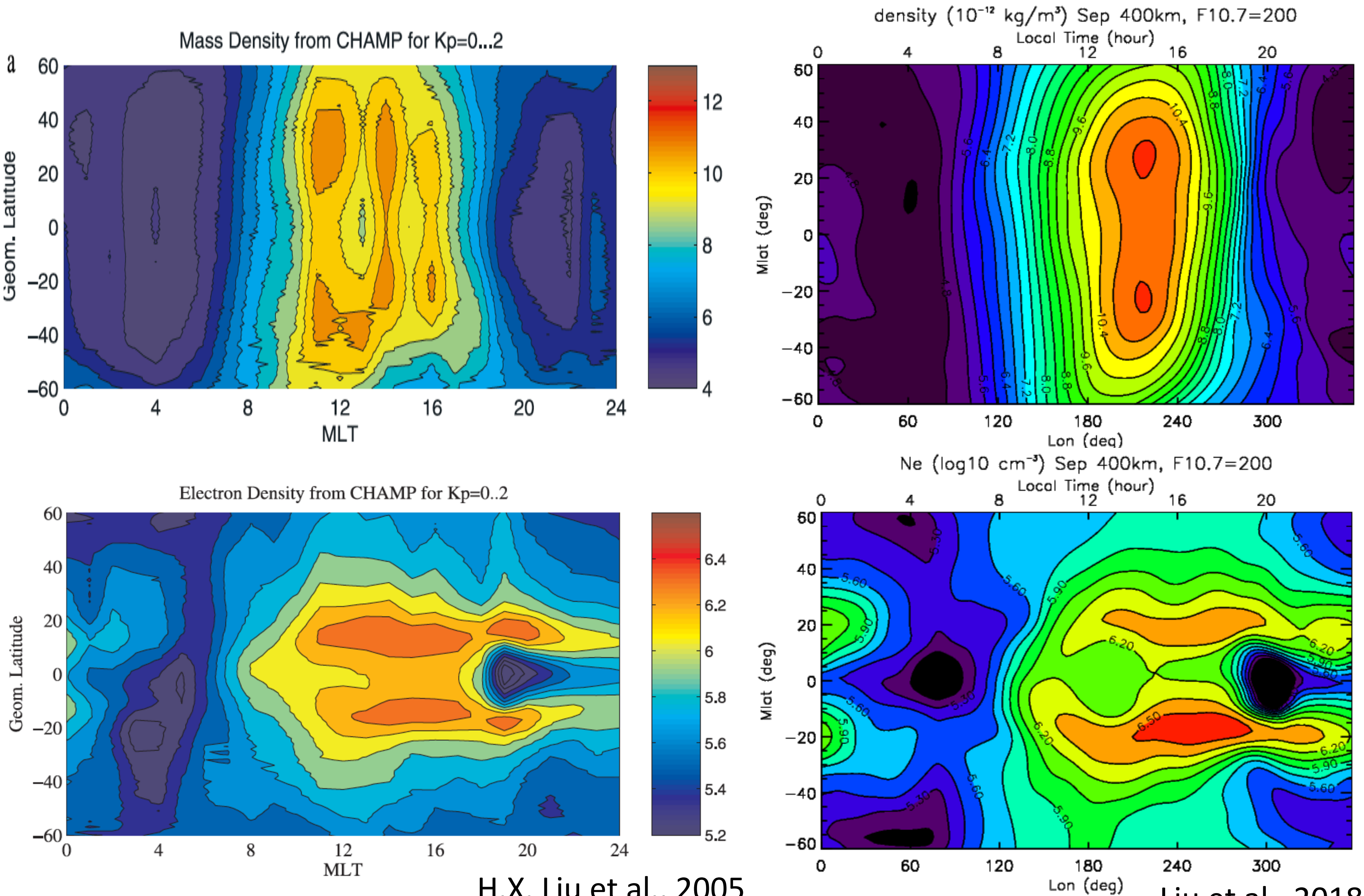
▪ WACCM-X Tutorial during 2017 CEDAR Workshop
▪ WACCM-X has been released as part of CESM2.

Thermal Structure



Liu et al., 2018

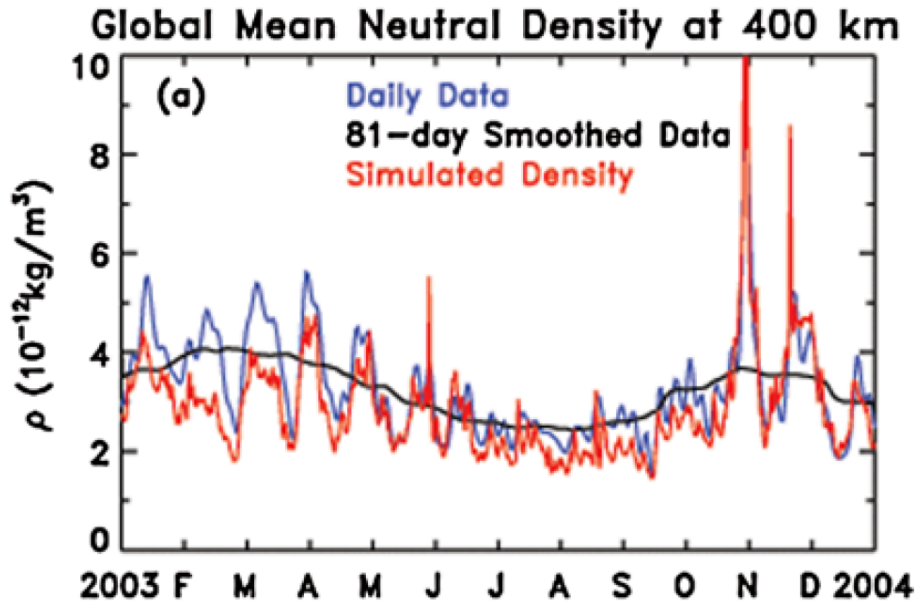
Mass and Electron Density at 400km

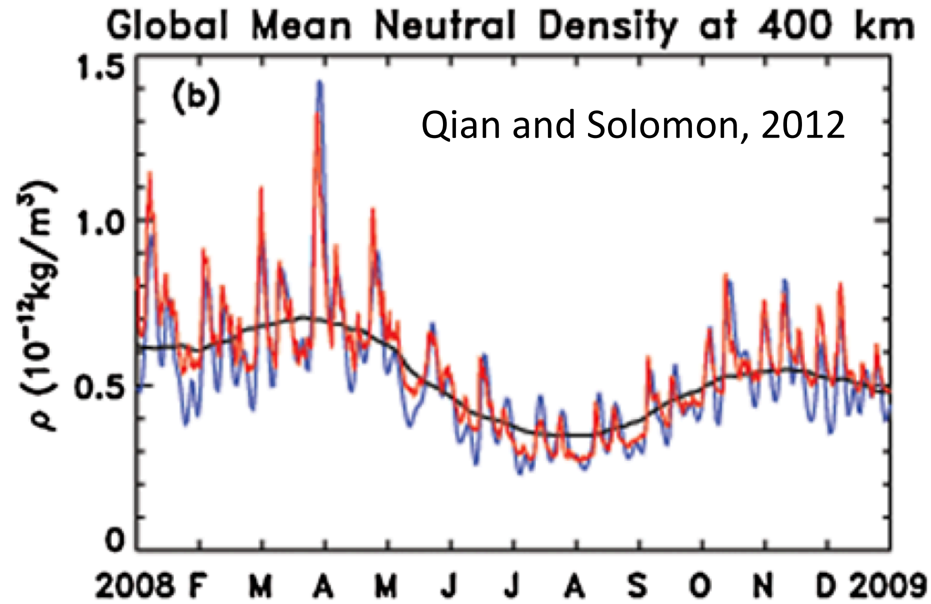


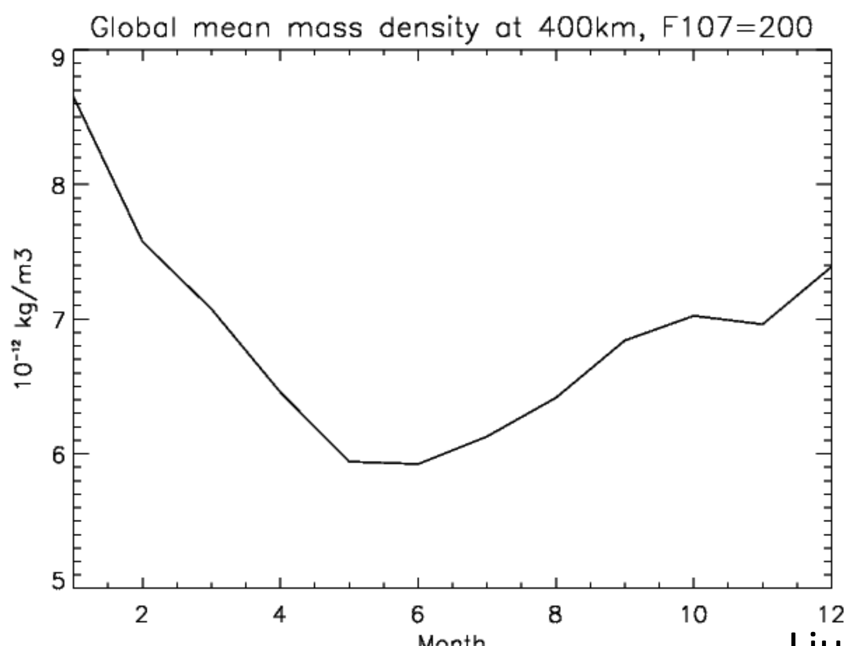
H.X. Liu et al., 2005

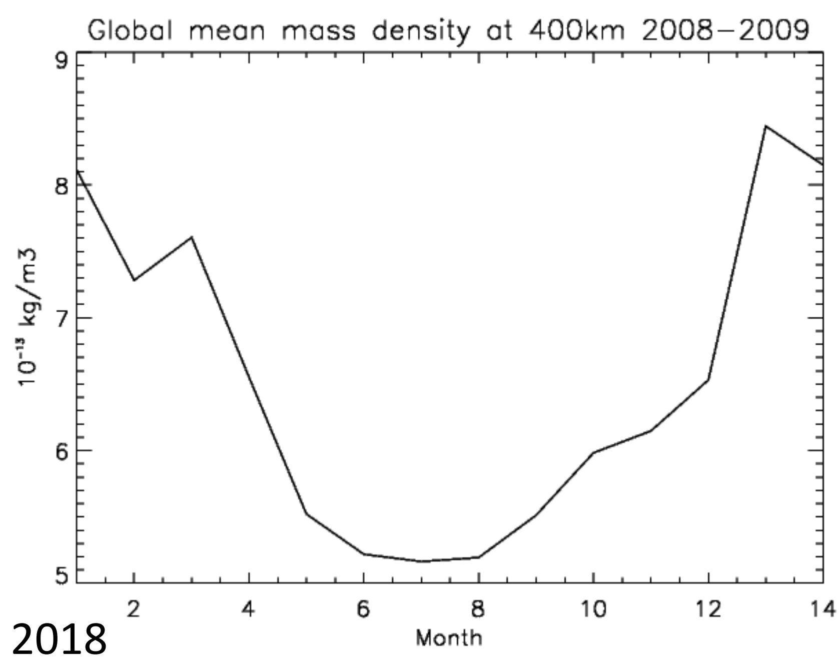
Liu et al., 2018

Annual Variation of Neutral Density



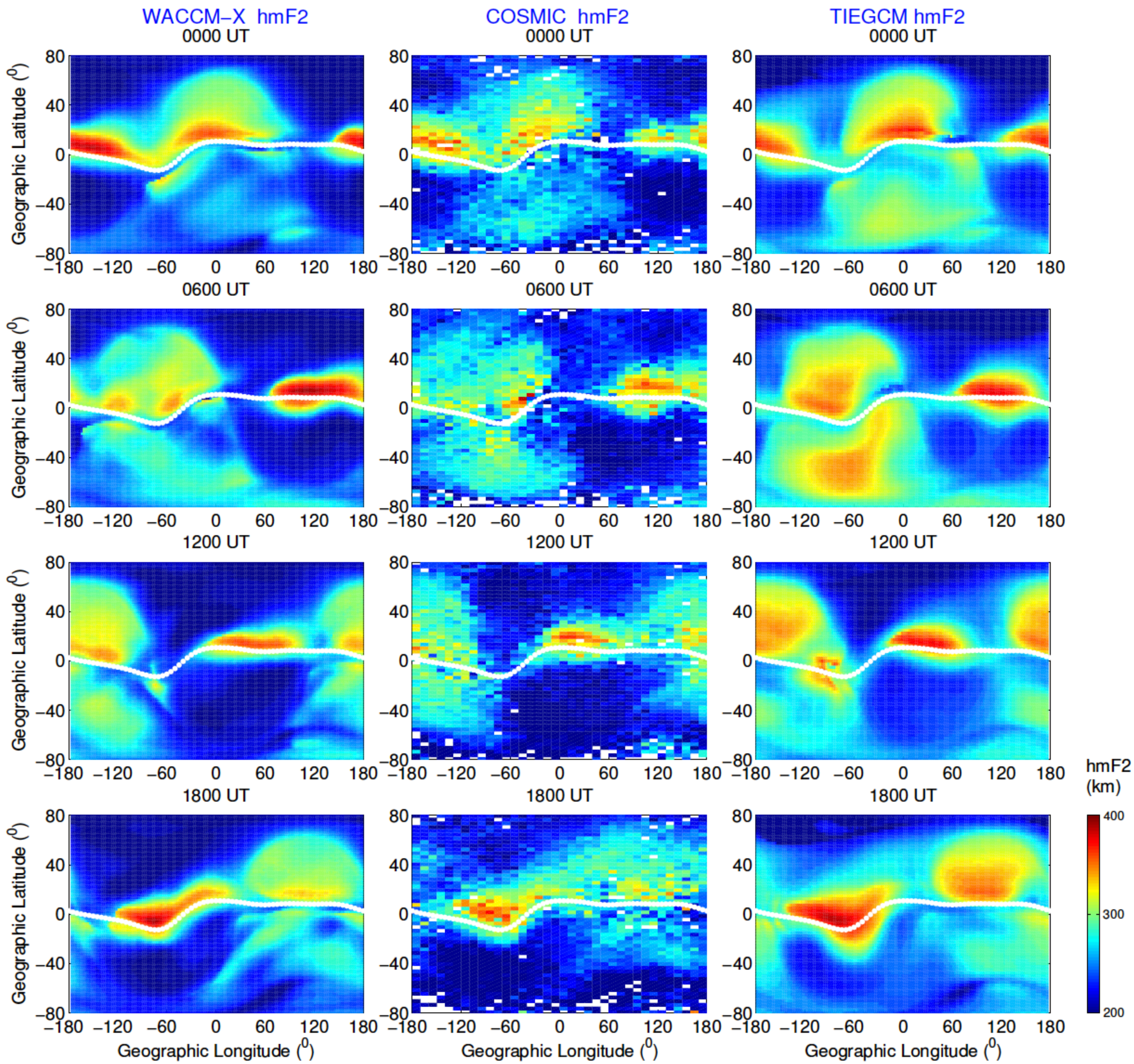






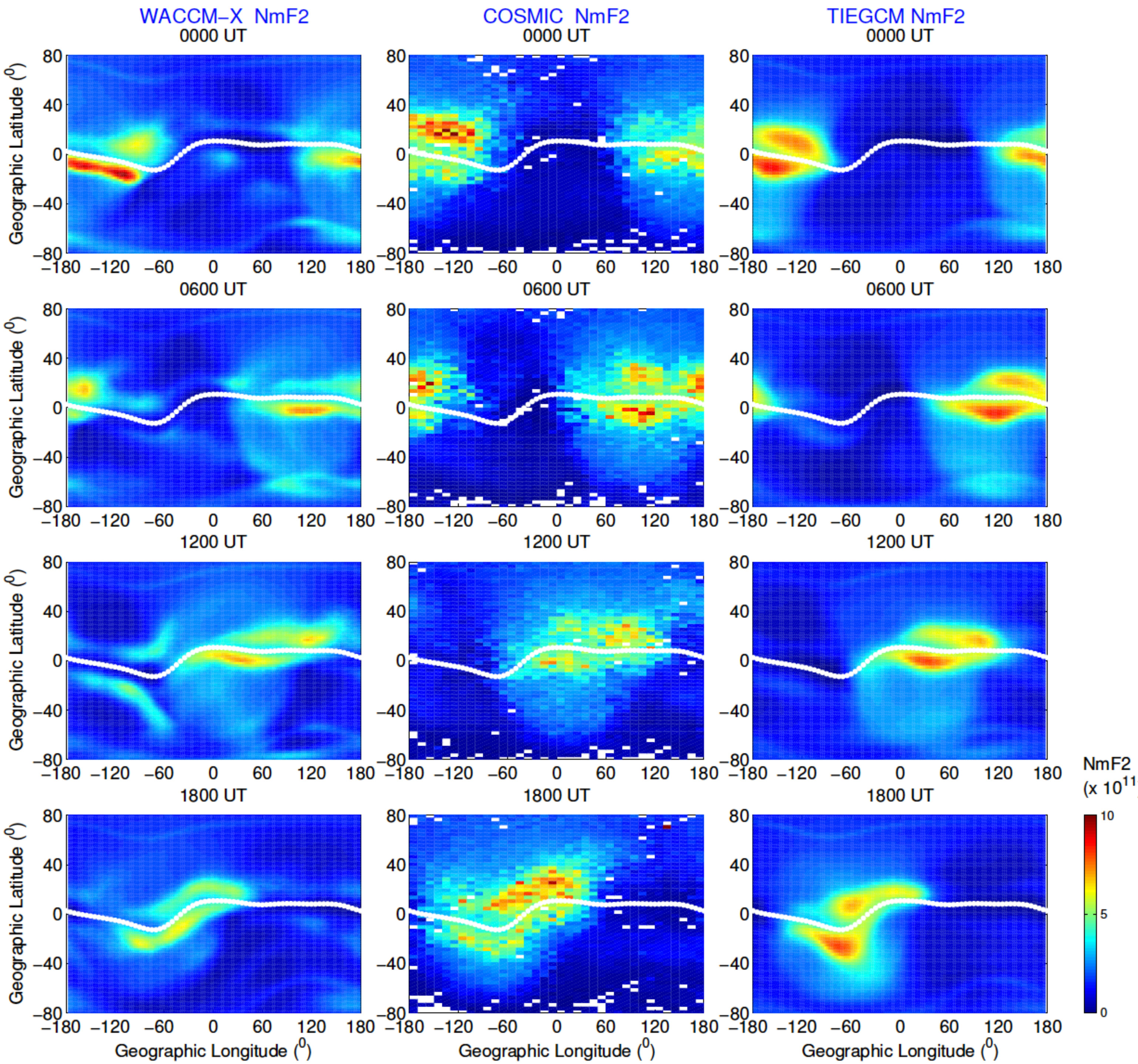
Liu et al., 2018

Comparison with COSMIC 2008 June



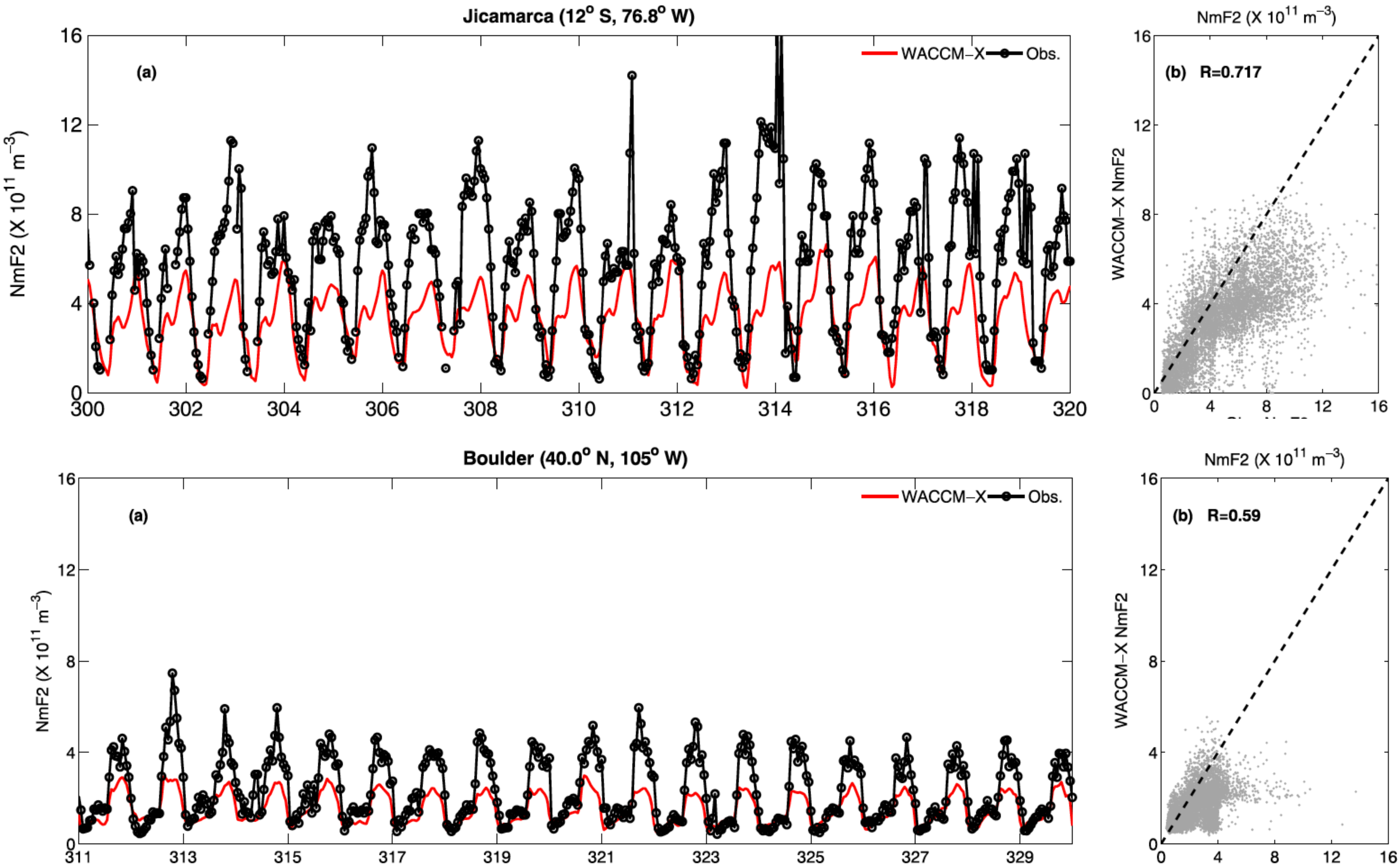
J. Liu et al. 2018

Comparison with COSMIC 2008 June



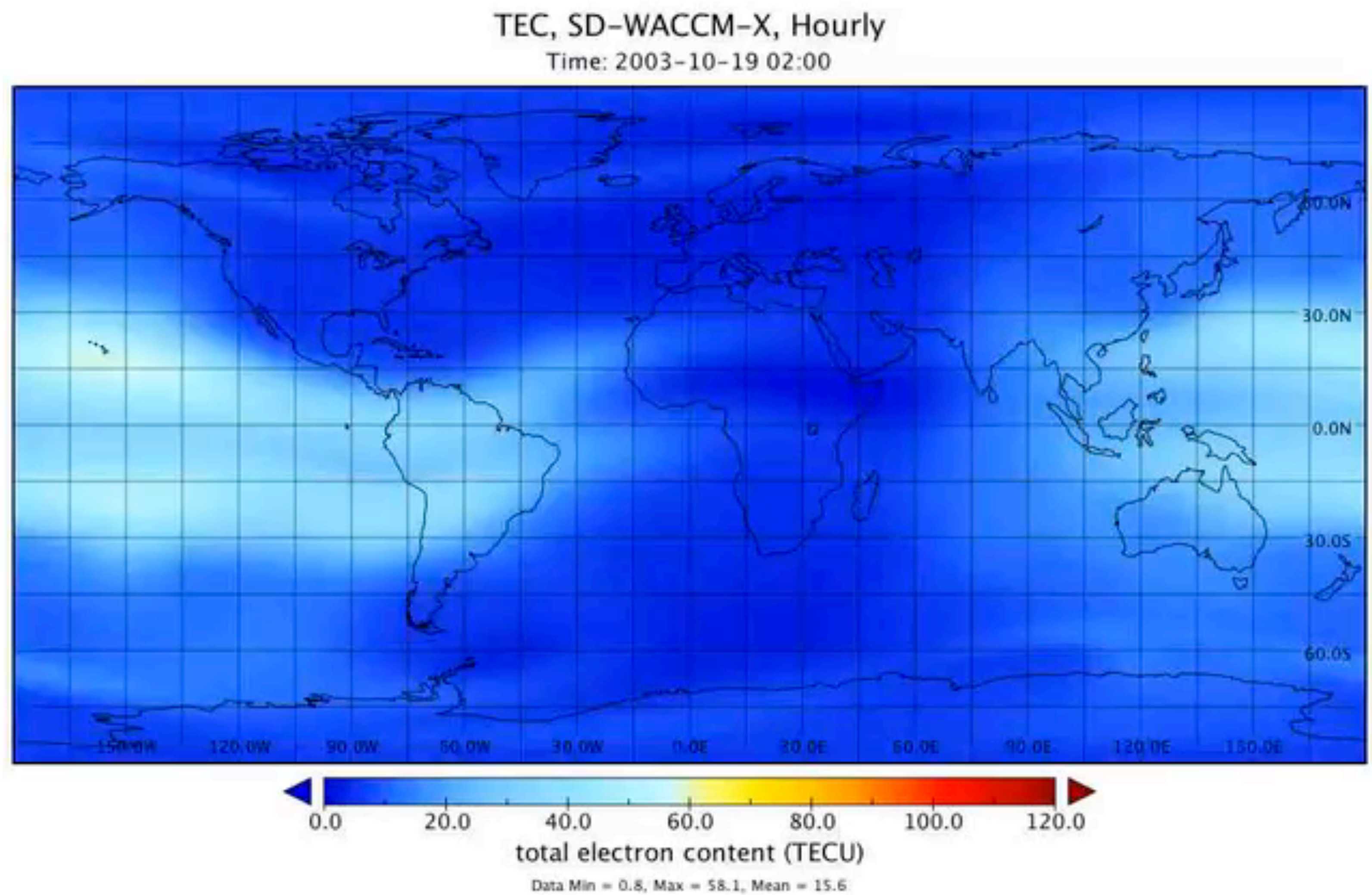
J. Liu et al. 2018

NmF2 From WACCM-X



J. Liu et al., 2018

2003 Halloween Storm Simulated by WACCM-X



Courtesy of Chuck Bardeen

WACCM-X has also been used for:

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL077723

Special Section:
New understanding of the solar eclipse effects on geospace: The 21 August 2017 Solar Eclipse

Simulation of the 21 August 2017 Solar Eclipse Using the Whole Atmosphere Community Climate Model-eXtended

Joseph M. McInerney[1], Daniel R. Marsh[1,2], Han-Li Liu[1], Stanley C. Solomon[1], Andrew J. Conley[2], and Douglas P. Drob[3]

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL077867

Key Points:
- WACCM-X simulations demonstrate the impact of lower atmosphere variability during a geomagnetic storm

The Influence of Internal Atmospheric Variability on the Ionosphere Response to a Geomagnetic Storm

N. M. Pedatella[1,2] and H.-L. Liu[1]

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2017JA024998

Key Points:
- In the mesopause, hydrogen density is higher in summer than in winter, and higher at solar minimum than at

Temporal Variability of Atomic Hydrogen From the Mesopause to the Upper Thermosphere

Liying Qian[1], Alan G. Burns[1], Stan S. Solomon[1], Anne K. Smith[2], Joseph M. McInerney[1], Linda A. Hunt[3], Daniel R. Marsh[1,2], Hanli Liu[1], Martin G. Mlynczak[3], and Francis M. Vitt[1,2]

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL076950

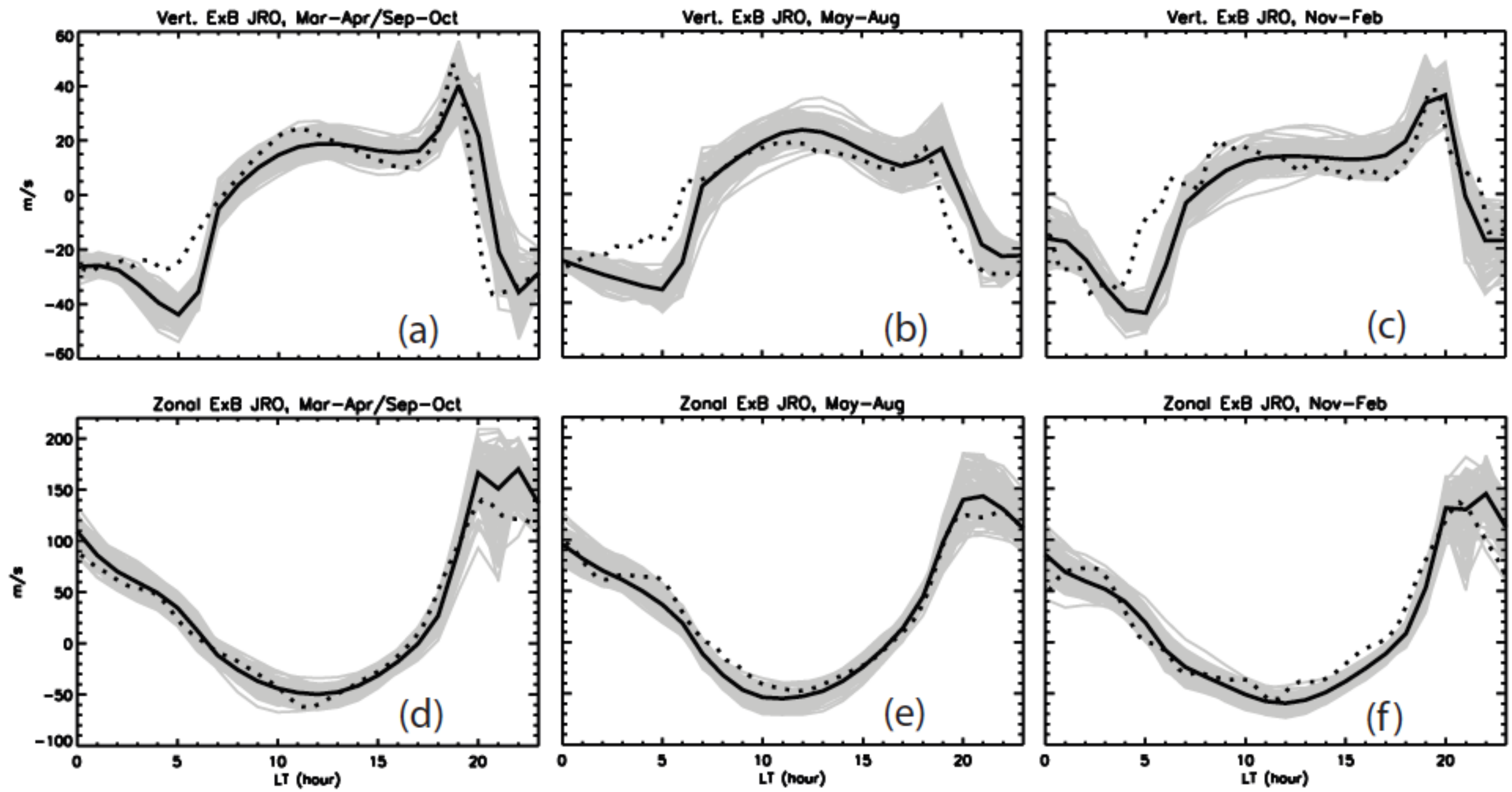
Key Points:
- We have performed the first comprehensive whole-atmosphere climate change simulations, including

Whole Atmosphere Simulation of Anthropogenic Climate Change

Stanley C. Solomon[1], Han-Li Liu[1], Daniel R. Marsh[1], Joseph M. McInerney[1], Liying Qian[1], and Francis M. Vitt[1]

Equatorial Ionosphere Weather

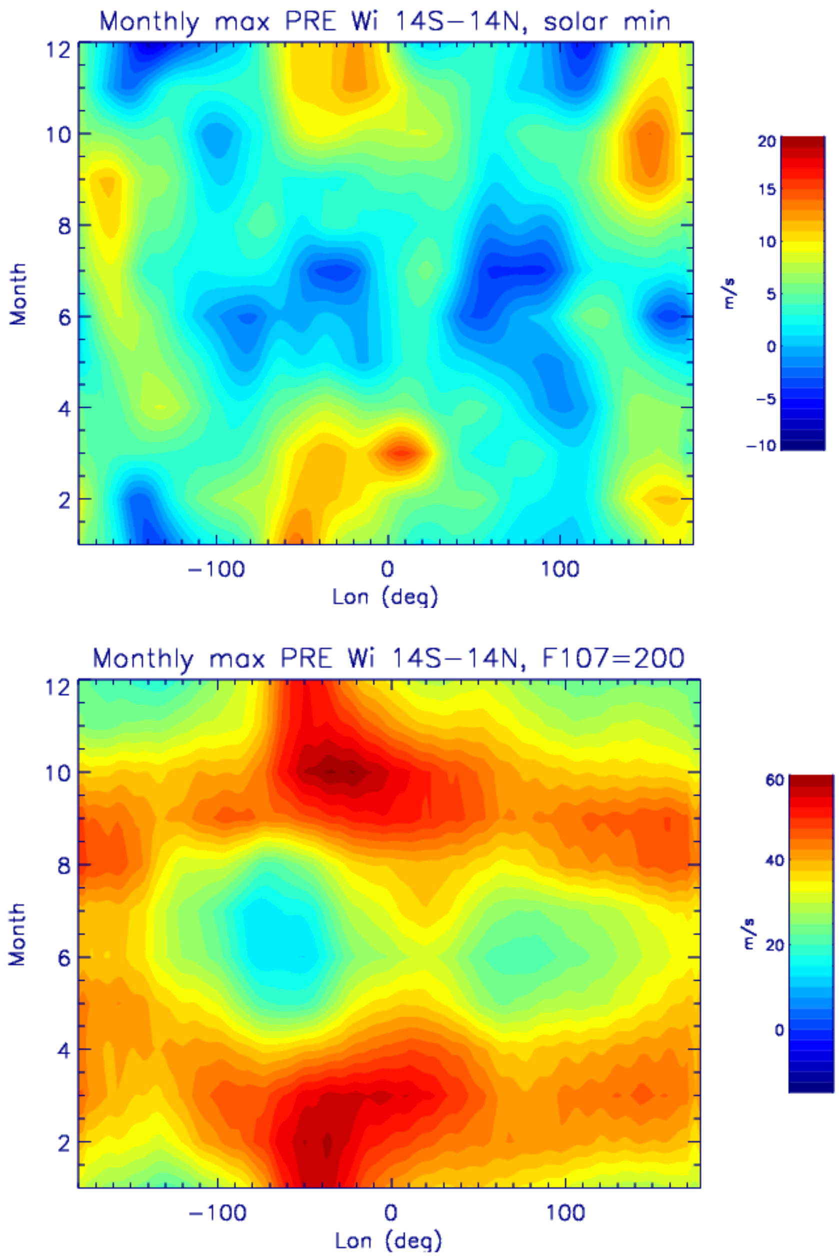
ExB Drifts: WACCM-X vs Climatology

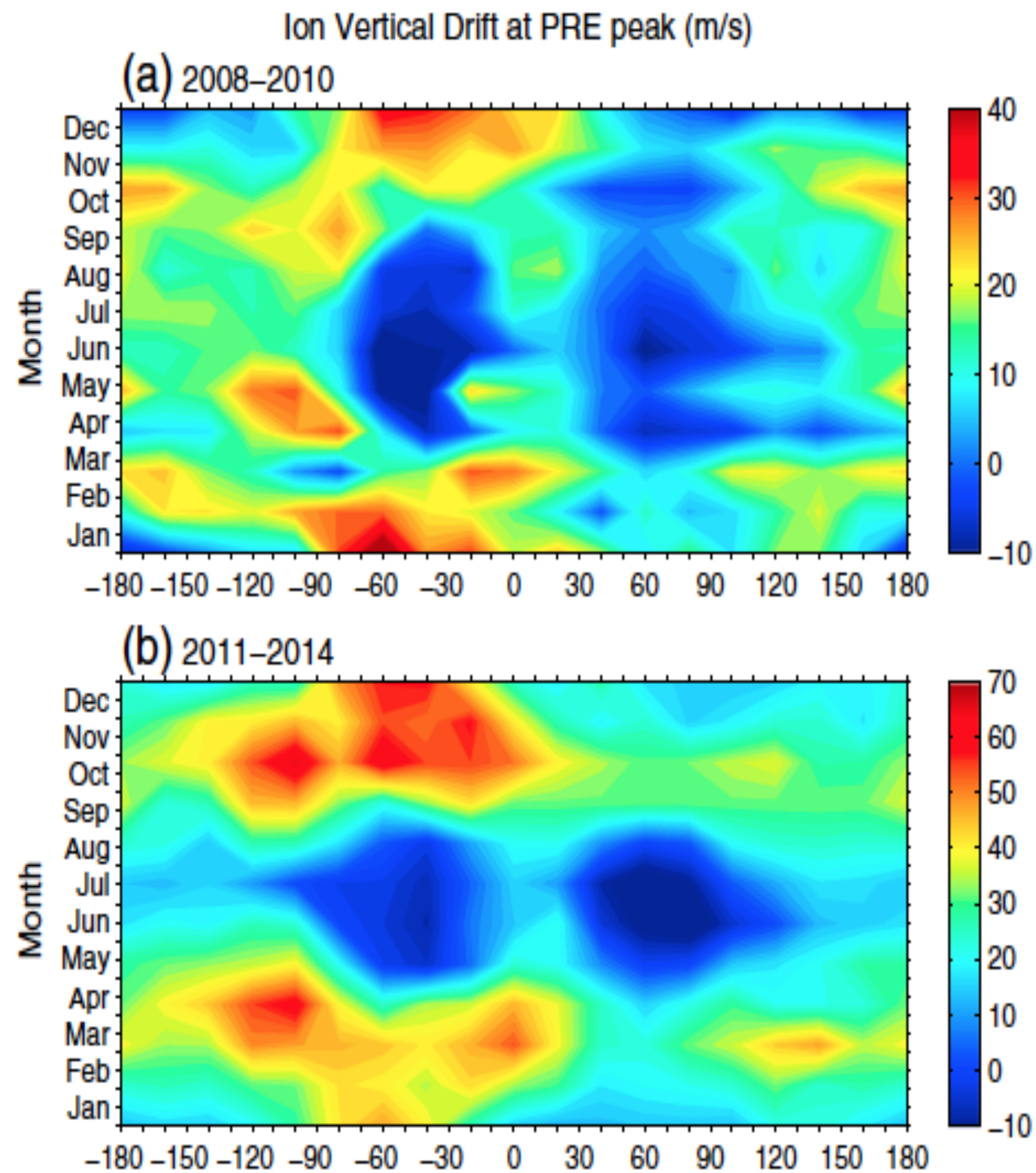


Liu et al., 2018

Dotted line: JRO climatology (Fejer et al., 1991)

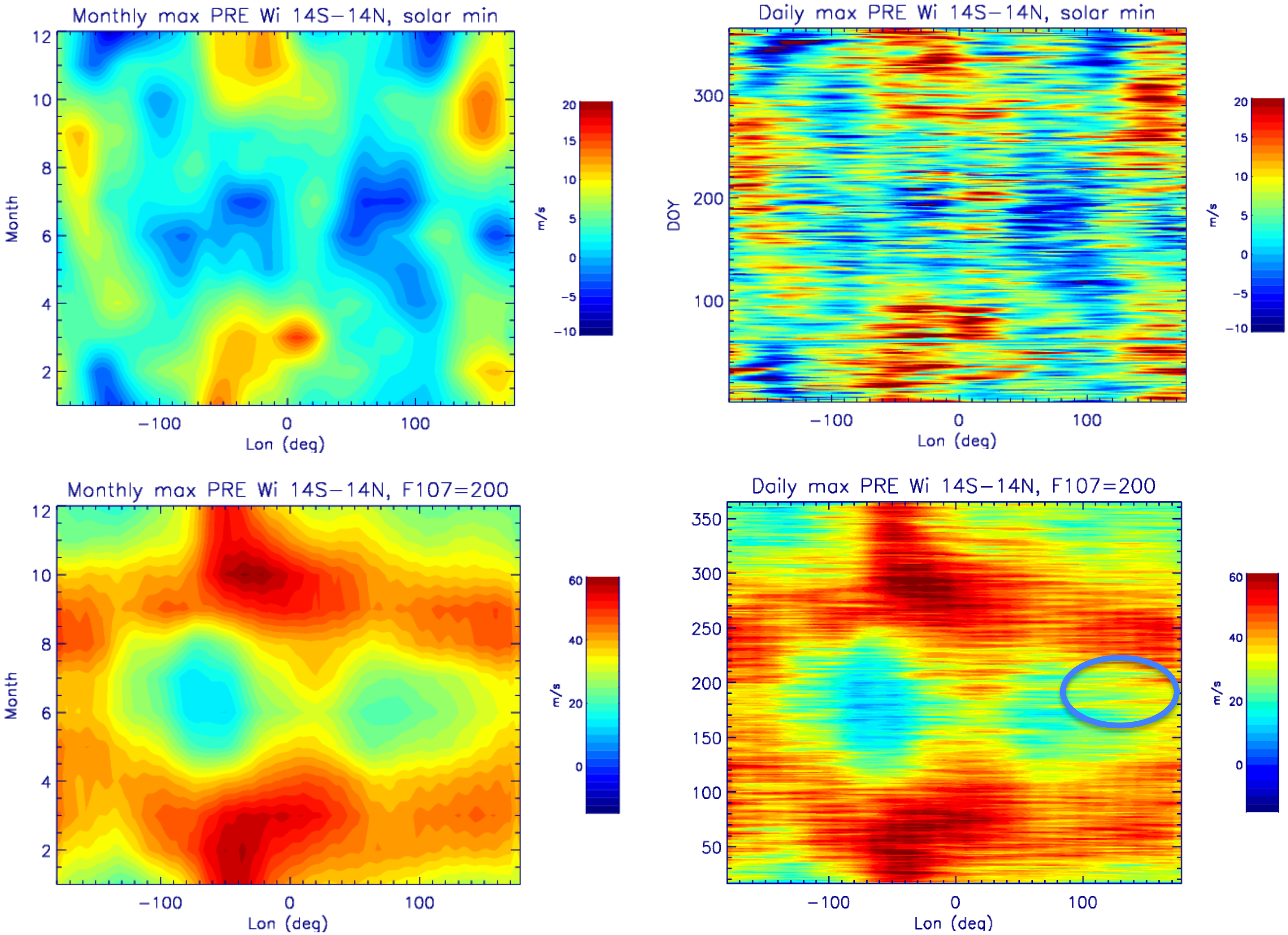
Monthly Mean PRE Peak



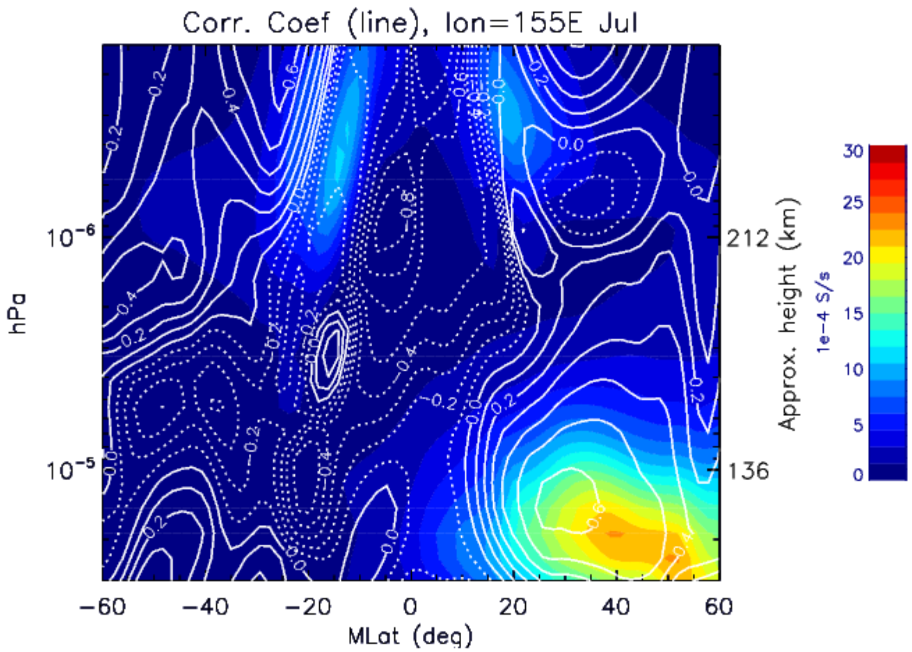


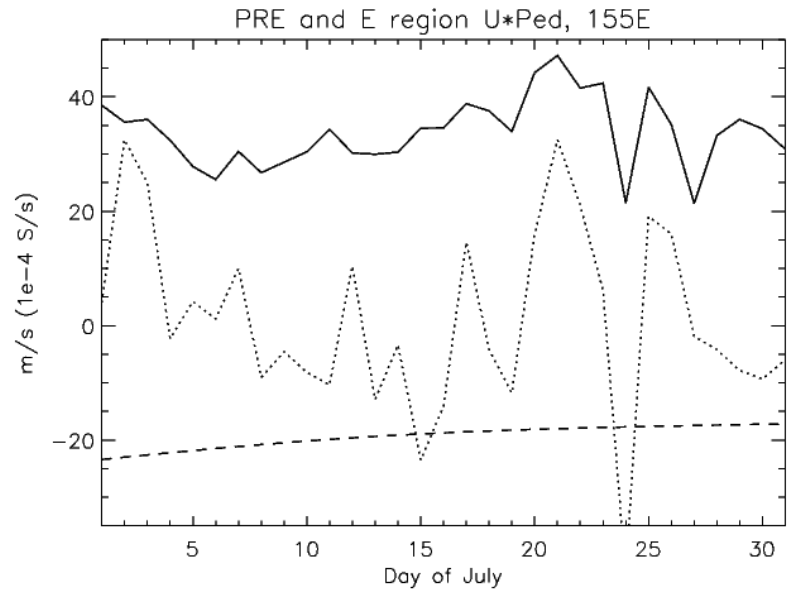
Huang and Hairston, 2015

Monthly vs Daily Variability



Variability of PRE and E-region Dynamo

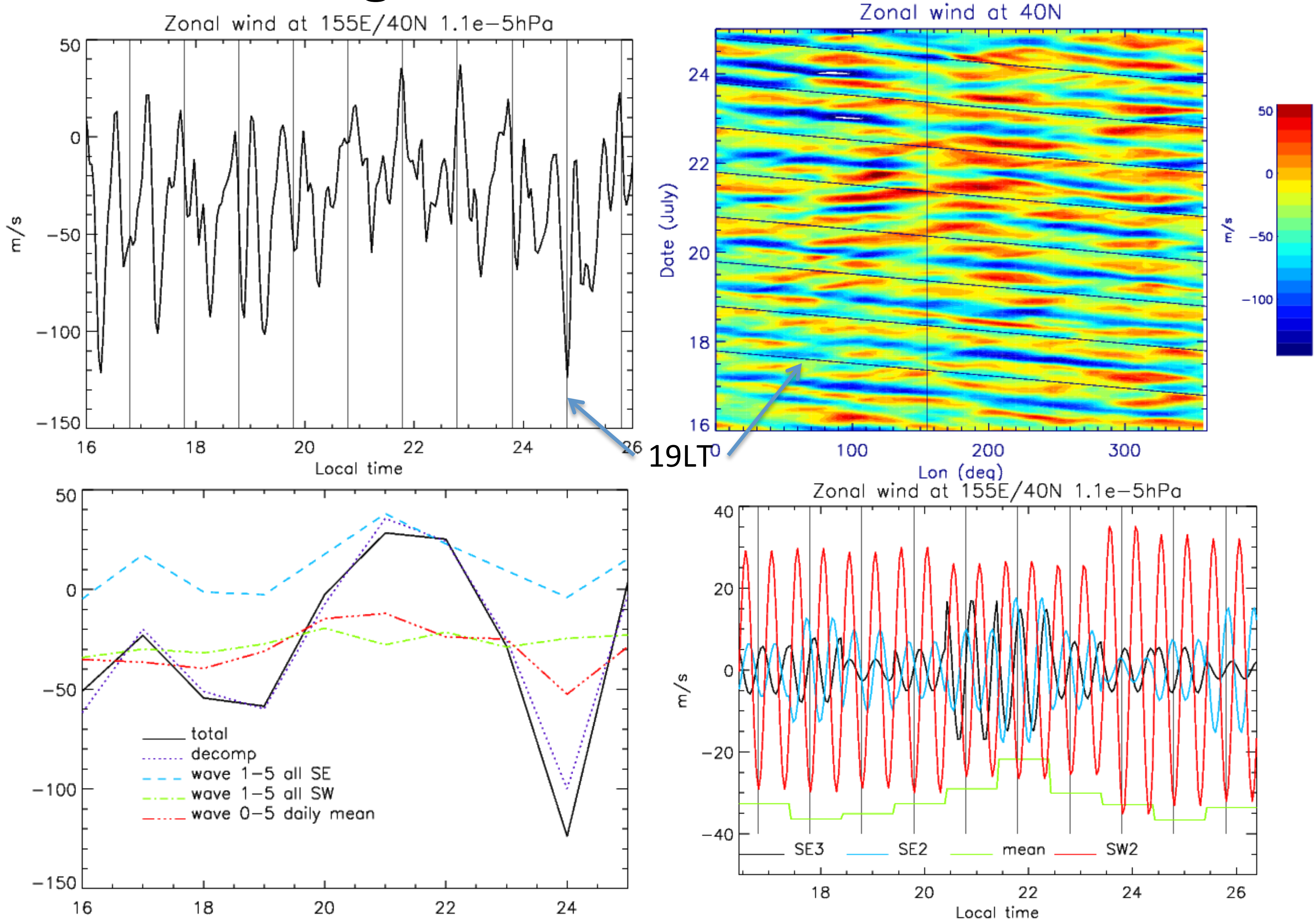




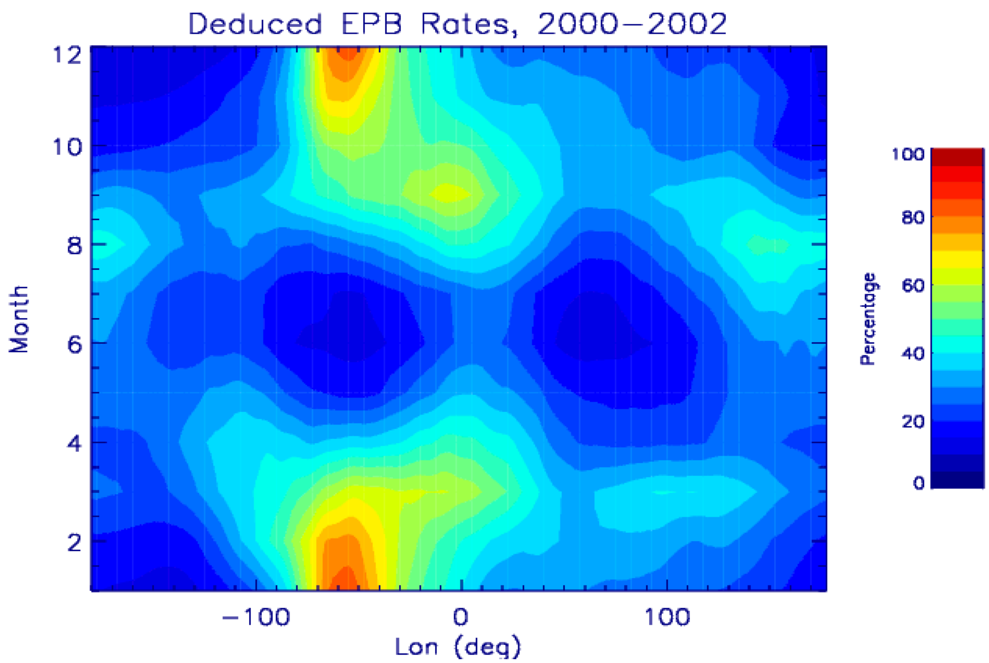
Line contour: Cor(PRE,U*Ped(19LT)); color: StdDev(U*Ped(19LT))

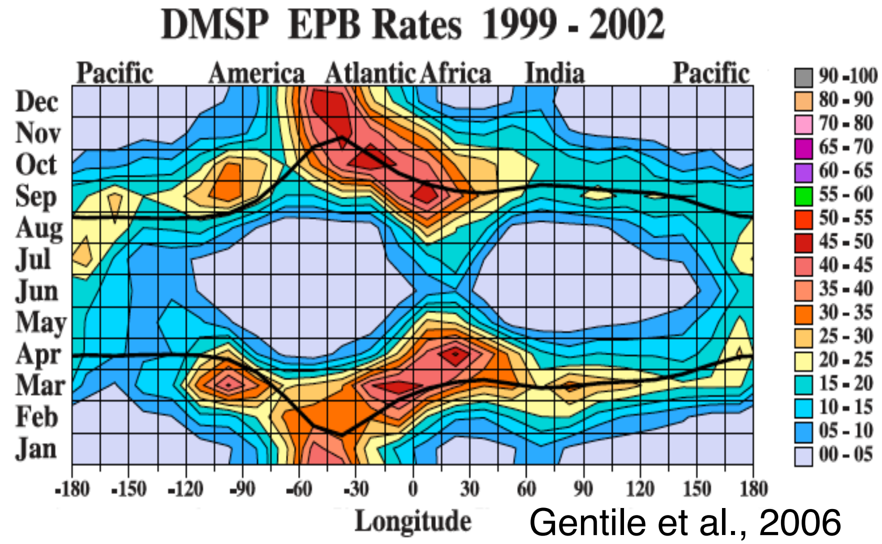
- Summer side E-region neutral wind variability at sunset time strongly affects PRE variability.
- E-region is strongly affected by lower atmospheric waves.

E-region Zonal Wind Variability

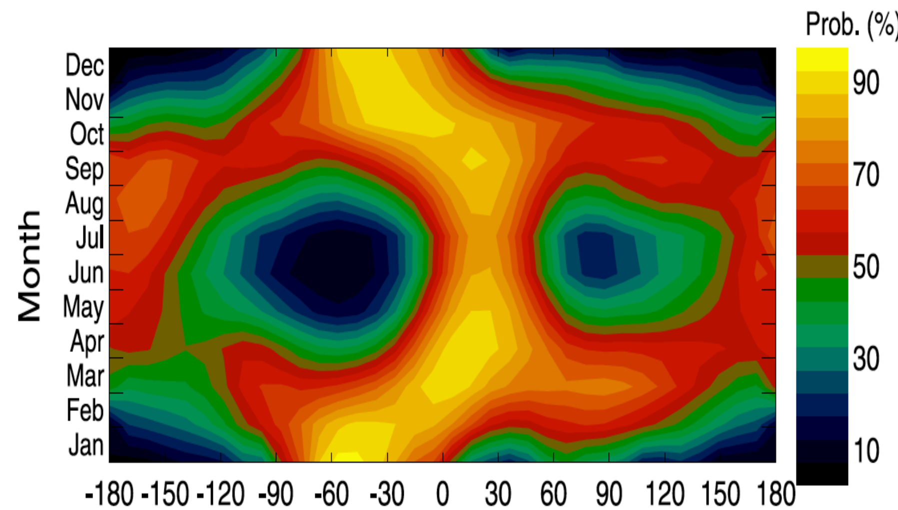


Occurrence Frequency of Equatorial Plasma Bubbles





Gentile et al., 2006

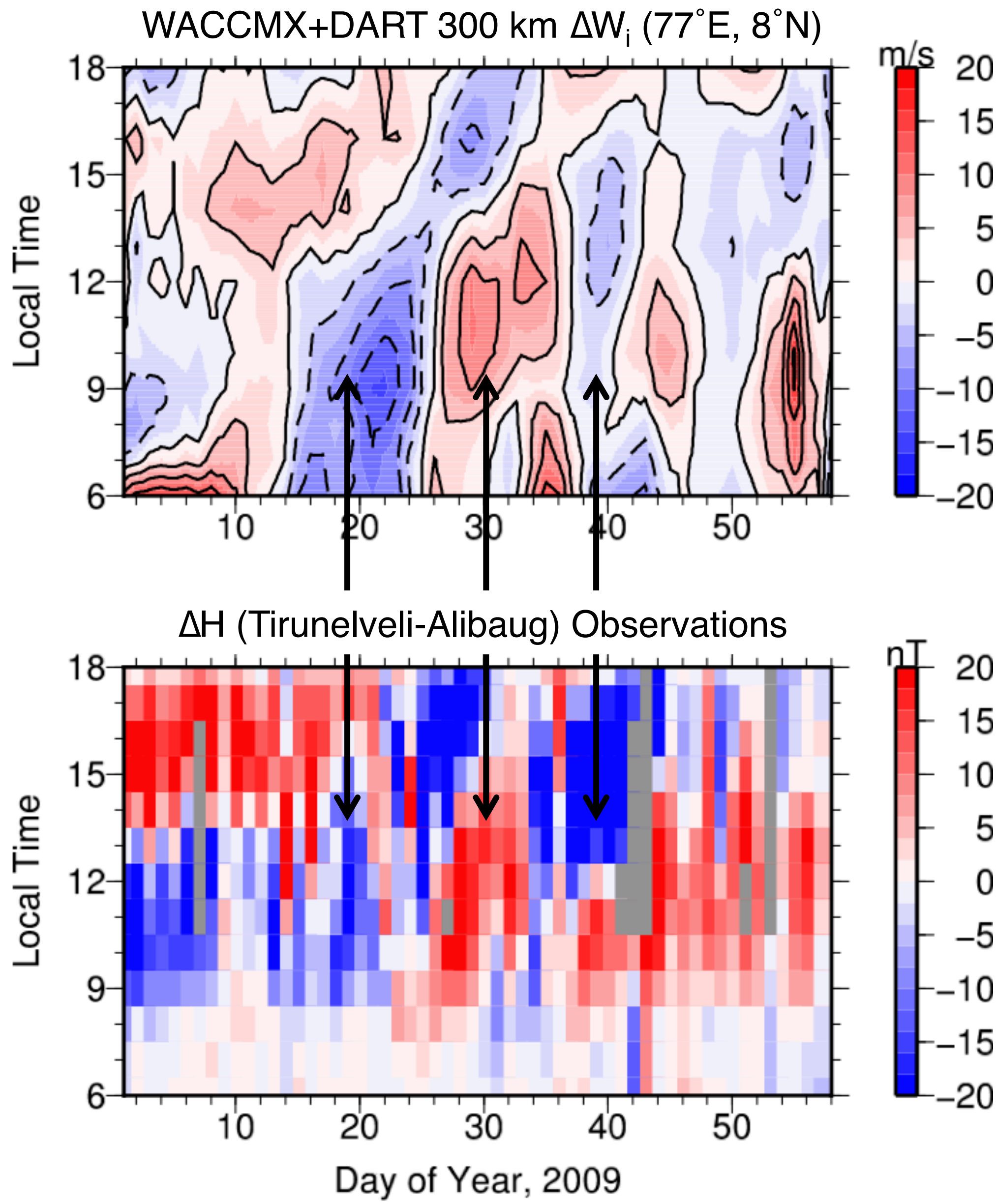


Kil et al., 2009

- The agreement between deduced EPB rates and the observed rates suggest
  - Large-scale dynamics and electrodynamics play a key role in preconditioning EPB
  - Feasibility for **probabilistic forecast** of EPB—an outlook/warning (analogous to tornado forecast).
- Resolving EPB requires high-resolution capability.

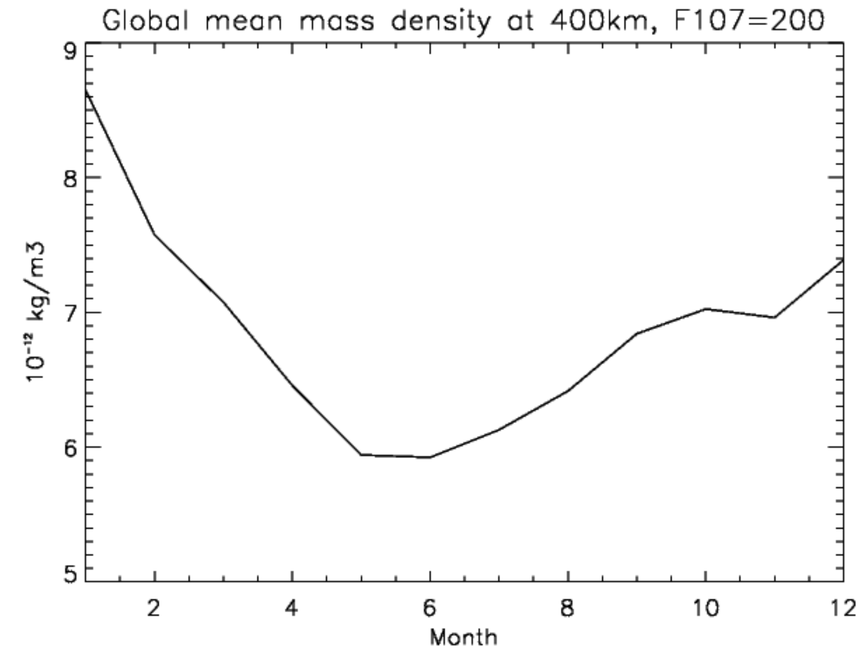
WACCM-X Data Assimilation: WACCM-X+DART

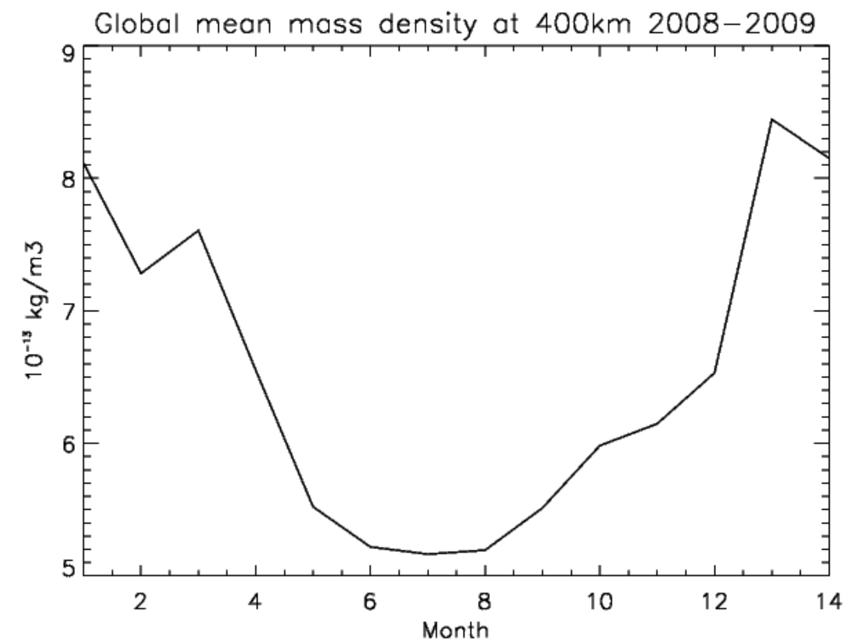
Ionosphere results based on assimilating data only below 100km (meteorological observations, Aura/MLS, and TIMED/SABER): **Large-scale ionospheric features may be forecast 10-20 days in advance.**

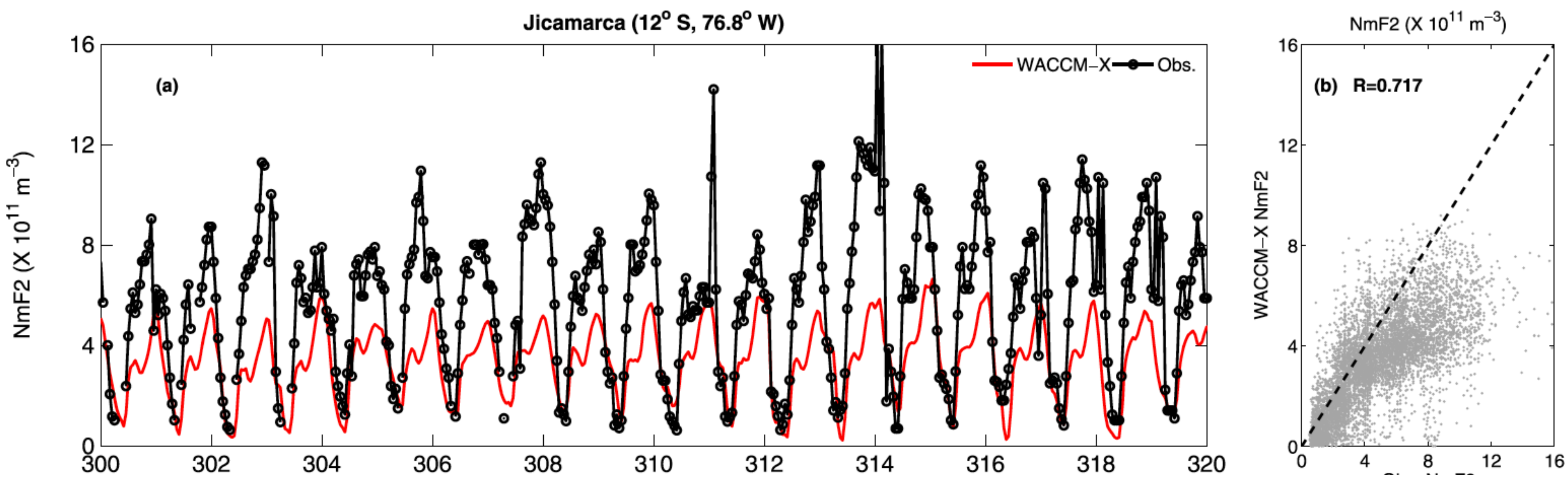


Pedatella et al., 2018

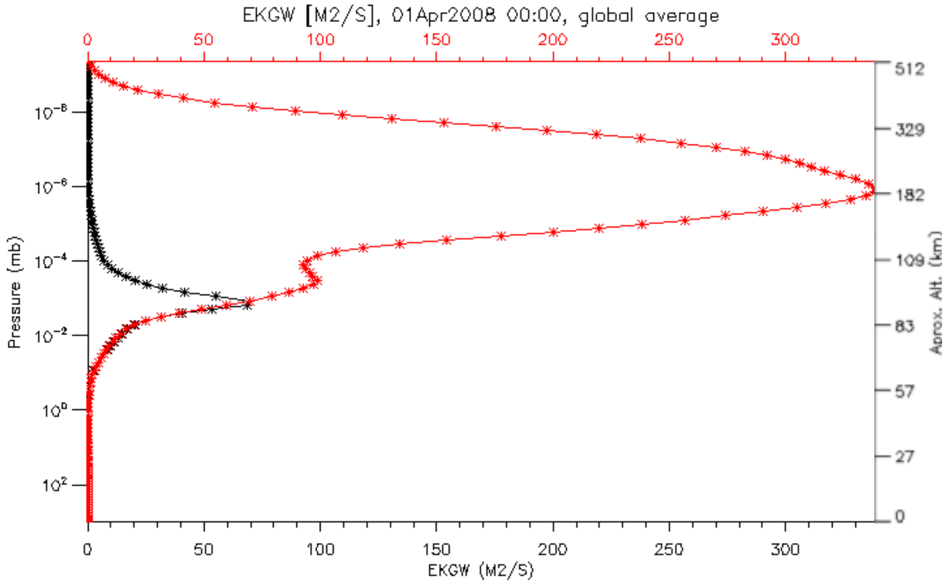
Model Biases and Uncertainties

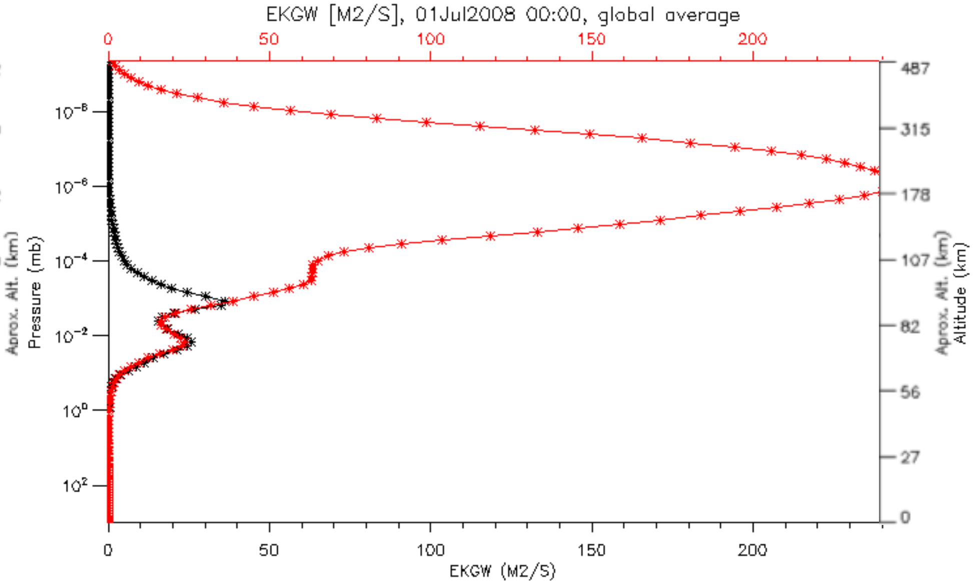


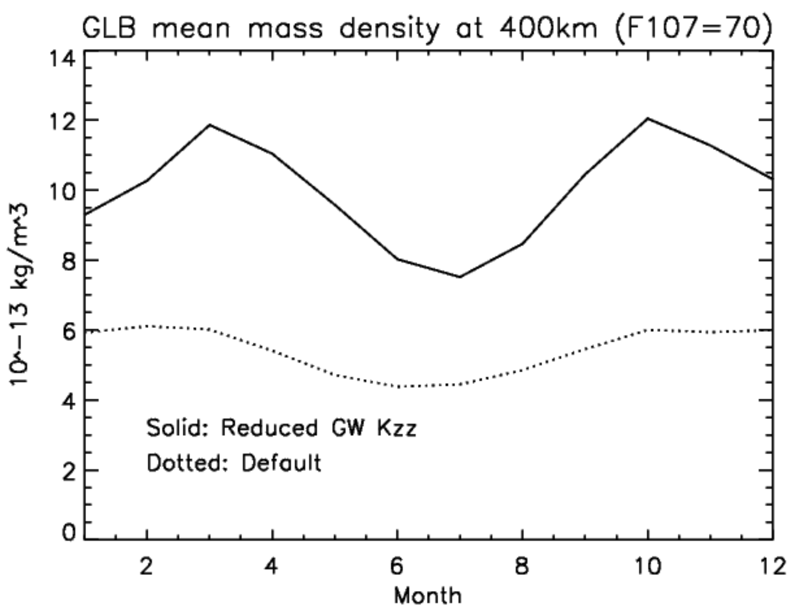


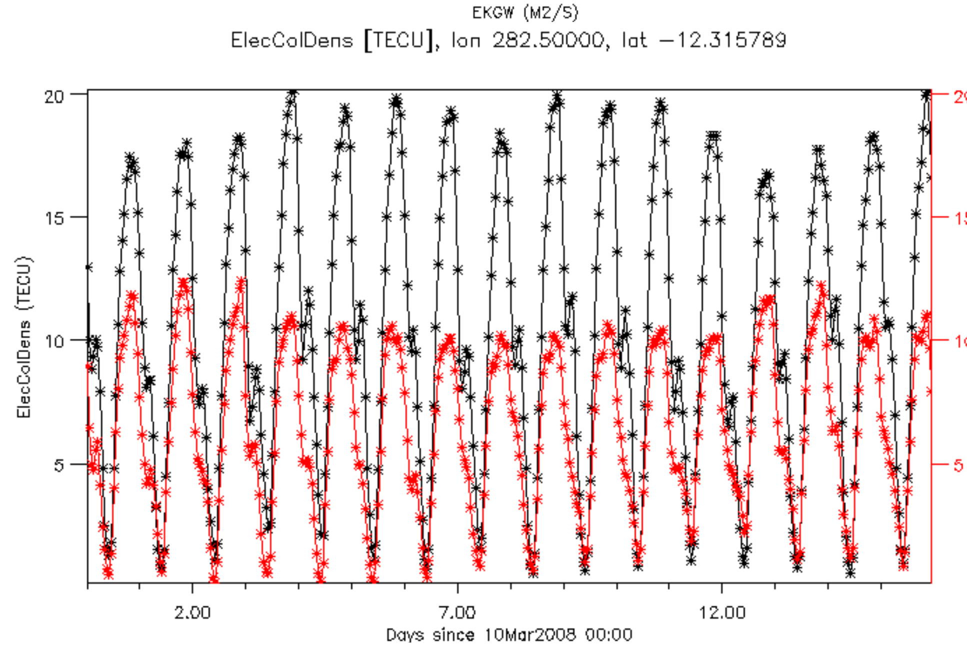


Model Biases and Uncertainties: Mixing by Subgrid Scale Waves

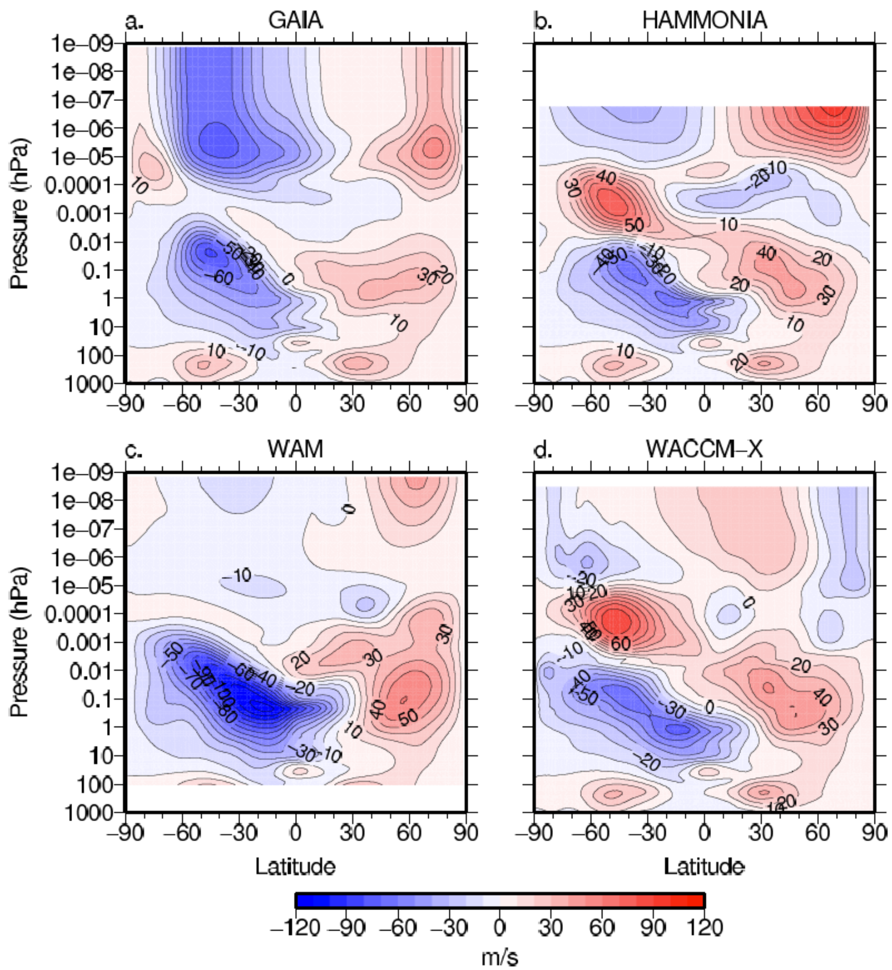


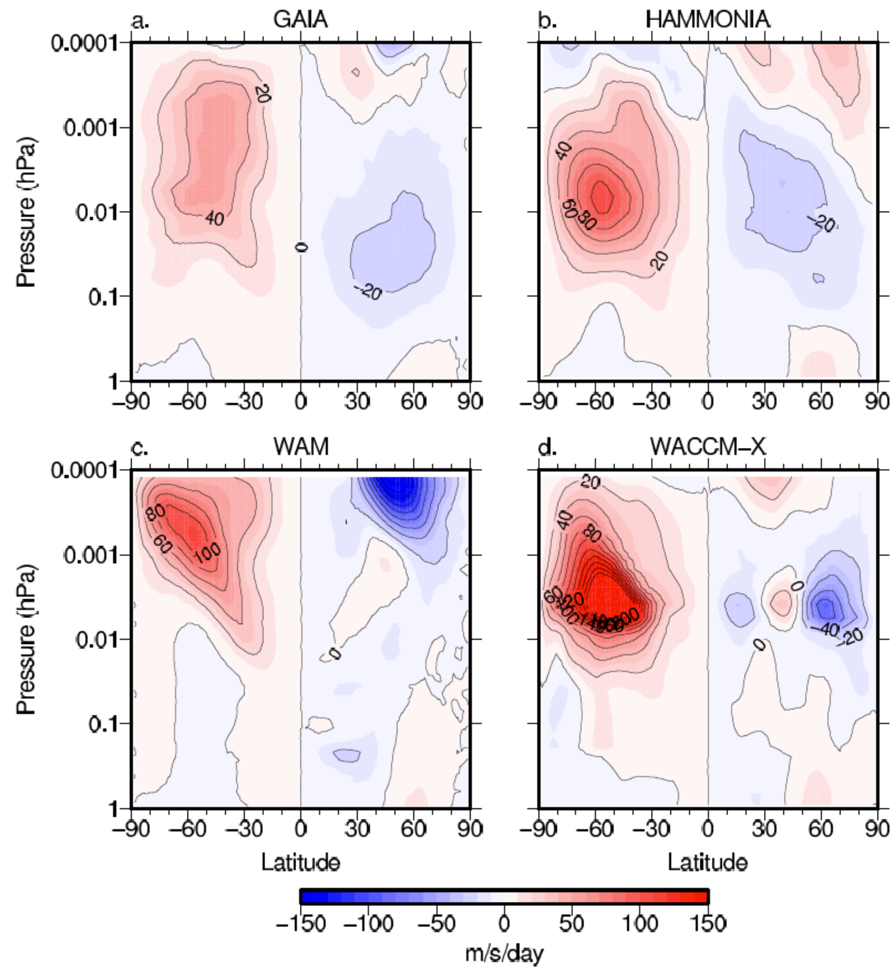






Model Biases and Uncertainties: Forcing by Subgrid Scale Waves





Pedatella et al. (2014)

Model Biases and Uncertainties

- A crucial missing physics is the gravity waves
  - Gravity waves are the major driver of upper atmosphere dynamics.
  - Not well represented due to insufficient spatial resolution.
  - Usually parameterized: a major source model bias and leads to predictive errors.
- Need to:
  - resolve them, and/or
  - Better parameterization and constraints, and/or
  - perform whole atmosphere data assimilation.

Summary

- Key WACCM-X capabilities have been developed, and validated against thermospheric and ionospheric observations for climatology, variability during geomagnetic quiet and disturbed conditions, and long-term space climate change.
- Simulated PRE, an important quantity for the formation of EPB, shows longitudinal and seasonal variation similar to observations.
  - Simulated PRE varies significantly from day-to-day. Deduced EPB rate is similar to observations.
- Model biases in mesosphere, thermosphere and ionosphere can be caused by issues with gravity wave parameterization (both drag and mixing) (déjà vu…)

CESM2/WACCM-X v2: A Community Model

CESM2/WACCM-X is a community model—play with it!

- WACCM-X Link:

https://www2.hao.ucar.edu/modeling/waccm-x

- CESM Link:

http://www.cesm.ucar.edu/

Ongoing/Future WACCM-X Developments

- Perform WACCM-X simulations in support of upcoming satellite missions (ICON, GOLD, and COSMIC-2) as well as ground-based observations, including their use in data assimilation.
  - Can be a powerful tool integrating and interpreting observations.
- Develop generic 3D mapping capability between new WACCM-X dynamical core grids and geomagnetic grid.
- Develop WACCM-X with mesoscale-resolving capability.
- Assimilation of ionospheric observations.
- Including Helium as a major species.
- Ionospheric E-region transport and metal ion chemistry.
- D-region chemistry.
- Whole geospace modeling by coupling WACCM-X to magnetosphere and plasmasphere models.

Acknowledgements

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