Overview of the Community Earth System Model (CESM) & Whole Atmosphere Community Climate Model with thermosphere-ionosphere eXtension (WACCM-X)

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Outline

- **Overview of CESM**
- **WACCM-X overview and capabilities**
- **Recent/upcoming developments**

WACCM-X Overview & Science Goals

- WACCM-X is one of the atmospheric components of the NSF NCAR Community Earth System Model (CESM)
- Models the chemistry, dynamics, and physics of the atmosphere-ionosphere from the surface to the upper thermosphere
- Science goals:
    - Impacts of the Sun on the Earth system
    - Understand and quantify couplings between atmospheric layers through chemical, physical, and dynamical processes
    - Implications of the coupling to climate (downward coupling) and to the space environment (upward coupling)

WACCM-X is one of the atmosphere components of the NSF NCAR Community Earth System Model (CESM)

External Forcings:
- Greenhouse gases
- Anthropogenic aerosols
- Volcanic eruptions
- Solar variability

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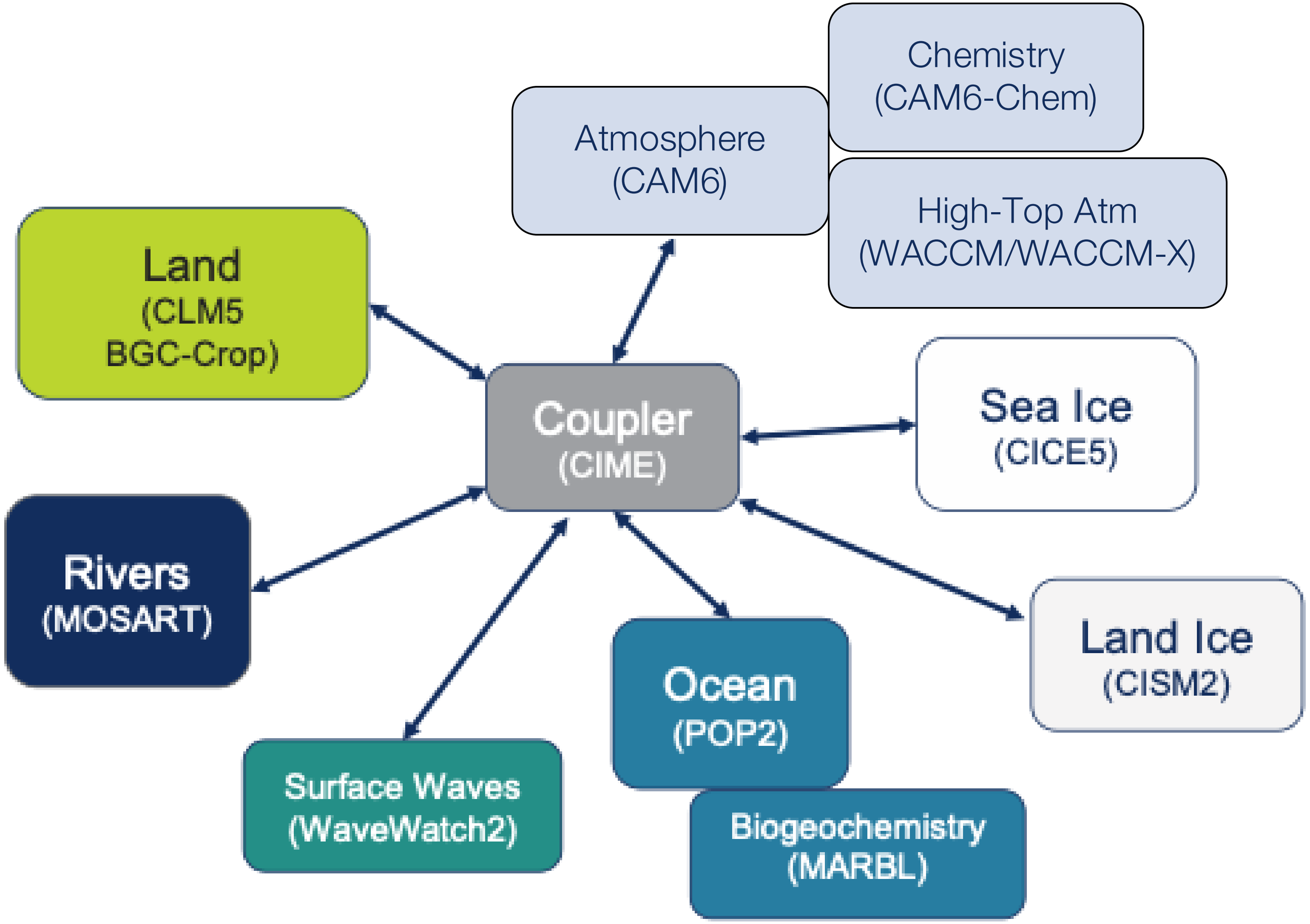
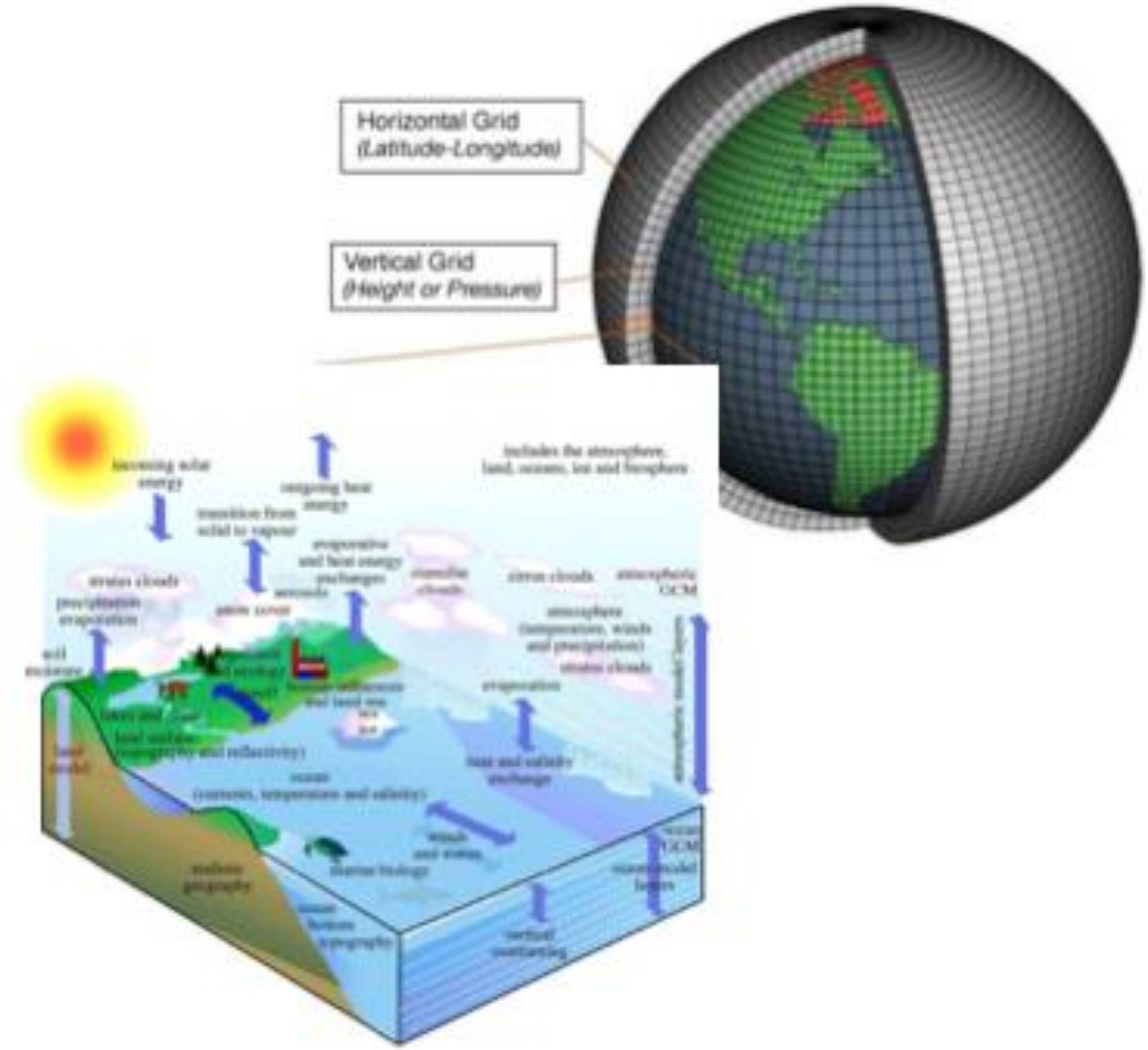


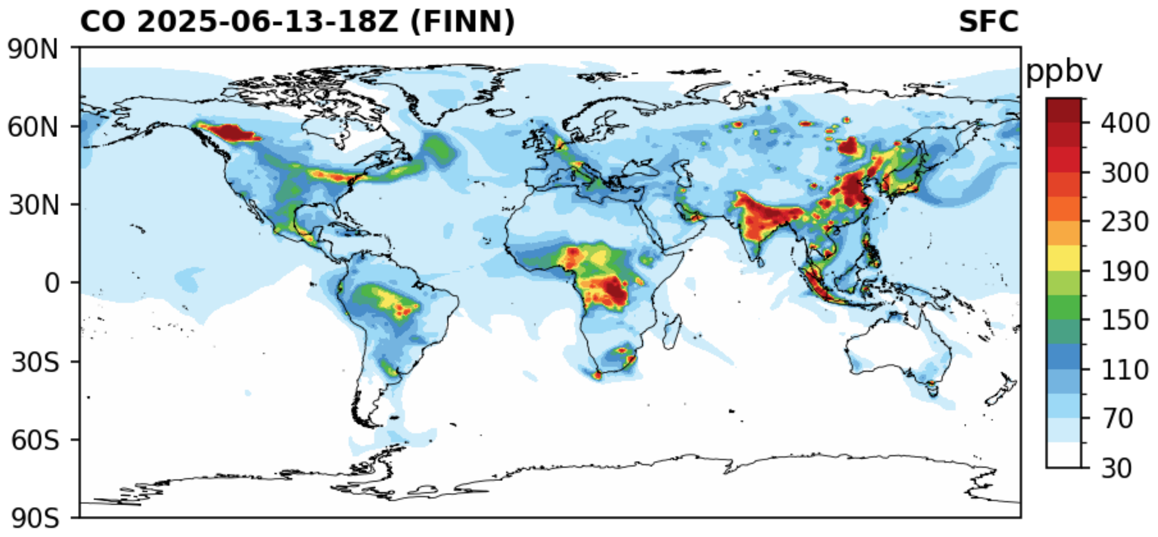
What is an Earth System model?

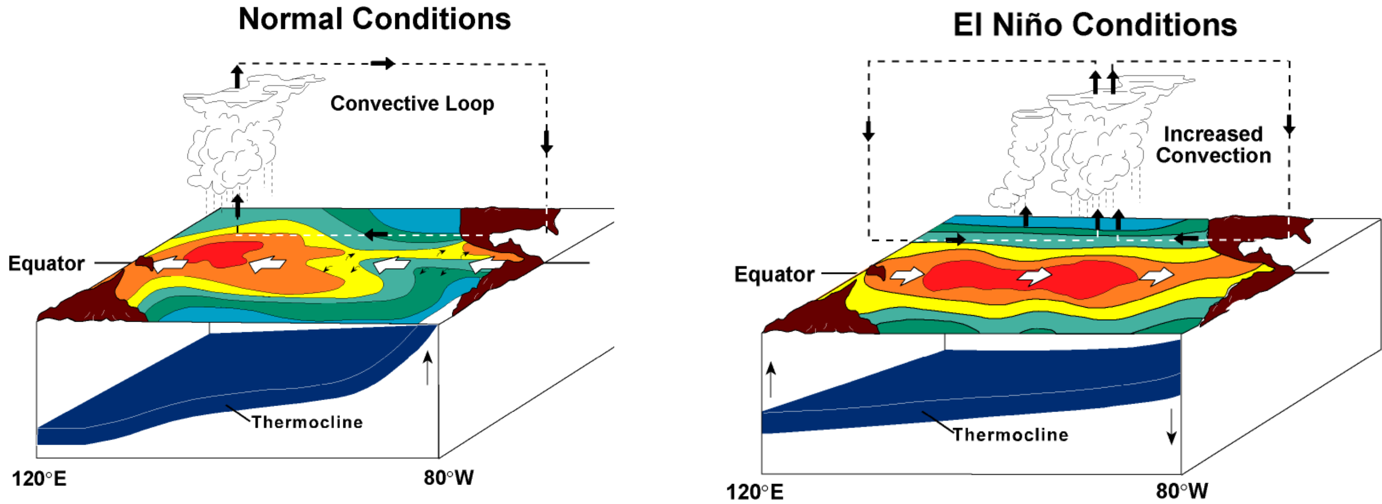
- Use physical equations to simulate key fields and processes in the atmosphere, ocean, land, sea-ice, land-ice, etc. and their couplings
- Processes that are below the grid resolution need to be parameterized
- Build on our understanding of processes from observations and highly-detailed models



Applications of Earth System Models

- Earth system variability and change
- Air quality
- Biogeochemical cycles
- Sun-climate connections and space weather
- Process understanding
- Land-atmosphere and ocean-atmosphere interactions
- Ice sheet – climate interactions
- Hydrology and ecology
- Earth system predictability
- Weather from local to global scales
- …





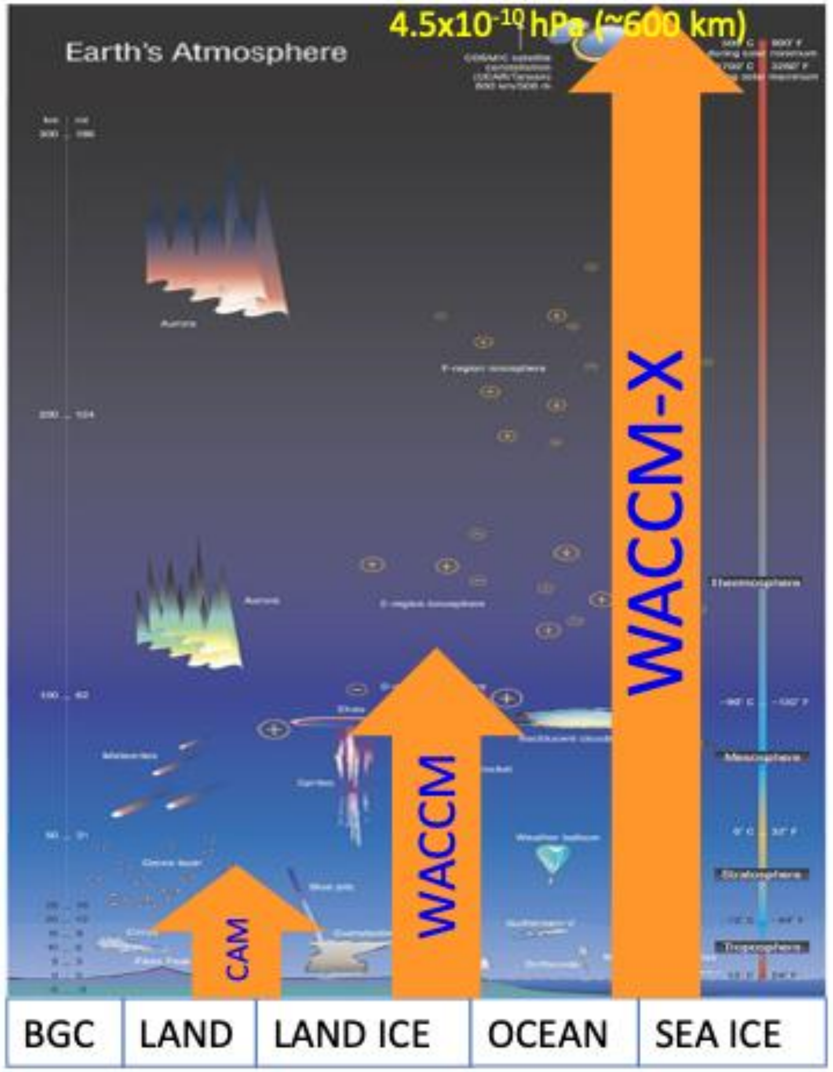
(NOAA, NSF NCAR)

CESM has a large community of developers and users, including large simulation datasets and support for community users

- CESM is based on over 30 years of model development
- A true community model with external developers and support for users
- Community participation through working groups (2000+ researchers)
- Widely used, e.g., 400+ talks using CESM at AGU 2024
- 2.8 million lines of Fortran code, > 1000 geophysical variables
- Available on github: https://github.com/NCAR/cesm

WACCM-X is built upon the underlying CESM infrastructure and the CESM atmospheric models

- WACCM-X leverages the capabilities and developments in the lower-middle atmosphere that are part of the Community Atmosphere Model (CAM) and Whole Atmosphere Community Climate Model (WACCM)
- Detailed treatment of troposphere, stratosphere, and mesosphere processes, including detailed chemistry, are included in WACCM-X
- Dynamical core and physics developments and improvements can be adopted by WACCM-X
- Designed for climate, not necessarily weather timescales



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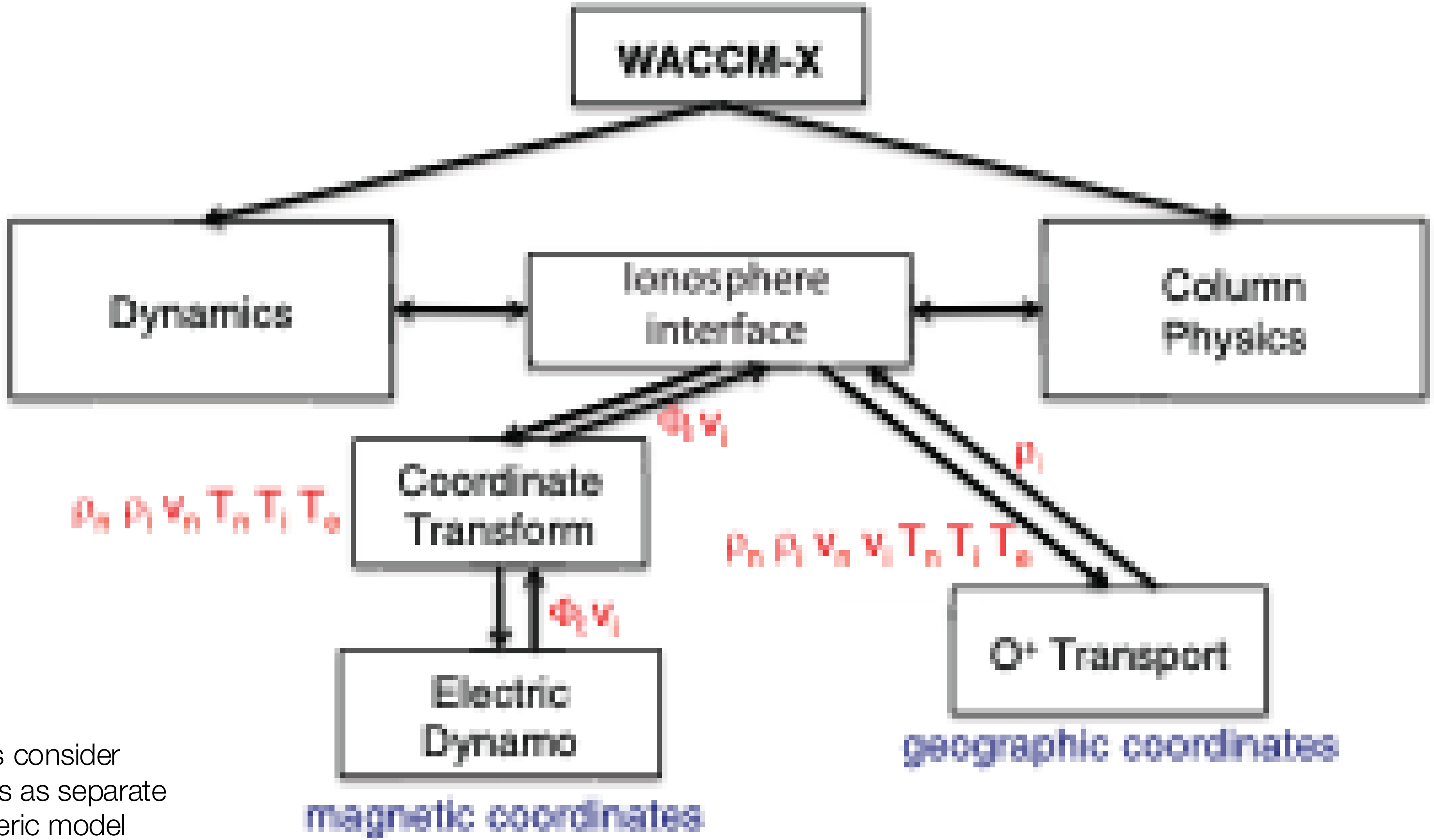
Major CESM WACCM/WACCM-X Components

Model Framework	Chemistry	Neutral Atm. Physics	Ionosphere Physics	Resolution
Atmosphere component of NCAR CESM Extension of the NCAR Community Atmosphere Model (CAM) Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m)	MA/Ion Chemistry (~100 species) Fully-interactive with dynamics	Long wave/short wave/EUV RRTMG IR cooling (LTE/non-LTE) Modal Aerosol Model (MAM) CARMA Convection, precip., and cloud parameterization (CLUBB) Parameterized GW Major/minor species diffusion (+UBC) Horizontal/Vertical molecular viscosity and thermal conductivity (+UBC) Species dependent Cp, R, and m	Parameterized electric field at high latitudes. IGRF geomagnetic field Auroral processes, ion drag and Joule heating Ion/electron energy equations Ambipolar diffusion Ionospheric dynamo Coupling with plasmasphere/magnetosphere	Horizontal (lat x lon): 1.9 x 2.5 0.9 x 1.25 0.47 x 0.625 Vertical: 130, 145 levels (0 - ~600 km)

Key WACCM-X Capabilities

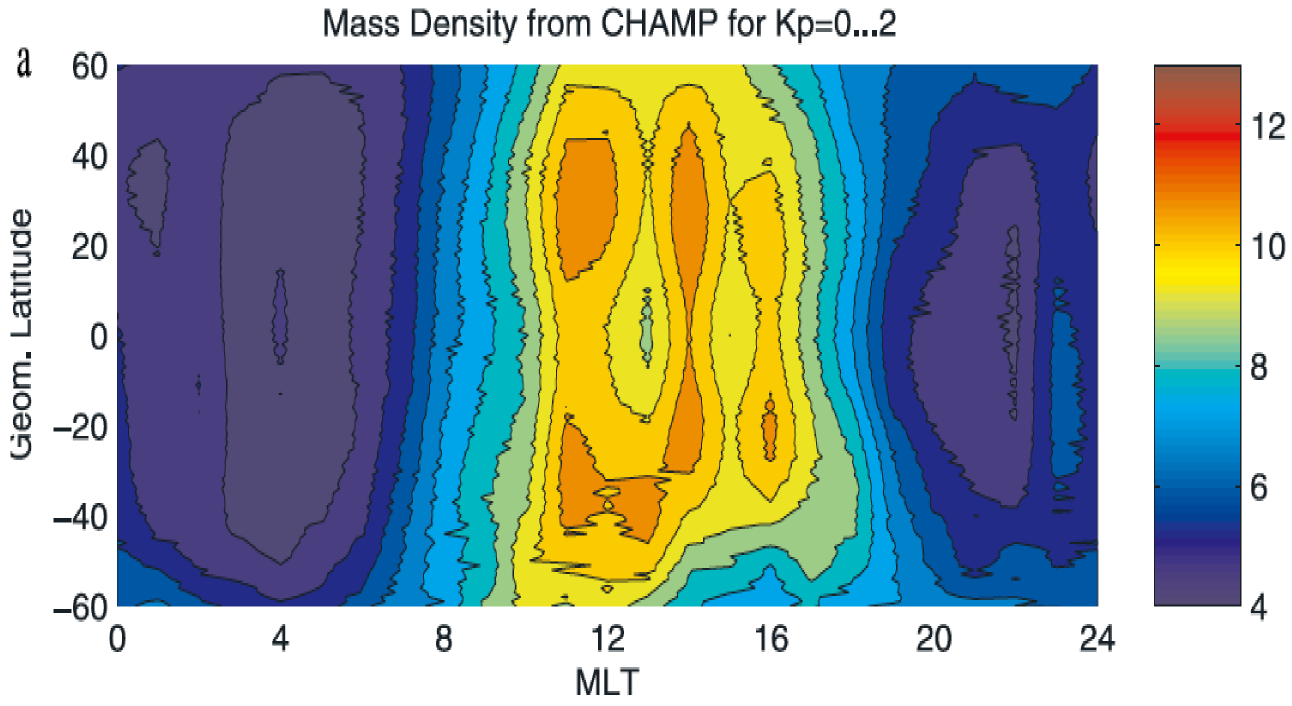
- Fully interactive chemistry, including ion chemistry
- Ionospheric electrodynamics using fully interactive dynamo
- Ion transport in the F-region
- Solar inputs from F107/EUVAC or FISM for solar flares
- Magnetospheric inputs using empirical (Heelis/Weimer) or specifications (AMIE, GAMERA)
- Coupling with SAMI3 plasmasphere model (NRL/Syntek Tech.)
- Specified dynamics to constrain meteorology up to ~50 km
- Whole atmosphere data assimilation for specification and forecast using DART (Data Assimilation Research Testbed)

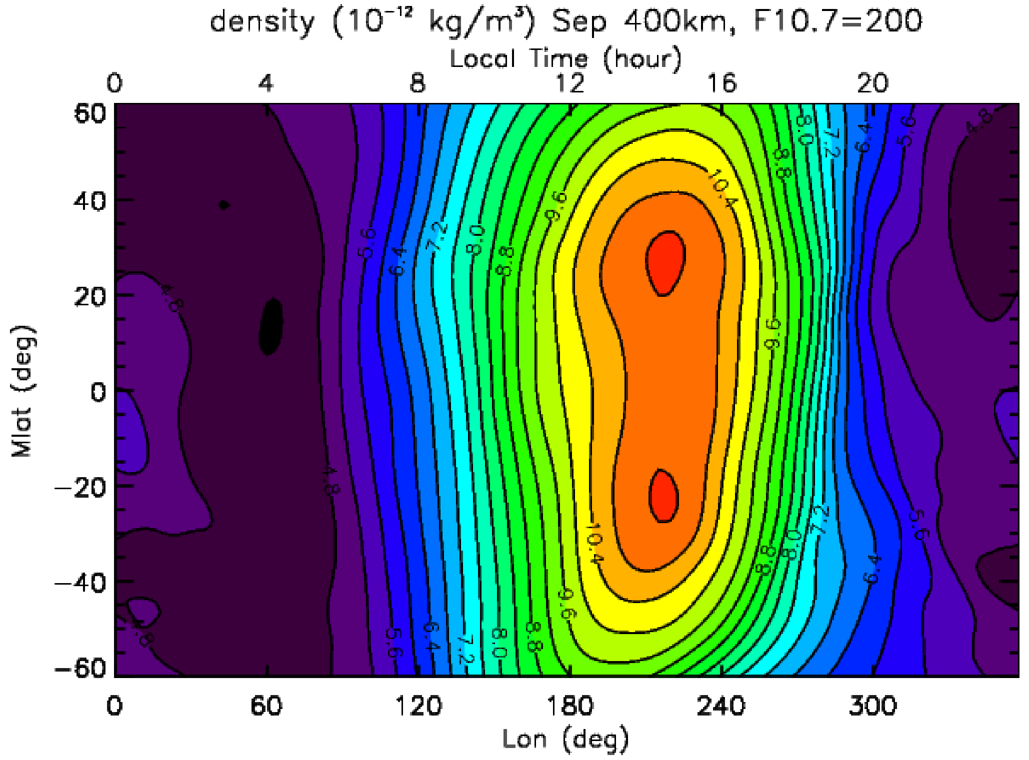
WACCM-X integrates the model dynamics and physics through an ionospheric module that enables electrodynamics and O^+ transport



Note: Climate models consider dynamics and physics as separate parts of the atmospheric model

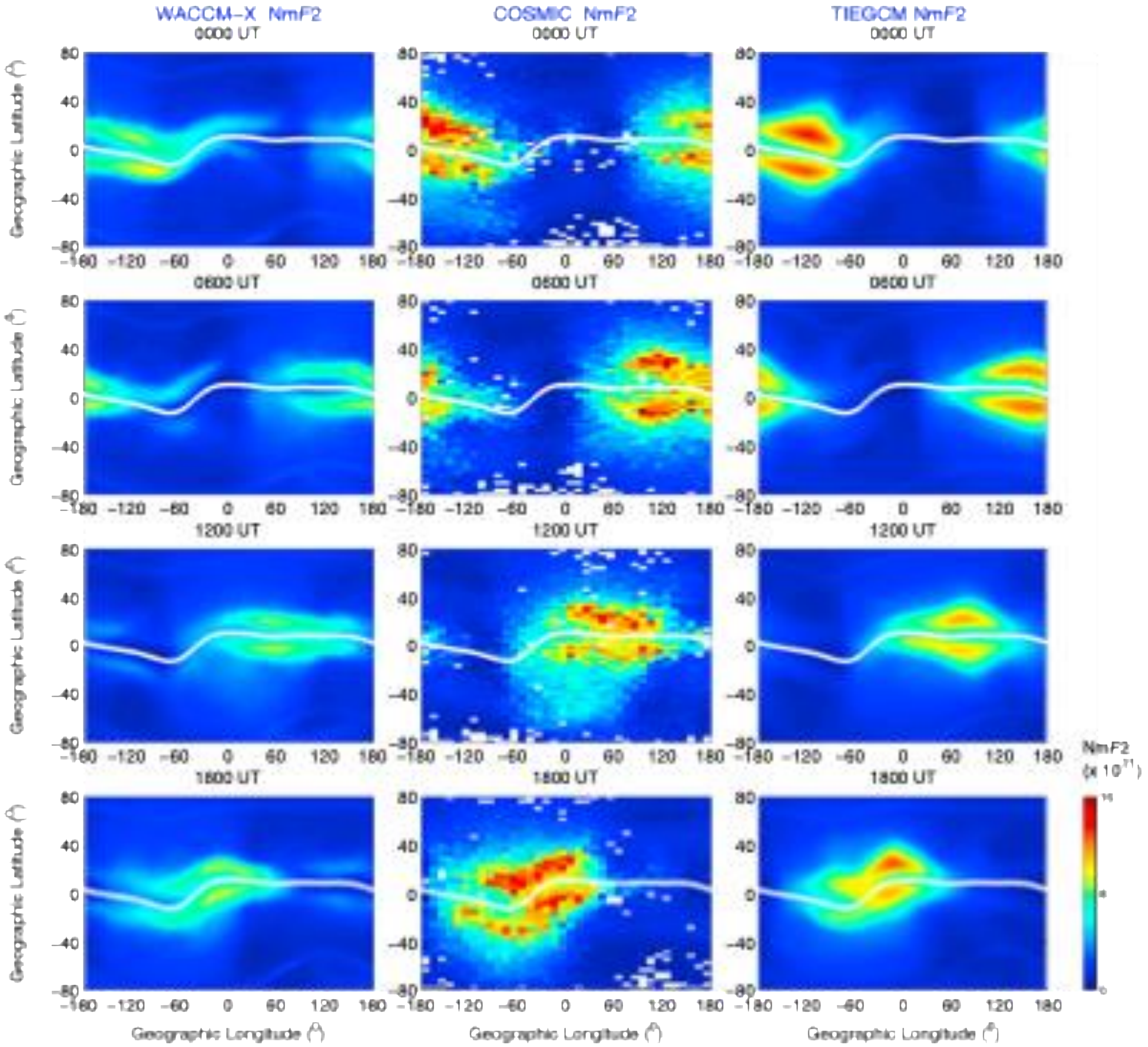
WACCM-X simulated thermosphere mass density is in general agreement with CHAMP satellite observations





(H. Liu et al., 2005; H.-L. Liu et al., 2018)

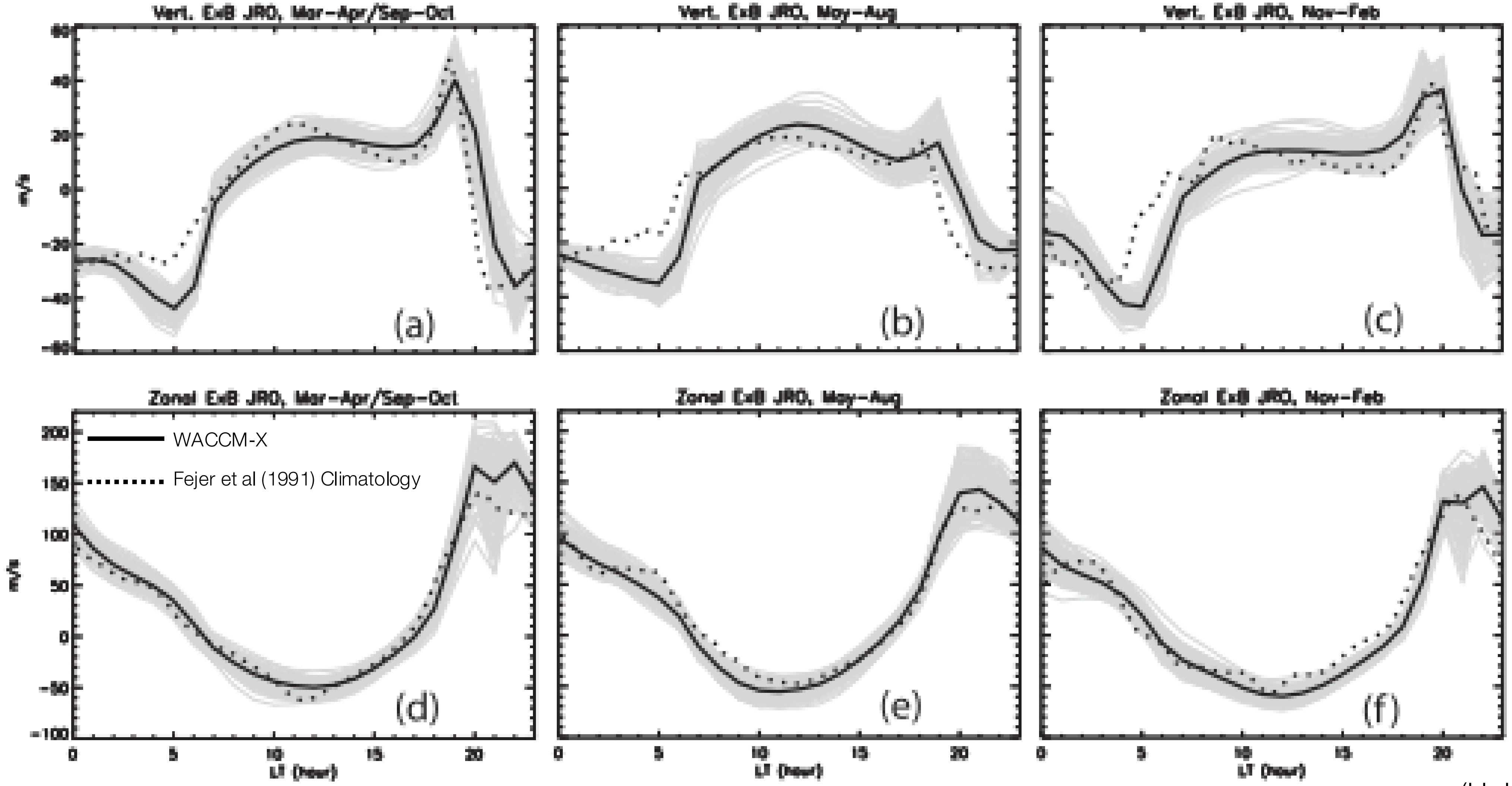
Morphology of electron density climatology is consistent with observations and TIEGCM



*Underestimation of NmF2 due to excessive GW diffusion WACCM-X v2.0 is largely fixed in v2.1

(J. Liu et al., 2018)

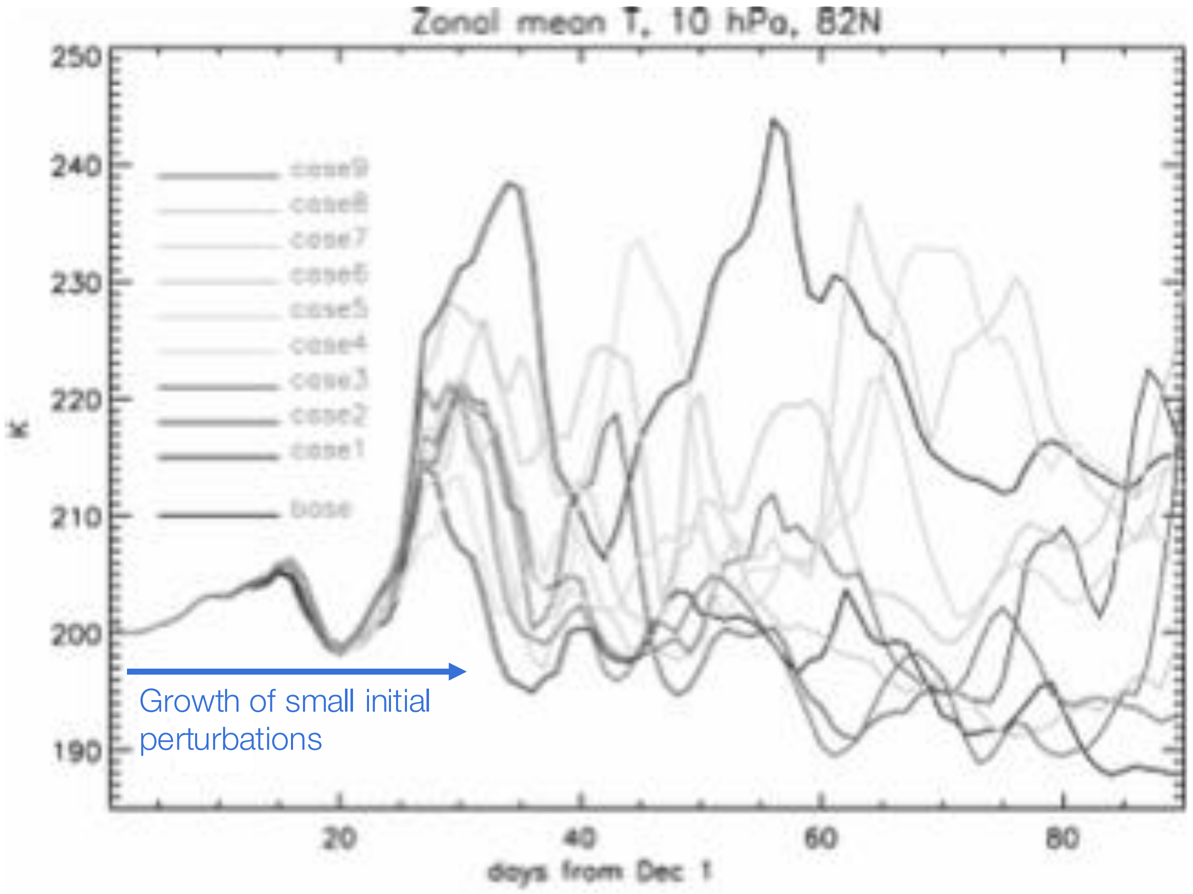
Simulated equatorial vertical drifts in WACCM-X generally agree with climatology and exhibit day-to-day variability due to lower atmosphere variability



(H.-L. Liu et al., 2018)

Lower atmosphere: Free-run versus Specified Dynamics

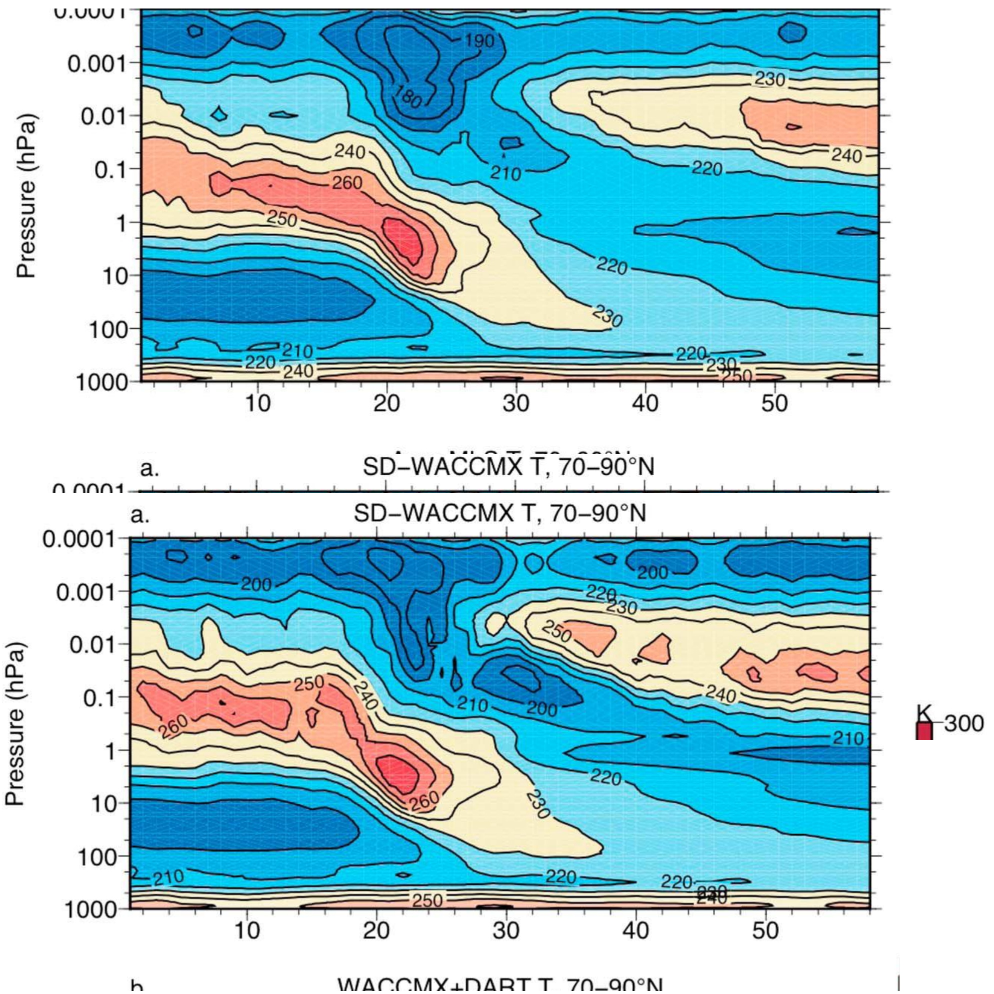
- WACCM-X can be configured as either a free-run or with specified dynamics
- Free-run simulations are unconstrained, and the model generates its own “weather” that is representative of climatological behavior
- Free-running simulations are useful for studying general behavior of the system, long-term simulations and/or time periods when reanalyses are unavailable
- Because of internal model variability, ensemble simulations are often required



(Liu et al., 2009)

Lower atmosphere: Free-run versus Specified Dynamics

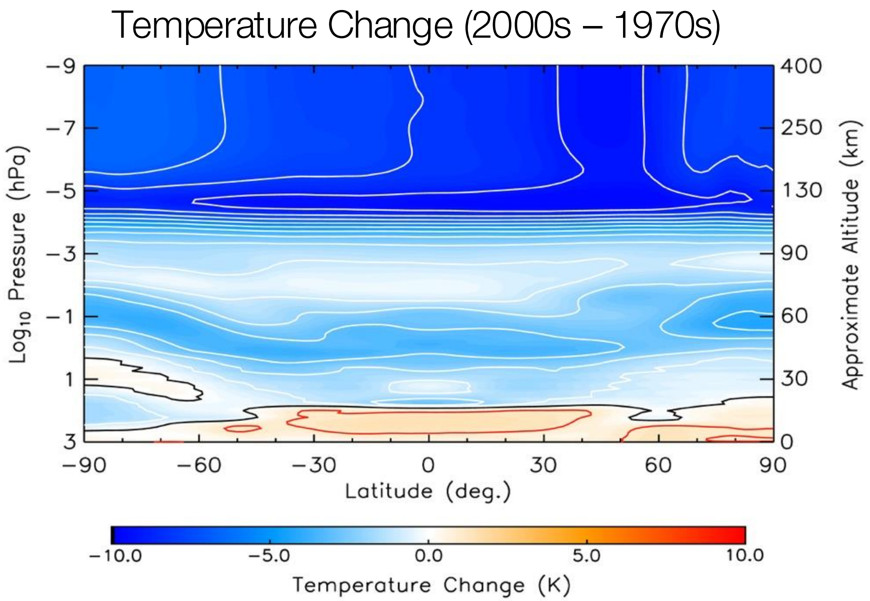
- WACCM-X can be configured as either a free-run or with specified dynamics
- Specified Dynamics (SD) simulations constrain the model meteorology to external fields. $X_{model} = \alpha(X_{met} - X_{model})$
- Default SD configuration is to nudge the model fields to MERRA-2 reanalysis up to ~50 km
- Assumption is that middle-upper atmosphere variability is controlled by dynamics in the troposphere-stratosphere
- Useful for simulating specific time periods and/or comparing to observations

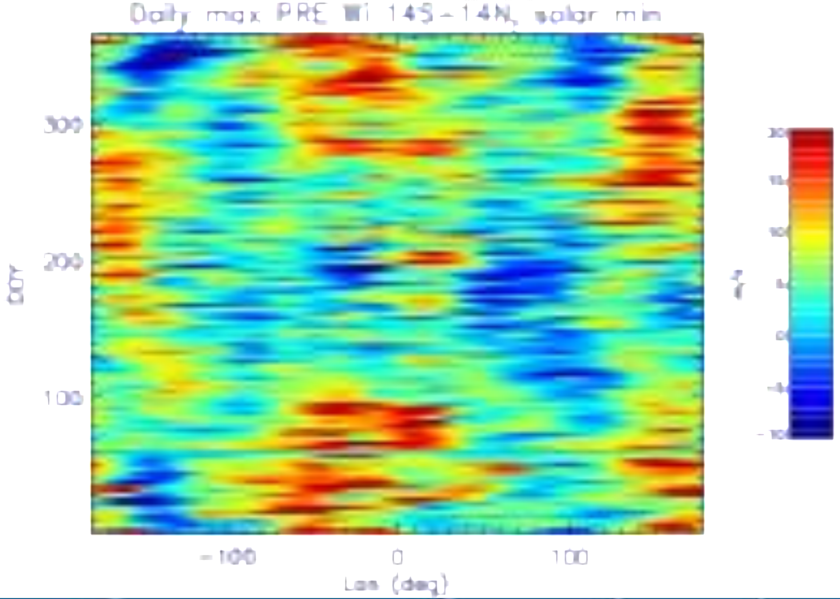


(Pedatella et al., 2018)

Example science use cases of WACCM-X

- Day-to-day variability in the ionosphere and thermosphere
- Long-term trends (historical and projection)
- Sudden stratospheric warmings: dynamics, chemistry, and ionospheric effects
- Effects of gravity waves, tides, and planetary waves on the circulation and chemistry of the MLT
- Geomagnetic storms
- …





(Liu et al., 2018; Solomon et al., 2018)

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From CESM2 to CESM3

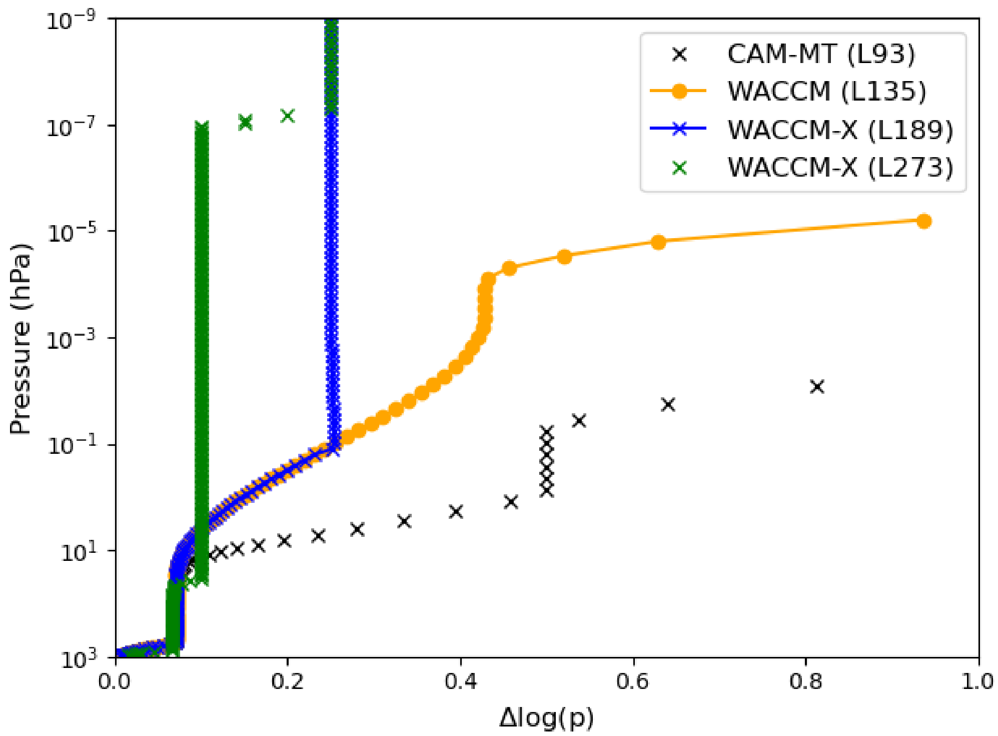
- CESM2 was released in 2018 and included the initial release of WACCM-X
- Subsequent CESM2.x model releases include developmental (i.e., not scientifically supported) updates and bug fixes
- NSF NCAR intends to release CESM3 in the near future
- CESM3 will include many new features, including a new dynamical core and significant updates to the atmospheric physics and chemistry (CAM7/WACCM7/WACCM7-X)

Major CESM WACCM/WACCM-X Components

Model Framework	Chemistry	Neutral Atm. Physics	Ionosphere Physics	Resolution
Atmosphere component of NCAR CESM Extension of the NCAR Community Atmosphere Model (CAM) Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m) Species dependent spectral element (SE) dynamical core Regridding scheme MPAS-A CESM2 WACCM-X CESM3 WACCM-X WACCM Development	MA/Ion Chemistry (~100 species) Fully-interactive with dynamics	Long wave/short wave/EUV RRTMG IR cooling (LTE/non-LTE) Modal Aerosol Model (MAM) CARMA Convection, precip., and cloud parameterization (CLUBB) Parameterized GW (+ MM parameterization) Major/minor species diffusion (+UBC) Horizontal/Vertical molecular viscosity and thermoal conductivity (+UBC) Species dependent Cp, R, and m	Parameterized electric field at high latitudes. IGRF geomagnetic field Auroral processes, ion drag and Joule heating Ion/electron energy equations Ambipolar diffusion Ionospheric dynamo Coupling with plasmasphere/magnetosphere	Horizontal (lat x lon): 1.9 x 2.5 0.9 x 1.25 0.47 x 0.625 NE16, 30, 60, 120 120 km Vertical: 70, 135 levels (0 – 140 km) 130, 145 levels (0 - ~600 km) 130, 189, 273 (0 - ~600 km)

WACCM & WACCM-X for CESM3

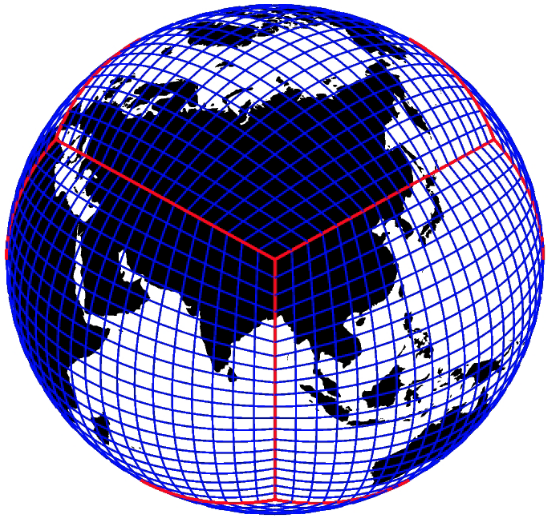
	Dyn. Core	Resolution	# levels	Chemistry	Physics
WACCM6	FV	1°, 2°	70 (110)	TSMLT, MA	CAM6
WACCM7	SE	ne30, ne16	135	t1ma, t4ma	CAM7
WACCM-X 2.1	FV	1°, 2°	130	TSMLT, MA, IT chemistry	CAM6
WACCM-X v?	SE	ne30, ne16 (ne120)	189 (273)	t1ma, t4ma IT chemistry	CAM7



Priority development objectives:
- Good QBO at both 1° and 2° resolutions
- Seasonal cycle of winds/temperatures in the stratosphere-mesosphere and the impact on chemistry
- Thermosphere extension of SE dycore, ionosphere-thermosphere climatology

Extension of Spectral Element (SE) dynamical core into the thermosphere

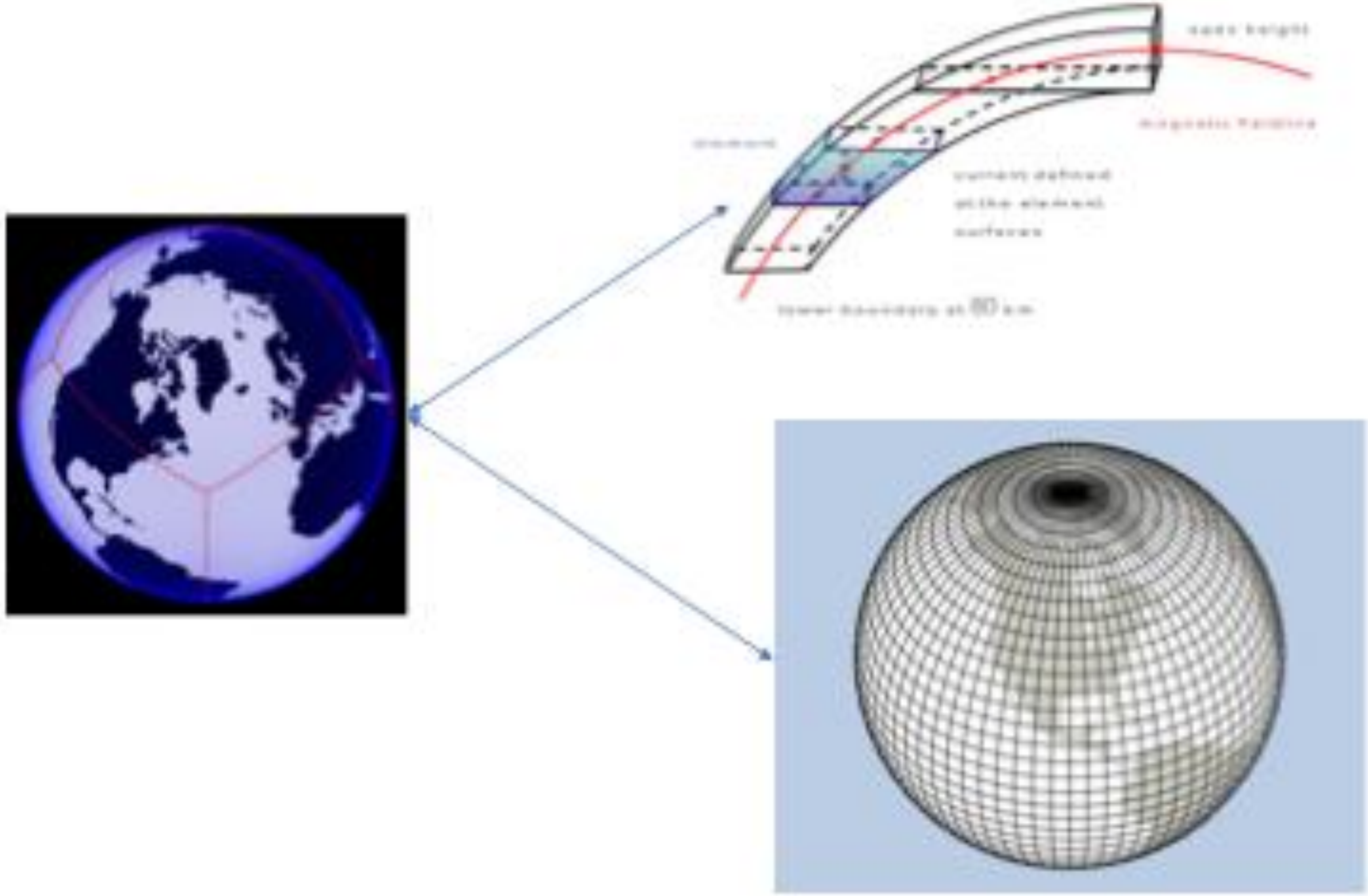
- Spectral Element (SE) dynamical core will be used by future versions of CESM atmosphere models (CAM, WACCM, WACCM-X)
- Cubed sphere grid that eliminates polar singularity
- Capability for high-resolution and nested grids
- SE dynamical core has been extended into the thermosphere: species dependence; horizontal molecular viscosity/diffusion



New regridding scheme for mapping between regular/irregular grids

- Earth System Modeling Framework (ESMF) based regridding scheme maps fields between physics mesh and regular/irregular grids

- Independent of dynamical core grid

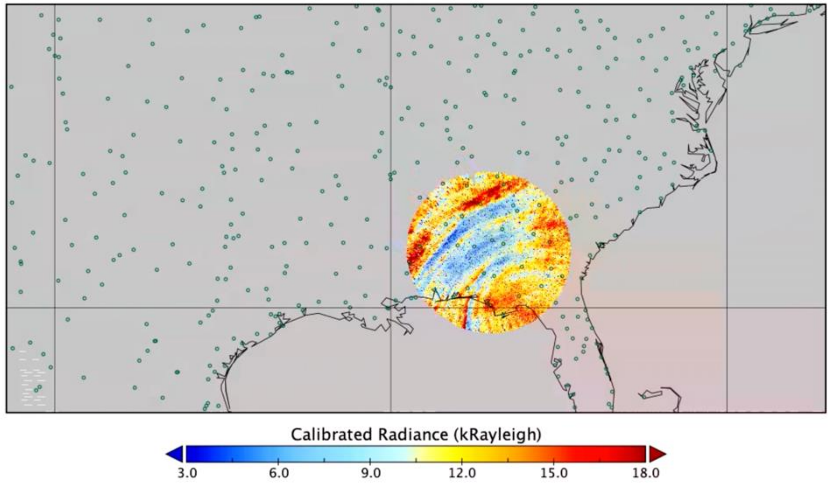


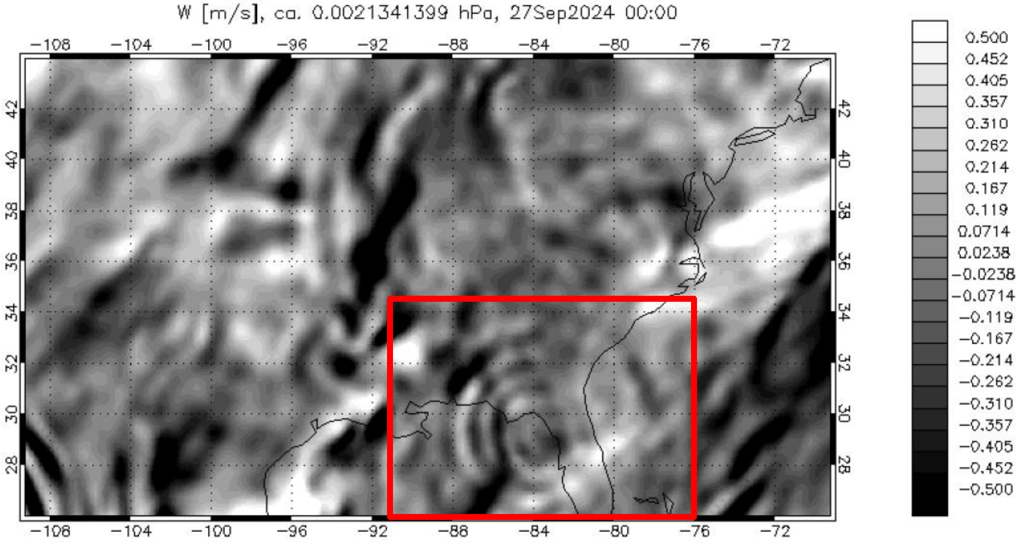
Implementation of meteorological constraint for high-resolution (ne120, ~0.25°) WACCM-X

- Recently implemented physics-side nudging for high-resolution WACCM-X simulations
- Enables simulations of the day-to-day variability of small-scale waves, and their impacts, on the middle and upper atmosphere
- Capability enables new scientific studies and is used to support current and future satellite missions

Gravity Waves from Hurricane Helene

NASA AWE Observation 02:49 UT, Sept 27, 2024 (~87 km)





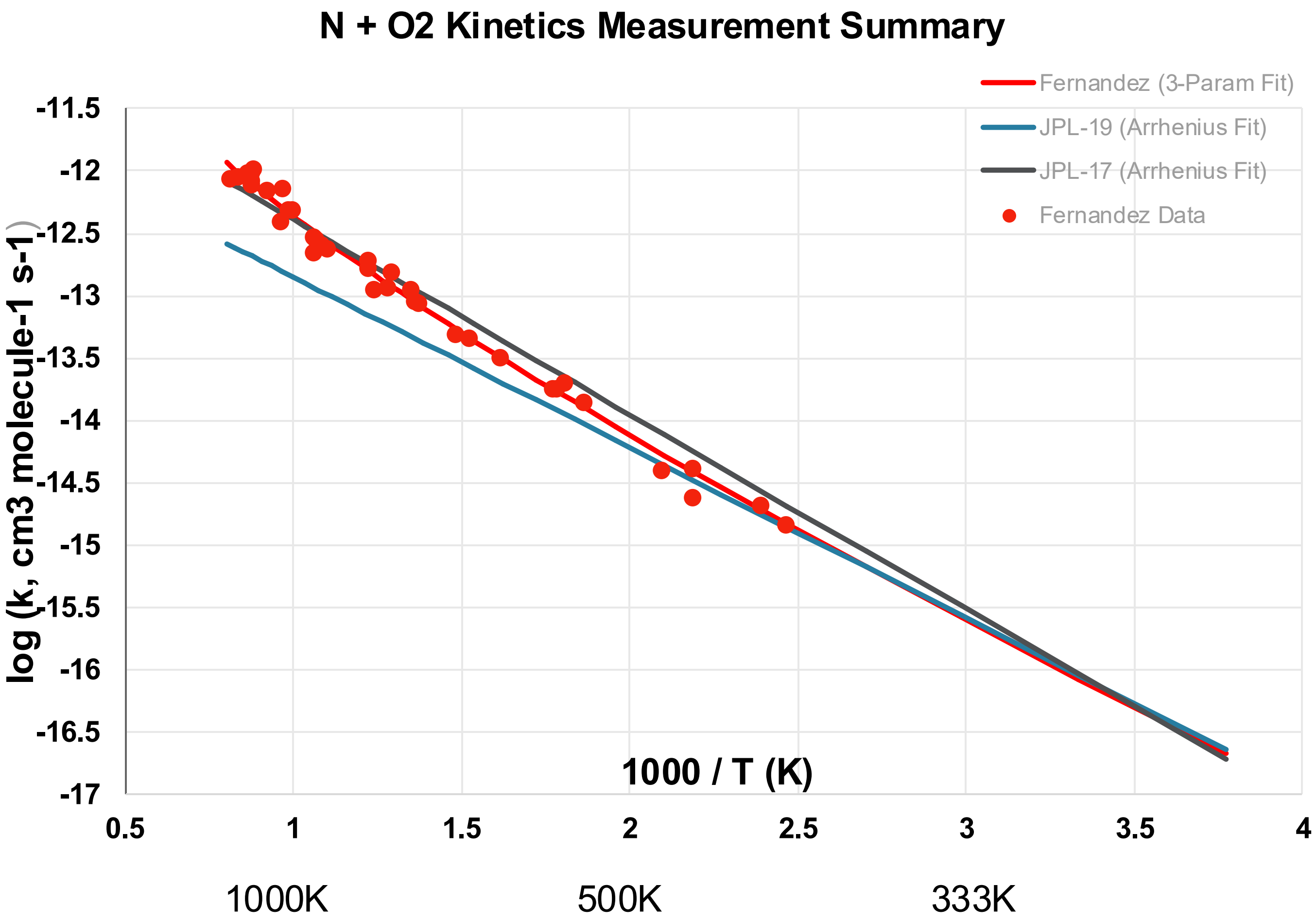
Credit: Hanli Liu (HAO), Jiarong Zhang (USU)

Chemistry Updates for the Mesosphere and Thermosphere

	Reaction	Original Rate Constant (A, Ea/R)	Updated	Comment
Updated rates	$N(^4S) + O_2$ -> NO + O	JPL-19 3.3e-12, 3150	3-parameter fit, Next slide	Fernandez et al., 1998
	$N(^2D) + O_2$ -> $NO + O(^1D)$	5e-12	K=6.2e-12 (T/300.)	Duff et al., 2003
New reactions	$N(^2D) + NO$ -> $N_2 + O(^1D)$	NA	K = 7.3e-11	Roble, 1995
	$N(^2D)$ -> $N(^4S)$ + hv	NA	K = 1.06e-5	Roble, 1995
	$N(^2D)$ + e -> $N(^4S)$ + e + 2.38 eV	NA	K = 3.6e-10_r8 * $(Te/300.0\_r8)^{1/2}$	Roble, 1995

Credit: Doug Kinnison, Jun Zhang (ACOM)

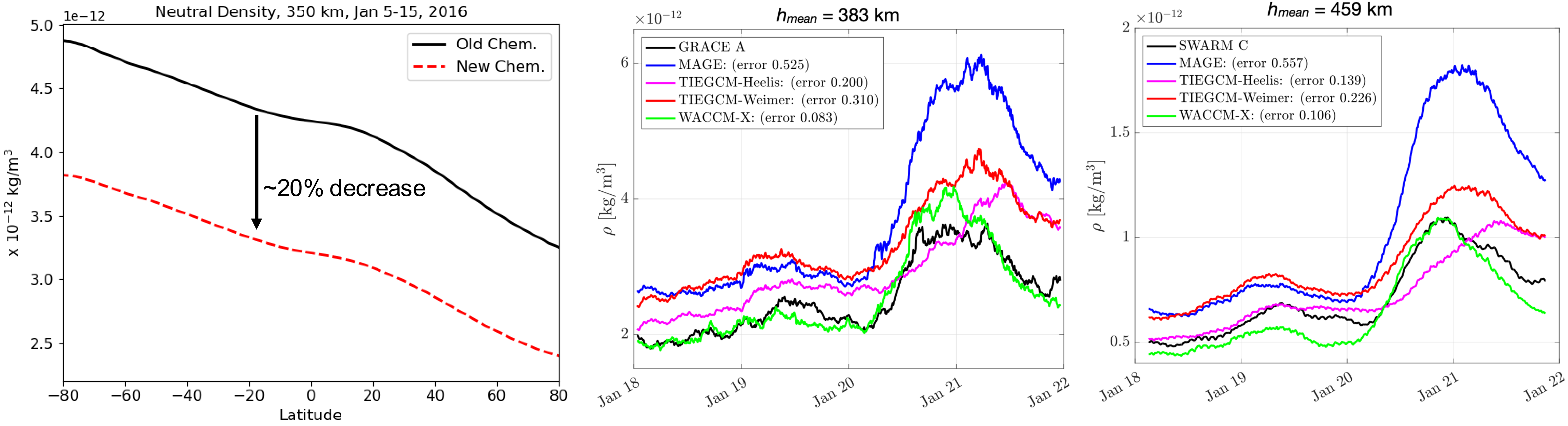
Updated N + O_2 Reaction Rate



- Decrease in reaction rate from JPL-17 (CESM2) to JPL-19 leads to less NO production at high temperatures
- NO cools the thermosphere, so less NO leads to larger temperatures and neutral densities

Credit: Doug Kinnison, Jun Zhang (ACOM)

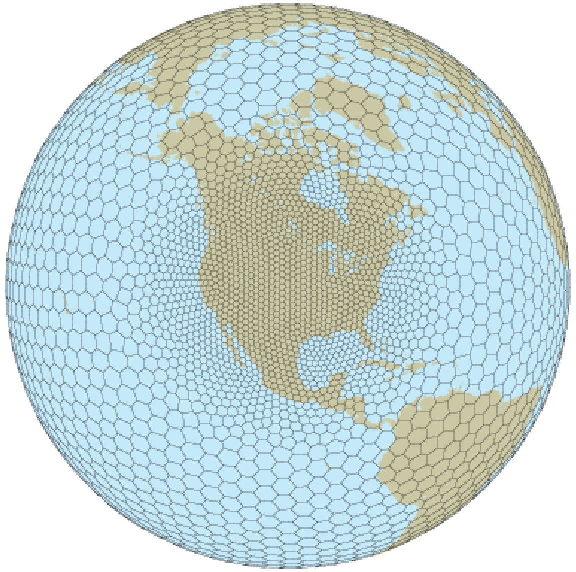
WACCM-X simulated neutral densities with updated reaction rates show good agreement with observations

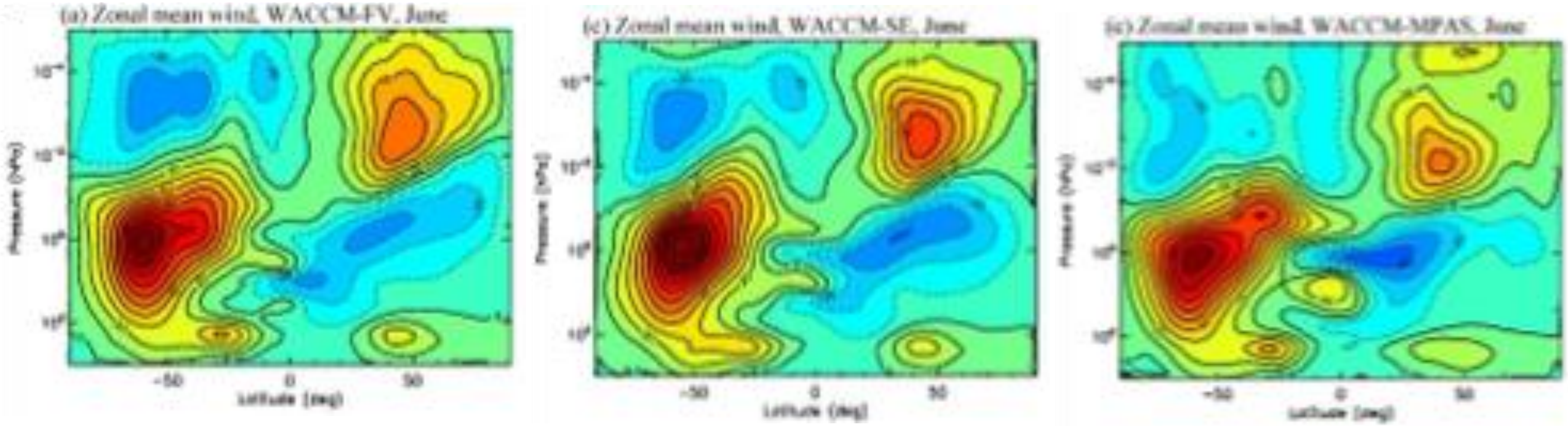


Credit: Jordi Vila Perez (HAO)

Model for Prediction Across Scales (MPAS) dynamical core

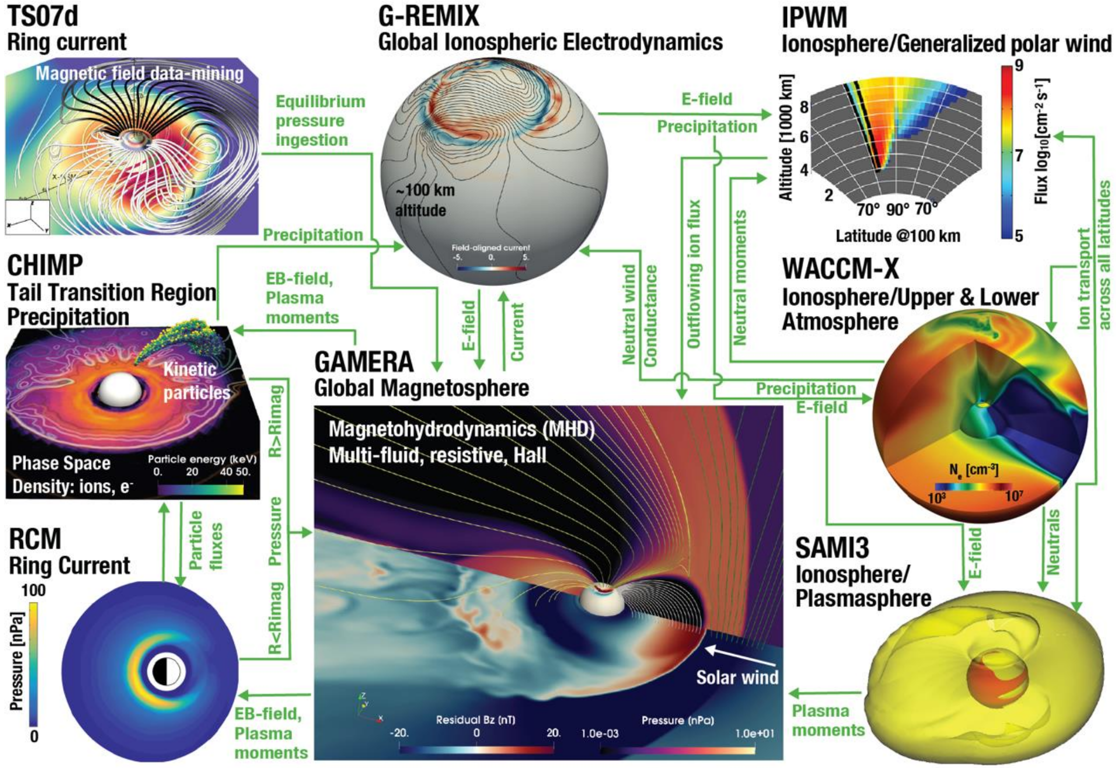
- MPAS-A is a non-hydrostatic dynamical core solved on centroidal Voronoi mesh
- MPAS has been extended into the lower thermosphere (Kamali et al., 2024)
- Further developing the MPAS dynamical core for future use as the dynamical core in WACCM-X





WACCM-X/GAMERA: Towards a whole geospace model

Model Framework for CGS MAGE



NASA Center for Geospace Storms (CGS) and HAO have recently completed ***two-way coupling*** between WACCM-X and the GAMERA magnetosphere model, paving the way for a whole geospace model

MAGE: Multiscale Atmosphere-Geospace Environment Model

Summary

- CESM/WACCM-X is an open source, community, model of the whole atmosphere-ionosphere coupled system
- CESM2 (WACCM-X v2.x) has significantly advanced scientific understanding of day-to-day variability, SSWs, wave-driven variability, long-term trends, …
- Release of CESM3 (WACCM7-X) will provide new modeling capabilities, including SE dynamical core that enables high-resolution simulations
- CESM is a community model and we welcome scientific and development collaborations

References