

Toward a Whole Geospace Model

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NCAR



Outline

1. Where we are with the Whole Atmosphere Community Climate Model — eXtended
(WACCM-X)
2. Where we are with the Coupled Magnetosphere Ionosphere Thermosphere model
(CMIT)
3. Development concept for a Whole Geospace Model
(WACCM-X + CMIT = Acronym TBD)

What is WACCM-X?

The Whole Atmosphere Community Climate Model - eXtended

WACCM-X is a model of the entire atmosphere that extends into the thermosphere to ~500 km altitude and includes the ionosphere.

WACCM-X is built on **WACCM**

WACCM is built on **CAM**

CAM is the NCAR *Community Atmosphere Model*

Which is a component of **CESM**

The *Community Earth System Model*

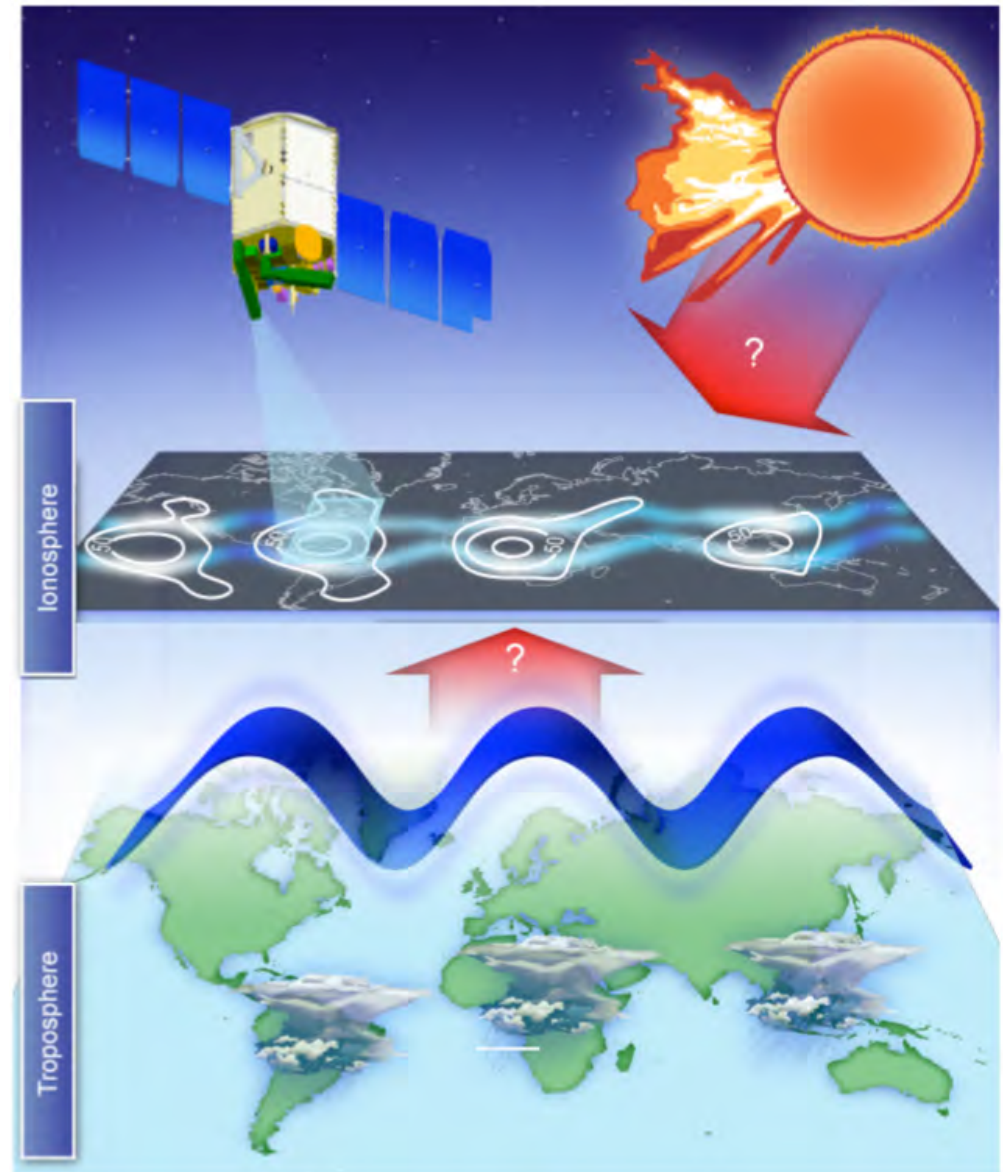
All of which is an open-source, publicly available resource for research

Why WACCM-X?

Because the thermosphere-ionosphere system responds to variability from the Earth's lower atmosphere as well as solar-driven space weather

Including:

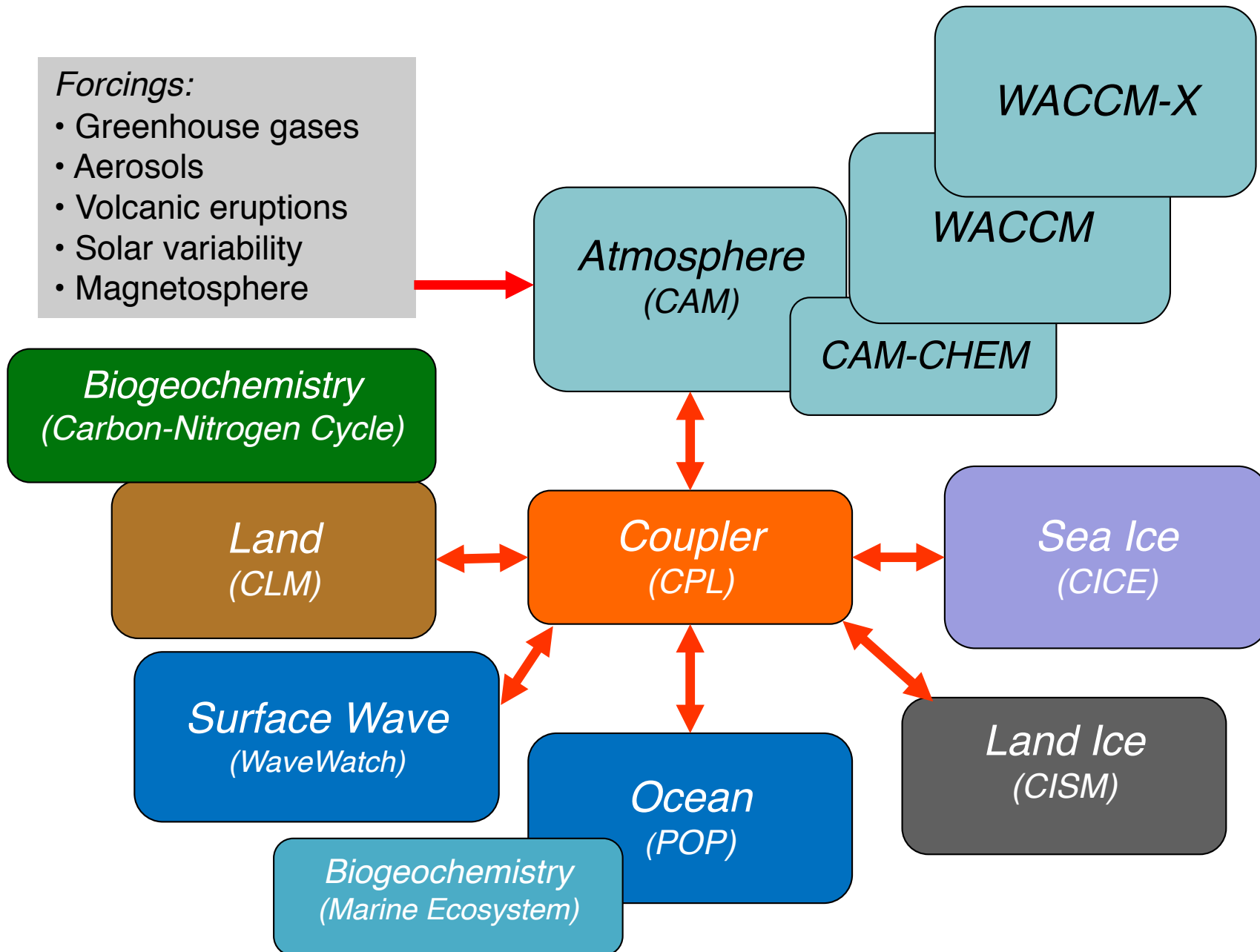
- Waves and tides
- Tropospheric weather
- Middle-atmosphere events
- Seasonal variations
- Anthropogenic trace gases



WACCM-X Objectives

- How do solar and geomagnetic influences affect the whole atmosphere?
- What are the interactions between lower atmosphere and solar/geomagnetic forcing on the ionosphere-thermosphere system?
- How do atmospheric waves affect the energy and momentum coupling between the lower atmosphere and the ionosphere-thermosphere?
- Can we improve specification and forecast atmospheric drag on satellites, and on hazards from orbital debris?
- What are the connections between large and small scale features in the system, e.g., ionospheric instabilities or “plasma bubbles”?

WACCM-X is Built on the Community Earth System Model (CESM)



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
- Magnetospheric inputs using empirical or data assimilation
- Ion transport in the *F*-region
- Coupling with plasmasphere model
- Whole atmosphere data assimilation

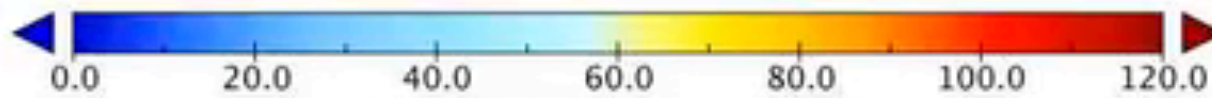
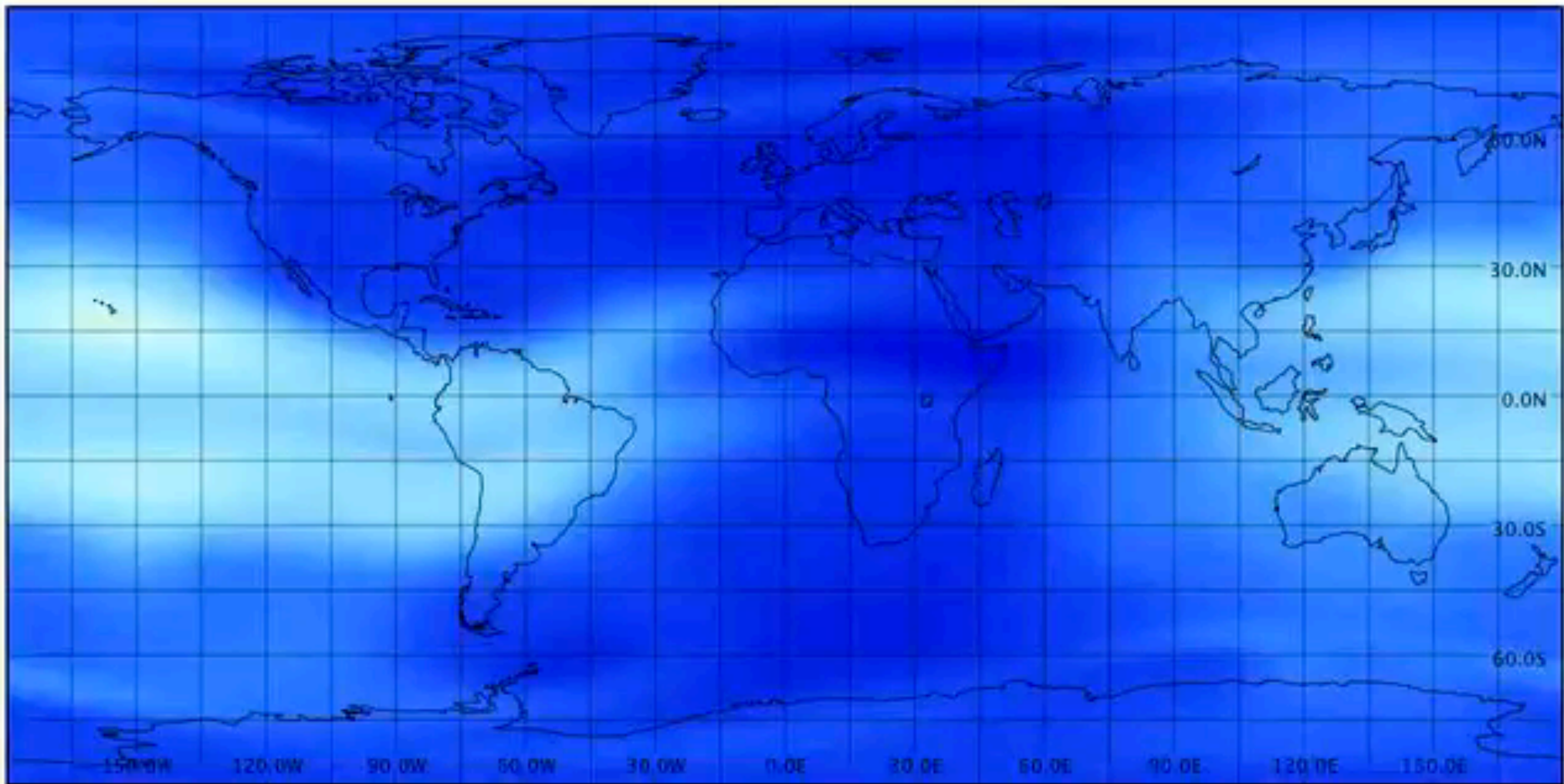
Recent Progress on WACCM-X

- Ion and electron energetics included:
 - Now calculating T_i and T_e in WACCM-X.
- Equatorial electrodynamico installed:
 - Mostly parallel, ESMF interpolation from geographic to geomagnetic coords.
- Ionospheric dynamics implemented:
 - Vertical diffusion and horizontal transport of O^+ in the upper ionosphere.
- Variable mean molecular mass and heat capacity (C_p) included in dynamical core
- Capability for using Assimilative Mapping of Ionospheric Electrodynamics (AMIE)
- Capability for data assimilation using DART
- WACCM-X v. 2.0 has been released as a component of CESM 2
 - Still based on “CAM 4” physics
 - Functional release, not fully scientifically validated

WACCM-X Ionosphere

Electron Column Density during a Major Geomagnetic Storm

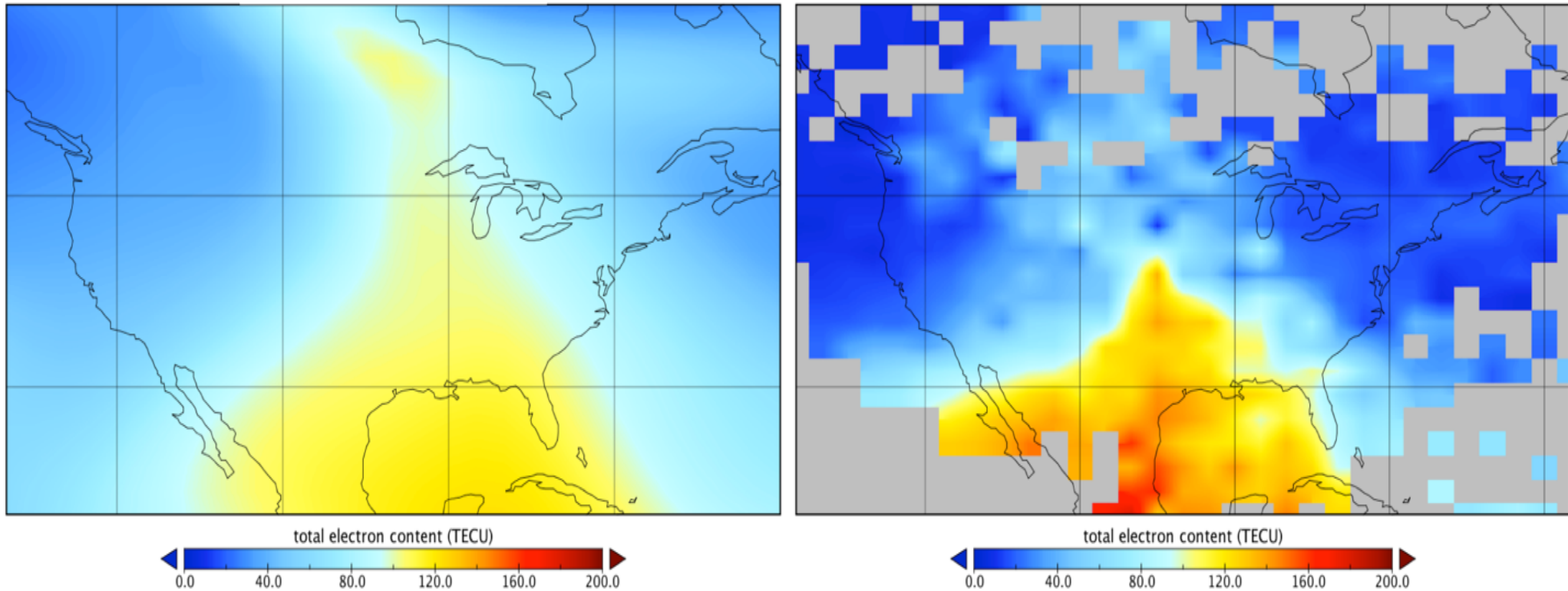
TEC, SD-WACCM-X, Hourly
Time: 2003-10-19 02:00



total electron content (TECU)

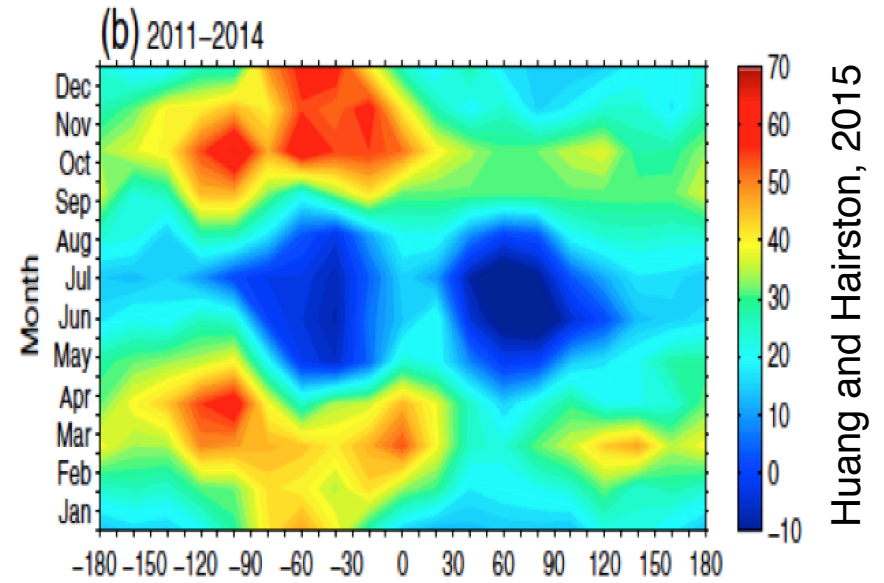
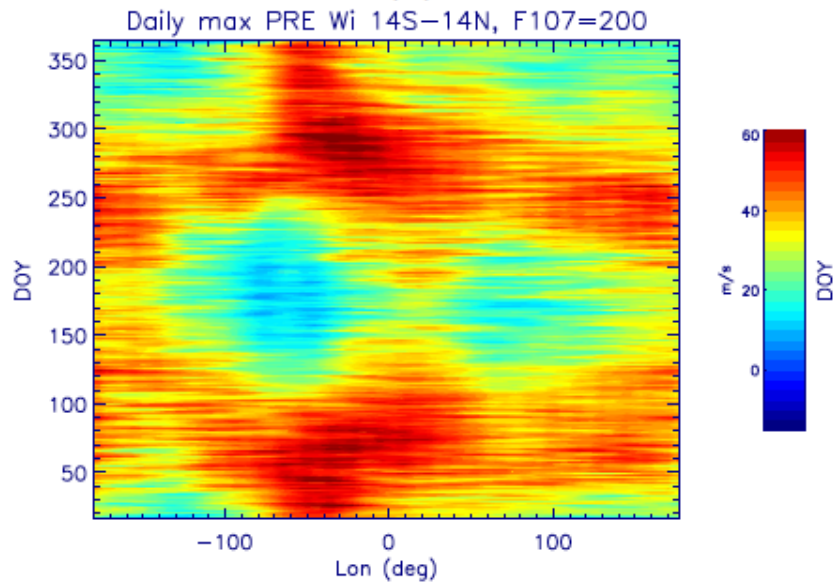
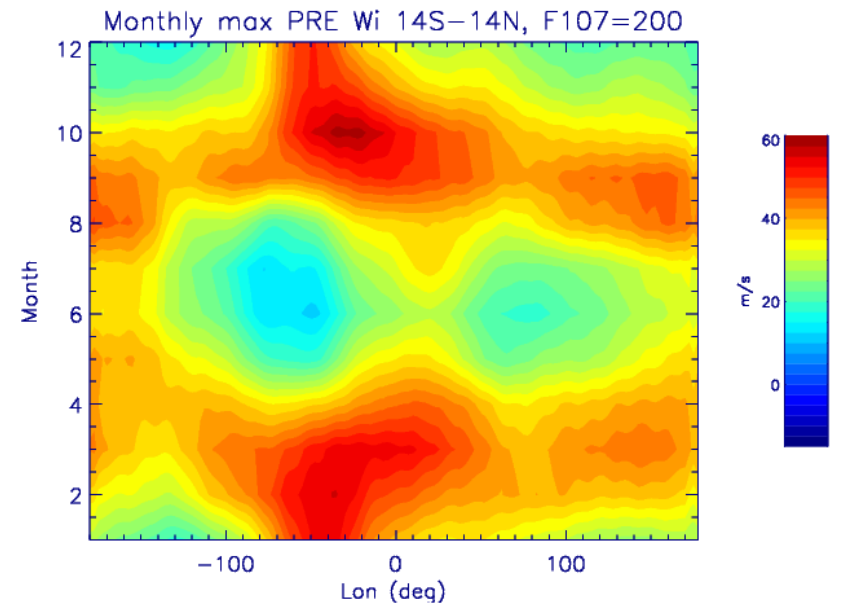
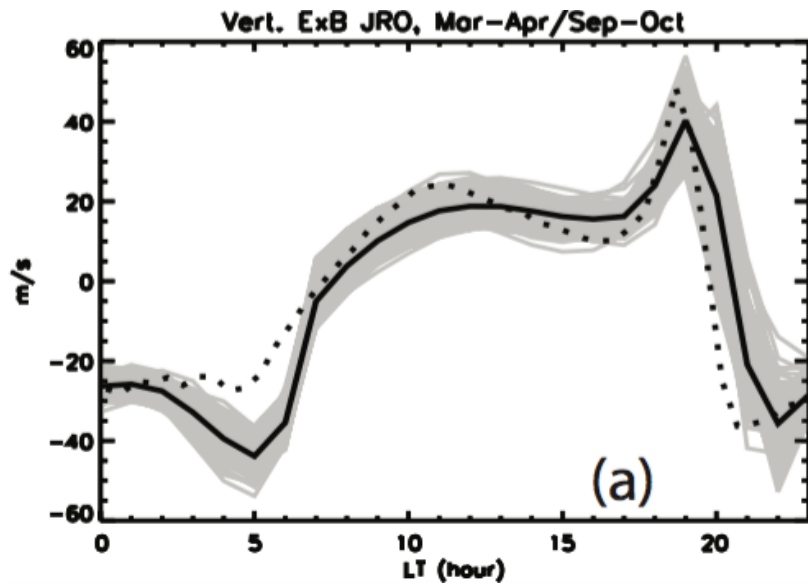
Data Min = 0.8, Max = 58.1, Mean = 15.6

Comparison with GPS Total Electron Content Measurements

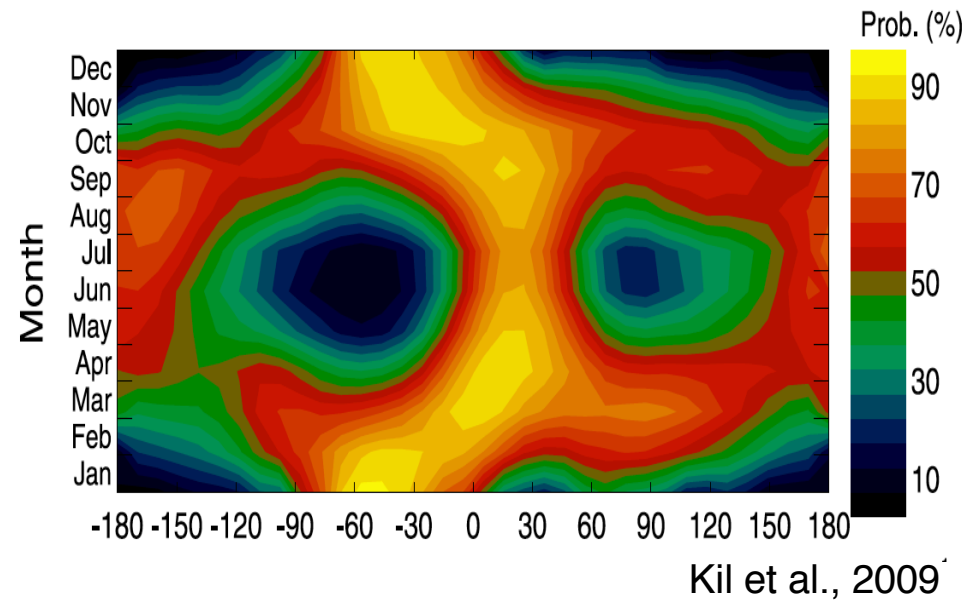
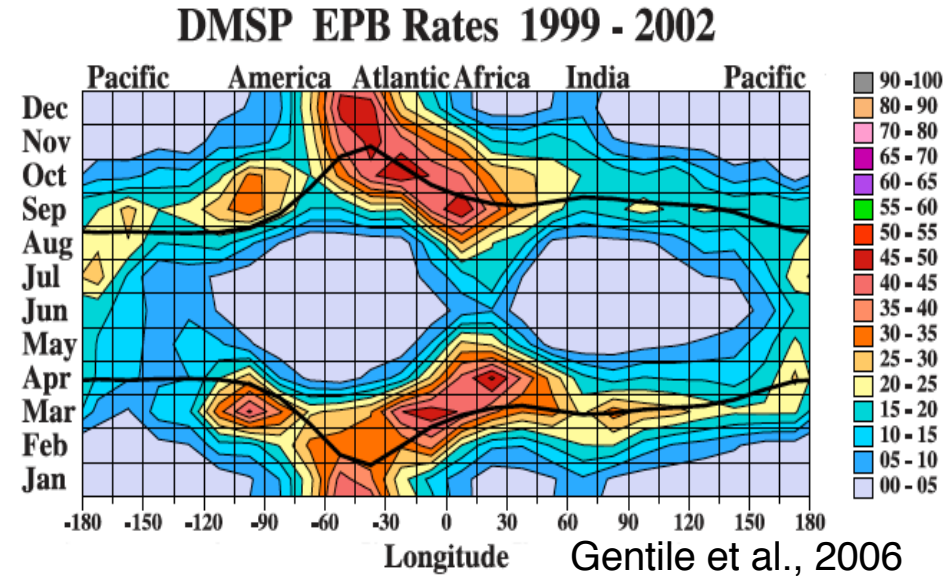
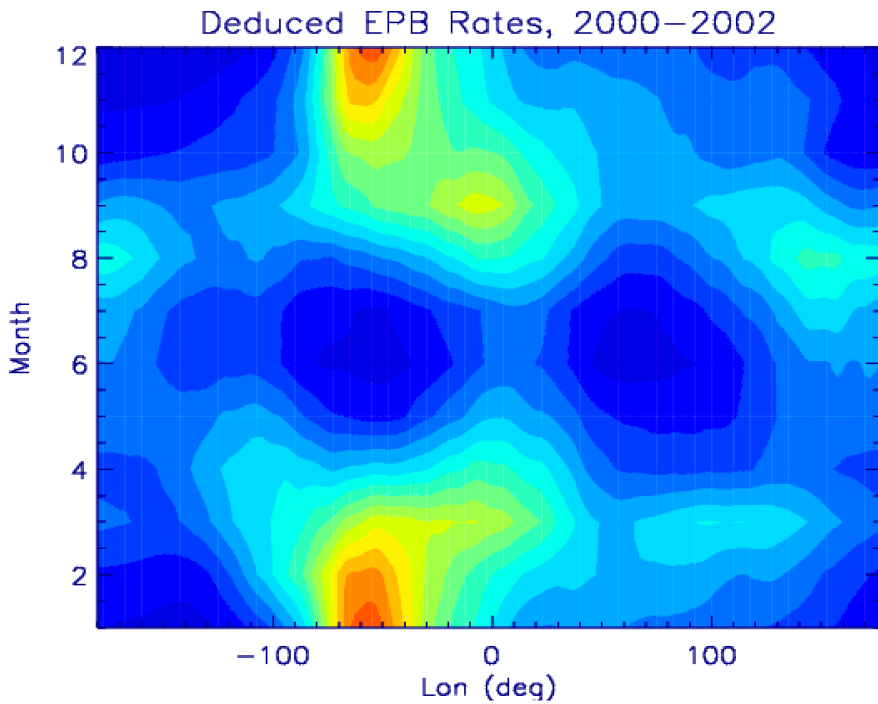


Comparison of a WACCM-X simulation (left) of verticalized total electron content (TEC) (in units of 10^{12} cm^{-2}) to ground-based GPS measurements (right), during the geomagnetic storm on 30 October 2003.

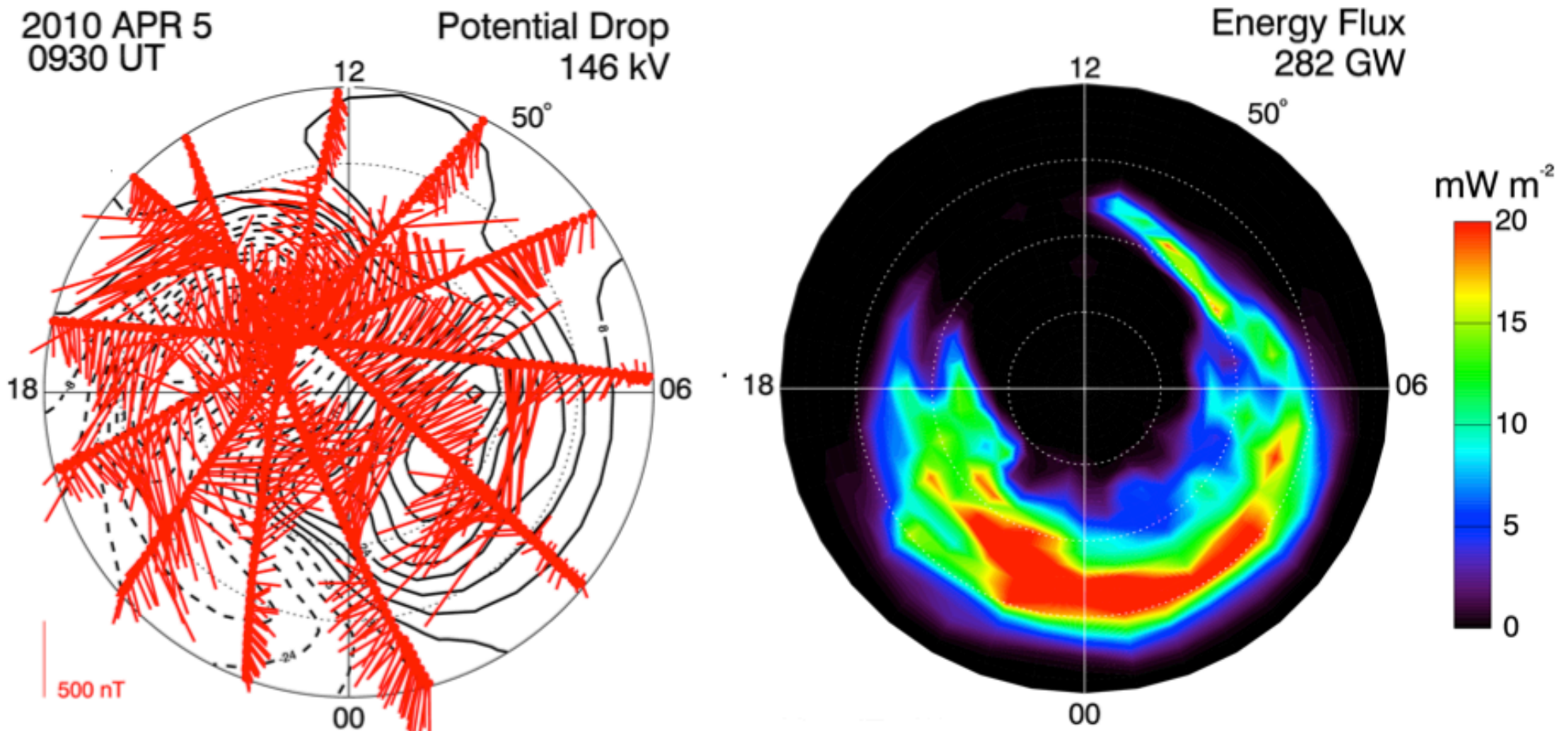
Daily Variability of Equatorial Electrodynamics



Occurrence Frequency of Equatorial Plasma Bubbles

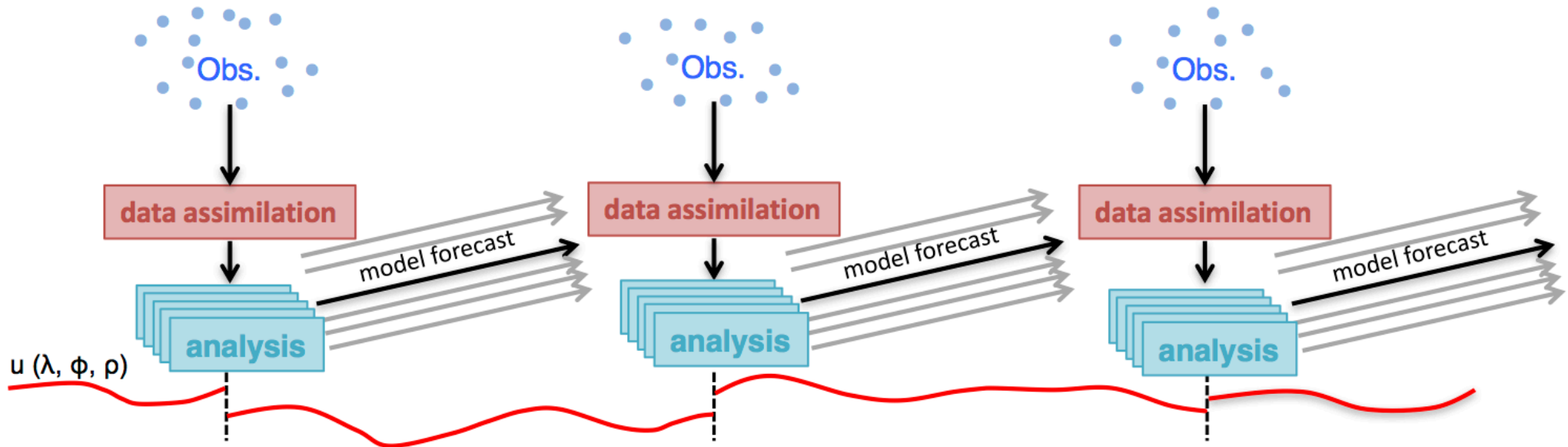


Using AMIE and AMPERE to Drive WACCM-X



Ionospheric convection pattern in black with overplots of AMPERE magnetometer data in red. Right: AMIE fitted auroral energy flux pattern derived from DMSP SSUSI and ground magnetometer data. All plots corresponds to the storm condition at 09:30 UT on 5 April 2010.

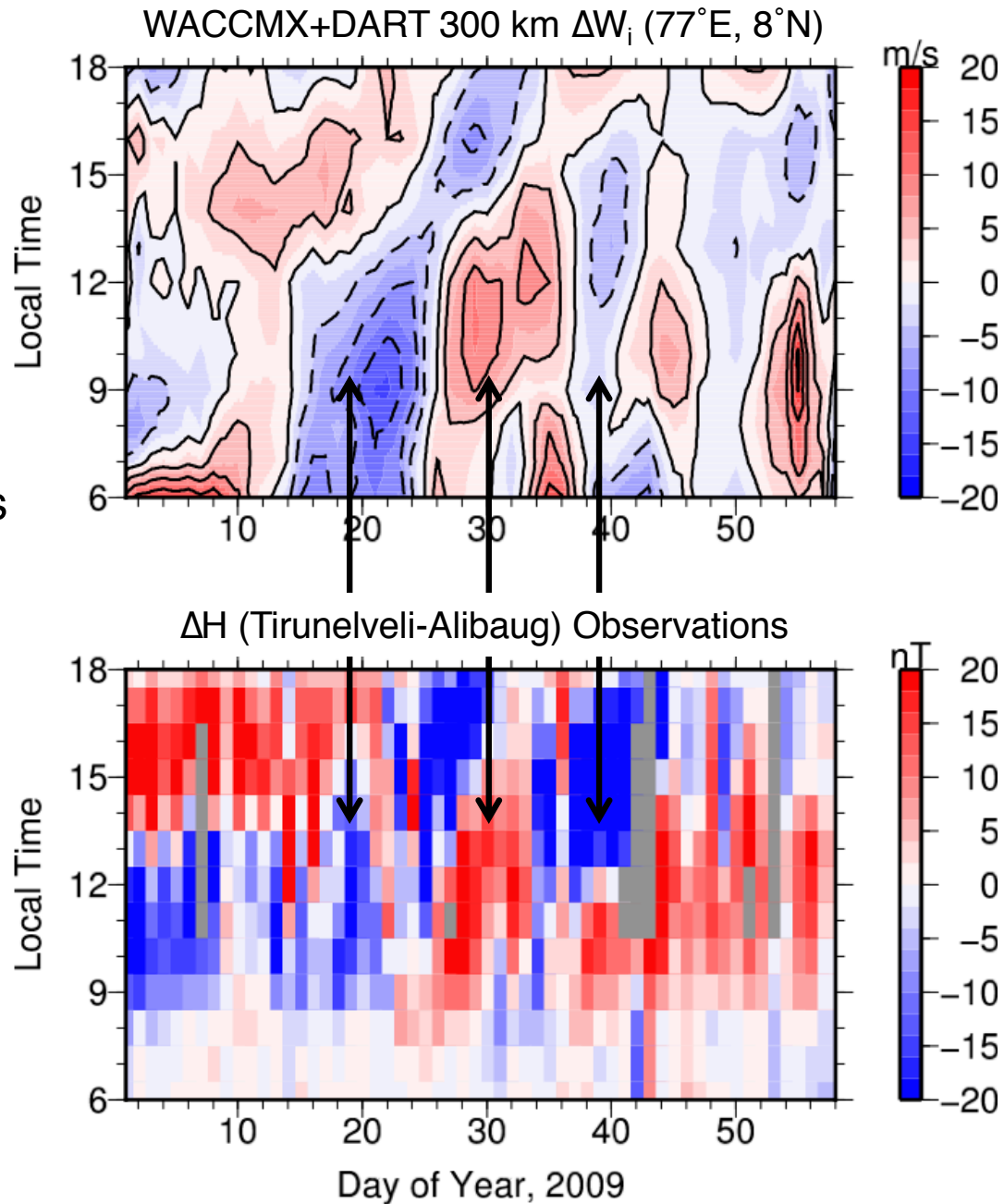
Data Assimilation in WACCM-X



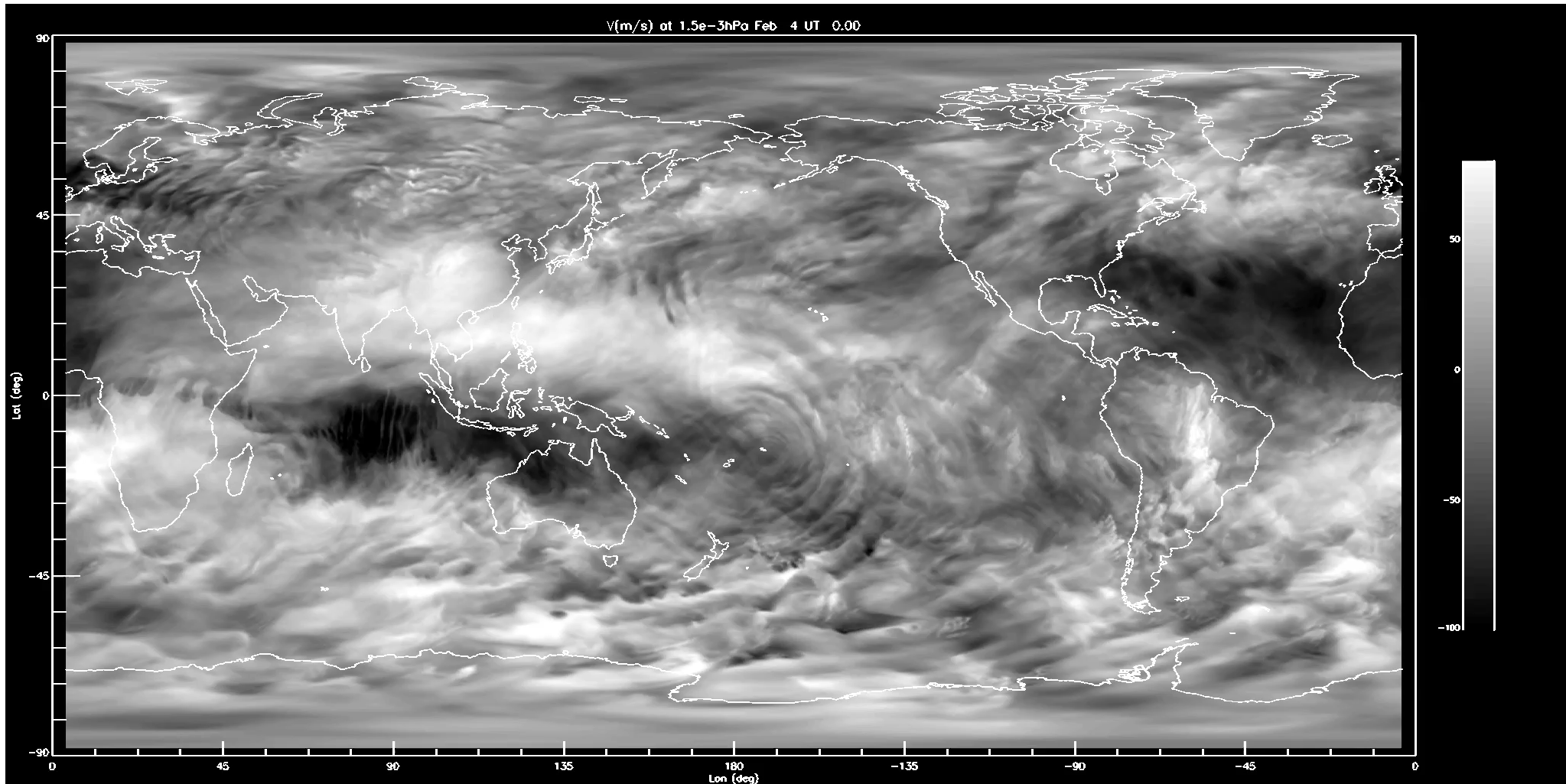
- Data assimilation capability in WACCM-X using ensemble Kalman filter method
 - Troposphere-stratosphere meteorological observations
 - Middle atmosphere (~20-100 km) satellite temperature observations
 - COSMIC (COSMIC II and OneWeb) ionosphere electron density profiles and ground-based TEC
- Provides initial conditions for ensemble-based forecasting
- Provides representation of uncertainty for state specification and forecast

Ionospheric Response to Stratospheric Warming Event

Ionosphere results based on assimilating data only below 100km



High-Res Simulation of Gravity Waves at the Turbopause



Recently Published in JAMES

RESEARCH ARTICLE

10.1002/2017MS001232

Key Points:

- The Whole Atmosphere Community Climate Model has been extended to include ionospheric electrodynamics
- WACCM-X simulates the interaction of lower atmosphere and solar influences in the ionosphere
- Preliminary validation demonstrates agreement with observations

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Development and Validation of the Whole Atmosphere Community Climate Model With Thermosphere and Ionosphere Extension (WACCM-X 2.0)

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Abstract Key developments have been made to the NCAR Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension (WACCM-X). Among them, the most important are the self-consistent solution of global electrodynamics, and transport of O^+ in the F-region. Other ionosphere developments include time-dependent solution of electron/ion temperatures, metastable O^+ chemistry, and high-cadence solar EUV capability. Additional developments of the thermospheric components are improvements to the momentum and energy equation solvers to account for variable mean molecular mass and specific heat, a new divergence damping scheme, and cooling by $O(^3P)$ fine structure. Simulations using this new version of WACCM-X (2.0) have been carried out for solar maximum and minimum conditions. Thermospheric composition, density, and temperatures are in general agreement with measurements and empirical models, including the equatorial mass density anomaly and the midnight density maximum. The amplitudes and seasonal variations of atmospheric tides in the mesosphere and lower thermosphere are in good agreement with observations. Although global mean thermospheric densities are comparable with observations of the annual variation, they lack a clear semiannual variation. In the ionosphere, the low-latitude $E \times B$ drifts agree well with observations in their magnitudes, local time dependence, seasonal, and solar activity variations. The prereversal enhancement in the equatorial region, which is associated with ionospheric irregularities, displays patterns of longitudinal and seasonal variation that are similar to observations. Ionospheric density from the model simulations reproduces the equatorial ionosphere anomaly structures and is in general agreement with observations. The model simulations also capture important ionospheric features during storms.

WACCM-X Development Plans:

Next Steps

- Merge up to WACCM6 / CAM6 physics
- Move to 1° grid finite-volume dynamical core with 1° O⁺ transport
- Improve high latitude filtering of ion dynamics

Longer Term

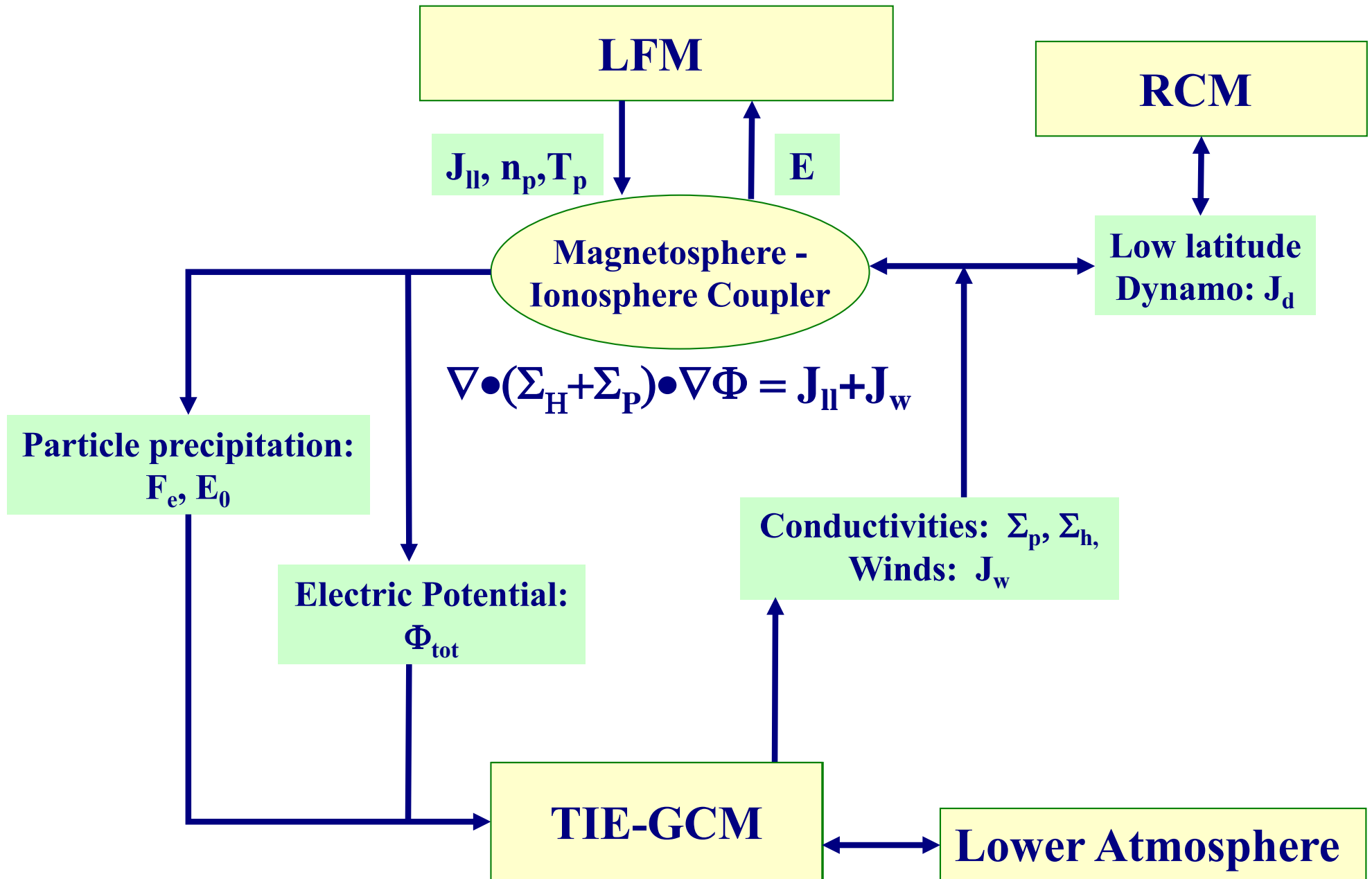
- Use spectral element (or other) dynamical core at high resolution
 - Need coordinate-transform regridding infrastructure to accomplish this
- Ionosphere-plasmasphere module in geomagnetic coordinate system
 - Collaboration with NRL

Toward a Whole Geospace Model

- For now, “Whole Geospace” means:
 - One-way inputs from the magnetosphere
 - Specified, assimilated, or modeled
 - Coupled ionosphere-plasmasphere model in geomagnetic coordinates

- Next goal is to integrate a fully two-way-coupled MHD magnetosphere model
 - Could be any model
 - But we need a robust interface

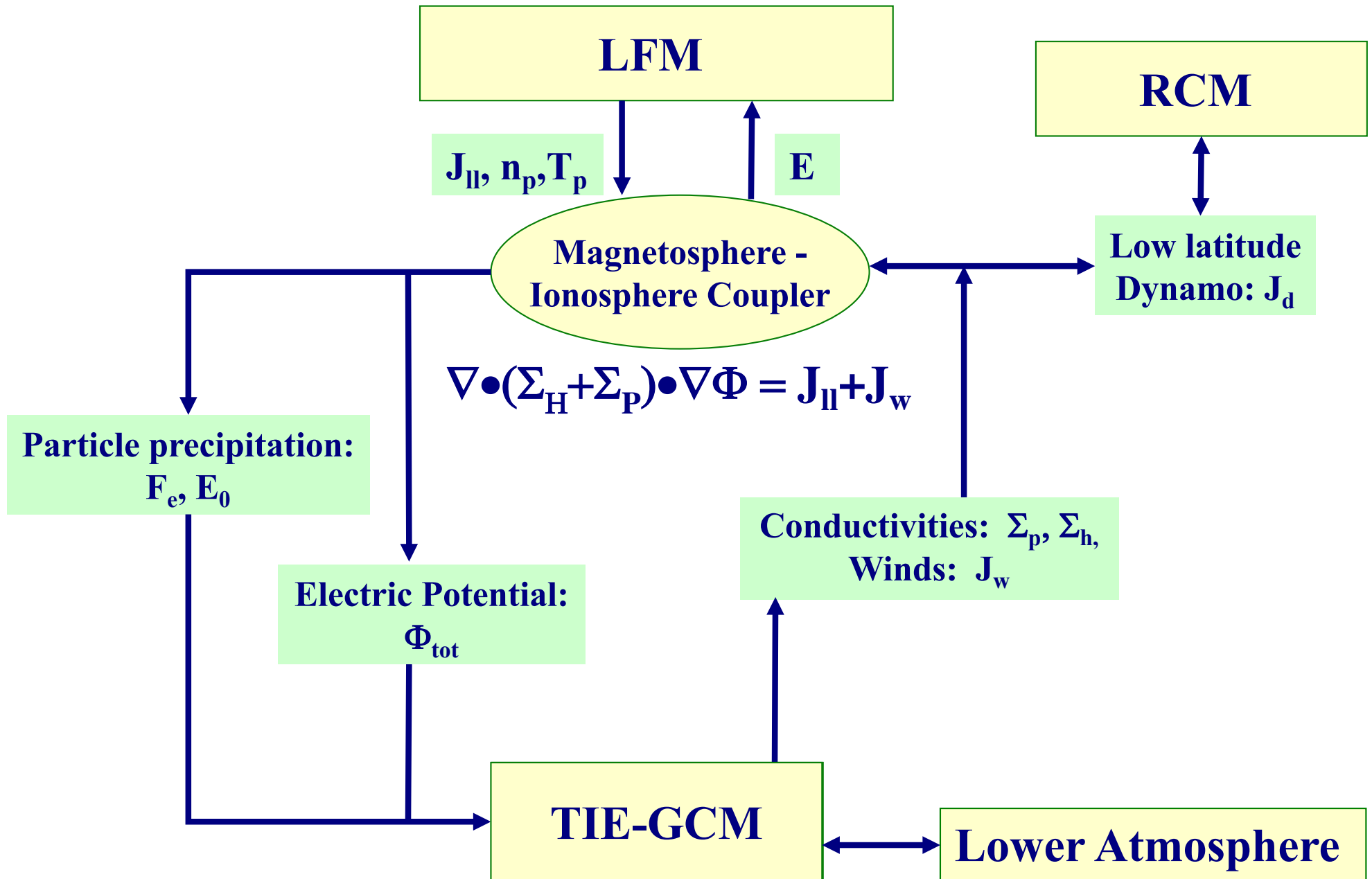
Coupled Magnetosphere-Ionosphere-Thermosphere Model



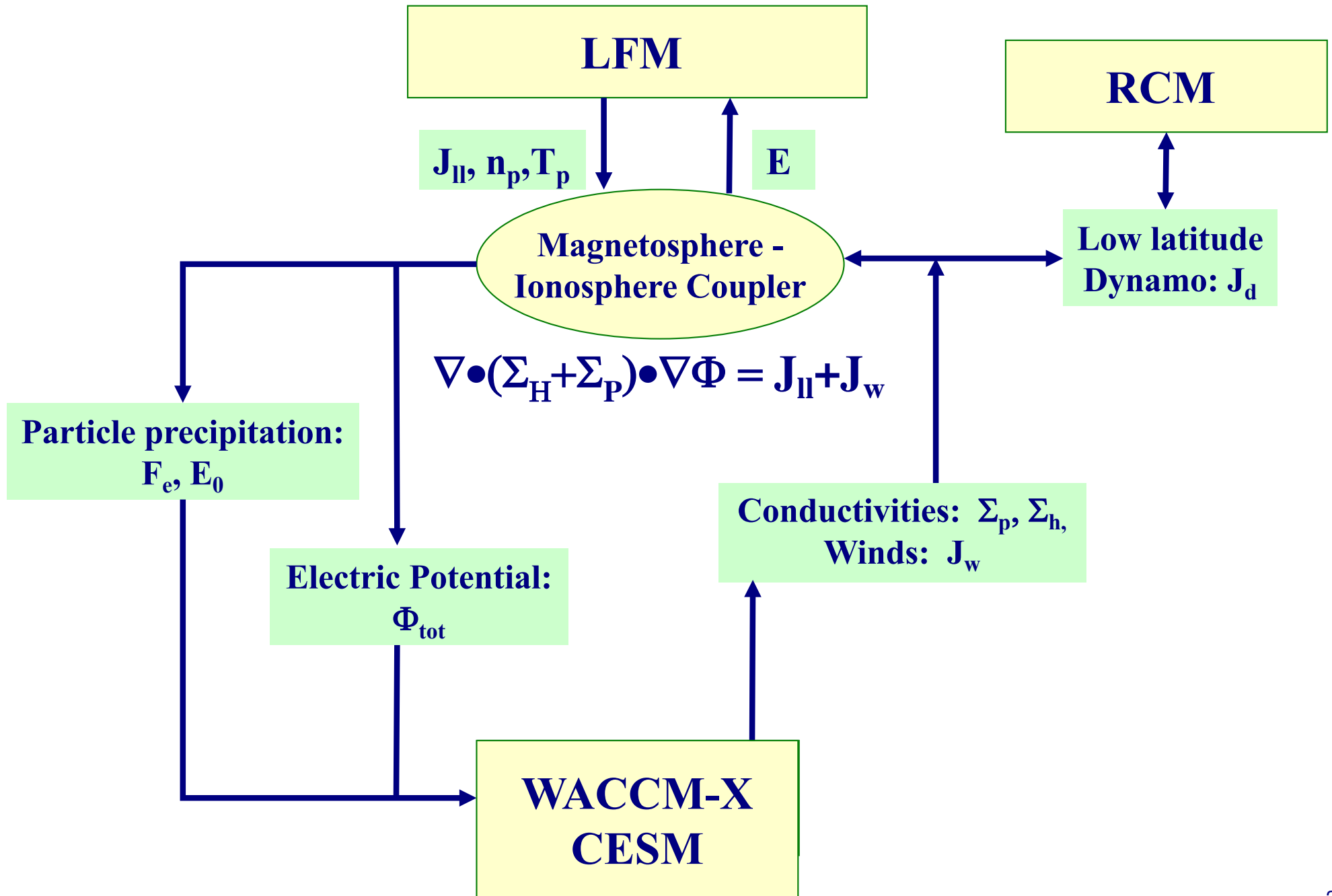
CMIT Animation



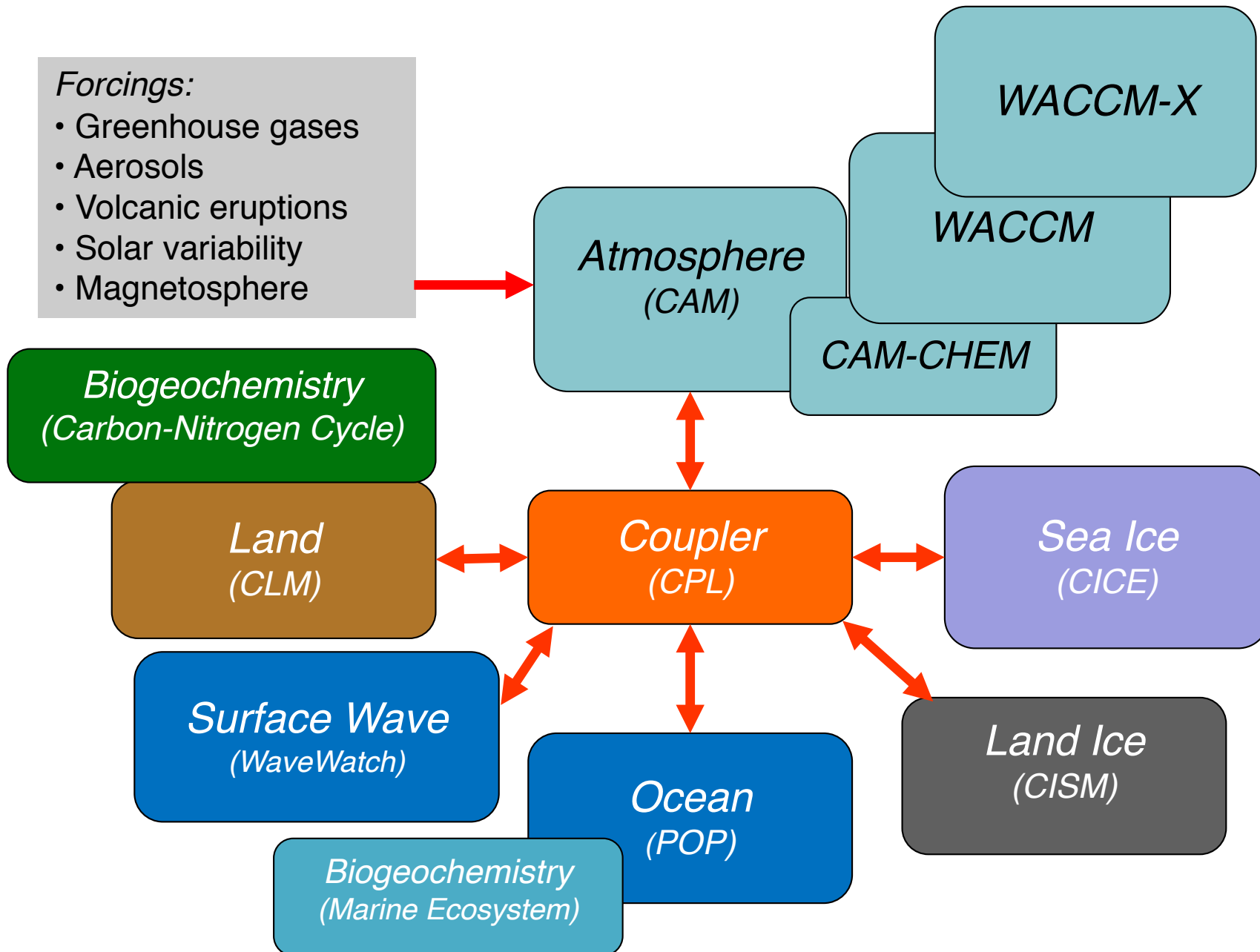
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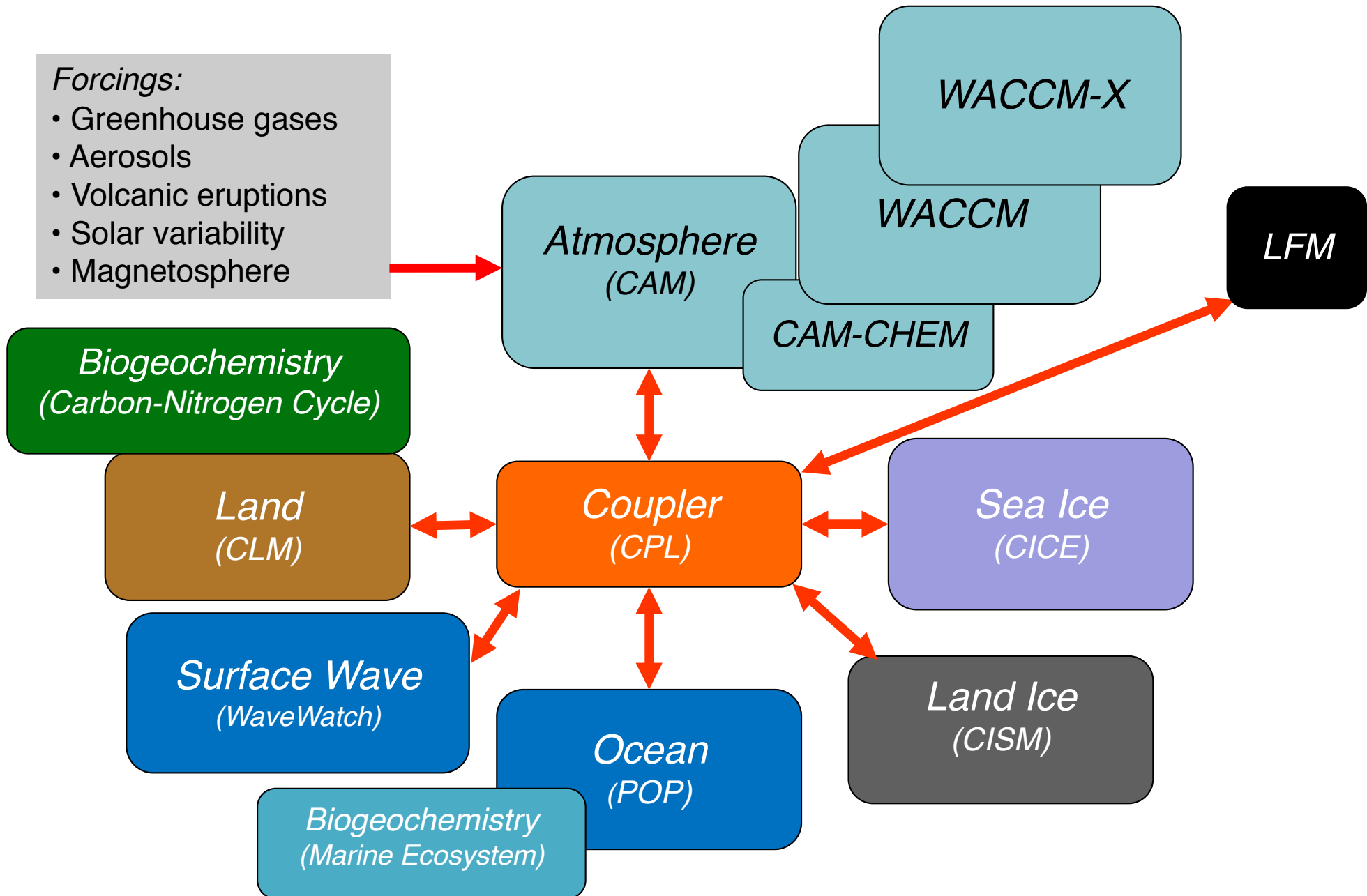
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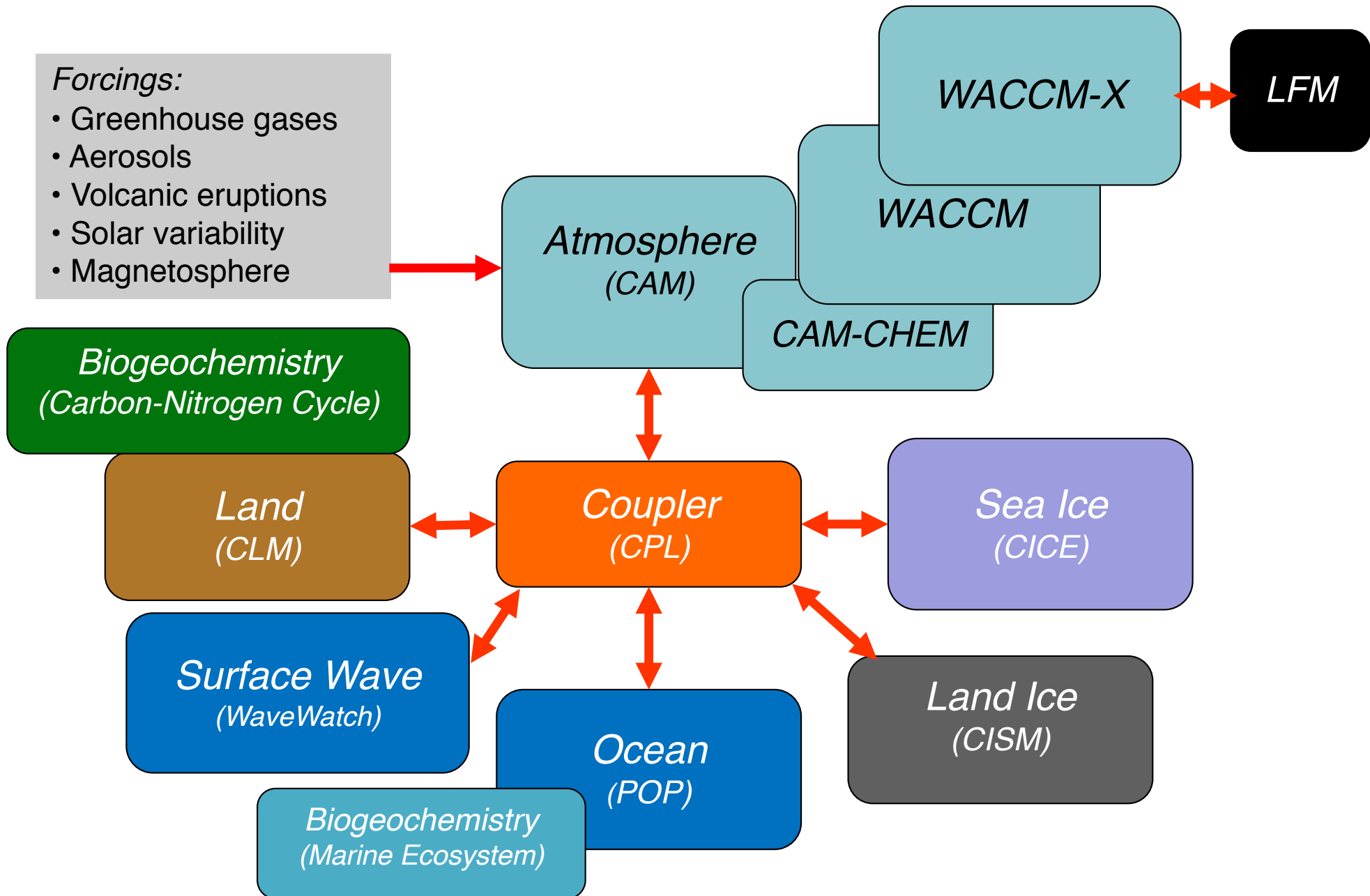
WACCM-X is Built on the Community Earth System Model (CESM)



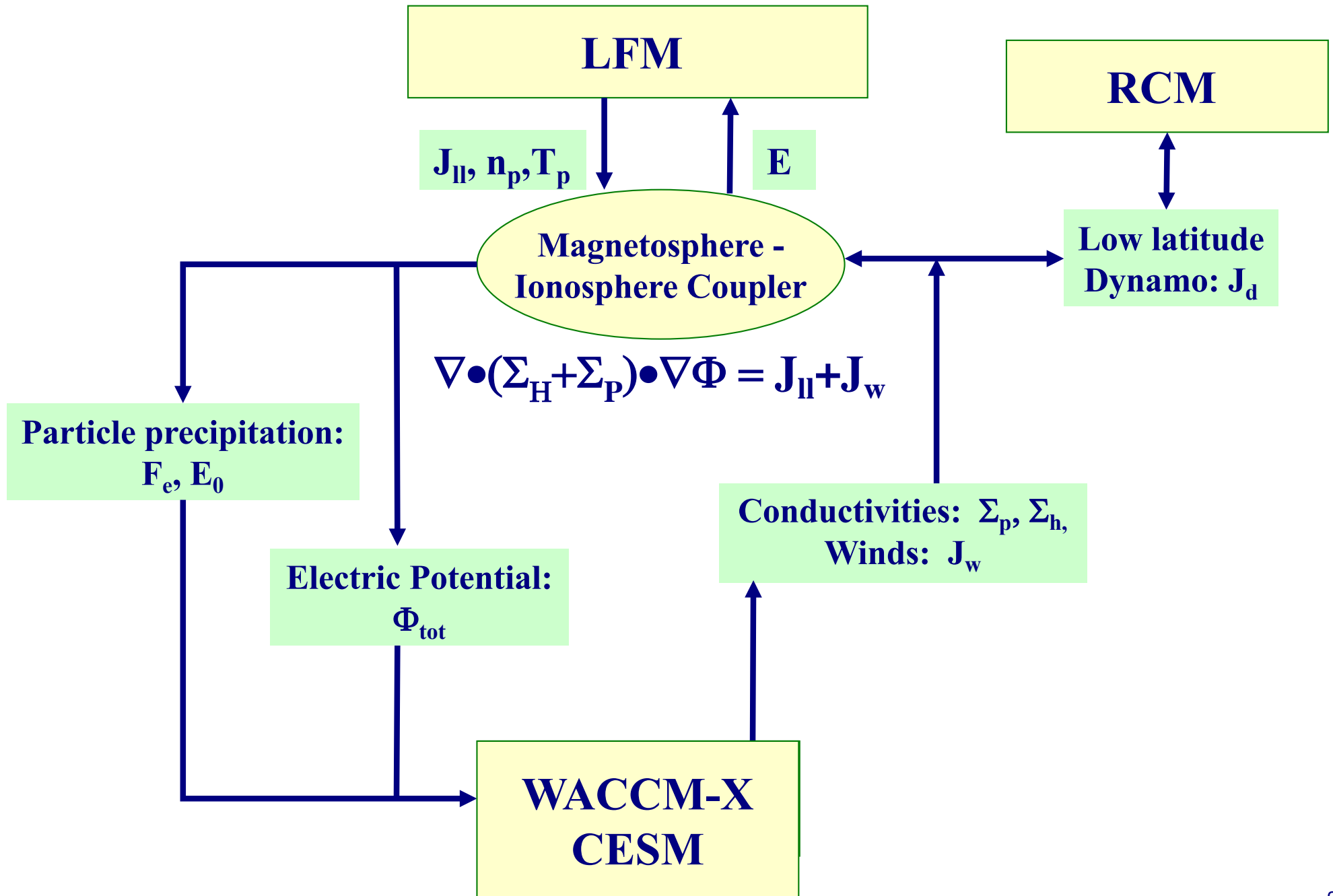
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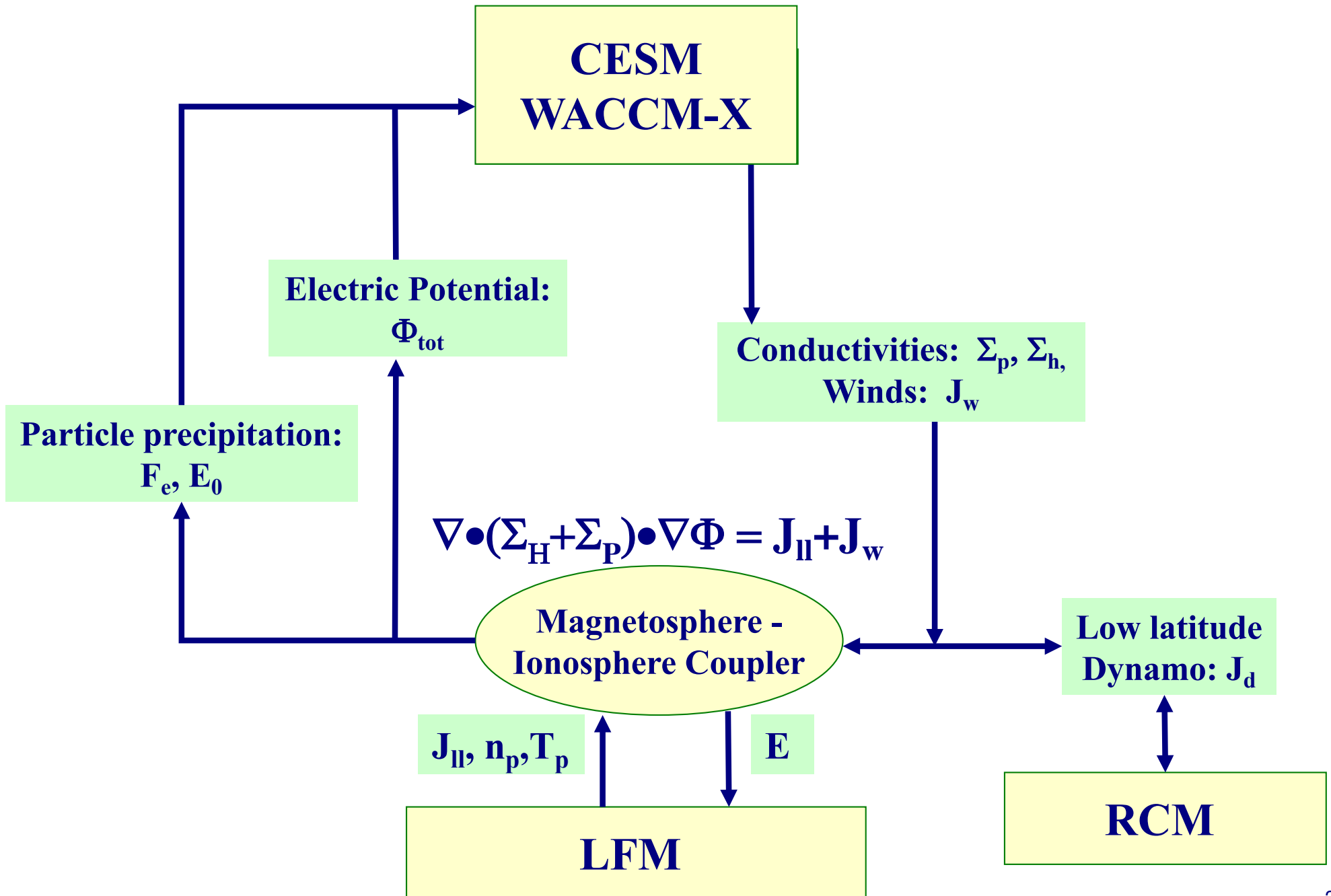
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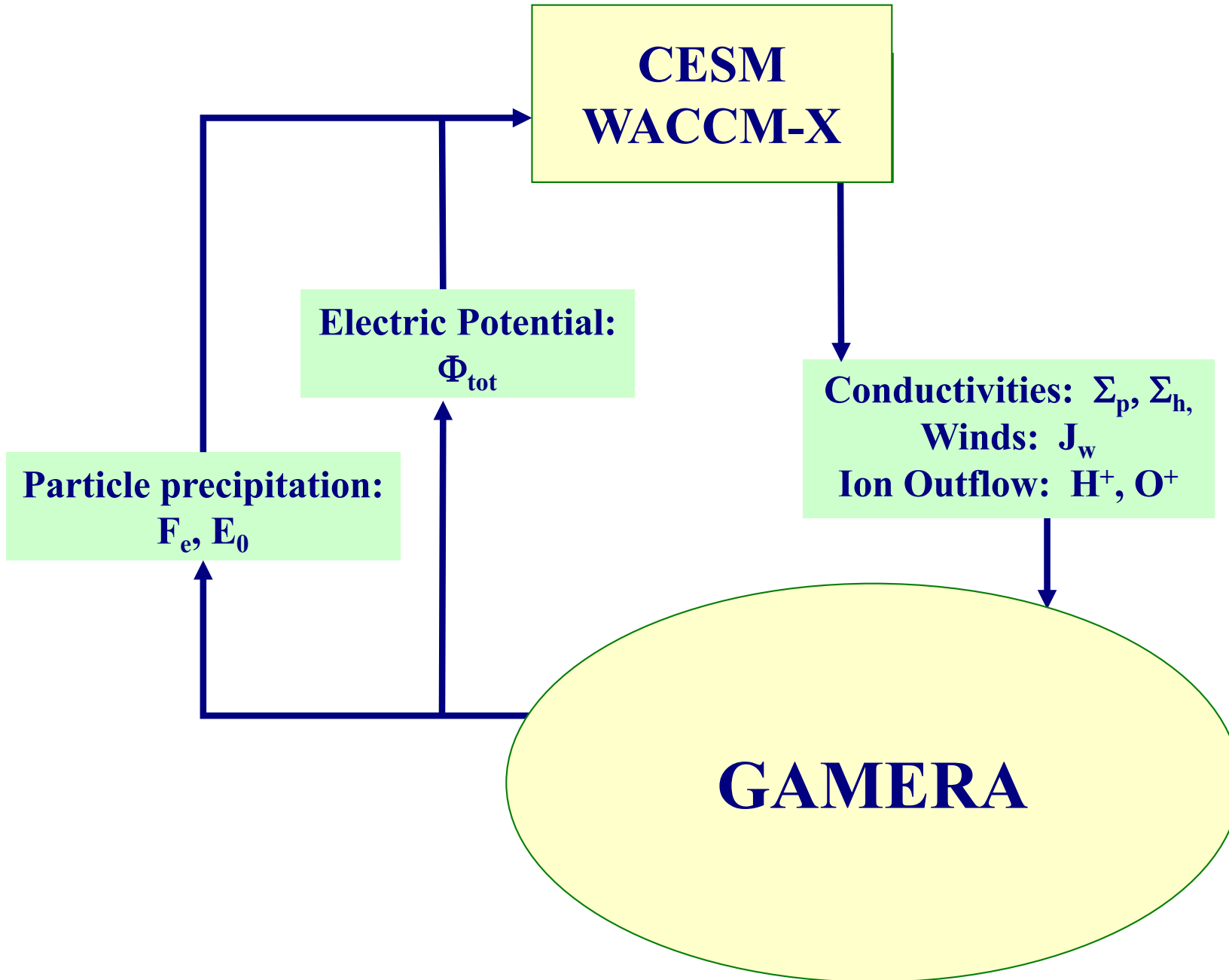
Coupled Magnetosphere-Ionosphere-Thermosphere Model



Whole Geospace Model



Whole Geospace Model



Summary

1. The Whole Atmosphere Community Climate Model — eXtended (WACCM-X) version 2.0 has been released as an open-source community resource. It still needs extensive testing, validation, and improvement.
2. The Coupled Magnetosphere Ionosphere Thermosphere model (CMIT) still exists and still runs, but its infrastructure is operating under a DNR. The future is something called GAMERA.
3. We are beginning development of a “Whole Geospace Model” to integrate the magnetosphere into the atmosphere-ionosphere system.