TIE-GCM and WACCM-X:
Atmosphere-Ionosphere Model Development at NCAR

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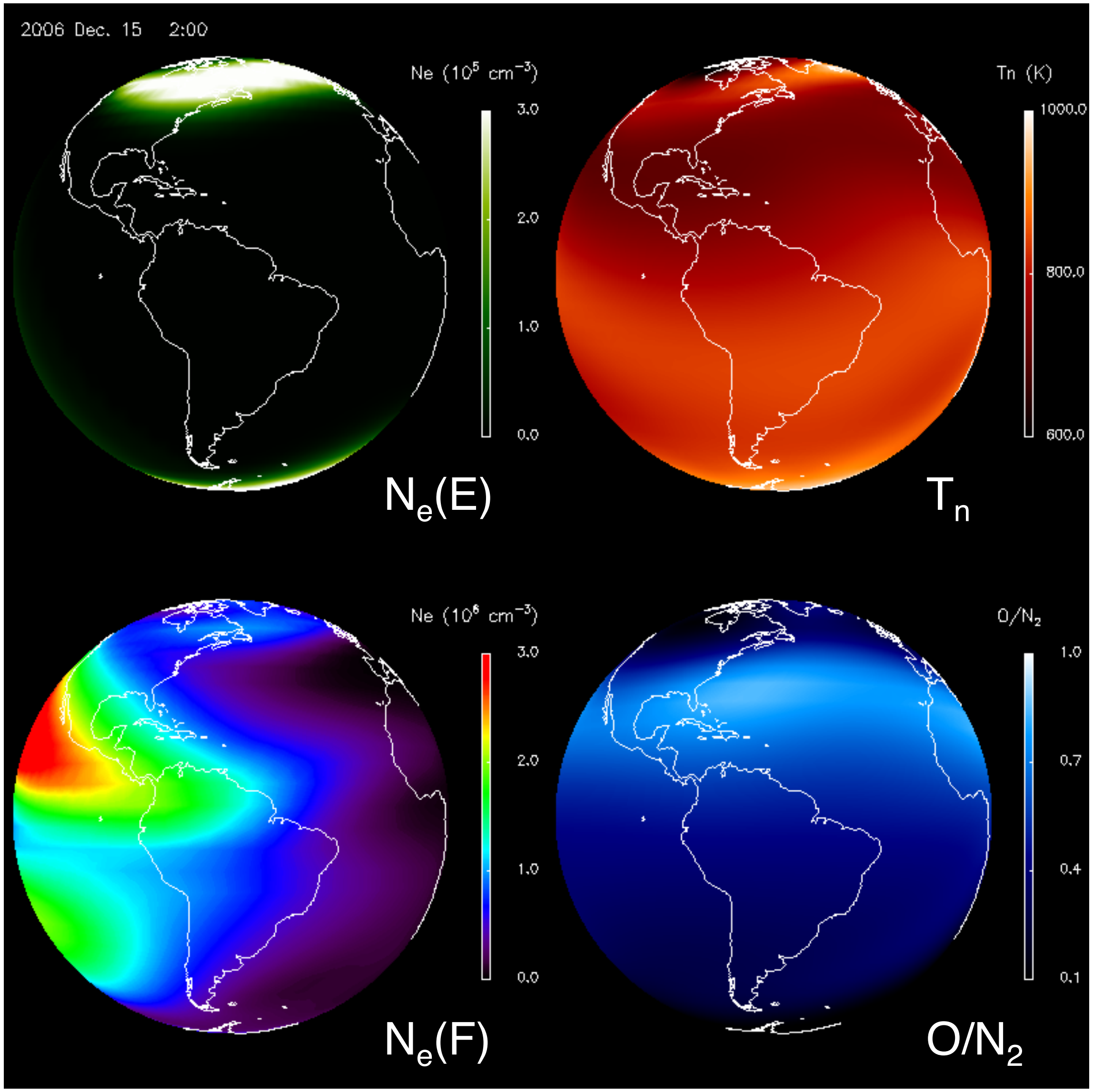
HAO

Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM)

- Original development by Ray Roble, Bob Dickinson, Art Richmond, et al.
- The atmosphere/ionosphere element of the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) and LFM-TIE-RCM (LTR) models
- Cross-platform community model, under open-source academic research license
- v. 2.0 release, 2016
- User guide complete
- Documentation mostly complete
- Runs-on-request at CCMC



- More information at: http://www.hao.ucar.edu/modeling/tgcm

What's New in TIE-GCM v. 2.0?

- TIE-GCM v. 2.0 released in March 2016
  - "Double Resolution" (2.5° x 2.5° x H/4) supported
  - Helium included as a major species
  - Electrodynamics calculations parallelized

- Recommend 30-second time step for double res., 60-second time step for single-res.

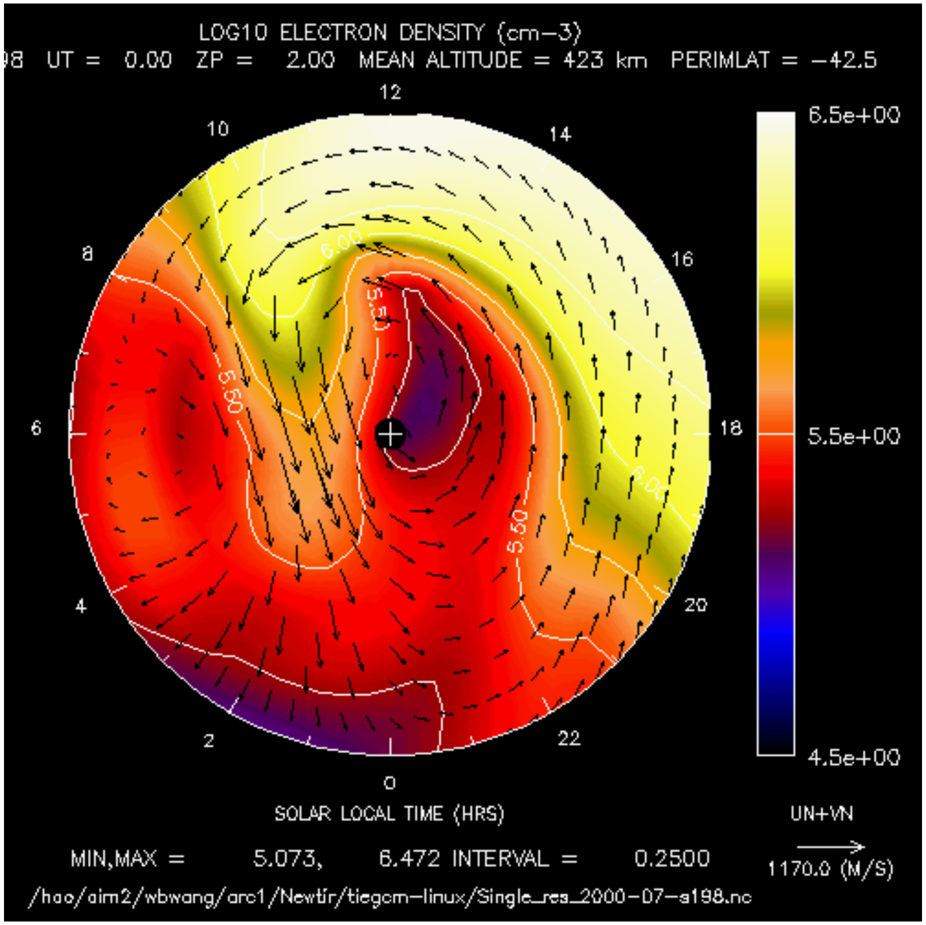
- Other new features:

  Argon as a minor species
  IGRF12 and secular variation
  Non-migrating GSWM tides turned on in default inputs for high-res only
  Lower boundary zonal mean climatology
  CTMT (Oberheide/Forbes) tidal option
  AMIE interface merged to trunk
  CMIT interface updated
  ZG and (optionally) ZGmid output to secondaries
  N_2 now its own field, optionally output to secondaries
  Many other optional secondary diagnostics (not all of these are new):

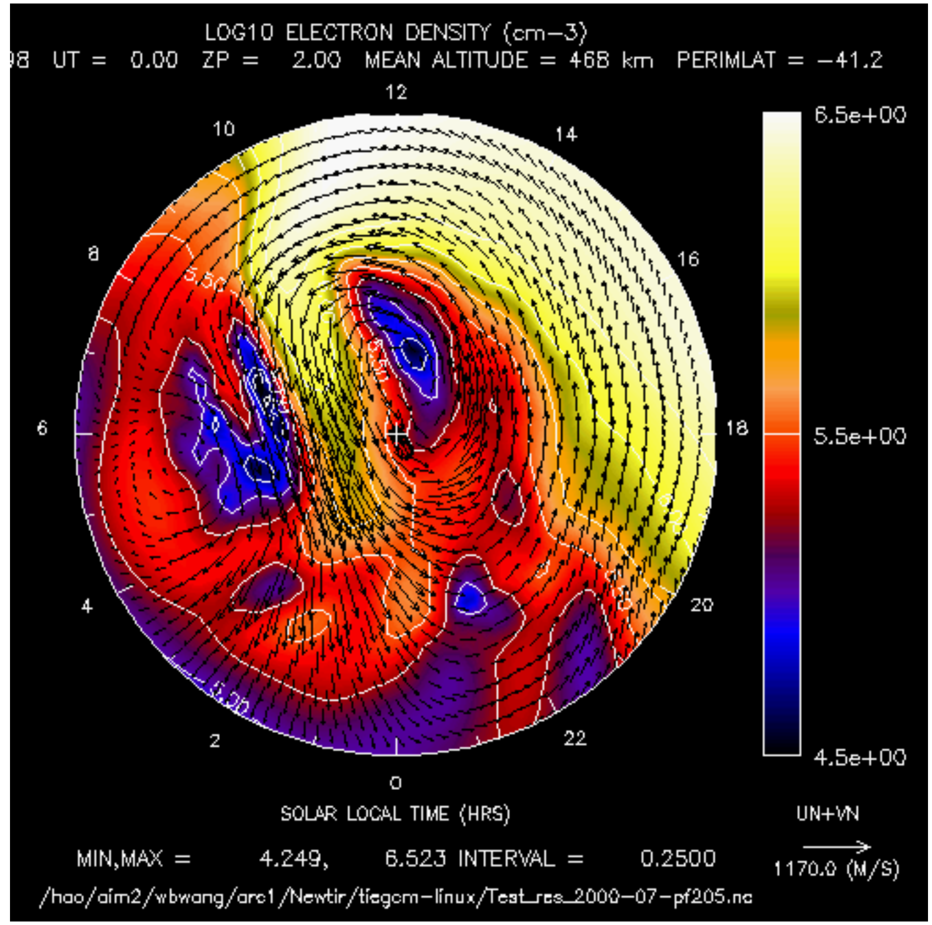
    Mass density, He, O/N_2, Scale Height, μ_{bar}
    N_mF_2, H_mF_2, TEC, vi_{EXB}, σ_H, σ_P, λ_H, λ_P, **B**, **E**, Φ
    CO_2 and NO cooling rates, EUV heating Joule heating
    Aurora, cusp, and drizzle parameters

Normal (5°) vs. Double (2.5°) Resolution: Auroral Dynamics

Normal Resolution

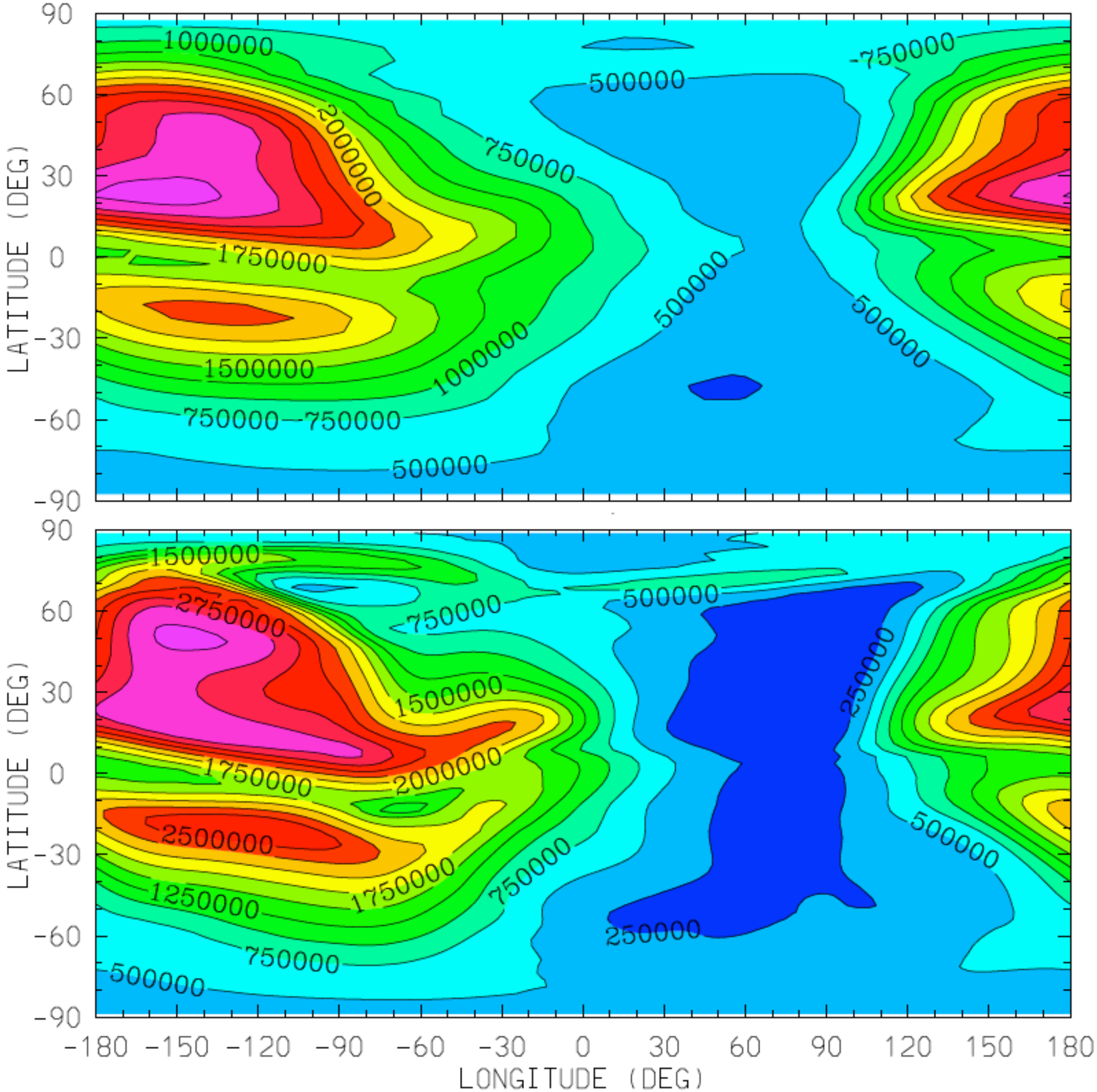


Double Resolution



Electron densities with neutral wind vectors superimposed over the southern hemisphere polar region during a geomagnetic storm. The “tongue” of ionization is significantly more resolved in the double-resolution version of the model.

Normal (5°) vs. Double (2.5°) Resolution: Global N_mF_2

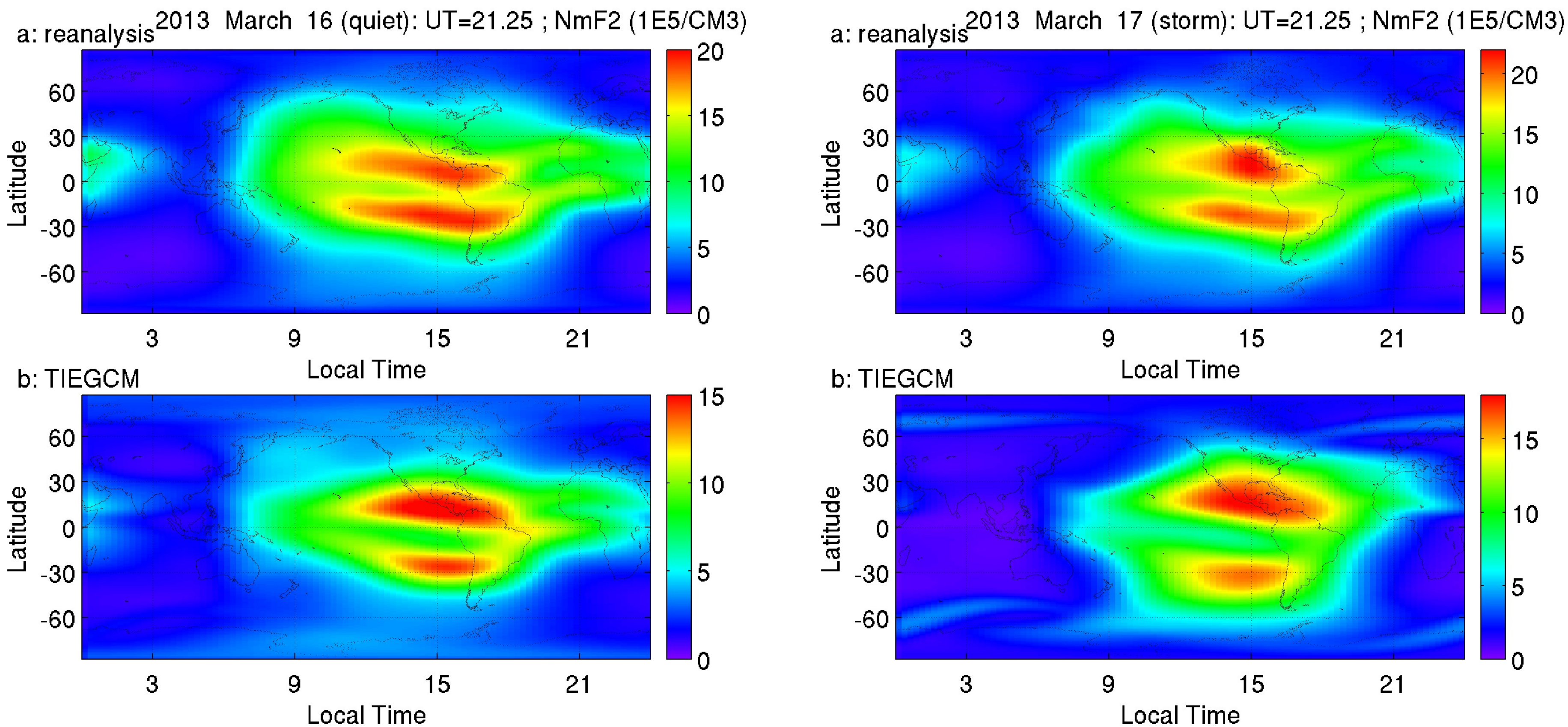


Normal Resolution

Double Resolution

December Solstice, 0 UT, Solar Maximum

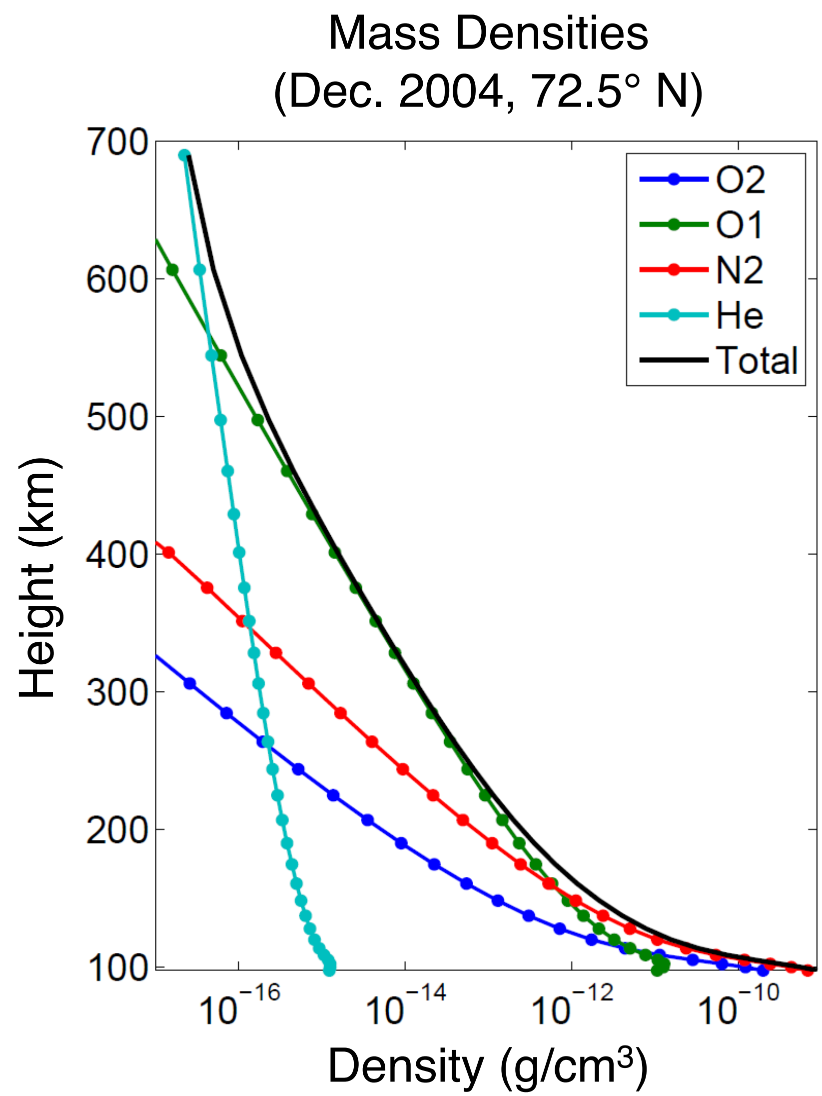
Comparison of COSMIC Re-analysis to the TIE-GCM



Work by Xinan Yue and the UCAR COSMIC team, comparing ionospheric measurements combining space-based and ground based GPS data with the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model.

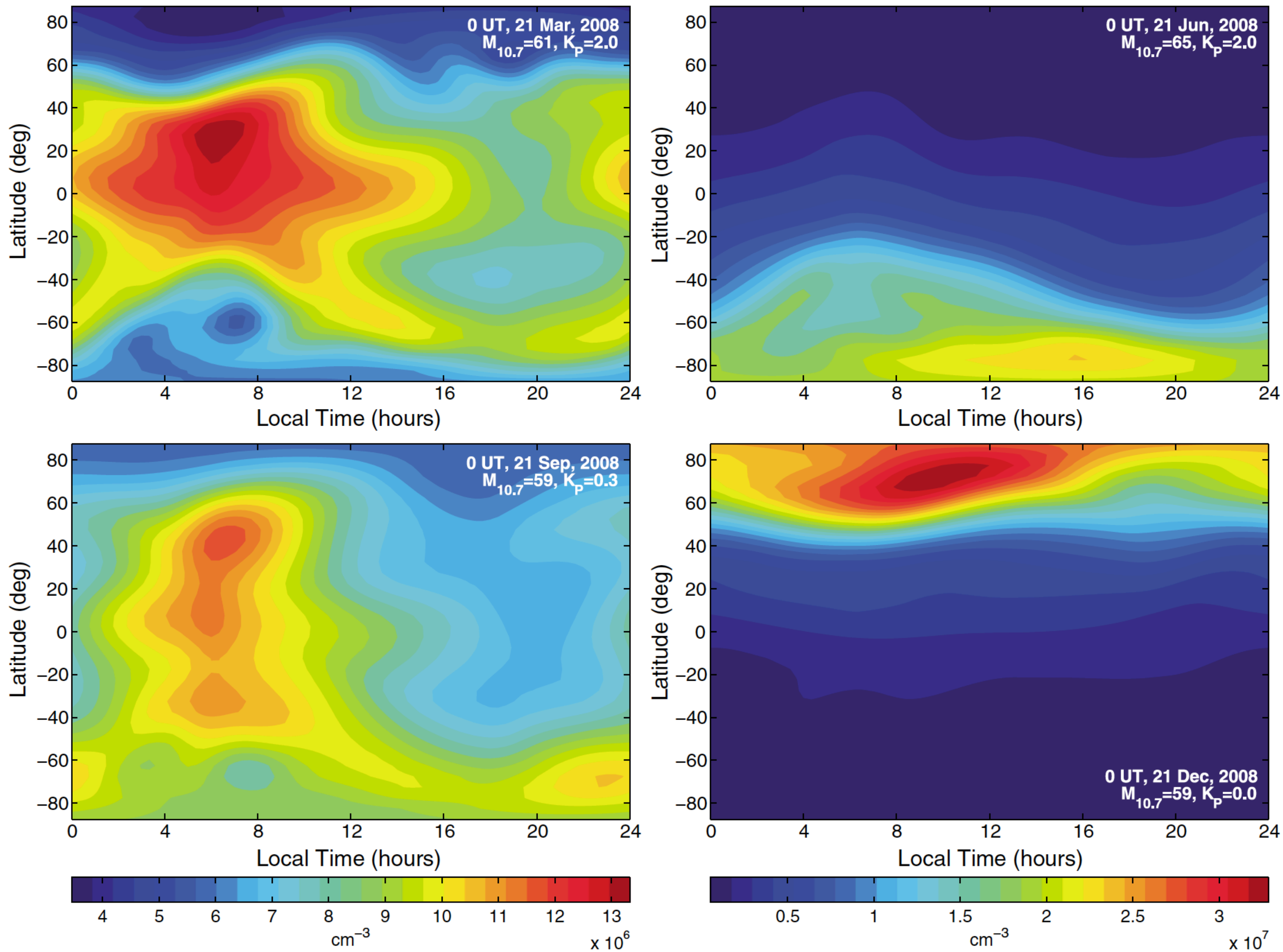
Inclusion of Helium as a Major Species

- Helium has very small concentration from ground level through the turbopause
- Diffusive separation causes the mixing ratio to increase, approaching unity near the exobase
- Seasonal variation termed "Winter Helium Bulge"
- Local Time preference near ~8:00 LT
- Helium scale height is less sensitive to solar cycle variations (i.e. temperature changes) than are other species
- Helium can be important for satellite drag calculations, particularly at 500–700 km, and partiuclarly during solar minimum



Sutton et al., J. Geophys. Res., 2015

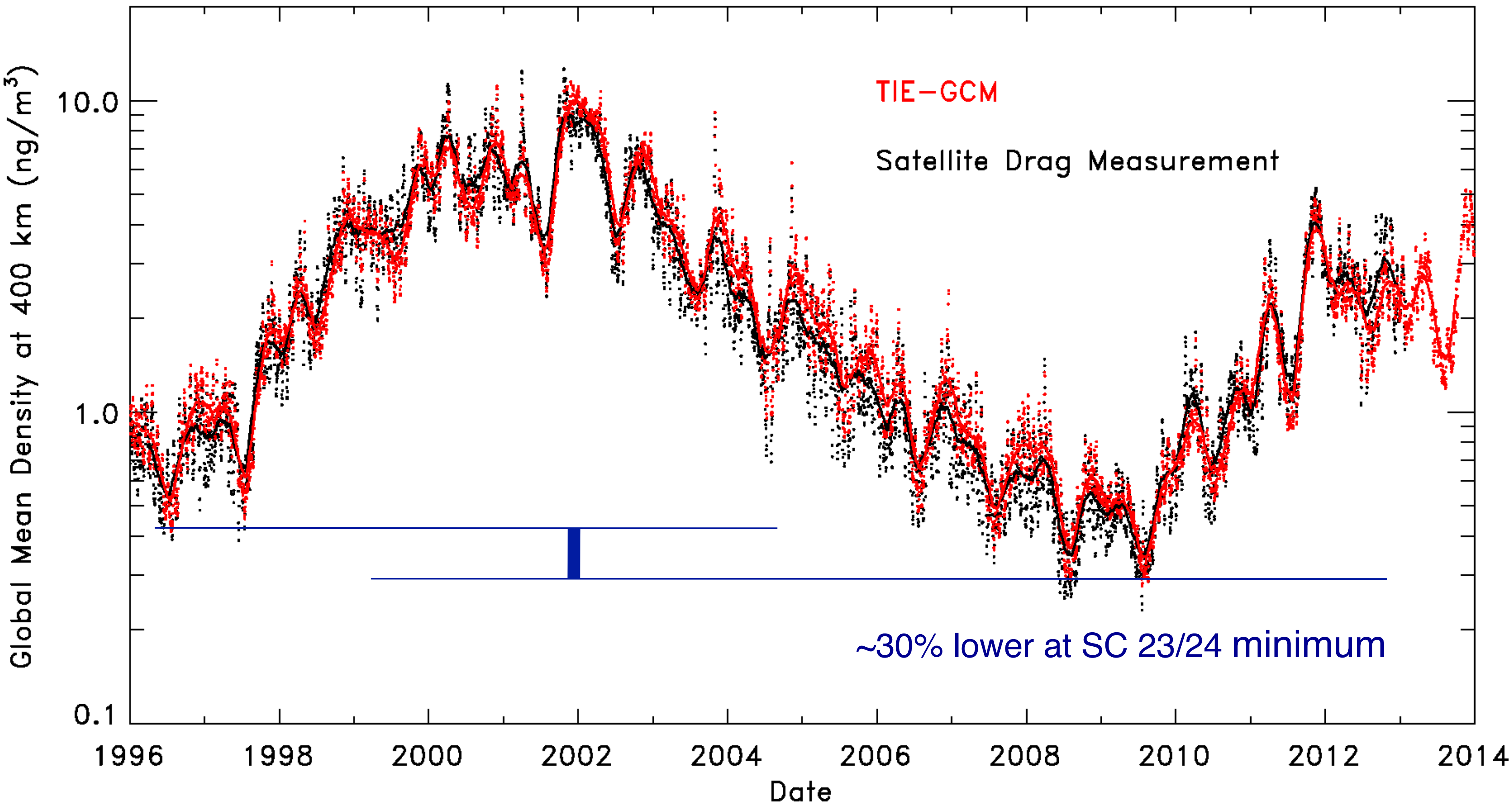
Simulation of the Winter Helium Bulge



Equinox

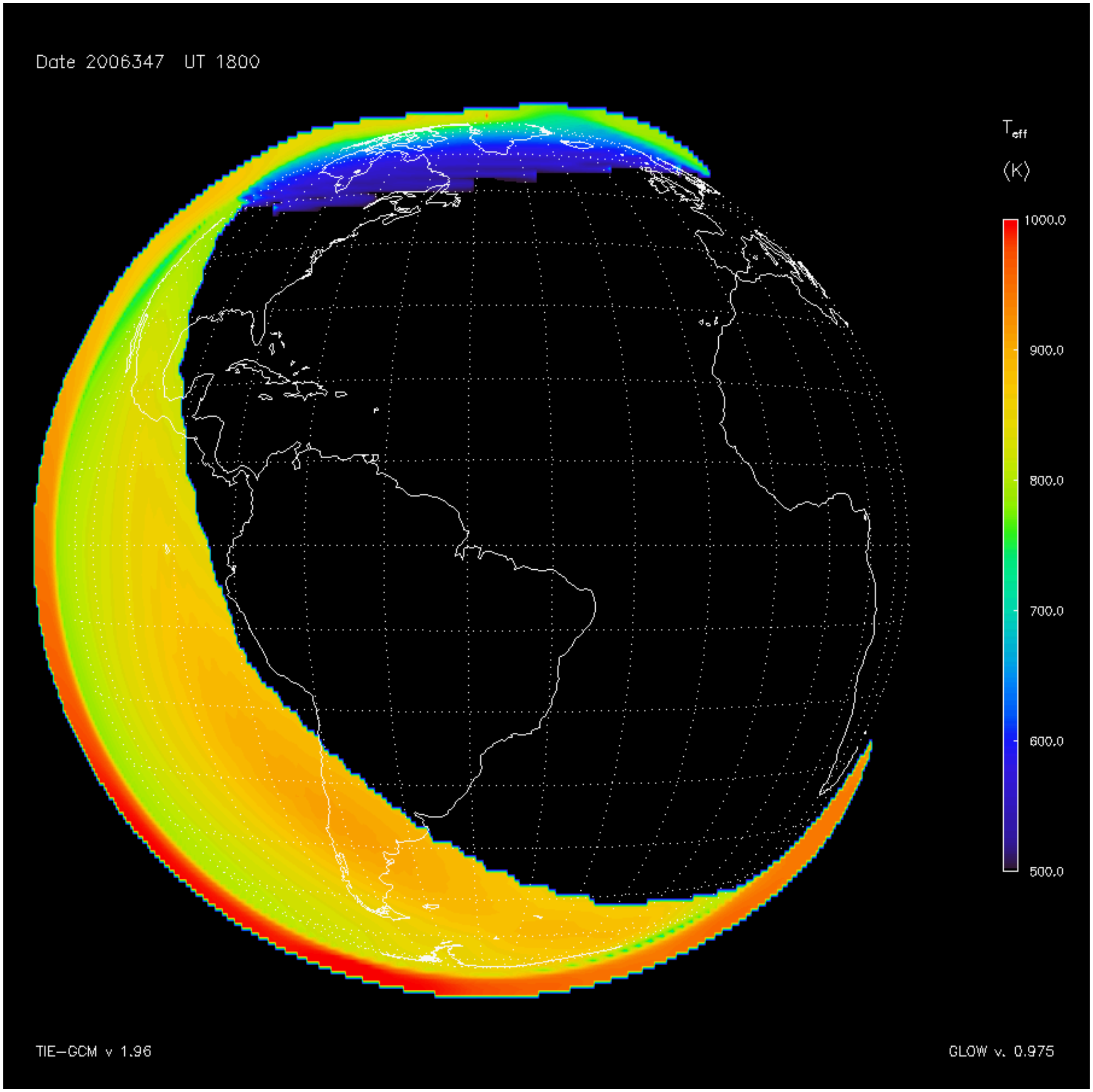
Solstice

Thermospheric Density over 1.5 Solar Cycles



Simulation of Temperature Derived from N_2 LBH Bands

GLOW model using TIE-GCM inputs

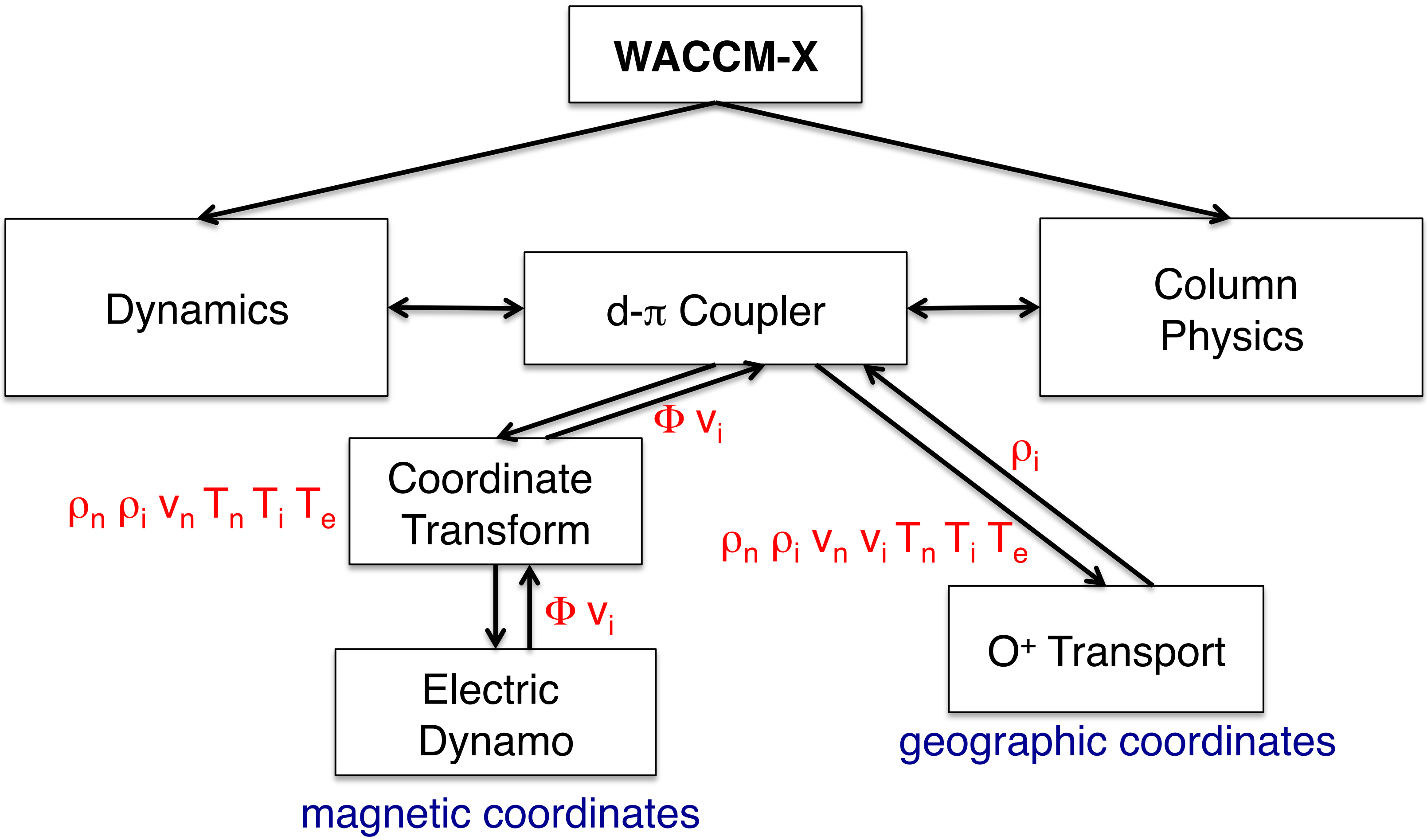


Simulations for the NASA GOLD mission

Whole Atmosphere Community Climate Model – eXtended (WACCM-X)

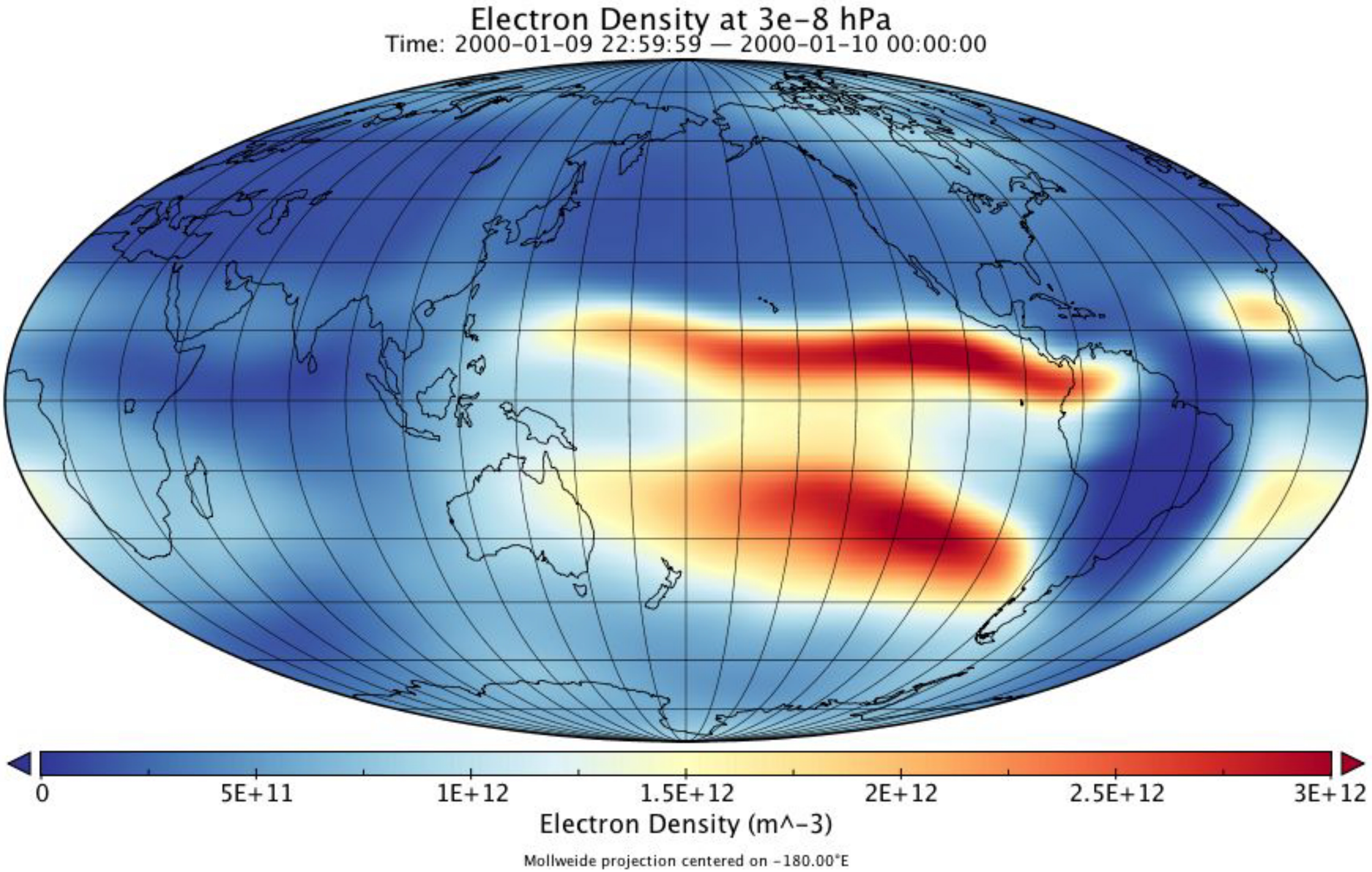
- WACCM-X is the thermosphere-ionosphere extension of WACCM
- WACCM is the upper atmosphere version of the Community Atmosphere Model (CAM)
- CAM is the atmosphere component of the Community Earth System Model (CESM)
- Recent developments:
  - Ion and electron energetics implemented:
    - — Calculating T_i and T_e in WACCM column physics.
  - Equatorial electrodynamo installed:
    - — ESMF interpolation from geographic to geomagnetic coords.
  - Ionospheric dynamics installed:
    - — Ambipolar diffusion and 3D transport of O^+.

Integrating Ionospheric Dynamics into WACCM-X



d-π Coupler: dynamics-physics-ionosphere-electrodynamics (D-PIE) coupler
Electric Dynamo: calculates global electric potential resulting from wind-driven ions
ρ: density v: velocity T: temperature n: neutral i: ion e: electron Φ: electric potential

WACCM-X Ionosphere at ~250 km



Current Development and Future Plans

- TIE-GCM v. 2.0 released March 2018.
  - Still some "known issues"
  - See the release notes for more information
  - User Guide sgnificantly enhanced
- WACCM-X development ongoing
  - Targeting ionosphere module for inclusion in CESM v. 2 release next winter
  - Next step is to include a fully-coupled ionosphere-plasmasphere module
  - Running an interactive climate model is complex and computationally intensive
    - Not clear whether this is a good fit for CCMC
- Other key research developments include:
  - Lower boundary conditions:
    - Seasonal/spatial variation of lower boundary eddy diffusion
    - Tidal forcing options using data-driven methods
  - External forcing:
    - Solar EUV updates
    - Magnetospheric inputs (AMIE, AMPERE, LFM, other)
  - Modeling support for upcoming NASA missions, including ICON and GOLD.

Information, User Guide, Documentation, Source Code...

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Models

TIE-GCM

TIME-GCM

Global Mean

Processors

intro to processors

tgcmproc_f90

tgcmproc_idl

ncl

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Documentation

TIEGCM2.0 Release Notes [html]-&-[pdf]

User Guide [html]-&-[pdf]

Draft Model Description [pdf]

Forums

tgcm mailing list

Research

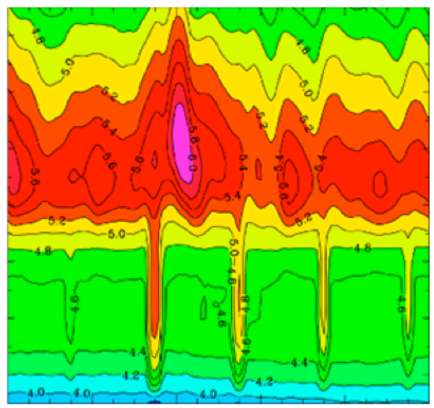
Highlights

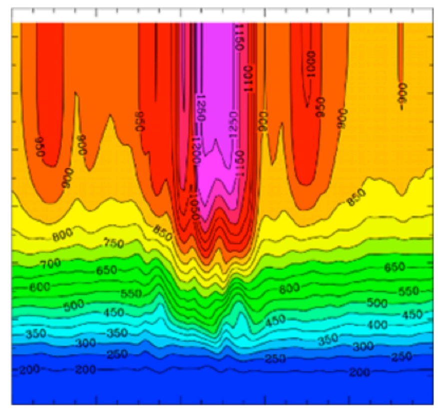
Highlights (archived)

The Thermospheric General Circulation Models (TGCM's)

Announcing Release of TIEGCM v2.0:

Selected Results of the TIEGCM2.0 Benchmark Runs | TIEGCM2.0 Release Document





Introduction

The High Altitude Observatory at the National Center for Atmospheric Research has developed a series of numeric simulation models of the Earth's upper atmosphere, including the upper Stratosphere, Mesosphere, and Thermosphere. The Thermospheric General Circulation Models (TGCM's) are three-dimensional, time-dependent models of the EARTH's neutral upper atmosphere. The models use a finite differencing technique to obtain a self-consistent solution for the coupled, nonlinear equations of hydrodynamics, thermodynamics, continuity of the neutral gas and for the coupling between the dynamics and the composition.

Recent models in the series include a self-consistent aeronomic scheme for the coupled Thermosphere/Ionosphere system, the Thermosphere Ionosphere Electrodynamic General Circulation Model (TIEGCM), and an extension of the lower boundary from 97 to 30 km, including the physical and chemical processes appropriate for the Mesosphere and upper Stratosphere, the Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model (TIME-GCM). A global mean, or column model, has also been developed in parallel with the TGCM's. The global mean model is used as a time-dependent, one-dimensional platform from which new chemical, dynamic and numeric schemes are developed and tested before being introduced into the 3-d GCM's.

http://www.hao.ucar.edu/modeling/tgcm

Backup

Numerical Approach

• The TIE-GCM is a comprehensive, first-principles, three-dimensional, non-linear representation of the coupled thermosphere and ionosphere system that includes a self-consistent solution of the low-latitude electric field.

• The model solves the three-dimensional momentum, energy and continuity equations for neutral and ion species at each time step, using a semi-implicit, fourth-order, centered finite difference scheme, on each pressure surface.

• Low-res. latitude/longitude grid is 5° x 5°; high-res grid is 2.5° x 2.5°.

• Low-res. uses 29 pressure levels in the vertical at H/2, ~97 km to ~500 km altitude.

• High-res. uses 57 pressure levels in the vertical at H/4, ~97 km to ~500 km altitude.

• Assumes Hydrostatic equilibrium, constant gravity, incompressibility on constant pressure surfaces, and steady-state ion/electron energetics. Ion velocities are specified by the potential field and ExB drifts.

• Implemented in F90 and MPI. Runs on 1 to ~64 processors. Uses netCDF for I/O.

• Time step is 60 s for low-res., 30 s for high-res.

External Forcing of the Thermosphere/Ionosphere System

- Solar XUV, EUV, FUV (0.05-175 nm)
  - Solar energy and photoelectron parameterization (Solomon & Qian, 2005)
  - Default: F10.7-based solar proxy model (EUVAC)
  - Optional: solar spectral measurements; other empirical models

- Magnetospheric forcing
  - High latitude electric potential: empirical models (Heelis et al., 1982; Weimer, 2005), or data assimilation model (e.g., AMIE), or magnetosphere model (LFM)
  - Auroral particle precipitation: analytical auroral model linked to potential pattern (Roble & Ridley, 1987), or magnetospheric model (LFM)

- Lower boundary wave forcing
  - Tides: Global Scale Wave Model (GSWM , Hagan et al, 1999)
  - Eddy diffusion (with option for seasonally-varying term, Qian et al., 2009)

Equations and Numerics

- **Equations:**
  Momentum equation: *u, v*
  Continuity equation: *w,* O, O_2, N(^{4}S), NO, O^+
  Hydrostatic equation: *z*
  Thermodynamic equation: T_N, T_e
  Quasi-steady state energy transfer—electron, neutral, ion: T_I
  Photochemical equilibrium: N(^{2}D), O_2^+,N_2^+,N^+,NO^+

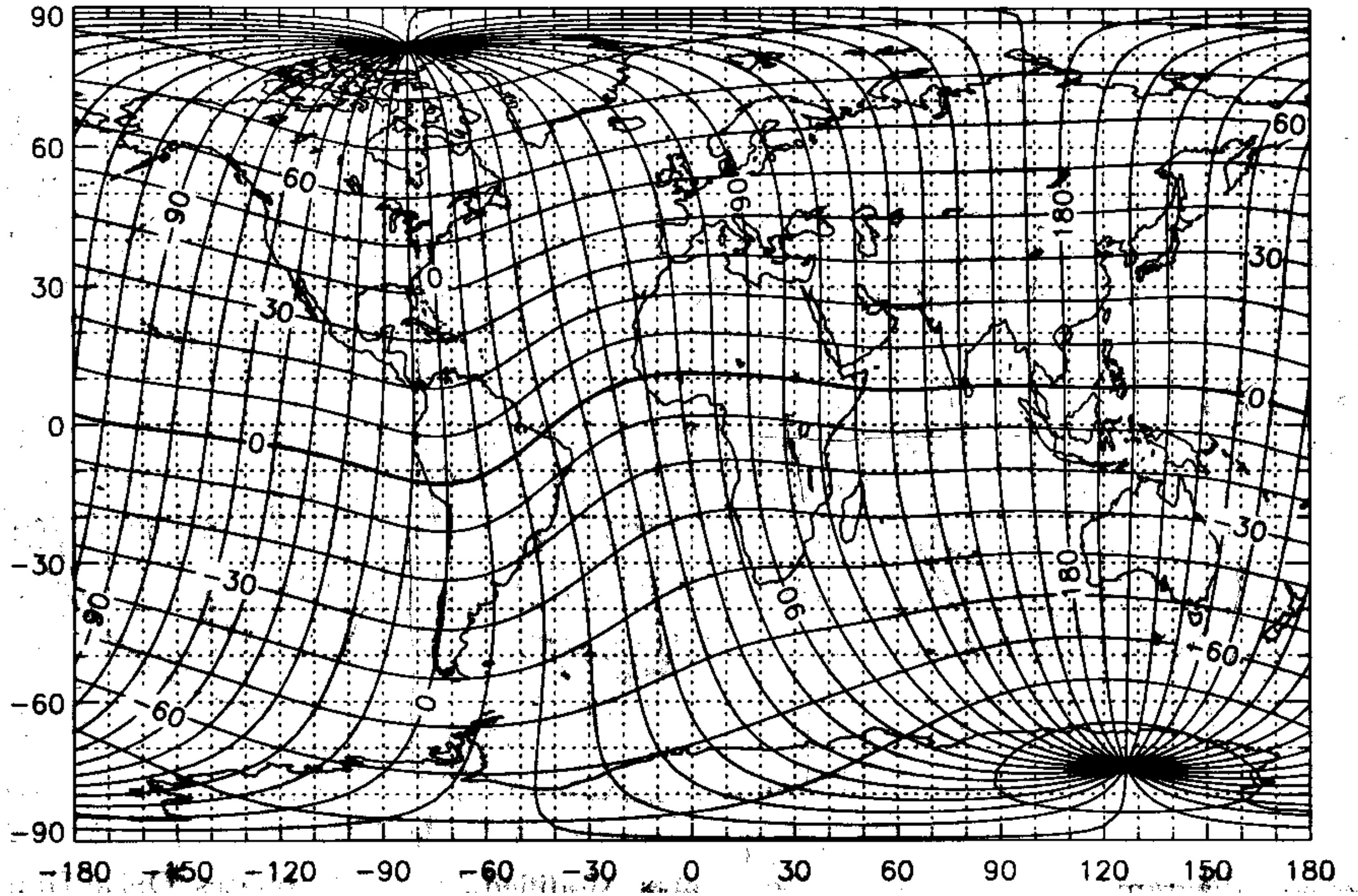
- **Coordinate system:**
  Horizontal: rotating spherical geographical coordinates, 5°x 5° grid
  Vertical: pressure surface (hydrostatic equilibrium), 0.5 scale height grid
  High resolution version (2.5° x 2.5° x H/4) in test.

- **Numerics:**
  Horizontal: explicit 4th order centered finite difference
  Vertical: Implicit 2nd order centered difference
  Time: 2nd order centered difference
  Shapiro filter: achieve better numerical stability
  Fourier filter: remove spurious high frequency zonal waves at high latitudes

Boundary Conditions

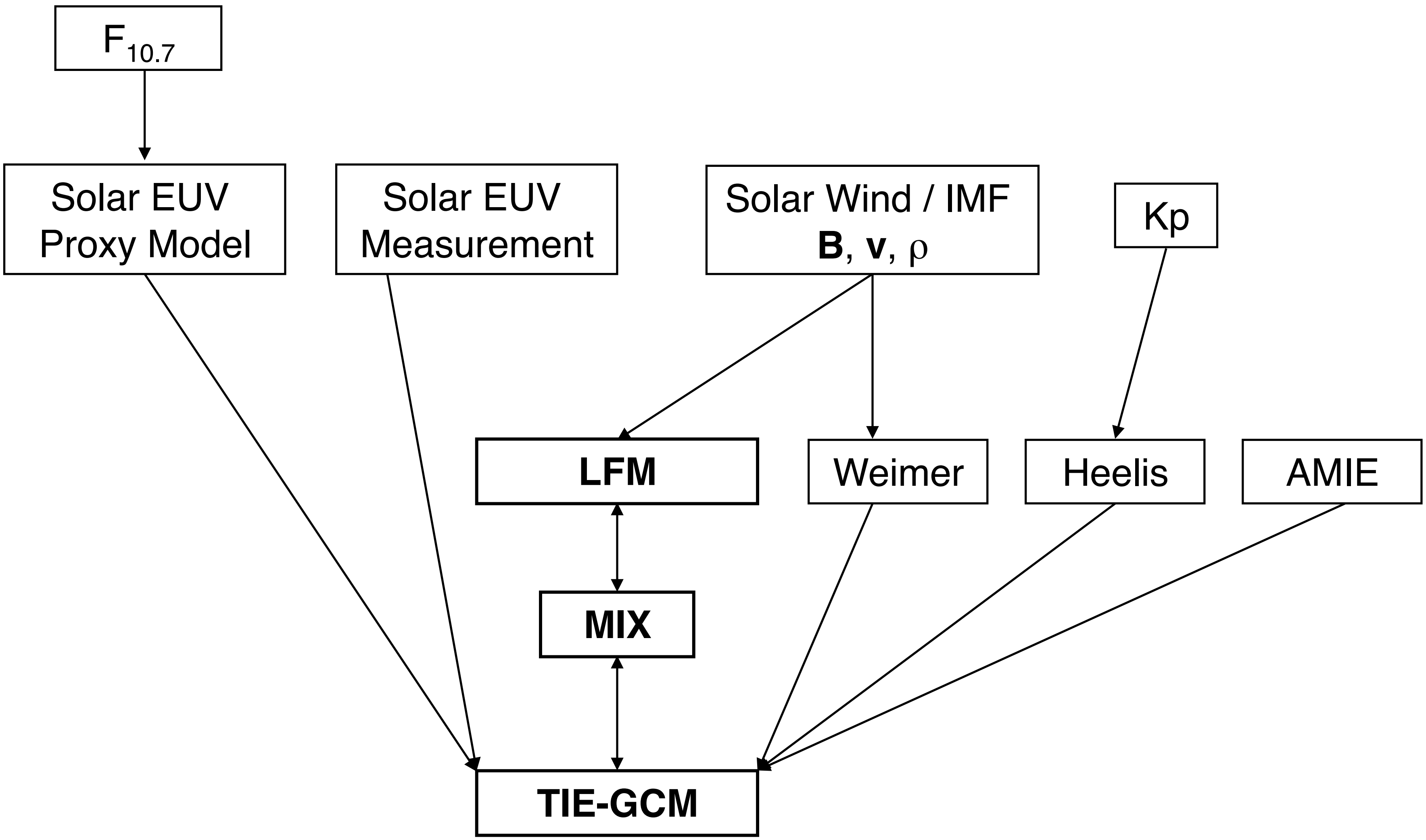
- **Upper boundary conditions:**
  - u, v, w, T_N, O_2, O: diffusive equilibrium;
  - $N(^4S)$, NO: photochemical equilibrium;
  - O^+: specify upward or downward O^+ flux;
  - T_e: specify upward or downward heat flux.
- **Lower boundary conditions:**
  - u, v: specified by tides (GSWM)
  - T_N: 181 K + perturbations by tides (GSWM)
  - O_2: fixed mixing ratio of 0.22
  - O: vertical gradient of the O density is zero
  - $N(^4S)$, O^+: photochemical equilibrium
  - NO: constant density of $(8x10^6)$
  - T_e: equal to T_N.

Electrodynamics

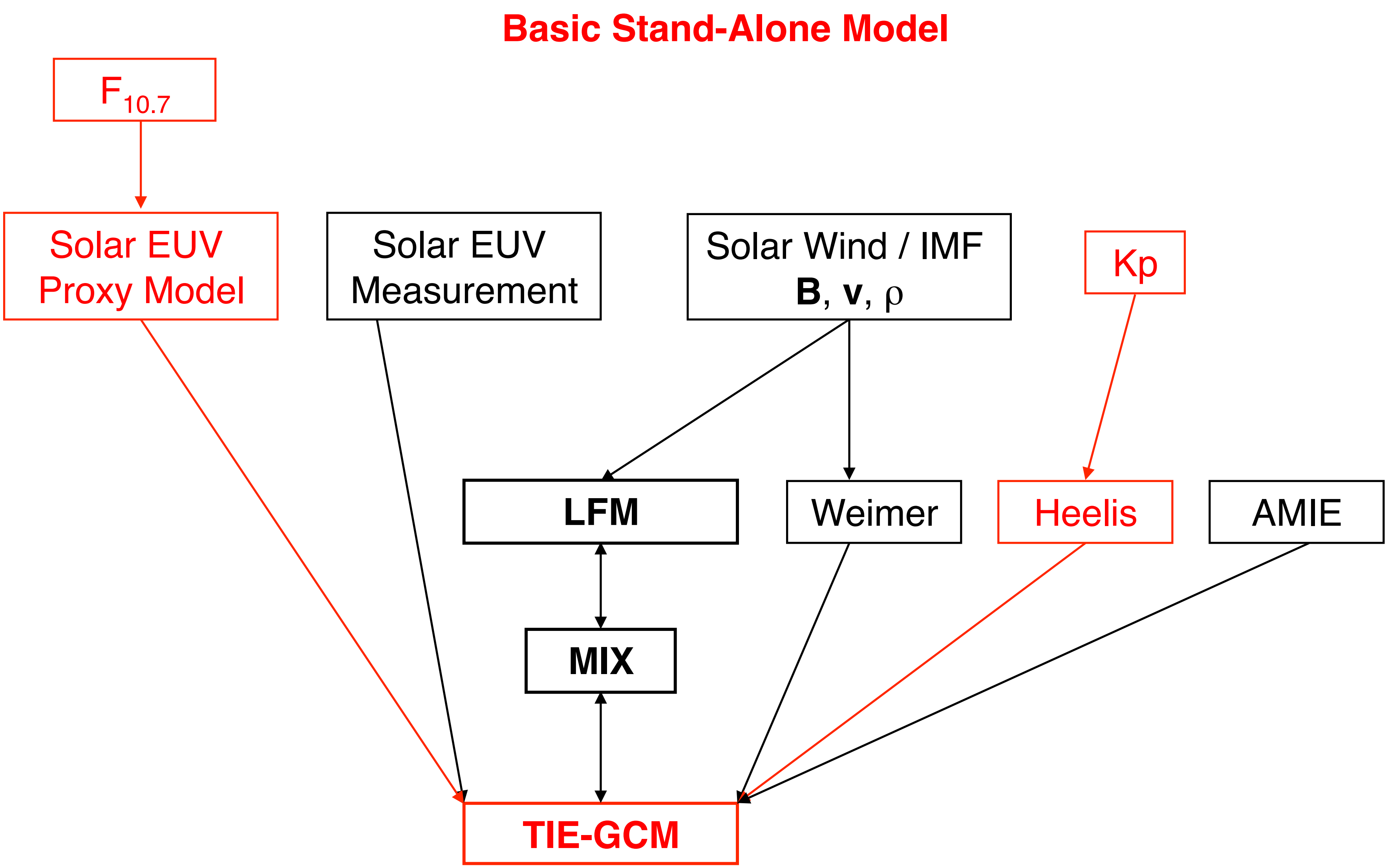


- Low and mid-latitude: neutral wind dynamo equations solved in geomagnetic Apex coordinates [Richmond et al., 1992; 1995].
- High latitude: specified by convection models such as Heelis, Weimer, or AMIE, or coupled to the LFM Magnetosphere Model.

TIE-GCM "Extraterrestrial" Inputs and Options

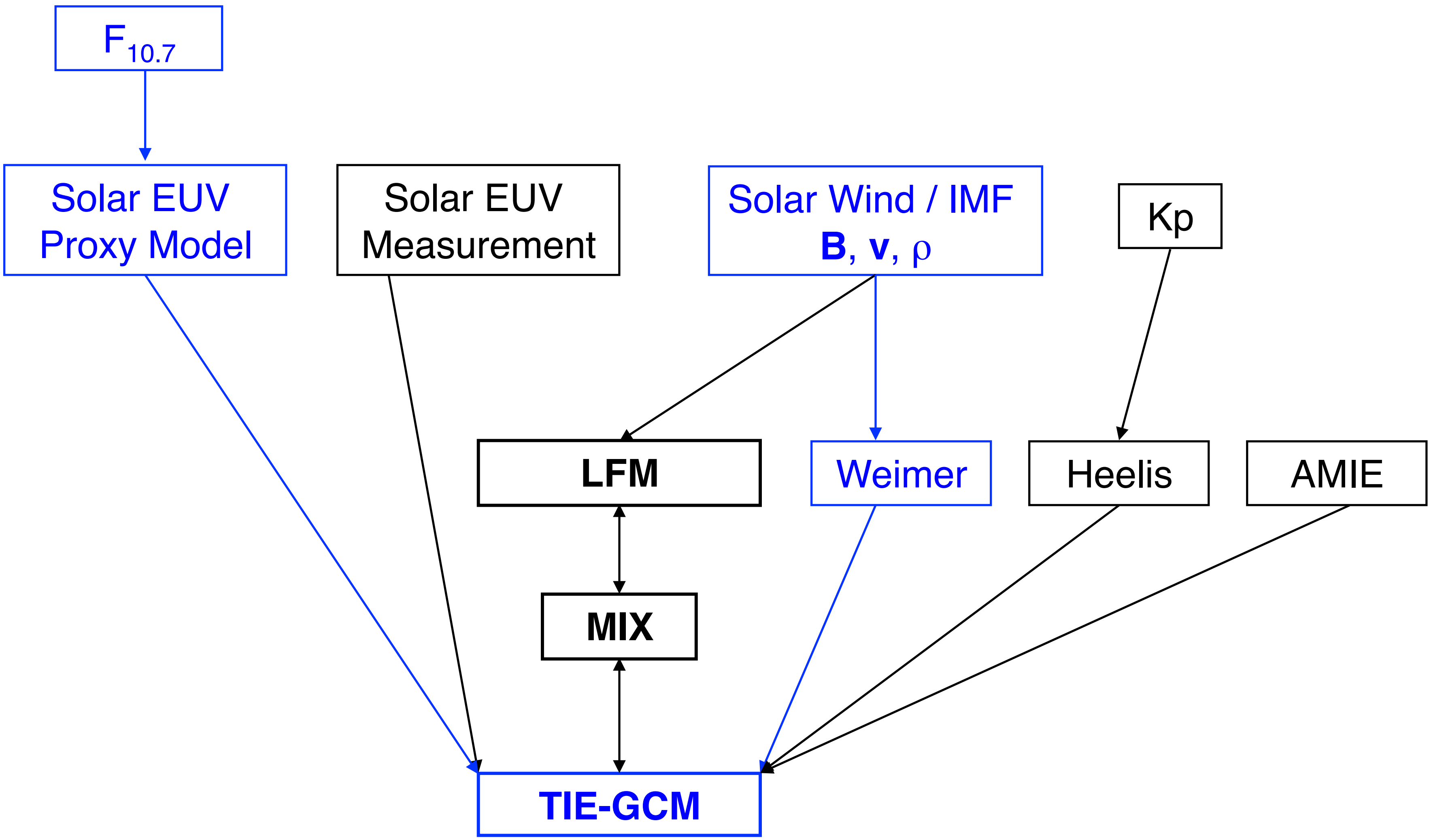


TIE-GCM "Extraterrestrial" Inputs and Options



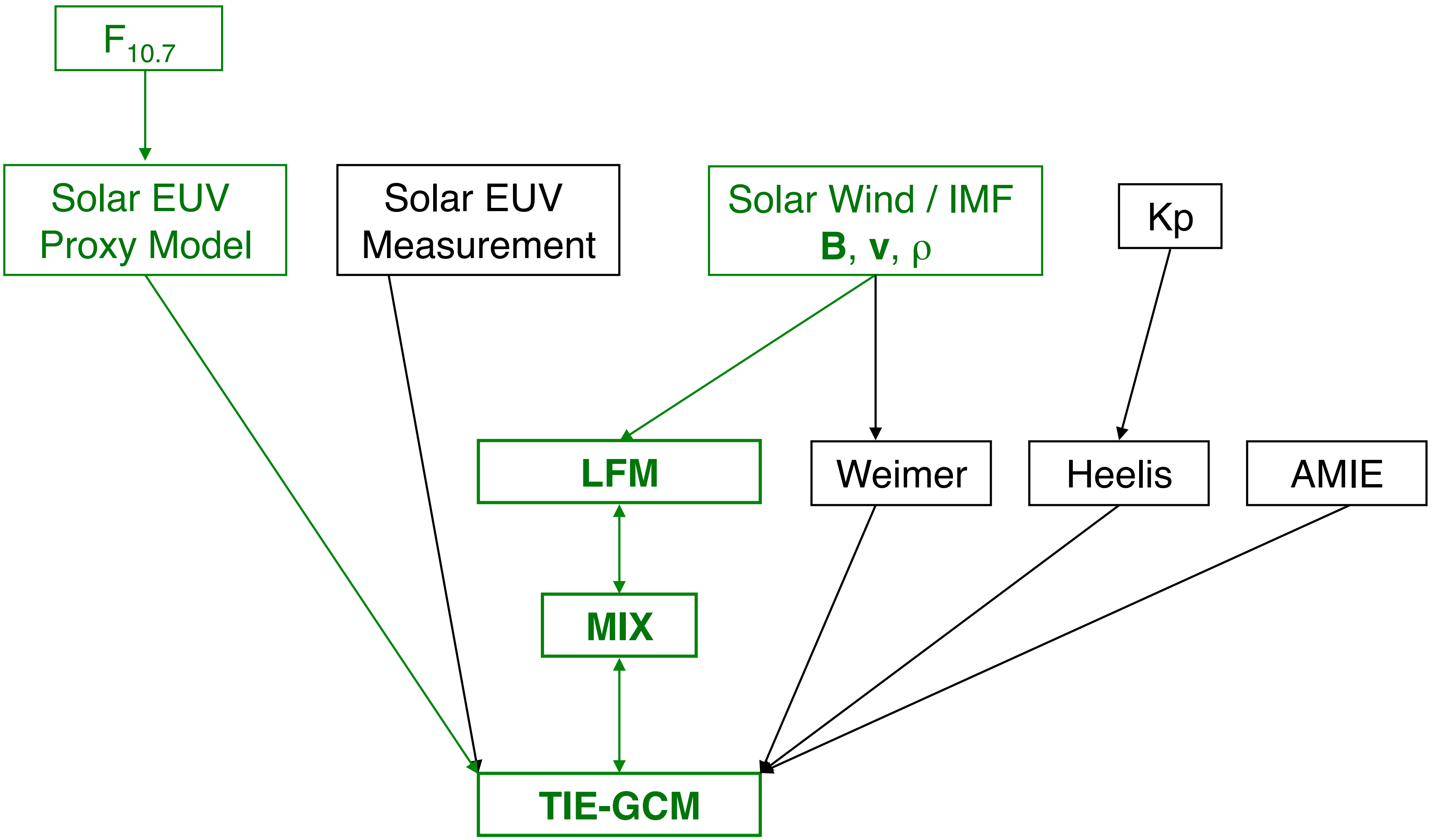
TIE-GCM “Extraterrestrial” Inputs and Options

Stand-Alone Model using Weimer ’05 High-Latitude Potential

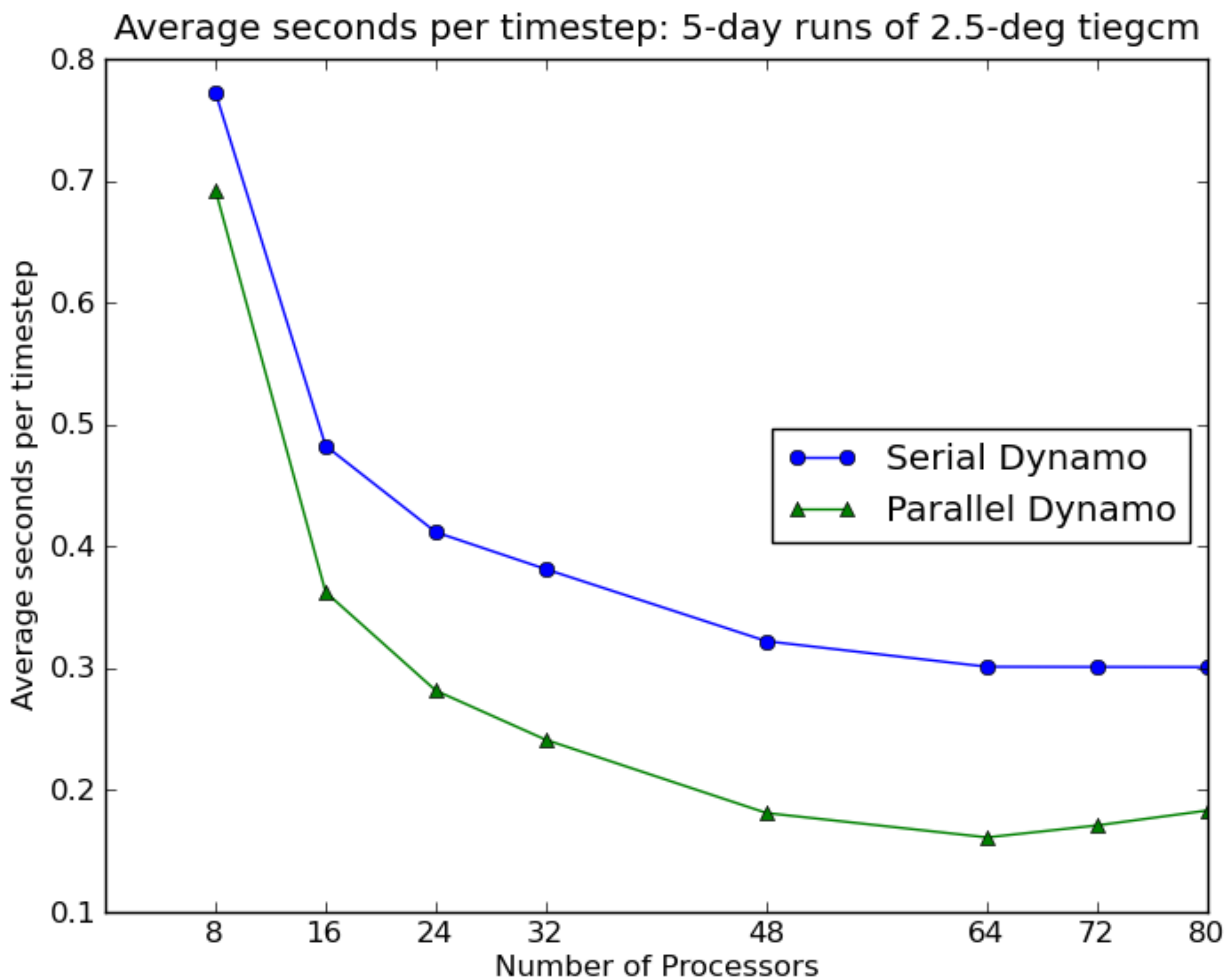


TIE-GCM "Extraterrestrial" Inputs and Options

CMIT Configuration



Performance Scaling using new Parallel Dynamo Module



- Low-res (5.0°) model runs at ~900 x wallclock, 60 s timestep on 16 processors.
- High-res (2.5°) model runs at ~200 x wallclock, 30 s timestep on 64 processors.

(yellowstone 2.6-GHz Intel Xeon E5-2670)

Performance Examples

	Low-res (5.0°) (60 s time step)	High-res (2.5°) (30 s time step)
yellowstone IBM iDataPlex Cluster (2.6 GHz Intel Xeon) Intel compiler	16 processors 0.07 s per step ~900 x wallclock 1 GB memory	64 processors 0.15 s per step ~200 x wallclock 5 GB memory
tethysv Dell Precision T7800 (3.1 GHz Intel Xeon) Intel compiler	8 processors 0.10 s per step ~600 x wallclock 1.5 GB memory	8 processors 0.60 s per step ~50 x wallclock 5 GB memory

Information, User Guide, Documentation, Source Code...

Main Page:
http://www.hao.ucar.edu/modeling/tgcm

Release Notes:
http://www.hao.ucar.edu/modeling/tgcm/tiegcm2.0/release/html/

User Guide:
http://www.hao.ucar.edu/modeling/tgcm/tiegcm2.0/userguide/html/

Documentation:
http://www.hao.ucar.edu/modeling/tgcm/doc/description/model_description.pdf

Post-Processors:
http://www.hao.ucar.edu/modeling/tgcm/doc/userguide/html/postproc.html

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