TIE-GCM v. 2.0

**Stan Solomon, Alan Burns, Barbara Emery, Ben Foster,
Hanli Liu, Gang Lu, Astrid Maute, Joe McInerney, Nick Pedatella,
Liying Qian, Art Richmond, Ray Roble, Wenbin Wang, and Qian Wu**

High Altitude Observatory
National Center for Atmospheric Research

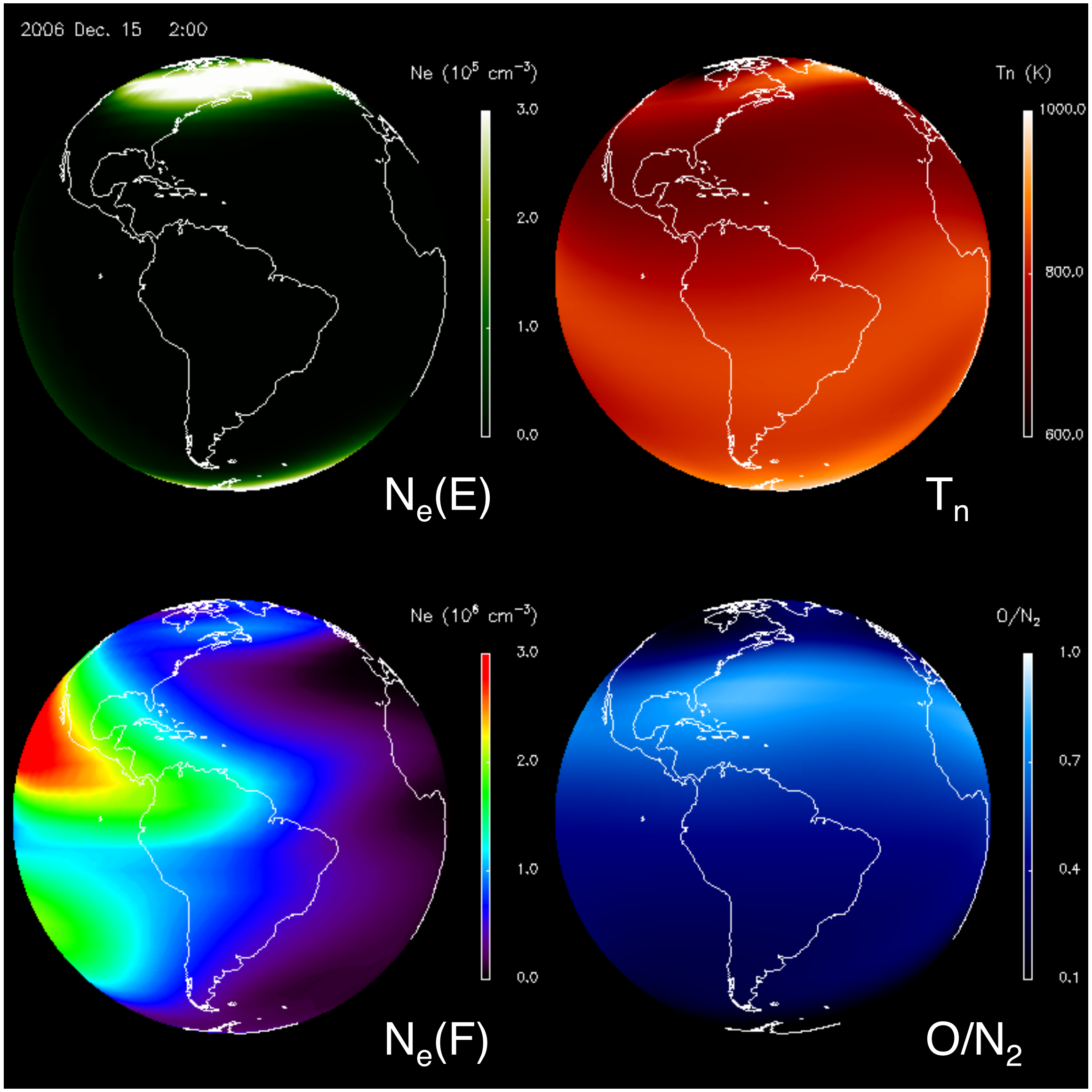
Eric Sutton

Air Force Research Laboratory

NCAR

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

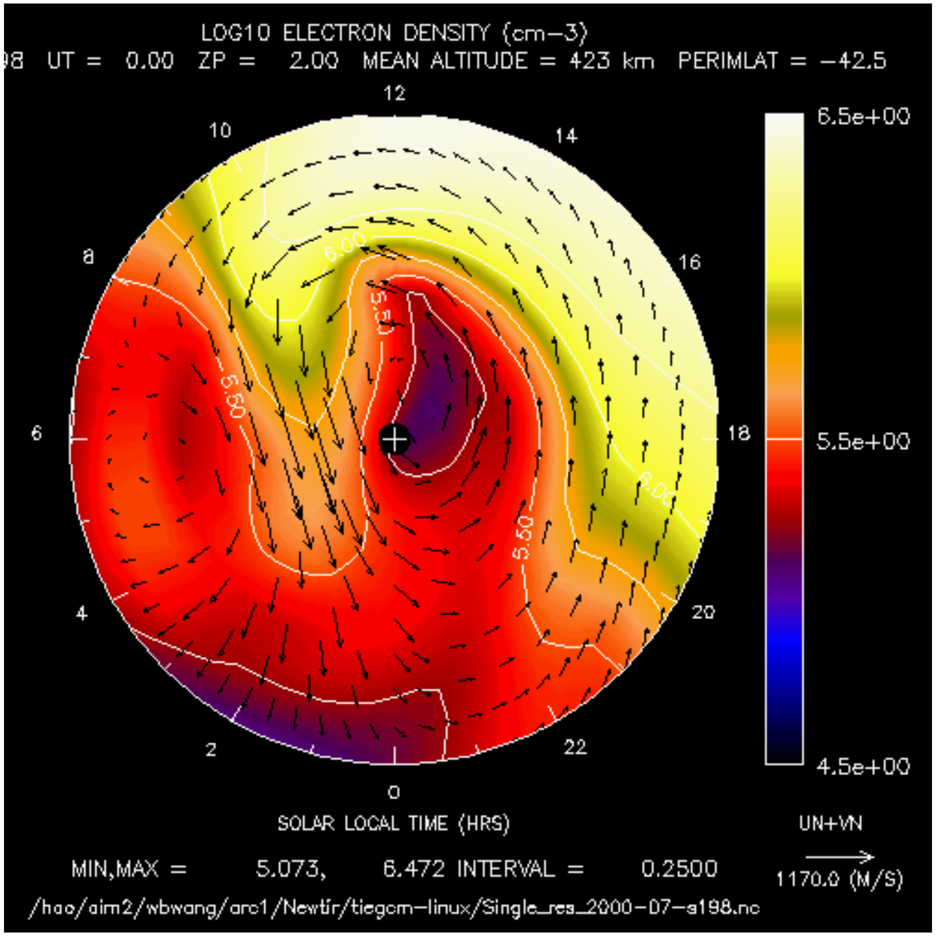
- Recommend 30-second time step for double res., 60-second time step for single-res.

- Other new features:

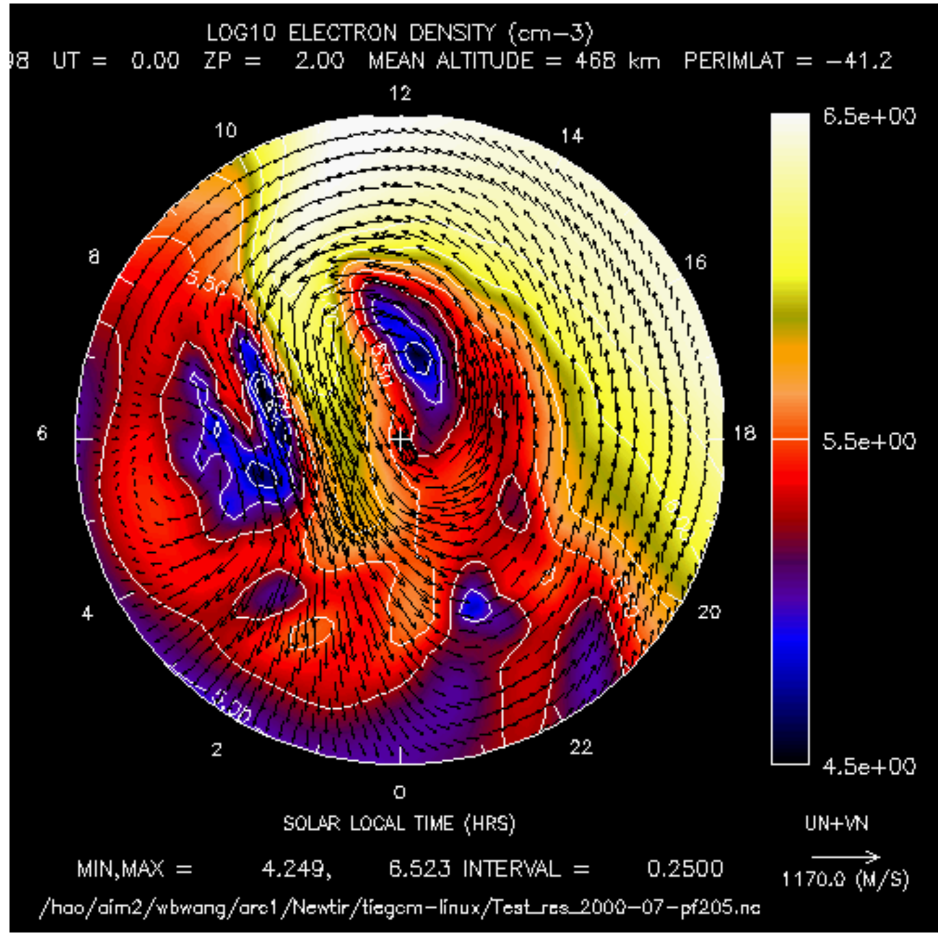
  Argon as a minor species
  IGRF12 and secular variation
  Non-migrating GSWM tides turned on in default inputs for high-res only
  Lower boundary zonal mean climatology
  CTMT (Oberheide/Forbes) tidal option
  AMIE interface merged to trunk
  CMIT interface updated
  Geometric Altitude ZG and (optionally) 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



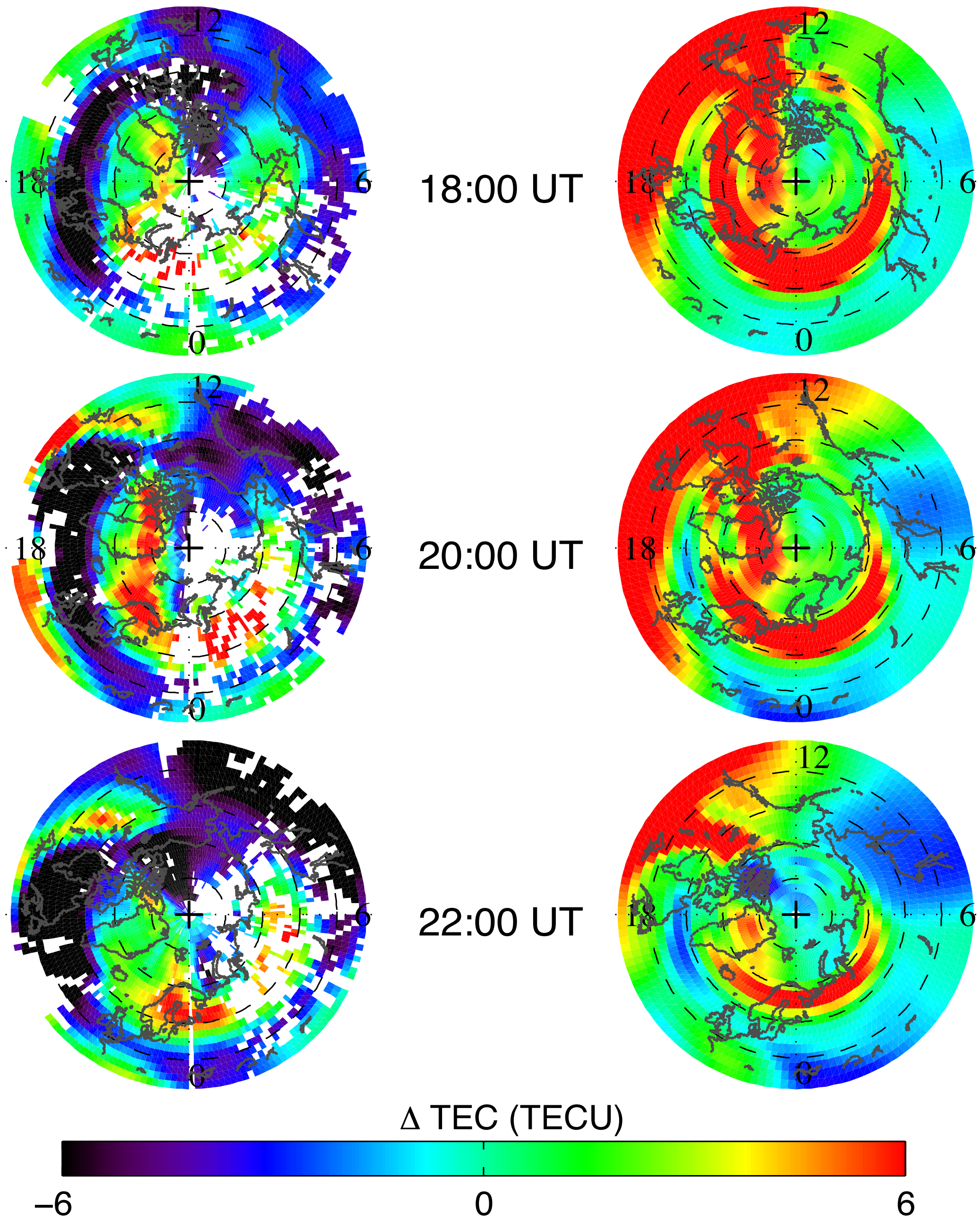
Double Resolution



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.

“Tongue of Ionization” Compared with GPS TEC

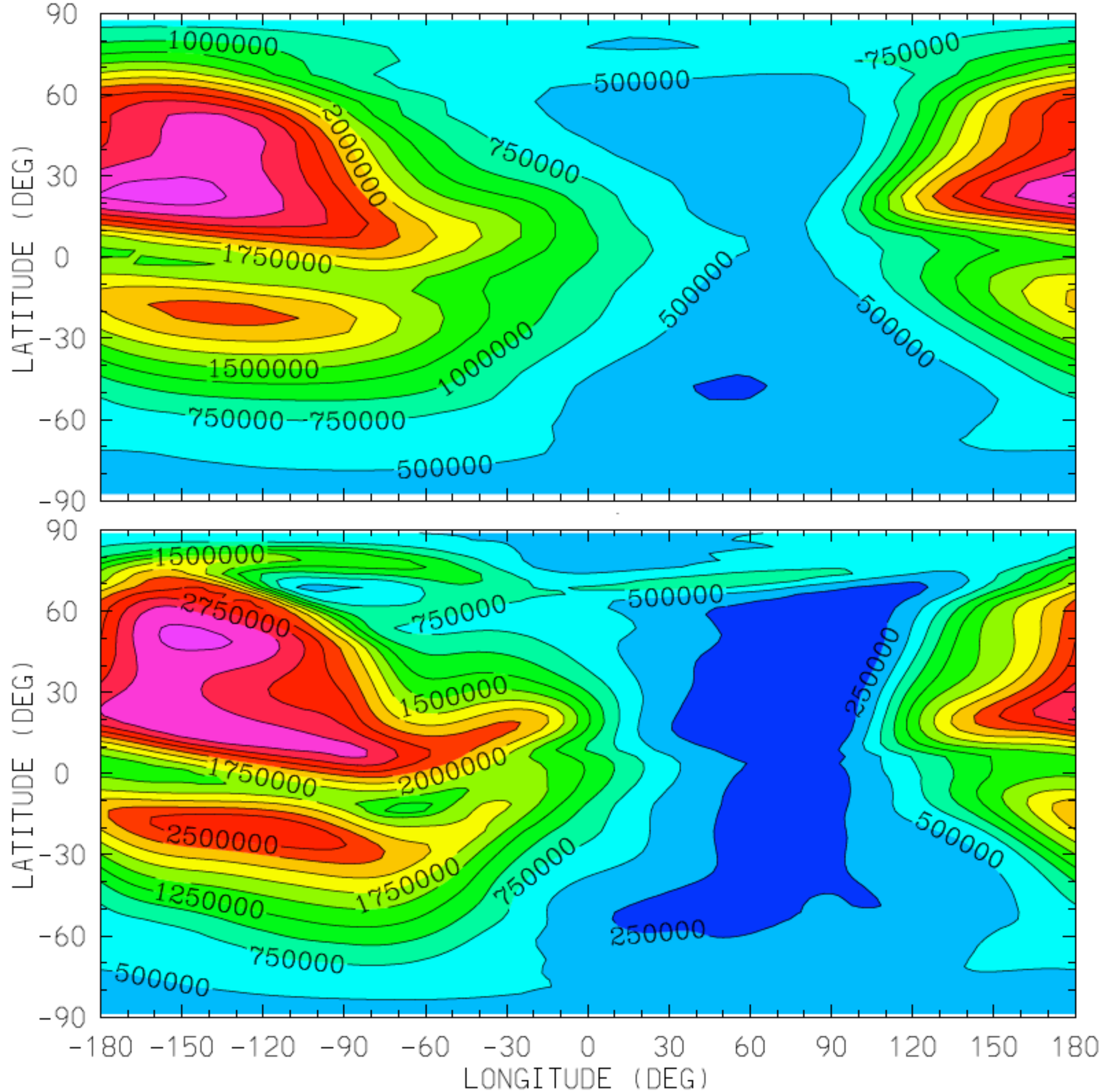
GPS Obervations of ΔTEC



TIE-GCM Simulations of ΔTEC

Jing Liu, et al., *JGR*, submitted, 2016.

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

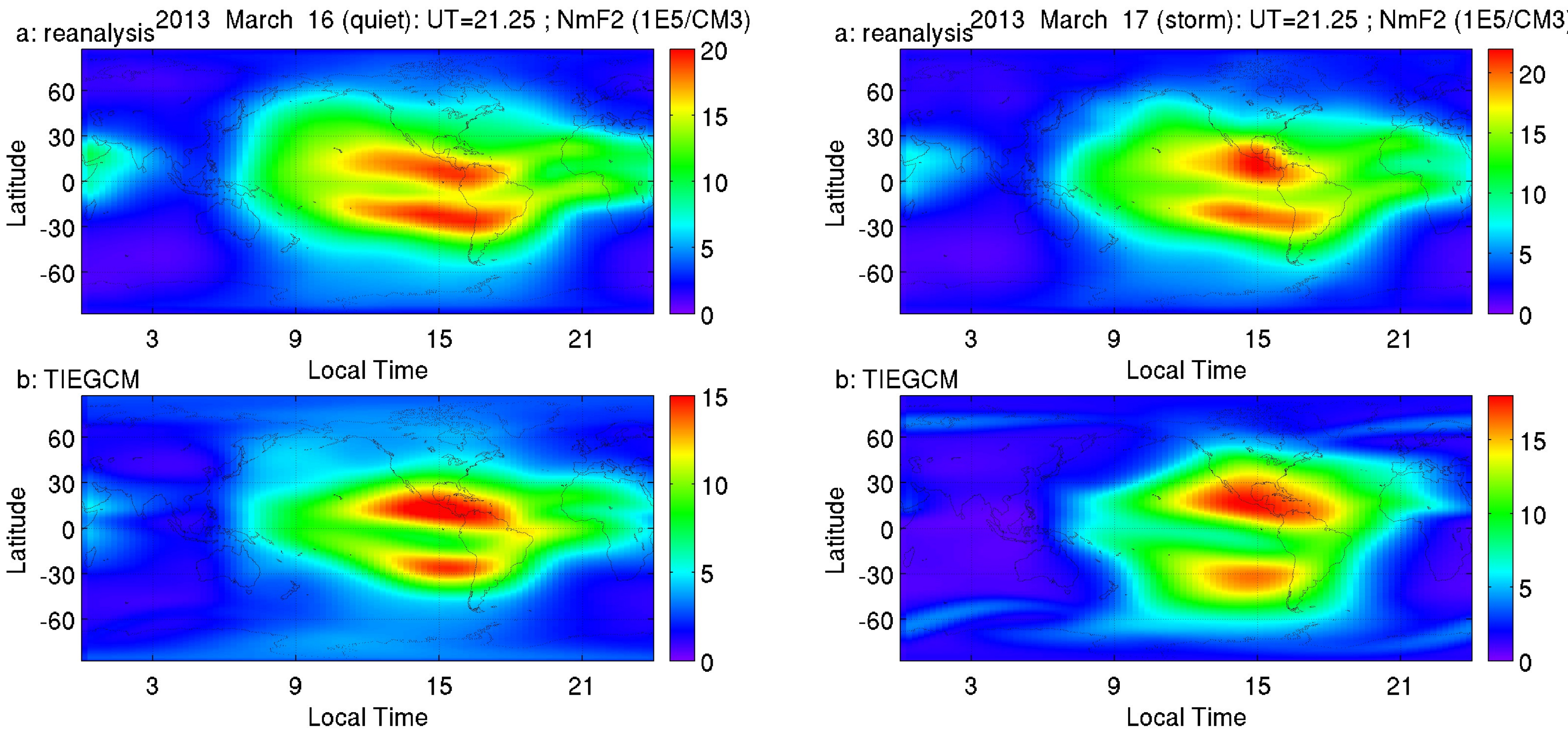


Normal Resolution

Double Resolution

December Solstice, 0 UT, Solar Maximum

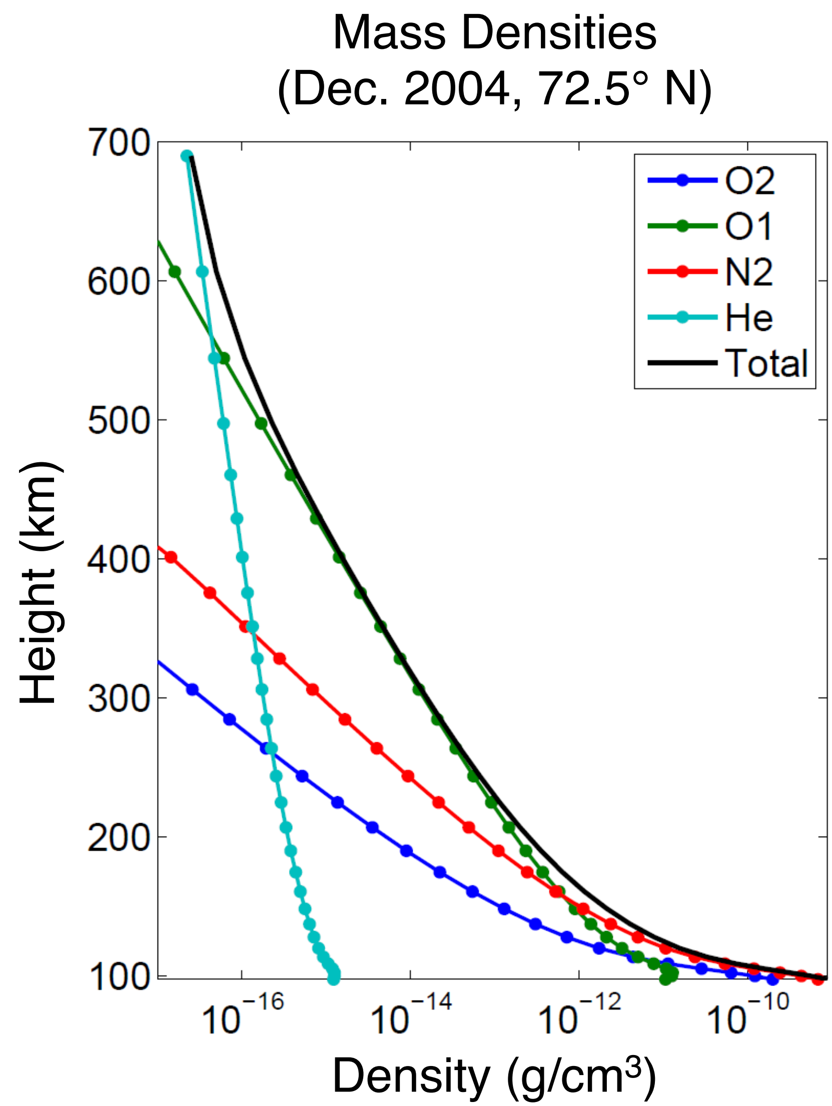
Comparison of COSMIC Re-analysis to the TIE-GCM



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.

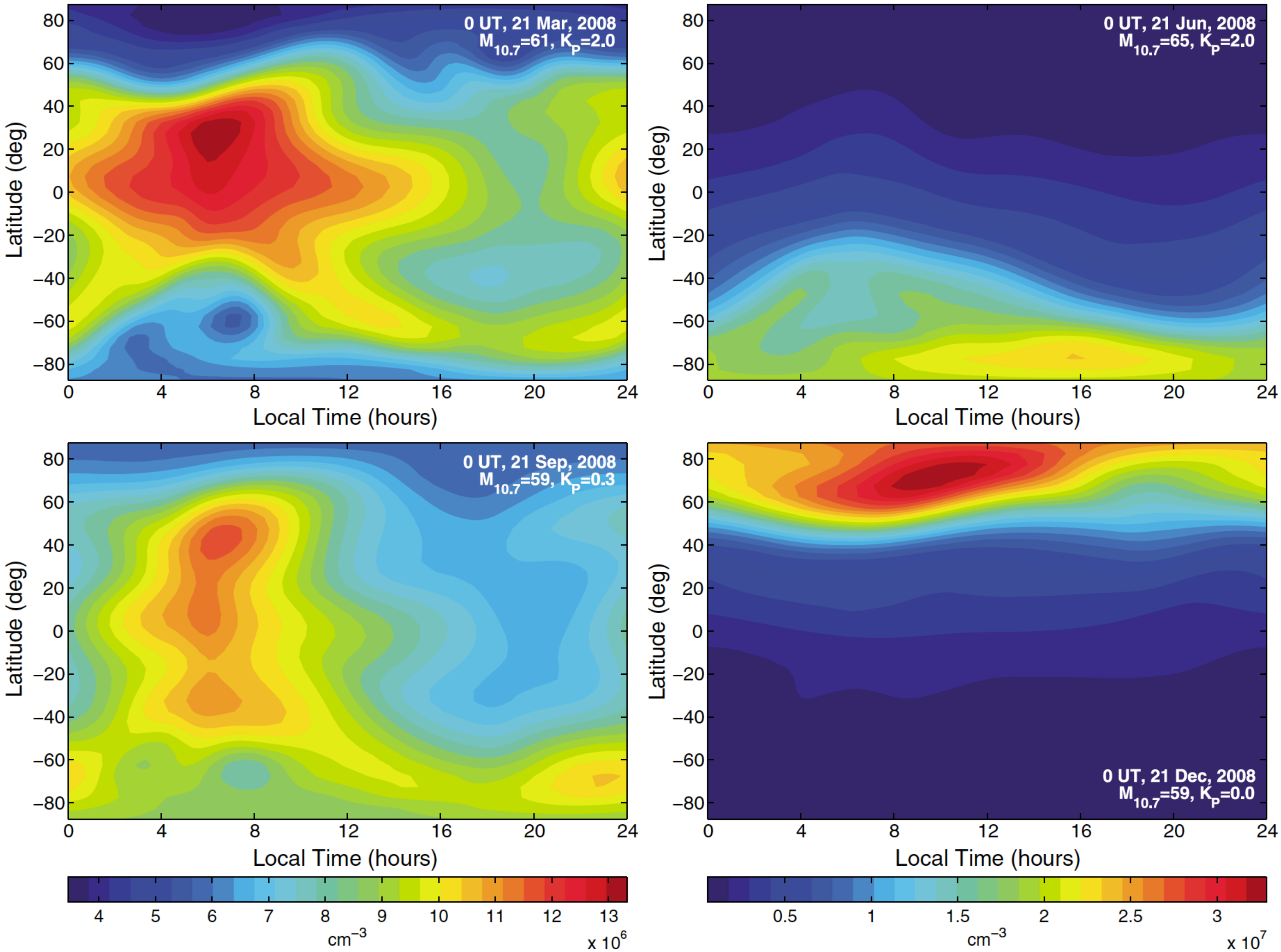
Inclusion of Helium as a Major Species

- 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

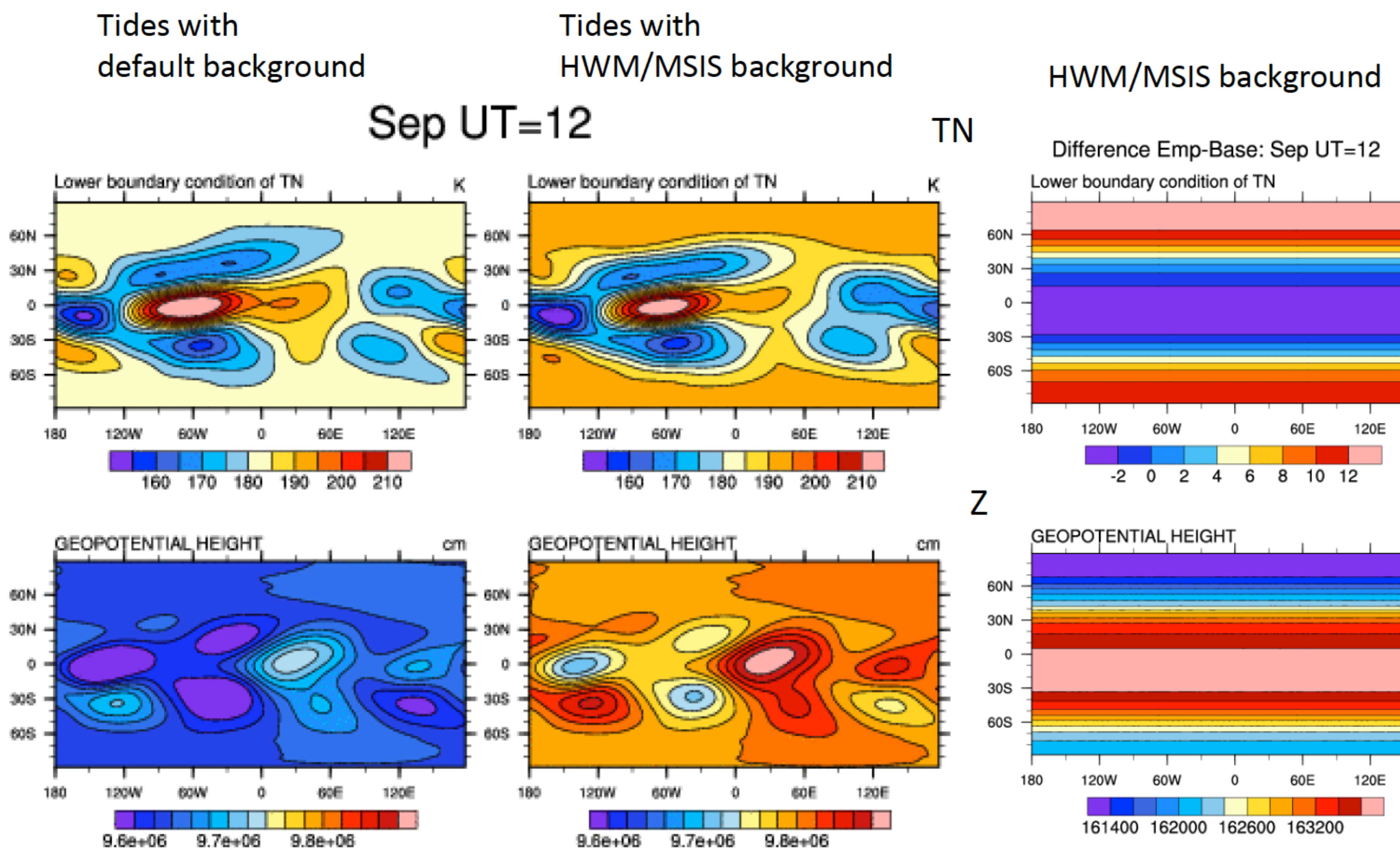
Simulation of the Winter Helium Bulge



Equinox

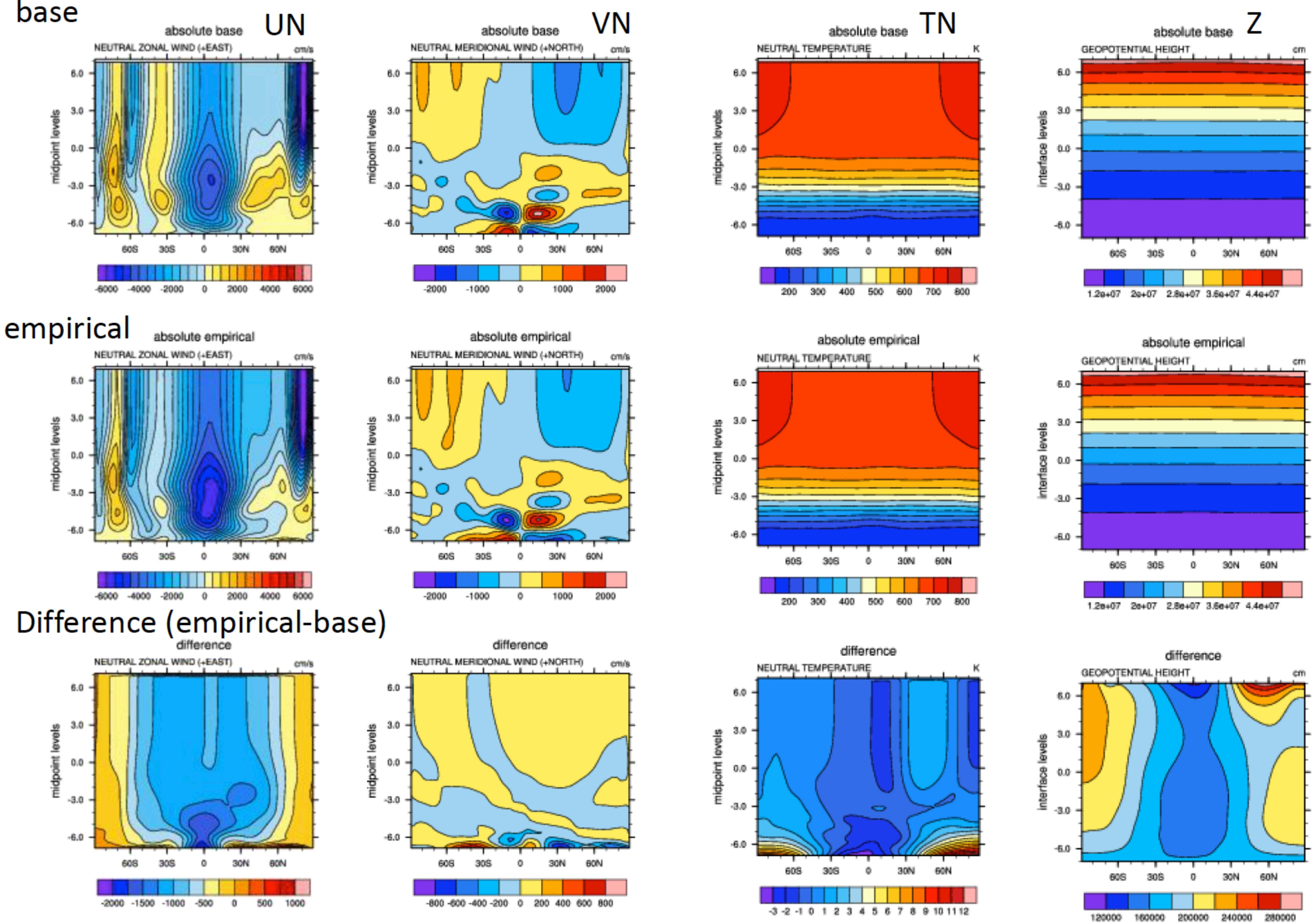
Solstice

Zonal Mean Climatology Option at Lower Boundary

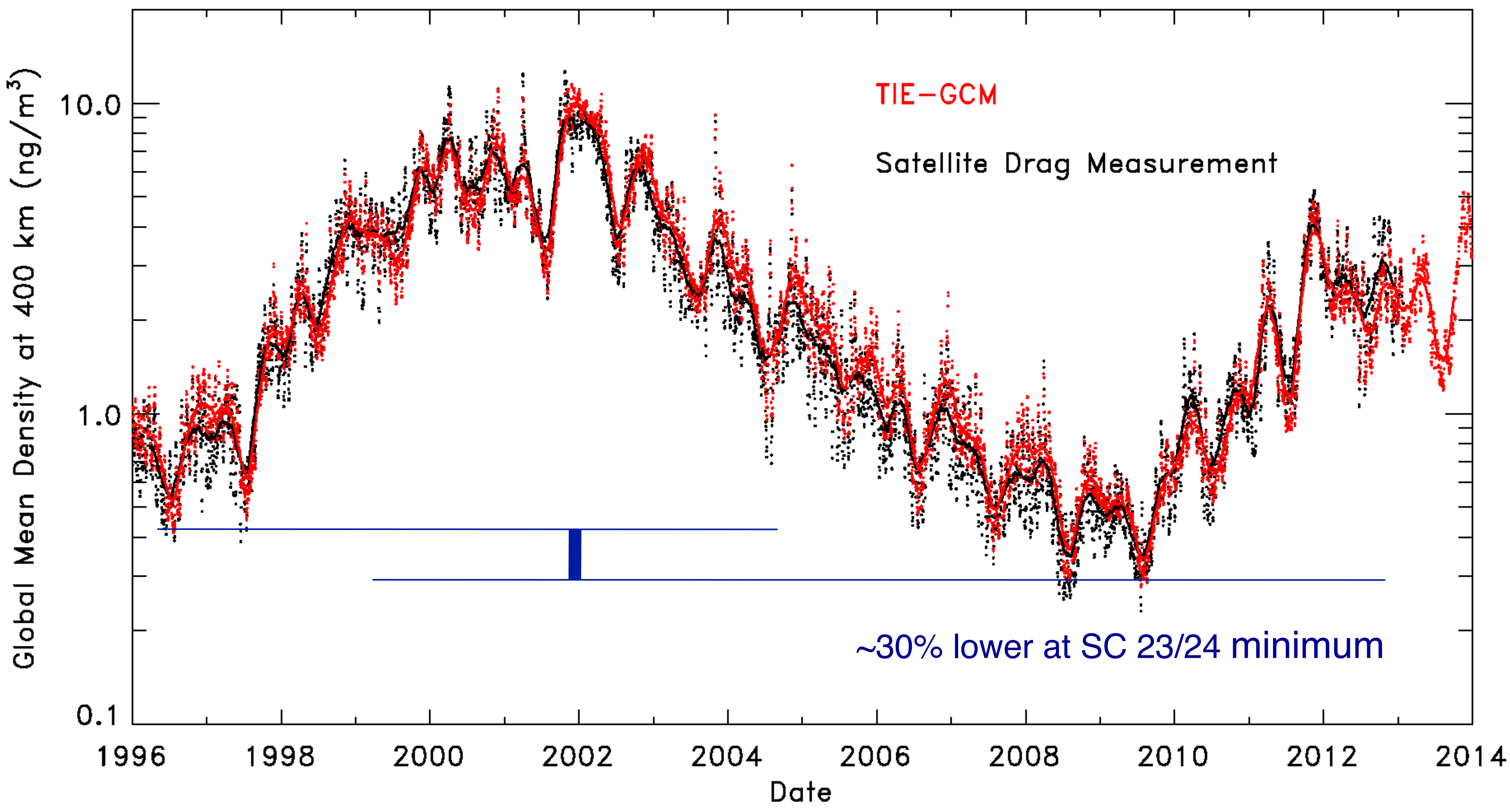


Mac Jones et al., JGR, 2014, implemented in v. 2.0 by Astrid Maute

Zonal Mean Climatology Option at Lower Boundary

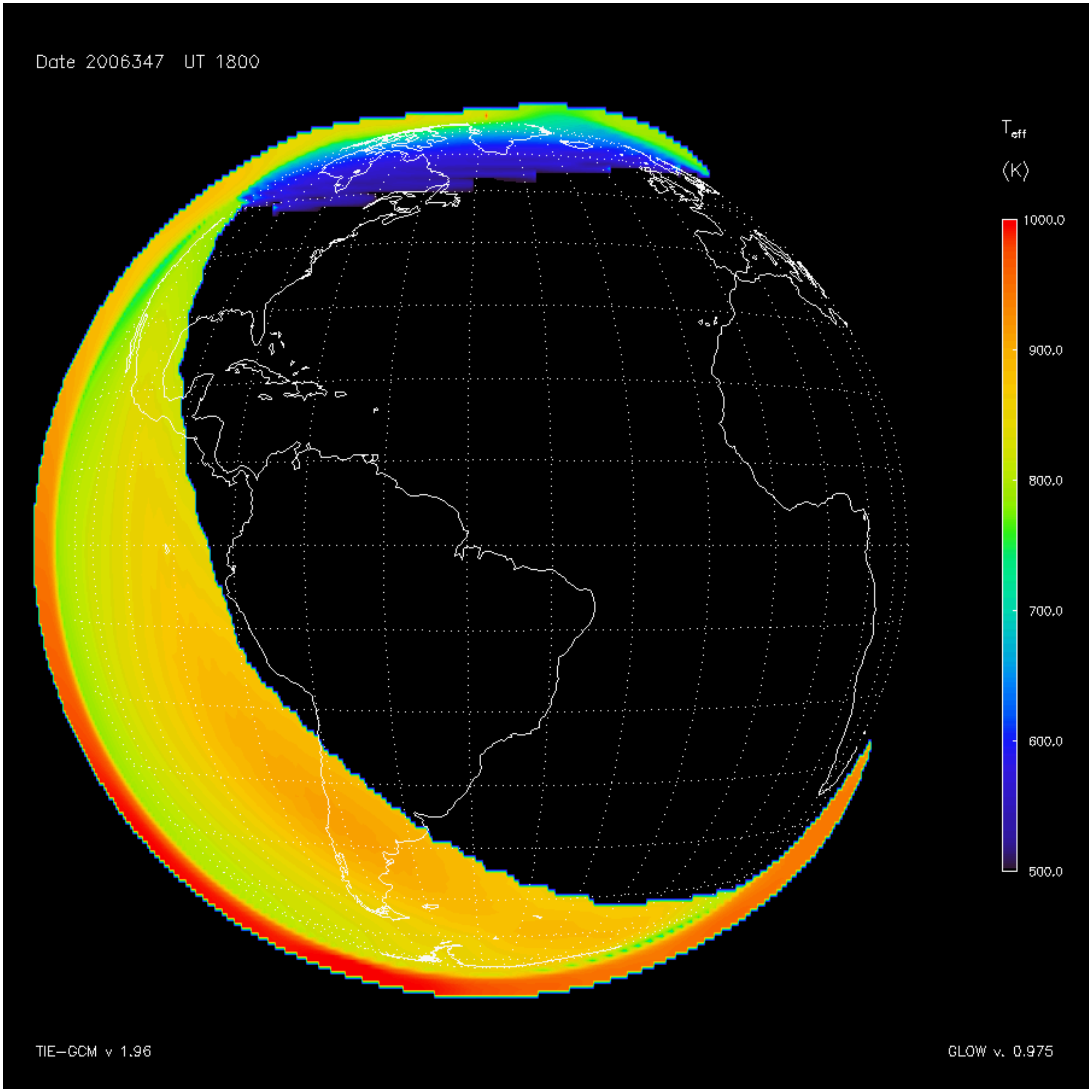


Thermospheric Density over 1.5 Solar Cycles



Simulation of Temperature Derived from N_2 LBH Bands

GLOW model using TIE-GCM inputs



Simulations for the NASA GOLD mission

What Else is New?

- Bug Fixes:
  - T_r mis-definintion in O^+
  - Decomposition fix so model can run with 4 processors
  - ZG, ZGmid and DEN extrapolation to top level
  - Restored $O^+_{(n-1)}$ to primary histories (for restart)
  - Fixed problem using ESMF with single processor

- Filters and Patches:
  - Default time step now 60 s at 5°, 30 s at 2.5°
  - Shapiro filter reduced as function of time step
  - FFT filter re-tuned for 2.5° resolution
  - O^+ Gaussian floor at low-mid latitudes (namelist switchable)
  - Optional O^+ diffusion limiter as namelist input

- Functional Improvements:
  - Runs on Intel, PGI, and gnu compilers on Linux (Intel on yellowstone)
  - Automated testing and benchmarks
  - Improved memory allocation
  - Improvements to file handling for continuation runs
  - Must compile with MPI even if using one processor
  - Users guide updates
  - Standardized namelist comment character (!)

Other recent minor changes, updates, & bug fixes (v. 1.94 to v. 1.95)

Fixed Kp so it can't go negative
Modified FFT filters for double-res version
Fixed error in GSWM interpolation
Added time-dependent CO_2 concentration at lower boundary
Added new diagnostics for magnetic and electric fields,
Introduced refactored Apex code apex.F90.
Change minimum EUVAC solar flux from 0.8 x Refspec to 0.1 x Refspec
Fixed bug in eddy and molecular viscosity coefficients in duv.F
Various yellowstone-specific script mods
Various performance improvements

Items Deferred to v. 2.1...

Upper Boundary O^+ and e^- heat flux
Electron heating rate parameterization
Revise seasonal/latitudinal variability of K_{zz} at lower boundary
Variable critical latitudes in CMIT and AMIE
Improve auroral ionization rate profile parameterization and dependence on E_0
Revise auroral precipitation oval for Heelis and Weimer
Re-evaluate JOULEFAC and COLFAC
Long-term secular variation
Make He a true major species:
- should be included in minor species diffusion calculation
- should be included in ionization/heating rate calculations
- should generate He^+

Add H as minor species
Add H^+ and charge exchange reactions
Replace quartic equation solver with time-dependent / iterative method
New solar model
New solar ionization scheme
Re-tuning of solar heating and radiative cooling

“Known Issues”

Technical:

Model will crash in debug mode due to an underflow error in filter2.
Will get some differences from changing time step (especially in O^+ and N_e).
Still may need to reduce time step for some large storms (for 2.5-degree model).
Setting CTPOTEN to near-zero results in an artificial electric field at high latitude.
Some fields may be incorrect at the top of the altitude array, so avoid the top level.
Zonal mean climatology at lower boundary doesn’t work with Hough-mode tides.
Problems with AMIE input at 5° resolution (although it’s OK at 2.5° resolution).
The model will stop after 2025 because IGRF doesn’t extrapolate further.
Quartic solver for electron density can be inaccurate.
TEC diagnostic is defined as only the integrated model column electron density.
Should force He, N_2, and maybe Mbar and/or ρ, onto secondary histories.

Scientific:

E-region electron density is still too low, particularly around the peak near 110 km.
Day/night T_n and density gradients in the upper thermosphere are too small.
Summer NmF2 and HmF2 are too low, particularly in the northern hemisphere.
Ionospheric winter anomaly, nighttime F-region, etc.need to be evaluated.
Minor error identified in vertical velocities for Joule heating calculation
CO_2 cooling rates are too low (compared to SABER), despite high CO_2 LBC.
Nitric Oxide is still not quite right (see Friday morning T-I heating/cooling session).
Optional seasonally-varying Kzz probably has too much amplitude.

...not an exhaustive list!

Current Development and Future Plans

- TIE-GCM v. 2.0 released March 2016.
  — Already found some minor problems
  — Many items on the wish-list for v. 2.1

- Moving from SubVersion (svn) to GitHub in September 2016
  — NCAR is discontinuing support for svn
  — In the meantime, we are reluctant to do a lot of updates in svn

- WACCM-X development ongoing
  — Ionosphere module will be included in CESM v. 2 release next winter
  — Next step is to include a fully-coupled ionosphere-plasmasphere module

- 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.

- Whither TIME-GCM?

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

Home | About HAO | Research | **Modeling** | Observations/Data | News & Events | Partnerships | Education | For Staff

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Modeling Home

TGCM Home

Models

TIE-GCM

TIME-GCM

Global Mean

Processors

intro to processors

tgcmproc_f90

tgcmproc_idl

ncl

Downloads

tiegcm

Documentation

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

User Guide [html]-&-[pdf]

Draft Model Description [pdf]

Forums

tgcm mailing list

Research

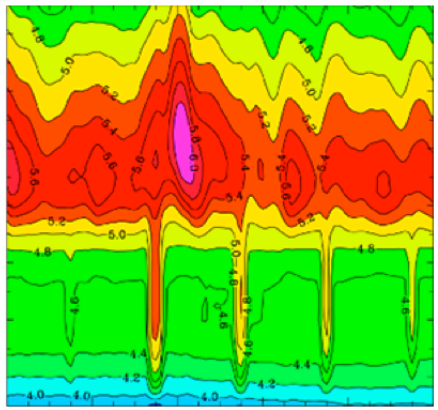
Highlights

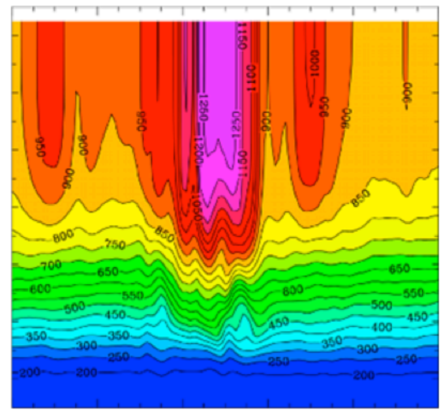
Highlights (archived)

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

RTFM!

(Read the Foster Manuals!)

Release Notes (html or pdf):

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

User Guide (html or pdf):

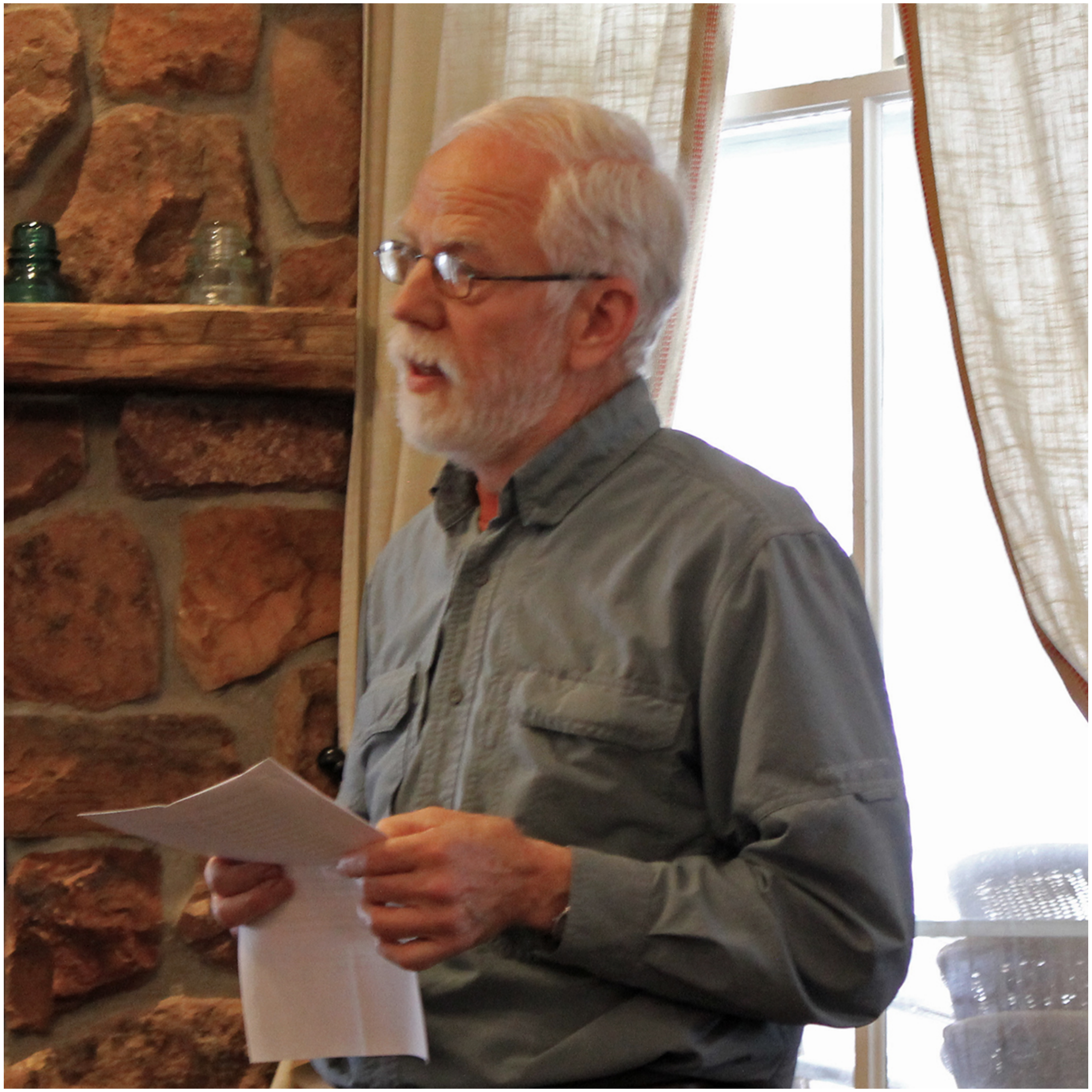
http://www.hao.ucar.edu/modeling/tgcm/tiegcm2.0/userguide

Also see the Draft Model Description:

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

This document is primarily the work of Astrid Maute, working off of notes from Cicely Ridley and Ray Roble, and is always a work in progress. Feel free to send in clarifications, corrections, and contributions!

Ben Foster



Ben speaking at his retirement party, Chautauqua, Boulder, Colorado, March 2016

Quo Vadimus?

TGCMgroup mailing list:

join at: http://mailman.ucar.edu/mailman/listinfo/tgcmgroup

mail to: tgcmgroup@mailman.ucar.edu

— messages to this list are "moderated"
  — we will try to answer questions, if we can, or,
  — if something is of general interest, we will post it to the group

My "Known Issues" and "Development Goals" logs:

http://download.hao.ucar.edu/pub/stans/tgcm

(linked from http://www.hao.ucar.edu/modeling/tgcm under "development logs"

...if you see something, say something!

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.

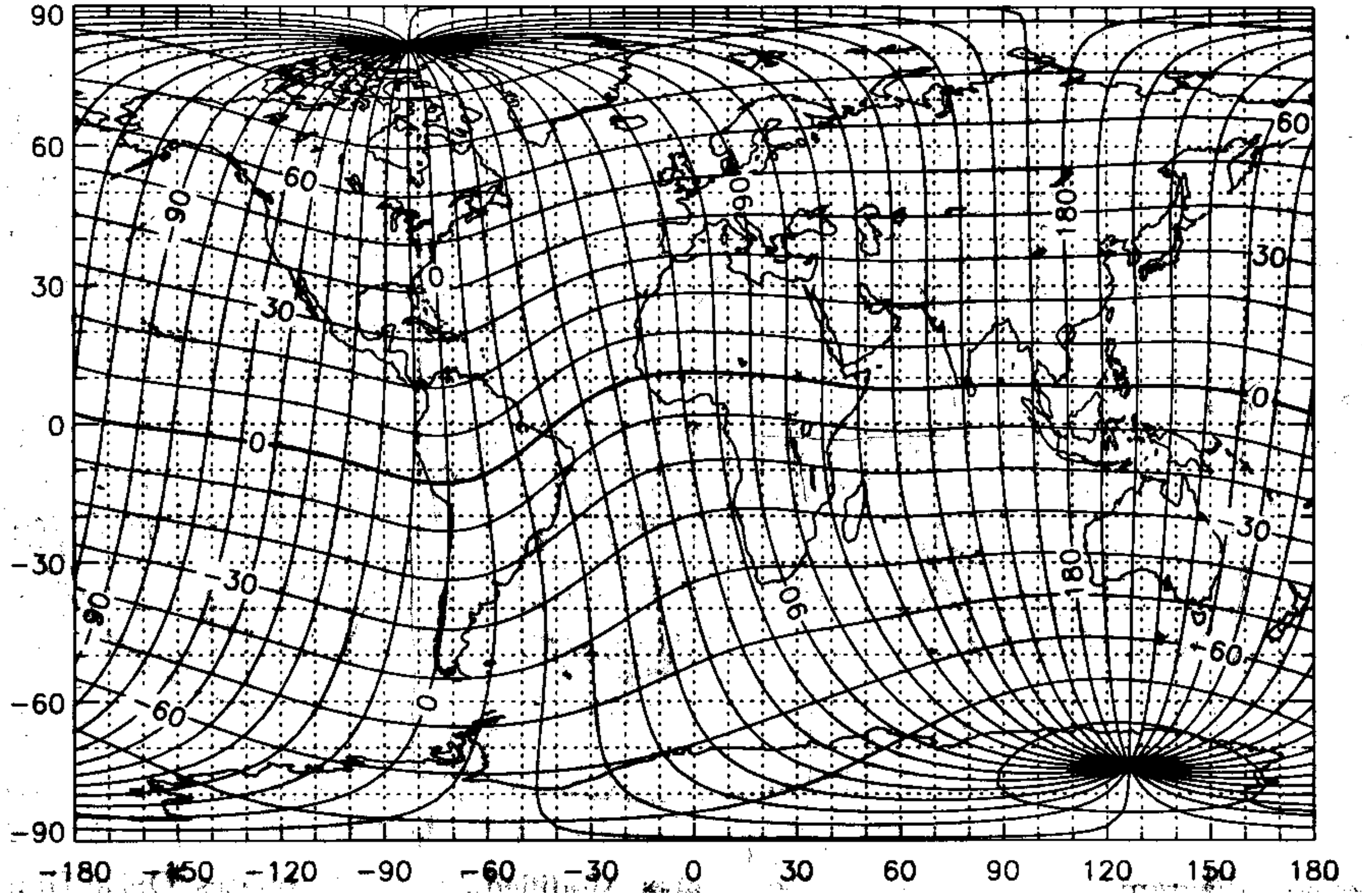
- **Numerics:**
  Horizontal: explicit 4th order centered finite difference
  Vertical: Implicit 2nd order centered difference
  Time: 2nd order centered difference
  Shapiro filter: achieve better numerical stability
  Fourier filter: remove spurious high frequency zonal waves at high latitudes

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.

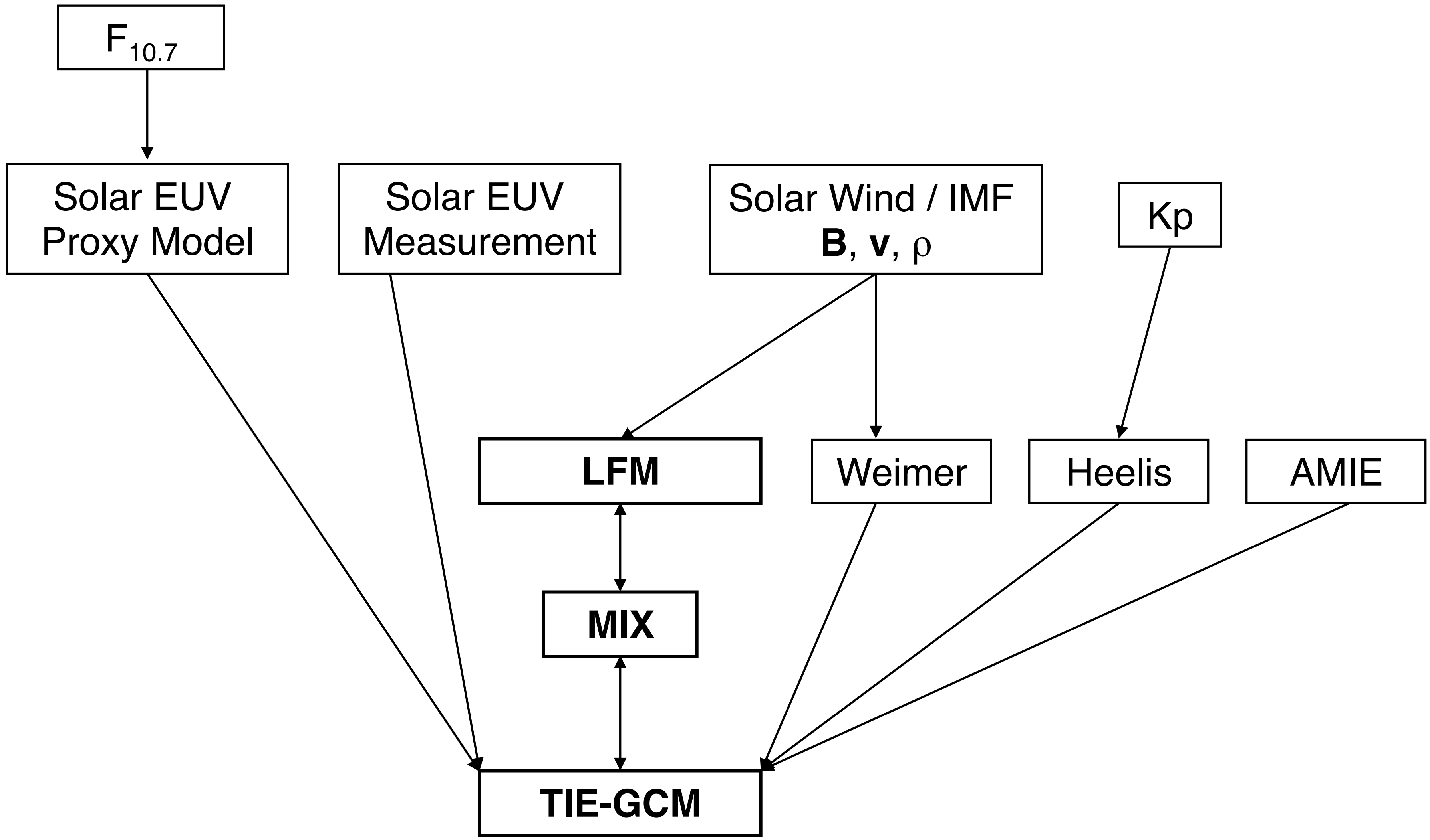
- **Lower boundary conditions:**
  u, v: specified by tides (GSWM)
  T_N: 181 K + perturbations by tides (GSWM)
  O_2: fixed mixing ratio of 0.22
  O: vertical gradient of the O density is zero
  $N(^4S)$, O^+: photochemical equilibrium
  NO: constant density of (8×10^6)
  T_e: equal to T_N.

Electrodynamics



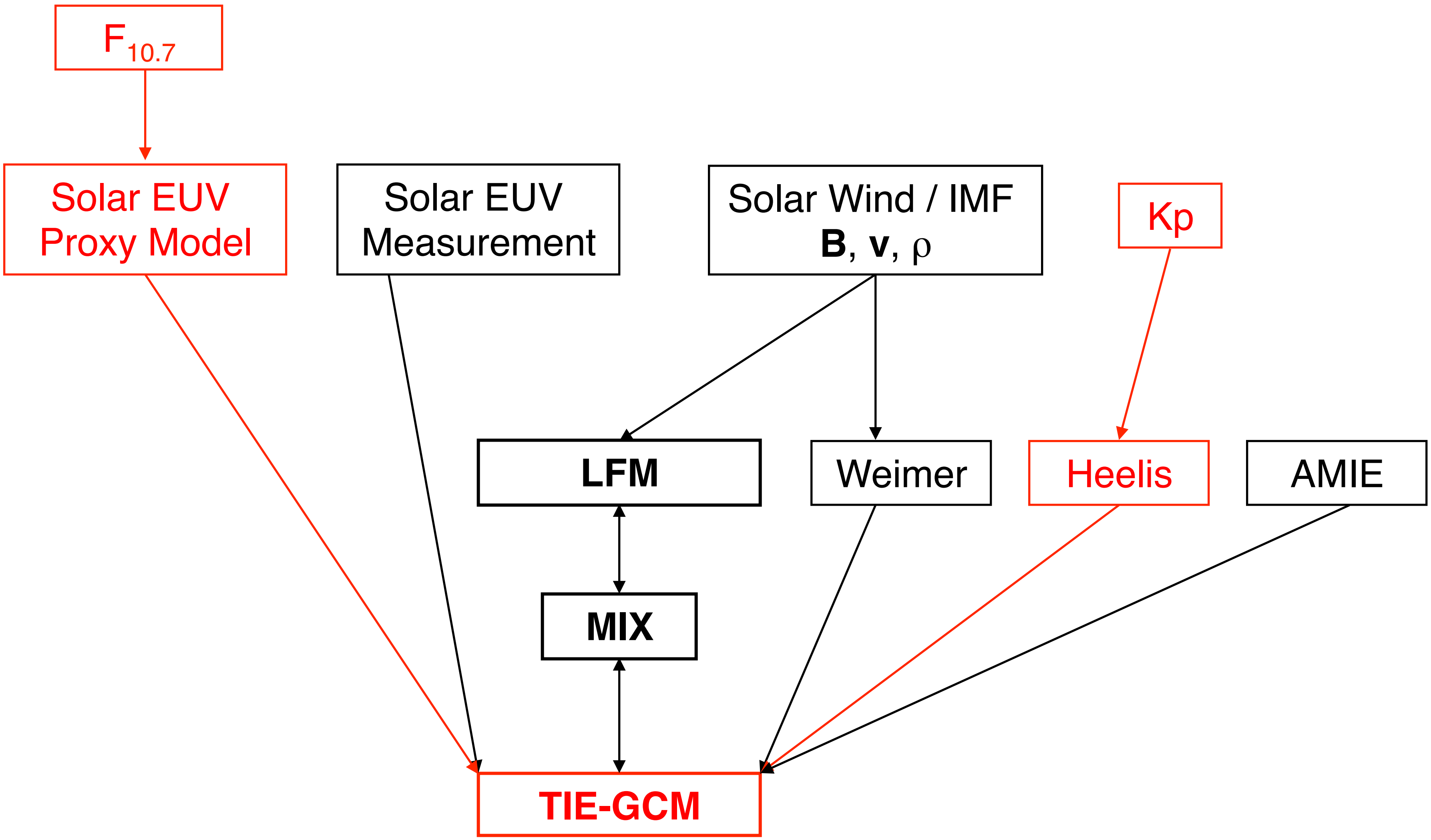
- Low and mid-latitude: neutral wind dynamo equations solved in geomagnetic Apex coordinates [Richmond et al., 1992; 1995].
- High latitude: specified by convection models such as Heelis, Weimer, or AMIE, or coupled to the LFM Magnetosphere Model.

TIE-GCM "Extraterrestrial" Inputs and Options



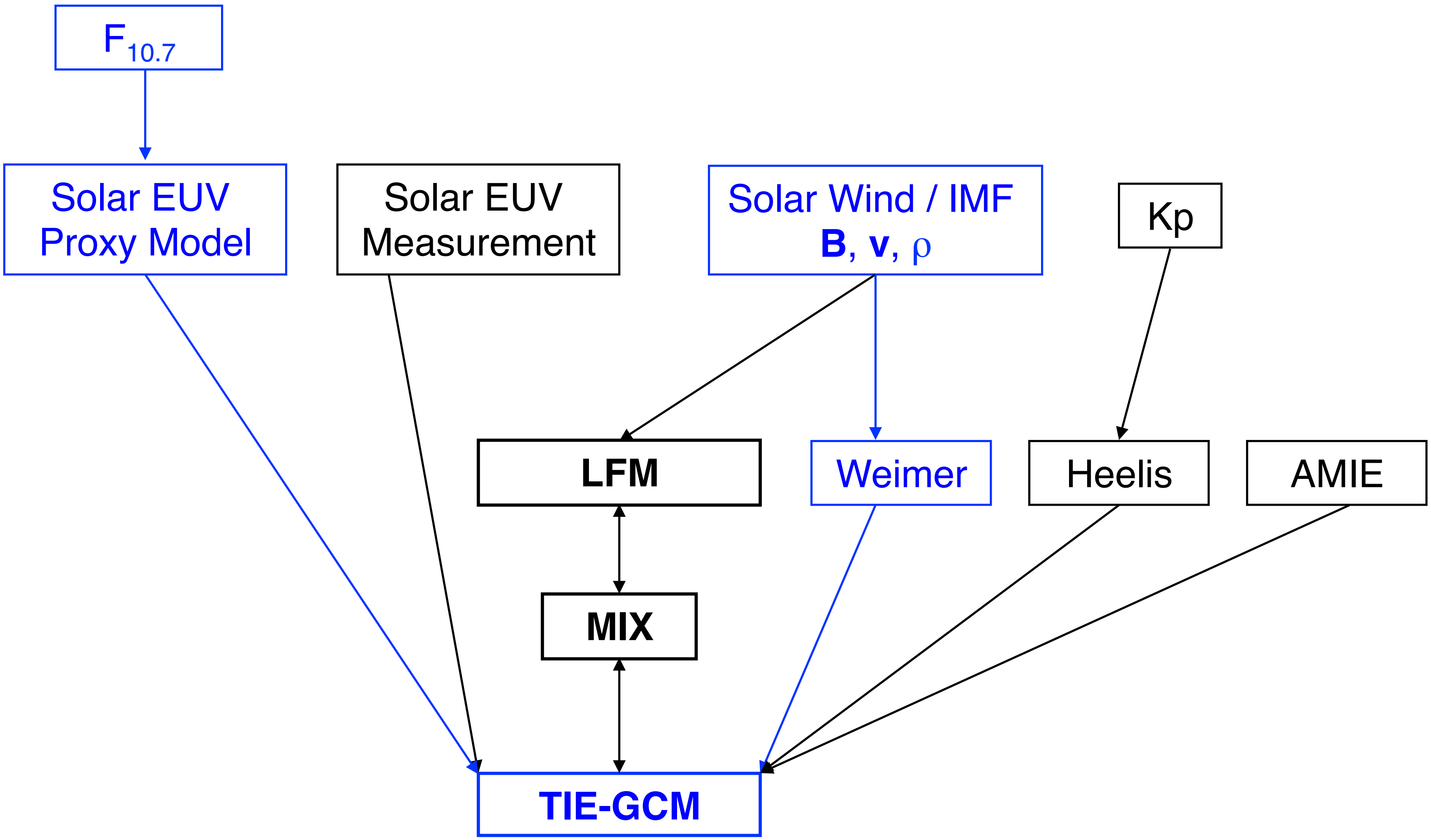
TIE-GCM "Extraterrestrial" Inputs and Options

Basic Stand-Alone Model

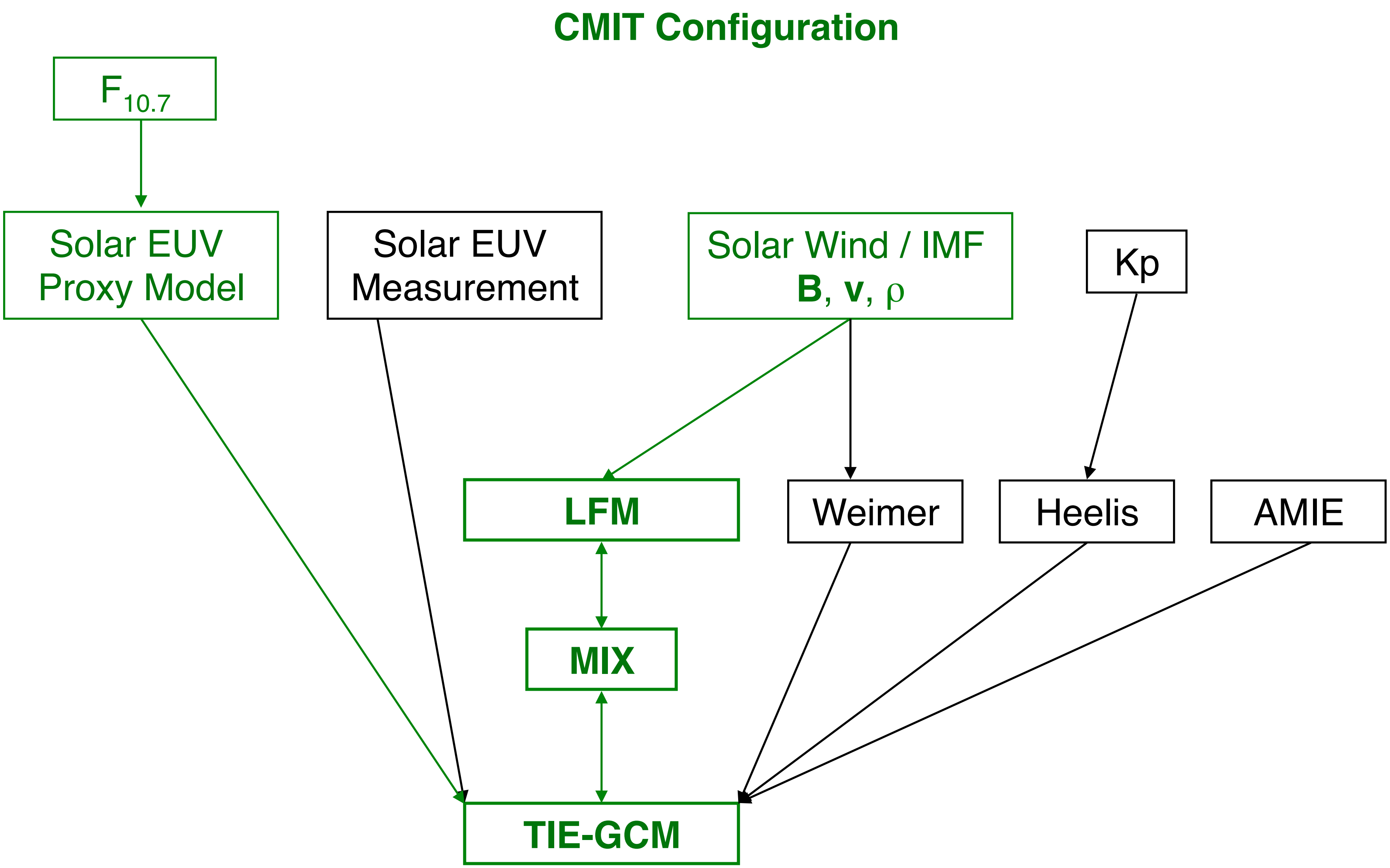


TIE-GCM “Extraterrestrial” Inputs and Options

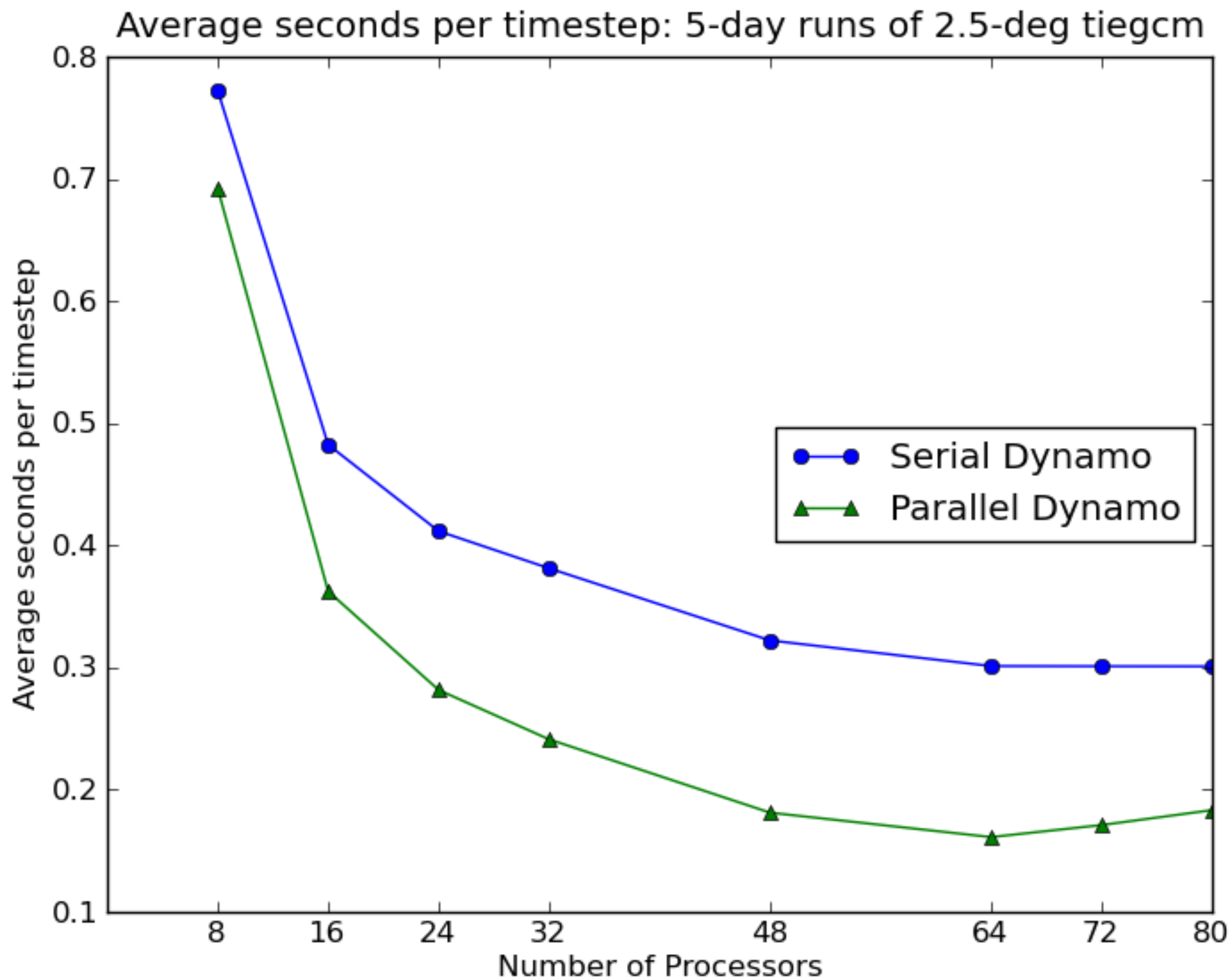
Stand-Alone Model using Weimer ’05 High-Latitude Potential



TIE-GCM "Extraterrestrial" Inputs and Options



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)

TIE-GCM 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

Altitude Coordinates

See the chapter in the Users Guide:

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

Or the file at:

http://download.hao.ucar.edu/pub/stans/tgcm/Zcoordinates.pdf

The TIE-GCM and TIME-GCM use a log-pressure coordinate system, with each pressure level defined as ln(P_0/P), where $P_0 = 5 \times 10^{-4}$ dynes/cm^2 = 5×10^{-5} Pascal = 5×10^{-7} hPa = 5×10^{-7} mb. (Native units in these models are cgs, i.e., dynes/cm^2.) This pressure occurs at ~200 km altitude, depending on conditions.
The TIE-GCM vertical coordinate extends from -7 to +7 (~97 km to ~600 km) and the TIME-GCM vertical coordinate extends from -17 to +7 (~30 km to ~600 km). Each integer interval in pressure level is one scale height apart, so the low-res (5°x5°xH/2) versions are spaced at half-integer intervals and the high-res (2.5°x2.5°xH/4) versions of the models are spaced at quarter-integer intervals:

First, we define the *geopotential height z.* Geopotential height is the height that the pressure surface would be, assuming that the acceleration due to gravity *g* is constant at the value used in the model calculations (870 cm/s^2 for the TIE-GCM and 950 cm/s^2 for the TIME-GCM). However, it is *not* the appropriate altitude coordinate for comparison with real-world data. Also note that this definition of geopotential height is *not* the same as what is used in, e.g., tropospheric meteorology, because it is referenced to value of *g* that is different from the value of *g* at the surface (~980 cm/s^2).

We can correct the *geopotential height z* to obtain *geometric height* z_g. This is performed inside the models by subroutine zgcalc, using an empirical formulation of the variation of *g* over the globe (including centripetal force), and vertical integration, to account for the variation with altitude. It can also be done, using the same subroutine, in the Fortran model processers, and is also available in various IDL processing routines.
Geometric height z_g is now forced onto secondary histories. However, some older secondary history files may not include z_g which necessitates that it be calculated in the post-processing if needed for data comparison.

Now we come to the final complication, the distinction between model *interfaces* and model *mid-points*...

Some Recent Publications

Solomon, S. C., A. G. Burns, B. A. Emery, M. G. Mlynczak, L. Qian, W. Wang, D. R. Weimer, and M. Wiltberger, Modeling studies of the impact of high-speed streams and co-rotating interaction regions on the thermosphere-ionosphere, *J. Geophys. Res.*, *117*, A00L11, doi: 10.1029/2011JA017417, 2012.

Qian, L., A. G. Burns, B. A. Emery, B. Foster, G. Lu, A. Maute, A. D. Richmond, R. G. Roble, S. C. Solomon, and W. Wang, The NCAR TIE-GCM: A community model of the coupled thermosphere/ionosphere system, *Modeling the Ionosphere-Thermosphere System*, *AGU Geophy. Mono.*, *201*, 73, doi:10.1002/9781118704417.ch7, 2014.

Richmond, A D., and A. Maute, Ionospheric electrodynamics modeling, *Modeling the Ionosphere-Thermosphere System*, *AGU Geophys. Mono.*, *201*, 57, doi:10.1029/2012GM001331, 2014.

Burns, A. G., W. Wang, S. C. Solomon, and L. Qian, Energetics and composition in the thermosphere, *Modeling the Ionosphere-Thermosphere System*, *AGU Geophys. Mono.*, *201*, 39, doi:10.1002/9781118704417.ch4, 2014.

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