The NCAR TIE-GCM:
Model Description, Development, and Validation

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

- Original development by Ray Roble, Bob Dickinson, Art Richmond, et al.
- The atmosphere/ionosphere element of CMIT and the CISM model chain
- Cross-platform community release (v. 1.93), under open-source academic research license
  - v. 1.94 release, May 2011
  - User manual complete
  - Documentation mostly complete
- Runs-on-request at CCMC
Development History

Thermosphere General Circulation Model
TGCM, 97~500 km, *Dickinson et al., 1981; 1984; Roble et al., 1982*

Thermosphere-Ionosphere General Circulation Model
TIGCM, 97~500 km, *Roble et al., 1987; 1988*

Thermosphere-Ionosphere-Electrodynamics General Circulation Model
TIE-GCM, 97~500 km, *Richmond et al., 1992; Richmond, 1995*

Thermosphere-Ionosphere-Mesosphere-Electrodynamics GCM
TIME-GCM, 30~500 km, *Roble and Ridley, 1994; Roble, 1995*

Whole Atmosphere Community Climate Model
WACCM, 0~140 km, *Marsh et al., 2007; Garcia et al., 2007*

Extended Whole Atmosphere Community Climate Model
WACCM-X, 0~500 km, *Liu et al., 2010*
Equations

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

Coordinate system: horizontal: rotating spherical geographical coordinates; vertical: pressure surface (hydrostatic equilibrium)

Resolution: horizontal: 5° x 5°; vertical: 0.5 pressure scale height. High resolution version (2.5° x 2.5° x H/4) in test.
Numerical Techniques

- **Horizontal**: explicit 4\textsuperscript{th} order centered finite difference;
- **Time**: 2\textsuperscript{nd} order centered difference;
- **Vertical**: Implicit 2\textsuperscript{nd} order centered difference;
- **Shapiro filter**: achieve better numerical stability;
- **Fourier filter**: remove high frequency zonal waves generated by finite difference (high latitudes)
External Forcing of the Thermosphere/Ionosphere System

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

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

- **Lower boundary wave forcing**
  - Tides: Global Scale Wave Model (GSWM, Hagan et al., 1999)
  - Eddy diffusion
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 mixing ratio is zero
- N(4S), O+: photochemical equilibrium
- NO: constant density of (8x10$^6$)
- $T_e$: equal to $T_N$. 
Low and mid-latitude: neutral wind dynamo equations solved on geomagnetic apex coordinates. [Richmond et al., 1992; 1995]

High latitude: specified by convection models such as Heelis, Weimer, and AMIE, or coupled to the LFM Magnetosphere Model.
Some Model Validation Examples

- Thermosphere
  - Neutral density data from satellite drag
  - Neutral density data from CHAMP
  - Composition data from GUVI

- Ionosphere
  - Electron density measurements from COSMIC
  - Ground-based incoherent scatter radar measurements
  - Ground-based GPS data
Thermospheric Density—Declining Phase of SC #23

Satellite #12388
TIEGCM with EUVAC

Solar EUV Flux (W/m²)

TIMED/SEE

F₁₀.₇

[Qian et al., J. Geophys. Res., 2009]
Ionospheric Climatology, 2008

COSMIC, 2008, February–April

May–July

August–October

November–December

IRI

TIEGCM

cm$^{-3}$

1.0e+06

8.0e+05

6.0e+05

4.0e+05

2.0e+05

0.0e+00
Electron Density Profiles

03/30/2007, UT=17, Millstone Hill

06/21/2007, UT=17, Millstone Hill

LT=12

LT=15

ISR
ISR Model
TIE-GCM
Ionospheric Response to X17 flare on 28 October 2003
Current Development and Future Plans

• TIE-GCM v. 1.94 is undergoing benchmark tests and will be released soon
• Significant new feature is inclusion of the Weimer high-latitude potential model, using solar wind / IMF input
• High-resolution version (2.5° x 2.5° x H/4) is also in test
• Other key research developments include:
  • Lower boundary conditions:
    — Seasonal/spatial variation of lower boundary eddy diffusion
    — Tidal forcing derived from TIMED TIDI & SABER data
  • External forcing:
    — Solar EUV from TIMED/SEE, SDO/EVE, and alternative proxies
    — Auroral precipitation derived from GUVI data
• Global Ionosphere Plasmasphere (GIP) model (closed field lines)
• Continued development of the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model

• More information at:  http://www.hao.ucar.edu/modeling/tgcm
Backup Material
Strengths and Weaknesses

Strengths:
• Fully coupled neutral dynamics and ionospheric electrodynamics
• Accurate treatment of solar EUV and photoelectron processes, including capability of using EUV measurements
• Comprehensive photochemistry and thermodynamics
• Flexible high latitude inputs: Heelis, Weimer, AMIE, or coupling to magnetospheric models (CISM/CMIT)

Weaknesses:
• Lower boundary — only migrating tides included
• Upper boundary — no plasmasphere
• Uniform spherical grid — problems near the poles
• Hydrostatic equilibrium assumed
X17 flare on October 28, 2003—Thermosphere Responses
Infrared Cooling

- CO$_2$ cooling at 15 μm (peaks ~ 120 km)
- NO cooling at 5.3 μm (peaks ~ 150 km)
- O($^3$P) fine structure cooling at 63 μm (maximizes > 200 km)
Thermosphere (O/N₂)

04/01/2007, LT=9:00, TIE-GCM

06/21/2007, LT=17:18, TIE-GCM

04/01/2007, LT=9:00, GUVI

06/21/2007, LT=17:18, GUVI