The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

310/1749-29

ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

---

# *Thermosphere-Ionosphere-Electrodynamics General Circulation Model TIEGCM*

*Maura HAGAN*
*National Center for Atmospheric Research*
*1850 Table Mesa Drive*
*Boulder, CO 80307-3000*
*U.S.A.*

---

Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

# Thermosphere-Ionosphere-Electrodynamics General Circulation Model TIEGCM


**Maura Hagan**

**Jiuhou Lei, Gang Lu**

**Ray Roble, Art Richmond, Stan Solomon**
**Ben Foster, Astrid Maute, Liying Qian**

**High Altitude Observatory**
**National Center for Atmospheric Research**
**Boulder, Colorado**
**USA**

# TIEGCM Objectives

- **Describe** the chemistry, dynamics and electrodynamics of the Earth's upper atmosphere within a mathematical framework
- **Diagnose** the Earth's upper atmosphere; develop understanding by comparing model results with observations
- **Predict** future conditions of the Earth's upper atmosphere (e.g., thermospheric cooling associated with increased $CO_2$)
- Strategies:
  – 1-D: column model (global mean)
  – 2-D: zonal averages (height & latitude)
  – 3-D: global

# Historical Development of TIEGCM

- TGCM; an adaptation of the NCAR climate model (ca.1970)
  - 97 to 500 km (solar minimum)
  - solar EUV heating
  - thermospheric composition
  - molecular diffusion
  - parameterized ionosphere
- TIGCM (ca. 1988)
  - added ionospheric chemistry and dynamics
  - parameterized electric fields
- TIEGCM (ca. 1992)
  - added self-consistent low and middle latitude electrodynamics
  - parameterized high-latitude electrodynamics

Ray Roble

Art Richmond

# Thermosphere-Ionosphere-Electrodynamics General Circulation Model TIEGCM

## Part 1: Model Overview

- functional description
- references
- select formulations and numerical schemes

# TIEGCM Functional Description

- comprehensive, first-principles, three-dimensional, non-linear representation of the coupled thermosphere and ionosphere system, including a self-consistent solution of the middle and low-latitude dynamo field,
- solves the 3-D momentum, energy and continuity equations for neutral and ion species at each time step (typically 120–180s),
- employs a semi-implicit, fourth-order, centered finite difference scheme on each pressure surface in a staggered vertical grid,
- runs in either serial or parallel mode on a variety of platforms, including Linux workstations and supercomputers.

The standard low-resolution grid parameters are:

- Latitude: -87.5° to 87.5° in 5° increments
- Longitude: -180° to 180° in 5° increments
- Altitude: 29 pressure levels from -7 to +6.5 in increments of 2 grid points per scale height
- Lower boundary: ~97 km
- Upper boundary: ~500–700 km depending on solar activity

# NCAR TIEGCM Development

**References:**

Dickinson, R. E., E. C. Ridley and R. G. Roble, A three-dimensional general circulation model of the thermosphere, *J. Geophys. Res.*, 86, 1499-1512, 1981.

Dickinson, R. E., E. C. Ridley and R. G. Roble, Thermospheric general circulation with coupled dynamics and composition, *J. Atmos. Sci.*, 41, 205-219, 1984 .

Richmond, A. D., E. C. Ridley and R. G. Roble, A Thermosphere/Ionosphere General Circulation Model with coupled electrodynamics, *Geophys. Res. Lett.*, 19, 601-604, 1992.

Roble, R. G., and E. C. Ridley, An auroral model for the NCAR thermospheric general circulation model (TGCM), *Annales Geophys.*, 5A, 369-382, 1987.

Roble, R. G., E. C. Ridley and R. E. Dickinson, On the global mean structure of the thermosphere, *J. Geophys. Res.*, 92, 8745-8758, 1987.

Roble, R. G., E. C. Ridley, A. D. Richmond and R. E. Dickinson, A coupled thermosphere/ionosphere general circulation model, *Geophys. Res. Lett.*, 15, 1325-1328, 1988.

Roble, R. G., and E. C. Ridley, A thermosphere-ionosphere-mesosphere-electrodynamics general circulation model (time-GCM): equinox solar cycle minimum simulations (30-500 km), *Geophys. Res. Lett.*, 21, 417-420, 1994.

Roble, R. G., Energetics of the mesosphere and thermosphere, AGU, *Geophysical Monographs*, eds. R. M. Johnson and T. L. Killeen, 87, 1-22, 1995.

# Thermodynamic equation - general form

$$\frac{\partial T}{\partial t} = -(\Gamma + \frac{\partial T}{\partial Z})\omega - \underline{U} \cdot \nabla T + \frac{(Q_{tot} - L_{tot})}{C_p}$$

adiabatic heating

heat advection

diabatic heating & cooling

| | |
|---|---|
| $T$ | temperature |
| $\Gamma$ | atmospheric stability |
| $Z$ | vertical coordinate $ln(P_o/P)$ |
| $\omega$ | vertical velocity = $\partial Z / \partial t$ |
| $\underline{U}$ | horizontal velocity vector |
| $Q_{tot}$ | total heating rate |
| $L_{tot}$ | total cooling rate |
| $C_p$ | specific heat per unit mass |

# TIEGCM Thermodynamic equation

$$\frac{\partial T}{\partial t} = \frac{ge^{Z}}{P_o C_p}\frac{\partial}{\partial Z}\left\{\frac{K_T}{H}\frac{\partial T}{\partial Z} + K_E H^2 C_p \rho\left[\frac{g}{C_p} + \frac{1}{H}\frac{\partial T}{\partial Z}\right]\right\}$$

$$-\underline{U}\cdot\nabla T - \omega\left[\frac{\partial T}{\partial Z} + \frac{RT}{C_p \overline{m}}\right] + \frac{(Q-L)}{C_p}$$

| | |
|---|---|
| $g$ | gravitational acceleration |
| $P_o$ | reference pressure; 5x10$^{-4}$ μbar |
| $K_T$ | molecular thermal conductivity |
| $H$ | scale height |
| $K_E$ | eddy diffusion coefficient = eddy thermal conductivity |
| $\underline{\rho}$ | total mass density |
| $m$ | mean molecular mass |
| $Q$ | heating rate |
| $L$ | total cooling rate |

# TIEGCM Thermodynamic equation

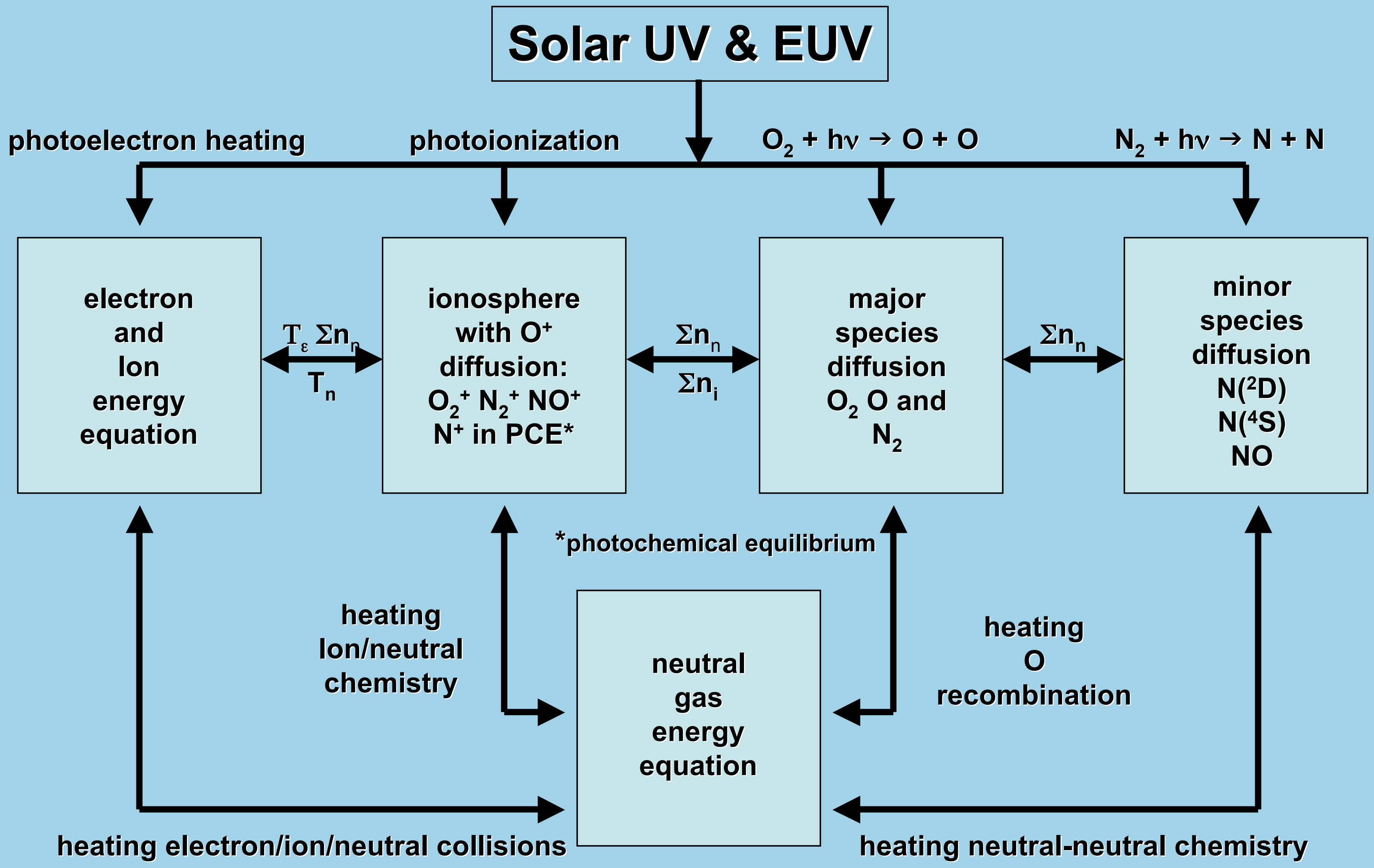
**diabatic heating**

- absorption of solar radiation - UV and EUV
- absorption of energetic particles
- chemical heating - exothermic reactions
- ion - neutral collisions; Joule heating

Schematic absorption of UV and EUV…. up next

**diabatic cooling**

- airglow
- $CO_2$ infrared cooling
- nitric oxide (NO) infrared cooling


Solar UV & EUV
photoelectron heating
photoionization
$O_2 + h\nu \rightarrow O + O$
$N_2 + h\nu \rightarrow N + N$
electron and Ion energy equation
$T_\varepsilon$ $\Sigma n_n$
$T_n$
ionosphere with $O^+$ diffusion: $O_2^+$ $N_2^+$ $NO^+$ $N^+$ in PCE*
$\Sigma n_n$
$\Sigma n_i$
major species diffusion $O_2$ O and $N_2$
$\Sigma n_n$
minor species diffusion N($^2$D) N($^4$S) NO
*photochemical equilibrium
heating Ion/neutral chemistry
neutral gas energy equation
heating O recombination
heating electron/ion/neutral collisions
heating neutral-neutral chemistry

# Continuity Equation - general form

$$\frac{\partial \rho_n}{\partial t} + \nabla \cdot \left( \rho_n \underline{U} \right) = CS_n - CR_n$$

transport

chemical production & loss

| | |
|---|---|
| $\rho_n$ | mass density of species, $n$ |
| $\underline{U}$ | wind velocity vector |
| $CS_n$ | mass source of minor species, $n$ |
| $CR_n$ | mass sink of minor species, $n$ |
| $\Psi_n = \frac{\rho_n}{\rho}$ | mass mixing ratio of species, $n$, for total mass density, $\rho$ |

$$\frac{\partial \Psi_n}{\partial t} + \underline{U} \cdot \nabla \Psi_n = S_n - R_n$$

| | |
|---|---|
| $S_n$ | source of minor species, $n$ |
| $R_n$ | sink of minor species, $n$ |

$$S_n - R_n = \frac{CS_n - CR_n}{\rho_n}$$

# TIEGCM Minor Neutral Species Transport:

$$\frac{\partial \Psi_n}{\partial t} = -e^{-Z}\frac{\partial}{\partial Z}D_n\left[\frac{\partial}{\partial Z} - E_n\right]\Psi_n + S_n - R_n$$

$$-\left[\underline{V}\cdot\nabla\Psi_n + \omega\frac{\partial \Psi_n}{\partial Z}\right] + e^{Z}\frac{\partial}{\partial Z}e^{-Z}K_E(Z)\left[\frac{\partial}{\partial Z} + \frac{1}{\overline{m}}\frac{\partial \overline{m}}{\partial Z}\right]\Psi_n$$

$\Psi_n$ mass mixing ratio of minor species, $n$

$D_n$ molecular diffusion coefficient

$E_n$ gravitational, thermal diffusion, and frictional interaction with the major species; $\left[1 - \frac{m_n}{\overline{m}} - \frac{1}{\overline{m}}\frac{\partial \overline{m}}{\partial Z}\right] - \alpha_n \frac{1}{T}\frac{\partial T}{\partial Z} + \underline{F}\Psi_n$

$m_n$ mass of the minor species, $n$

$\overline{m}$ average mass of the major species

# TIEGCM Solution - Continuity Equations - 1

derivatives become finite differences at model grid points

- for each specie, $i$
- at every grid point, x        grid spacing, $\Delta x$
- at every time, $t$        time step, $\Delta t$

## Chemistry

$$\frac{\partial \Psi_i}{\partial t} = S_i - R_i$$

**Sufficiently small time step - explicit:**

$$\Psi_i^{m+1} = \Psi_i^m + \Delta t \cdot \left[ S_i\left(t_m, \Psi_i^m\right) - R_i\left(t_m, \Psi_i^m\right) \right]$$

**Otherwise - implicit:**

$$\Psi_i^{m+1} = \Psi_i^m + \Delta t \cdot \left[ S_i\left(t_{m+1}, \Psi_i^{m+1}\right) - R_i\left(t_{m+1}, \Psi_i^{m+1}\right) \right]$$

# TIEGCM Solution - Continuity Equations - 2

derivatives become finite differences at model grid points

- for each specie, $i$
- at every grid point; grid spacing, $\Delta x$
- at every time step, $\Delta t$

## Eulerian Transport

$$\frac{\partial \Psi_i}{\partial t} + \frac{\partial F_i}{\partial x} = 0 \qquad \text{for flux, } F_i = c\Psi_i$$

**leap-frog method:**

$$\Psi_{i,j}^{m+1} = \Psi_{i,j}^{m-1} - \frac{\Delta t}{\Delta x} \cdot \left[ F_{i,j+1}^{m} - F_{i,j-1}^{m} \right]$$

$$\text{if} \quad |c| \frac{\Delta t}{\Delta x} \le 1 \qquad \text{(CFL stability condition)}$$

# TIEGCM Solution - Continuity Equations - 3

derivatives become finite differences at model grid points

- for each specie, $i$
- at every grid point; grid spacing, $\Delta x$
- at every time step, $\Delta t$

## Diffusion

$$\frac{\partial \Psi_i}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial \Psi_i}{\partial x}\right)$$ for diffusion coefficient, $K > 0$

**explicit:**

$$\frac{\Psi_{i,j}^{m+1} - \Psi_{i,j}^{m}}{\Delta t} = \frac{K}{(\Delta x)^2}\left(\Psi_{i,j+1}^{m} - 2\Psi_{i,j}^{m} + \Psi_{i,j-1}^{m}\right)$$ stable if $2K \frac{\Delta t}{(\Delta x)^2} \leq 1$

**implicit:**

$$\frac{\Psi_{i,j}^{m+1} - \Psi_{i,j}^{m}}{\Delta t} = \frac{K}{(\Delta x)^2}\left(\Psi_{i,j+1}^{m+1} - 2\Psi_{i,j}^{m+1} + \Psi_{i,j+1}^{m-1}\right)$$

# Equations of Neutral Motion

$$\frac{\partial}{\partial t}U_\theta = -\frac{U_\theta}{r}\frac{\partial}{\partial\theta}U_\theta - \frac{U_\phi}{r\sin\theta}\frac{\partial}{\partial\phi}U_\theta - \omega\frac{\partial}{\partial p}U_\theta - \frac{g}{r}\frac{\partial}{\partial\theta}Z + \left(2\Omega + \frac{U_\phi}{r\sin\theta}\right)V_\phi\cos\theta + g\frac{\partial}{\partial p}\left[\left(\mu_m + \mu_T\right)\frac{p}{H}\frac{\partial}{\partial p}U_\theta\right] - \nu_{ni}\left(U_\theta - V_\theta\right)$$

$$\frac{\partial}{\partial t}U_\phi = -\frac{U_\theta}{r}\frac{\partial}{\partial\theta}U_\phi - \frac{U_\phi}{r\sin\theta}\frac{\partial}{\partial\phi}U_\phi - \omega\frac{\partial}{\partial p}U_\phi - \frac{g}{r}\frac{\partial}{\partial\phi}Z - \left(2\Omega + \frac{U_\phi}{r\sin\theta}\right)U_\theta\cos\theta + g\frac{\partial}{\partial p}\left[\left(\mu_m + \mu_T\right)\frac{p}{H}\frac{\partial}{\partial p}U_\phi\right] - \nu_{ni}\left(U_\phi - V_\phi\right)$$

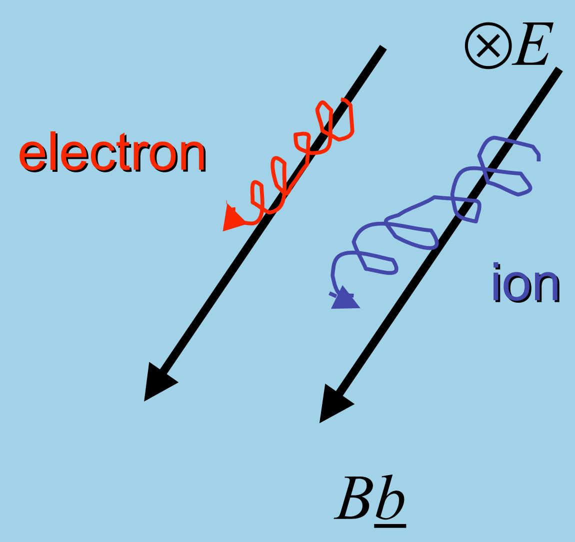
**advection** **pressure gradient** **Coriolis** **viscosity** **ion drag**

$$\frac{1}{p}\frac{\partial p}{\partial Z} = -\frac{g}{RT} \qquad U_z = \left(\frac{\partial Z}{\partial t}\right)_p - \frac{\omega}{\rho g} \qquad \frac{\partial\omega}{\partial p} = -\nabla_p \cdot \underline{U}$$

| | |
|---|---|
| $r$ | radius of the Earth |
| $\Omega$ | rotation rate of the Earth |
| $\nu_{ni}$ | ion-neutral collision frequency |
| $V_k$ | *k* component of ion velocity, $V$ |
| $\mu_m$ | molecular viscosity coefficient |
| $\mu_T$ | thermal viscosity coefficient |

# TIEGCM Ionosphere

## Continuity Equation




$$\frac{\partial[n]}{\partial t} = q - l - \underline{\nabla} \cdot [n]\underline{V}$$

$$q_e = \sum_i q_i \qquad n_e = \sum_i n_i$$

$\underline{V} = \underline{V}_{\parallel} + \underline{V}_{\perp}$ where $\underline{V}_{\parallel}, \underline{V}_{\perp}$ are the parallel, perpendicular components of $\underline{V}$

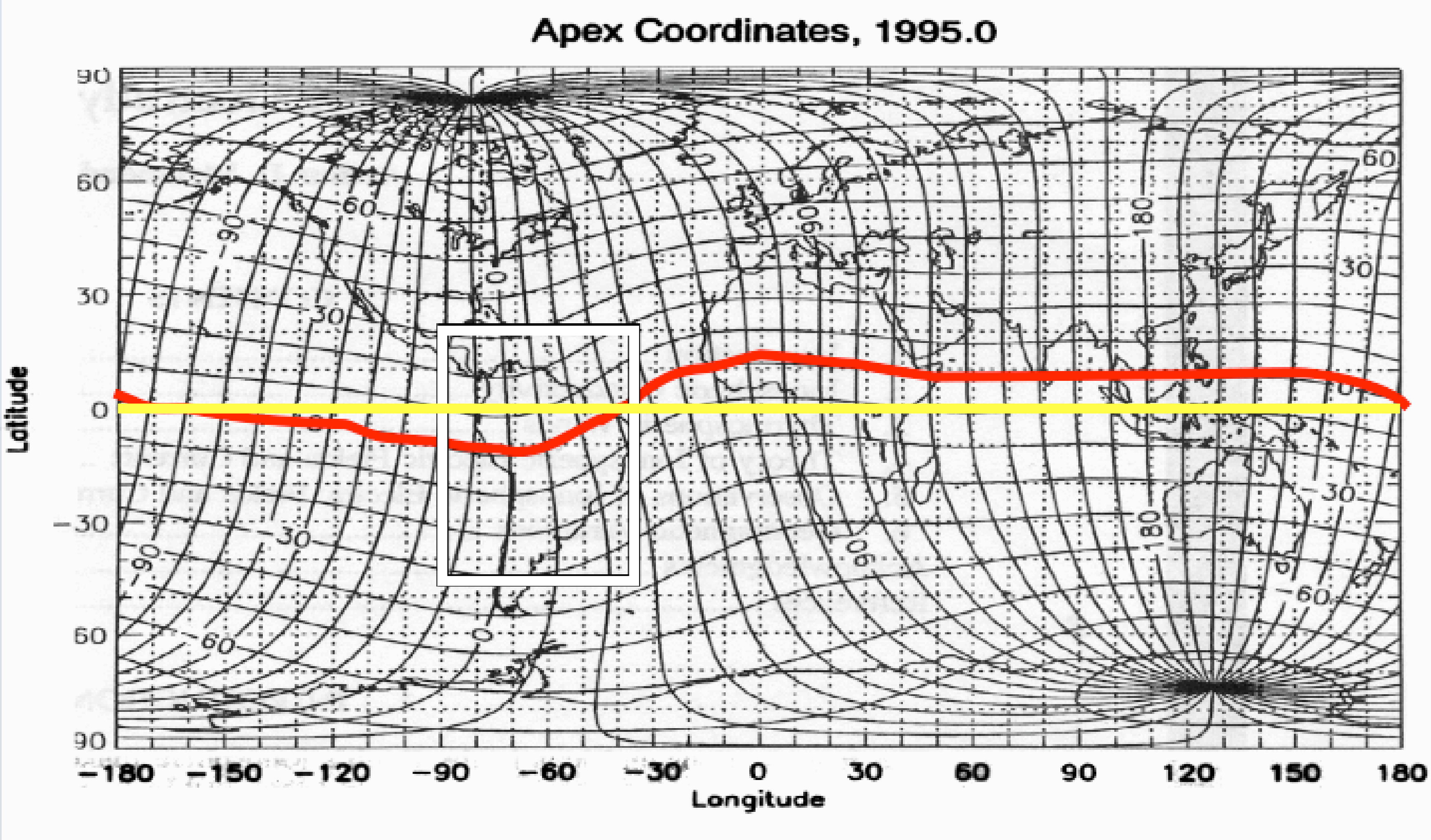
**For example, O+**

$$\underline{V}_{\parallel} = \left\{ \underline{b} \cdot \frac{1}{\nu} \left[ g - \frac{1}{\rho_i} \nabla (p_i + p_e) \right] + \underline{b} \cdot \underline{U} \right\} \underline{b}$$

$$\underline{V}_{\perp} = \frac{1}{|B|} \underline{E} \times \underline{b}$$

**Need a global specification of $\underline{B}$ in order to solve for $\underline{E}$ and $\underline{V}$**

# TIEGCM Geomagnetic Coordinates

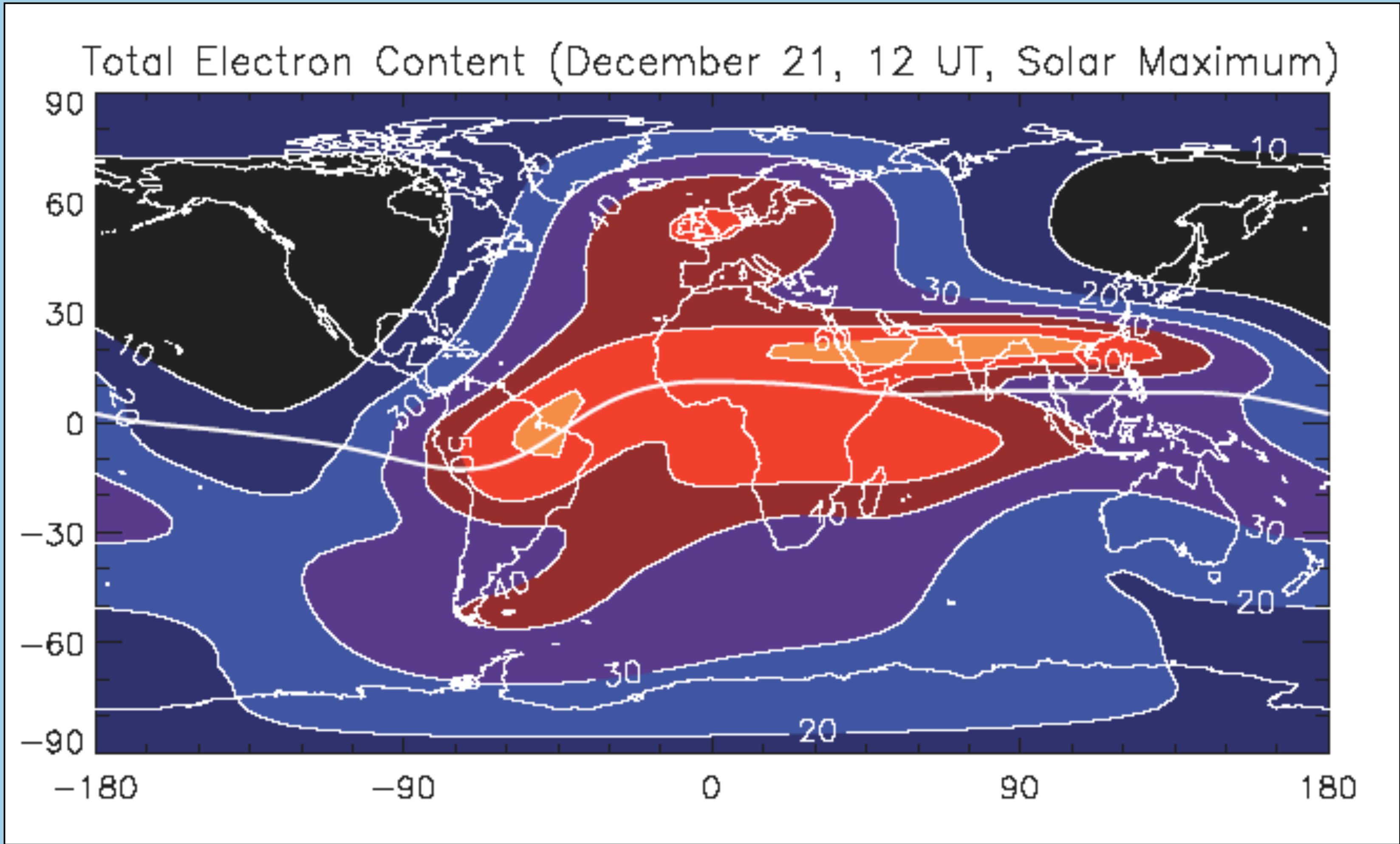



**Note the offset between the geographic and geomagnetic poles.**

# TIEGCM Calculations

- **Upper Boundary - specify**
  - solar flux
  - aurora
  - high latitude convection electric field (cross-cap potential drop)
- **Lower Boundary - specify**
  - tides coming from the lower atmosphere
- **specify some initial state of the T-I system**
- **on the geographic grid**
  - calculate composition (neutral and ion)
  - solve the thermal energy equations
  - solve the neutral equation of motion
- **on the geomagnetic grid**
  - solve the dynamo equation (low-mid latitudes)
  - solve the ion and electron equations of motion

# TIEGCM Ionosphere-Thermosphere Coupling

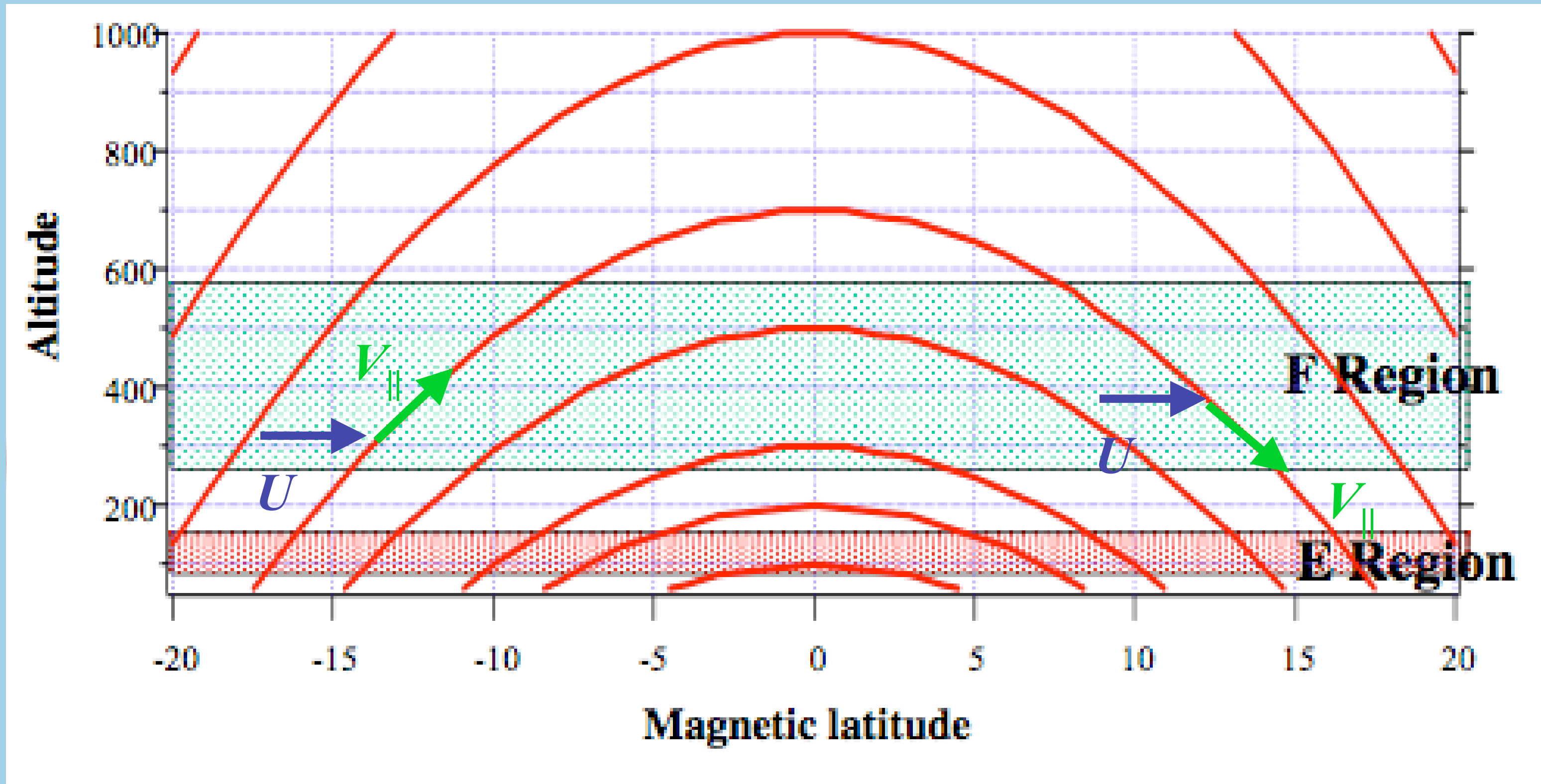



**Why is TEC largest near 0$^o$ longitude?**

**Why is TEC comparatively larger in the summer hemisphere?**

# TIEGCM Ionosphere-Thermosphere Coupling

**The sub-solar point is at 0° longitude at 12UT; in the Southern hemisphere during December.**




**Thermospheric winds blow from "hot" to "cold" (pressure gradient-ion drag balance) ⇒ decreased (increased) Recombination in the Southern (Northern) hemisphere**

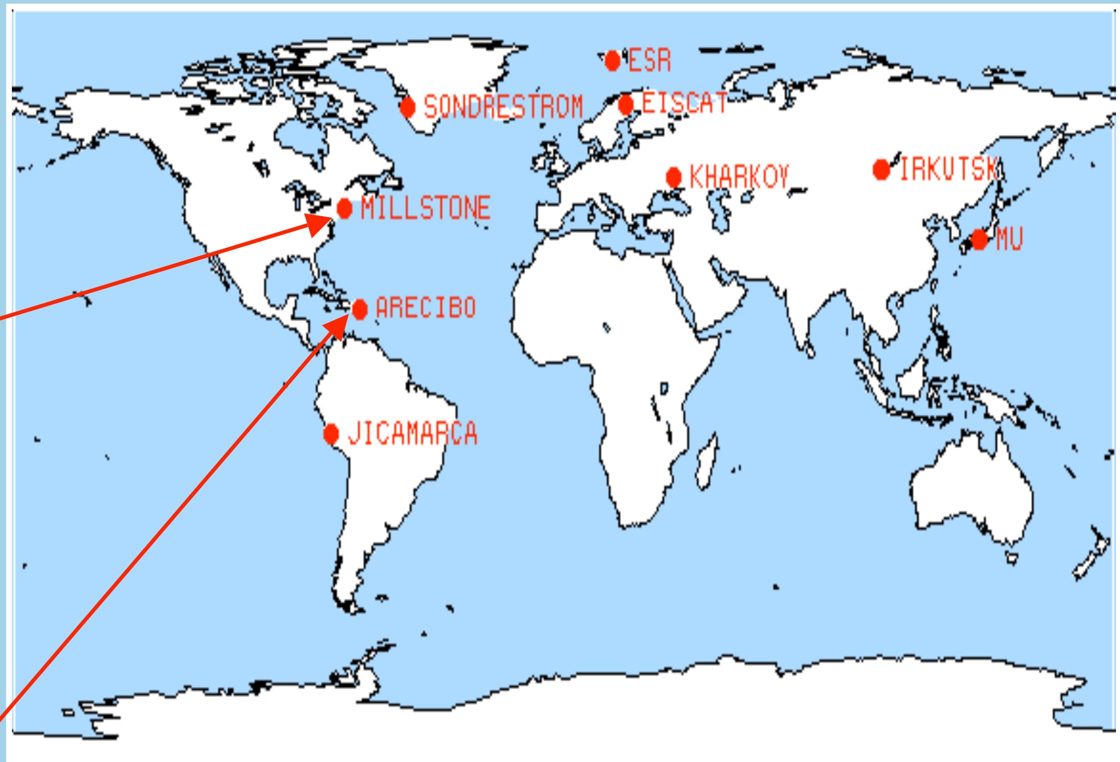
# Thermosphere-Ionosphere-Electrodynamics General Circulation Model TIEGCM

## Part 2: Model Validation

- exemplary effort
- highlights of a recent study
- a set of 1-D assessments
- climatologies of Incoherent Scatter Radar (ISR) data
- led by Jiuhou Lei
- HAO/ASP Postdoctoral Fellow
- PhD 2005, Chinese Academy of Sciences

# Global Incoherent Scatter Radar Network

Millstone Hill, Massachusetts, USA




Arecibo, Puerto Rico

**Primary measurements:**

- electron density, $N_e$
- electron temperature, $T_e$
- ion temperature, $T_i$
- line-of-sight ion velocity, $V_i$

# Sample ISR Climatologies

- **electron density ($N_e$)**
- **electron temperature ($T_e$)**
- **ion temperature ($T_i$)**
  - Millstone Hill: 1976-2002
  - Arecibo: 1966-2000

- **geomagnetically undisturbed**
  - Ap < 30

- **solar cycle**
  - minimum: $F_{10.7} < 100$
  - maximum: $F_{10.7} > 170$

- **season**
  - equinox: March & April
  - summer: June & July
  - winter: December & January

after *Lei et al.*, 2006

# TIEGCM Validation

**Objective: account for ionosphere - plasmasphere coupling**

**1- Assess Upper Boundary Conditions using ISR data**

- electron heat flux **before**:

$$F_{day} = -6\ x10^7(F_{10.7}A(\theta)) - 4.8\ x10^7(F_{10.7})$$

$$A(\theta) = 1 \quad \text{for } \theta > 45^o \text{ latitude}$$

$$= \sin\theta \text{ for } \theta < 45^o$$

$$F_{night} = F_{day}/2 \text{ at night}$$

- electron heat flux **after**:

$$F_{day} = -4\ x10^7(F_{10.7}A(\theta)) - 2\ x10^7(F_{10.7})$$

$$A(\theta) = 1 \quad \text{for } \theta > 45^o \text{ latitude}$$

$$= \sin\theta \text{ for } \theta < 45^o$$

$$F_{night} = F_{day}/B(\theta) \text{ at night}$$

$$B(\theta) = 5 \text{ for } \theta = 45^o$$

$$= 10 \text{ for } \theta = 0^o$$

after *Lei et al.*, 2006

# TIEGCM Validation

## 2 - Assess Upper Boundary Conditions using ISR data

- $O^+$ flux **before**:

$\Phi_{day}$ = 2 x$10^8$ $cm^{-2}$ $s^{-1}$ during daytime (out)

$\Phi_{night}$ -2 x$10^8$ $cm^{-2}$ $s^{-1}$ at night (in)

- no seasonal or solar cycle dependence

- $O^+$ flux **after**:

$$\Phi_{day} = [1 + F_{10.7}r - (.25 + .25F_{10.7}r)\beta] \times 10^8 \ cm^{-2} \ s^{-1}$$
$$= [1 + F_{10.7}r - .1\beta] \times 10^8 \ cm^{-2} \ s^{-1}$$

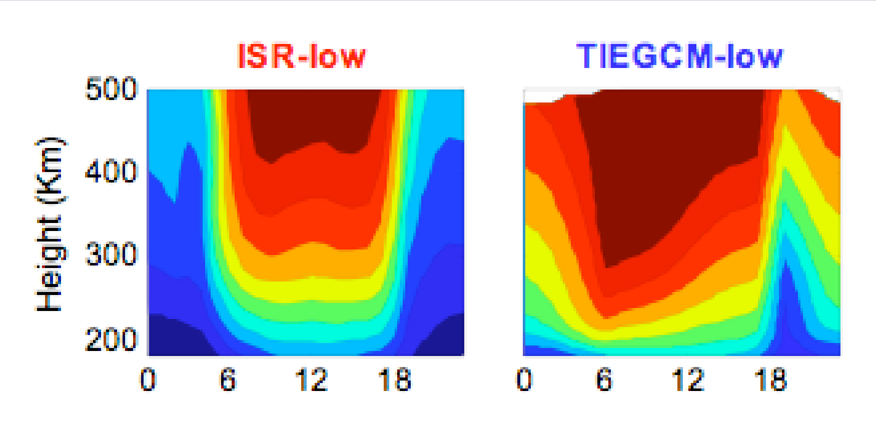
$$\Phi_{night} = -[.5 + .7F_{10.7}r - (.5 + .8F_{10.7}r)\beta] \times 10^8 \ cm^{-2} \ s^{-1}$$
$$= -[.5 + .7F_{10.7}r - .1\beta] \times 10^8 \ cm^{-2} \ s^{-1}$$

$$\beta = 1 + \sin(\pi[(\varphi - \pi/8)/(\pi/4)]) \qquad \varphi = (d - 171.25)/(\pi/365)$$
$$F_{10.7}r = 8.3 \times 10^{-3} F_{10.7} - 0.67$$

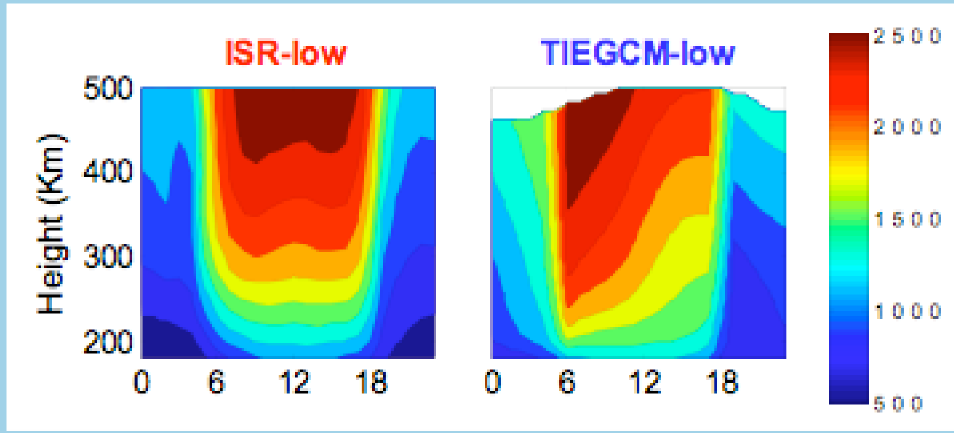
after *Lei et al.*, 2006

# Improving the TIEGCM Upper Boundary Condition

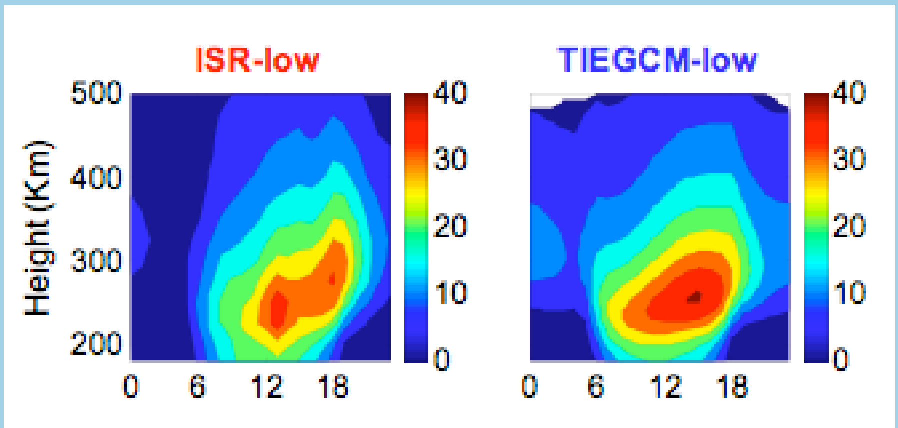
## $T_e$ before



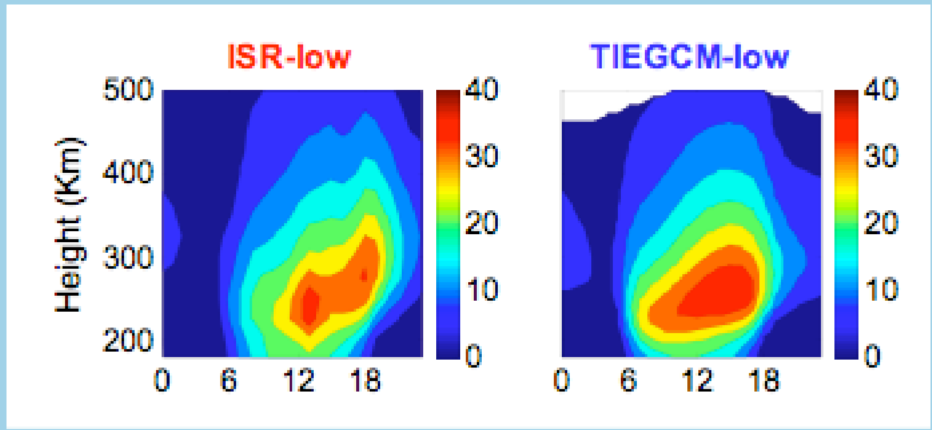

## $T_e$ after




## $N_e$ before




## $N_e$ after



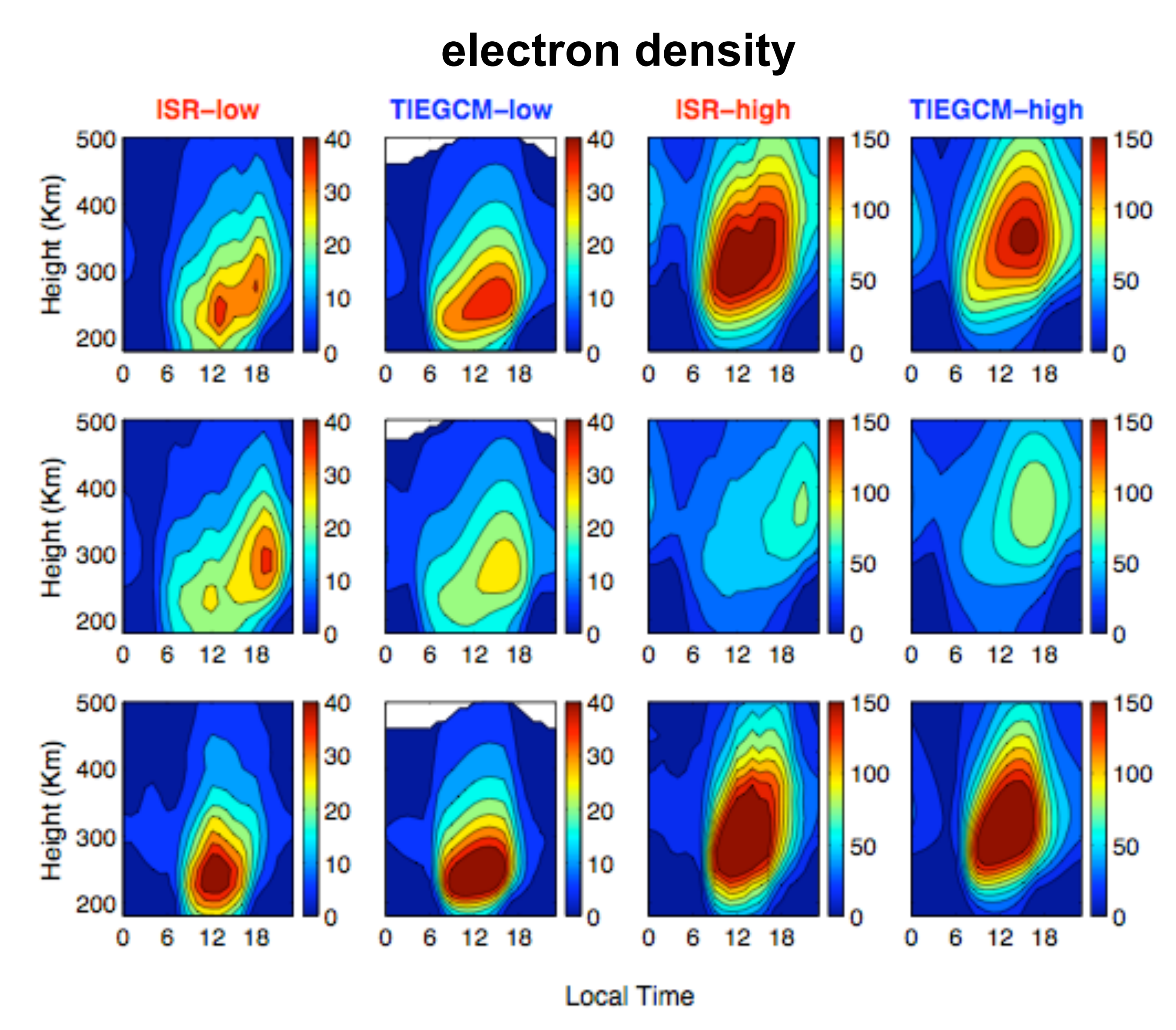

after *Lei et al.*, 2006

# TIEGCM/ISR Comparisons - Millstone (42.6$^o$N, 71.5$^o$W)

equinox

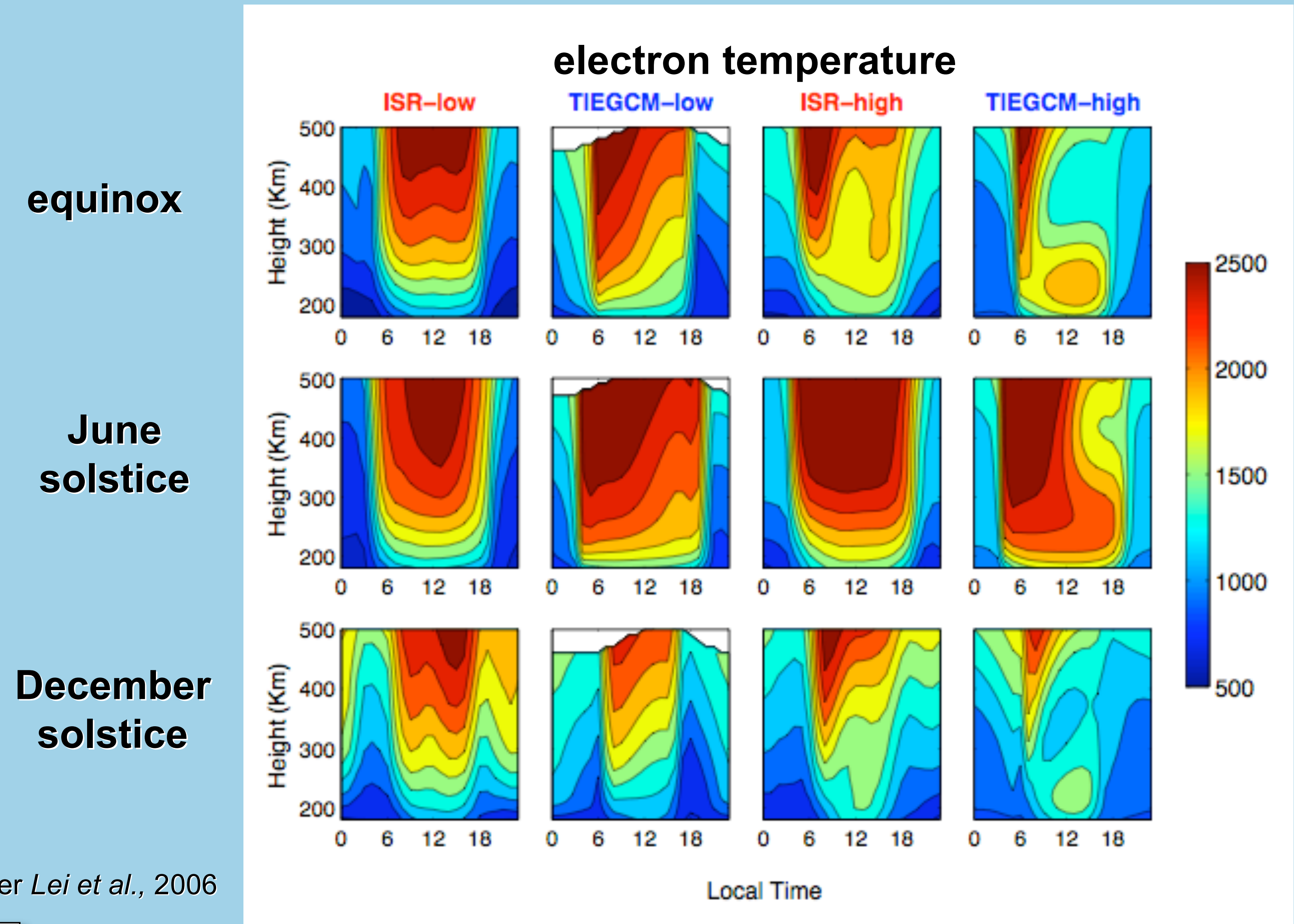
June solstice

December solstice



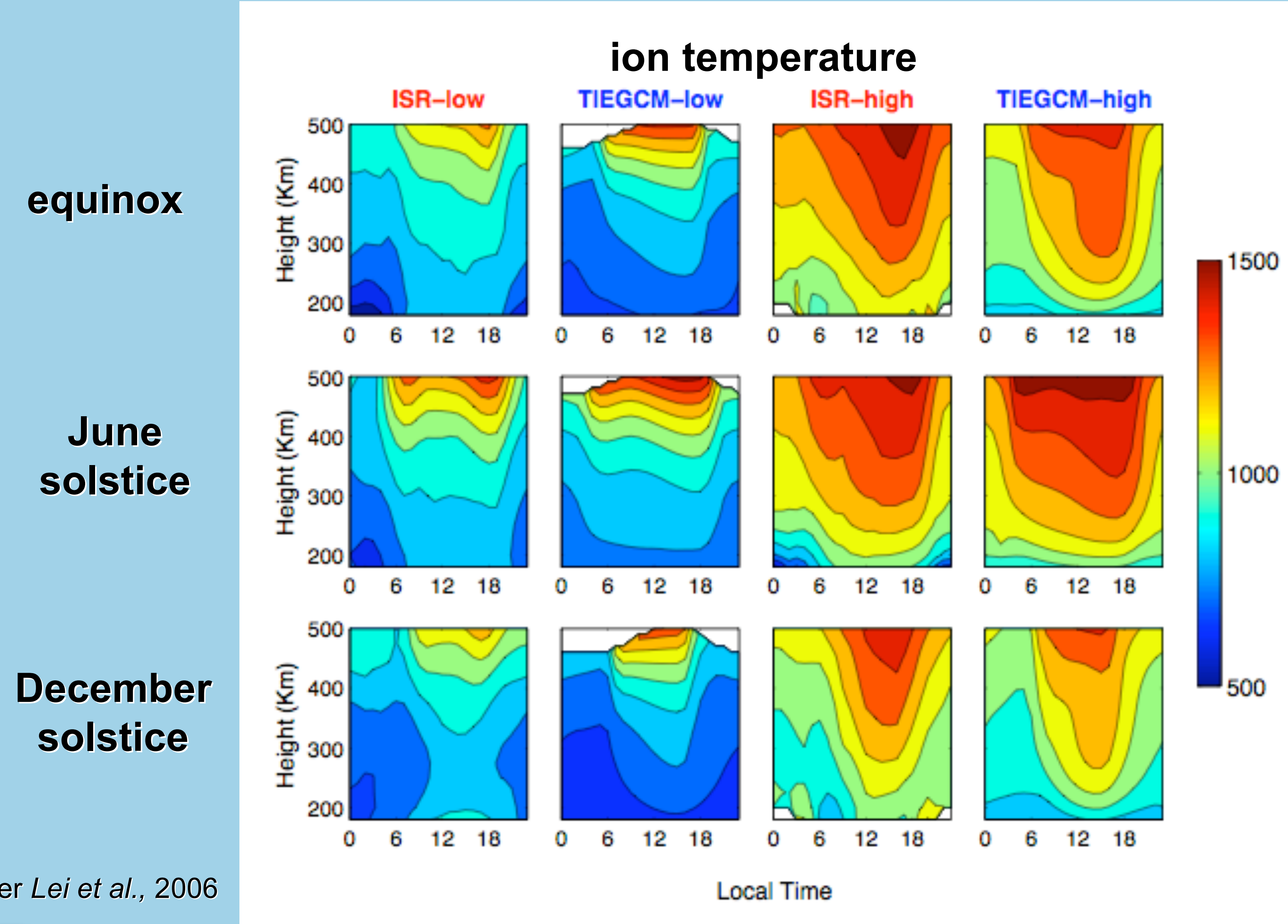

after *Lei et al.*, 2006

# TIEGCM/ISR Comparisons - Millstone (42.6°N, 71.5°W)




after *Lei et al.*, 2006

# TIEGCM/ISR Comparisons - Millstone (42.6°N, 71.5°W)



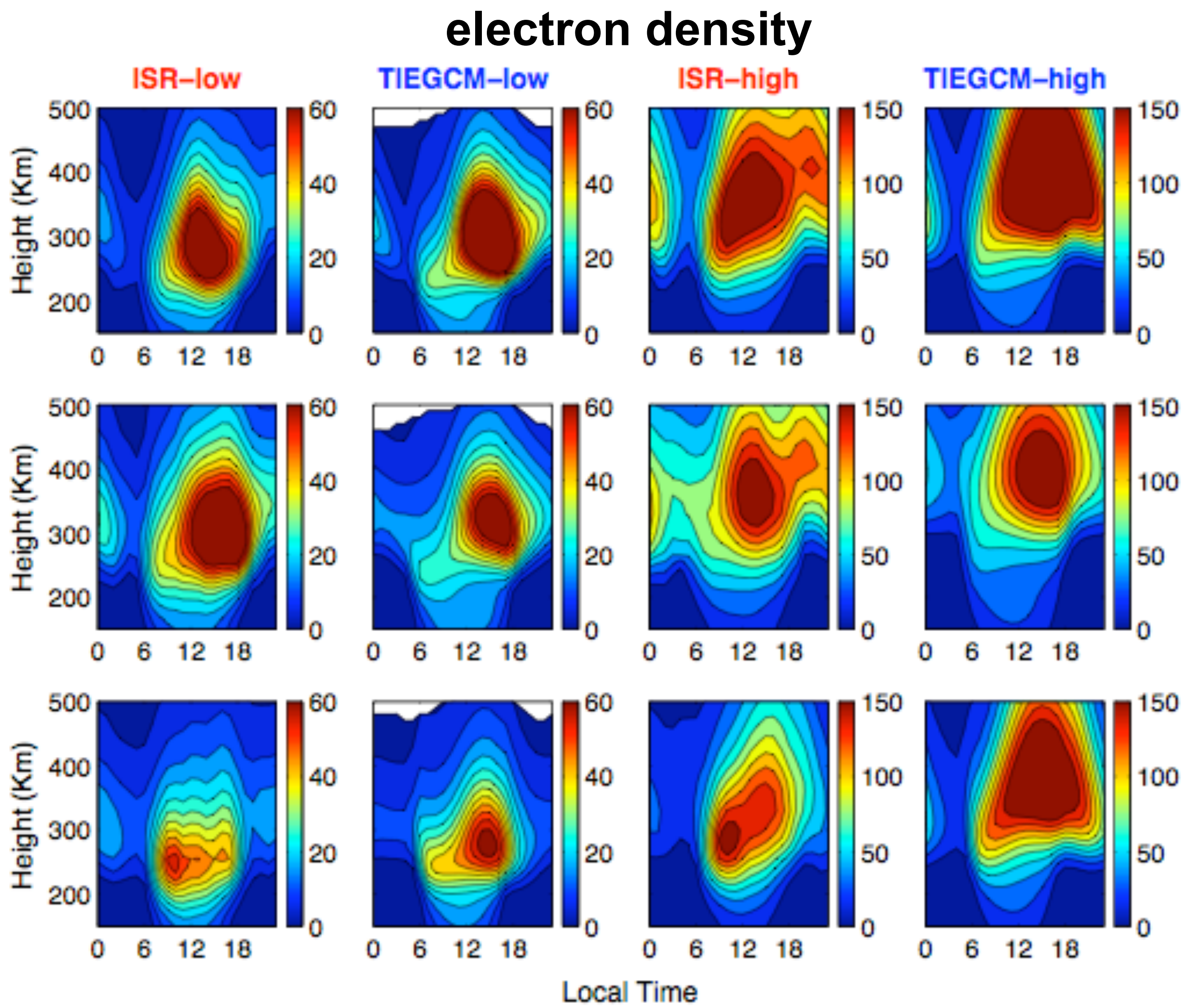

after *Lei et al.*, 2006

# TIEGCM/ISR Comparisons - Arecibo (18.3°N, 66.7°W)

equinox

June solstice

December solstice



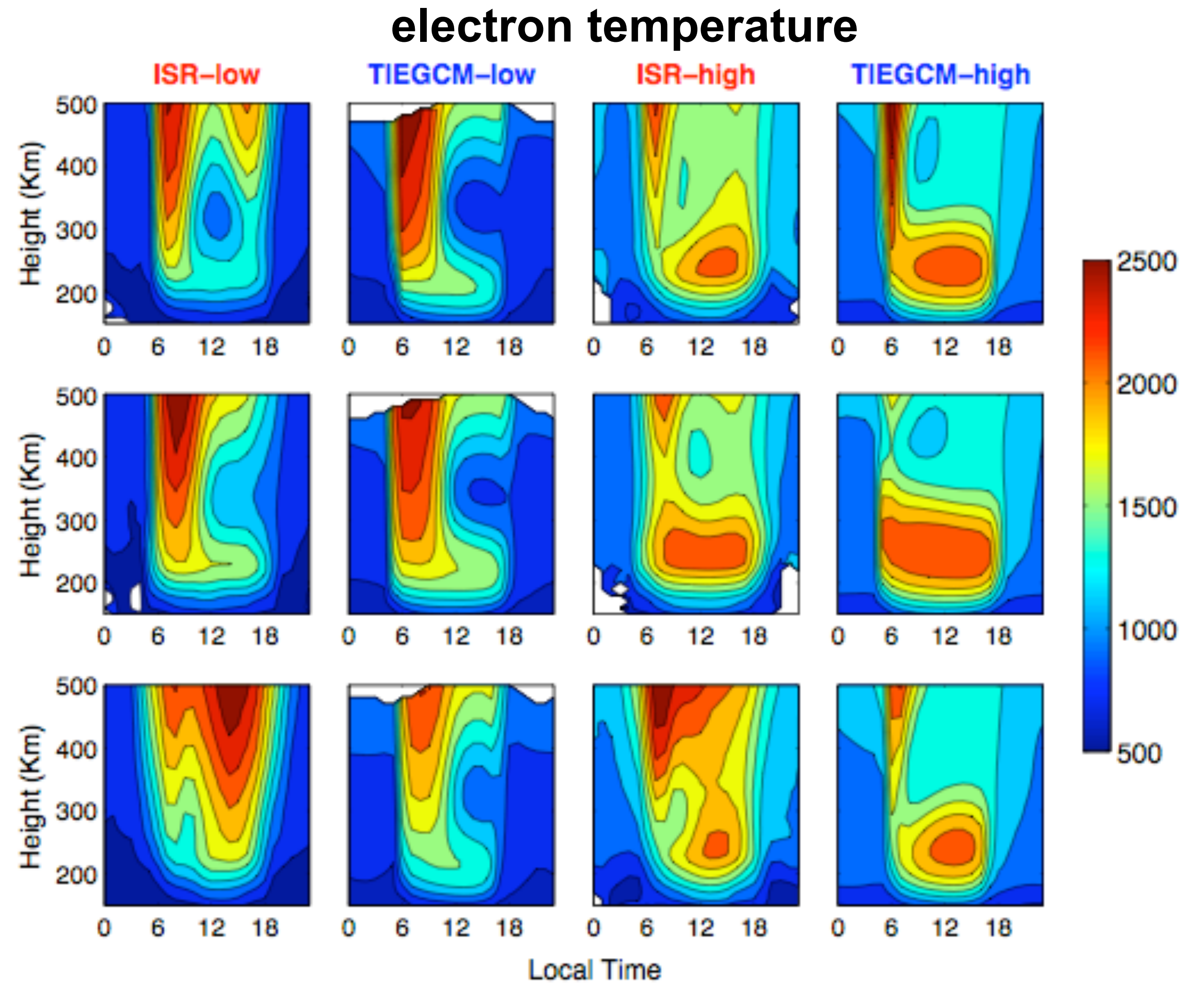

after *Lei et al.*, 2006

# TIEGCM/ISR Comparisons - Arecibo (18.3°N, 66.7°W)

equinox

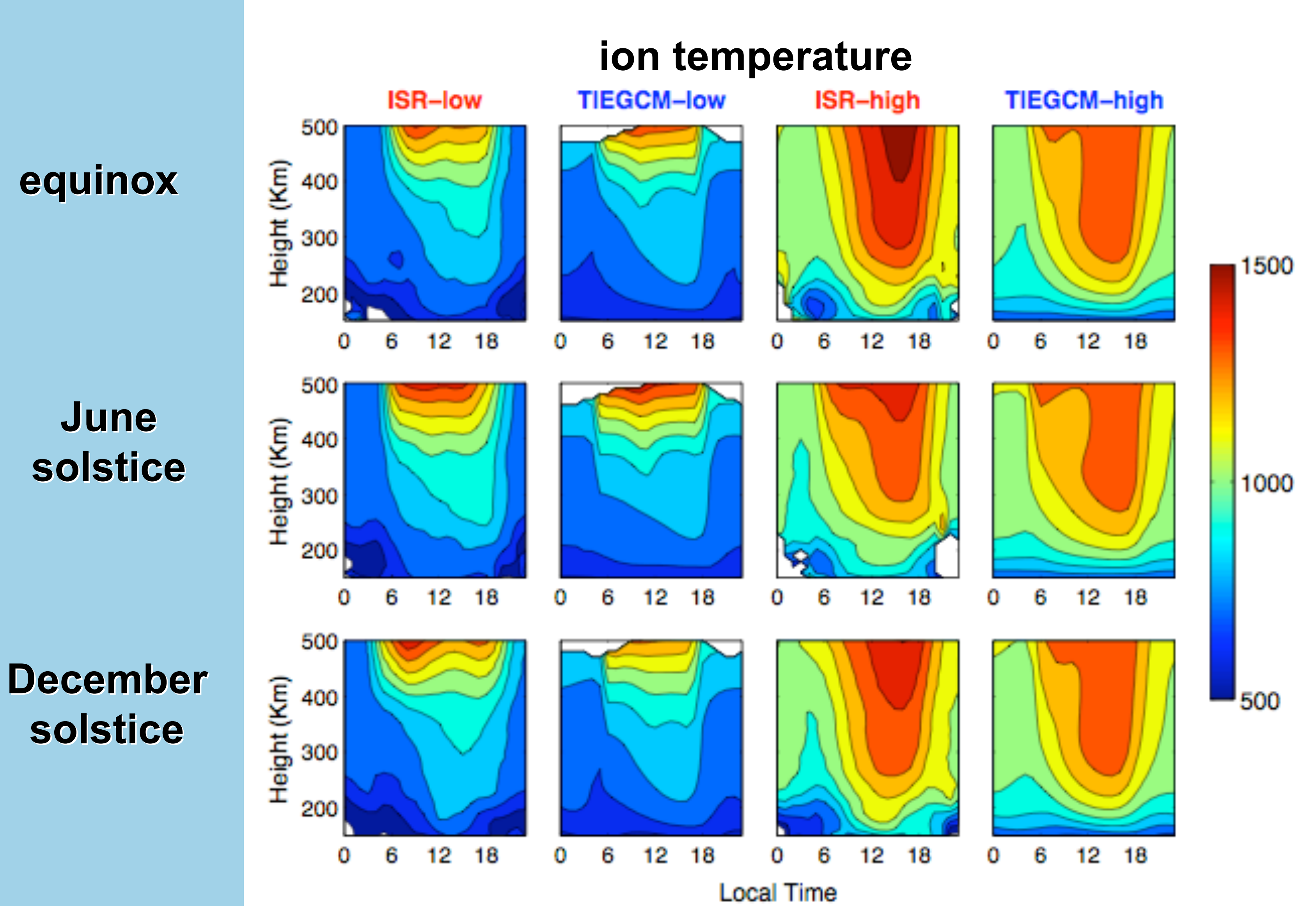
June solstice

December solstice



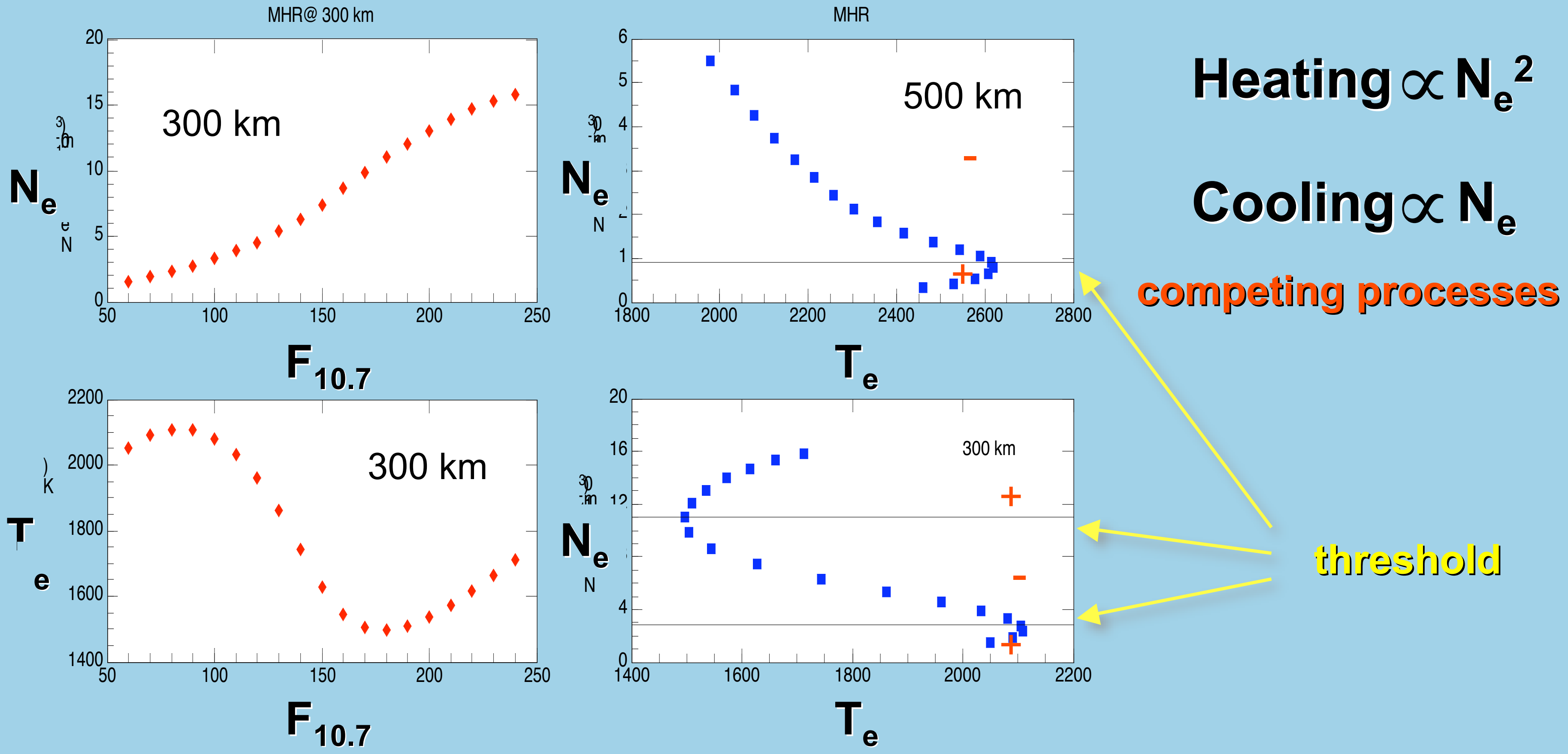

after *Lei et al.*, 2006

# TIEGCM/ISR Comparisons - Arecibo (18.3°N, 66.7°W)




after *Lei et al.*, 2006

# TIEGCM $T_e$-$N_e$ Relationship over Millstone




Electron temperature, $T_e$, is expected to decrease with solar activity, as electron density, $N_e$, increases. But, *Lei et al*. (2006) show that ..

after *Lei et al*., 2006

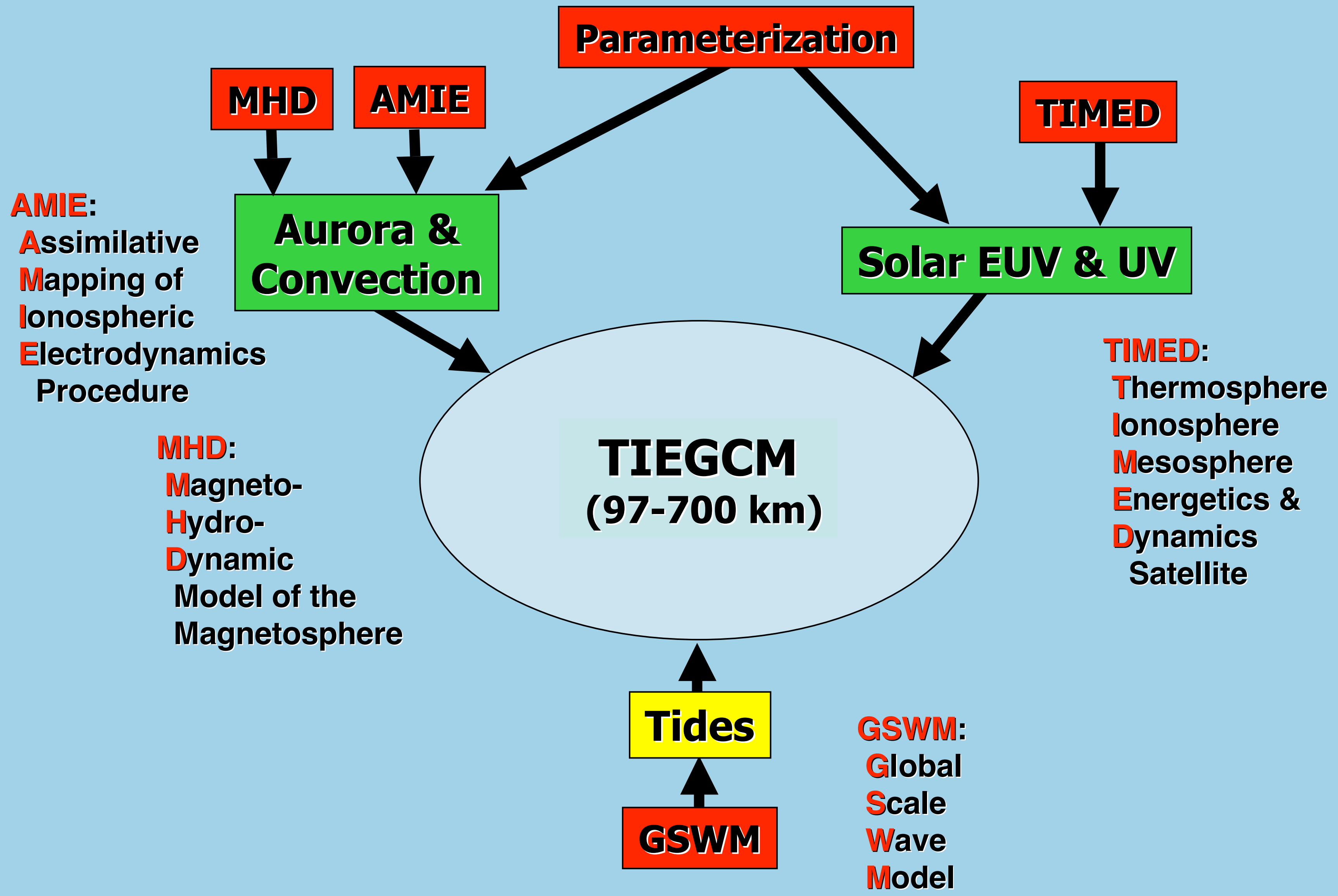
Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

# Thermosphere-Ionosphere-Electrodynamics General Circulation Model TIEGCM

## Part 3: Case Studies

- October-November 2003 Halloween Storms
- community effort - realistic drivers - assimilated data
- led by Gang Lu
  HAO Scientist

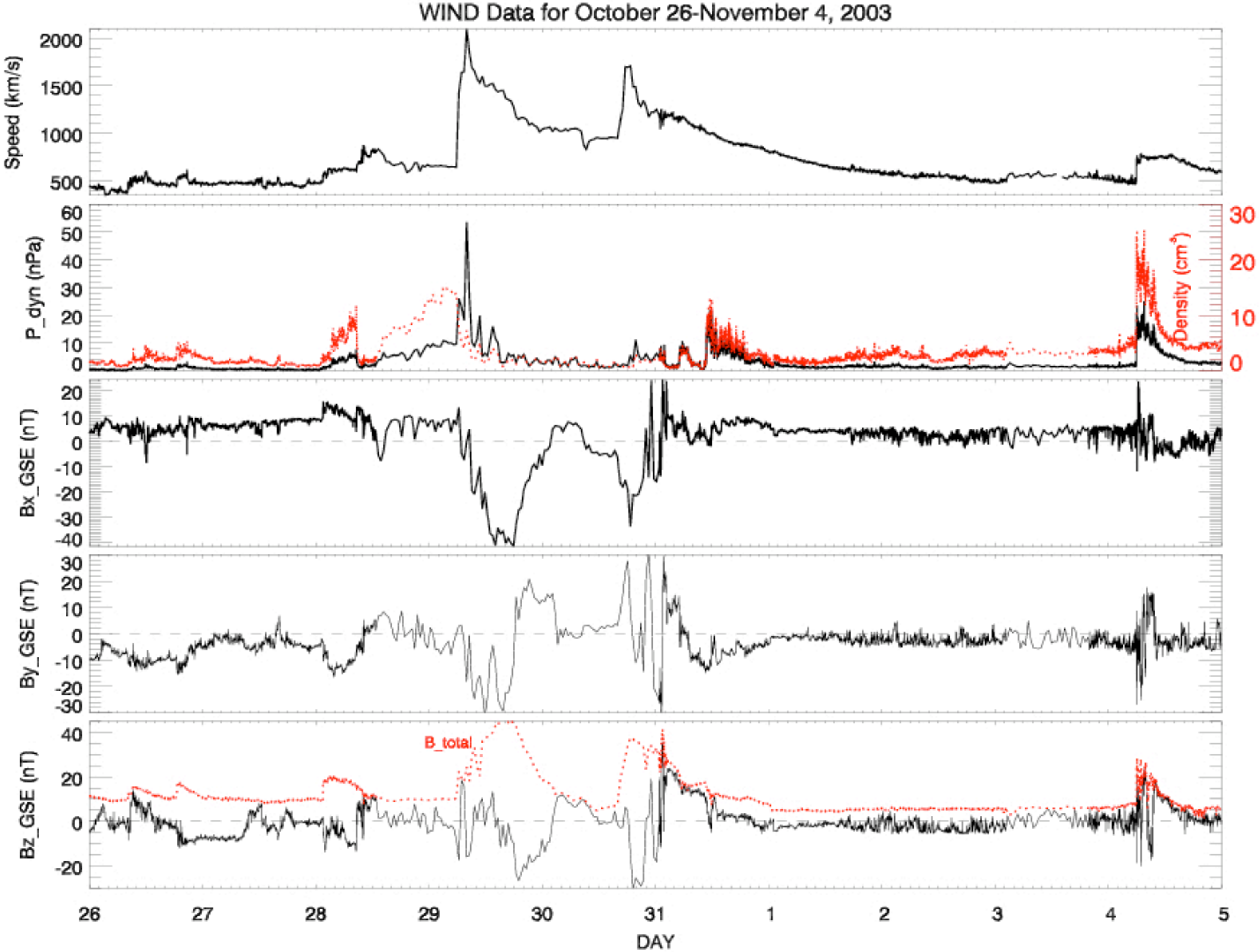

Parameterization
MHD
AMIE
TIMED
Aurora & Convection
Solar EUV & UV
TIEGCM
(97-700 km)
Tides
GSWM
AMIE:
Assimilative
Mapping of
Ionospheric
Electrodynamics
Procedure
MHD:
Magneto-
Hydro-
Dynamic
Model of the
Magnetosphere
TIMED:
Thermosphere
Ionosphere
Mesosphere
Energetics &
Dynamics
Satellite
GSWM:
Global
Scale
Wave
Model

# Case Studies with the NCAR/HAO GCMs
## High-Latitude Forcing

- **GPI forcing:**
  GeoPhysical Indices ⇒ Kp & $F_{10.7}$
  empirical convection electric fields, aurora and solar irradiance forcing
- **SPE forcing:**
  **S**olar **P**roton **E**vent ⇒ energetic particle observations (TIME-GCM)
- **AMIE forcing:**
  convection electric fields and auroral forcing from assimilated ground-based and satellite observations

**October - November 2003**
**Halloween Storms**

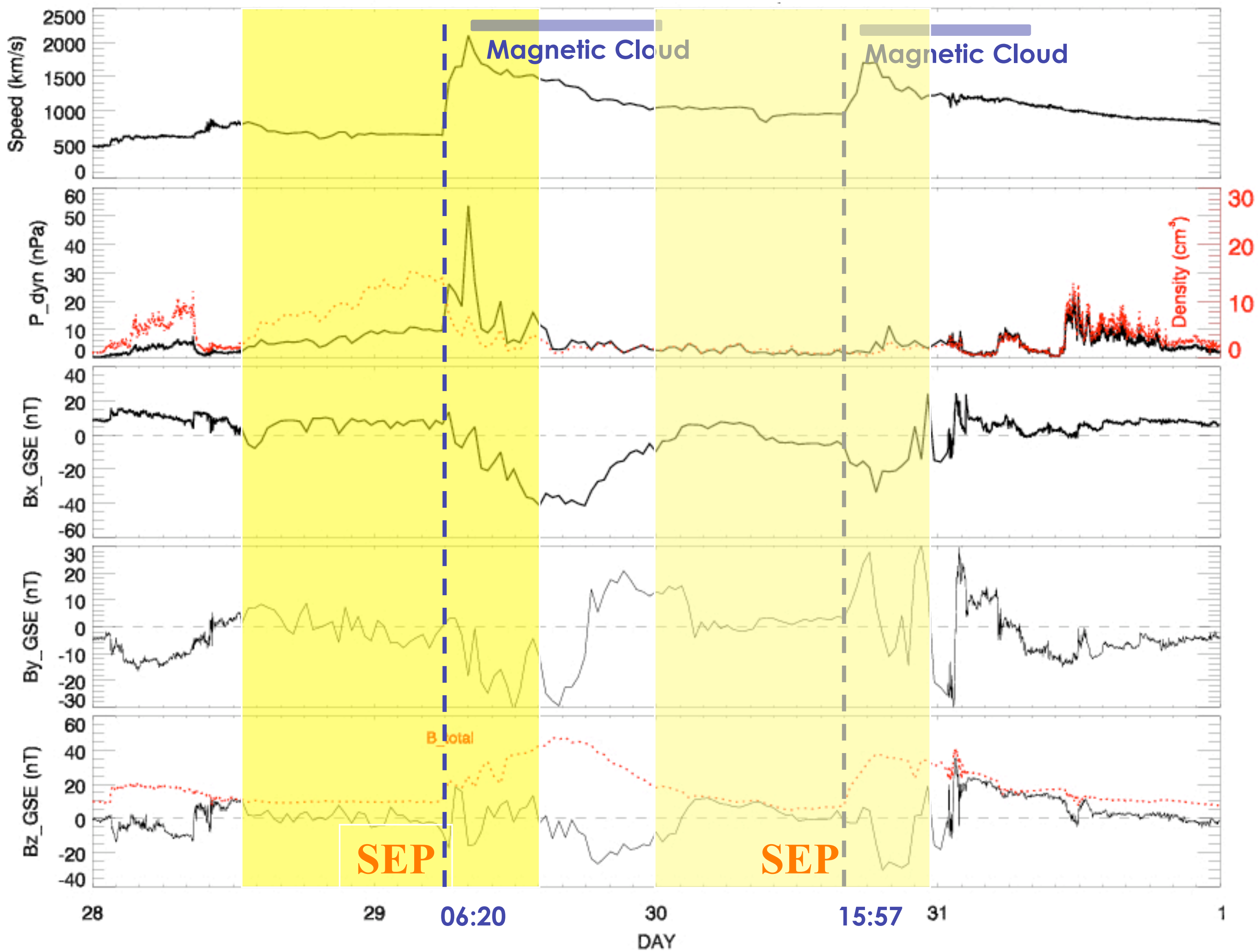
# Prevailing Space Weather: Solar Wind and IMF



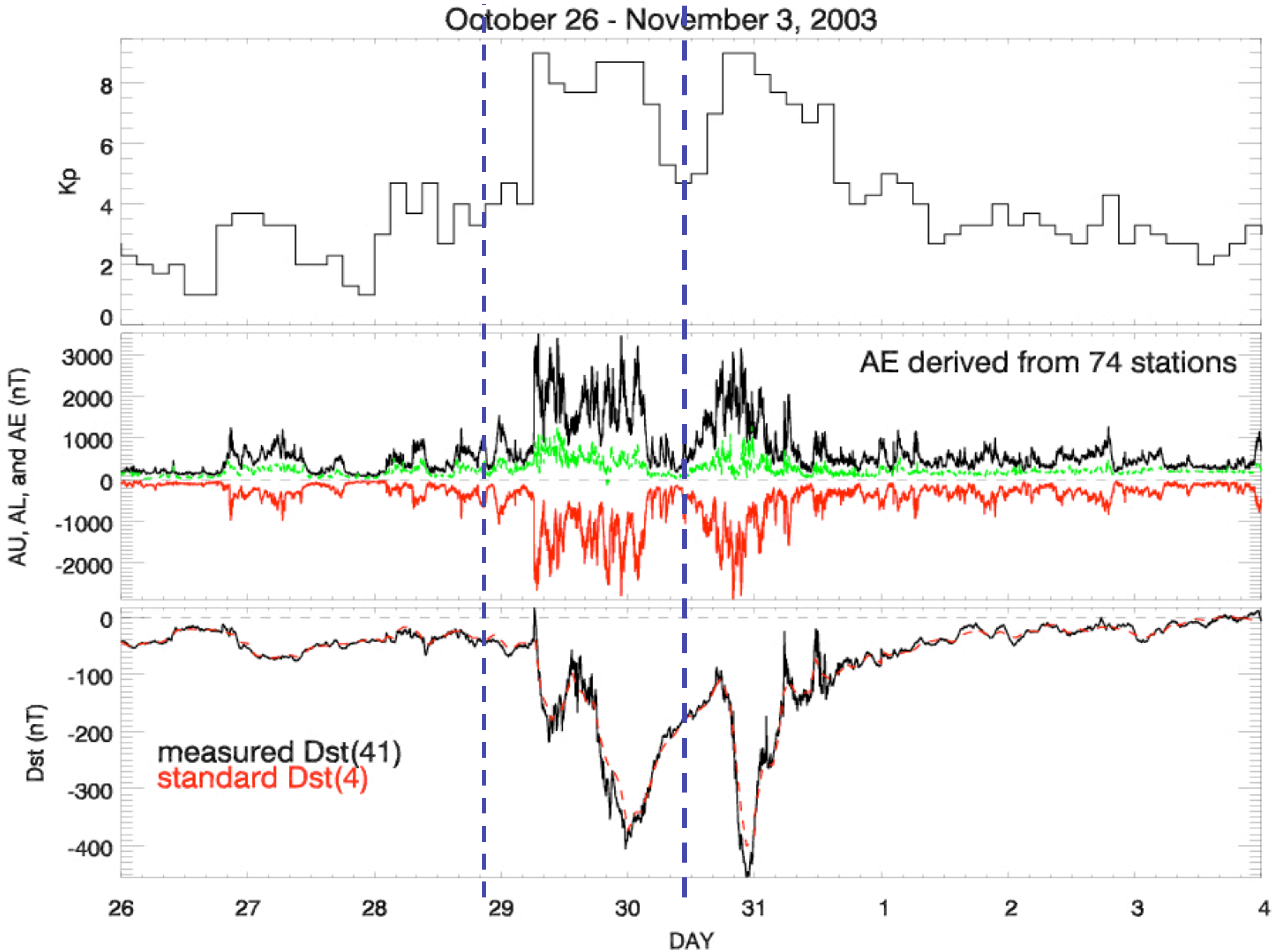
# Prevailing Space Weather: Solar Wind and IMF

## ACE Data for October 28 – November 1, 2003

…a closer look



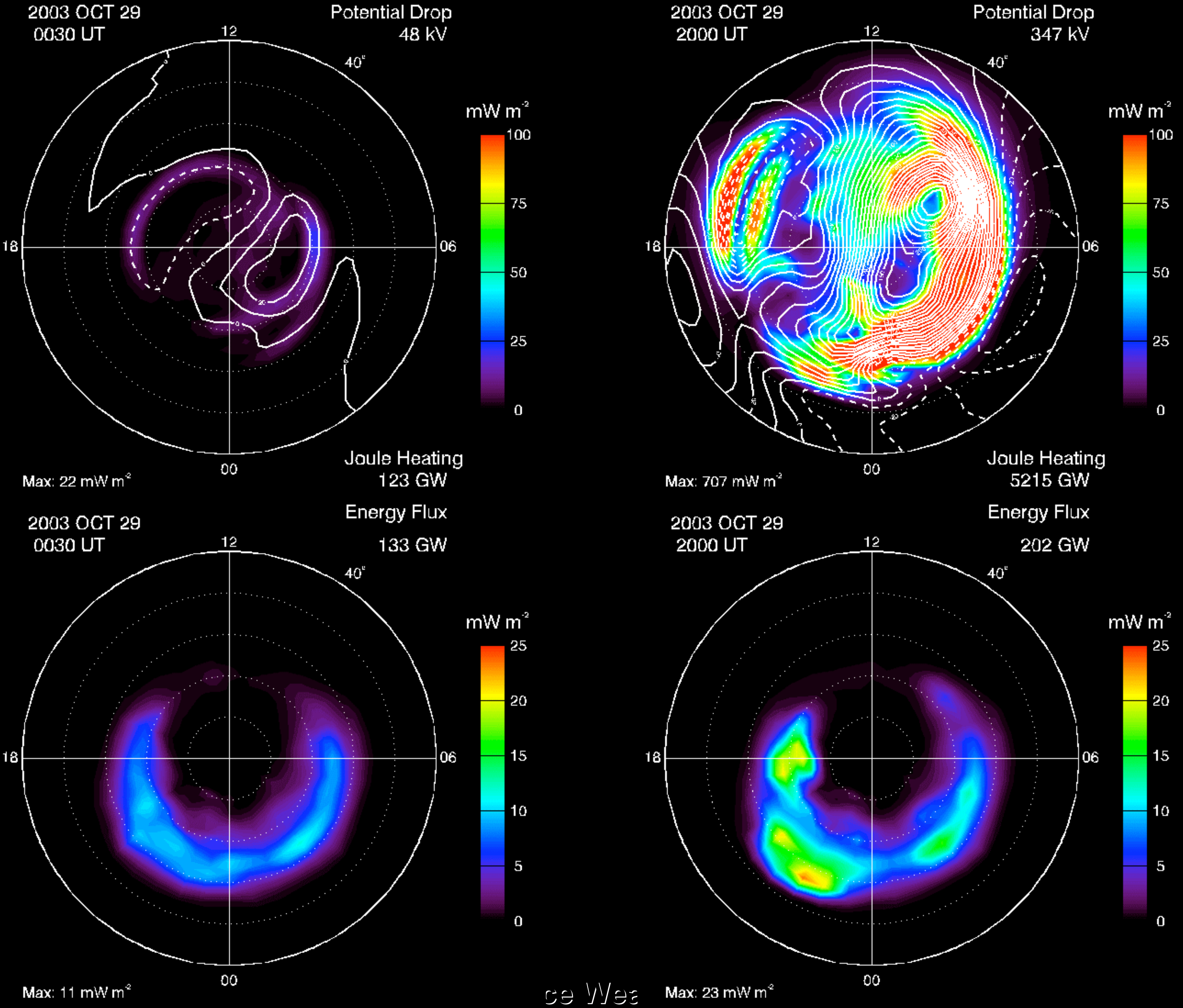
# Prevailing Space Weather: Geomagnetic Activity



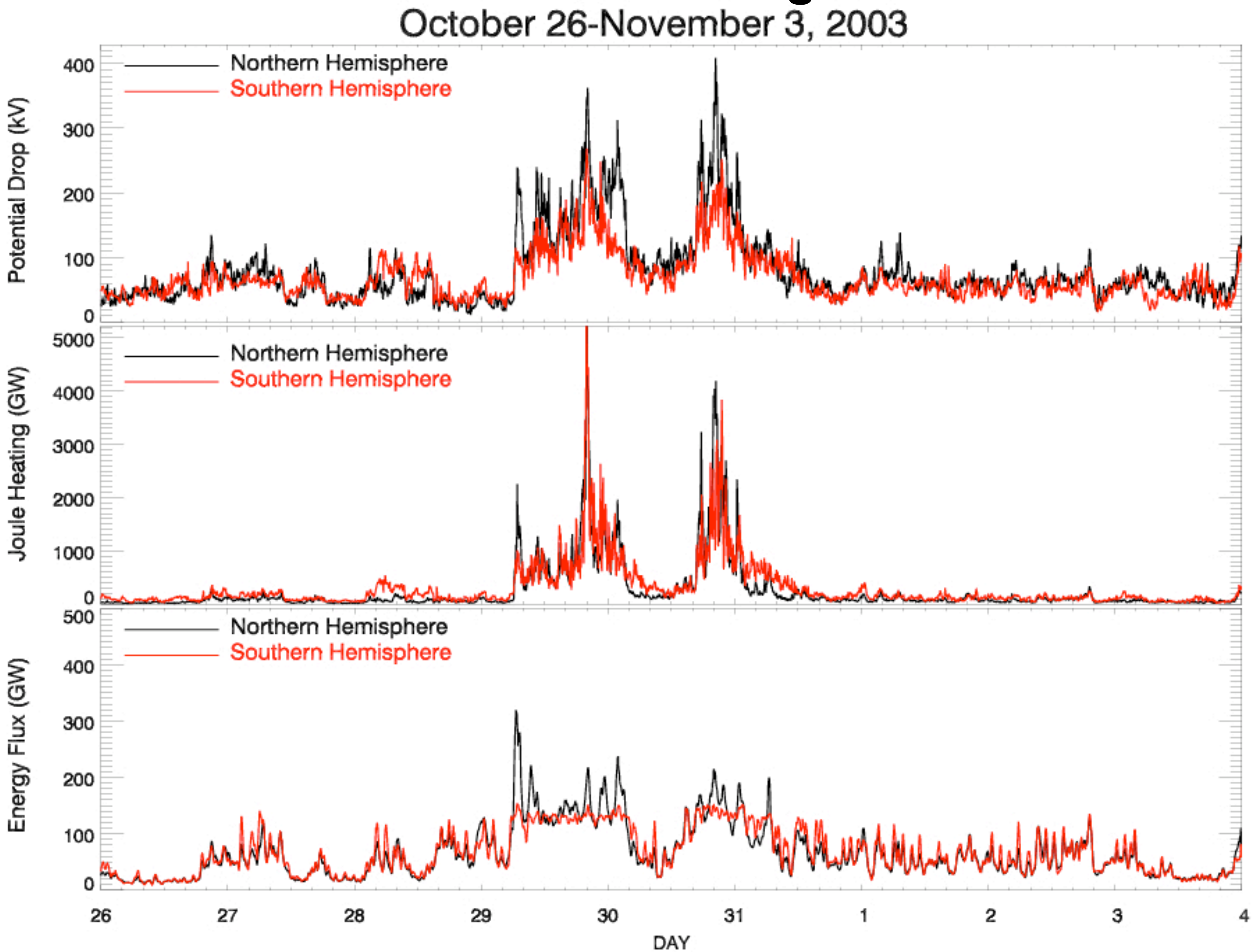
# AIME Forcing

## Quiet Time

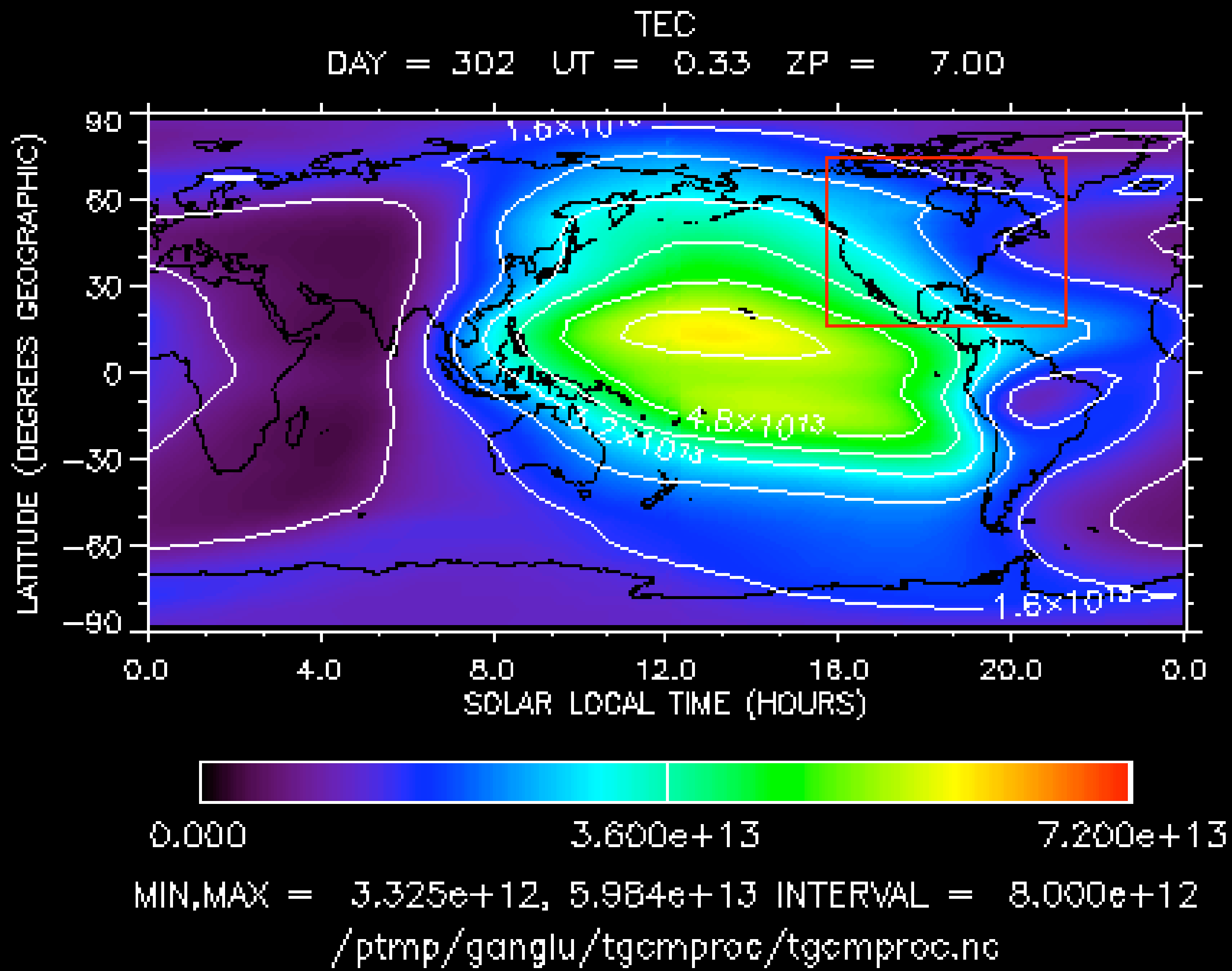
## Storm Time



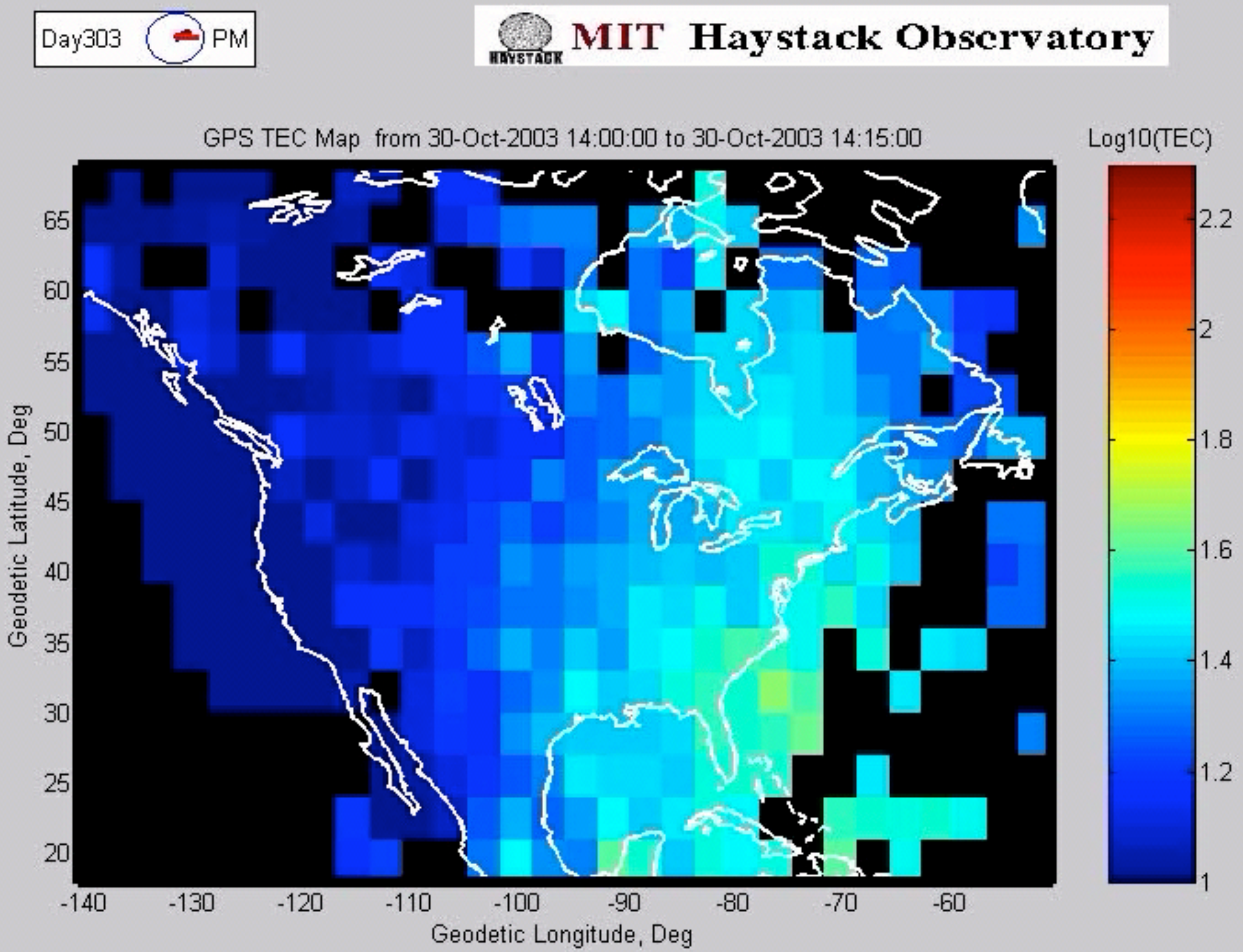
# AIME Forcing



# TIEGCM Electron Column Densities on 29 October 2003

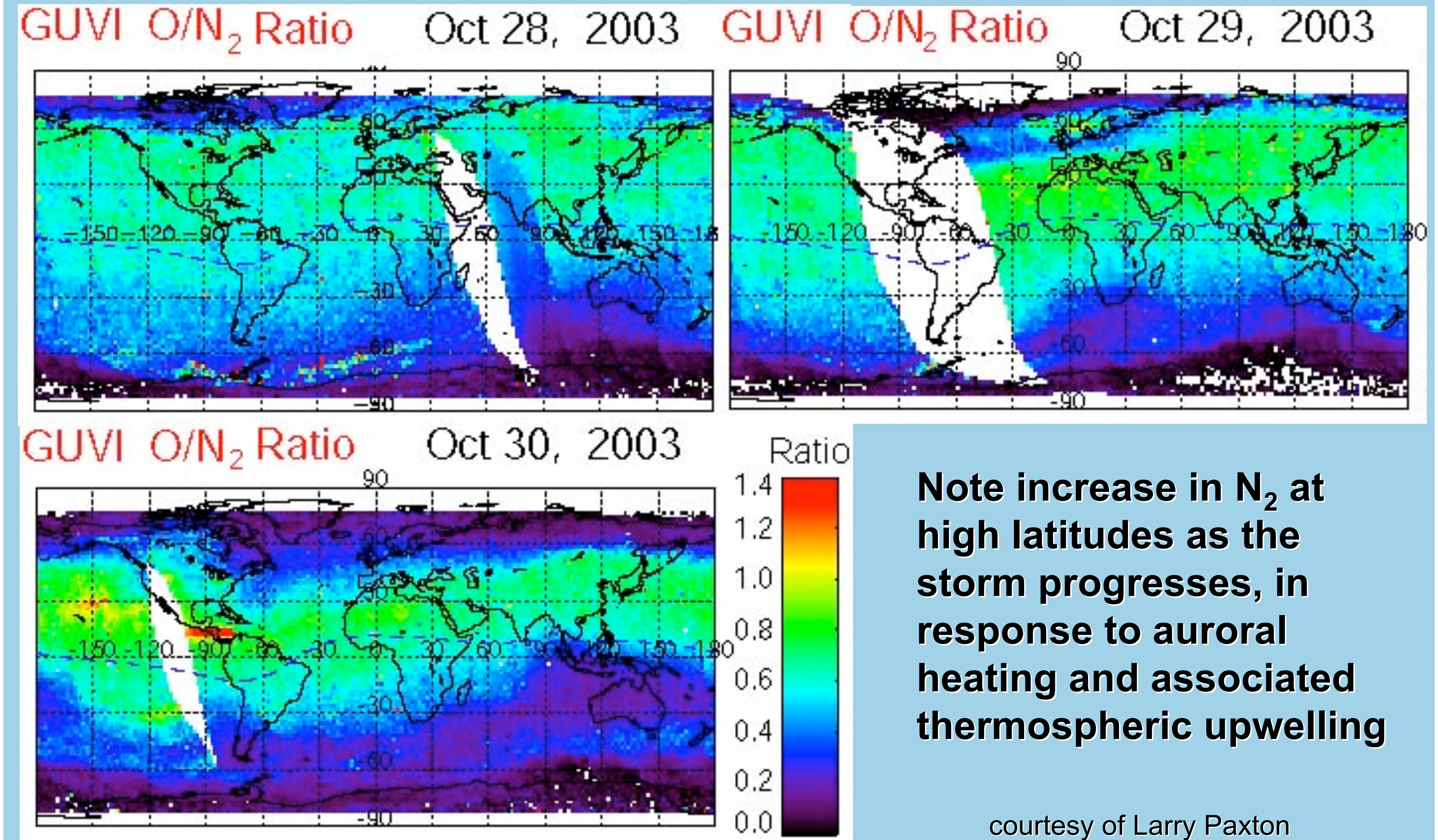


# GPS Total Electron Content




courtesy of Anthea Coster and Bill Rideout

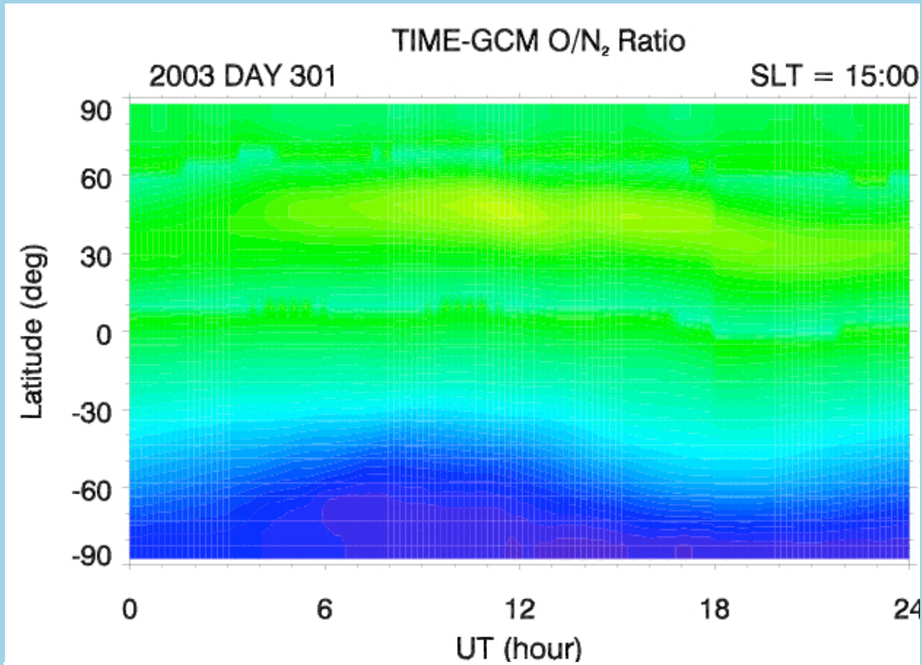
# TIMED-GUVI Observations of Neutral Composition

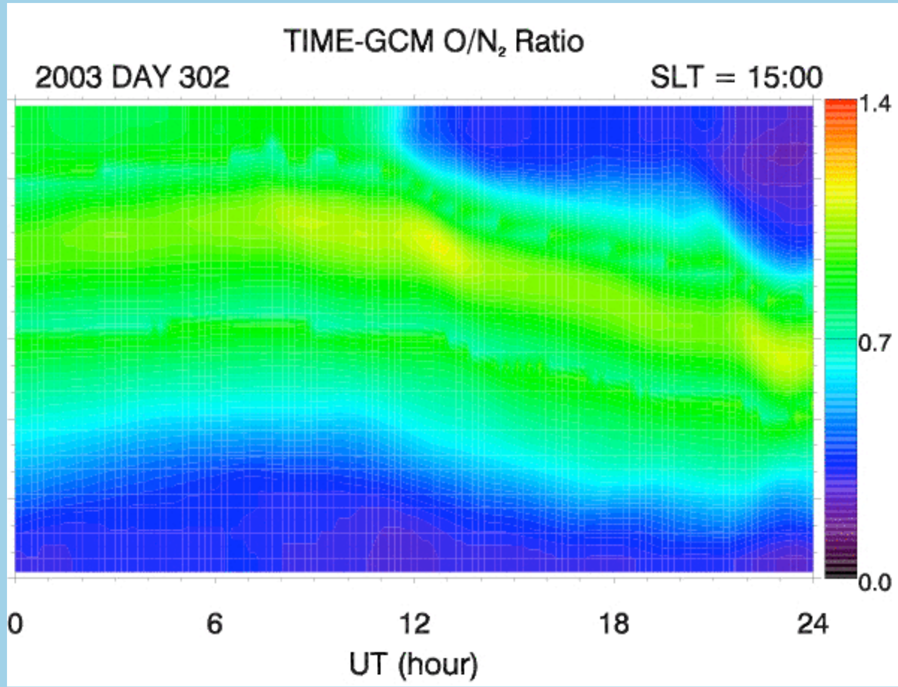


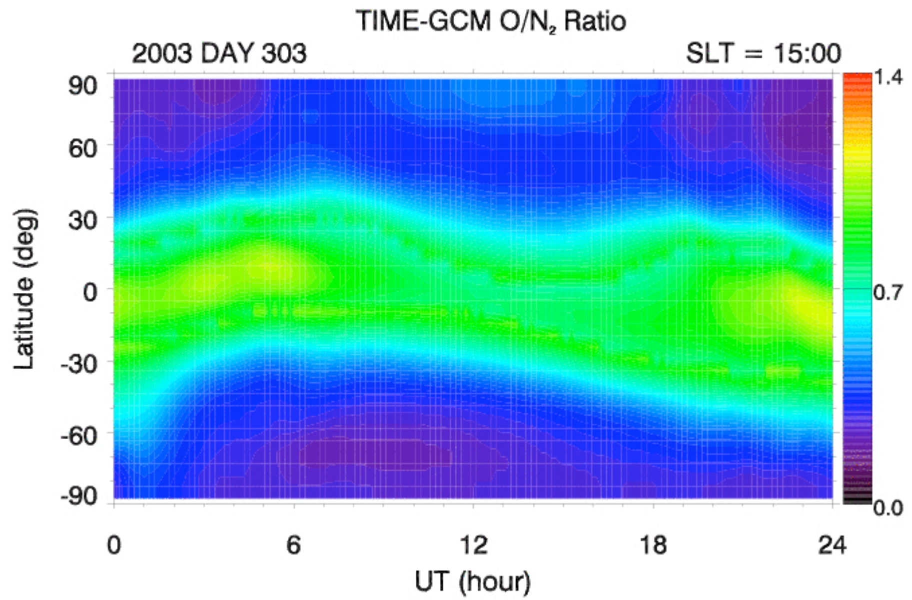

**Note increase in $N_2$ at high latitudes as the storm progresses, in response to auroral heating and associated thermospheric upwelling**

courtesy of Larry Paxton

# Simulated O/$N_2$ Ratios

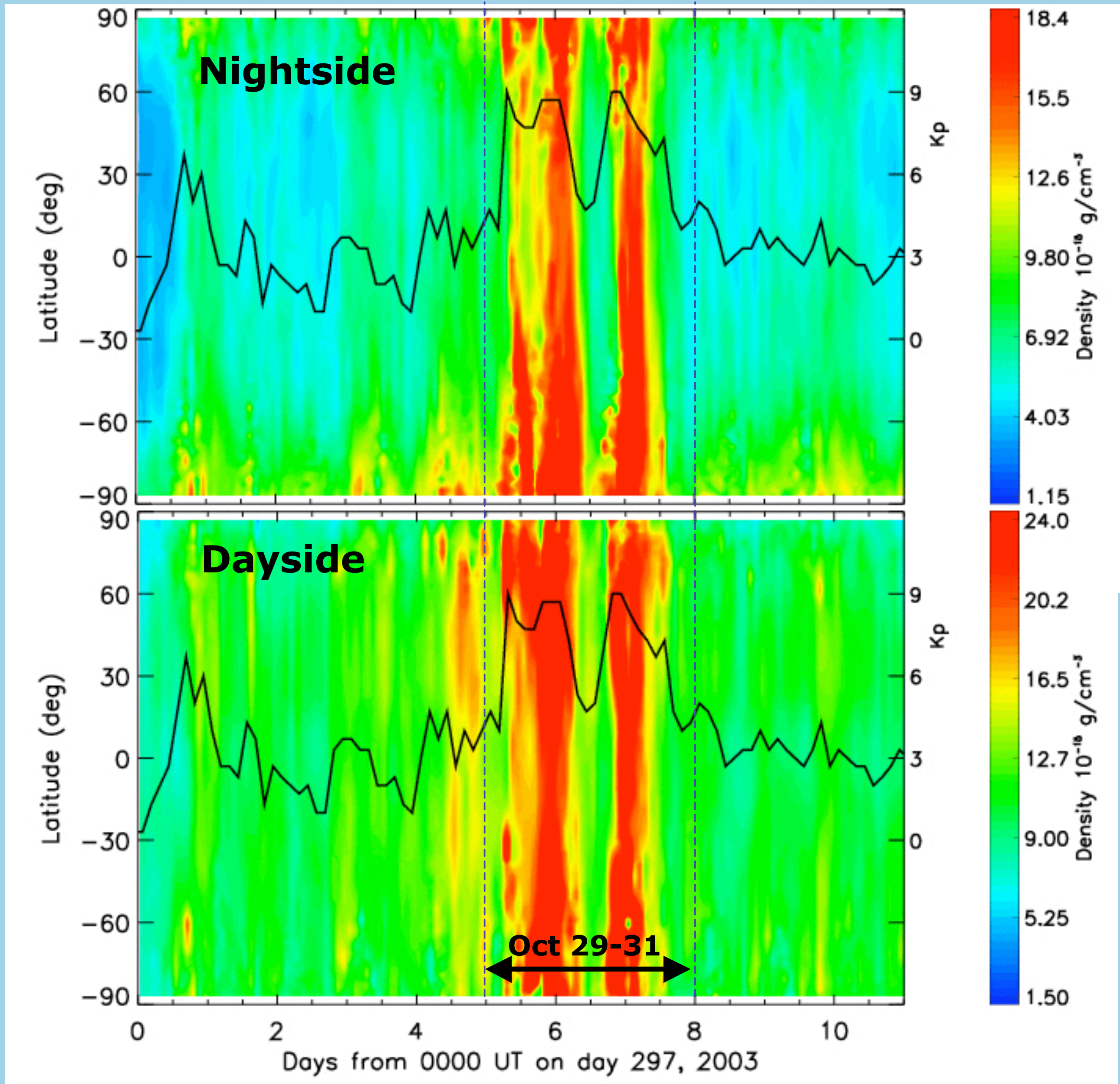



**The GCM captures the salient features of the O/$N_2$ TIMED-GUVI observations**

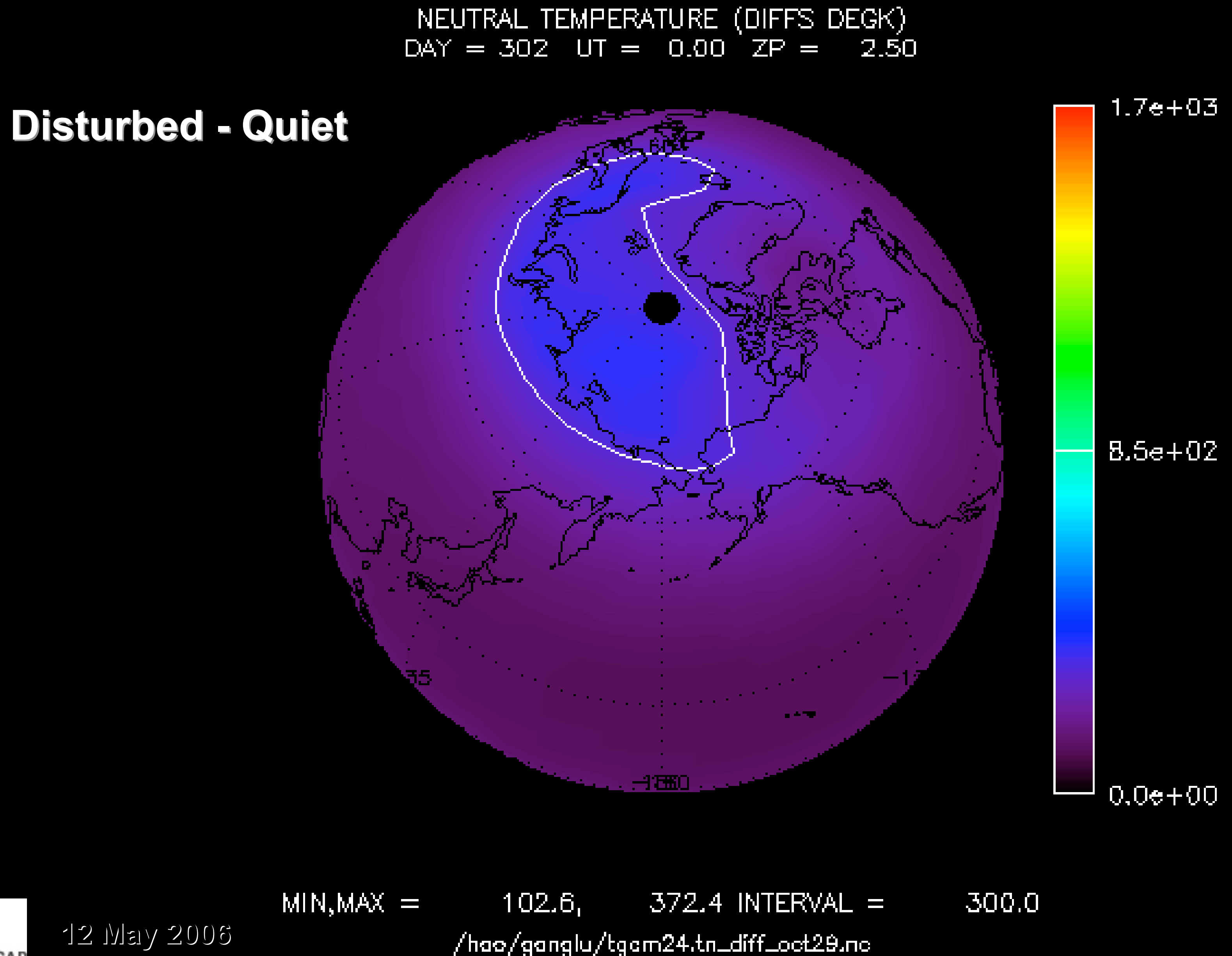
# CHAMP Neutral Density Observations at 400km



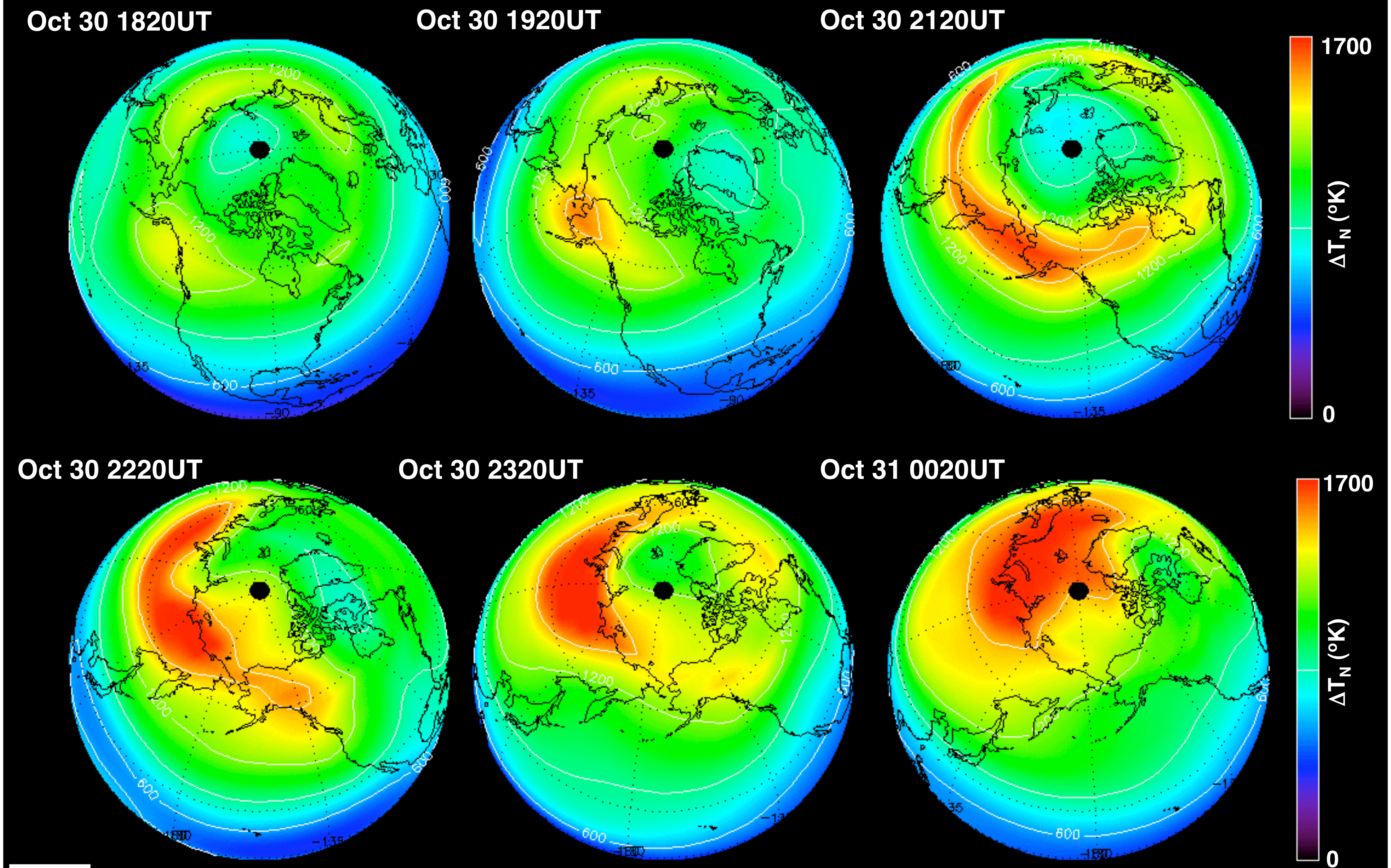

**Note, comparisons with TIEGCM in notes from Jeff Forbes' lecture on 11 May 2006**

courtesy of
Jeff Forbes
and
Xiaoli Zhang

# Neutral Temperature Difference at ~400 km

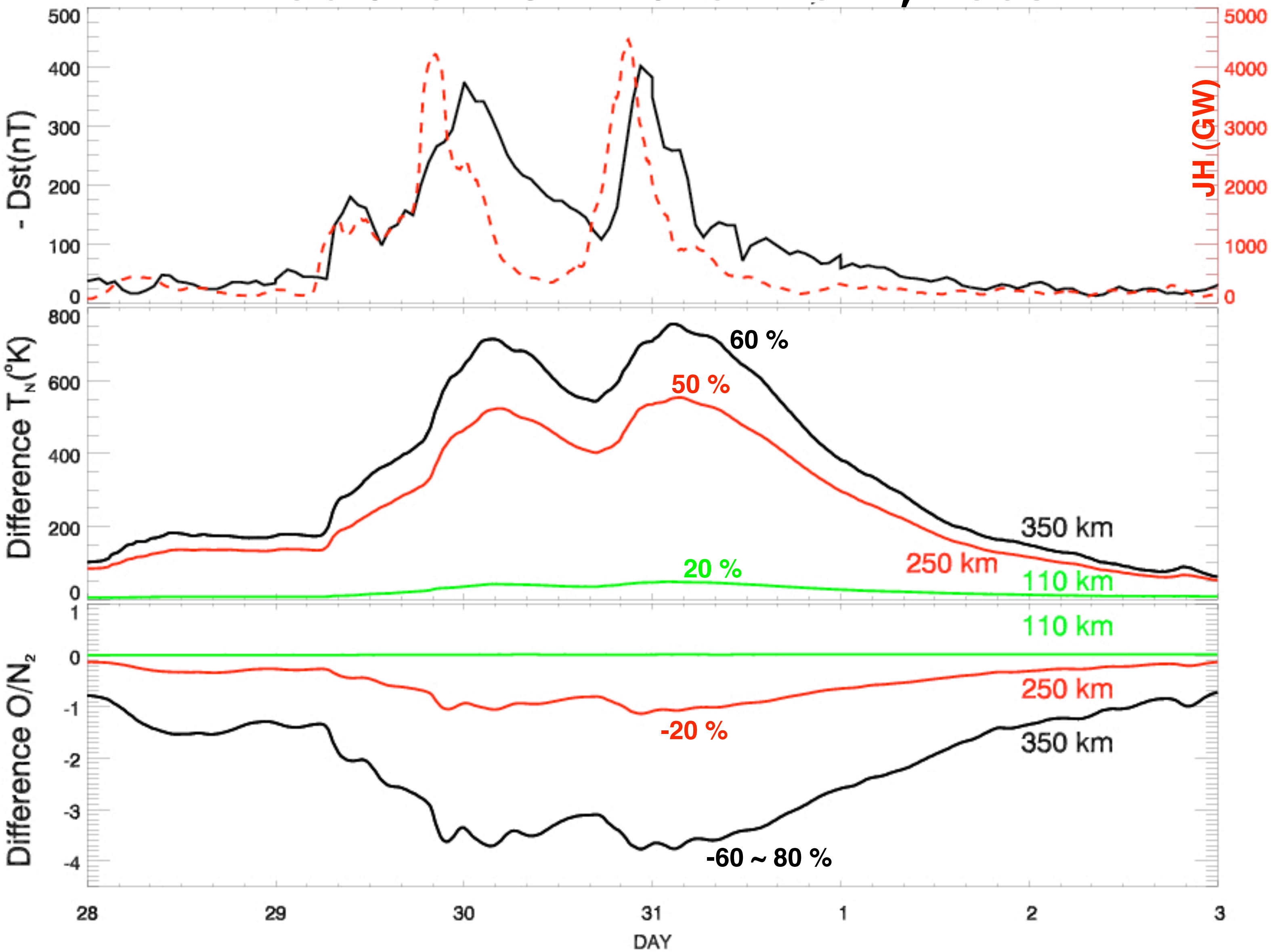


# TIEGCM Neutral Temperature Difference at ~400 km



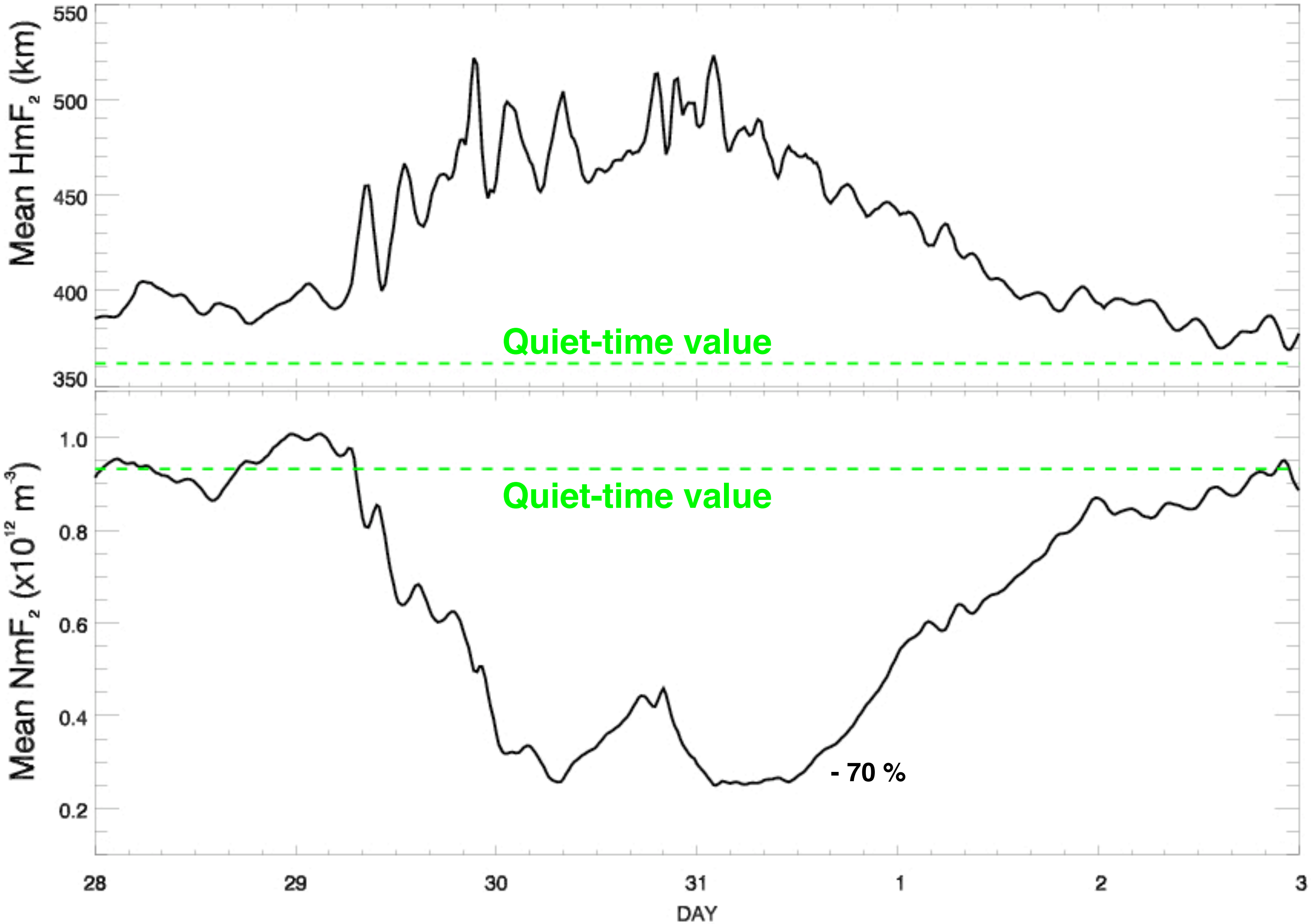
# TIEGCM Diagnostics - Thermosphere

## October 28 – November 2, 2003



# TIEGCM Diagnostics - Ionosphere

## October 28 – November 2, 2003



# Recap - Halloween Storm Simulation

- Strong geomagnetic activity with Dst ~ - 450 nT, AE ~ 3500 nT; cross-polar-cap potential drop reaches 350 ~ 400 kV, and Joule heating peaks ~ 5000 GW
- Solar energetic protons produce significant ionization in the D-region, causing enhanced riometer absorption in both northern and southern polar regions in TIME-GCM
- Large Joule heating dissipation increases $T_N$ in the thermosphere by 700$^o$K (global average), and reaches ~1700$^o$K in local regions
- Significant decrease of $O/N_2$ ratio in the middle latitude region and auroral and subauroral zones
- The global average $HmF_2$ increased by more than 100 km and $NmF_2$ decreased by 70%

# Other GCM Development Efforts

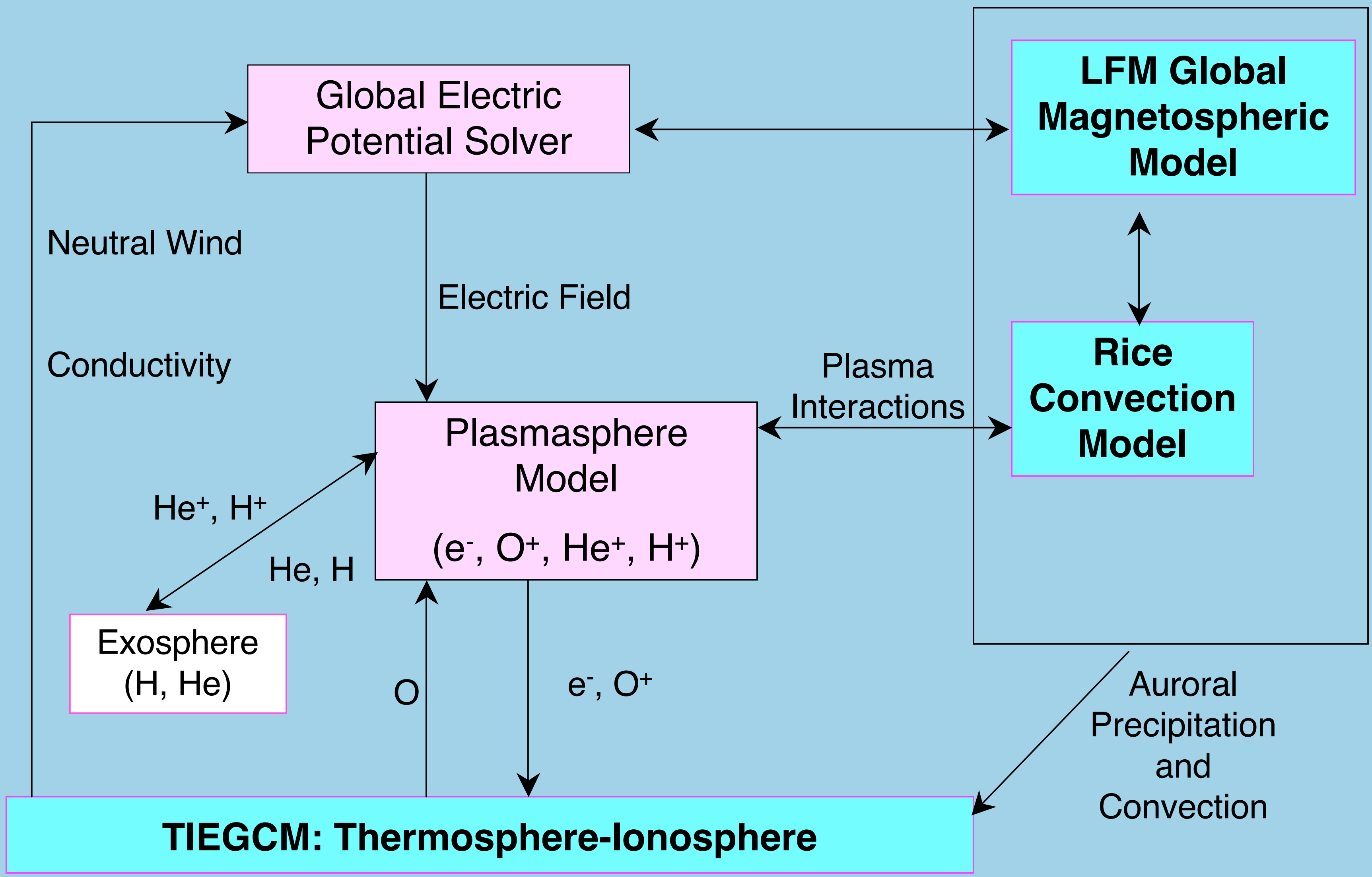
- TIME-GCM (ca. 1992)
  - moved lower boundary down to 30km
  - added stratospheric and mesospheric constituents and chemistry
  - added parameterized gravity wave effects
- Ongoing
  - adding a self-consistent plasmasphere
  - contributing to the Center for Integrated Space Weather Modeling (CISM) effort
  - working with other NCAR scientists to extend the Whole Atmosphere Community Climate Model (WACCM) into the thermosphere

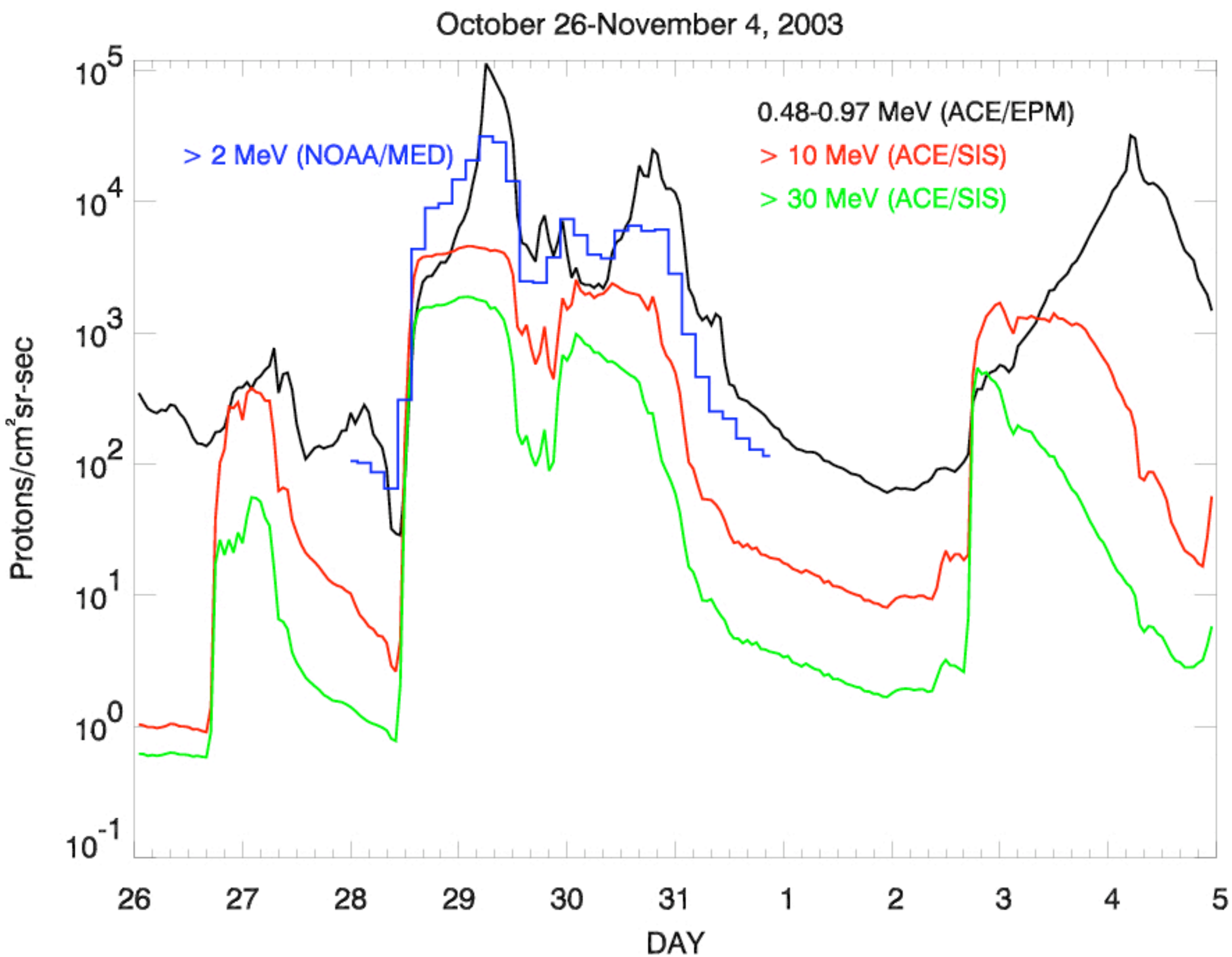
**Extra Slides:**

**Plasmaspheric Model Development**

**SEP during Halloween Storms**

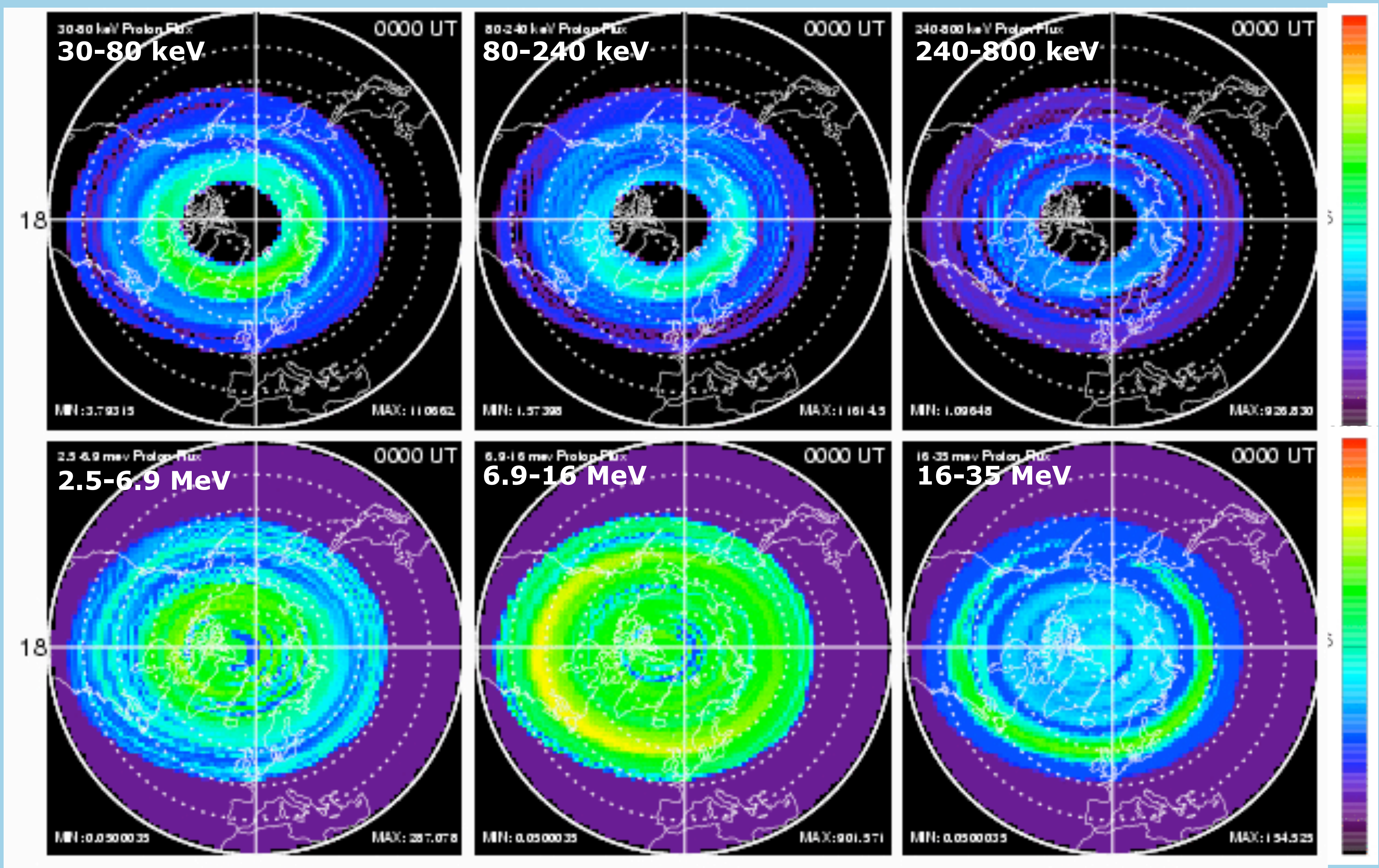
# Plasmasphere Model Development Plan




October 26-November 4, 2003
0.48-0.97 MeV (ACE/EPM)
> 2 MeV (NOAA/MED)
> 10 MeV (ACE/SIS)
> 30 MeV (ACE/SIS)
Protons/cm²sr-sec
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
26
27
28
29
30
31
1
2
3
4
5
DAY

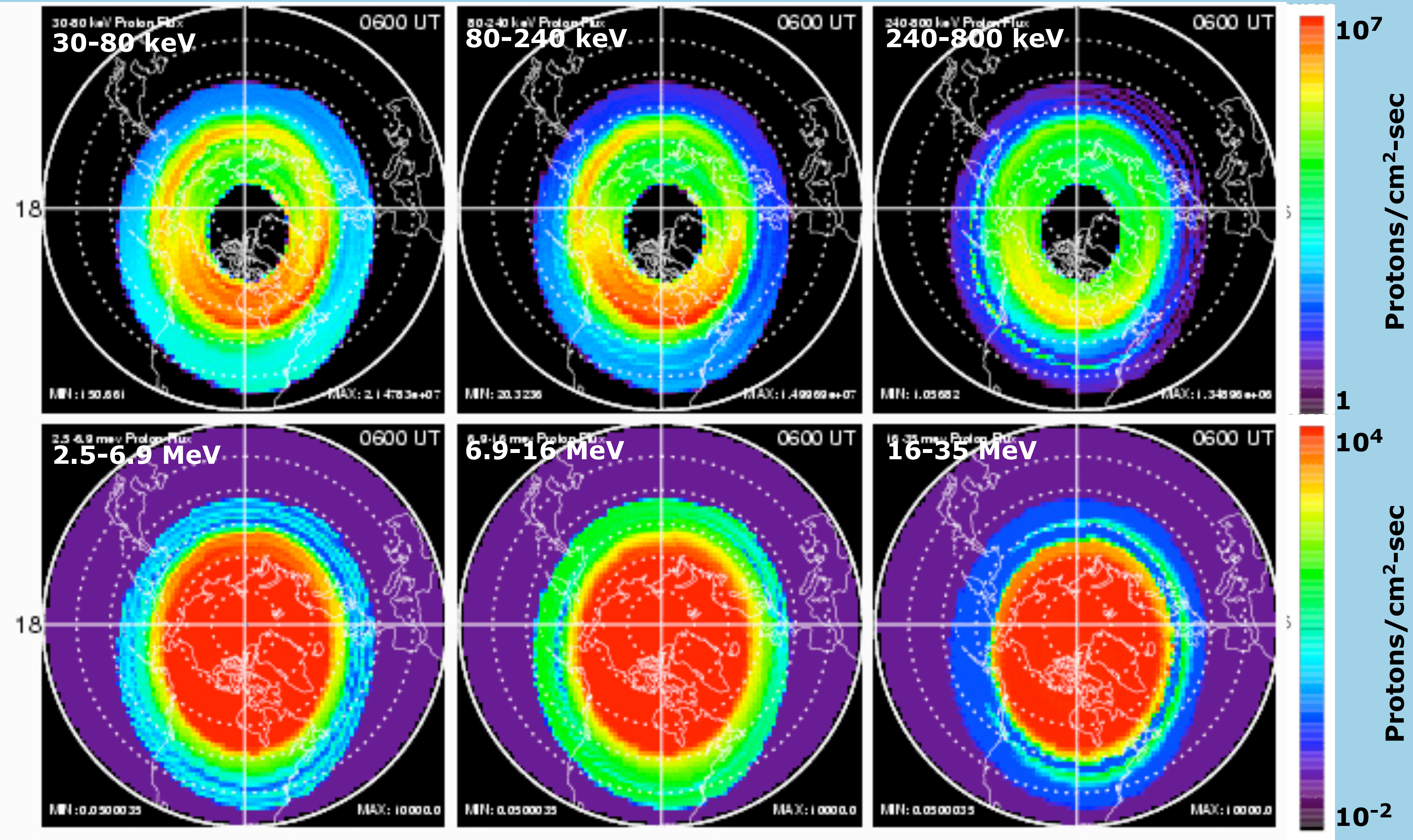
# Solar Energetic Protons Observed by NOAA-POSE

## 00 UT, 28 October 2003



# Solar Energetic Protons Observed by NOAA-POSE

## 06 UT, 29 October 2003



# Electron Density Enhancement due to SEP