

# Whole Atmosphere Simulation of Anthropogenic Climate Change

Stan Solomon, Hanli Liu, Dan Marsh, Joe McInerney, Liying Qian, and Francis Vitt

High Altitude Observatory  
National Center for Atmospheric Research

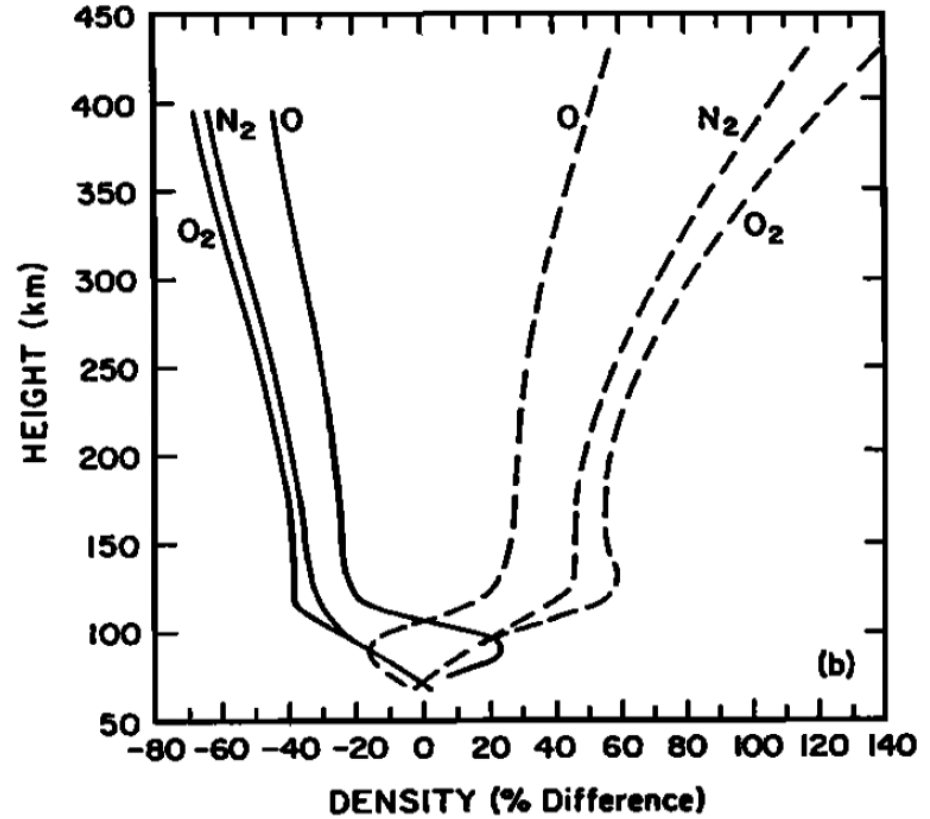
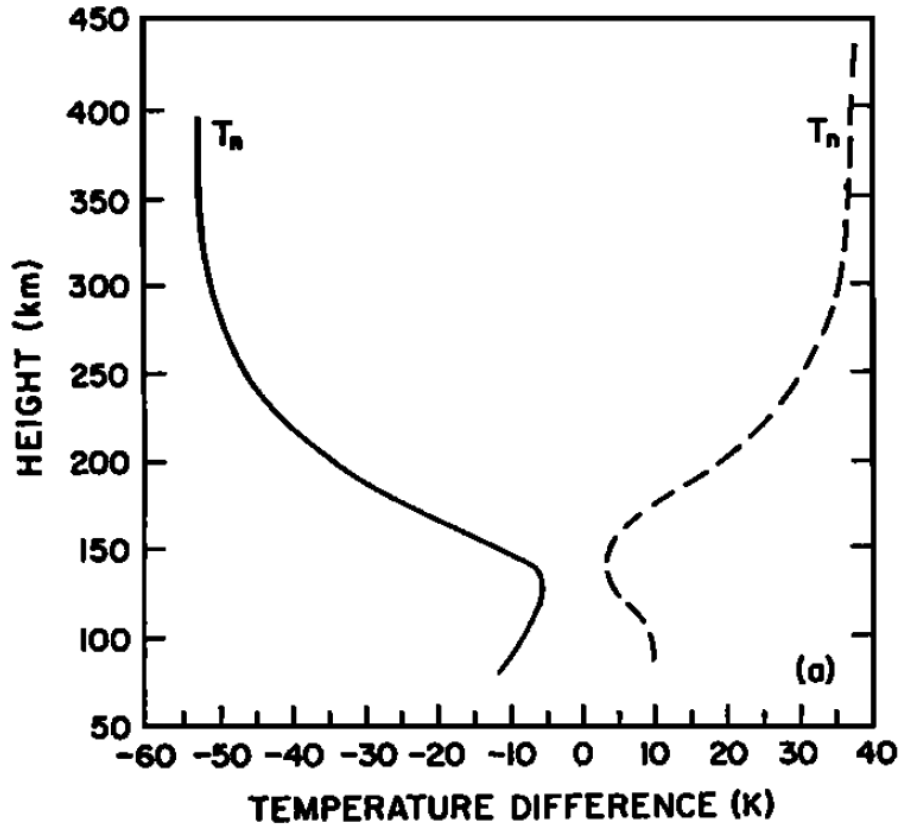


**NCAR**



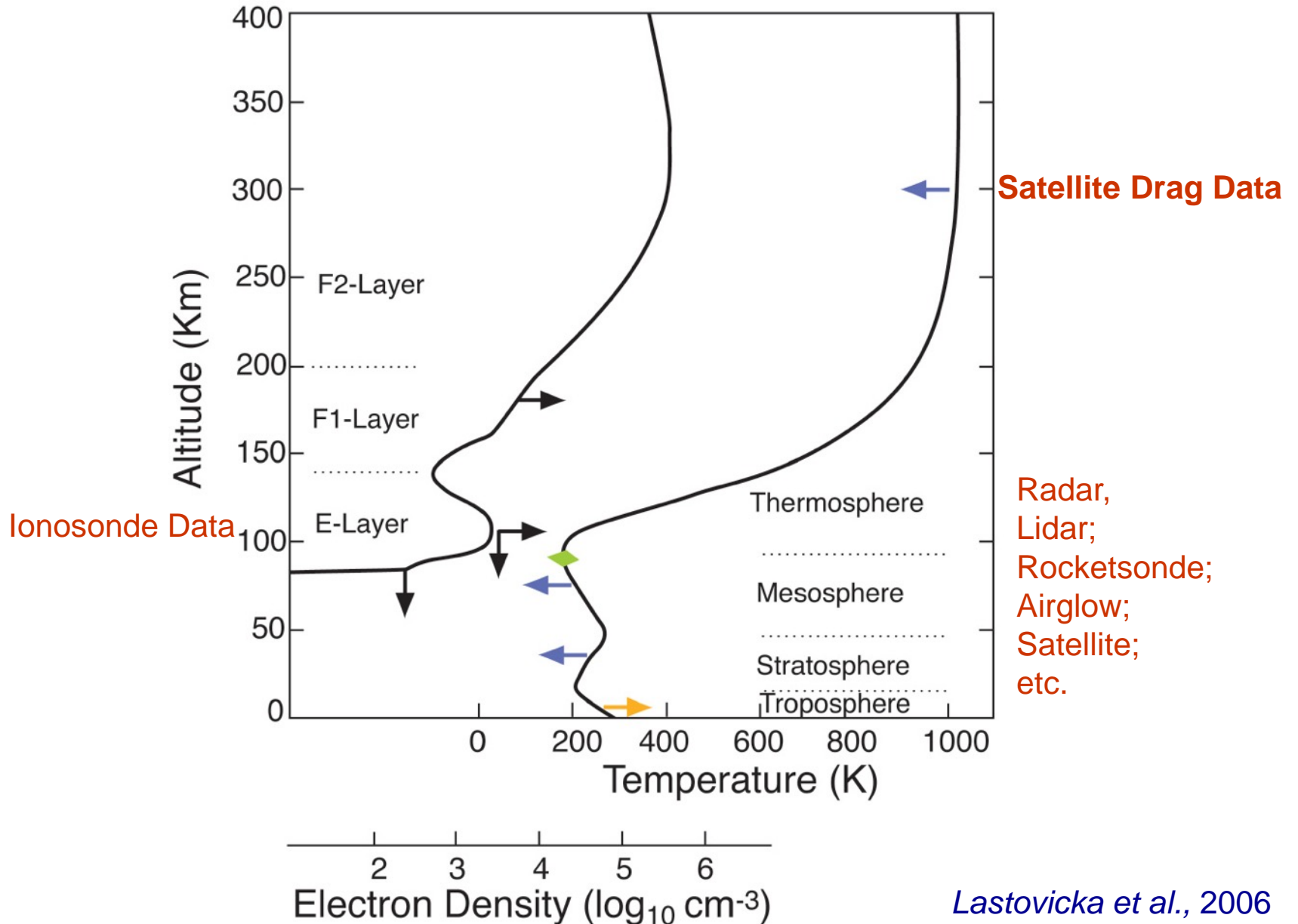
# Model Prediction of Global Change in the Thermosphere

*Roble & Dickinson [1989]*



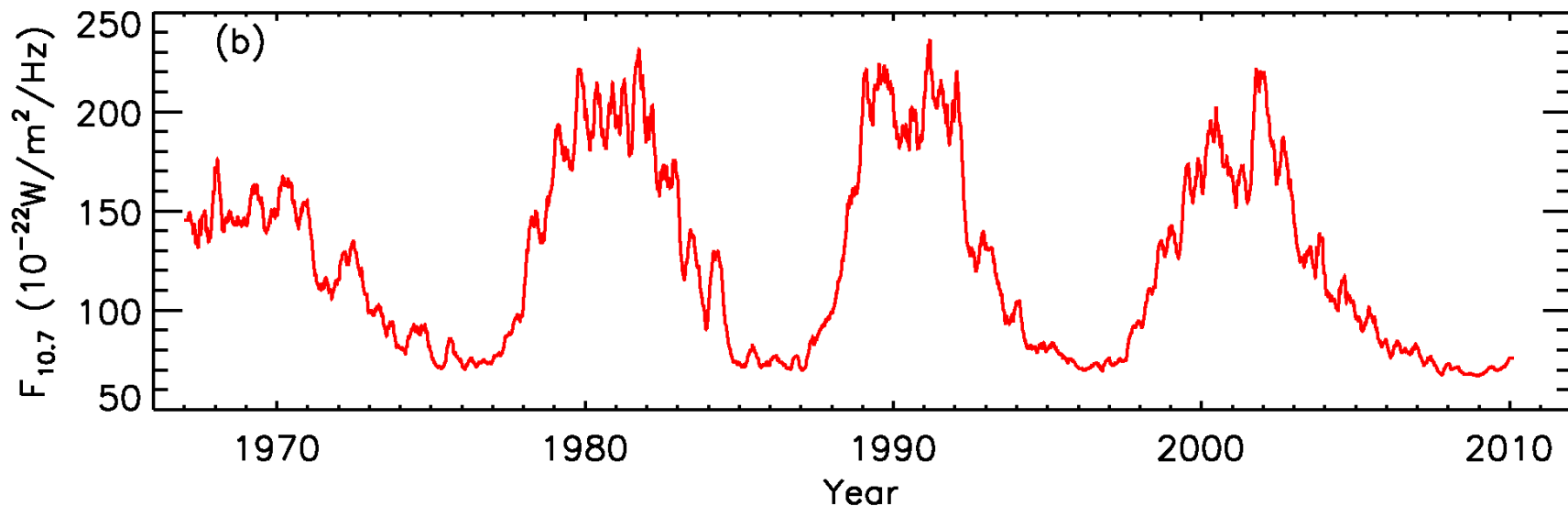
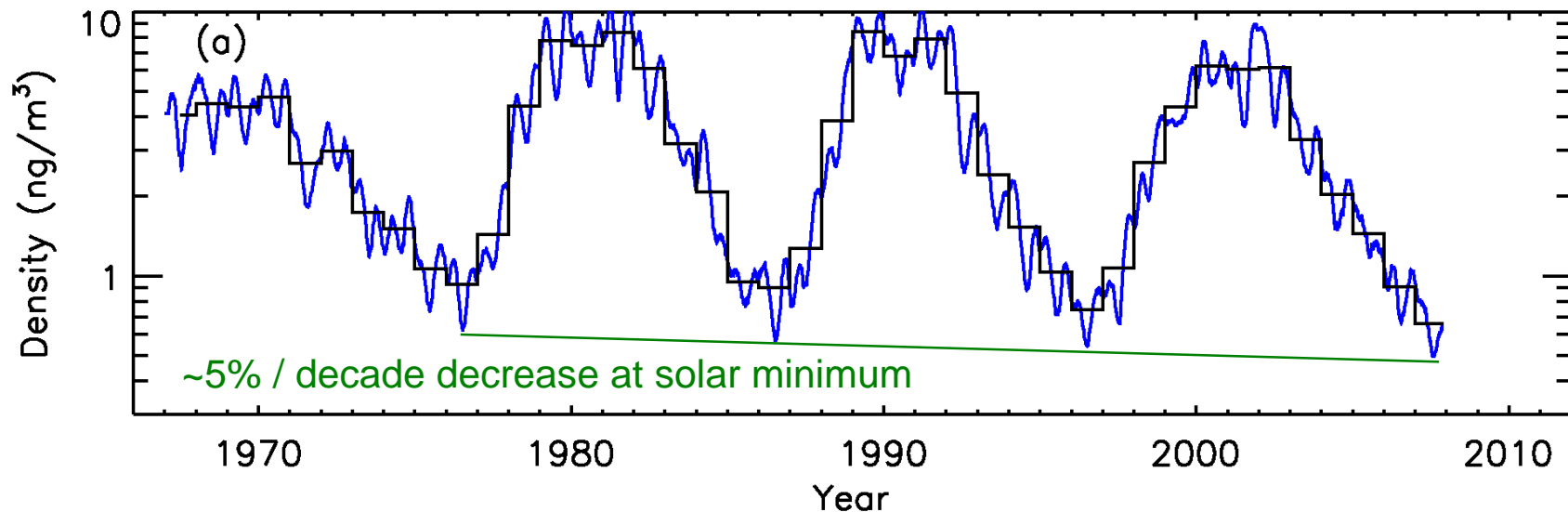
Global mean temperature, density, and composition study  
for doubled and halved  $CO_2$  and  $CH_4$

# Observed / Inferred Global Change Scenario



*Lastovicka et al., 2006*

# Strongest Evidence for Upper-Atmosphere Global Change



Top: Global average neutral density at 400 km, 81-day average and annual average  
*Emmert et al., 2010; (c.f., Keating et al., 2000; Marcos et al., 2005; Saunders et al., 2010)*

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

WACCM-X is WACCM with additional physics and extended vertical range through the thermosphere/ionosphere (~500km)

Whole Atmosphere Community Climate Model (WACCM) is CAM with additional chemistry/physics and extended vertical range into the lower thermosphere (~120km)

Community Atmosphere Model (CAM) is atmospheric component of CESM

NCAR Community Earth System Model (CESM)

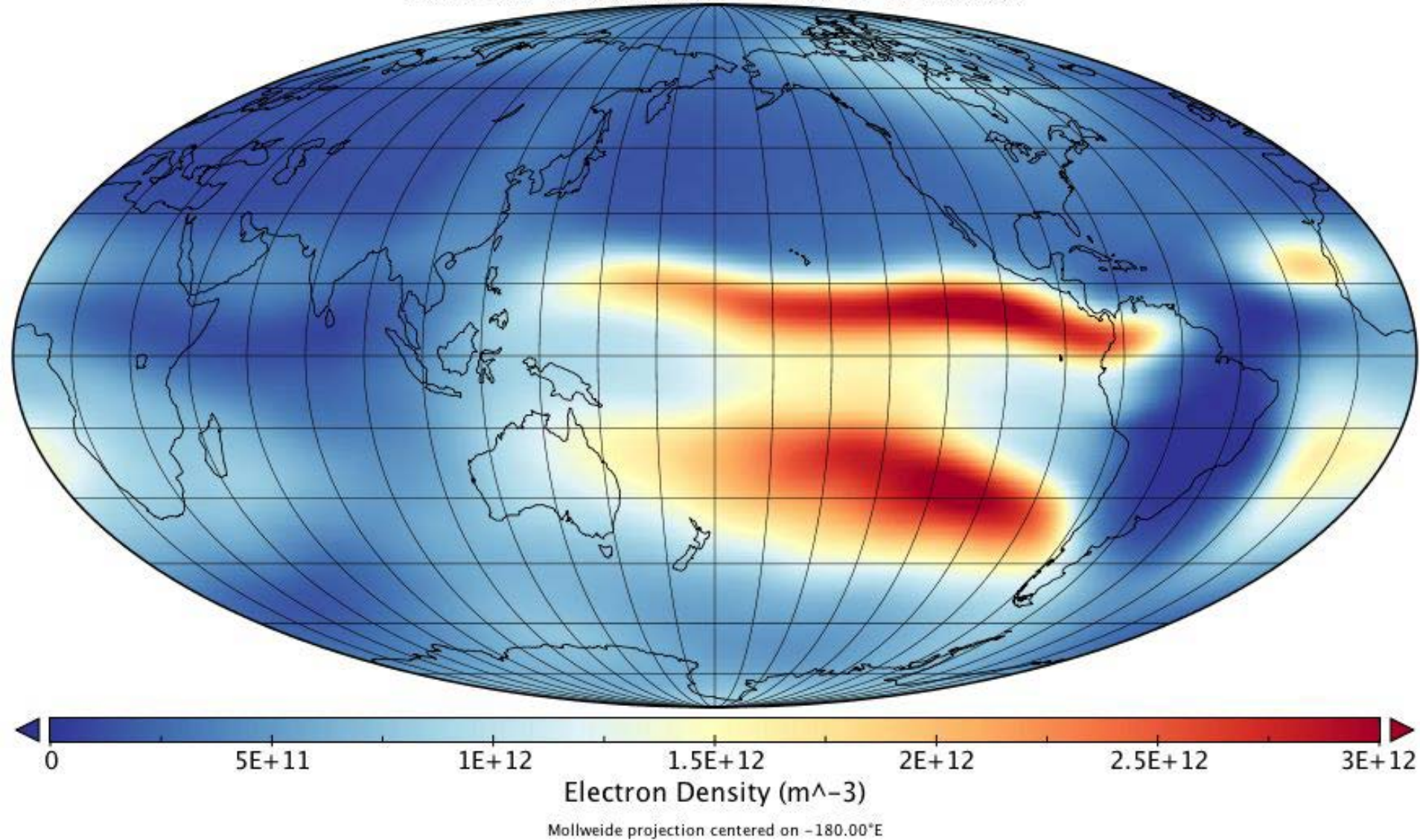
# Recent Progress on WACCM-X

- Ion and electron energetics implemented:
  - Now calculating  $T_i$  and  $T_e$  in WACCM-X.
- Equatorial electrodynamic 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)
- WACCM-X v. 2.0 released as a component of CESM 2  
(but still based on CAM 4 physics)

*H.-L. Liu et al. (2018), J. Adv. Mod. Earth Sys., doi:10.1002/2017MS001232*

# WACCM-X Ionosphere at ~250 km

Electron Density at  $3e-8$  hPa  
Time: 2000-01-09 22:59:59 — 2000-01-10 00:00:00



# WACCM-X Global Change Simulation Methodology

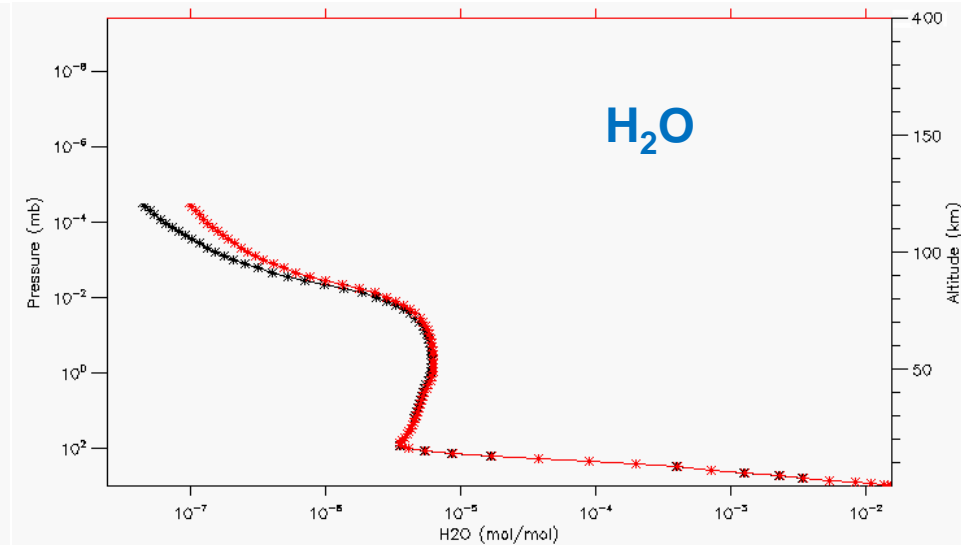
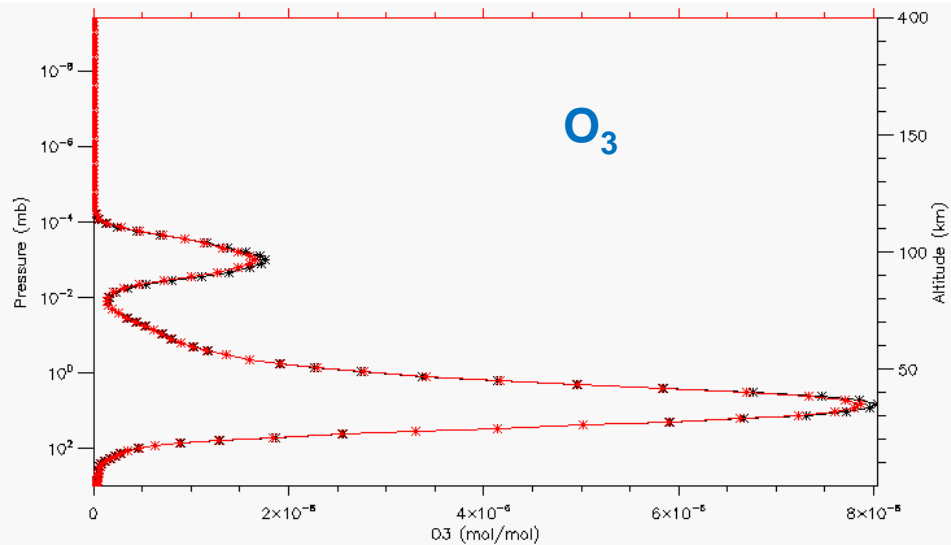
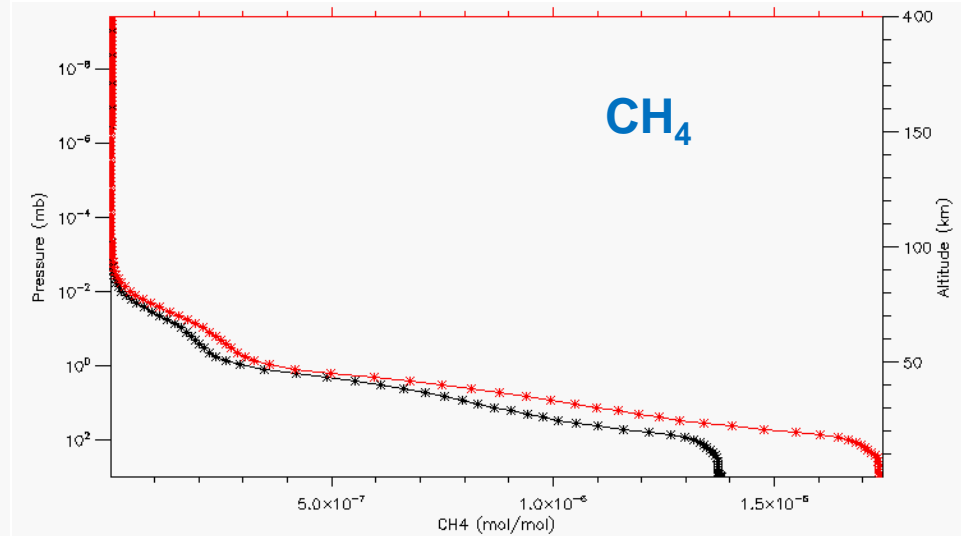
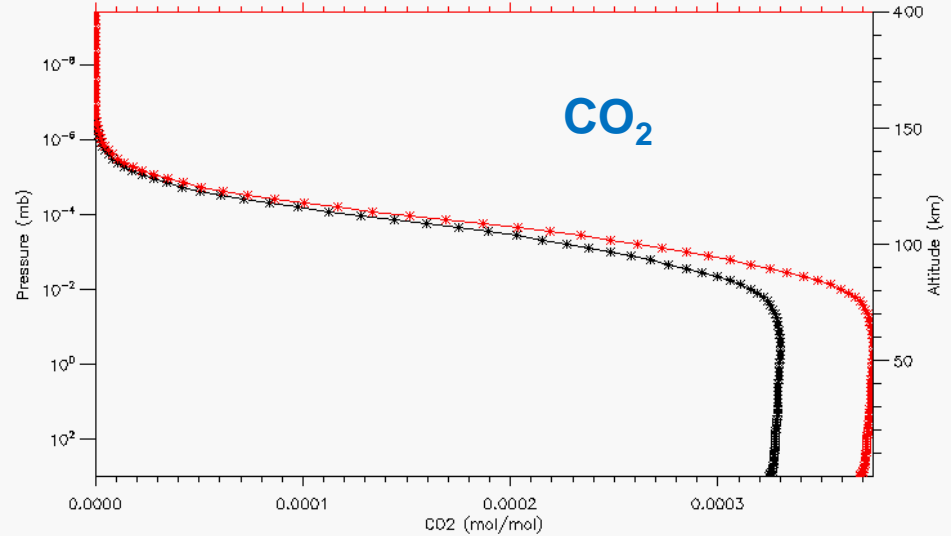
- Solar minimum conditions:

$$F_{10.7} = 70, K_p = 0.3$$

- Two sets of five-year runs to simulate change in a 29-year interval:
  - one with CO<sub>2</sub>, CH<sub>4</sub>, and CFCs from 1972–1976
  - one with CO<sub>2</sub>, CH<sub>4</sub>, and CFCs from 2001–2005
- Full WACCM-X free-running climate simulations
  - but using specified SSTs — no interactive ocean or sea ice, etc.
  - 2° resolution using FV dycore
- Decadal change rates estimated by scaling from 29-year interval to 10 years

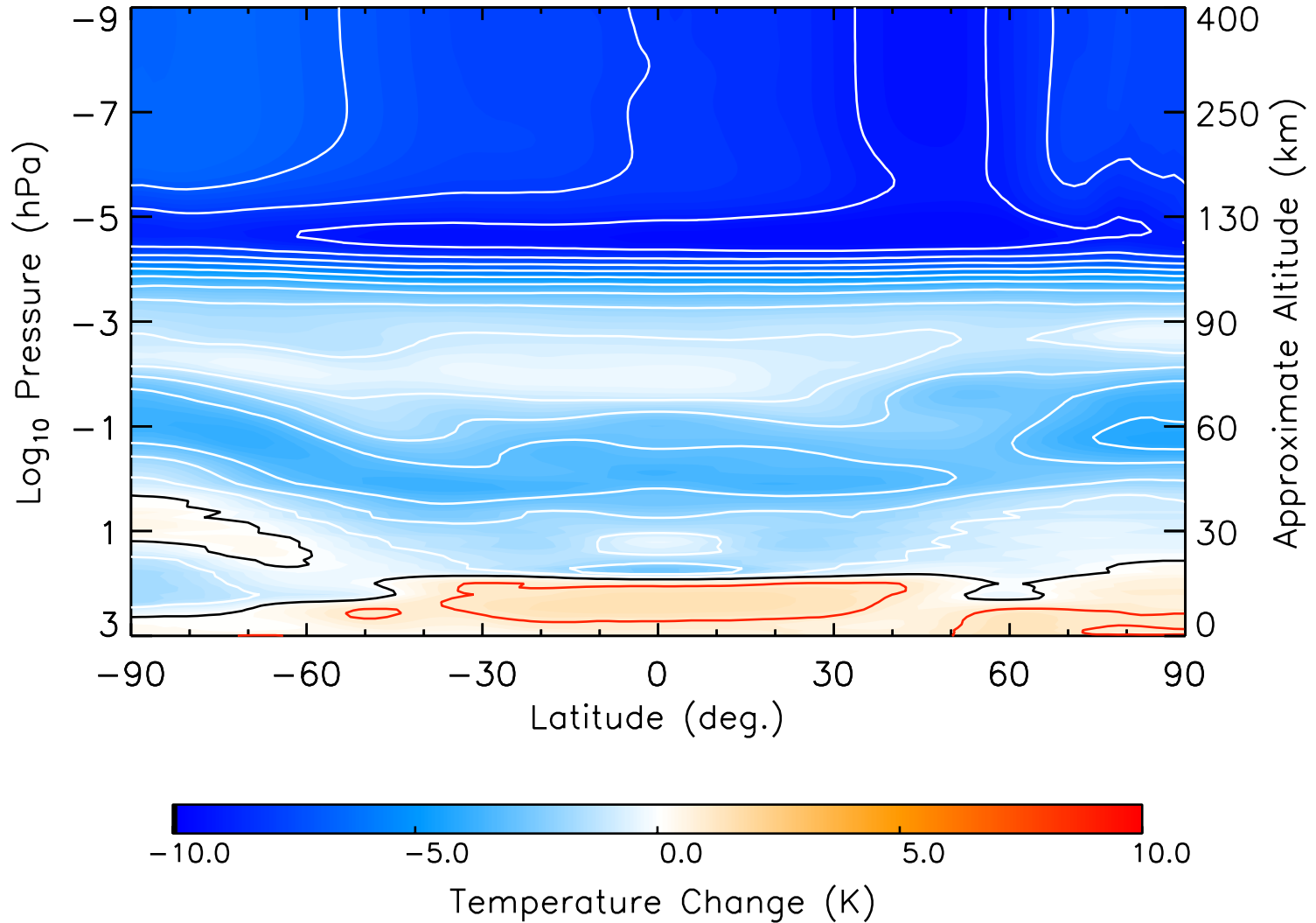


# Anthropogenic Global Change, 1974 to 2003



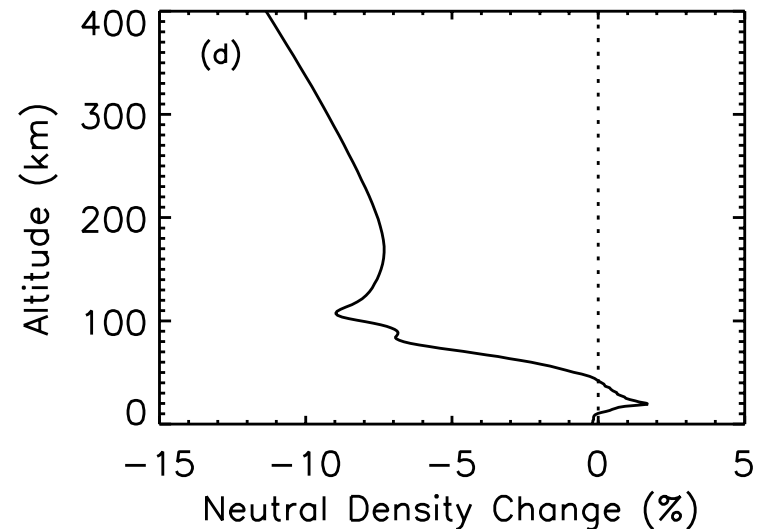
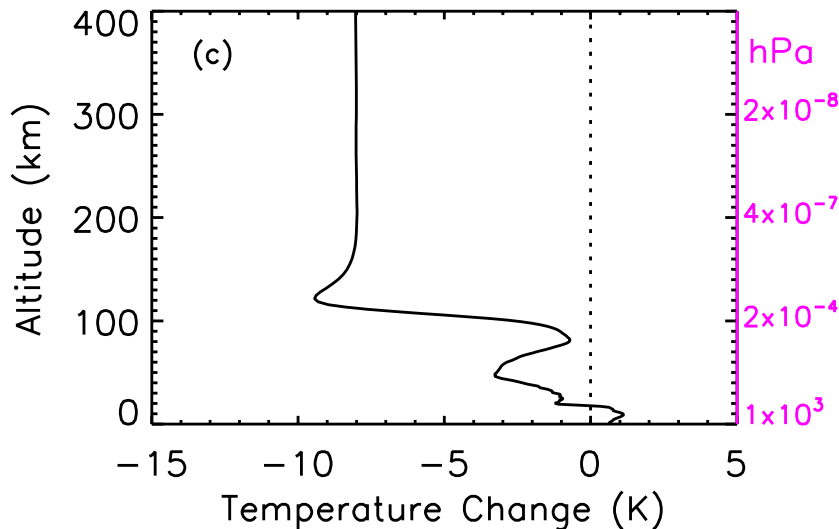
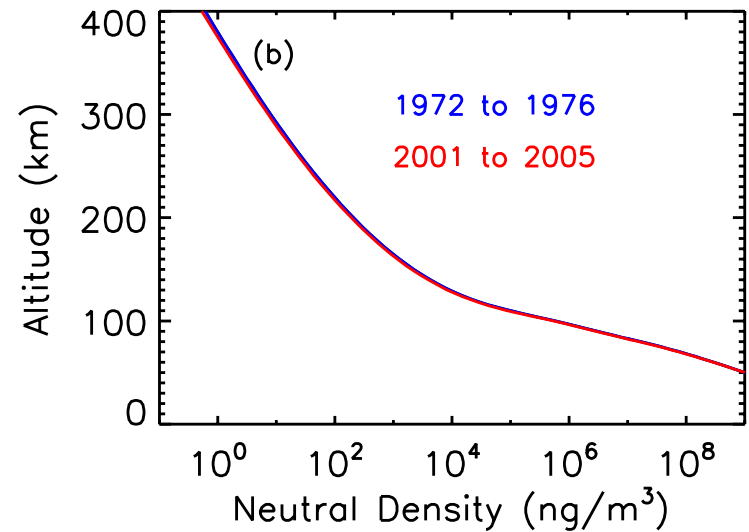
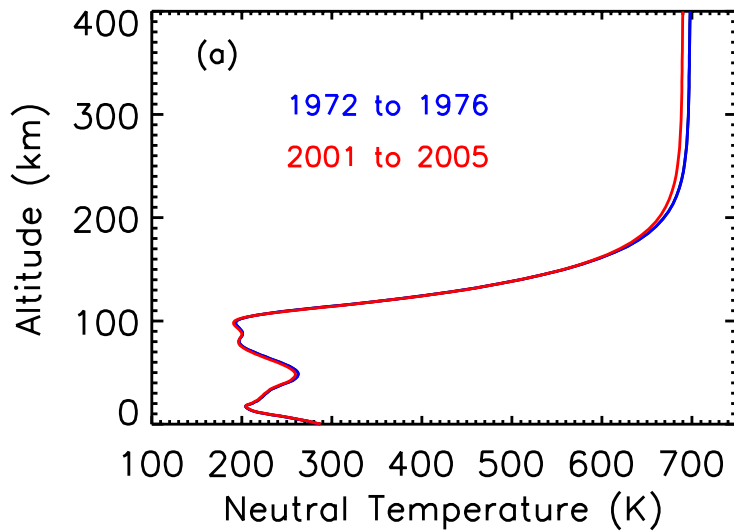
# Zonal Mean Temperature Change, 1974 to 2003

## Solar Minimum, June Monthly Average

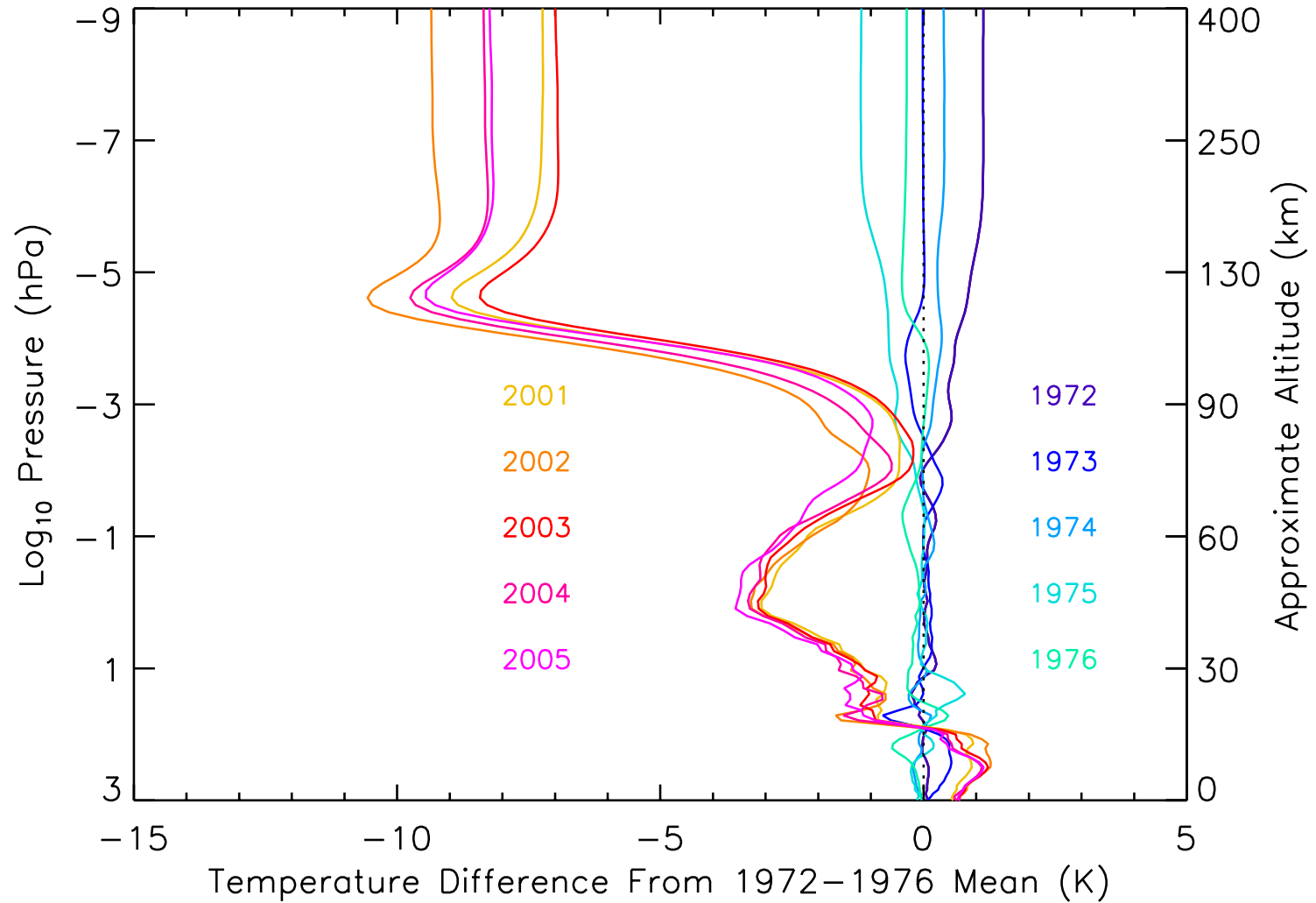


# Global Annual Mean Temperature Change, 1974 to 2003

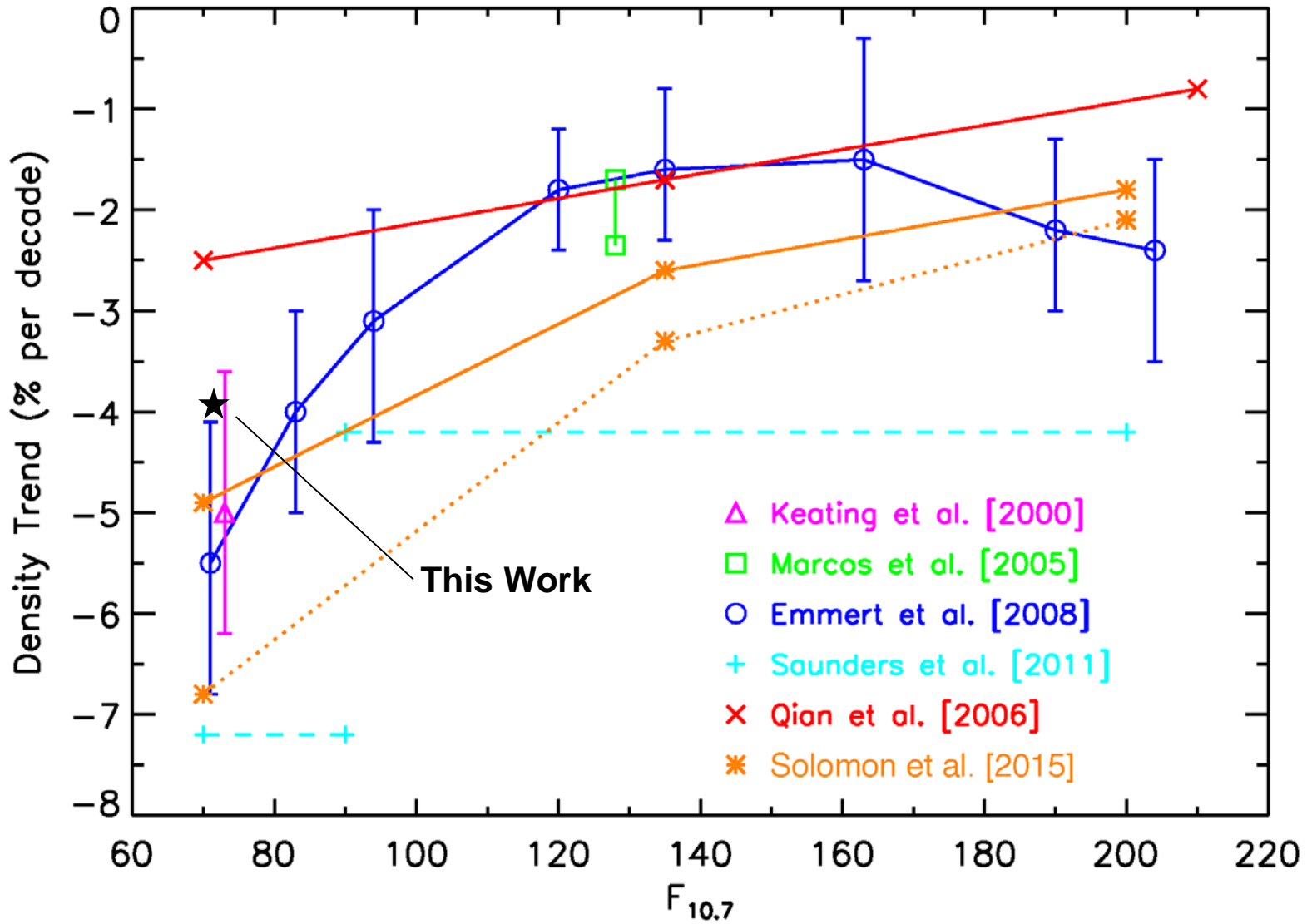
## Solar Minimum Conditions



# Interannual Variability of Global Mean Temperature



# Comparison of Density Trends at 400 km



# Summary and Conclusions

- Observations and model simulations demonstrate that the upper atmosphere, particularly the thermosphere/ionosphere, is cooling and contracting in response to anthropogenic change, primarily increases in CO<sub>2</sub>.
- Simulations using the Whole-Atmosphere Community Climate Model — eXtended show how global change occurs throughout the atmosphere, but in different ways.
- Solar variability makes it challenging to quantify anthropogenic change above the stratopause, and to verify whether our models are calculating it correctly.
- There is considerable interannual variability in global mean annual mean temperature change, especially near the mesopause.

# Recently Published in GRL

## Whole Atmosphere Simulation of Anthropogenic Climate Change

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and Francis M. Vitt<sup>1</sup>

<sup>1</sup>National Center for Atmospheric Research, High Altitude Observatory, Boulder, CO 80301

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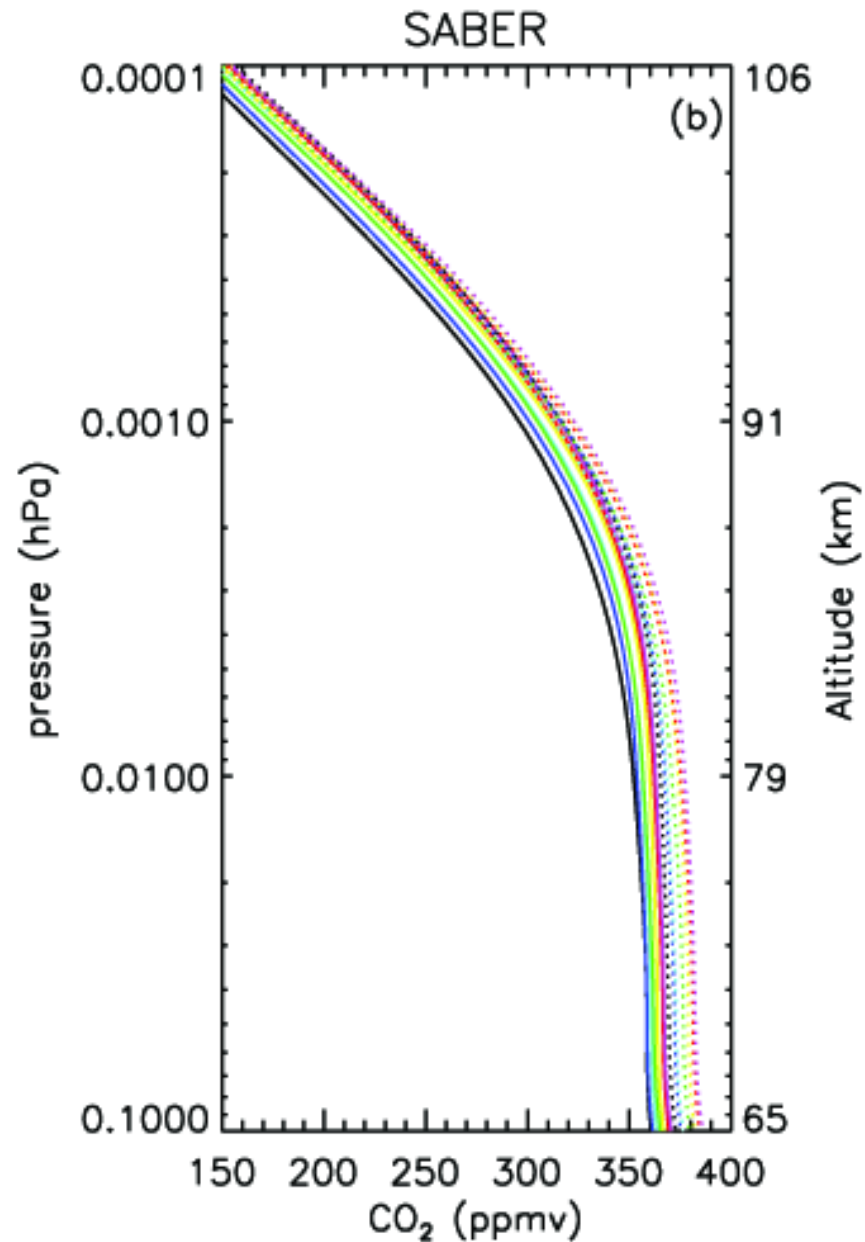
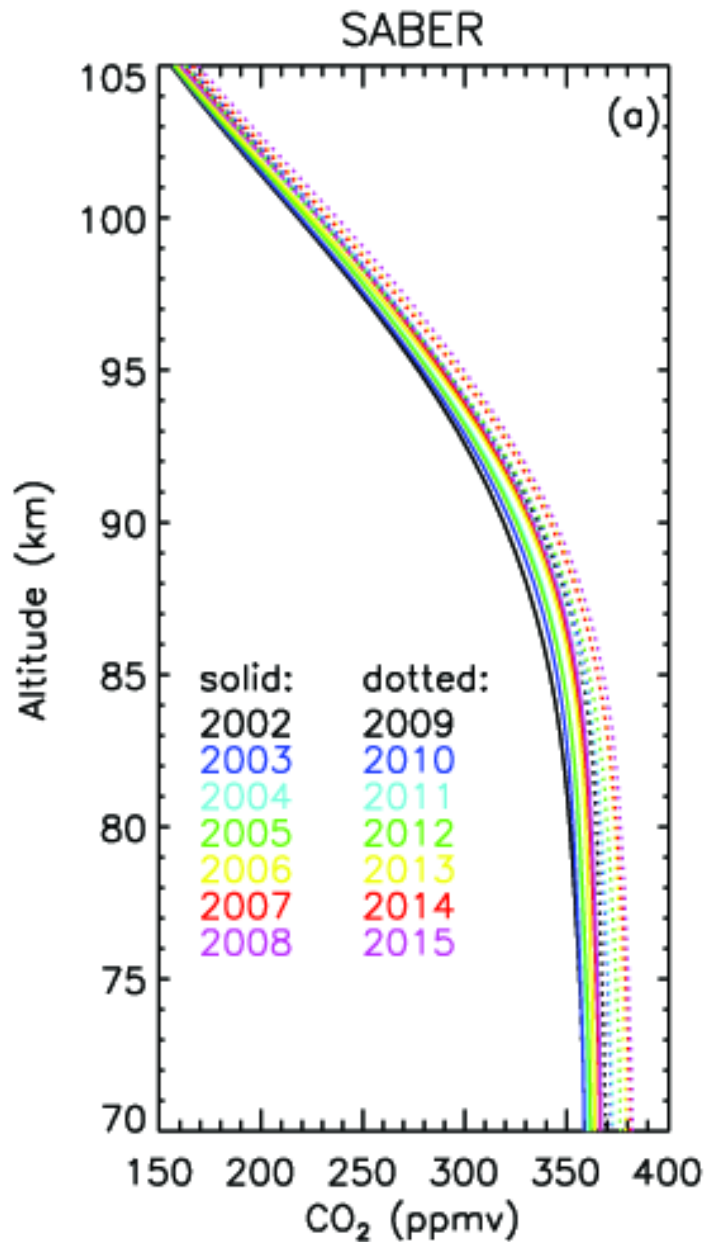
### Key points

- We have performed the first comprehensive whole-atmosphere climate change simulations, including the thermosphere and ionosphere.
- Results for solar minimum conditions indicate slow warming in the troposphere, changing to rapid cooling in the upper atmosphere.
- In the mesopause region, systematic change was very small, but exhibited considerable interannual variability.

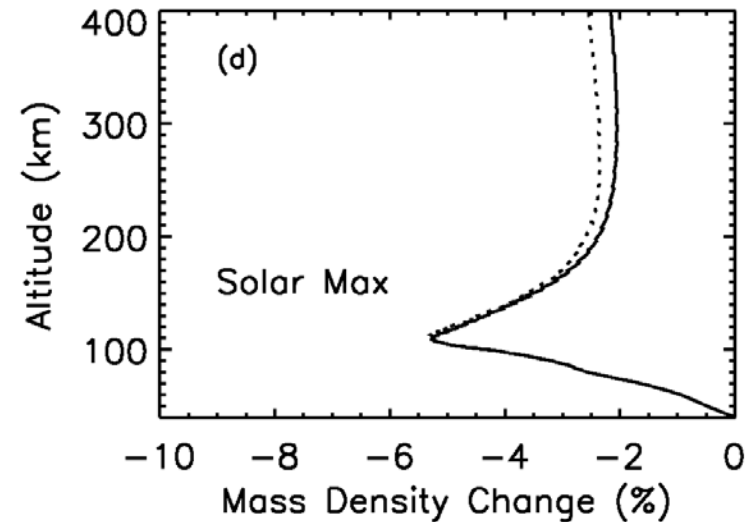
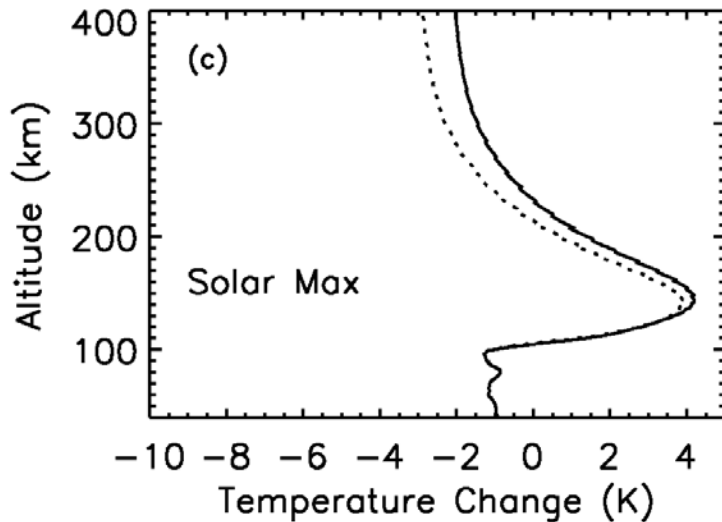
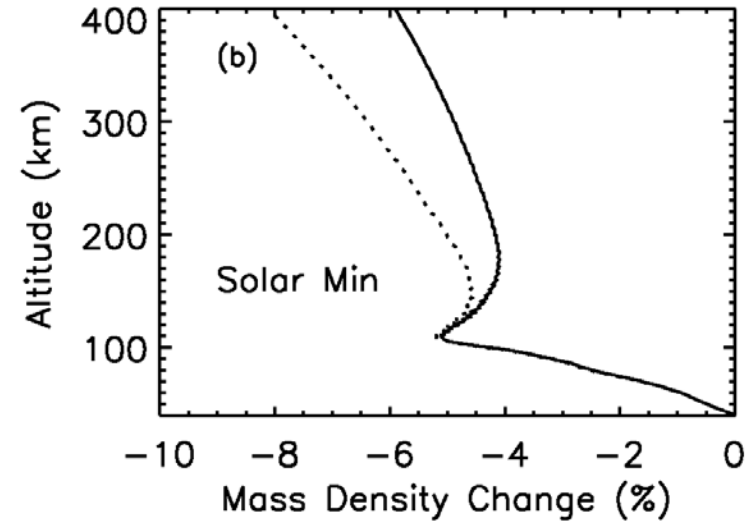
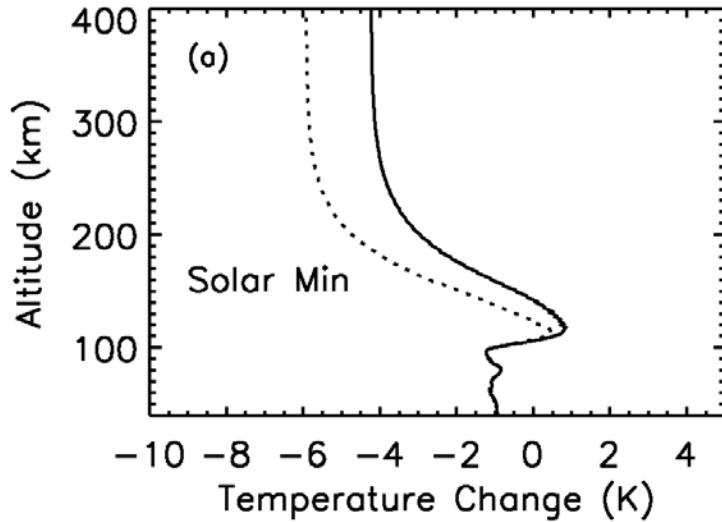
# Backup



# SABER CO<sub>2</sub> Profiles

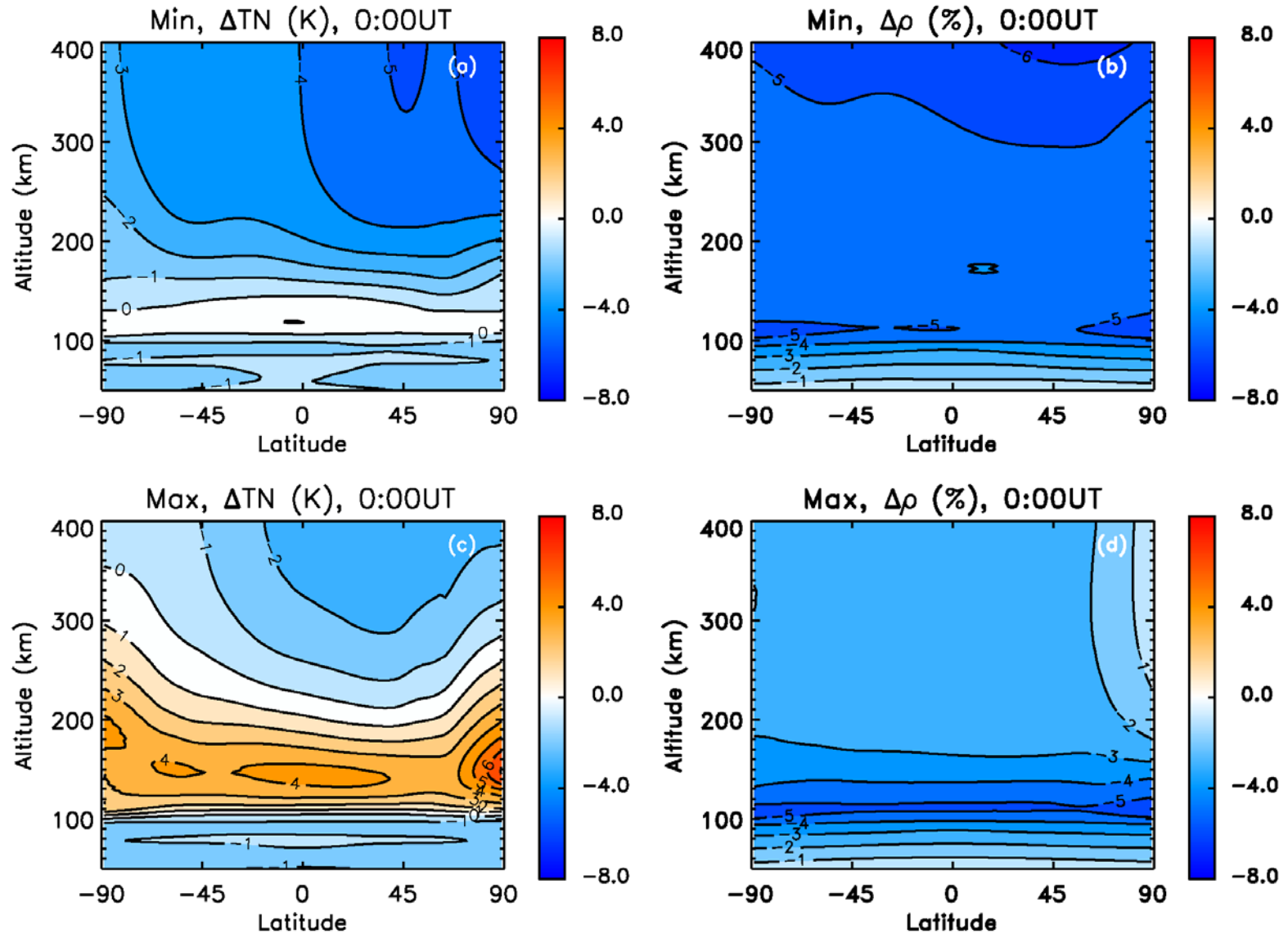


# Review of Previous Work



Simulations of thermospheric global change using the NCAR TIME-GCM  
*Solomon et al., J. Geophys. Res., 2015*

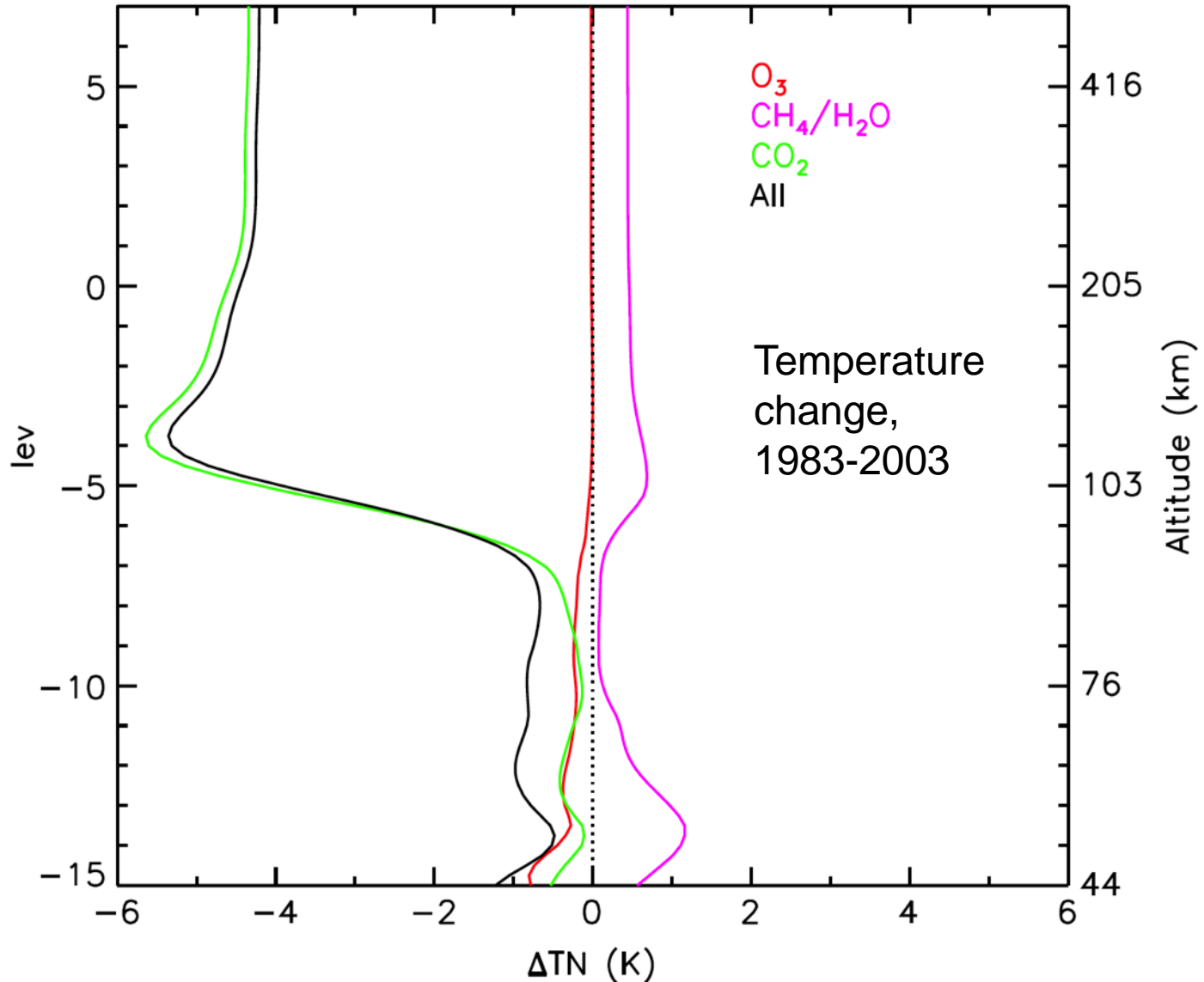
# TIME-GCM Simulation of Thermospheric Global Change



Simulations of thermospheric global change using the NCAR Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model

*Solomon et al., J. Geophys. Res., 2015*

# Review of Previous Work



Study of global change drivers using WACCM and Global Mean Model  
*Qian et al.*, J. Geophys. Res., 2013

# What is WACCM-X?

## *The Whole Atmosphere Community Climate Model - eXtended*

WACCM-X is the work of many people at the National Center for Atmospheric Research in the Atmosphere-Ionosphere-Magnetosphere section of the High Altitude Observatory, and in the Atmospheric Chemistry, Observations, and Modeling Laboratory, including the co-authors of this presentation, and several others.

### *Goals of the WACCM-X Development project:*

- How do solar and geomagnetic influences affect the whole atmosphere?
- What are the relative roles of 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?
- What are the connections between small and large scale features in the system, e.g., “plasma bubbles”?
- How does anthropogenic change affect the thermosphere and ionosphere?
- How does the ionosphere-thermosphere vary over multiple time scales, e.g., “space weather” and “space climate”?

# Recent Progress on WACCM-X

- Ion and electron energetics implemented:

Now calculating  $T_i$  and  $T_e$  in WACCM-X.

(Still set  $T_i=T_e=T_n$  in WACCM, which is a good approximation up to  $\sim 150$  km.)

- Equatorial electrodynamic installed:

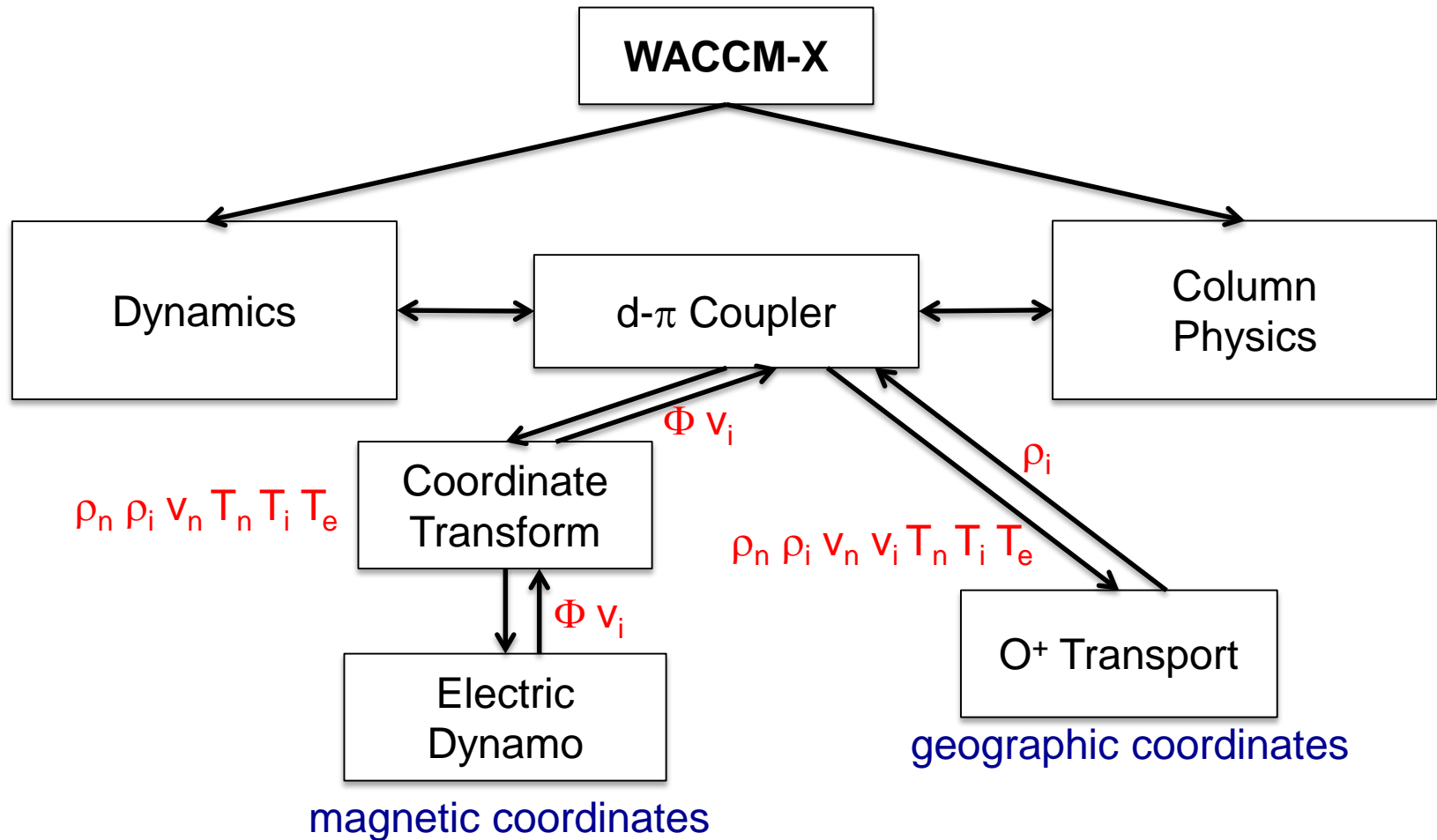
Mostly parallel, with ESMF interpolation from geographic to geomagnetic coords.

- Ionospheric dynamics implemented:

Vertical diffusion (“ambipolar diffusion”) of  $O^+$ .

Horizontal transport of  $O^+$  in the upper ionosphere.

# Integrating Ionospheric Dynamics into WACCM-X



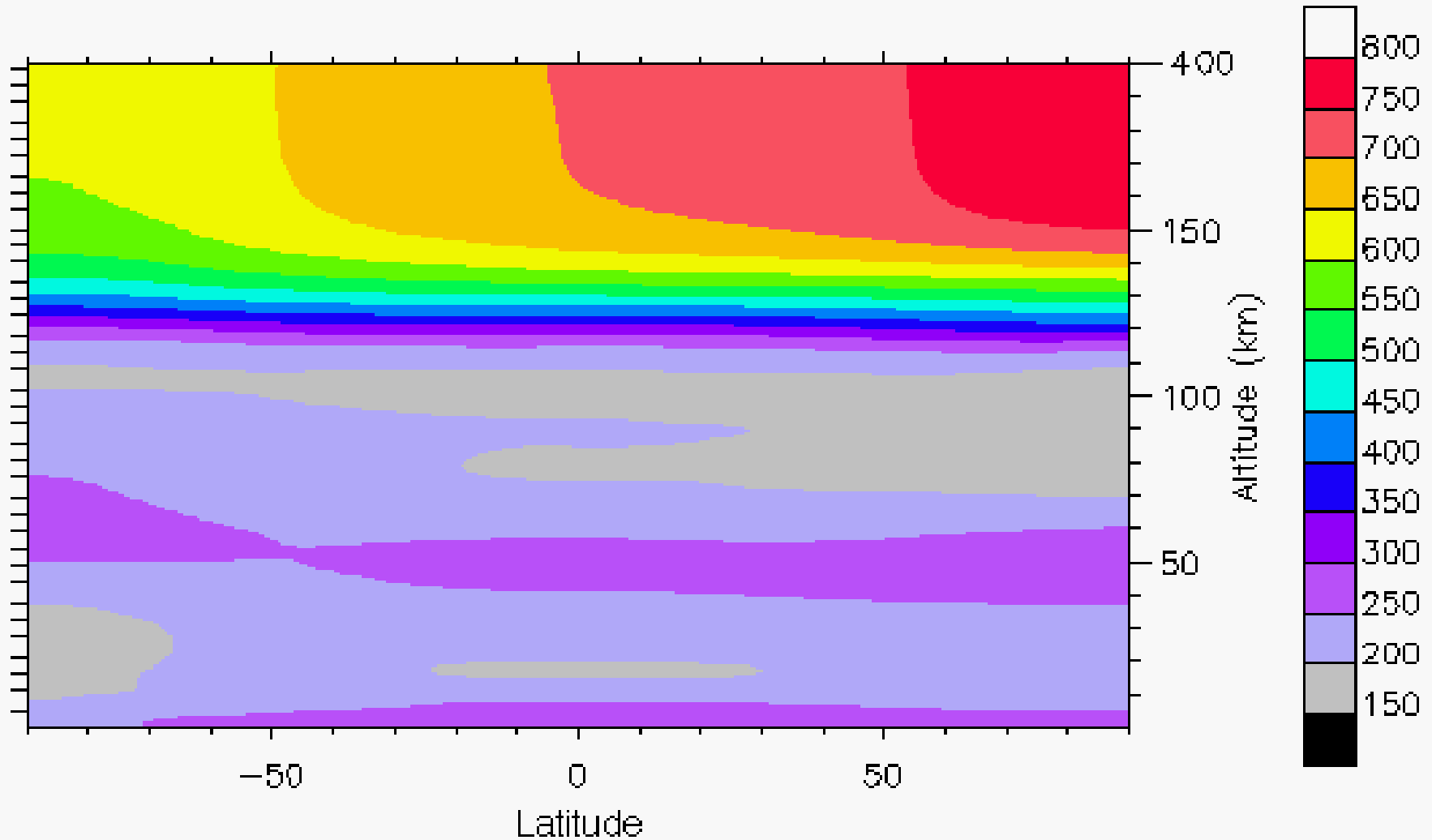
d- $\pi$  Coupler: dynamics-physics-ionosphere-electrodynamics (D-PIE) coupler

Electric Dynamo: calculates global electric potential resulting from wind-driven ions

$\rho$ : density     $v$ : velocity     $T$ : temperature     $n$ : neutral     $i$ : ion     $e$ : electron     $\Phi$ : electric potential

# Zonal Mean Temperature

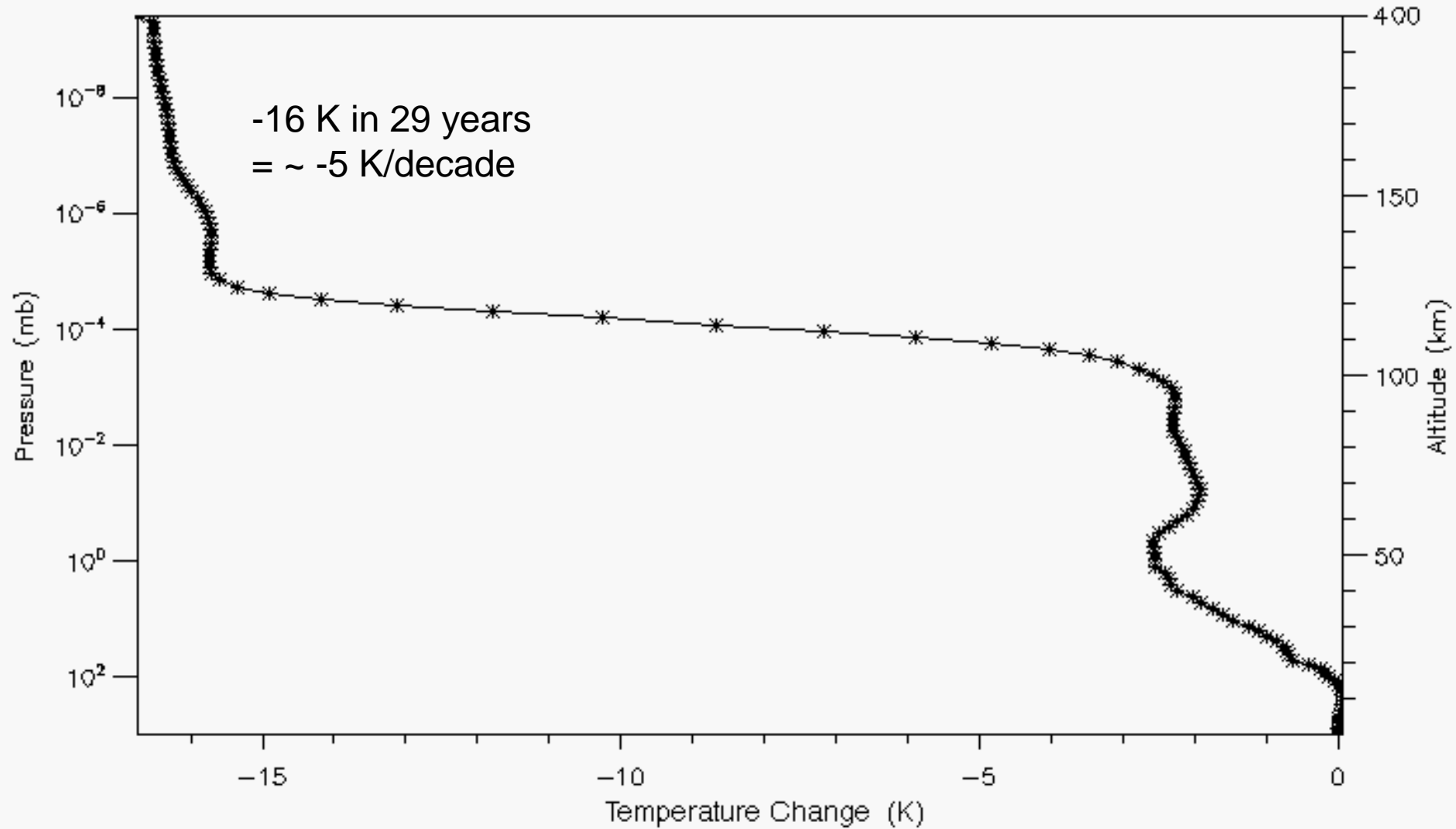
## Solar Minimum, June Monthly Average



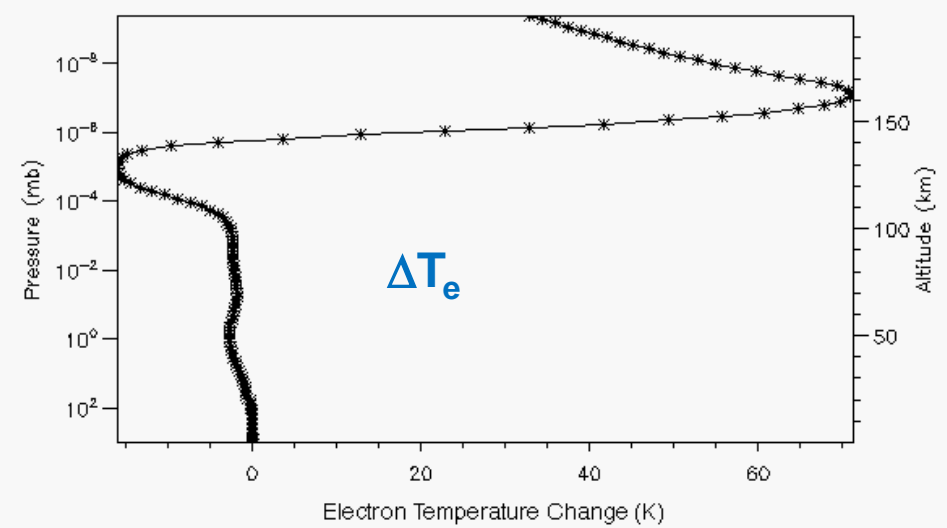
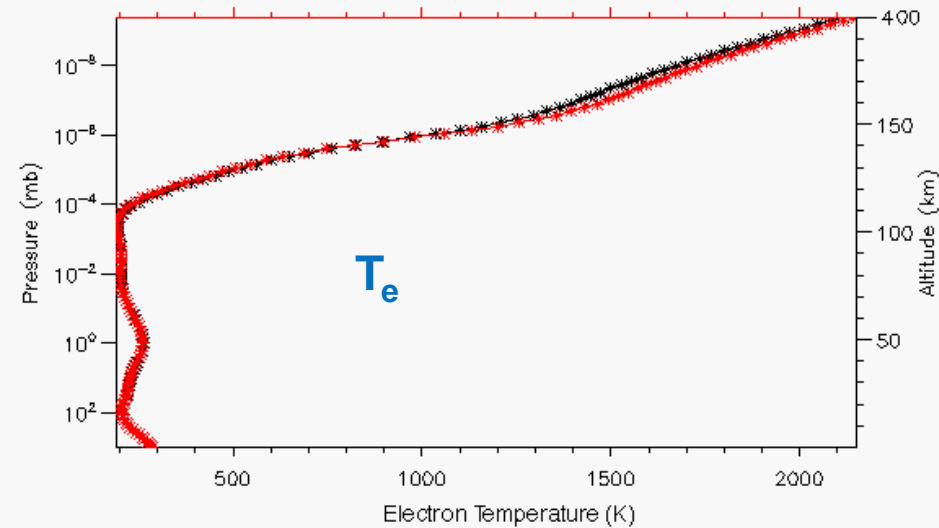
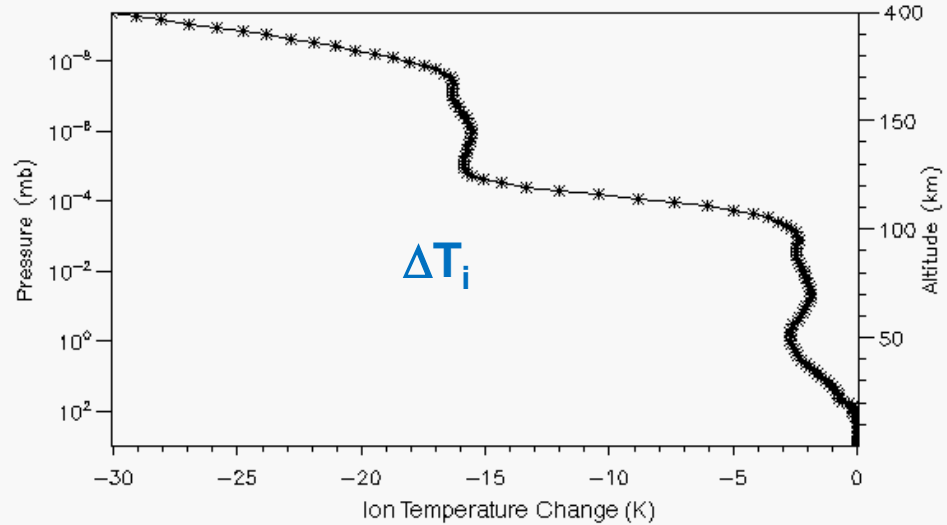
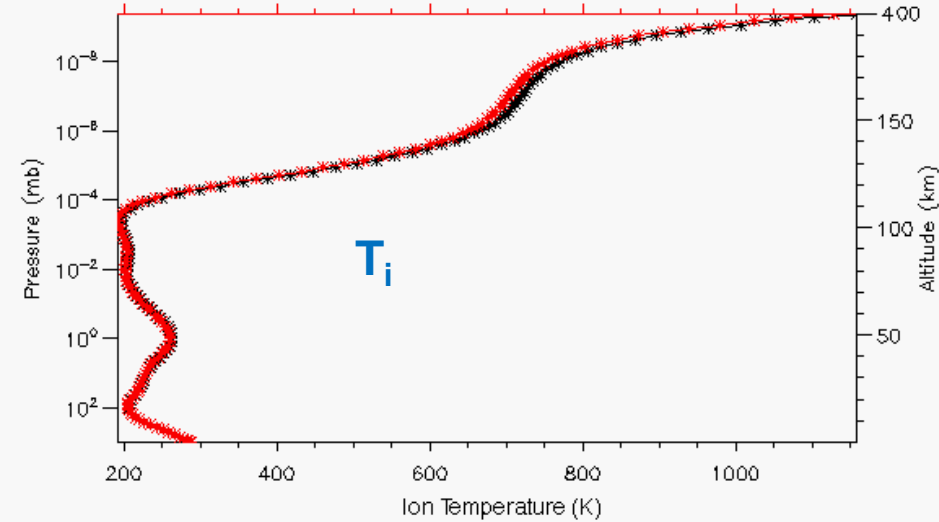


# Global Annual Mean Temperature Change, 1971 to 2000

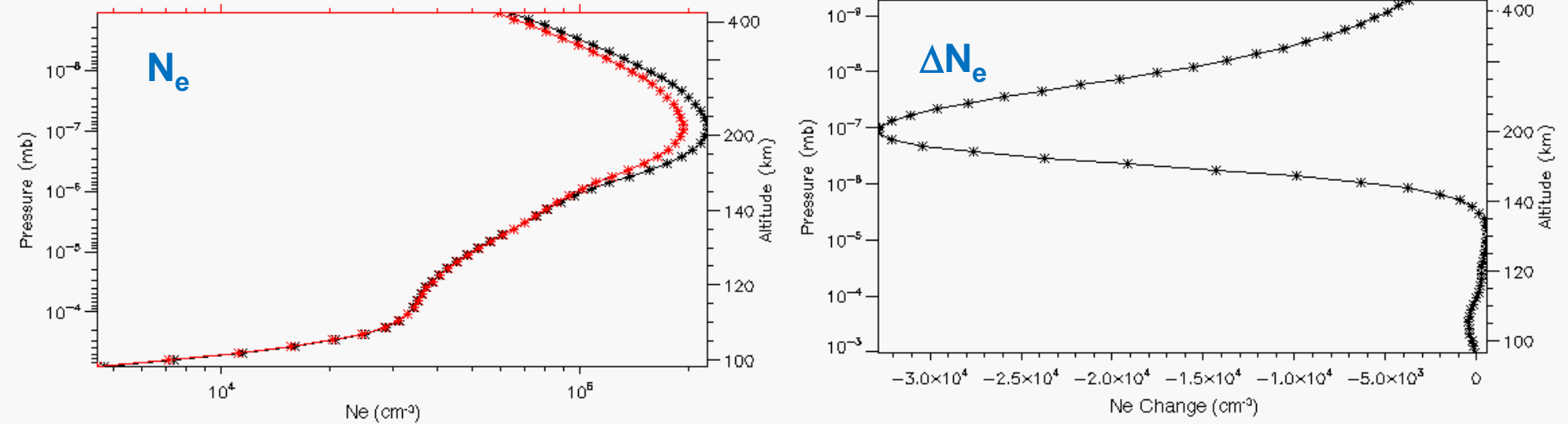
## Solar Minimum Conditions



# Ionospheric Changes, 1971 to 2000



# Ionospheric Changes, 1971 to 2000



Decrease in electron density causes increase in electron temperature.

Note that all these comparisons are in pressure coordinates.

# Comparison to Previous Modeling Work

- Thermosphere/Ionosphere

~5 K/decade cooling is commensurate with previous modeling and satellite drag measurements, but at the low end of the envelope.

We are getting some fairly significant ion temperature decreases in the topside; too early to make much of this due to boundary condition sensitivity, but there are indications of convergence with the observational data.

- Stratosphere/Mesosphere

Garcia et al. [2007] found cooling of ~0.6 K/decade at the stratopause for a similar period with an earlier version of WACCM. Here, single-year runs yield ~0.9K/decade, possibly because of an unusual SH stratwarm. The altitude morphology in the stratosphere-mesosphere is similar. This is also in general agreement with results by Fomichev et al. [2007] using CMAM, and Lübken et al. [2013] using LIMA.

Schmidt et al. [2006], Garcia et al. [2007], Fomichev et al. [2007] and Lübken et al. [2013] found little or no temperature trend at the mesopause [cf., Beig, 2011]. Here, we are seeing cooling of ~0.7K/decade at the mesopause. But...