WACCM-X Simulations of Climate Change in the Upper Atmosphere

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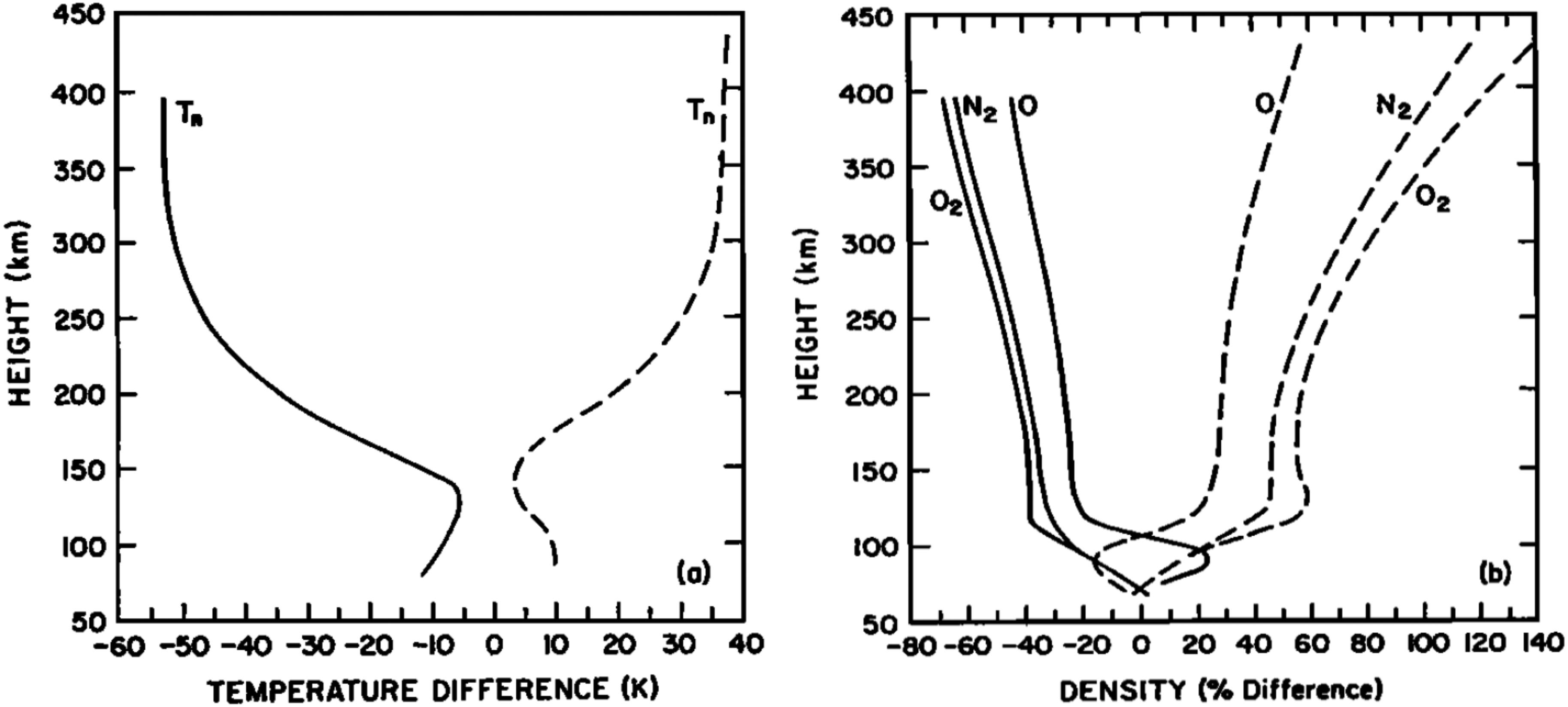
NCAR

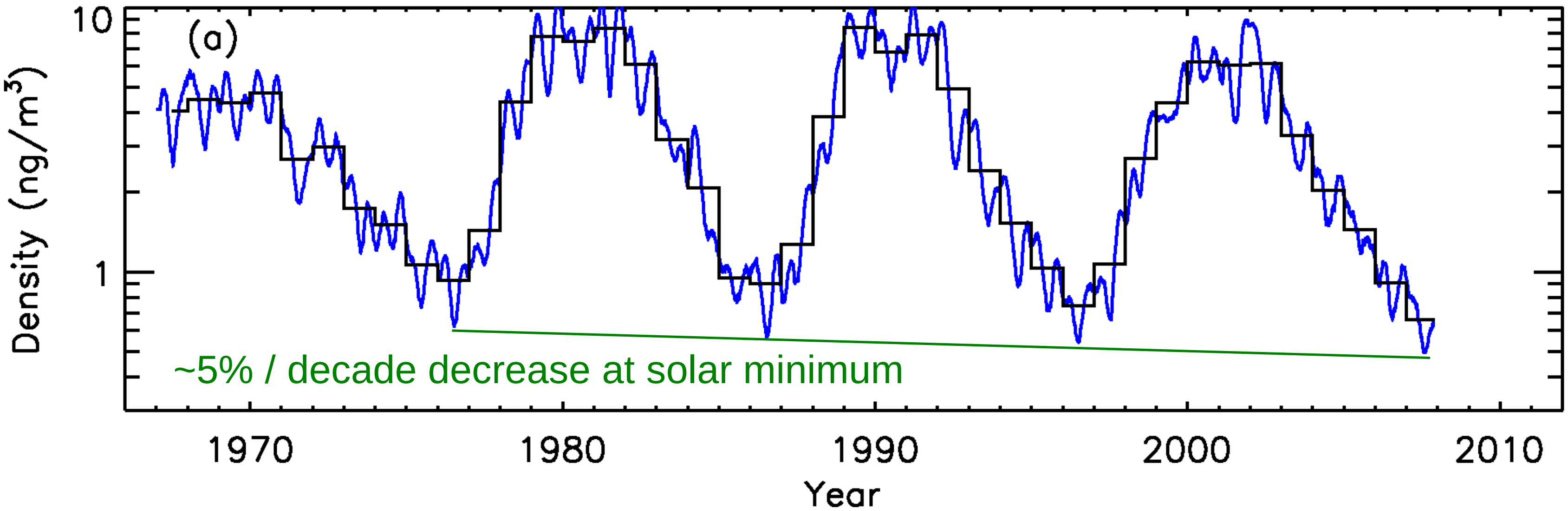
Model Prediction of Global Change in the Thermosphere

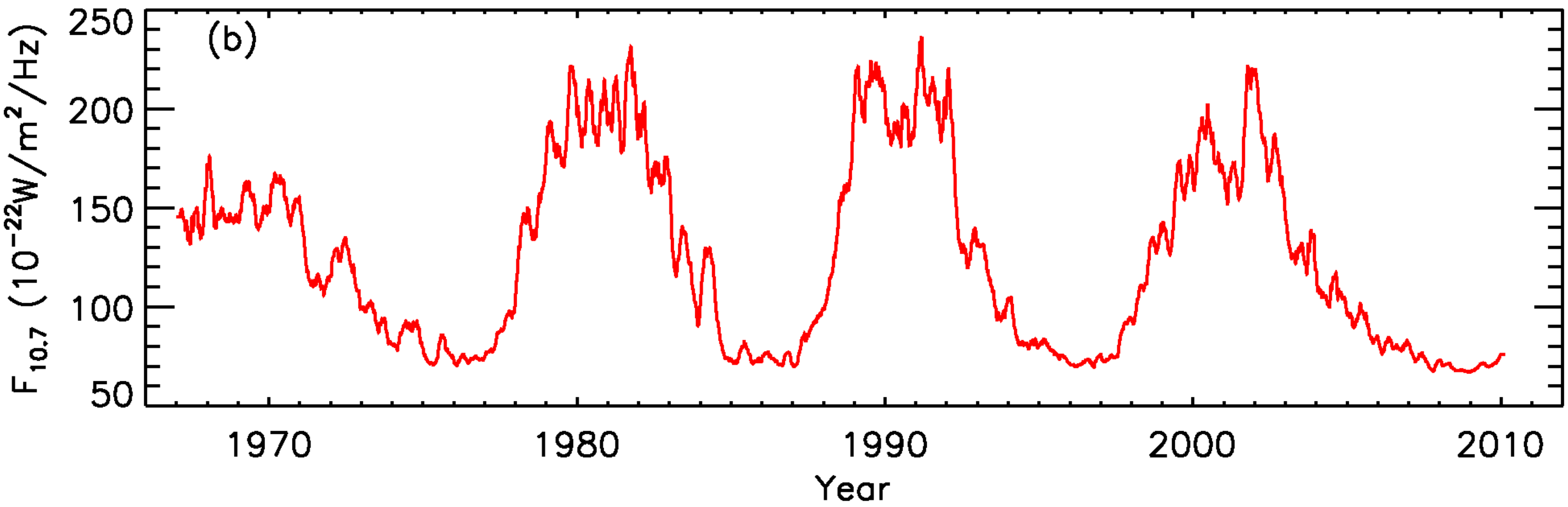
***Roble & Dickinson* [1989]**



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

Strongest Evidence for Upper-Atmosphere Global Change

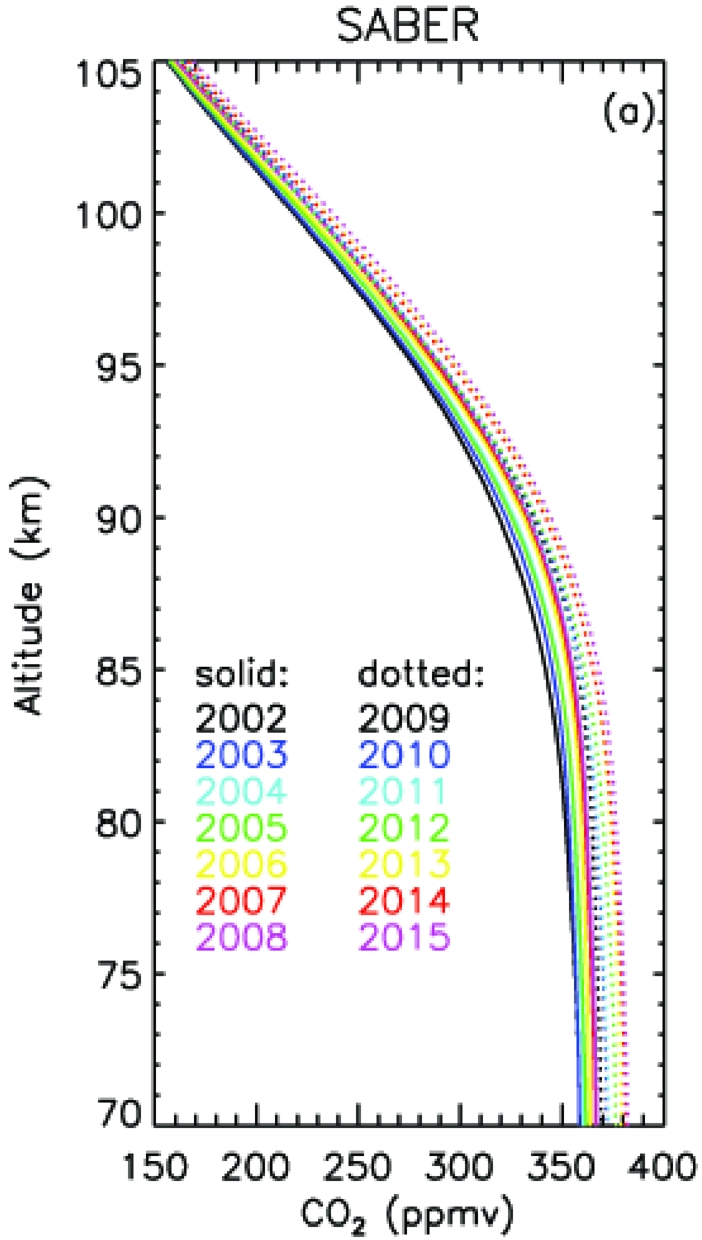


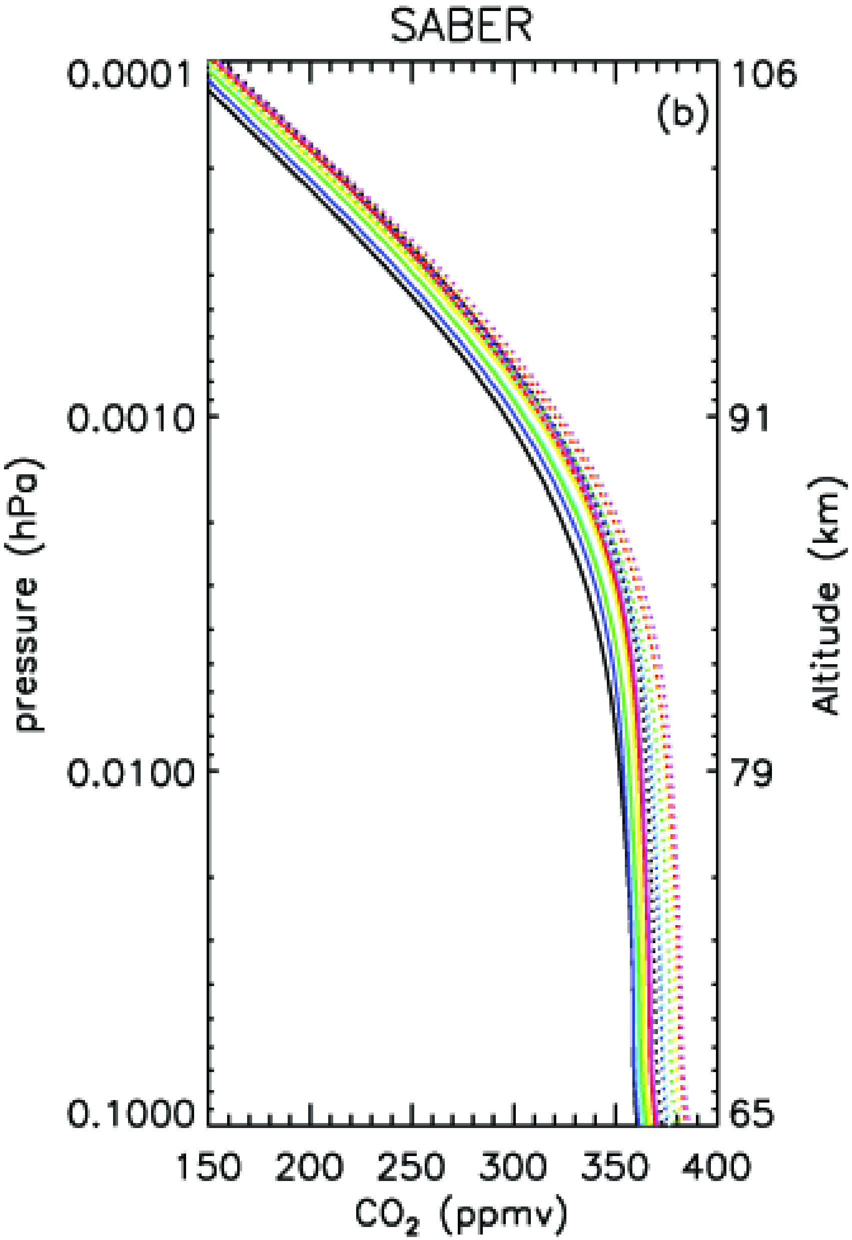


Top: Global average neutral density at 400 km, 81-day average and annual average

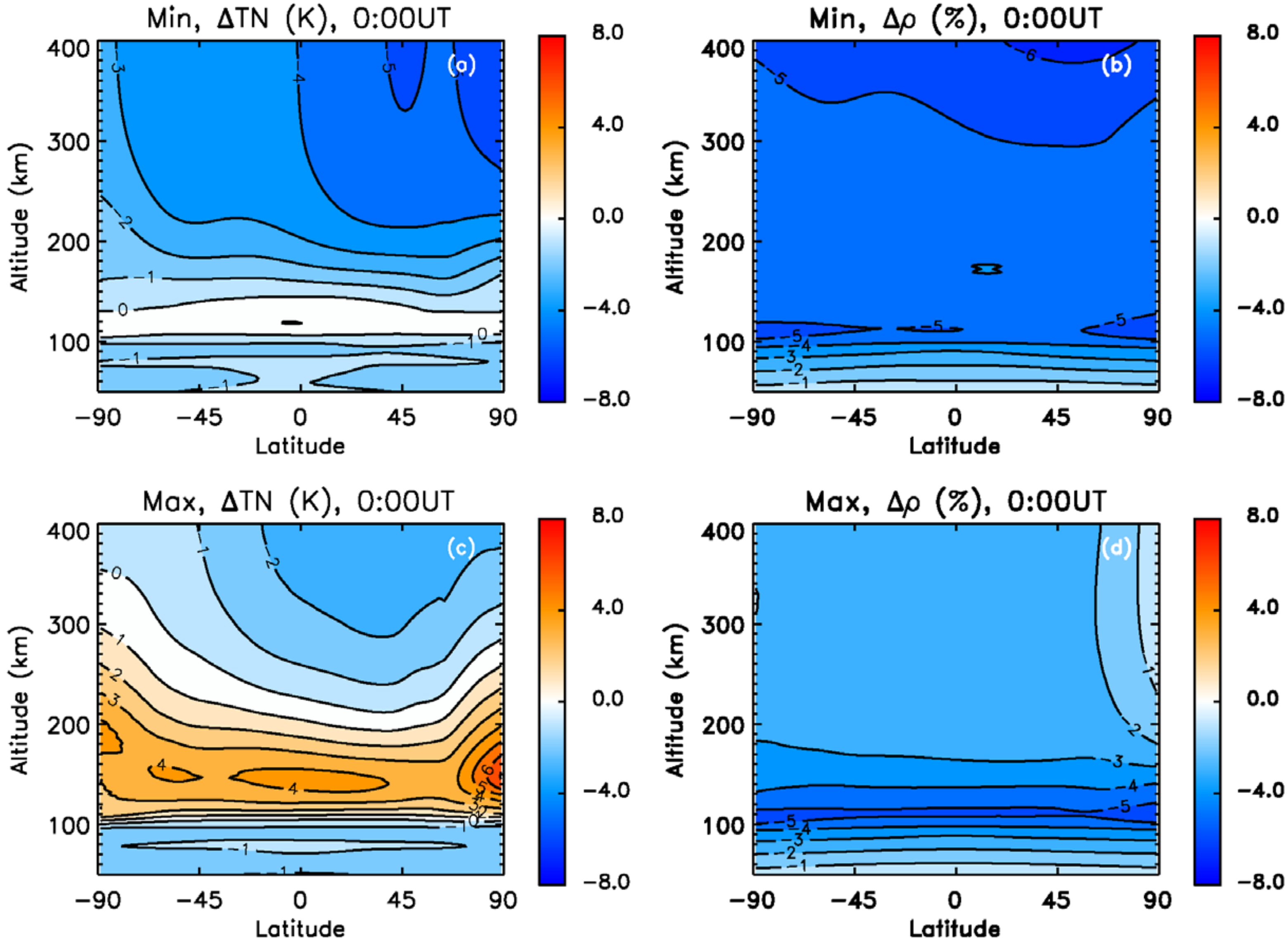
Emmert et al., 2010; (c.f., Keating et al., 2000; Marcos et al., 2005; Saunders et al., 2010)

SABER CO_2 Profiles





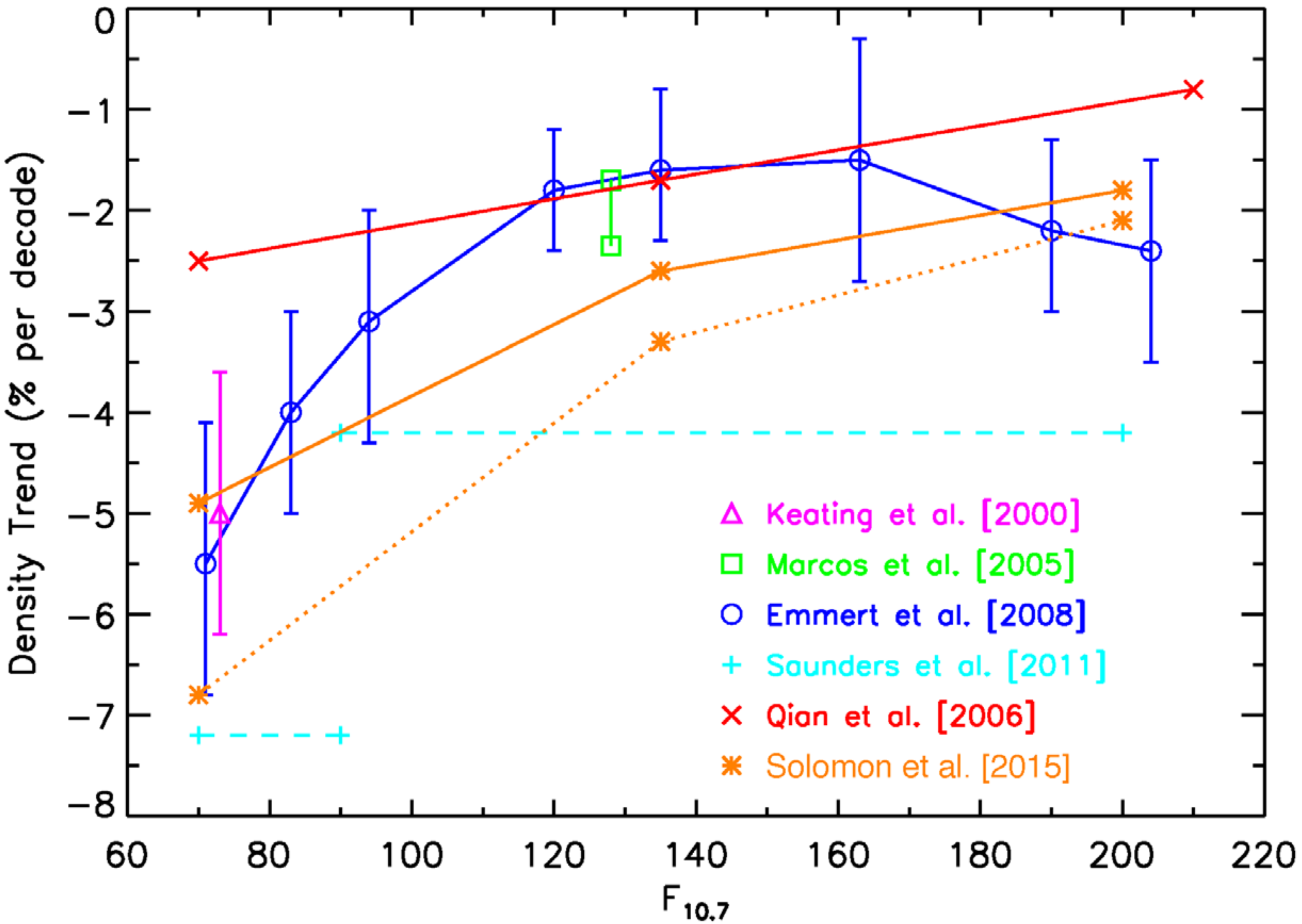
TIME-GCM Simulation of Thermospheric Global Change



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

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

Comparison to Density Trends at 400 km



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

WACCM-X Global Change Simulation Methodology

- Solar minimum conditions:
  $F_{10.7}$ = 70, K_p = 0.3

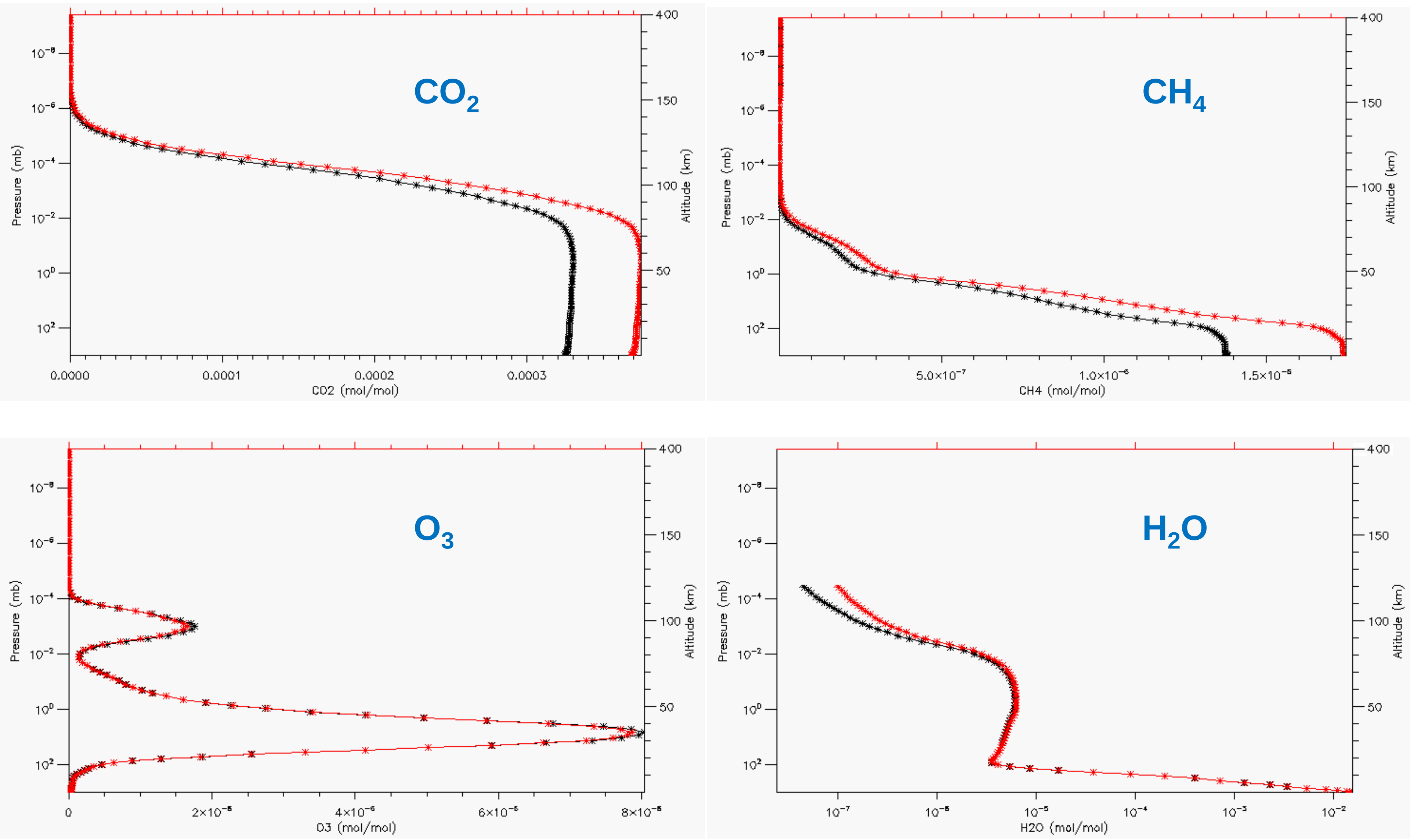
- Two sets of runs one-year runs to simulate change in a 30-year interval:
  one with CO_2, CH_4, and CFCs from 1971
  one with CO_2, CH_4, and CFCs from 2000

- Full WACCM-X free-running climate simulations
  but using specified SSTs — no interactive ocean or sea ice, etc.

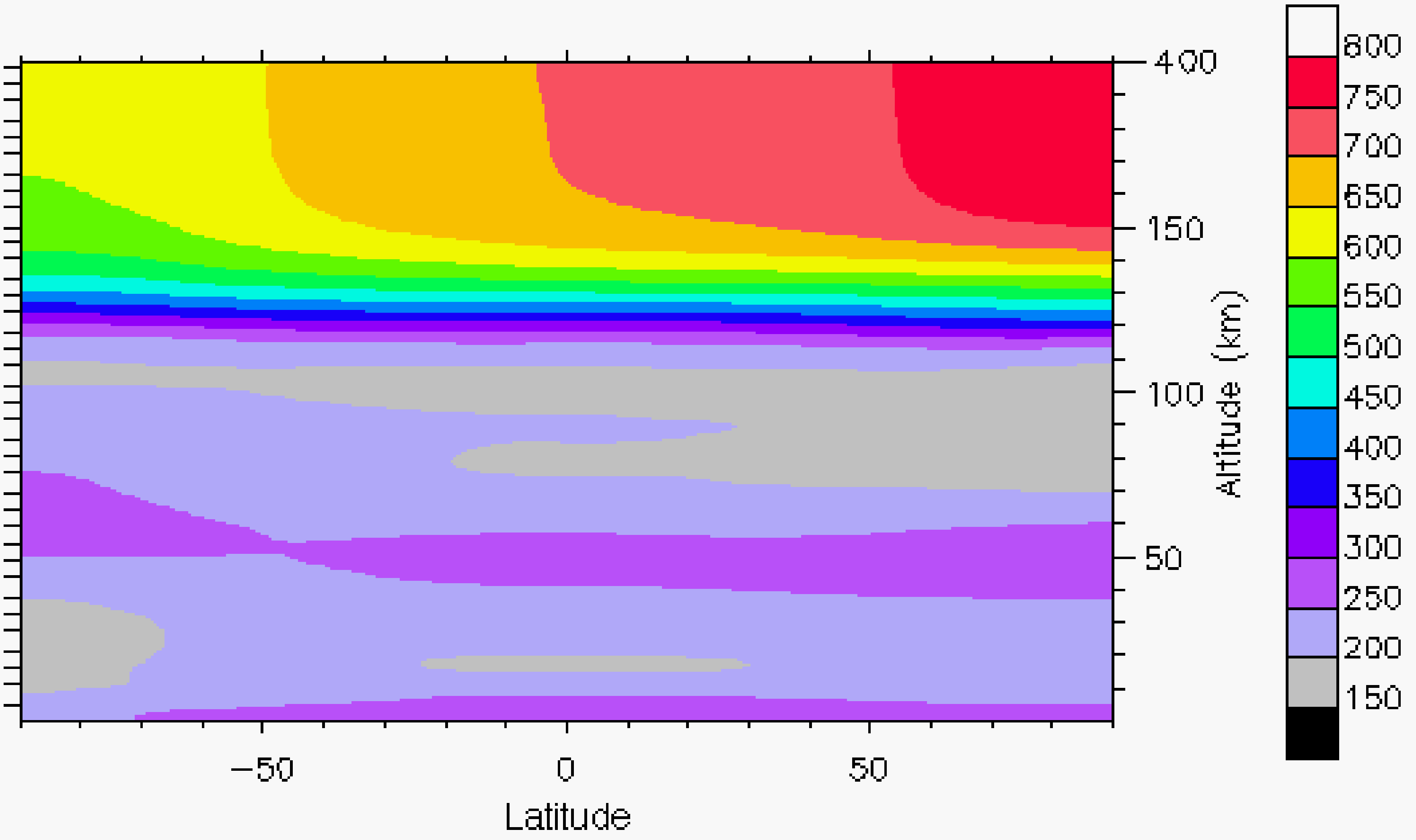
- Three-month burn-in period to allow thermosphere to equilibrate

- Decadal change rates estimated by scaling from 30-year interval to 10 years

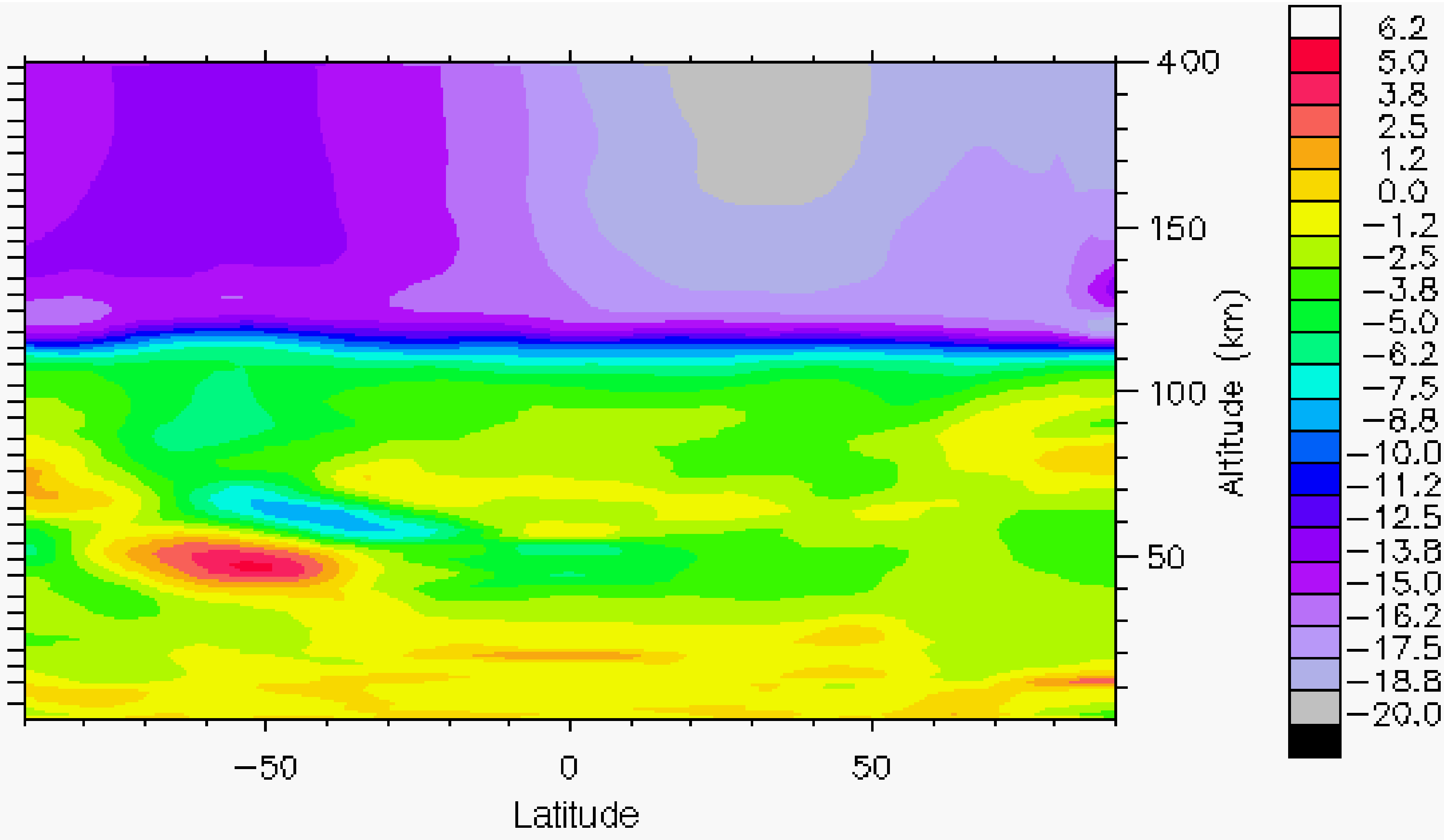
Anthropogenic Global Change, 1971 to 2000



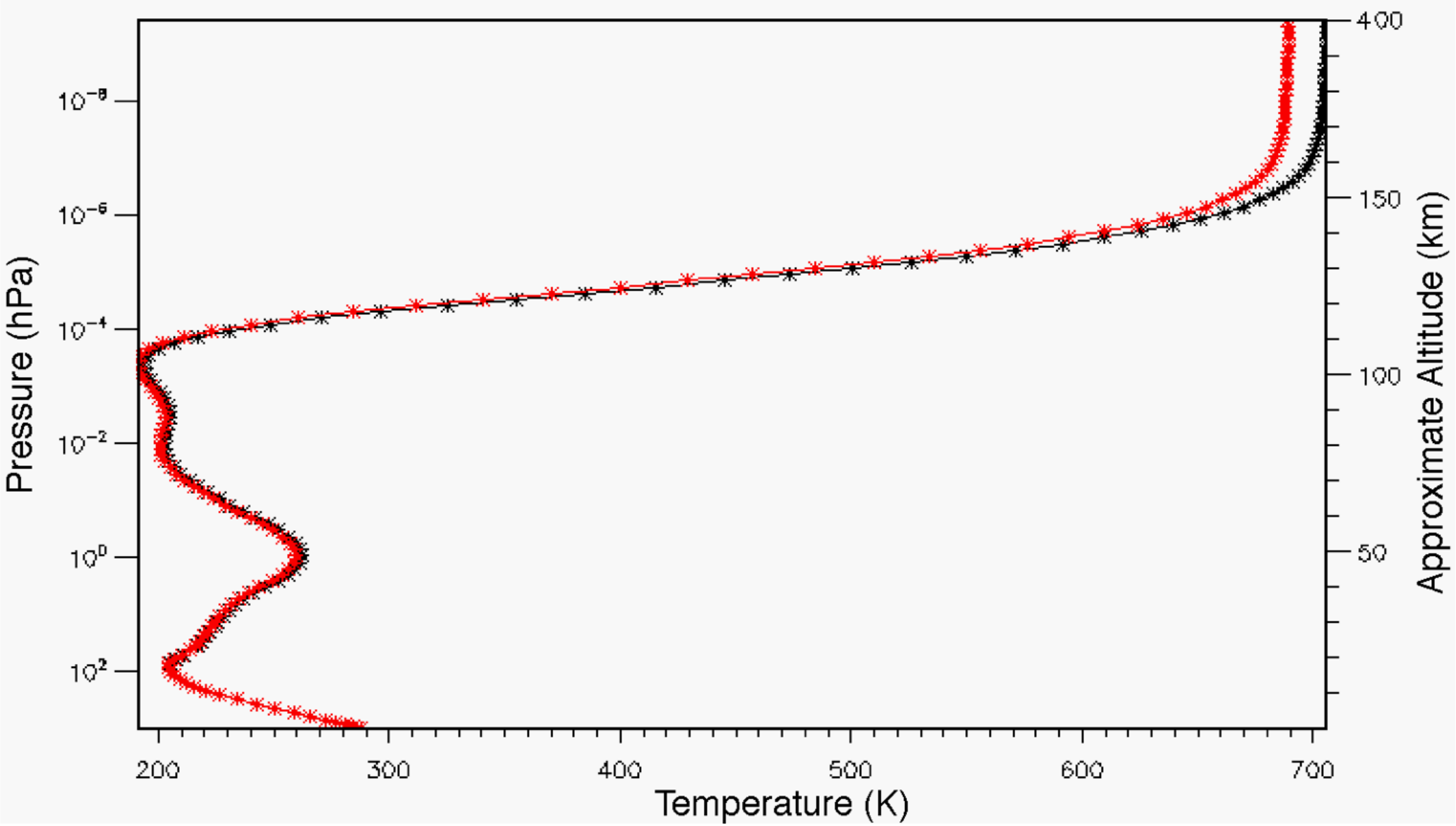
Zonal Mean Temperature
Solar Minimum, June Monthly Average



Zonal Mean Temperature Change, 1971 to 2000
Solar Minimum, June Monthly Average



Global Annual Mean Temperature Change, 1971 to 2000
Solar Minimum Conditions



Global Annual Mean Temperature Change, 1971 to 2000
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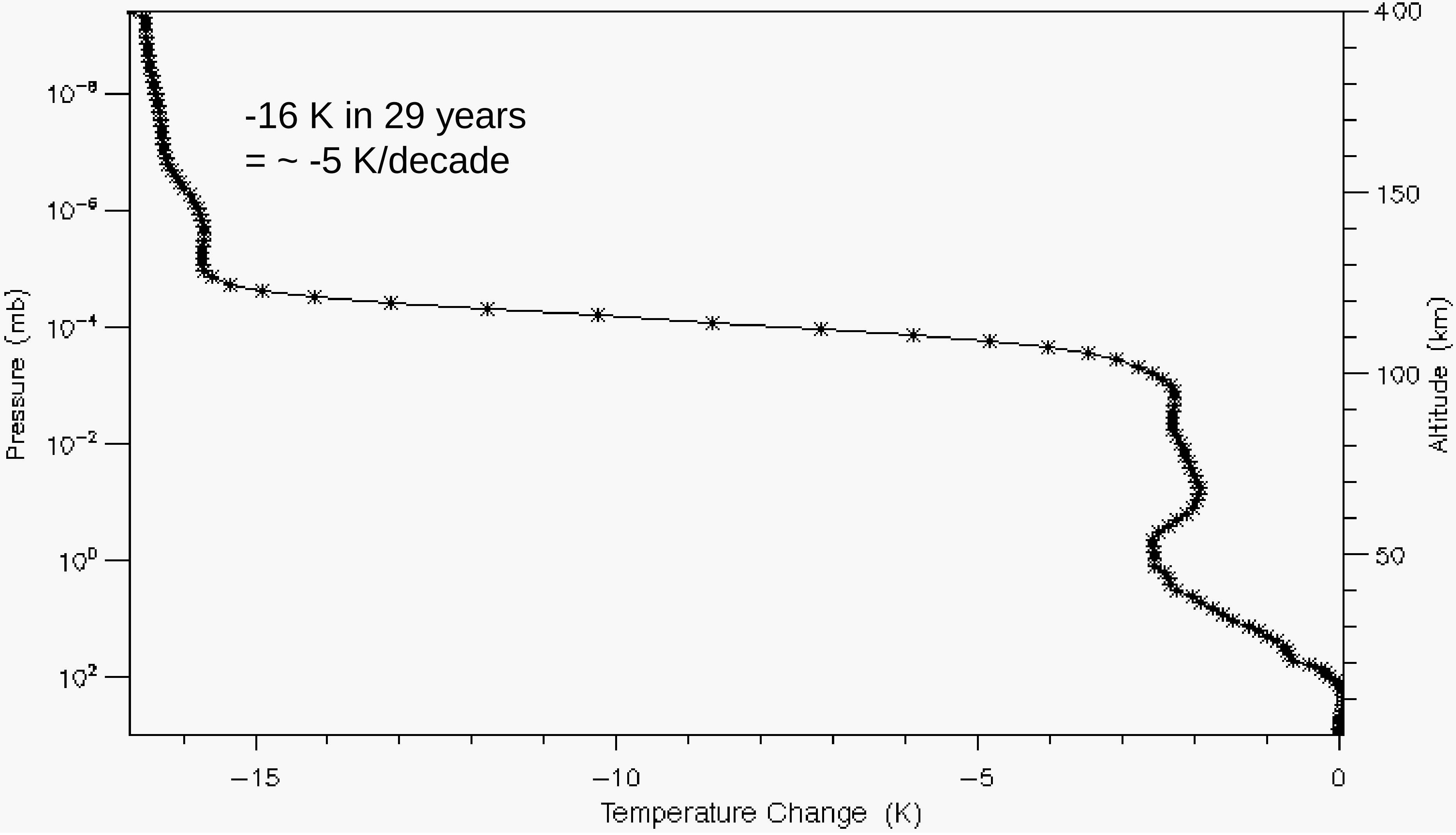
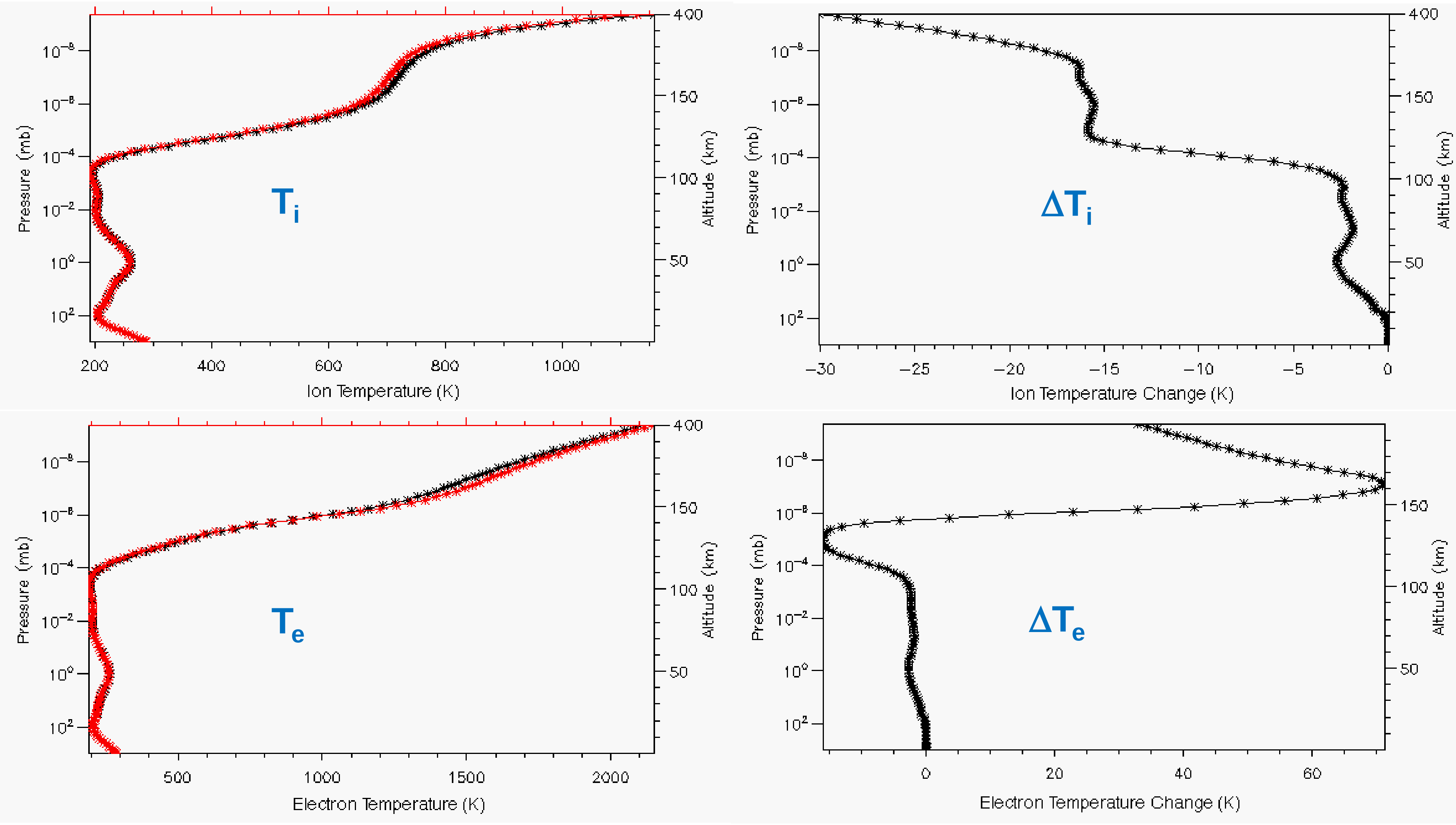
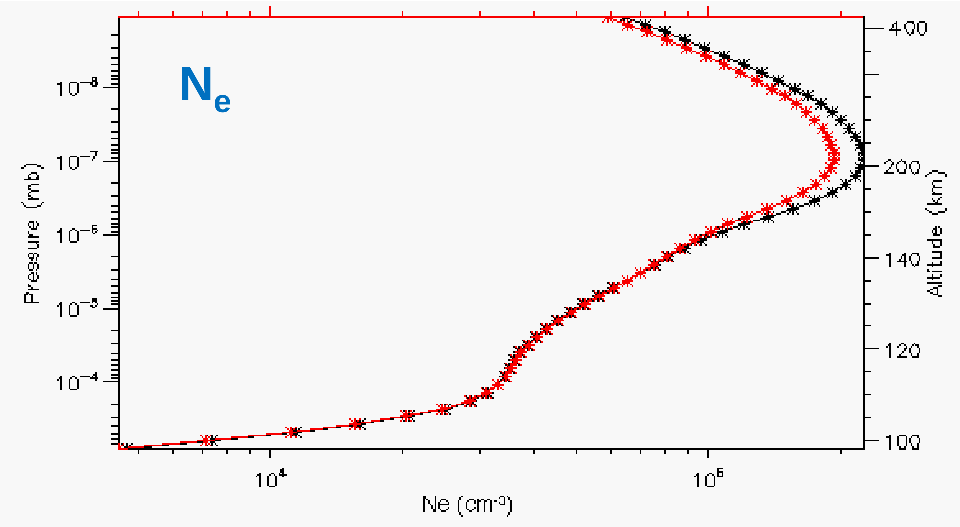
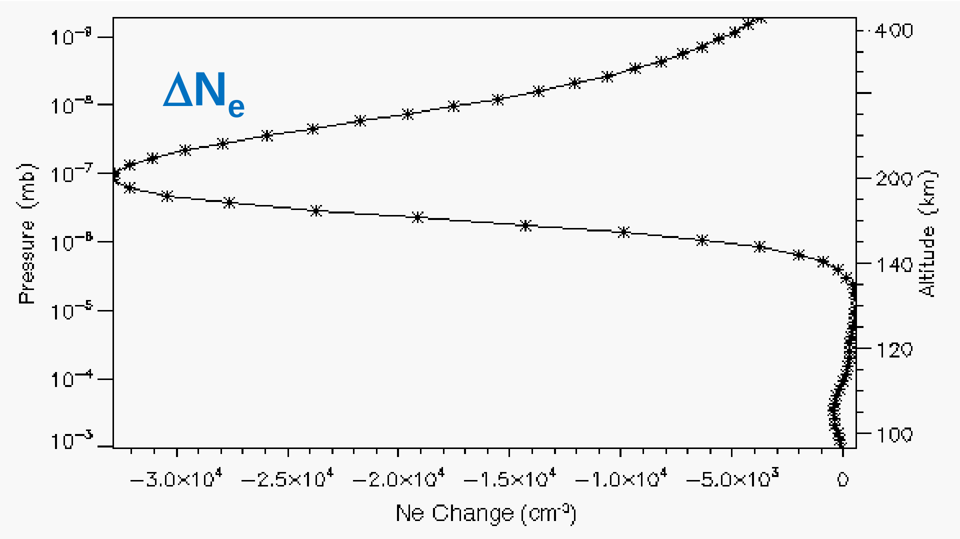


Ionospheric Changes, 1971 to 2000



Ionospheric Changes, 1971 to 2000

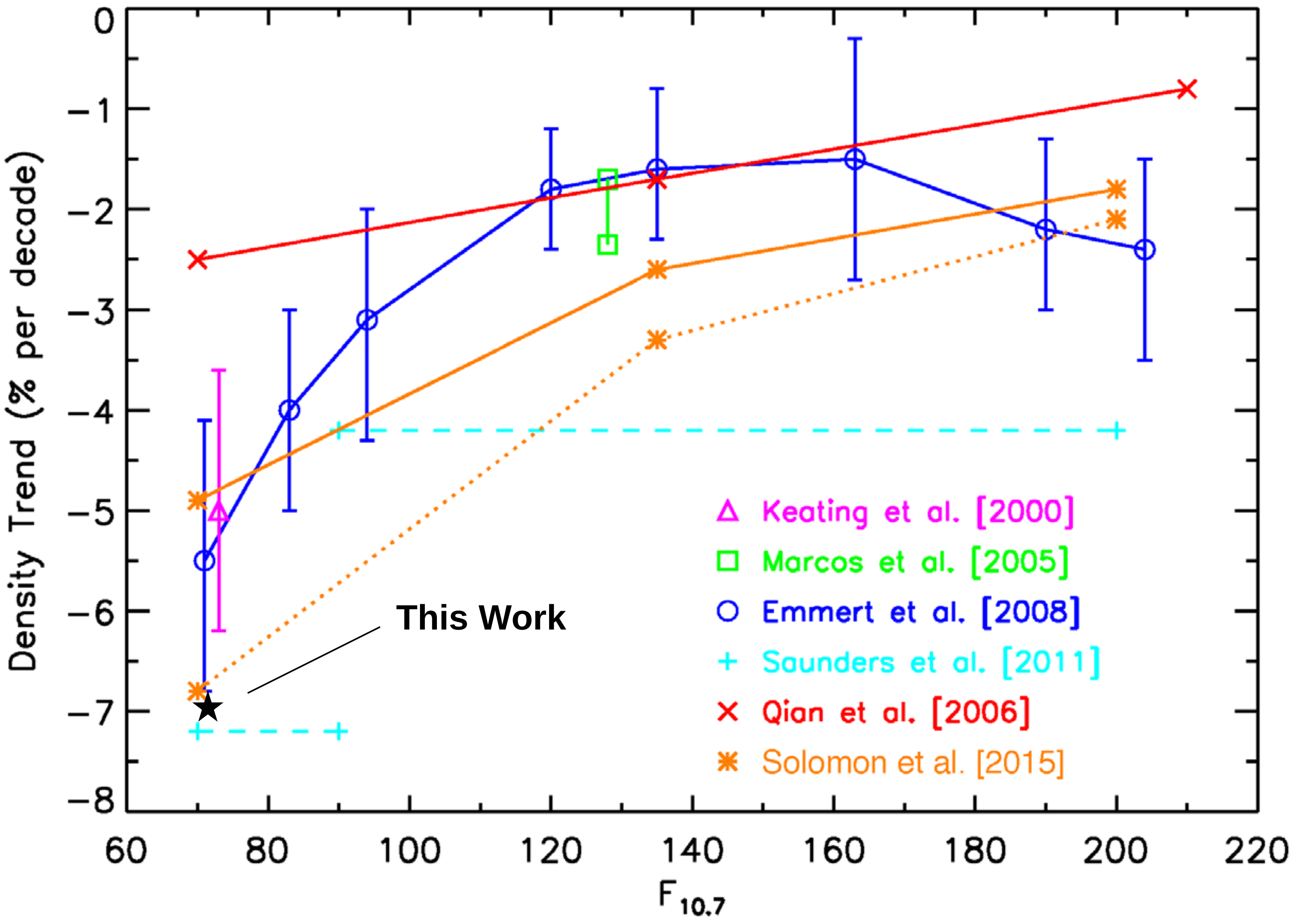




Decrease in electron density causes increase in electron temperature.

Note that all these comparisons are in pressure coordinates.

Comparison to Previous Work — Density Trends at 400 km



Some Caveats

• These are one-year runs, sufficient for describing thermosphere/ionosphere changes, but inter-annual variability in the troposphere and middle atmosphere requires multi-year ensembles (or averaging over several consecutive years).

• As previously, thermosphere results are sensitive to the CO_2 collisional activation/deactivation rates.

• Mesospheric odd-hydrogen species driven by methane changes were mostly equilibrated after the three-month burn-in period, but small changes continued during the runs. Again, longer runs are needed for definitive mesospheric results.

• Ionospheric dynamics are still under development. The effects of geomagnetic activity are largely unexplored. Considerable tuning ahead.

• Need to perform solar max and variable solar/geomagnetic activity runs.

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_2.

• Simulations using the Whole-Atmosphere Community Climate Model — eXtended show how global change occurs throughout the atmosphere, but in different ways.
  — Caveats: these results are preliminary until multi-year ensemble simulations are performed.

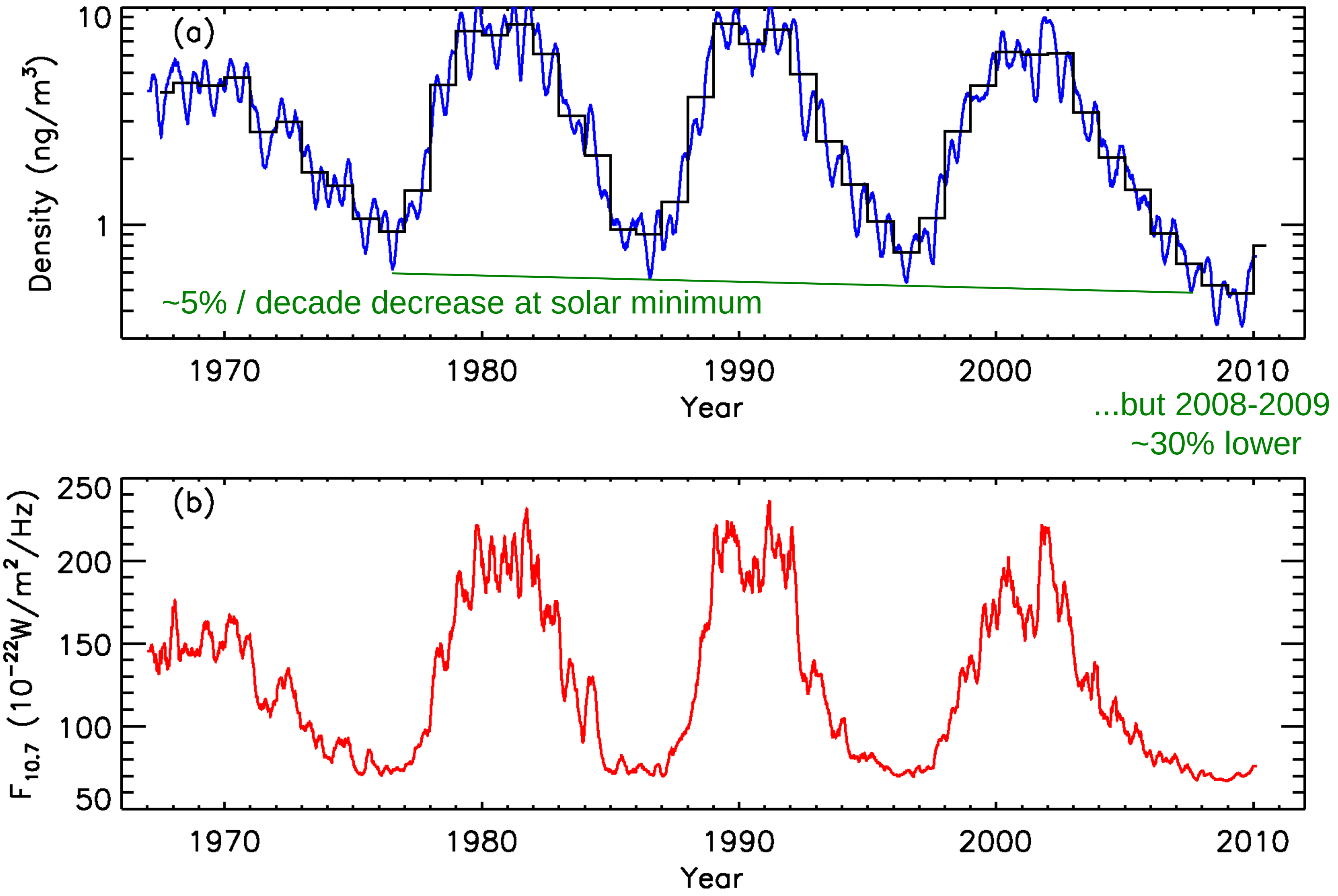
• Solar variability makes it challenging to quantify anthropogenic change, and to verify whether our models are calculating it correctly.

• There is additional uncertainty with regard to the altitude dependence of CO_2 trends.

• We need:
  — Continuing long-term observations of mesopause-region CO_2 and temperature
  — Continuing long-term observations of solar spectral irradiance variation
  — Continuing analysis of satellite orbits to infer thermospheric density change

Backup

Complication #1 — Are All Solar Minima Alike?

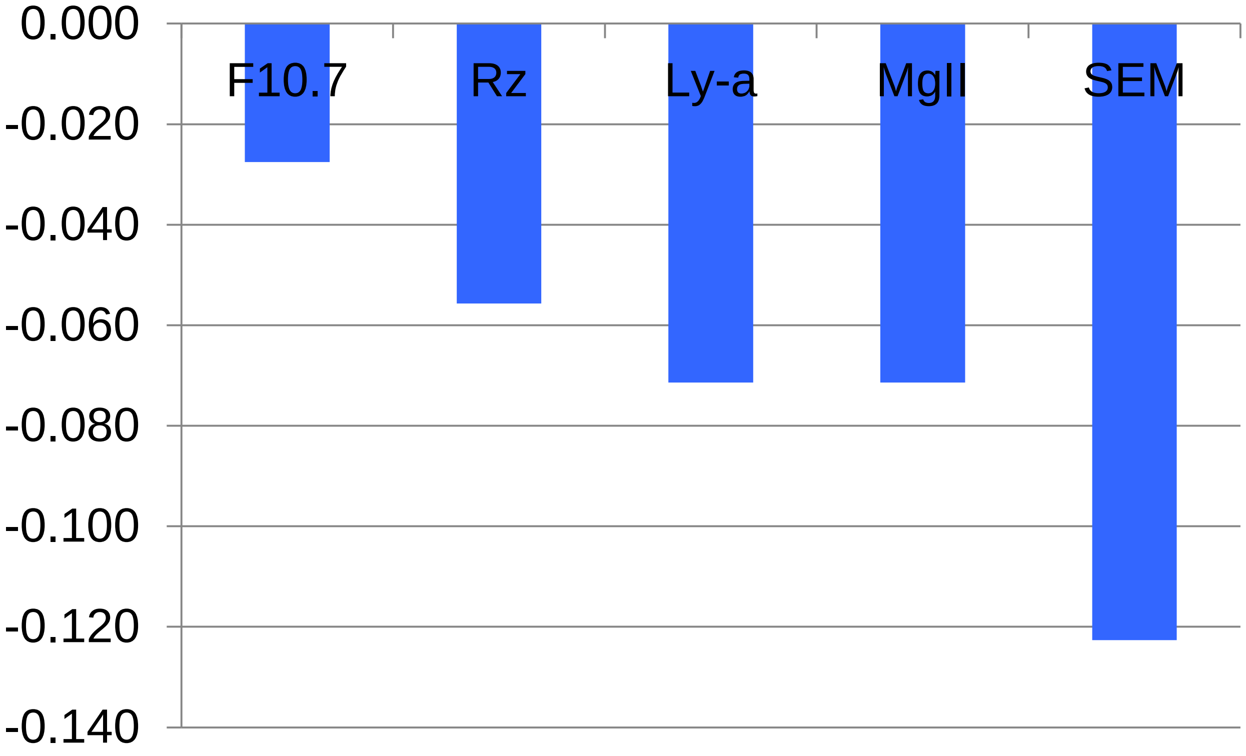


Top: Global average neutral density at 400 km, 81-day average and annual average

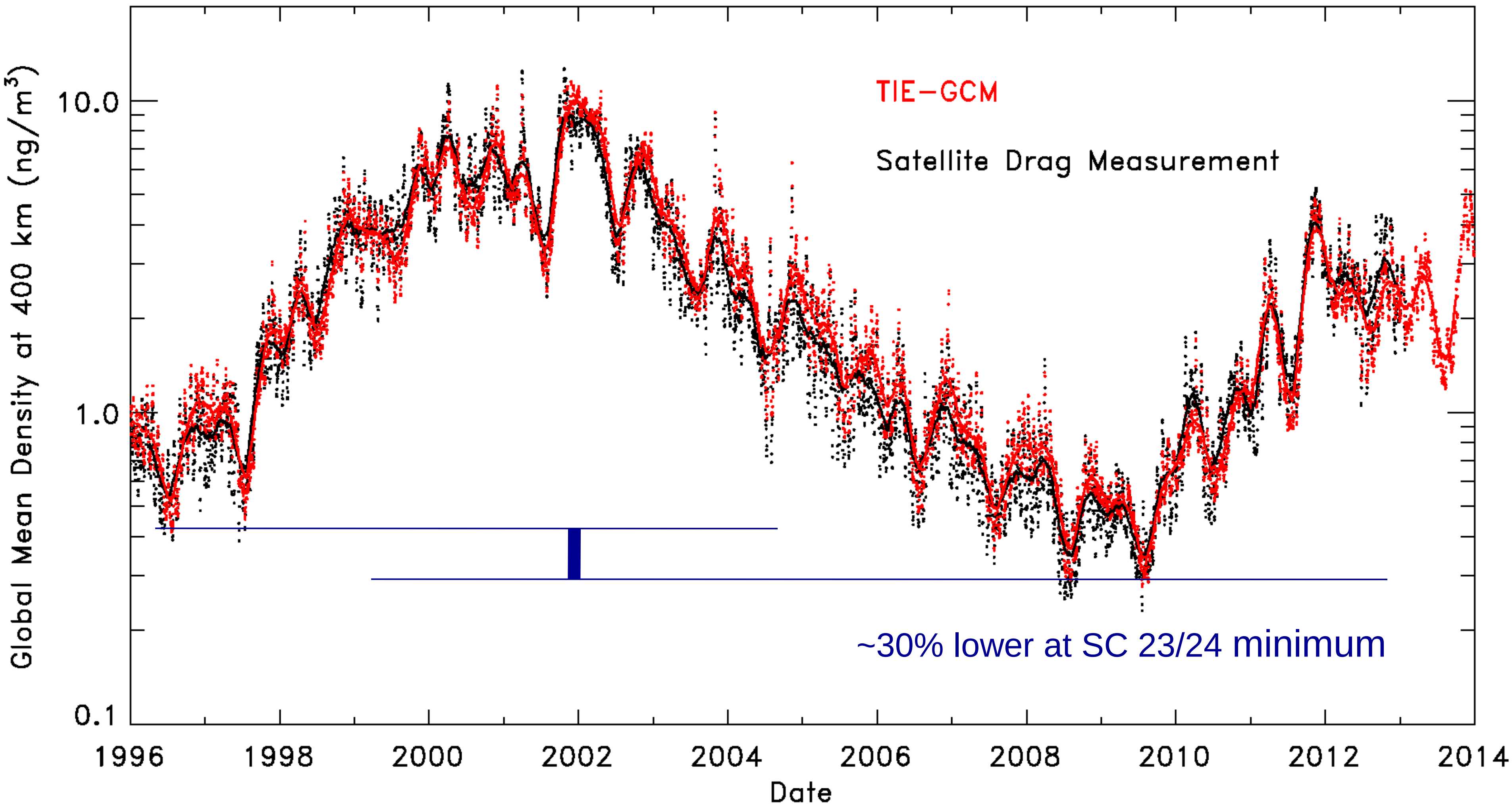
Change in Various Solar Indices and Measurements

Values normalized to solar cycle range:

$$R = (I_{2008} - I_{1996}) / (I_{2001} - I_{1996})$$

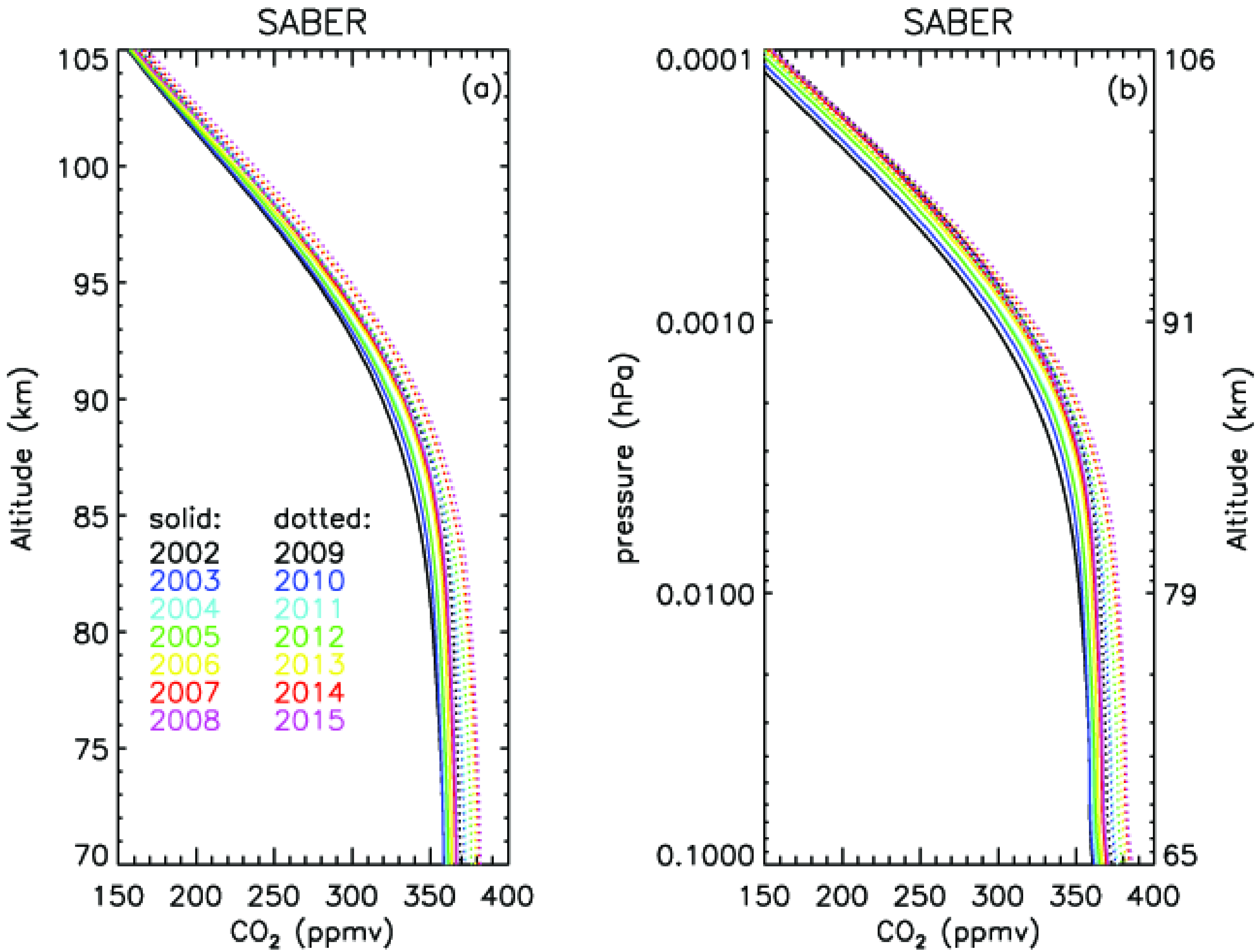


Comparison of Density Simulation to Satellite Drag Data

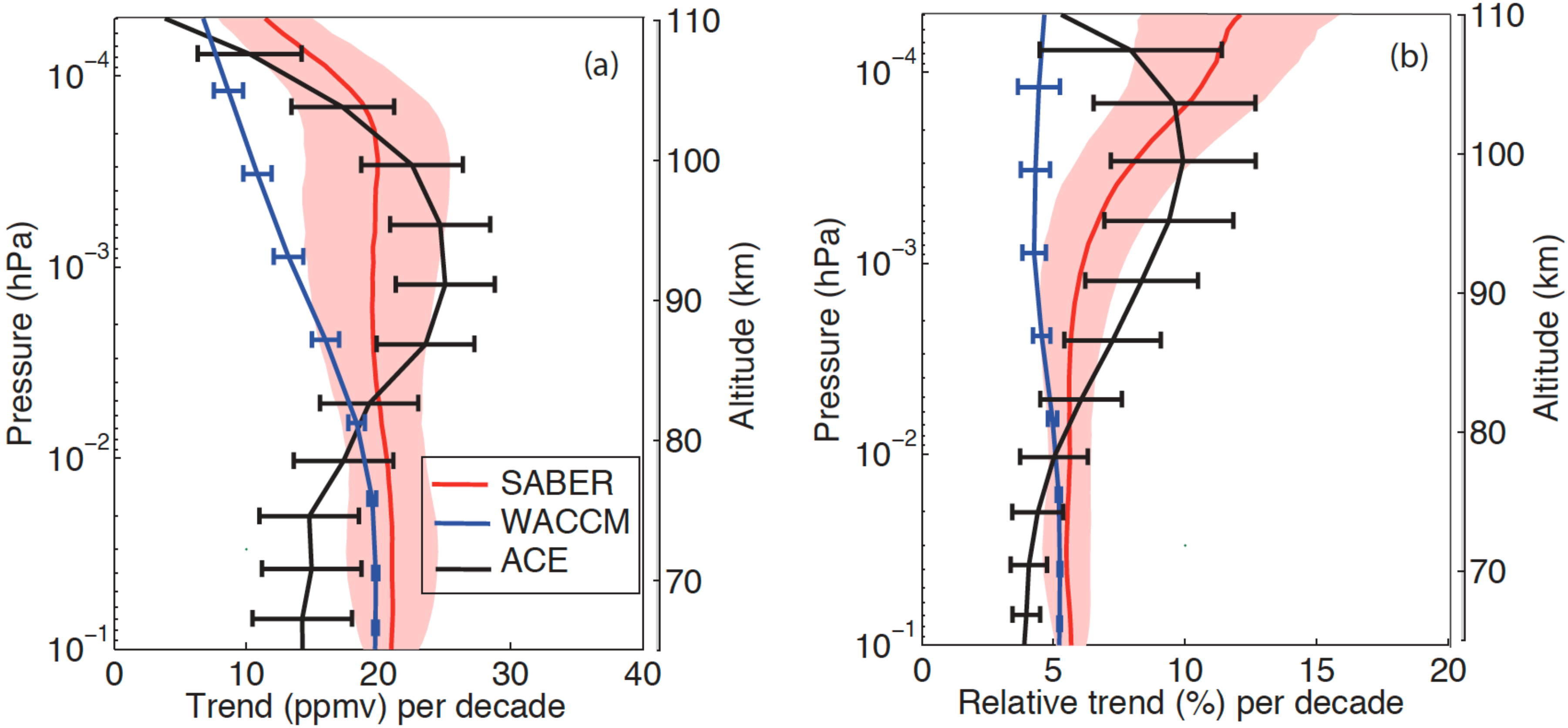


Simulation of neutral density at 400 km by the NCAR TIE-GCM
Mg II c/w ratio used as proxy solar input, yields ~10% EUV decrease 1996-2008

Complication #2 — Is There a Differential Trend in CO_2?



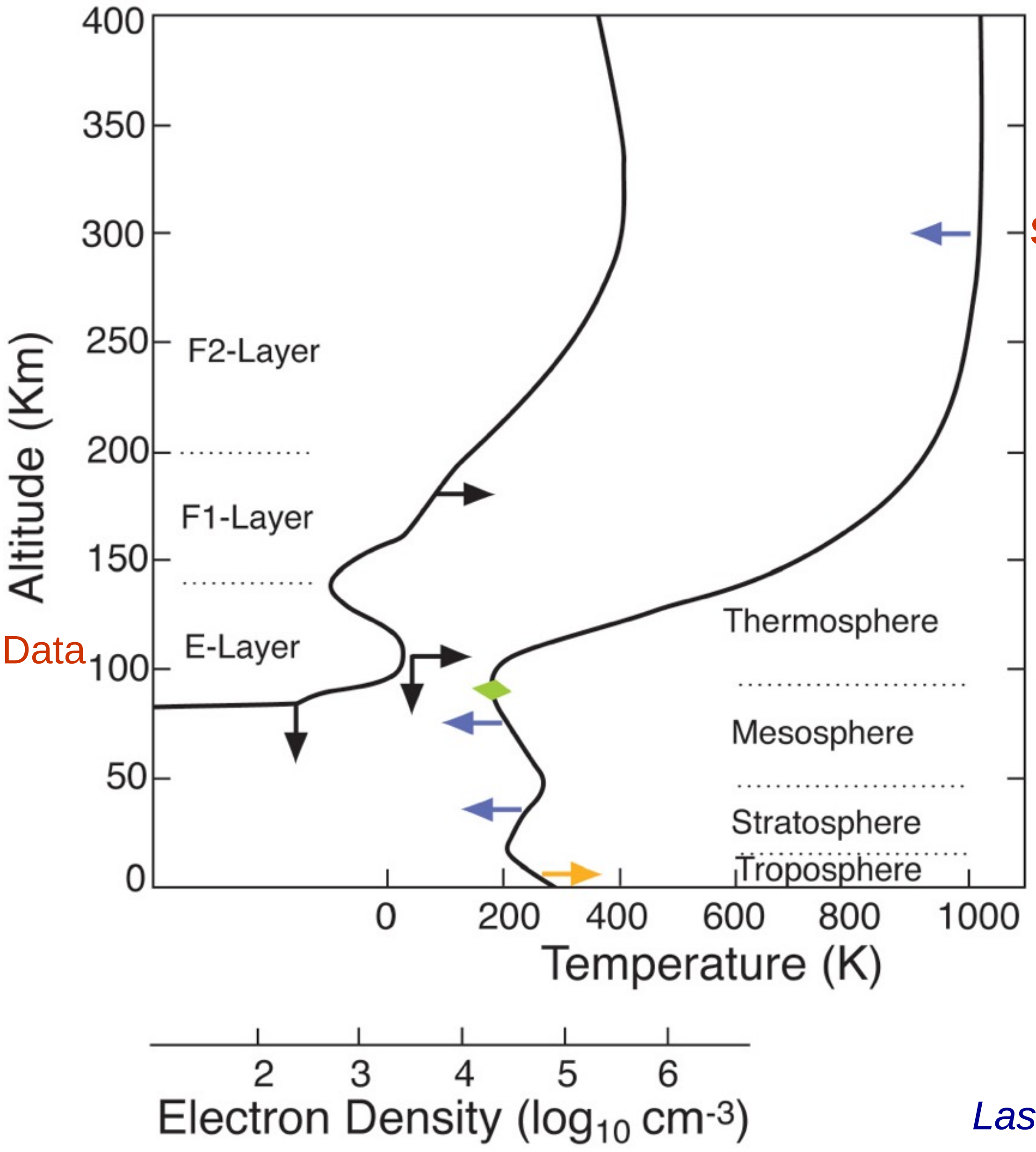
Complication #2 — Is There a Differential Trend in CO_2?



Data from the Atmospheric Composition Experiment (ACE) analyzed by Emmert et al. [2012], and data from TIMED/SABER analyzed by Yue et al. [2015], appear to indicate that, on a percentage basis, CO_2 is increasing more rapidly above the mesopause than in the fully-mixed atmosphere below. However, the uncertainties are large.

Observed / Inferred Global Change Scenario

Ionosonde Data

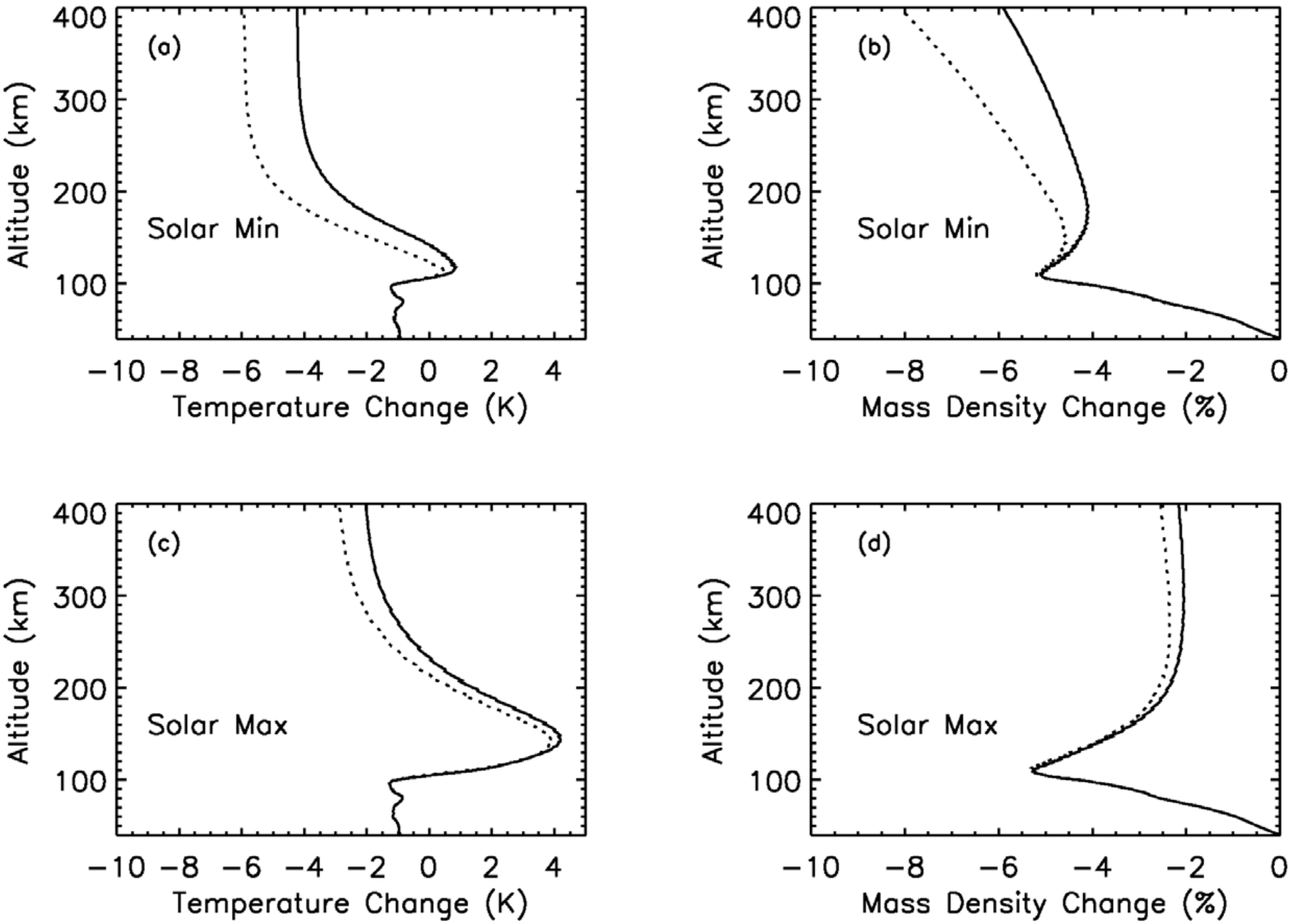


Satellite Drag Data

Radar,
Lidar;
Rocketsonde;
Airglow;
Satellite;
etc.

Lastovicka et al., 2006

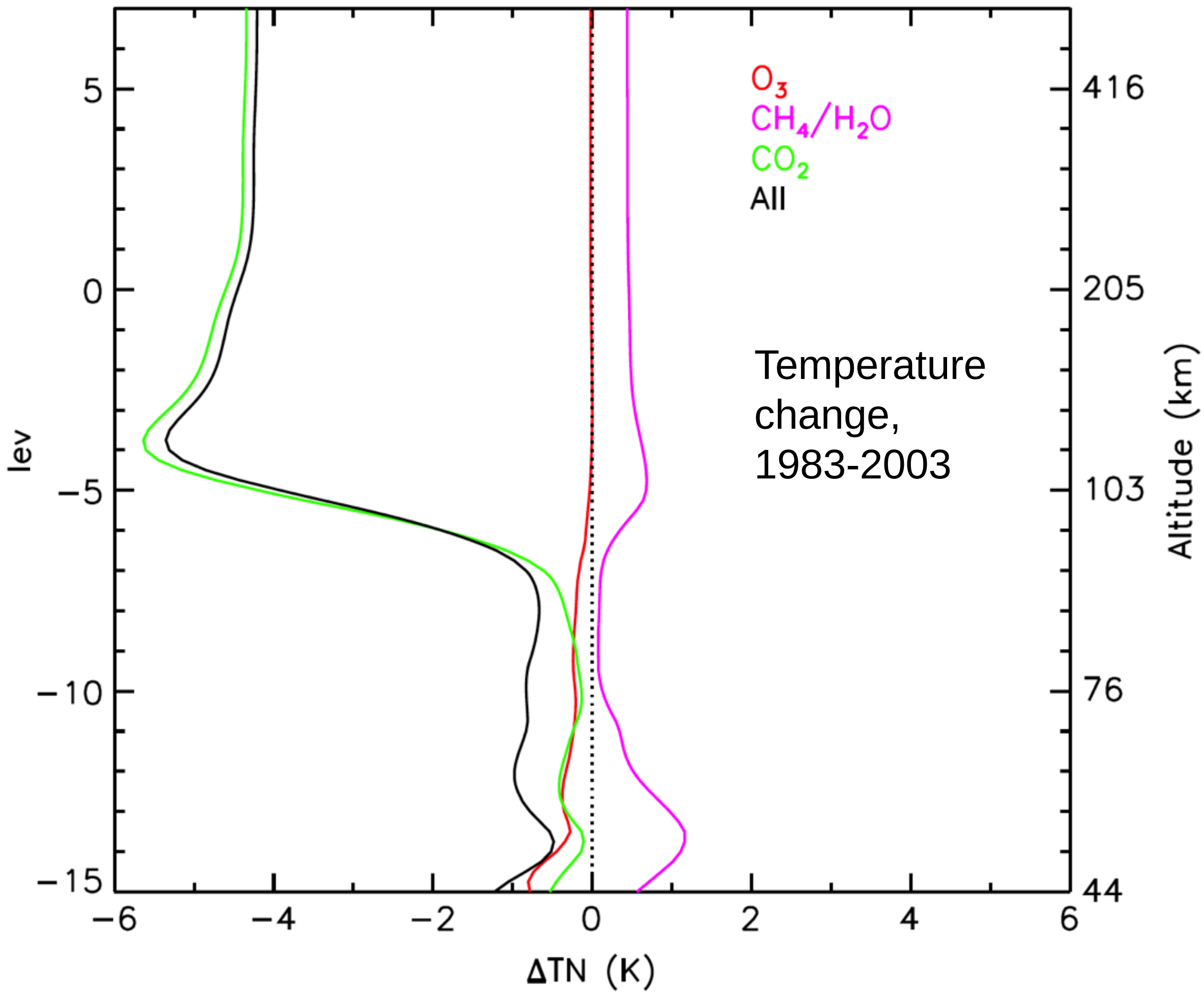
Review of Previous Work



Simulations of thermospheric global change using the NCAR TIME-GCM

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”?

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.

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

- Equatorial electrodynamo installed:

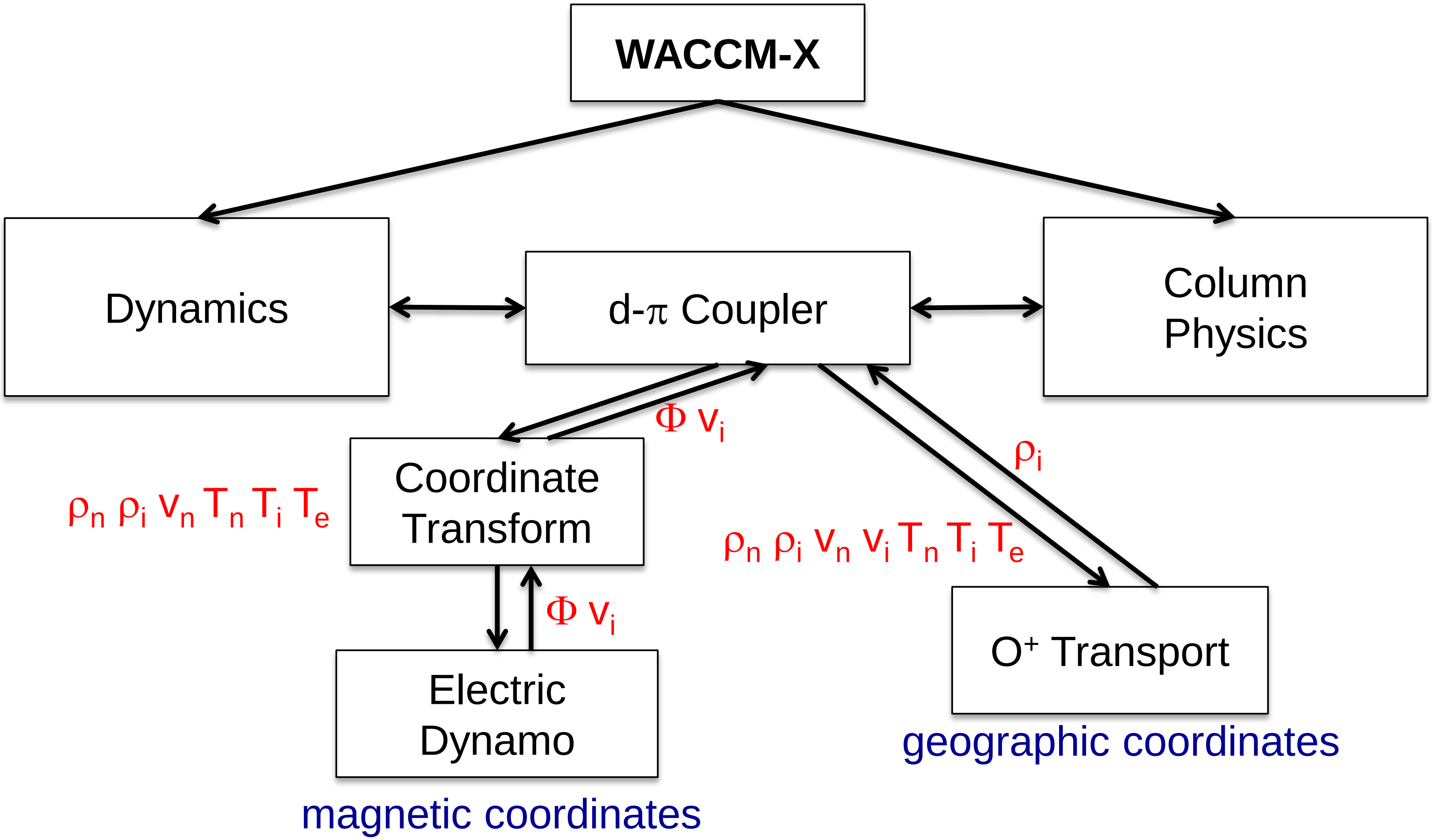
  Mostly parallel, with ESMF interpolation from geographic to geomagnetic coords.

- Ionospheric dynamics implemented:

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

  Horizontal transport of O^+ in the upper ionosphere.

Integrating Ionospheric Dynamics into WACCM-X



d-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

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; to 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…