Modeling Efforts to Explain Observed Trends in the Upper Atmosphere and Ionosphere

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NCAR

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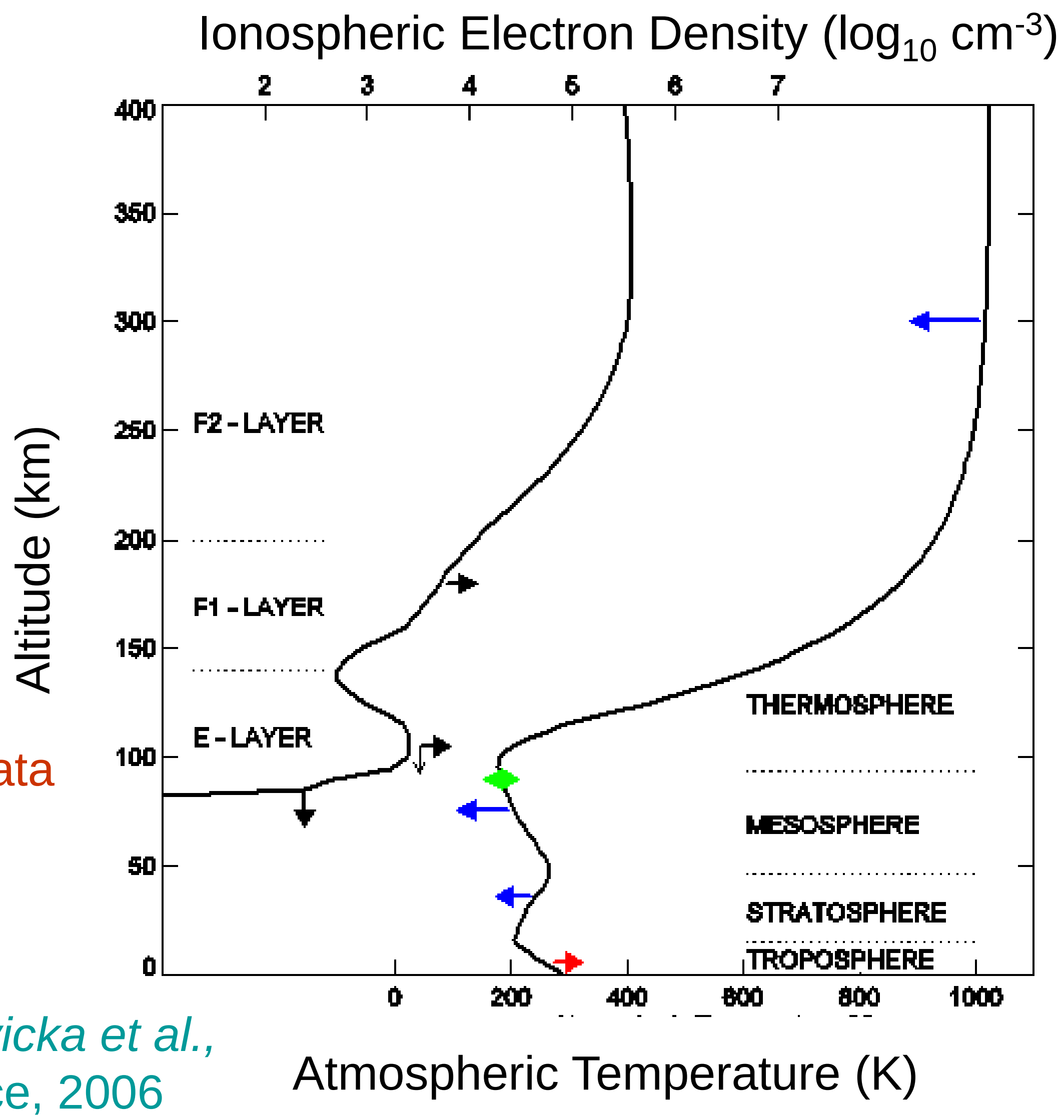
Global Change in the Upper Atmosphere and Ionosphere

Roble & Dickinson, 1989:

"…Global change will occur in the upper atmosphere and ionosphere as well as in the lower atmosphere…"

Doubling CO_2 and CH_4: ~ -10K in the mesosphere, ~ -50K in the thermosphere

Observed Pattern of Global Change in the Upper Atmosphere and Ionosphere



Satellite Drag Data

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

Ionosonde Data

Lastovicka et al., Science, 2006

Global Change: Modeling Studies

Following Roble & Dickinson, 1989, other modeling studies confirm and elaborate on this work, for example:

Akmaev et al., 1998, 2000, 2006; MLT (CO_2, O_3, H_2O)
Gruzdev & Brasseur, 2005;
Mesosphere (*CO_2, CH_4, H_2O, N_2O, CFCs*, GW drag and diffusion)

Garcia et al.,2007;
WACCM, stratosphere and mesosphere, specification of GHGs from 1950-2003 defined by scenario A1B of IPCC

Rishbeth & Roble, 1992; Thermosphere and Ionosphere (CO_2, CH_4)
Qian et al., 2006, 2008, 2009; Thermosphere and Ionosphere (CO_2)
Cnossen et al., 2008; Ionosphere (Earth's magnetic field)

Global Change: Progresses and Challenges

- Progresses:
  - consistent results on trends of mesospheric temperature (↓), thermospheric density (↓), electron density (E, F1) (↑), and hmE (↓), support the hypothesis of cooling and contraction due to greenhouse effect;
- Challenges
  - Controversies in trends of hmF2 and NmF2: *sign, magnitude, and origin of trends (geomagnetic or greenhouse effect)?*
  - Trends that have uncertainties due to limited studies, for example:
    - *ion temperature*
    - *wind, tidal and wave activity in the mesopause region (80-100 km)*

⇨ more observational and modeling studies.

NCAR/TIMEGCM

(Thermosphere-Ionosphere-Mesosphere Electrodynamics General Circulation Model)

TGCM [*Dickinson et al., 1981, 1984*]
TIGCM [*Roble et al., 1987,1988*]
TIEGCM [*Richmond and Roble, 1987; Richmond , 1995*]
TIMEGCM [*Roble and Ridley, 1994; Roble, 1995*]

- Solves continuity, momentum, and energy equations for the coupled mesosphere/thermosphere/ionosphere system.
  - 2.5° x 2.5° grid in latitude and longitude;
  - hydrostatic equilibrium: H/4 vertical resolution;
  - 30 km to ~600 km.
  - Fully coupled thermosphere/ionosphere, neutral wind dynamo [*Richmond et al., 1992*]

NCAR/TIMEGCM - continued

- **Input**
  - *Solar EUV/UV (F10.7 based solar proxy model/measurements)*
  - *Imposed magnetospheric electric field (Heelis or Weimer)*
  - *Tidal forcing (GSWM, Hagan et al., 1999)*
- **Boundary conditions of long-lived species** [*Garcia and Solomon*, *1994*]
- **Solar EUV energy deposition scheme** [*Solomon and Qian, 2005*]
- **Chemical heating** [*Mlynczak and Solomon*, *1992*]
- **Radiative cooling:**
  - *O(^{3}p) (63 μm), upper thermosphere [Bates, 1951]*
  - *NO (4.3 μm), 120-200km [Kocharts, 1980]*
  - *CO_2 (15 μm), below 120km, [Fomichev et al., 1993]*
  - *O_3 (9.6 μm), below 120km [Fomichev and Shved, 1985]*
- **Output**
  - *neutral wind, temperature, major/minor species density;*
  - *Electron and ion temperature and density, dynamo electric field*

Model Simulations

Global Mean Model Simulation:

- Use measured CO_2 and solar activity to study the long-term change in the thermosphere from 1970 to 2000.

3D Model Simulation:

- Change CO_2 concentrations:

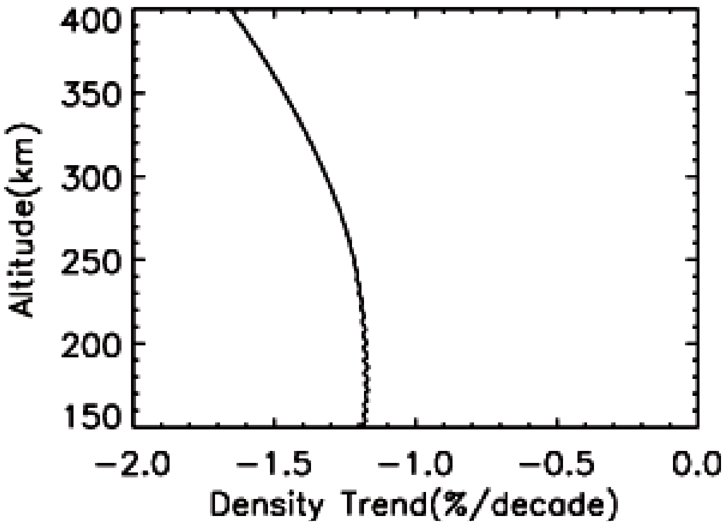
  base case: 365 ppmv (2000)

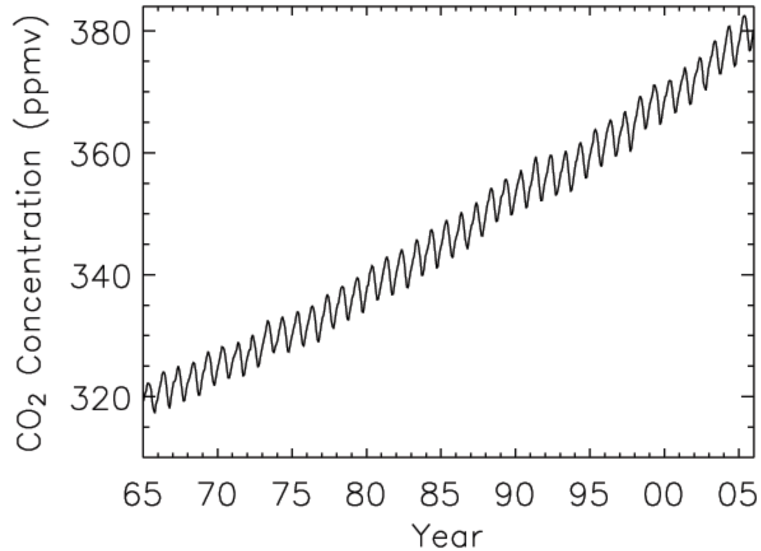
  double case: 730 ppmv (2100, IPCC projection).
- Geomagnetic Quiet (k_p=1)
- Spring Equinox
- June Solstice
- Solar minimum ($F_{10.7} = \overline{F_{10.7}} = 70$) and

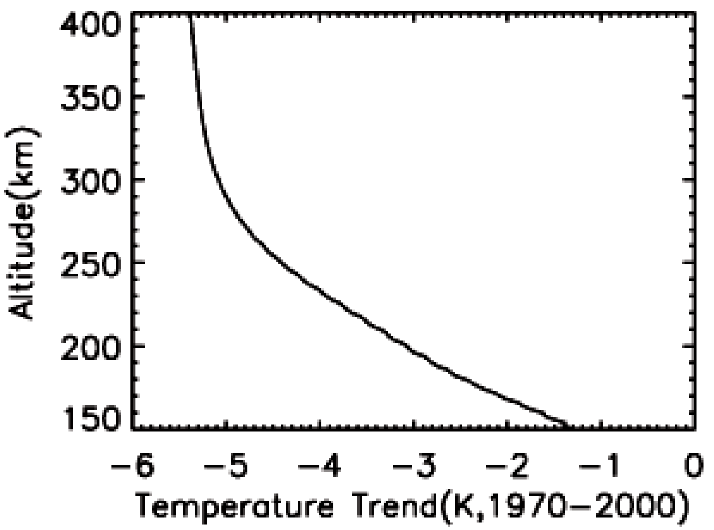
  solar maximum ($F_{10.7} = \overline{F_{10.7}} = 200$).

Mass Density Trends

Qian et al., GRL, 2006
1970-2000: -1.7%/decade at 400 km







1970-2000: -5.4K

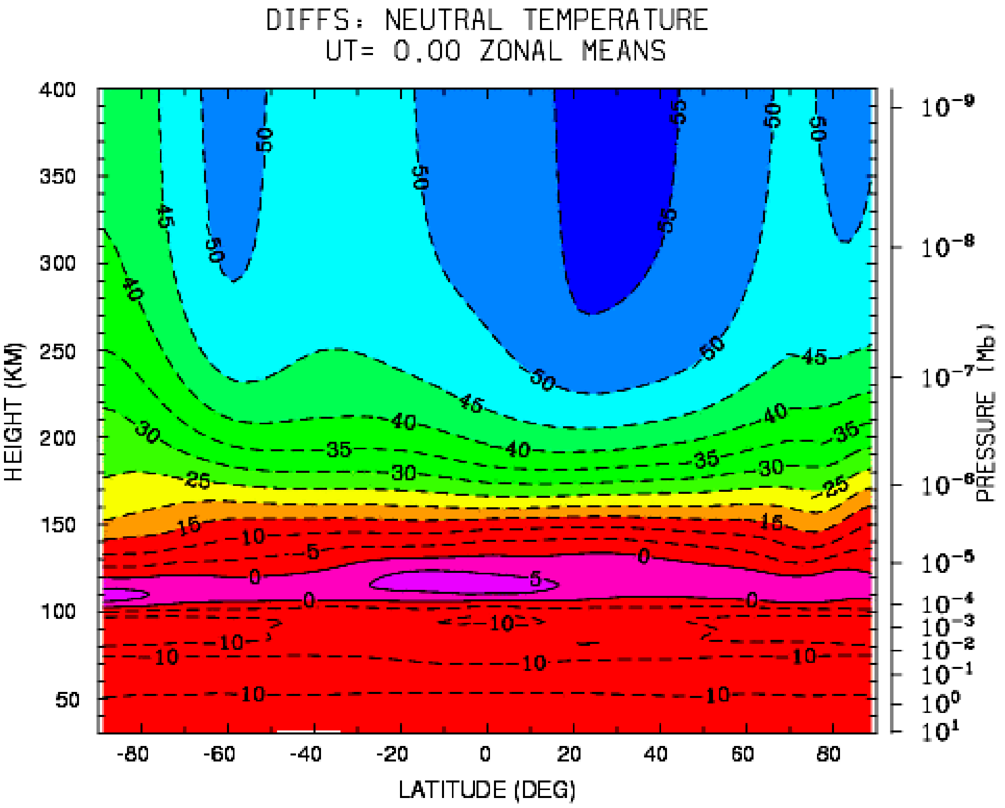
Marcos et al., 2005
1970-2000: -1.7%/decade at 400 km

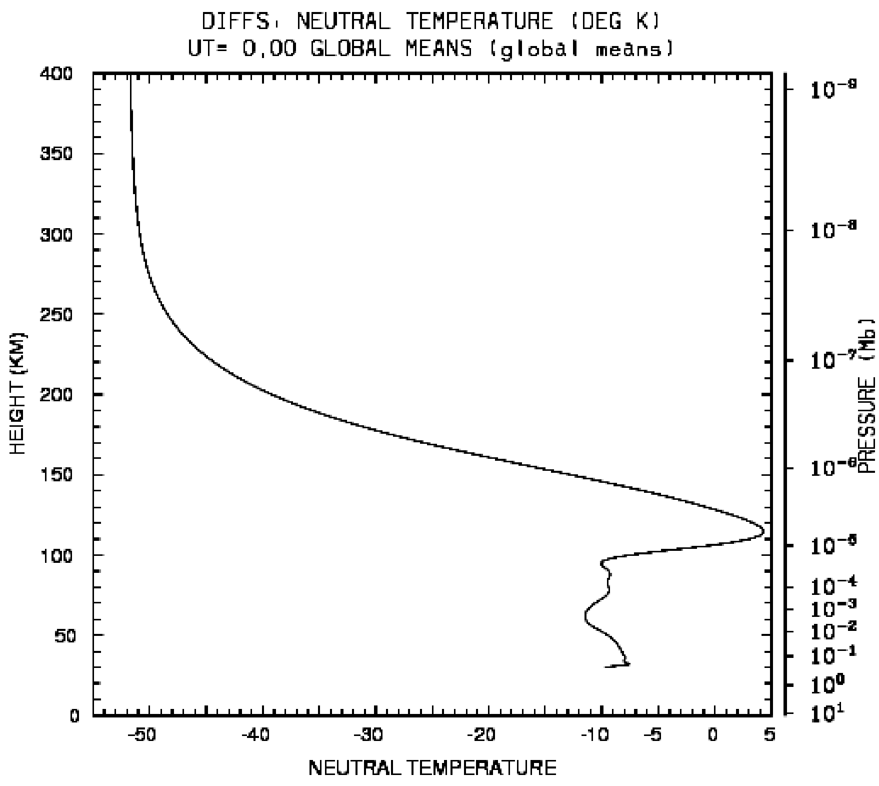
Emmert et al., 2008

1967-2007: –2.68 ± 0.49 % per decade at 400km

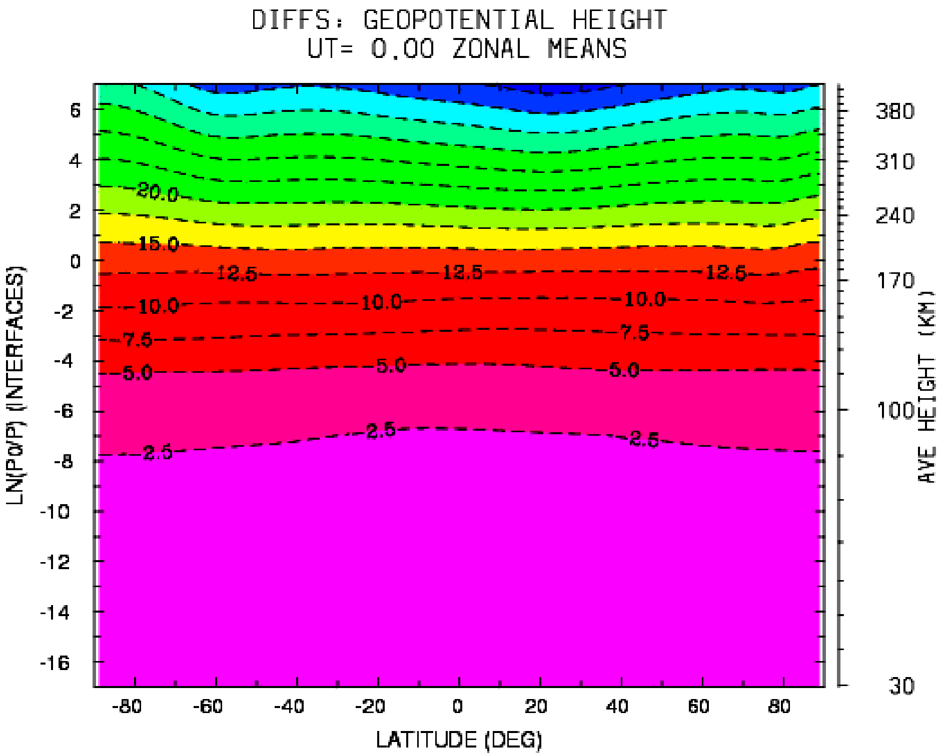
Solar max: -1 – -2%/decade
Solar min: -3 – -5%/decade

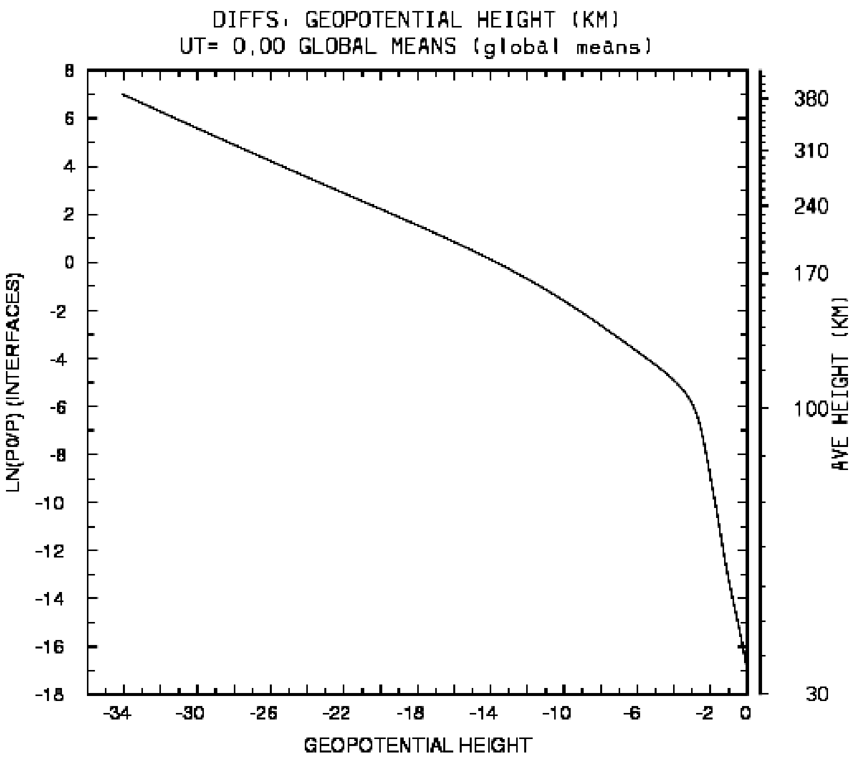
Simulation Results:
–Cooling and Contraction





Simulation Results
–Cooling and Contraction





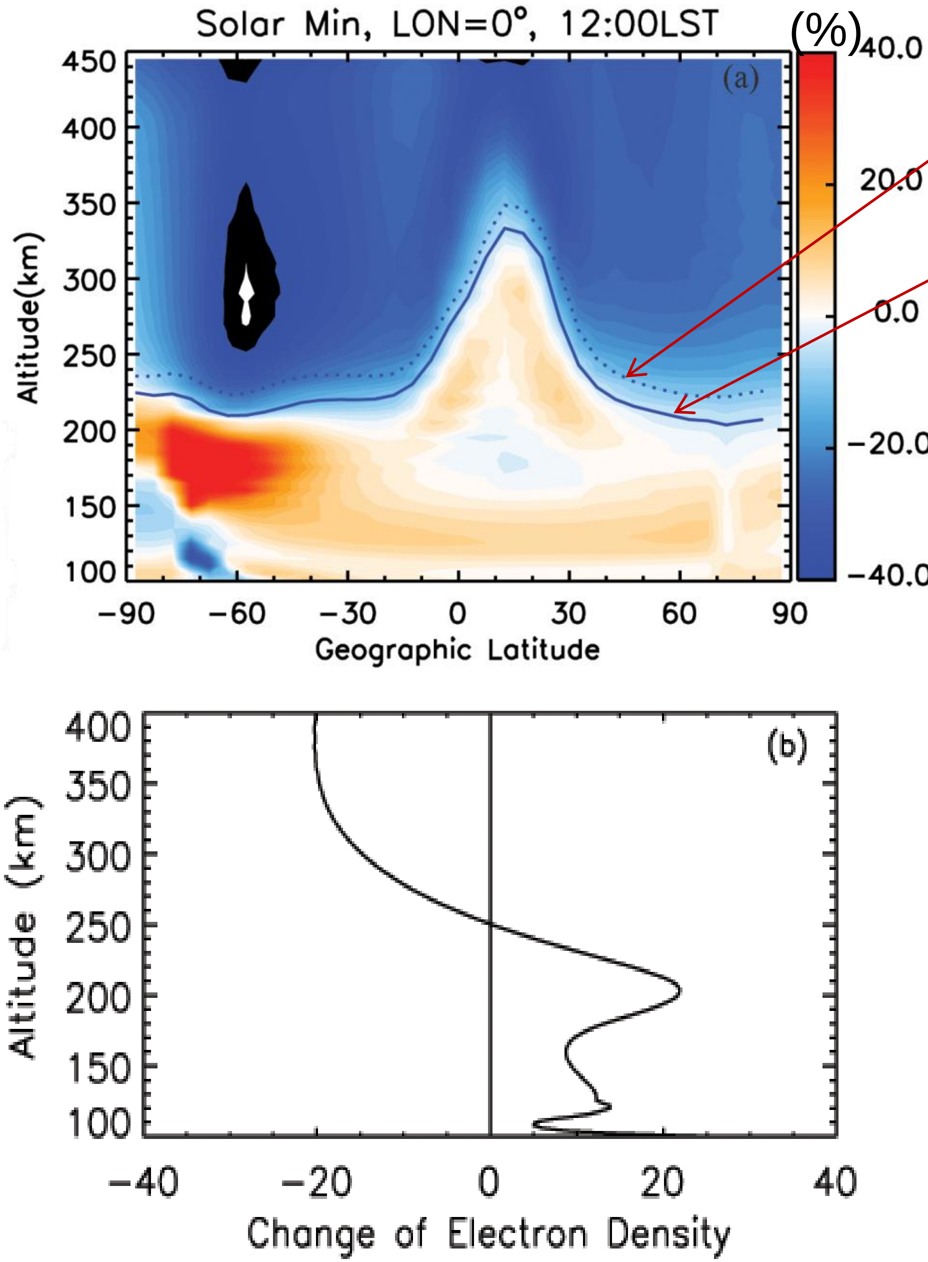
Rishbeth, 1990 (theoretical analysis)
Rishbeth and Roble, 1992 (TIGCM)

Double CO_2 and CH_4

- The cooling and contraction would lower the E- and F2-layer peaks by about 2 km and 20 km respectively;

- Changes of the F2-layer critical frequency will be small.

Simulation Results: Understand F2 Trends



hmF2: base

hmF2: double

Rishbeth, 1998:

F2 peak remains on the same pressure surface as temperature changes

$$\Delta NE(\%) = \frac{(double - base)}{base} \times 100$$

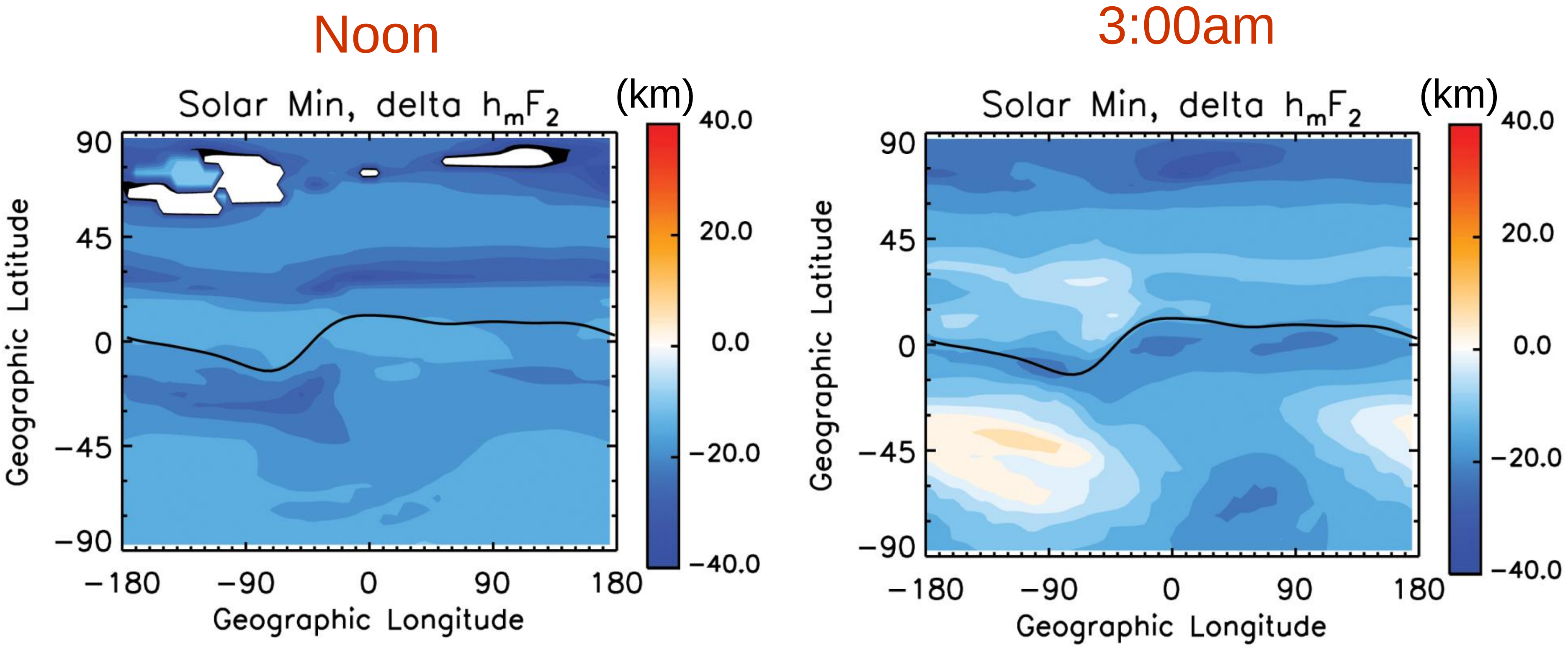
Daytime:

ΔNE: Negative at F2 peak and above
Positive in the E and F1 regions

$\Delta hmF2$: Negative

Qian et al., 2008

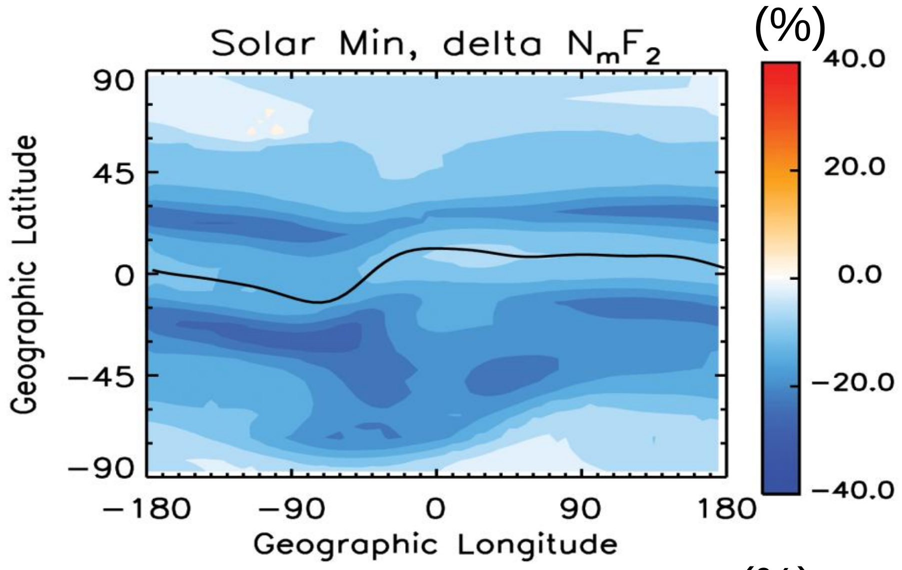
Local-Time and Regional Variations



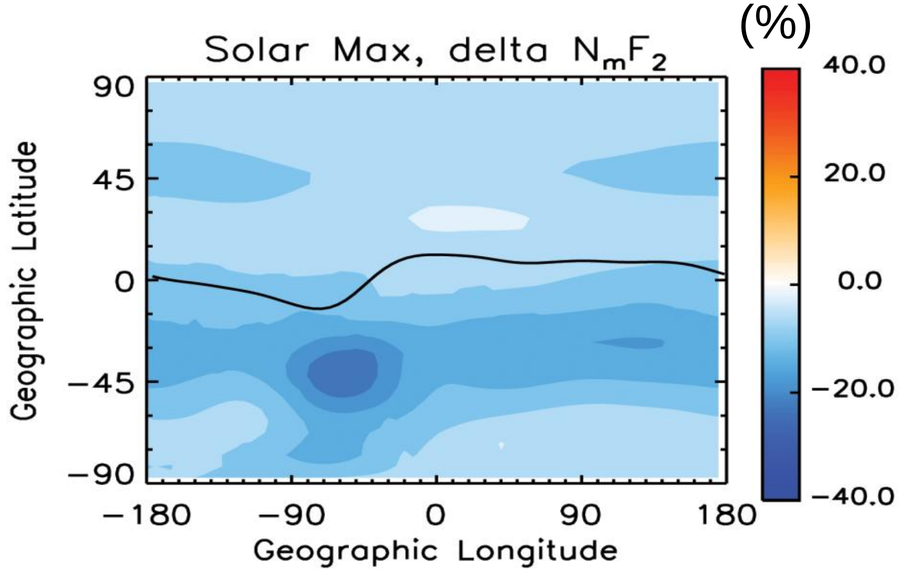
- Strong local time variation; Variation depend on locations;
- Strong latitudinal and longitudinal variation

Qian et al., 2009

Solar Cycle and Seasonal Variations



Solar Minimum

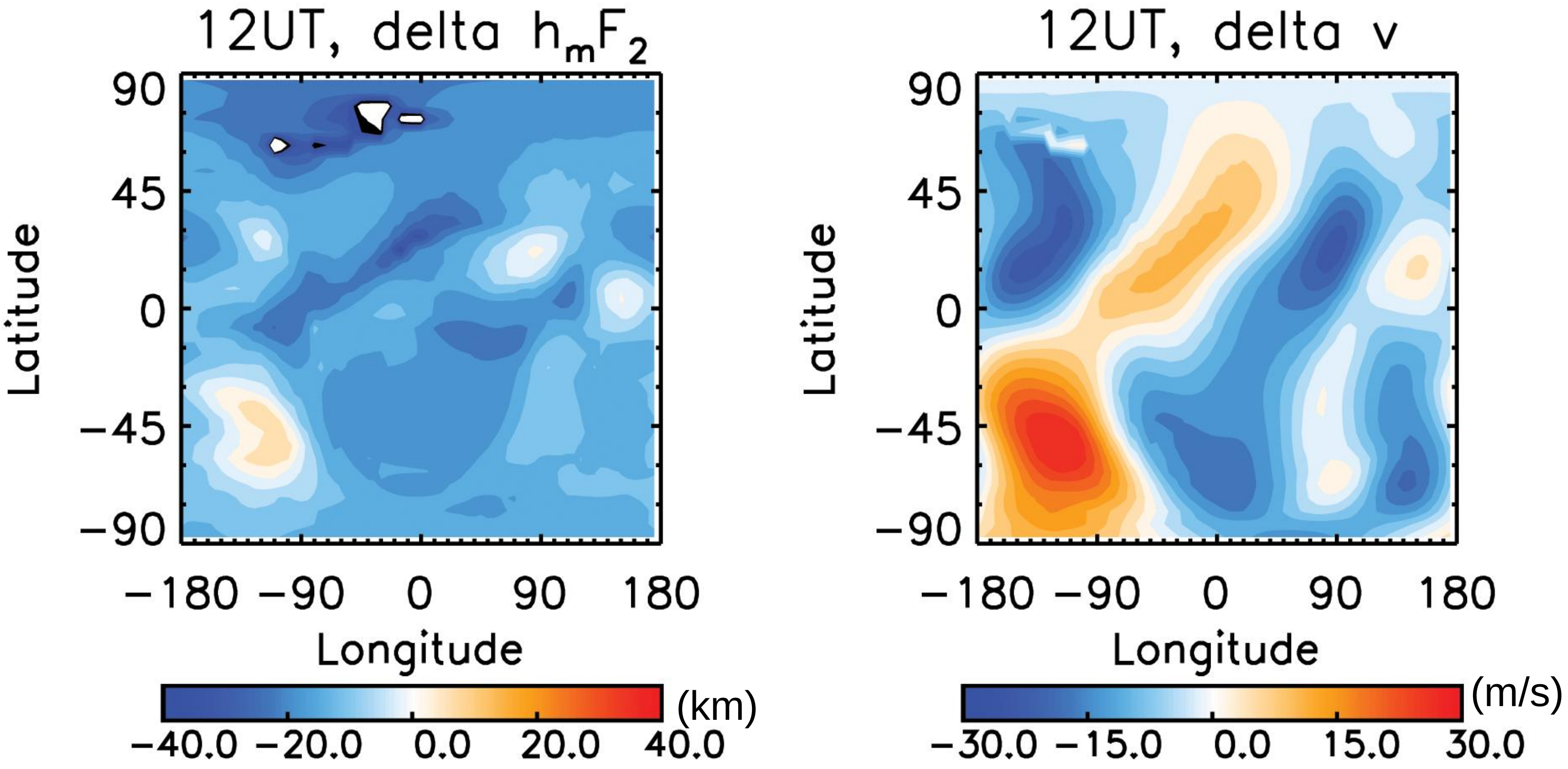


Solar Maximum

- Greater change under solar minimum than solar maximum;
- Greater change in the winter hemisphere.

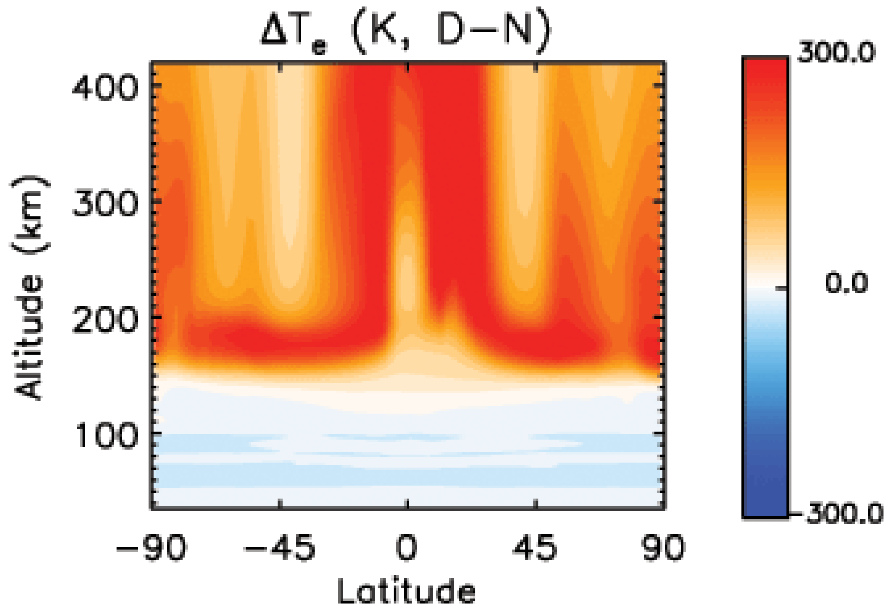
Changes in Dynamics and its Effect

Solar Minimum



Dynamical forcing causes positive change of hmF2 at night, with stronger effect under solar minimum condition.

Changes of Electron and Ion Temperature

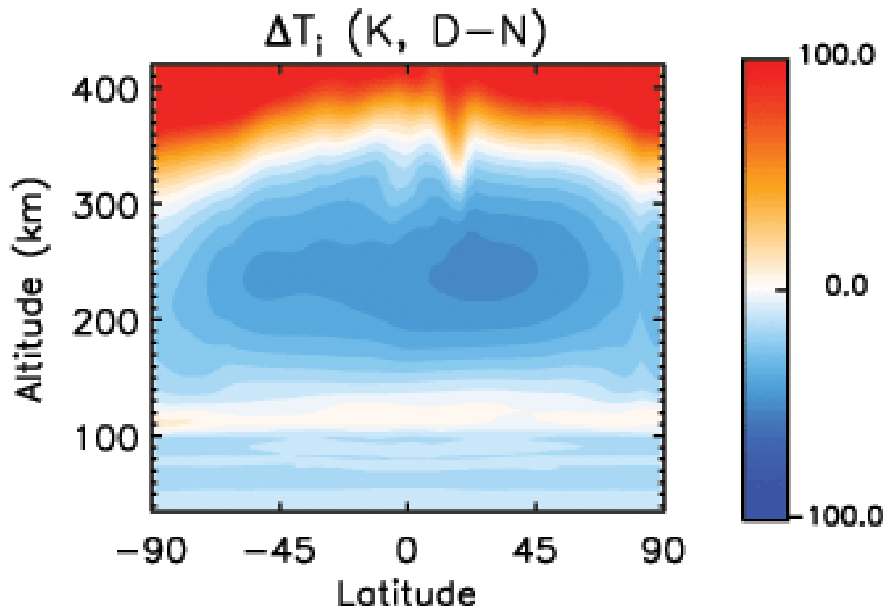


Zhang et al., 2005:

-17K/decade at 350 km

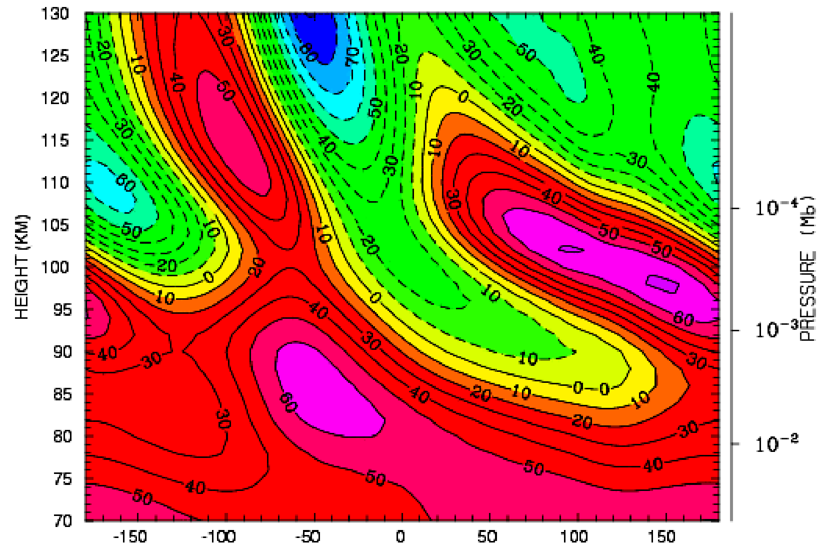
Holt and Zhang, 2008:

-4.7 K/year at 375 km
from 1978-2007

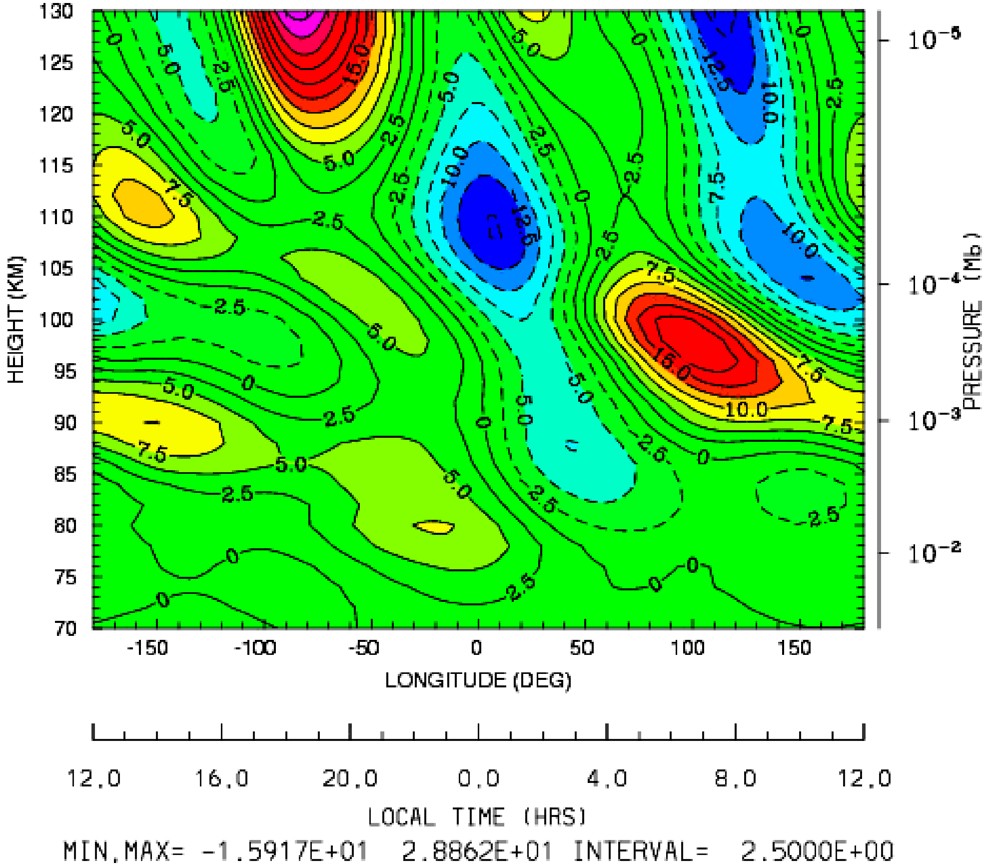


Simulation Results
– Changes of MLT Dynamics

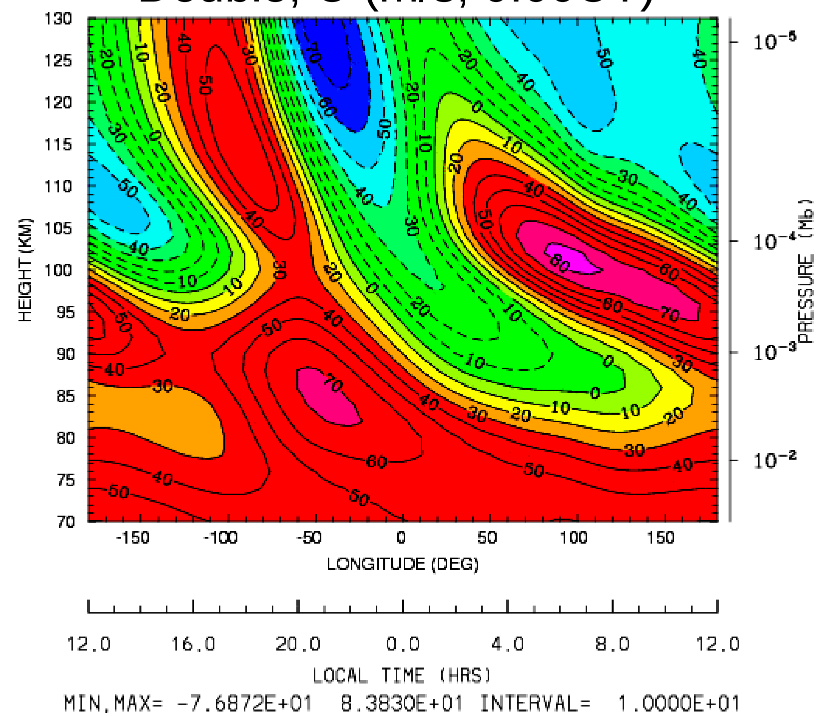
Base, U (m/s, 0:00UT)



Difference, U (m/s, 0:00UT)



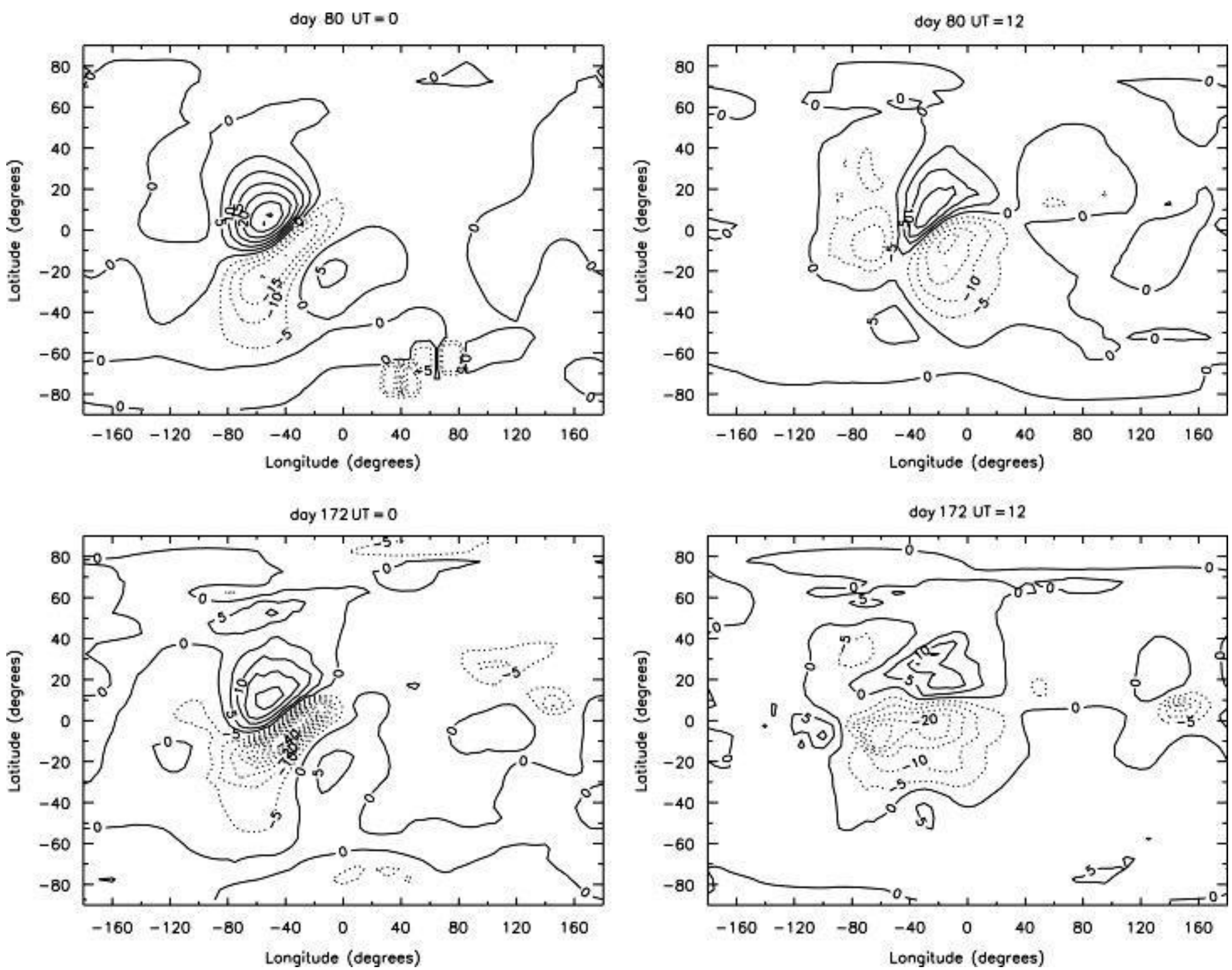
Double, U (m/s, 0:00UT)



Zonal Wind at 41.25ºN

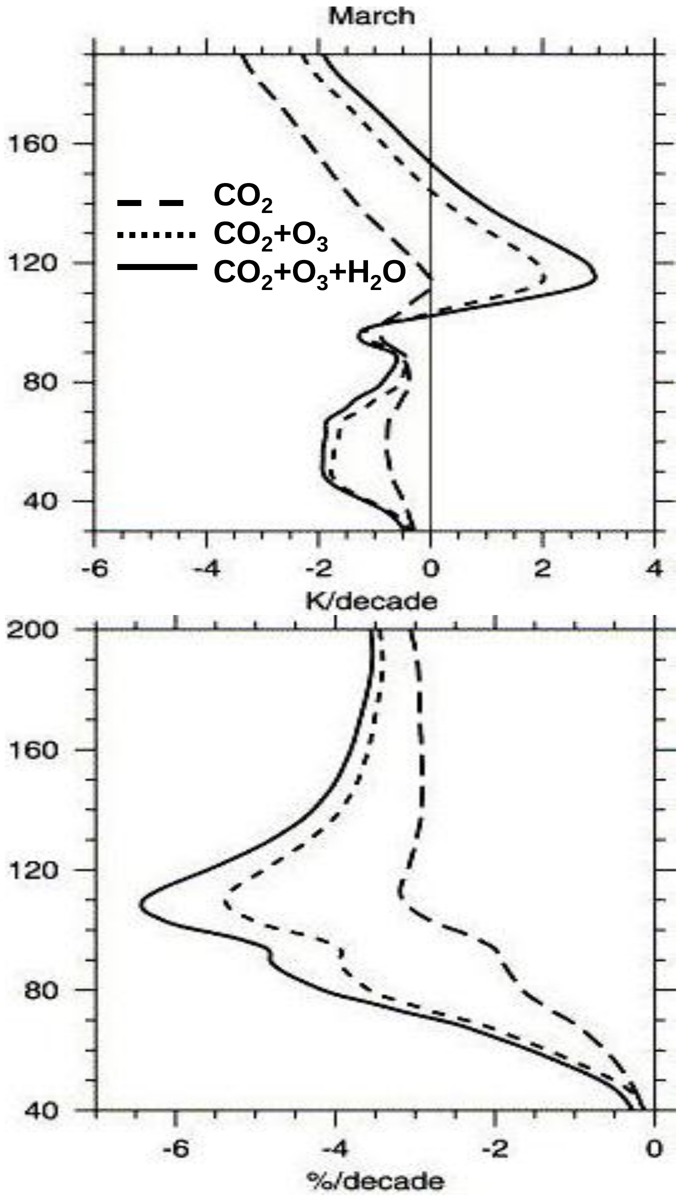
Other Forcing Mechanisms –Geomagnetic Field

Change of *hmF2* due to change of the geomagnetic field from 1957 to 1997, *Cnossen and Richmond*, *2008*.

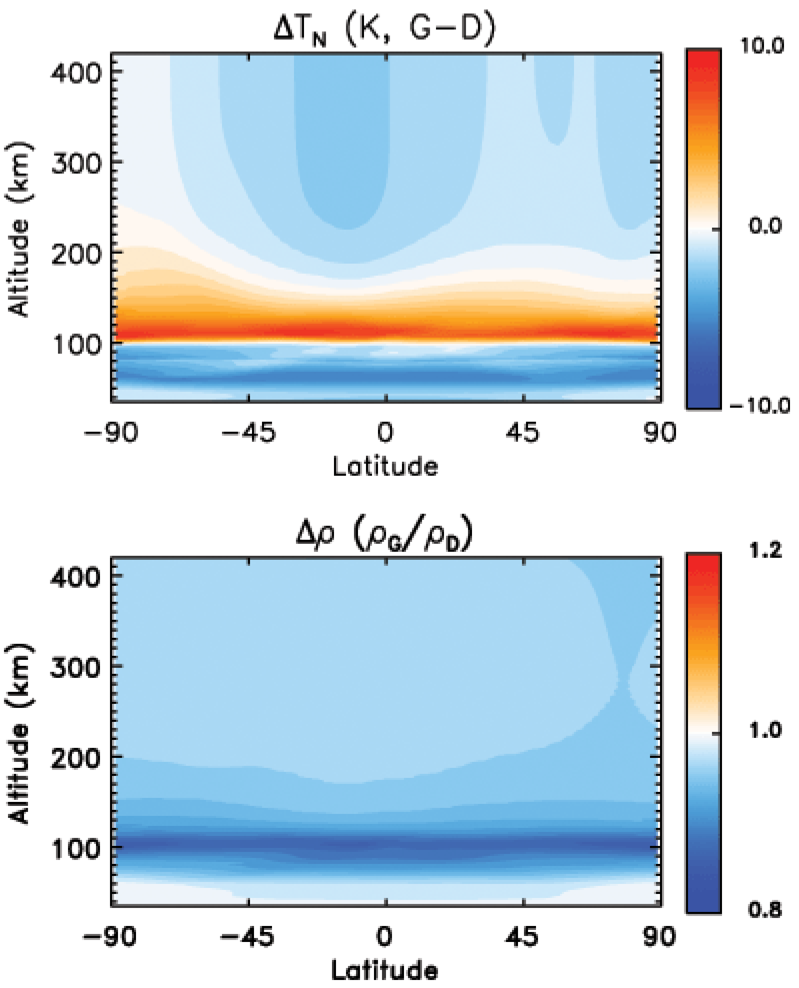


Global Mean Trend from 1980-2000

Other Forcing Mechanisms –Other Trace Gases



Akmaev et al., 2006



CH_4, H_2O, O_3

Conclusions

- Model simulations on trends in the upper atmosphere and ionosphere using CO_2 forcing is able to explain:
  - the overall cooling and contraction in the upper atmosphere, as well as the resulting changes in the E and F1;
  - specifically, the thermospheric mass density trends;
  - variability (sign and magnitude) in trends of hmF2 and NmF2 such as regional and diurnal variations.
- These model simulations also show:
  - trends of wind/tides in the MLT;
  - smaller trends of Ti compared to data, and a positive trends of Ti at higher altitude that has not been found in data.
- Model studies show that additional forcing, including other trace gases (CH_4, H_2O, O_3) and the Earth's geomagnetic field, can cause additional trends and trend variability in the upper atmosphere and ionosphere.