Anthropogenic and Natural Variability in the Earth's Upper Atmosphere:

Unraveling Solar Cycle Variations and Decadal Trends

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Outline

A Few Basic Characteristics of the Upper Atmosphere

• inherent quasi-decadal scale (i.e., solar cycle) variability of thermospheric structure and composition

• characteristics of the imbedded ionosphere

• effects of neutral winds on the low and middle latitude ionosphere

Evidence of Anthropogenic Effects

• seminal numerical experiments of *Roble and Dickinson* (1989)

• cooling over Millstone Hill, Massachusetts (*Holt and Zhang*, 2008)

• thermospheric contraction (*Emmert et al.*, 2008)

Caveat: Evolution of the Geomagnetic Field

• impact on thermosphere-ionosphere coupling (*Cnossen and Richmond*, 2008)

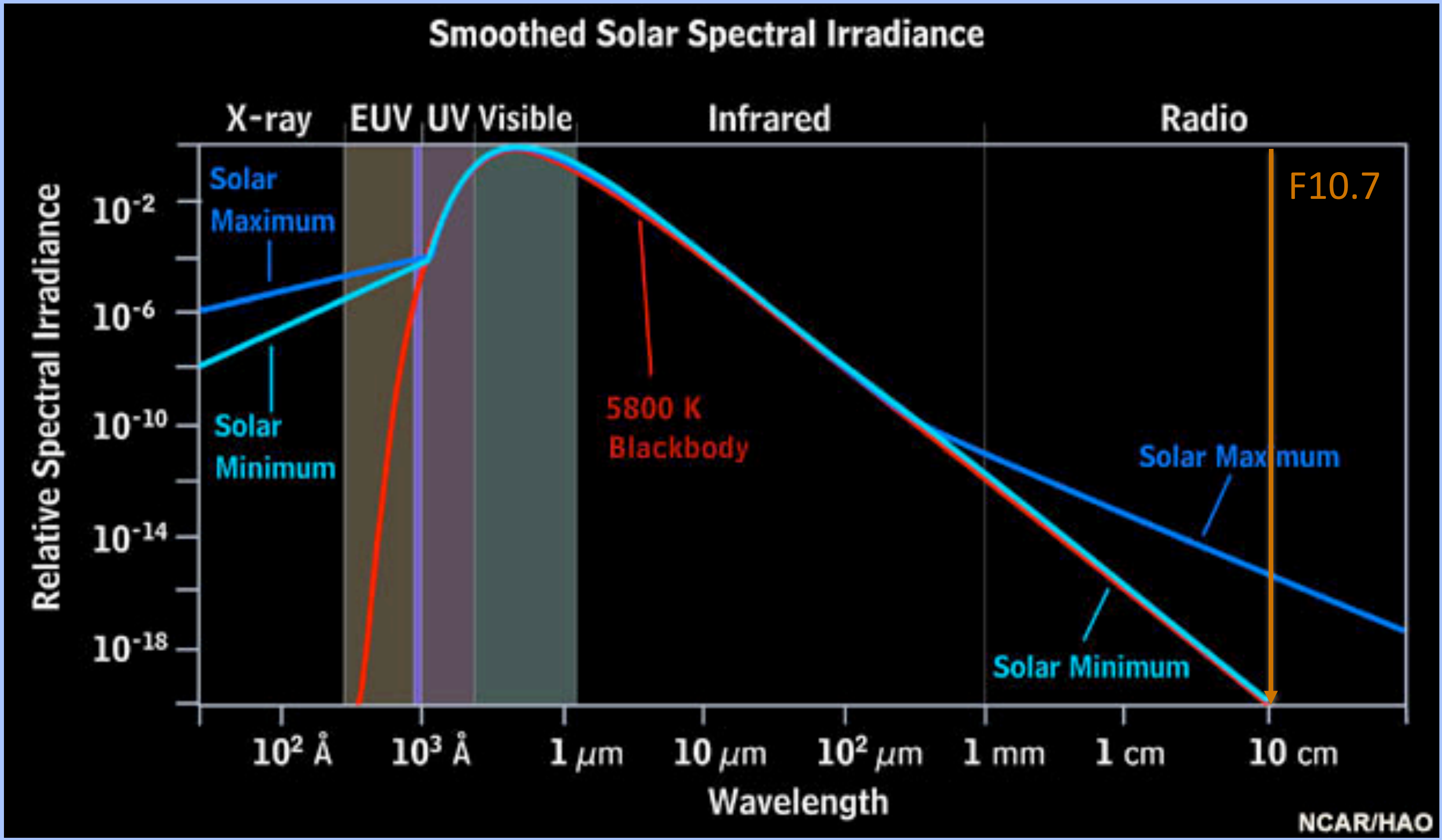
• another look at global change in geomagnetic storm occurrence (*Clilverd et al.*, 1998; *Macmillan and Droujinina*, 2007)

Some
Basic Characteristics
of the
Upper Atmosphere

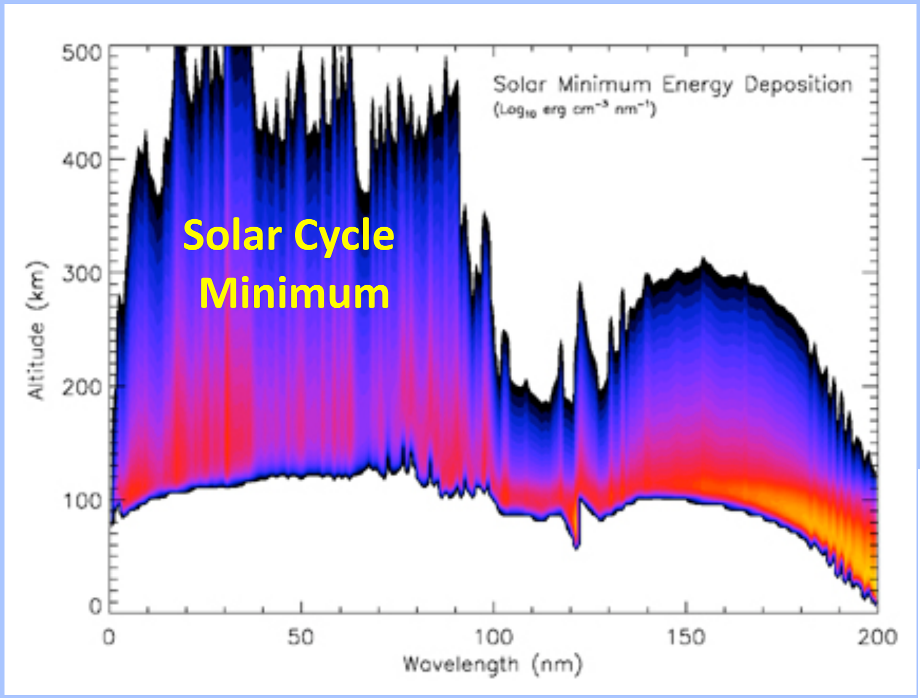
The Fundamental Sun-Earth Connection

The upper atmosphere absorbs solar EUV radiation

➔ Inherent seasonal and solar cycle variability

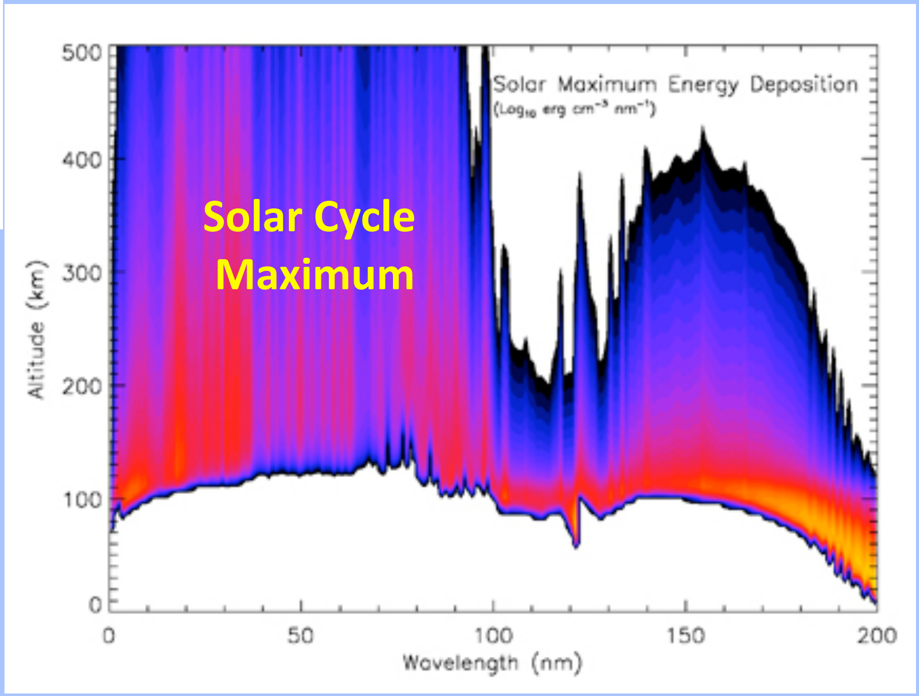


Solar FUV and EUV Energy Deposition in the Earth's Upper Atmosphere



EUV variations of ~30% →

- variable thermospheric heating
- variable thermospheric density
- variable satellite drag

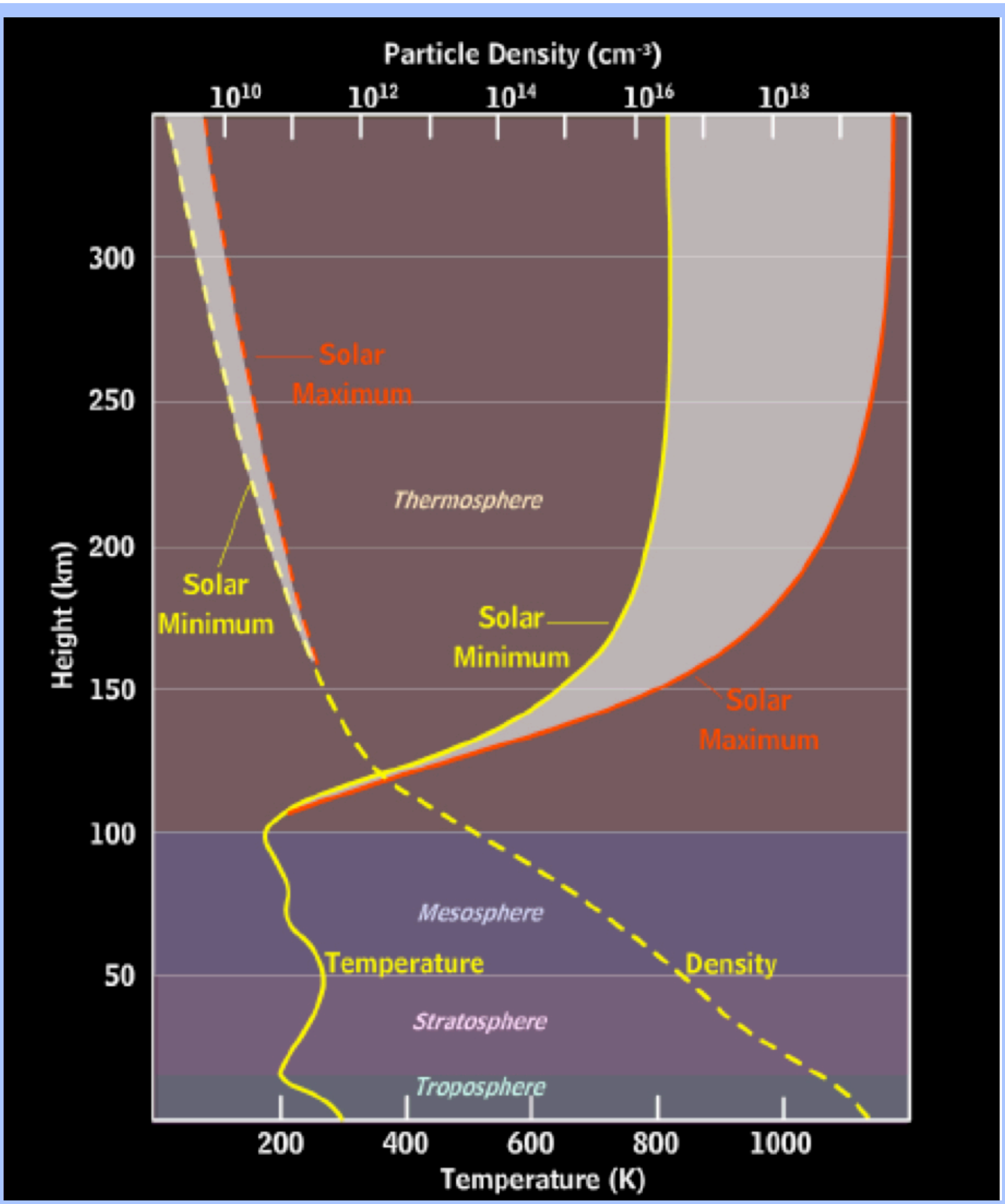


Courtesy of Stan Solomon

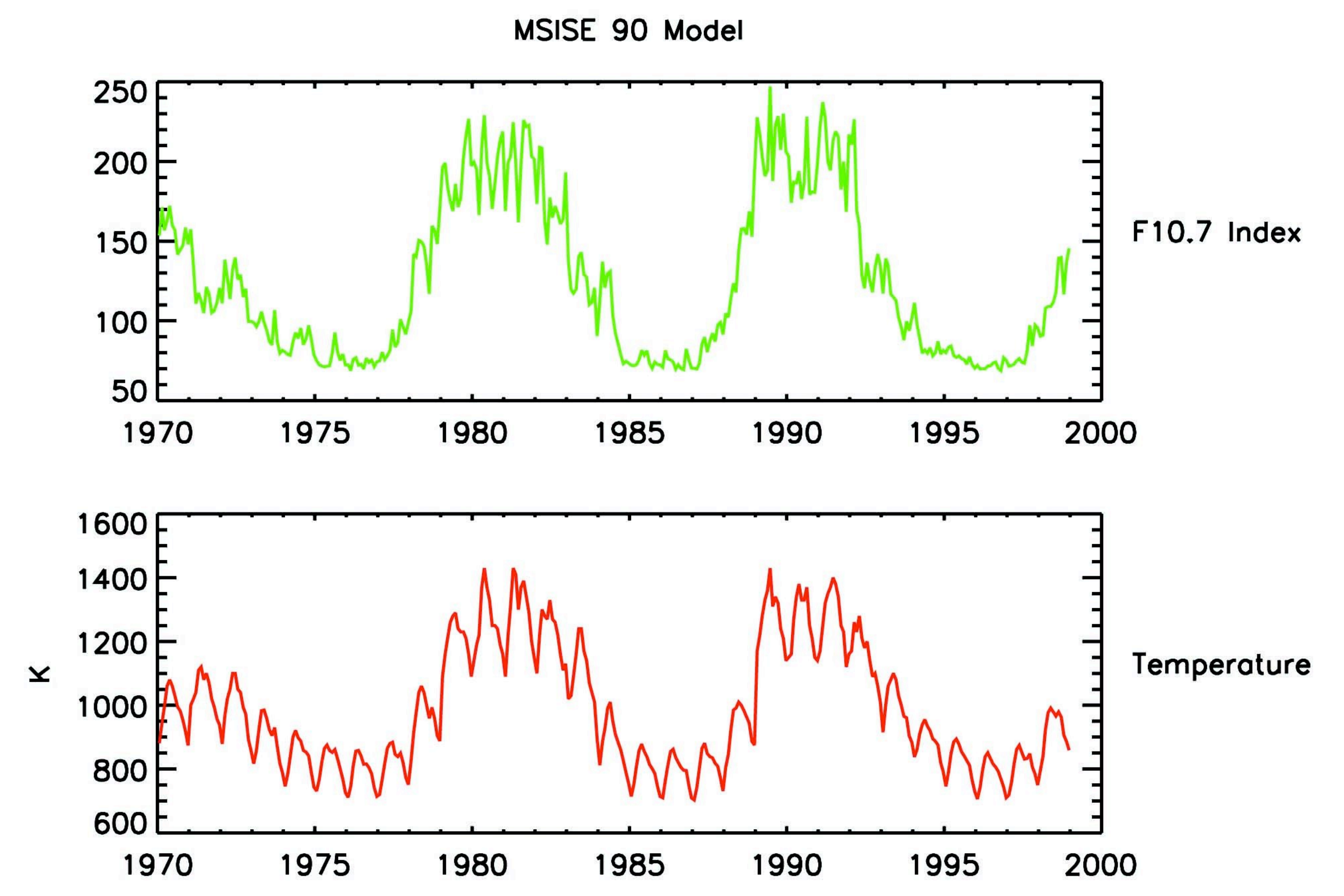
Global Mean Atmospheric Structure

Inherent solar cycle variability of the thermosphere →

- exospheric temperatures ~800-1200°K
- thermospheric expansion and contraction
- thermospheric density changes at 400km ~.5x10^{9}cm^{-3}
- implications for drag on satellites



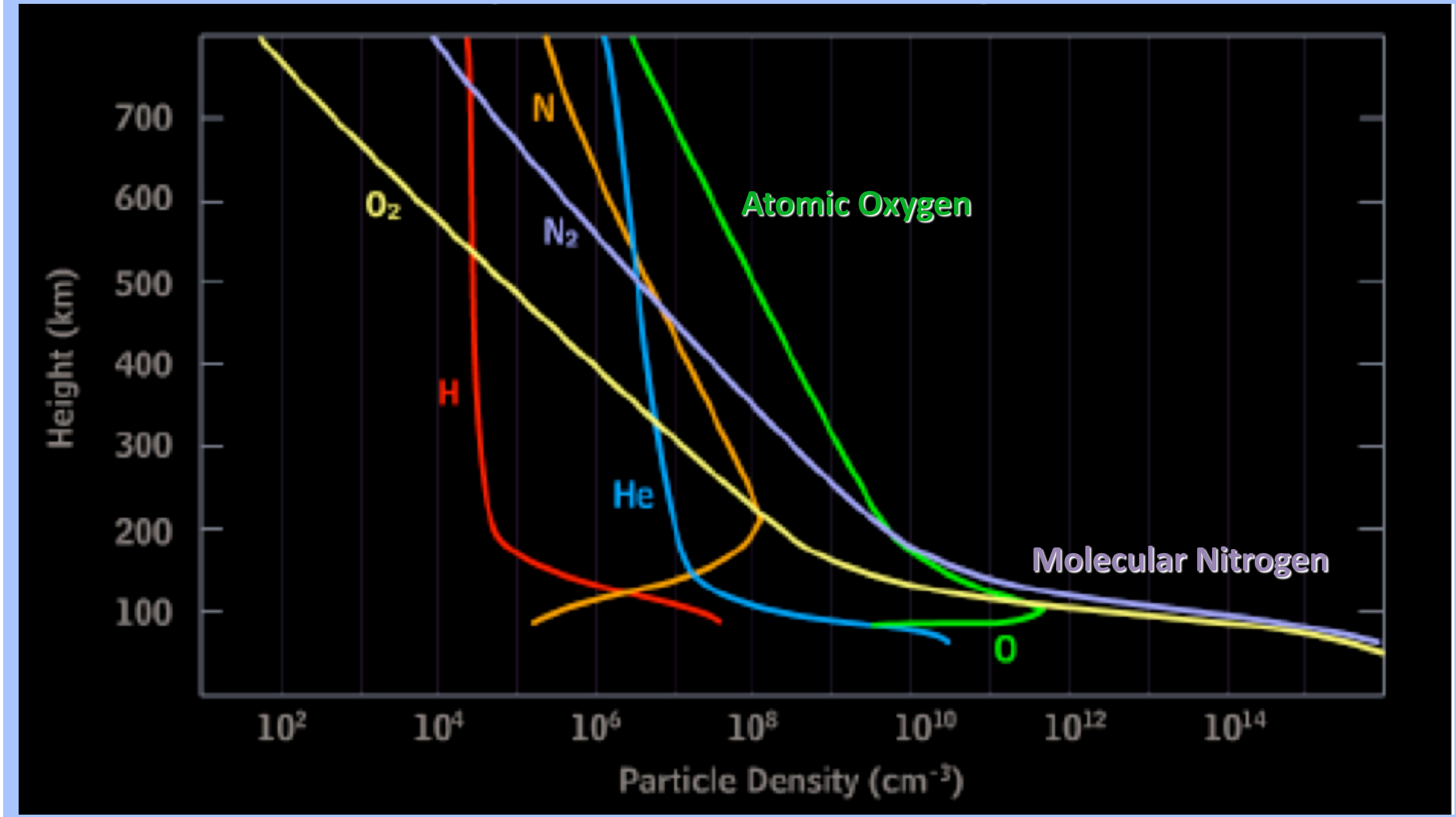
Variability of Exospheric Temperature



Courtesy of Ingo Mueller-Wodarg

Principle Constituents of the Thermosphere

Vertical Structure → Diffusive Separation

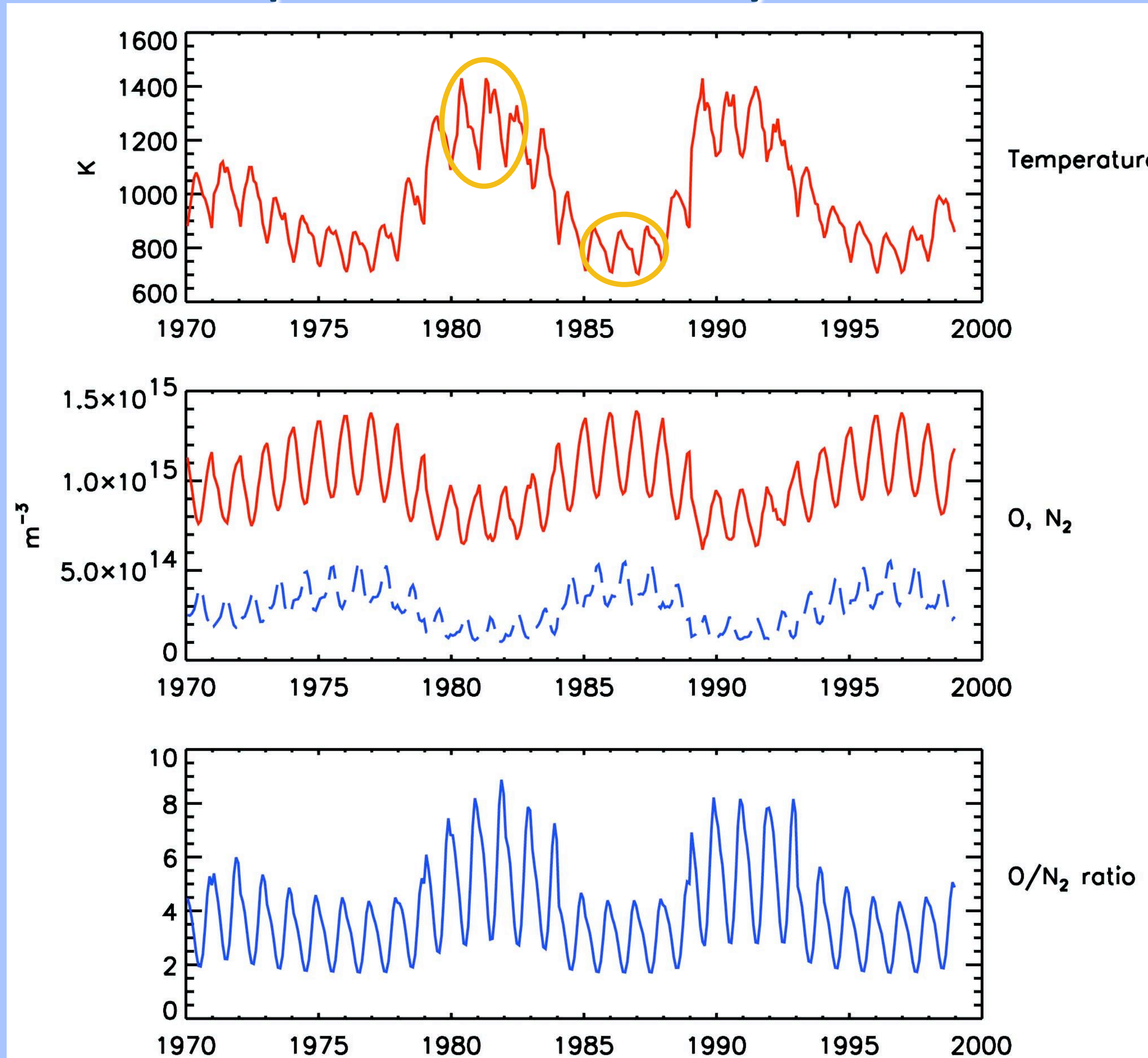


Thermospheric Variability

MSISE90 seasonal Tex changes are stronger during solar maximum

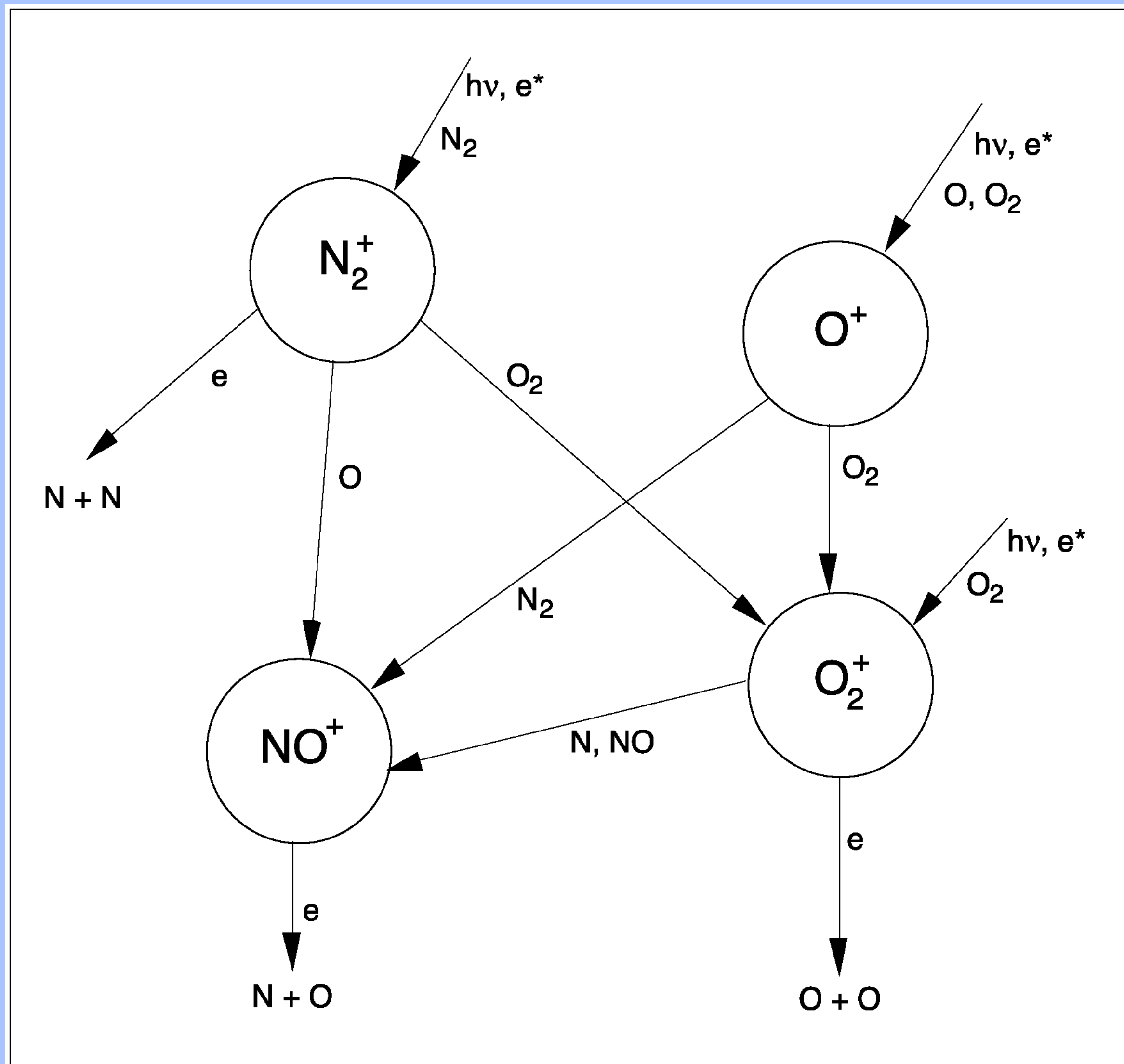
Number densities of O and N_2 at 300 km 50°N vary with solar cycle and season

Proportionally more O than N_2 during solar maximum due to stronger photodissociation



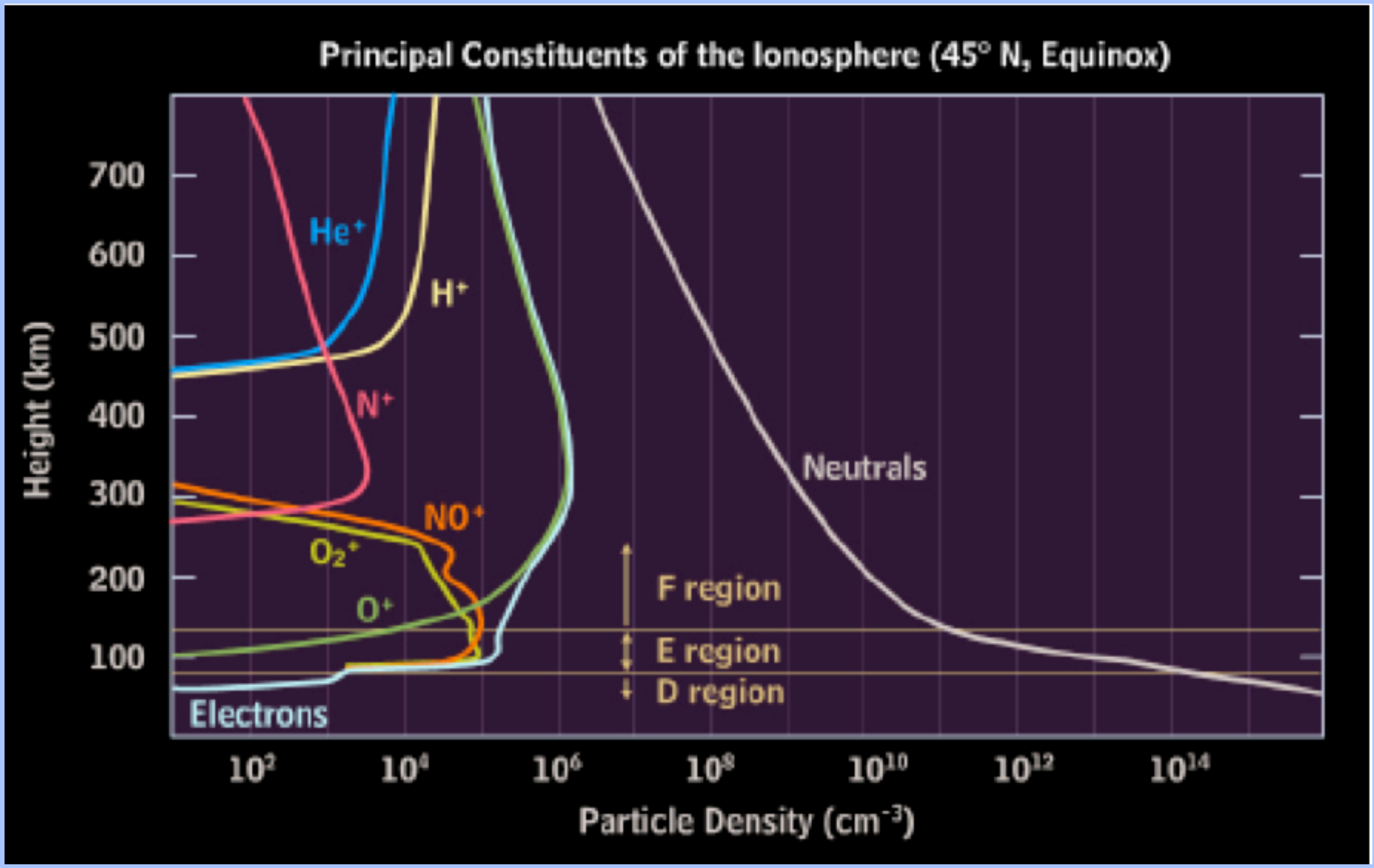
Courtesy of Ingo Mueller-Wodarg

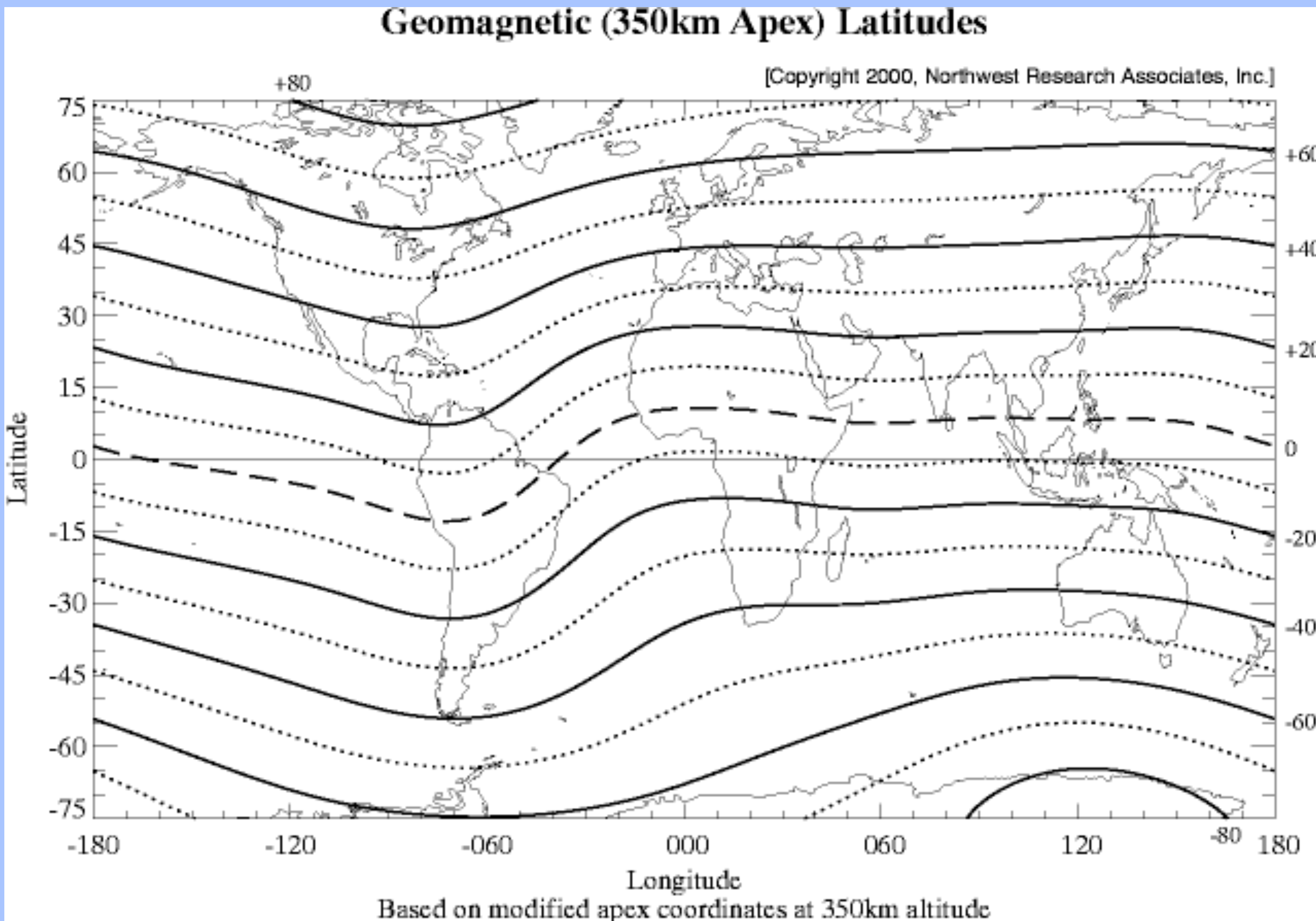
Principle Ionization Processes



Ionospheric Composition

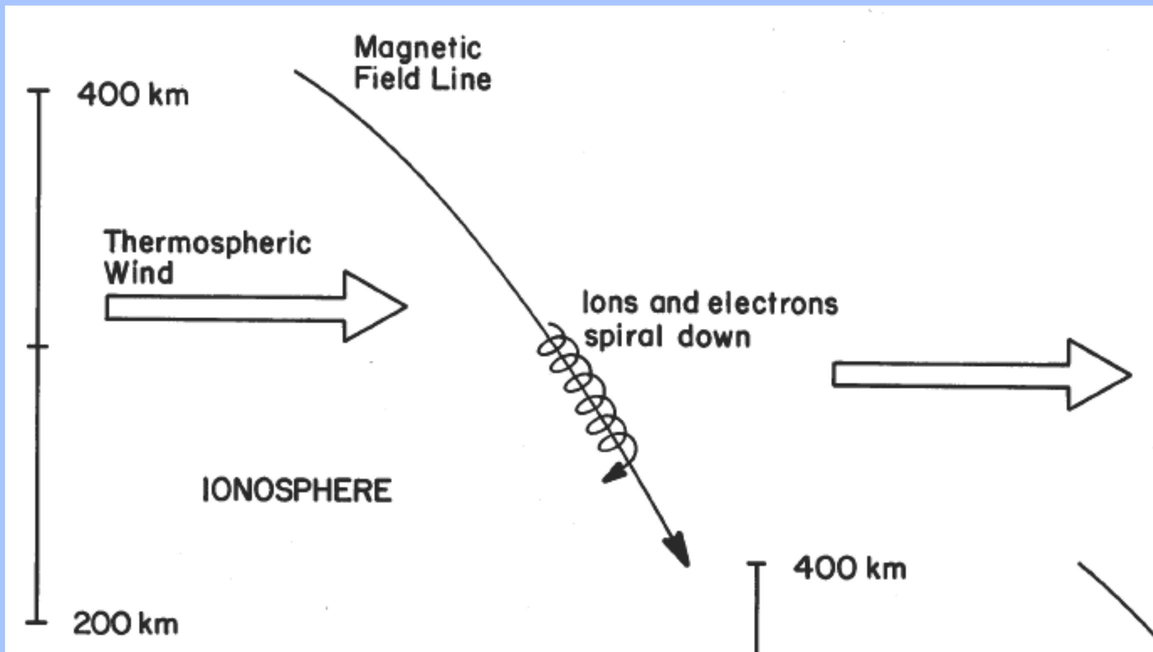
→ reminiscent of the thermosphere





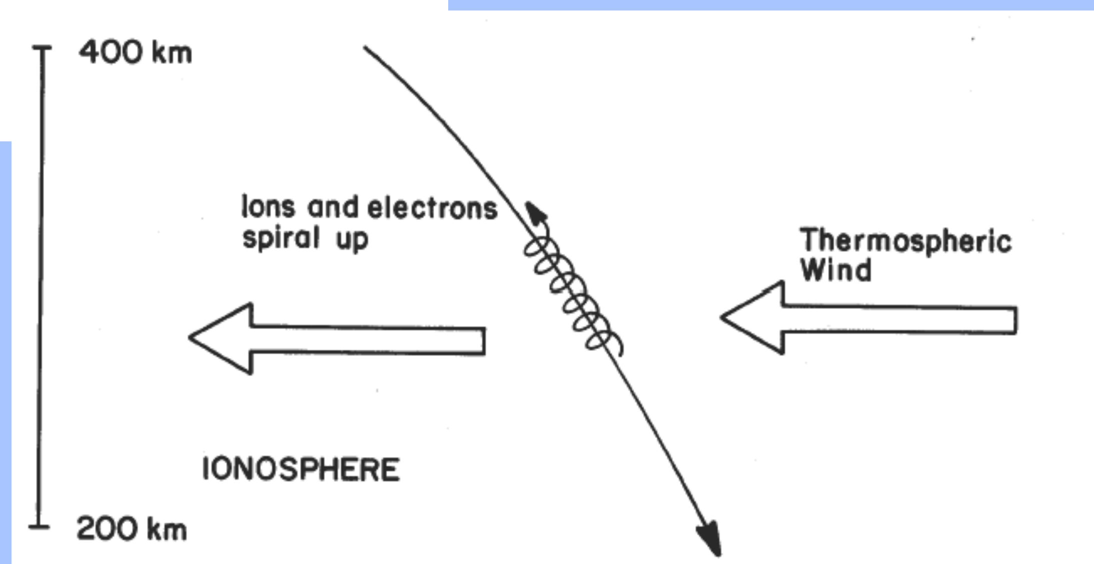
Geomagnetic (350km Apex) Latitudes
[Copyright 2000, Northwest Research Associates, Inc.]
+80
75
60
45
30
15
0
-15
-30
-45
-60
-75
Latitude
+60
+40
+20
0
-20
-40
-60
-80
-180
-120
-060
000
060
120
180
Longitude
Based on modified apex coordinates at 350km altitude

Effects of Thermospheric Winds on the Ionosphere



Ion/electron density depletions

- ➔ higher neutral density
- ➔ increased recombination



Ion/electron density enhancements

- ➔ lower neutral density
- ➔ decreased recombination

Courtesy of Art Richmond

Evidence of Anthropogenic Effects in the Thermosphere and Ionosphere

Roble and Dickinson (1989)

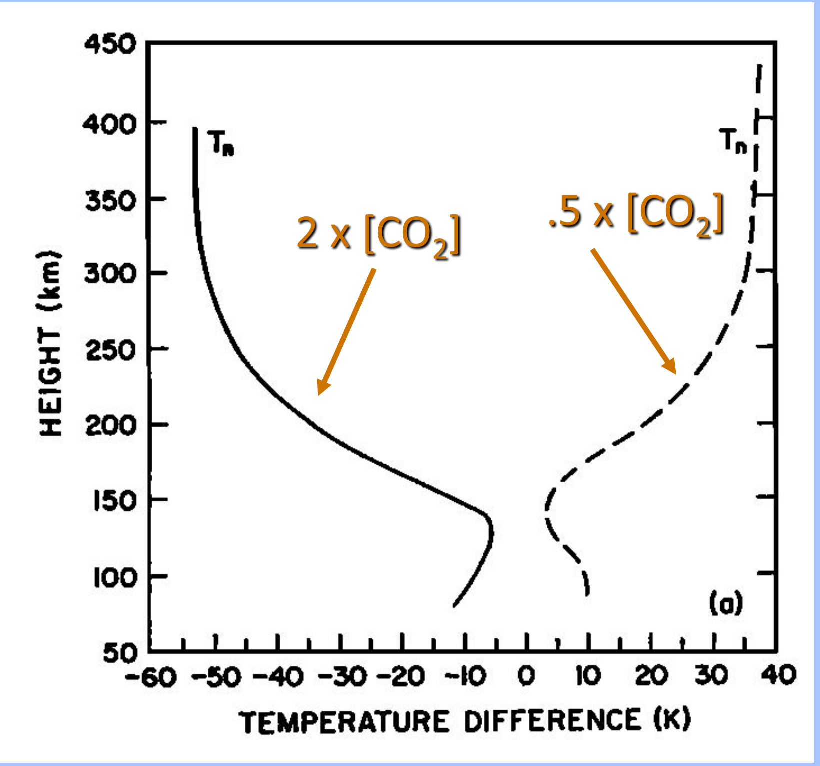
Conducted numerical experiments with a global mean model of the mesosphere, thermosphere, and ionosphere (60-500km)

Predicted that global change will occur in the upper atmosphere and the ionosphere as well as in the lower atmosphere:

Role of CO_2 →

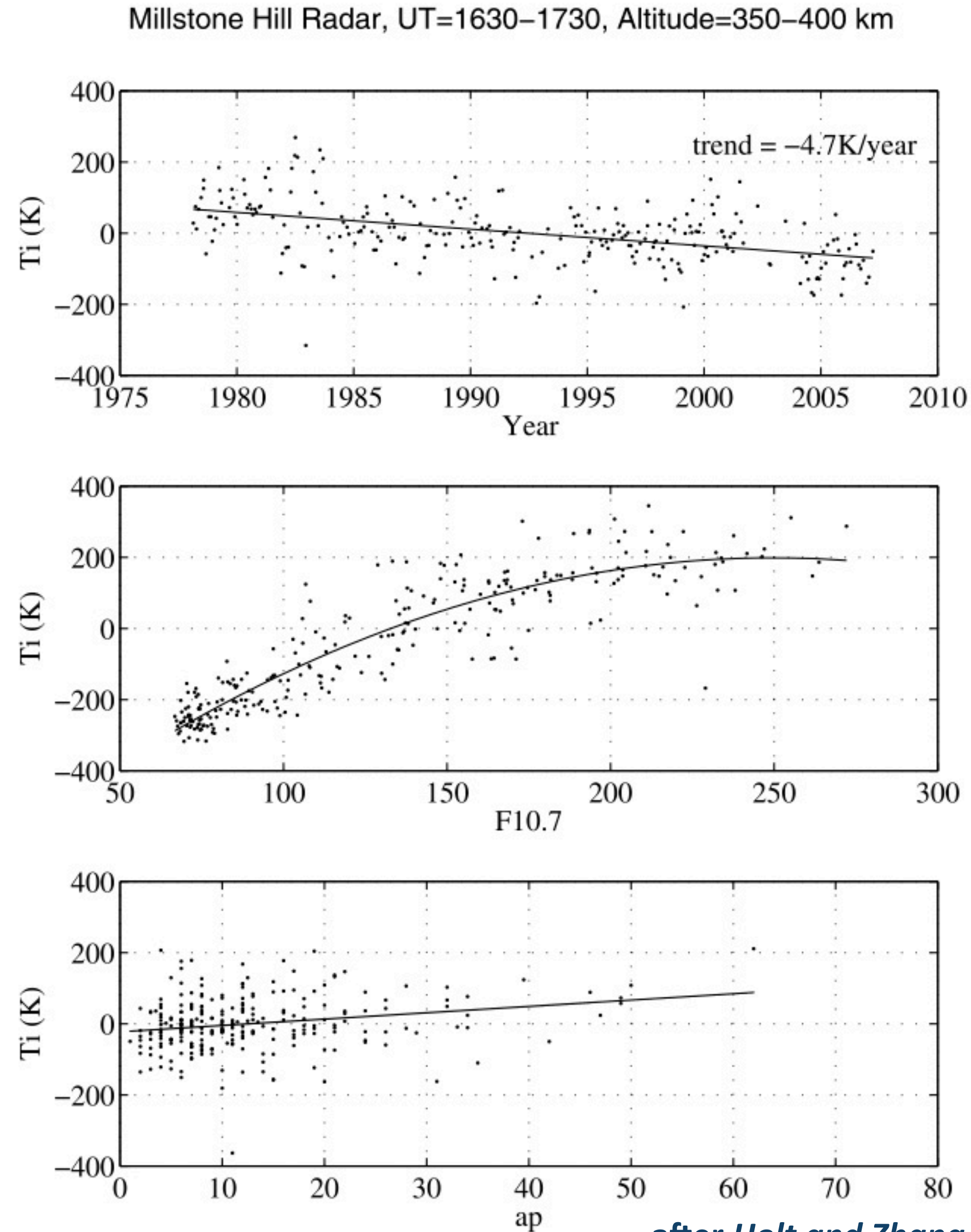
- traps radiation in the optically thick lower atmosphere
- radiatively cools the optically-thin upper atmosphere

CO_2 doubling → -50°K above ~275km



Monthly Median Ionospheric Temperature over Millstone Hill Massachusetts: 1978 – 2007

After accounting for solar cycle (F10.7) and geomagnetic activity (ap) effects ➔ cooling trend -4.7°K/yr

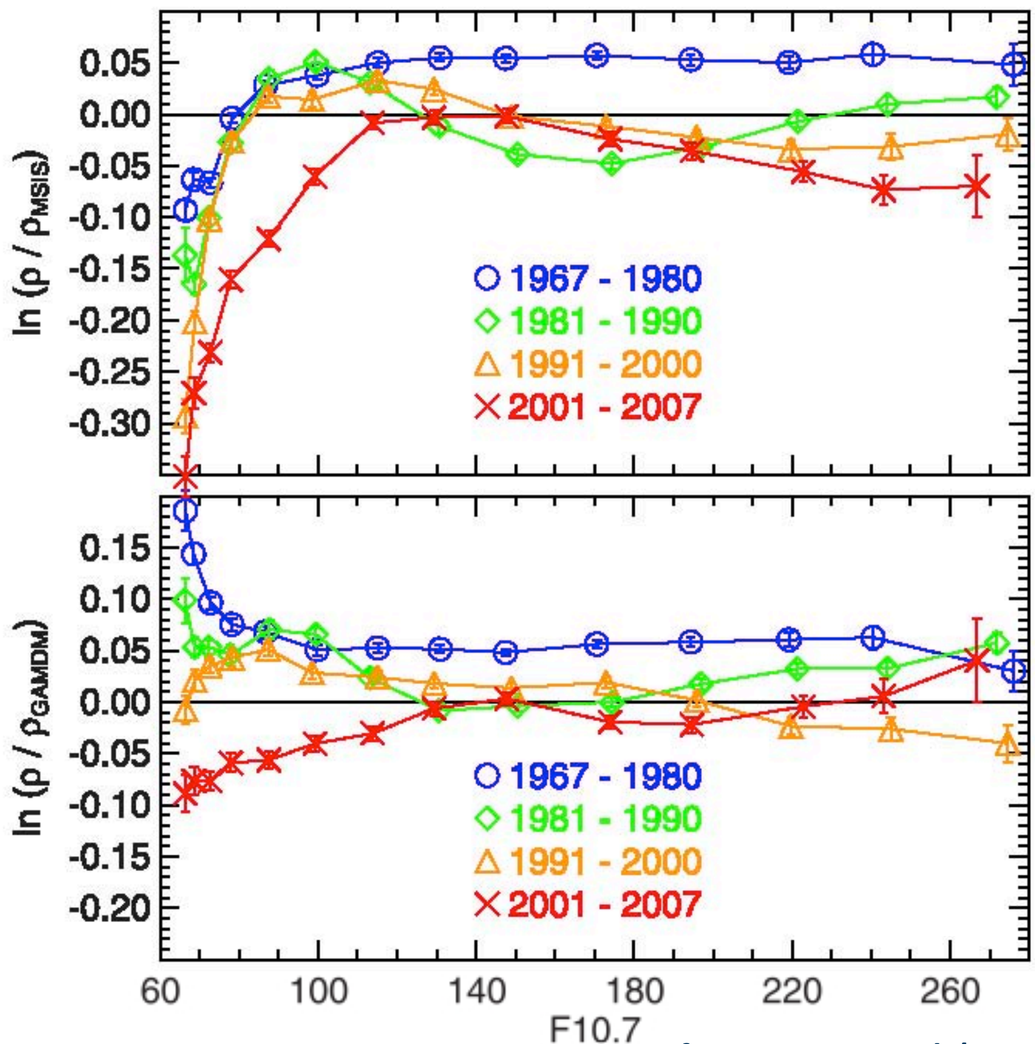


after *Holt and Zhang* (2008)

Uncovering and Correcting a Solar Cycle Dependent Bias in Empirical Density Models

Analysis of orbital drag data from ~5,000 objects in the thermosphere during 1967-2007, 400-800 objects per year

- Ratios of global average log-density residuals (data to NRLMSIS-00) decrease with time, especially during solar minimum
- A revised empirical model illustrates an evolving solar cycle minimum dependence

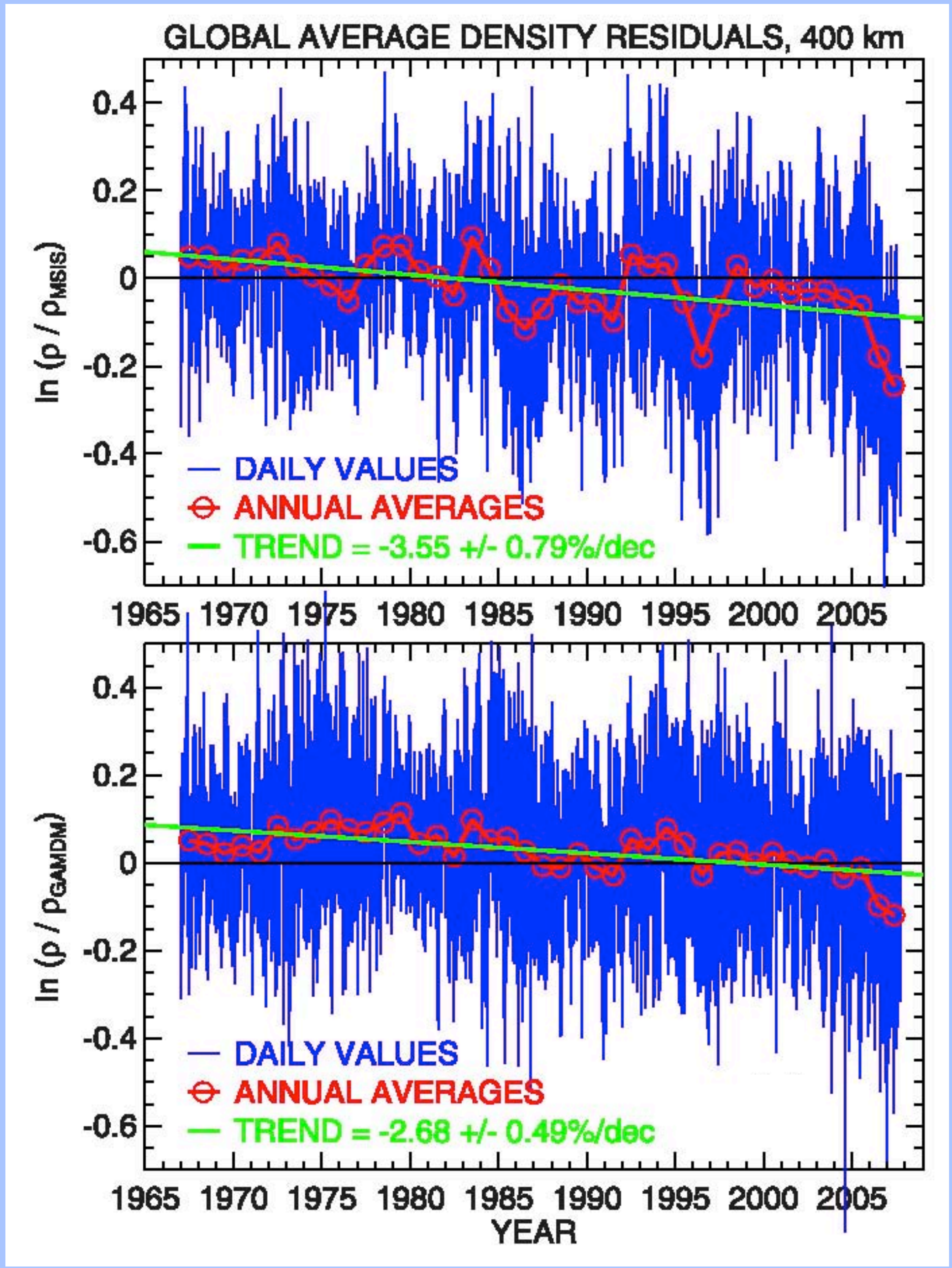


after *Emmert et al.* (2008)

Global Averaged Thermospheric Contraction from Density Measurements 1967 – 2007

After correcting for a solar cycle bias in the initial long-term trend estimate…

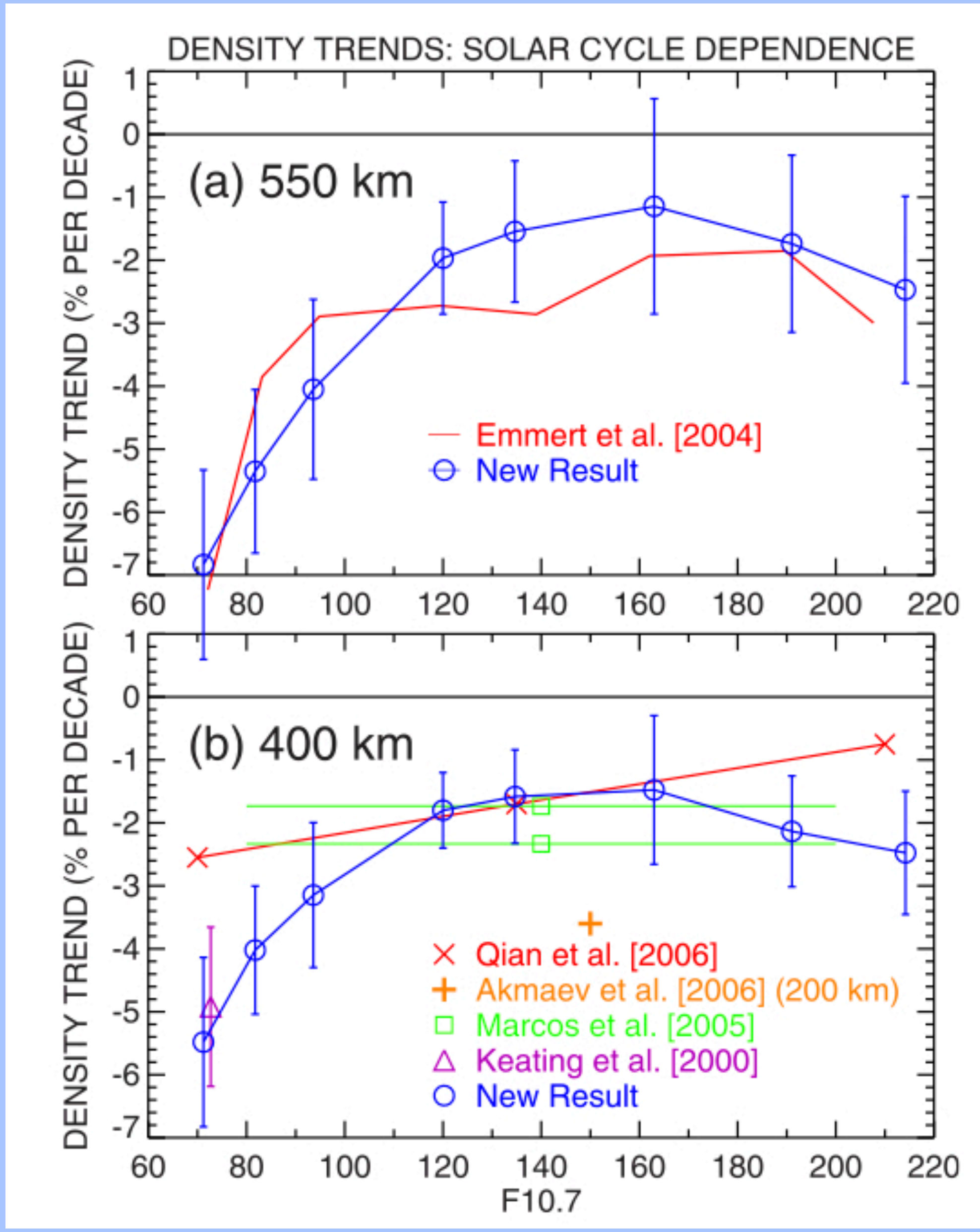
-2.68% +/-.49% per decade



after *Emmert et al.* (2008)

Comparison of Solar Cycle Dependent Thermospheric Contraction Trends

- trend magnitudes decrease with increasing solar activity
- fairly good agreement in the empirical trend estimates
- related to the efficiency of plasma transport driven up/down the magnetic field by the neutral winds



after *Emmert et al.* (2008)

Caveats Associated with Interpreting Trends: What about the Evolution of the Geomagnetic Field?

Evolution of the Earth's Magnetic Field: 1957-1997

Magnetic field strength (nT) in 1957

Difference in magnetic field strength: 1997-1957

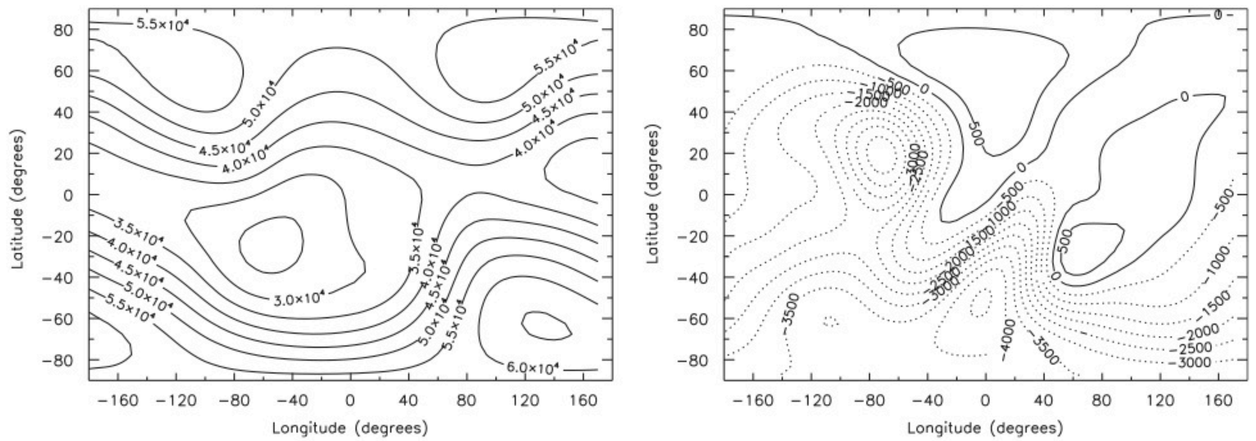


Fig. 1. The magnetic field strength (nT) in 1957 (left) and the difference with 1997 (1997–1957, right). Dashed contours represent negative values, solid contours positive values.

Difference in declination: 1997-1957

Difference in inclination: 1997-1957

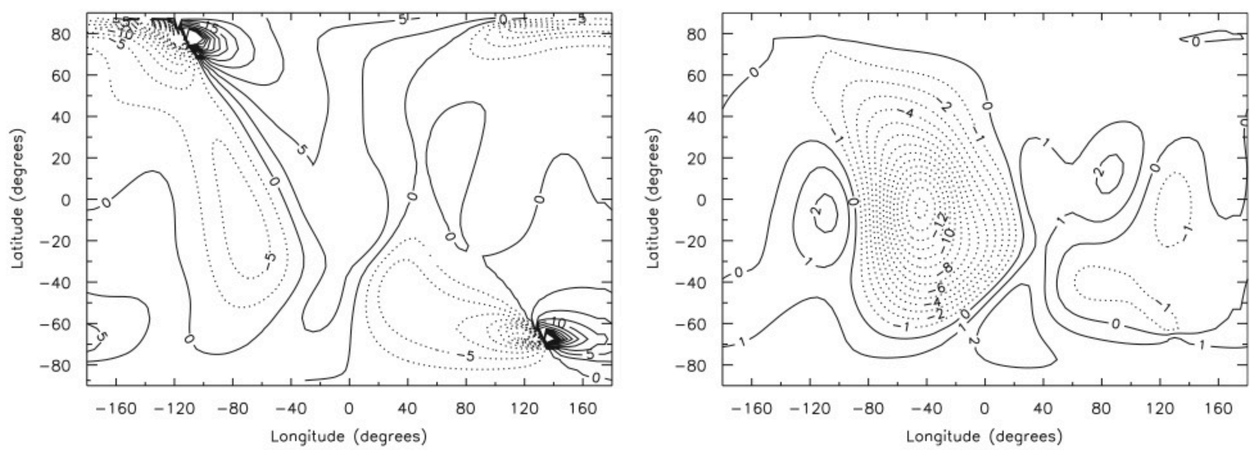


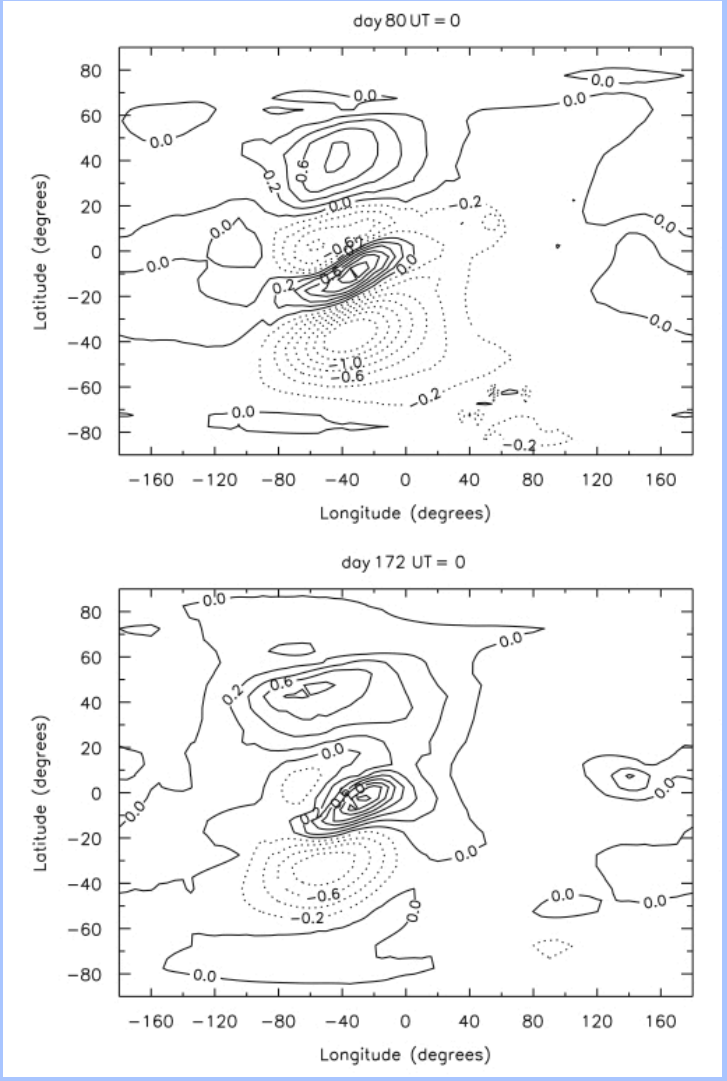
Fig. 2. The difference in declination (left; contour interval 2.5°) and inclination (right; contour interval 1°) between 1997 and 1957 (1997–1957). Dashed contours represent negative values, solid contours positive values.

after *Cnossen and Richmond* (2008)

Global Change in Ionospheric Density due to the Evolution of the Earth's Magnetic Field: 1957-1997

Numerical experiments demonstrate the effects on the ionosphere, only change is magnetic field

- on average → ~5% changes in the altitude (+/- 20 km; not shown) and ~10% changes in magnitude of the peak density (foF2 = +/- .5mHz)
- related to the efficiency of plasma transport driven up/down the magnetic field by the neutral winds
- largely attributable to changes in magnetic field inclination



Peak Density Change

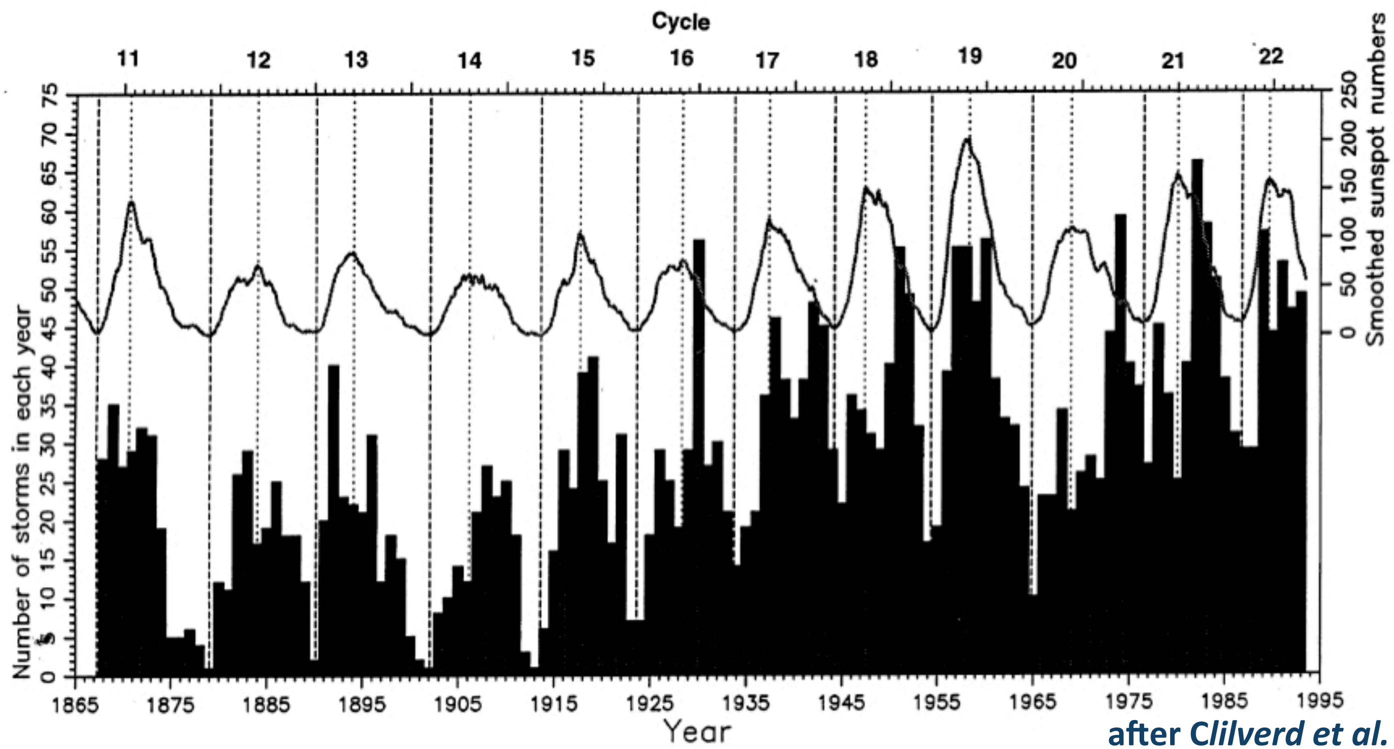
March Equinox

September Equinox

after *Cnossen and Richmond* (2008)

Global Change in Geomagnetic Storm Occurrence: 1868-1998

Storms with aa* index > 40nT; aa*= 24-hour averaged aa values



after *Clilverd et al.* (2008)

- Note the apparent increase in storm occurrence, particularly during solar minimum
- Neglects the long-term trend in the internal magnetic field, decreasing in strength with increased spatial variability (*Macmillan and Droujinina*, 2007)

NCAR HAO

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Selected References

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Global Change in the Thermosphere and Ionosphere One Person's Perspective…

Some about what we know:

- variations in solar irradiance have profound effects on T-I system temperatures and densities
- there are significant challenges associated with accurately isolating trends in long-term data sets; some are related to the shortcomings of the F10.7 proxy and biases in extant empirical models

Some about what we don't know, or what we don't know well enough:

- the altitudinal structure and variability of thermospheric winds on multiple horizontal and temporal scales
- how to address the known shortcomings of the F10.7 proxy, and/or to develop a better solar UV and EUV irradiance proxy
- whether, when and how to account for the evolution in magnetic field inclination in T-I system models and analyses