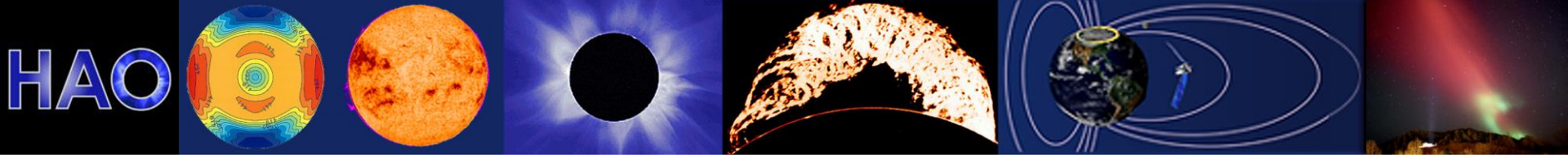

Solar Irradiance Impact on the Climate and Climate Change in the Upper Atmosphere

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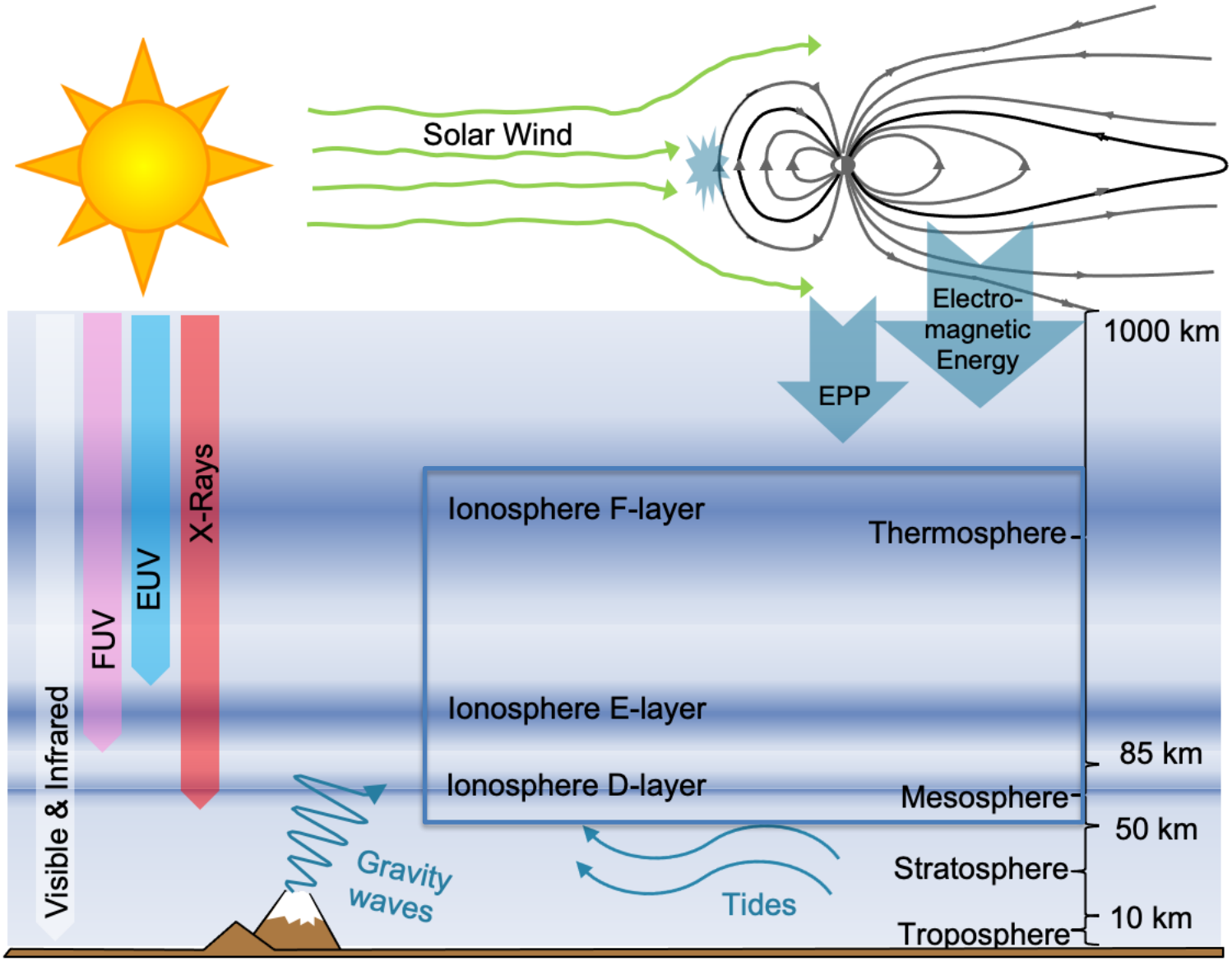
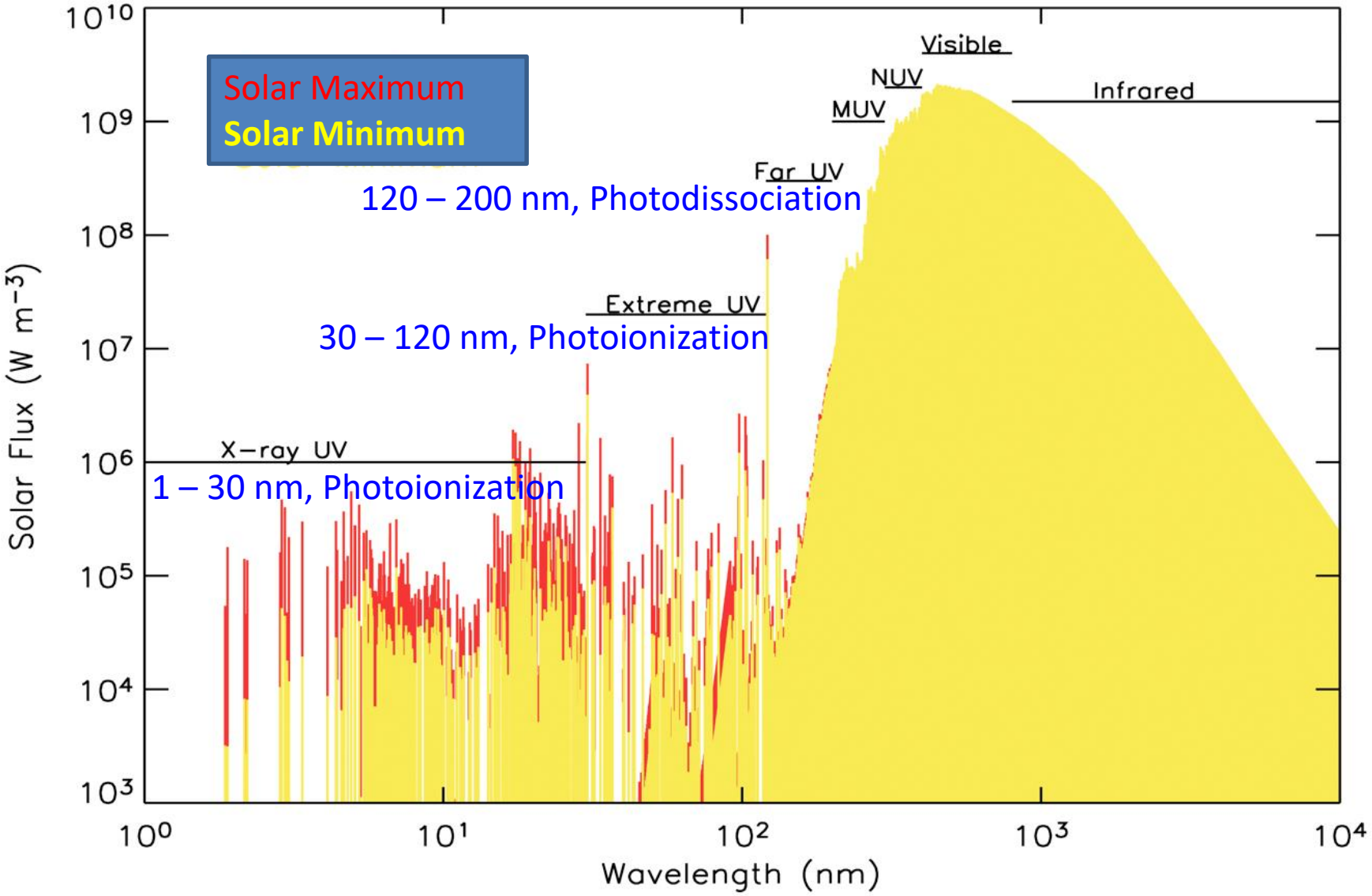
The High Altitude Observatory (HAO) at the National Center for Atmospheric Research (NCAR).

The National Center for Atmospheric Research is sponsored by the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The Sun-Earth System



Solar Spectrum

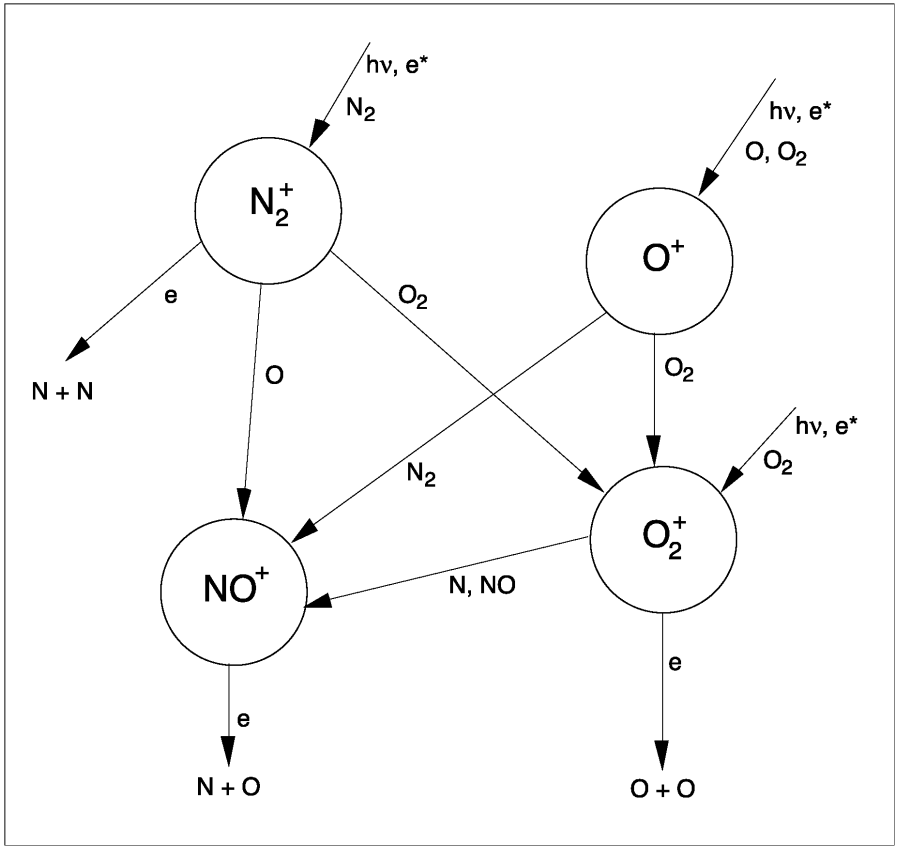


The Creation of the Ionosphere

N_2

O

O_2



e^-

O^+

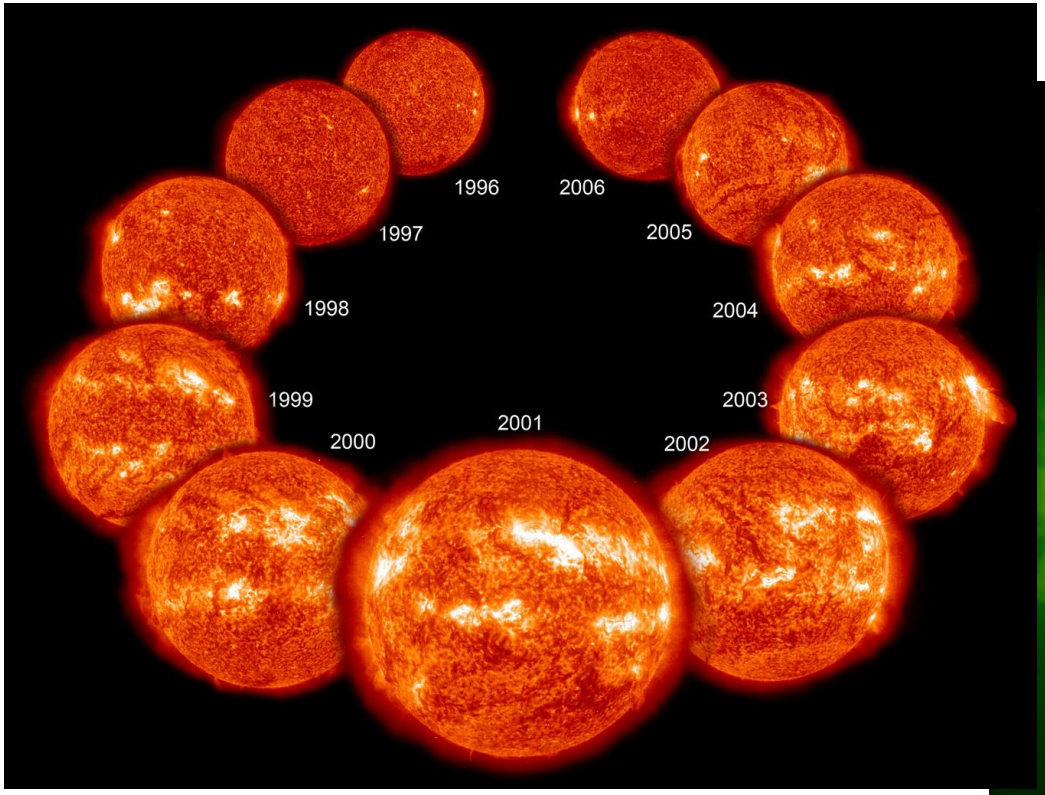
NO^+

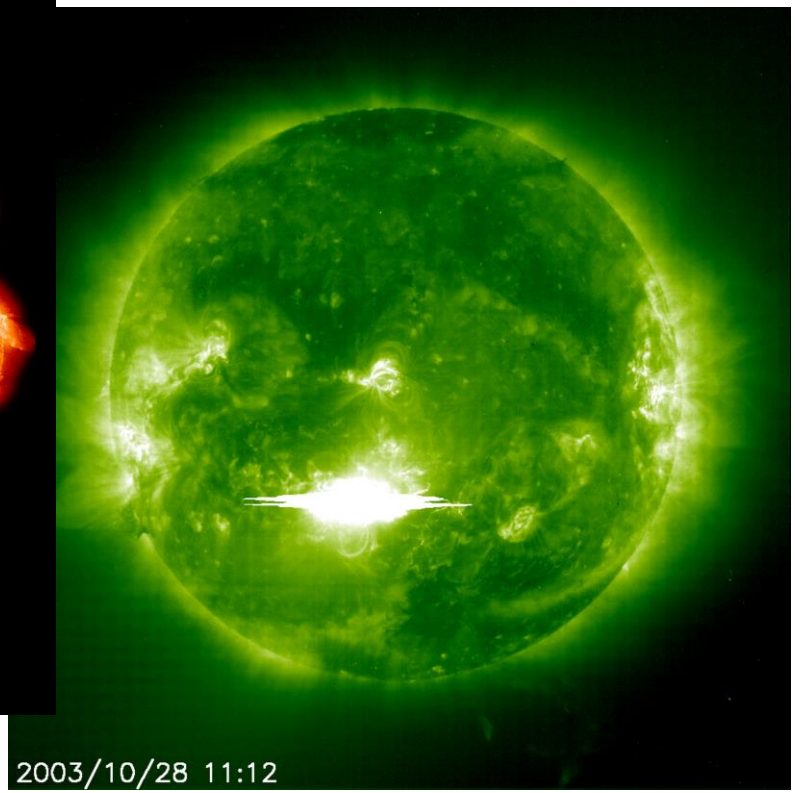
O_2^+

Ionization processes convert photon energy to chemical potential energy

Dissociative recombination converts ionization energy to dissociation products and kinetic energy (heat)

Solar Irradiance Variations





Credit: NASA/ESA

Outline

- Climate Change (~1960s – 2000s)
- Climate
  - Solar Rotational
  - Annual/Semiannual
  - Solar Cycle

Whole Atmosphere Community Climate Model eXtended (WACCM-X)

WACCM-X is WACCM with additional physics and extended vertical range through the thermosphere/ionosphere (~600km)

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)

Other Models, and Data

NCAR TIME-GCM

Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model

NCAR TIE-GCM

FISM (Flare Irradiance Spectral Model)

Satellite drag data: mass density data

TIMED/GUVI: composition (O/N_2)

Outline

- Climate Change (~1960s – 2000s)
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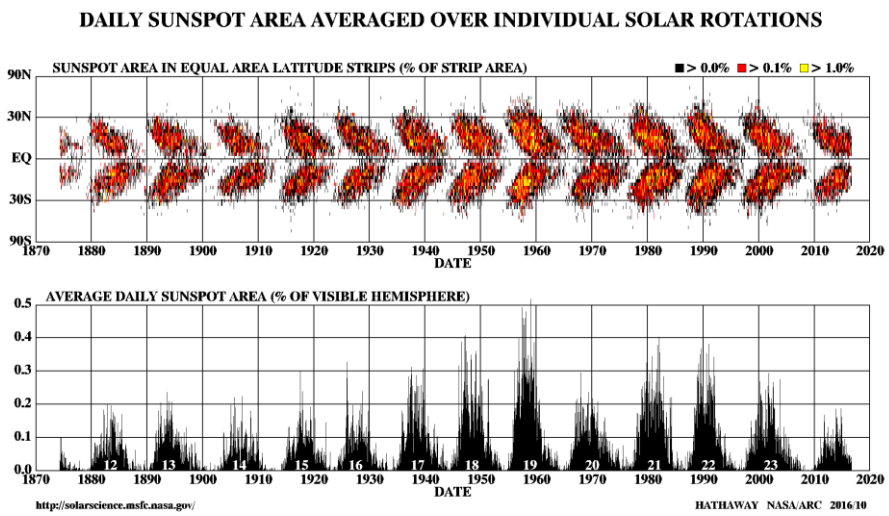
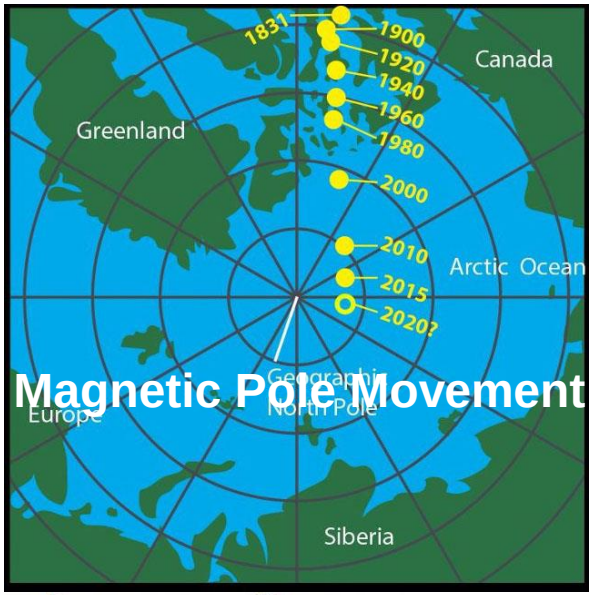
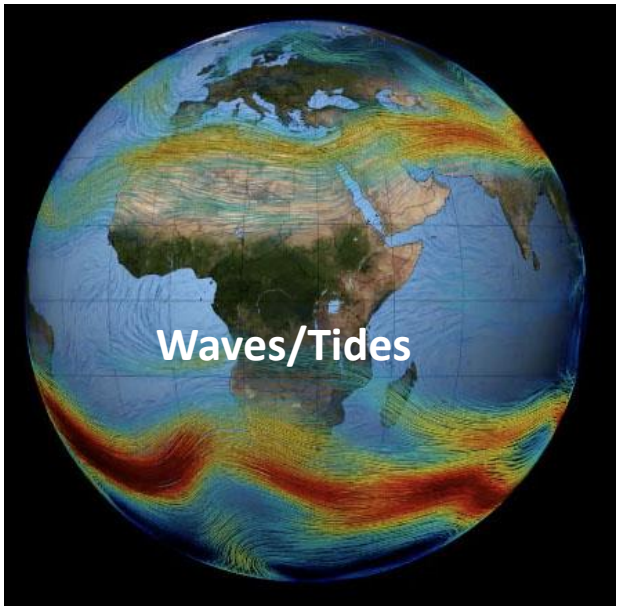
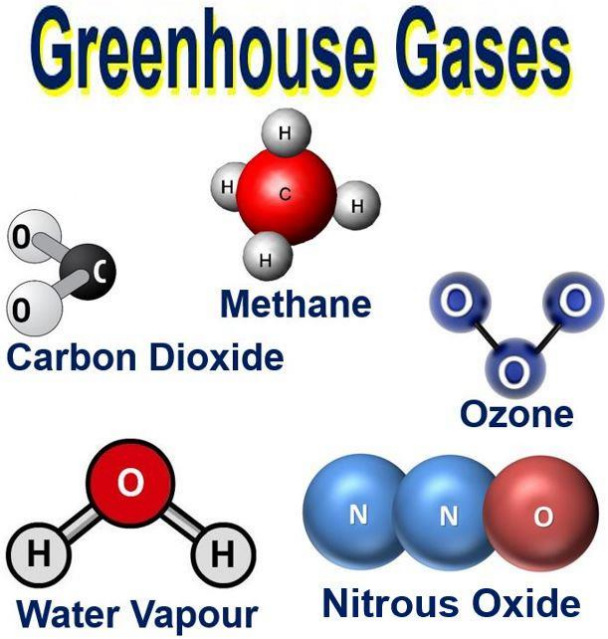
  - Solar Rotational
  - Annual/Semiannual
  - Solar Cycle

Drivers of the Climate Change in the Upper Atmosphere





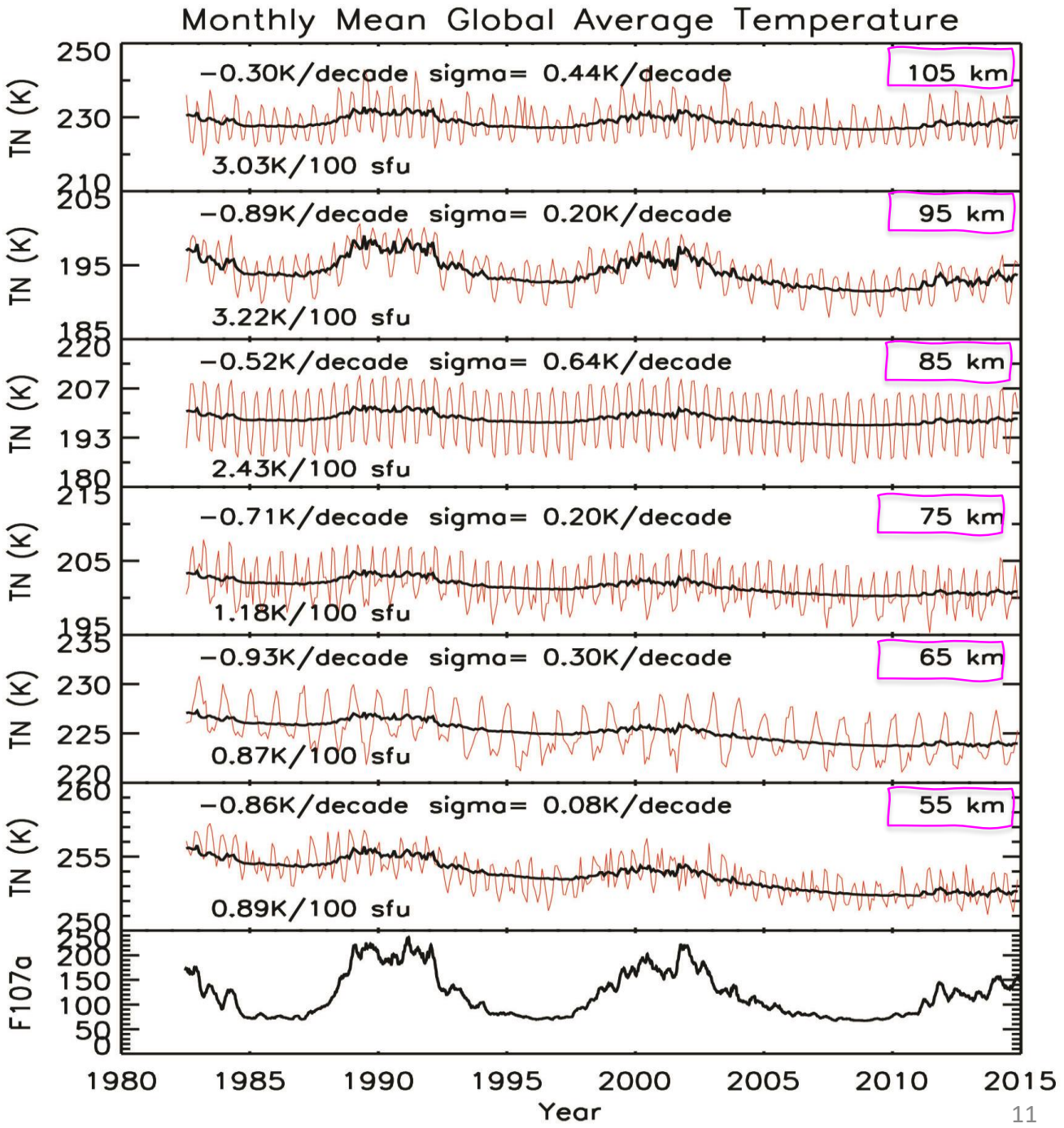




Mesosphere

--Trends and Solar Effects

- solar cycle variation

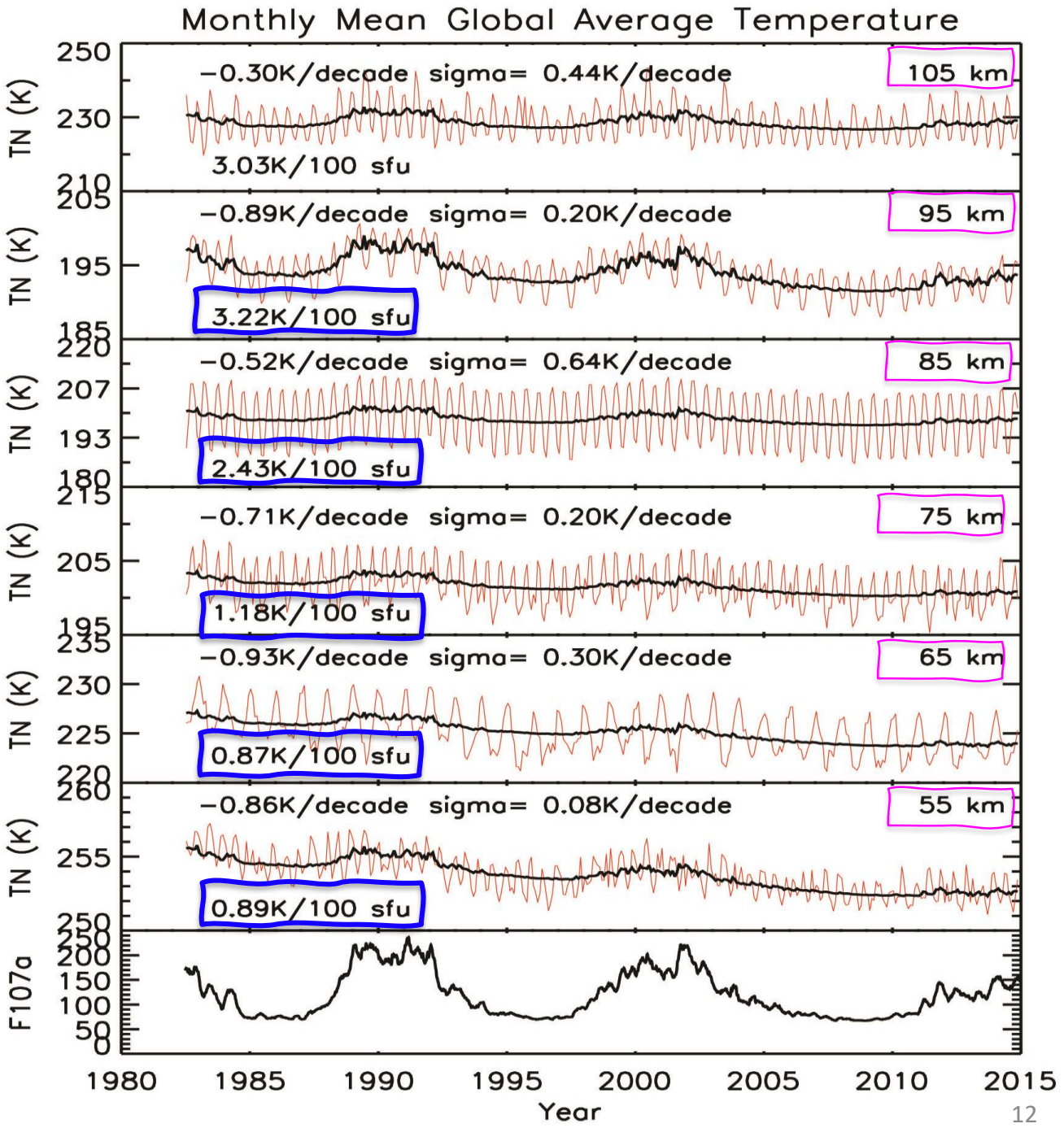


Qian et al., 2019

Mesosphere

--Trends and Solar Effects

- solar cycle variation
- solar effects decrease with altitude

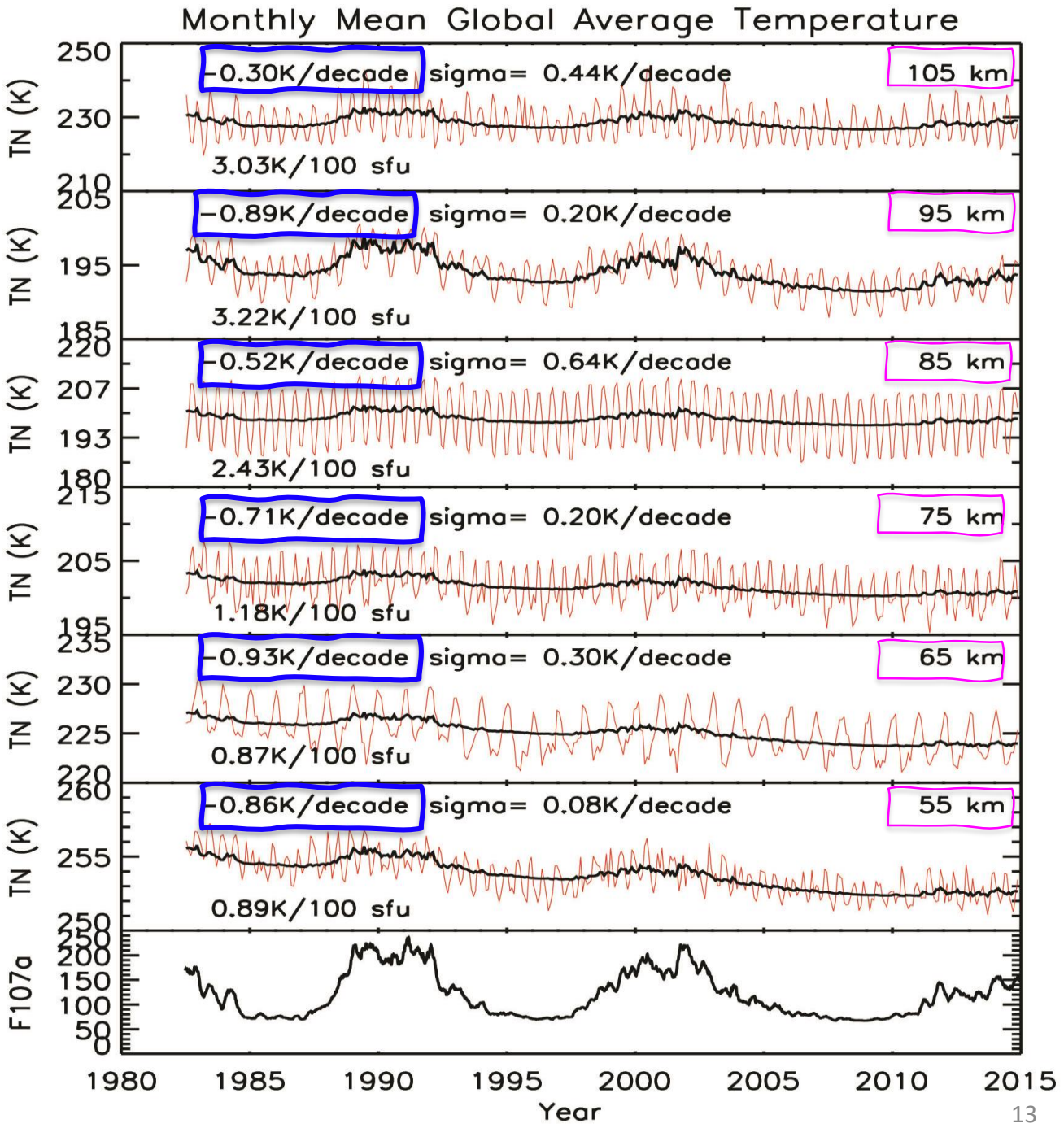


Qian et al., 2019

Mesosphere

--Trends and Solar Effects

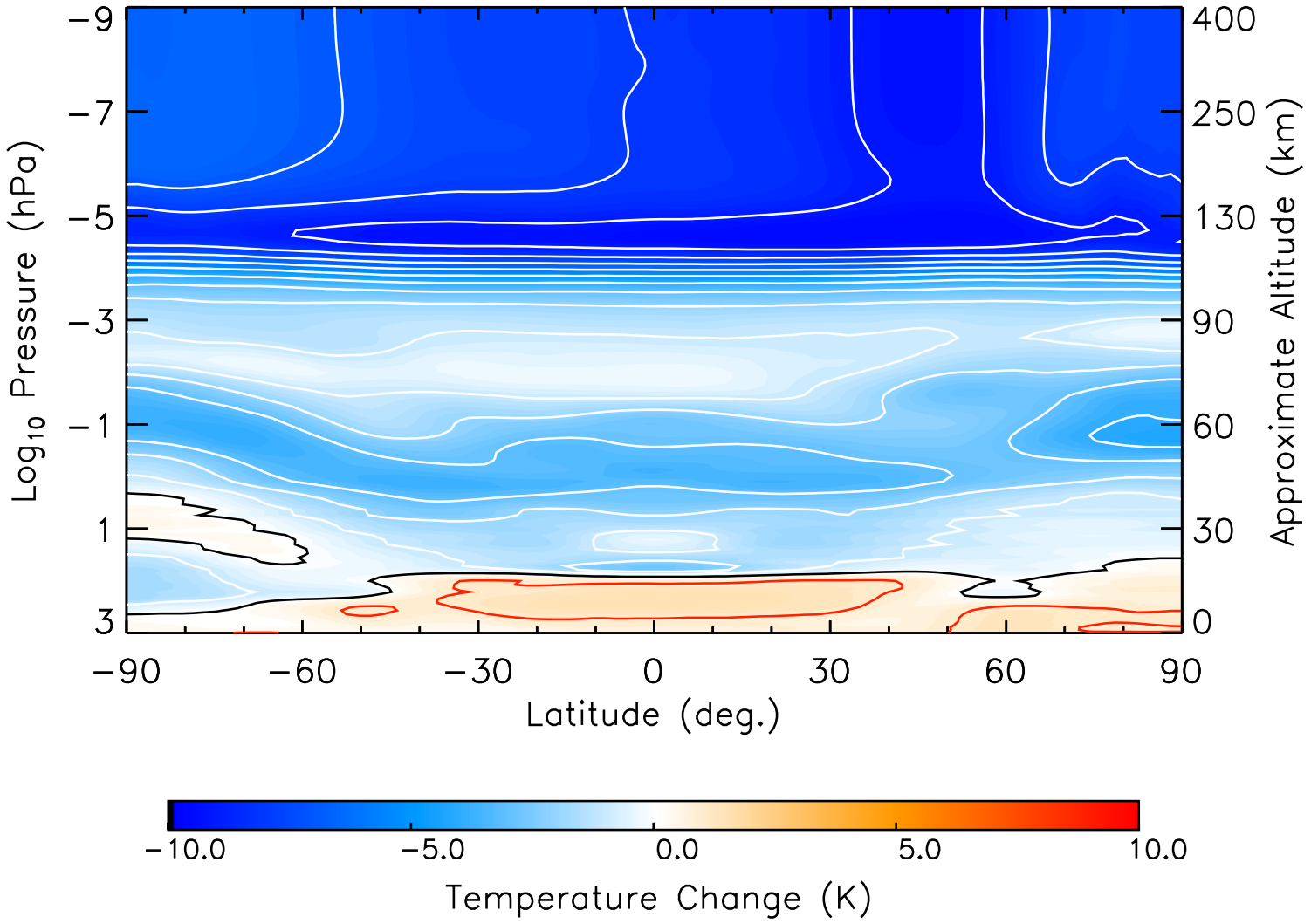
- solar cycle variation
- solar effects decrease with altitude
- negative trends, maximum in the middle mesosphere



Qian et al., 2019

WACCM-X Simulated Climate Change

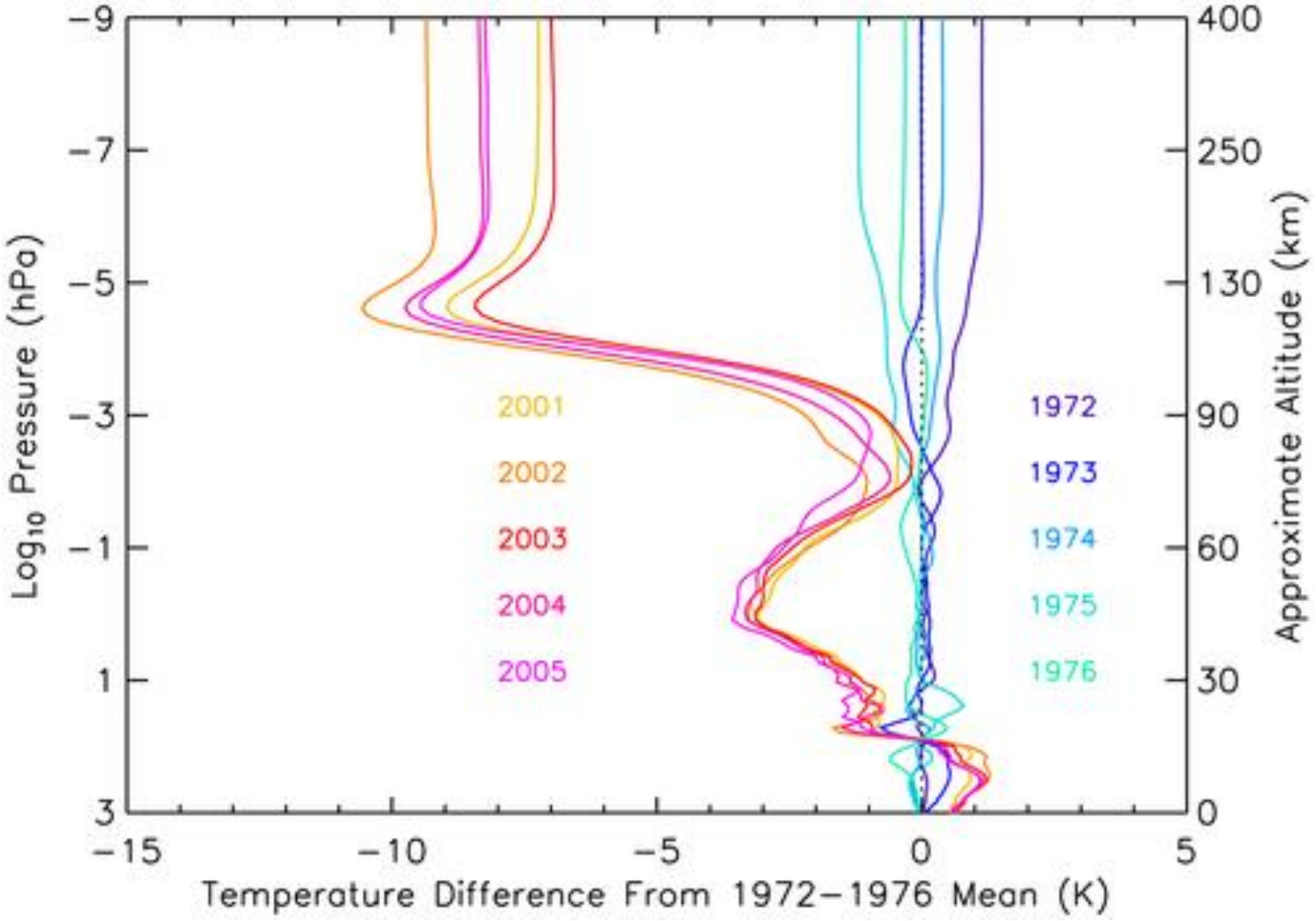
1970s – 2000s, Solar Minimum



Solomon et al., 2018

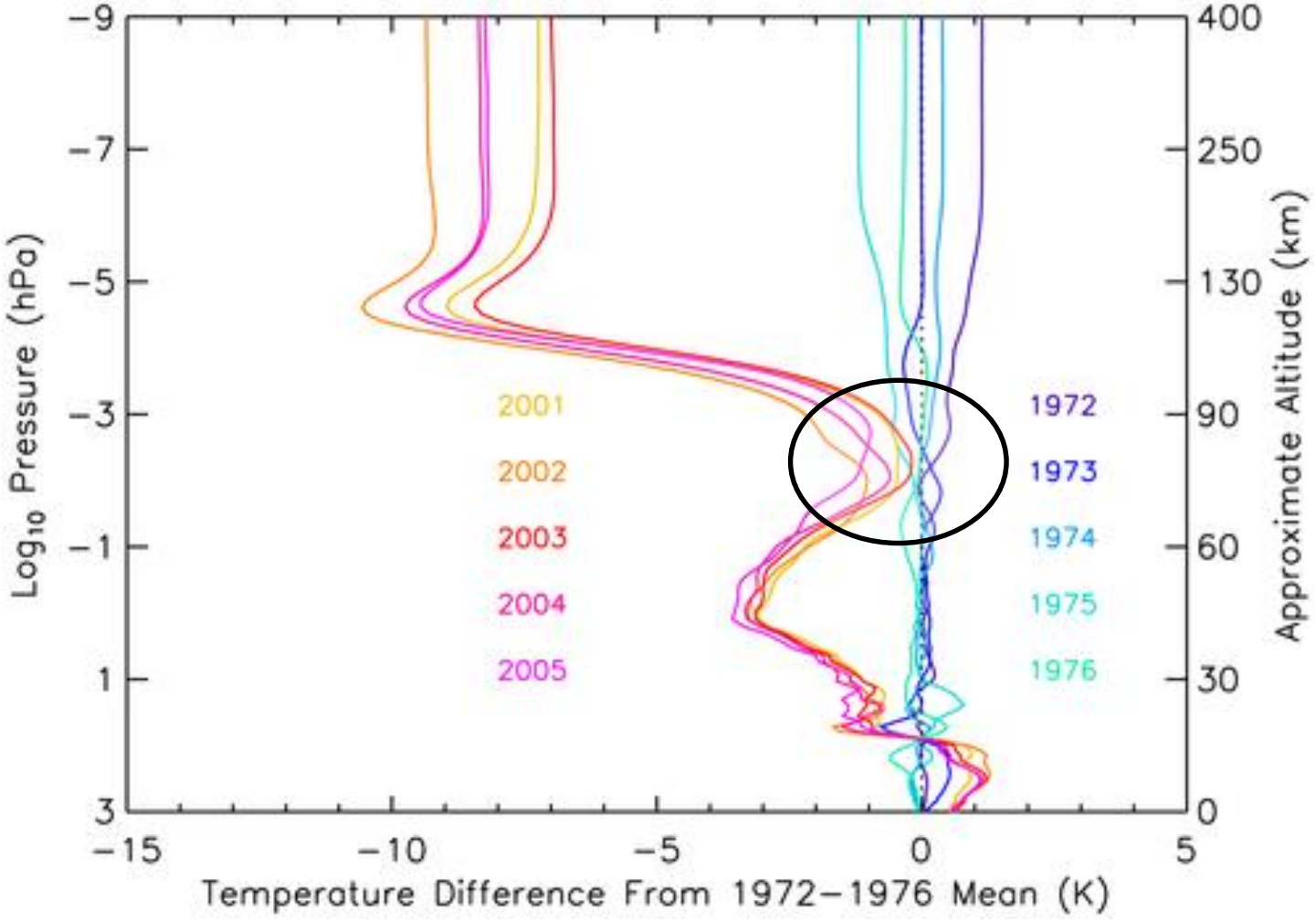
WACCM-X Simulated Climate Change

1970s – 2000s, Solar Minimum



Inter-Annual Variability

1970s – 2000s, solar minimum



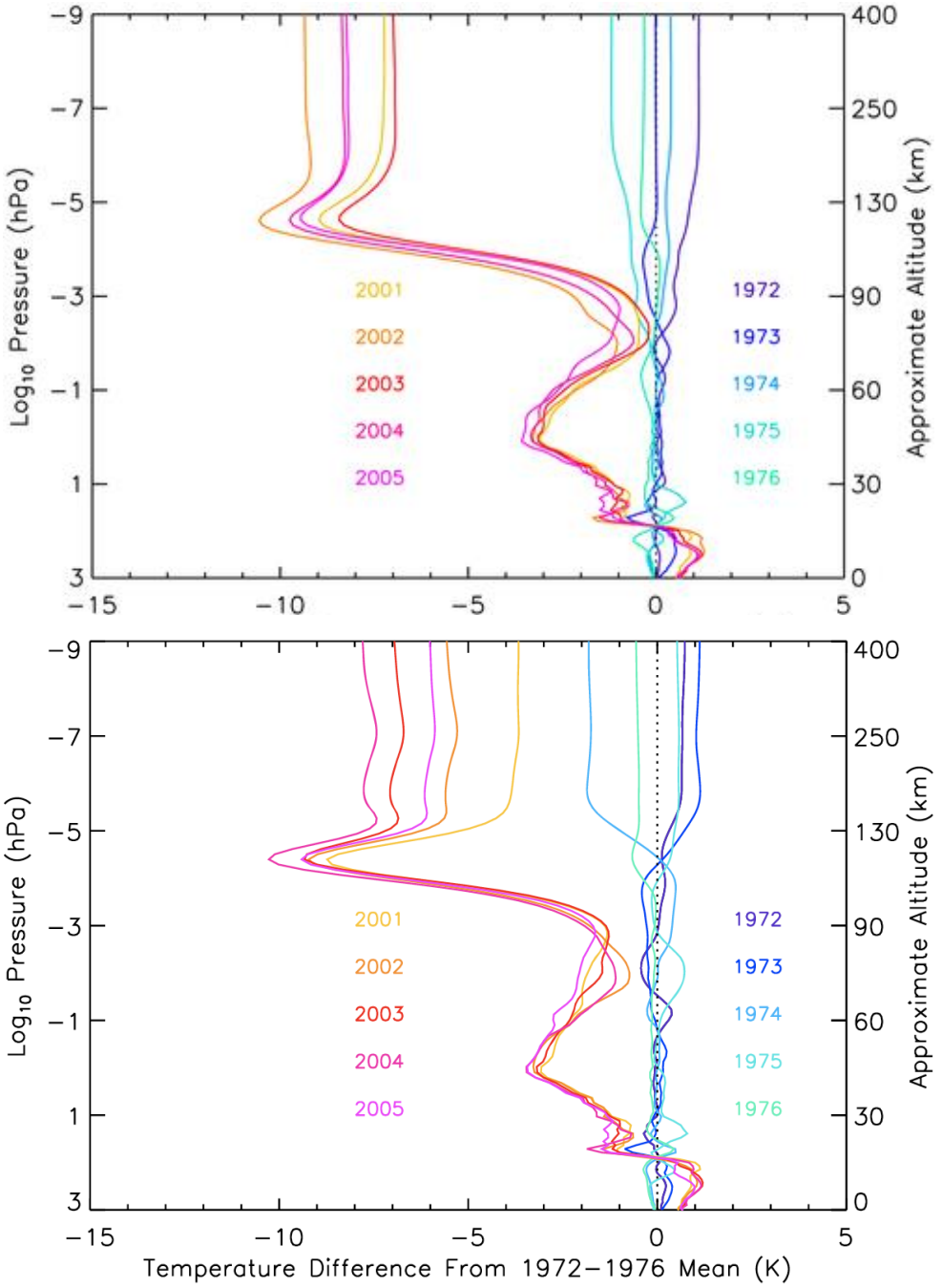
Solomon et al., 2018

Large inter-annual variability in the mesopause region

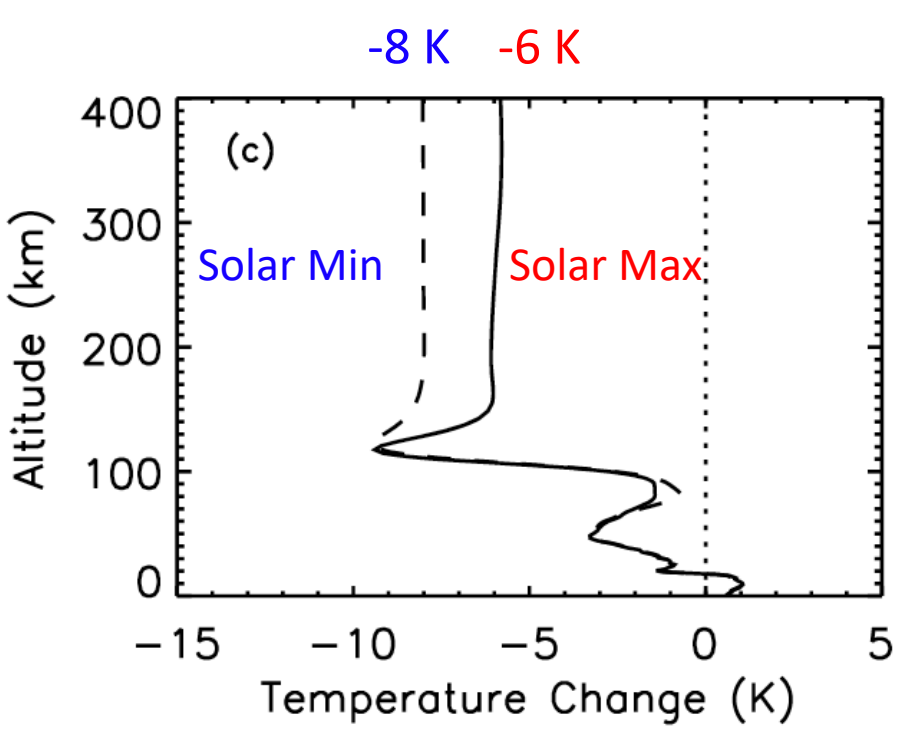
Solar Cycle Dependency

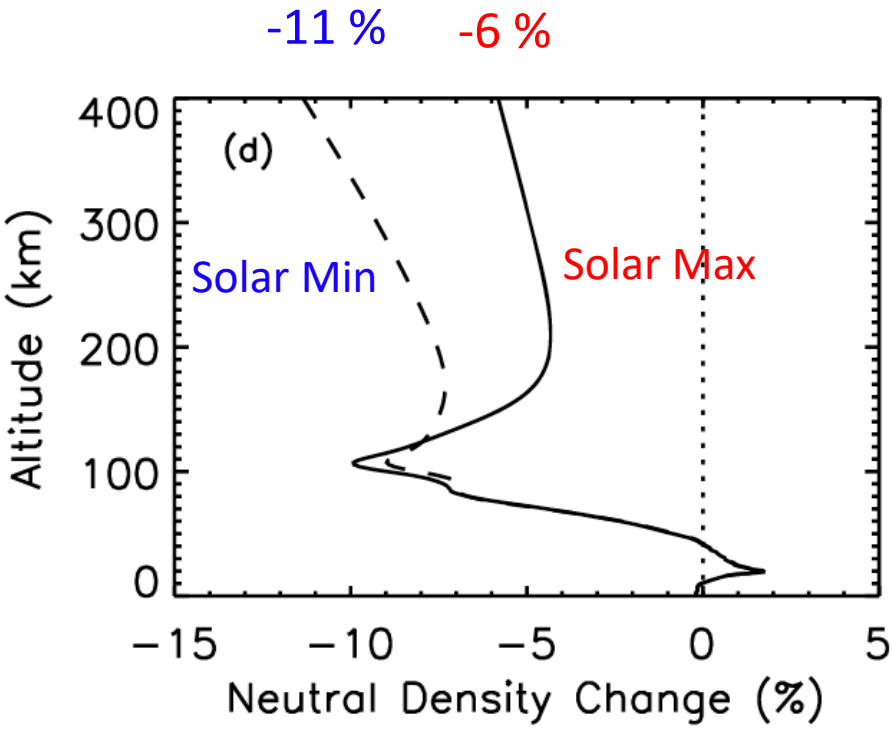
Solar Minimum, F10.7=70
-2.8 K/decade

Solar Maximum, F10.7=200
-2 K/decade



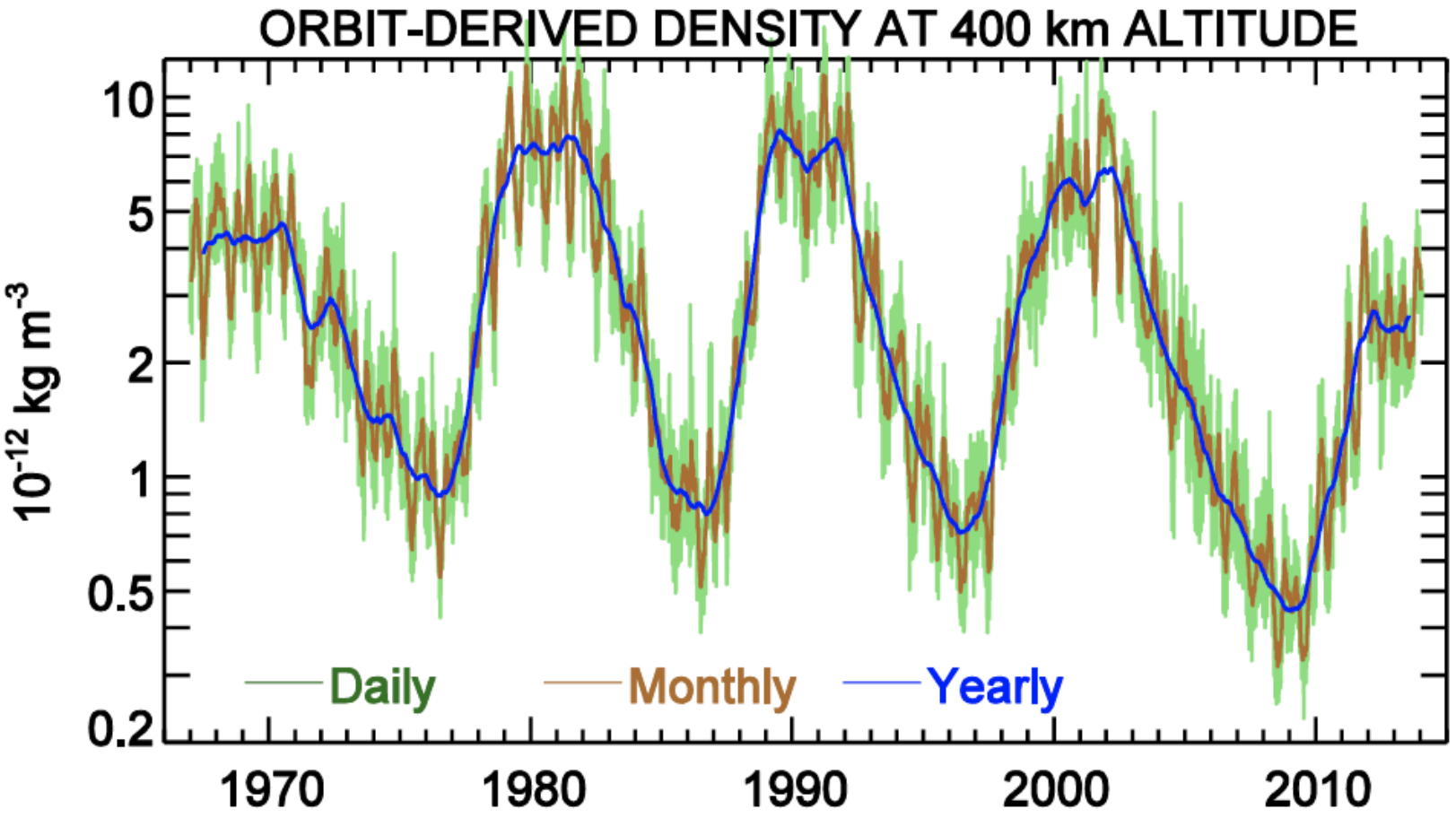
1970s – 2000s


-8 K
-6 K
(c)
Solar Min
Solar Max
Altitude (km)
400
300
200
100
0
−15
−10
−5
0
5
Temperature Change (K)


-11 %
-6 %
(d)
Solar Min
Solar Max
Altitude (km)
400
300
200
100
0
−15
−10
−5
0
5
Neutral Density Change (%)

Drag Derived Mass Density

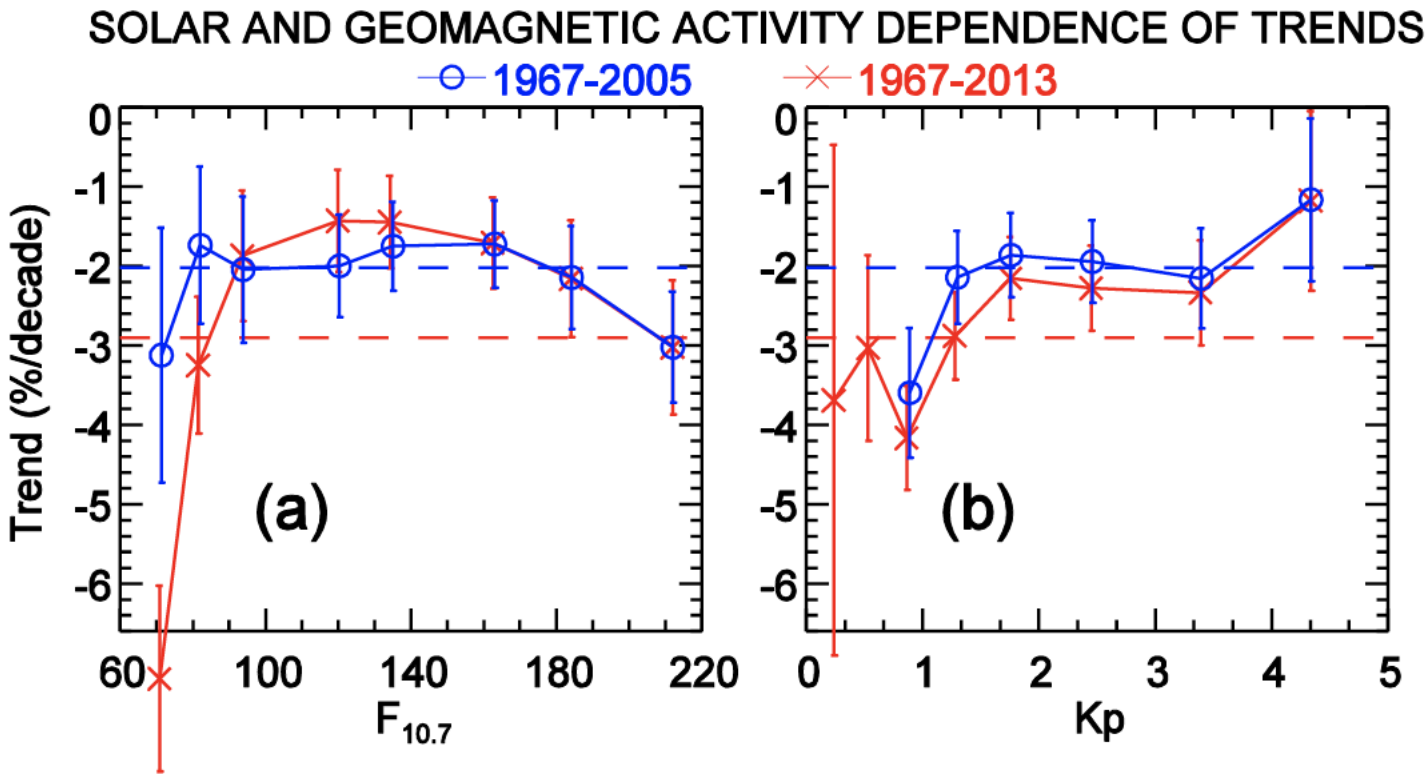
400 km



~ 5000 space Objects

Emmert 2015

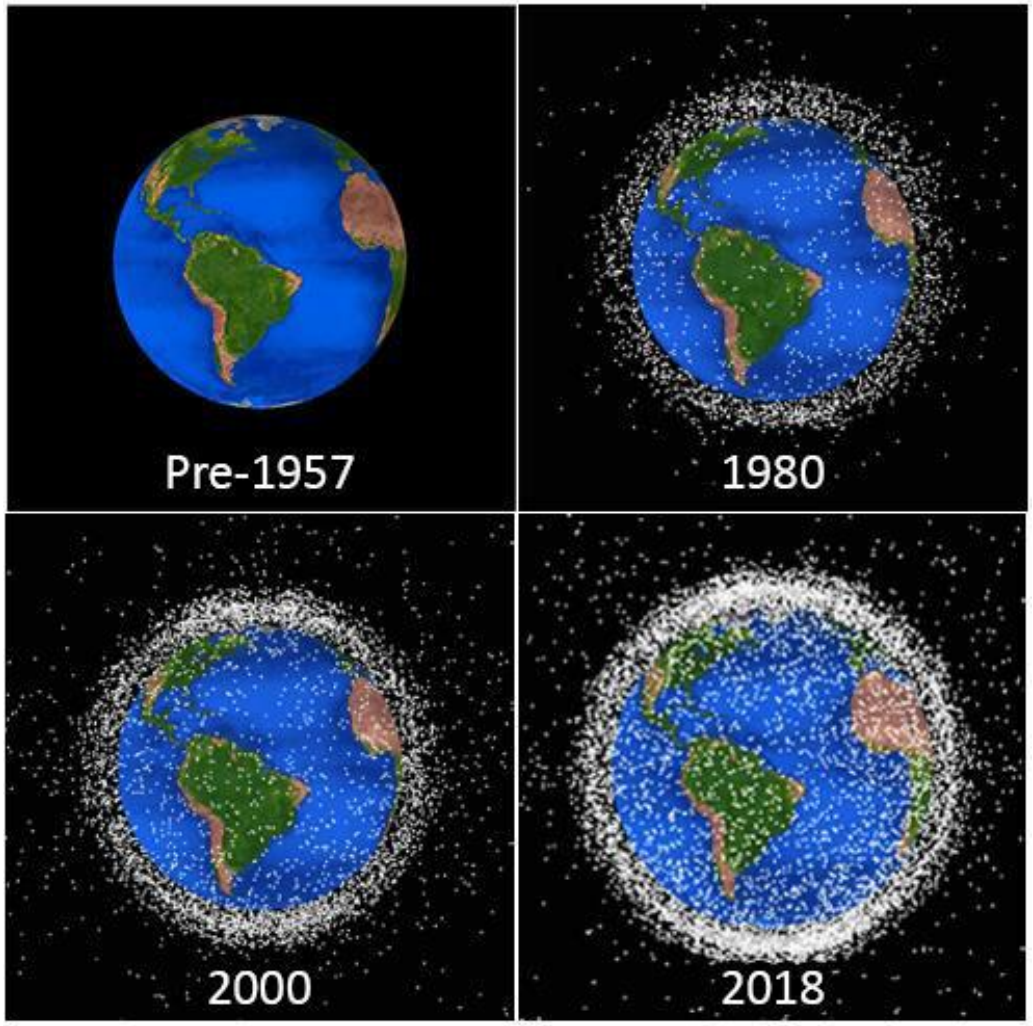
Drag Derived Mass Density Trends
-- Solar and Geomagnetic Activity Dependence



~ -2 %/decade

Emmert 2015

Effects of Space Climate Change
-- Space debris



Credit: NASA Orbital Debris Program Office

955 satellites launched in 2020

SpaceX alone planning on launch 30k-40k

Speed: ~ 17,500 mph

Outline

- Climate Change (~1960s – 2000s)
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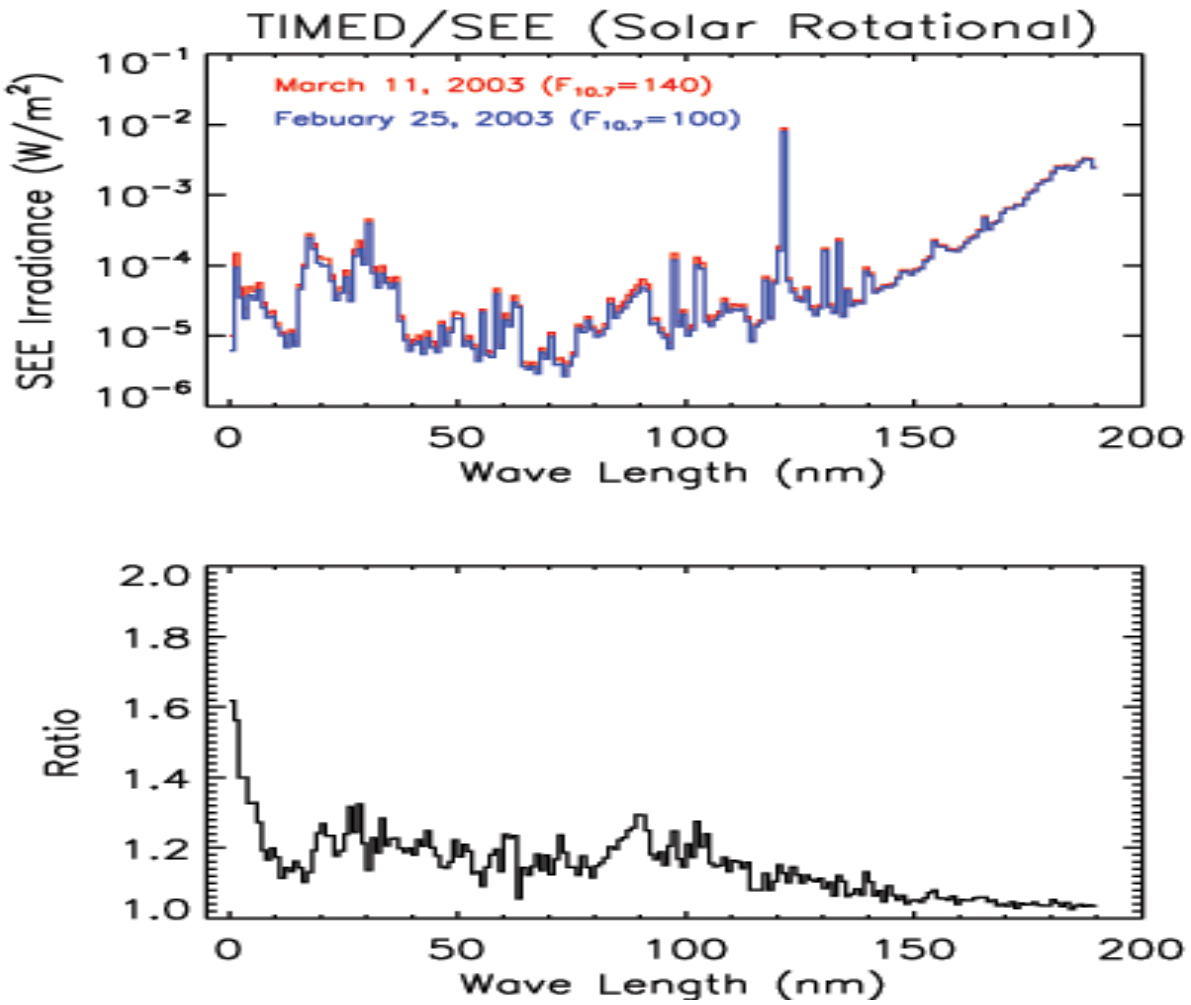
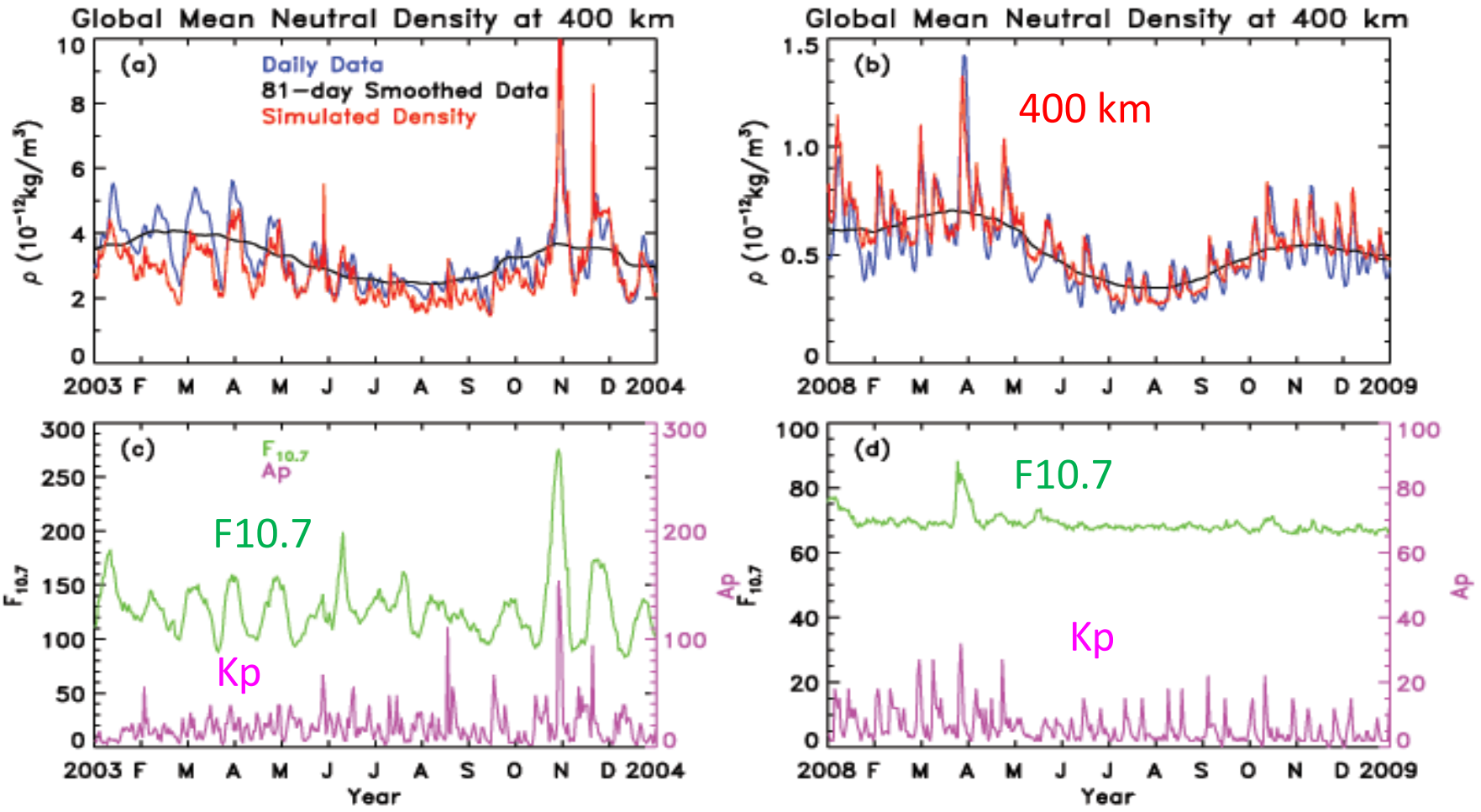
Solar Rotational Variation



Driven by the appearance and disappearance of the Sun's active regions as the Sun rotates in ~27-day period.

Solar Rotational Variation at Low and High Solar Activity

2003 2008



The amplitude of mass density (ρ) at 400 km is on the order of ~100% for high solar activity and decreases for lower solar activity.

Qian and Solomon, 2011

Outline

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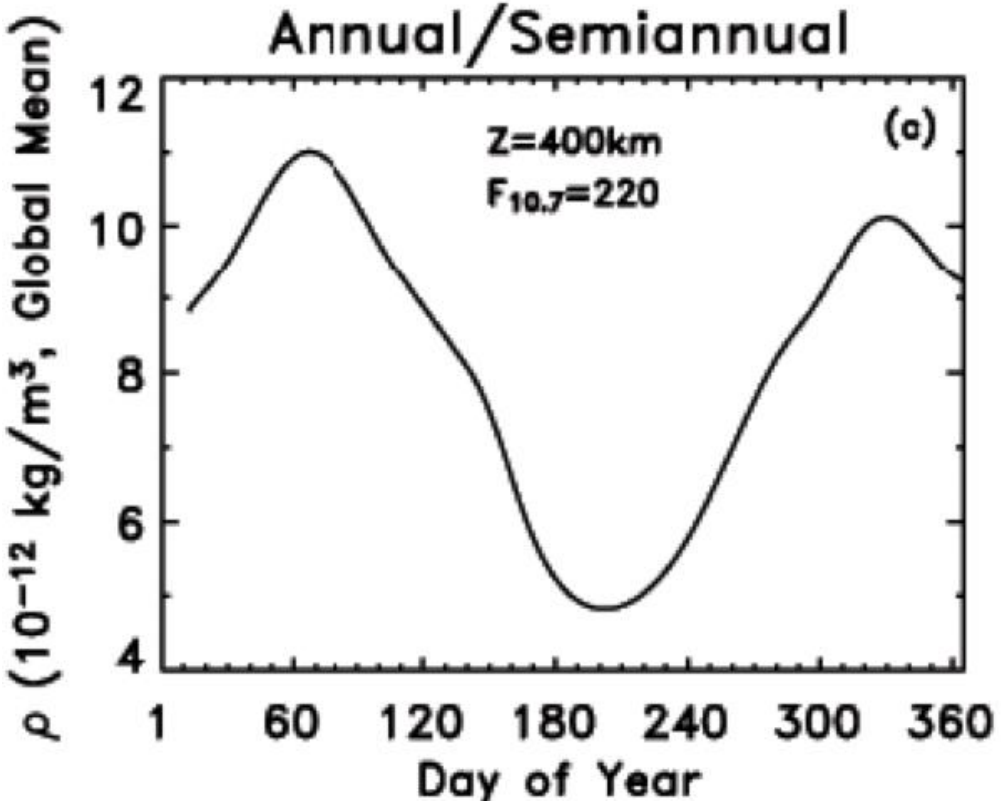
Annual and Semiannual Variation



F10.7=220

Driven by the annual variation of the Sun–Earth distance (7%), semi-annual variation of seasonal solar illumination, and lower atmospheric forcing. The amplitude for ρ at 400 km from annual minimum (~July) to annual maximum (equinoxes) is from ~30% to ~250%.

Qian and Solomon, 2011

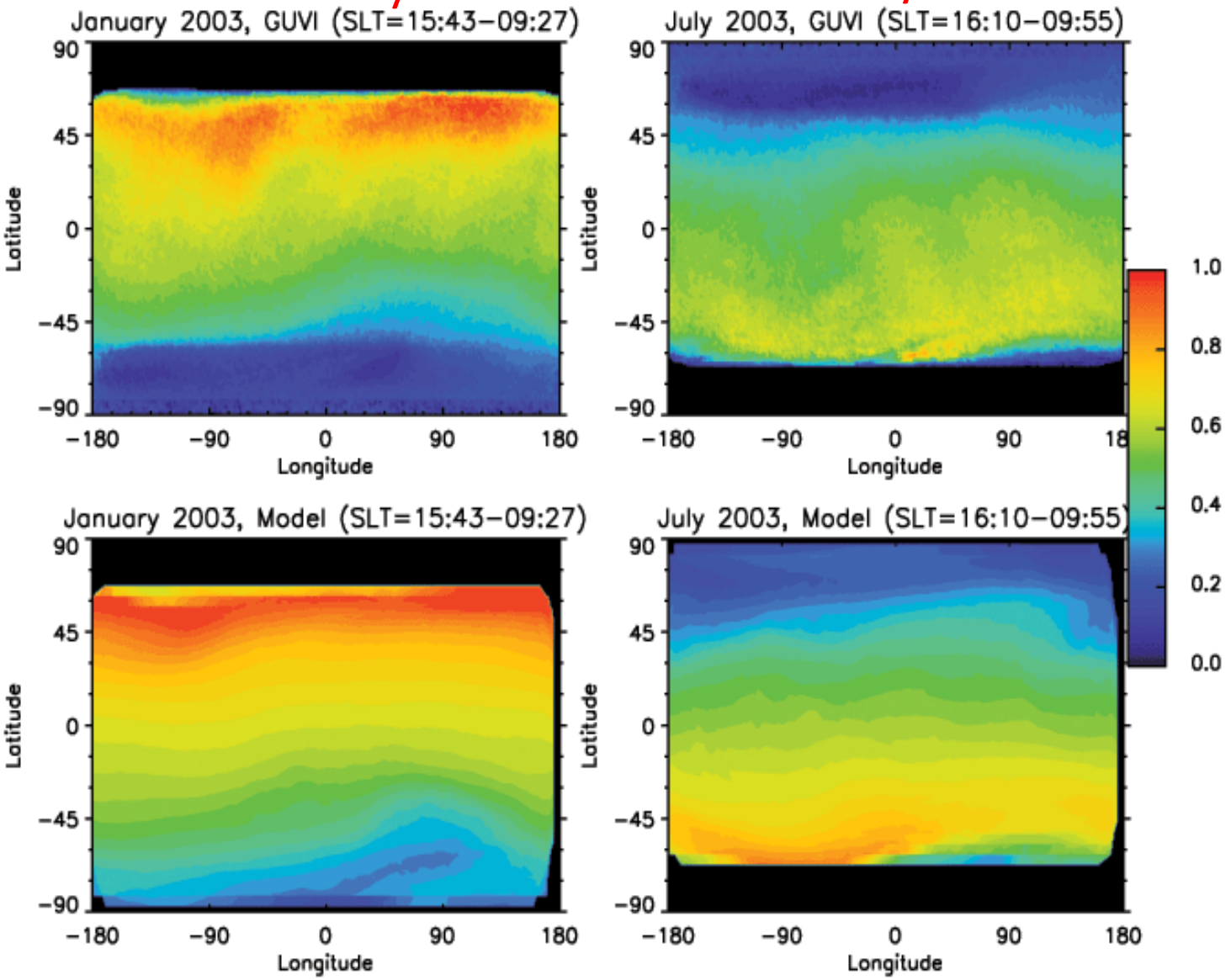
Annual Changes in Composition (O/N_2)

January

July

GUVI

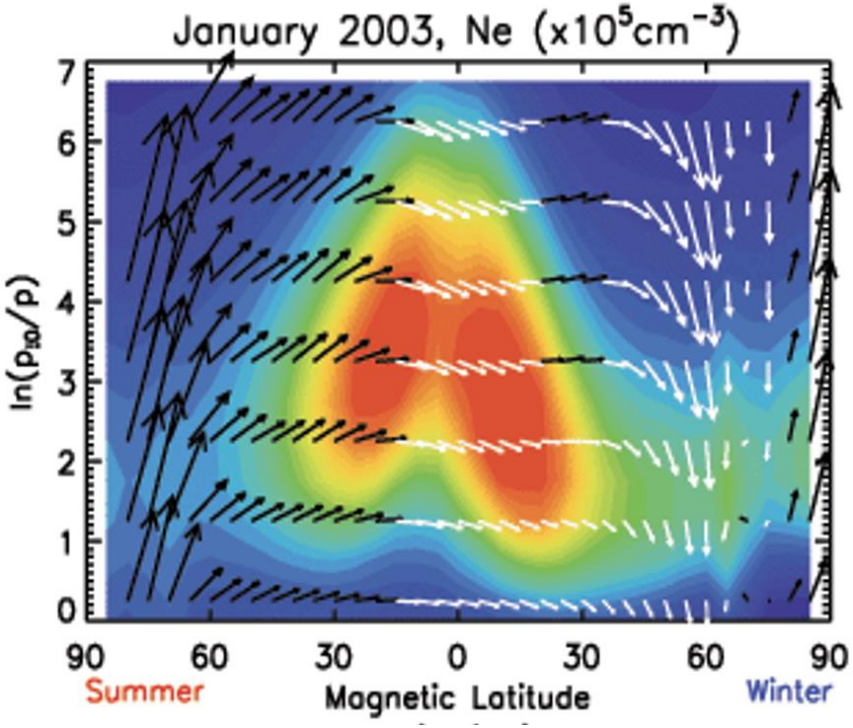
TIE-GCM



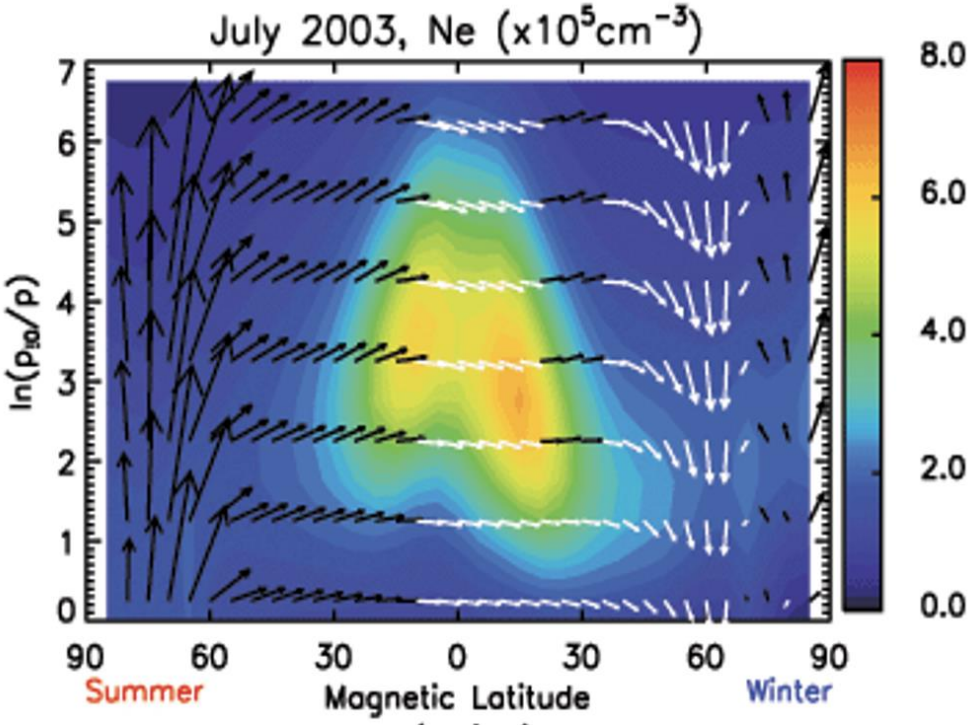
Qian et al., 2016a

Annual Changes in Electron Density

January



July



Outline

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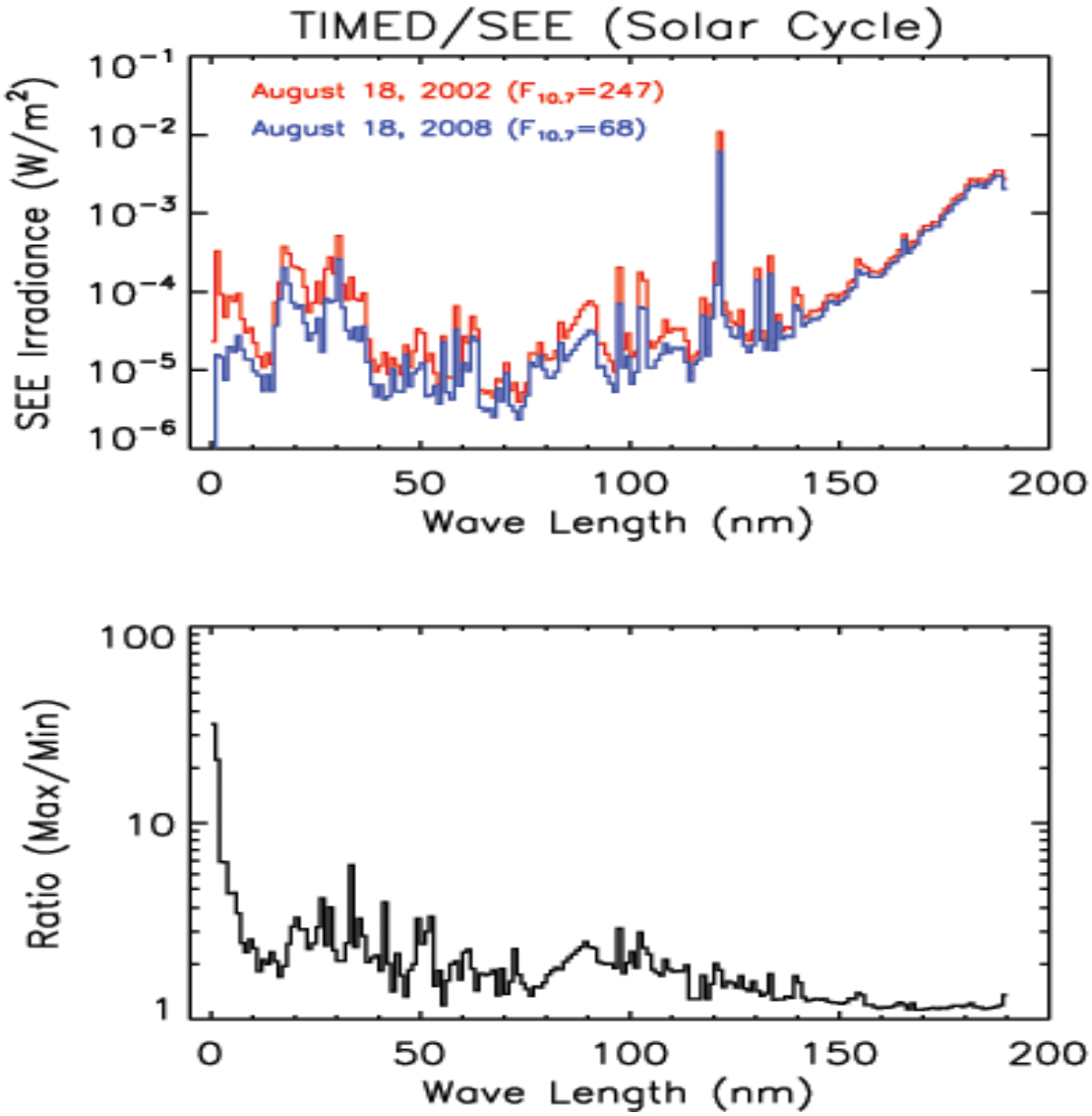
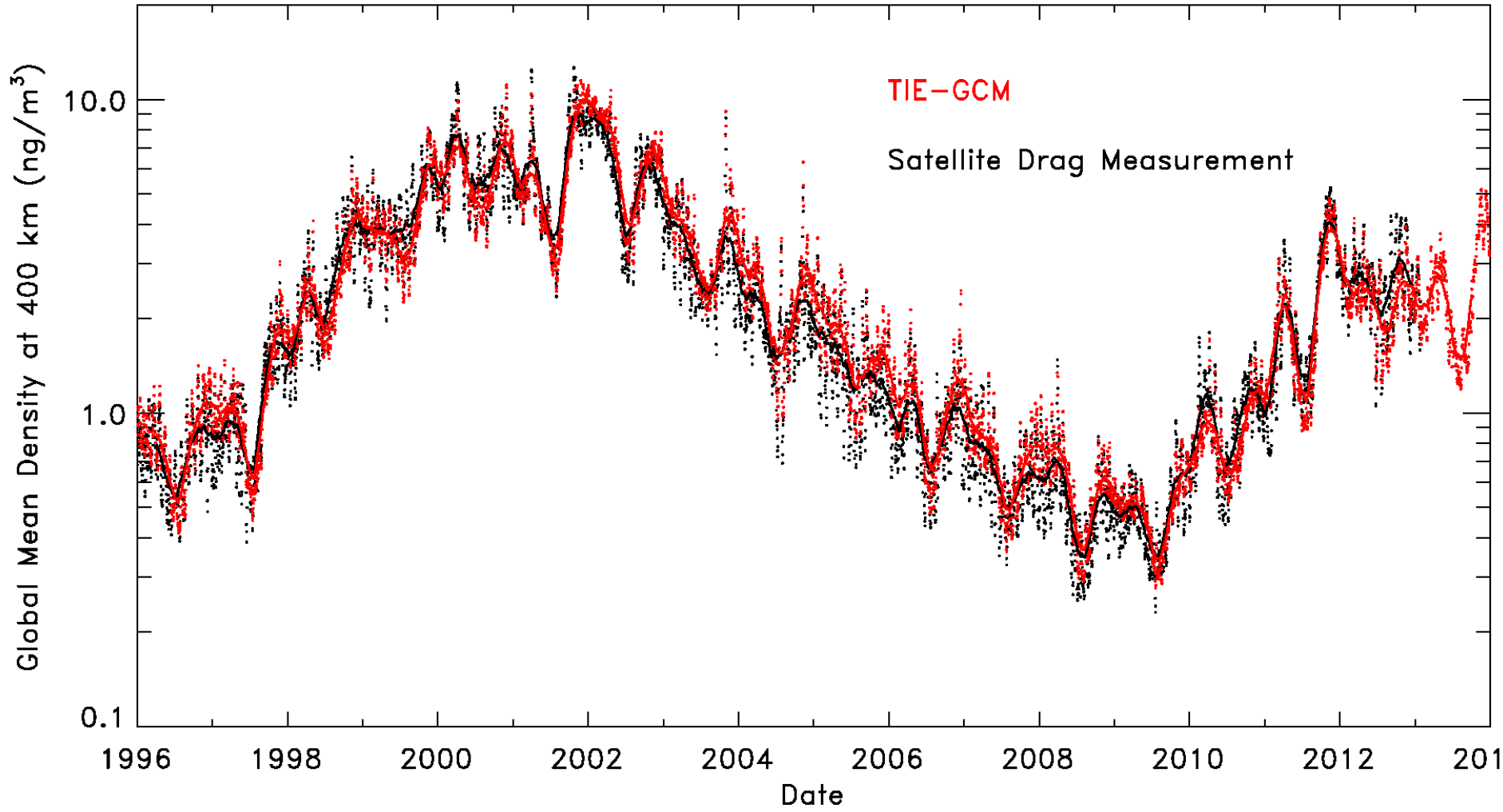
Solar Cycle Variation



The intrinsic ~11-year variability in the Sun.

Solar Cycle Variation – Model Data Comparison

400 km



The amplitude for mass density (ρ) at 400 km of the solar-cycle variation is about one order of magnitude.

Composition (O/N_2) changes Over a Solar Cycle

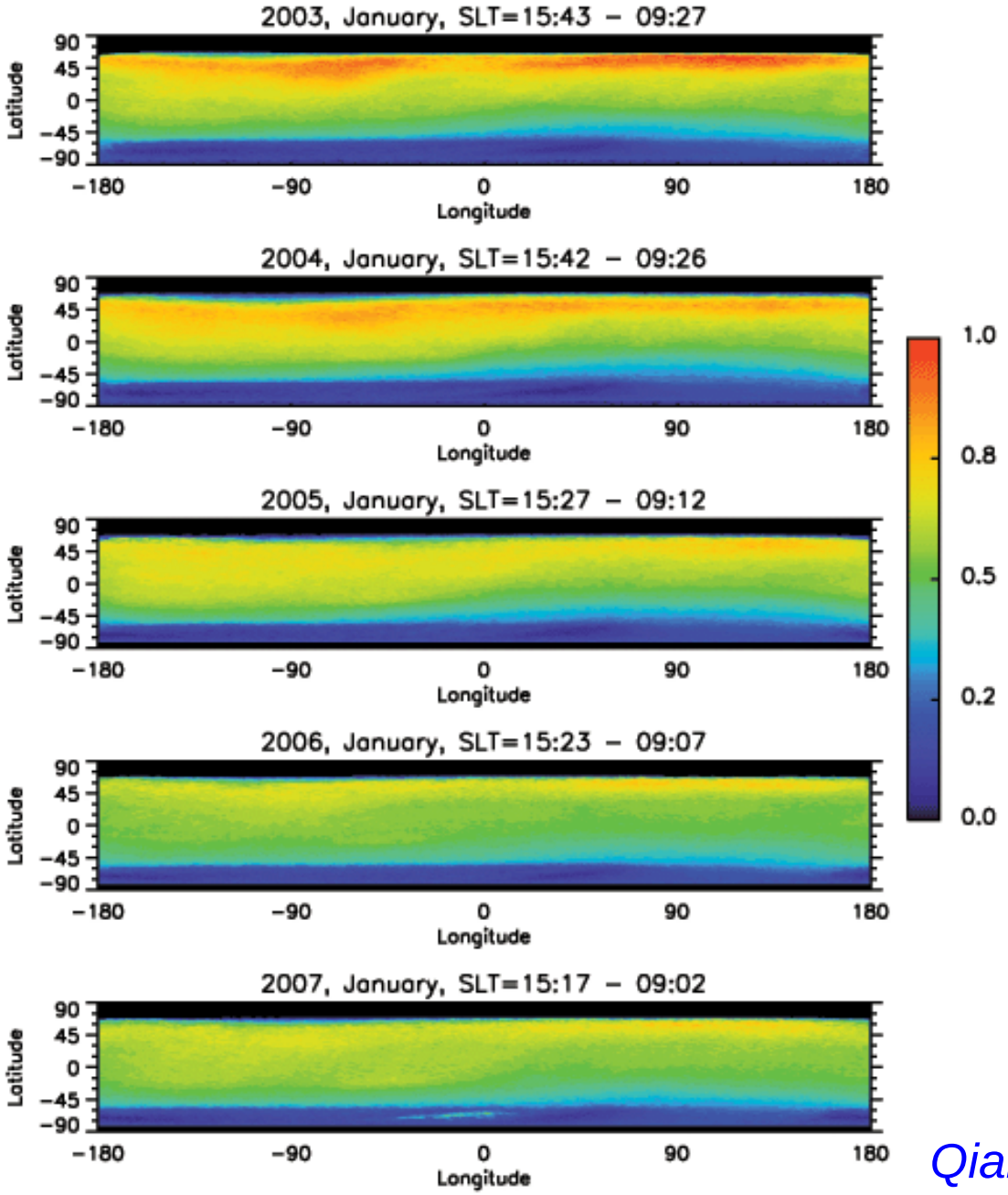
2003

2004

2005

2006

2007



Qian et al., 2016b

Summary

- **Effects on the Upper Atmosphere Climate**
  - **Rotational**: ~100% change in mass density at 400 km at high solar activity. Larger rotational variation at higher solar activity.
  - **Annual and semiannual**: ~30% to ~250% change in mass density at 400 km. Coupling between the ionosphere and thermosphere in the annual variation due to the annual variation in thermosphere composition (O/N_2).
  - **Solar-cycle**: ~ one order of magnitude change in mass density at 400 km.

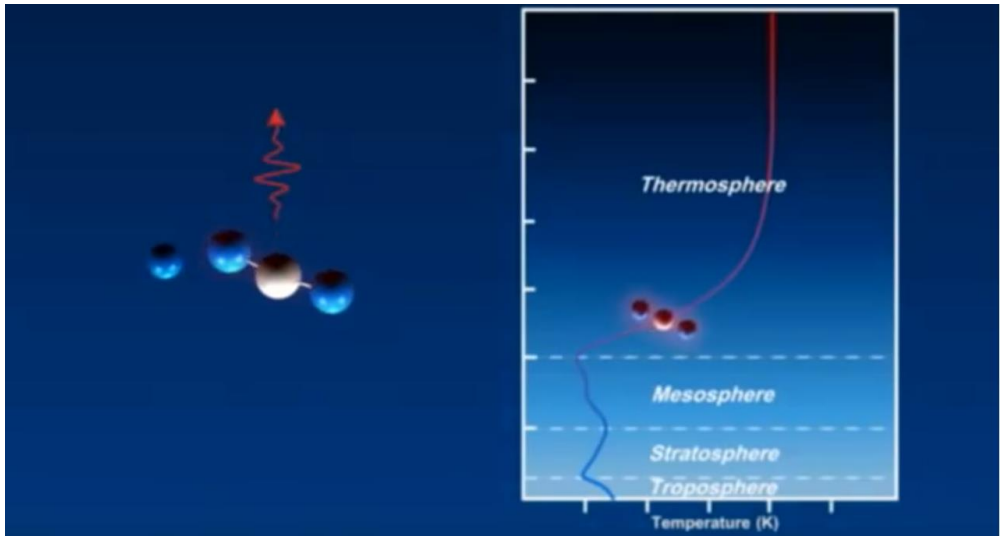
Summary

- **Impact on Climate Change**
  - Observations and model simulations demonstrate that the upper atmosphere is cooling and contracting during recent decades, even after removing solar effects, mainly due to increases in CO_2.
  - Solar variability impacts climate change. Temperature trends driven by the increase of CO_2 is smaller at higher solar activity.
  - There is significant interannual variability in global mean temperature change, especially near the mesopause, where it is challenging to determine trends.

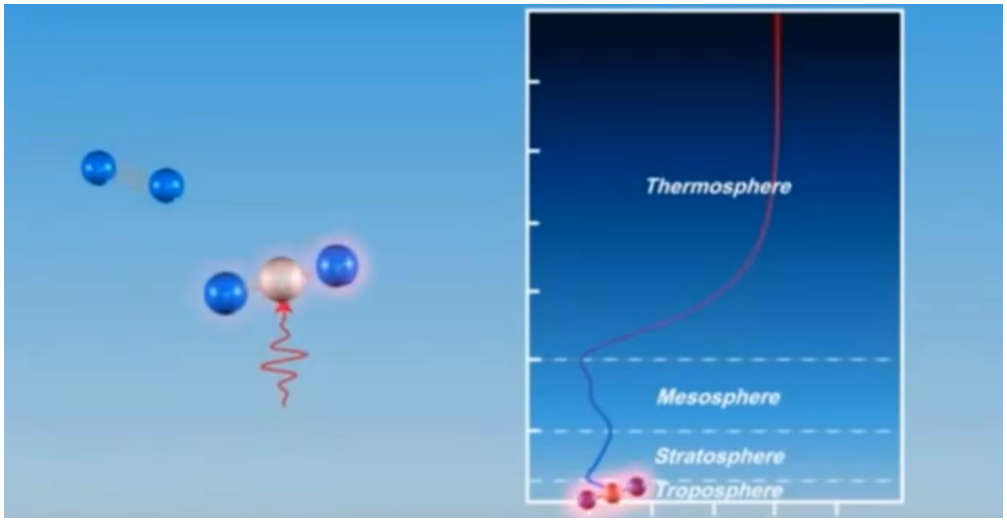
Why is it Warming Down, Cooling Up?

Thermosphere

Stratosphere



Troposphere



Credit: Stanley Solomon, HAO/NCAR