Long-term temperature trends in the middle atmosphere

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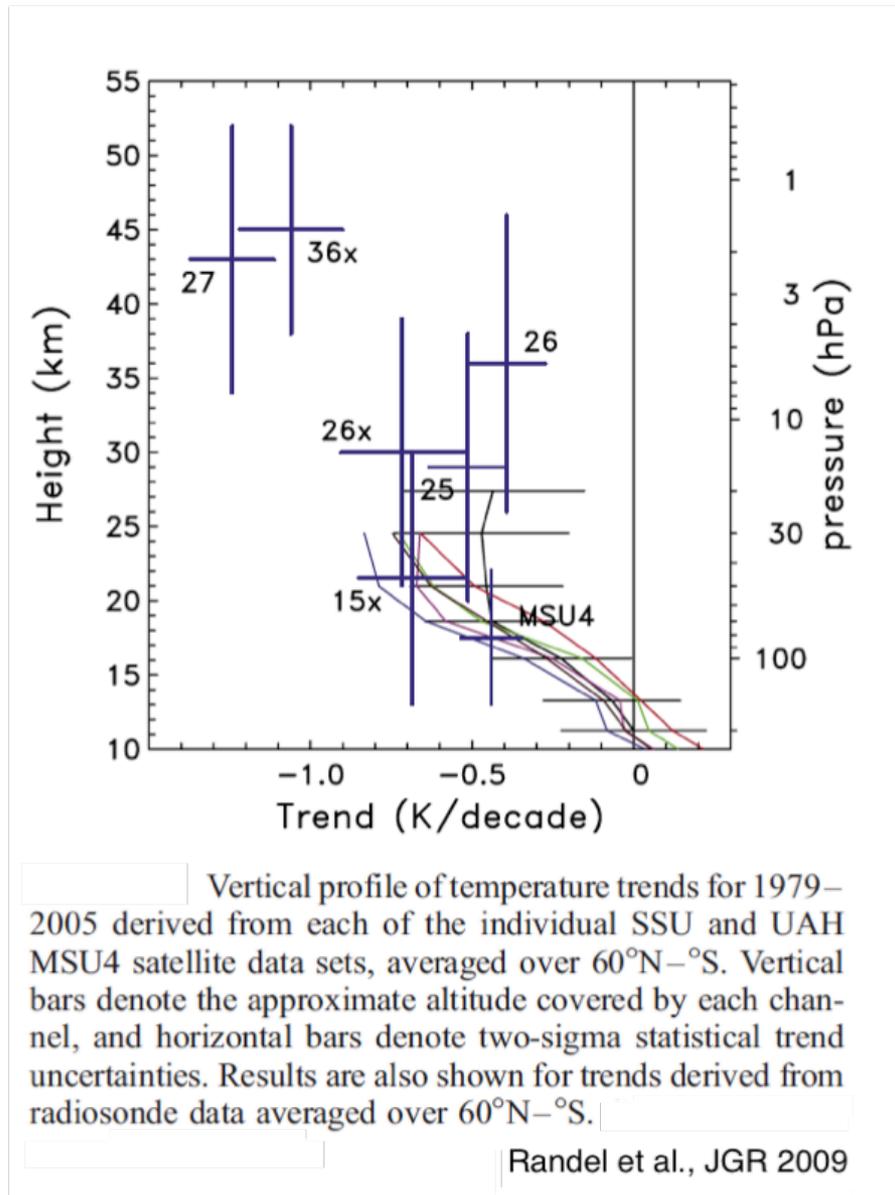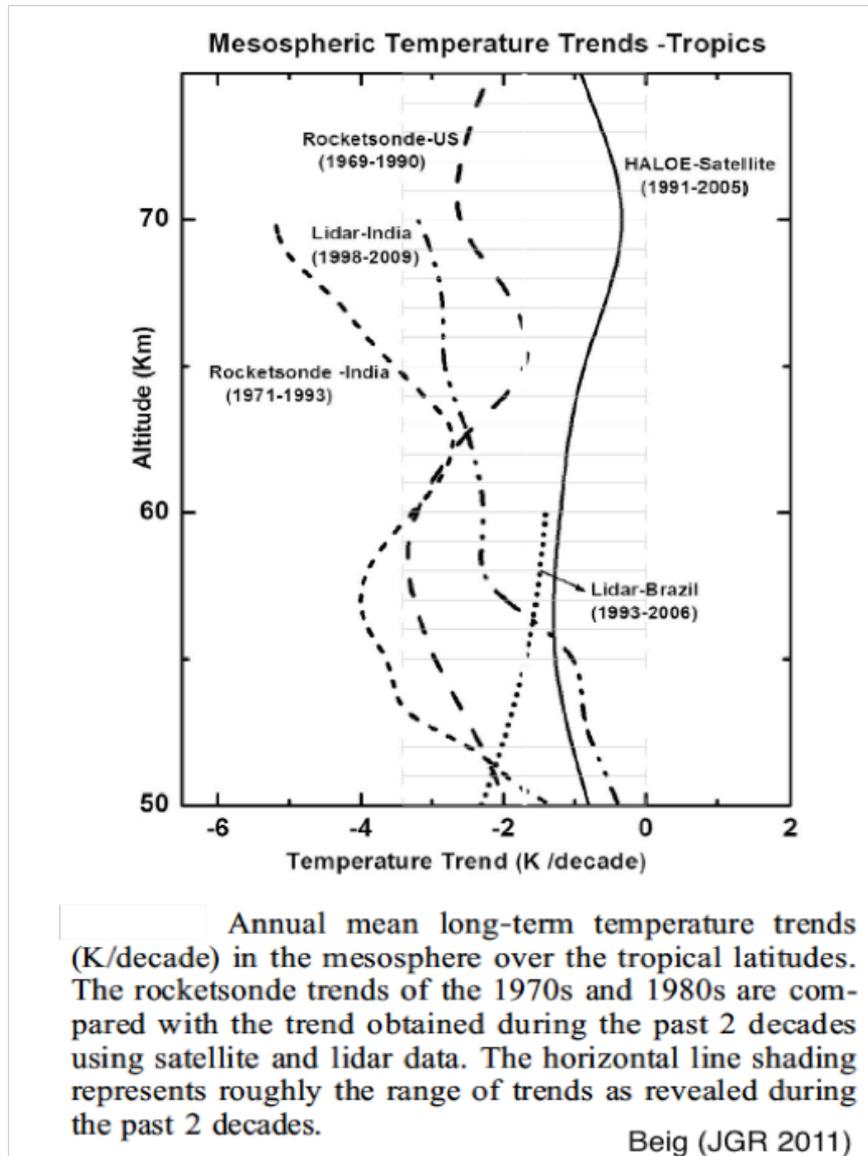
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motivation

- increasing burden of GHG is expected to cool the middle atmosphere while the troposphere warms

- middle atmosphere cooling is a characteristic signature of GHG-induced global change

- trends in temperature since ~1980 are available from satellite and other measurements

- can models explain observations to date?

- what future trends do models predict?
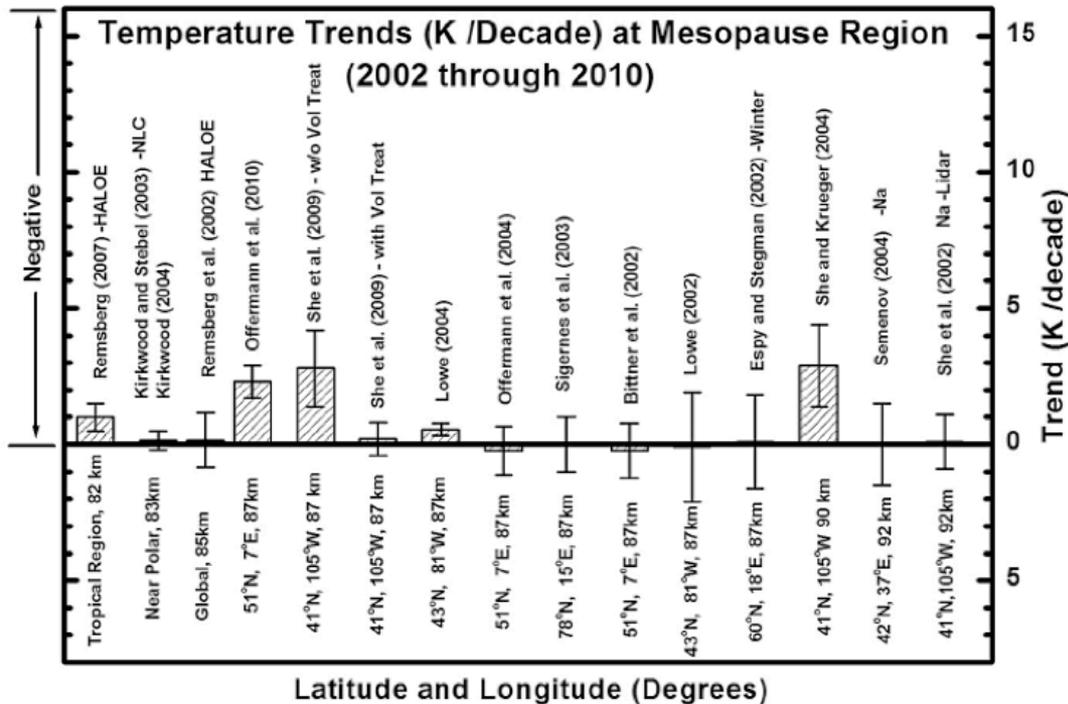
observed stratospheric T trends

Vertical profile of temperature trends for 1979–2005 derived from each of the individual SSU and UAH MSU4 satellite data sets, averaged over 60°N–°S. Vertical bars denote the approximate altitude covered by each channel, and horizontal bars denote two-sigma statistical trend uncertainties. Results are also shown for trends derived from radiosonde data averaged over 60°N–°S.

Randel et al., JGR 2009

observed mesospheric T trends

Mesospheric Temperature Trends -Tropics

Annual mean long-term temperature trends (K/decade) in the mesosphere over the tropical latitudes. The rocketsonde trends of the 1970s and 1980s are compared with the trend obtained during the past 2 decades using satellite and lidar data. The horizontal line shading represents roughly the range of trends as revealed during the past 2 decades.

Beig (JGR 2011)

mesospheric trends are not well constrained by observations

insignificant trend at the mesopause?

BEIG: TEMPERATURE TRENDS IN MLT REGION (JGR 2011)

Figure 2. Annual mean long-term temperature trends (K/decade) as reported in the recent literature for the mesopause region in the Northern Hemisphere after *Beig et al.* [2003]. Here "w/o Vol Treat" indicates without volcanic term and "with Vol Treat" means with volcanic treat considered in the analysis.

nevertheless, many observations suggest that trends near the mesopause (80-90 km) are small, and even statistically insignificant

Can the observations be reproduced by chemistry-climate models?

- use NCAR's Whole Atmosphere Community Climate Model (WACCM4)

- examine free-running (coupled ocean) simulations for 1950-2100

- simulations use IPCC scenario RCP6.0 (radiative forcing of 6 W m^{-2}) in 21st century—after 2005

- Results: MLR of de-seasonalized output on time, solar cycle and two QBO indices

WACCM trends, late 20th century

T trend (K per decade)
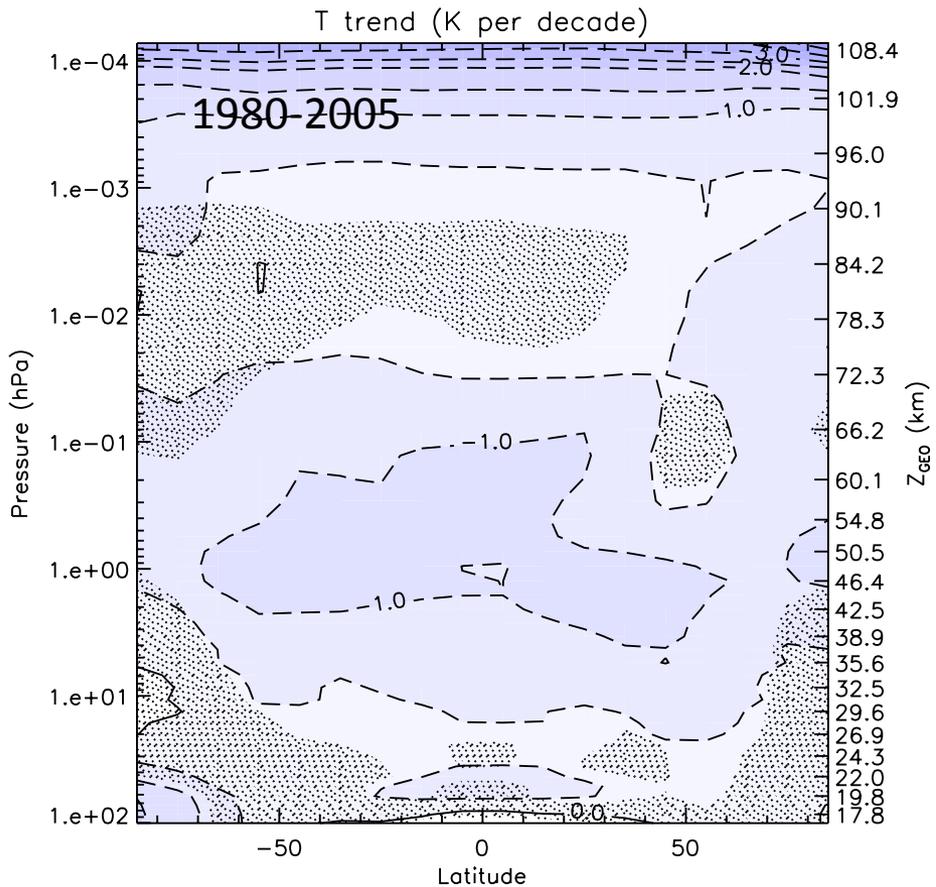
1980-2005

shaded not significant at 95%   1980—2005 np=4 bin=10

/Users/rgarcia/lacie2/refc2.002/concat_zm_refc2.002_O,CH4,CO,CO2,H2O,NO,NOX,NOY,O1D,O3,Z3,EKGWSPEC,Op,U,QRL_TOT,QRS_TOT,QRS_CO2

In common with observations:

- large trend (~ −1.2 K /decade at ~ 50 km)

- small, insignificant trend at ~ 80-95 km

➤ nthe trend minimum at the mesopause is global—therefore, not due mainly to changes in adiabatic heating and cooling

➤ trend is not due to "shrinking" of the atmosphere either—trends are shown on isobaric surfaces

➤ results are very similar to those reported by Garcia et al (2007) using an earlier version of WACCM → apparently robust

globally-averaged T trend profile

mesopause minimum:

~0.3 K per decade near 85 km, not quite statistically significant at 95%

stratopause maximum:

~1.2 K per decade, highly significant

How do these trends change with time?

1980-2005

bars: 2σ

1980−2005 np=4 ave=(−90, 90)

/Users/rgarcia/lacie2/refc2.002/concat_zm_refc2.002_O,CH4,CO,CO2,H2O,NO,NOX,NOY,O1D,O3,Z3,EKGWSPEC,Op,U,QRL_TOT,QRS_TOT,QRS_CO2

SPARC Victoria 2015
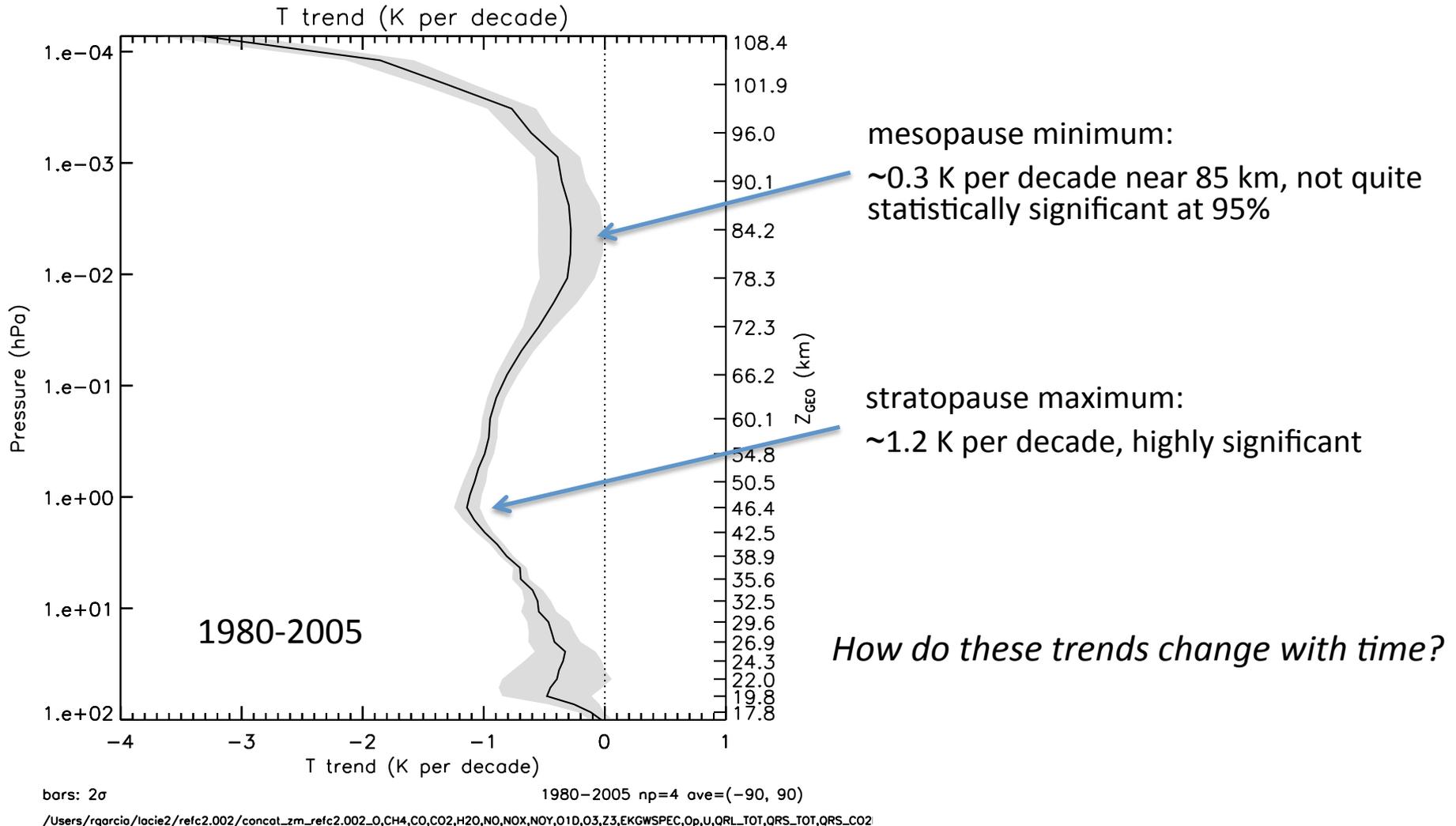
# evolution of T trend profiles
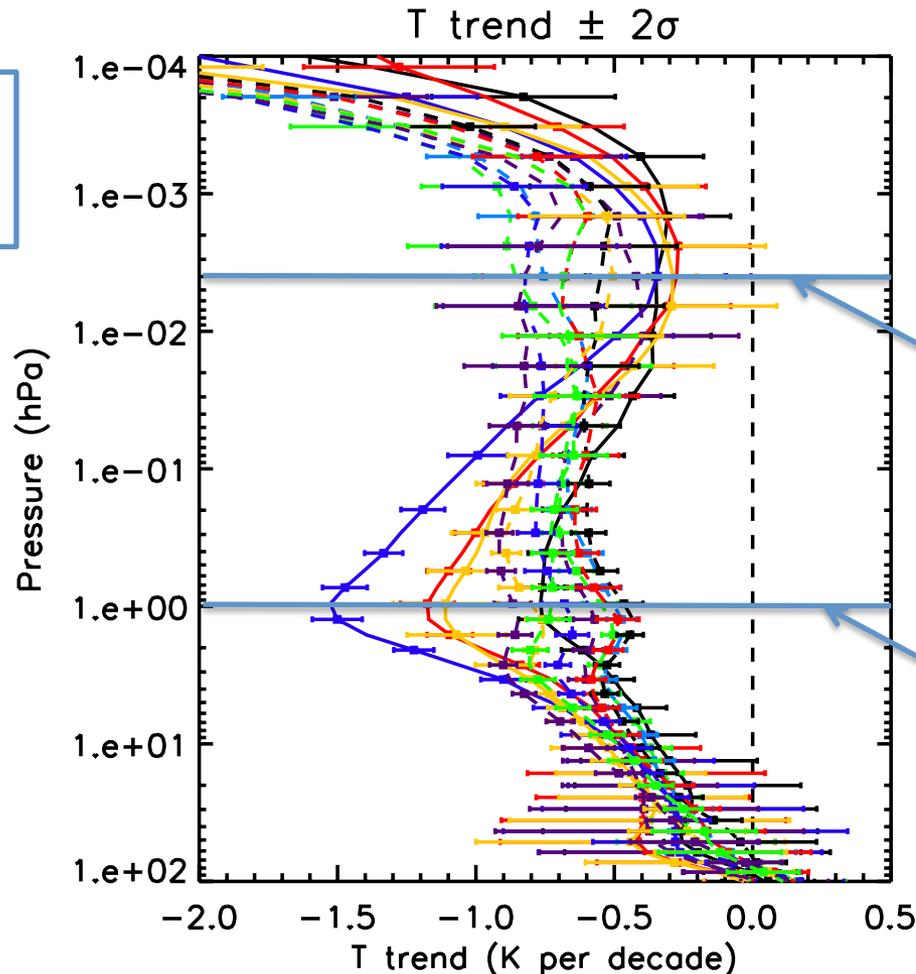
- 25-year trends calculated every 5 years: 1950-1975, 1955-1980, ..., 2065-2090, 2070-2095 (only half of these are shown here)

- small/insignificant trend at the mesopause is present in the 20th century results (solid curves)

- in the 21st century (dashed), the stratospheric trend decreases while the mesospheric trend increases (and the mesopause minimum disappears)

SPARC Victoria 2015

# 20ᵗʰ vs. 21ˢᵗ century trend profiles
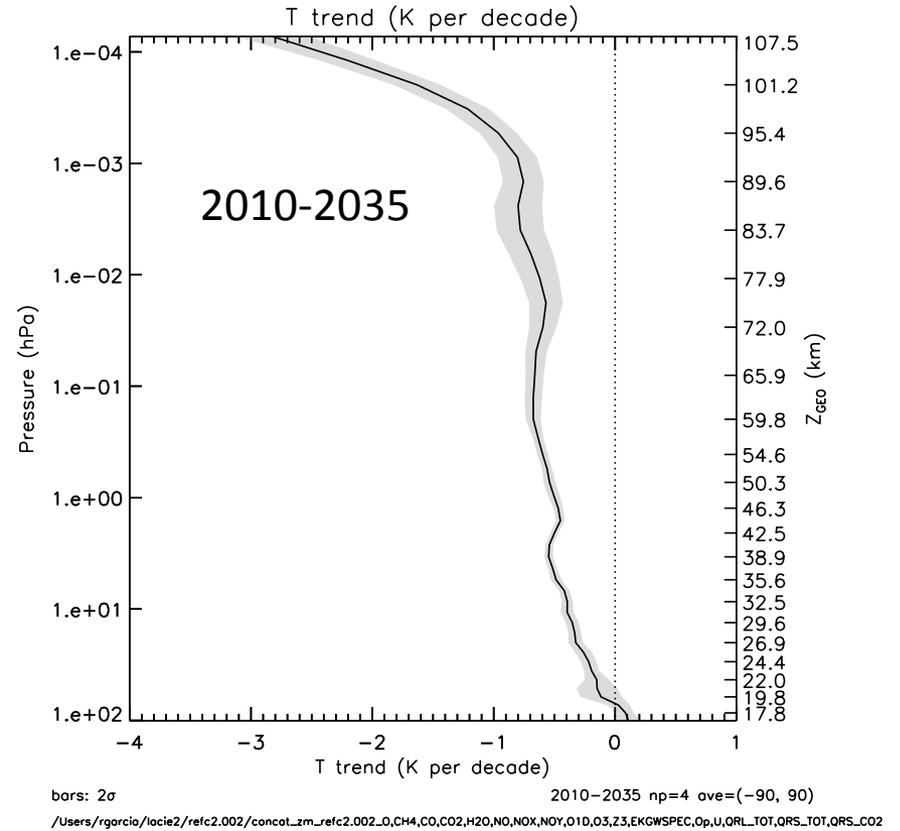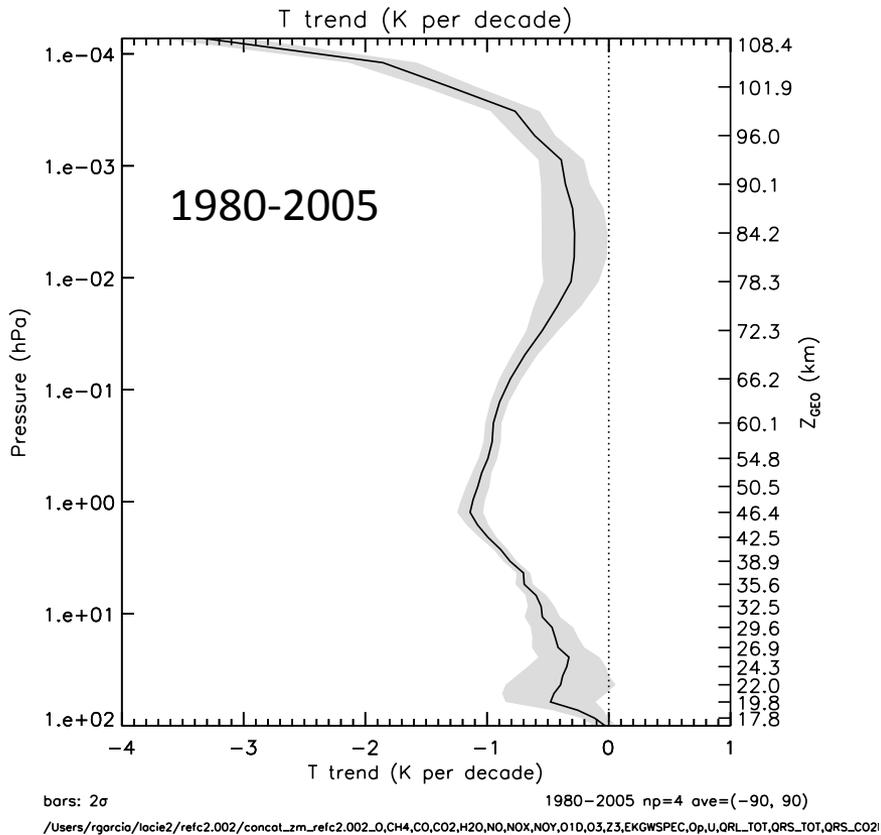
- why do the extrema of the 20ᵗʰ century profiles, at the stratopause and mesopause, disappear in the 21ˢᵗ century?

evolution of trends in the stratosphere
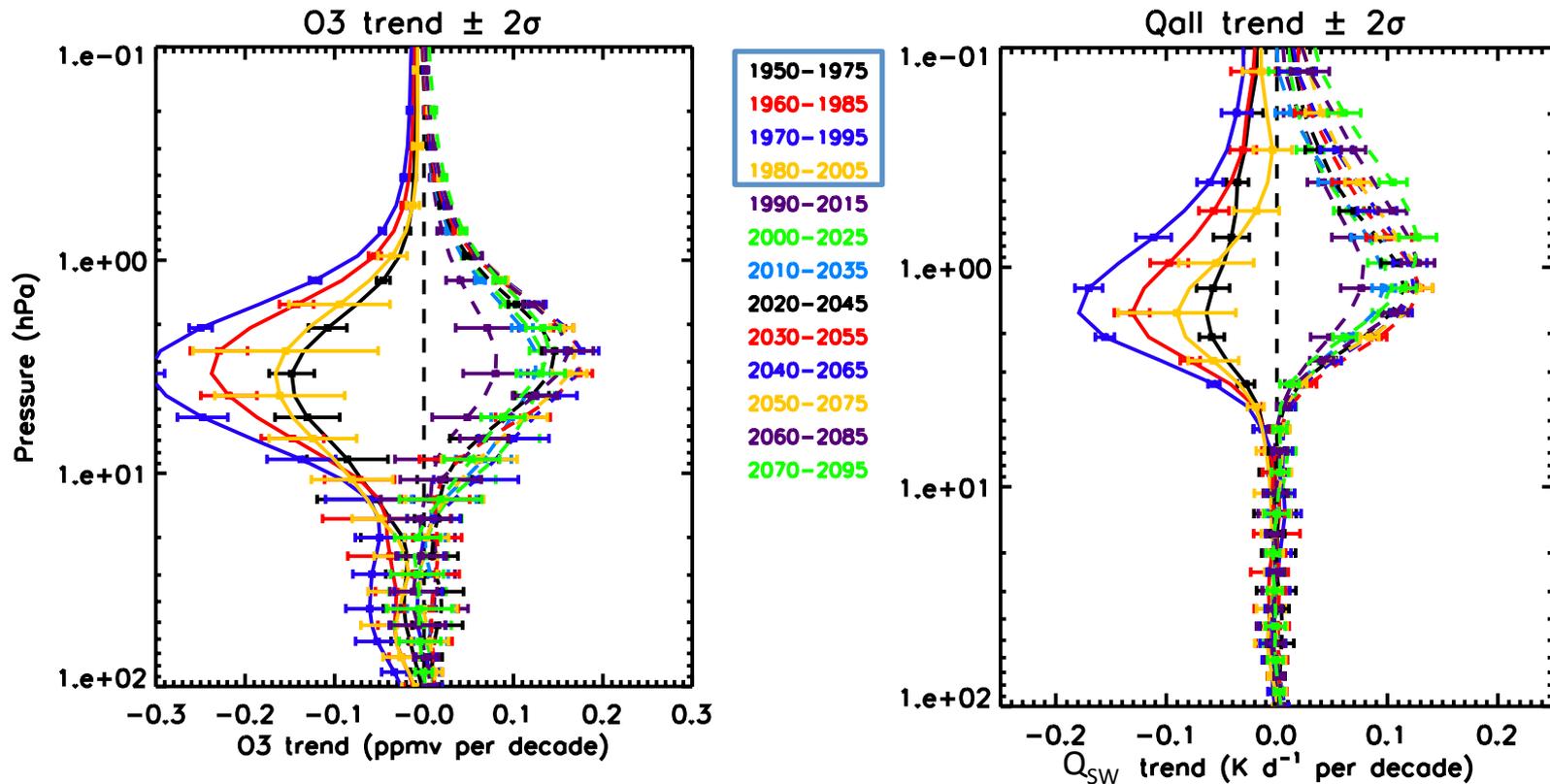
- the large T trends in the 20th century are evidently due to the combined effects of CO_2 increase and halogen-induced decreases in O_3 (left), which reduce UV heating (right) (20th century results: solid; 21st century: dashed)

T vs. O₃ trends near the stratopause

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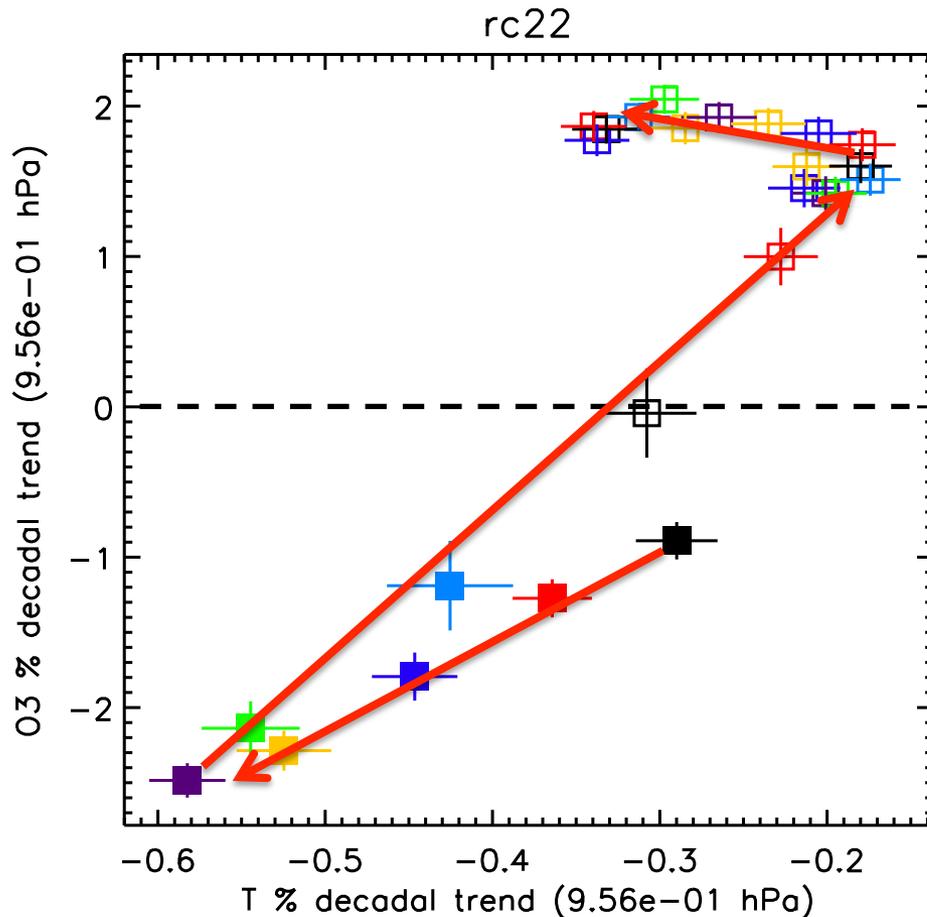
- T and O₃ trends in the 20th century (filled symbols) are positively correlated (both trends are negative)

- as halogen load decreases, T and O₃ trends in the 21st century (open symbols) become negatively correlated, as expected from simple photochemical equilibrium

- towards end of the 21st century, the relationship between ozone and temperature follows photochemical equilibrium $O_3 \sim \exp(B/T)$ with $B \sim 1500$ K

T trends in the mesosphere
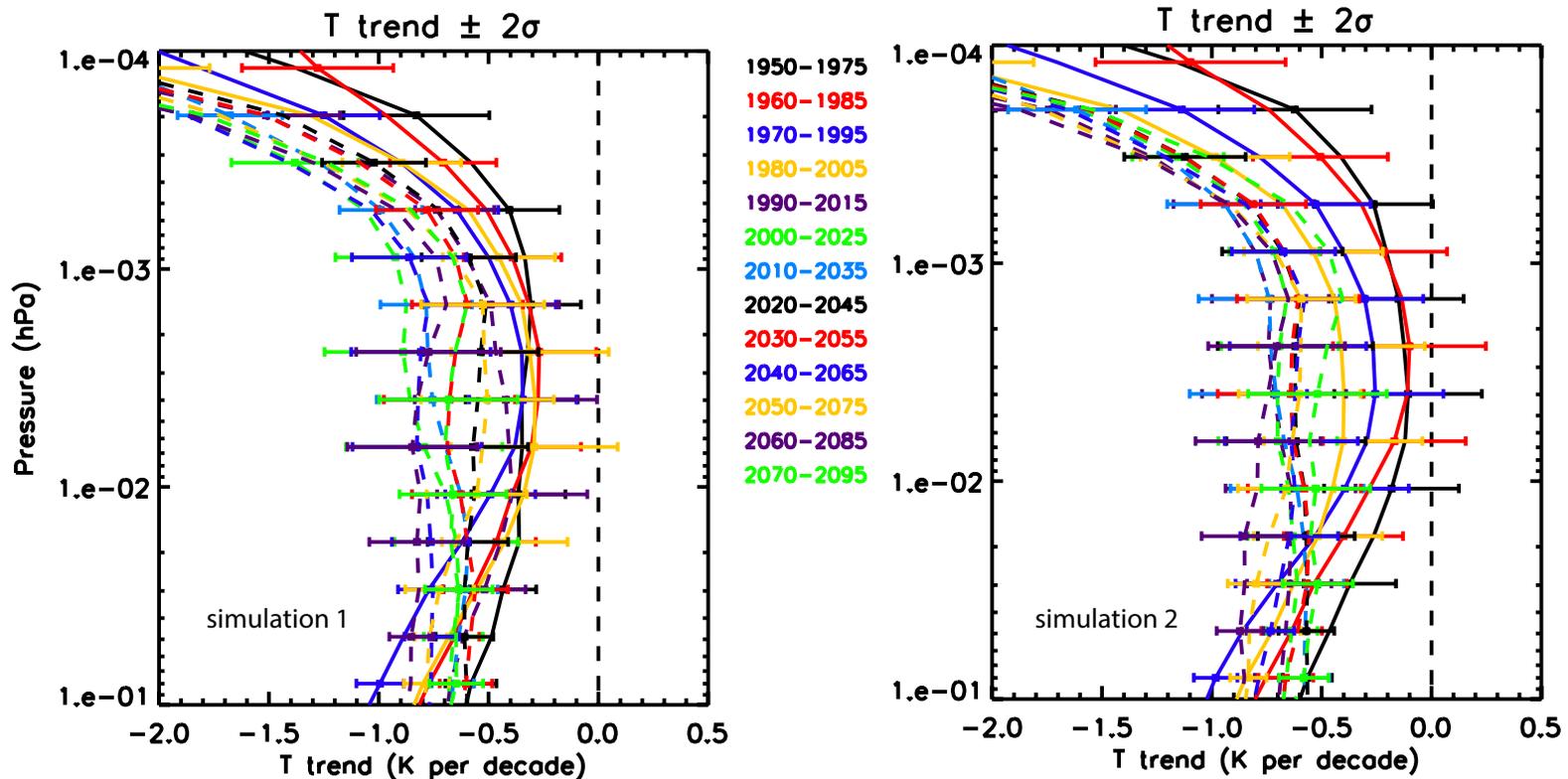
- trend minimum near the mesopause in the 20th century (solid curves)
- trend minimum disappears in the 21st century (dashed curves)
- robust result: present in multiple independent simulations (two examples shown)
- is there a simple cause for this behavior?

mesopause T and CO$_2$ trends

1950−1975 to 2070−2095

trend (% per decade) vs central year

T trend
CO2 trend x −0.1
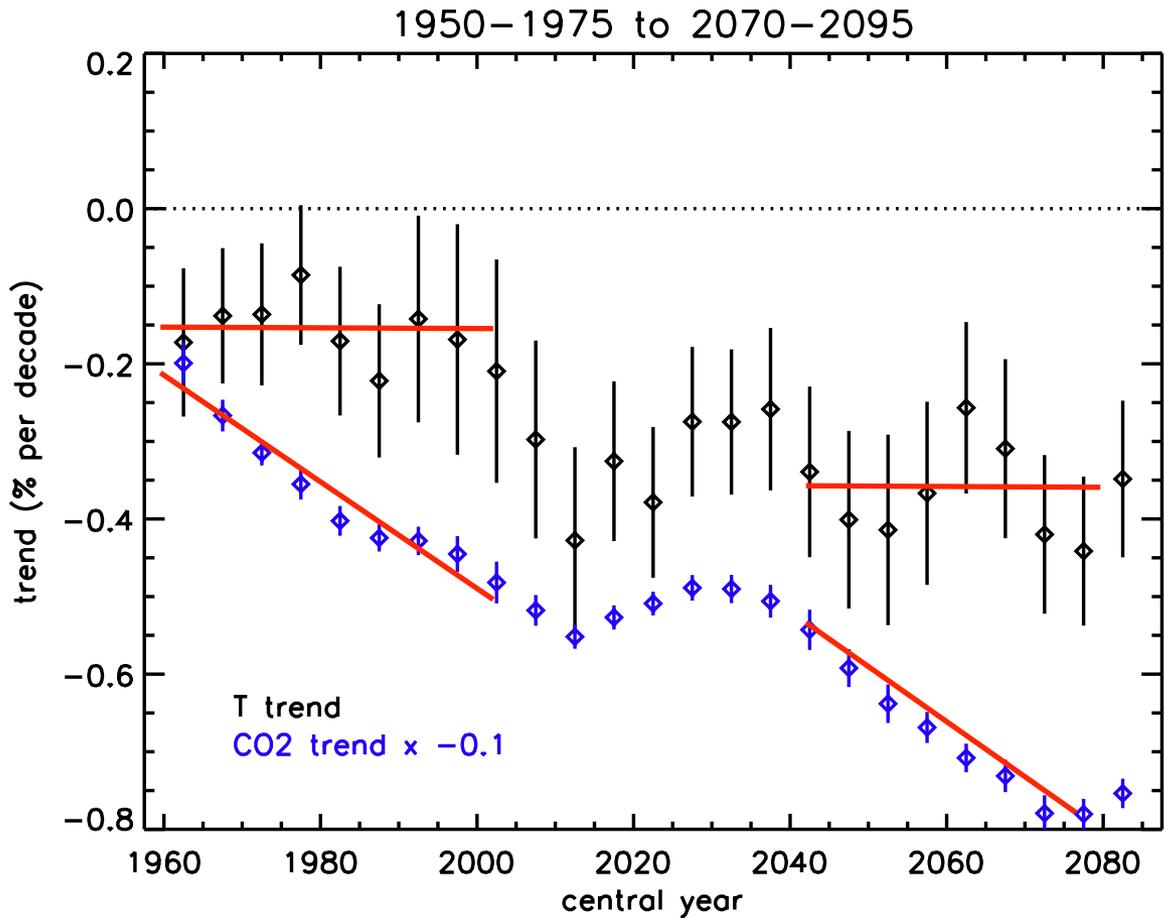
- T trend does not follow closely the trend in CO$_2$

- e.g., there is little change in the T trend during the 20th century, while the CO$_2$ trend increases rapidly

- the same is broadly true in the 21st century

- → T does not respond *only* to CO$_2$

energy balance at the mesopause

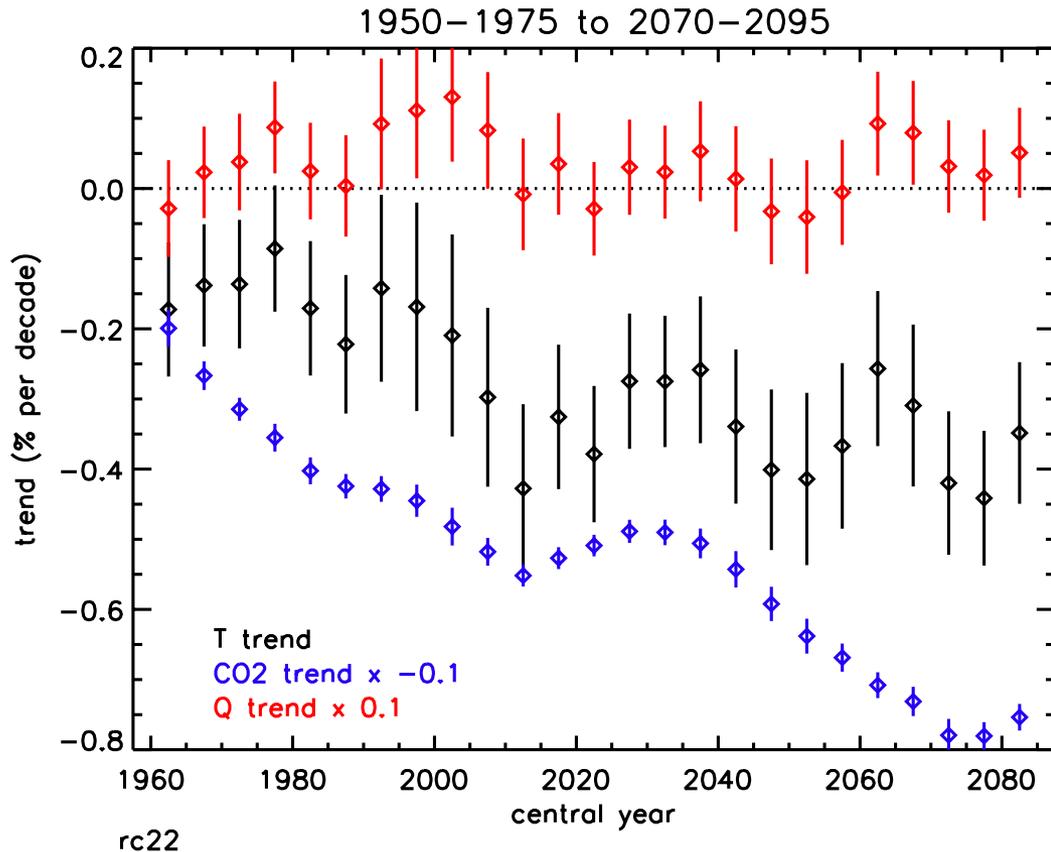- in the global average, total heating and IR cooling must balance:

$$Q_{SW} + Q_{DYN} = Q_{IR}[CO_2, O_3 \ H_2O; T]$$

where Q_{SW}, Q_{DYN} and Q_{IR} denote shortwave heating, dynamical heating and IR cooling, respectively

trends in the abundance of any of the above could be responsible for the trend in T at the mesopause. Most importantly:
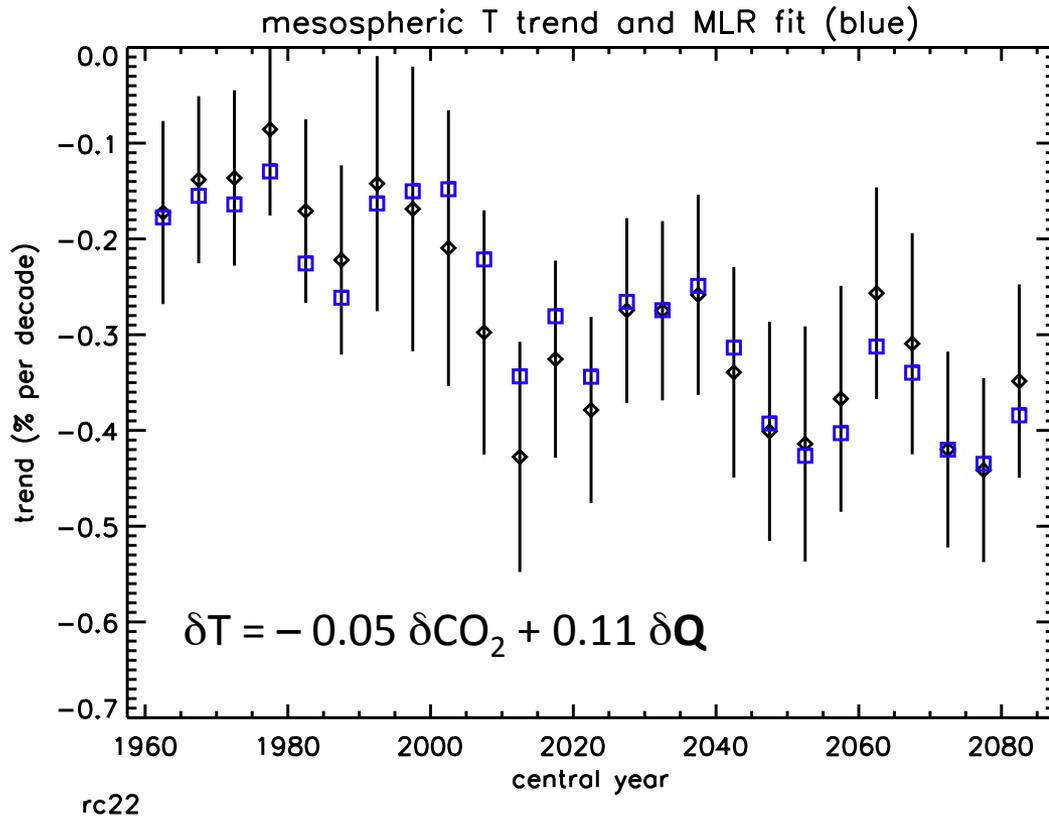
$$\delta T(z_m) = (\delta Q_{IR} / \delta T)^{-1} [\ \delta Q_{SW} + \delta Q_{DYN} - (\delta Q_{IR} / \delta CO_2) \ \delta CO_2]$$

more mesopause trends

1950−1975 to 2070−2095

T trend
CO2 trend x −0.1
Q trend x 0.1

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- trend in heating **Q** by all processes (SW heating, gravity wave diffusion and dissipation; in red) varies little with time and is often not significant

- But it may explain some of the interannual variability beyond the effect of CO_2

MLT trend fit $\delta T = f\,[\delta CO_2,\ \delta \mathbf{Q}]$

mesospheric T trend and MLR fit (blue)

$\delta T = -0.05\ \delta CO_2 + 0.11\ \delta \mathbf{Q}$

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- it turns out that the evolution of the mesopause T trend can be fit rather well as a function of the trends of CO_2 and **Q**

- this includes the transition from small T trends in the 20th century to larger T trends in the 21st century

- also captures much of the internannual variability

Conclusions

- the globally-averaged temperature trend profile observed in the 20th century (maximum trend at the stratopause; minimum, statistically insignificant trend at the mesopause) is reproduced by WACCM

- the trend profile changes abruptly in simulations of the 21st century: the stratopause maximum and the mesopause minimum disappear

- part of the large temperature trend at the *stratopause* in the 20th century is attributable to halogen-driven O_3 decrease (which reduces UV heating); this disappears in the 21st century

- the evolution of the temperature trend at the *mesopause* depends on the trends in CO_2 and heating at the mesopause