Energy Balance and Long-Term Change in the Mesosphere and Lower Thermosphere

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Acknowledgements and Dedication

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- G & A Technical Software

Dedicated to all of the students of science who work to advance our knowledge of the Earth System
i.e,
Everyone in attendance today

Outline

- Introduction
  - Including visits by Richard Feynman and Verner Suomi
- Role of Carbon Dioxide in the Climate of the MLT
- Energy Budgets, Energy Balance, Energy Conservation
- How Does the MLT Cool when Carbon Dioxide is Added?
- The Cooling and Contracting MLT of Today
- Summary
- A View to the Future

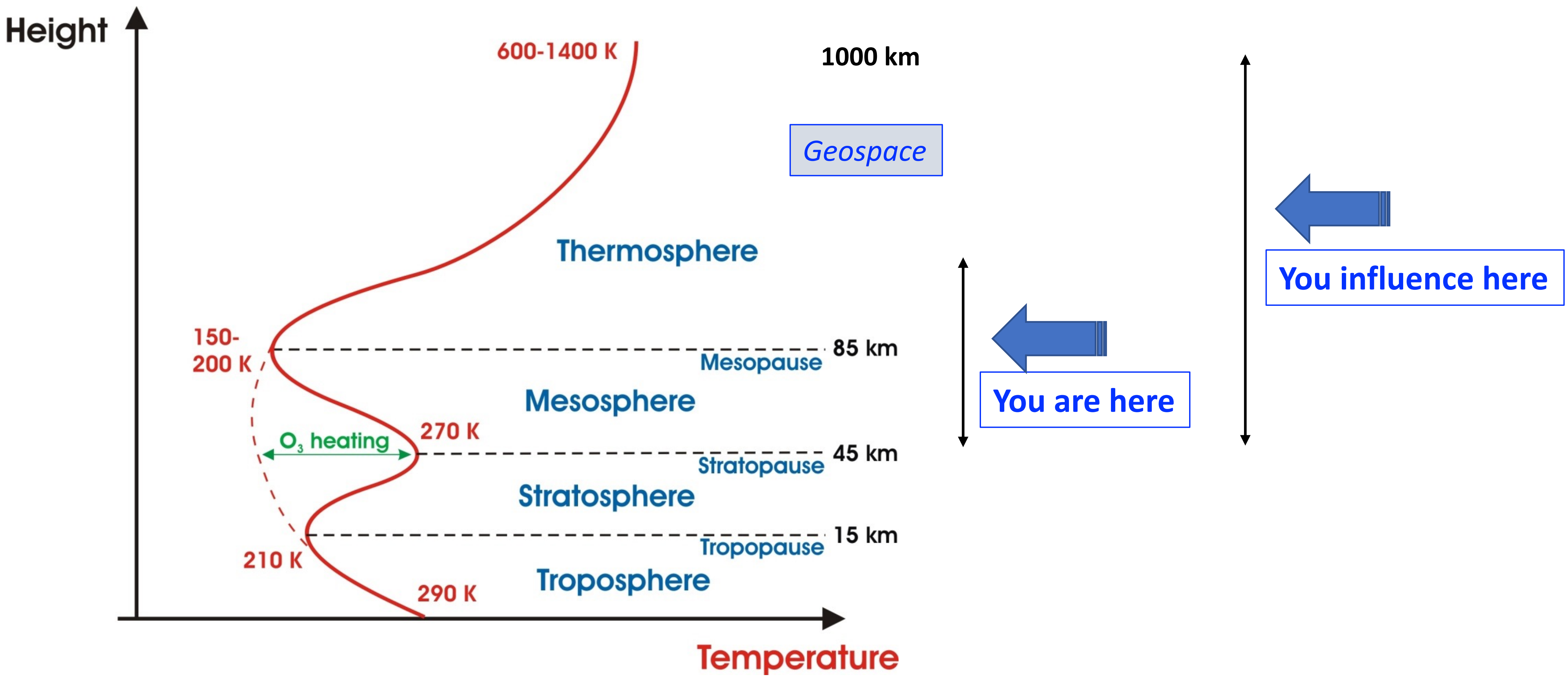
An Observation about Energy

It is important to realize that in physics today,
we have no knowledge of what energy *is.*

There is a fact, or if you wish, *a law*, governing all
natural phenomena that are known to date.
There is no known exception. It is exact as far as we know.
That law is called *the conservation of energy.*

Richard P. Feynman, in Six Easy Pieces

Earth's Mesosphere and Lower Thermosphere



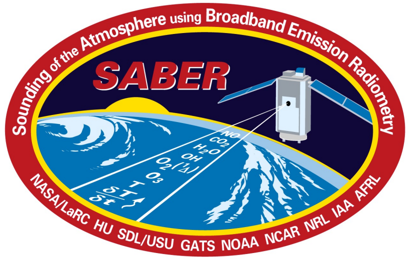
What makes Mesosphere and Lower Thermosphere (MLT) Interesting and Worthy of Study?

- **Blend of classical photochemistry and aeronomy**
  - **Ozone is still the main radiative drive in the mesosphere and up to 90 km**
  - **Solar UV variability and particle precipitation influence thermal structure and composition**
- **Atomic species become significant**
  - **Low density means long lifetimes for atomic oxygen and hydrogen**
  - **Remarkable influence on the energy budget of the 80-100 km region and above**
- **MLT is part of the complex Ionosphere-Thermosphere-Mesosphere *system***
- **Climate change due to increasing CO_2 in the MLT influences the entire perceptible atmosphere above it – to the edge of Space!**

Sounding of the Atmosphere using Broadband Emission Radiometry

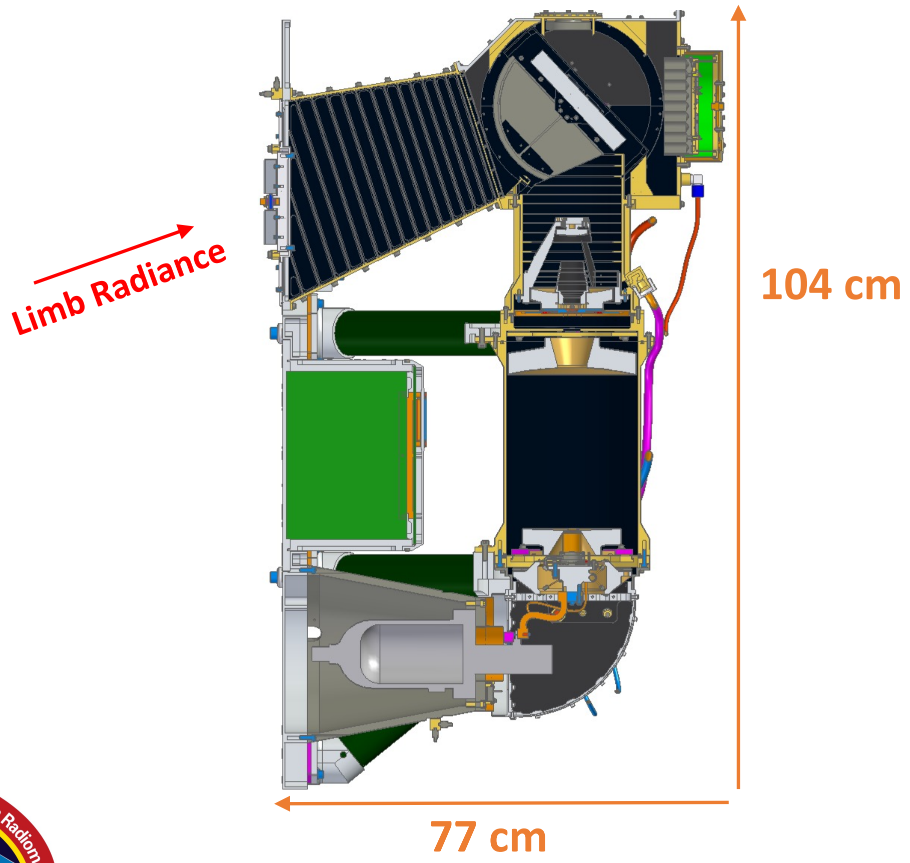
SABER Instrument

- Limb viewing, 400 km to Earth surface
- Ten channels 1.27 to 16 μm
- Over 30 routine data products including *temperature, constituents, and rates of radiative heating and cooling*
- Over 98% of all possible data collected
- Focus on energetics of MLT region
- Nearly 20 years of on-orbit operation!
- Approved through September 2023



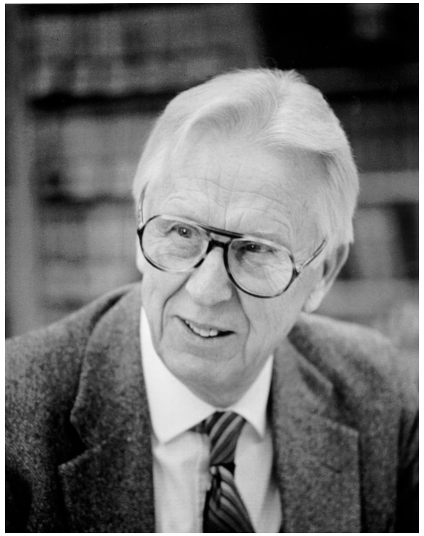
SABER Instrument

75 kg, 77 watts; 4 kbs



The Hypothesis of Climate Change Science

For more than a century, we have been aware that changes in the composition of the atmosphere could affect its ability to trap the sun's energy for our benefit. We now have incontrovertible evidence that the atmosphere is indeed changing and that we ourselves contribute to that change. Atmospheric concentrations of carbon dioxide are steadily increasing, and these changes are linked with man's use of fossil fuels and exploitation of the land. ***Since carbon dioxide plays a significant role in the heat budget of the atmosphere, it is reasonable to suppose that continued increases would affect climate.***

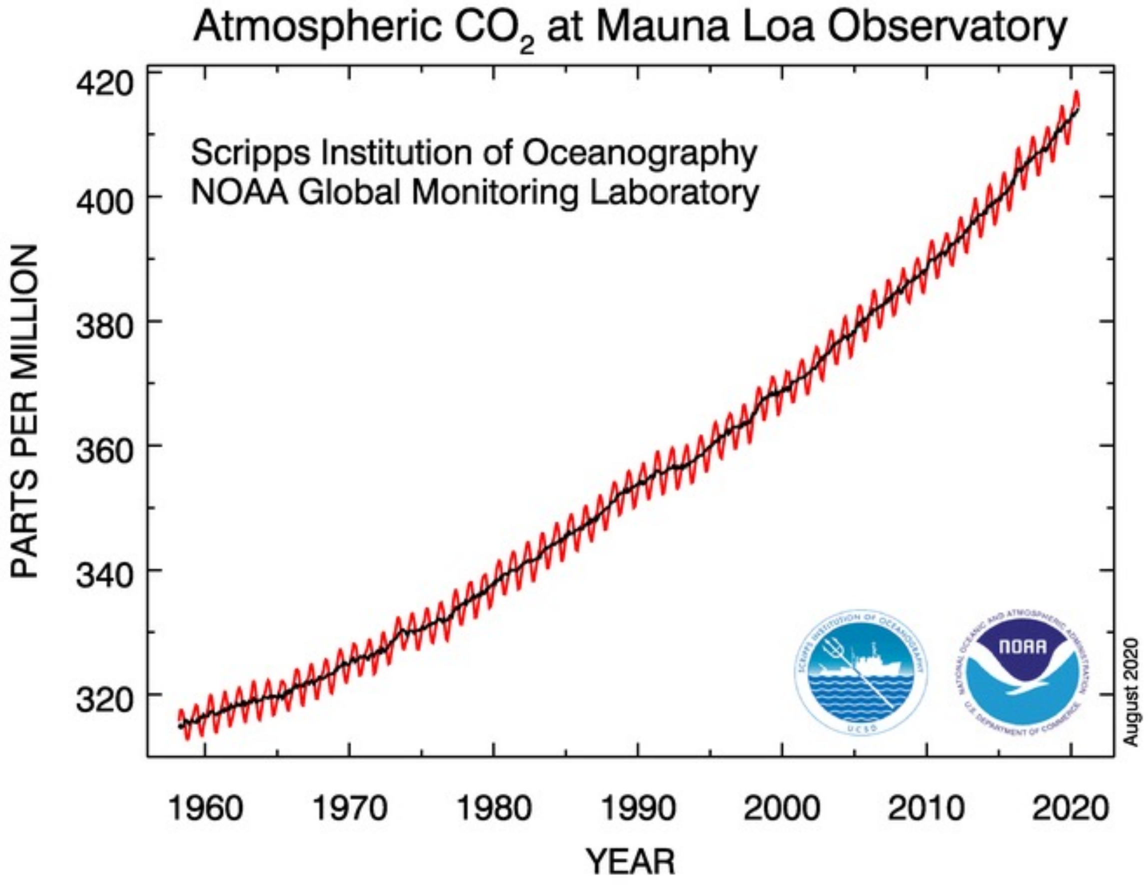


Verner E. Suomi

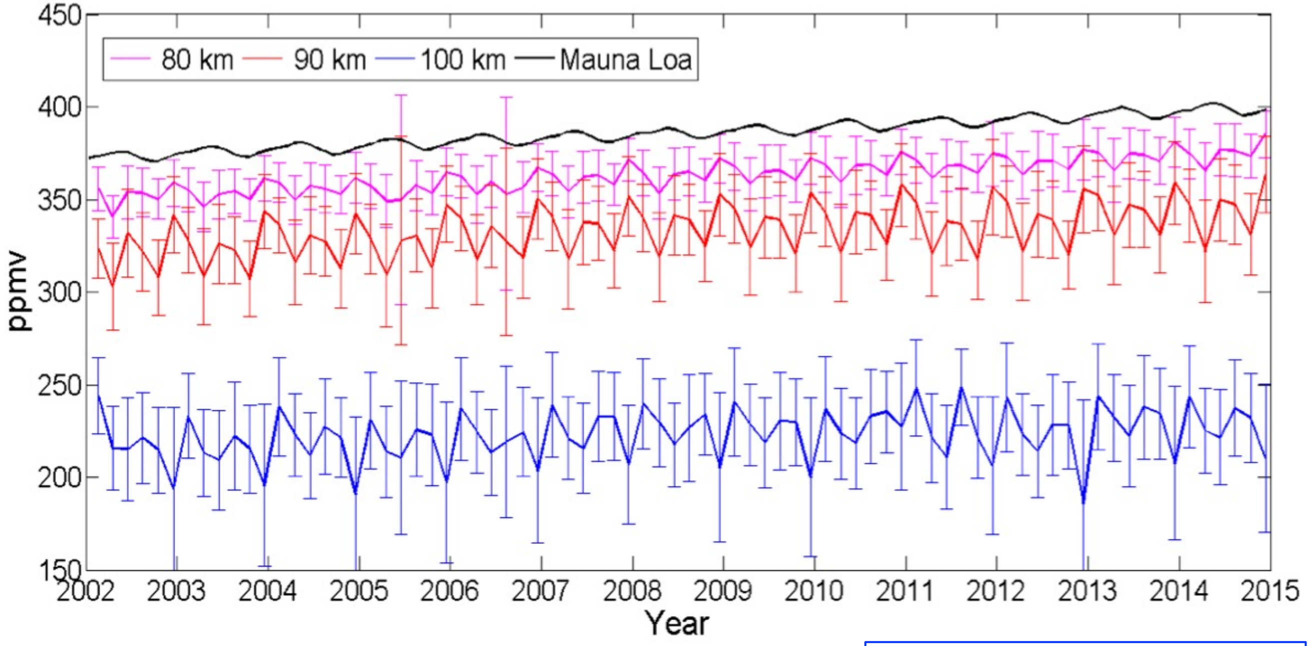
From "Carbon Dioxide and Climate: A Scientific Assessment," aka "The Charney Report", June, 1979

Article on 40th anniversary of "Charney Report:"
https://phys.org/news/2019-07-charney-years-scientists-accurately-climate.html

Carbon Dioxide at Earth's Surface and in the MLT



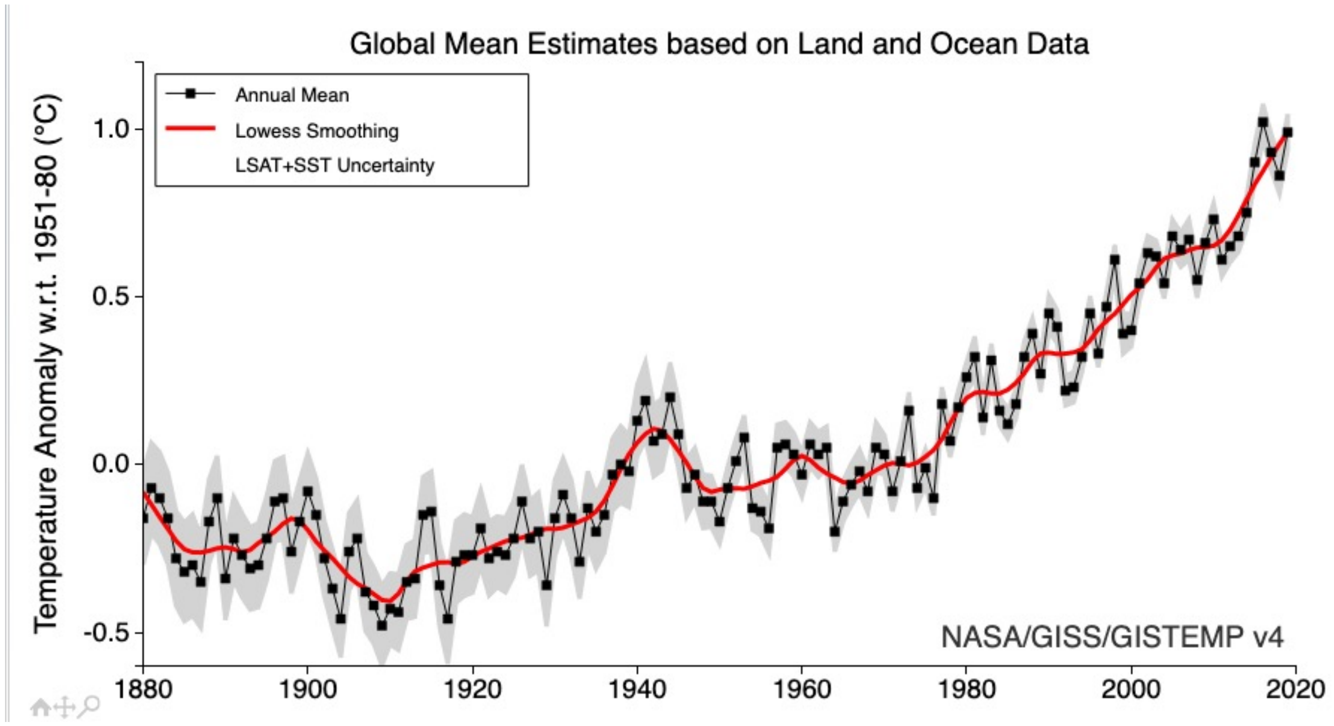
Measured CO_2 in the MLT (SABER)



Yue et al., GRL, 2015

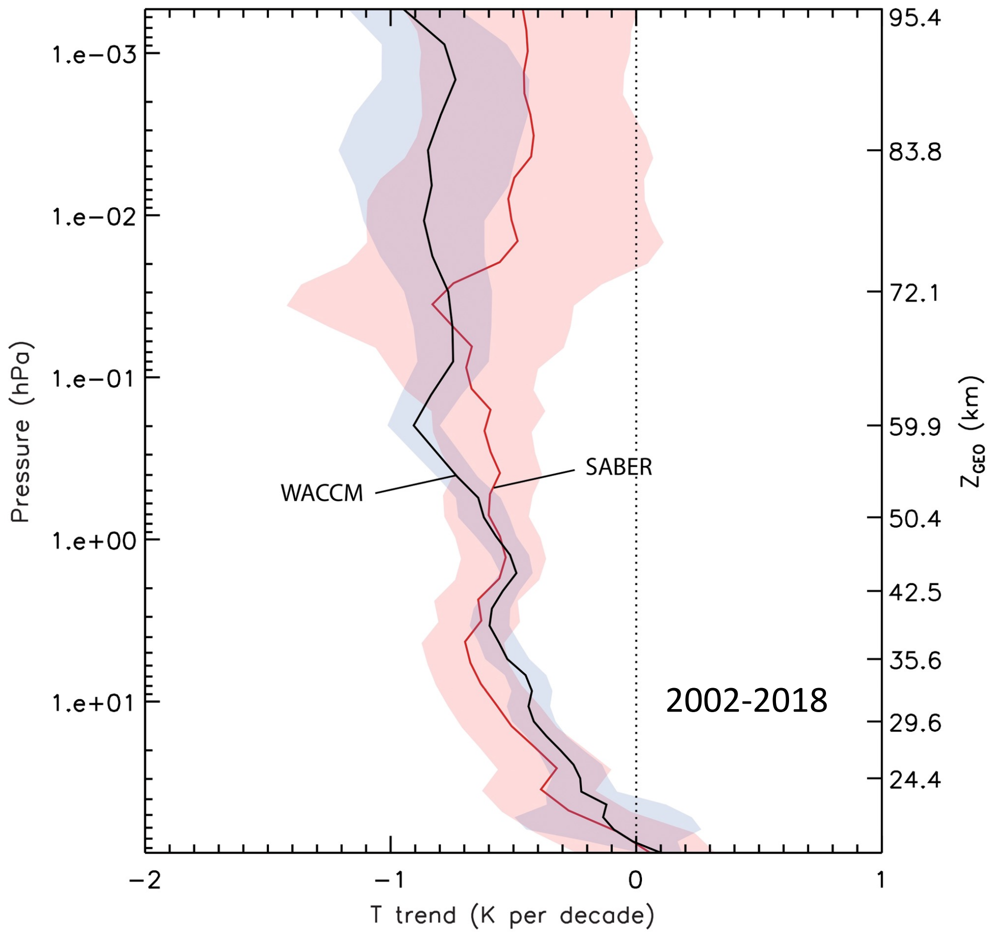
- **CO_2 is increasing at the surface and in the MLT**
- **Rate of CO_2 increase is comparable in both locations**

Consequences of CO_2 Increase: *Simultaneous* Surface Warming, MLT Cooling



Observed Global Surface Warming

https://data.giss.nasa.gov/gistemp/graphs_v4/



Observed Global MLT Cooling

Garcia et al., JGR, 2019

Role of CO_2 in the MLT Heat/Energy Budget

Energy Budget of the Mesosphere and Lower Thermosphere

- To understand role of CO_2 in the MLT climate we must examine the ‘heat budget’ of the MLT
- The energy (heat) budget is an accounting of all the known, significant sources and sinks of energy
- We will see that CO_2 “*plays a significant role in the heat budget*” of the MLT and therefore it “*is reasonable to suppose that continued increases would affect*” the climate of the MLT
- We will examine the heat/energy budget largely through the evaluation of *radiative heating and cooling rates*
- These express the rate, in Kelvin per day, at which radiation is working to warm or cool the atmosphere

What are Radiative Heating and Cooling Rates?

- **Radiative heating/cooling rates are really just an expression of the first law of thermodynamics**
- **The first law is just an expression of *conservation of energy*:**

$$\frac{\partial Q(z)}{\partial t} = \rho\, C_p \frac{\partial T(z)}{\partial t}$$

Heating/cooling rate, K/day

Energy gain or loss, per unit volume, per time

Density

Specific heat @ constant pressure

- **Simple example: Heating by absorption of solar radiation by O_2 (e.g., Ly-α)**

$$\frac{\partial Q}{\partial t} = J * O_2 * (h\nu) = \rho\, C_p \frac{\partial T}{\partial t}$$

- **Use SABER (and SORCE) to determine *$\partial Q/\partial t$* and *$\partial T/\partial t$* in the MLT**

Elements of the Energy Budget in the M/LT

Energy In

Energy Out

Solar Heating

Ozone Hartley

Ozone Huggins, Chappuis Bands

Oxygen A, B, γ bands

Oxygen Schumann-Runge Continuum

Oxygen Lyman-α

Oxygen Schumann-Runge Bands

Carbon dioxide @ 2.0, 2.7, 4.3 μm

Chemical Heating

$H + O_3 \rightarrow OH + O_2$

$H + O_2 + M \rightarrow HO_2 + M$

$OH + O \rightarrow H + O_2$

$O + HO_2 \rightarrow OH + O_2$

$O + O_3 \rightarrow 2\, O_2$

$O + O_2 + M \rightarrow O_3 + M$

$O + O + M \rightarrow O_2 + M$

Infrared Cooling

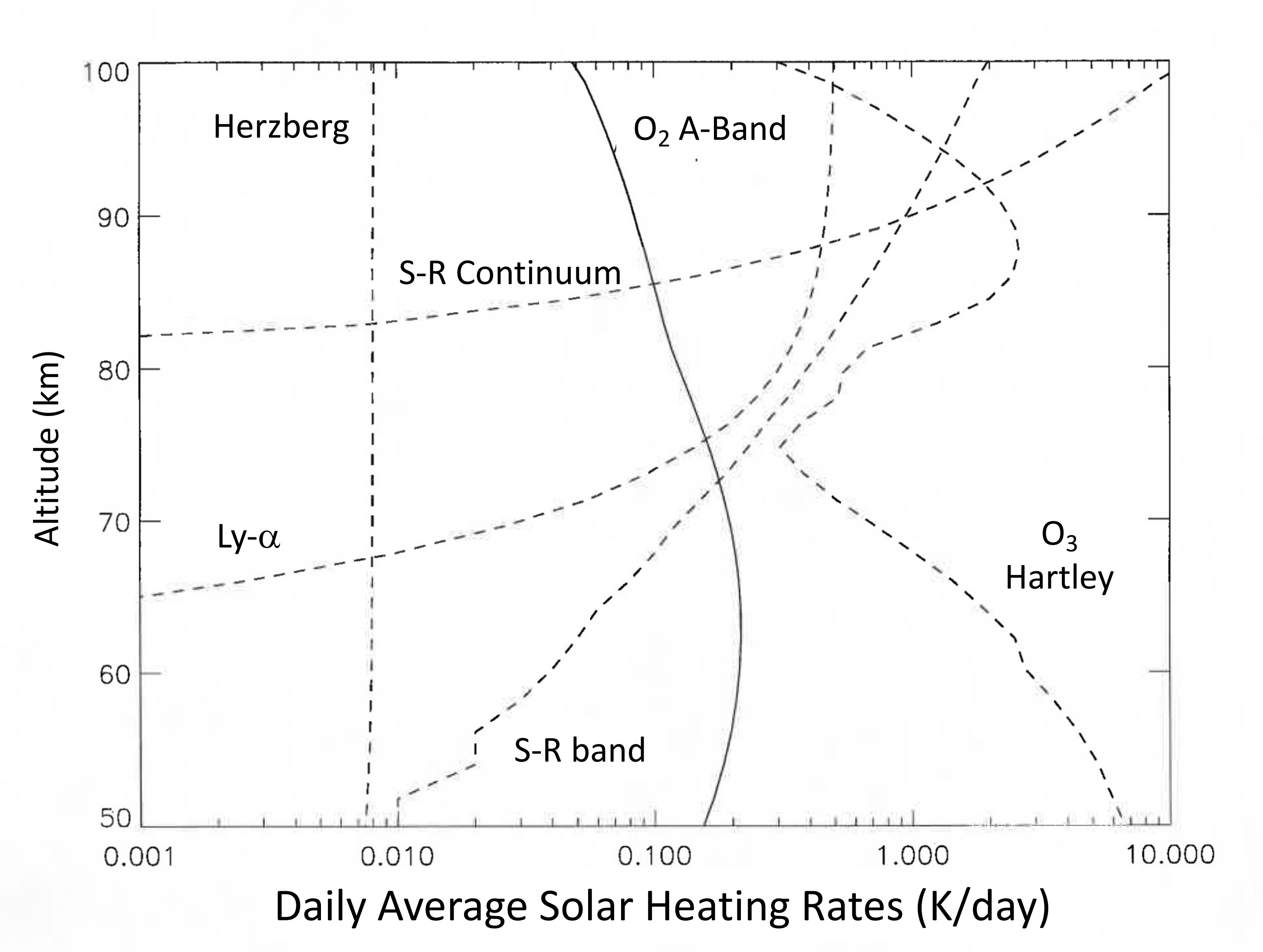
Carbon Dioxide @ 15 μm

Ozone @ 9.6 μm

Water Vapor (far-IR)

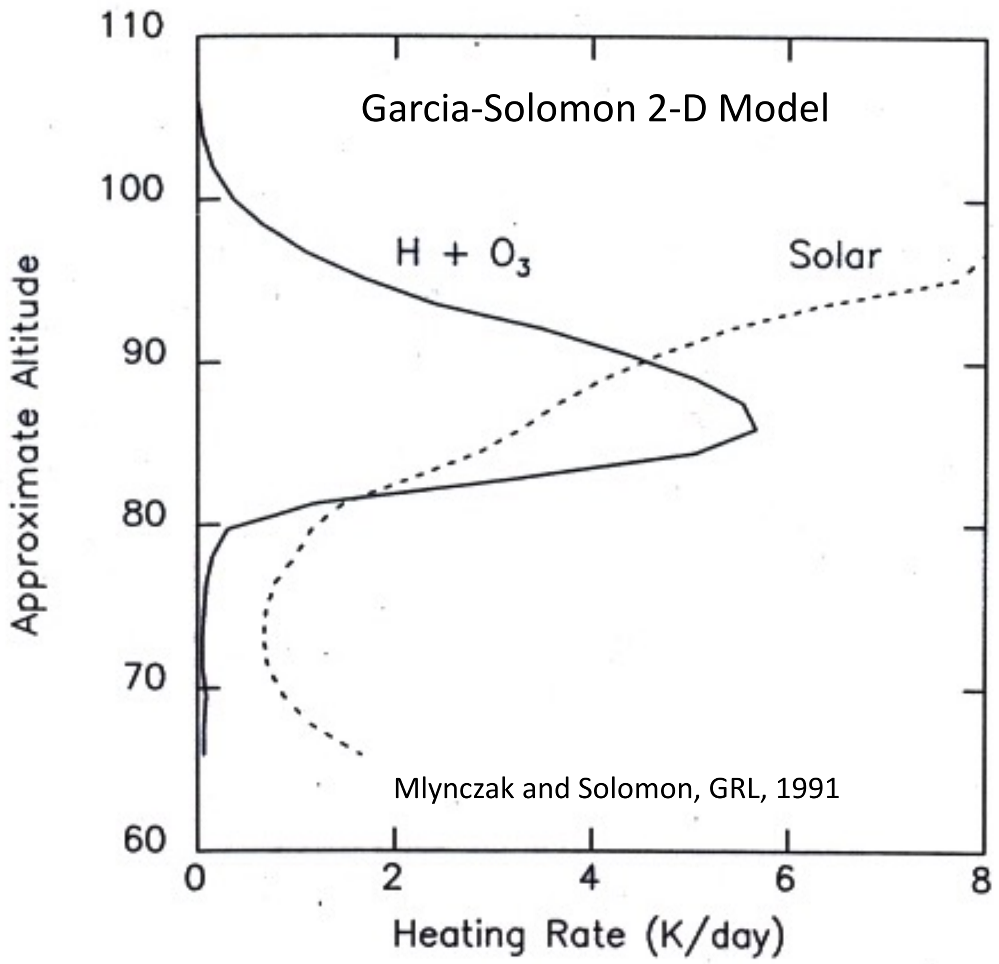
- ***Over 30 Terms!***
- **All Measured, Derived, or Computed with SABER**

Solar Heating Rates (K/day) in the M/LT



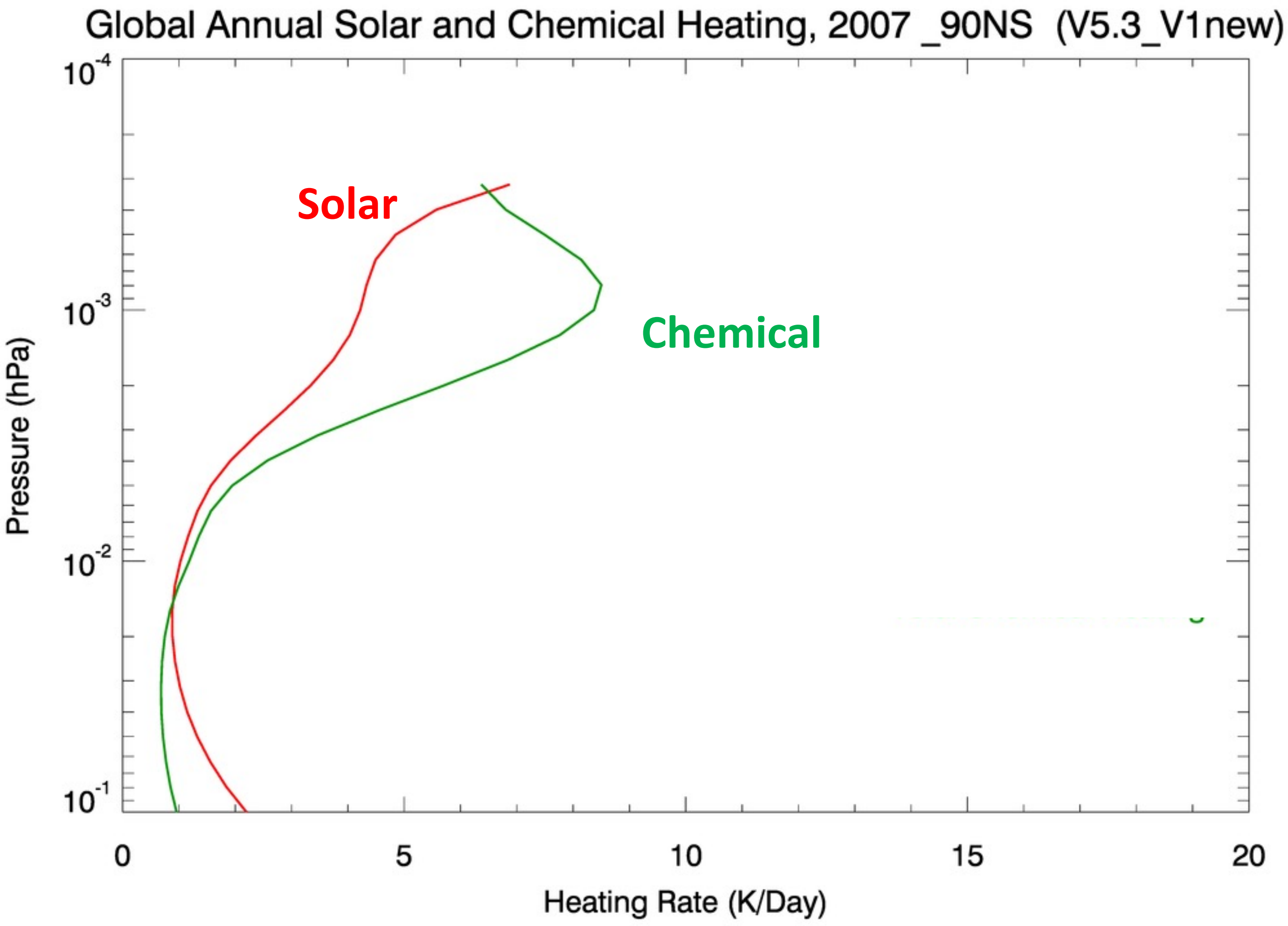
Mlynczak and Marshall, GRL, 1996

Predicted Effects of Chemical Potential Energy

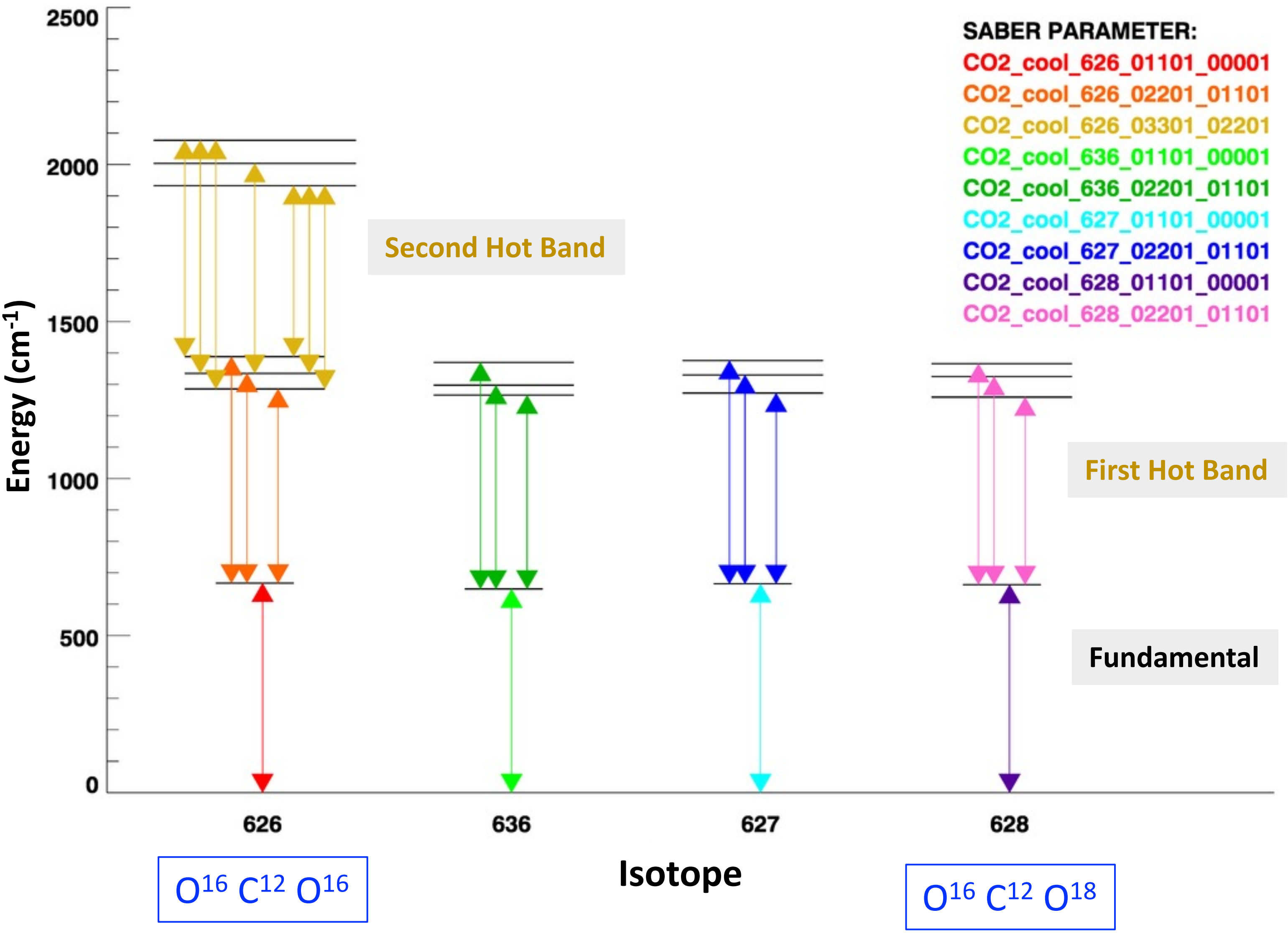


Exothermic Chemical Reactions are the Dominant Source of Heat in the Mesopause Region

SABER Confirms Role Chemical Heating in Mesopause Region

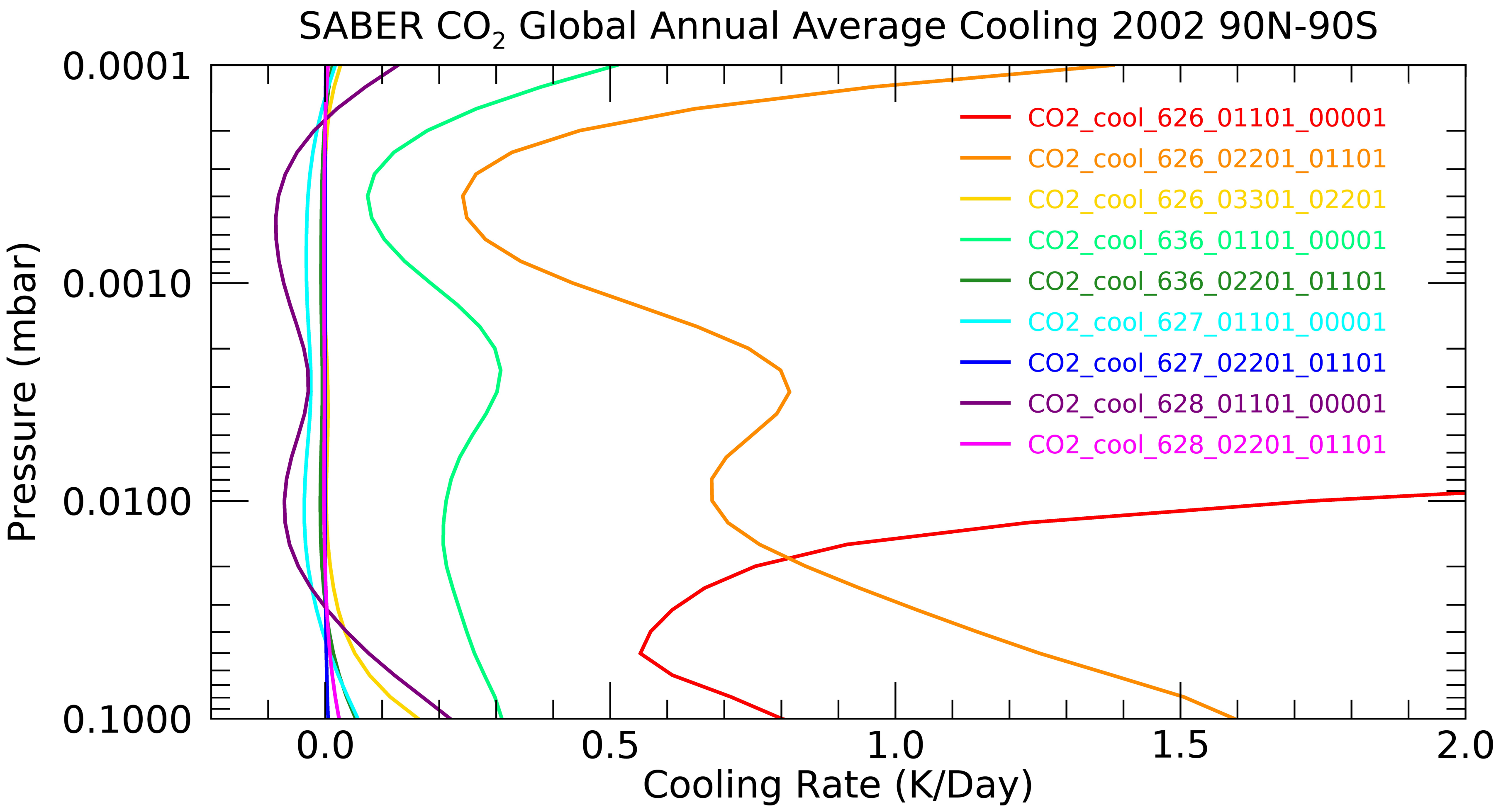


CO_2 Radiative Cooling

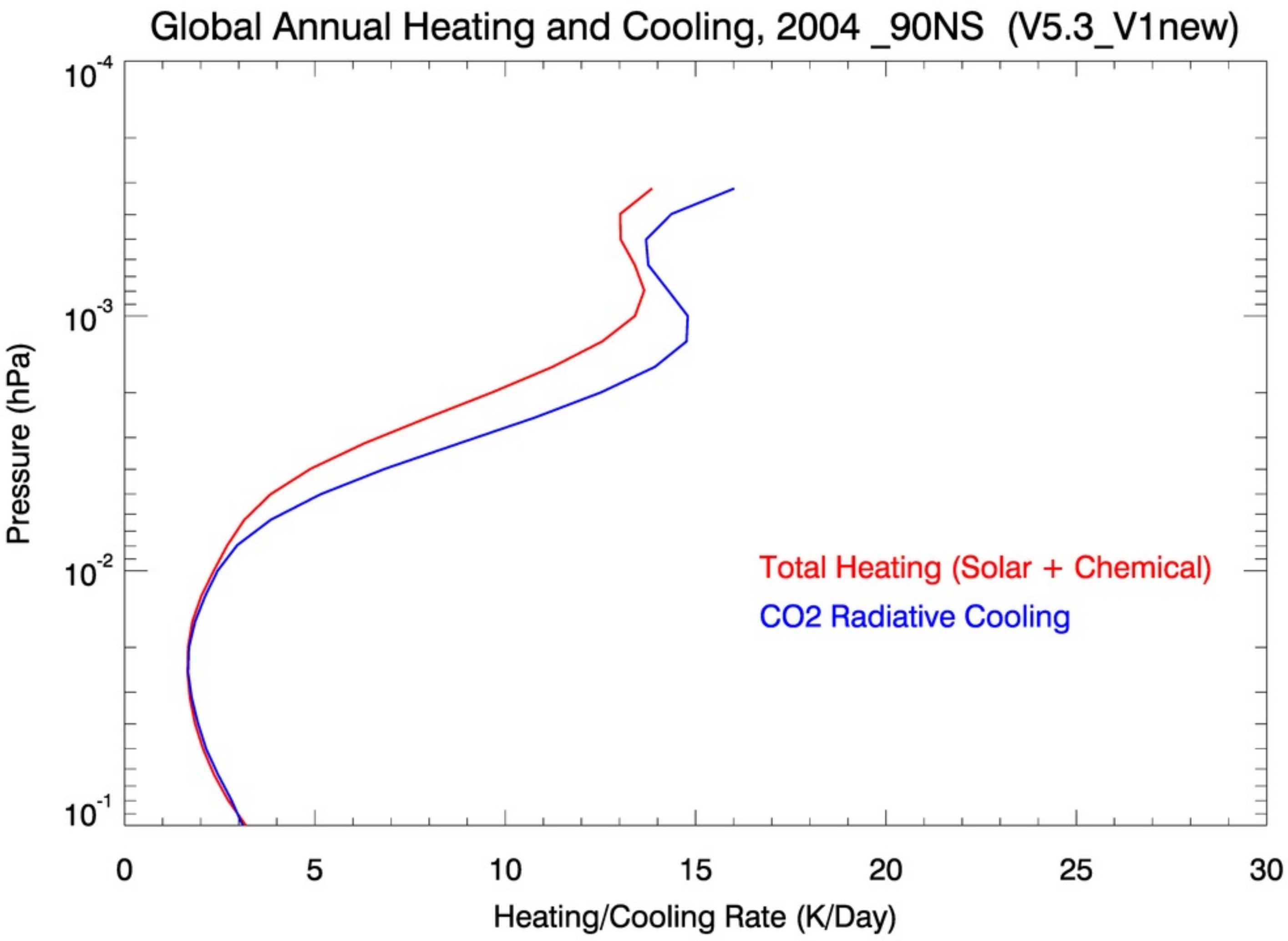


- CO_2 emission at 15 μm cools the MLT
- These are vibration-rotation transitions
- CO_2 possesses a complex vibrational structure
- At least 9 different vibration-rotation bands are important
- These involve **fundamental** and hot bands
- Also involve minor isotopes that are less than 1% of the total CO_2 amount

CO_2 Radiative Cooling Rates in the MLT



SABER Global Annual Mean Energy Balance – 2004



- CO_2 does indeed "play a significant role in the heat budget" of the mesosphere
- A near balance with total computed heating on global annual mean timescales is observed
- Energy is conserved
- So how does increasing CO_2 cool the mesosphere?

Mlynczak et al., GRL, 2018

Energy Budgets, Energy Balance, Energy Conservation

How does increasing CO_2 cause the MLT to cool?

How Does CO_2 Cool the Mesosphere and Lower Thermosphere?

Option A

- CO_2 is increasing in the MLT
- CO_2 cools the MLT through emission of infrared radiation
- Doesn't more CO_2 mean "more cooling" (i.e., *more infrared radiation*), and hence, T decreases?

Option B

- But the atmosphere is observed to have a decreasing temperature
- By fundamental infrared physics, objects emit less infrared radiation at lower temperatures
- Doesn't a colder atmosphere mean *less infrared radiation* from CO_2 as CO_2 increases?

- *Which Option is correct?*

How Does CO_2 Cool the Mesosphere and Lower Thermosphere?

Option A

- **CO_2 is increasing in the MLT**
- **CO_2 cools the MLT through emission of infrared radiation**
- **Doesn't more CO_2 mean "more cooling" (i.e., *more infrared radiation*), and hence, T decreases?**

Option B

- **But the atmosphere is observed to have a decreasing temperature**
- **By fundamental infrared physics, objects emit less infrared radiation at lower temperatures**
- **Doesn't a colder atmosphere mean *less infrared radiation* from CO_2 as CO_2 increases?**

- ***Which Option is correct? --- NEITHER!***

Why is this?

Infrared Radiation Exiting the MLT

- Infrared radiation is the "exhaust" of the climate system
- IR radiation expels the energy that is deposited into the MLT system
- The only way to change (+ or -) the energy out of the MLT is to change the energy coming in
- On climate timescales (annual to decadal) the energy leaving the MLT has to balance the energy coming into it (*energy has to be conserved*)
- The MLT cannot be made to radiate more or less energy by changing its composition
- If there is no long-term change to the energy input to the MLT, there will be no long-term change to the energy output from the MLT

Using the Cooling Rates "in Reverse" to compute Energy Fluxes

- **First law of thermodynamics**:

$$\frac{\partial Q(z)}{\partial t} = \rho\, C_p \frac{\partial T(z)}{\partial t}$$

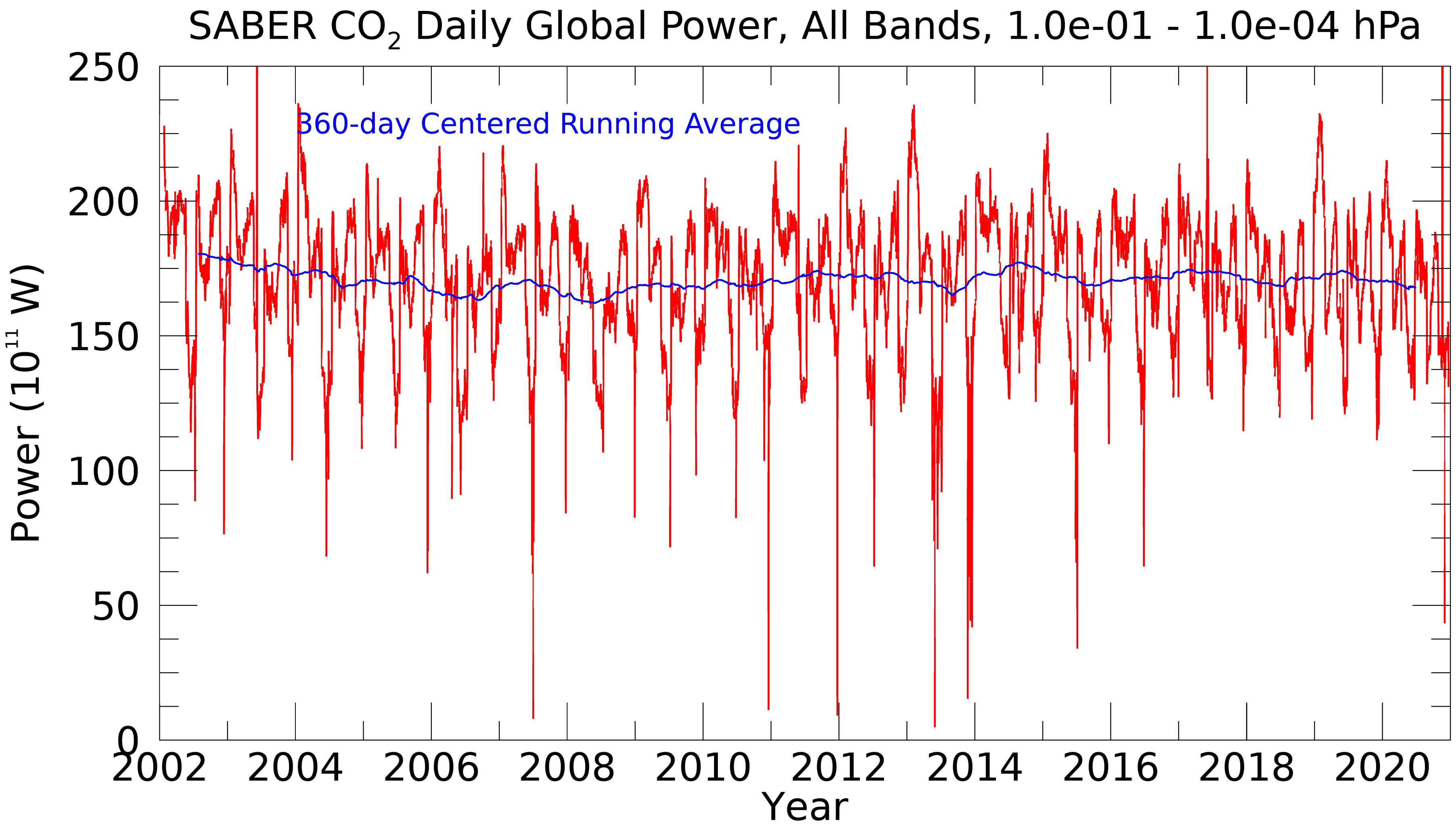
- **Use derived cooling rates (K/day) to get $\partial Q/\partial t$ (W/m^3)**

- **Vertically integrate ∂Q/∂t w/r/to pressure get net flux of IR exiting MLT:**

$$Flux(Wm^{-2}) = -\frac{C_p}{g} \int_{p_1}^{p_2} \frac{\partial T(p)}{\partial t}\, dp$$

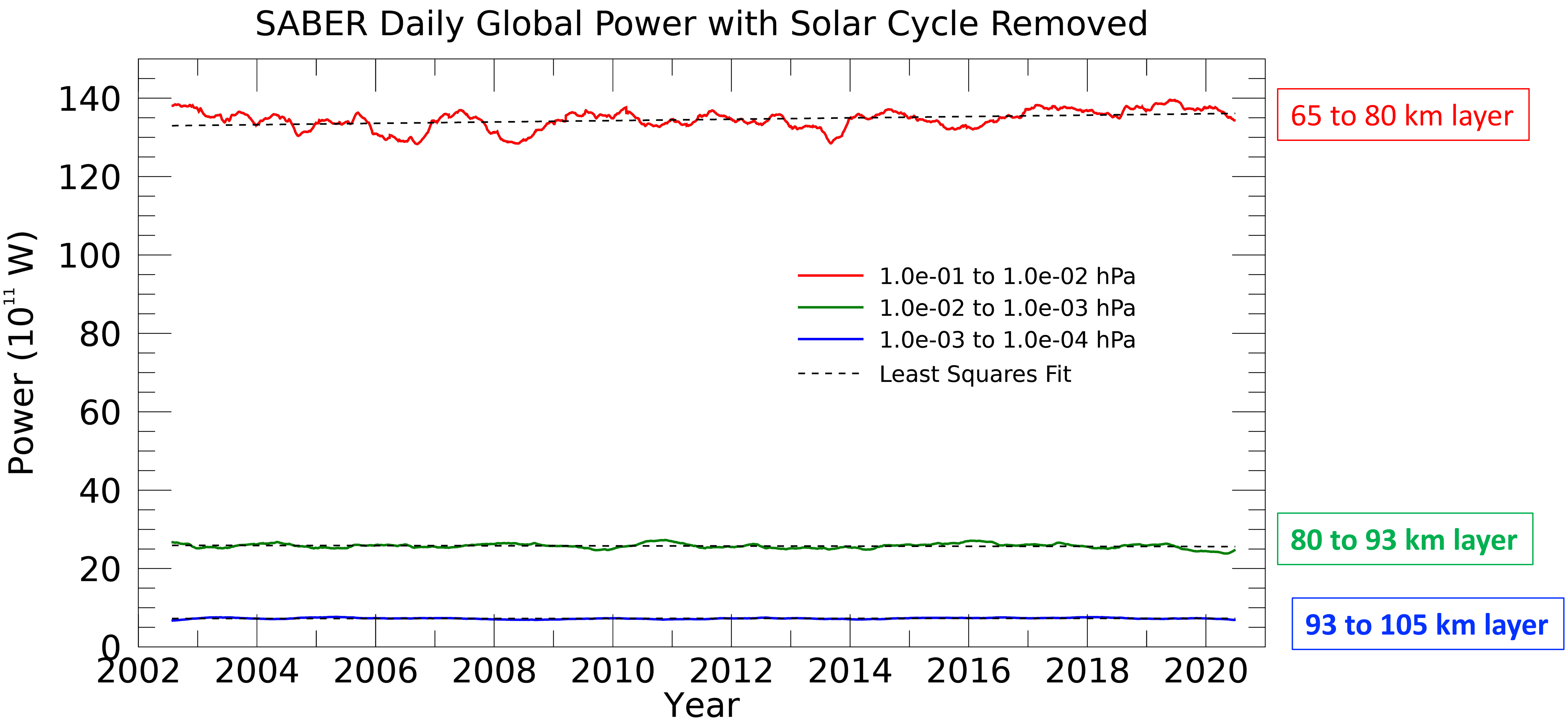
- **What Does the Satellite Record Show?**

Daily Global Power (W) Exiting the MLT



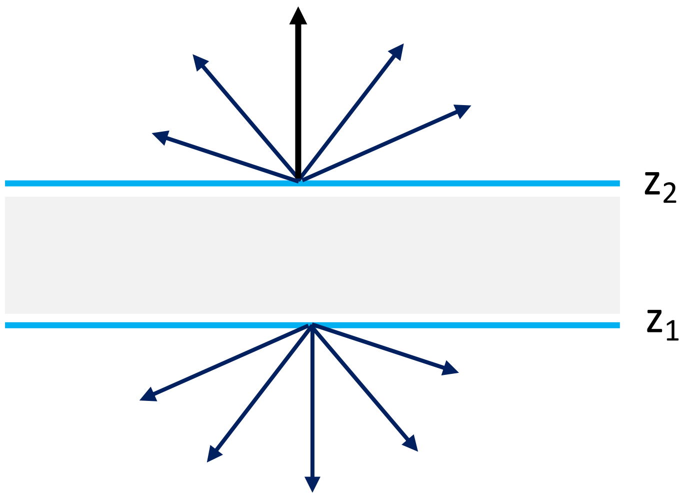
- **Power (W) exiting MLT between 65 km and 105 km (Global)**
- **Red – 7000 days of data**
- **Blue – Running annual average**
- **~ 42 mW per square meter**
- **What is the long-term trend in energy?**

No Trend in Infrared Energy Leaving the MLT



How Does CO_2 Cool the Mesosphere and Lower Thermosphere?

- The radiance (R_ν) emitted from a layer of atmosphere is the product of two terms, ε_ν and J_ν
- The emissivity (ε_ν)depends on the CO_2 amount
- The source function (J_ν) depends on the temperature
- In the long-term, if the energy into the system is constant, R_ν must be constant
- Adding CO_2 increases ε_ν. If R_ν is constant, J_ν (i.e., temperature) must decrease to keep it so



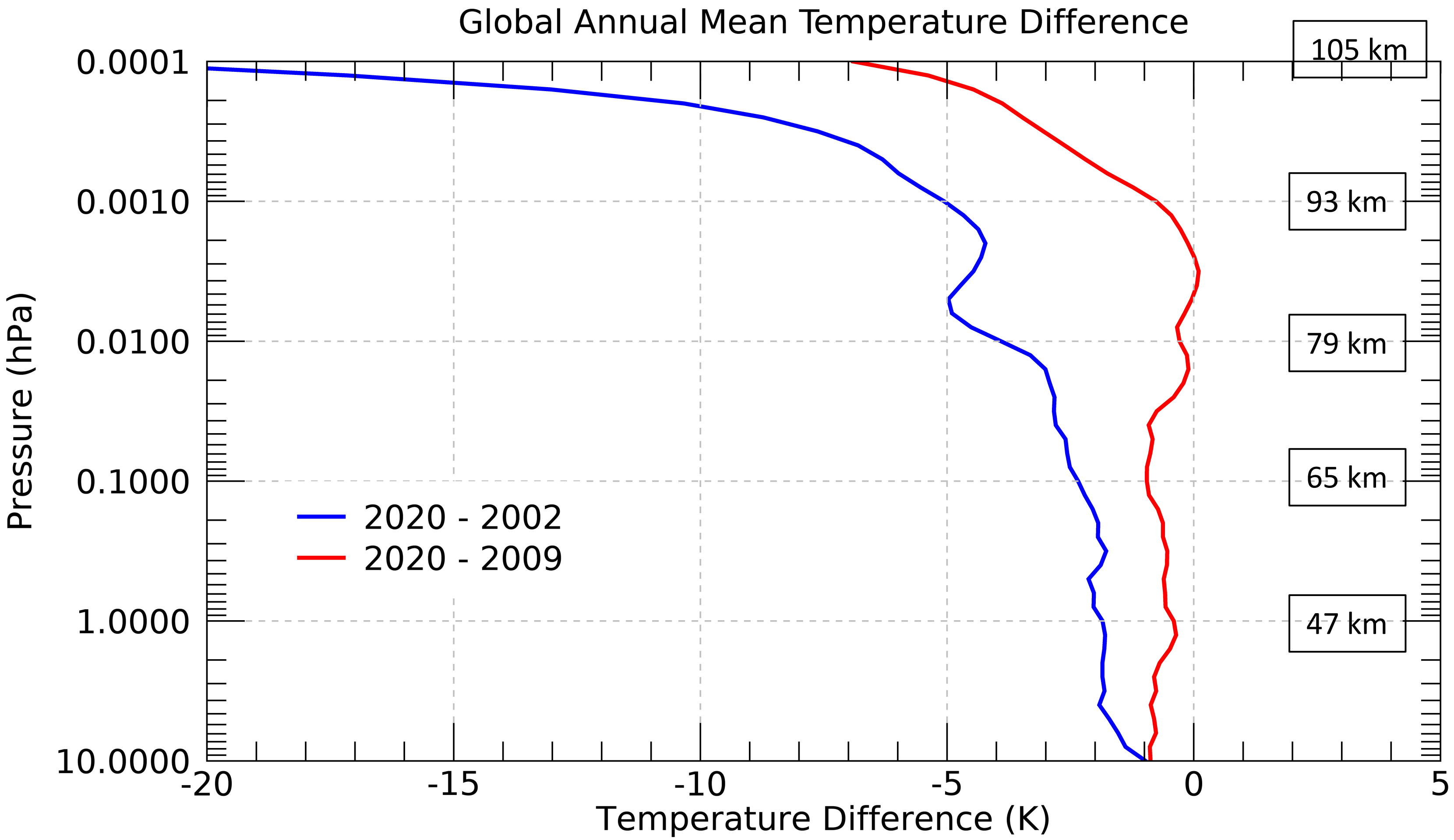
$$R_\nu = \varepsilon_\nu \times J_\nu$$

Thus, adding CO_2 allows the MLT to radiate the same amount of energy, but at a lower temperature

Disclaimer: Do not apply this concept to the troposphere – the physics is different

The Cooling and Contracting Mesosphere and Lower Thermosphere

Cooling of the MLT from 2002 to 2020



- Cooling MLT from 2002 to 2020
- Measured by SABER on TIMED
- Global annual mean temperatures
- MLT 2 K to 20 K colder in 2020
- Due to weakening solar cycles and increasing CO_2
- Substantial effect on structure of the MLT system

Definition of Geopotential Height

The geopotential $\Phi(h)$ is the gravitational potential energy per unit mass at altitude *h*

The geopotential is defined as:

$$\Phi(h) = \int_0^h g(z)\,dz$$

The geopotential height, $Z_g(h)$, is defined as the geopotential relative to the standard acceleration due to gravity at Earth's surface:

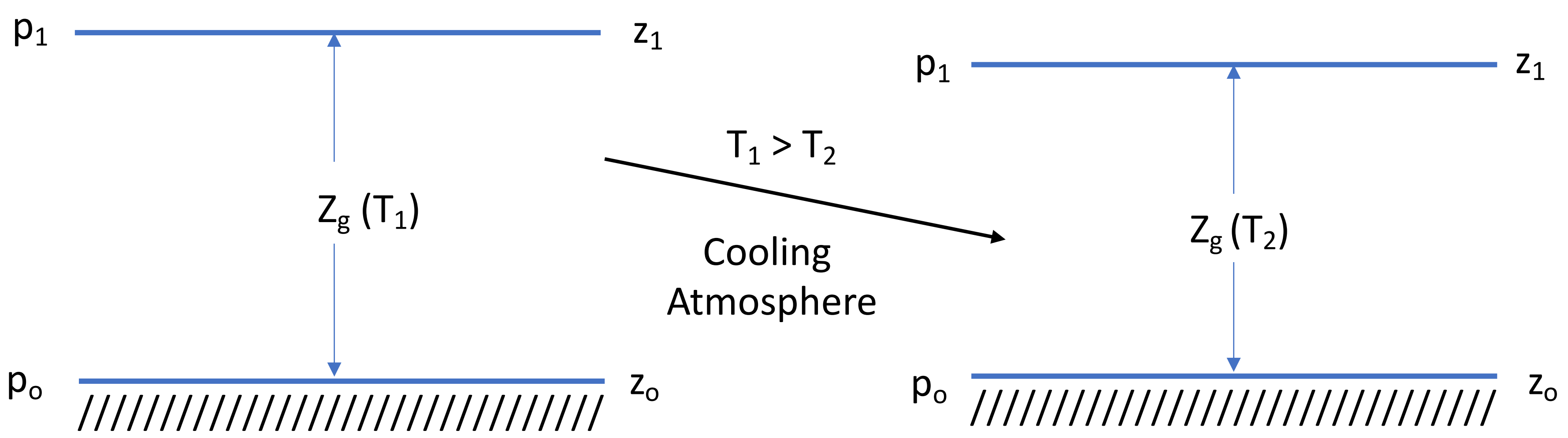
$$Z_g(h) = \frac{\Phi(h)}{g_0}$$

SABER provides $Z_g(h)$ of each point in pressure in the vertical

- **Examine $Z_g(h)$ to determine change in geopotential height of pressure surfaces**
- **Examine differences in $Z_g(h)$ between different pressure surfaces to examine "thickness" of layers**

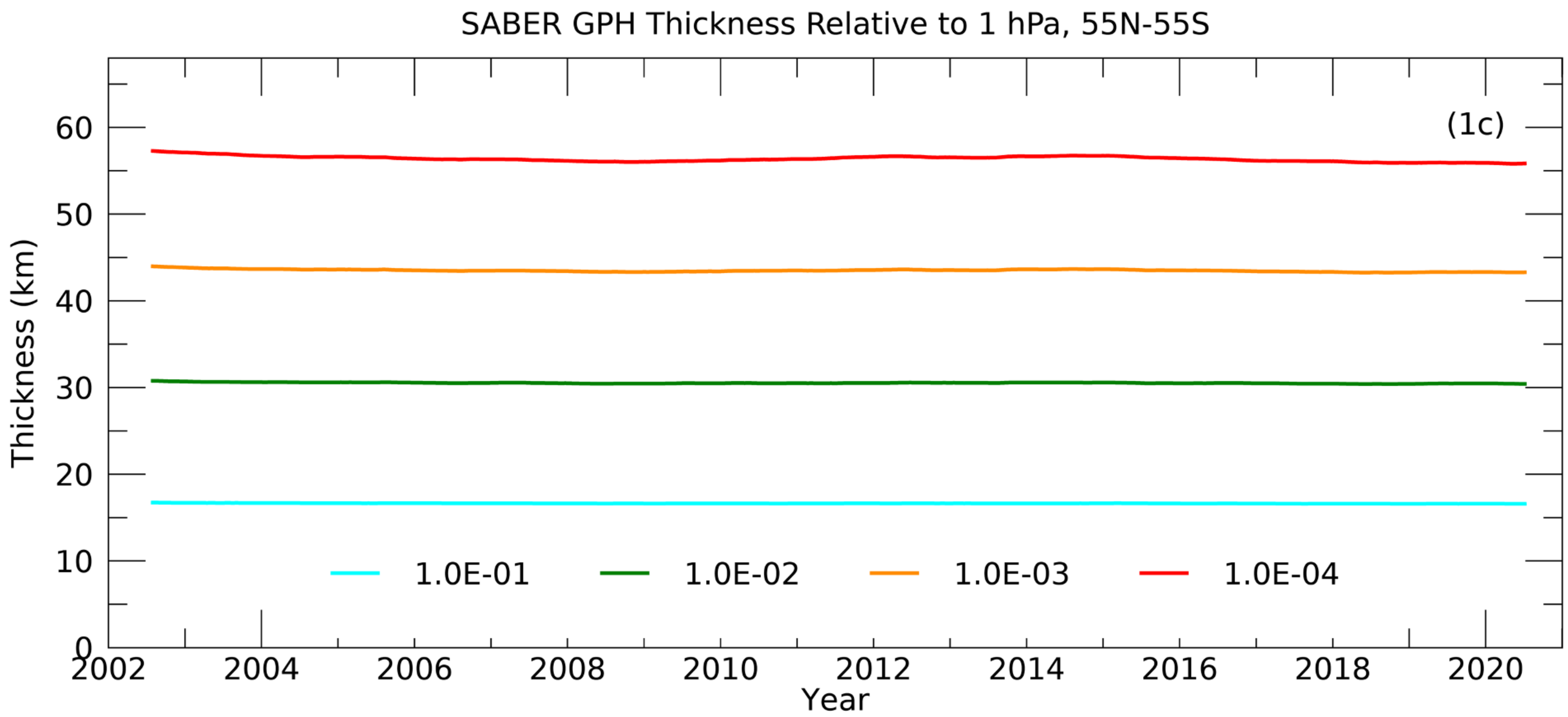
Concept of Thickness and Contraction of Atmospheric Layers

- **Pressure is the natural vertical coordinate of the atmosphere**
- **Compute the geopotential height (Z_g) between any two pressure surfaces**



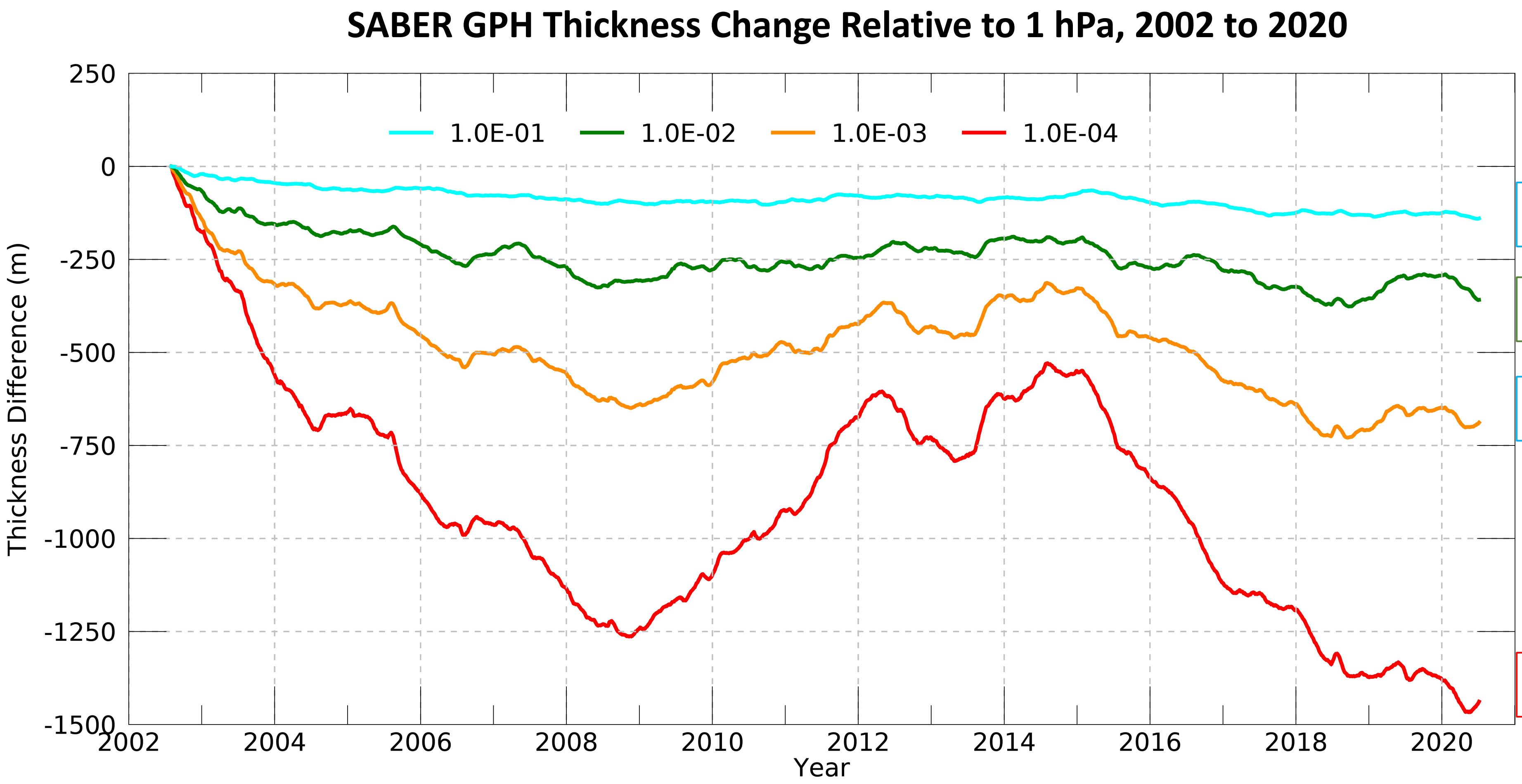
- **As the atmosphere cools, Z_g will decrease – that is, the "thickness" of the atmosphere decreases**
- **This decrease is observed over time in the mesosphere and lower thermosphere with Zg from SABER**

Global Annual Mean Thickness Relative to 1 hPa (47 km)



SABER Change in Geopotential Thickness from 2002 (meters)

The Entire MLT has Contracted from 2002 to 2020



ΔZ_g, 47 to 65 km ~ 130 m

ΔZ_g, 47 to 80 km ~ 375 m

ΔZ_g, 47 to 93 km ~ 700 m

ΔZ_g, 47 to 105 km ~ 1500 m

Summary

- Energy is conserved and CO_2 plays a significant role in the MLT heat budget
- CO_2 is increasing throughout the entire perceptible atmosphere
- This is causing simultaneous surface warming ***and*** MLT cooling - as predicted!
- CO_2 cools the MLT by allowing it to radiate the same amount of energy at a lower temperature
- The MLT today is 2 K to 20 K colder today than in 2002
- The MLT has contracted by 1500 m between 47 km and 105 km since 2002
- These changes are due to a combination of weak solar cycle activity and carbon dioxide increase
- The MLT is likely the coldest it has been in the past 250 years, and possibly than in tens to hundreds of thousands of years

A View to the Future

- The MLT has been under continuous observation since 2002
- No new missions or instruments in development or planned to continue this remarkable record
- A gap in observations seems unavoidable
- Continuity of observations is essential to understand the ongoing change in this region and its influence on the geospace (200 to 1000 km) above

https://eos.org/opinions/an-observational-gap-at-the-edge-of-space

Thank You!