Carbon Dioxide – A Force for Global Change Throughout the Earth's Atmosphere

Dr. Marty Mlynczak
NASA Langley Research Center, Hampton, VA
&
Co-Authors

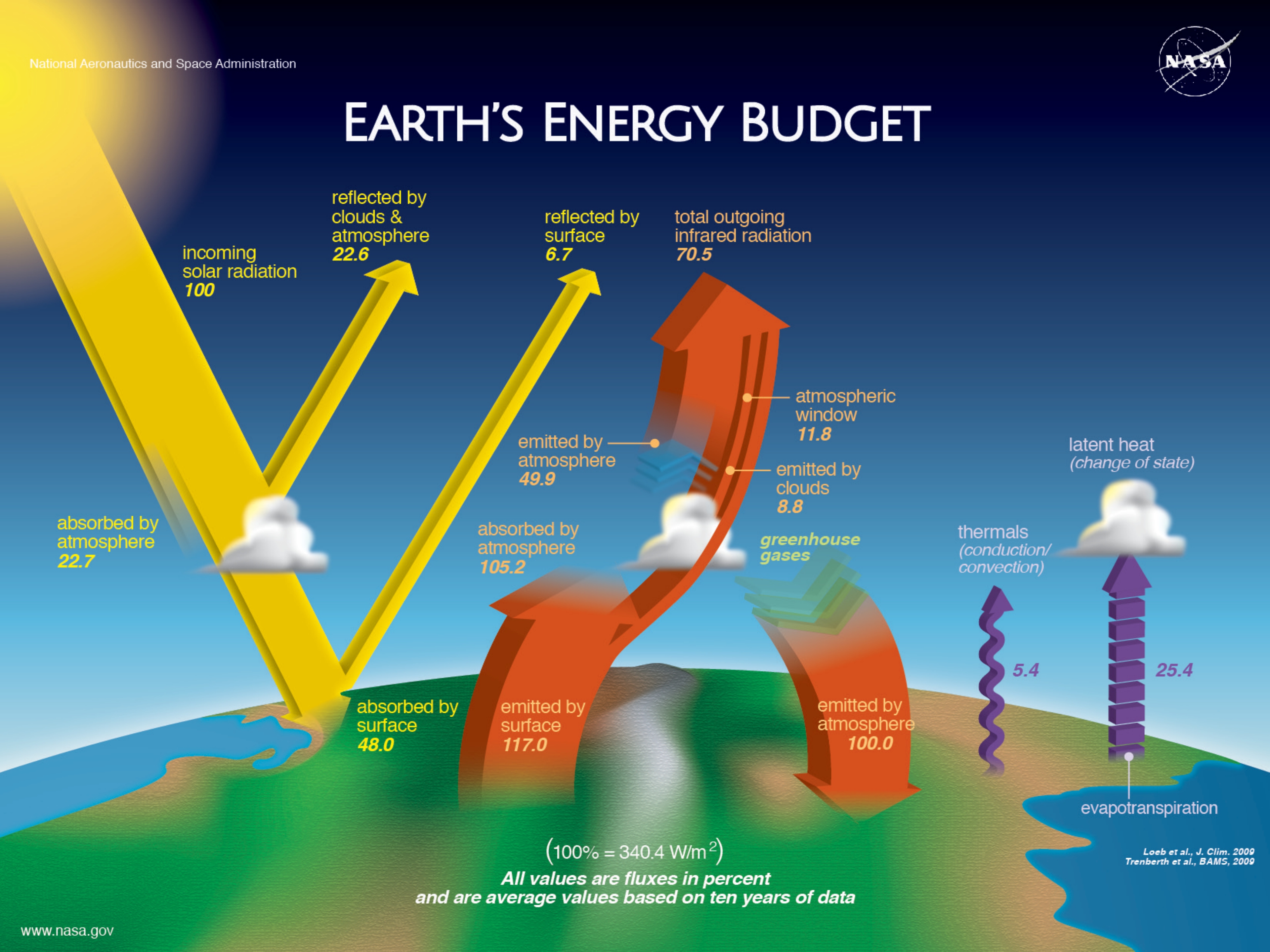
Co-Authors

- NASA Langley
  - Taumi Daniels
  - David Kratz
  - Jeffrey Mast
  - Linda Hunt
- AER
  - Eli Mlawer
  - Matthew Alvarado
- Lawrence Berkeley Lab
  - William Collins
  - Daniel Feldman
- NOAA ESRL
  - David Fahey
- University of Wisconsin
  - Wilmer Anderson
  - James Lawler
  - Susan Nossal

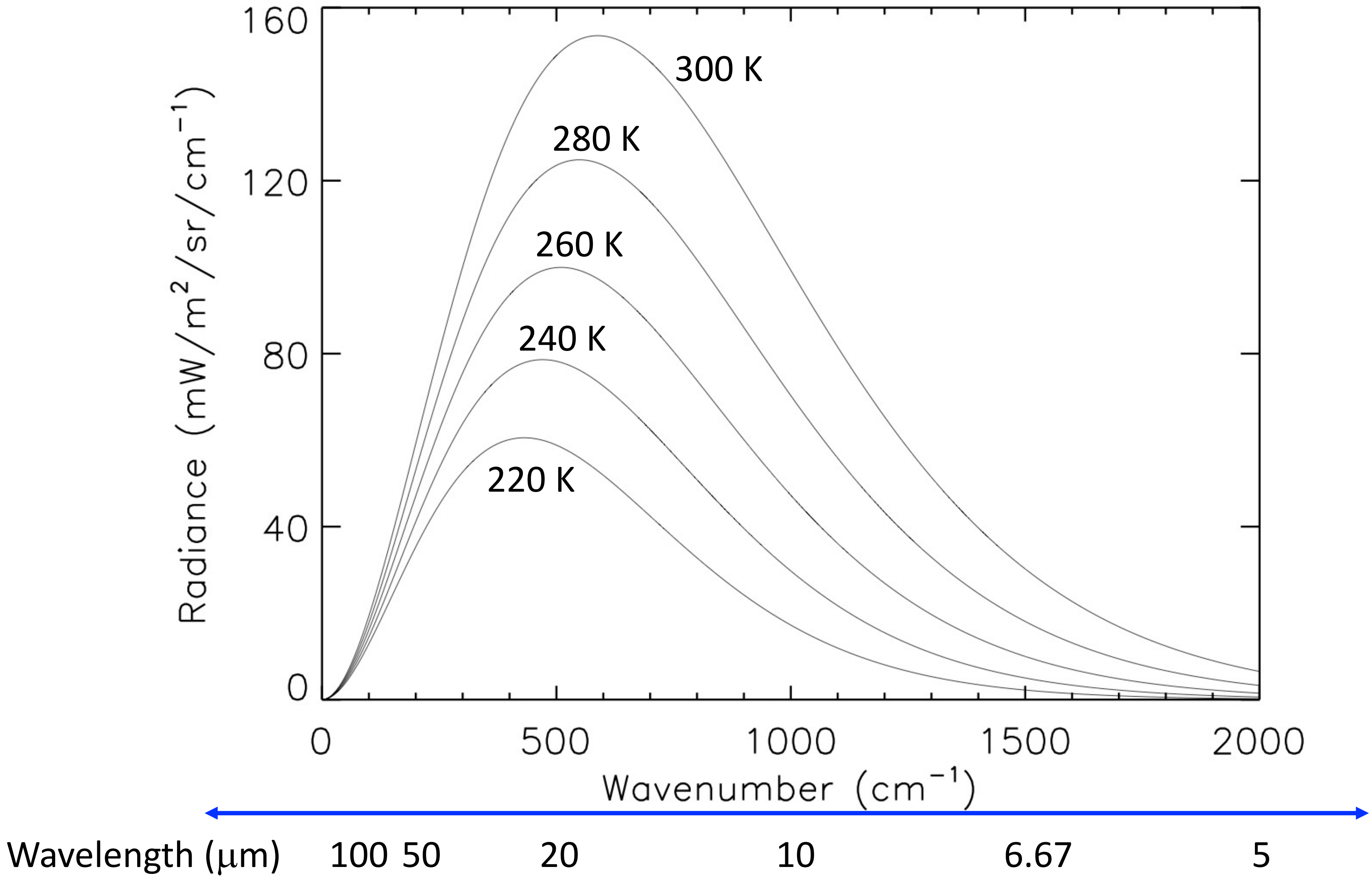
Outline

- **Earth's Energy Budget**
- **Earth's Infrared Emission Spectrum**
- **Concept of Transmittance and Absorptance – Role of CO_2**
- **Effects of Increasing CO_2 on Climate**
- **Radiative Forcing – Energetic effect of increasing CO_2**
- **Consideration of Spectral Line Shapes and Radiative Forcing**
- **Effects Increasing CO_2 on Near-Space Environment**
- **Space-based observations of these + Summary**

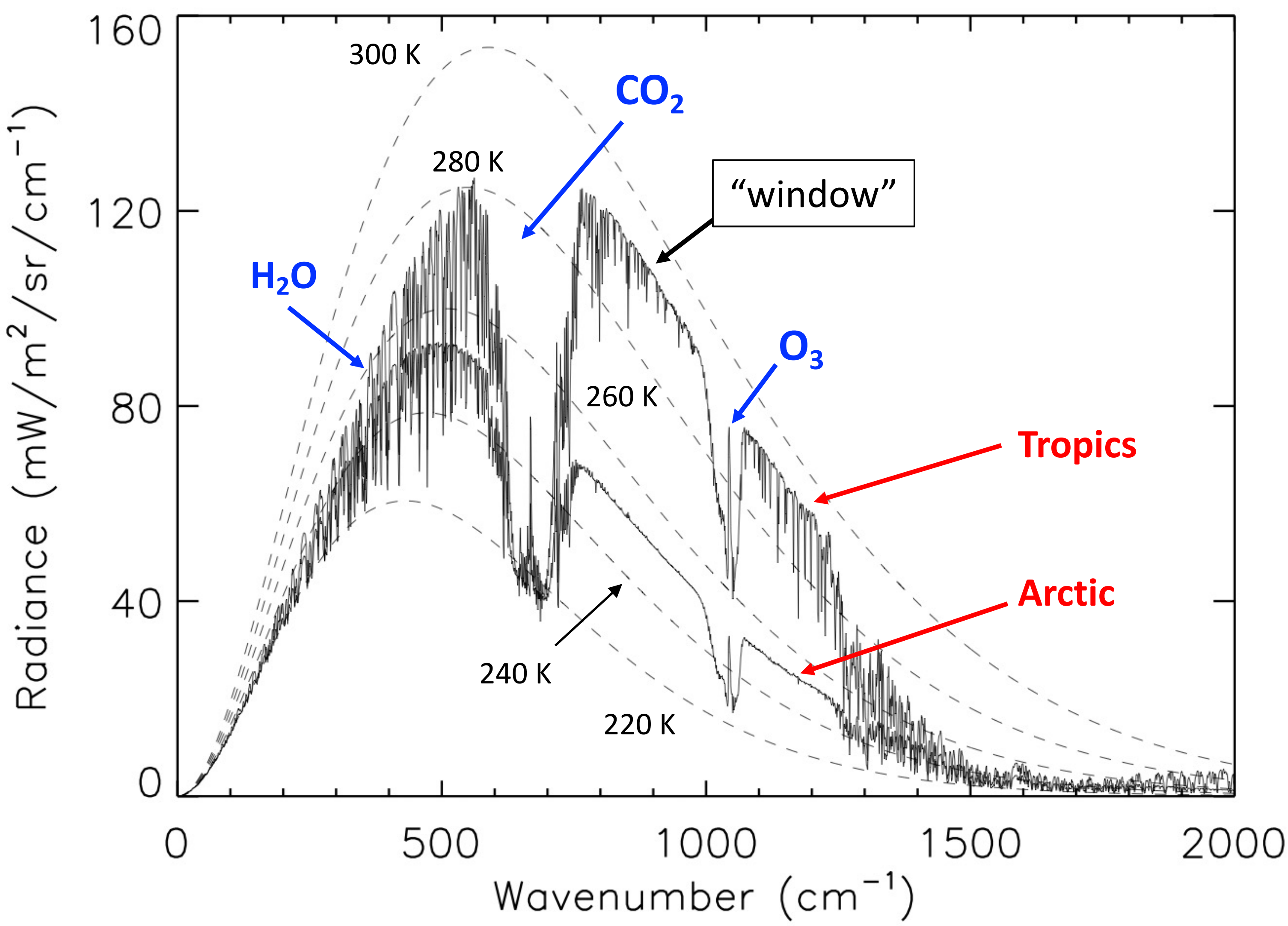
Increasing CO_2 Alters Climate from Earth's Surface to the Edge of Space!


National Aeronautics and Space Administration
NASA
EARTH'S ENERGY BUDGET
incoming solar radiation 100
reflected by clouds & atmosphere 22.6
reflected by surface 6.7
total outgoing infrared radiation 70.5
atmospheric window 11.8
emitted by atmosphere 49.9
emitted by clouds 8.8
latent heat (change of state)
absorbed by atmosphere 22.7
absorbed by atmosphere 105.2
greenhouse gases
thermals (conduction/ convection)
5.4
25.4
absorbed by surface 48.0
emitted by surface 117.0
emitted by atmosphere 100.0
evapotranspiration
(100% = 340.4 W/m²)
All values are fluxes in percent and are average values based on ten years of data
Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009
www.nasa.gov

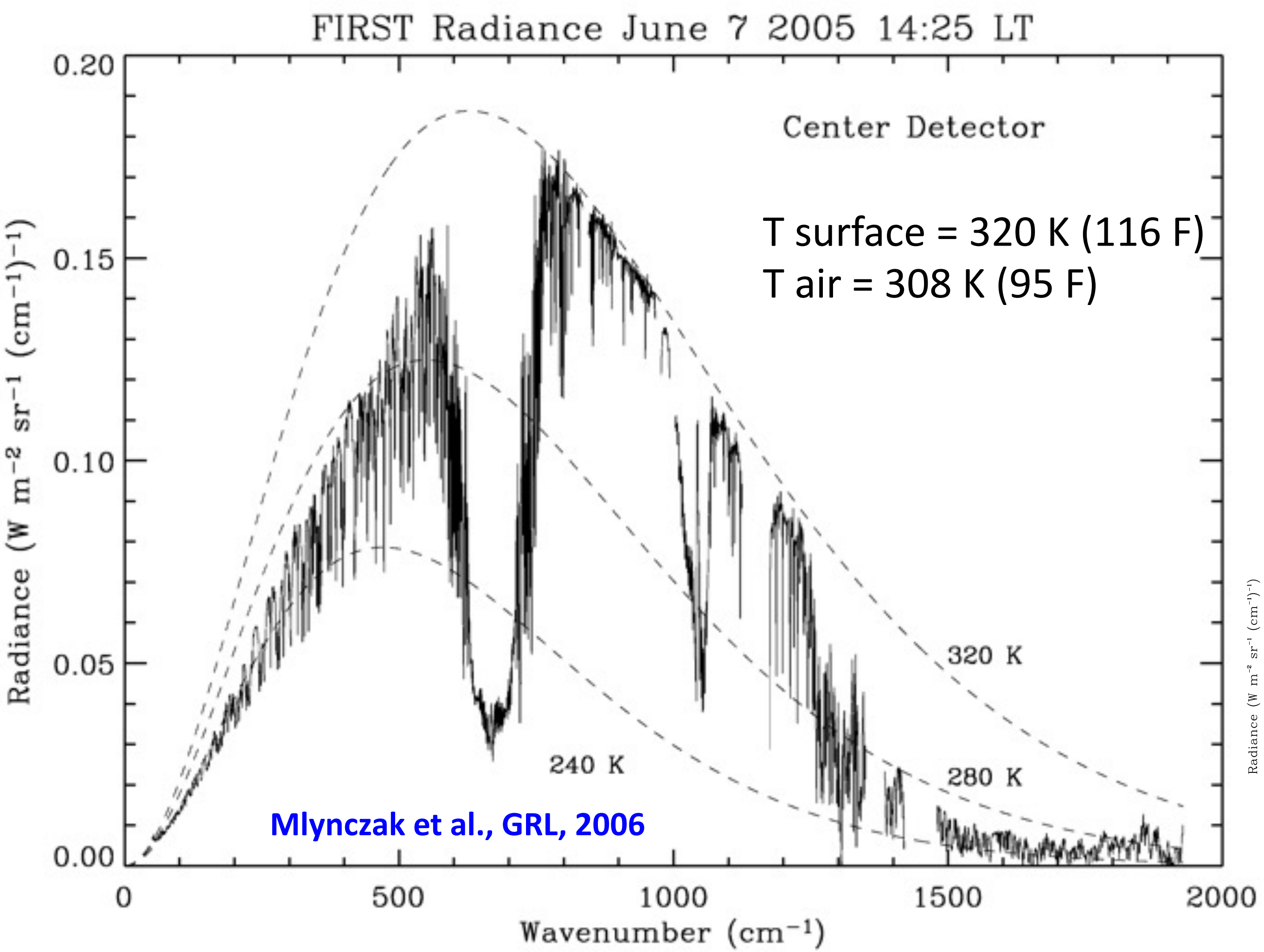
Idealized Earth Surface Infrared Emission
- Planck Blackbody Functions -



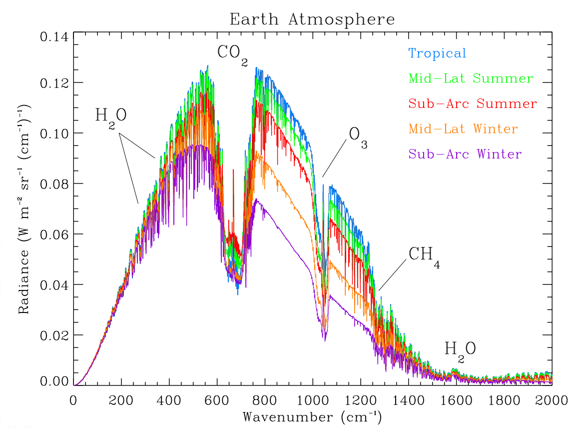
Tropical & Arctic Top-of-Atmosphere Emission Spectra



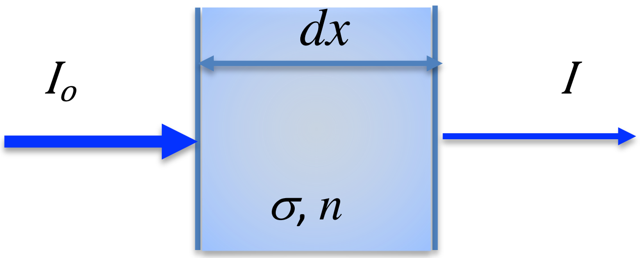
Measured Top-of-Atmosphere IR Spectrum



Ft. Sumner, NM



Concept of Atmospheric Transmittance and Absorptance



$$\frac{dI}{I} = -\sigma\, n\, dx$$

n = # molecules/cm^3
σ = cross section

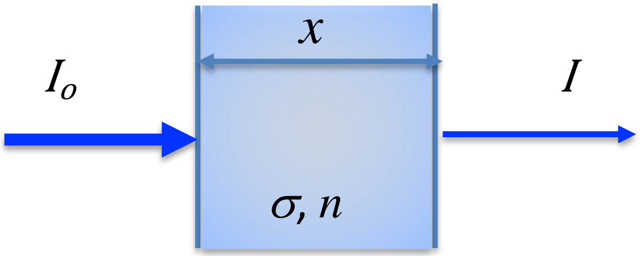
$$\frac{I}{I_o} = \exp(-\sigma\, n\, x) = \exp(-\,\tau\,)$$ = 'Transmittance'

Absorptance = 1 – exp (- $\sigma\, n\, x$) = 1 - Transmittance

Increase n (e.g., CO_2) → Absorptance Increases → More Energy Retained

Computing change in atmospheric transmittance due to increasing CO_2 is fundamental to understanding of climate change

Concept of Transmittance and Photon Mean Free Path



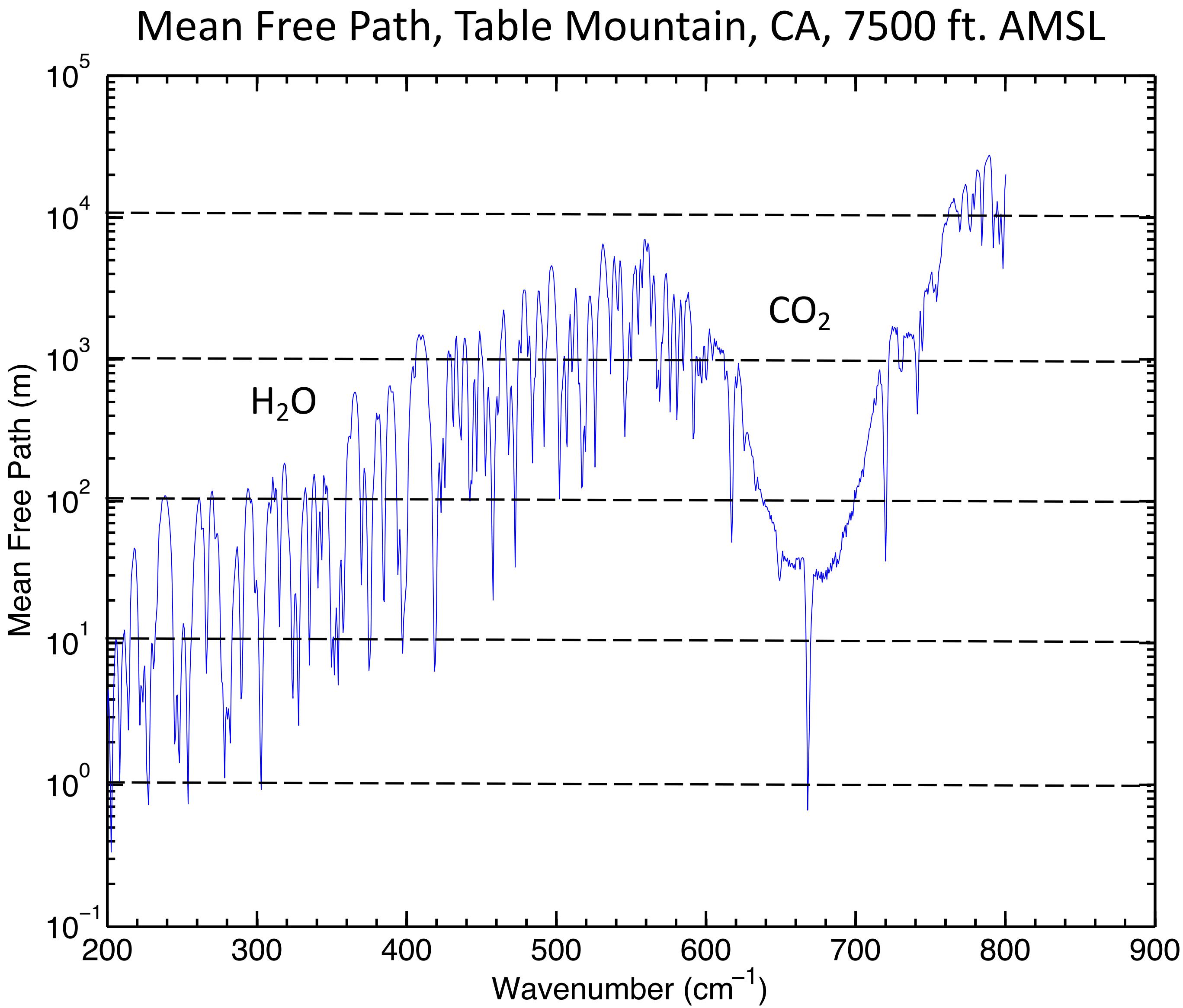
$$\frac{I}{I_o} = \exp(-\sigma\, n\, x) = \exp(-\tau) = \text{'Transmittance'} = t$$

n = # molecules/cm^3

σ = cross section

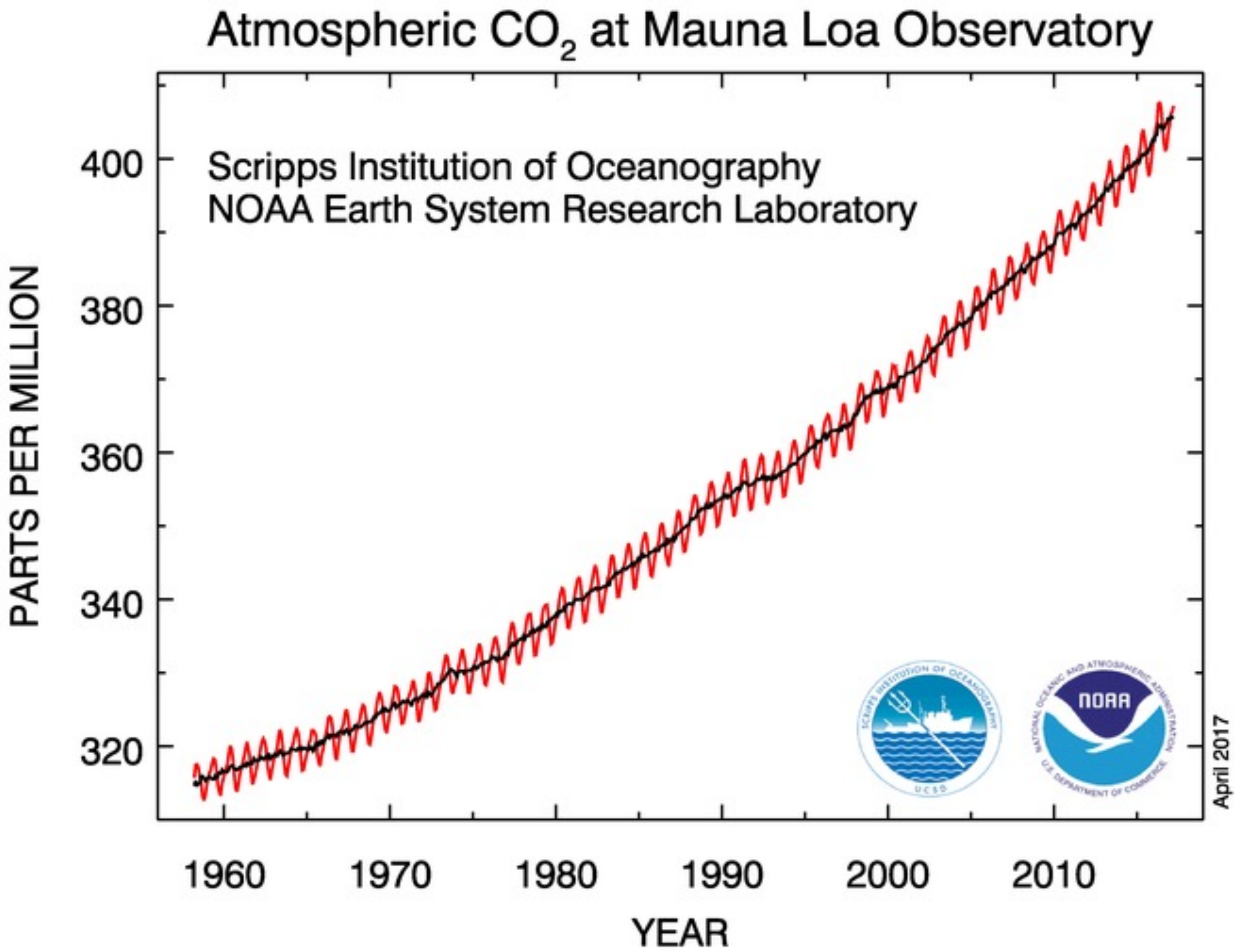
Mean Free Path is distance $\boldsymbol{x}$ to make $\boldsymbol{\tau} = 1$ → Transmittance = $1/e$

The mean free path allows us to see where the radiation emitted near Earth's surface is largely absorbed in the atmosphere



Mlynczak et al., JQSRT, 2016

CO_2 Has Been Rapidly Increasing for 60 Years!



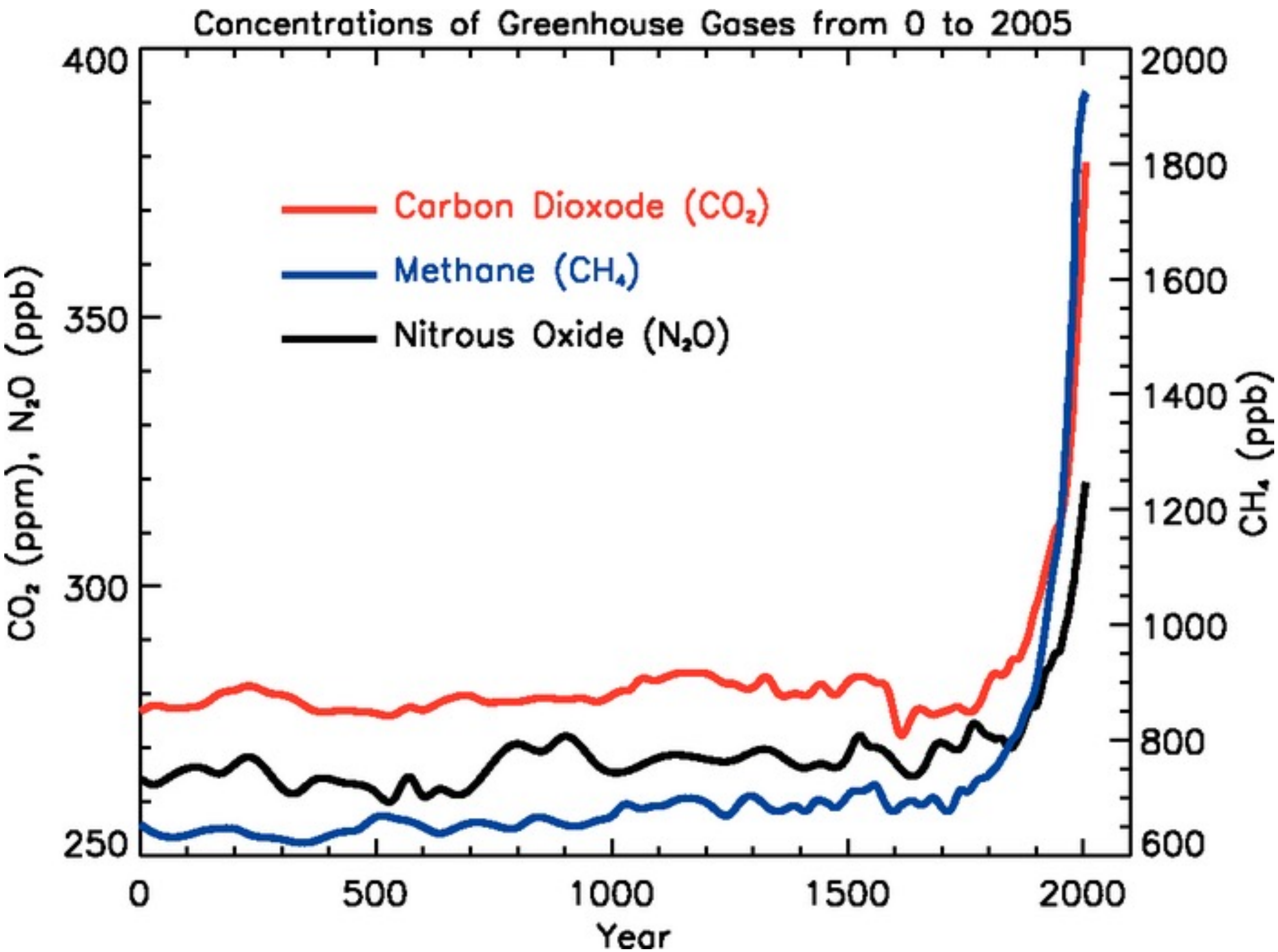
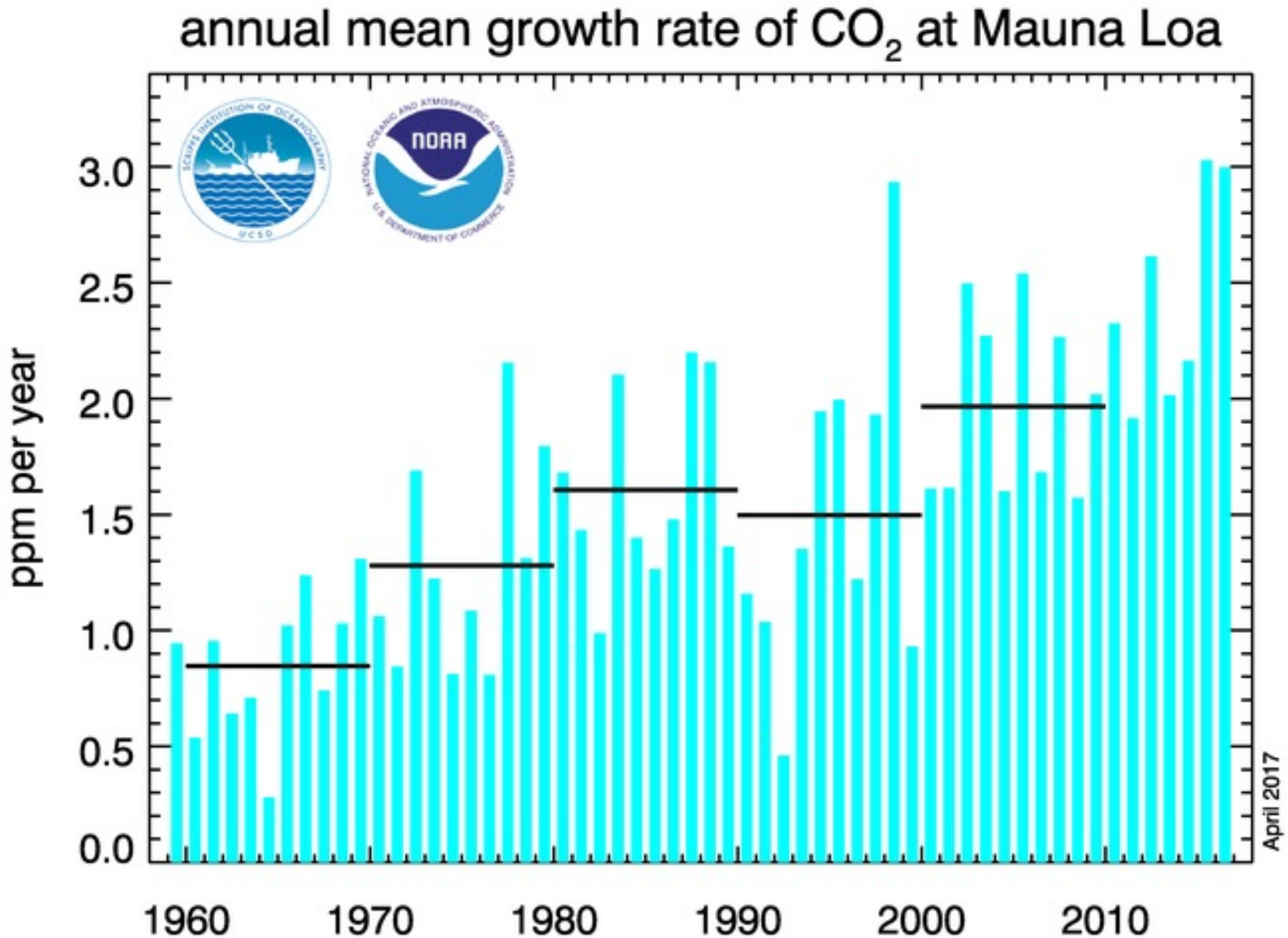


Figure 1, FAQ 2.1, IPCC Fourth Assessment Report (2007), Chapter 2



annual mean growth rate of CO_2 at Mauna Loa
ppm per year
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1960
1970
1980
1990
2000
2010
April 2017
NOAA

Digging Deeper – Transmittance Calculation

$$t = \exp(-\sigma_\nu\, n\, x)$$

$$\sigma_\nu = S \cdot g(\nu - \nu_0)$$

S is the "line strength" for each (tens of thousands) of spectral lines

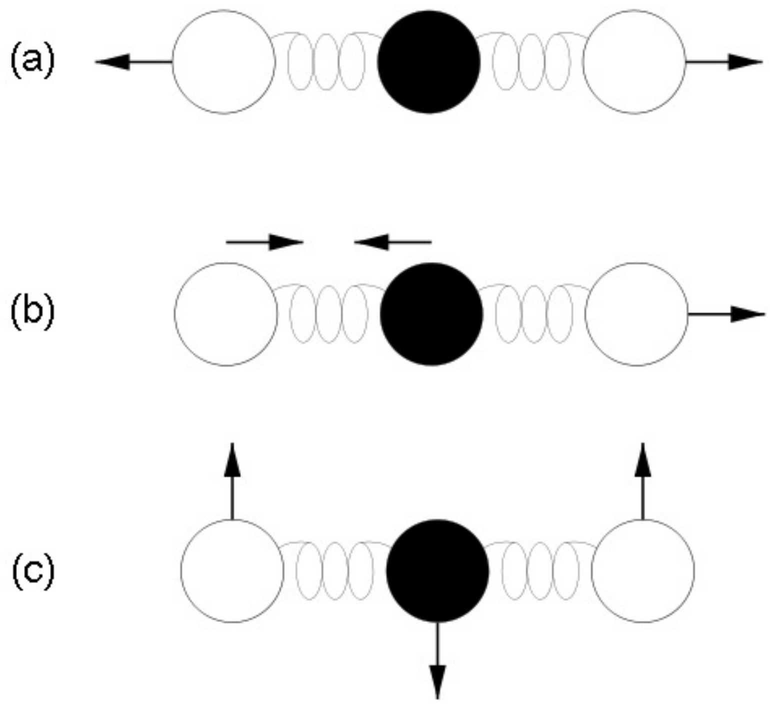
S is tabulated and obtained from a combination of measurements and Q-M calculations

$g(\nu - \nu_0)$ is the "line shape"

Lineshape function is critical to getting the transmittance – and hence, predictions of climate change, correct!

How Does CO_2 Absorb Infrared Radiation?

O --------- C --------- O



The chemical bonds holding the atoms together can be thought of as springs

They vibrate upon absorption of energy

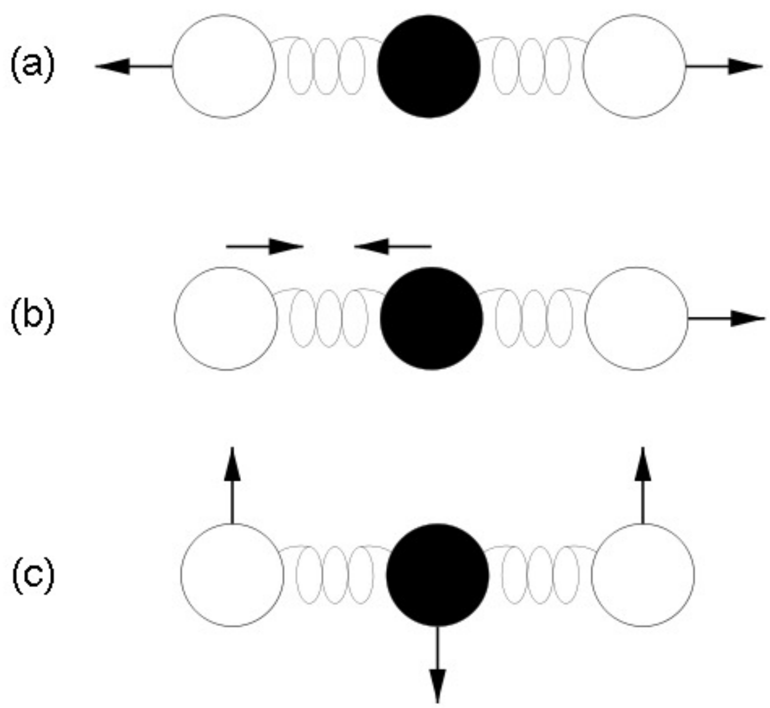
When vibration ceases, energy is lost from the molecule

This is sometimes in the form of an infrared photon of energy $E = h\nu$, where ν is the frequency of vibration

[Molecular Vibrations]

How Does CO_2 Absorb Infrared Radiation?

O --------- C --------- O



The chemical bonds holding the atoms together can be thought of as springs

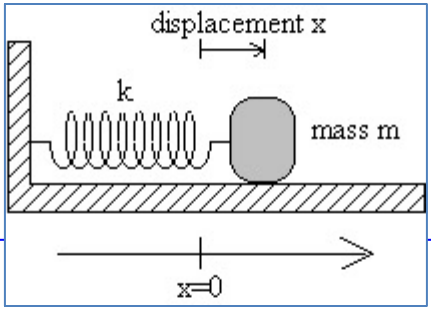
They vibrate upon absorption of energy

When vibration ceases, energy is lost from the molecule

This is sometimes in the form of an infrared photon of energy $E = h\nu$, where ν is the frequency of vibration

We model this as harmonic motion

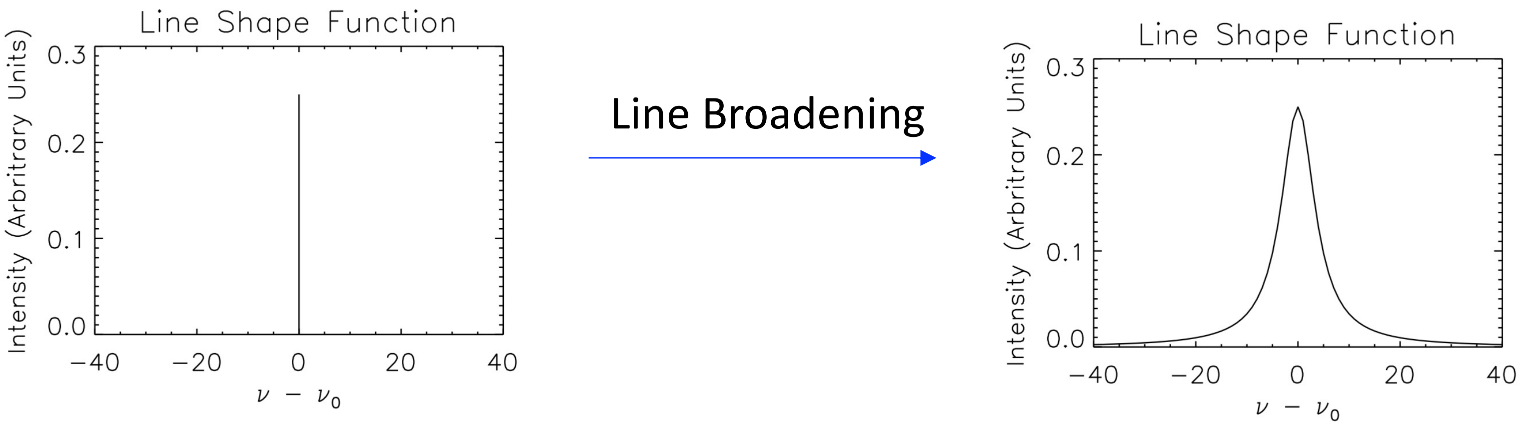
The quantum mechanical equivalent of the simple harmonic oscillator!



Molecular Vibrations

Shapes of Spectral Lines

Although we speak of spectral “lines”, these are not truly ”lines” – absorption and emission for a specific spectral “line” occurs over a finite spectral width



Causes of Line Broadening:

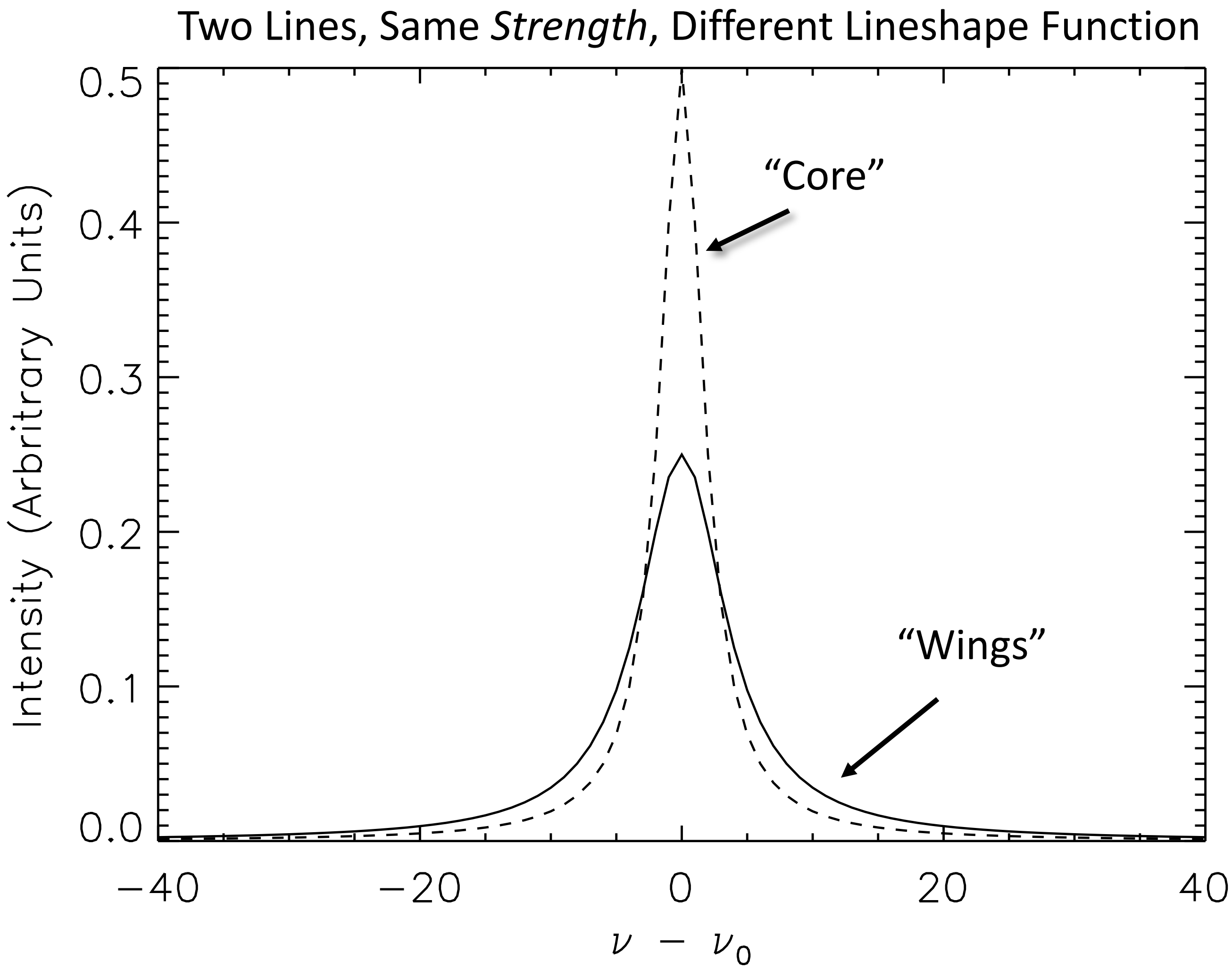
Heisenberg Uncertainty Principle: $\Delta E \Delta t \sim \hbar$ **→ Natural Broadening**

Doppler Effect → Doppler Broadening

Collisions with other atoms/molecules → Pressure broadening

A correct lineshape is essential to accurate computation of absorption -> climate change

Why Do Lineshapes Make Such a Difference?



Almost all the "growth" of absorption occurs in the line wings

Spectral Lineshapes - Overview

- **Natural Broadening, Collision Broadening**
  - “Lorentz” line shape
- **Doppler Broadening**
  - Gaussian line shape function
- **Mixed Collision and Doppler Broadening**
  - Voigt shape → Convolution of Lorentz, Gaussian Functions
  - Earth’s atmosphere below 65 km

- **Wings of lines can be larger or smaller than described by Voigt**
  - Due to “line mixing” (CO_2) or various “continua” (CO_2, H_2O, etc.)
- **There is a 50+ year history in Earth atmosphere radiative transfer modeling and consideration of line wing shapes**
  - Drayson, Appl. Opt., 1966

International Journal of Modern Physics A
Vol. 29, No. 7 (2014) 1460003 (34 pages)

DOI: 10.1142/S0217751X14600033

World Scientific
www.worldscientific.com

Why has global warming paused?*

William Happer

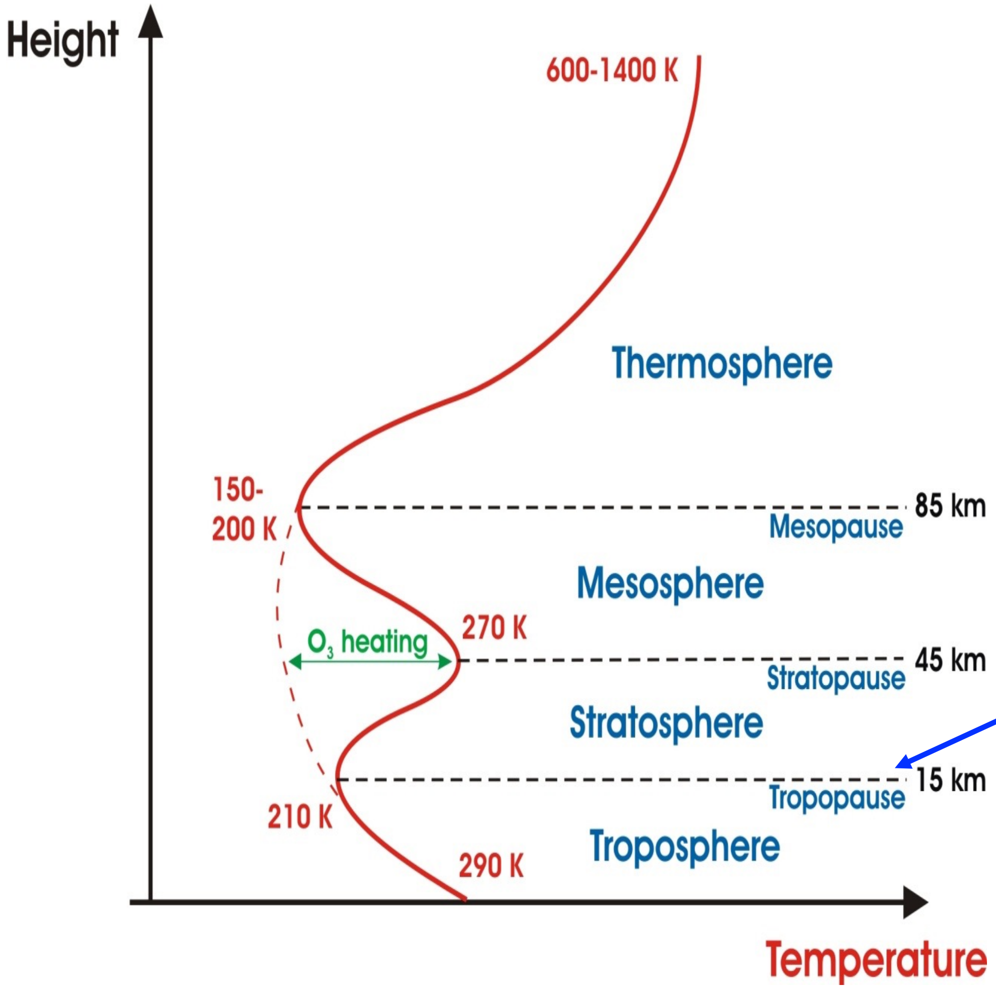
Department of Physics, Princeton University, Princeton, NJ 08544, USA
happer@princeton.edu

Received 29 November 2013
Revised 10 February 2014
Accepted 13 February 2014
Published 11 March 2014

How to Respond?

- **Our team decided to examine in detail the uncertainty in the spectroscopic parameters used to compute "radiative forcing"**
- **Essentially compute uncertainty in transmittance associated with S, σ_ν, and $g(\nu - \nu_o)$**
- **Does uncertainty in line shape really lead to large errors or overestimation of radiative forcing?**

- Quantifying the Effects of Increasing CO_2 -
The Concept of Radiative Forcing

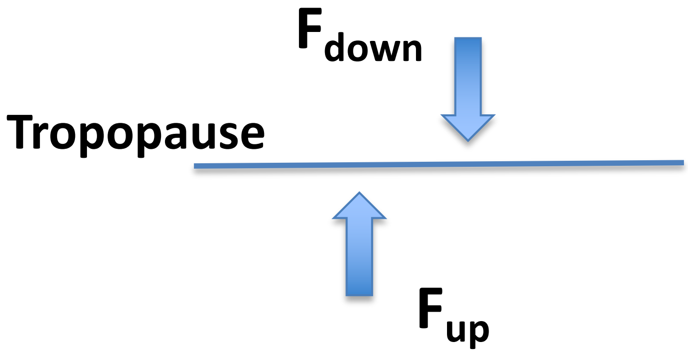


The tropopause is taken as the "top" of the climate system

Radiative forcing is defined as the change (increase) in energy absorbed in the troposphere due to increased CO_2

Definition of Radiative Forcing (RF) - 1

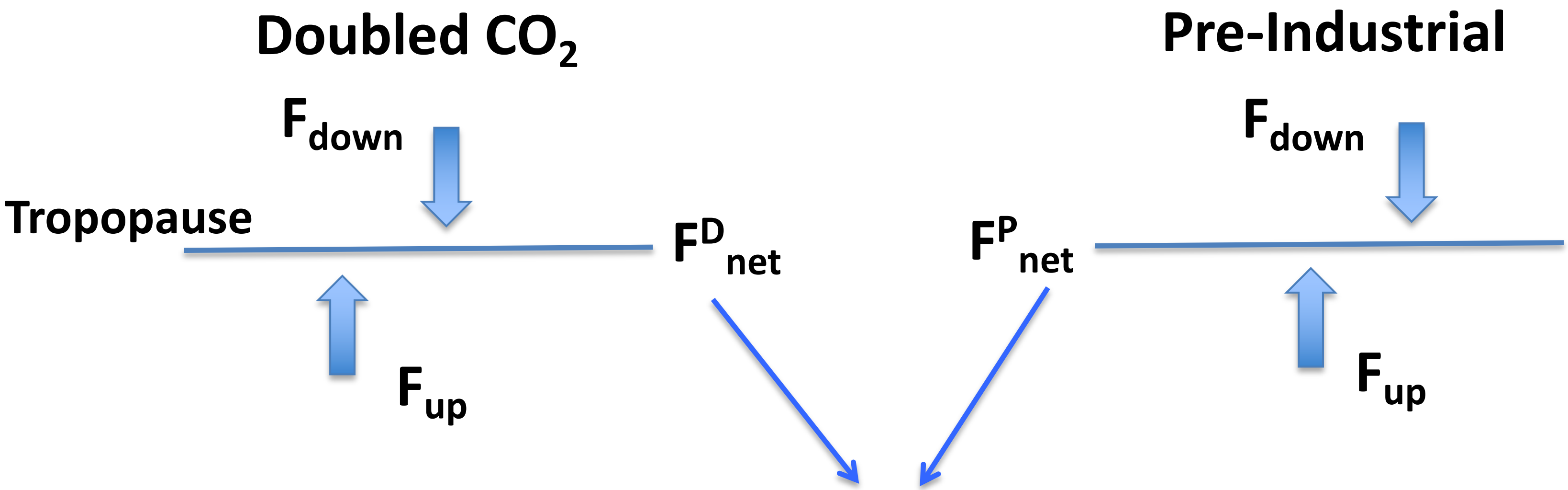
- **RF is the *change* in the *net* radiative flux at the *tropopause***
- ***Net flux* is defined as F(down) minus F(up)**



$$F_{net} = F_{down} - F_{up}$$

Definition of Radiative Forcing (RF) - 2

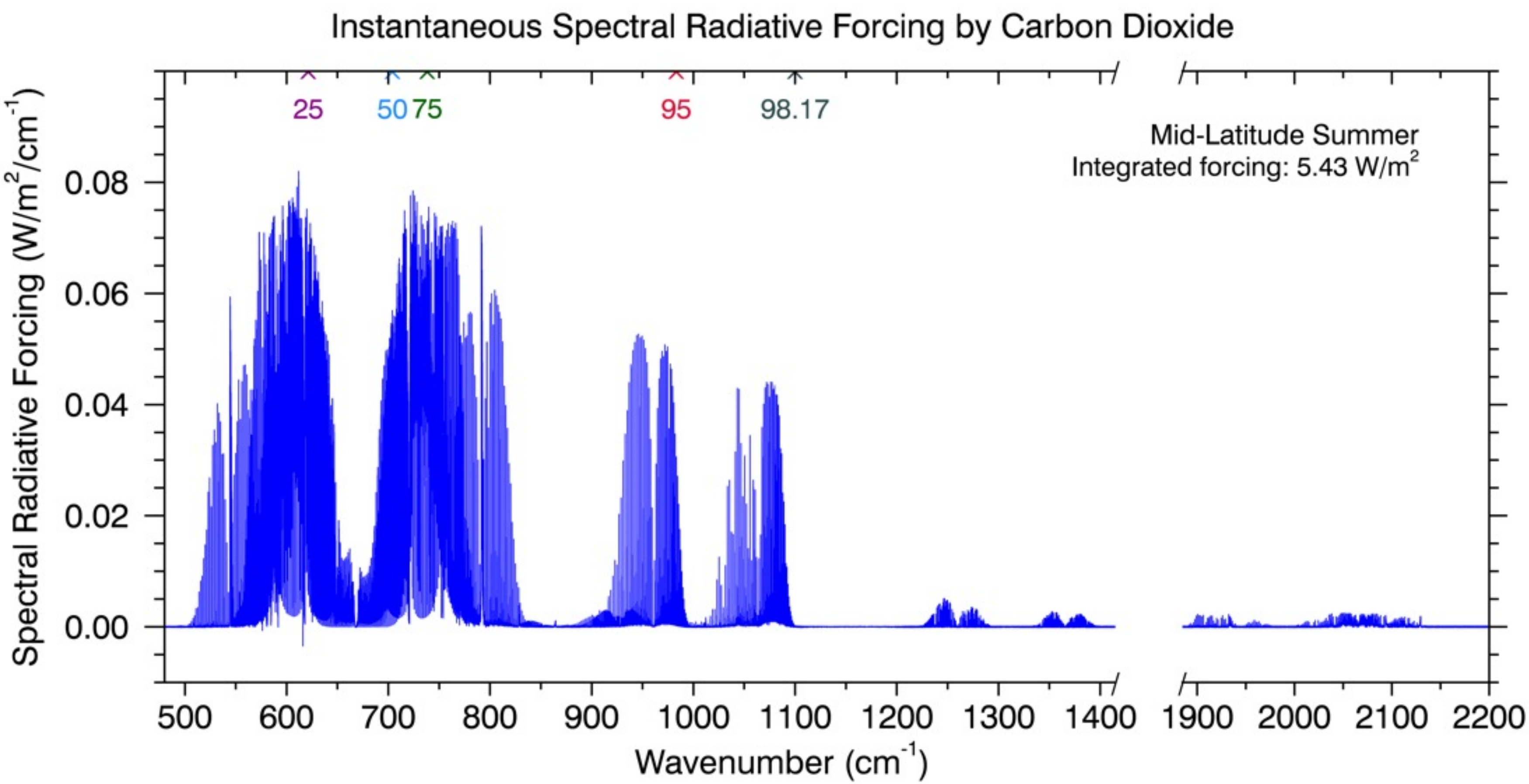
- ***Change*** **in net flux is difference for two different CO_2 burdens, typically doubled (D) from pre-industrial (P) minus P**



$$RF = F^D_{net} - F^P_{net}$$

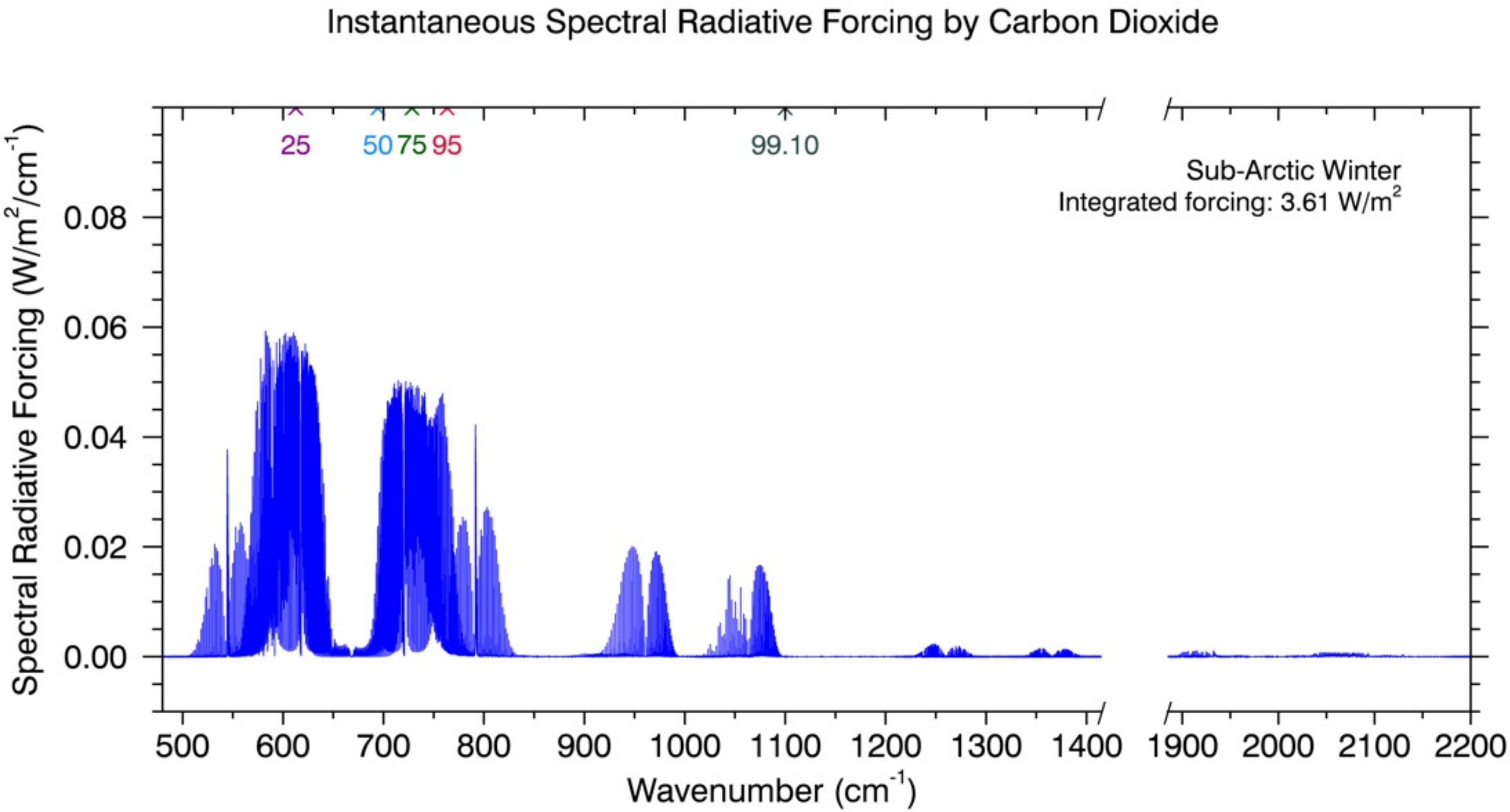
Use LBLRTM v12.2 to model radiances and fluxes in computation of RF

The Spectrum of Radiative Forcing for 2 x CO_2



Baseline Case, Mid-Latitude Summer

The Spectrum of Radiative Forcing for 2 x CO_2



Baseline Case, Sub-Arctic Winter

Approach to Computing Spectroscopic Uncertainty

- **Uncertainty determined by perturbation analysis**

- **Compute Radiative Forcing (RF) for "Baseline" case**

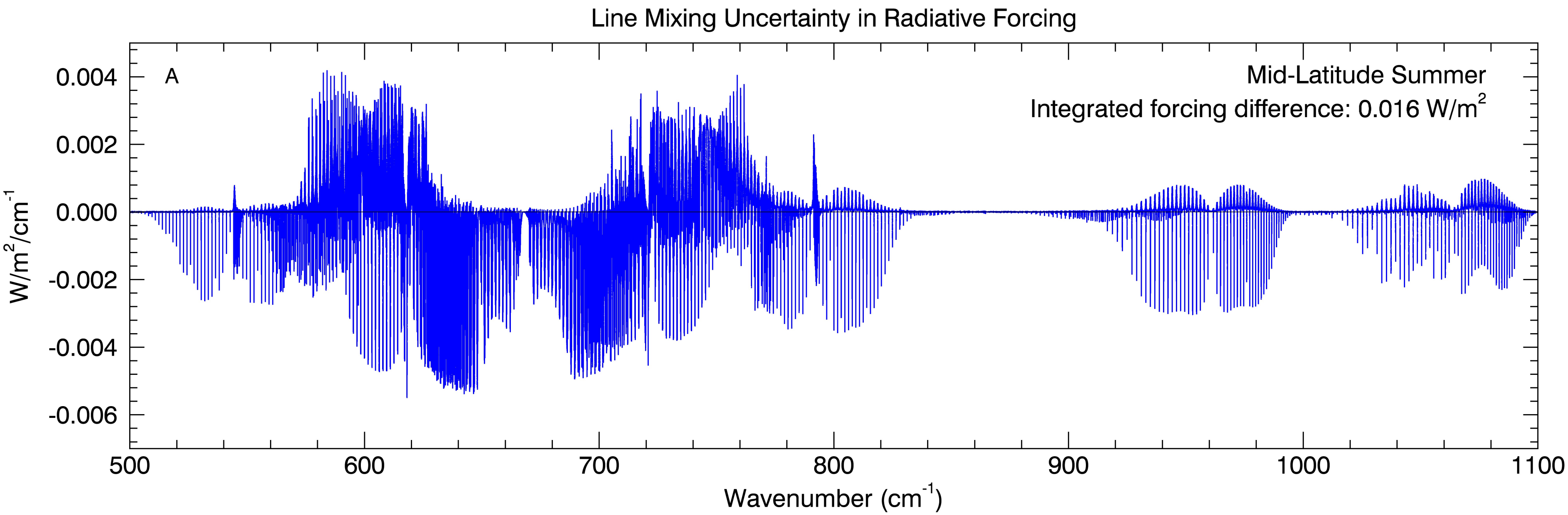
- **Compute RF for "Perturbed" case**
  - Perturb line shape functions by 20%
  - Perturb line strengths by assigned uncertainty on AER v3.2 database
  - Perturb line halfwidths by assigned uncertainty on AER v3.2 database

- **Compute Uncertainty = Perturbed minus Baseline**
  - Spectra, and spectrally integrated differences
  - RSS all uncertainties to get total uncertainty

Uncertainty in Radiative Forcing due to Line Mixing

RF (increased line shape function) – RF (baseline)

Mid-Latitude Summer Atmosphere



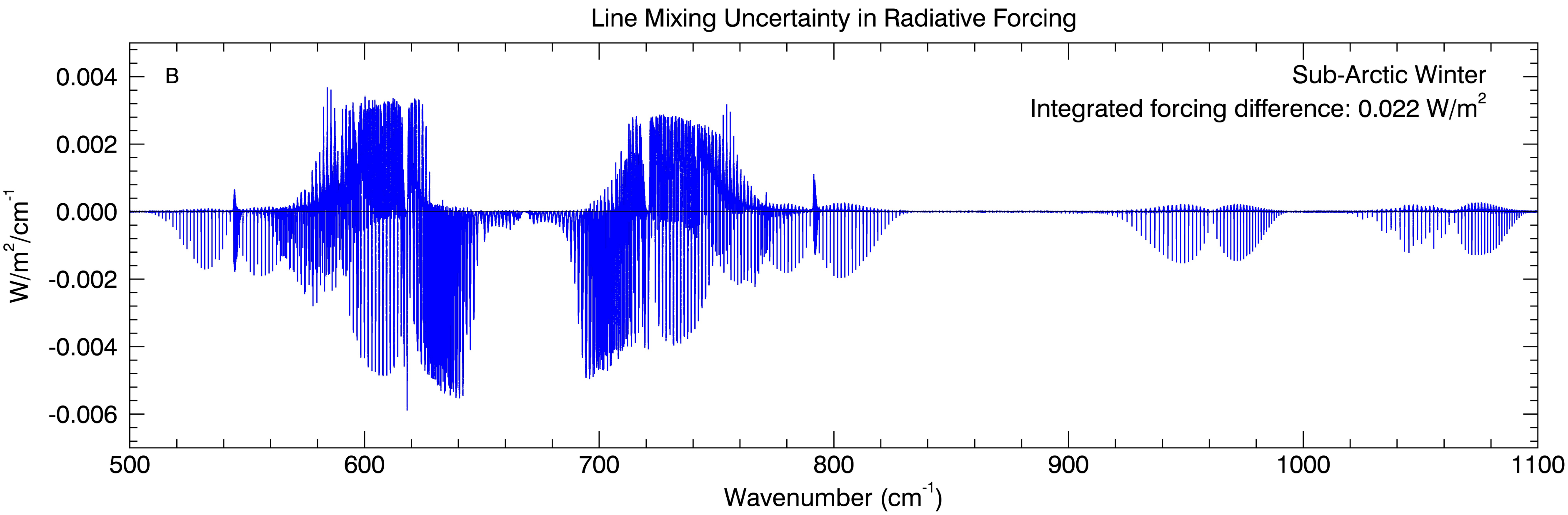
Significant but compensating spectral structure

RF difference is 0.016 W/m² or 0.3% of RF baseline

Uncertainty in Radiative Forcing due to Line Mixing

RF (increased line shape function) – RF (baseline)

Sub-Arctic Winter Atmosphere



Significant but compensating spectral structure

RF difference is 0.022 W/m^2 or 0.6% of RF baseline

Summary of Spectroscopic Uncertainty in RF

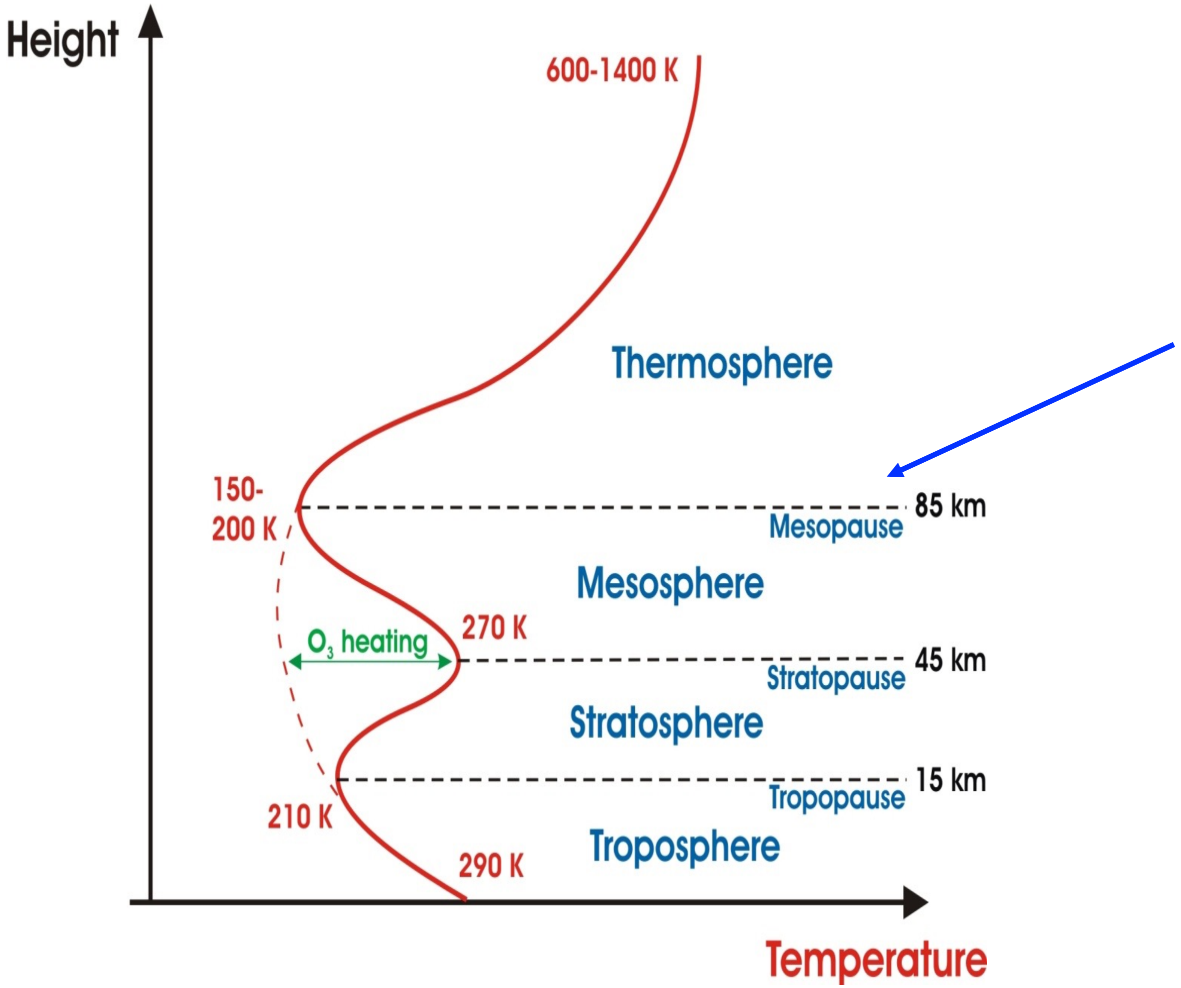
Atmosphere	Line Shape Uncertainty W/m^2	Line Strength Uncertainty W/m^2	Halfwidth Uncertainty W/m^2	RSS W/m^2	Error as % of Baseline RF
Mid-Latitude Summer	0.016	0.015	0.005	0.022	0.41
Mid-Latitude Winter	0.016	0.010	0.004	0.019	0.44
Sub-Arctic Summer	0.023	0.009	0.007	0.028	0.55
Sub-Arctic Winter	0.022	0.015	0.006	0.025	0.68
Tropical	0.010	0.014	0.002	0.017	0.51

Spectroscopic Uncertainty in RF is < 0.7% of Forcing in a Variety of Atmospheres

Summary

- **We have examined uncertainty in radiative forcing by CO_2 associated with spectroscopic parameters**
- **Combined uncertainty of line shape, line strength, and halfwidth is < 0.7% for a variety of standard atmospheres**
- **Line mixing is rigorously included in state of the art line-by-line models and in rapid codes used in climate models**
- **Foundation of climate modeling is robust with regards to uncertainties in spectroscopy – *and based on fundamental physical principles/laws.***

- Quantifying the Effects of Increasing CO_2 - Radiative Cooling of the Thermosphere



The thermosphere is the region above ~ 100 km

CO_2 infrared emission cools this region naturally

Increasing CO_2 leads to lower temperatures aloft

Infrared Radiative Cooling in the Thermosphere

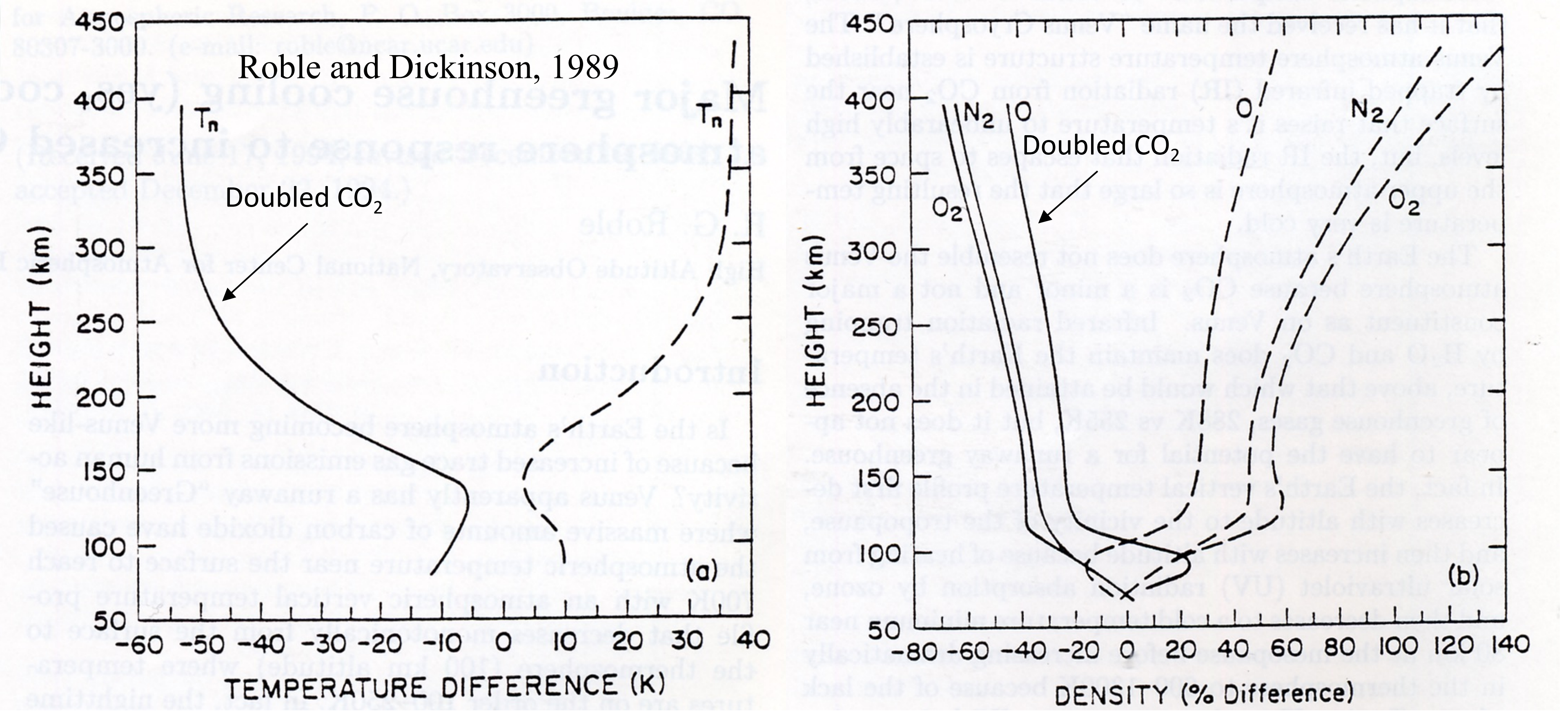
- **Radiative cooling is the action of infrared radiation to reduce the kinetic temperature of the neutral atmosphere**

- **It is accomplished almost entirely by two species:**
  - **Carbon Dioxide (CO_2, 15 μm)**
  - **Nitric Oxide (NO, 5.3 μm)**

- **Collisions between atomic oxygen (O) and CO_2 initiate the cooling process**
  - **CO_2 (υ = 0) + O → CO_2 (υ = 1) + O (Kinetic Energy Removal)**
  - **CO_2 (υ = 1) → CO_2 (υ = 0) + hν (15.3 μm) (Kinetic Energy Loss)**
  - **CO_2 (υ = 1) + O → CO_2 (υ = 0) + O (Kinetic Energy Returned)**

- **Collisional process are highly temperature dependent!**

Thermosphere Cooling due to Increasing CO_2



Understanding the future of the atmosphere above 100 km implies detailed understanding of the atmosphere and CO_2 80-120 km

Consequences of CO_2 Increase for Space Climate and Space Operations

- CO_2 increase will decrease temperature and density throughout the thermosphere (100 km and above)
- This increases the lifetime of all orbital assets – including space debris
- Space debris is increasing substantially with time
- ***Increased risk of collisions increases risk to all space assets – Space Station, astronauts, satellites***

Sounding of the Atmosphere using Broadband Emission Radiometry

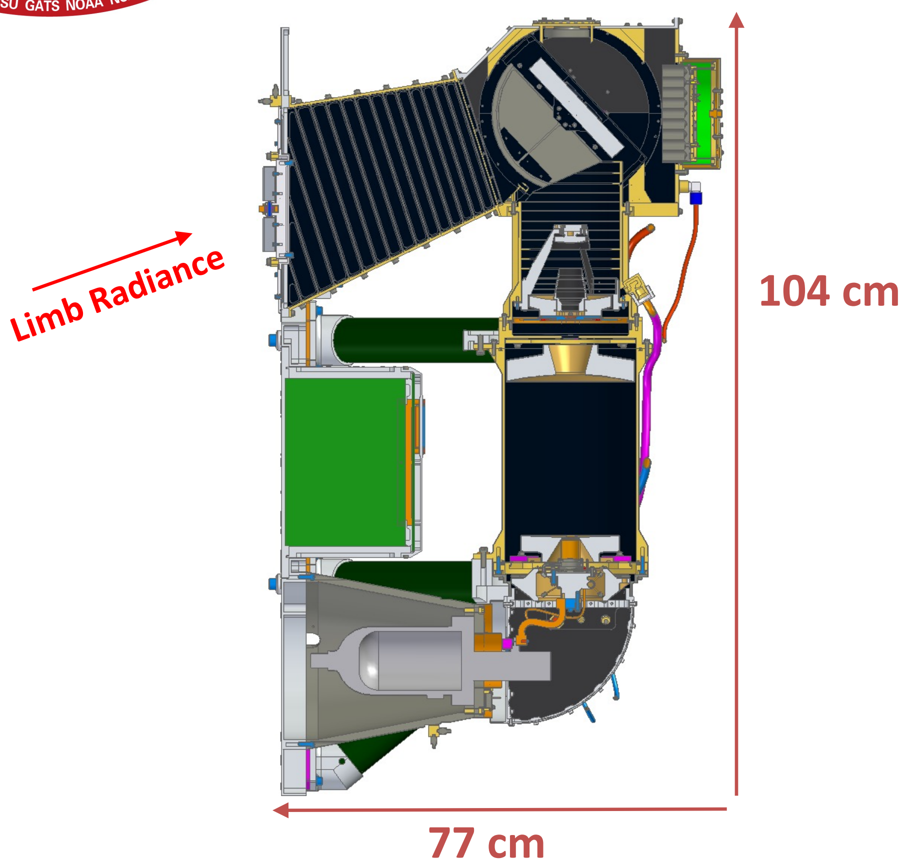
Launched 7 Dec. 2001

SABER Experiment

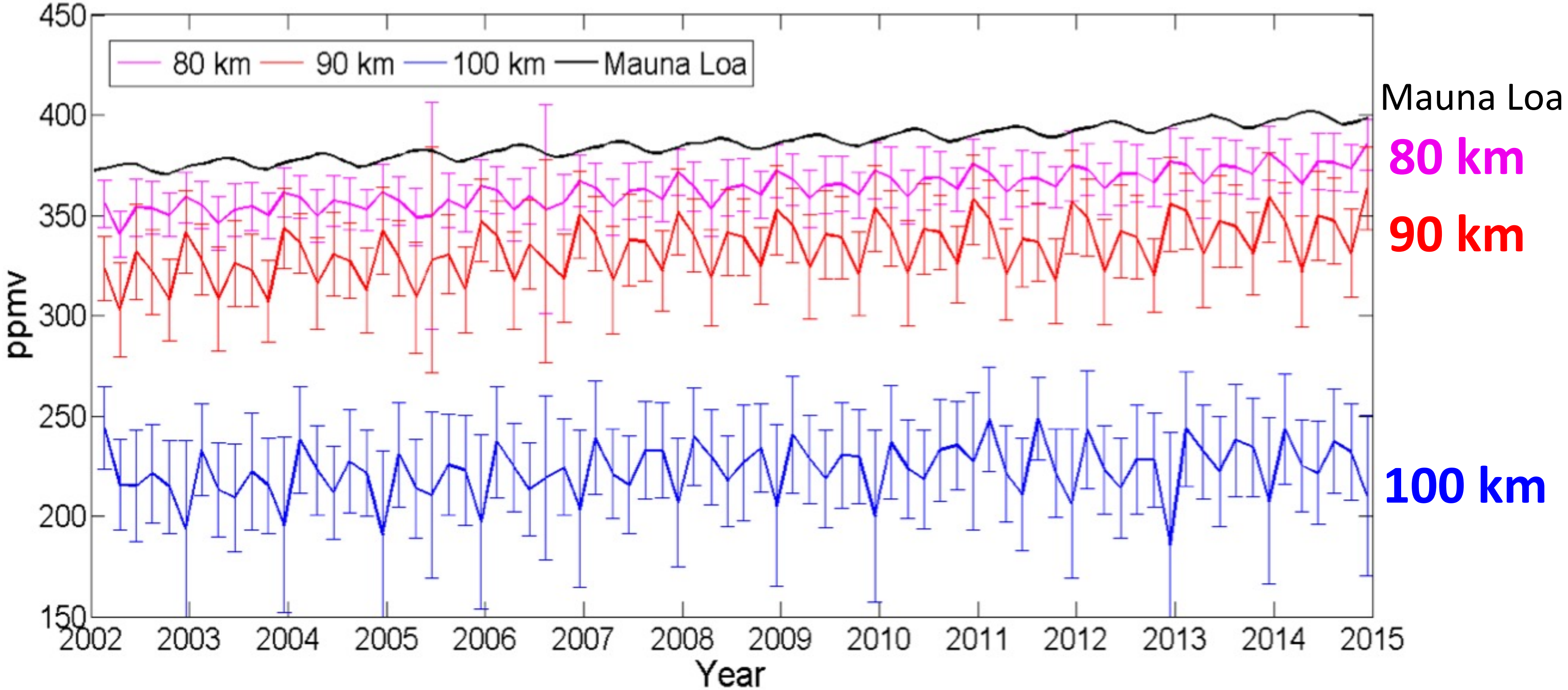
- Limb viewing, 400 km to Earth surface
- Ten channels 1.27 to 16 µm
- Over 30 routine data products including energetics parameters
- Over 98% of all possible data collected
  (8.2 million profiles – per channel!)
- Focal plane cryo-cooler operating excellently at 77 K
- SABER on-orbit performance is excellent and as-designed
- Noise levels at or better than measured on ground
- 15+ years of on-orbit operation

SABER Instrument

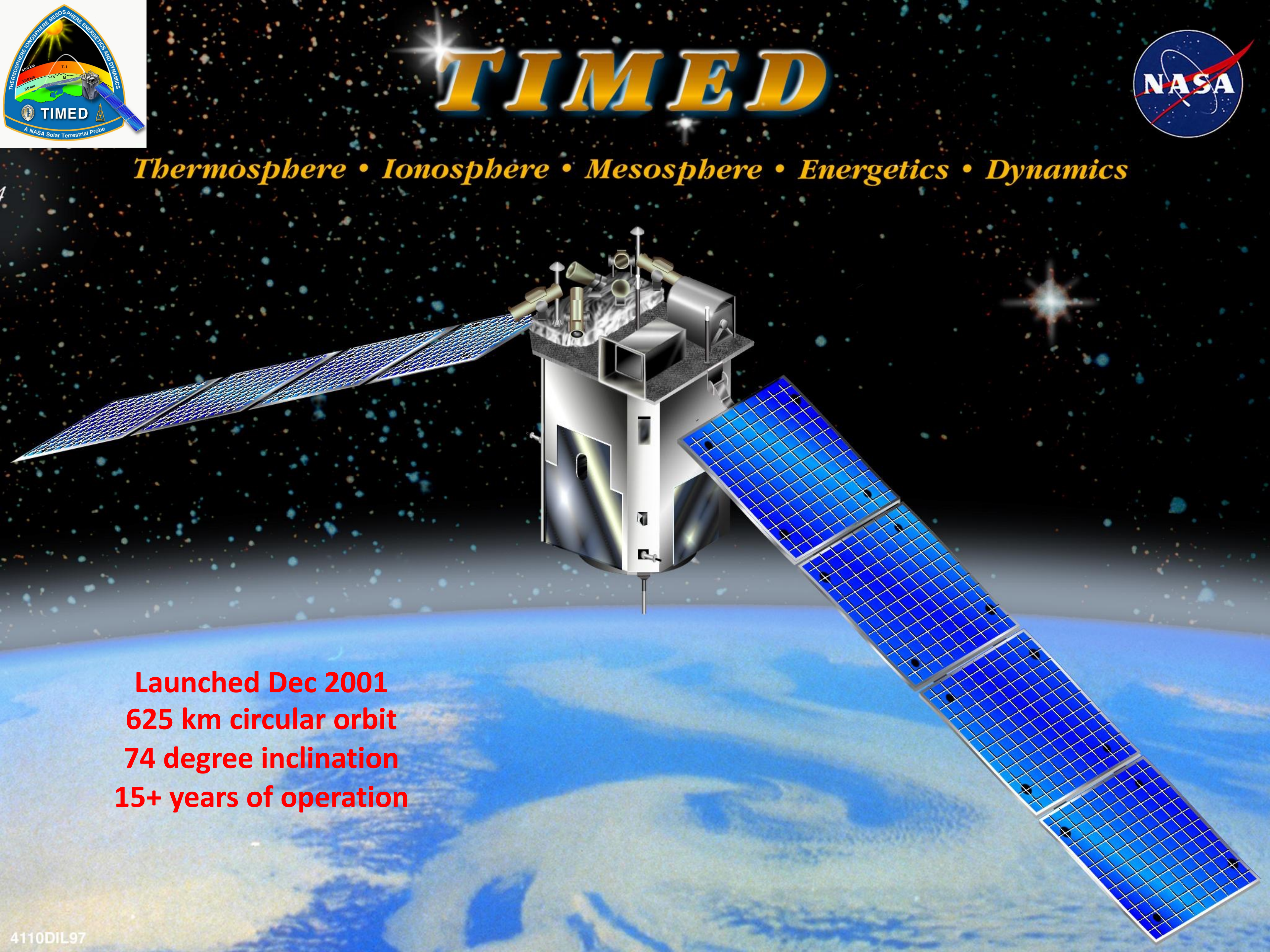
75 kg, 77 watts; 4 kbs



SABER Mesosphere and Lower Thermosphere CO_2



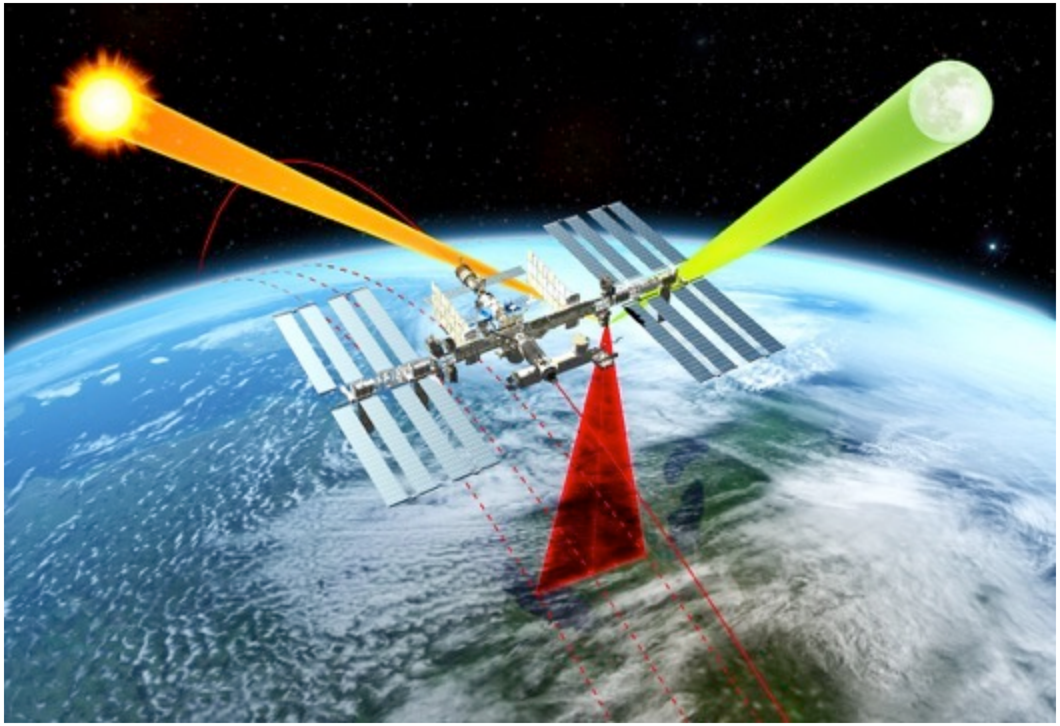
CO_2 is increasing the lower thermosphere as verified by SABER satellite observations and also by the ACE satellite


TIMED
Thermosphere • Ionosphere • Mesosphere • Energetics • Dynamics
NASA
Launched Dec 2001
625 km circular orbit
74 degree inclination
15+ years of operation
4110DIL97

CLARREO Pathfinder on ISS (2020)

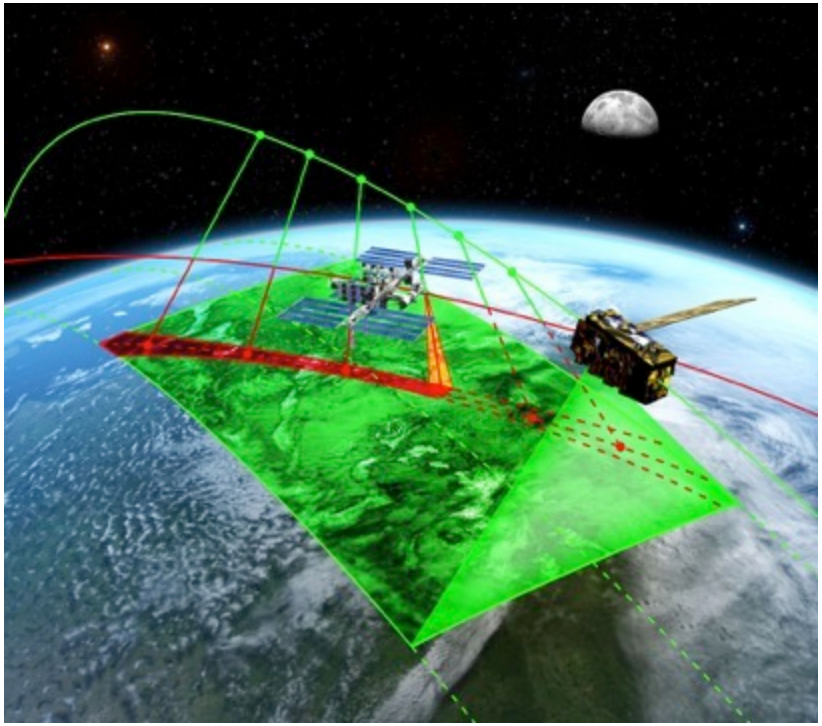
A Mission to Measure Climate Change!

Demonstrate high accuracy SI-Traceable Calibration



Objective #1: Demonstrate the ability to conduct, on orbit, SI-Traceable calibration of measured scene spectral reflectance with an advanced accuracy over current on-orbit sensors using a reflected solar spectrometer flying on the International Space Station.

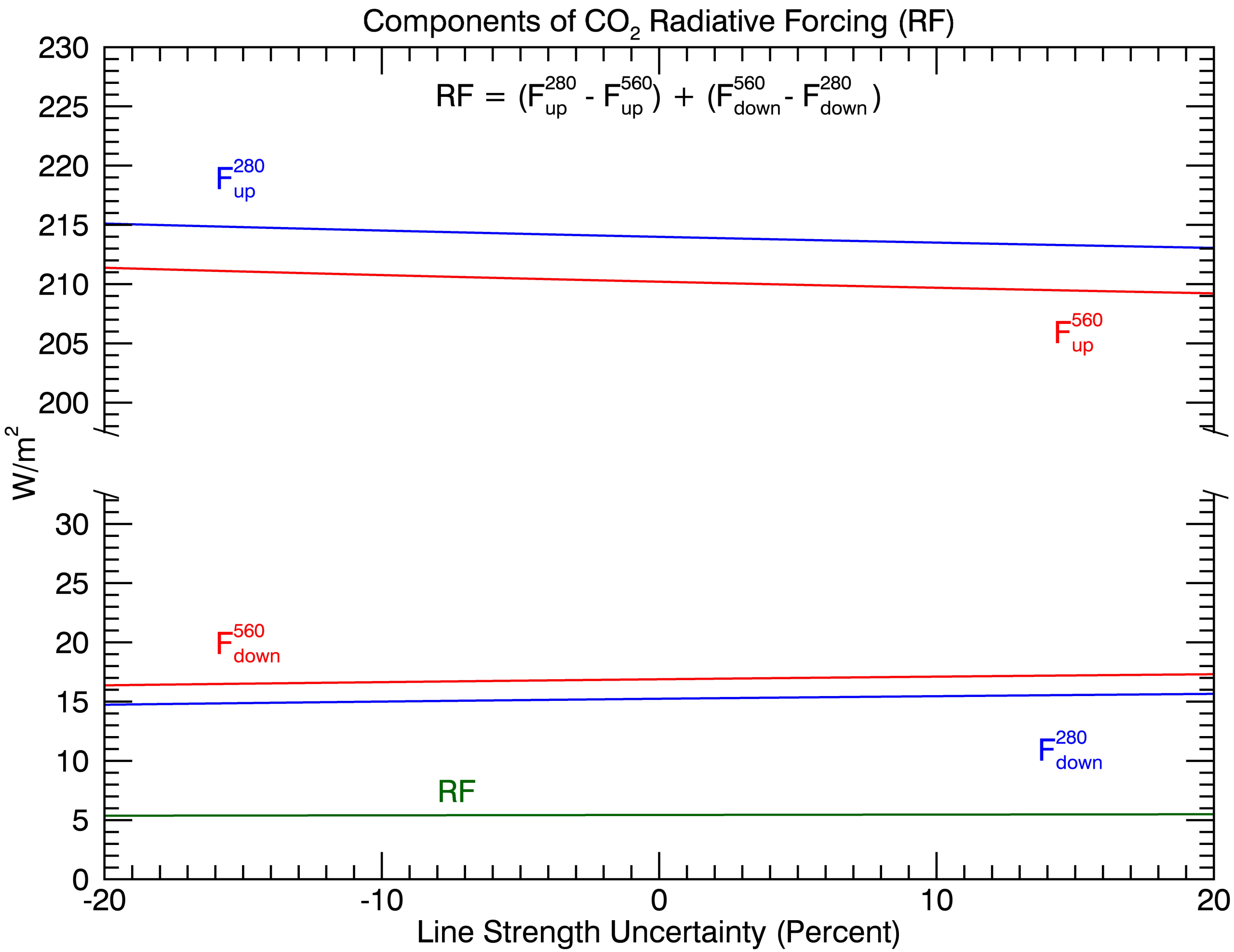
Demonstrate Inter-Calibration Capabilities



Objective #2: Demonstrate the ability to use that improved accuracy to serve as an in orbit reference spectrometer for advanced intercalibration of other key satellite sensors across the reflected solar spectrum (350-2300 nm).

Backup Slides

Radiative Forcing Uncertainty due to Line Strength



Virtually no change in RF with up to 20% increase/decrease in S