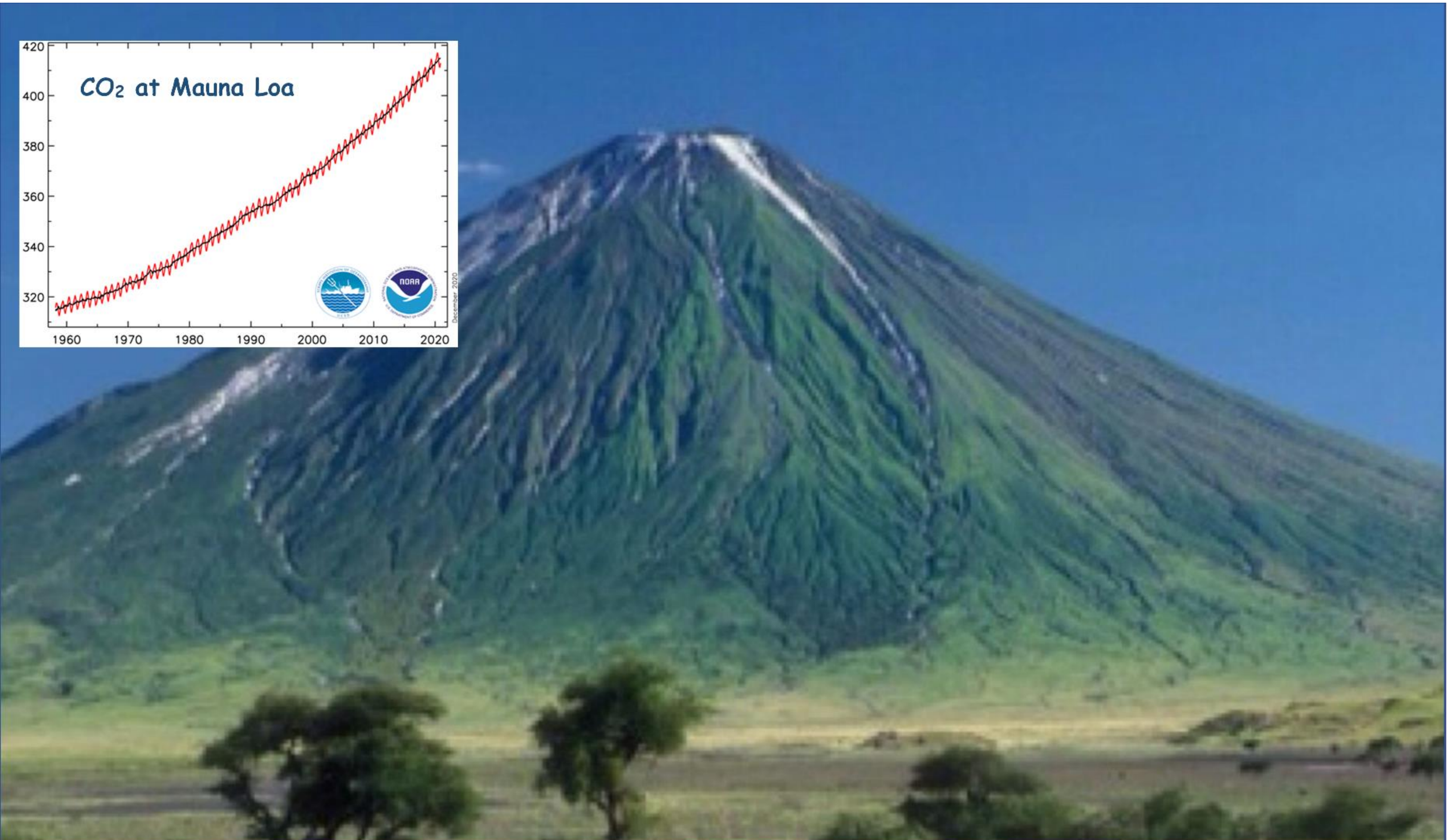
OSHER LIFELONG LEARNING INSTITUTE

Demystifying Climate Change



Session 3
The Atmosphere:
Greenhouse Gases & Clouds

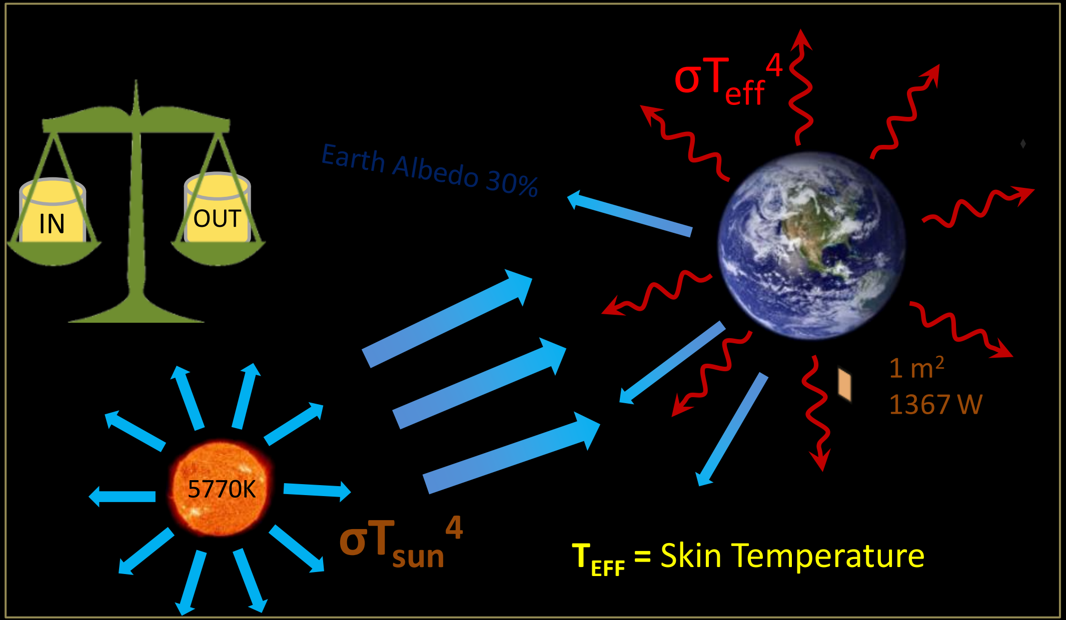
OLLI at Illinois
Spring 2021

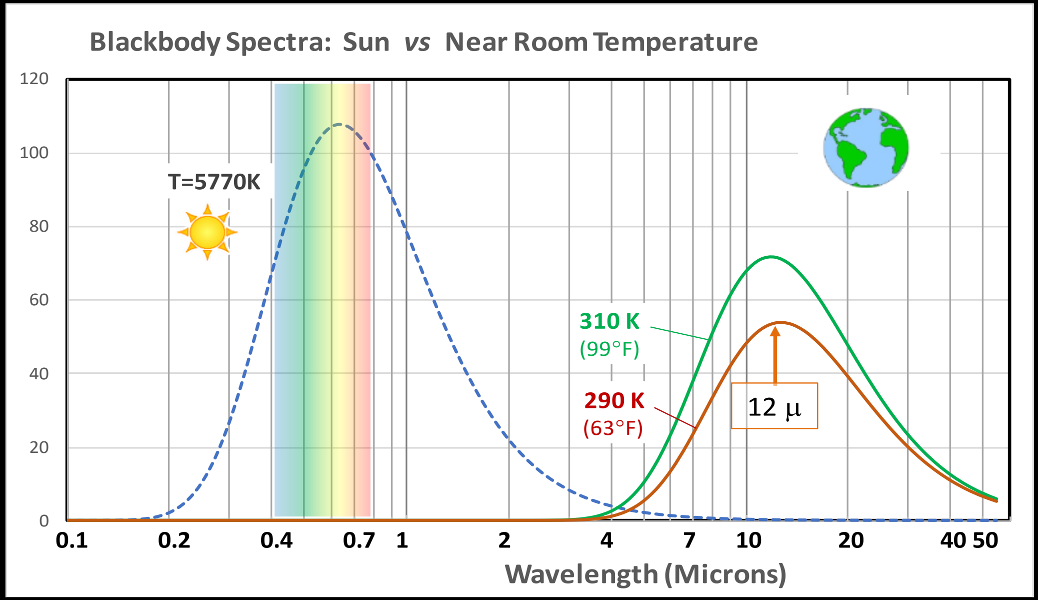
D. H. Tracy

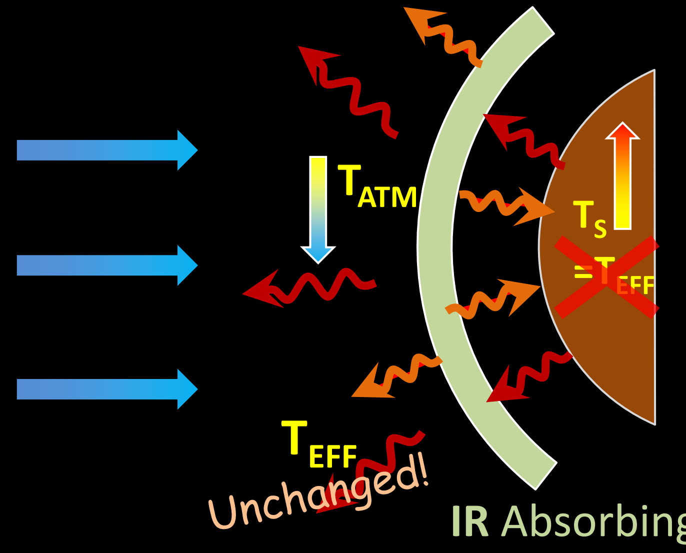
Course Outline

1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. **The Role of the Atmosphere: Greenhouse Gases & Clouds**
4. Global Circulation and Dynamics of the Earth System:
   Oceans, Atmosphere, Biosphere, Cryosphere, People, Plate Tectonics
5. Natural Variability of the Climate, short and long term. Ice Ages
6. Carbon Dioxide and other Greenhouse Gases: where do they come from,
   where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Adaptation and Amelioration Strategies. The Climate debate. Policy options.

Recap of Session 2

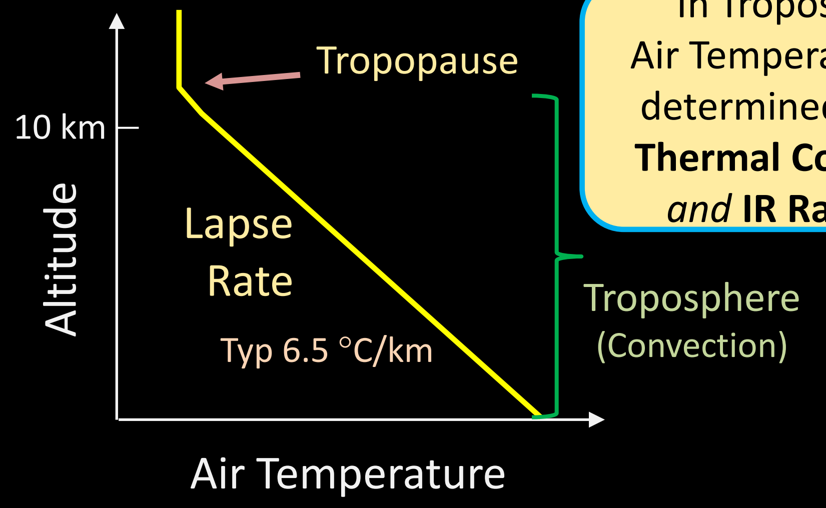






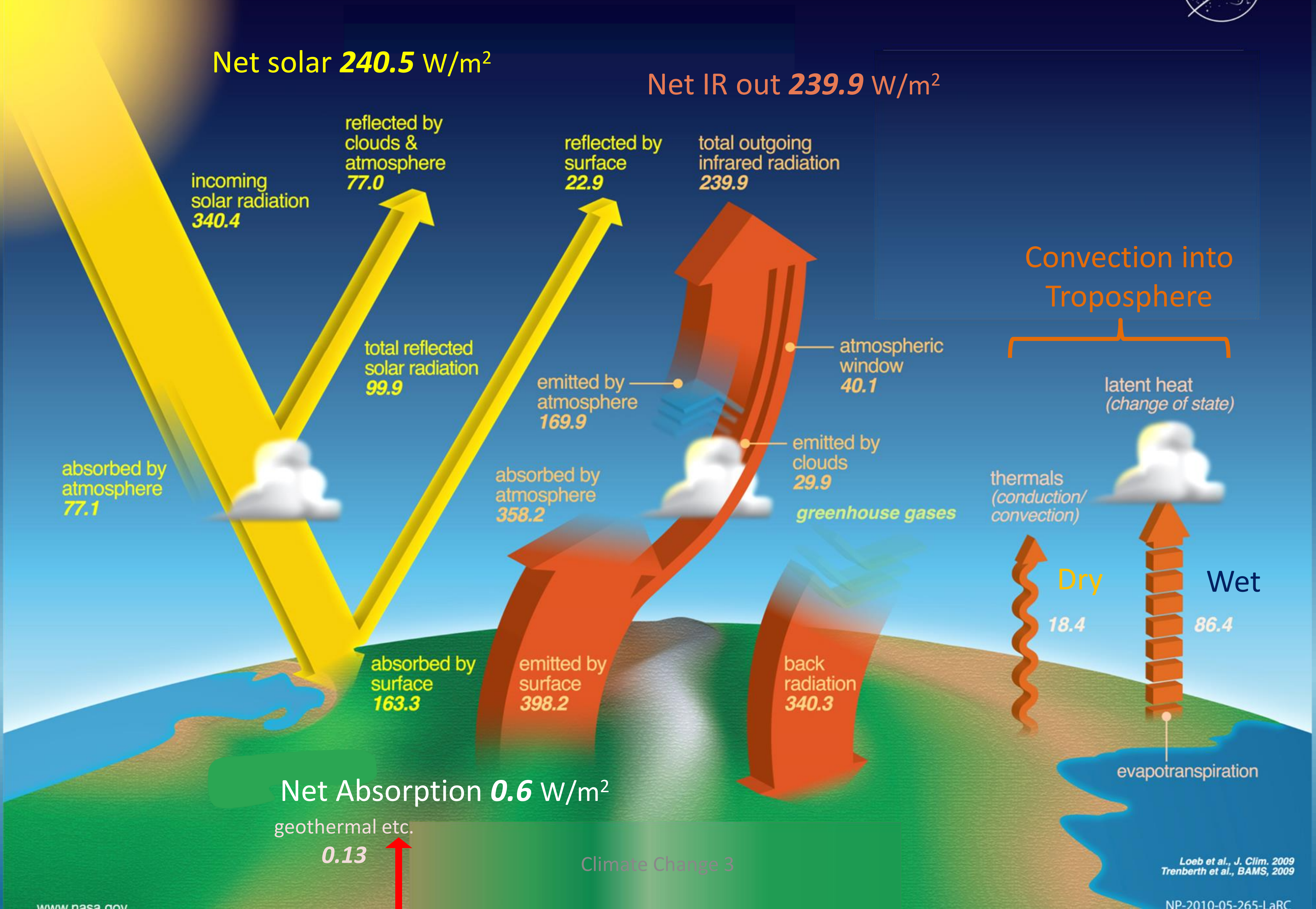
Greenhouse Effect:

- T_S up ↑
- T_{ATM} down ↓
- T_{EFF} same !

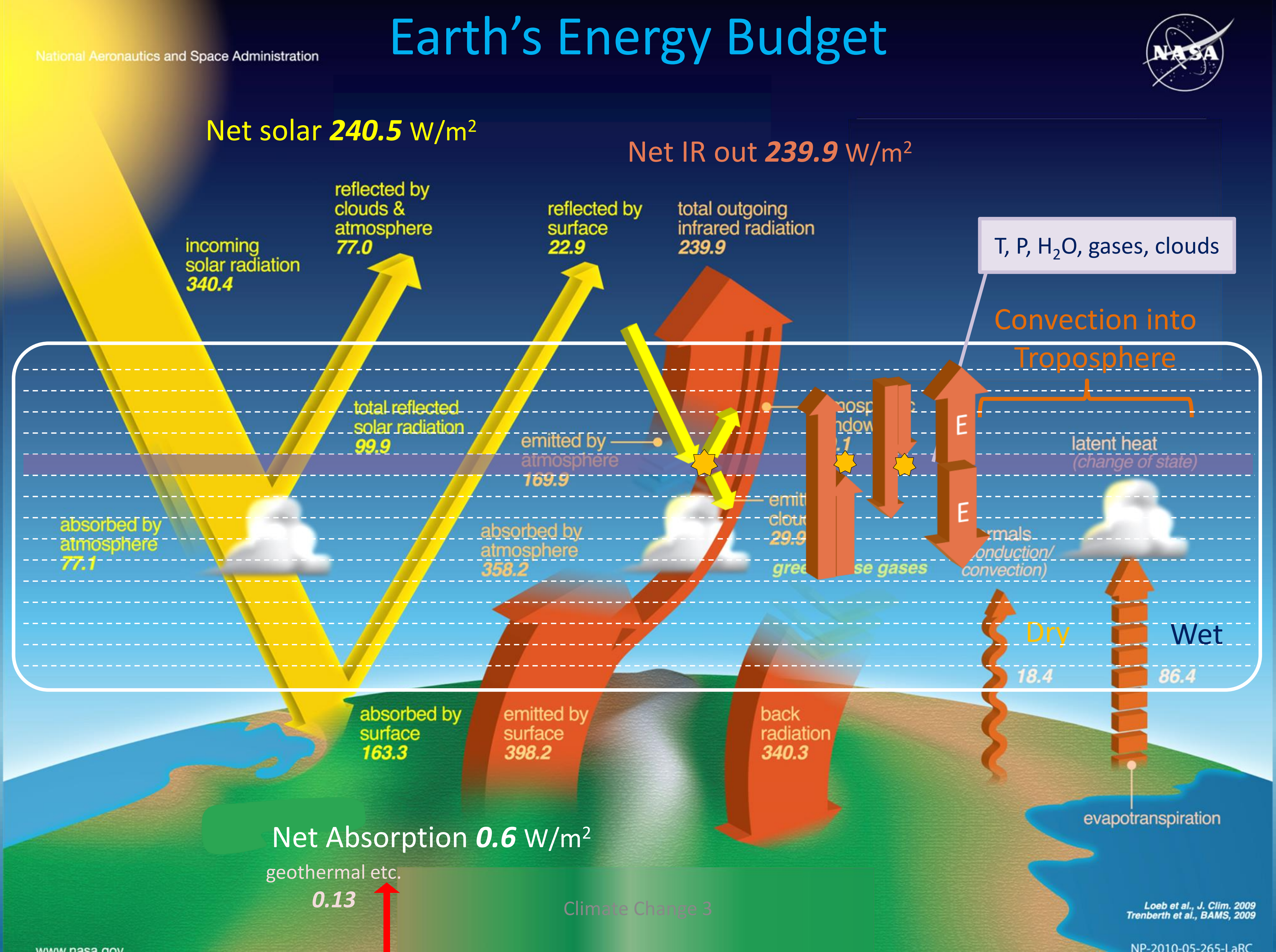


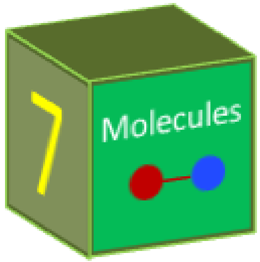
In Troposphere, Air Temperatures are determined by *both* **Thermal Convection** *and* **IR Radiation**

Earth's Energy Budget



Earth's Energy Budget

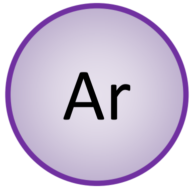




Gas Molecules in Air

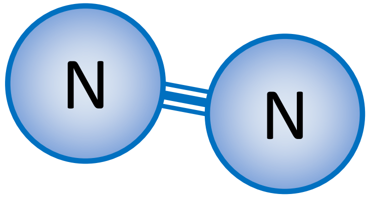
Do these Radiate or Absorb IR at normal Temperatures?

- Monatomic

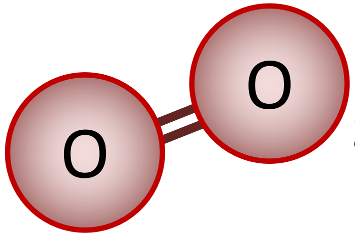


0.9%

- Diatomic
  (homonuclear)

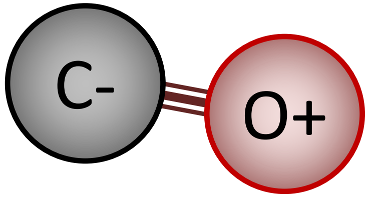


78%



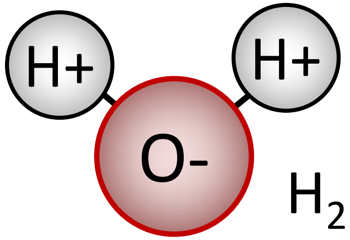
21%

- Diatomic
  (heteronuclear)

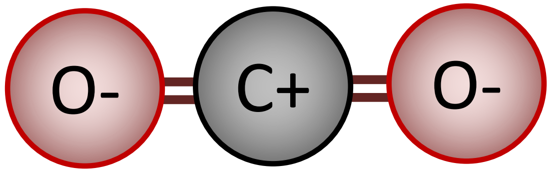


< 1 ppm

- Polyatomic



H_2O **0-4%**

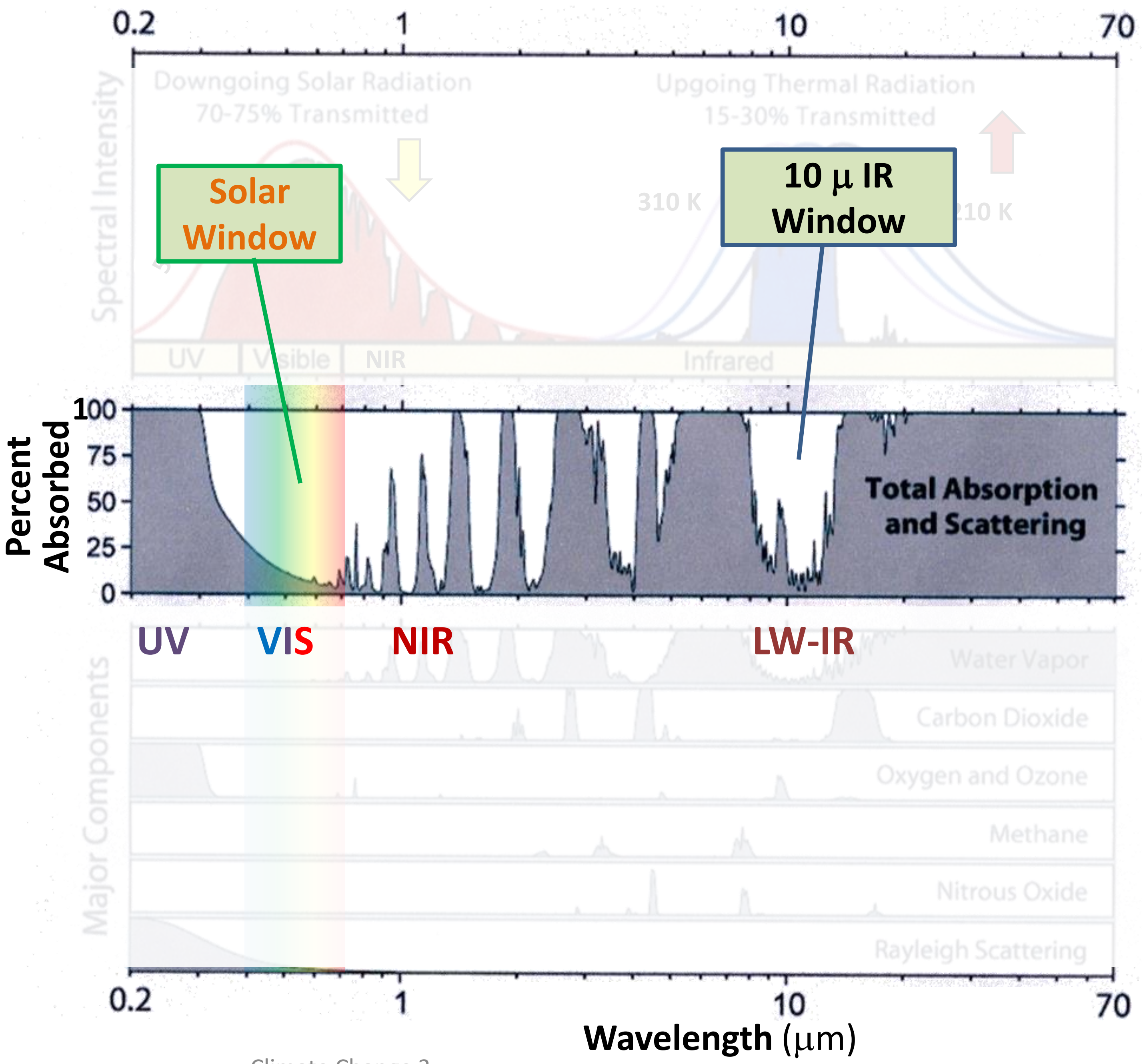


CO_2 **400 ppm**

Radiation Transmitted by the Atmosphere

(*to* and *from* the Surface)

Clear Day



thanks to Wikimedia
Robert Rohde

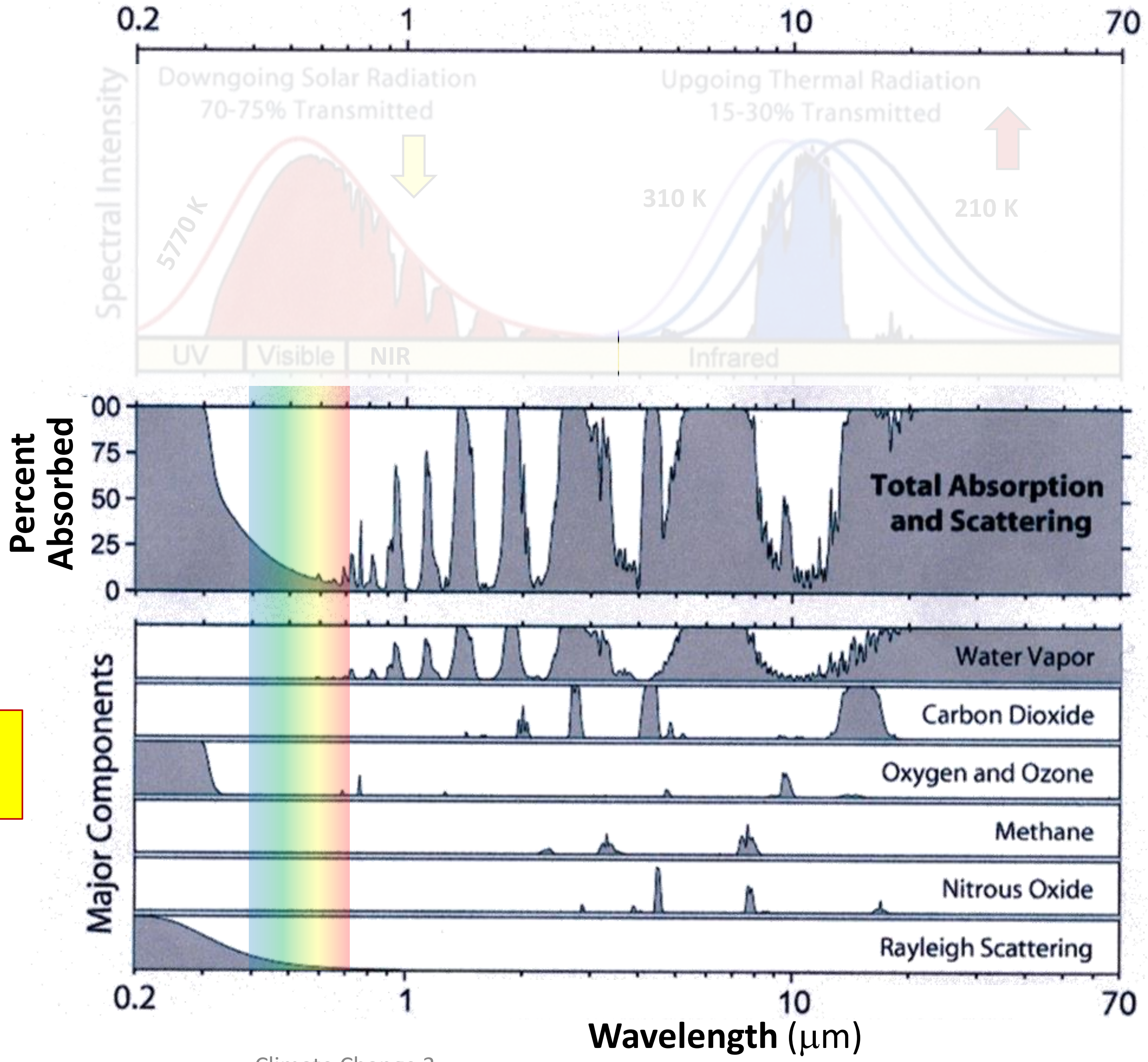
Radiation Transmitted by the Atmosphere

(*to* and *from* the Surface)

Clear Day

The gases that produce this result…

thanks to Wikimedia
Robert Rohde



Radiation Transmitted by the Atmosphere

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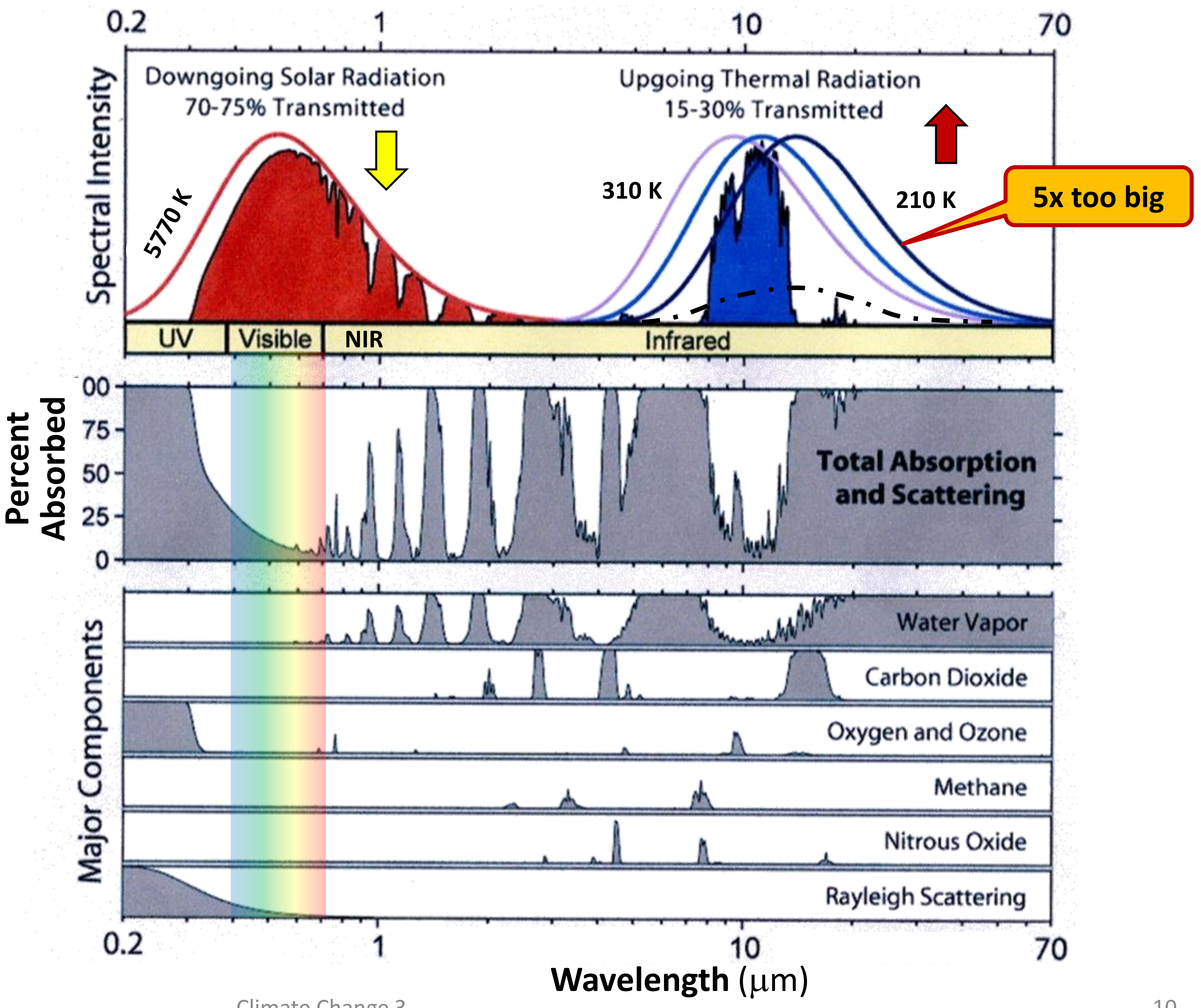
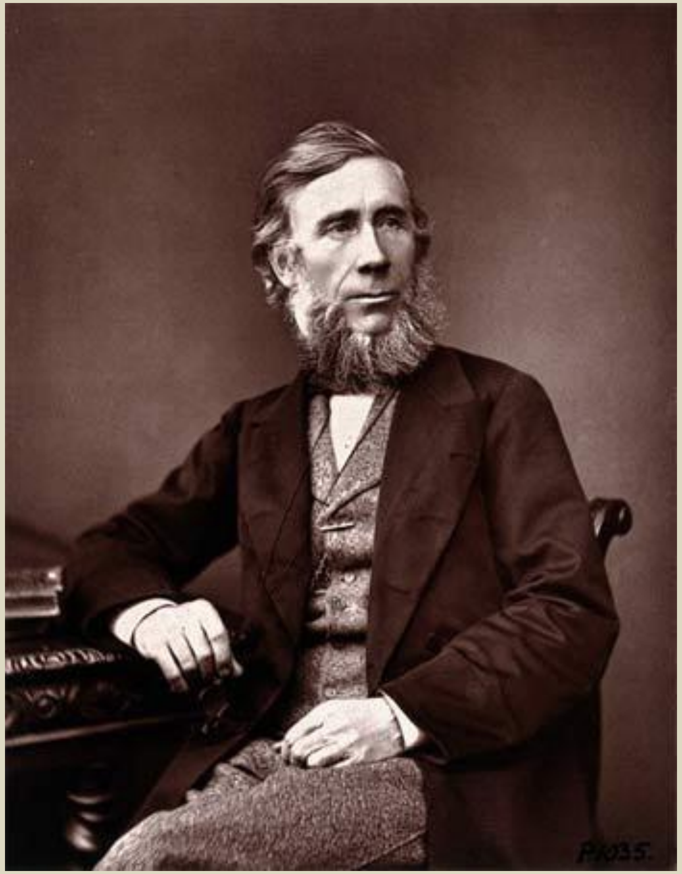
Clear Day

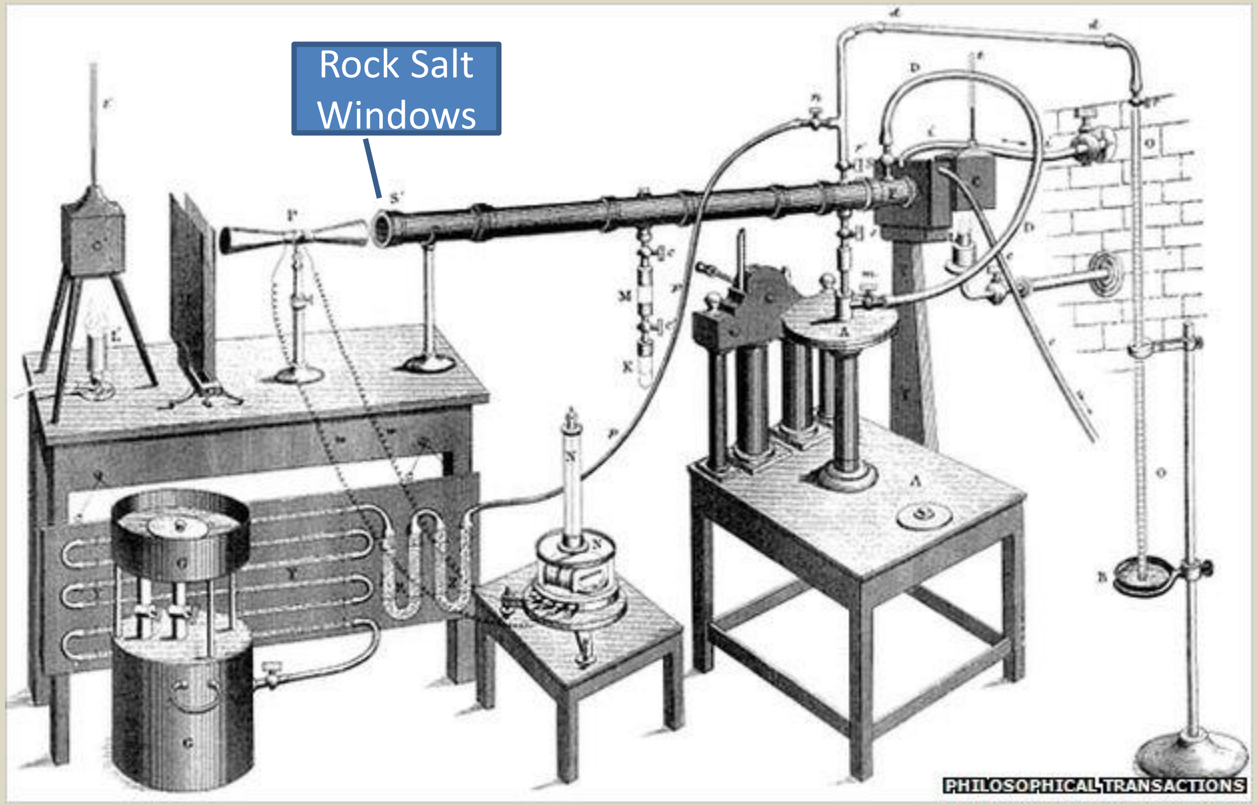


thanks to Wikimedia
Robert Rohde

1859 Measurements of IR Absorption of Water, CO_2, Ozone, Methane Gases



John Tyndall (1820-1893)
Irish Experimentalist



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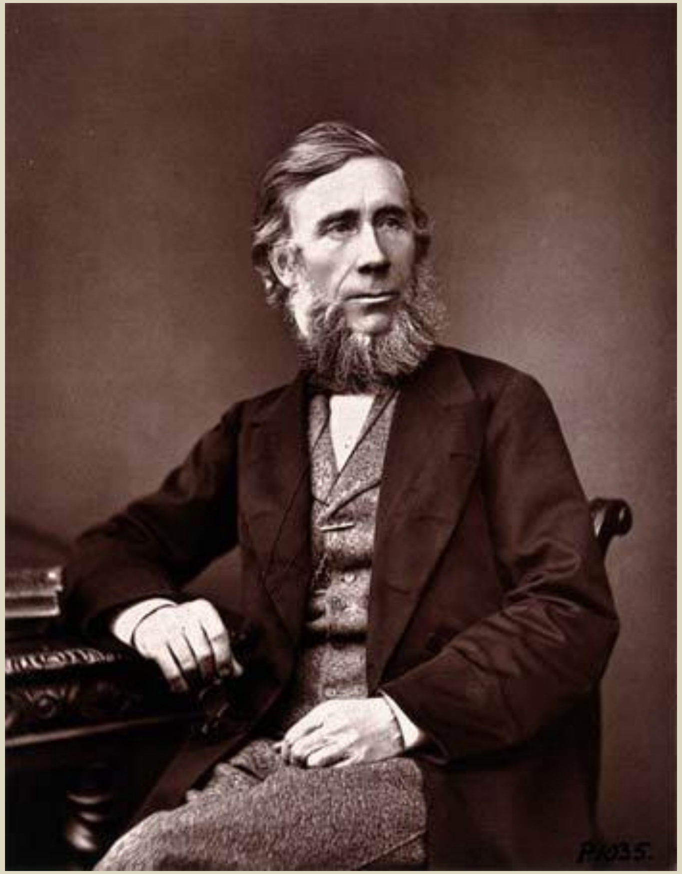

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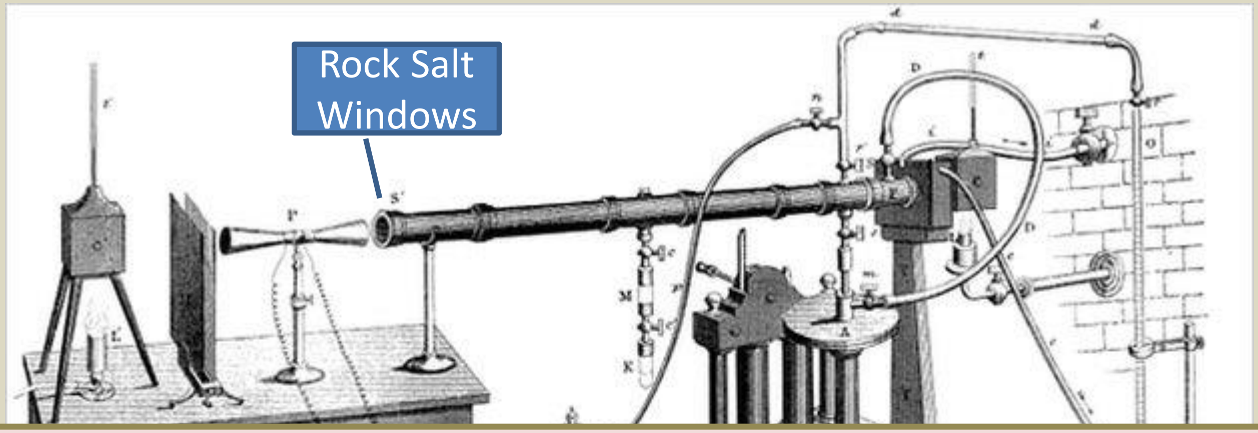
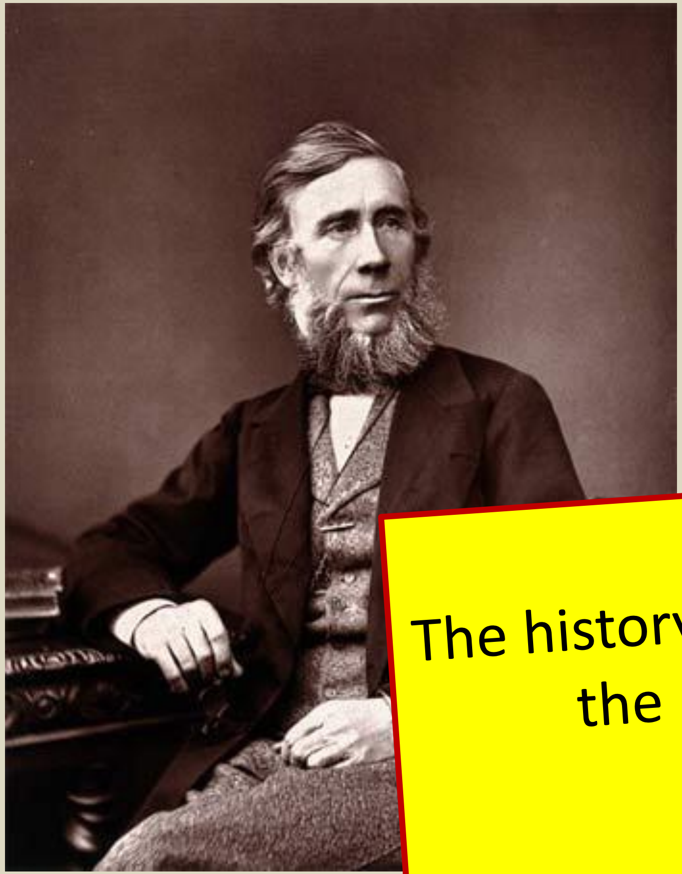


"As a dam built across a river causes a local deepening of the stream, so our atmosphere, thrown as a barrier across the terrestrial rays, produces a local heightening of the temperature at the Earth's surface."

* Blackbody Radiation from the Earth's Surface

1859 Measurements of IR Absorption of Water, CO_2, Ozone, Methane Gases



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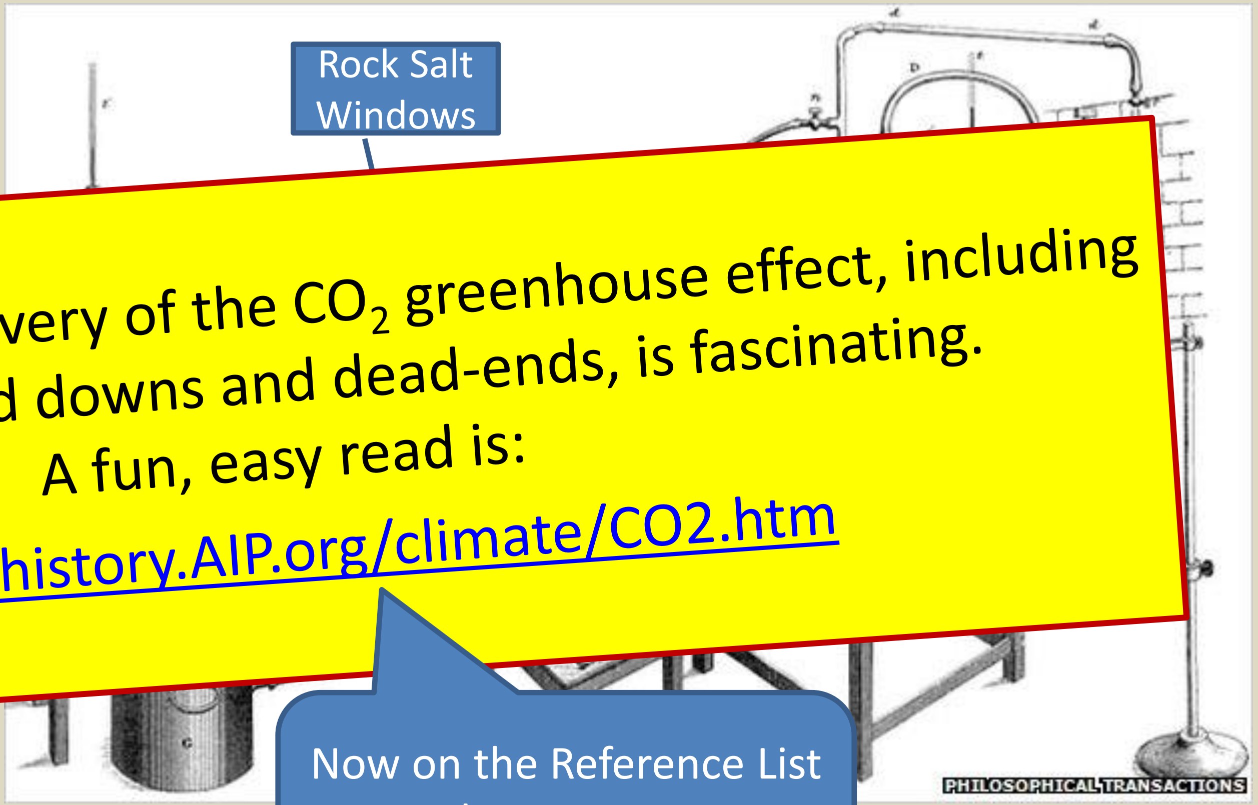
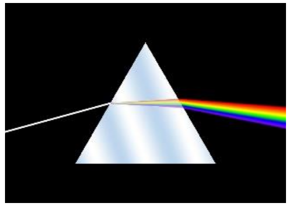


The history of the discovery of the CO_2 greenhouse effect, including the many ups and downs and dead-ends, is fascinating.
A fun, easy read is:
https://history.AIP.org/climate/CO2.htm

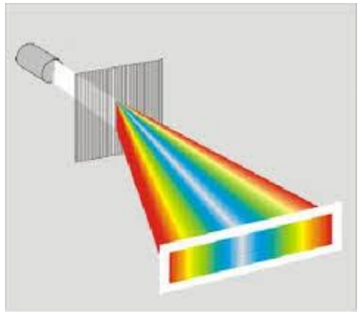
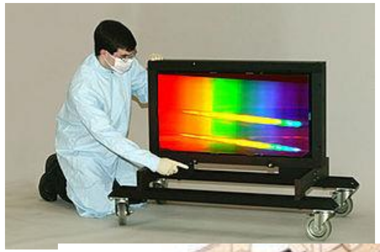
Now on the Reference List on the OLLI Course Download Site

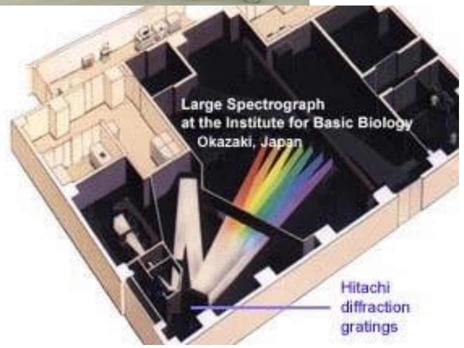
Analyzing the EM Radiation: Spectroscopy

Prism Spectrometers

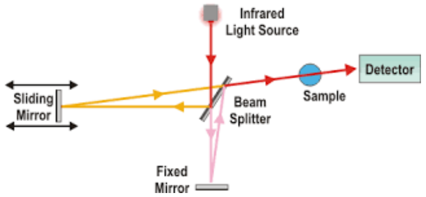


Diffraction Grating Spectrometers

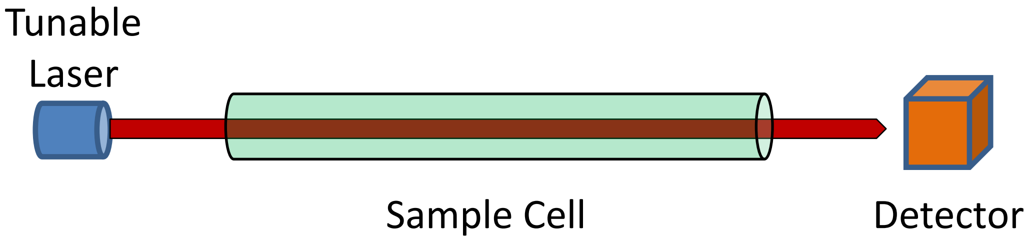


Fourier Transform Spectrometers



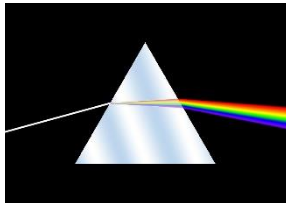
FTIR: Workhorse Infrared Spectrometers

Tunable Laser Spectrometers

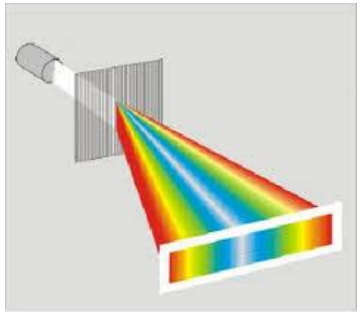
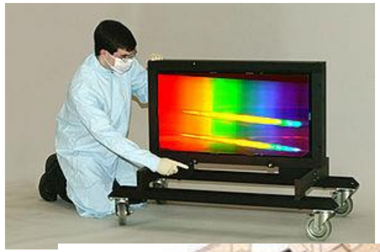


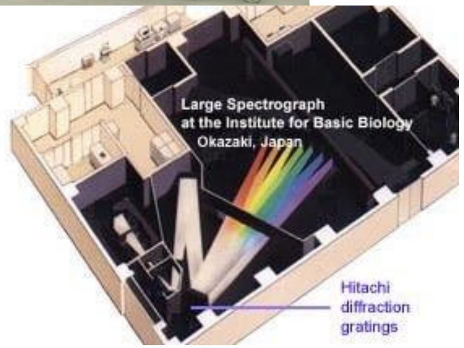
Analyzing the EM Radiation: Spectroscopy

Prism Spectrometers



Diffraction Grating Spectrometers



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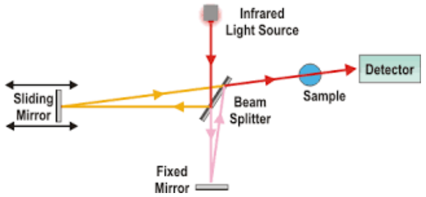
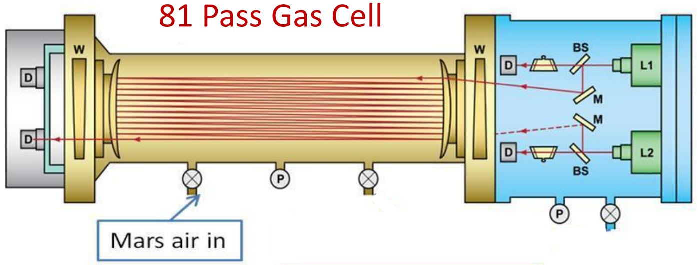


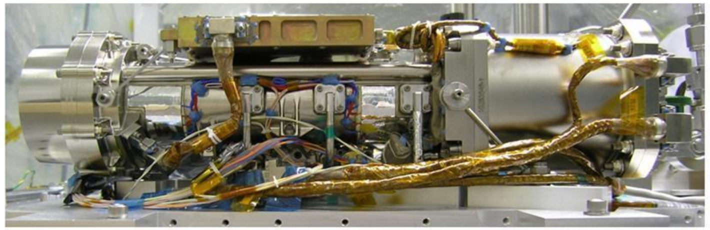
FTIR: Workhorse Infrared Spectrometers

Tunable Laser Spectrometers

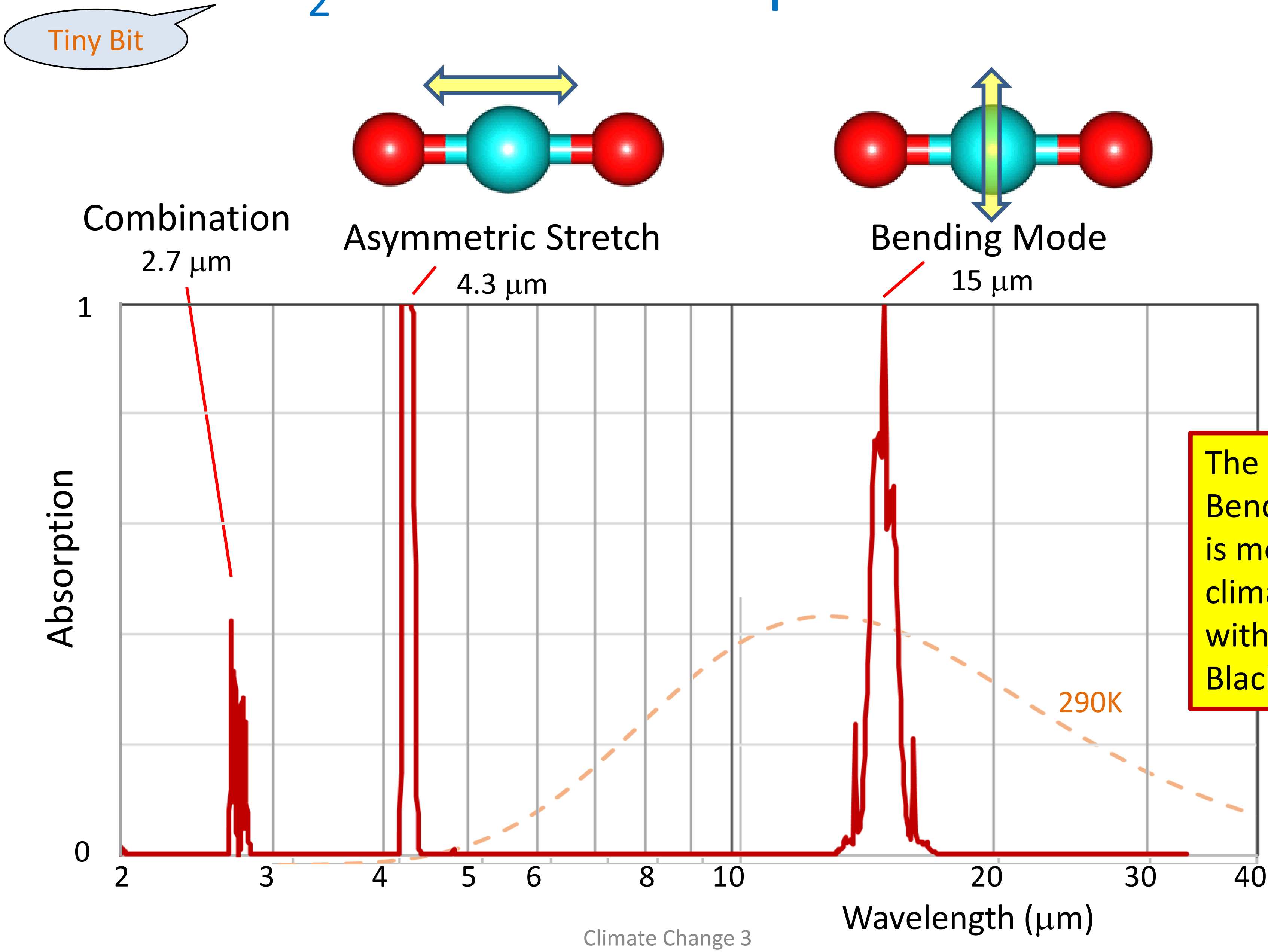
81 Pass Gas Cell



Laser Spectrometer on Mars Rover Curiosity

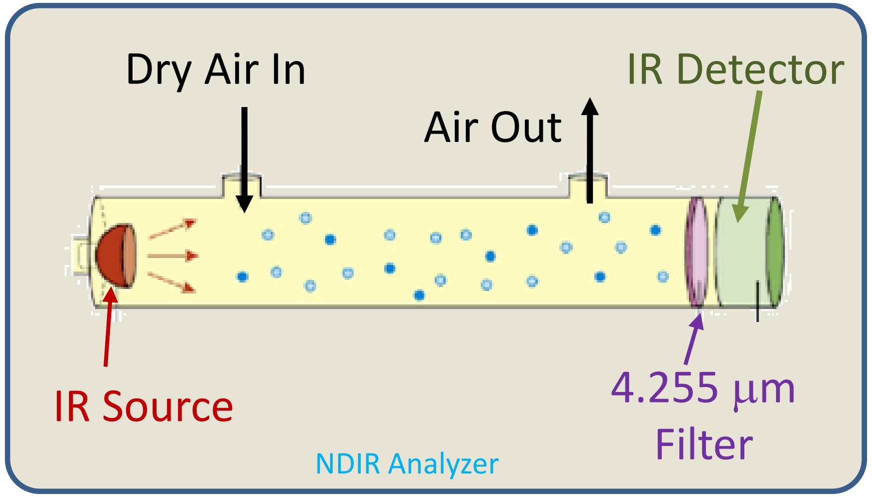


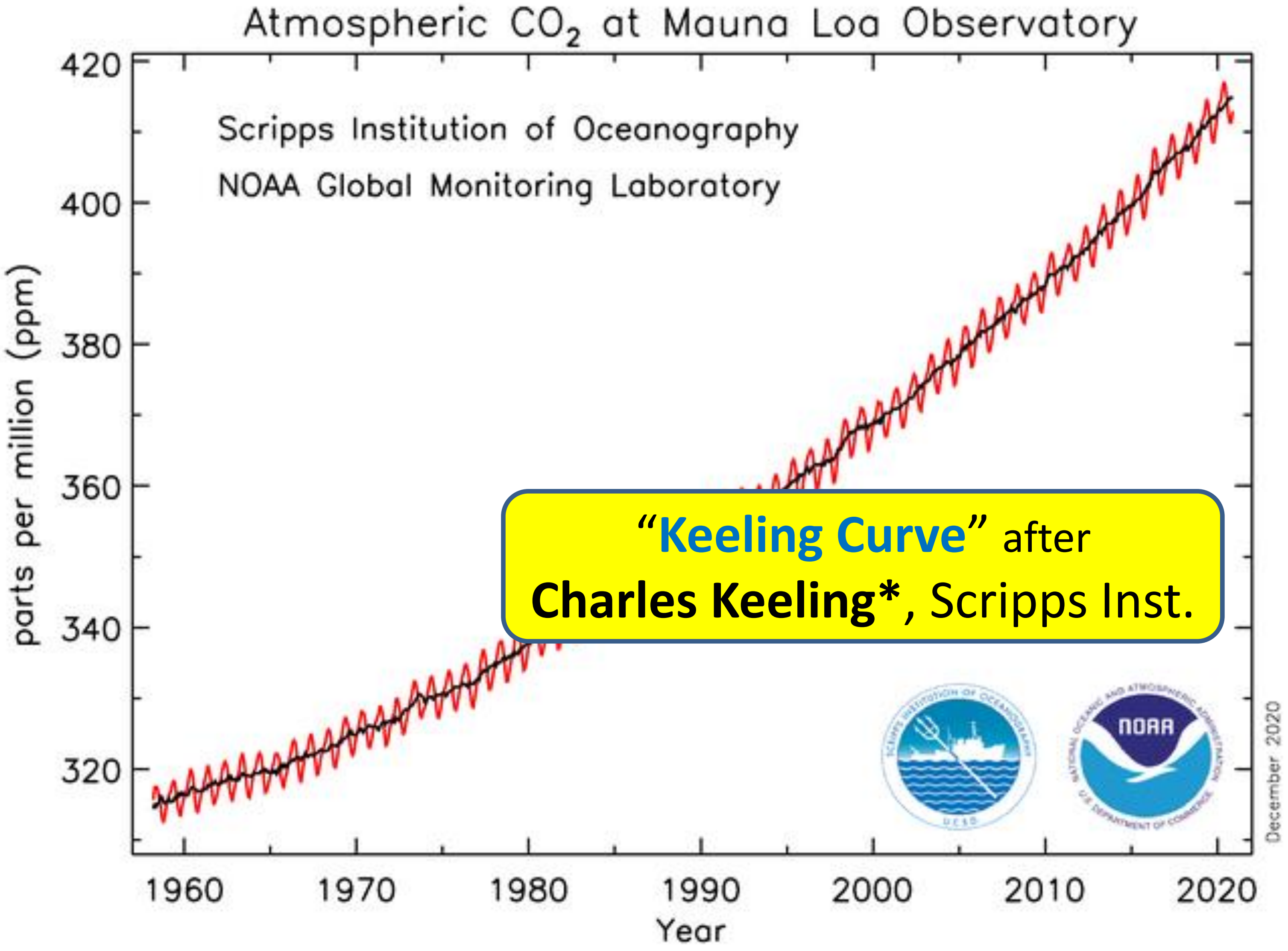

CO_2 Infrared Absorption Bands



The 15 micron Bending Mode band is most important for climate, as it falls within the Earth's Blackbody Spectrum

Measuring CO_2 in the Atmosphere

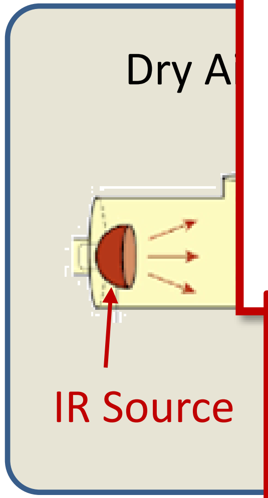


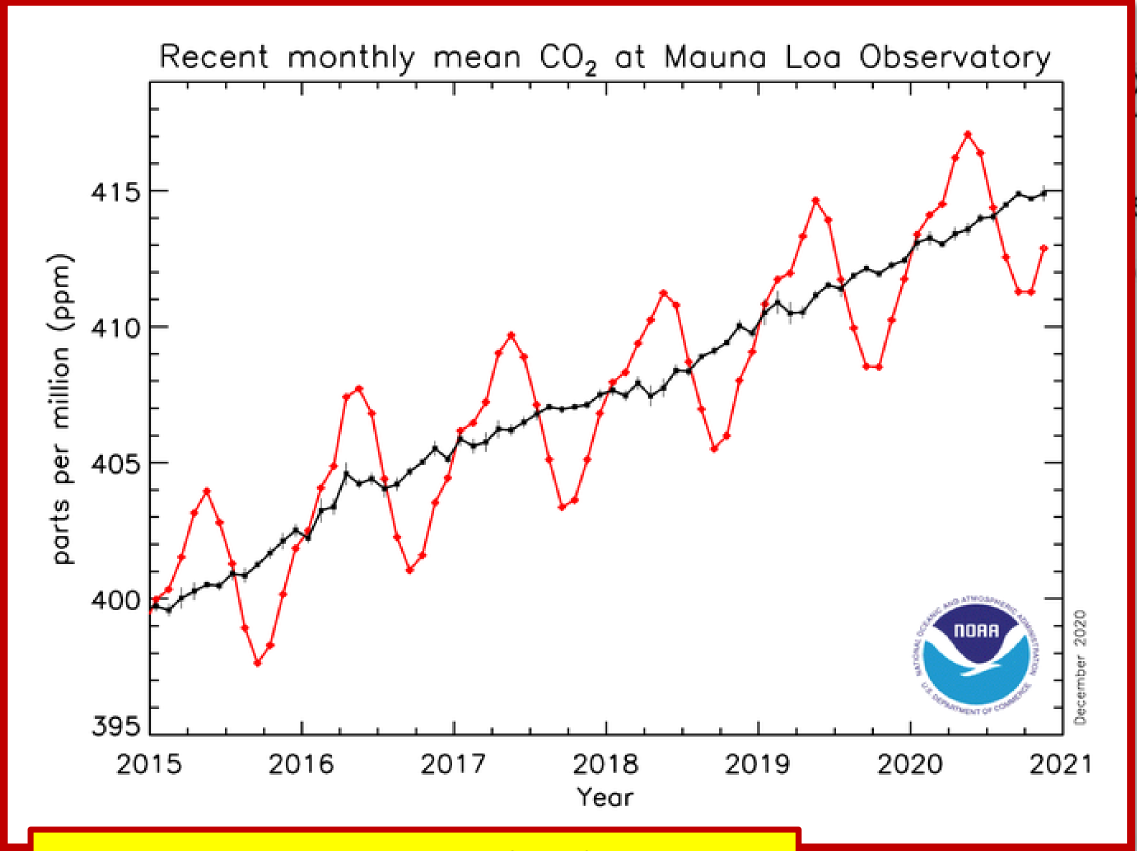


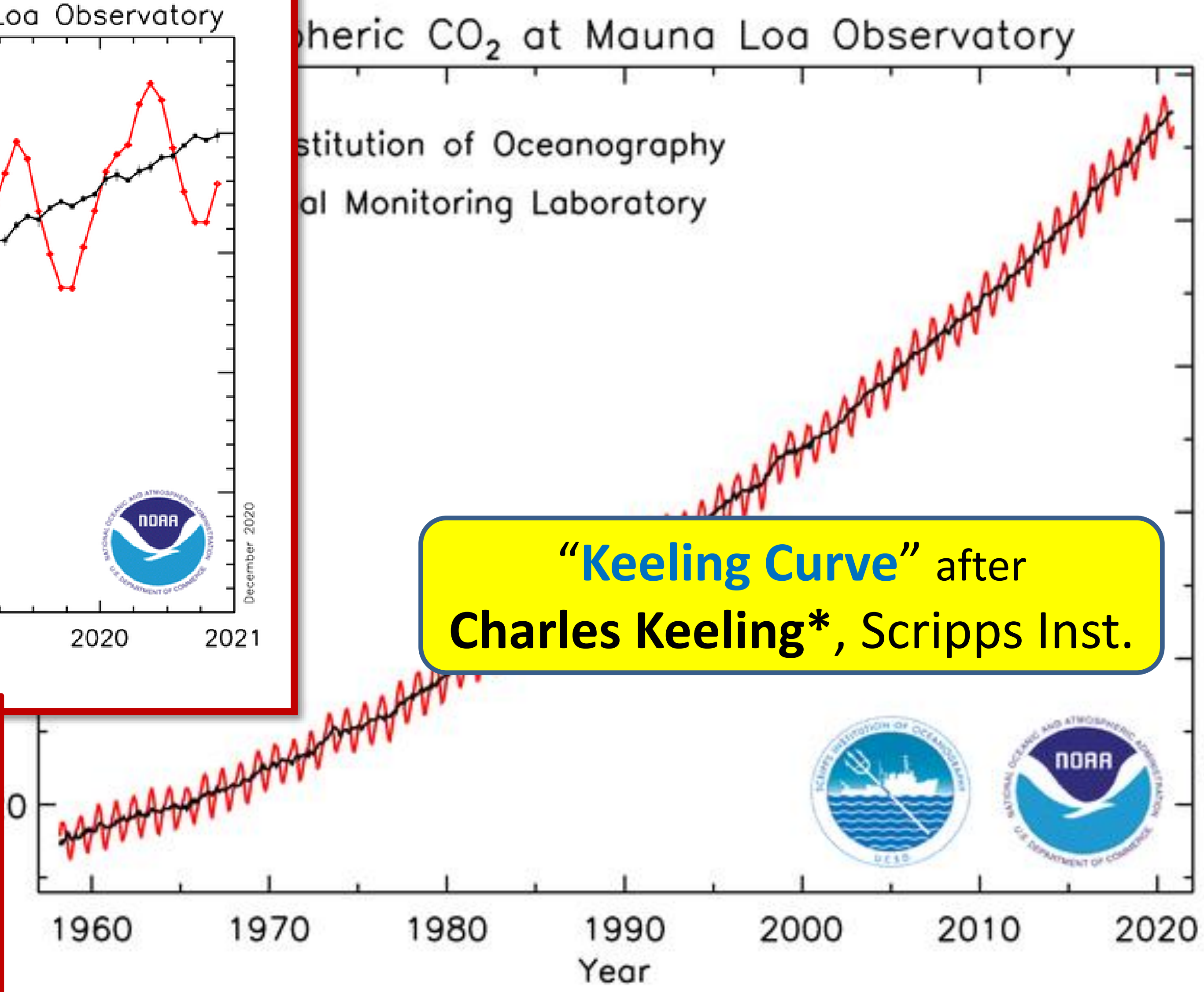
"**Keeling Curve**" after
Charles Keeling*, Scripps Inst.

* BS Chemistry, Illinois 1948

Measuring CO_2 in the Atmosphere





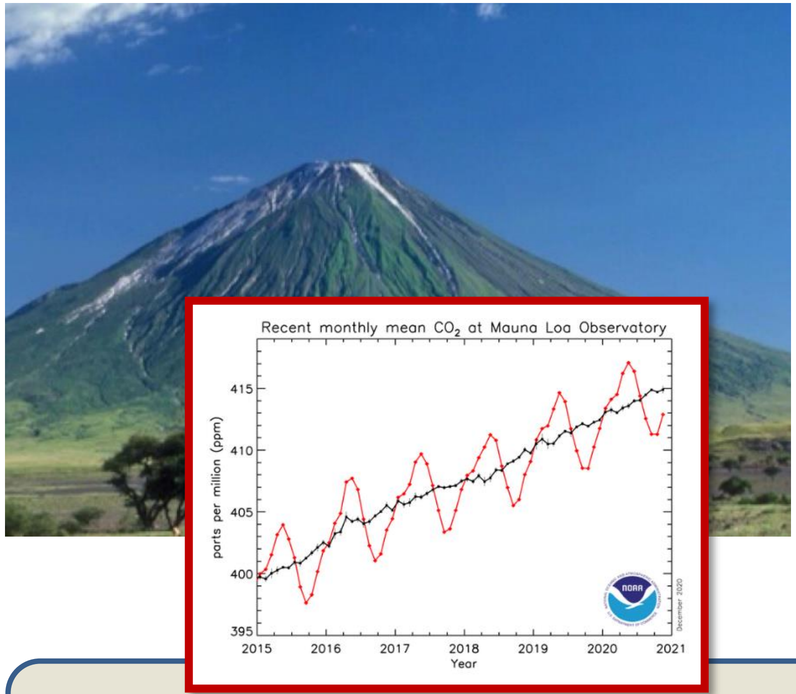


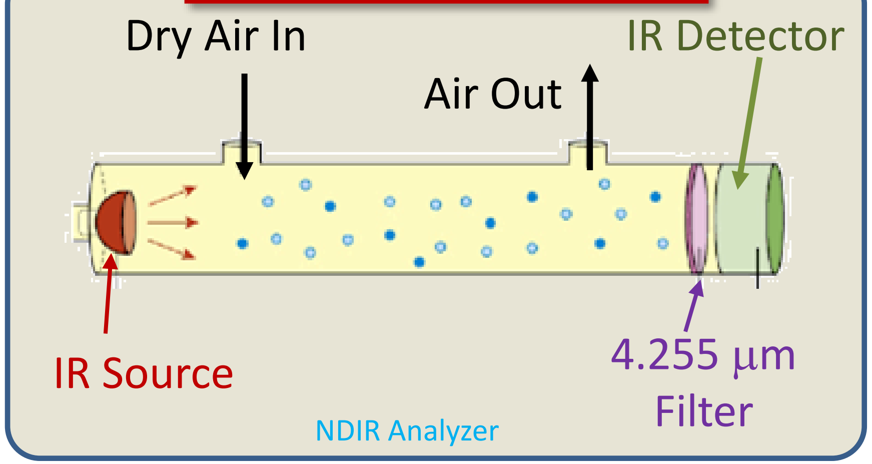
"**Keeling Curve**" after
Charles Keeling*, Scripps Inst.

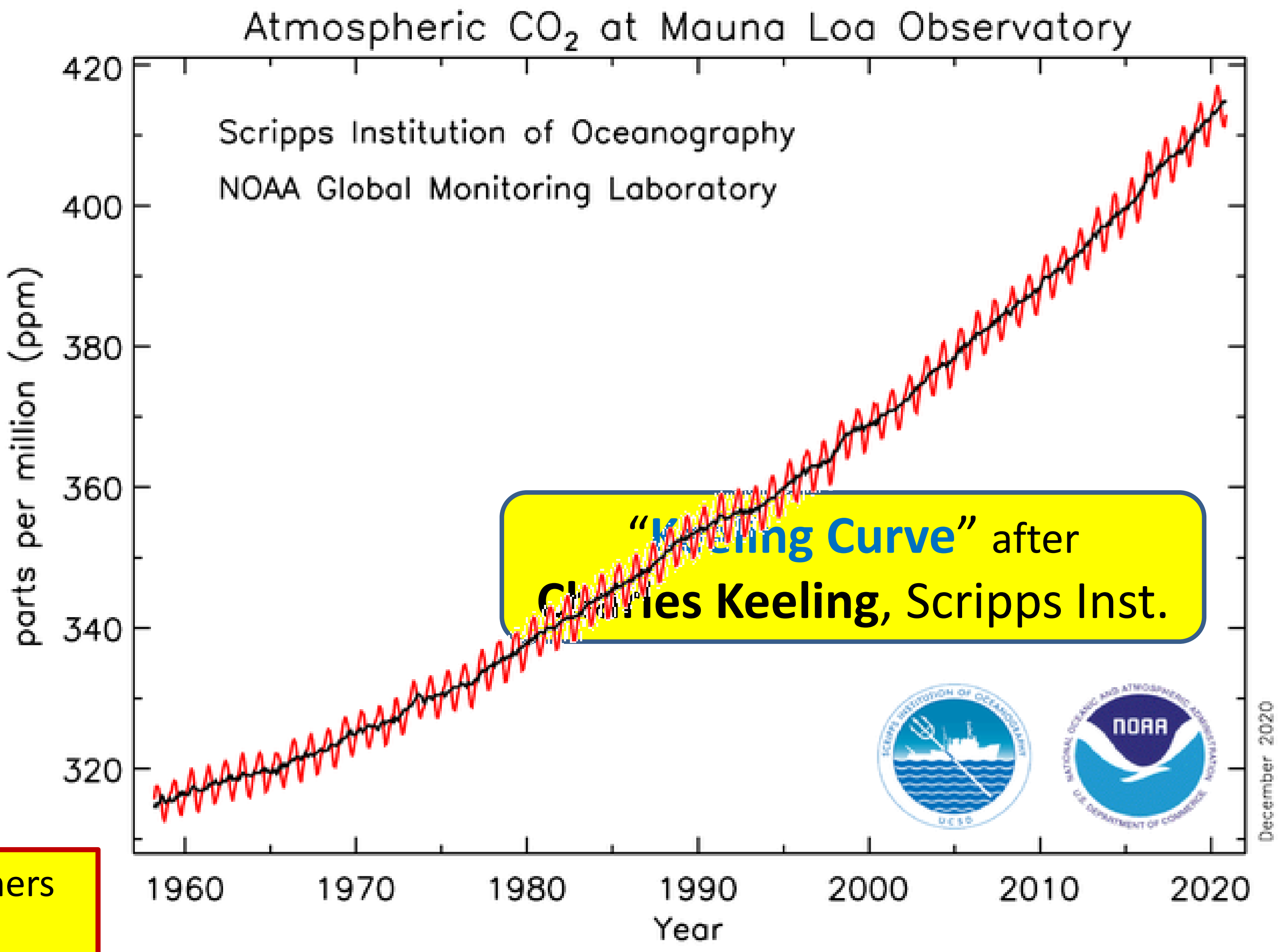
Annual ups and downs (red) due to Northern Hemisphere vegetation growing cycles. In spring, photosynthesis sucks CO2 out of the air. In winter, decaying vegetation returns the CO2 to the air. Black line is smoothed average.

* BS Chemistry, Illinois 1948

Measuring CO_2 in the Atmosphere



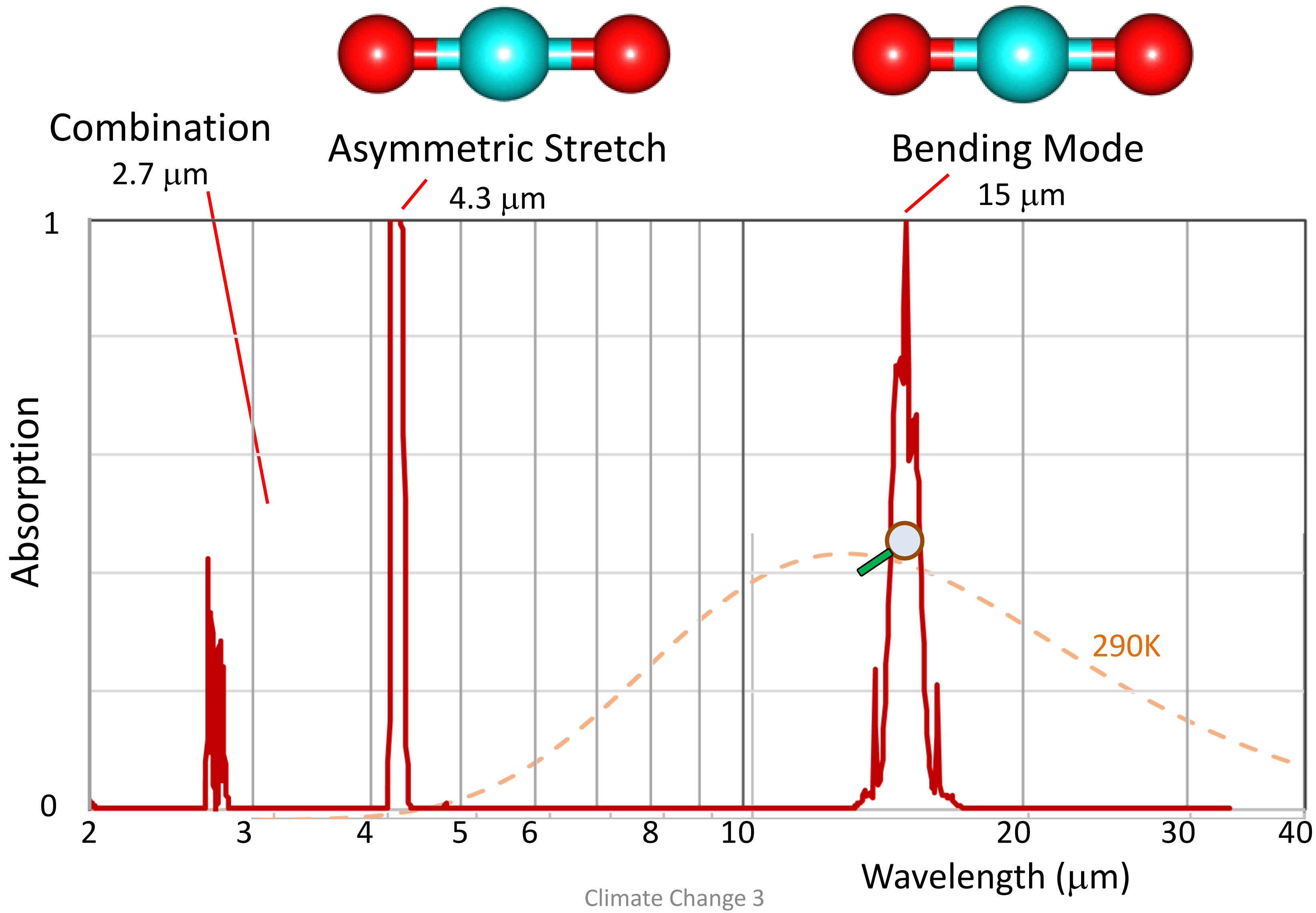




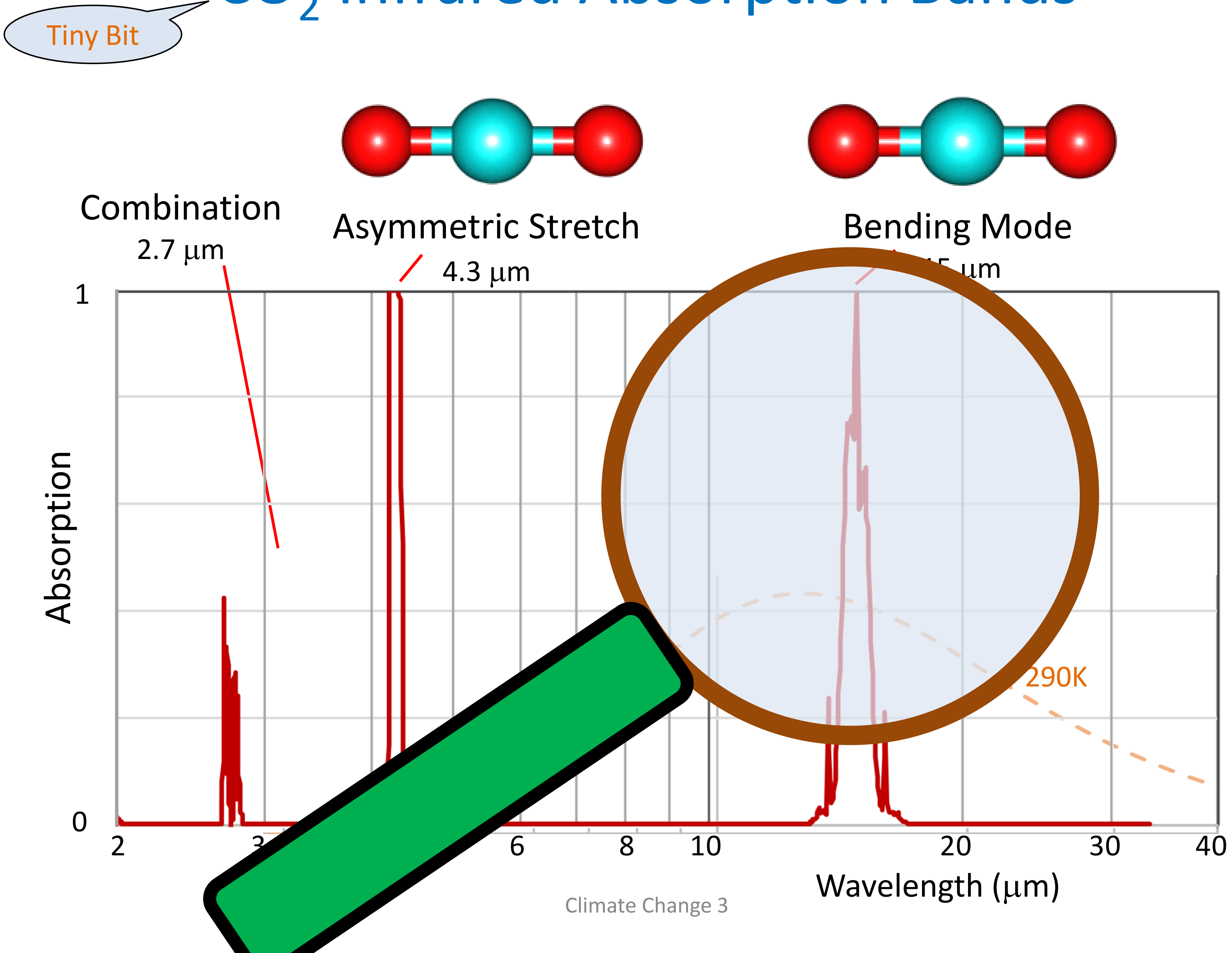
The Keeling curve (and many others like it around the world) are the proverbial “smoking gun”.....

CO_2 Infrared Absorption Bands

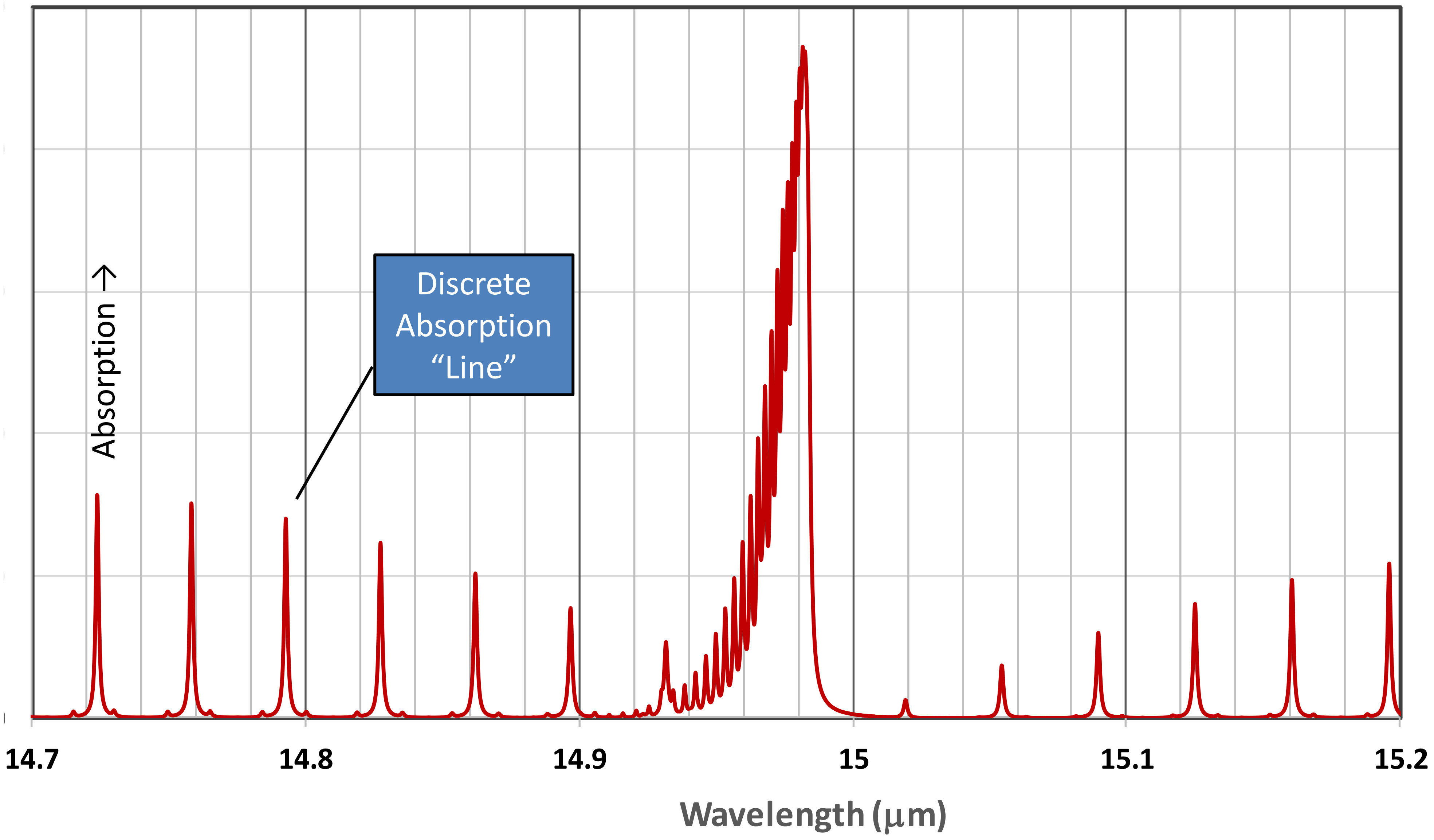
Tiny Bit



CO_2 Infrared Absorption Bands



Detail of Part of CO_2 Bending Band



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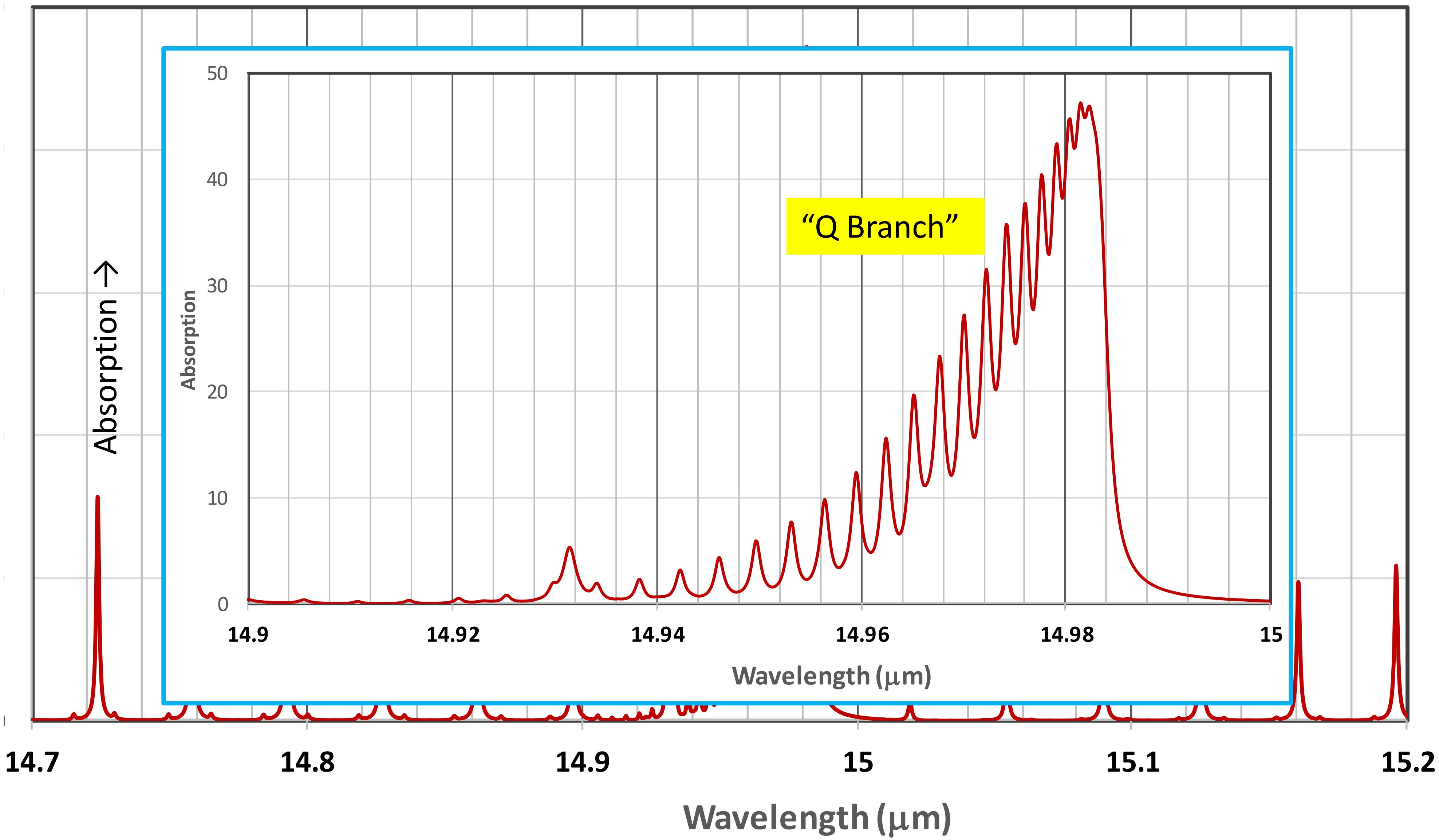
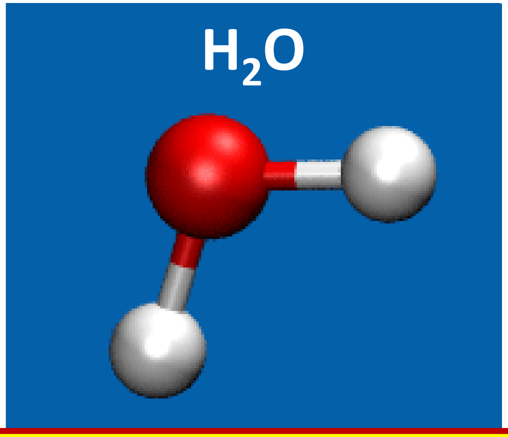
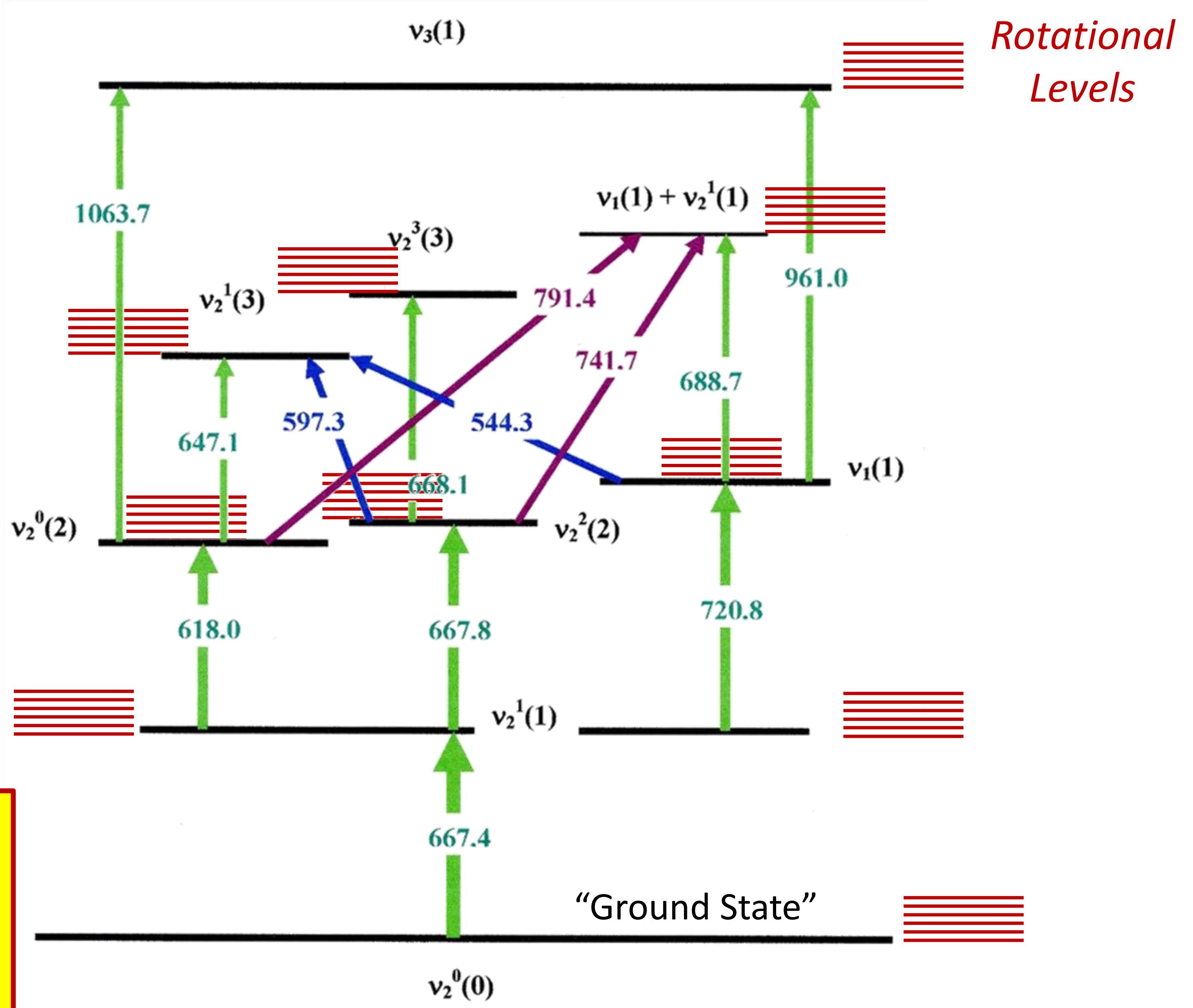


CO_2 Vibrational Energy Level Diagram

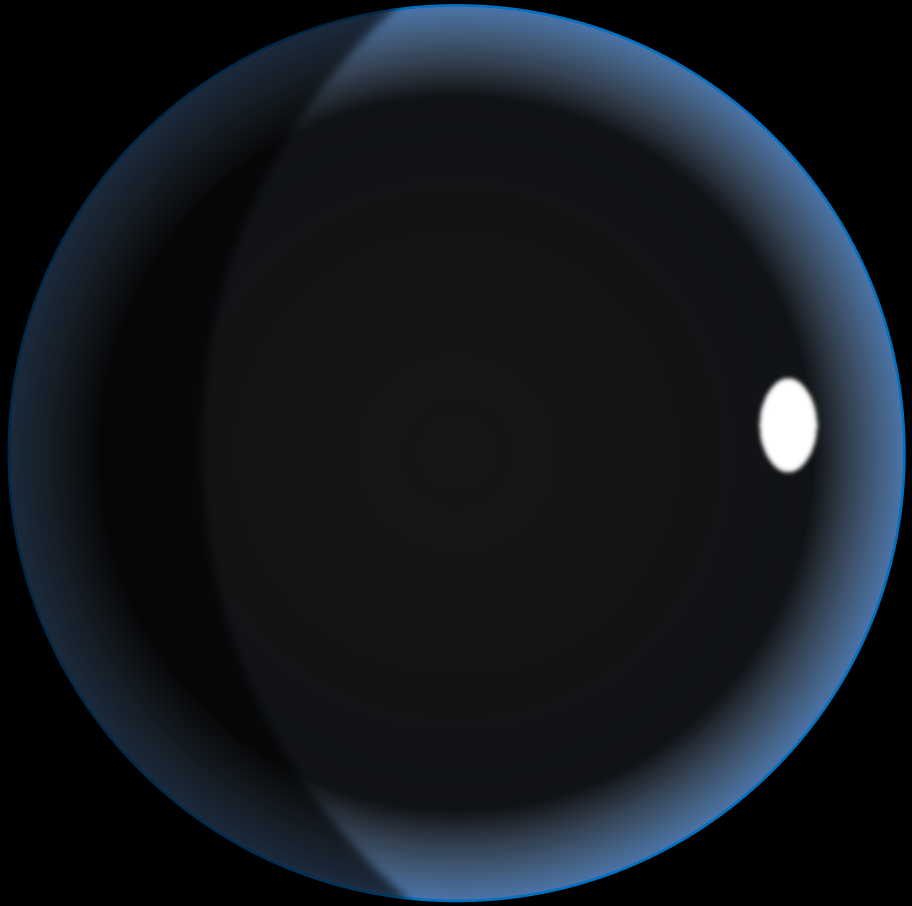


Energy



CO2 molecule can only exist in certain discrete energy states with particular vibrational and rotational quanta. Transitions between these many energy levels result in IR photons being absorbed or emitted at definite wavelengths.

Add Greenhouse Layer



Add Greenhouse Layer

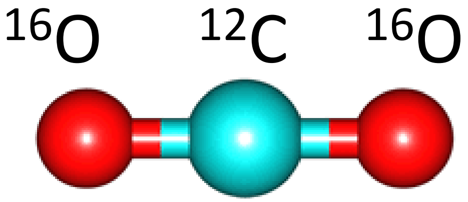
HITRAN*

*High-resolution Transmission Molecular Absorption Database

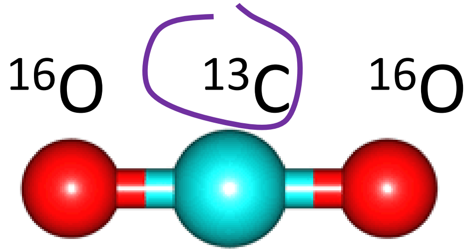
- Compilation of high accuracy data on molecular absorption lines
- Started by Air Force Cambridge Research Laboratories in 1960's
  - Cold war genesis
- Now maintained by Harvard-Smithsonian Center for Astrophysics
- Based on experimental measurements
  - extended and checked by quantum theory
- 49 molecules
  - 125+ **isotopologues** (12 for CO_2 alone)
  - **7.4** million absorption lines!
- Available free on-line

Polyatomic Molecules come in various versions, with different isotopes of the constituent atoms

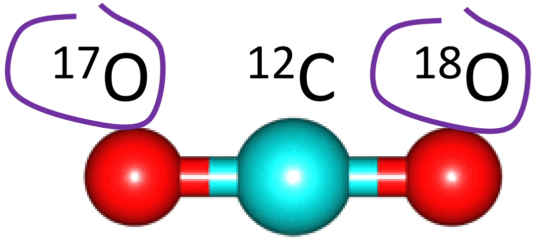
Isotopologue?



Garden Variety CO_2
(> 98%)



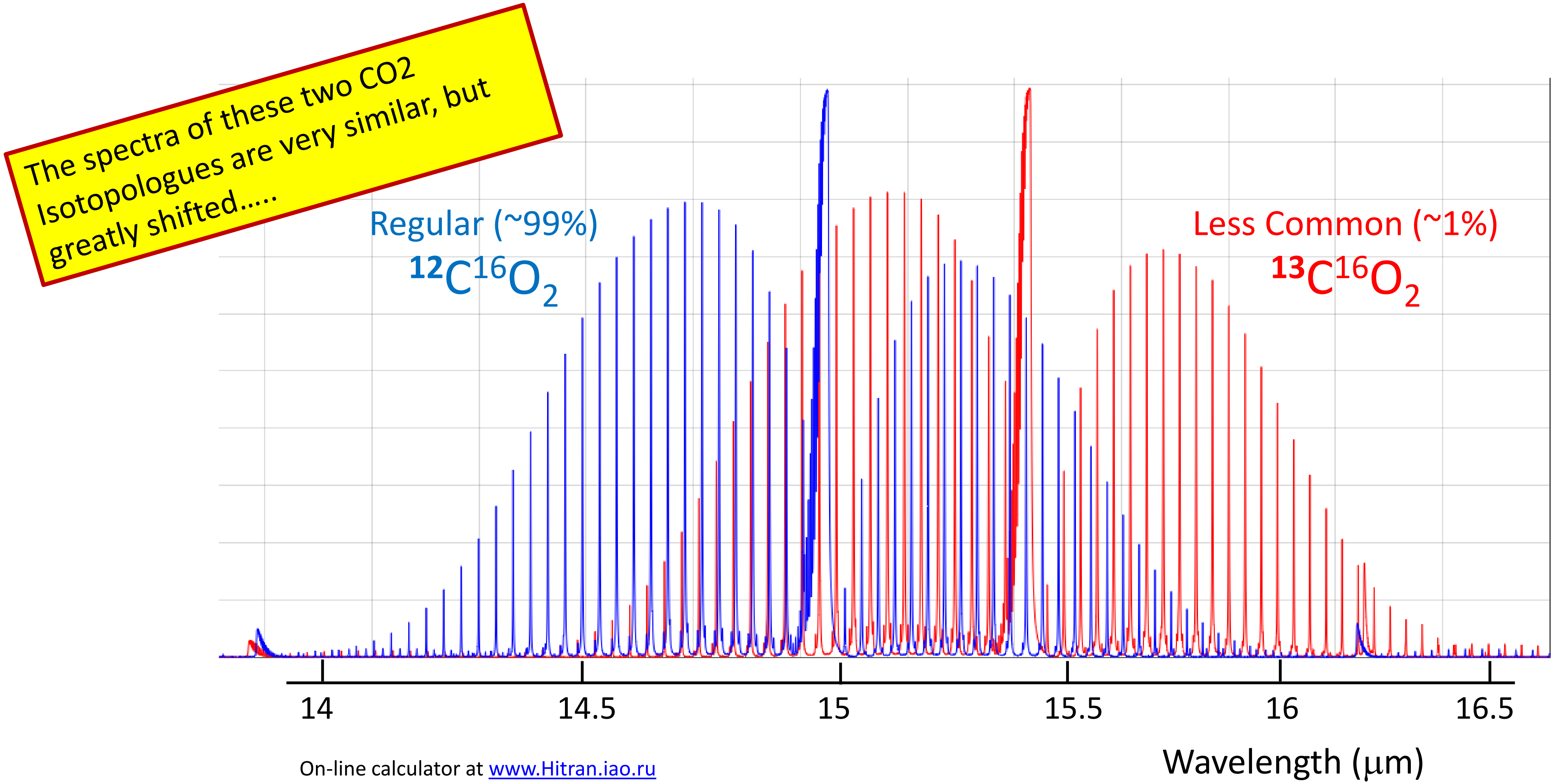
Another isotopologue
of CO_2 (>1%)



Yet another isotopologue
of CO_2 (very rare)

+ 9 more in HITRAN database…

Spectral Shift between Isotopologues



On-line calculator at www.Hitran.iao.ru

HITRAN*

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- Now ma... Astrophysics
- Based ...ents
  - ext... by quantum theory
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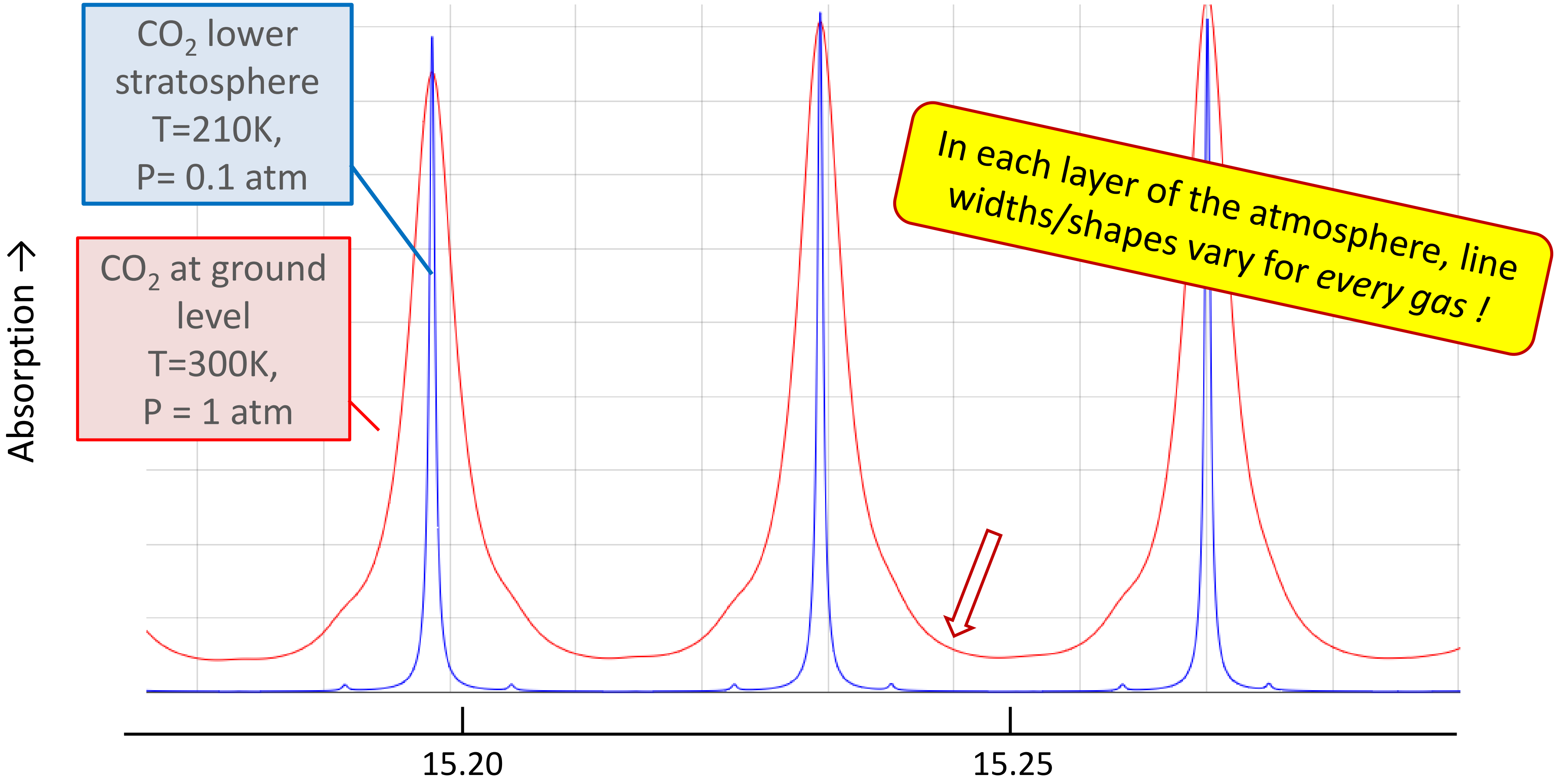
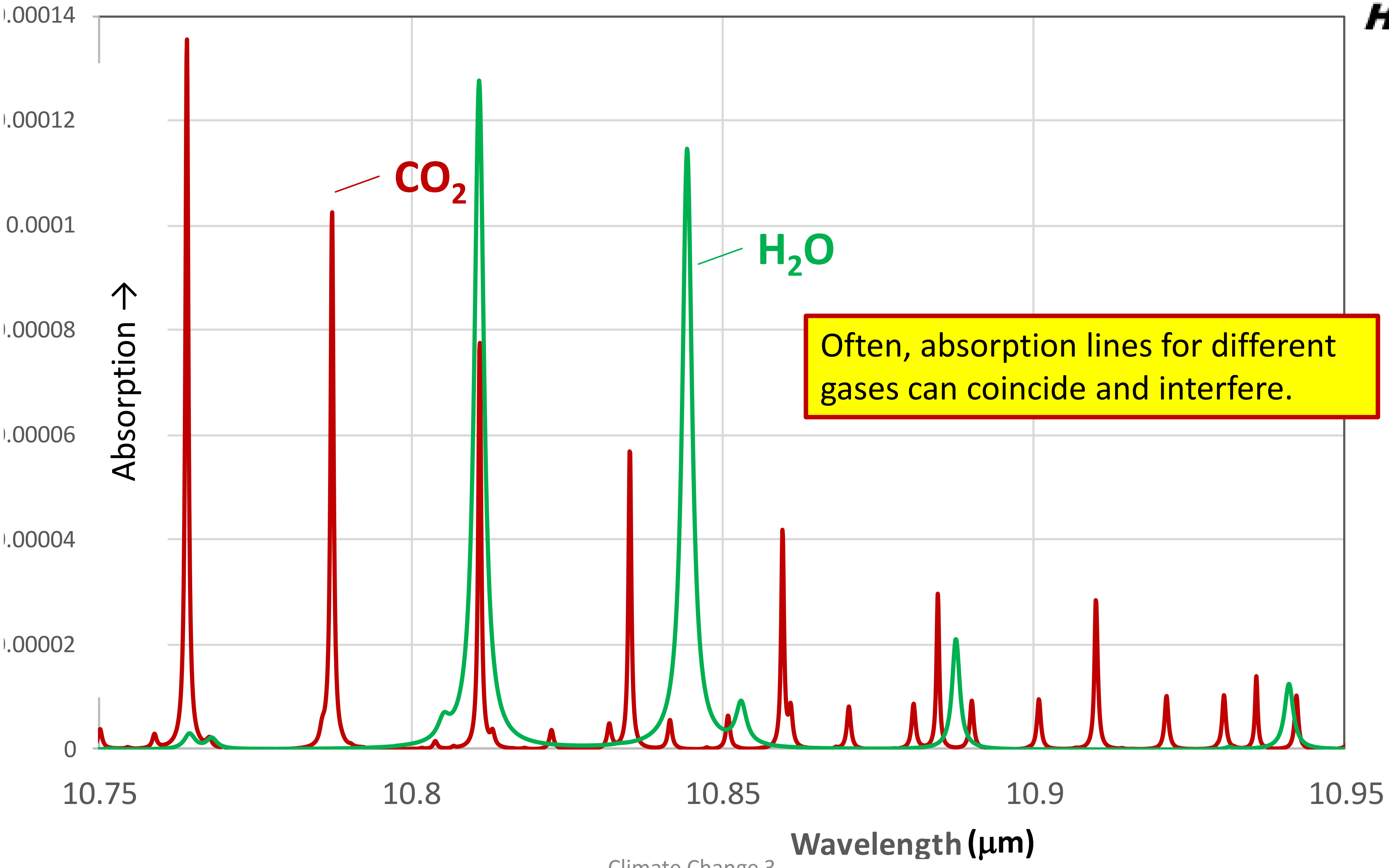
Basis for Atmospheric Radiation Calculations in almost all Climate Models

Lines Broaden Severely due to Temperature and Pressure

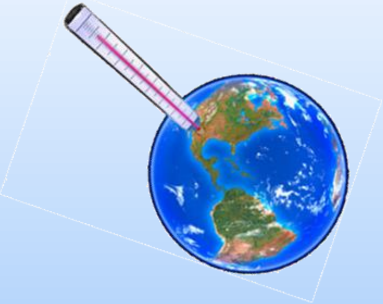


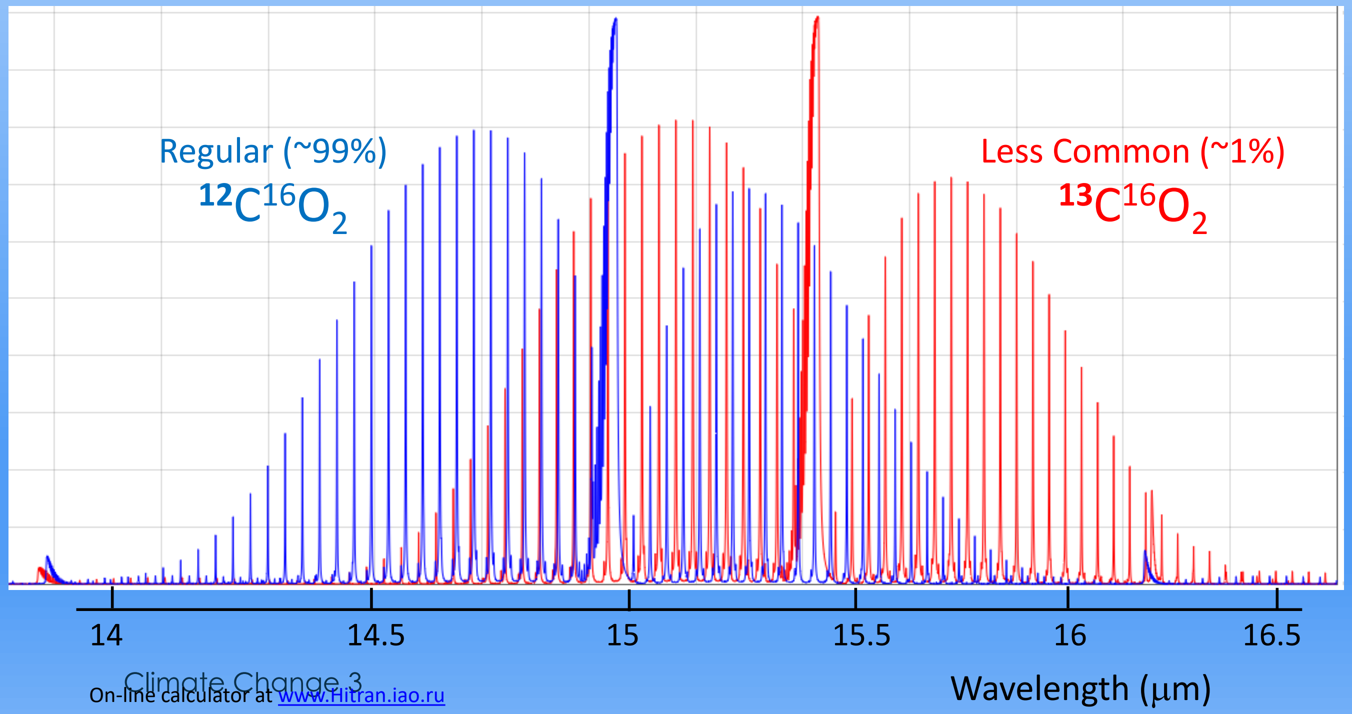
Mixed Gases



.00014
.00012
0.0001
.00008
.00006
.00004
.00002
0
Absorption →
CO2
H2O
Often, absorption lines for different gases can coincide and interfere.
10.75
10.8
10.85
10.9
10.95
Wavelength (μm)

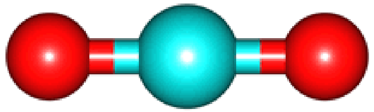
Questions about how CO_2 Absorbs (and therefore Emits) Infrared Radiation in the Atmosphere?

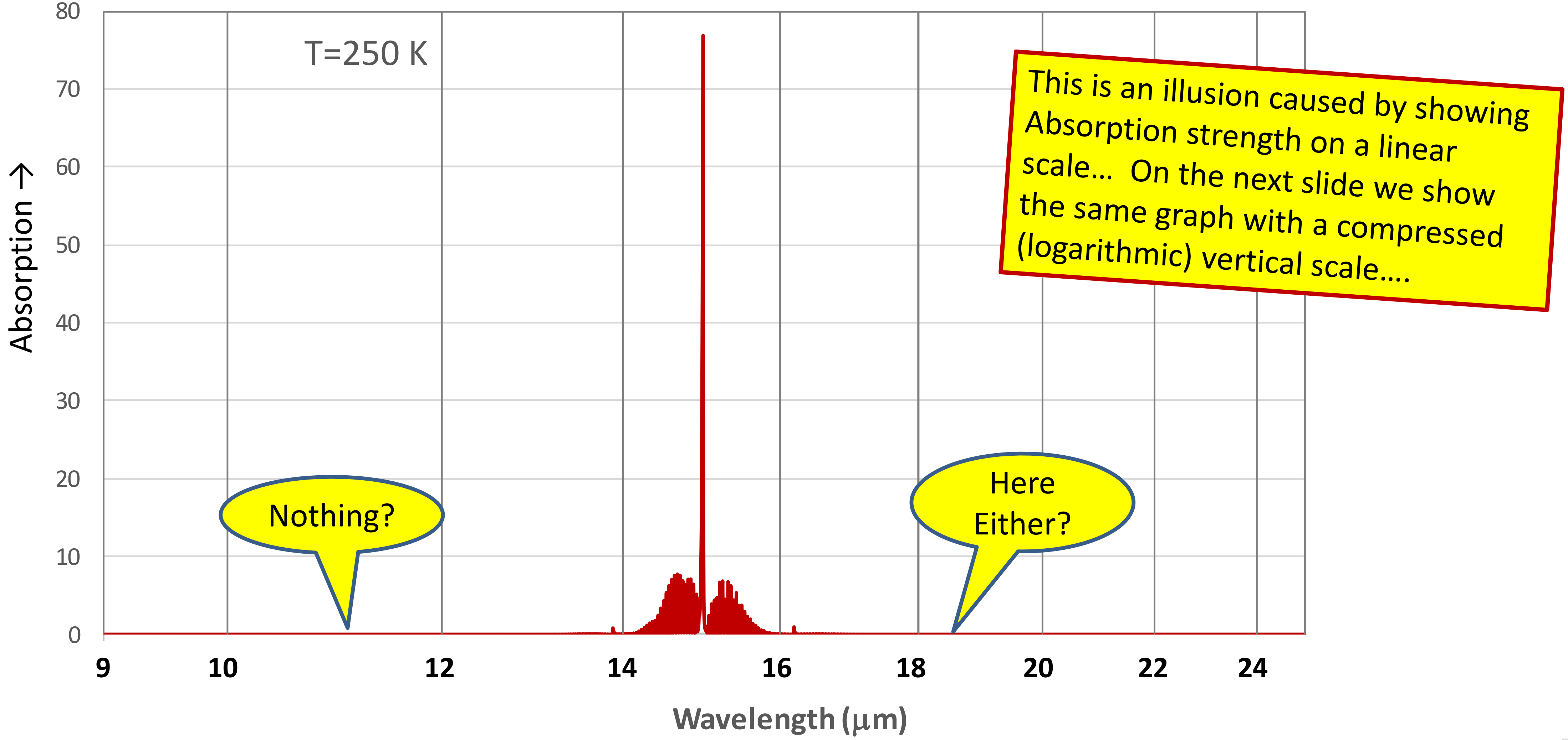




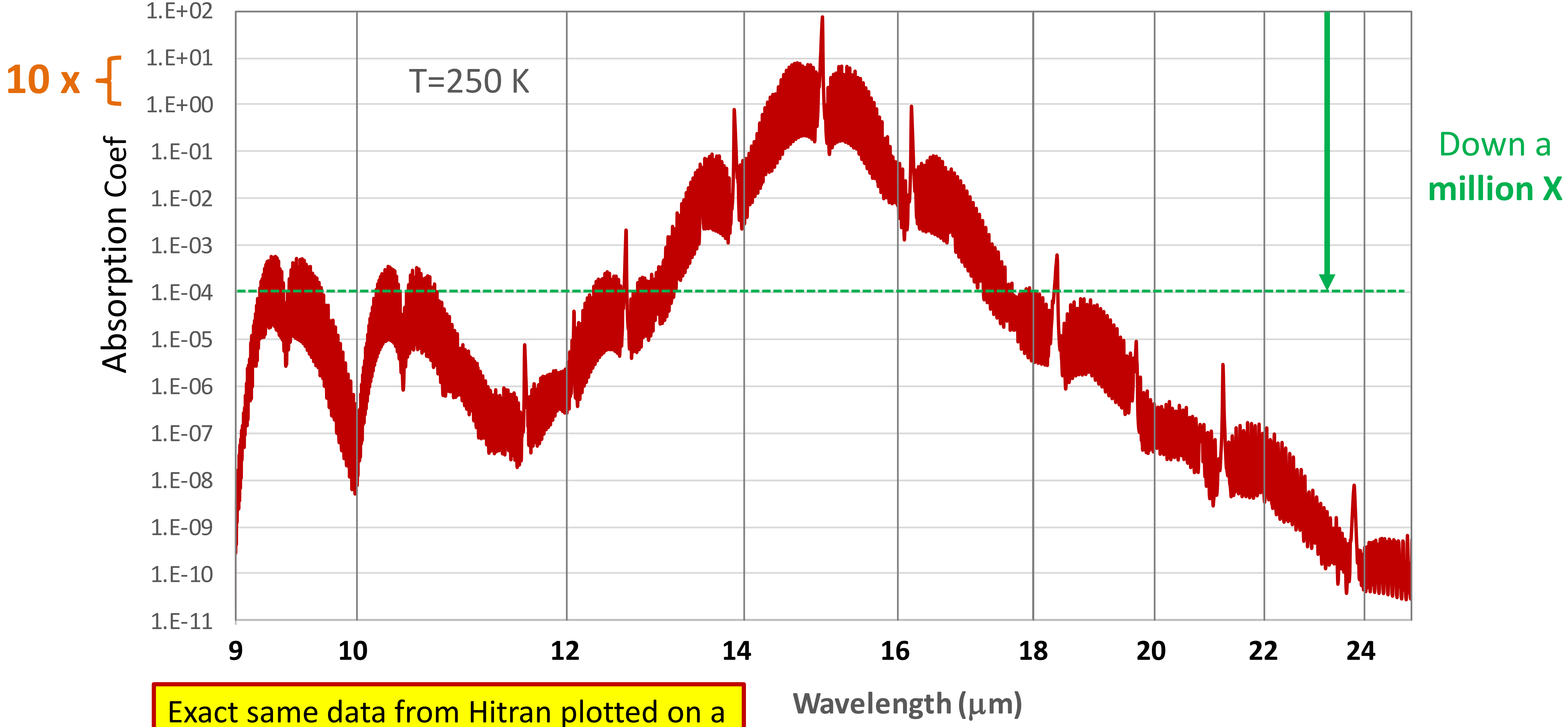
On-line calculator at www.Hitran.iao.ru

CO_2 Absorption (Bending Mode) Line Strengths

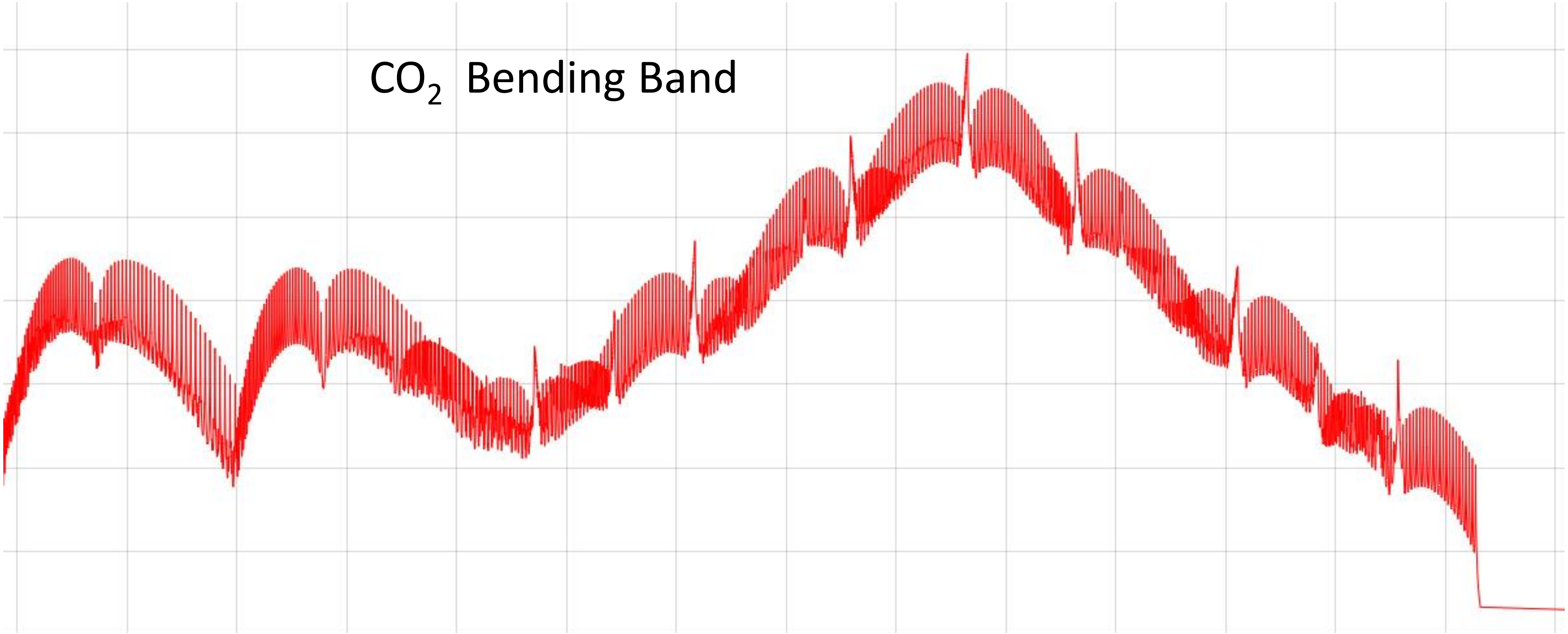




CO_2 Absorption (Bending Mode): Log Scale

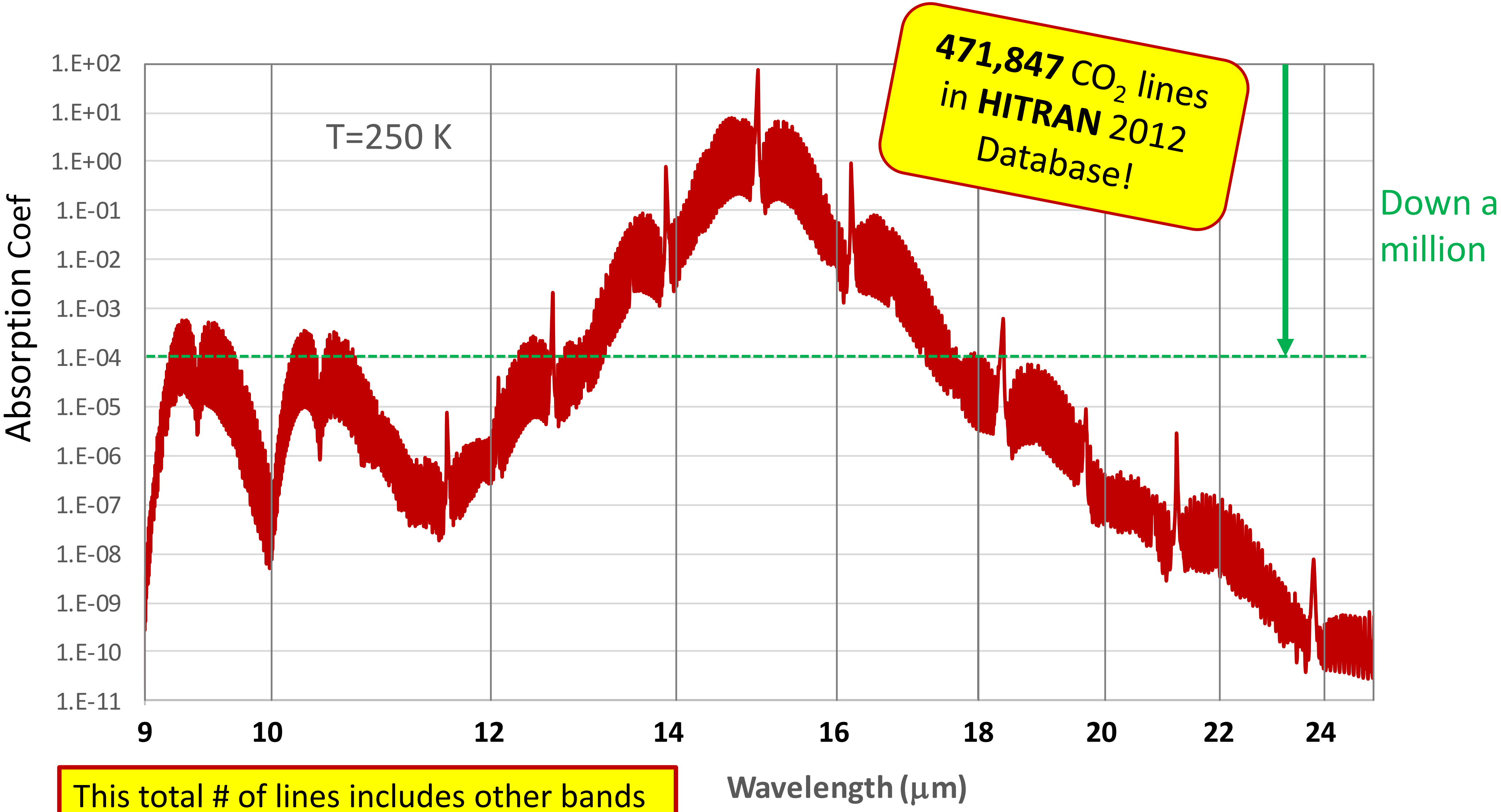


Exact same data from Hitran plotted on a log scale. We see lines everywhere.



Same plot using a "thinner" ink line shows individual spectral lines making up the curve.

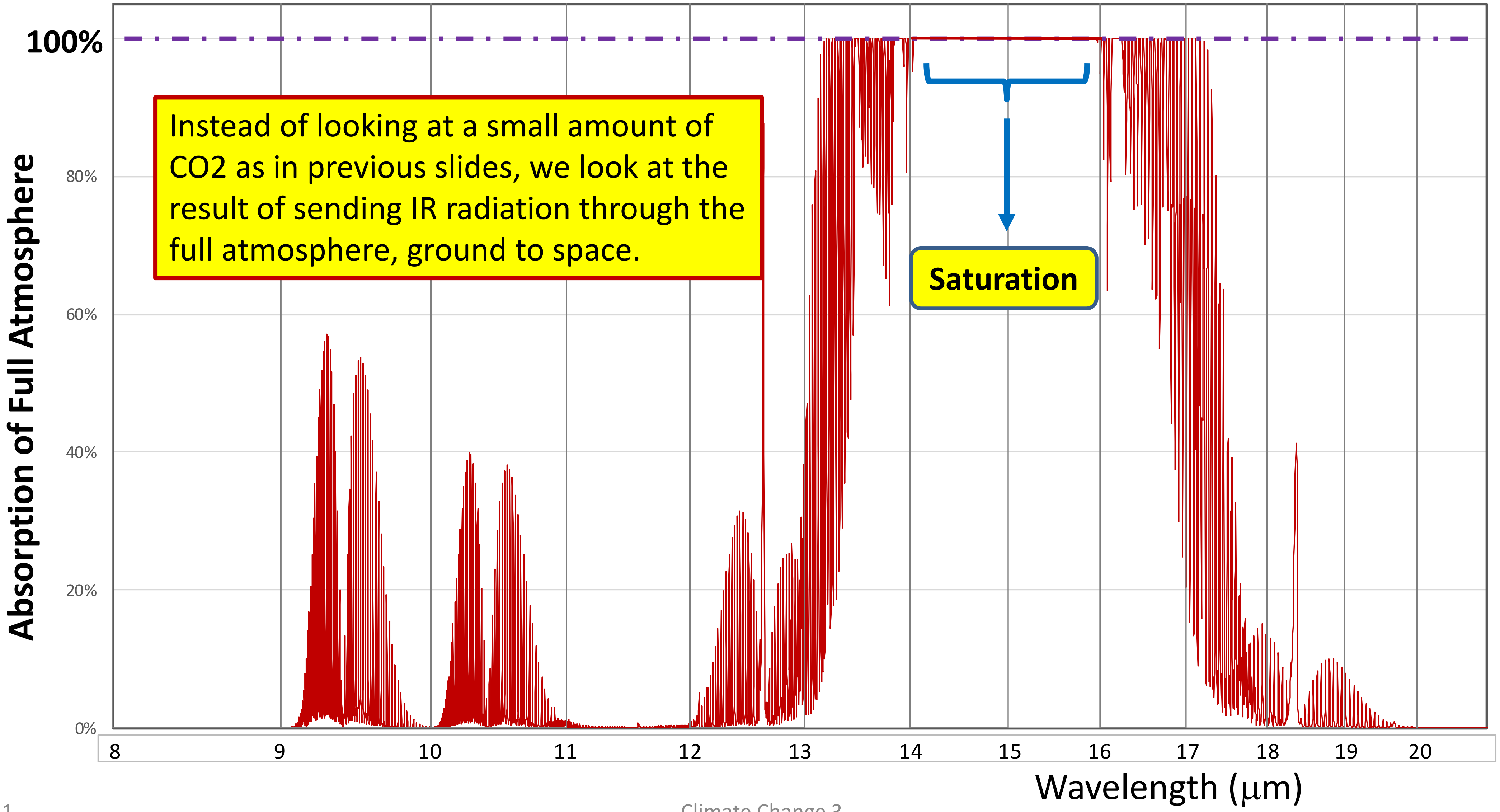
CO_2 Absorption (Bending Mode)



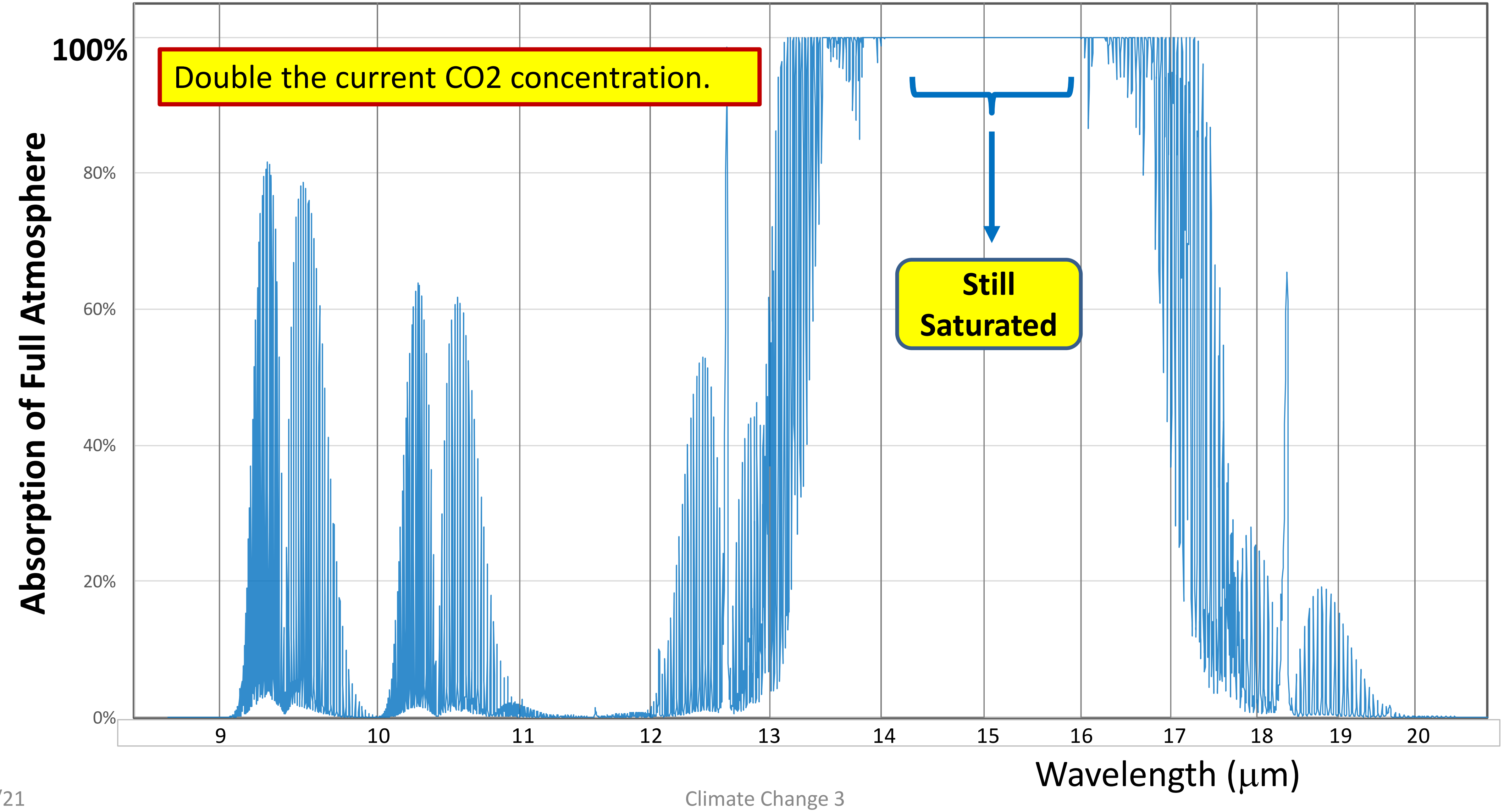
This total # of lines includes other bands and Isotopologues.

Full Atmosphere: 400 ppm CO_2

(No other gases)



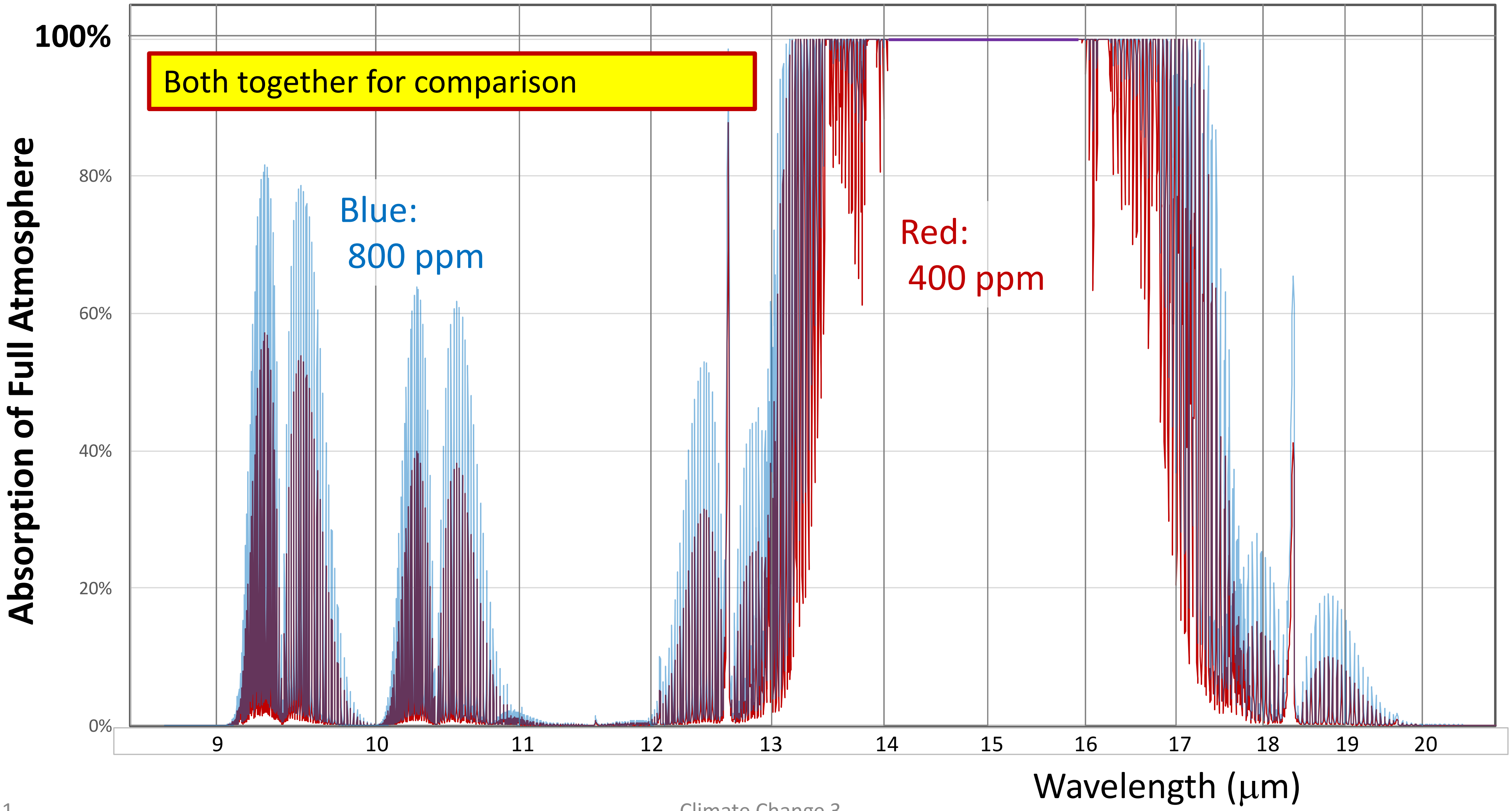
CO_2 800 ppm



Double the current CO2 concentration.
Still Saturated
100%
80%
60%
40%
20%
0%
Absorption of Full Atmosphere
9
10
11
12
13
14
15
16
17
18
19
20
Wavelength (μm)

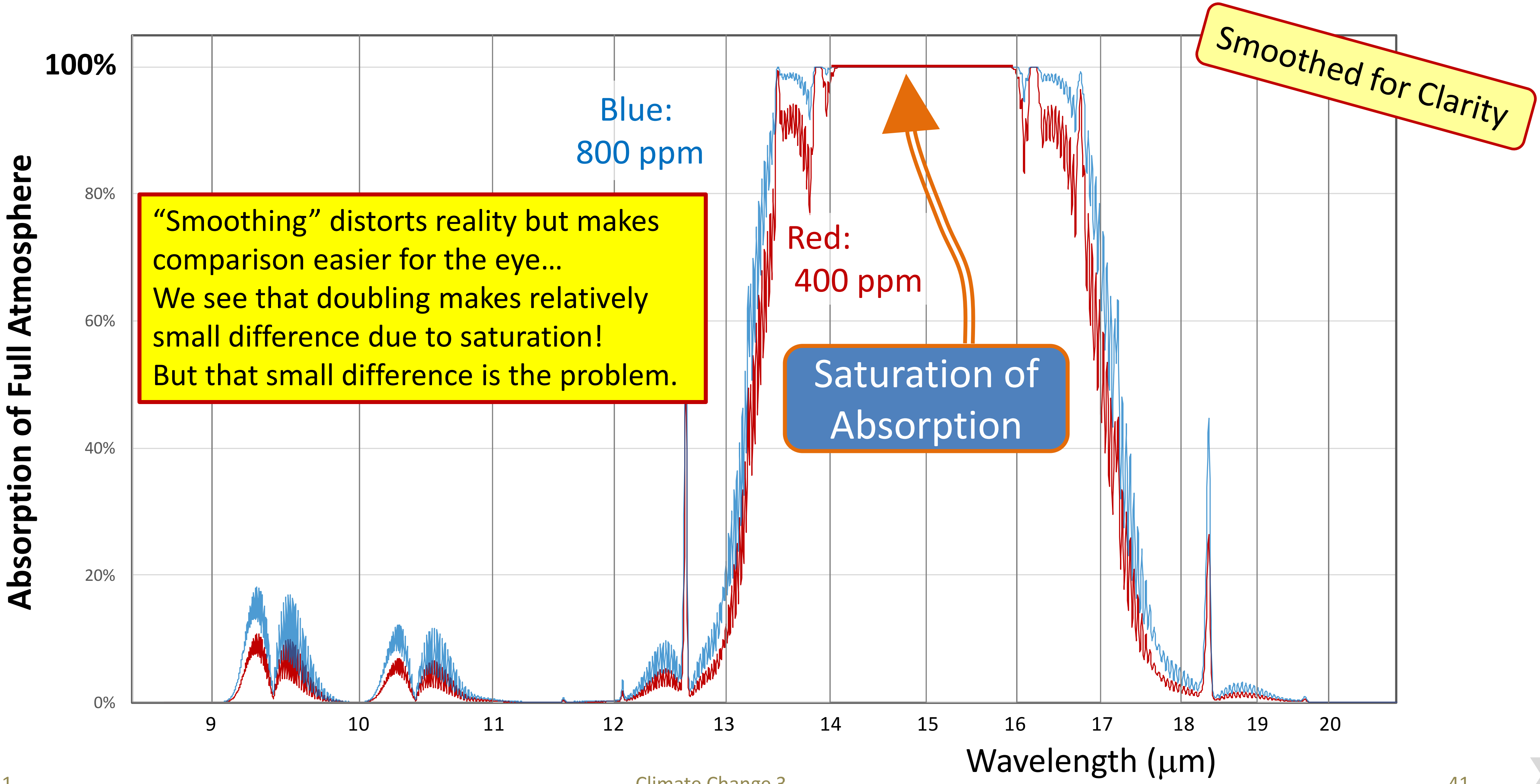
Full Atmosphere: 400 *vs.* 800 ppm CO_2

(No other gases)

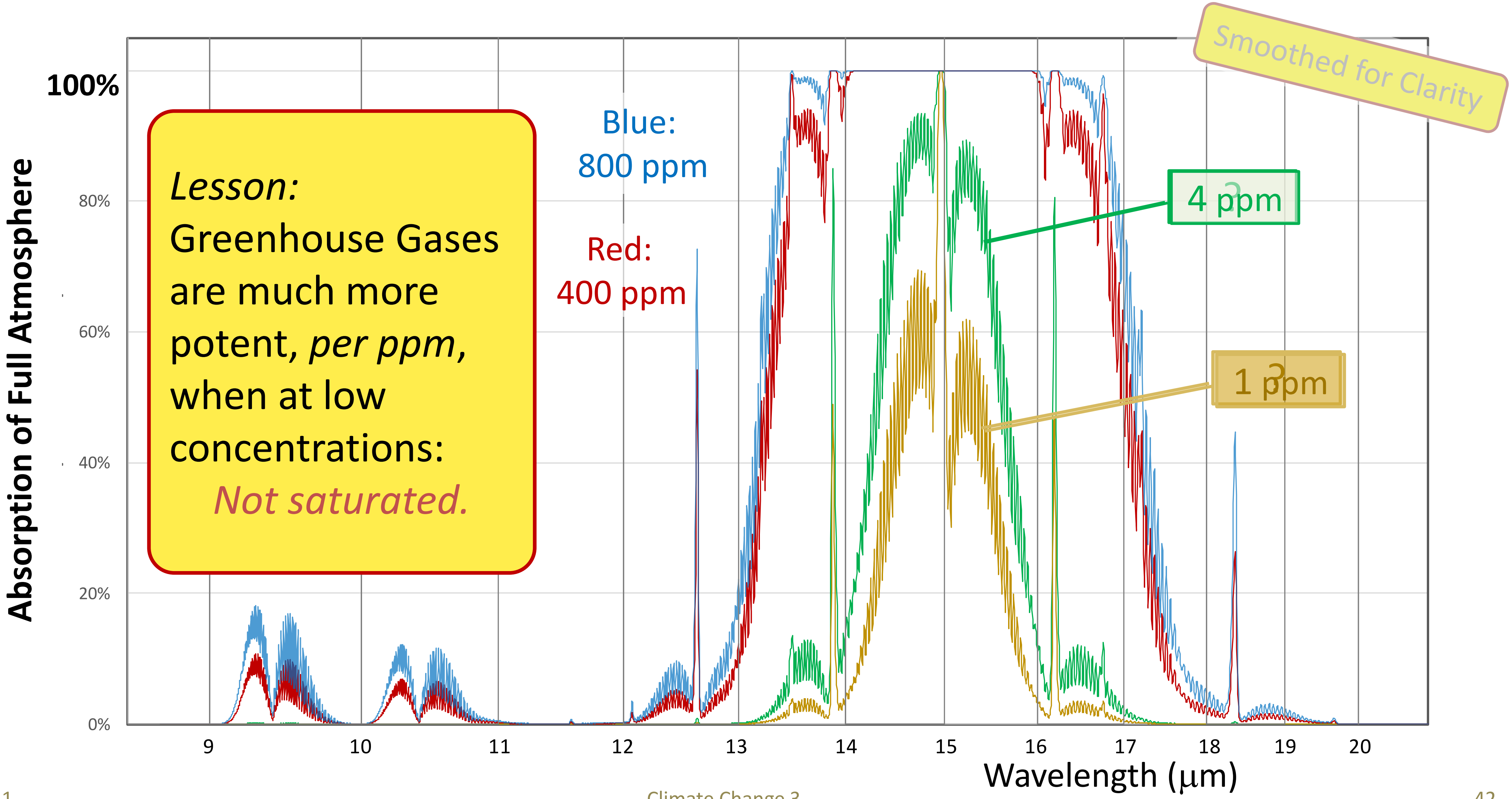


Full Atmosphere: 400 *vs* 800 ppm CO_2

(No other gases)

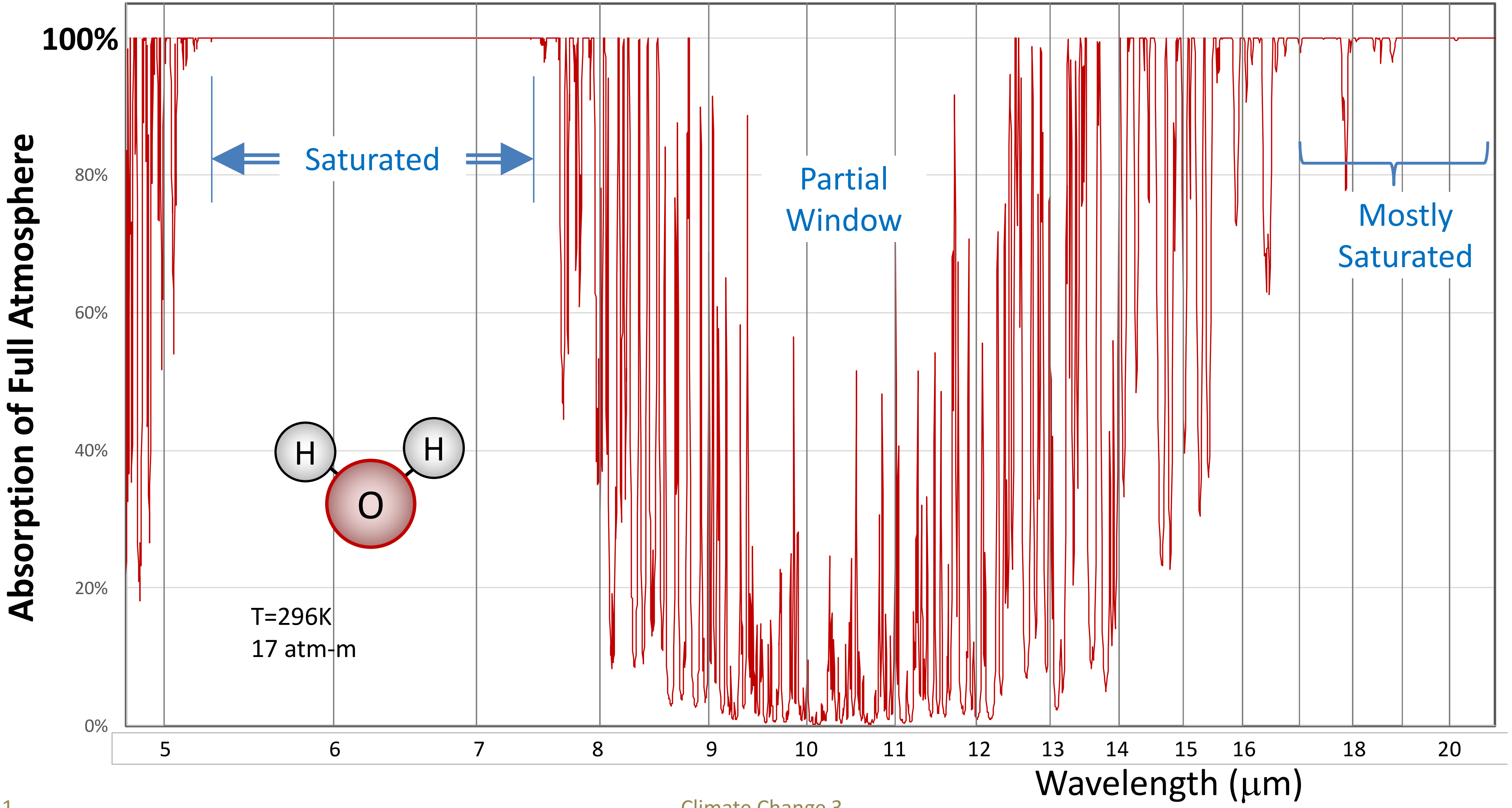


Full Atmosphere: Add Two More CO_2 Concentrations



Full Atmosphere: Water Vapor H_2O

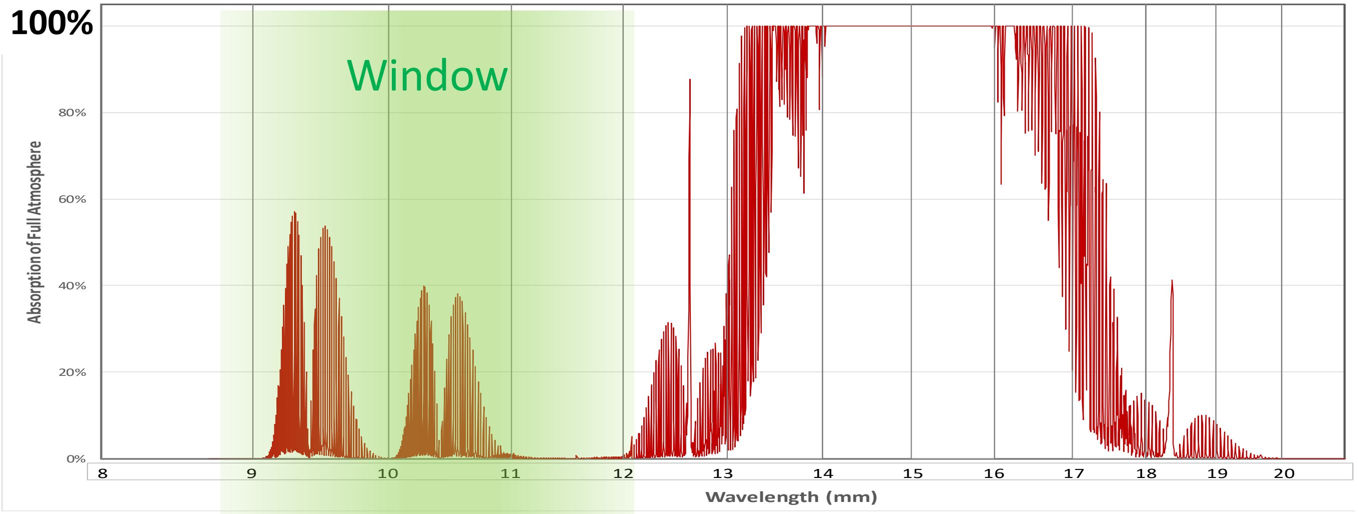
(Typical Humidity)



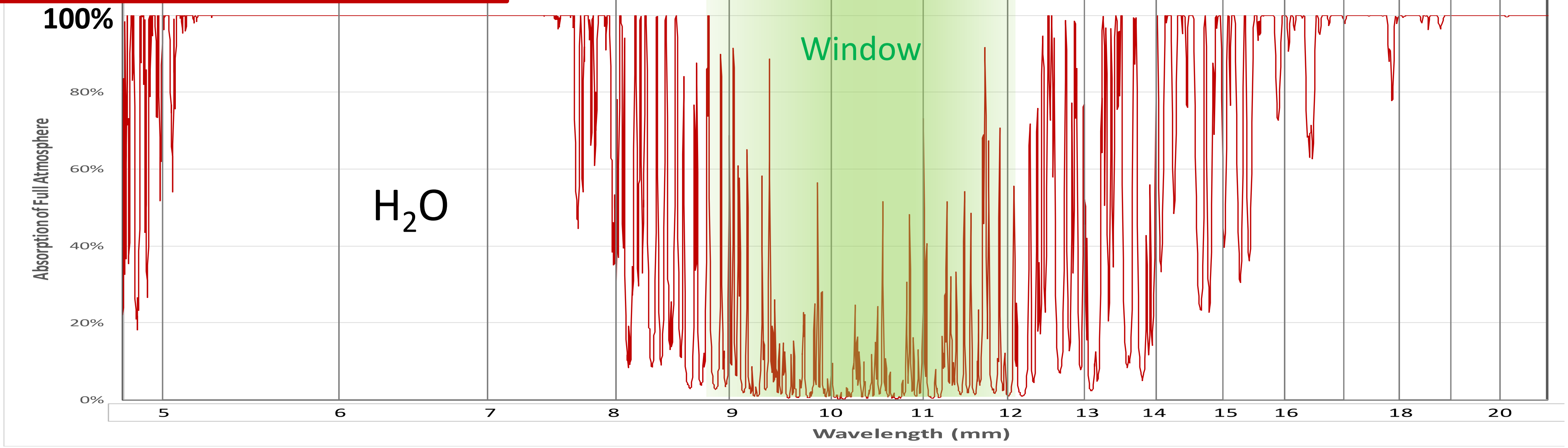
Full Atmosphere: Water Vapor + CO_2 Leave A Window at 10-11 μm

Origin of the LW IR Atmospheric Window

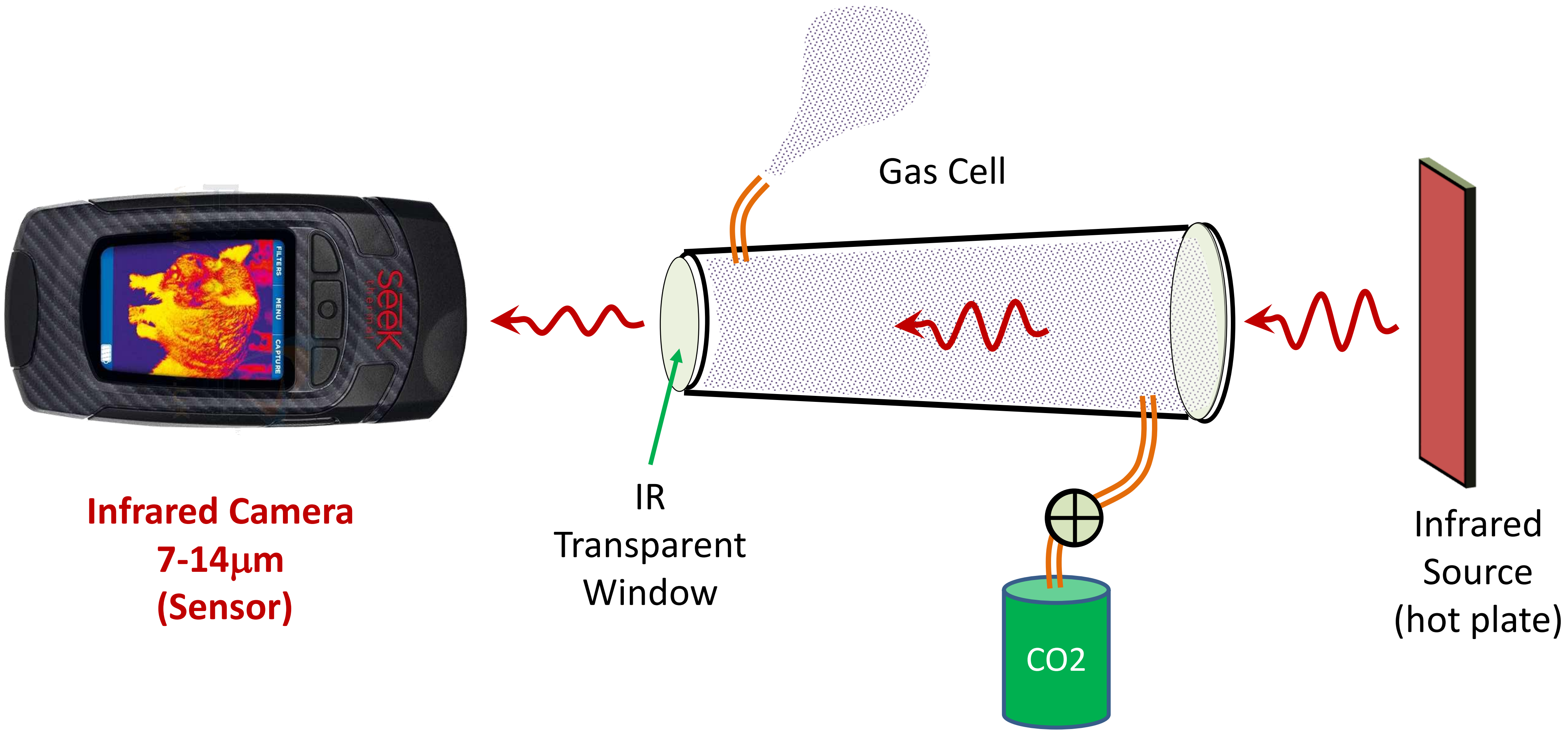
CO_2



Together, H2O and CO2 block most of the IR except in the 10 micron window.



Observing CO_2 Absorption in the LW Infrared

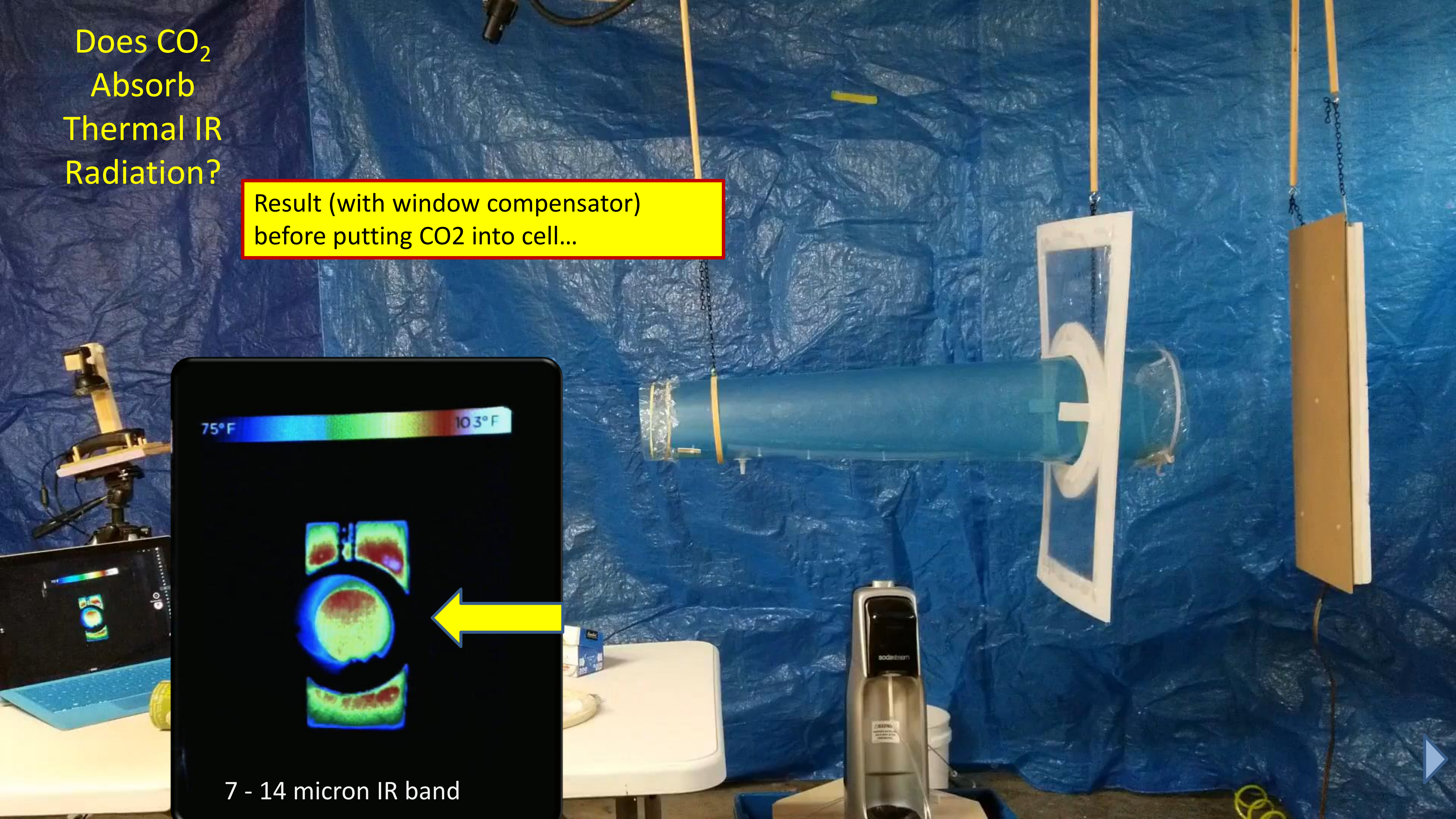


Equivalent thickness of CO_2
in atmosphere = 3.2 m


Does CO_2 Absorb Thermal IR Radiation?
The experimental setup.
75°F
103°F
7 - 14 micron IR band
sodastream

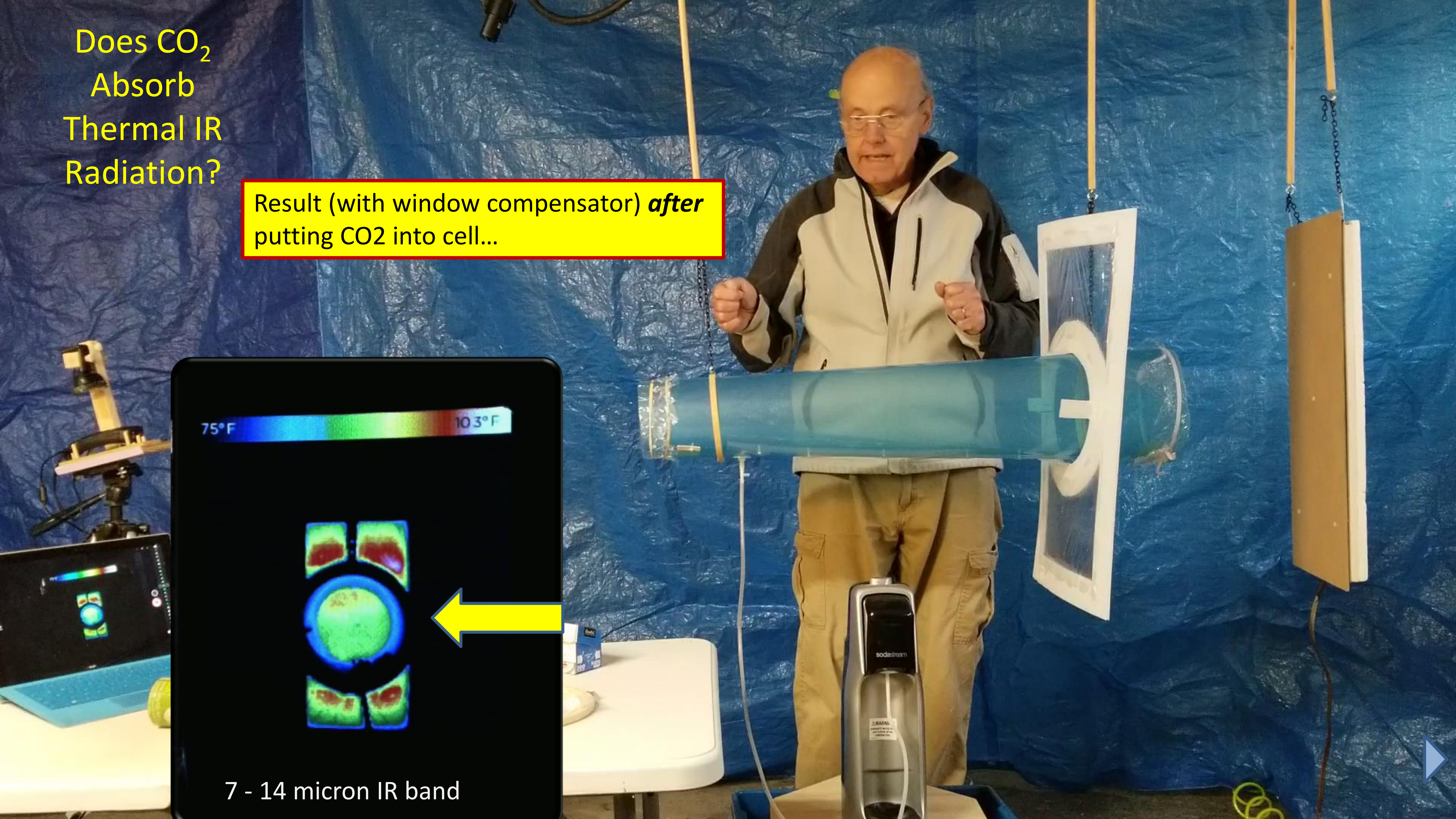
Does CO_2 Absorb Thermal IR Radiation?

Result (with window compensator) before putting CO2 into cell…

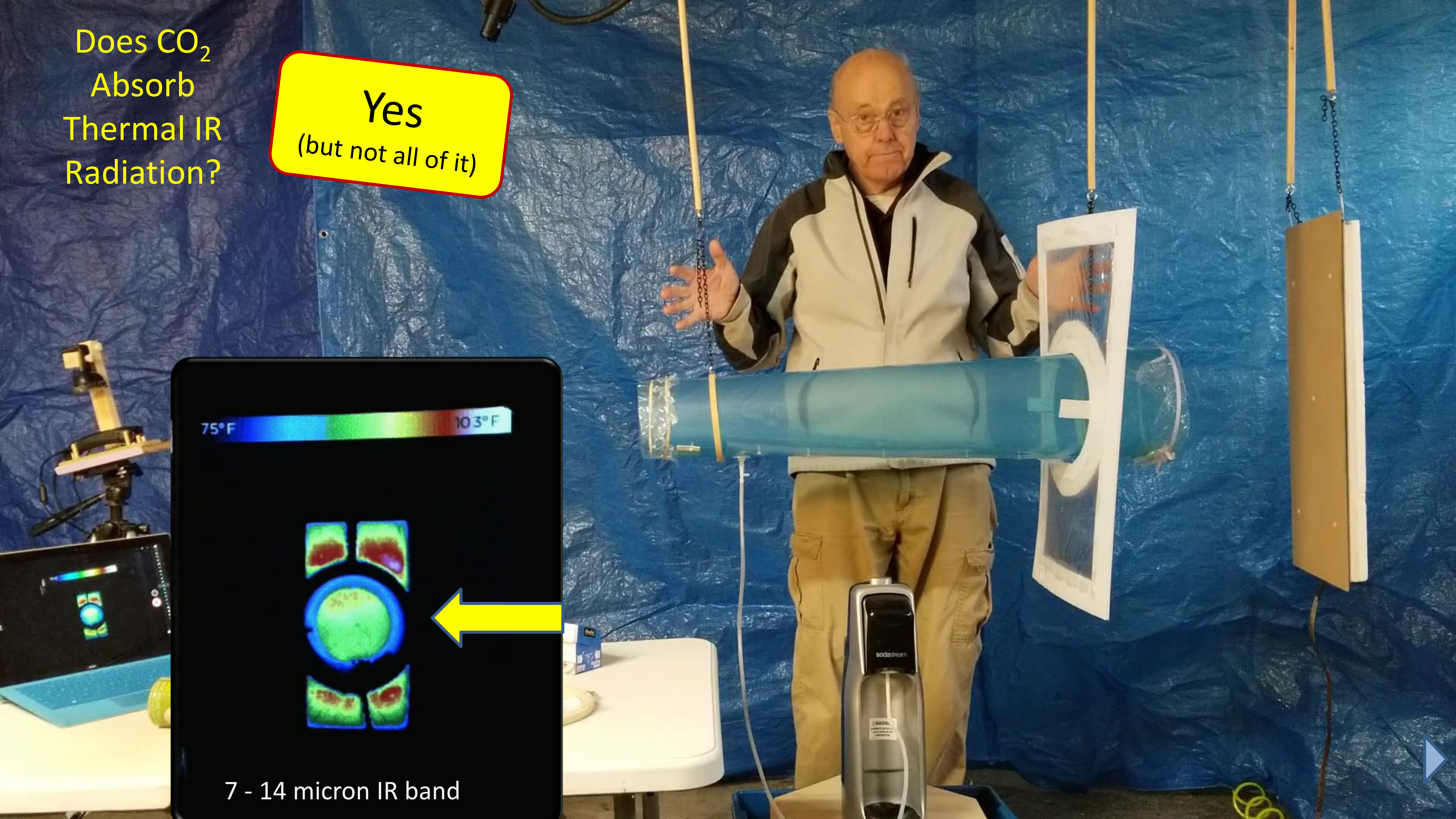


Does CO_2 Absorb Thermal IR Radiation?

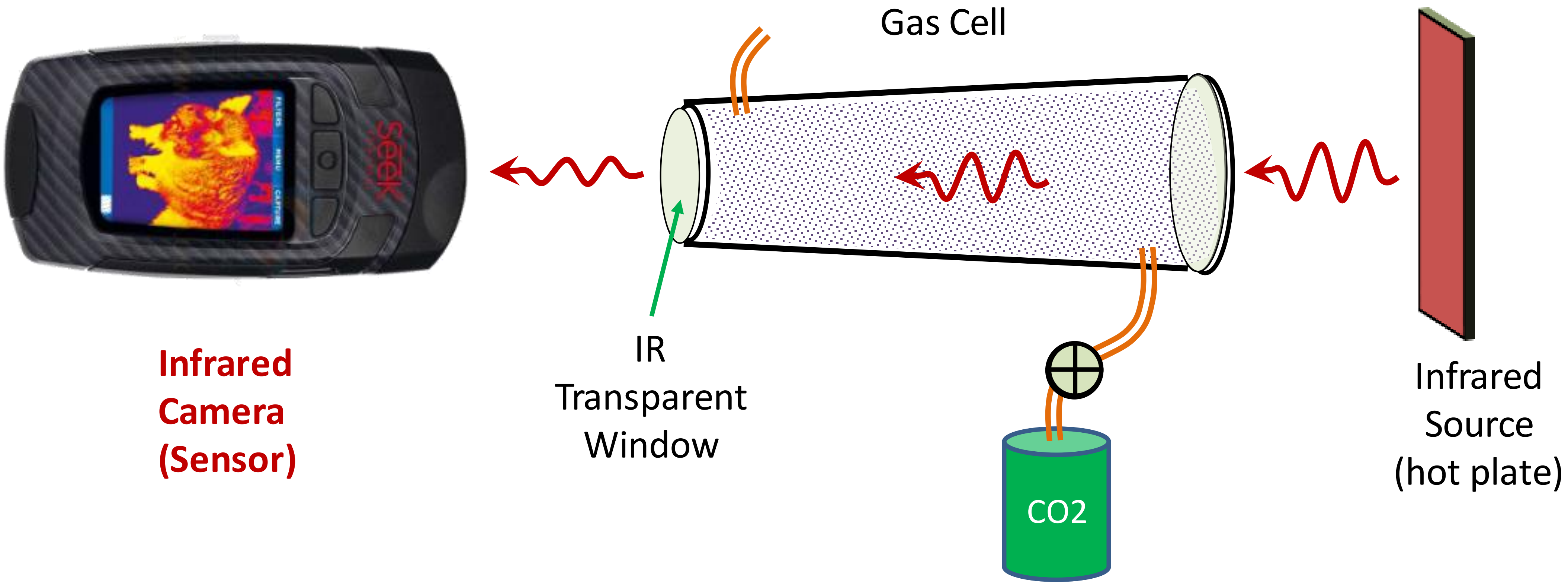
Result (with window compensator) ***after*** putting CO2 into cell…



7 - 14 micron IR band

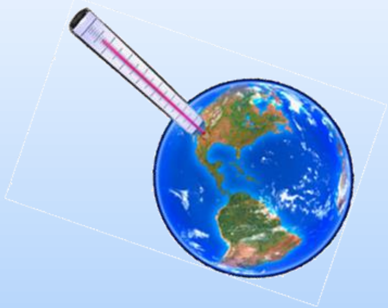

Does CO_2 Absorb Thermal IR Radiation?
Yes
(but not all of it)
75°F
103°F
7 - 14 micron IR band
sodastream

Observing CO_2 Absorption in the LW Infrared

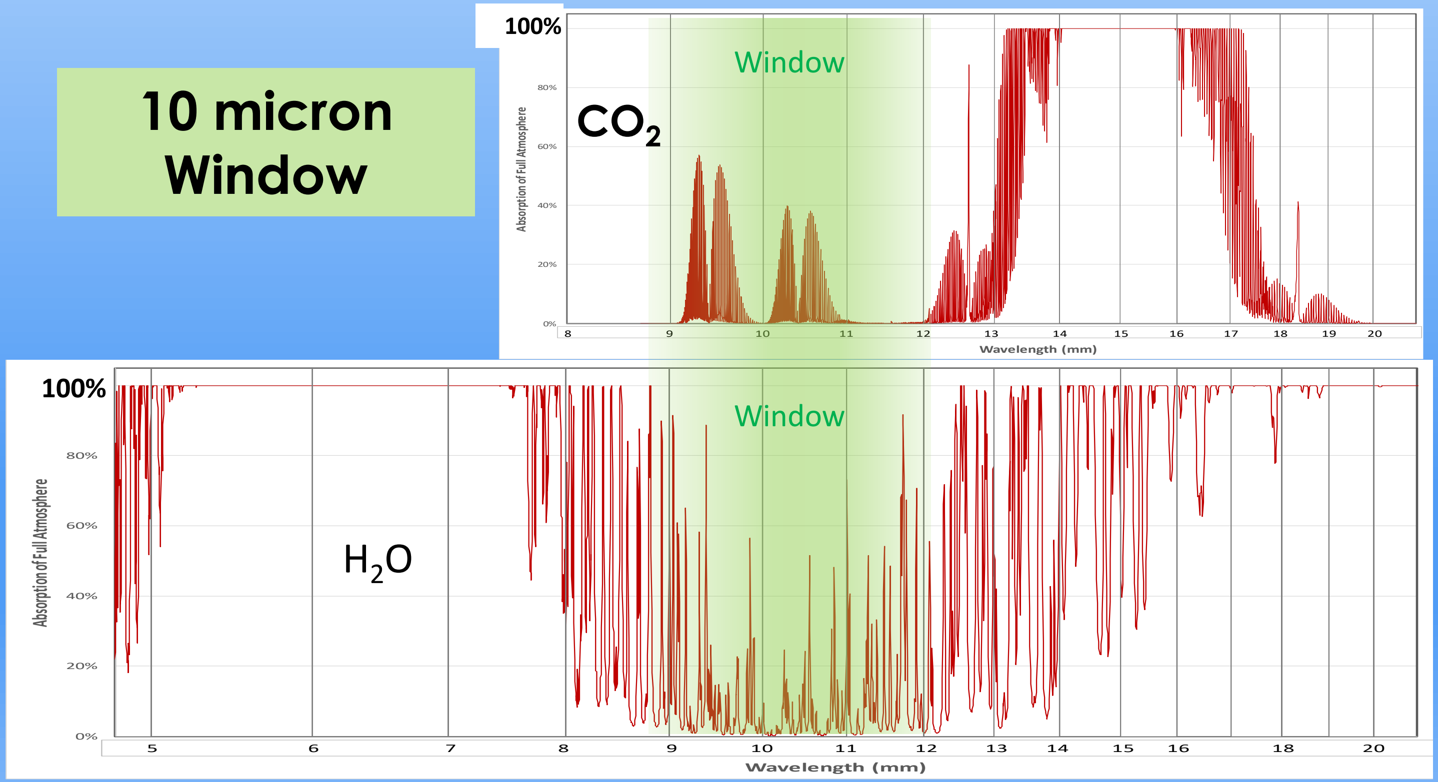


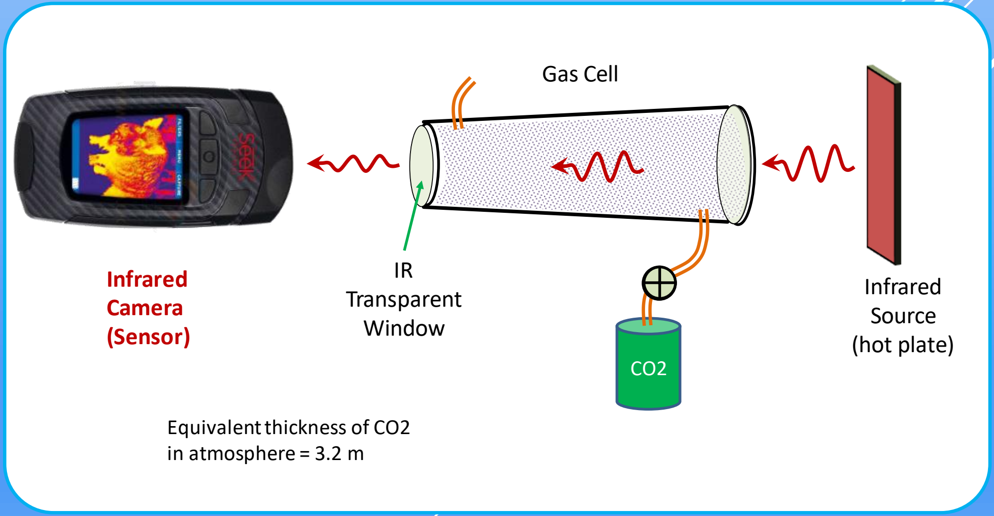
Equivalent thickness of CO2
in atmosphere = 3.2 m

Questions about how Infrared Radiation makes it through the Atmosphere to Space?



10 micron Window

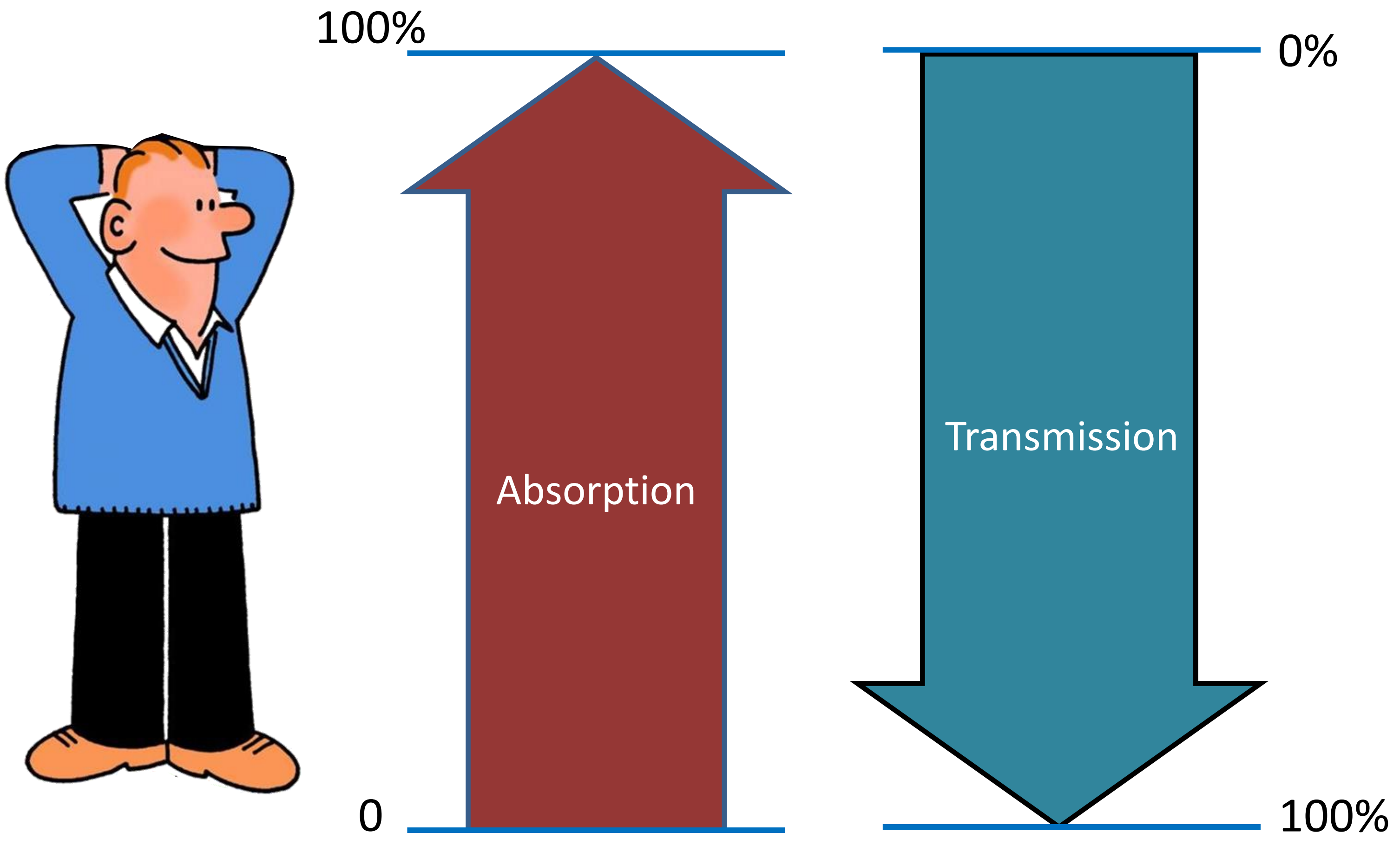


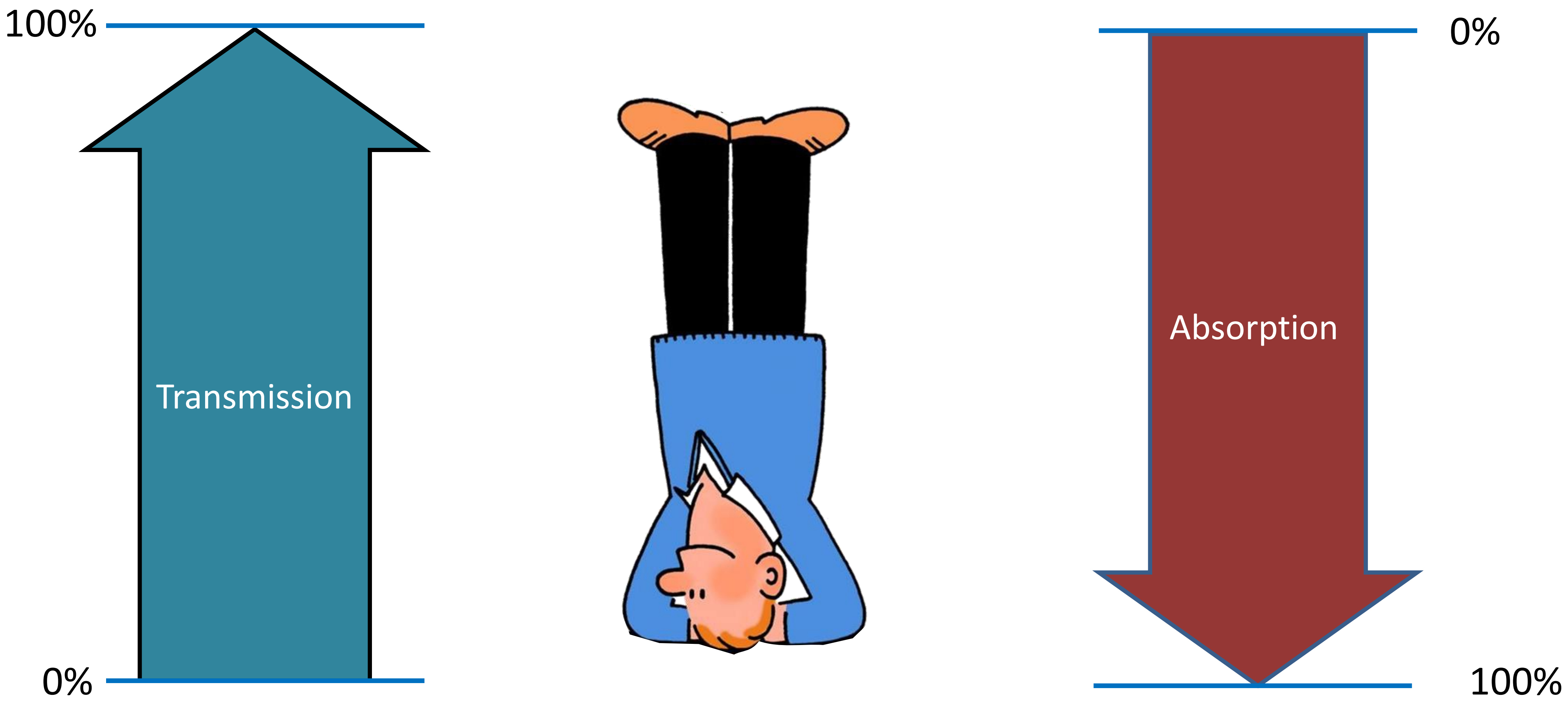


MODTRAN Model: Radiation Transfer in the Atmosphere

- MODerate resolution atmospheric TRANsmission
  - Created and Maintained by **US Air Force** & Spectral Sciences Inc.
- Reasonably good radiative transfer calculations
- On-line versions available for free use
  - Atmospheric transmission:
    - http://modtran.spectral.com/modtran_home
  - Atmospheric radiation (up and down):
    - http://ClimateModels.uchicago.edu/modtran/

Absorption *vs* Transmission

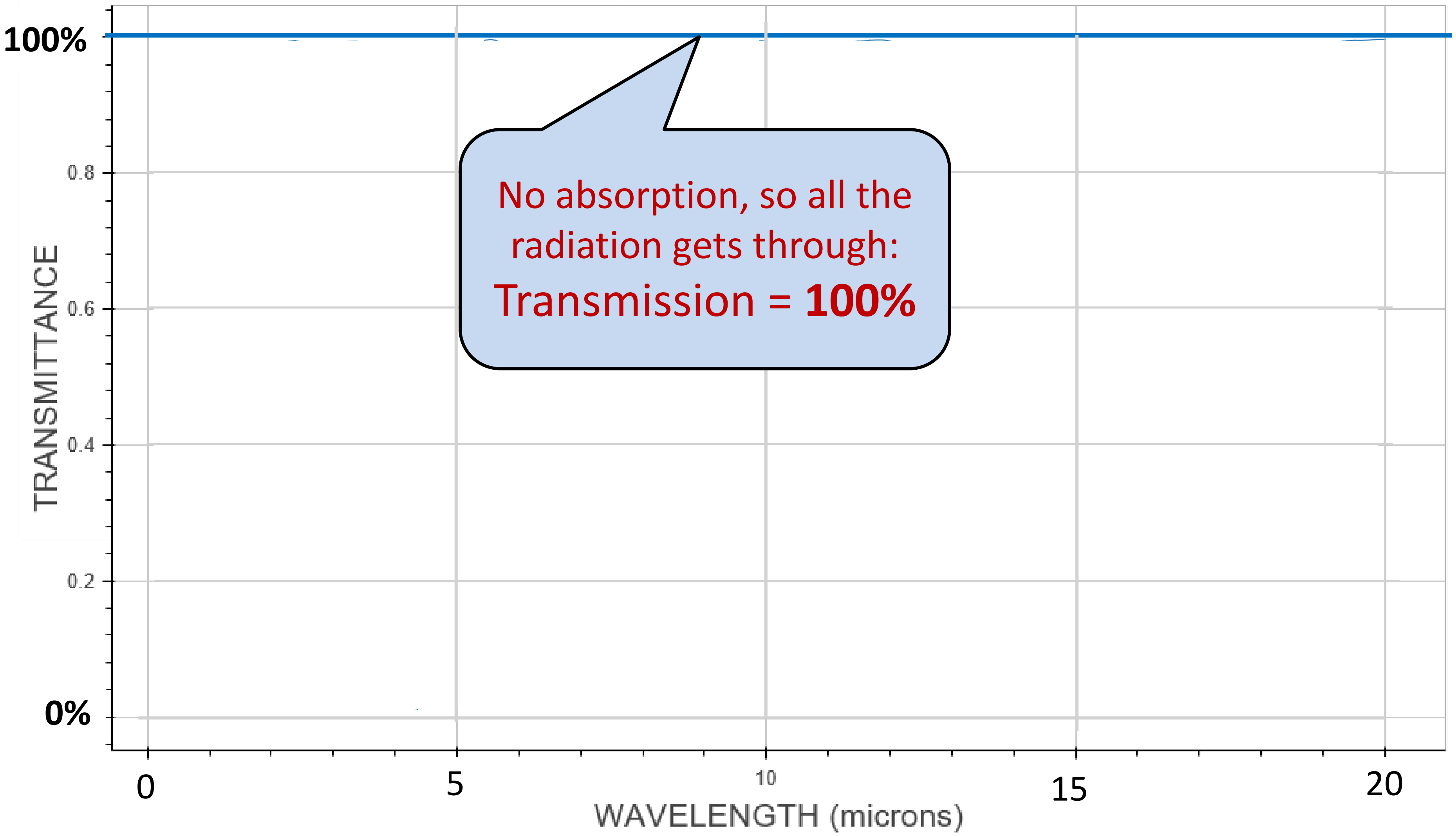




Up to now, we mostly looked at Absorption. Now we switch to the opposite, Transmission.

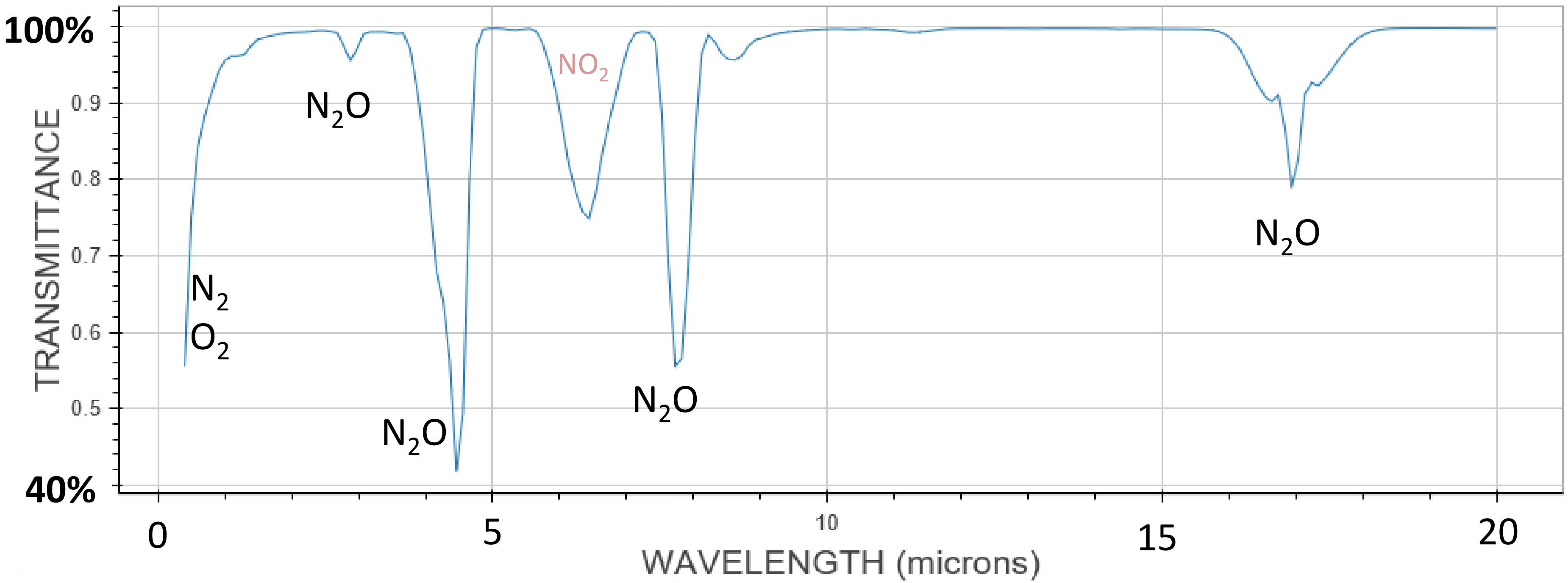
MODTRAN Atmosphere Transmission Model

No Absorbing Molecules at All



MODTRAN Atmosphere Transmission Model

Nitrogen, Oxygen, N_2O

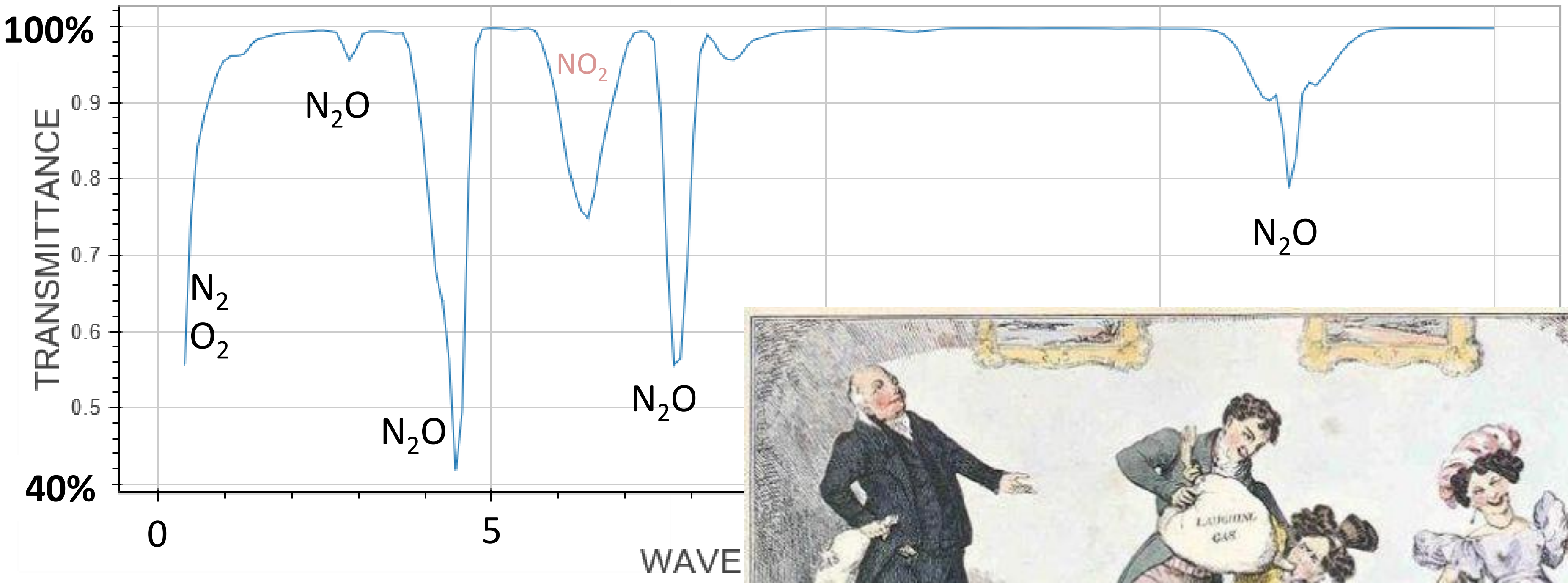


MODTRAN model takes account of Temperatures and Pressures at each layer of the atmosphere

www.modtran.spectral.com/modtran_home

MODTRAN Atmosphere Transmission Model

Nitrogen, Oxygen, N_2O

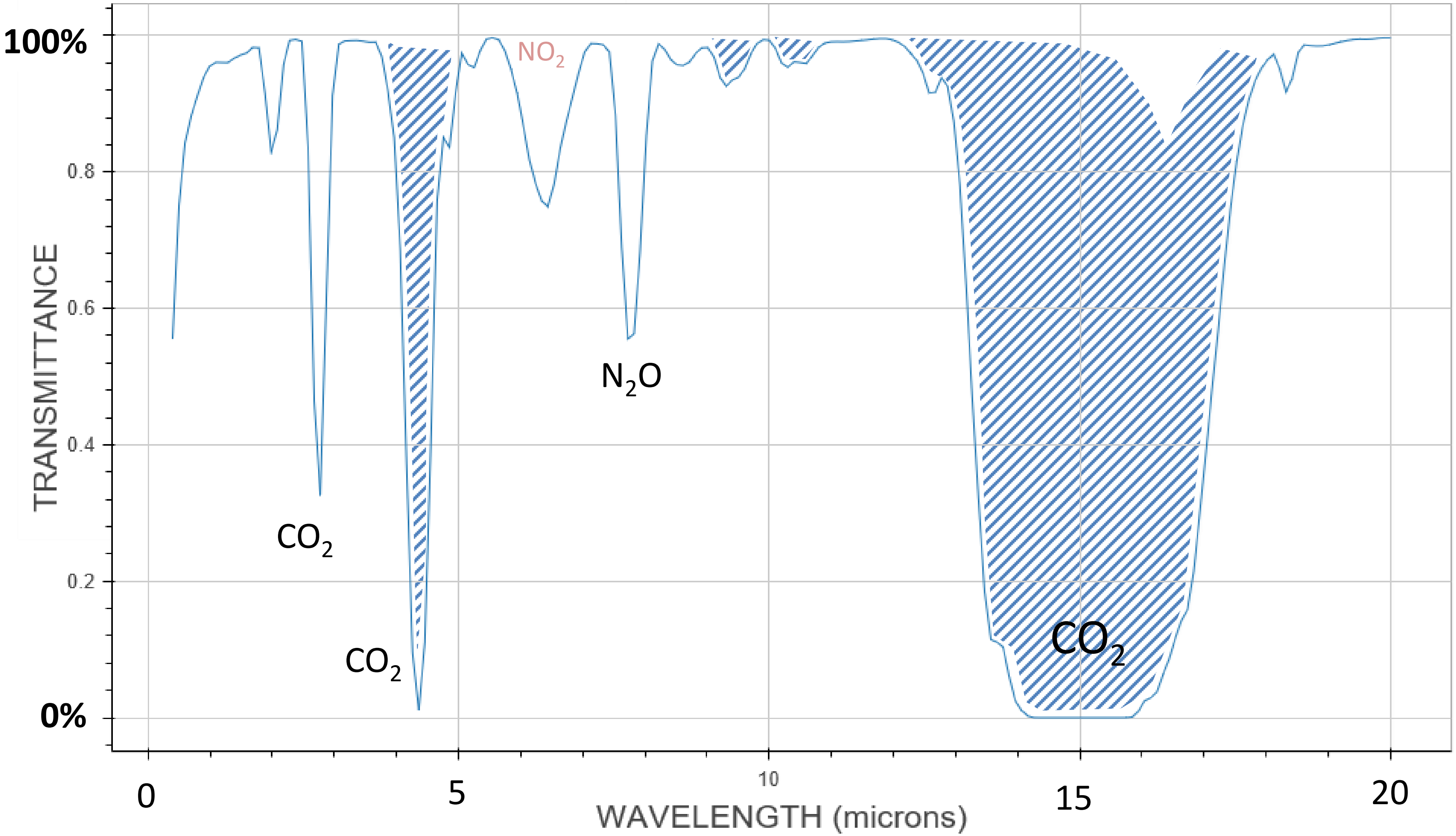


MODTRAN model takes account of Temperatures and Pressures at each layer of the atmosphere

N_2O (Nitrous Oxide) is Laughing Gas

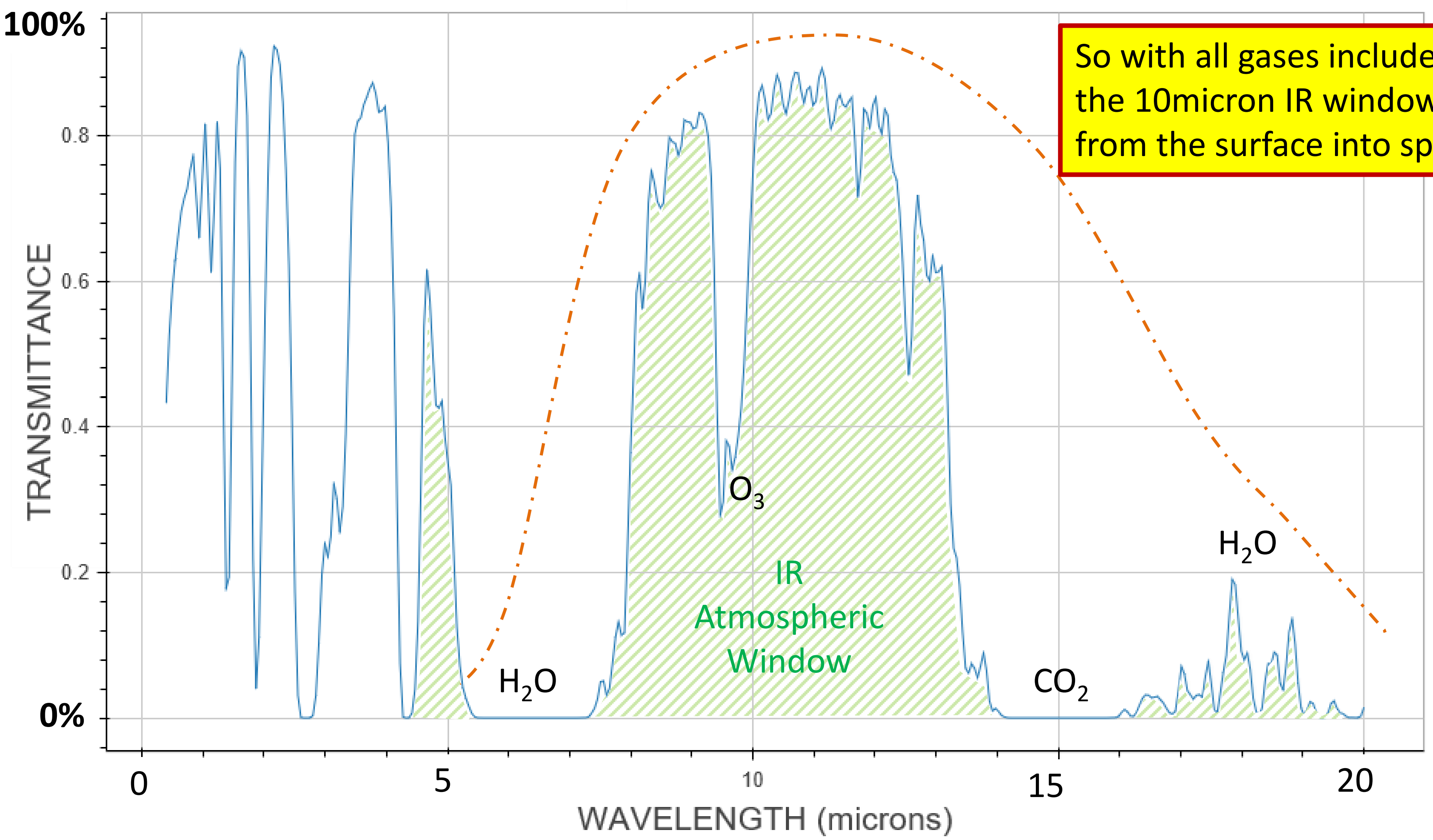
MODTRAN Atmosphere Transmission Model

Add CO_2 400 ppm



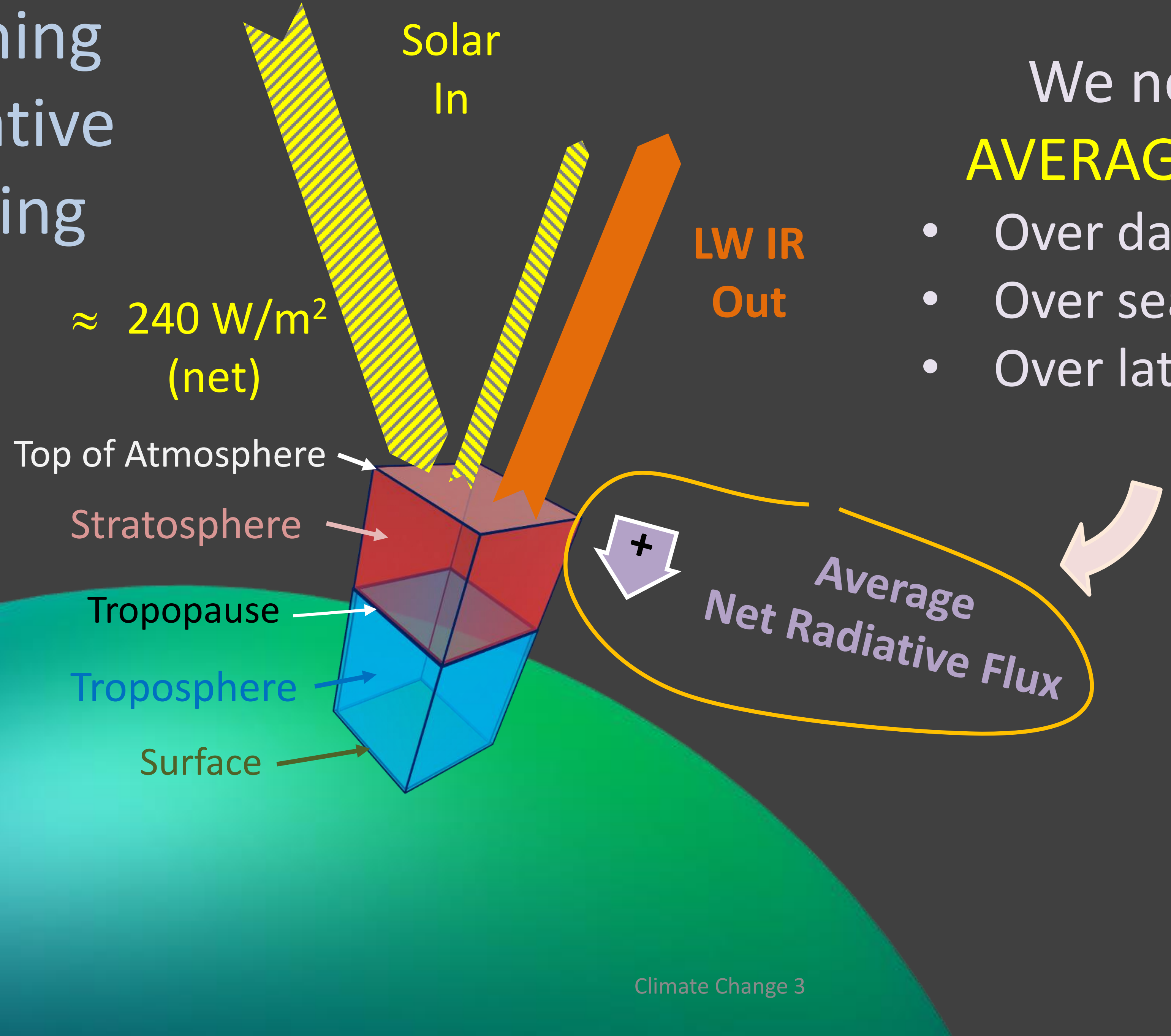
MODTRAN Atmosphere Transmission Model

All Major Gases Included: H_2O, CO_2, O_3, CH_4, N_2O



So with all gases included, we still have the 10micron IR window open to send IR from the surface into space….

Defining Radiative Forcing

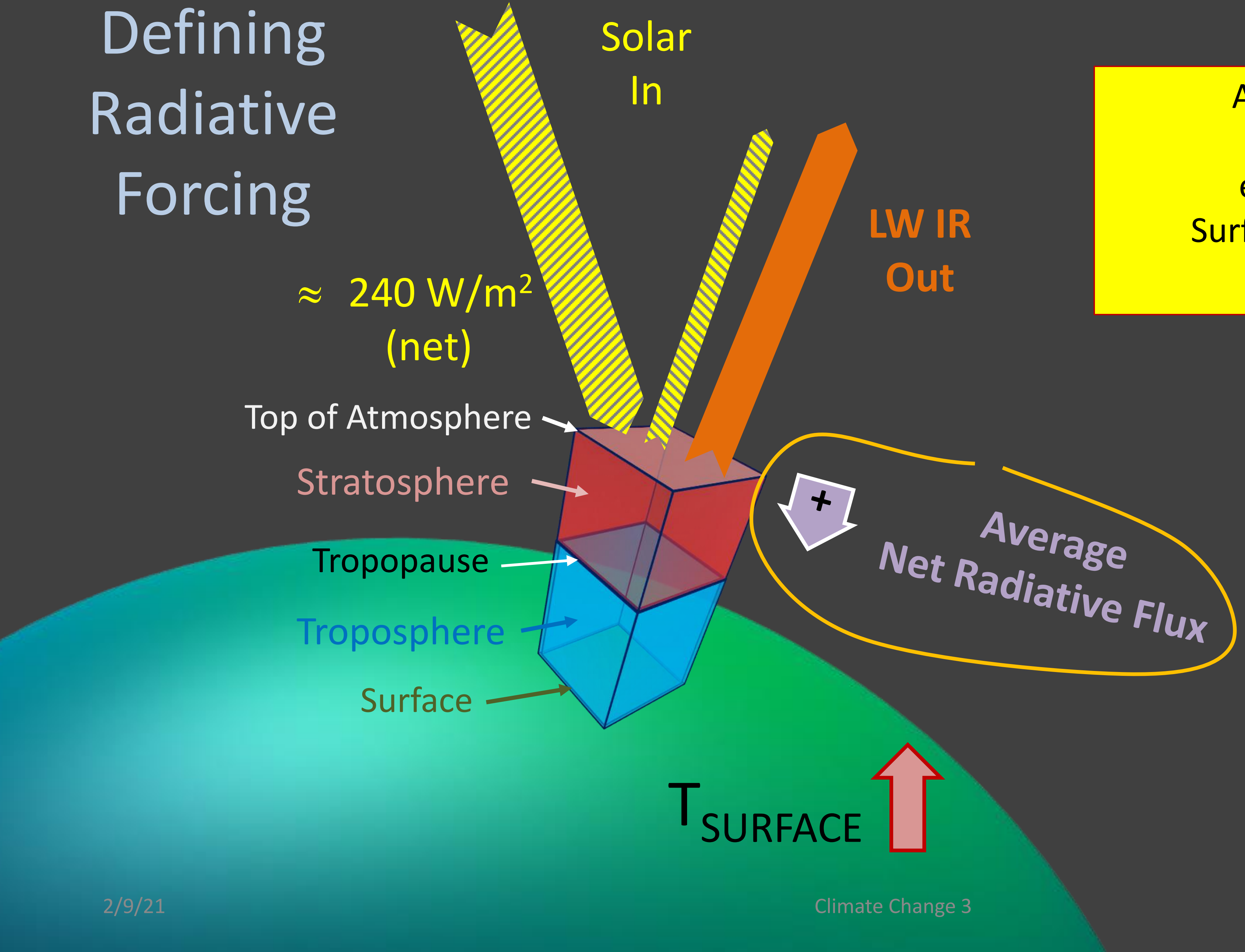


We need the **AVERAGE** net flux

- Over day & night
- Over seasons
- Over latitudes

Watts / m^2

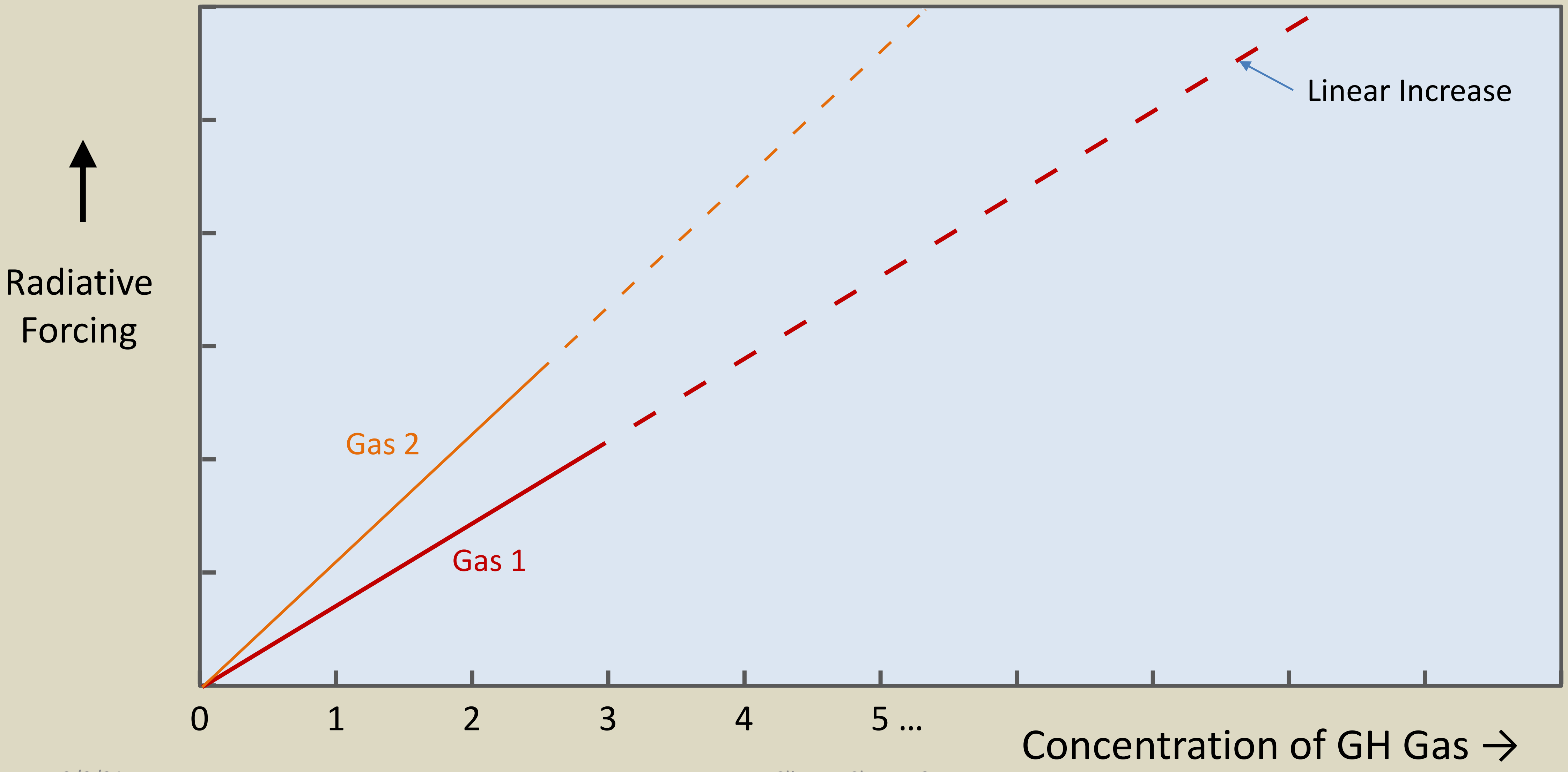
Defining Radiative Forcing



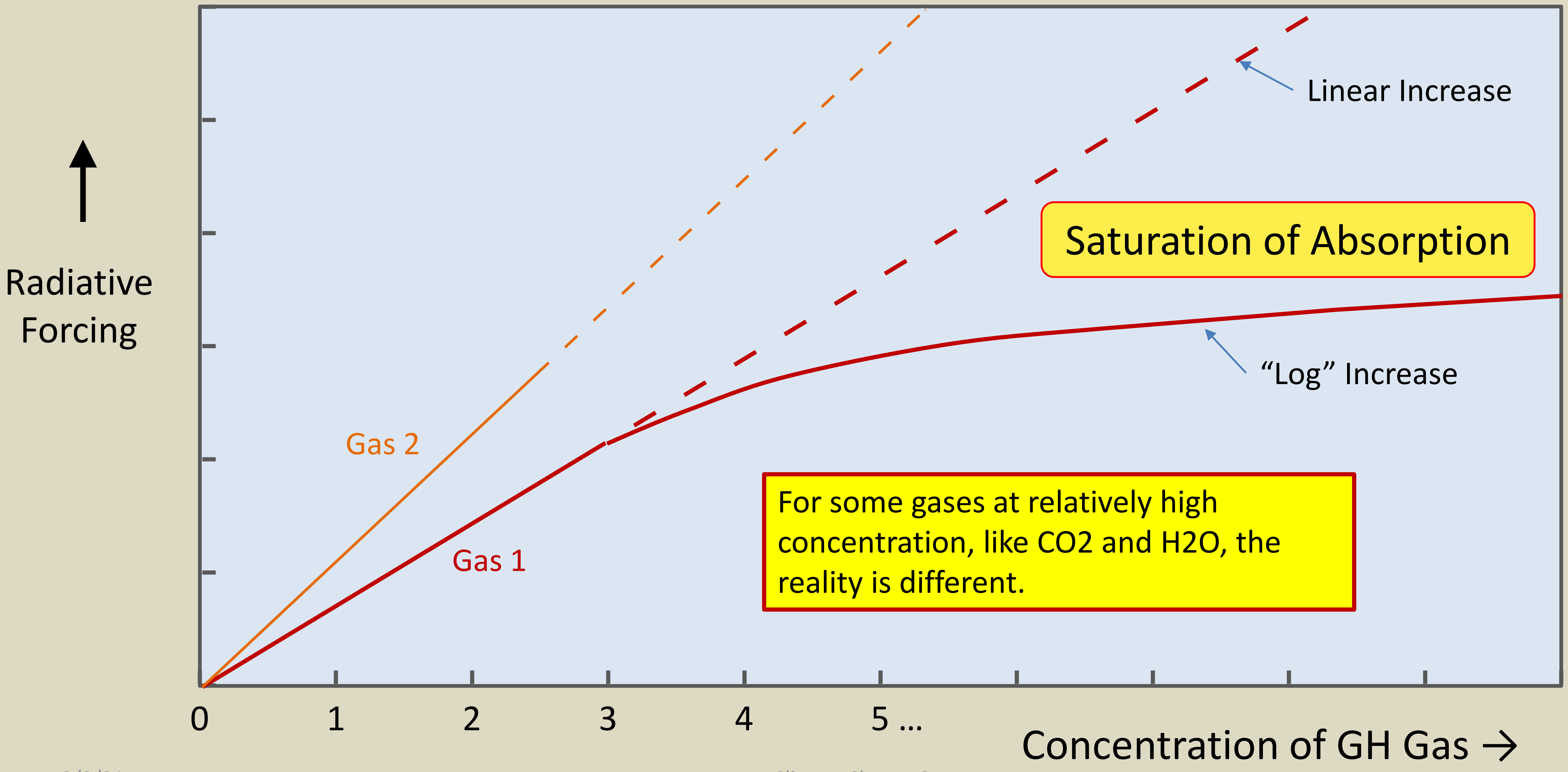
A Radiative Forcing of
1 Watt/m²
eventually produces a
Surface Temperature rise of
~0.27 °C (0.5 °F)

Watts / m²

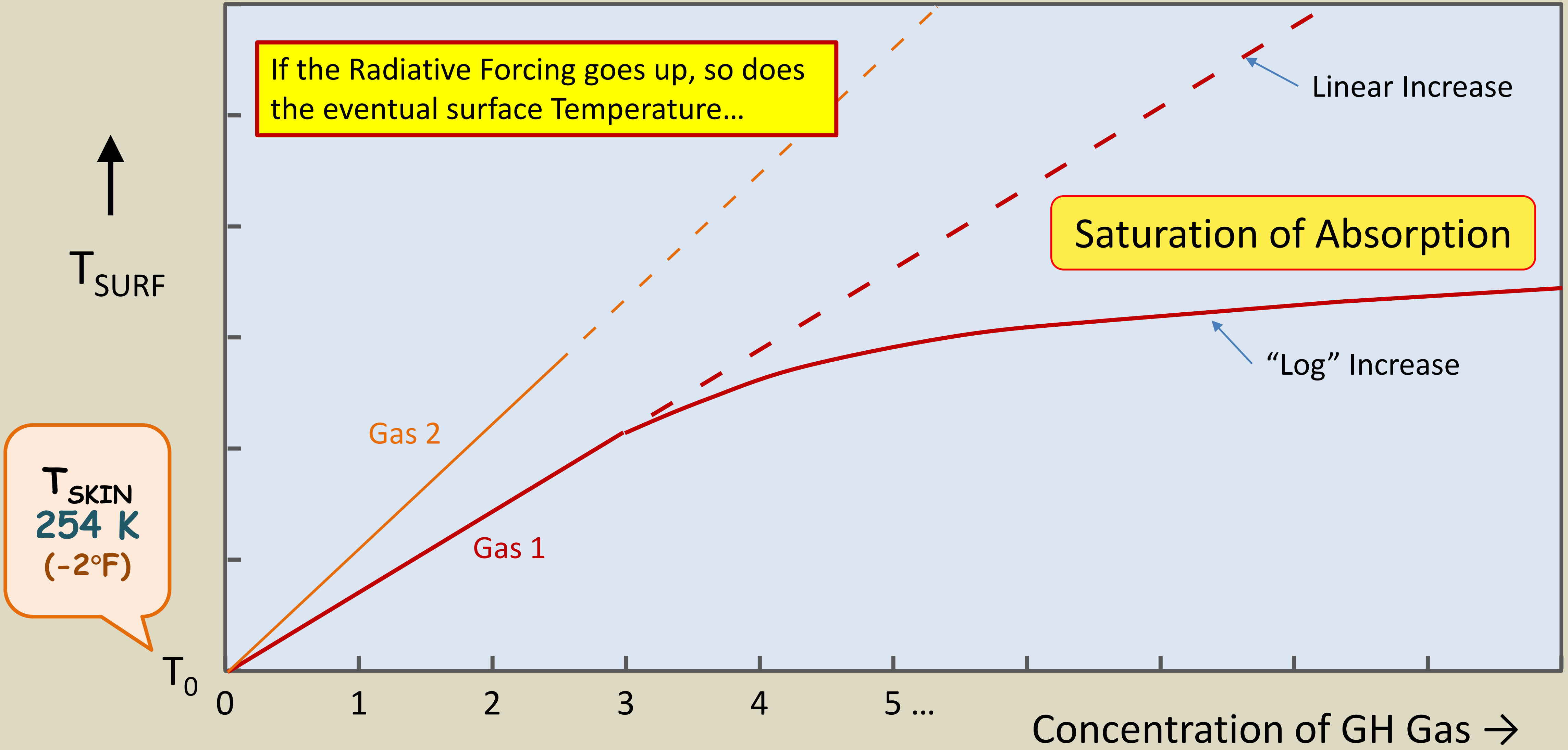
Naïve Expectation of Forcing *vs.* GH Gas Concentration



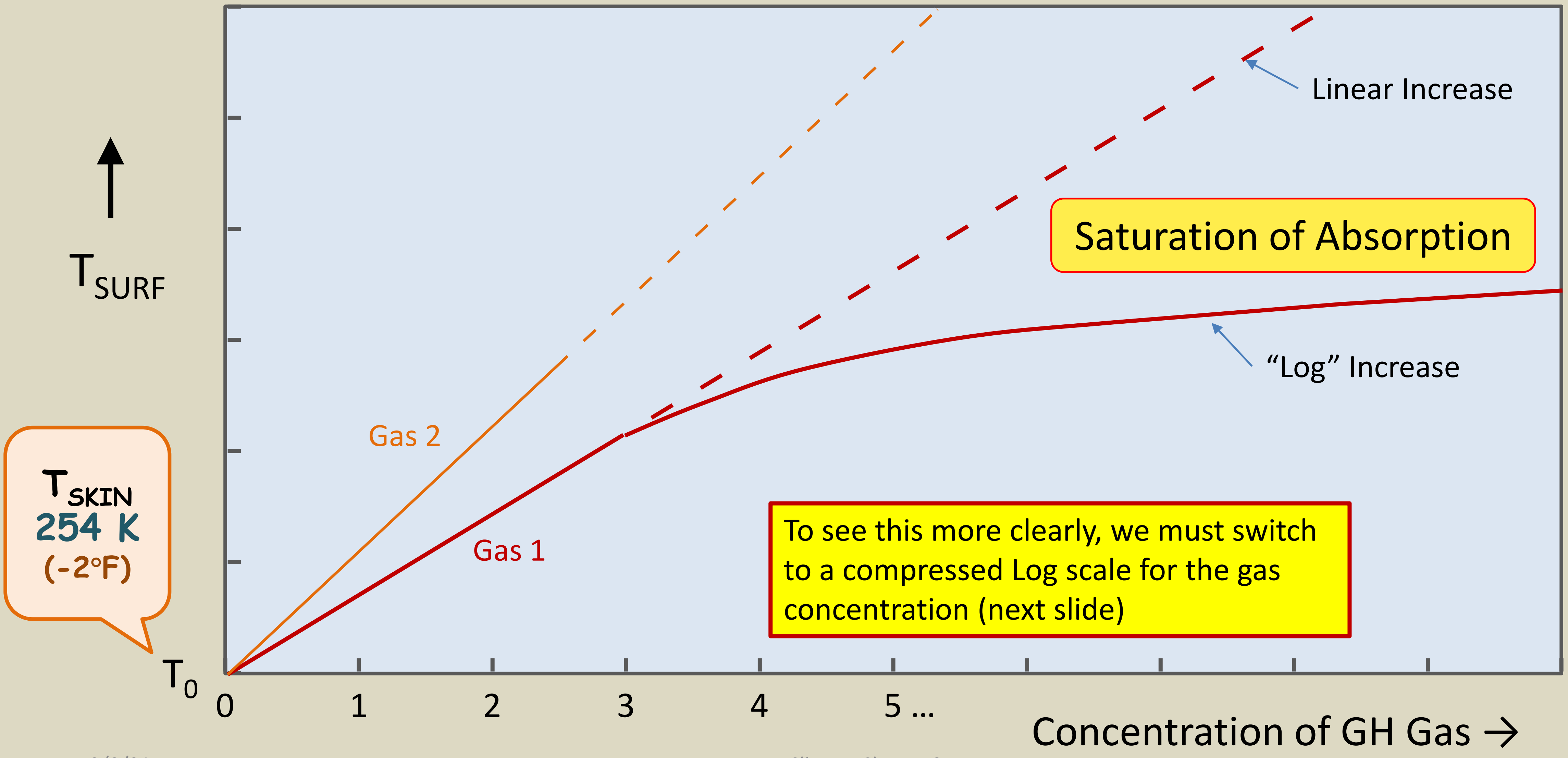
Naïve Expectation of Forcing *vs.* GH Gas Concentration



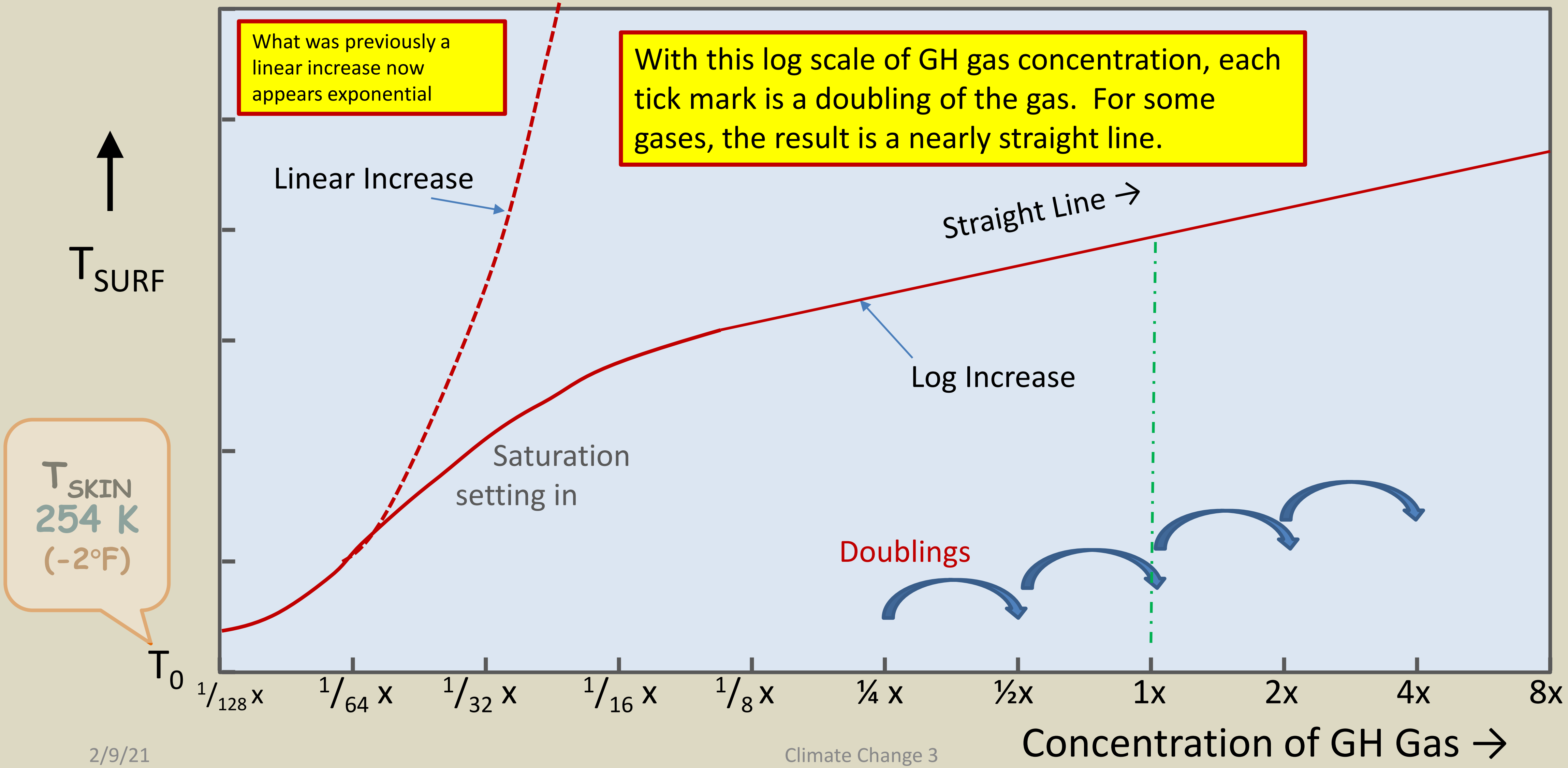
Naïve Expectation of Surface Temperature *vs.* GH Gas Concentration



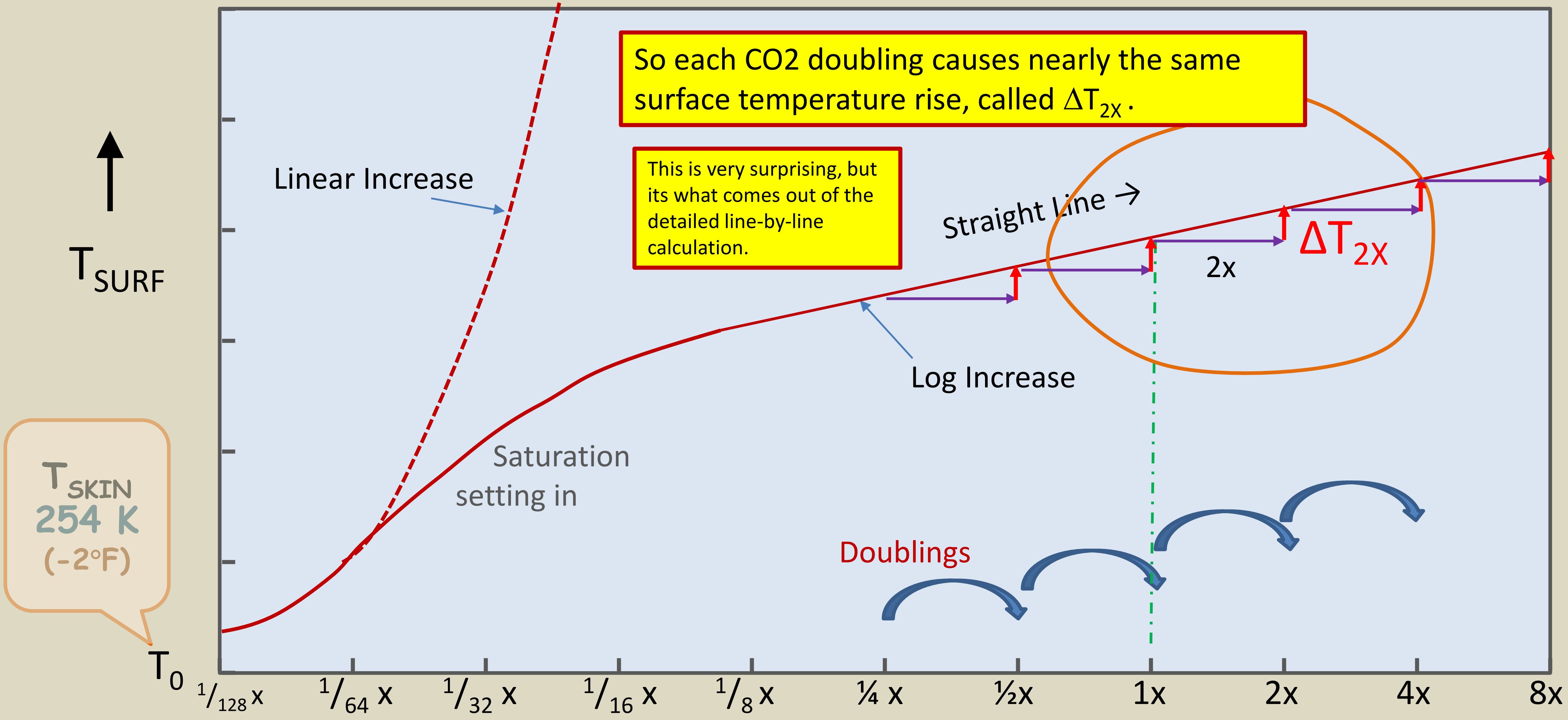
Naïve Expectation of Surface Temperature *vs.* GH Gas Concentration



Actual Surface Temperature
vs. GH Gas Concentration Doublings



Actual Surface Temperature
vs. GH Gas Concentration Doublings



ΔT_{2X}

The Big Summary Number….

If only CO_2 changes:
$\Delta T_{2X} \approx 1.0°C$

AKA:

ΔT_{2X}

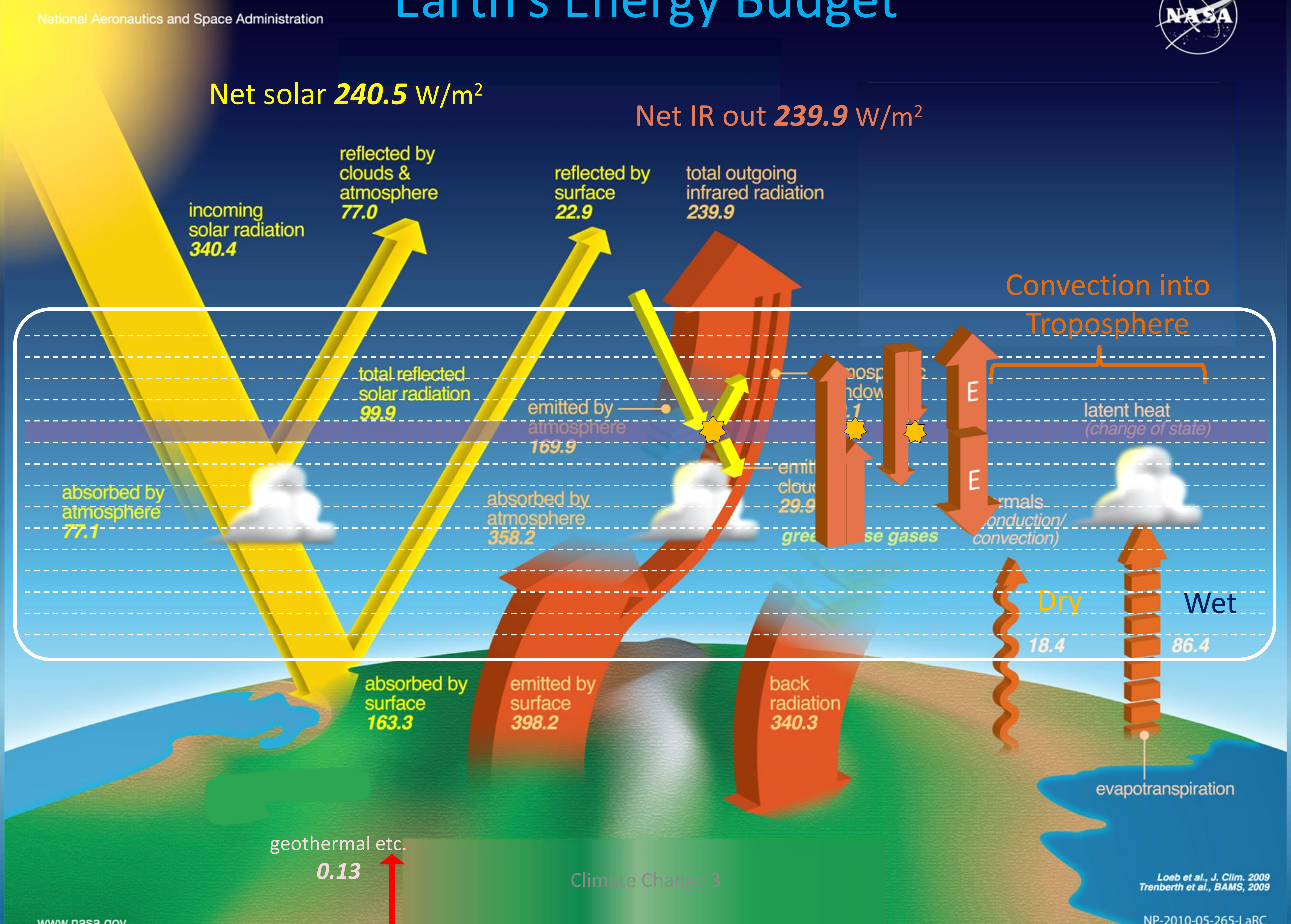
- CO_2 Doubling Sensitivity
- Climate Sensitivity
  - Transient Climate Sensitivity
  - Equilibrium Climate Sensitivity (ECS)
  - etc.

- Long delays – decades or centuries
- Large uncertainties due to feedbacks
- IPCC ***AR5*** : 1.5 °C to 4.5 °C [~ **3** °C]

IPCC ***AR6***:

3.6 °C ?

Earth's Energy Budget



Science

PERSPECTIVES

17 September 2018

It is hoped that this unnecessary source of "uncertainty" will be cleaned up in AR6

CLIMATE

Reducing uncertainties in climate models

Implementing accurate calculations of radiative forcing can improve climate projections

By **Brian J. Soden[1], William D. Collins[2,3], Daniel R. Feldman[2]**

Radiative fo… quantity fo… thropogenic… climate. It… which huma… emission of… the image] and natu… nic eruptions) pertu… and out of the climate system. This perturbation initiates all other changes of the climate in response to external forcings. Inconsistencies in the calculation of radiative forcing by…

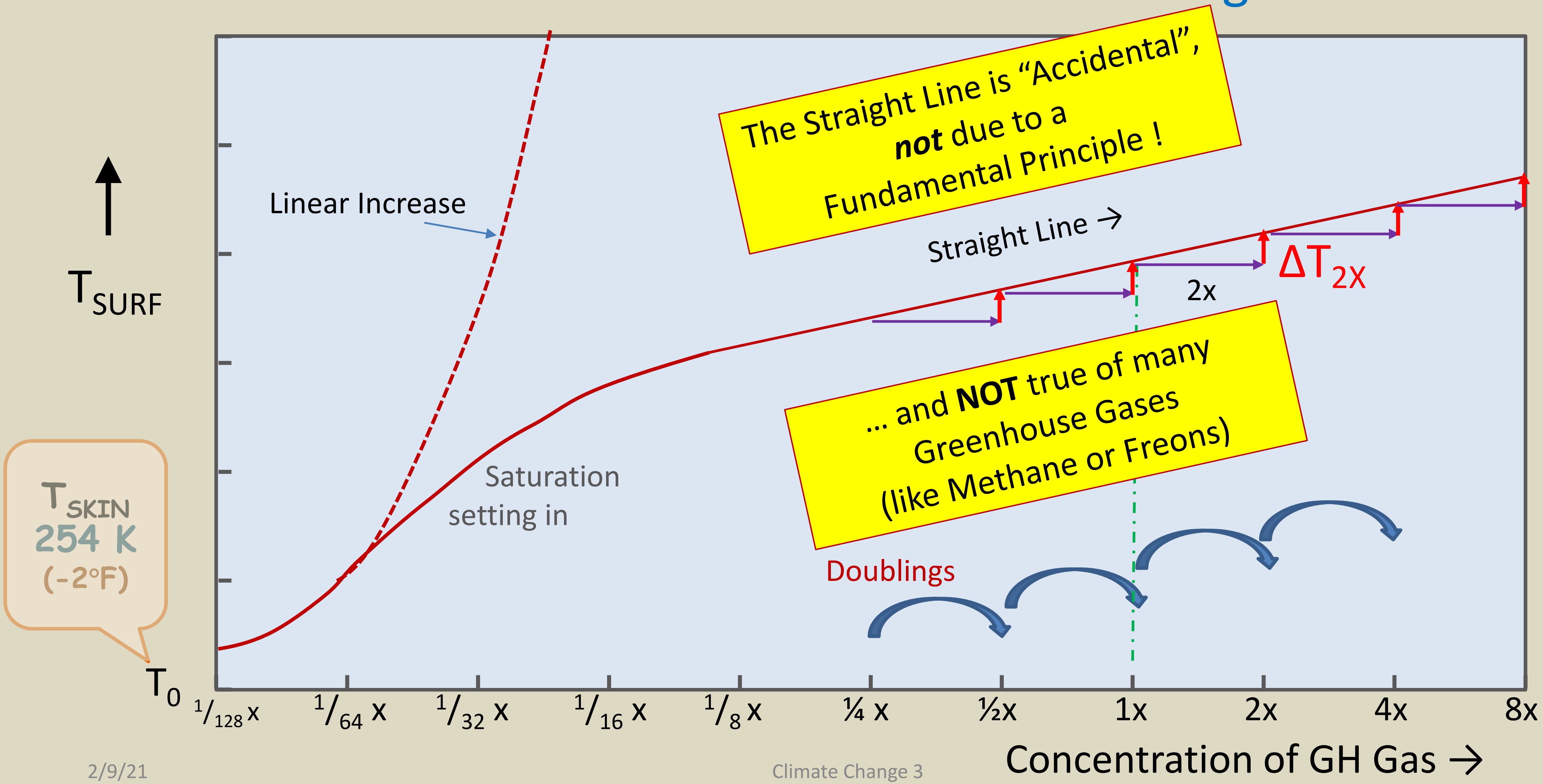
explicit calculation of radiative forcing and a careful vetting of radiative transfer parameterizations provid… …radiative forcing by CO_2 in global climate models (GCMs) (2). They found that when CO_2 was doubled, the radiative forcing differed substantially among 15 different GCMs, ranging from ~3.3 to 4.7 W/m² (see the graph; see the supplementary ma…

radiative forcing, … …ration of more than 20 … They …ilar ra… …ng at …he … …bling of …graph), wh… …was largely …d in the infrared component of …on. The authors also compared … forcing computed using line-…) calculations; the latter solve the equation of radiative transfer for each absorption line individually, rather than parameterizing their absorption over spectrally integrated bands. The forcing calculations between several different LBL models were in much better agreement (see the graph)…

…the impact of this inconsistency in the calculations of radiative forcing on estimates of climate sensitivity "is **nearly half** of the often quoted range of uncertainty of 1.5° to 4.5°C."

ΔT_{2X}

Actual Surface Temperature
vs. GH Gas Concentration Doublings



Aerosols

- Suspension of particles in a liquid: **Sol**

- Suspension of particles in a gas: **Aerosol**
  - Particles may be liquid or solid
  - In Climate Science, the gas is **air**

Aerosol Terminology in Climate Science

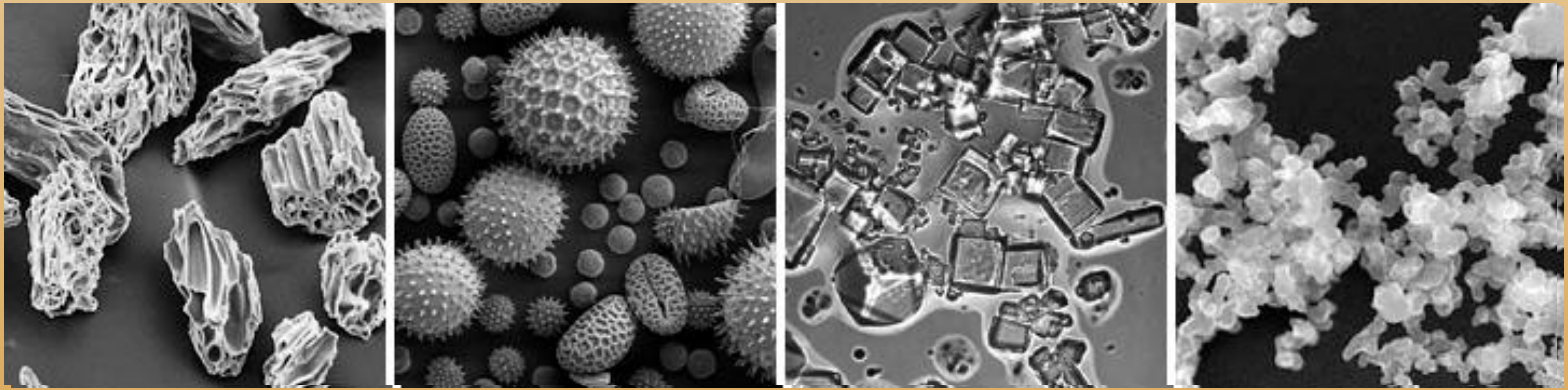
- When particles are made of water:
  - Call it a "**Cloud**"

- When particles are *anything else:*
  - Call it simply an "**Aerosol**"

Atmospheric Aerosol Particles

- All sorts of shapes
- Sizes from 0.01μm or less to ~ 30 μm (~ 0.001 inch) or more
- *Examples* (electron micrographs)

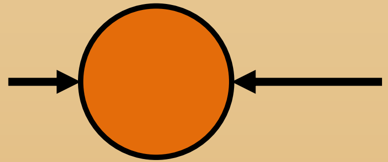
Typical density: 100,000 per cc



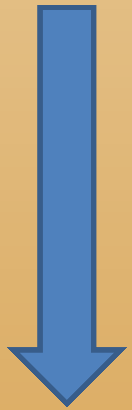
Volcanic Ash **Pollen** **Sea Salt** **Black Carbon Soot**

Aerosol Lifetime in Atmosphere

1 micron particle



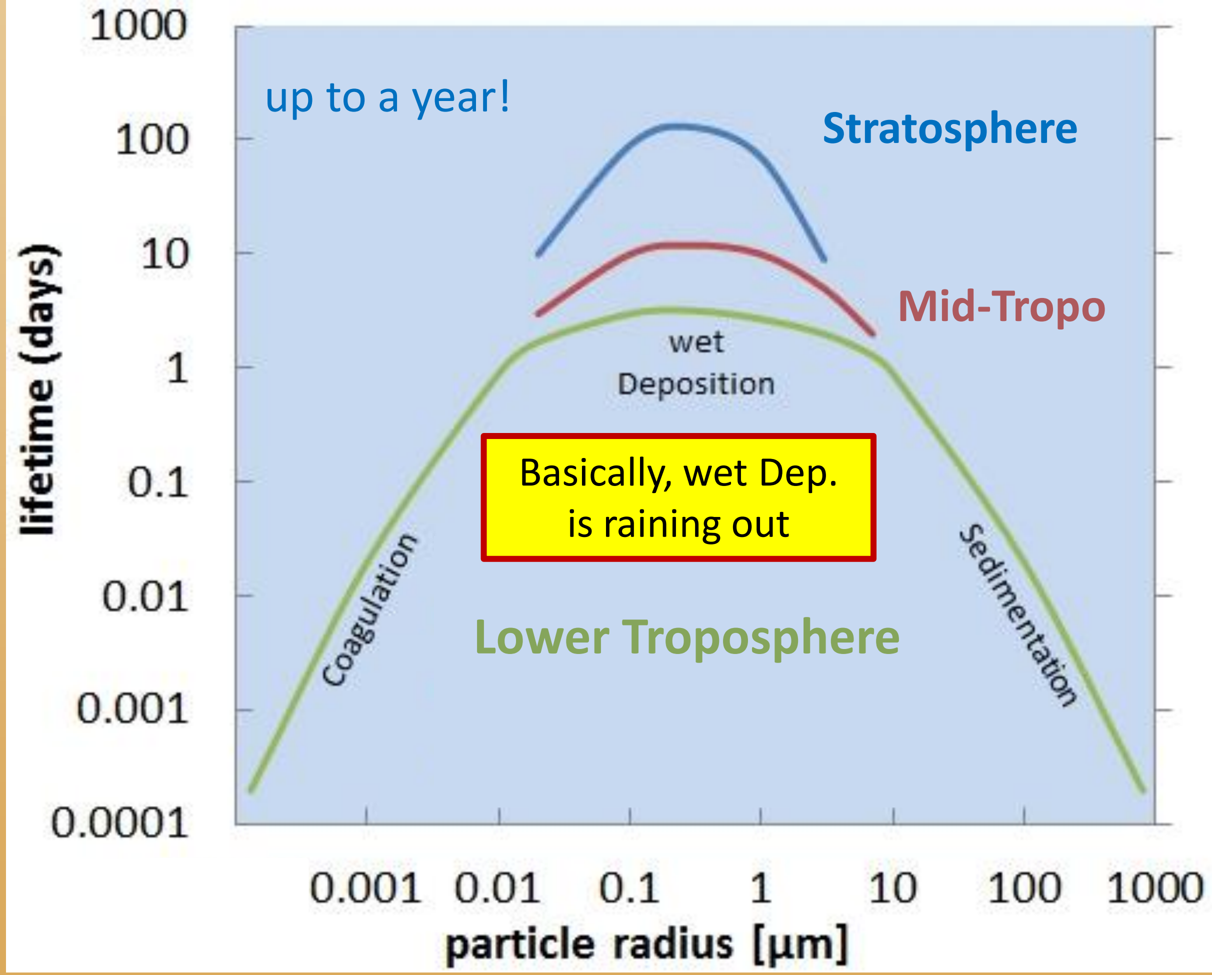
1 μm diameter



Settles about
10 feet/day

Smaller fall
much slower

Bigger fall
much faster



Some Sources of Aerosols

Mostly Natural, Some partly Anthropogenic *

Biologicals:
- **Pollen**
- **Fungal Spores**
- **Bacteria**
- **Algae**
- **Plant fragments**

Geophysical:
- **Mineral Dust**
- **Soil particles***
- **Sea Spray (salt)**
- **Volcanic**
  - **Ash**
  - **Sulfuric Acid**

Nucleation from Gases:
- Secondary Organic Aerosols from oxidized VOC's *
- **Inorganic Sulfates, Nitrates** from SO_2*, NOX*, Ammonia*, Di-Methyl Sulfide

Primary Organic Aerosols
- **e.g. lube oils from engines**

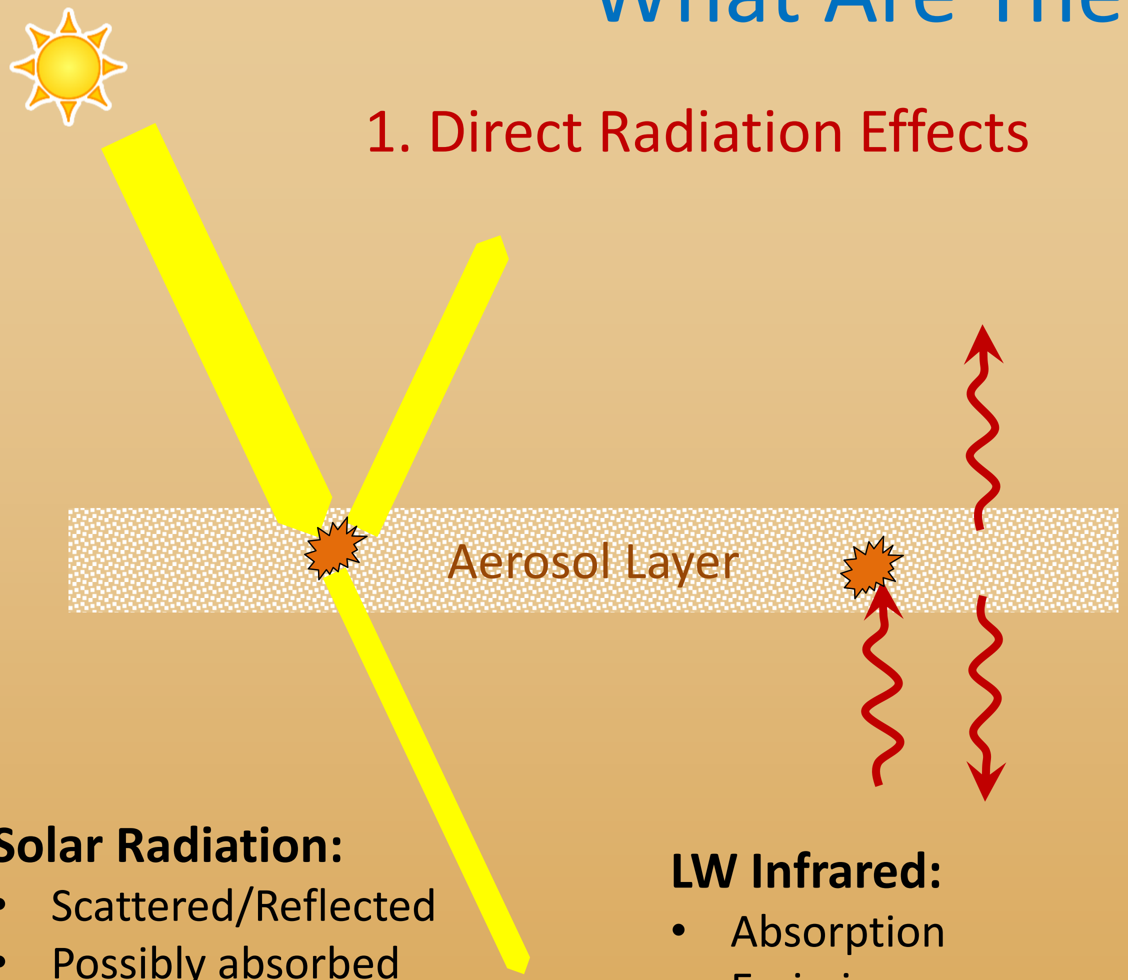
Smoke:
- **Forest Fires**
- **Industrial combustion***
- **Agricultural Burning***

Roughly 90% Natural
10% Anthropogenic?

Radiative Forcing

What Are Their Climate Effects?

1. Direct Radiation Effects



Solar Radiation:

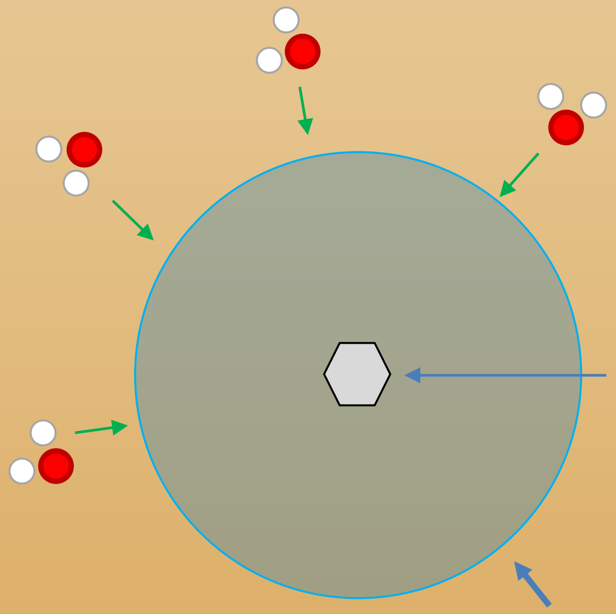
- Scattered/Reflected
- Possibly absorbed
  - e.g. Black Carbon

Big Albedo Effect

LW Infrared:

- Absorption
- Emission
- Broad wavelength range

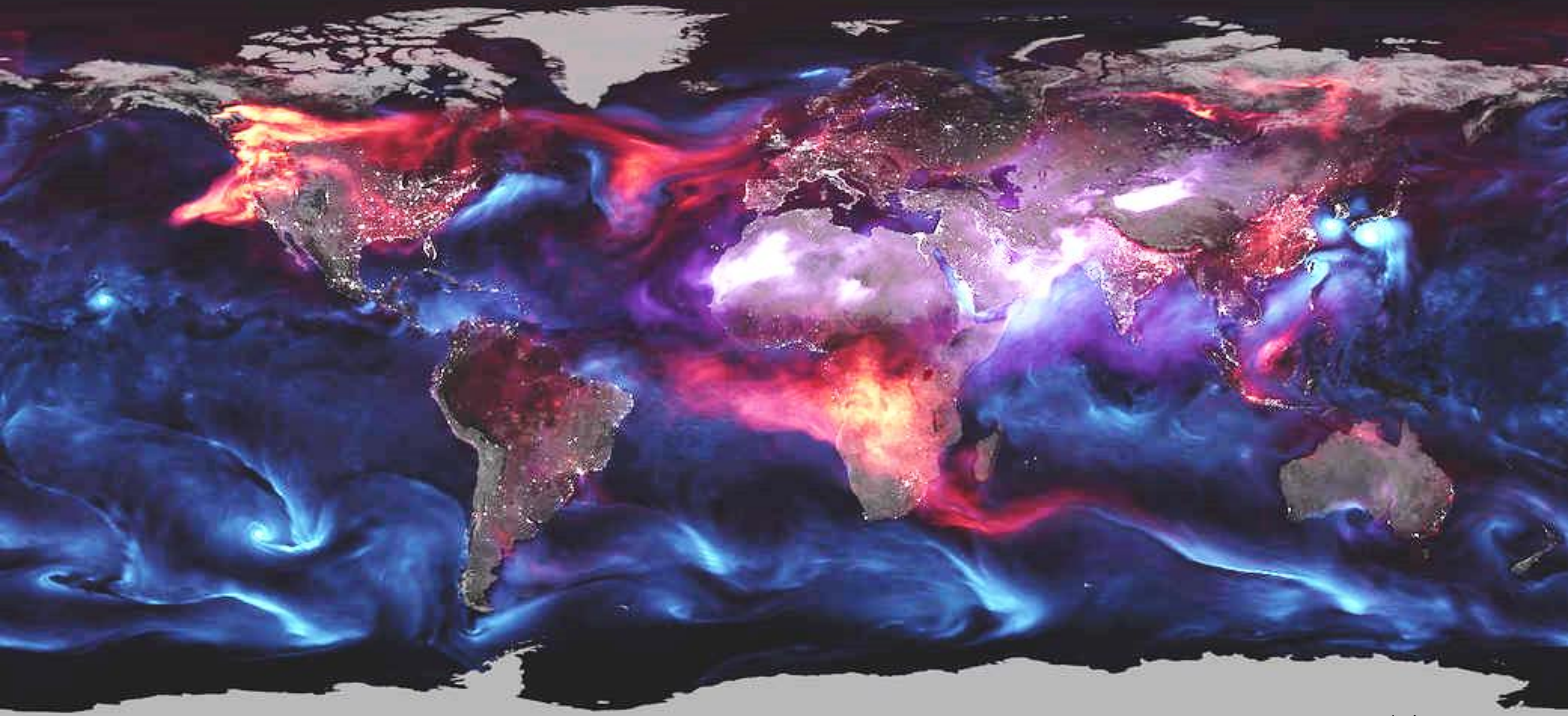
2. Indirect Cloud Nucleation



0.1 µm seed particle

10-15 µm typical cloud droplet diameter

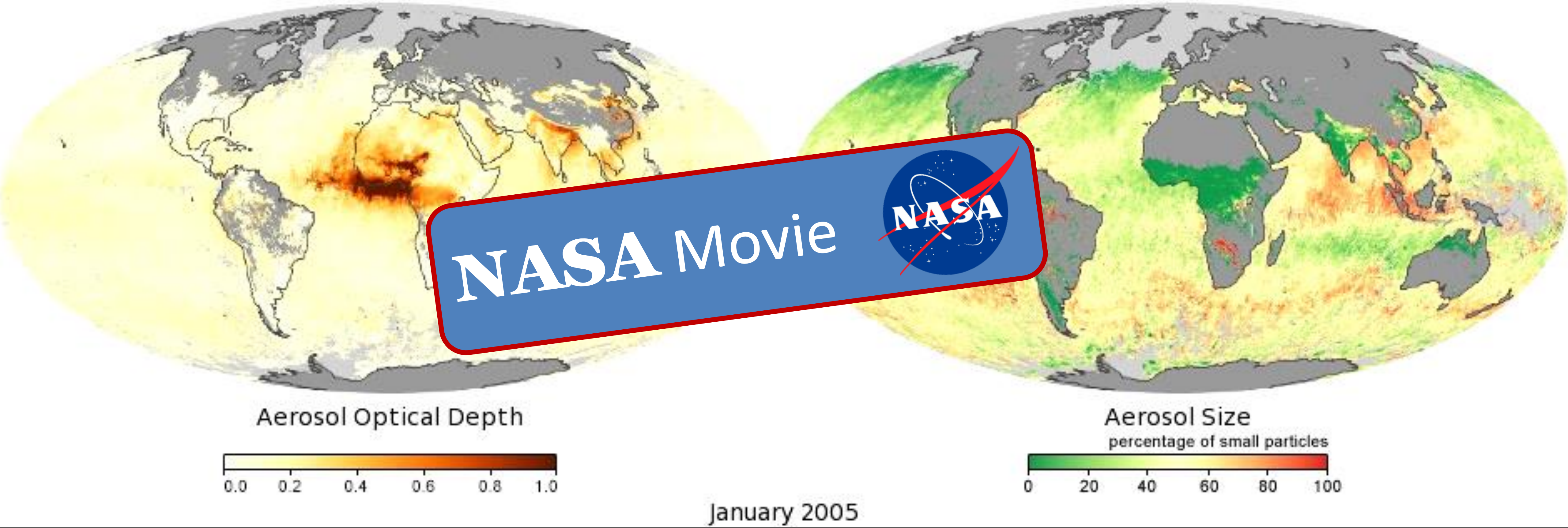
Aerosols on August 23, 2018 (False Color Visualization)



Sea Spray (Salt) | **Black Carbon** | **Dust**

NASA GEOS FP Model
Terra Satellite + others

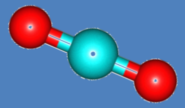
Density and Size of Aerosols (2005-2016)



https://earthobservatory.nasa.gov/global-maps /

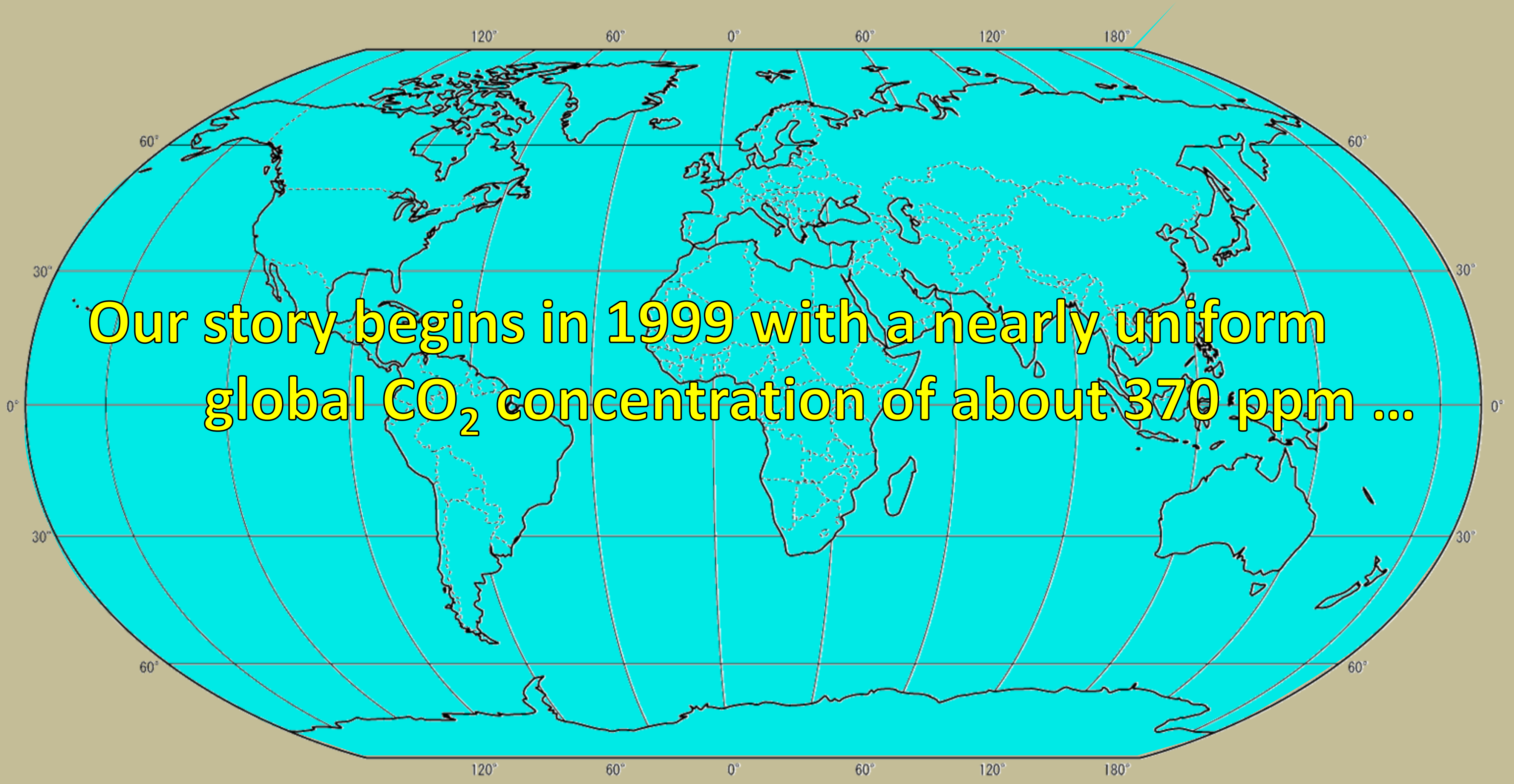
MODIS sensor on
NASA Terra satellite

Global Carbon Dioxide: The Movie

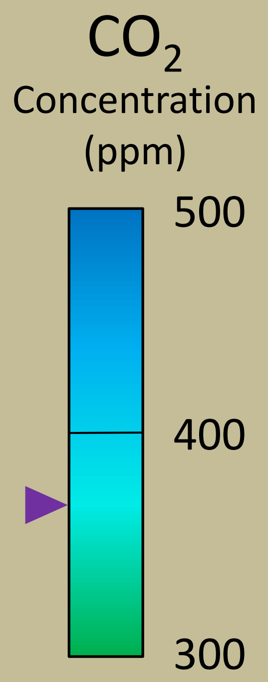


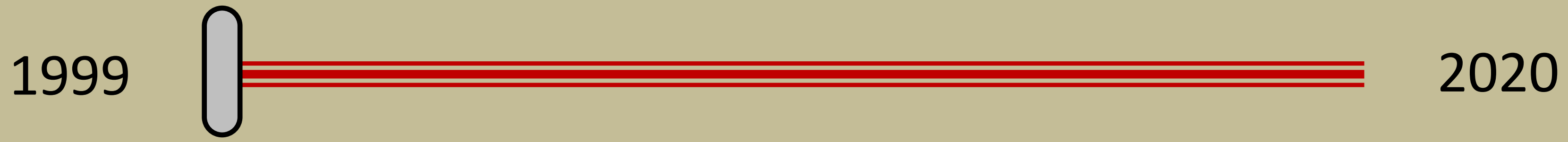
Osher Lifelong Learning Institute

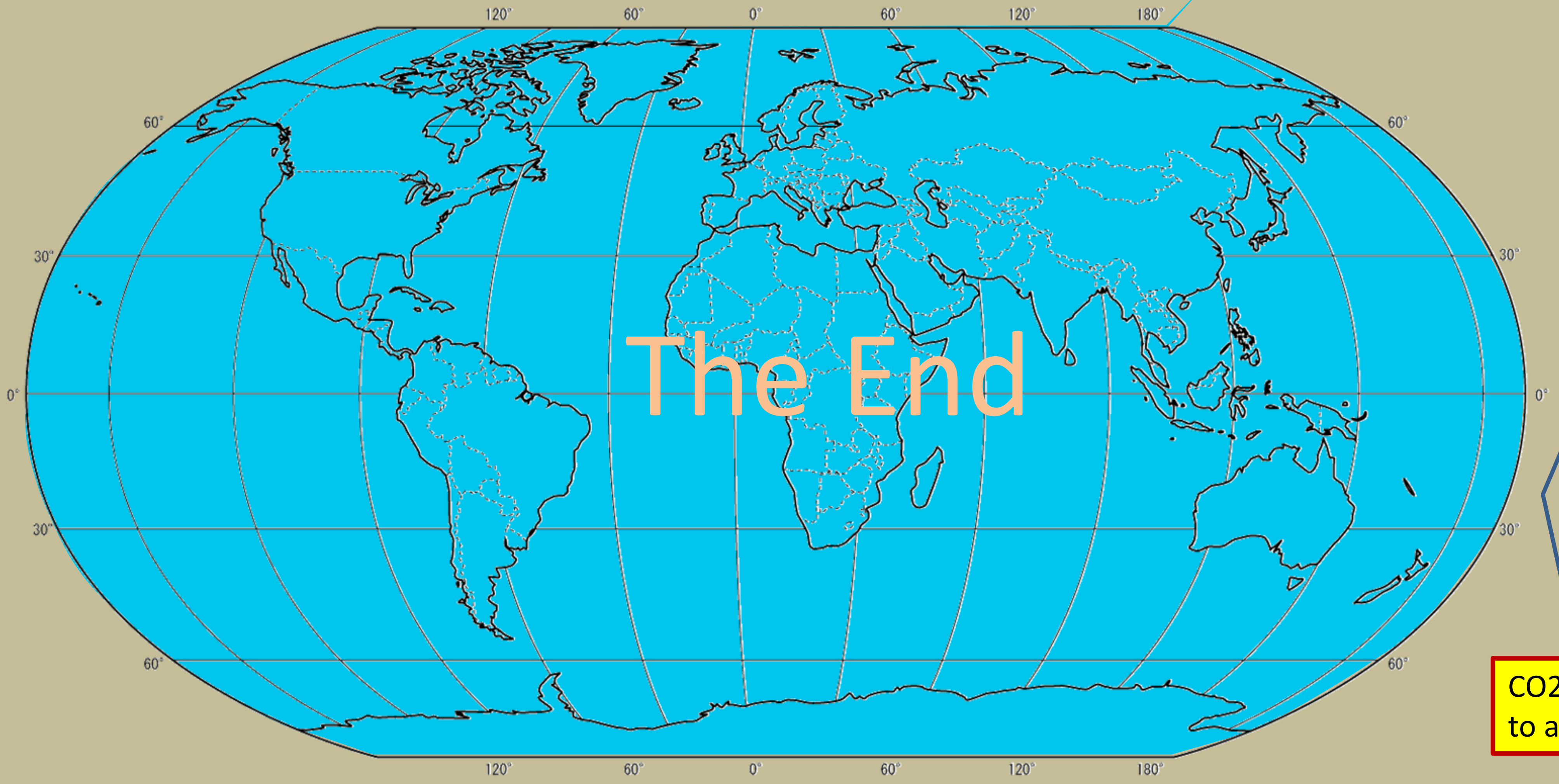
OLLI Studios

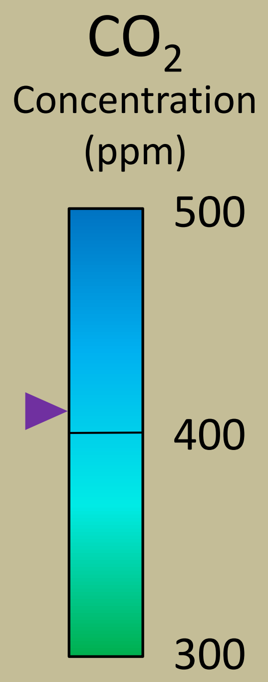


Our story begins in 1999 with a nearly uniform global CO_2 concentration of about 370 ppm …







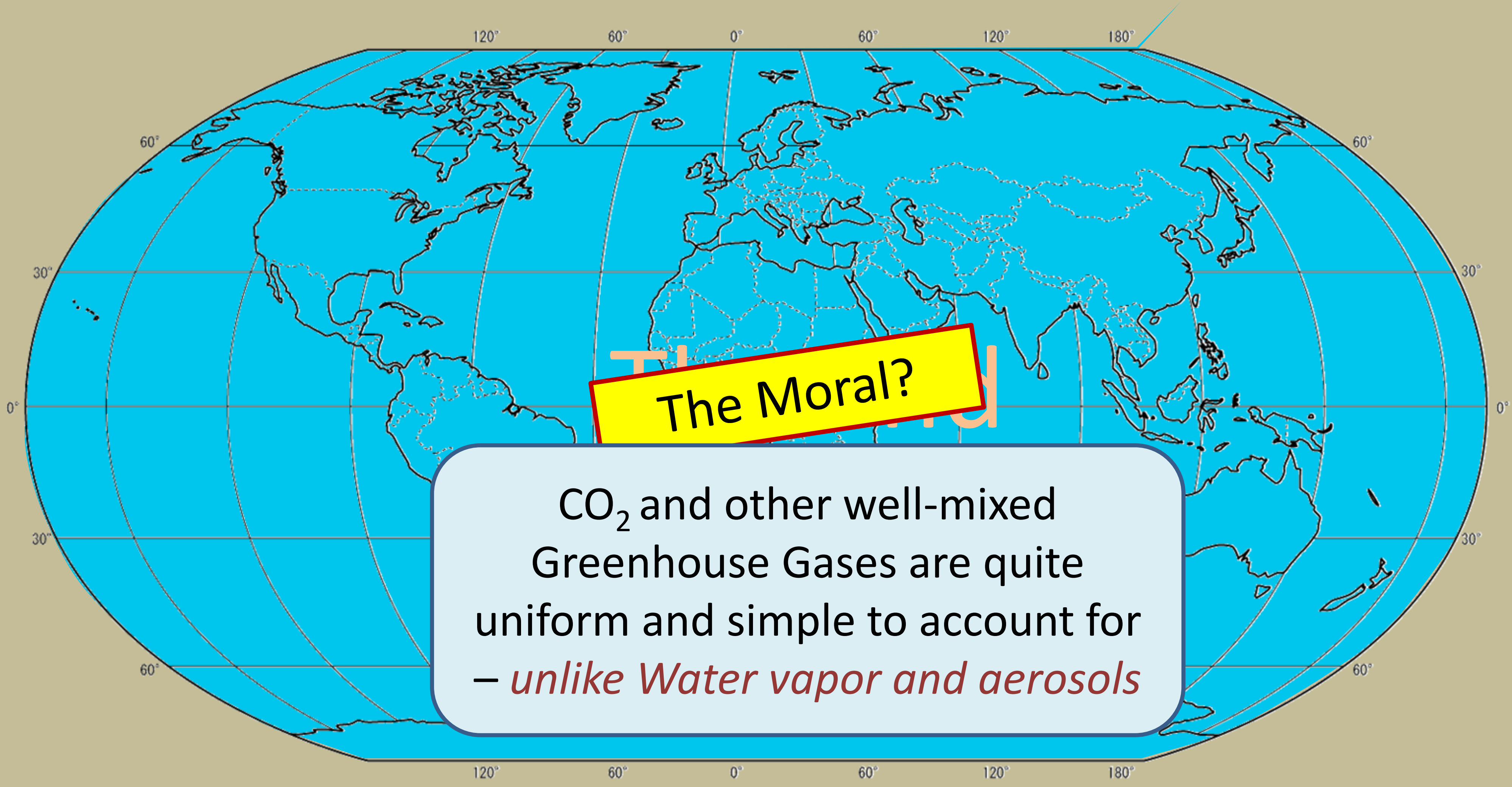


CO2 has increased to almost 420ppm

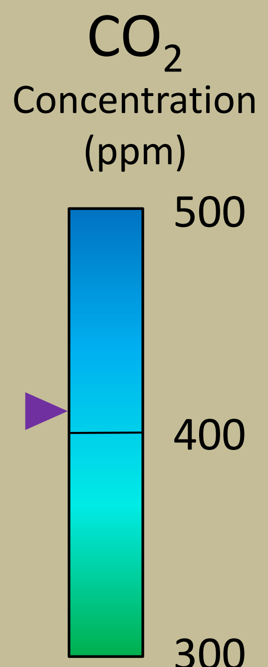
1999

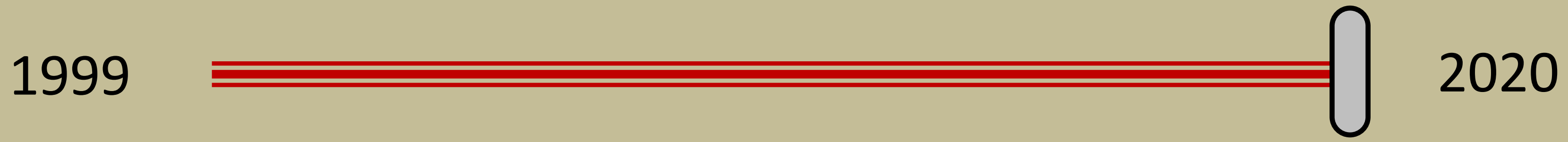
2020

The Moral?



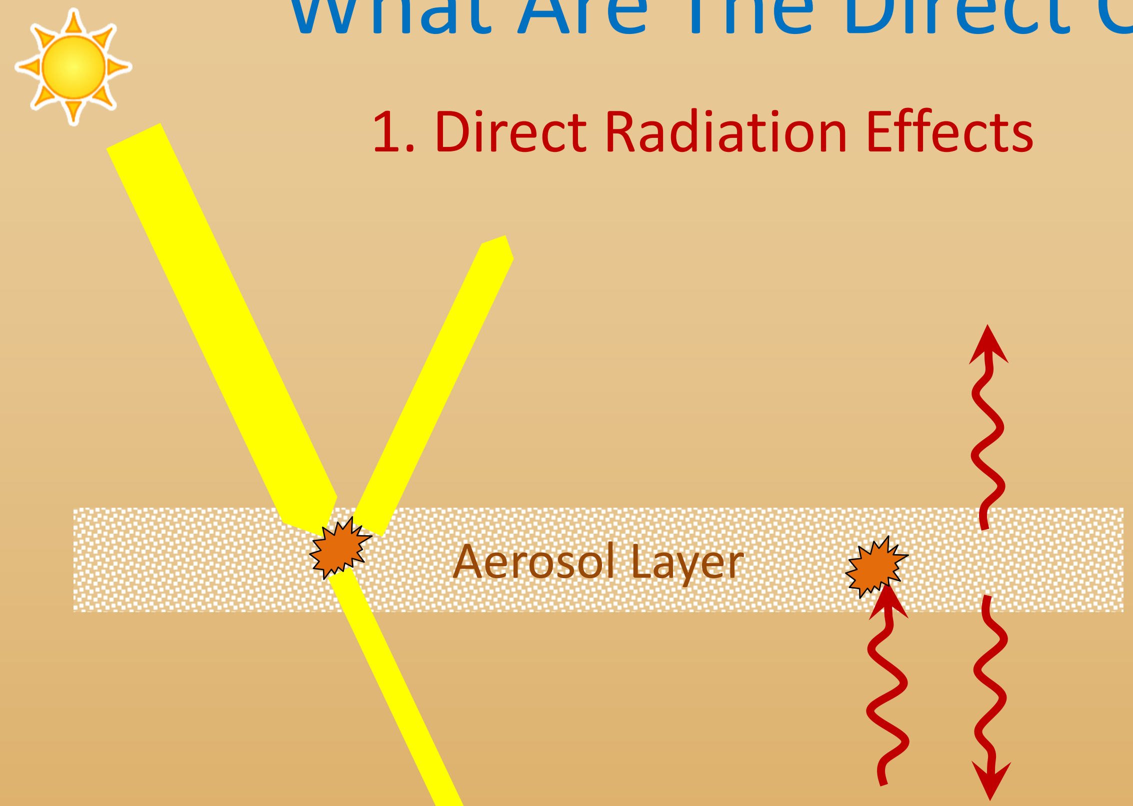
CO_2 and other well-mixed Greenhouse Gases are quite uniform and simple to account for – *unlike Water vapor and aerosols*





What Are The Direct Climate Effects of Aerosols?

1. Direct Radiation Effects



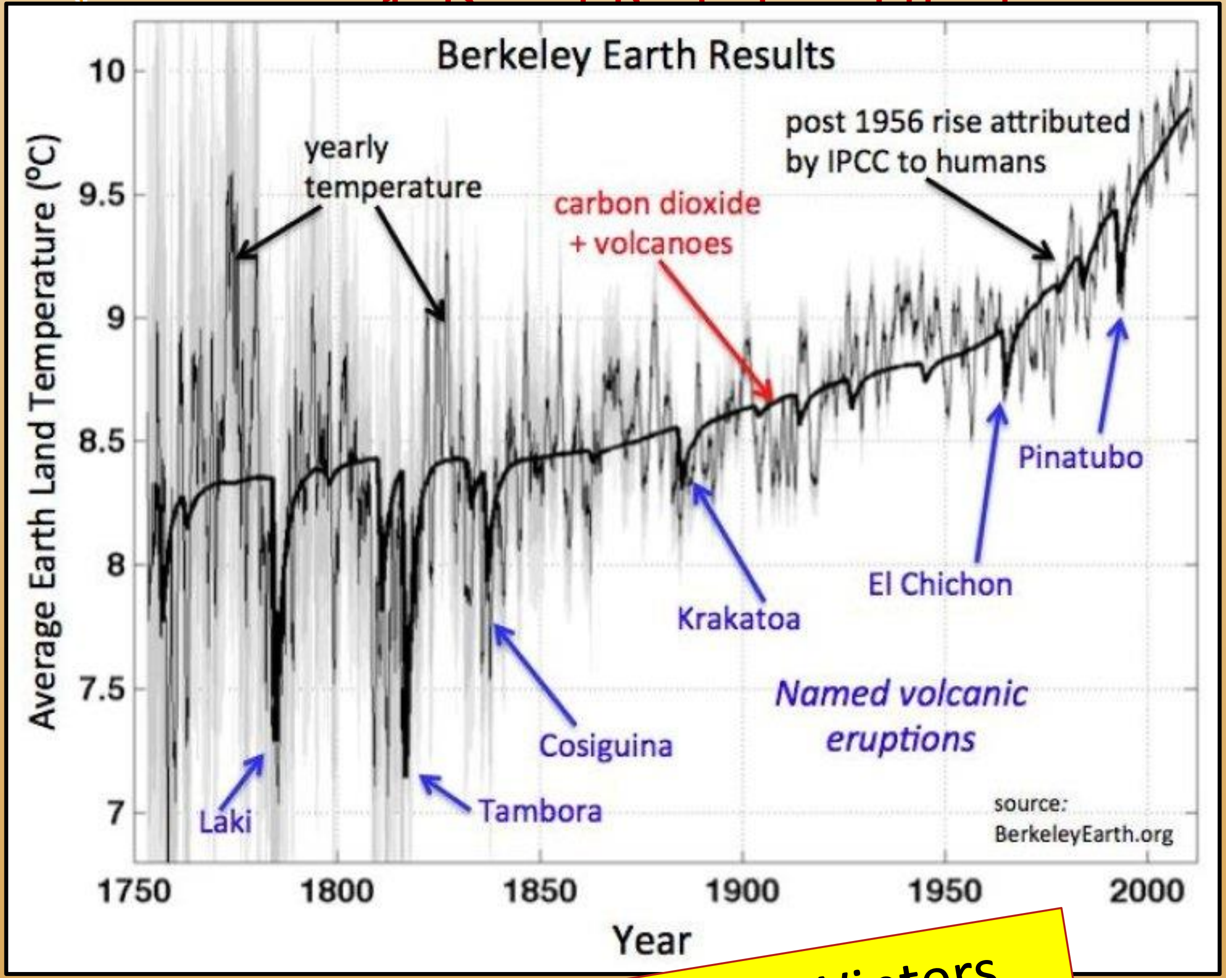
Solar Radiation:
- Scattered/Reflected
- Possibly absorbed
    - e.g. Black Carbon

Big Albedo Effect

LW Infrared:
- Absorption
- Emission
- Broad wavelength range

- They are complex and still uncertain
    - Chemistry of genesis
    - Sources, distributions, lifetimes
    - Radiation interactions
    - **Measurements are hard**
- Overall, a cooling effect due to Albedo
    - however, Black Carbon aerosols have a net heating effect.
- Historically, anthropogenic aerosol cooling has cancelled much of the GH gas heating.
    - but clean air policies are reducing this offset!

What Are The Direct Climate Effects of Aerosols?



Big Albedo Effect

Volcanic Winters

- They are complex and still uncertain
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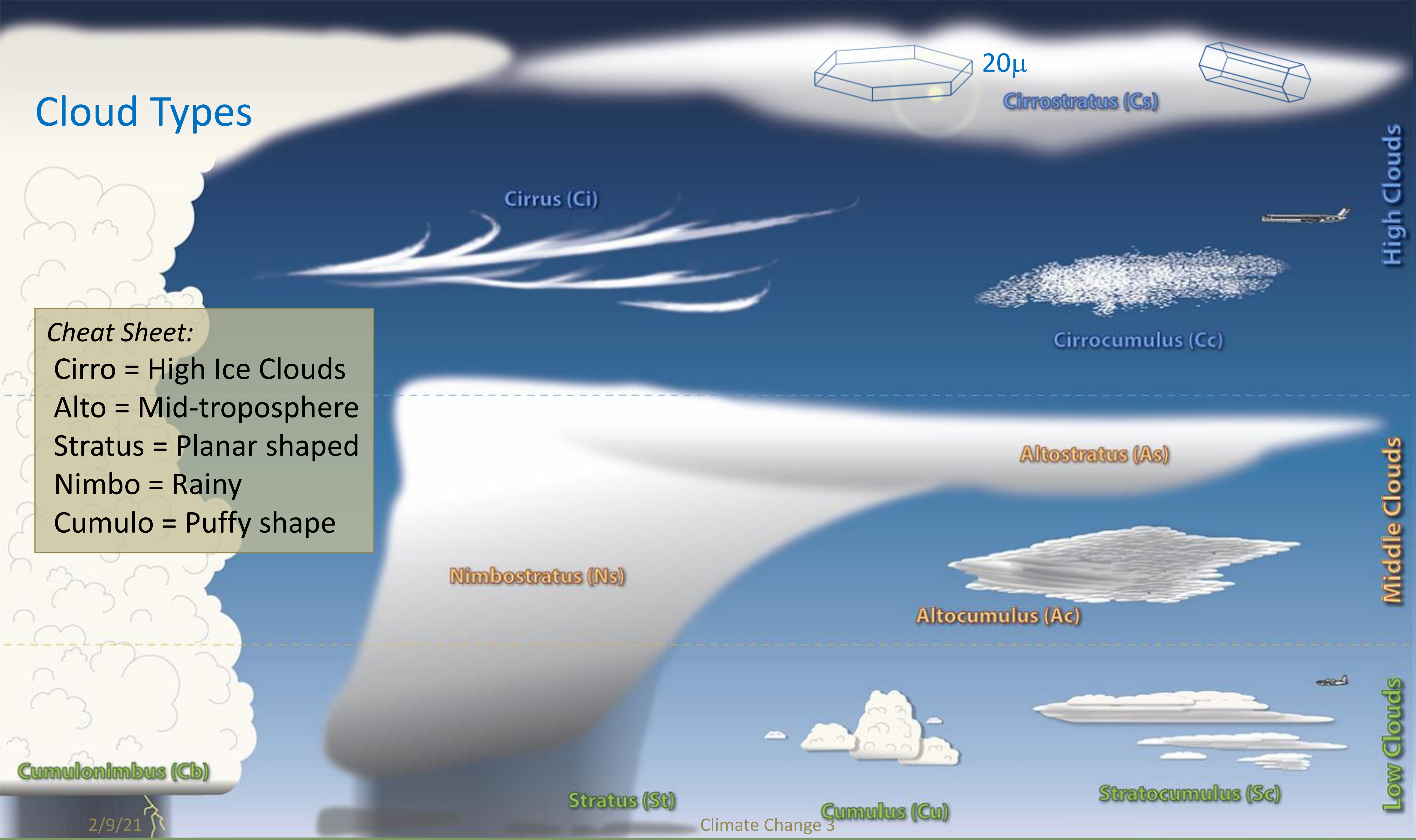
Cloud Types

Cheat Sheet:

Cirro = High Ice Clouds
Alto = Mid-troposphere
Stratus = Planar shaped
Nimbo = Rainy
Cumulo = Puffy shape



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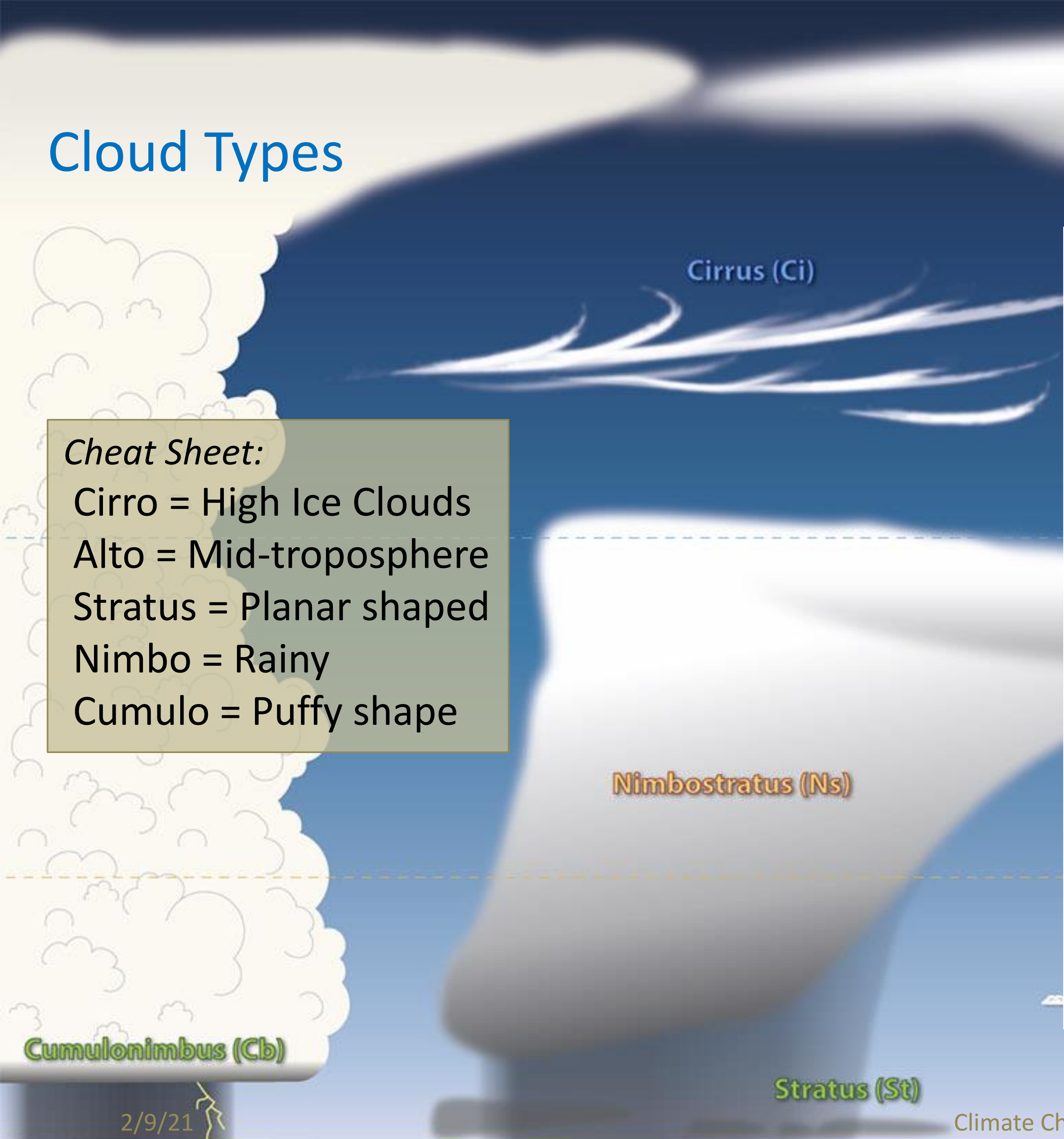

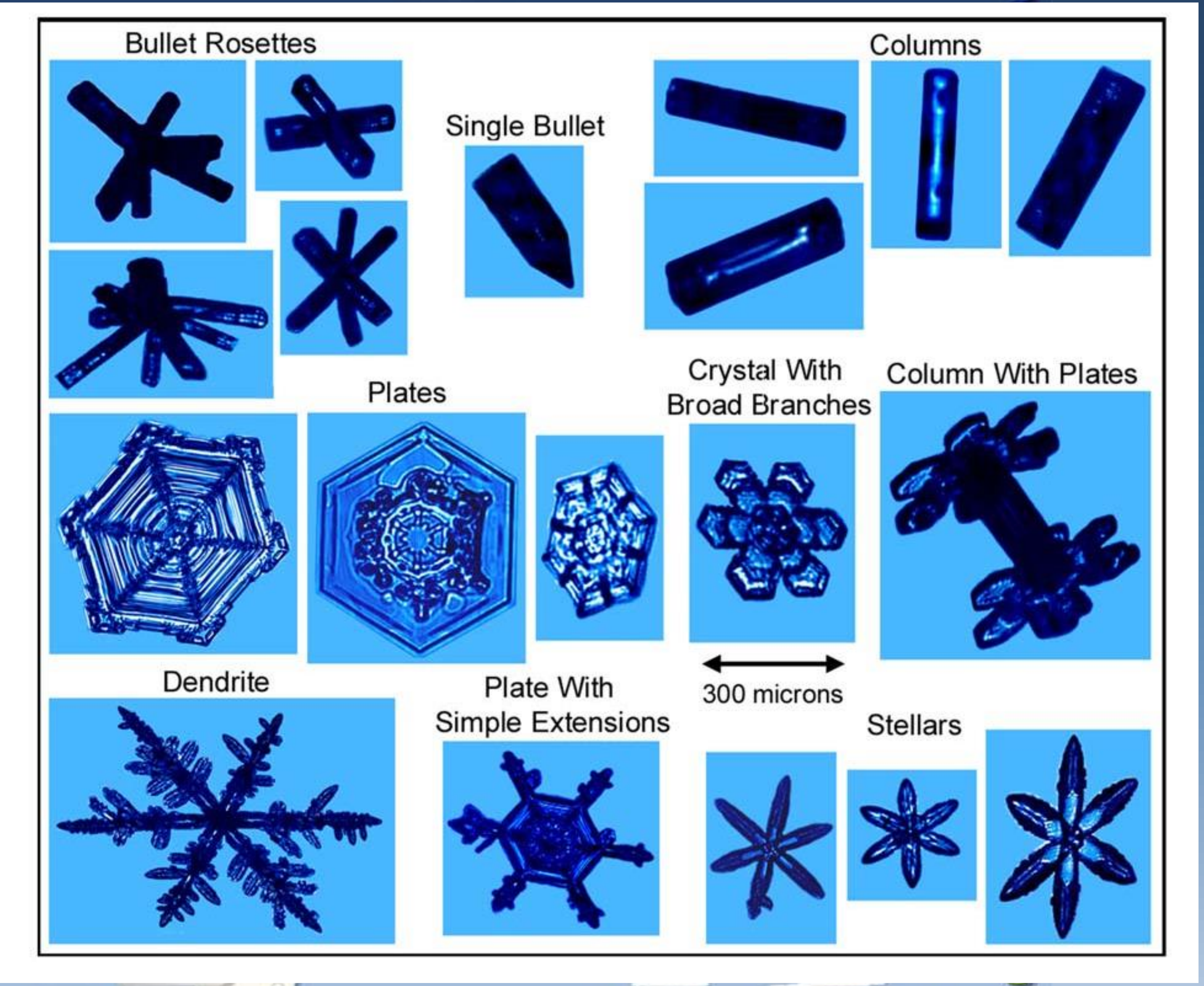

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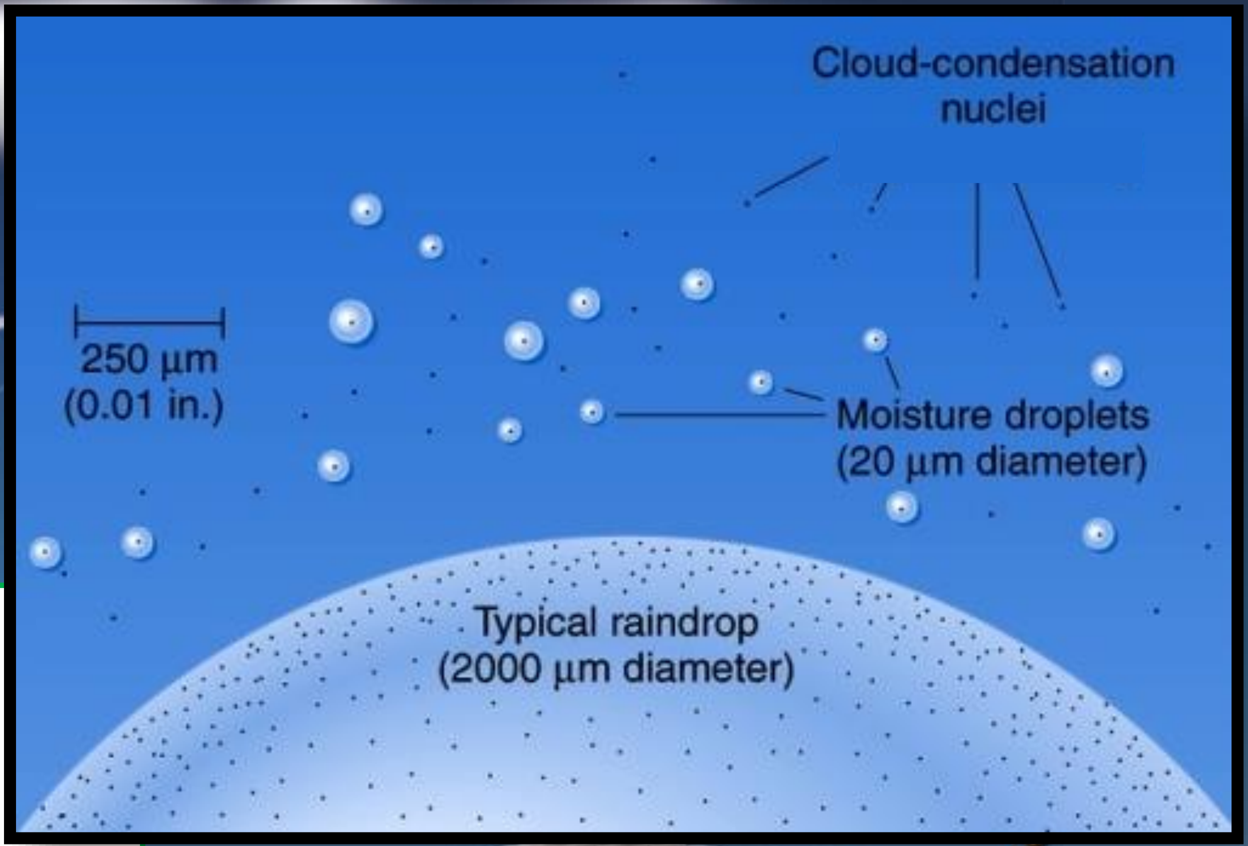
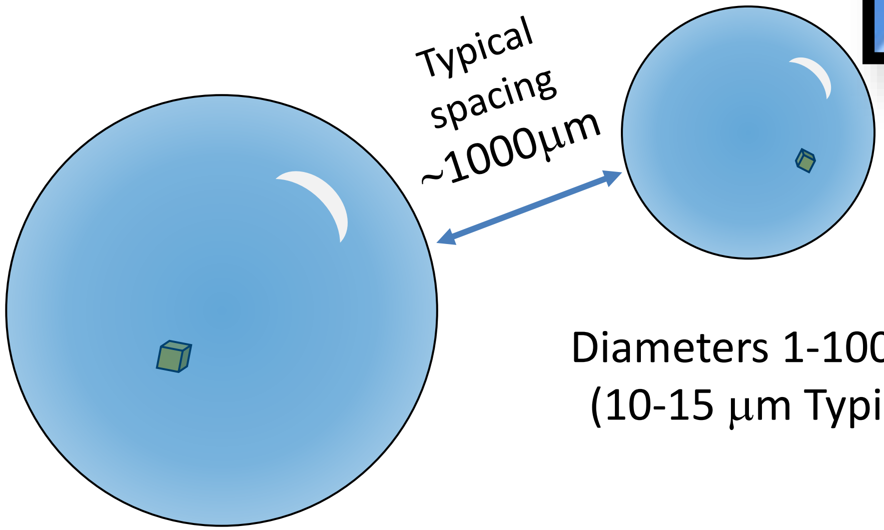


Lower clouds composed of spherical water droplets



Diameters 1-100 µm
(10-15 µm Typical)

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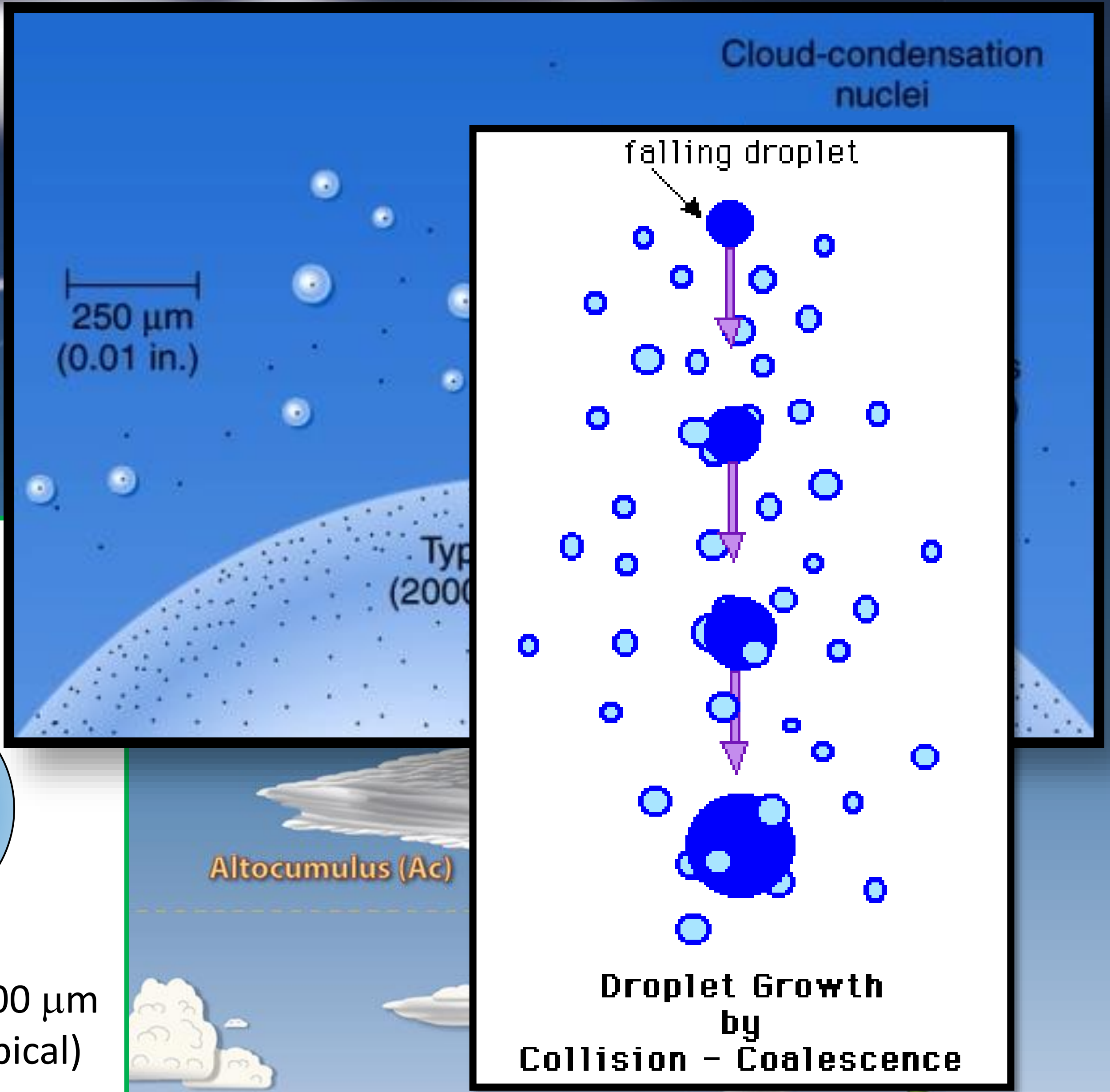

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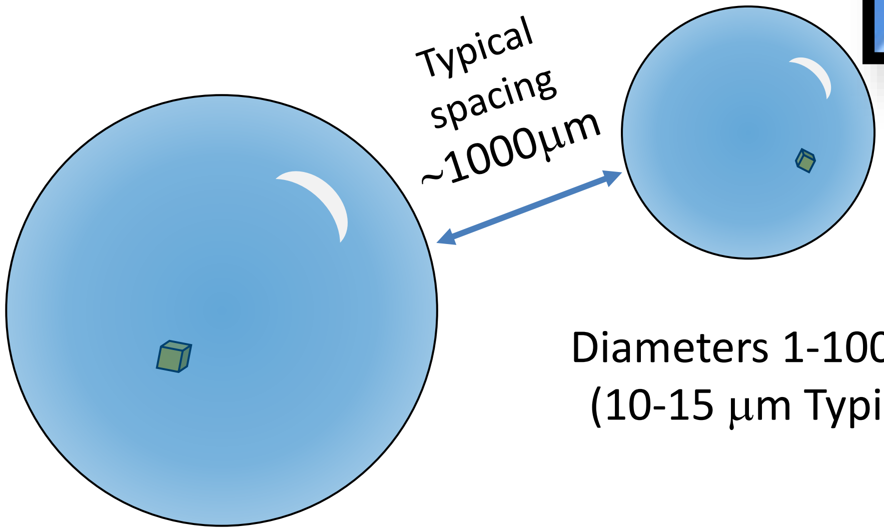

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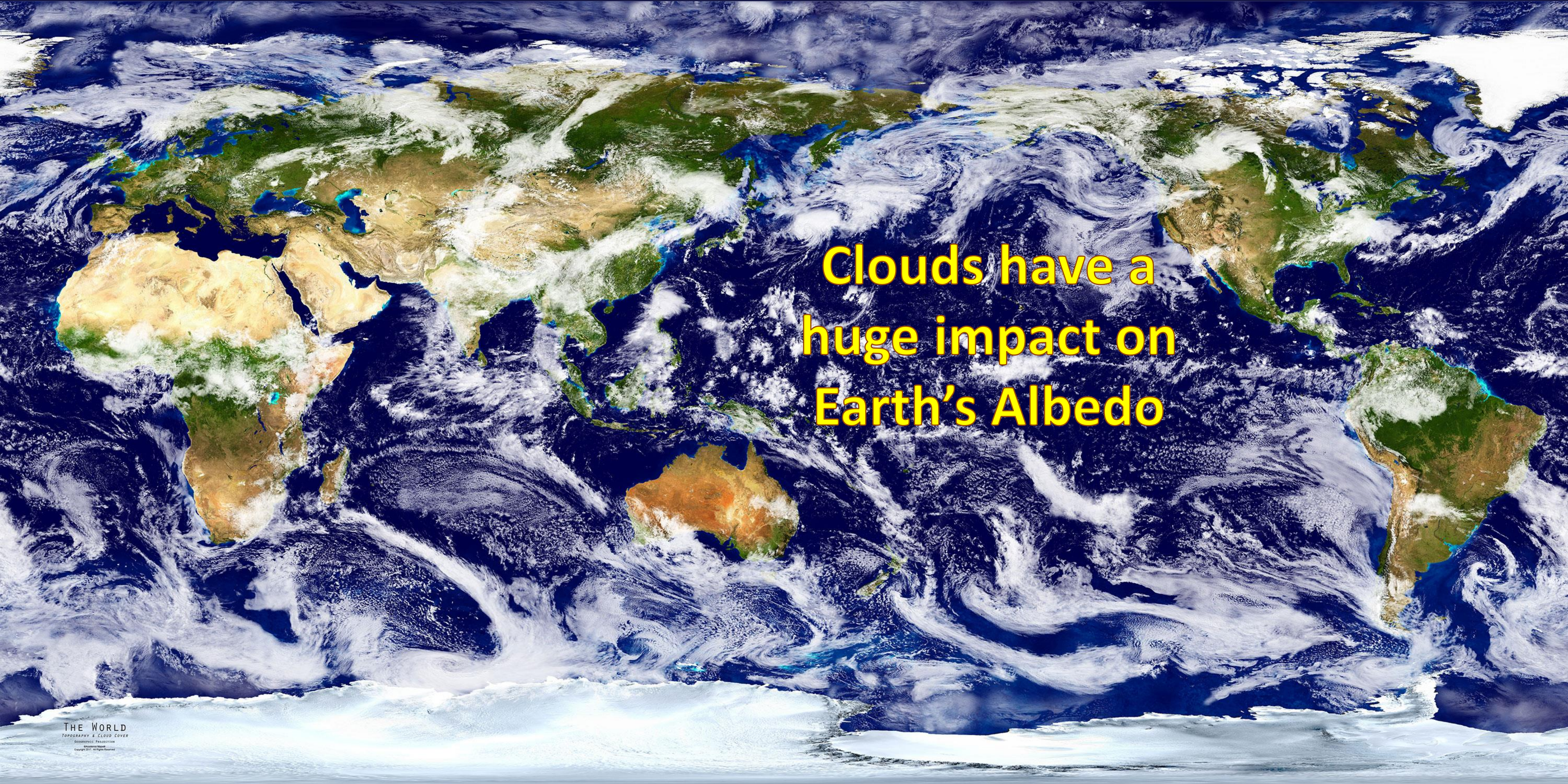
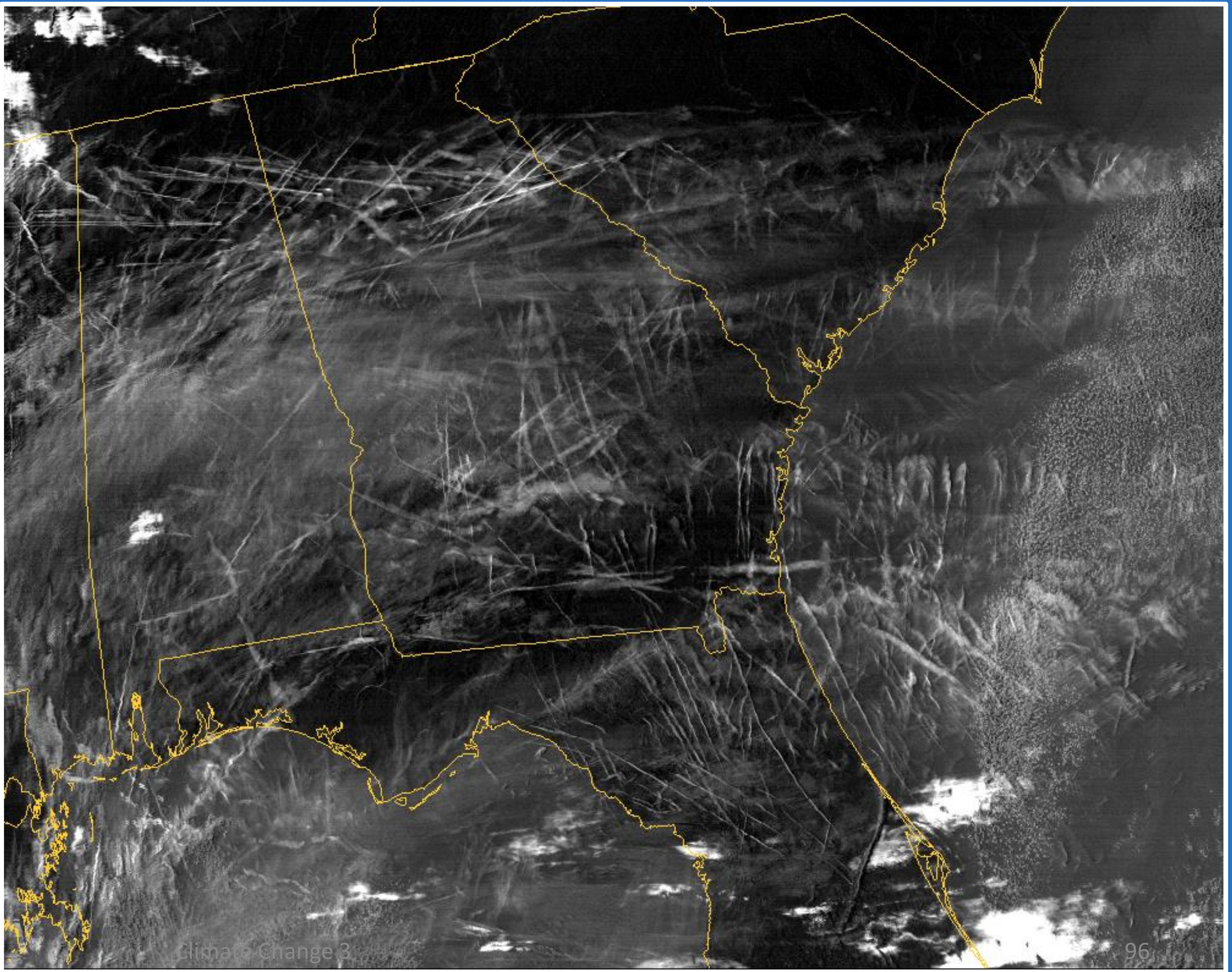


WorldMapsOnline.com (2017)

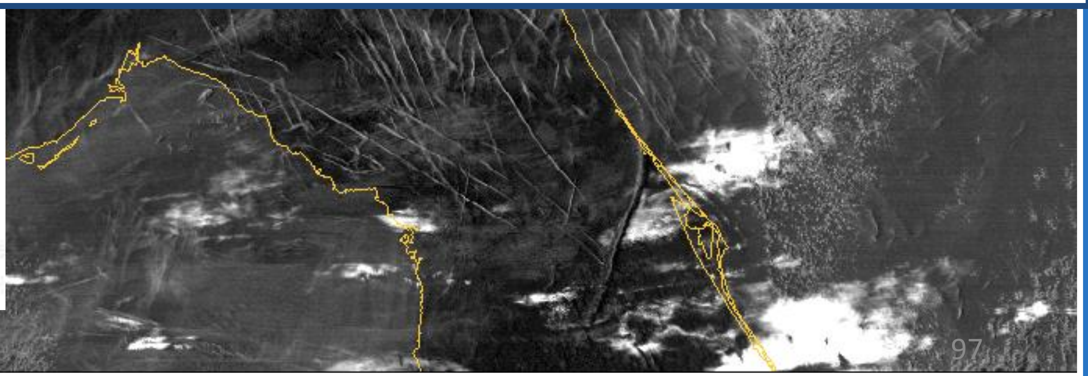
Clouds have a huge impact on Earth's Albedo

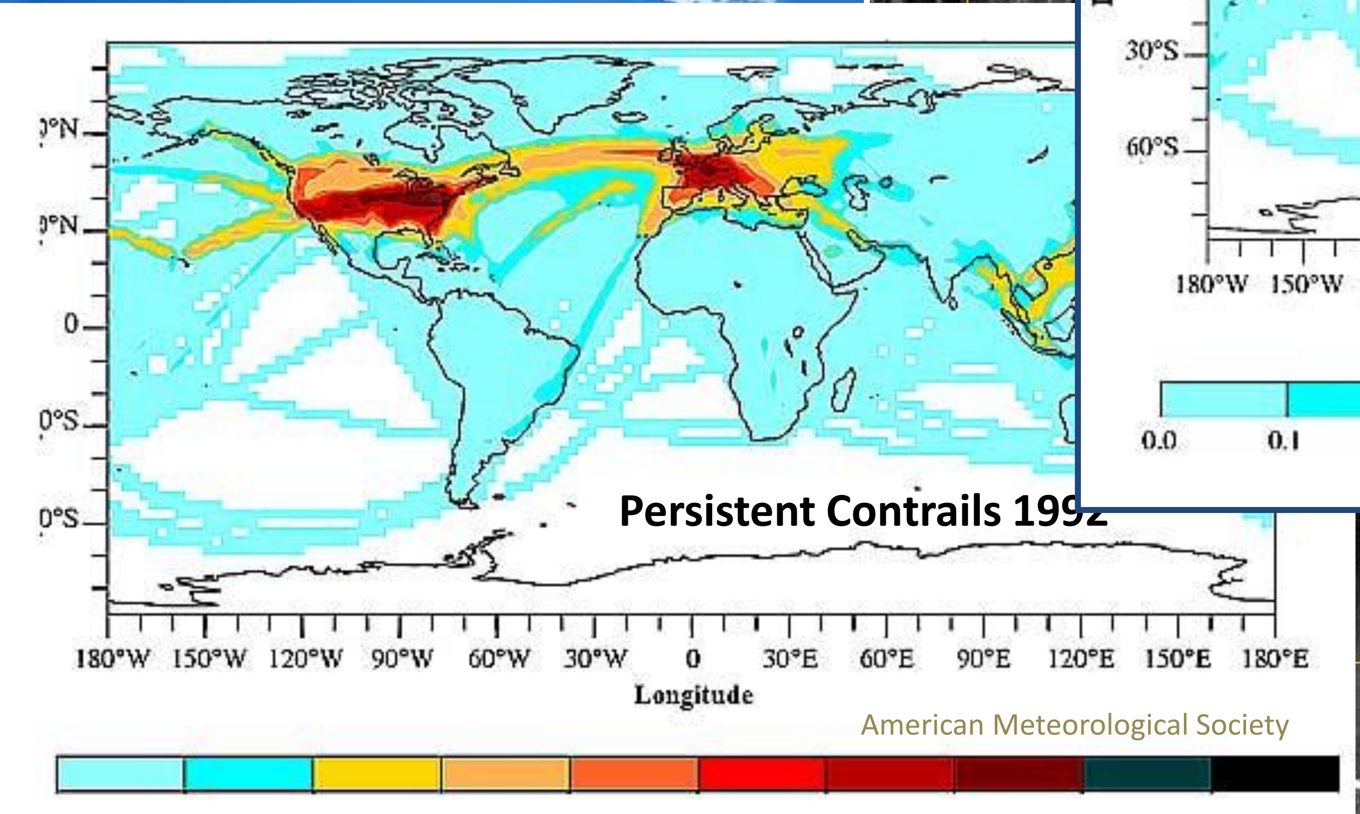
WorldMapsOnline.com (2017)

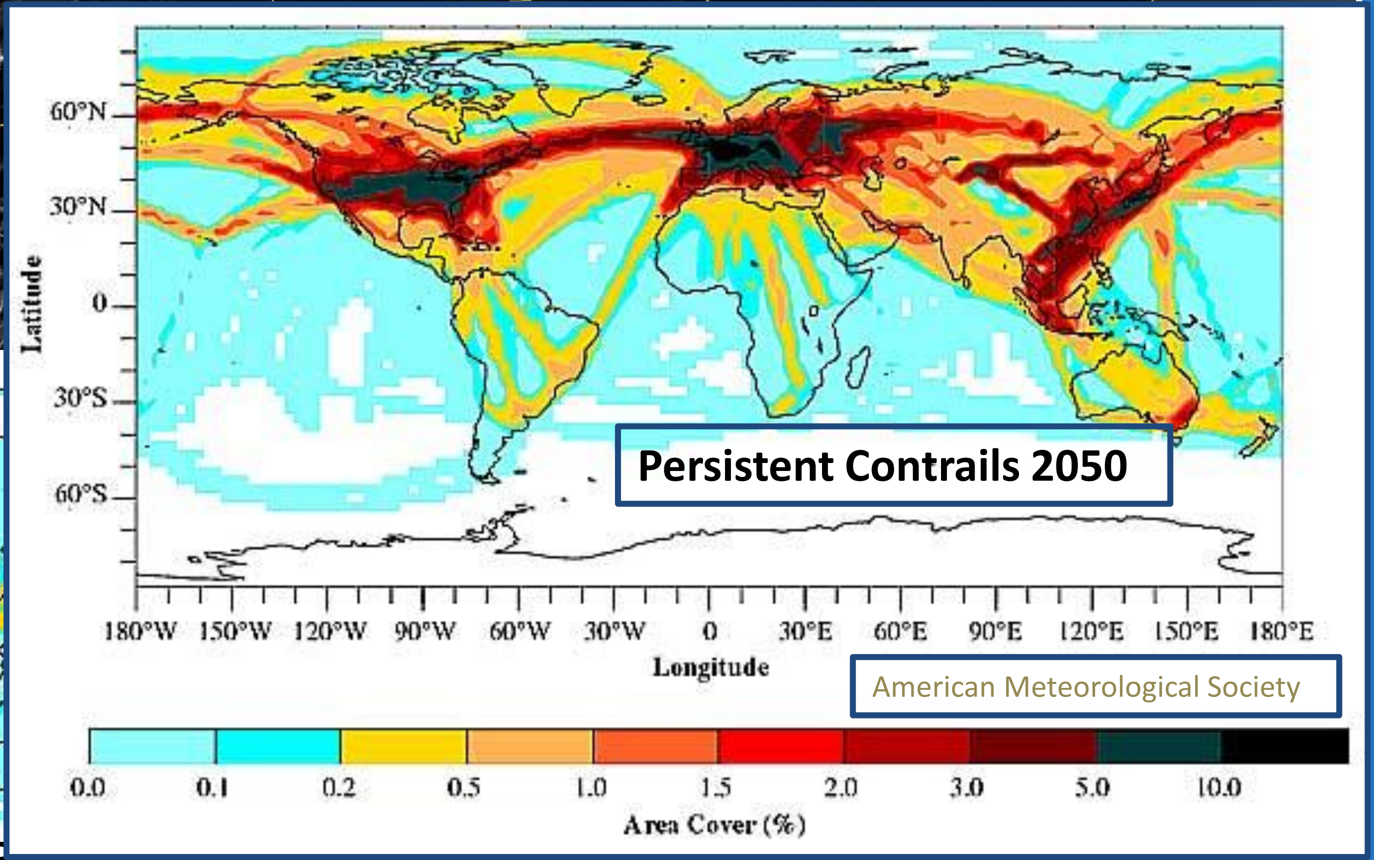
Contrails



Contrails

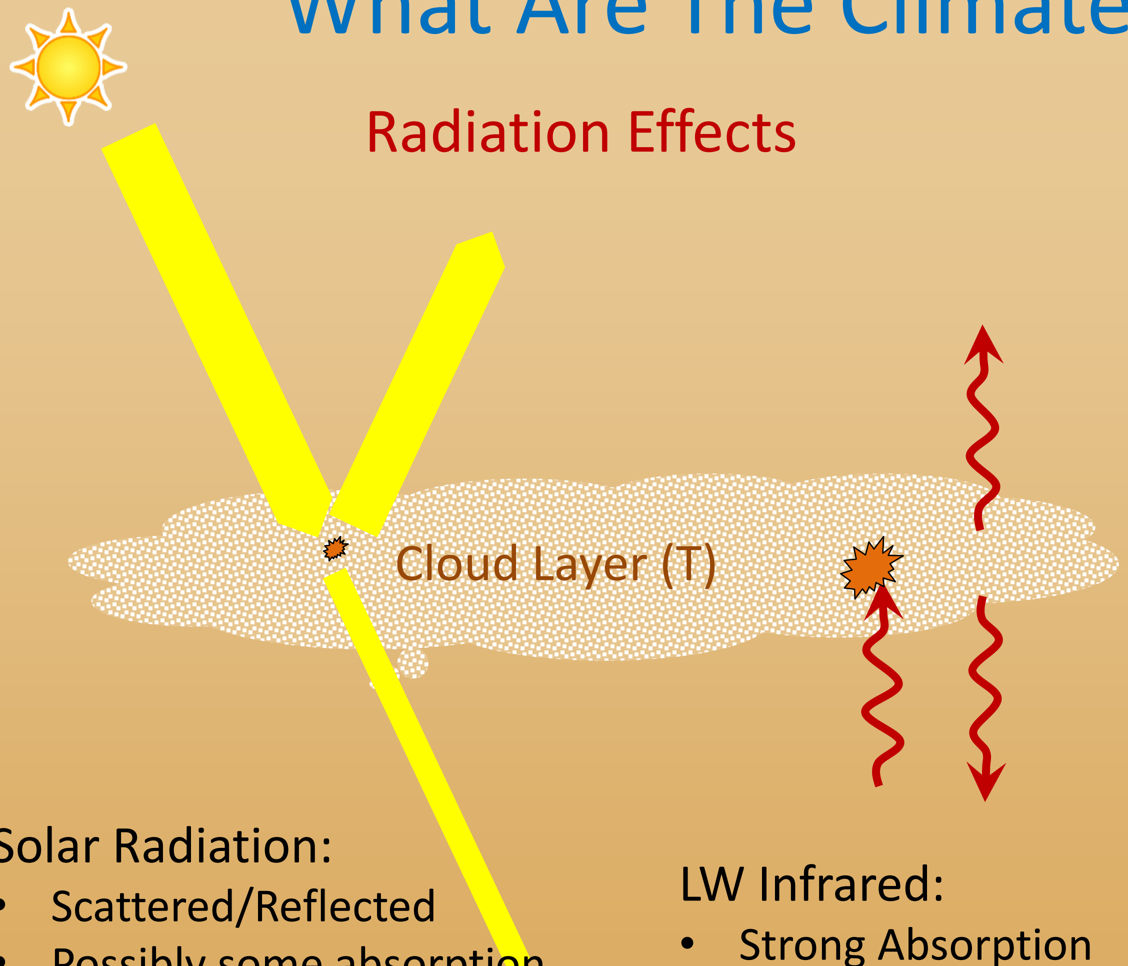



Persistent Contrails 1992
180°W 150°W 120°W 90°W 60°W 30°W 0 30°E 60°E 90°E 120°E 150°E 180°E
Longitude
American Meteorological Society


60°N
30°N
0
30°S
60°S
Latitude
Persistent Contrails 2050
180°W 150°W 120°W 90°W 60°W 30°W 0 30°E 60°E 90°E 120°E 150°E 180°E
Longitude
American Meteorological Society
0.0 0.1 0.2 0.5 1.0 1.5 2.0 3.0 5.0 10.0
Area Cover (%)

What Are The Climate Effects of Cloud Aerosols?

Radiation Effects



Solar Radiation:

- Scattered/Reflected
- Possibly some absorption
- Albedo depends on drop size

Strong Cooling Effect for Thick Clouds

LW Infrared:

- Strong Absorption
- Strong Emission (ε≈1)

Strong GH Heating Effect

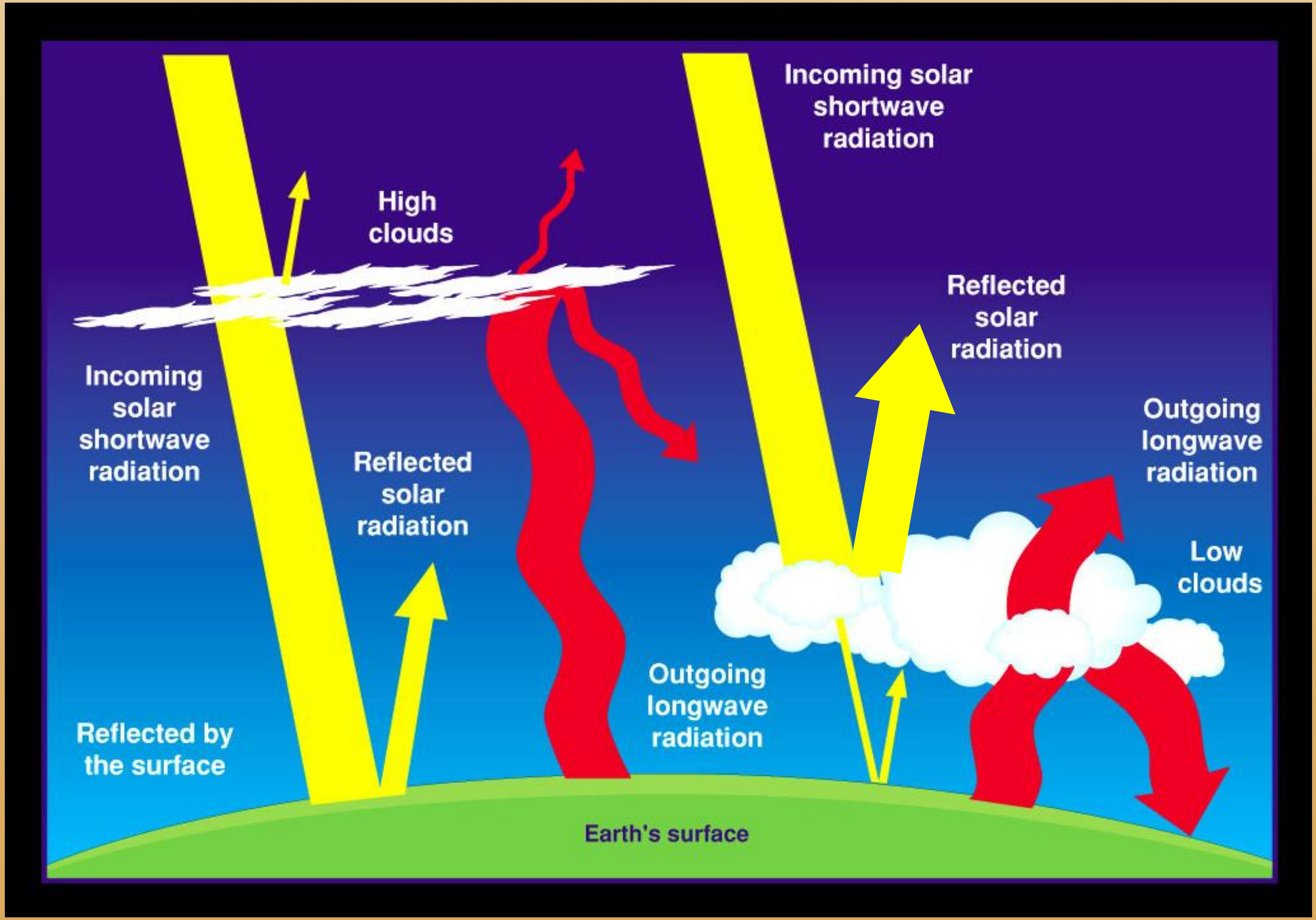
- Radiation Balance
  - Depends on cloud height and thickness (Temperature & Opacity)
- Precipitation Effects
- Cloud growth deposits latent heat in atmosphere

So which effect wins out?

High and Low Clouds have Opposite Effects

High Cirrus Clouds:
- Low opacity
  - Minor Albedo Effect
- High IR trapping
  Low emission

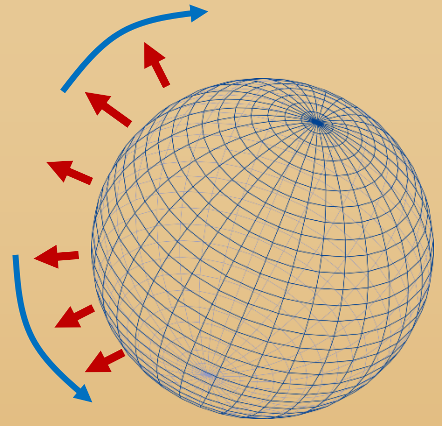
Result:
Net
Warming



Low Stratus Clouds:
- High opacity
  - Large Albedo Effect
- High IR trapping & Emission

Result:
Net
Cooling

Cloud Feedbacks due to Rising Global Temperature



Basic cloud changes due to GW thought to be “upward and poleward”

1. Rising tropospheric cloud layers **+**
   – Positive + feedback due to LWIR effect
2. Decreased tropical low cloud coverage **+**
   – Positive + due to less SW cooling
3. Increased high-latitude low cloud thickness **–**
   – Negative – feedback due to SW cooling

+

Overall: + ?

Large Uncertainties – Clouds are the biggest Wild Card

MODTRAN Infrared Light in the Atmosphere

climatemodels.uchicago.edu/modtran/

You can go to the above web site and play directly with this model!

Model Input

CO_2 (ppm)	400
CH_4 (ppm)	1.7
Trop. Ozone (ppb)	28
Strat. Ozone scale	1
Water Vapor Scale	1
Freon Scale	1
Temperature Offset, C	0
Holding Fixed	Relative Humidity
Locality	1976 U.S. Standard Atmosphere
	No Clouds or Rain
Altitude (km)	70
	Looking down

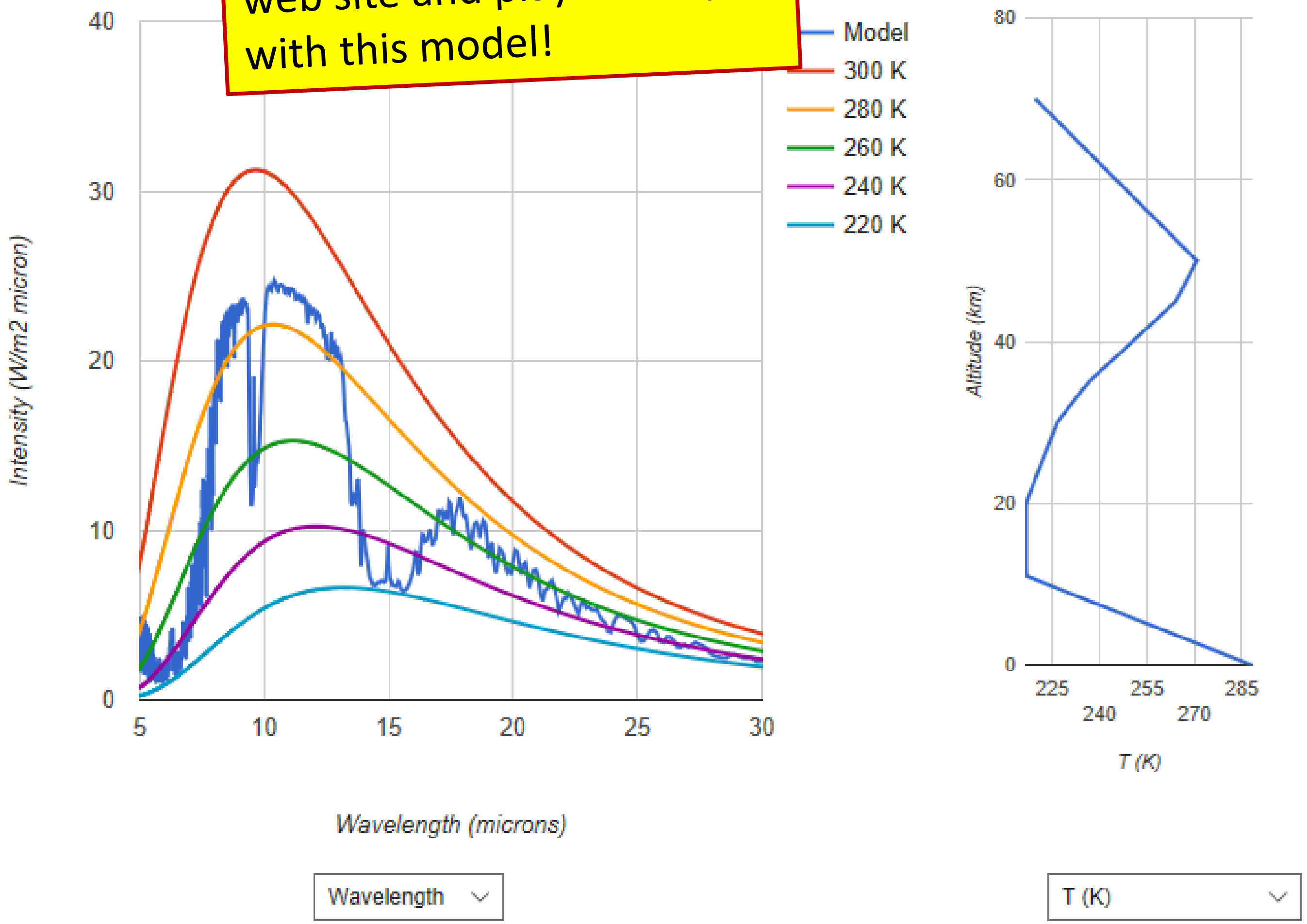
Looking down from space

Model Output

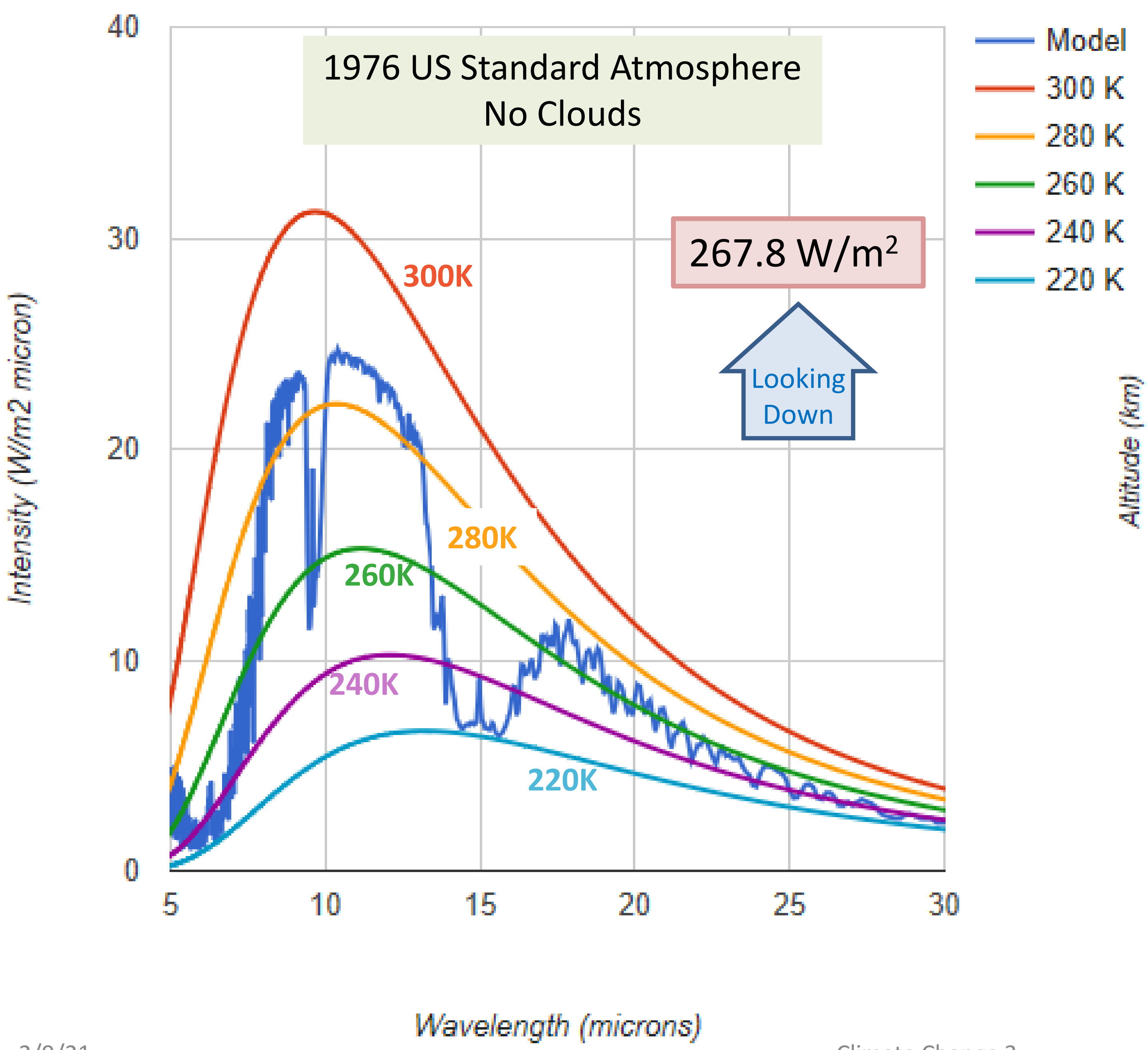
Upward IR Heat Flux **267.842** W/m²

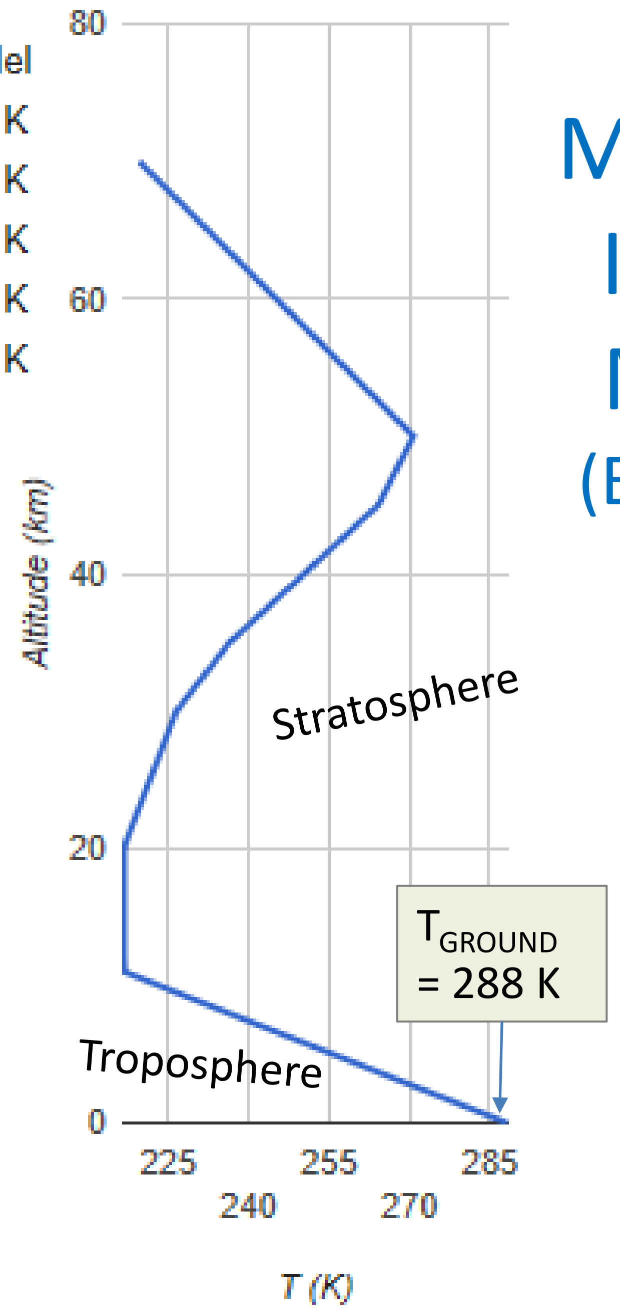
Ground Temperature **288.2** K

Spectrum expanded 5-11-17, changing the IR out value



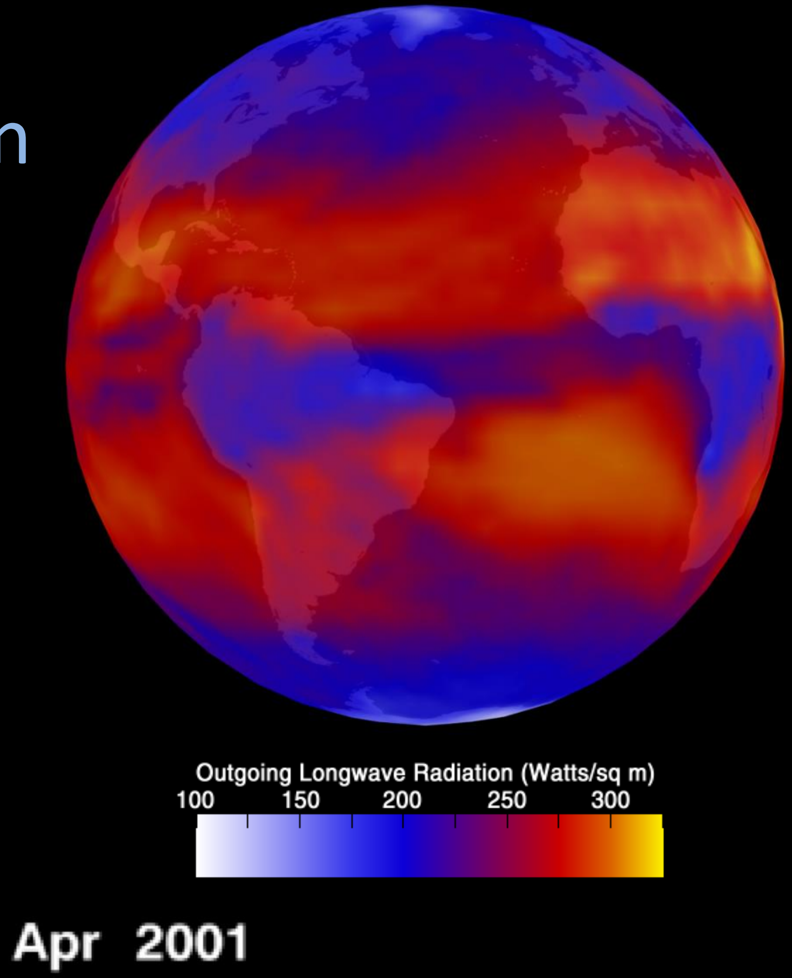
Modtran IR Flux Model (Example)



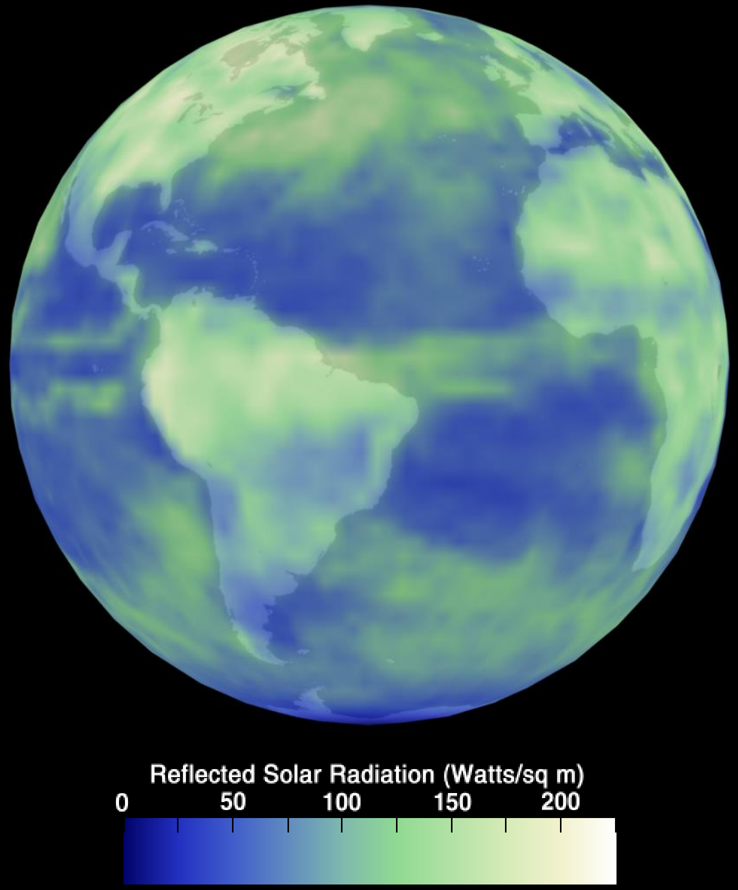


Satellite Measurements of Outgoing Earth Radiation

LW IR Outgoing Radiation



Solar Reflected Radiation

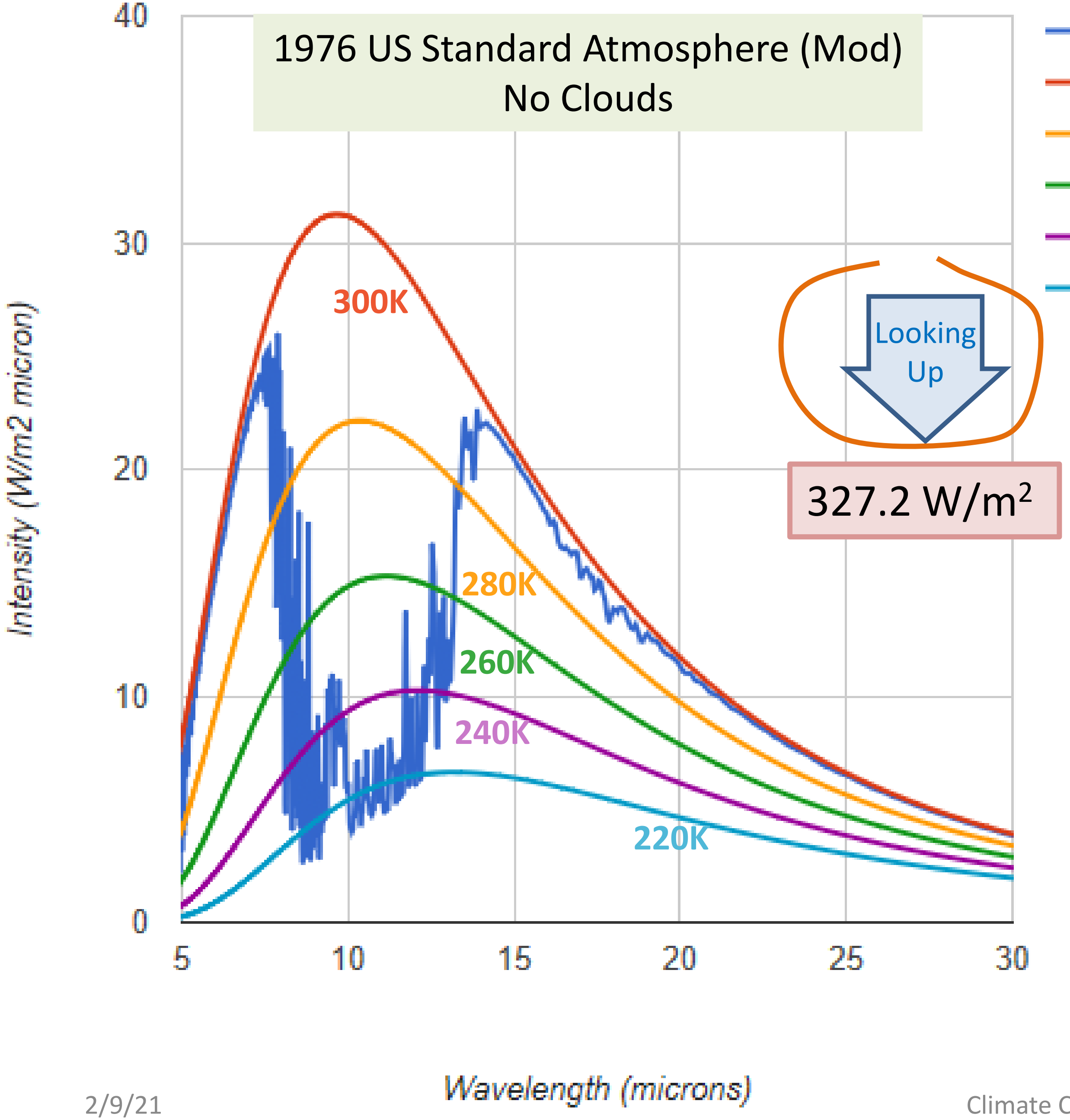


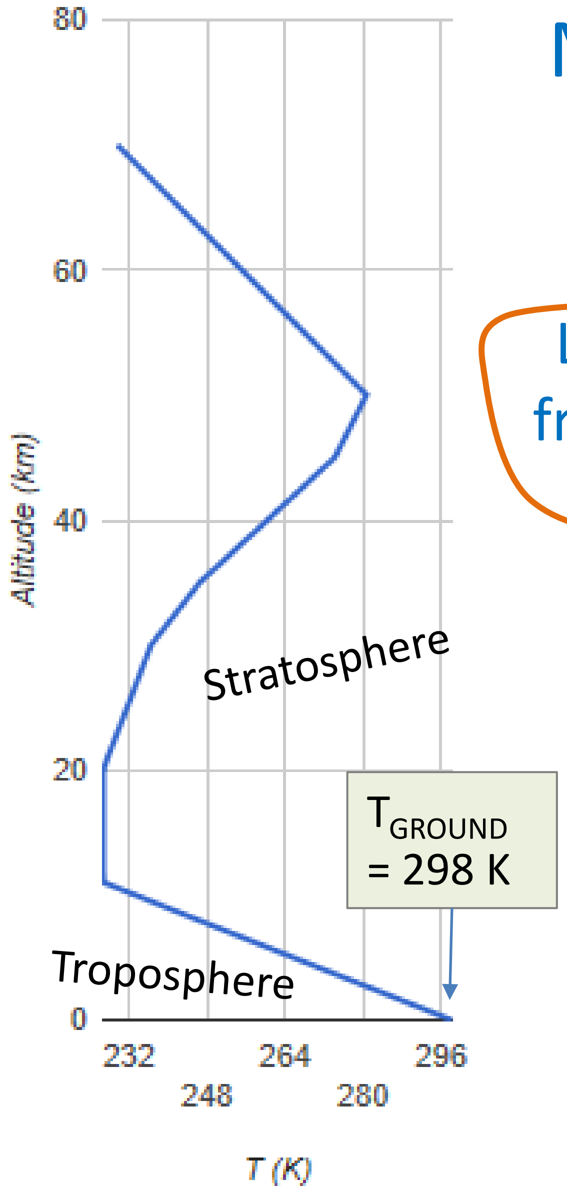
CERES Satellite Data

ceres.larc.nasa.gov/press_releases_images.php

Modtran IR Flux Model:

Looking Up from Ground

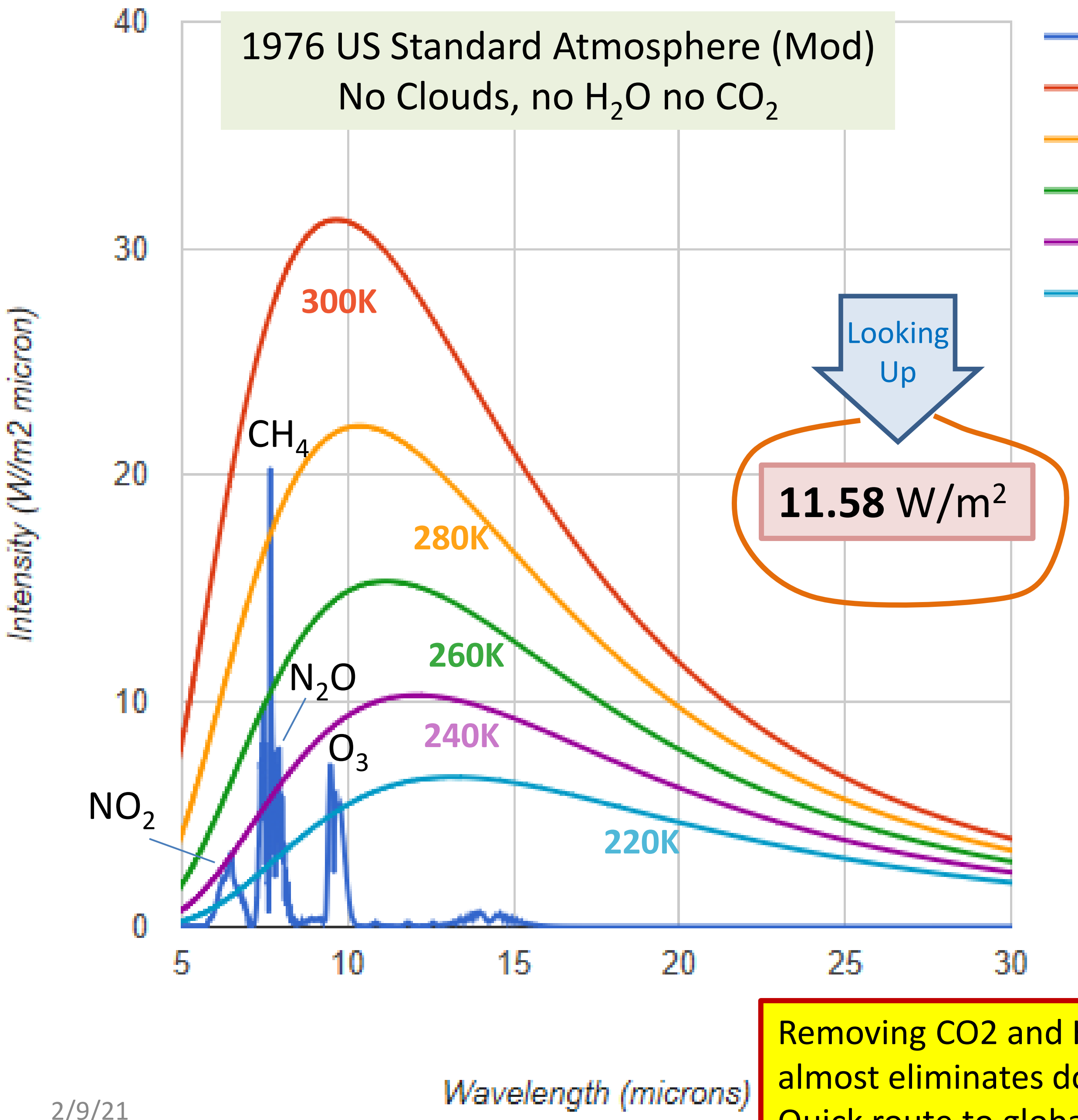


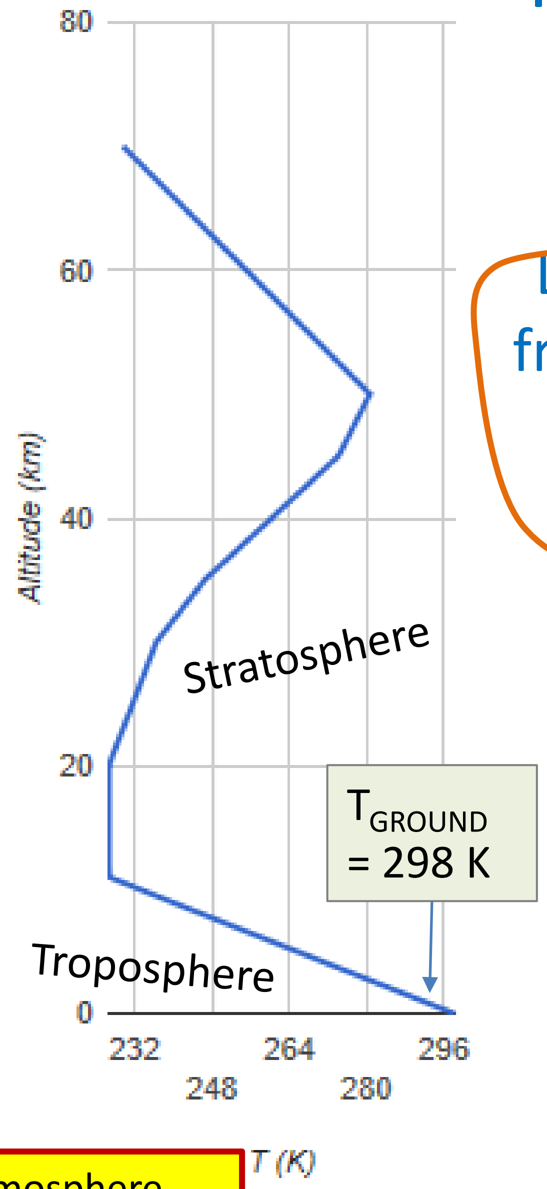


Ground radiates 447.1 W/m² upward

Modtran IR Flux Model:

Looking Up from Ground
No Water
No CO_2





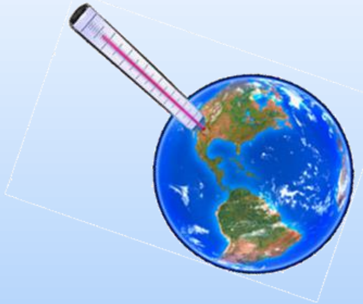
Ground radiates 447.1 W/m² upward

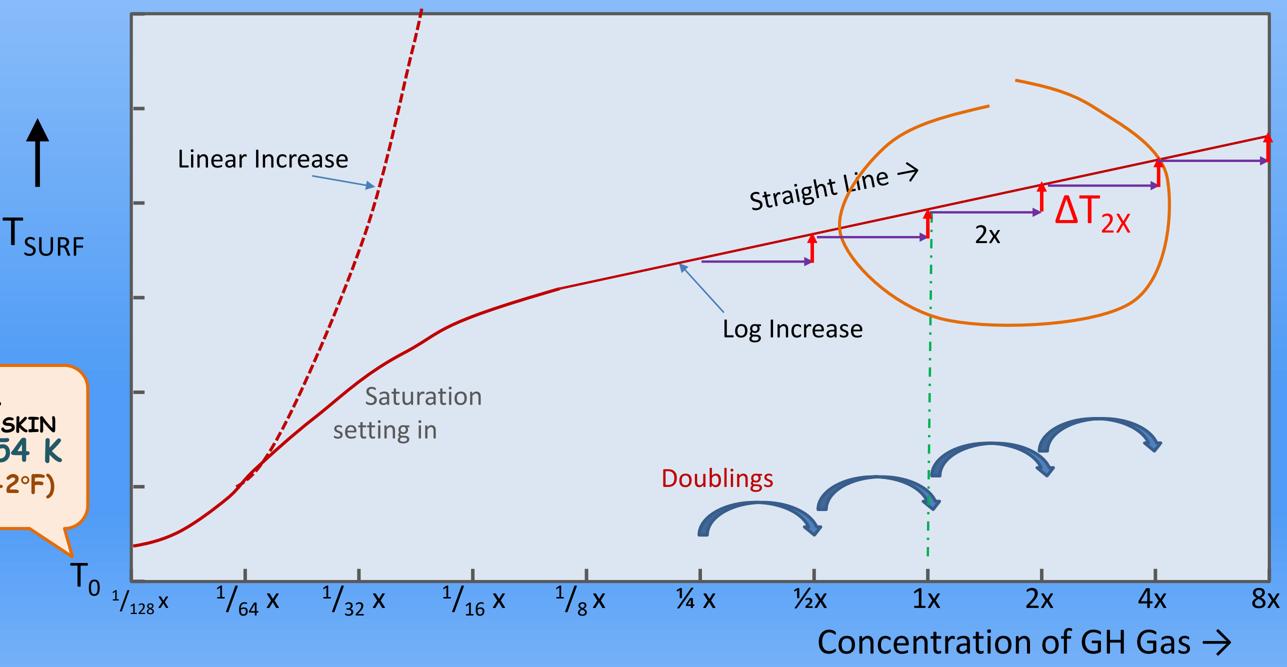
Removing CO2 and H2O from atmosphere almost eliminates downcoming IR radiation. Quick route to global deep freeze!

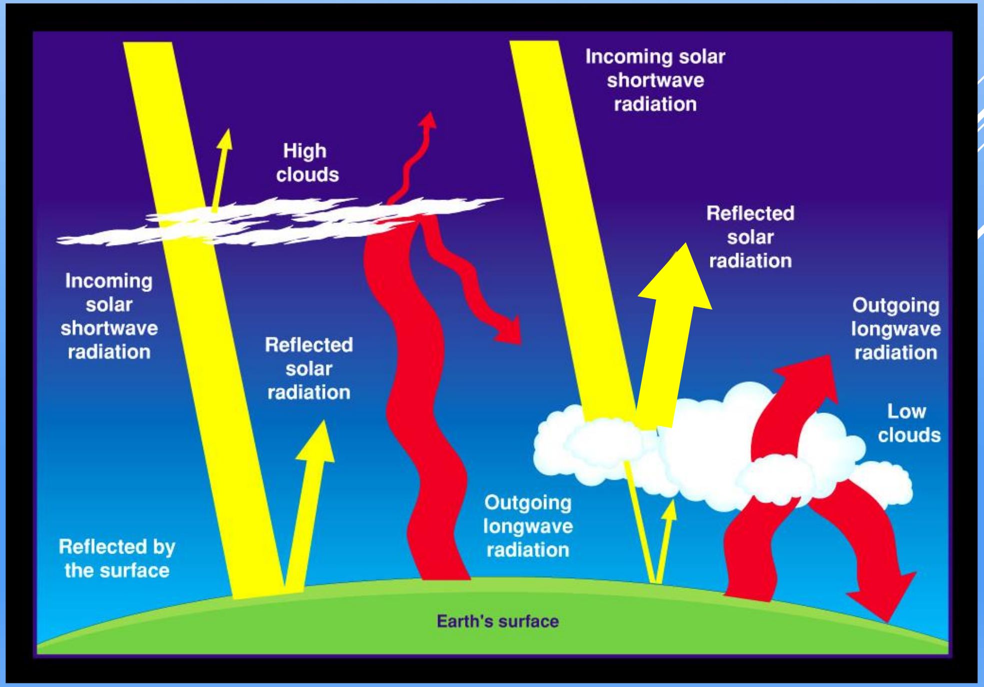
Bottom Line

- For clear air, the equations can be solved almost exactly
  - at least for the atmospheric part of the problem....
- Unfortunately, other parts of the problem are much harder
  - Clouds, e.g.

Questions about Climate Sensitivity, Aerosols & Clouds?



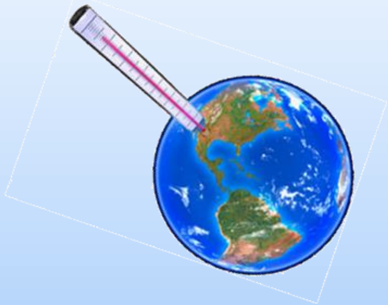




Course Outline

1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. **The Role of the Atmosphere: Greenhouse Gases & Clouds**
4. Dynamics of the Earth System: Oceans, Atmosphere, Biosphere, Cryosphere, People, Plate Tectonics
5. Natural Variability of the Climate, short and long term. Ice Ages
6. Carbon Dioxide and other Greenhouse Gases: where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Adaptation and Amelioration Strategies. The Climate debate. Policy options.

Questions about Earth's basic Effective Temperature?



Why is it about -2 ^{o}F ?

Radiometric Balance