Theodore B. Reinhart, P.E.

- 2011-now: Energy-PE, LLC
- 1985-2011: Laclede Gas Company
- 1984-1985: Londe-Parker-Michels
- M.S. 1984: University of Missouri – Columbia,
  Mechanical and Aerospace Engineering
- 1981-1982 & 1983: Industrial Engineering and Equipment Co.
- 1979-1981: Mary Institute
- B.A. 1978: Rice University, Physics/Space Physics

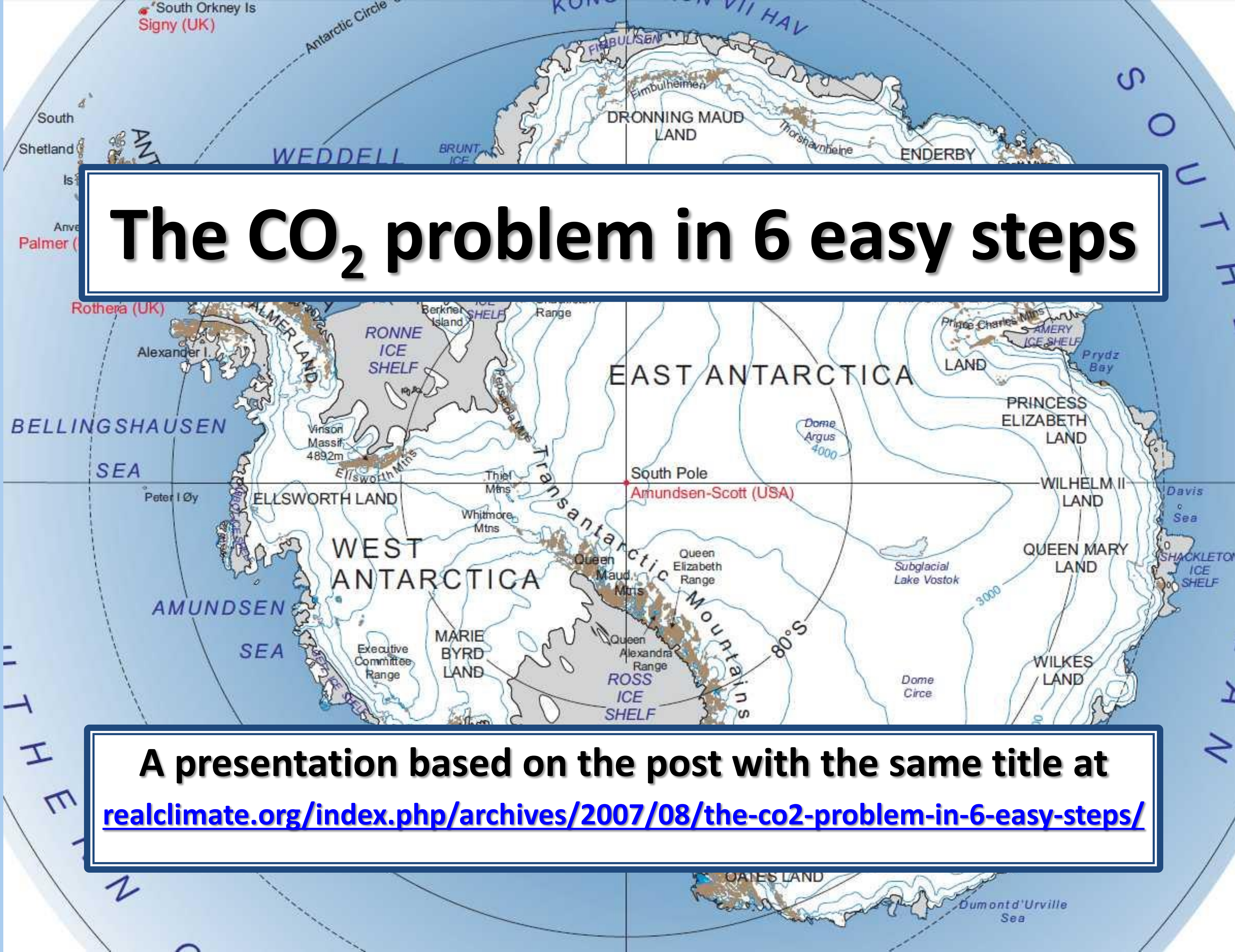
energy-pe.com

$\dot{E}$

The CO_2 problem in 6 easy steps

A presentation based on the post with the same title at

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/

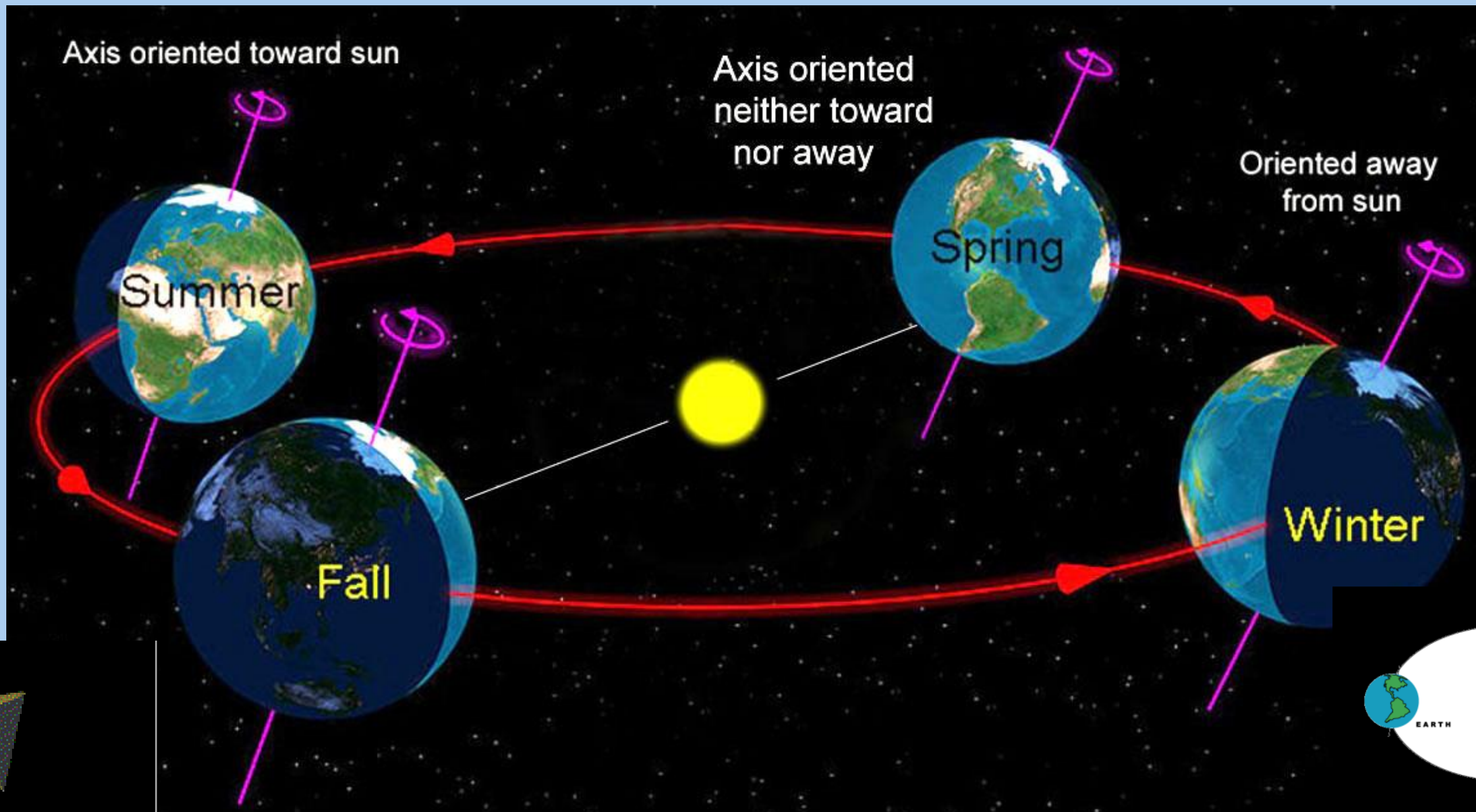


Learning Objectives

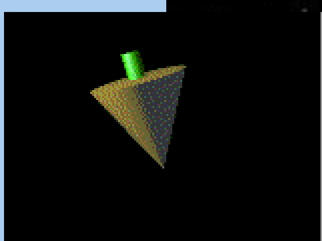
- Explain the difference between predictions and data
- Describe how greenhouse gases affect surface temperature and how a simple model illustrates the effect of change
- Understand how spectroscopy measures the radiative transfer absorbed by trace greenhouse gases
- Demonstrate the context of industrial age concentrations of trace greenhouse gases
- Use radiative forcing and climate sensitivity to calculate how the environment reacts to change

asu.cas.cz/~bezdek/vyzkum/rotating_3d_globe/

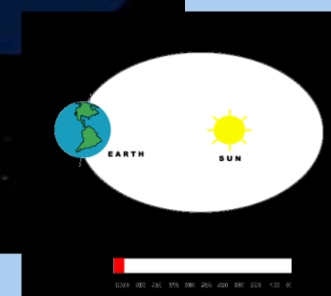
earthobservatory.nasa.gov/Features/Milankovitch/milankovitch_3.php



Astro Bob



26 000 & 40 000 years NASA



100 000 years USC

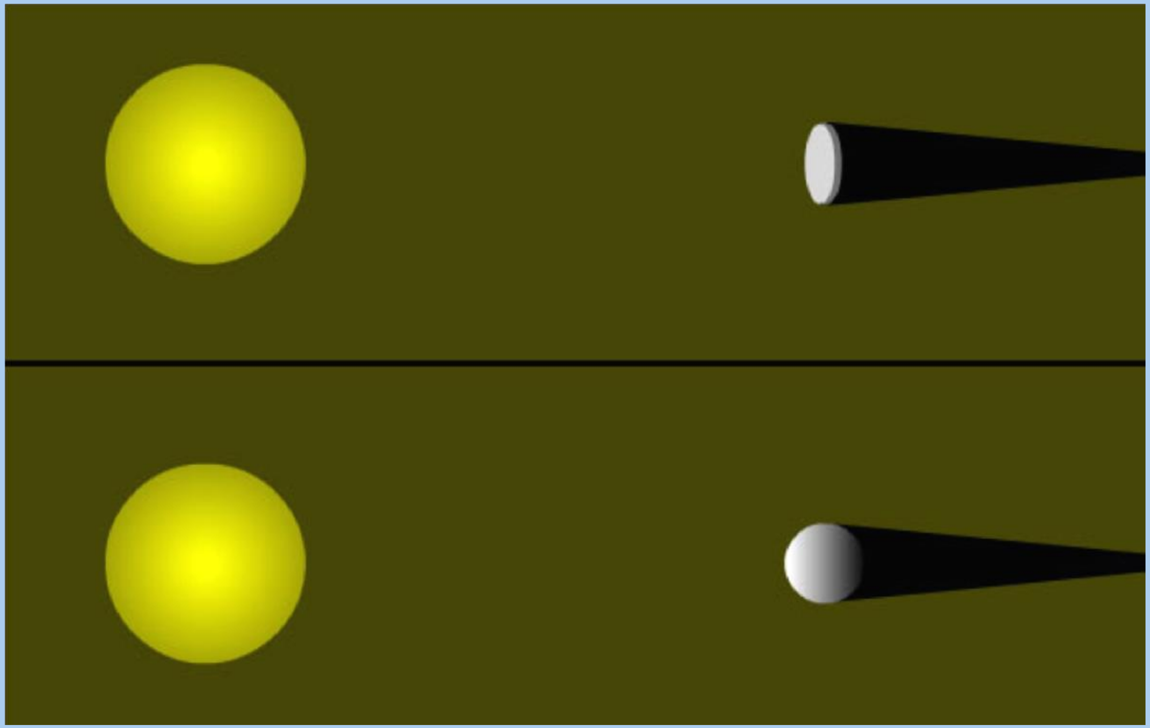
The obliquity and eccentricity of the Earth

Aphelion 152 098 232 km (first week of July, summer in northern hemisphere)

Perihelion 147 098 290 km (first week of January, winter in northern hemisphere)

The Earth is about 5 billion meters closer to the Sun at perihelion than at aphelion

$$\frac{A^2}{P^2} = 1.069$$



scienceblogs.com

Disk and sphere of same radius catch the same solar radiation

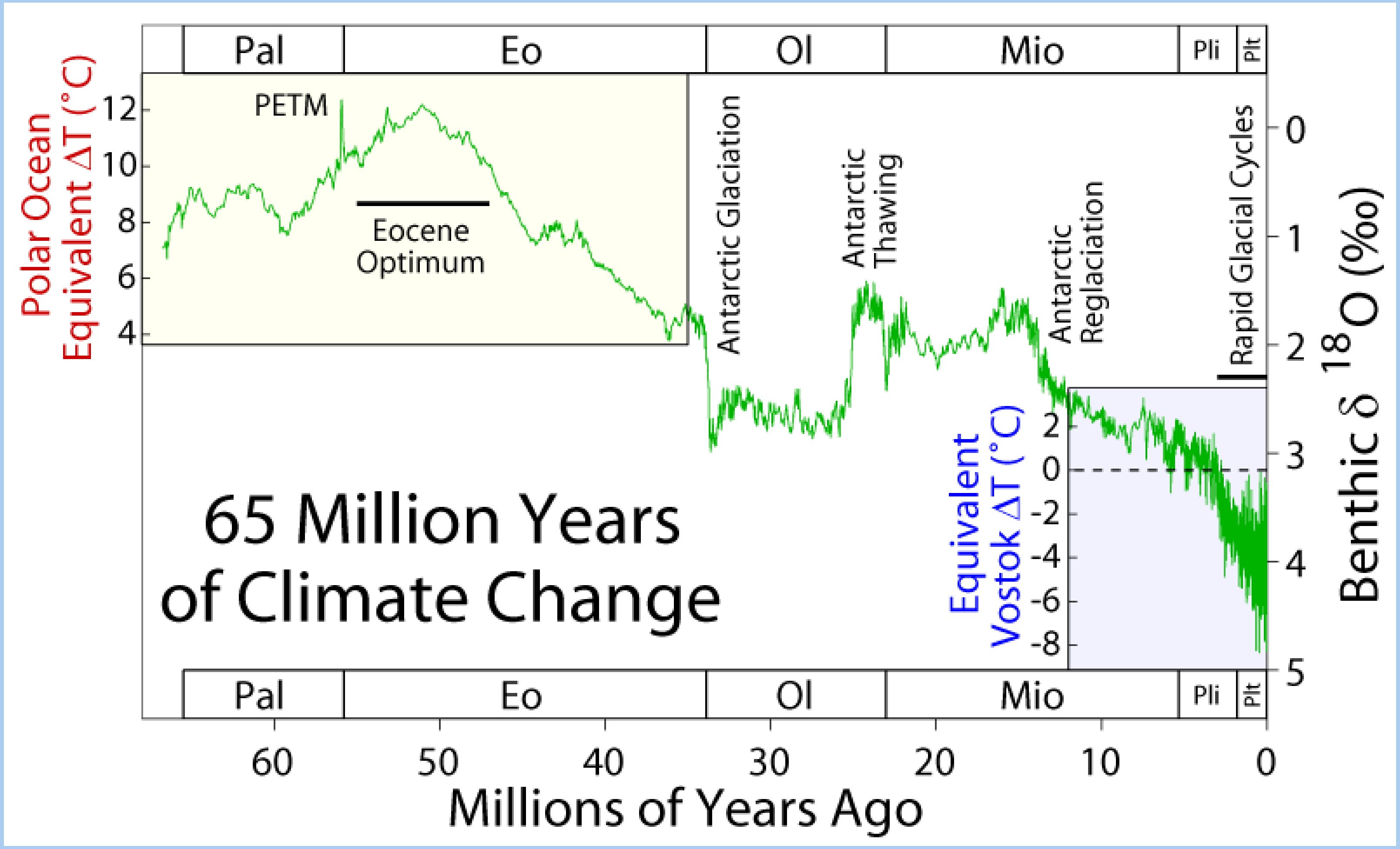
Area of disk = πr^2

Area of sphere = $4\pi r^2$

Ratio = 1:4

albedo: The fraction of power scattered back out into space from the total radiation incident on an astronomical body.

globalwarmingart.com/wiki/File:65_Myr_Climate_Change_Rev_png

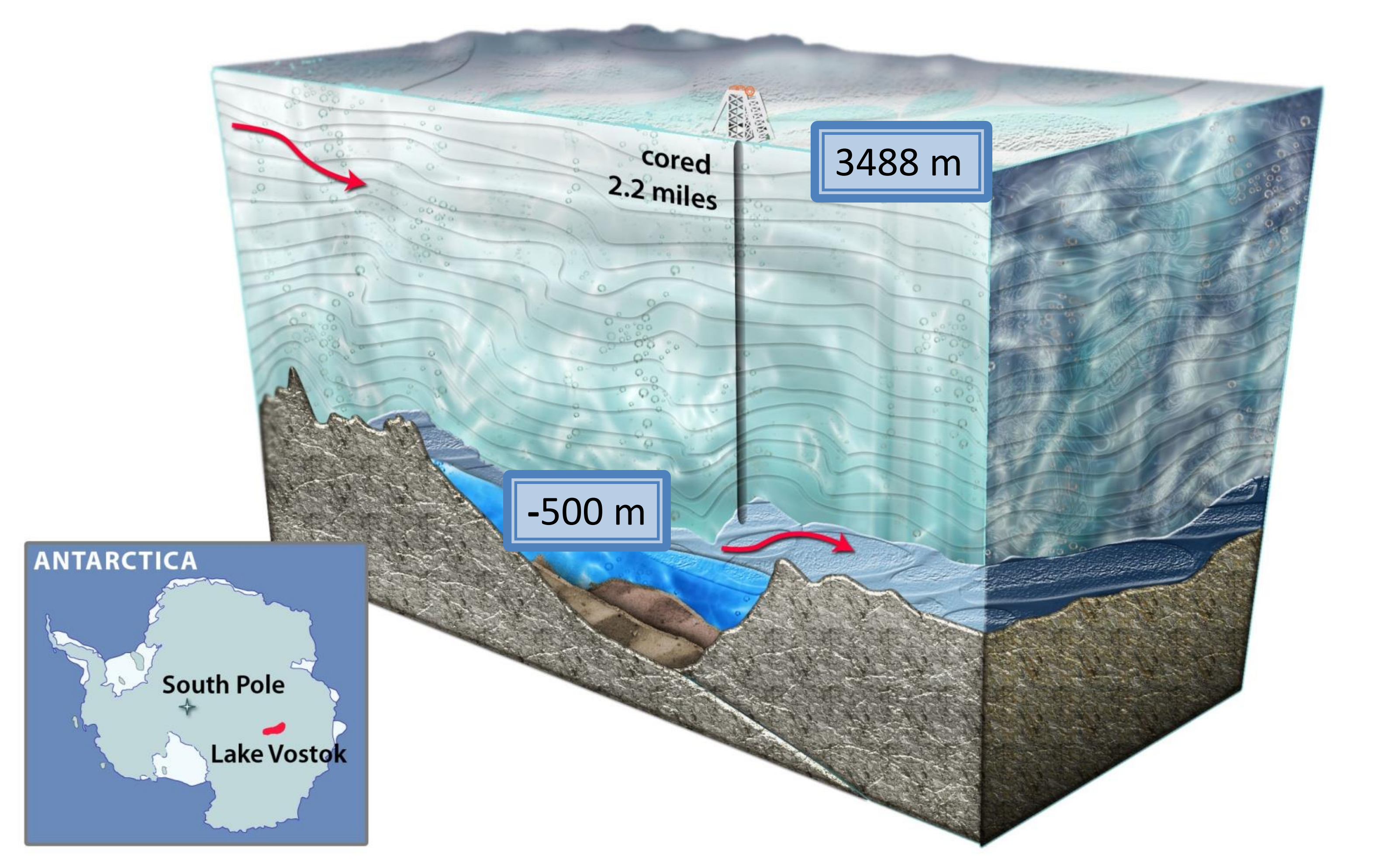


Cenozoic (new life) "Age of mammals" Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Holocene (not labeled)

Less than 1.5% of the age of the Earth

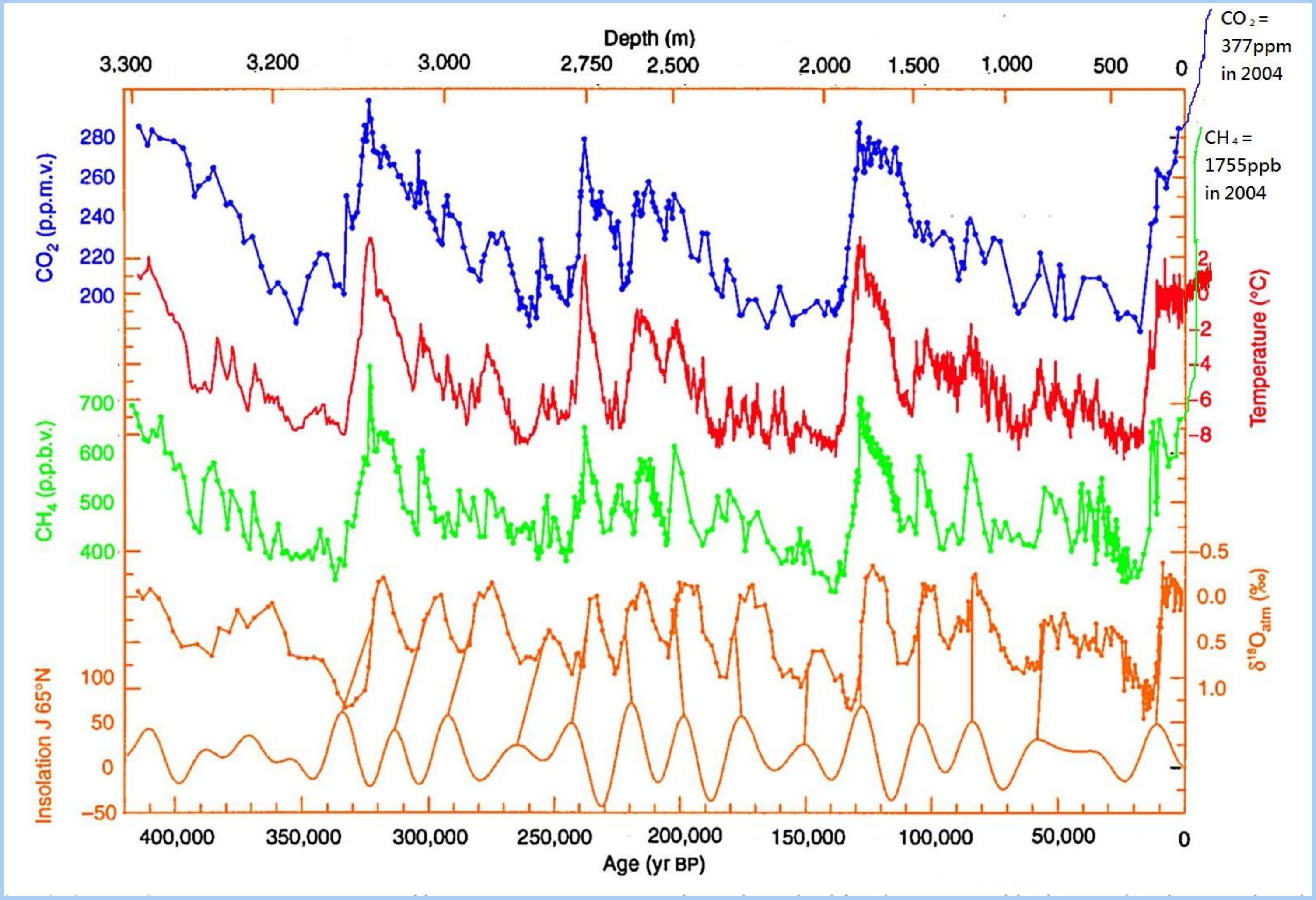
About 20% of the time since the sources of coal deposits lived (Carboniferous period)

ucmp.berkeley.edu/carboniferous/carboniferous.php



Wikimedia

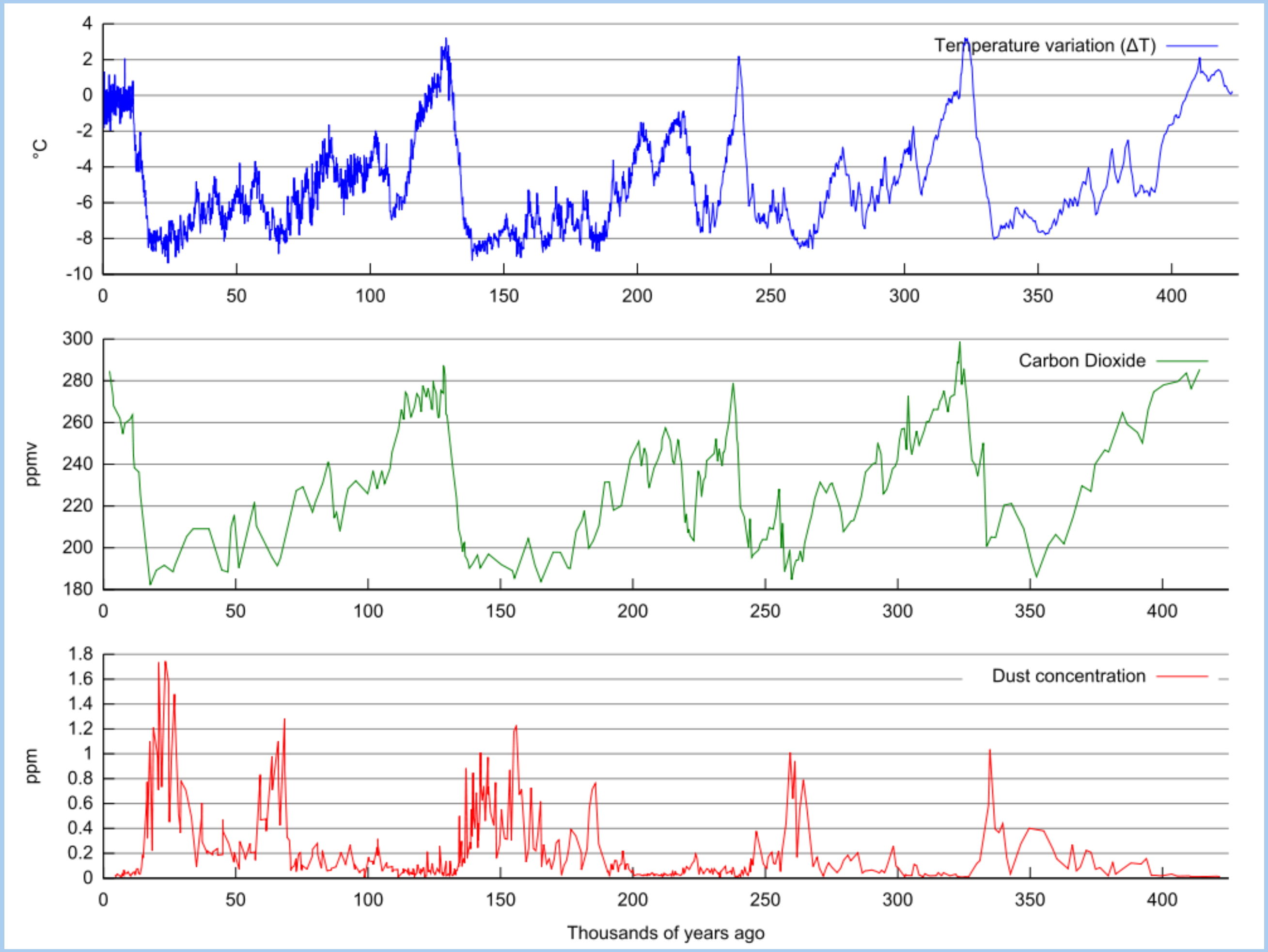
Lake Vostok ice core



derivative work: Alexchris Wikimedia

J. R. Petit, et al, "Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica" (1999)

nature.com/nature/journal/v399/n6735/fig_tab/399429a0_F3.html



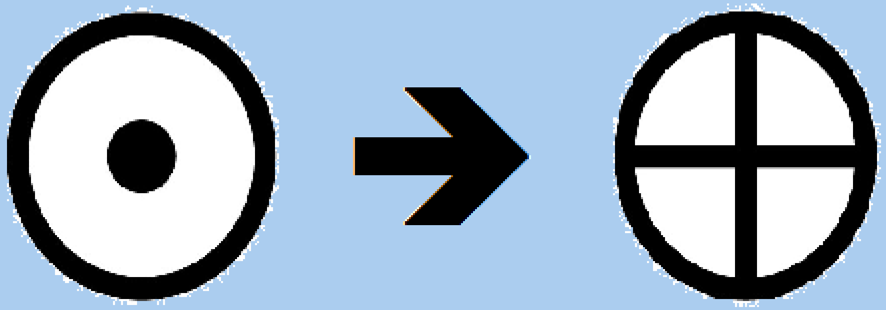
derivative work: Autopilot Wikimedia

J. R. Petit, et al, "Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica" (1999)

Quiz: Heat Transfer (Part One)

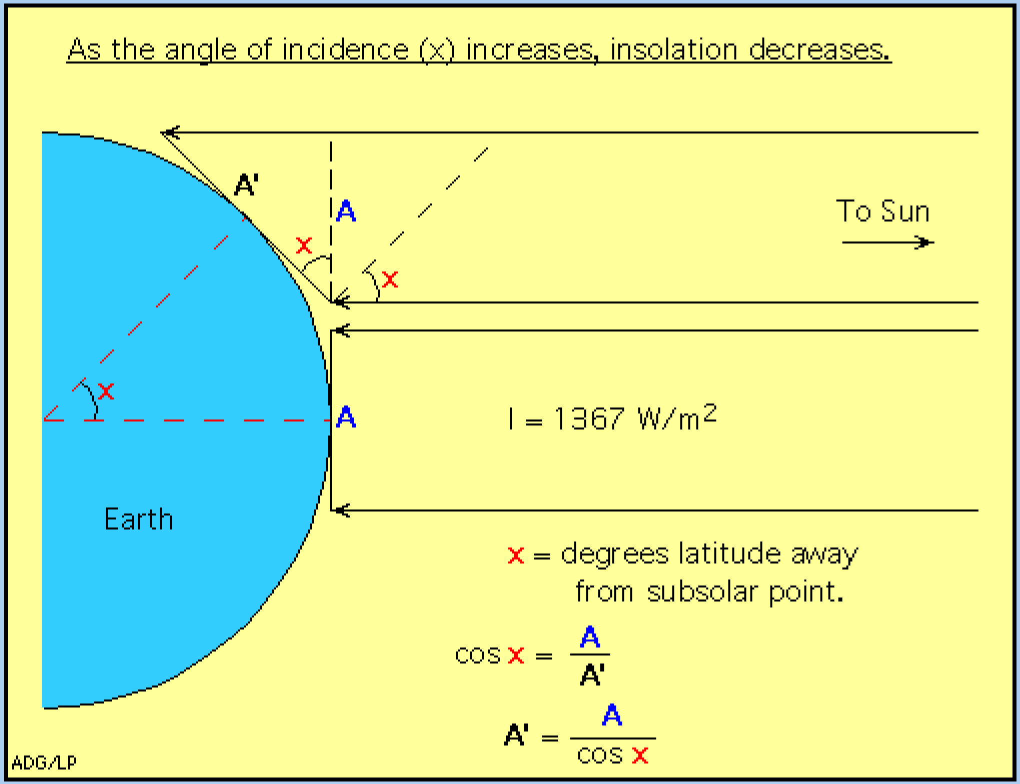
For **each of these three** mechanisms:

- **Conduction**
- **Convection**
- **Radiation**



What percentage is it of the total heat transfer

from the Sun to the Earth?



eesc.columbia.edu

Solar "constant," mean total solar irradiance, *TSI* = 1.36 x 10^6 ergs/cm^2 sec

Instantaneous insolation cycles annually; obliquity, eccentricity, changes cycle long term.

Quiz: Heat Transfer
(Part Two)

- **Conduction**
- **Convection**
- **Radiation**

Which one of these three mechanisms is **100%** of the total heat transfer

from the Earth to space?

The CO_2 problem in 6 easy steps

1. **There is a natural greenhouse effect**

Stefan-Boltzmann constant: $\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \text{ x } 10^{-8}\ Wm^{-2}K^{-4}$

Mean surface temperature, $\boldsymbol{T_s}$, $\cong$ **15**°C

produces upward surface flux of longwave radiation

$$\boldsymbol{G = \sigma T_s^4 \cong 390\frac{W}{m^2}}$$

Net solar radiation absorbed

$a = 0.306$

$$\boldsymbol{S = \frac{(1-a)TSI}{4} \cong 240\frac{W}{m^2}}$$

means 240 W/m^2 of longwave radiation is emitted

Atmosphere must absorb $\boldsymbol{150\ W/m^2}$ net

a number that would be zero without greenhouse gases

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/

Tidal power

$3.7\ TW$

$0.007\ W/m^2$

Geothermal power

$44.2\ TW$

$0.087\ W/m^2$

Wind power

$72\ TW$

$0.14\ W/m^2$

Solar power

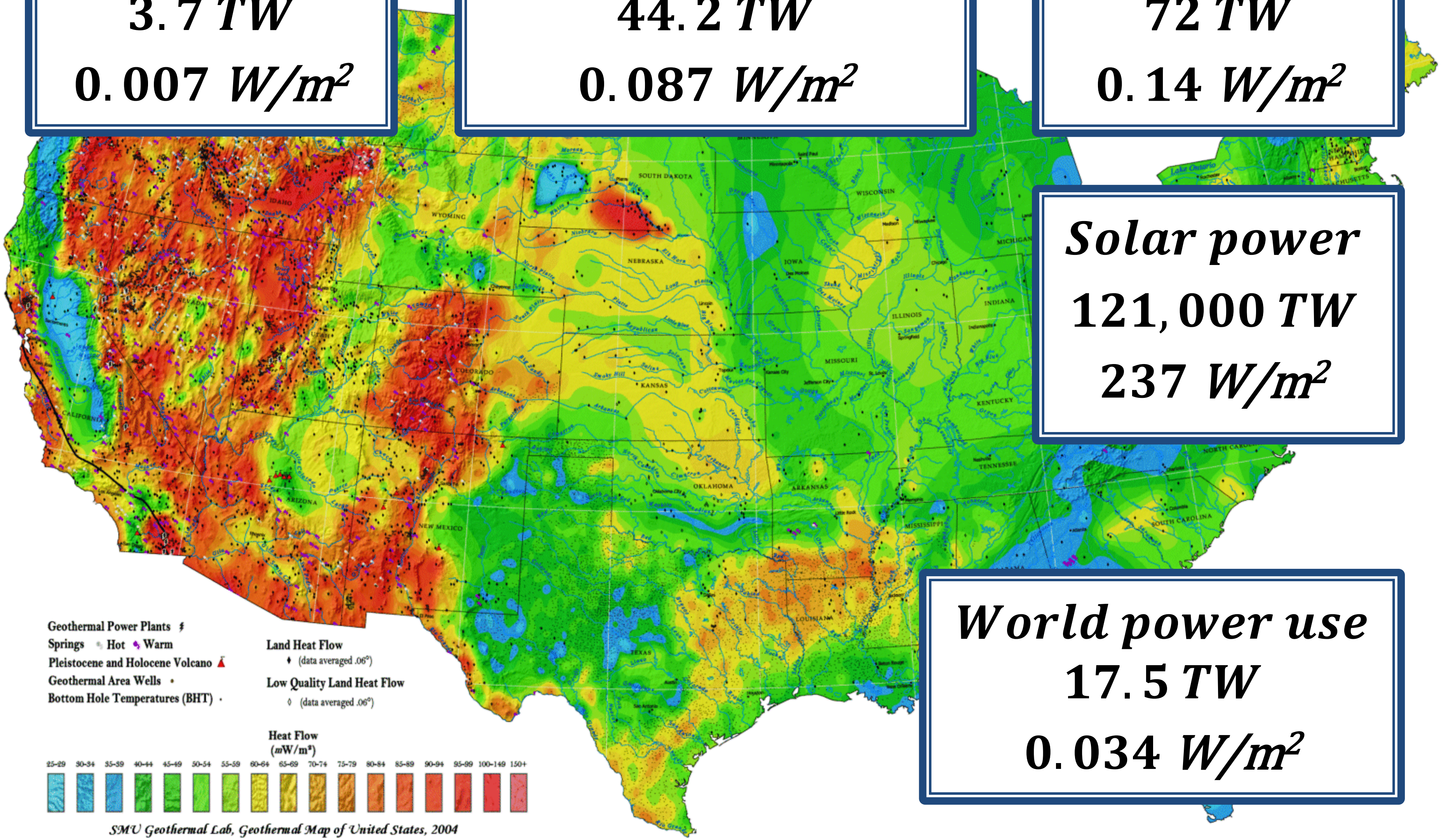
$121{,}000\ TW$

$237\ W/m^2$

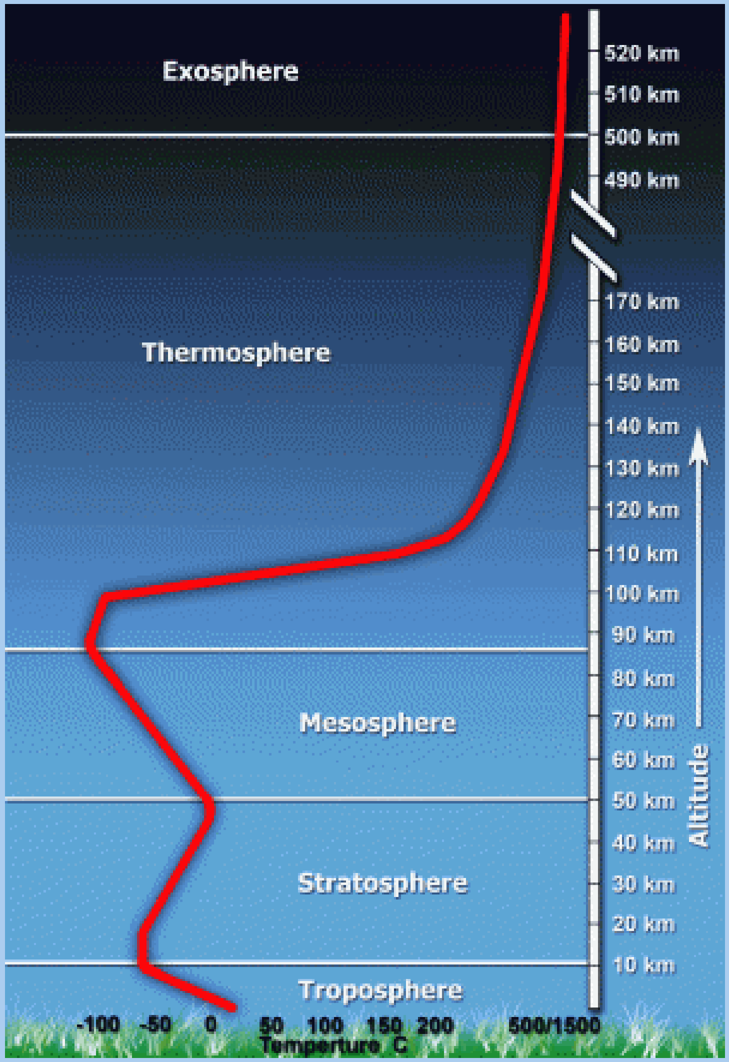
World power use

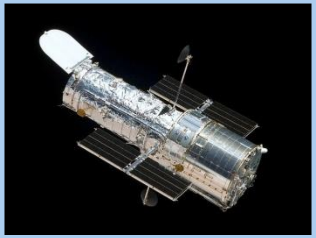
$17.5\ TW$

$0.034\ W/m^2$

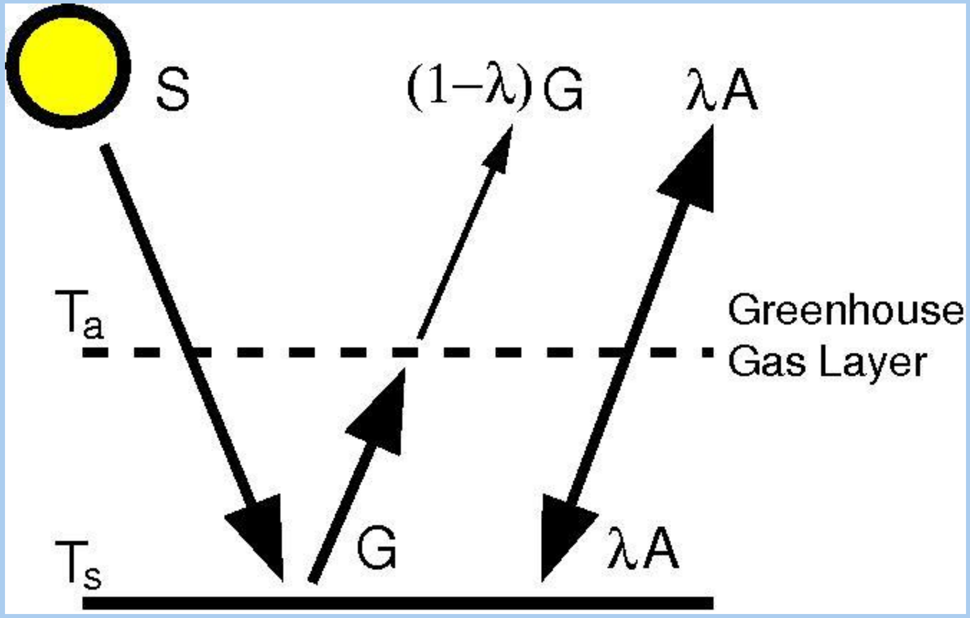


ces.fau.edu/nasa/module-2/atmosphere/earth.php





Layers in the Atmosphere



realclimate.org

$$S = (1 - a)TSI/4$$

$$G = \sigma T_s^4$$

$$\lambda A = \lambda \sigma T_a^4$$

λ = emissivity, effectively the strength of the greenhouse effect

Equations of equilibrium

Surface: $S + \lambda A = G$

Atmosphere: $\lambda G = 2\lambda A$

Planet: $S = \lambda A + (1 - \lambda)G$

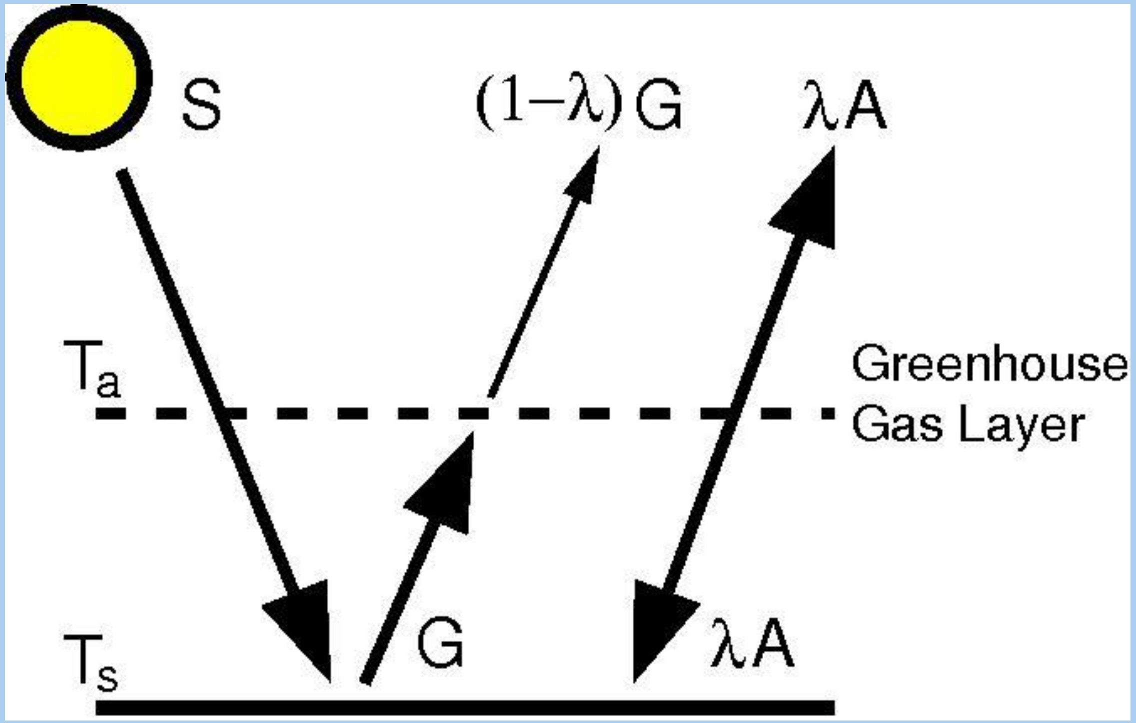
$$G = \sigma T_s^4$$

$$= \frac{S}{1 - 0.5\lambda}$$

$$\lambda = 0.769$$

$$T_s = 288°K$$

$$T_s = 15°C$$



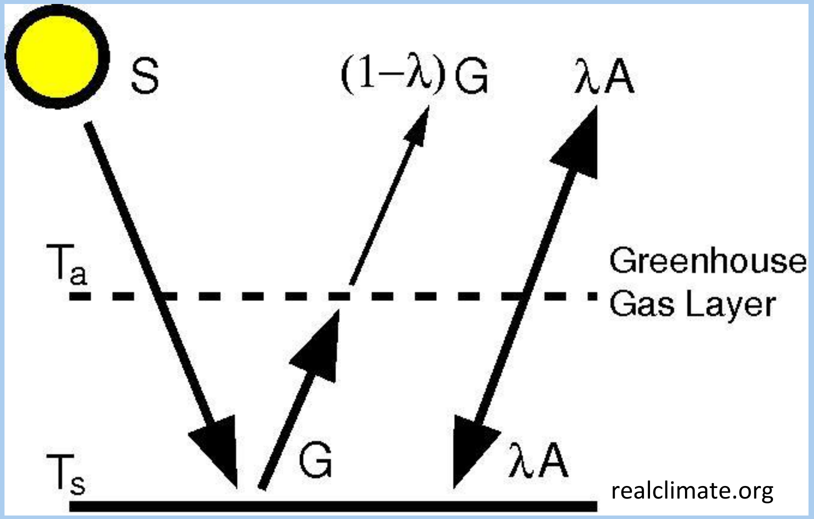
realclimate.org

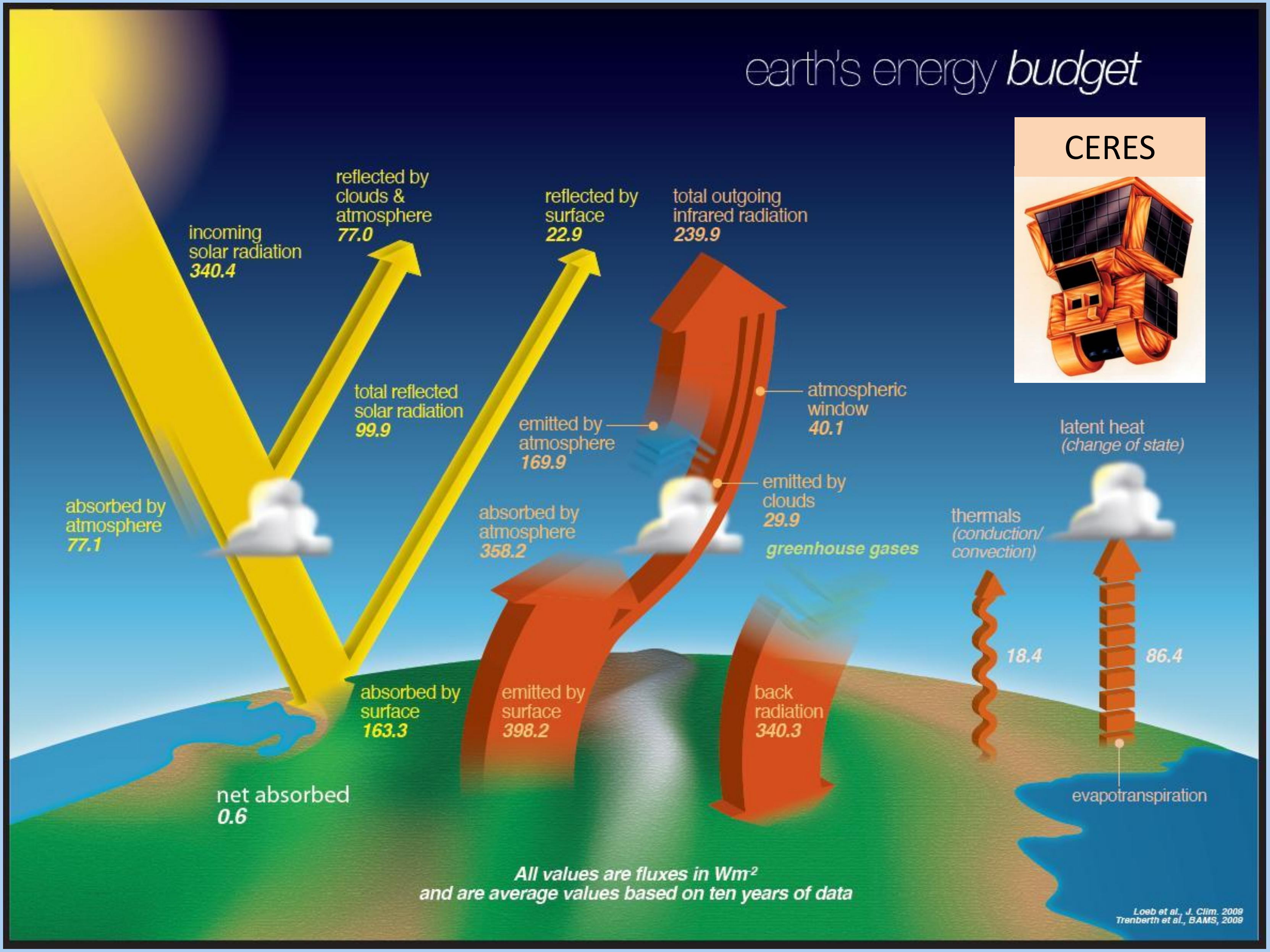
$$A = \sigma T_a^4 = \frac{S}{2 - \lambda}$$

$$T_a = 242°K$$

$$T_a = -31°C$$

λ	G	A	T_s	T_a
0	$240\ W/m^2$	-	$-18°C$	-
0.667	$360\ W/m^2$	$180\ W/m^2$	$9°C$	$-36°C$
0.769	$390\ W/m^2$	$195\ W/m^2$	$15°C$	$-31°C$
1	$480\ W/m^2$	$240\ W/m^2$	$30°C$	$-18°C$



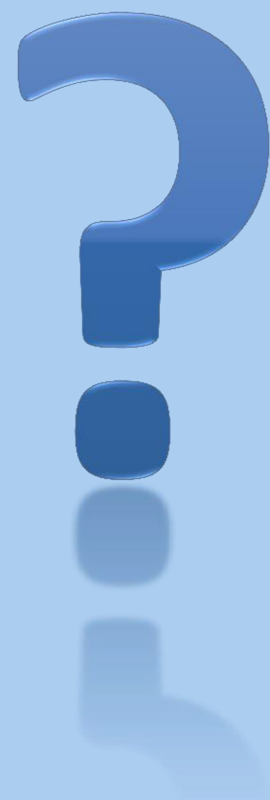


NASA

science-edu.larc.nasa.gov/energy_budget/

The CO_2 problem in 6 easy steps

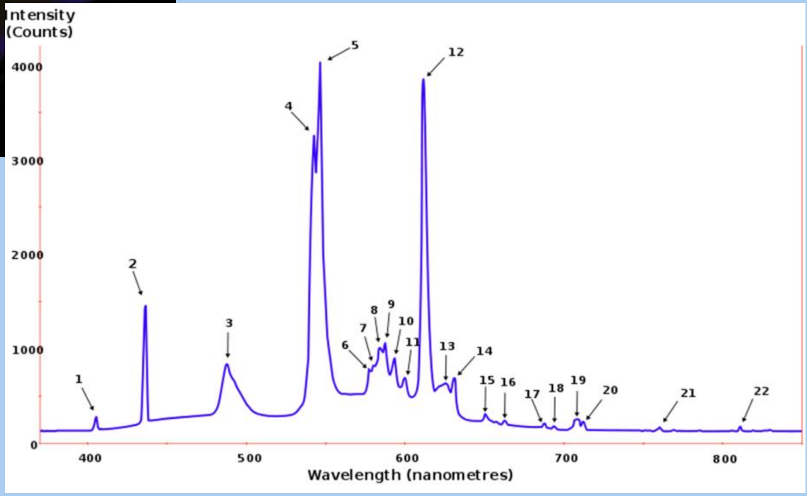
1. **There is a natural greenhouse effect**



The CO_2 problem in 6 easy steps

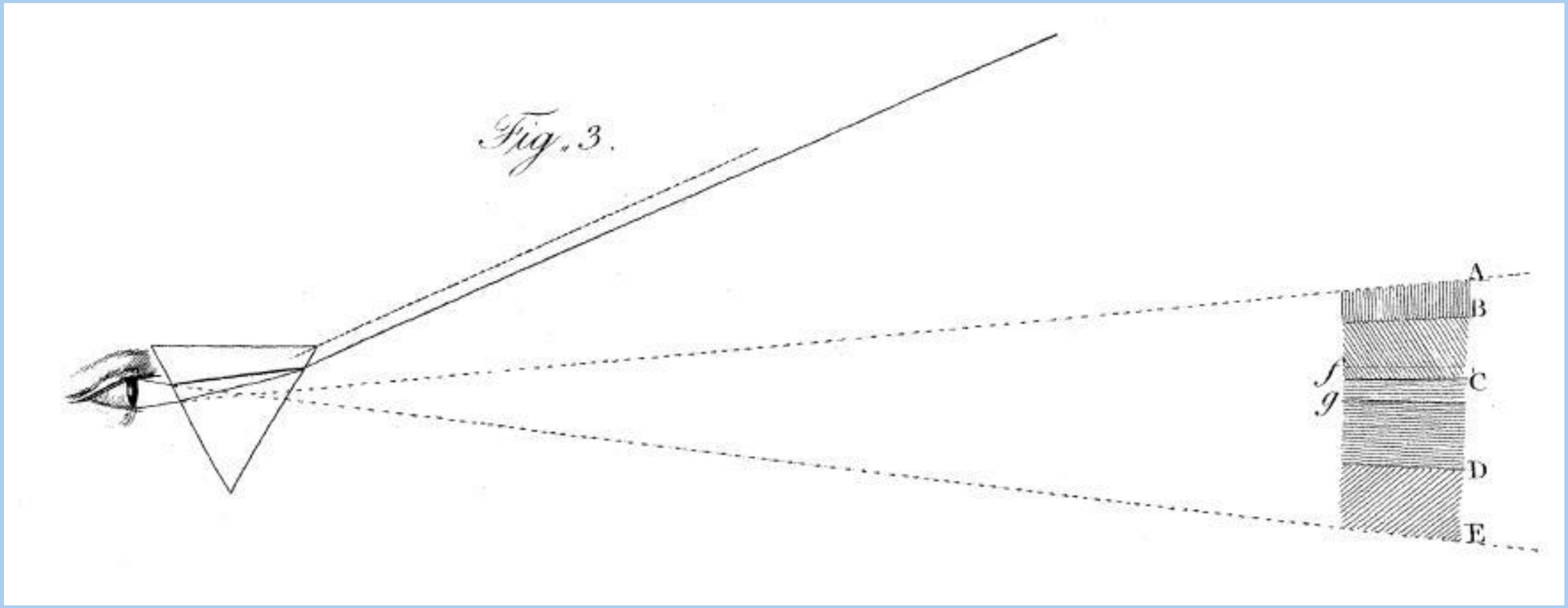
2. **Trace gases contribute to the natural greenhouse effect**

Wikipedia, Reguiieee



Wikipedia, Deglr6328

Fluorescent tube light reflected in a CD and fluorescent lighting spectrum



royalsocietypublishing.org

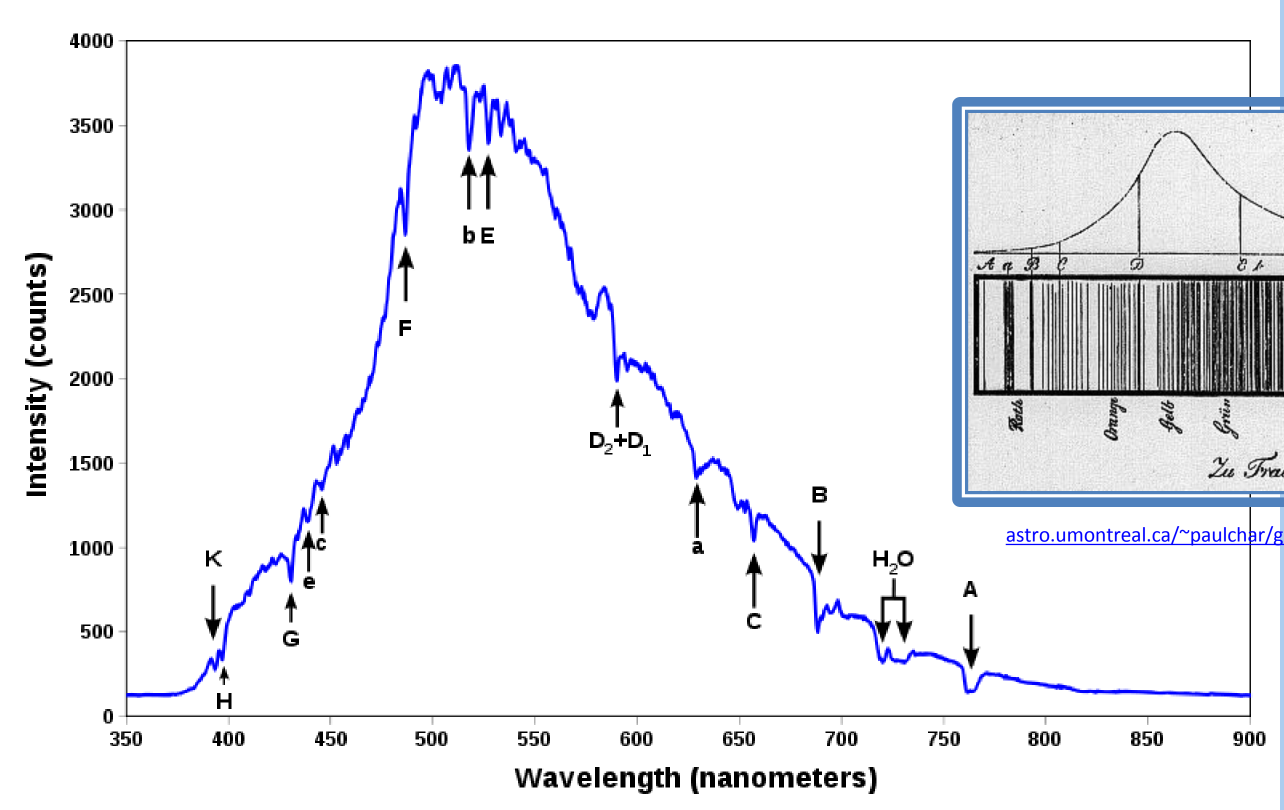
William Hyde Wollaston, A Method of Examining Refractive and Dispersive Powers, by Prismatic Reflection (1802)

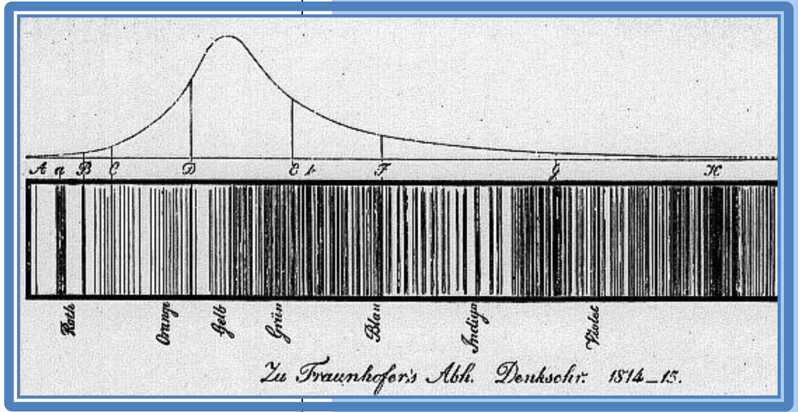
Day-light - dark room - crevice 1/20" - distance 10’ or 12’- through a prism of flint-glass, free from veins held near the eye - beam is separated into four colours only - red, yellowish green, blue, and violet; in the proportions in Fig. 3.

Other distinct dark lines, f and g, might be mistaken for the boundary of these colours. [bottom of page 378]

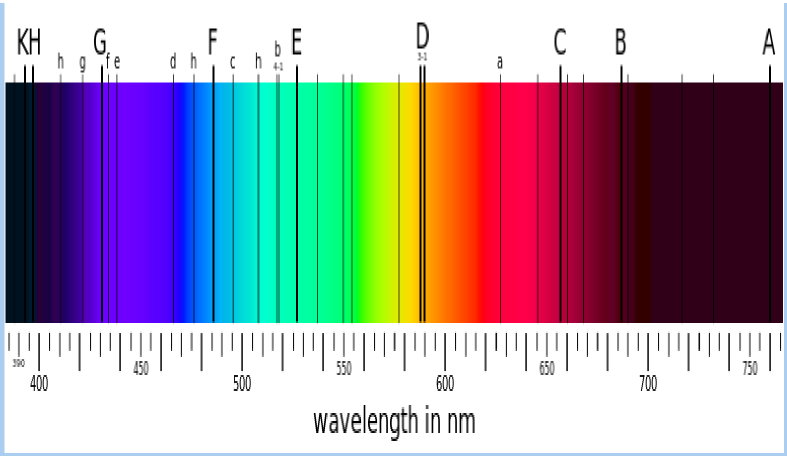
rstl.royalsocietypublishing.org/content/92/365.full.pdf

Fraunhofer lines (1814)

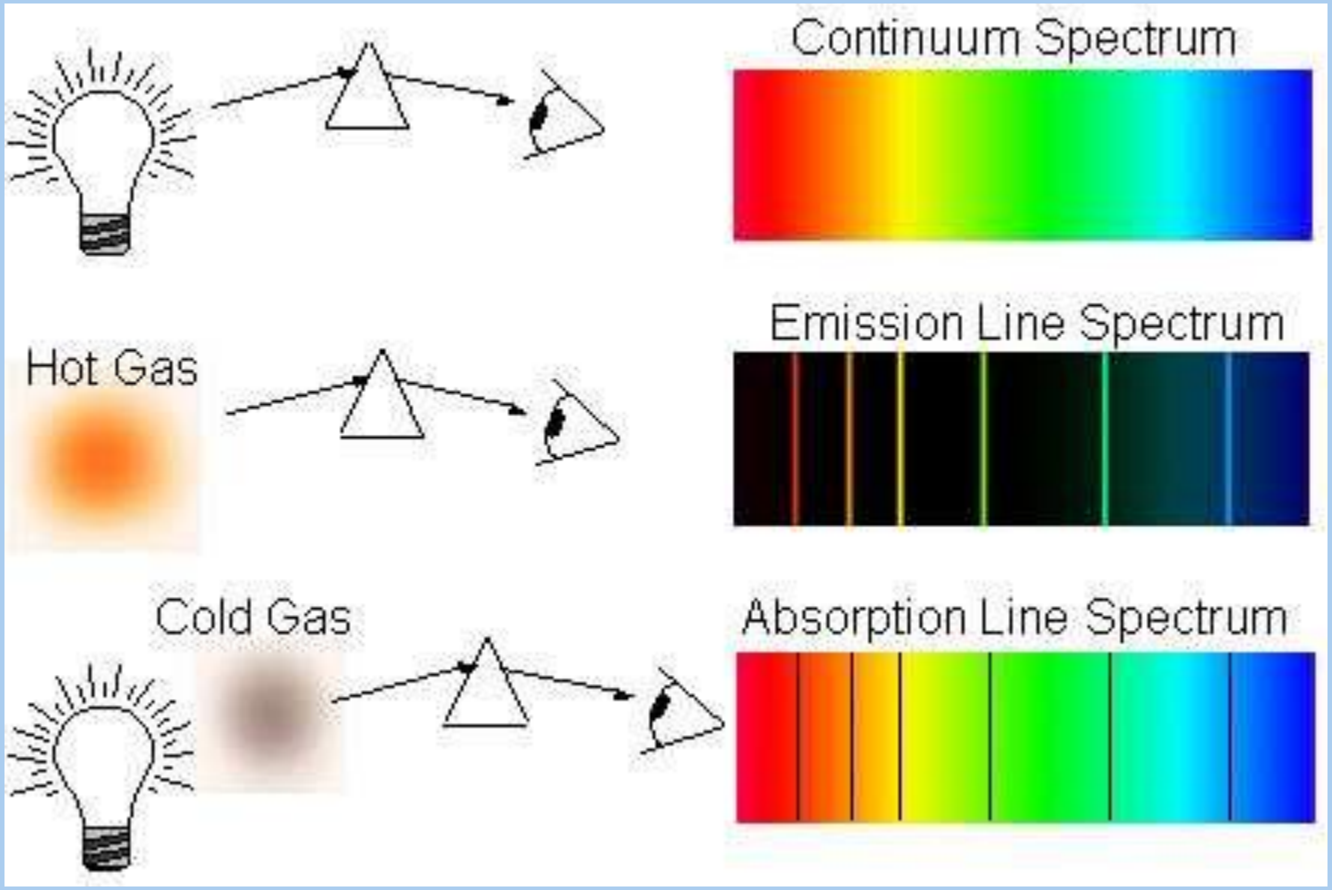


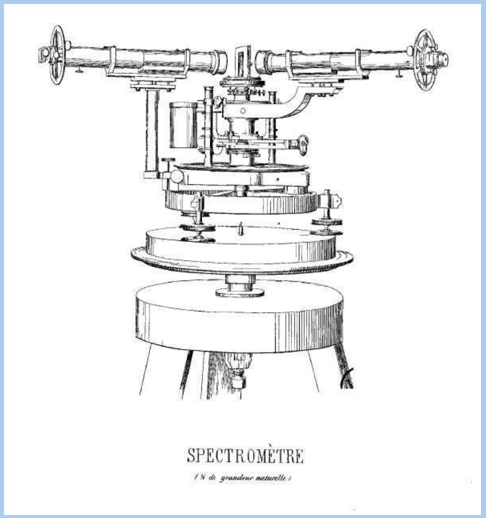


astro.umontreal.ca/~paulchar/grps/histoire/newsite/sp/great_moments_e.html



Wikipedia



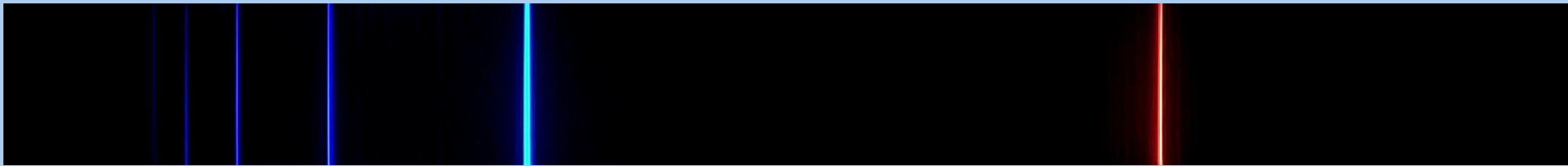


Ångström's spectrometer (1868)

iris.univ-lille1.fr/bitstream/handle/1908/1400/Q11406_1.pdf

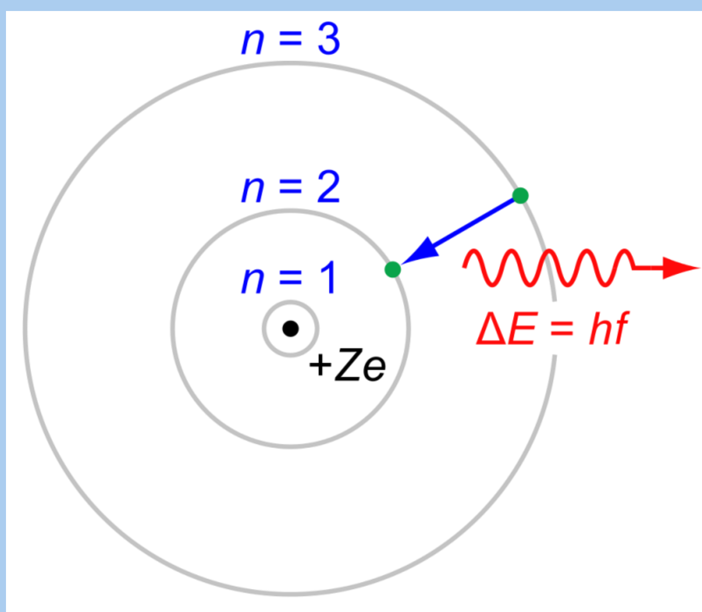
planetaryvision.blogspot.com/2013/01/the-fallacy-of-greenhouse-effect-4.html Planetary Vision

1849 - Jean Bernard Léon Foucault
1853 - Anders Jonas Ångström
Showed the emission and absorption lines matched for a given material



Wikipedia, Jan Homann

$$\lambda = \text{const.}\left(\frac{m^2}{m^2 - n^2}\right)$$



Wikipedia, JabberWok

1853 - Ångström discovered four visible lines of hydrogen

410, 434, 486, and 656 nm

The Balmer series

1885 - Johann Jacob Balmer discovered relationship between wavelengths; predicted others

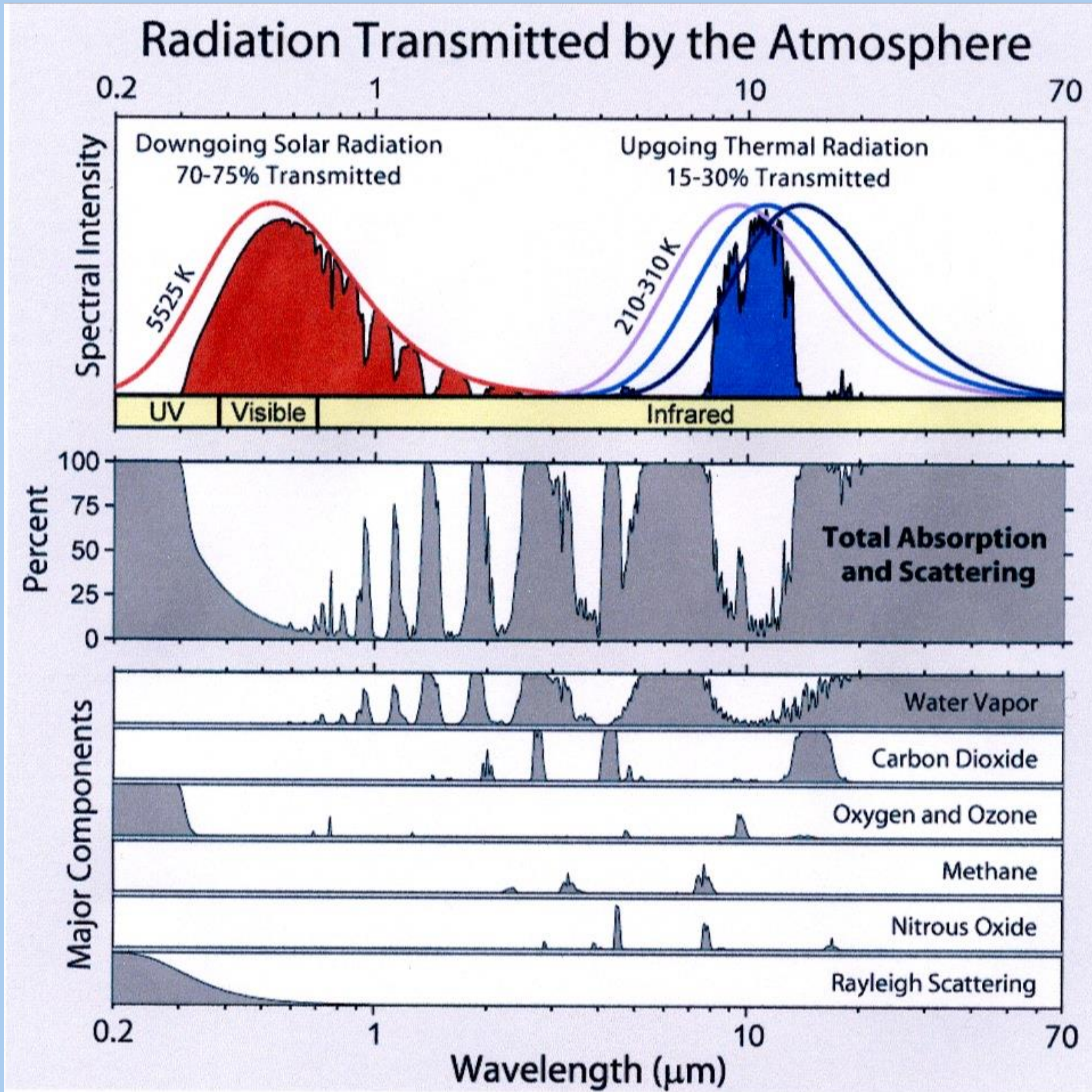
1913 - Niels Henrik David Bohr quantum theory of the atom

Designation	Element	Wavelength (nm)	Designation	Element	Wavelength (nm)
y	O_2	898.765	c	Fe	495.761
Z	O_2	822.696	F	Hβ	486.134
A	O_2	759.370	d	Fe	466.814
B	O_2	686.719	e	Fe	438.355
C	Hα	656.281	G'	H	434.047
a	O_2	627.661	G	Fe	430.790
D_1	Na	589.592	G	Ca	430.774
D_2	Na	588.995	h	Hδ	410.175
D_3 or d	He	587.5618	H	Ca^+	396.847
e	Hg	546.073	K	Ca^+	393.368
E_2	Fe	527.039	L	Fe	382.044
b_1	Mg	518.362	N	Fe	358.121
b_2	Mg	517.270	P	Ti^+	336.112
b_3	Fe	516.891	T	Fe	302.108
b_4	Mg	516.733	t	Ni	299.444

Wikipedia

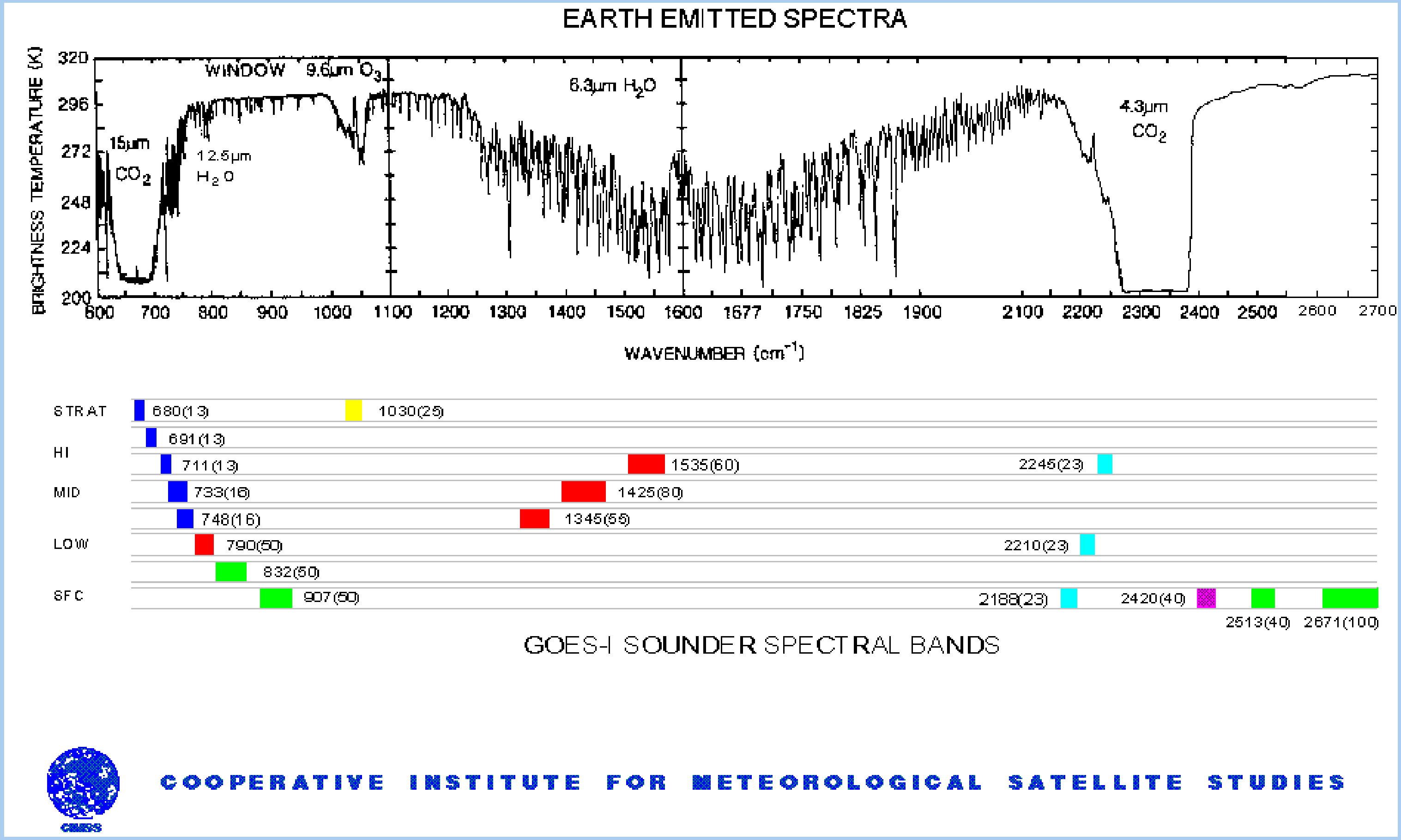
The major Fraunhofer lines, and the elements with which they are associated

From: www.barrettbellamyclimate.com/page15.htm



"… using line-by-line radiative transfer codes … removing the effect of CO_2 reduces the net LW absorbed by ~14%, or around 30 W/m^2."

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/



realclimate.org

Geostationary Operational Environmental Satellite - 1

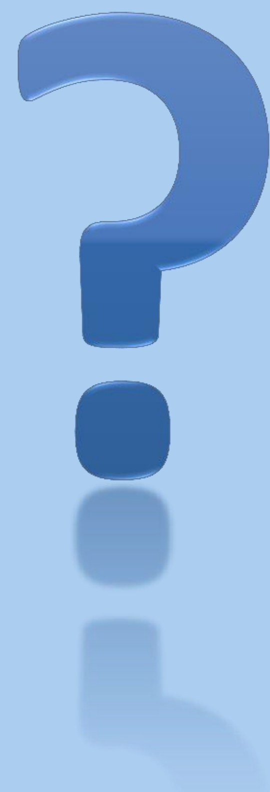
Launched: October 16, 1975 **Deactivated: March 7, 1985**

cimss.ssec.wisc.edu/goes/comet/radiative_transfer.html

goes.gsfc.nasa.gov/text/history/goes/goes.html

The CO_2 problem in 6 easy steps

2. **Trace gases contribute to the natural greenhouse effect**

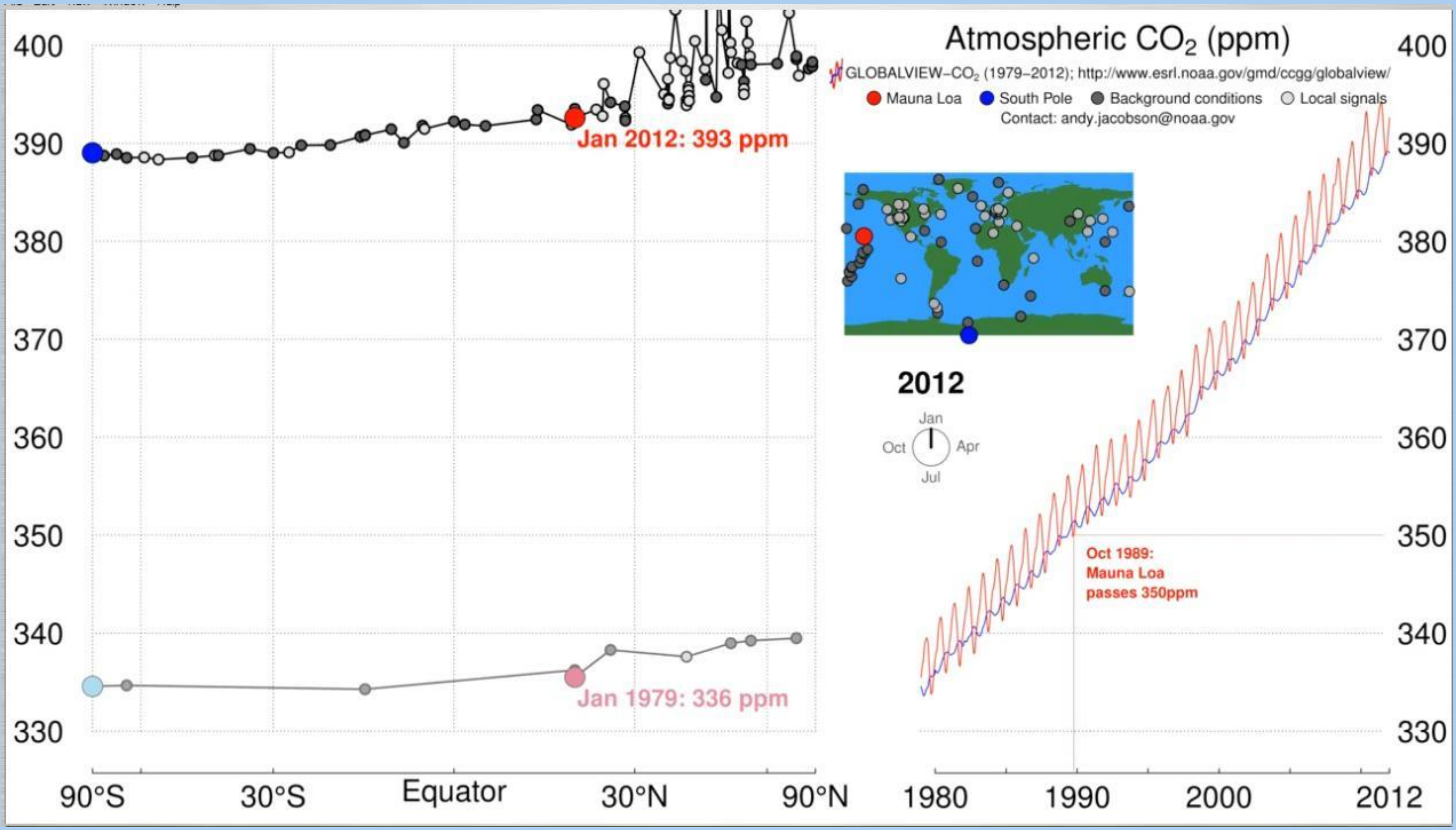


The CO_2 problem in 6 easy steps

3. **The trace greenhouse gases have increased markedly due to human emissions**

**“CO_2 is up more than 30%,
CH_4 has more than doubled,
N_2O is up 15%,
tropospheric O_3 has also increased.
New compounds such as halocarbons (CFCs, HFCs) did not exist in the pre-industrial atmosphere.”**

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/



NOAA

youtube.com/watch?v=vA7tfz3k_9A

Youtube movie of a time history of atmospheric carbon dioxide from 800,000 years ago until January, 2012, Earth System Research Laboratory, NOAA

http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html

The CO_2 problem in 6 easy steps

3. **The trace greenhouse gases have increased markedly due to human emissions**

The CO_2 problem in 6 easy steps

4. **Radiative forcing is a useful diagnostic and can easily be calculated**

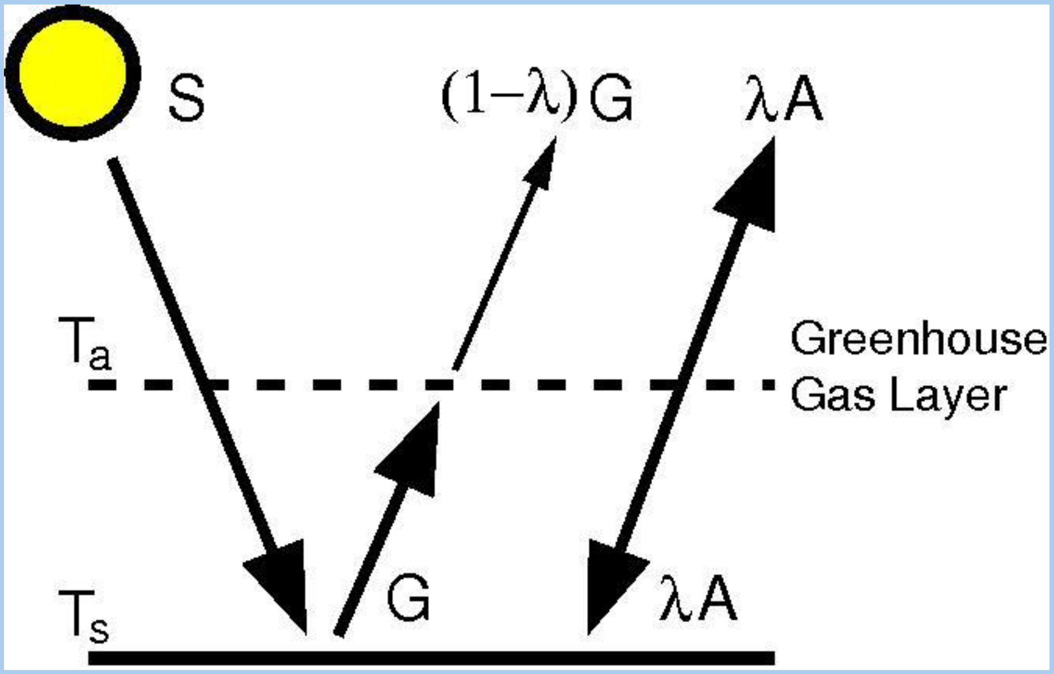
If sun became stronger by 2%

TOA radiation balance would change by

$$\mathbf{0.02 \times 1366 \times 0.7/4 = 4.8\, W/m^2}$$

(taking albedo and geometry into account)

This is the **radiative forcing** (RF). Changes in greenhouse absorbers, albedo have analogous impacts



$$\boldsymbol{S = \frac{(1-a)TSI}{4}}$$

$$\boldsymbol{\cong 245\, W/m^2}$$

$$\boldsymbol{T_s = \sqrt[4]{\frac{(1-a)TSI}{4\sigma(1-0.5\lambda)}}}$$

$$\boldsymbol{T_s \cong 289.5°K = 16.5°C}$$

$a = 0.306$ $TSI = 1366\, W/m^2$ $\sigma = 5.67 \times 10^{-8}\, Wm^{-2}K^{-4}$ $\lambda = 0.769$

Line-by-line codes accounting for atmospheric profiles of temperature, water vapor, and aerosols.

Simplified fits to the data, such as for CO_2

$$\boldsymbol{RF = 5.35\, ln(\frac{CO_2}{CO_{2\,orig}})\, W/m^2}$$

Logarithmic because some particular lines are already saturated.

Forcings for lower concentration gases (such as CFCs) are linear in concentration.

RF for a doubling of CO_2 is likely $\boldsymbol{3.7 \pm 0.4\, \frac{W}{m^2}}$

Same order of magnitude as 2% increase of solar forcing

Total forcing from trace greenhouse gases mentioned in Step 3, is currently about $\mathbf{2.5}\ \boldsymbol{W/m^2}$

Net forcing (including cooling impacts of aerosols and natural changes) is $\mathbf{1.6 \pm 1.0}\ \boldsymbol{W/m^2}$ since pre-industrial.

- uncertainty mostly related to aerosol effects.

Current forcings growth dominated by increasing CO_2, with potentially a small role for

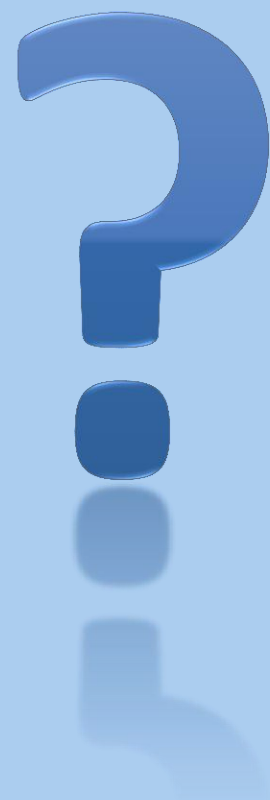
- decreases in reflective aerosols (sulphates, particularly in the US and EU)
- increases in absorbing aerosols (like soot, particularly from India and China and from biomass burning)

Step 3 - “CO_2 is up more than 30%, CH_4 has more than doubled, N_2O is up 15%, tropospheric O_3 has also increased. New compounds such as halocarbons (CFCs, HFCs) did not exist in the pre-industrial atmosphere.”

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/

The CO_2 problem in 6 easy steps

4. **Radiative forcing is a useful diagnostic and can easily be calculated**



The CO_2 problem in 6 easy steps

5. **Climate sensitivity is around 3 C° for a doubling of CO_2**

Climate sensitivity is response of global mean temperature to forcing, $\frac{C^\circ}{W/m^2}$

- **after** ‘fast feedbacks’ have occurred (atmospheric temperatures, clouds, water vapor, winds, snow, sea ice etc.)
- **before** ‘slow’ feedbacks have started (ice sheets, vegetation, carbon cycle etc.)

Sensitivity can be assessed from any particular period in the past where

- **changes in forcing** are known
- corresponding equilibrium **temperature change** can be estimated

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/

Last glacial period had large forcing, **~7 W/m^2**

from ice sheets, greenhouse gases, dust and vegetation

Large temperature response, **~5 ºC**

implying a sensitivity of about **3 ºC** with error

$$3.7\ W/m^2 \times 5\ ºC / 7\ W/m^2 = 2.6\ ºC$$

Provided link to 2006 estimate of response to volcanoes, the last millennium, remote sensing etc. which was also **3 ºC**.

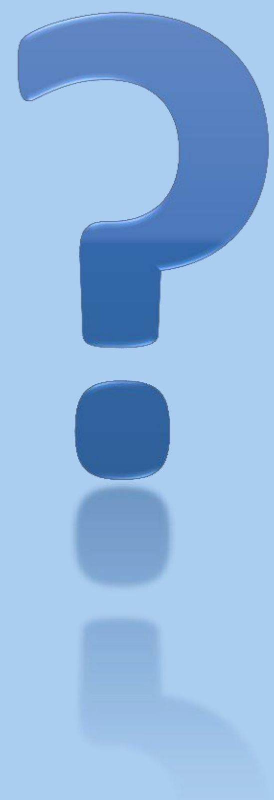
"Converting the estimate for doubled CO_2 to a more useful factor gives **~0.75 ºC/(W/m^2)**"

$$3\ ºC / 3.7\ W/m^2 = 0.81\ ºC/(W/m^2)$$

$$5\ ºC / 7\ W/m^2 = 0.71\ ºC/(W/m^2)$$

The CO_2 problem in 6 easy steps

5. **Climate sensitivity is around 3 C° for a doubling of CO_2**



The CO_2 problem in 6 easy steps

6. **Radiative forcing x climate sensitivity is a significant number**

Current forcings; **1.6 W/m^2 x 0.75 ºC/(W/m^2) = 1.2 ºC** at equilibrium. Oceans take time to warm up, ait is only up **0.7ºC** Remaining **0.5 ºC** ‘in the pipeline’.

Also estimated using changes in ocean heat content over last decade (about equal to radiative imbalance) of **~0.7 W/m^2**, implying that this ‘unrealised’ forcing will lead to another

$$0.7 \times 0.75\ ºC/(W/m^2) \cong 0.5\ ºC$$

Additional forcings in business-as-usual scenarios range roughly from **3 to 7 W/m^2**

Additional warming at equilibrium would be **2 to 5 ºC**.

realclimate.org/index.php/archives/2007/08/the-co2-problem-in-6-easy-steps/

The CO_2 problem in 6 easy steps

1. There is a natural greenhouse effect
2. Trace gases contribute to the natural greenhouse effect
3. The trace greenhouse gases have increased markedly due to human emissions
4. Radiative forcing is a useful diagnostic and can easily be calculated
5. Climate sensitivity is around 3 C° for a doubling of CO_2
6. Radiative forcing x climate sensitivity is a significant number