CLIMATE FORENSICS

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Albright College
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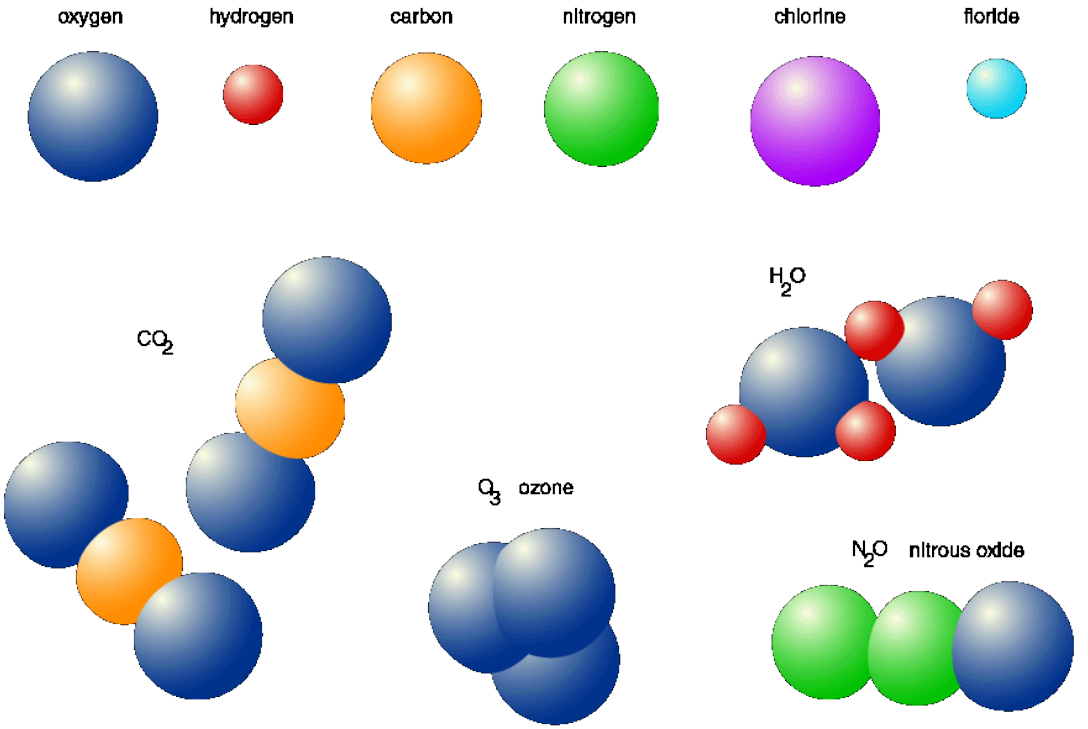
HS-ESS2-4. Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate. [Clarification Statement: Examples of the causes of climate change differ by timescale, over 1-10 years: large volcanic eruption, ocean circulation; 10-100s of years: changes in human activity, ocean circulation, solar output; 10-100s of thousands of years: changes to Earth's orbit and the orientation of its axis; and 10-100s of millions of years: long-term changes in atmospheric composition.] [*Assessment Boundary: Assessment of the results of changes in climate is limited to changes in surface temperatures, precipitation patterns, glacial ice volumes, sea levels, and biosphere distribution.*]

HS-ESS3-5 Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems. [Clarification Statement: Examples of evidence, for both data and climate model outputs, are for climate changes (such as precipitation and temperature) and their associated impacts (such as on sea level, glacial ice volumes, or atmosphere and ocean composition).] [*Assessment Boundary: Assessment is limited to one example of a climate change and its associated impacts.*]

HS-ESS3-6 Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity. [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] [*Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.*]

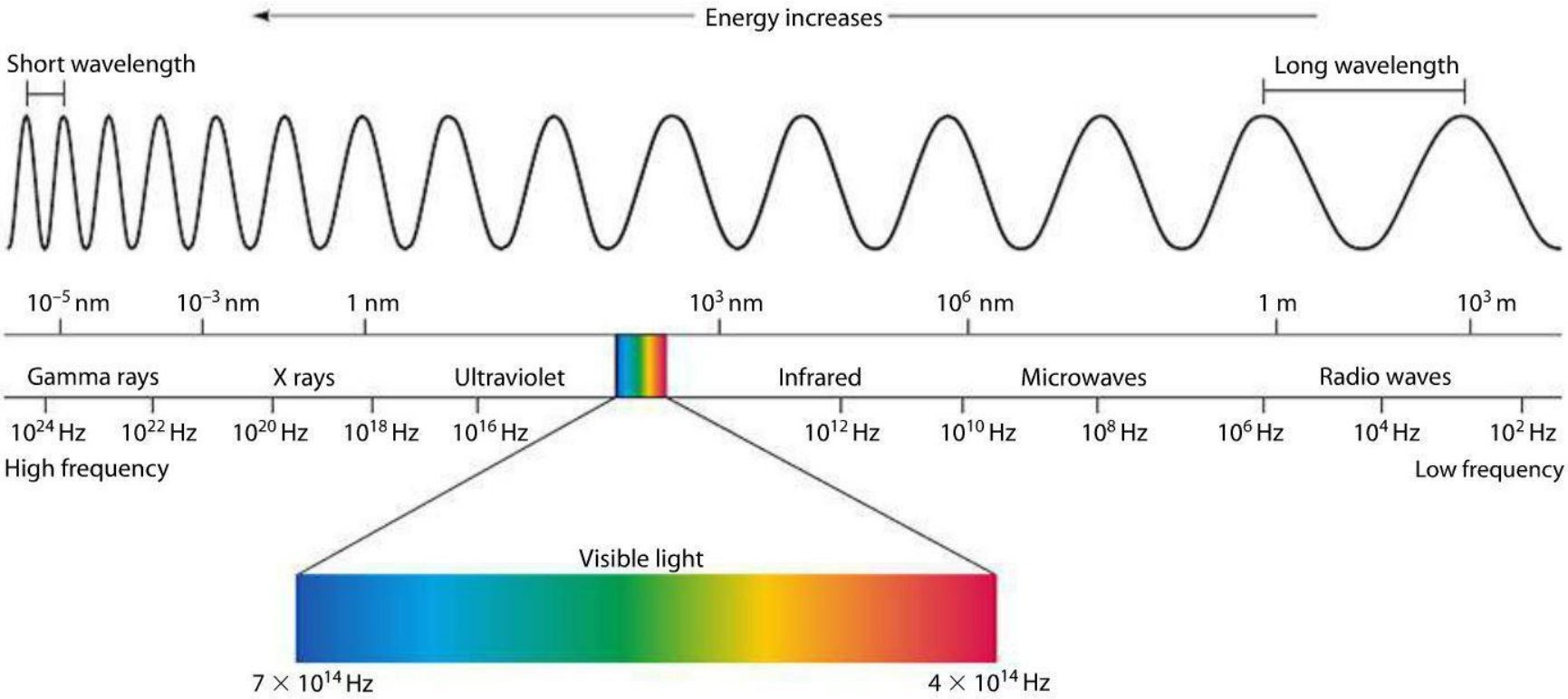
http://bakerstreet.wikia.com/wiki/Sherlock_Original_Television_Soundtrack

An atmospheric whodunit

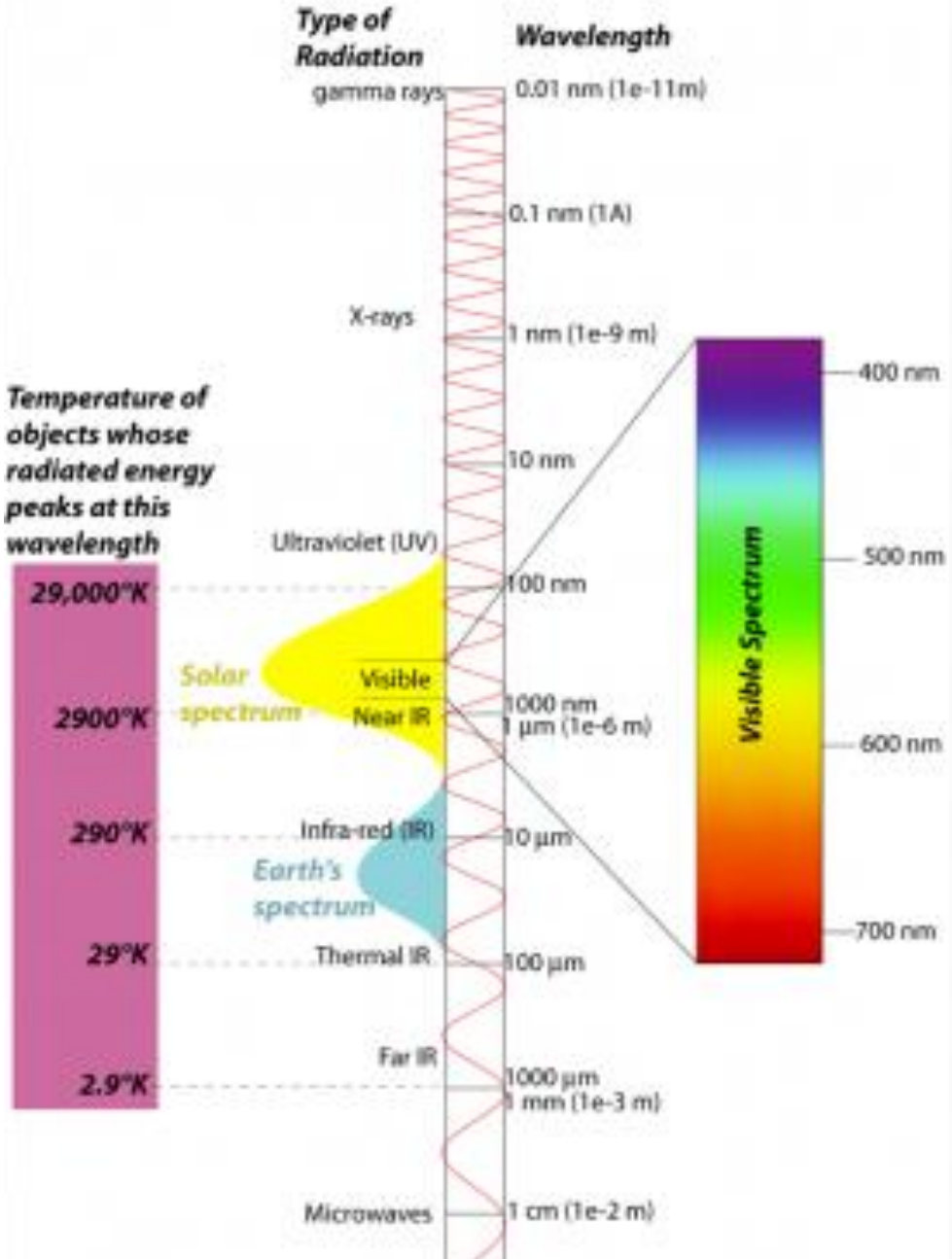


'It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.'
Sherlock Holmes
-A Scandal in Bohemia

WATSON, LOOK UP AT THE SKY AND TELL ME WHAT YOU SEE.

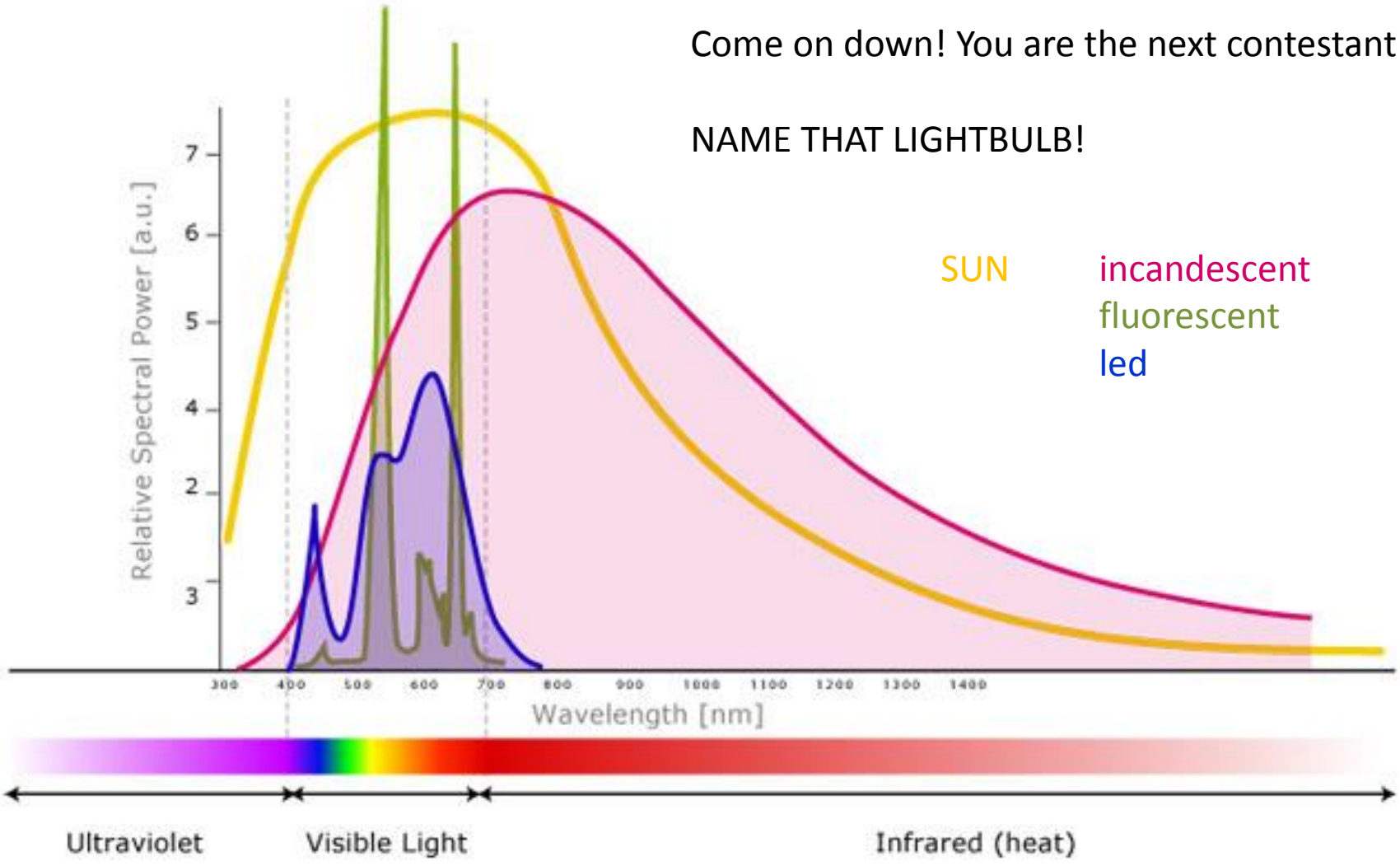


The Electromagnetic Spectrum



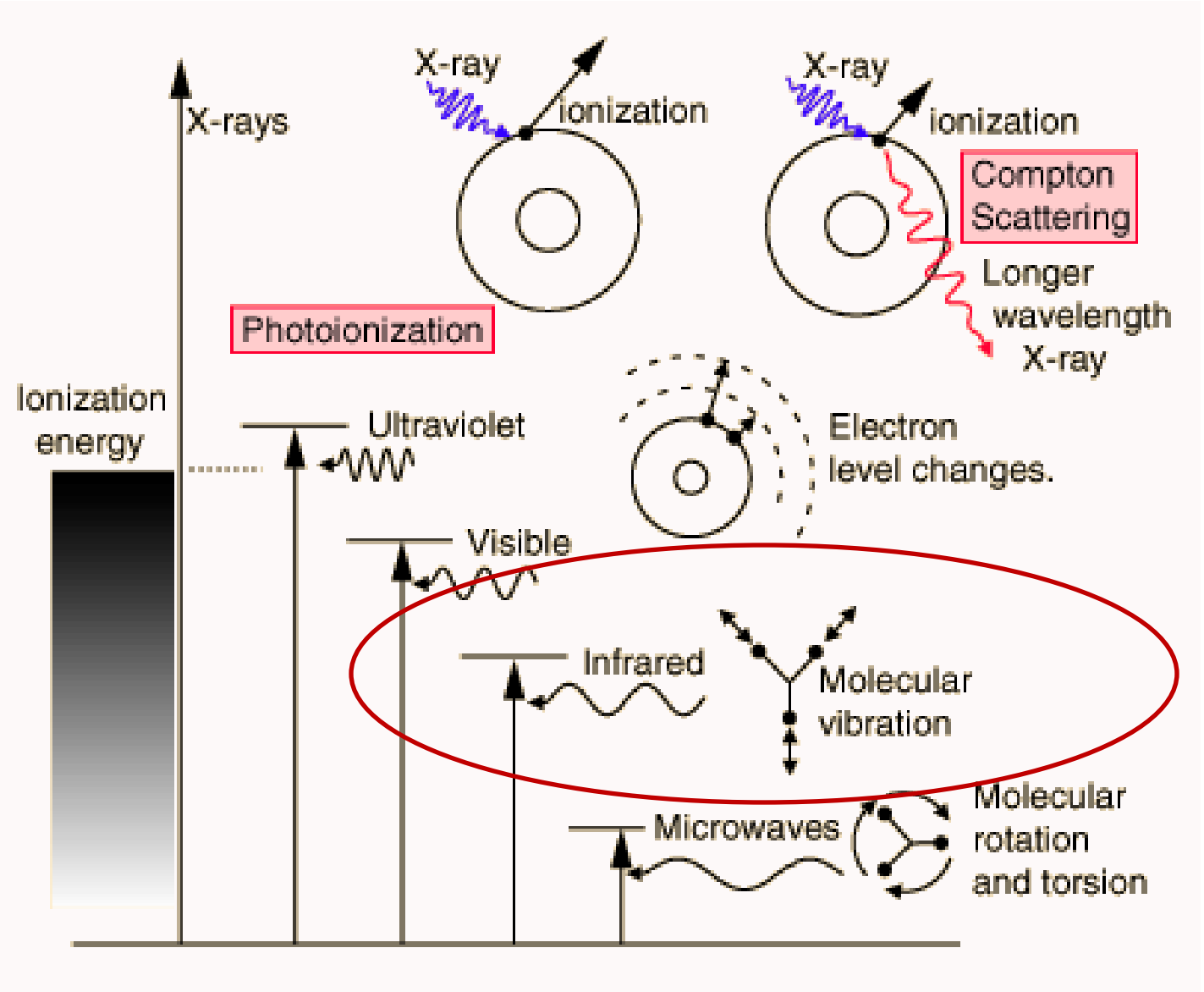
Come on down! You are the next contestant on

NAME THAT LIGHTBULB!



We hear that fluorescents were more efficient than incandescents, and that leds are more efficient than fluorescents. But do we know why?

The interaction of radiation with matter



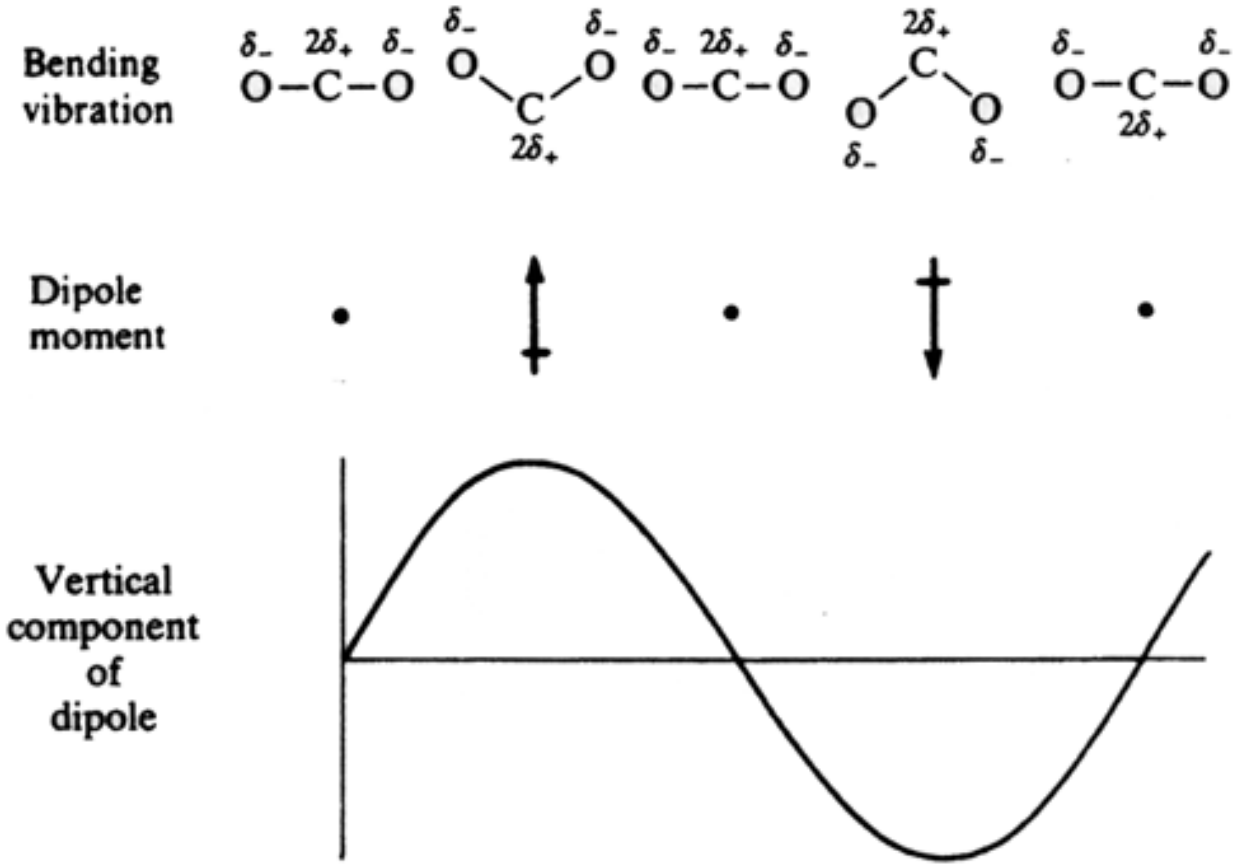
http://hyperphysics.phy-astr.gsu.edu/hbase/mod3.html

To absorb in the IR part of the spectrum a molecule must be able to vibrate by stretching or bending

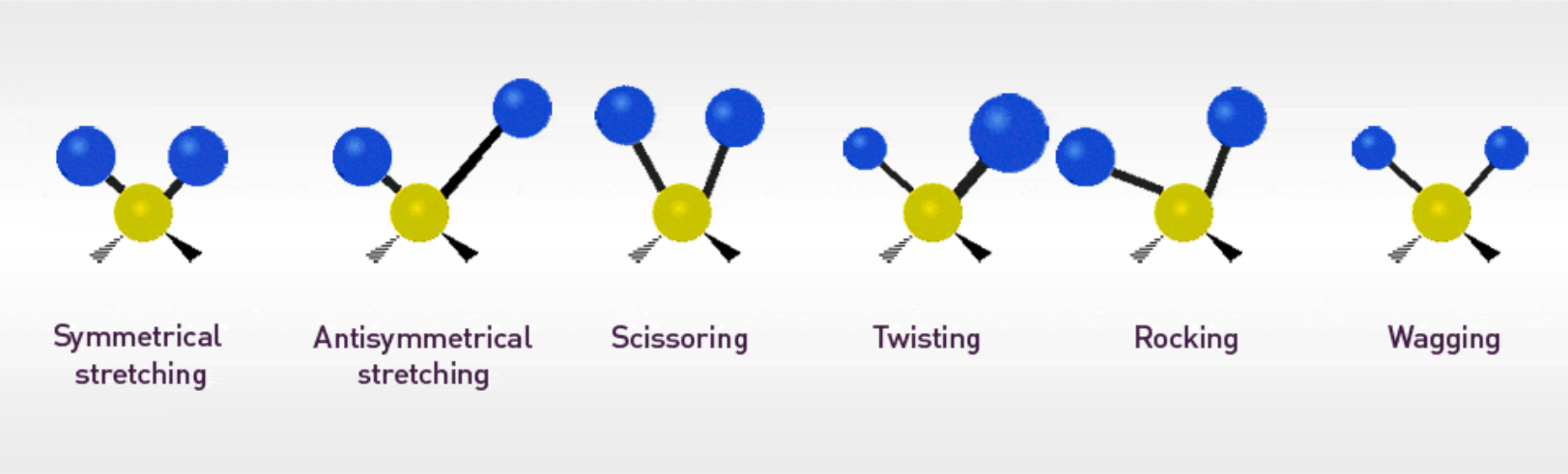
Types of Molecular Vibrations: Vibrations fall into the basic categories of **stretching** and **bending**.

- **Stretching** vibration involves a continuous change in the inter-atomic distance along the axis of the bond between two atoms.
- **Bending** vibrations are characterized by a change in the angle between two bonds and are of **four types**: **scissoring, rocking, wagging,** and **twisting**.

Bending motion of the CO_2

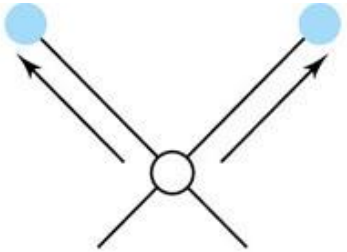


The bending motion of the carbon dioxide molecule and its associated dipole fluctuation.

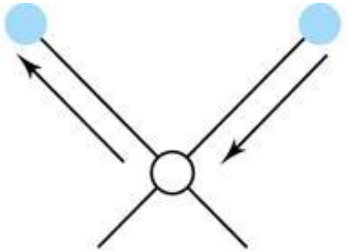


http://chemwiki.ucdavis.edu/Physical_Chemistry/Spectroscopy/Vibrational_Spectroscopy/Vibrational_Modes/Number_of_vibrational_modes_for_a_molecule

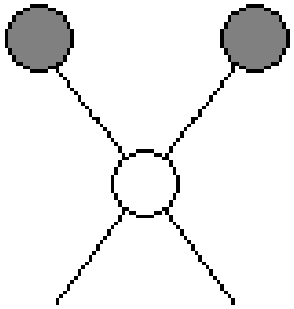
Stretching Vibration



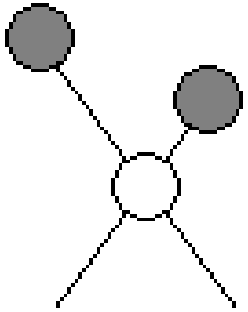
Symmetric



Asymmetric



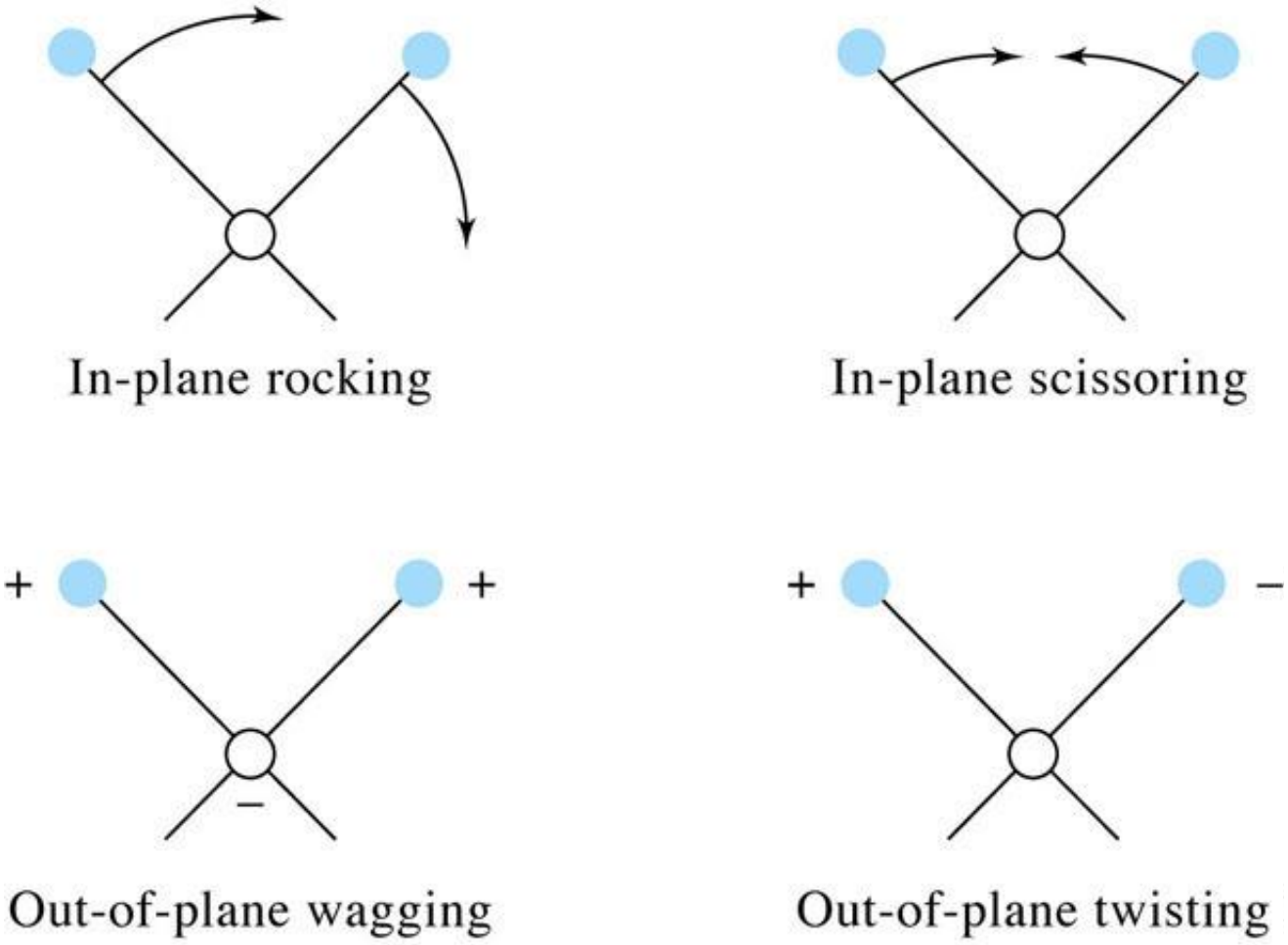
Symmetric



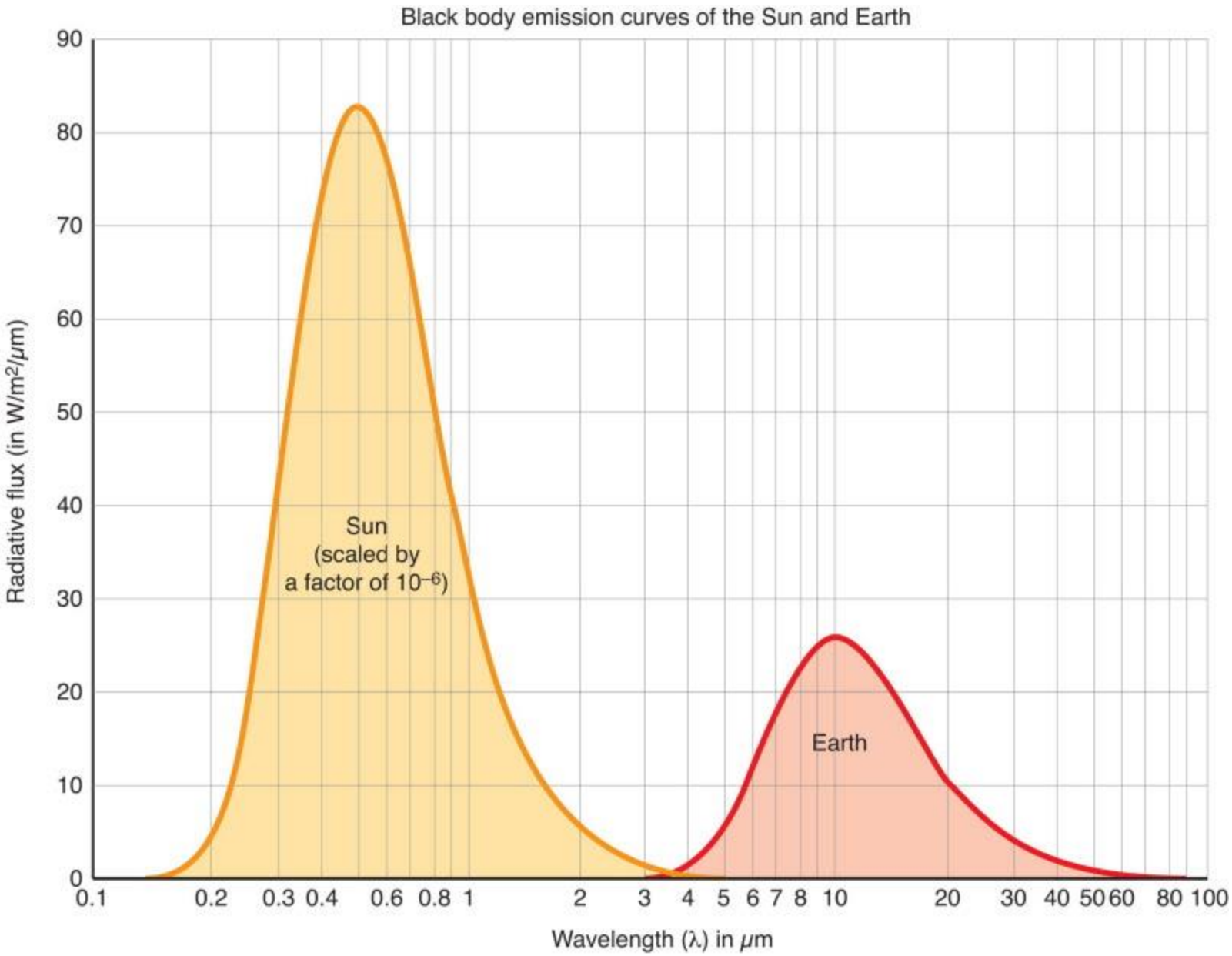
Asymmetric

https://www.youtube.com/watch?v=Lo2qQmj0_h4

Bending Vibration

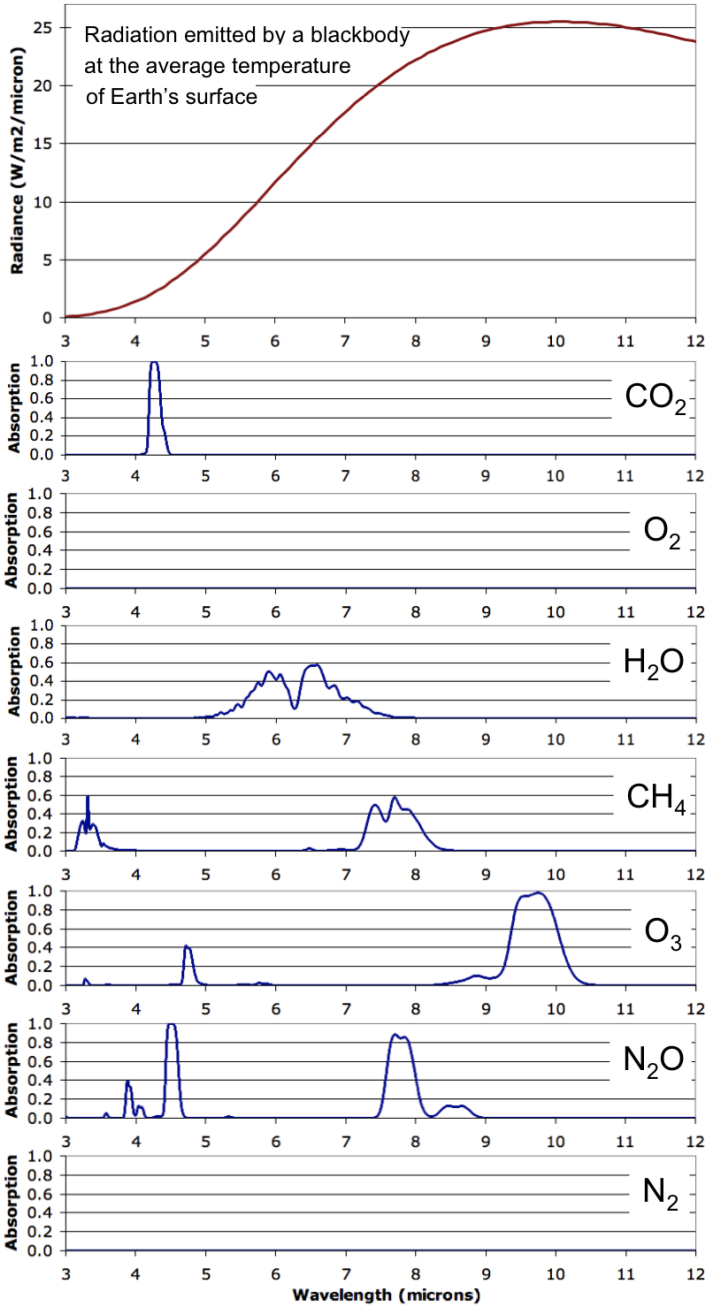


(b) Bending vibrations

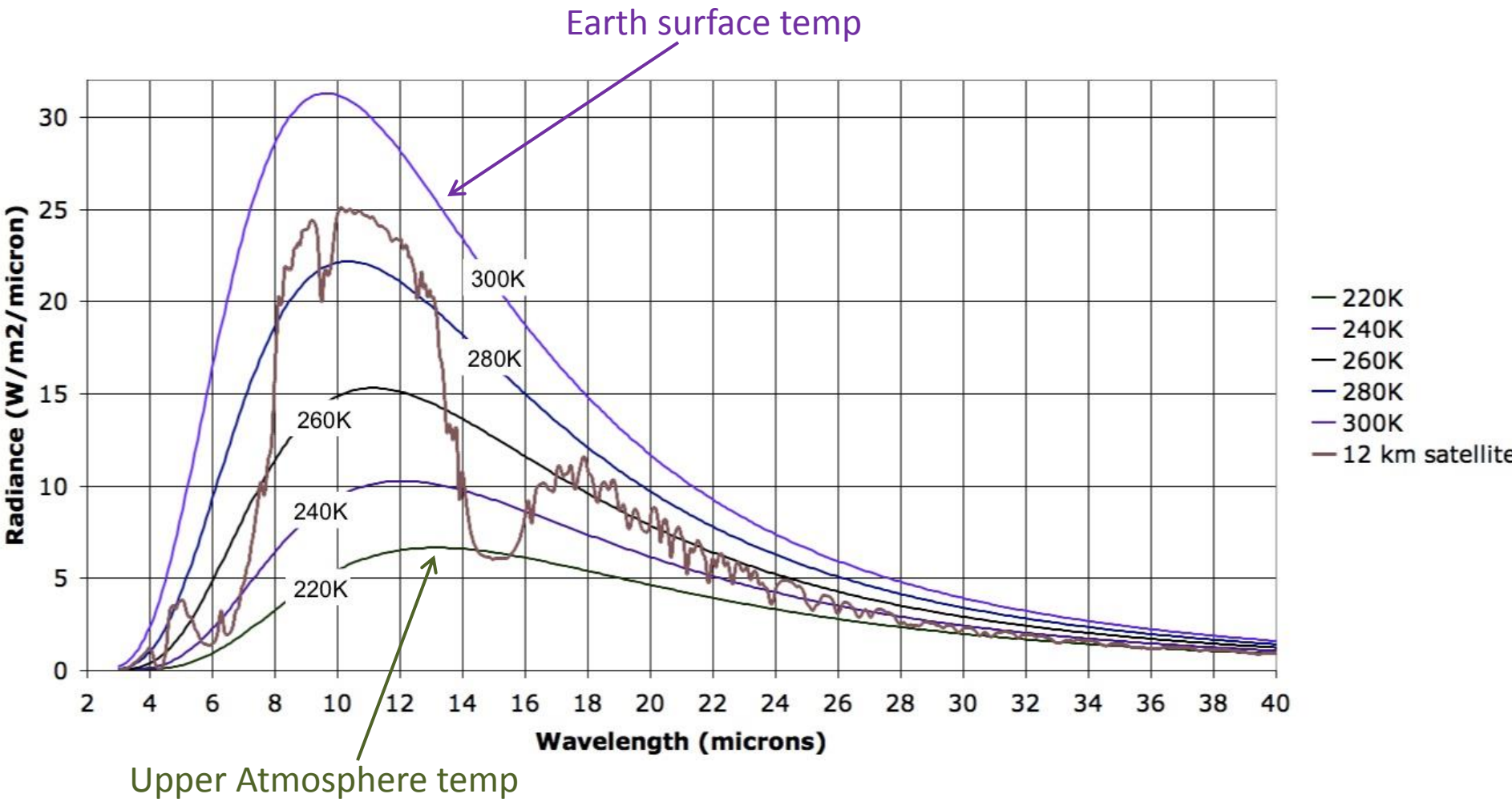

Black body emission curves of the Sun and Earth
Radiative flux (in W/m²/μm)
90
80
70
60
50
40
30
20
10
0
Sun
(scaled by
a factor of 10⁻⁶)
Earth
0.1
0.2
0.3
0.4
0.6
0.8
1
2
3
4
5
6
7
8
10
20
30
40
50
60
80
100
Wavelength (λ) in μm

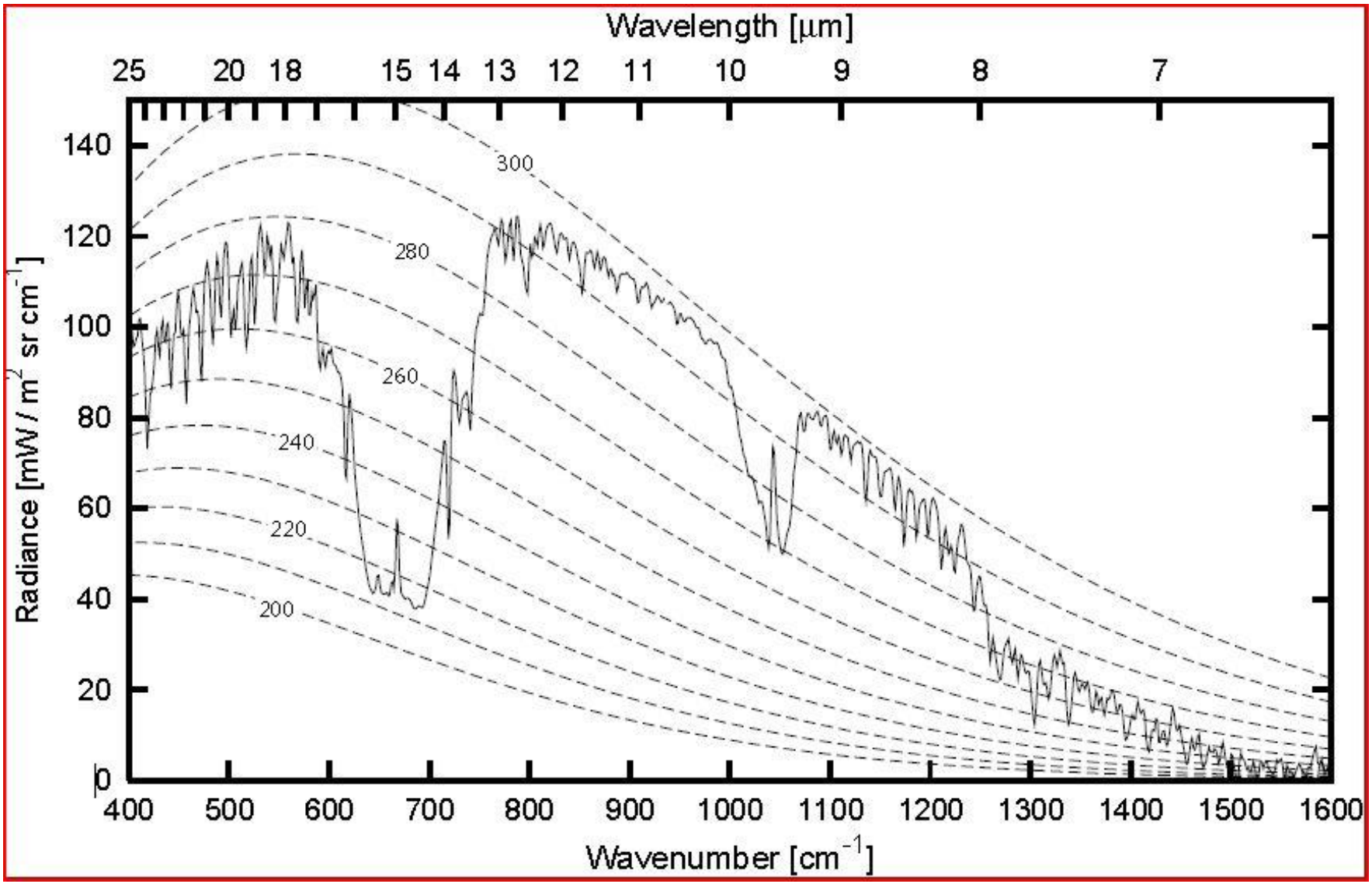
Absorption by atmospheric gases of incoming and outgoing radiation

adapted from http://cleanet.org/clean/community/activities/c4.html

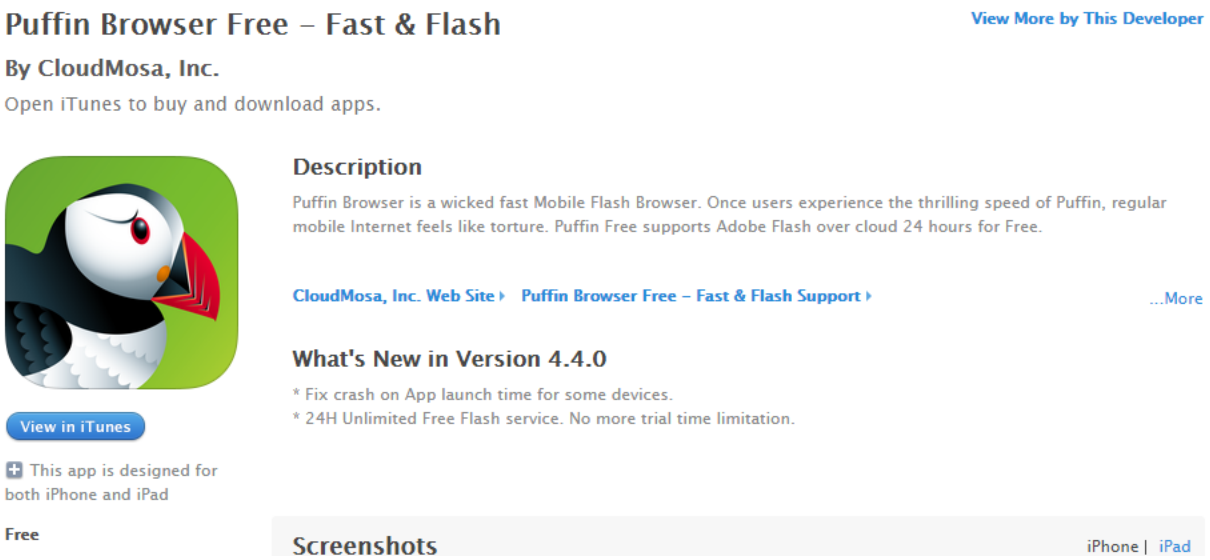


Let's take a look at the actual absorption spectrum and see if we can identify the gas absorption bands



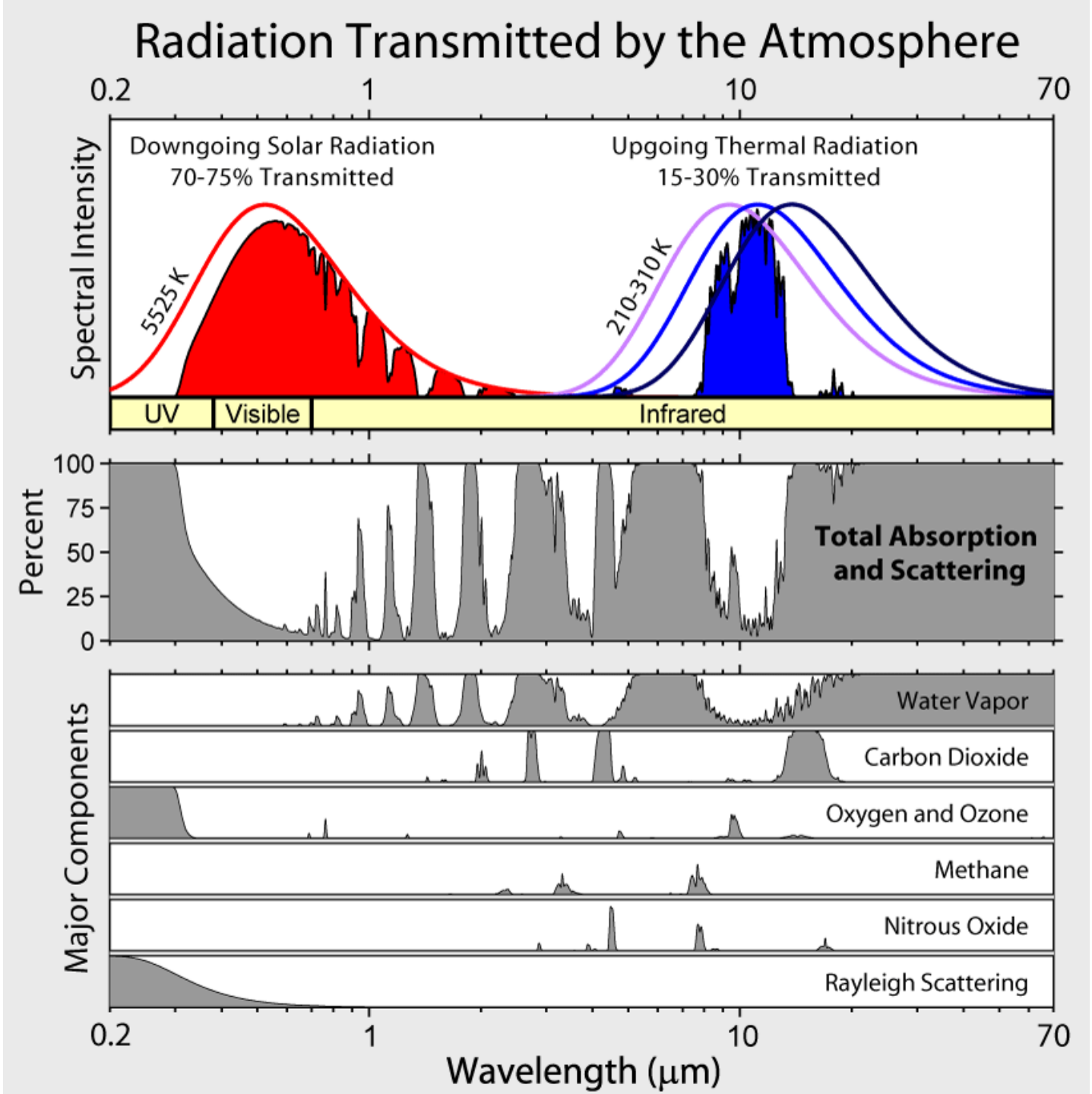

Wavelength [μm]
25
20
18
15
14
13
12
11
10
9
8
7
Radiance [mW / m^2 sr cm^{-1}]
140
120
100
80
60
40
20
0
300
280
260
240
220
200
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Wavenumber [cm^{-1}]

Let’s explore the absorption of IR by various gases
Load the PUFFIN browser app (this allows the ipad to use flash)



Use Puffin to go to this site:

http://www.chem.arizona.edu/chemt/C21/sim/gh/

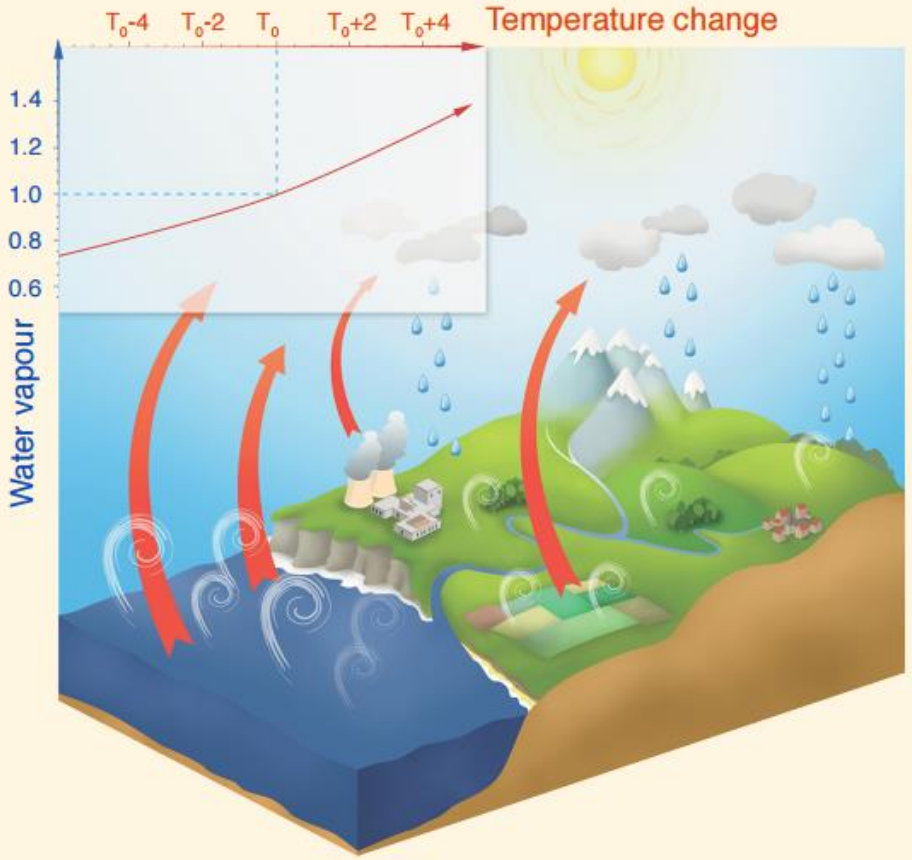

Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
0.2
1
10
70
Wavelength (μm)

What did we learn from this investigation?

1 . Water vapor has 2-3x the warming potential as carbon dioxide!

Because water vapor is controlled by temperature rather than emissions, scientists consider it a feedback agent - it is included in all climate models but is not a target for legislation

It is also able to condense and evaporate at T&P in the atmosphere and has a very short residence time

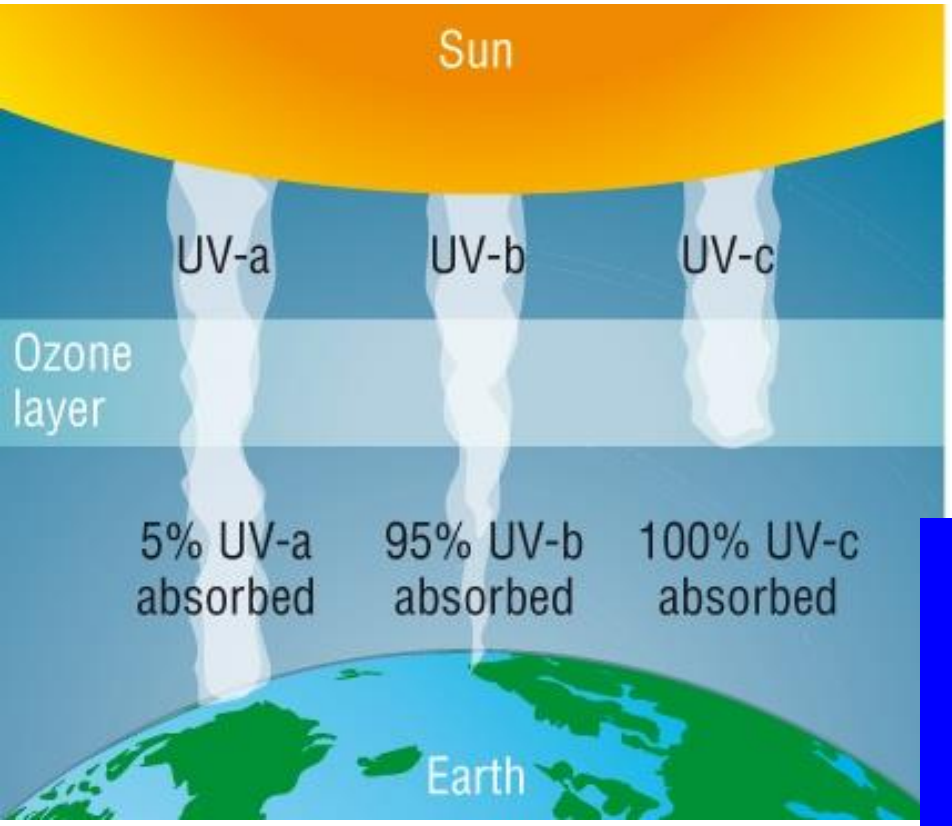


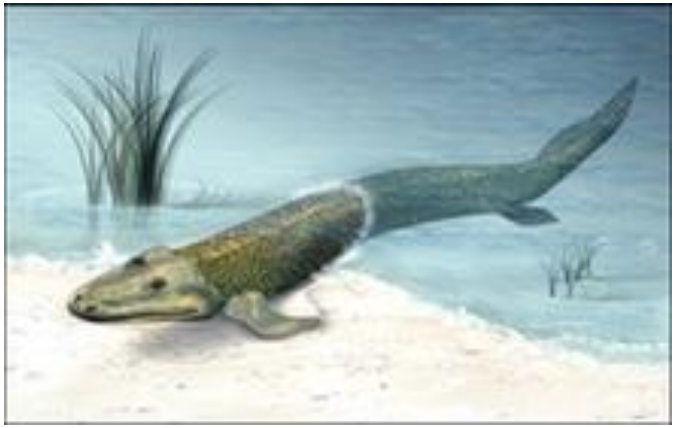
FAQ 8.1, Figure 1 | Illustration of the water cycle and its interaction with the greenhouse effect. The upper-left insert indicates the relative increase of potential water vapour content in the air with an increase of temperature (roughly 7% per degree). The white curls illustrate evaporation, which is compensated by precipitation to close the water budget. The red arrows illustrate the outgoing infrared radiation that is partly absorbed by water vapour and other gases, a process that is one component of the greenhouse effect. The stratospheric processes are not included in this figure.

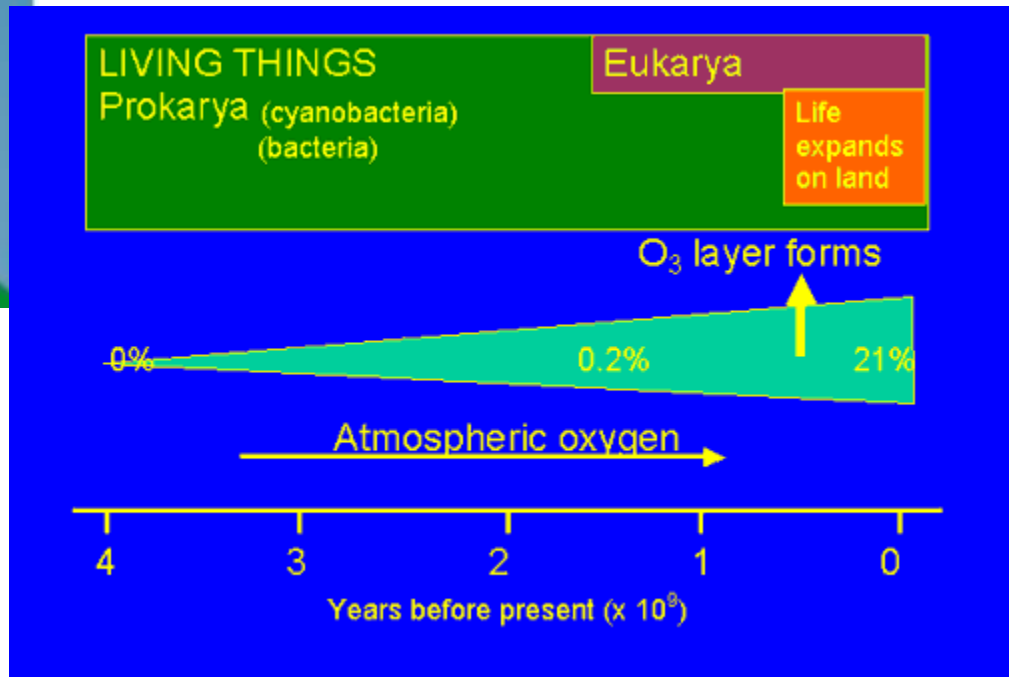
IPCC AR5

2. Ozone does a great job of absorbing incoming UV light as well as absorber of IR

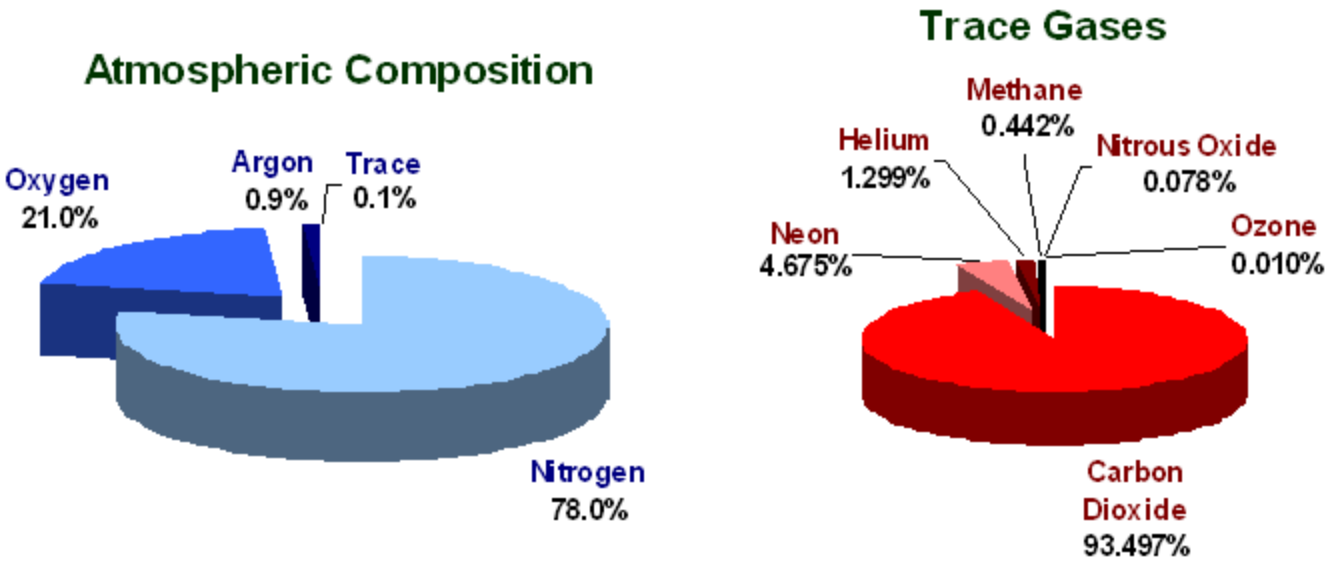
(Many believe it was creation of ozone in the atmosphere that allowed evolution of land dwellers – the water protected animals from UV radiation)



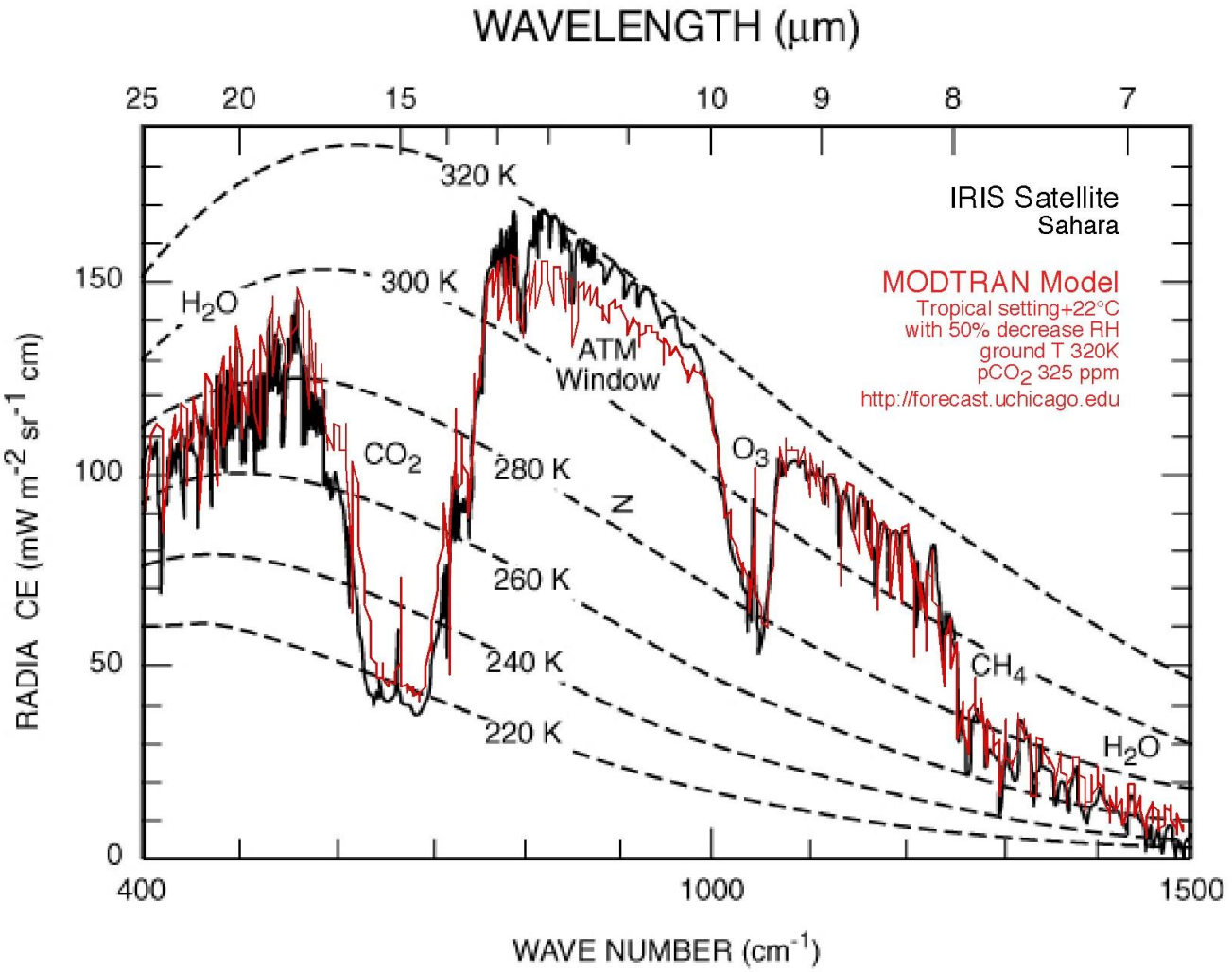




3. Oxygen and nitrogen, the two main components of the atmosphere absorb no IR radiation



4. Methane fills an open window in the absorption spectrum…

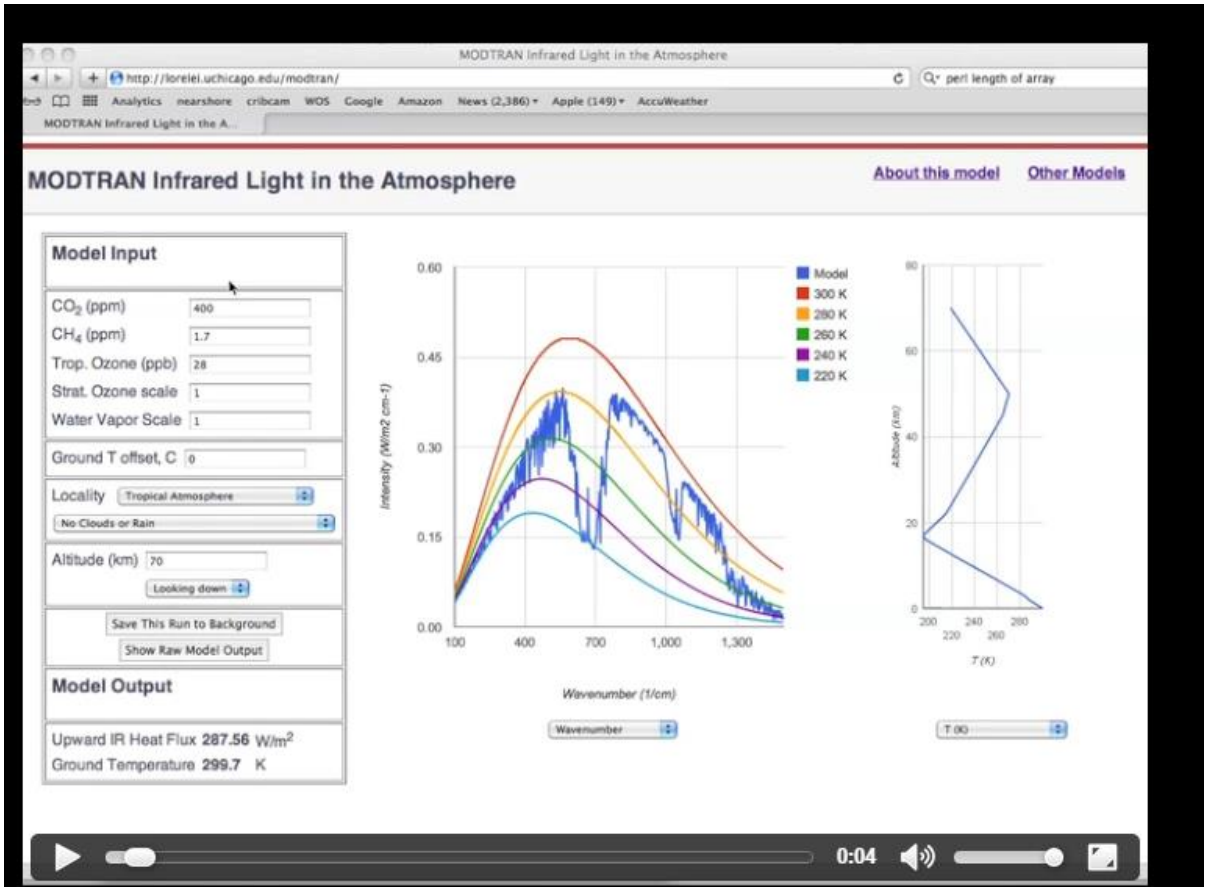


5. And, yes, carbon dioxide does absorb IR radiation

Iain Stewart demonstrates infrared radiation absorption by CO2

https://www.youtube.com/watch?v=Ot5n9m4whaw

Band ‘saturation’



http://climatemodels.uchicago.edu/modtran/modtran.mp4

Difference in gases

- Because gases absorb IR selectively some radiation bands are completely absorbed.

- Others are '*atmospheric windows*'

  - This leads to higher greenhouse forcing per molecule for some gases.

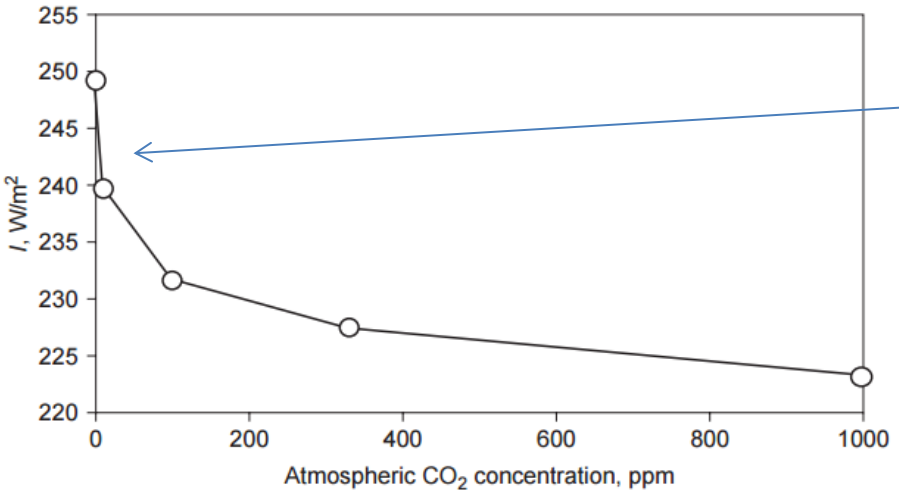


Figure 4-6 Band saturation viewed in a different way from Figure 4-5. This is a plot of the total energy flux carried by all infrared light, which is proportional to the area under the spectrum curves in Figure 4-5. The outgoing energy flux is less sensitive to CO_2 when the CO_2 concentration is high.

This same relationship is true of CH_4 methane (and other gases) which is why adding one molecule of CH_4 creates more warming than one CO_2 – methane concentrations fall on the steep part of this curve

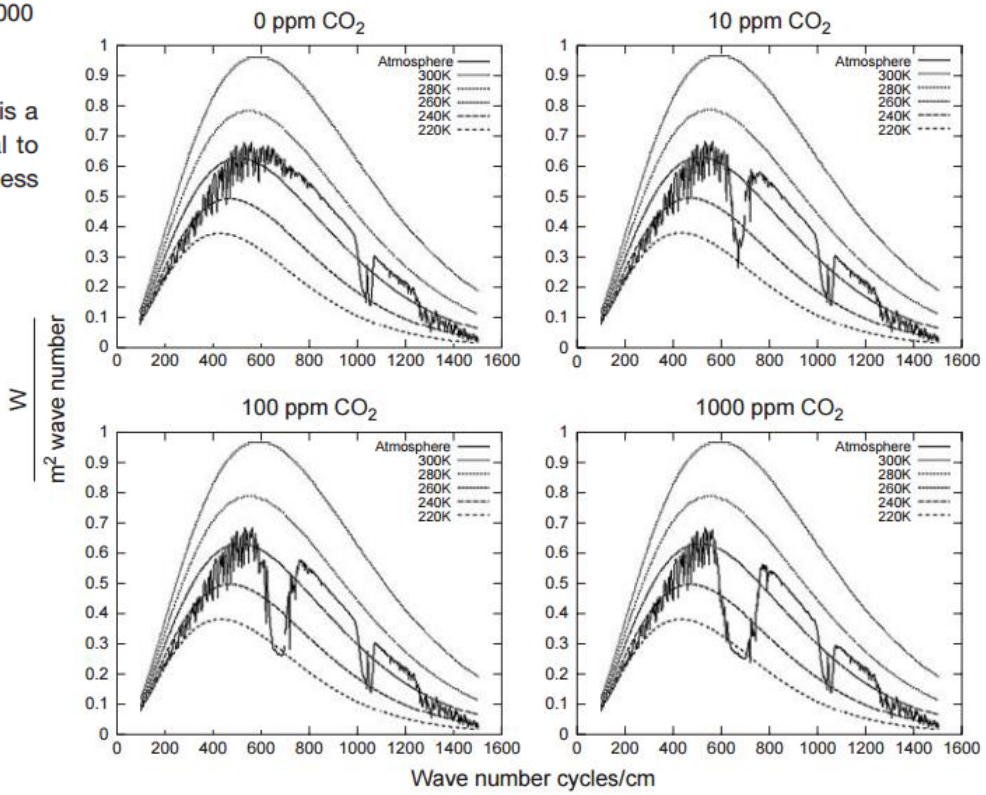
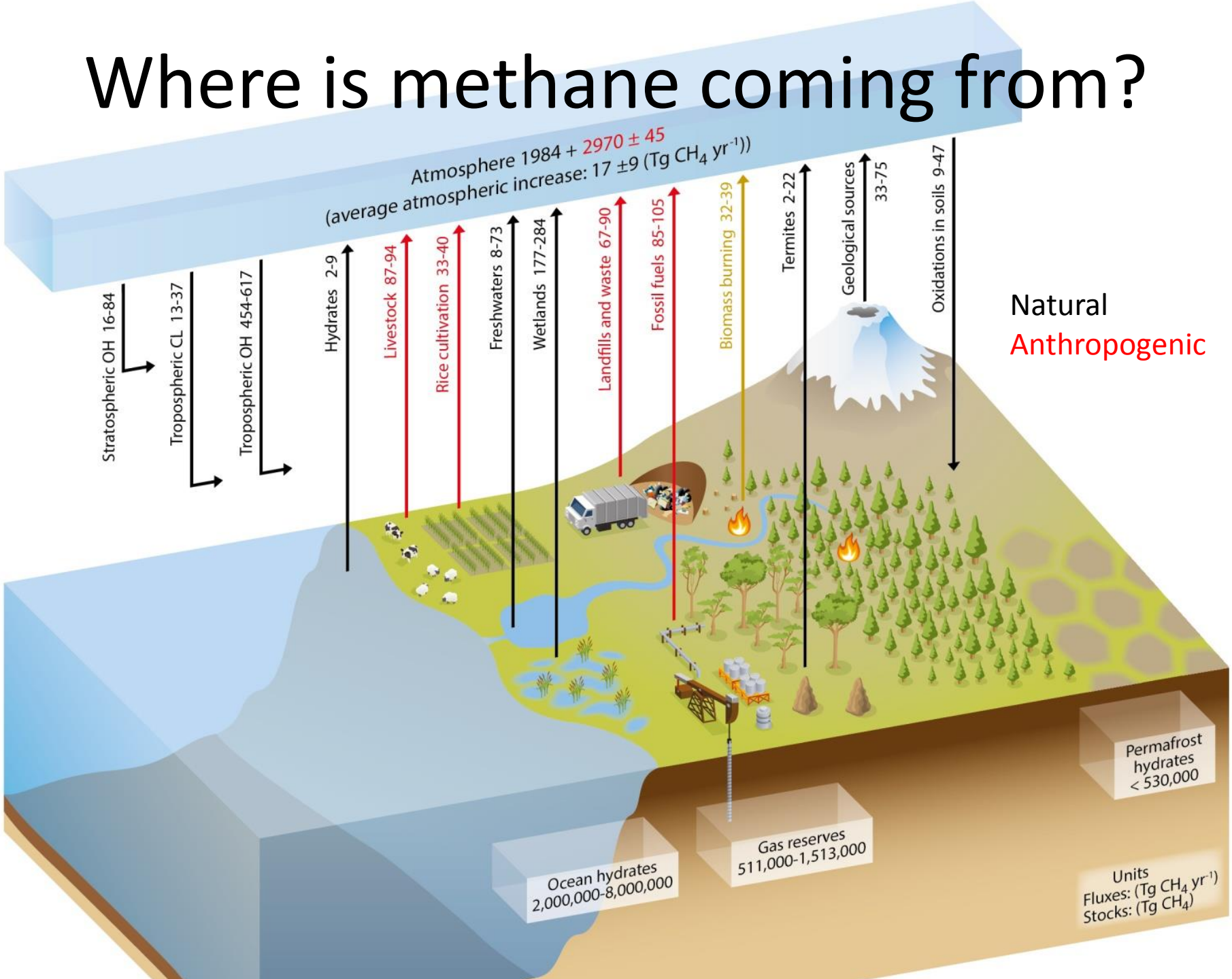


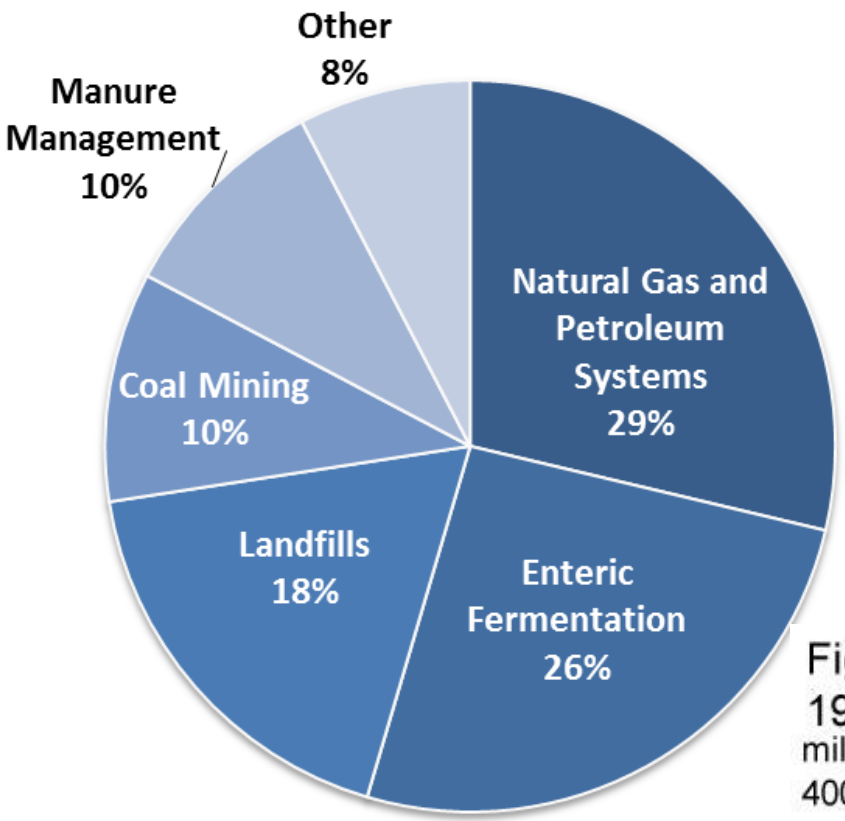
Figure 4-5 A demonstration of band saturation by CO_2. The addition of 10 ppm CO_2 (*upper right*) makes a huge difference to the outgoing infrared light spectrum relative to an atmosphere that has no CO_2 (*upper left*). Increasing CO_2 to 100 and 1,000 ppm (*lower panels*) continues to affect the spectrum, but you get less bang for your CO_2 buck as CO_2 concentration gets higher.

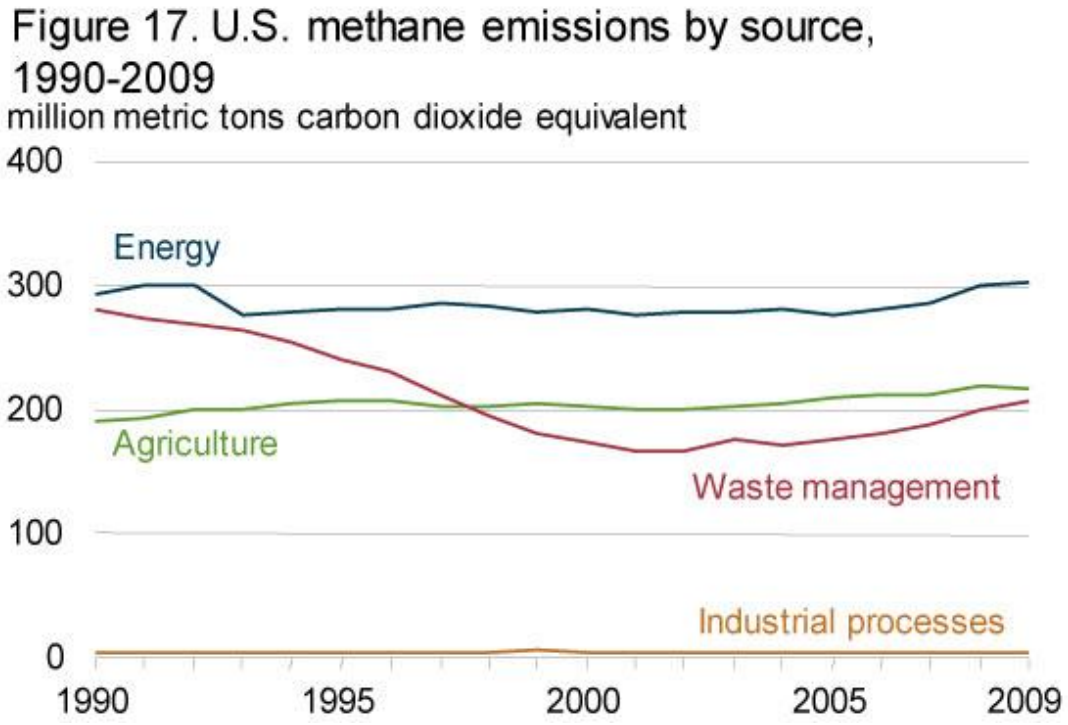
Methane hasn't 'filled' its bandwith yet, so it has greater widening potential than CO_2.

The band widens with increasing concentration.

Where is methane coming from?





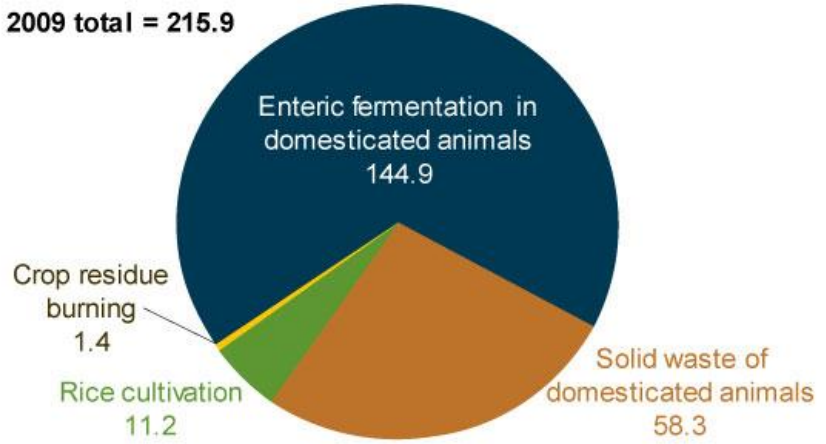


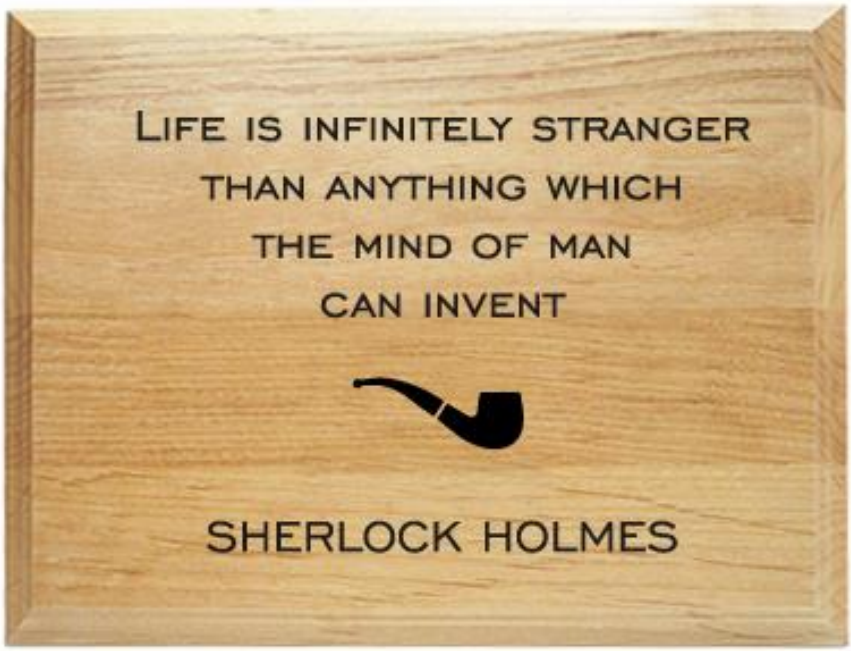
http://epa.gov/climatechange/ghgemissions/gases/ch4.html

http://www.eia.gov/environment/emissions/ghg_report/ghg_methane.cfm

Figure 19. U.S. methane emissions from agriculture by source, 2009

million metric tons carbon dioxide equivalent





Because of the band saturation issue,

- A molecule of CH_4 methane added to the atmosphere is about 25-75 times more powerful than is a molecule of CO_2

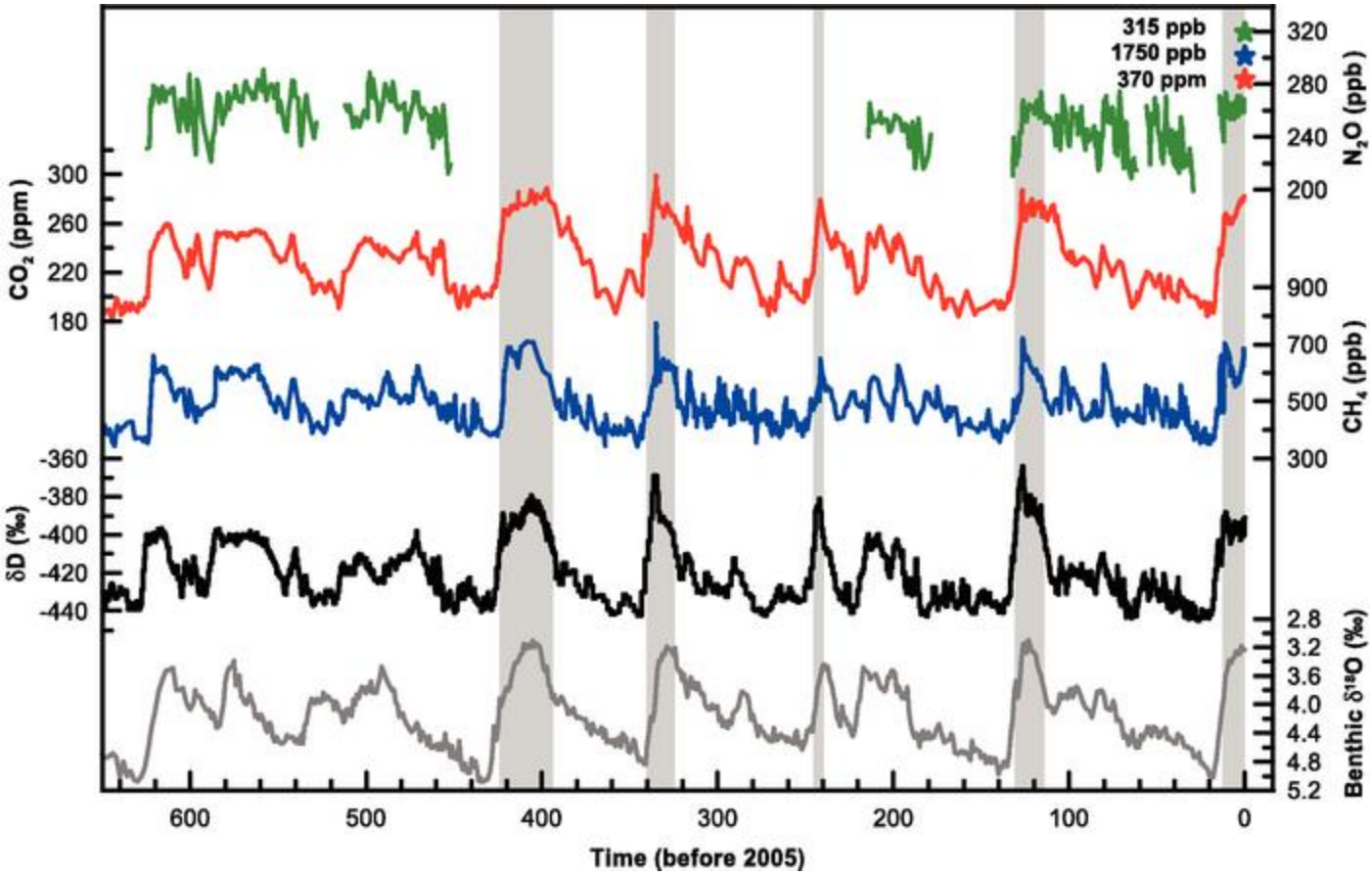
  (25-75x depending on time frame considered)

GWP (global warming potential) is defined as the total radiative forcing (i.e. heating) over 100 years or another time horizon caused by emitting a gas (such as methane), compared to emitting an equal amount of CO_2.

CH_4 has a relatively short residence time of 10 years in the atmosphere which is why it has greatest GWP over the shorter time horizon

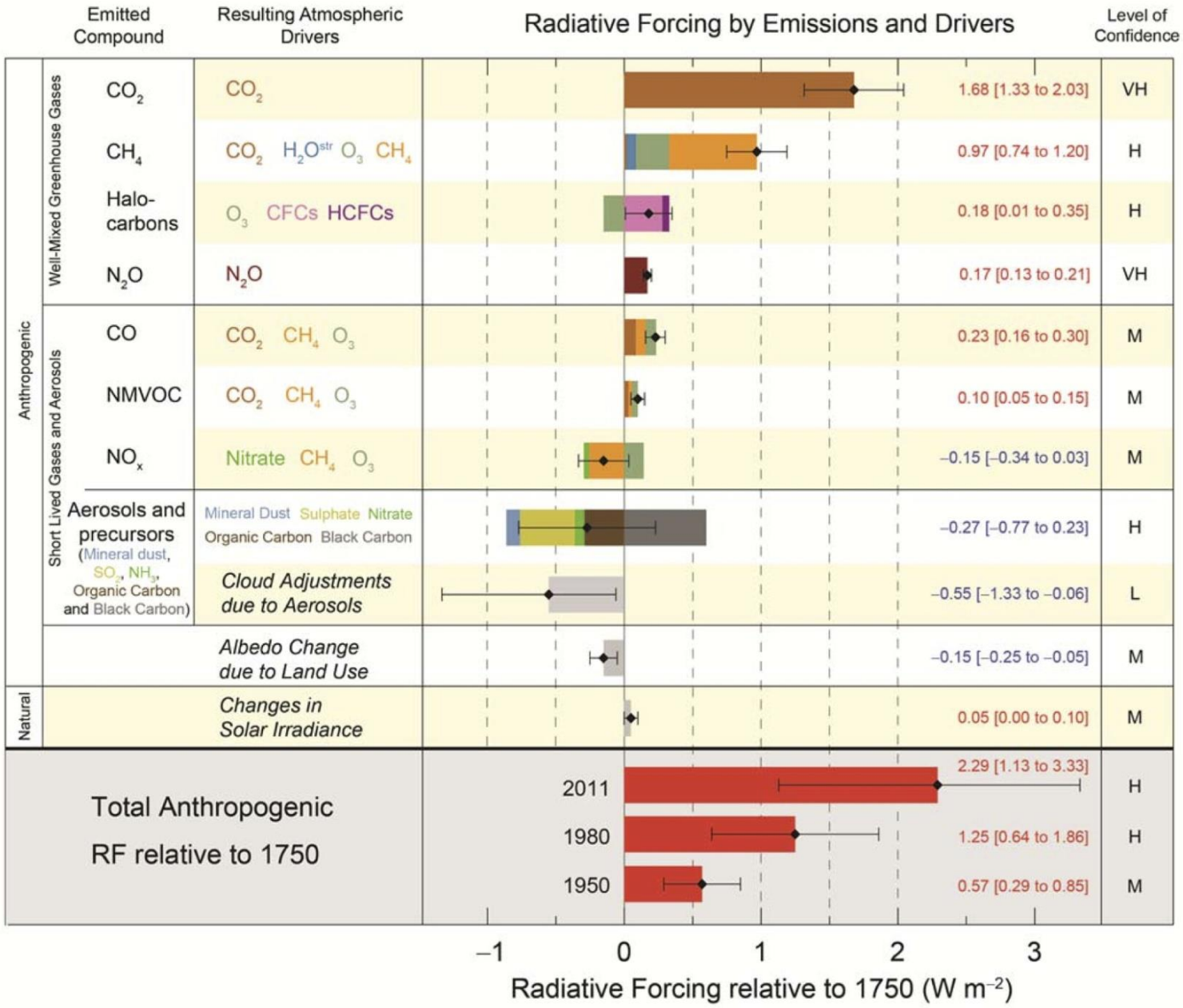
Greenhouse Gas	GWP After 20 Years	GWP After 100 Years
Carbon Dioxide	1	1
Methane	72	25
Nitrous Oxide	289	298
HCFC-22	5160	1810
HFC-23	12000	14800
HFC-125	6350	3500
HFC-134a	3830	1430
HFC-143a	5890	4470
CF_4	5210	7390
C_2F_6	8630	12200
SF_6	16300	22800

((We are investigating methane as an example, you can see that the fluorinated gases -- all are made by humans -- have enormous GWP. Although the Montreal Protocol regulates the phasing out of CFCs, there is currently no international agreement on the regulation of HFCs. Efforts are ongoing to develop a global approach…))

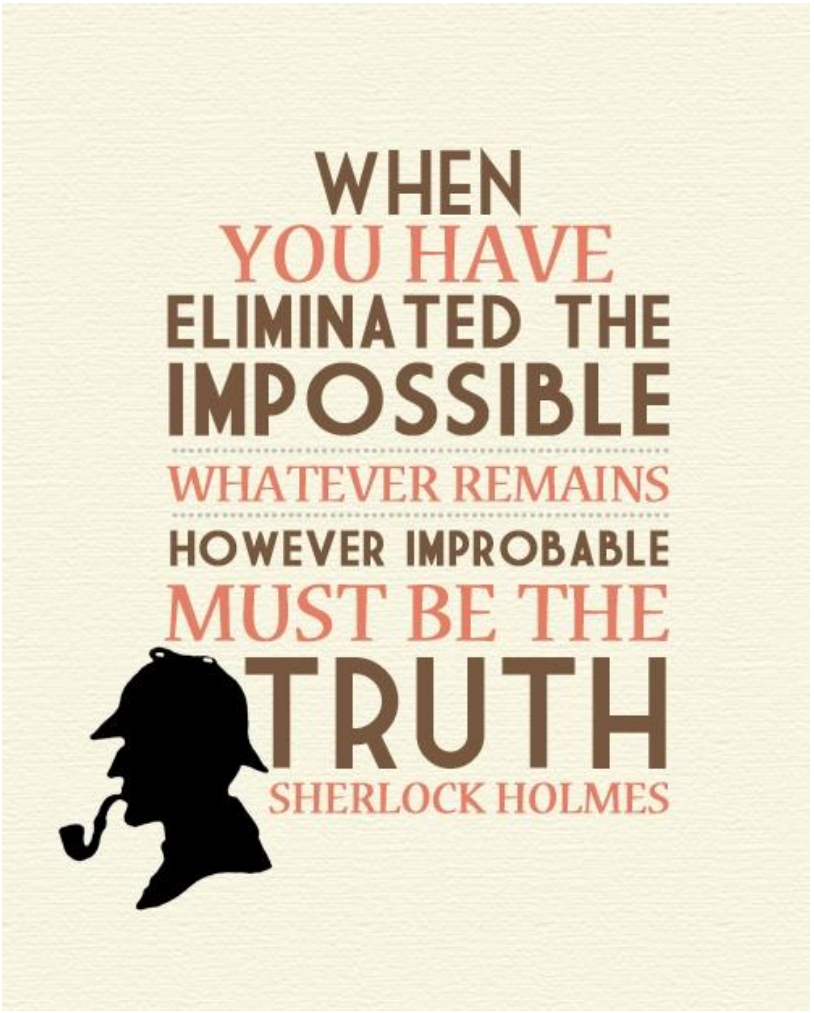


Ice core and ocean sediment core data. Grey bars represent interglacial periods. The stars and labels indicate atmospheric concentrations at year 2000.

https://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-6-3.html



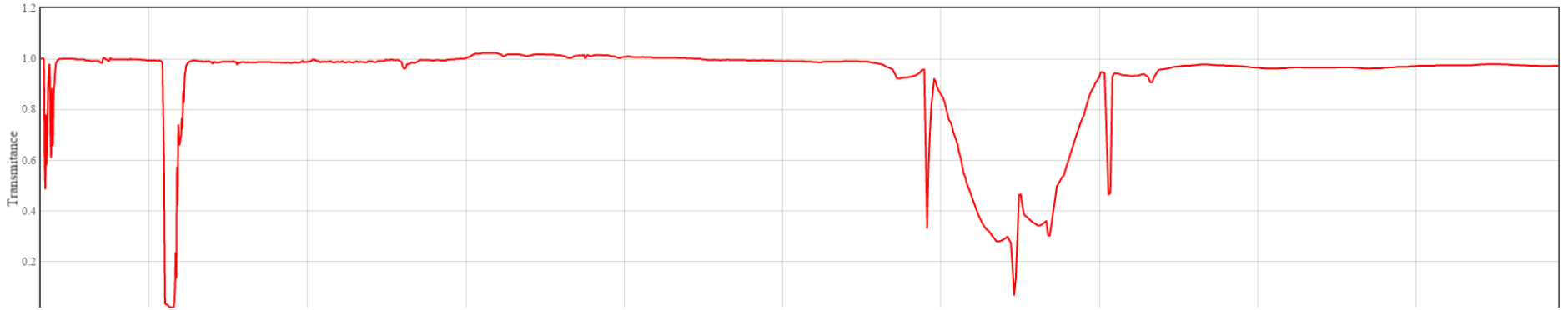
http://climatemodels.uchicago.edu/slugulator/slugulator.html



http://www.epa.gov/climatechange/science/causes.html#

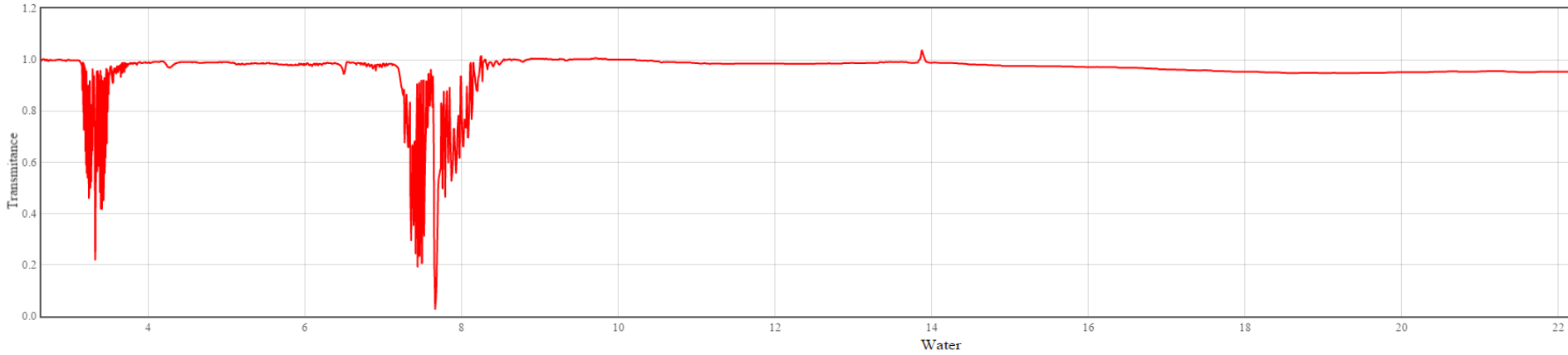
Carbon Dioxide

Infrared Spectrum



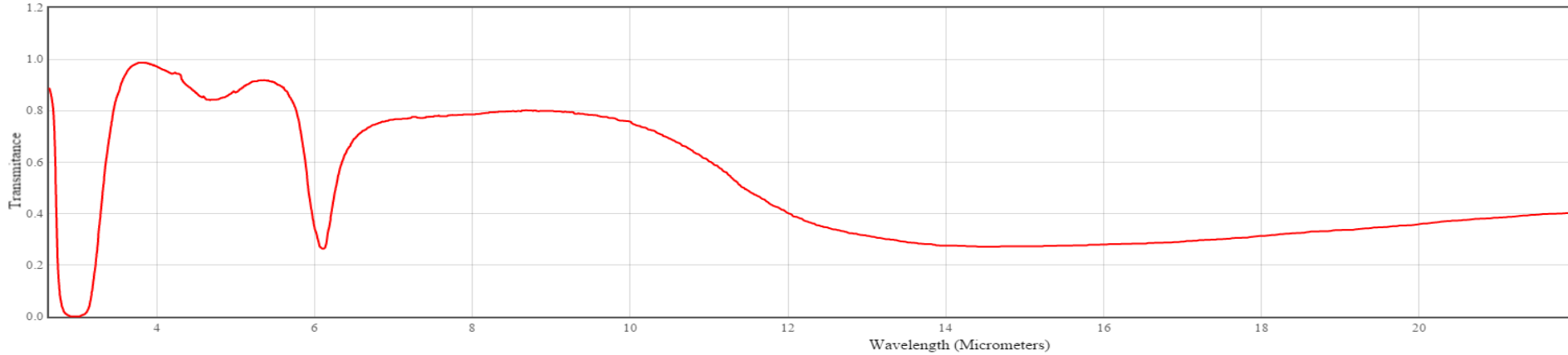
Methane

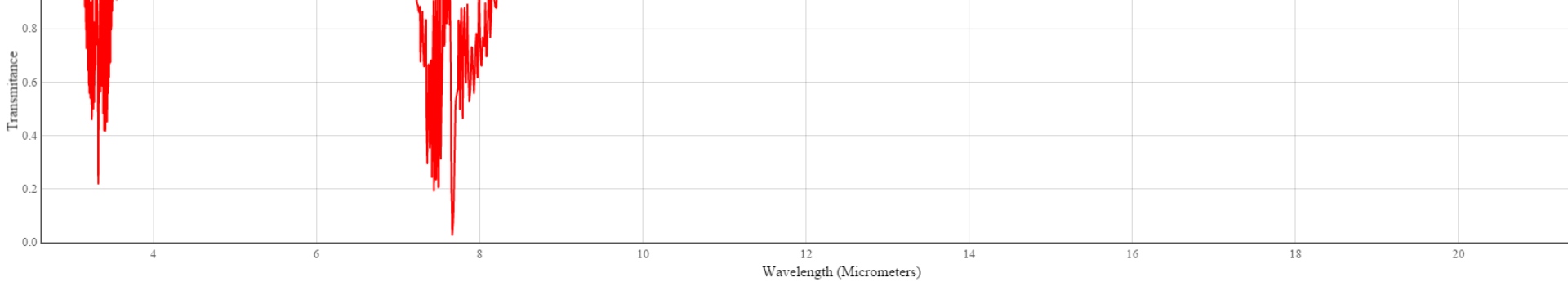
Infrared Spectrum



Water

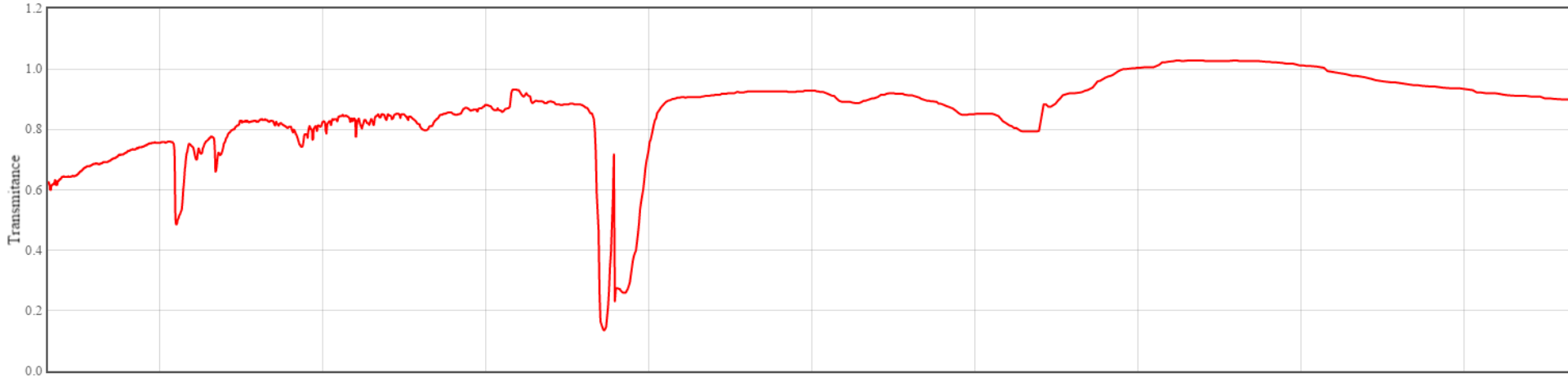
Infrared Spectrum





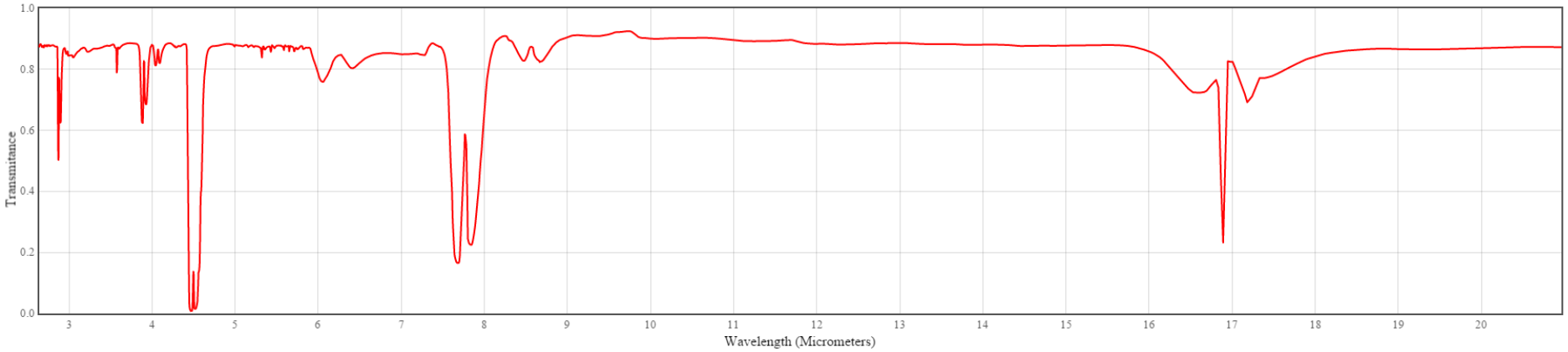
Ozone

Infrared Spectrum

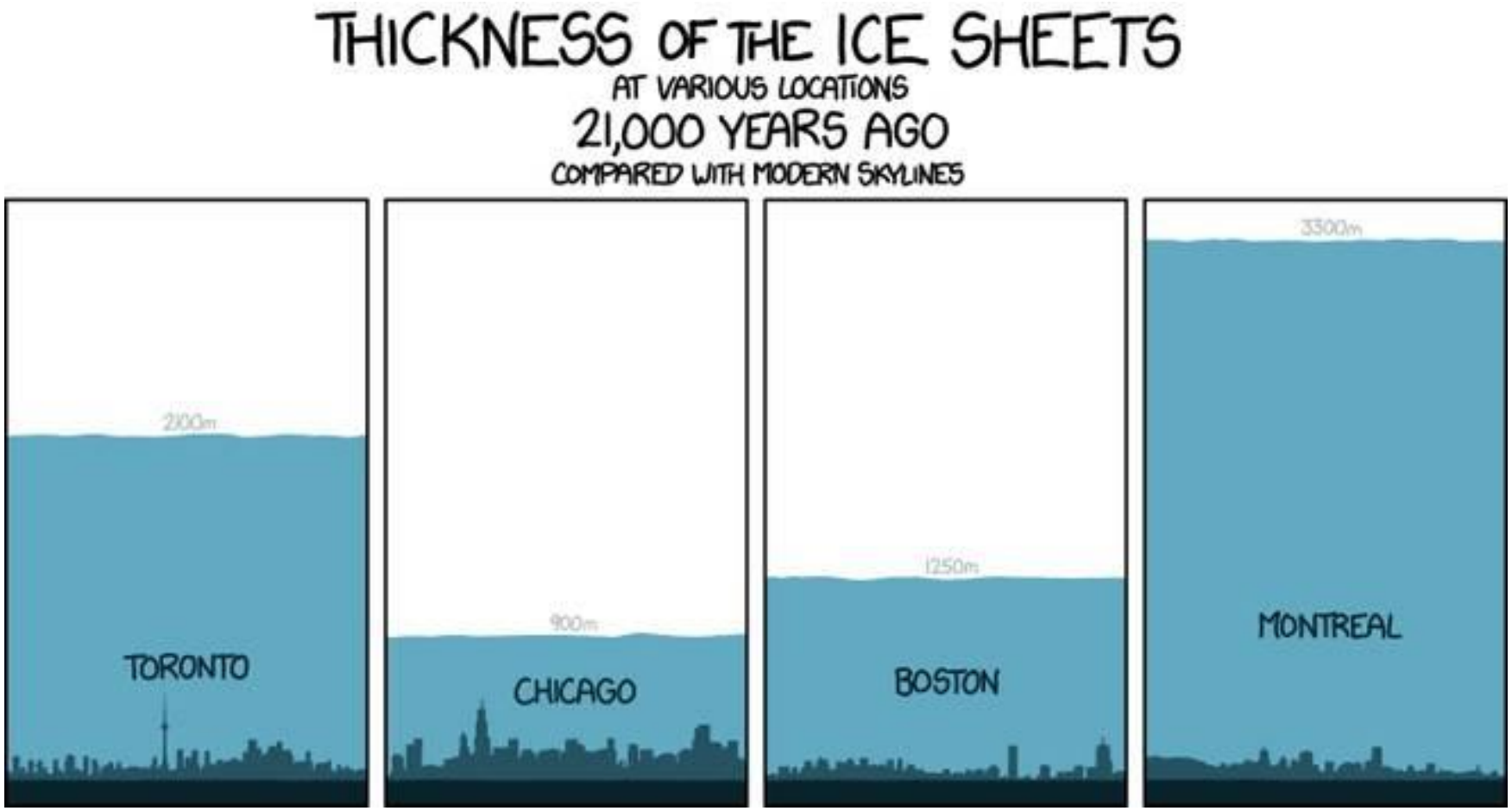


Nitrous oxide

Infrared Spectrum

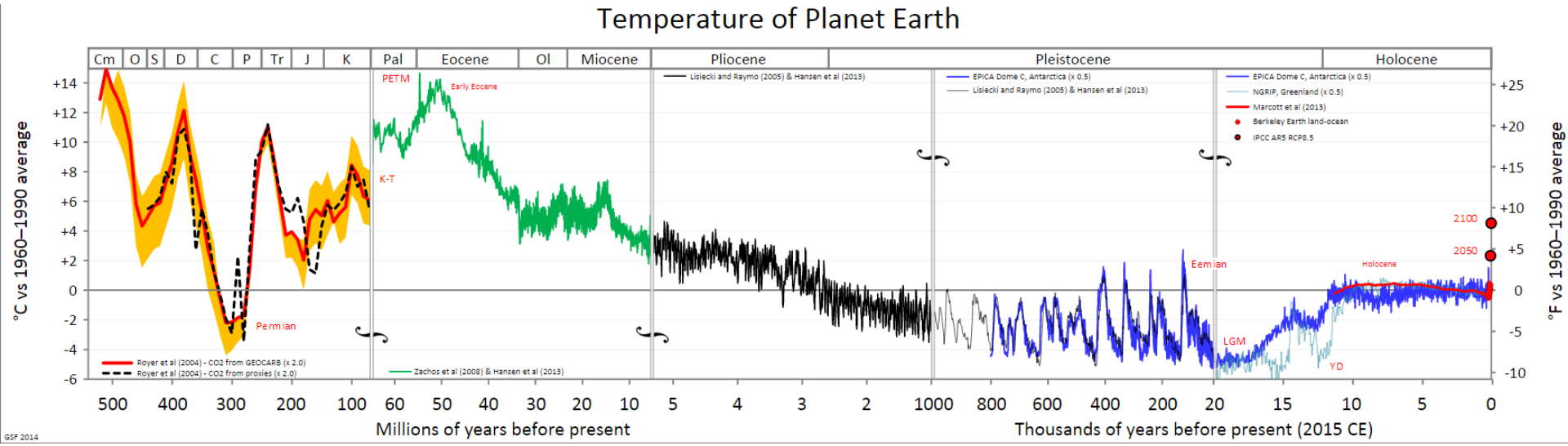


A geologists perspective:



XKCD.com

Are current temperatures the highest earth has ever seen?



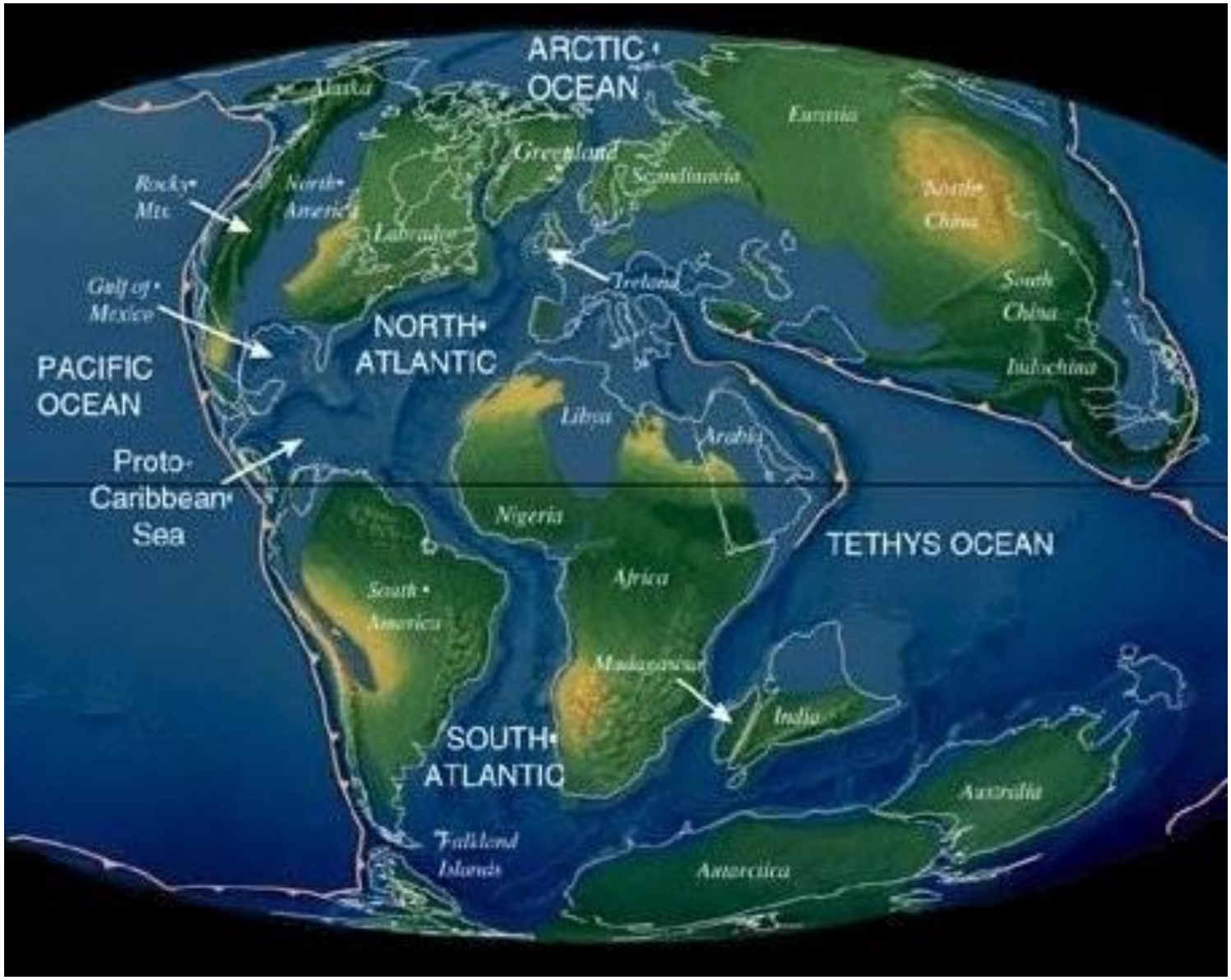
Not even close….

(but they are the highest modern creatures/plants have seen)

'There is nothing new under the sun. It has all been done before.'

Sherlock Holmes

-A Study in Scarlet

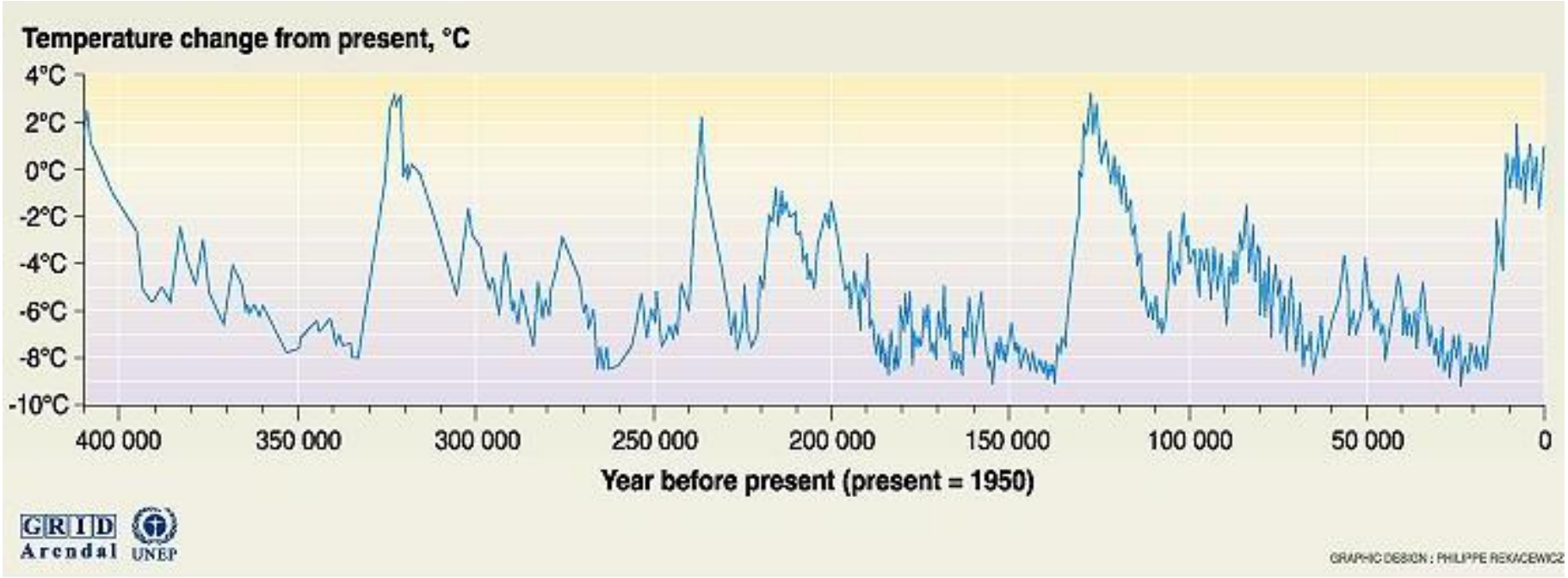


Cretaceous
(145 – 65 MYA)
paleo-map

…100 million years ago it was much hotter….
30% more land surface was covered with water!
(CO_2 was 2-4x what we have today)

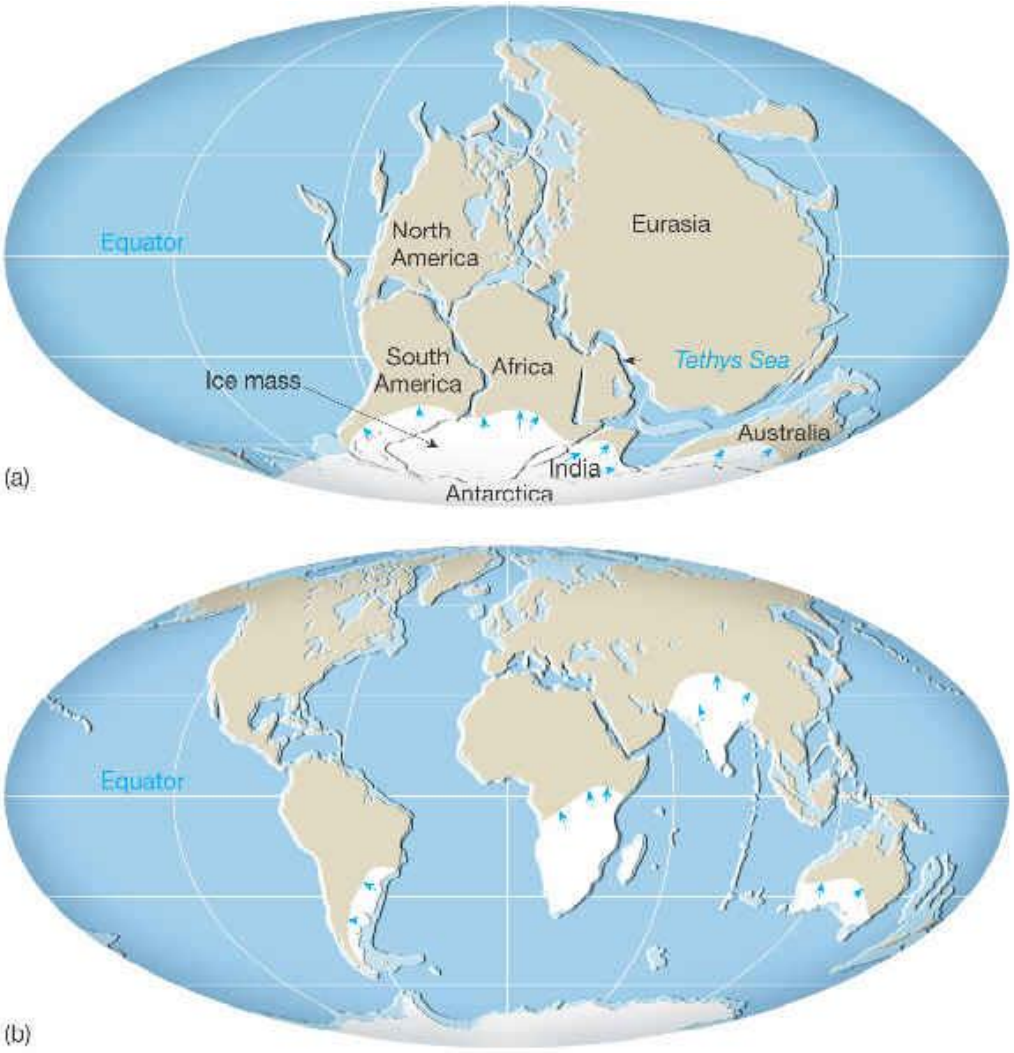
Ok, so global temperatures have fluctuated over earth's history…but why?

And why so cyclical?



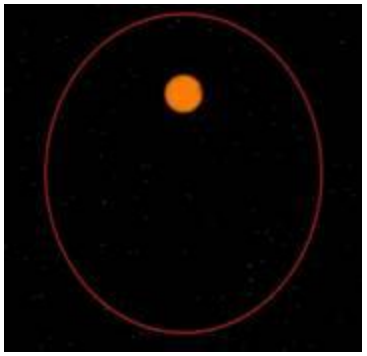
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3JUne), pp 429-436, 1999.

1. Plate tectonics

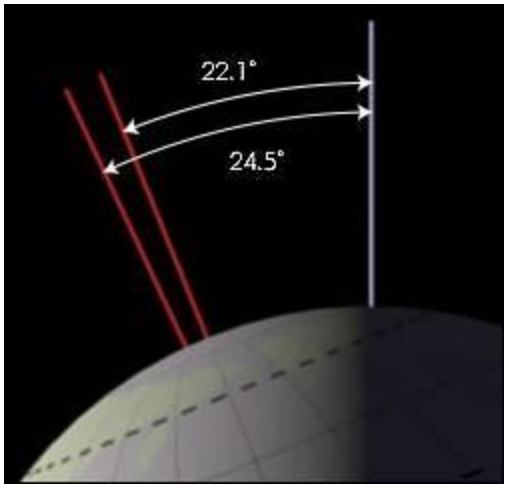


(time scale = millions of years…so what about variations on smaller time scales like tens of thousands of years, i.e. our glacial/interglacial periods?)

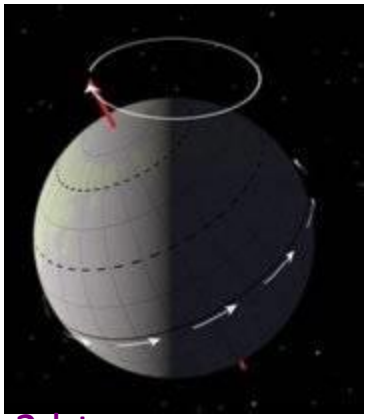
2. Milankovitch Cycles



- variations in shape of *earth's orbit* (eccentricity)
  - as orbit becomes more elliptical, seasonal heating and cooling is more pronounced



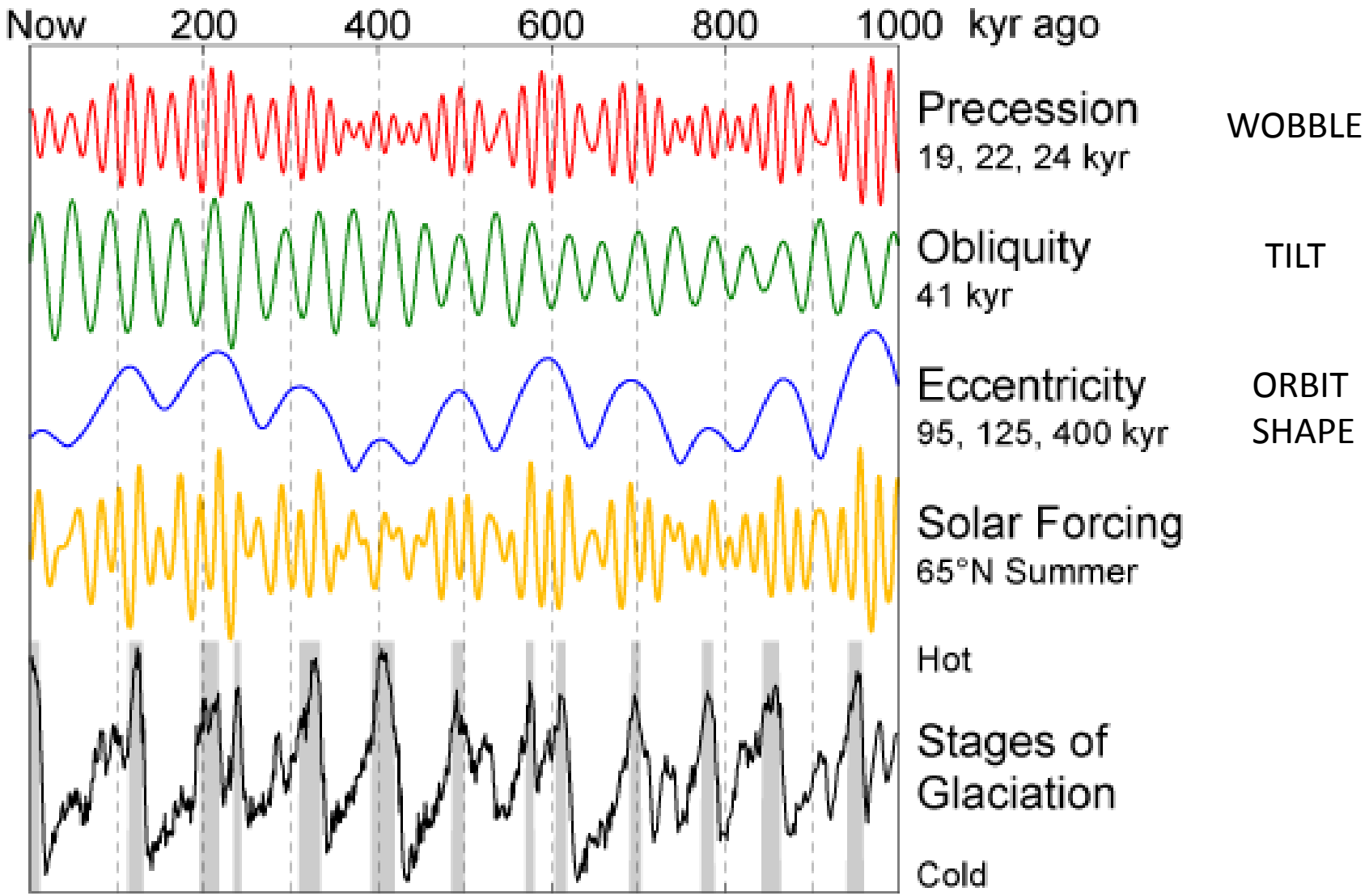
- variations in earth's *tilt angle* (obliquity)
  - increases seasonal variation at high latitudes



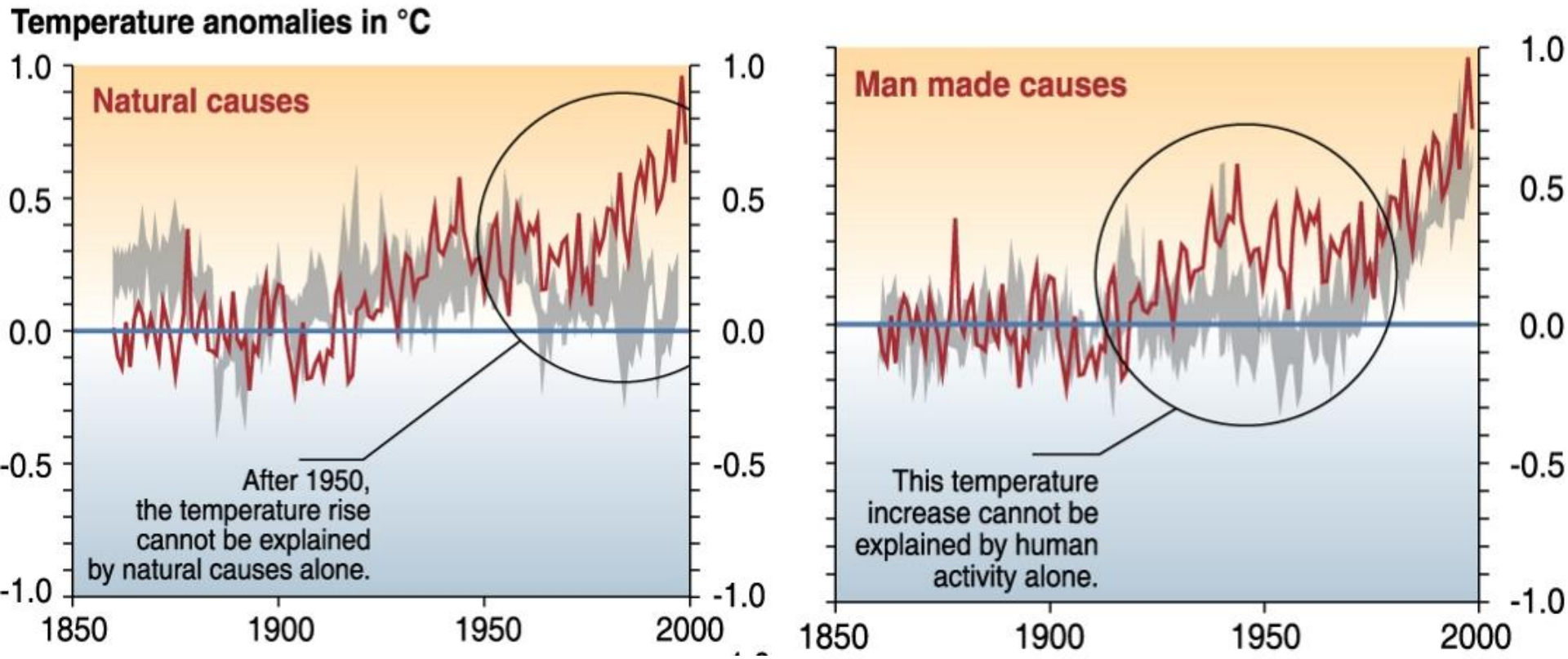
- wobbling of earth's *axis* (precession)
  - affects when seasons begin

http://www.wwnorton.com/college/geo/egeo2/content/animations/18_2.htm

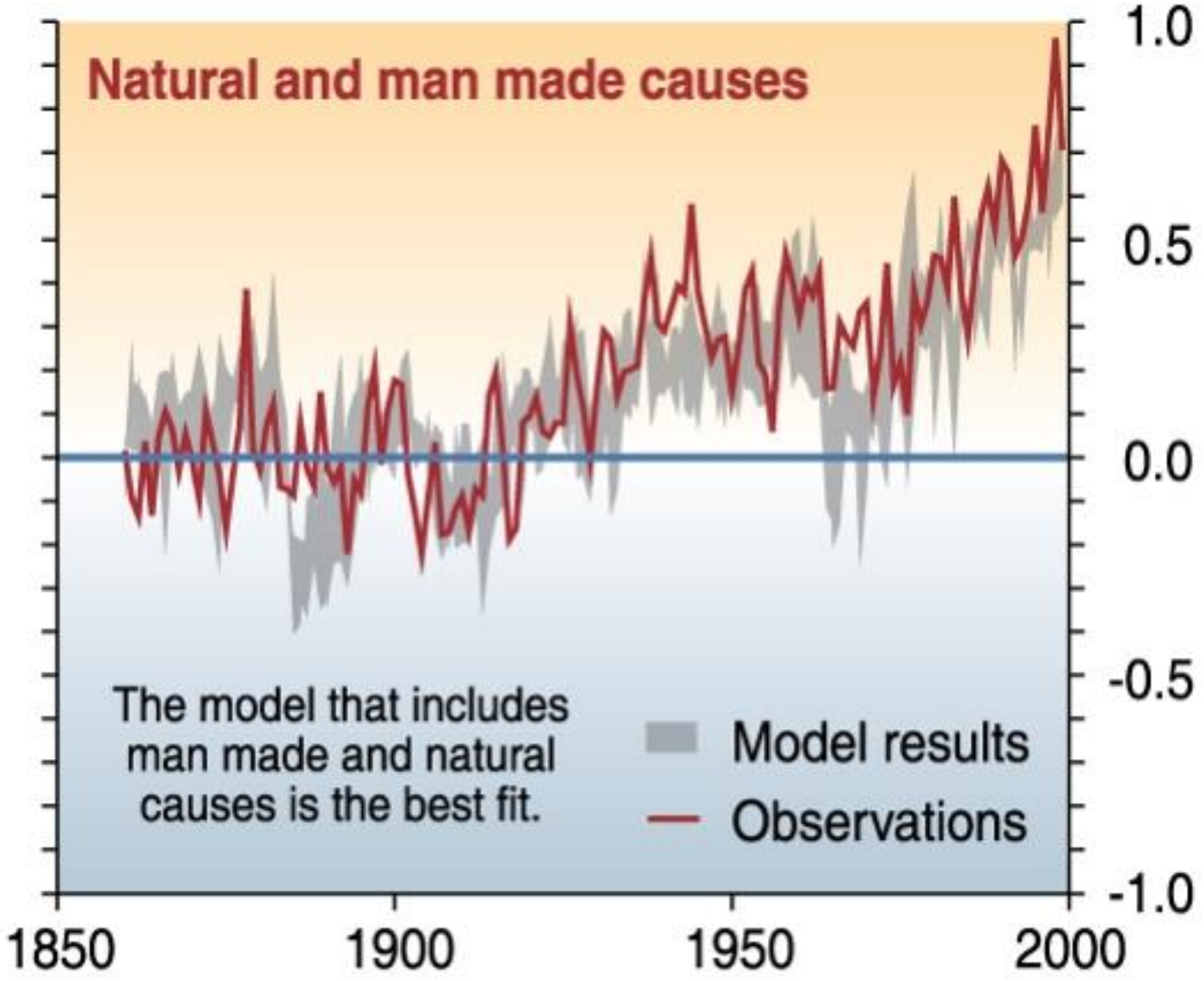
The combined effect results in glacial/interglacial periodicity of ~100,000 years



So are current warming trends just part of natural cycles?



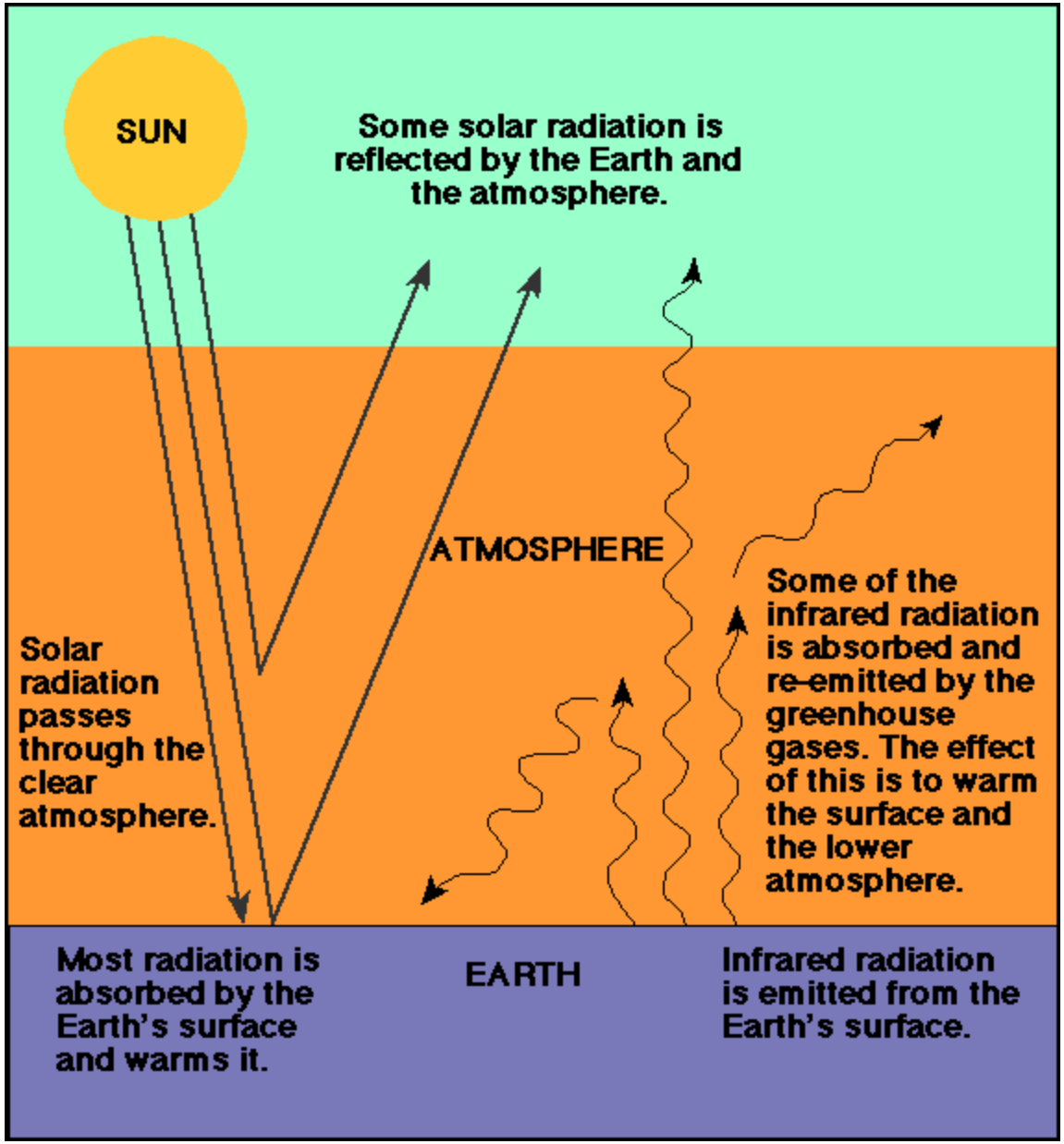
Computer models based on our best understanding of processes that control climate



UNEP | GRID Arendal

United Nations Environment Programme / GRID-Arendal

Greenhouse Effect



(GHG are not all bad -- without any GHGs earth would be 33^{o} C colder!)

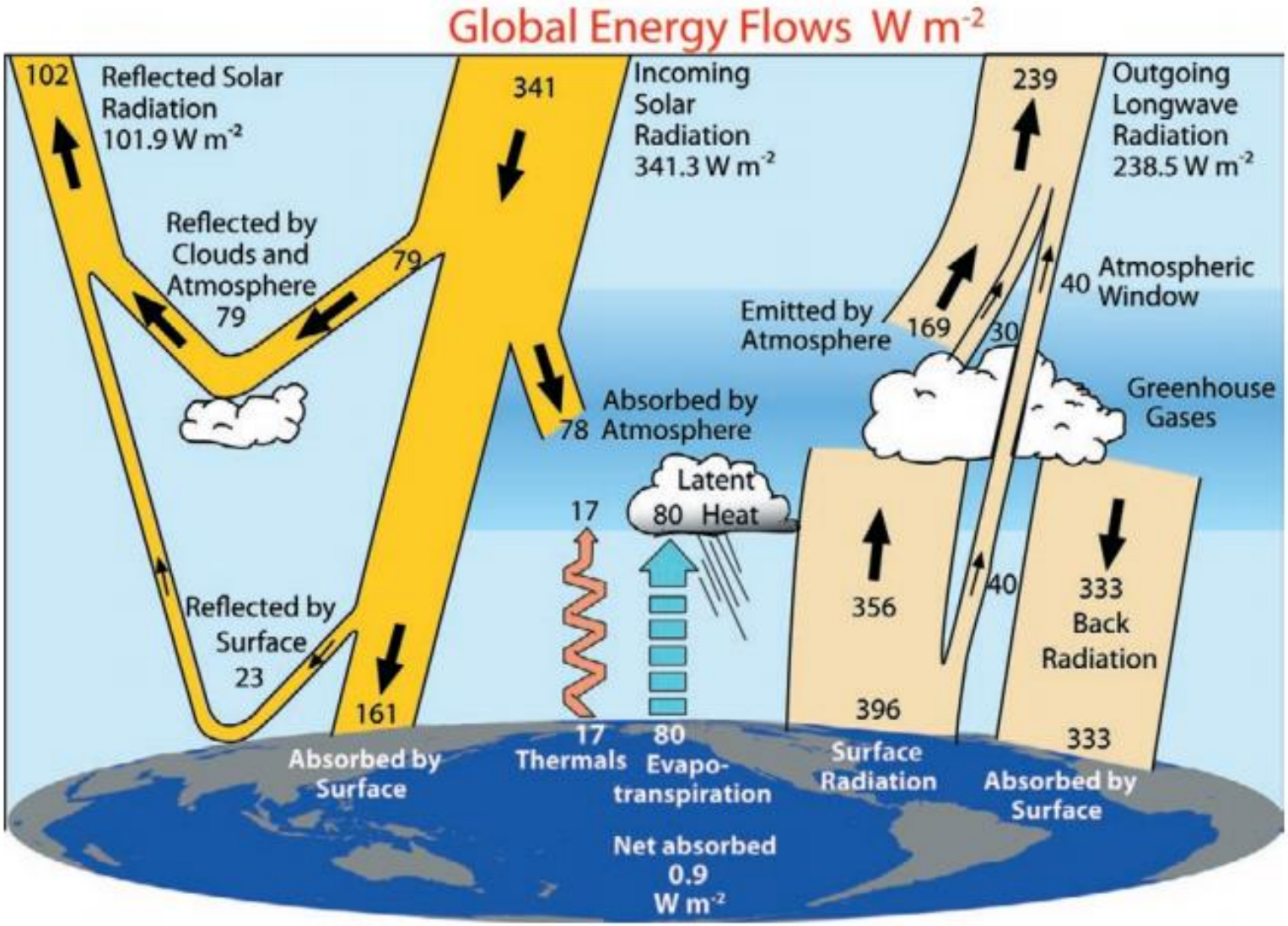
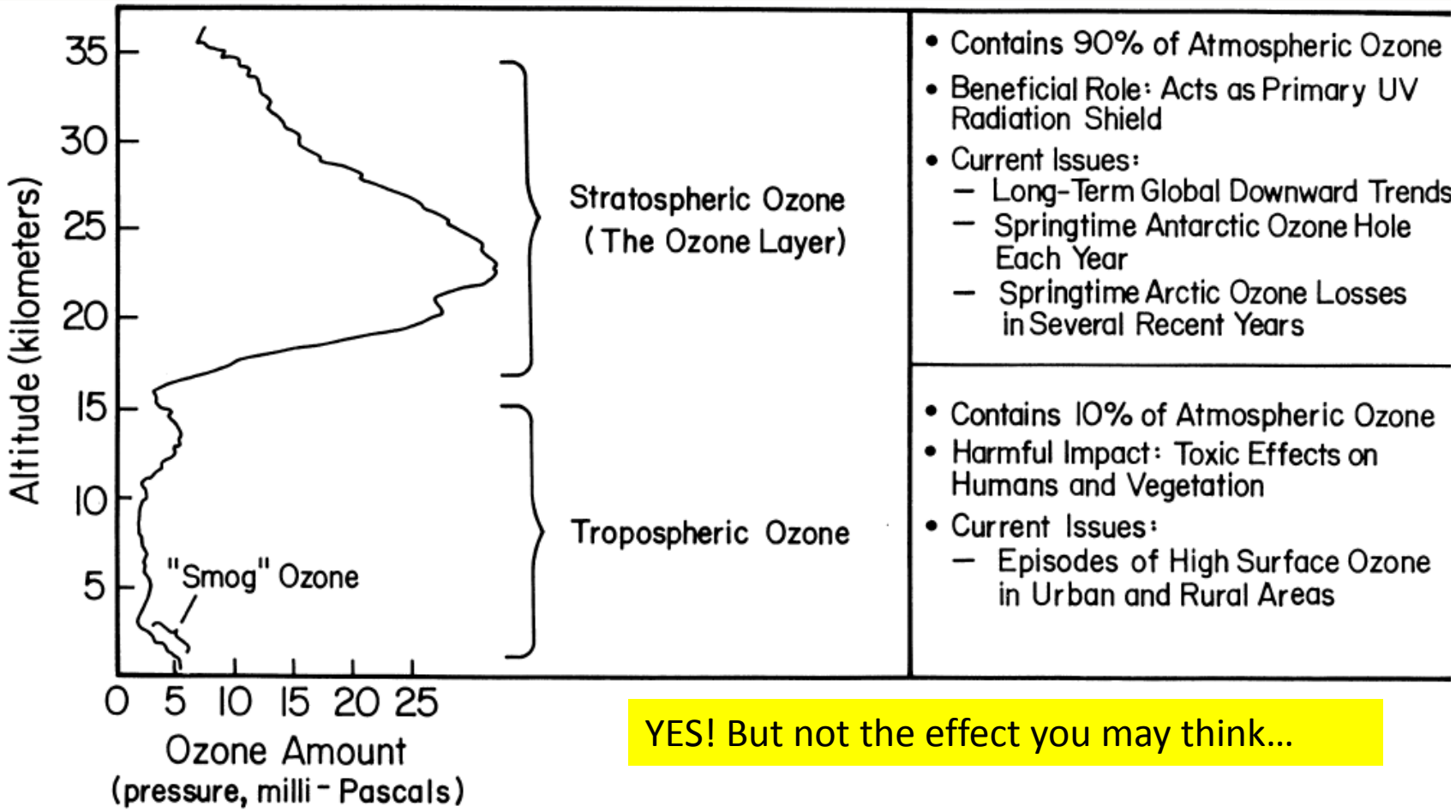


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Trenberth, Fasullo, and Kiehl 2009

What about the hole in the ozone? Doesn't it have an effect on warming?

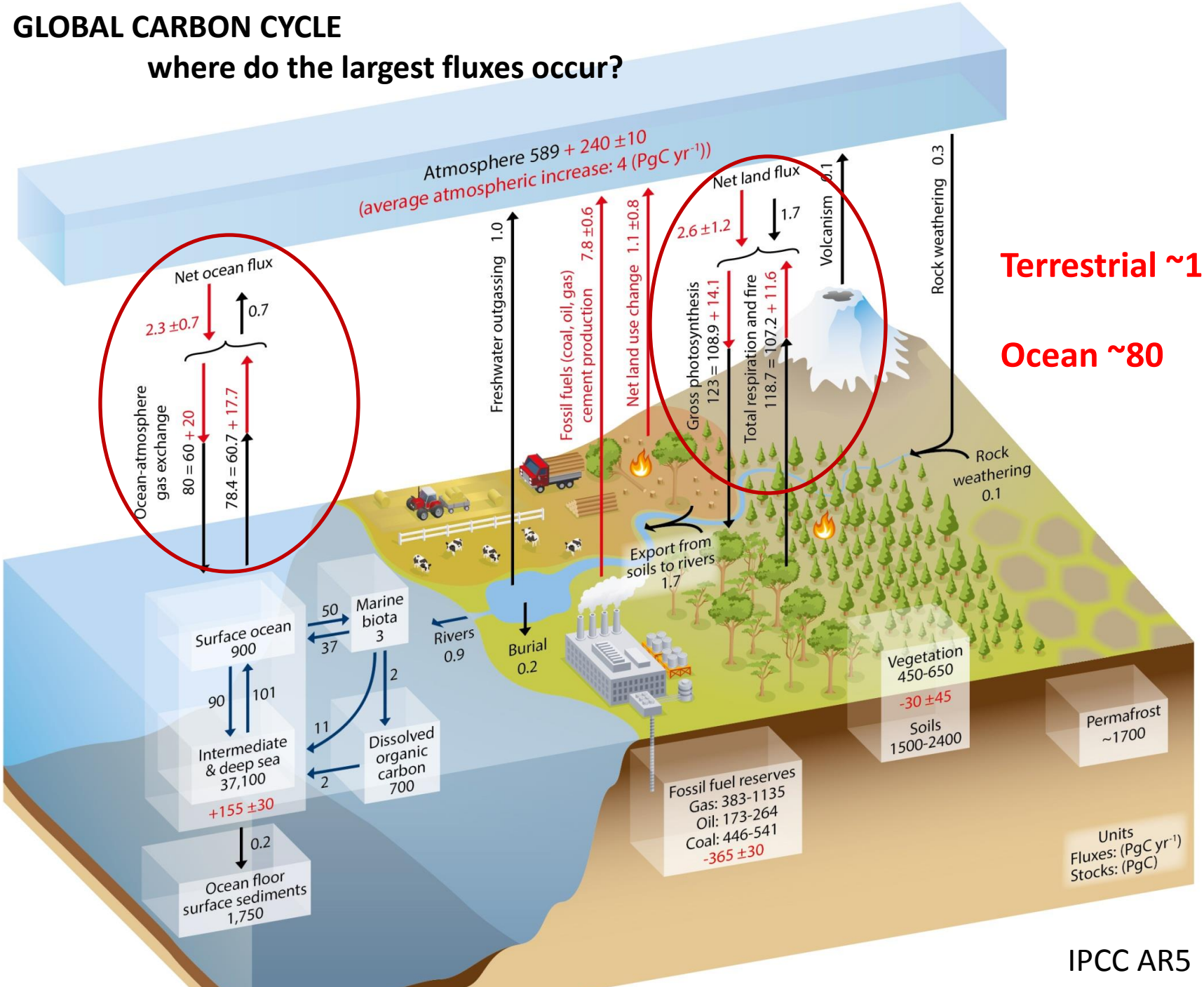


YES! But not the effect you may think…

Ozone generates heat in the stratosphere, both by absorbing the sun's ultraviolet radiation and by absorbing upwelling infrared radiation from the lower atmosphere (troposphere). Consequently, decreased ozone in the stratosphere results in lower temperatures. Observations show that over recent decades, the mid to upper stratosphere (from 30 to 50 km above the Earth's surface) has cooled by 1° to 6° C (2° to 11° F). This stratospheric cooling has taken place at the same time that greenhouse gas amounts in the lower atmosphere (troposphere) have risen.

GLOBAL CARBON CYCLE

where do the largest fluxes occur?

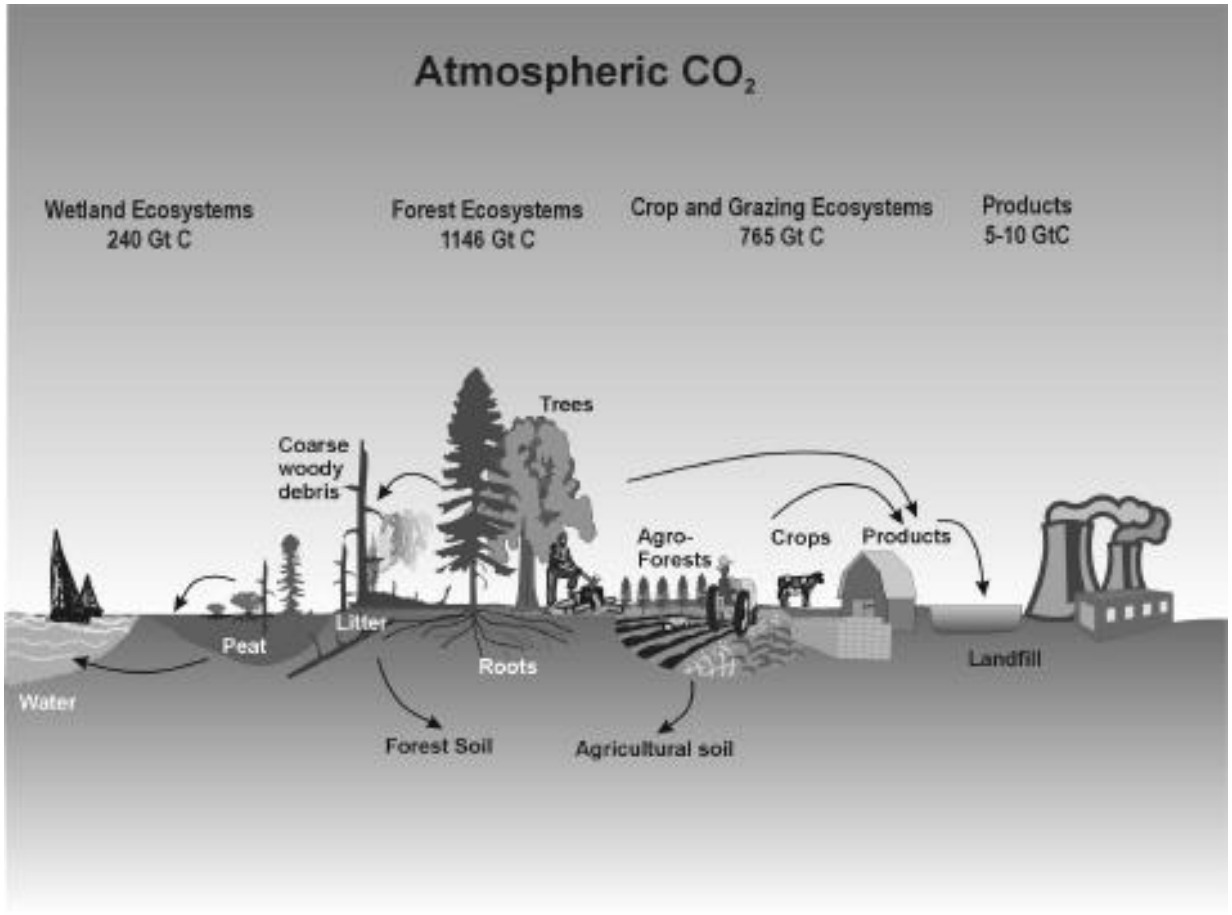


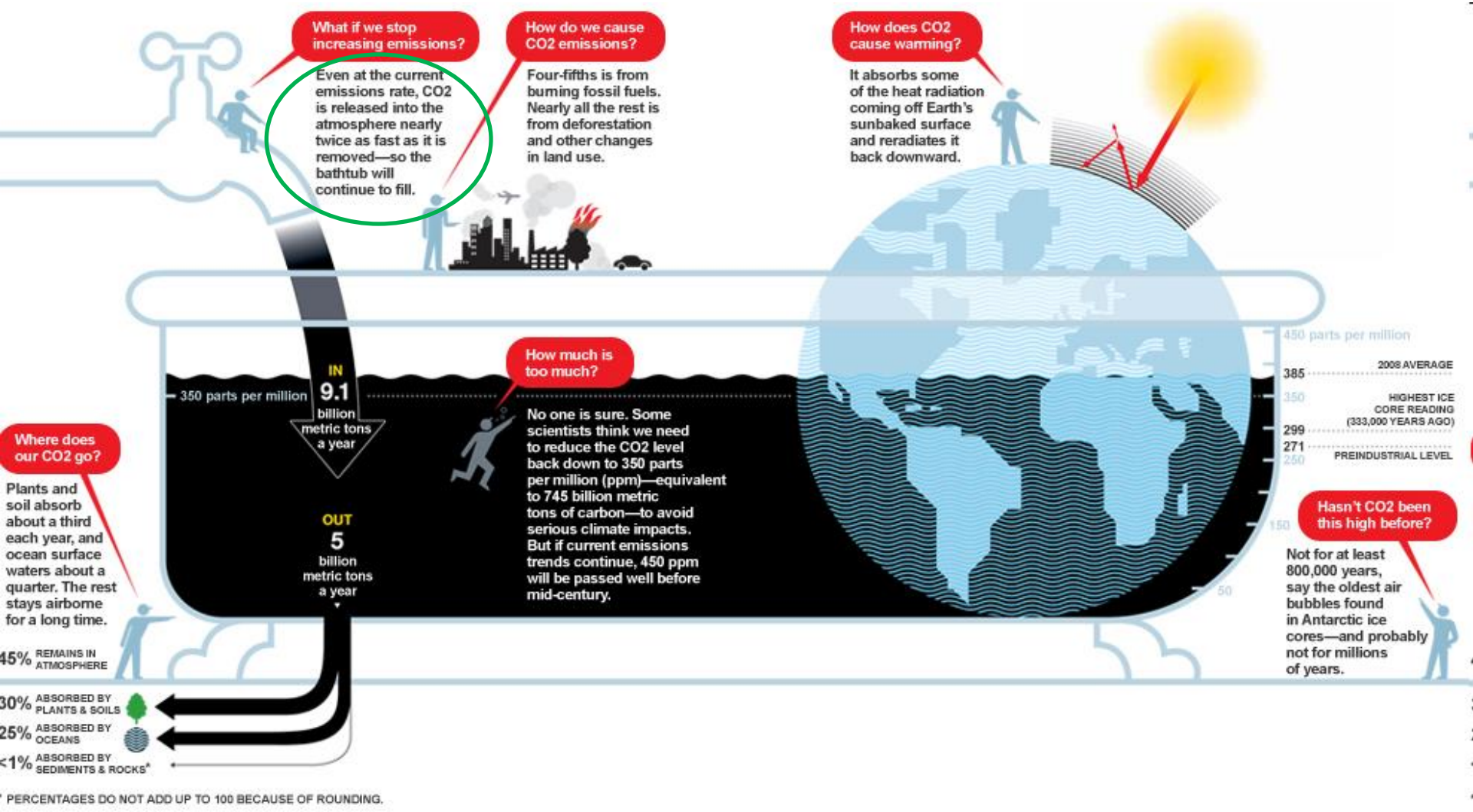
Terrestrial ~120

Ocean ~80

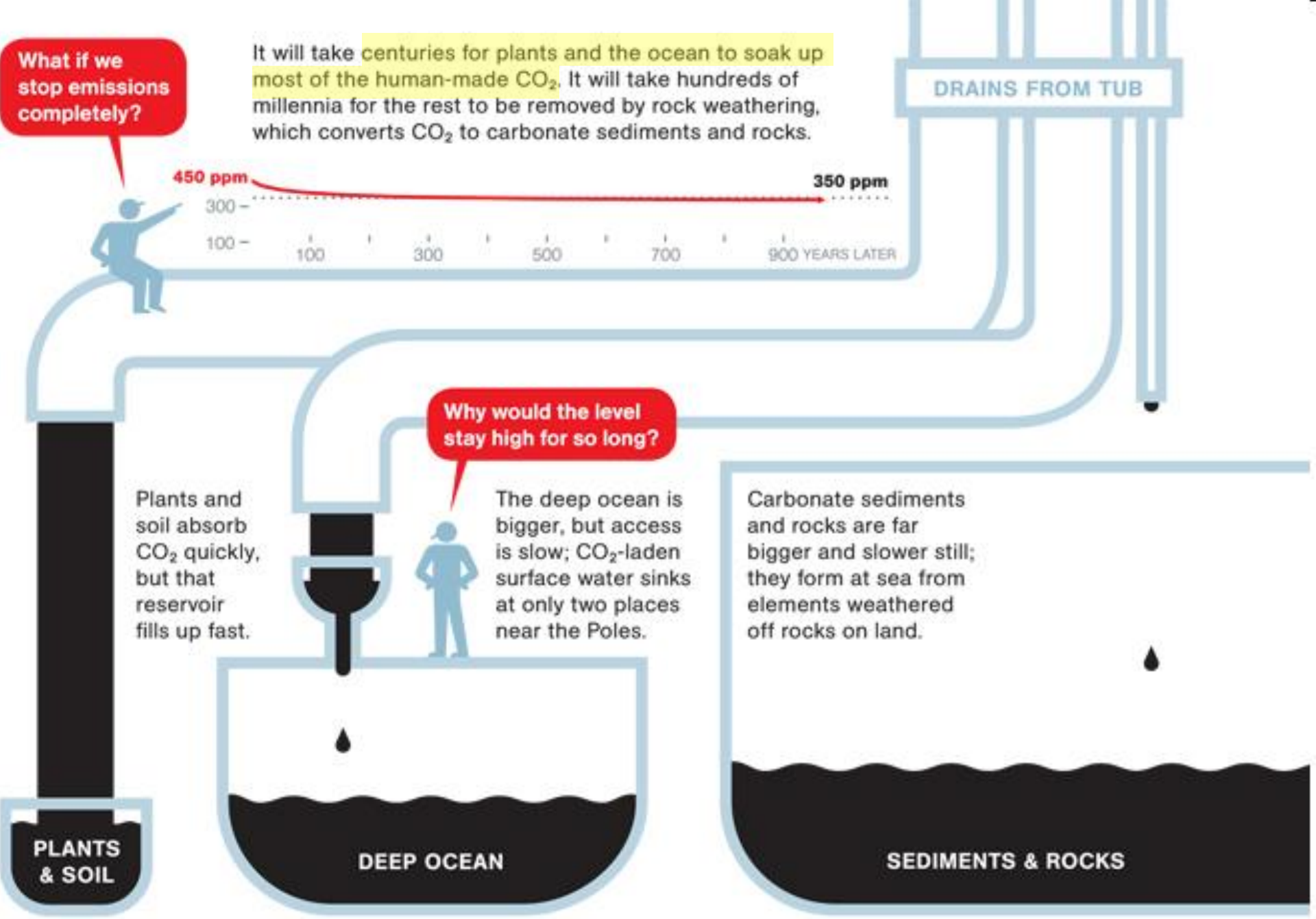
IPCC AR5

Even though our planet is ~75% water, the largest movement of carbon (flux) actually happens between the terrestrial ecosystem and the atmosphere (the greatest percent of that is cycled through forest systems).

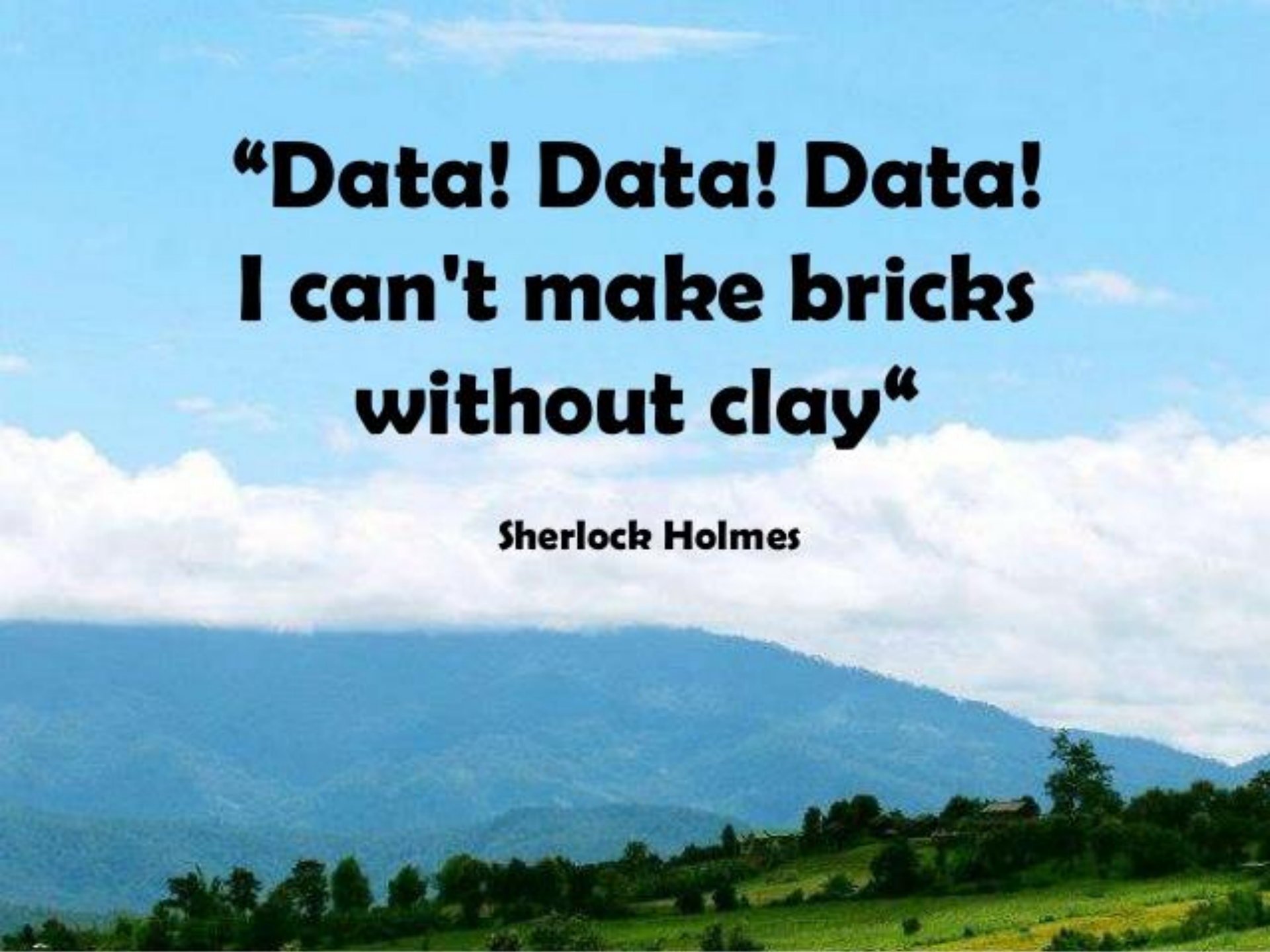


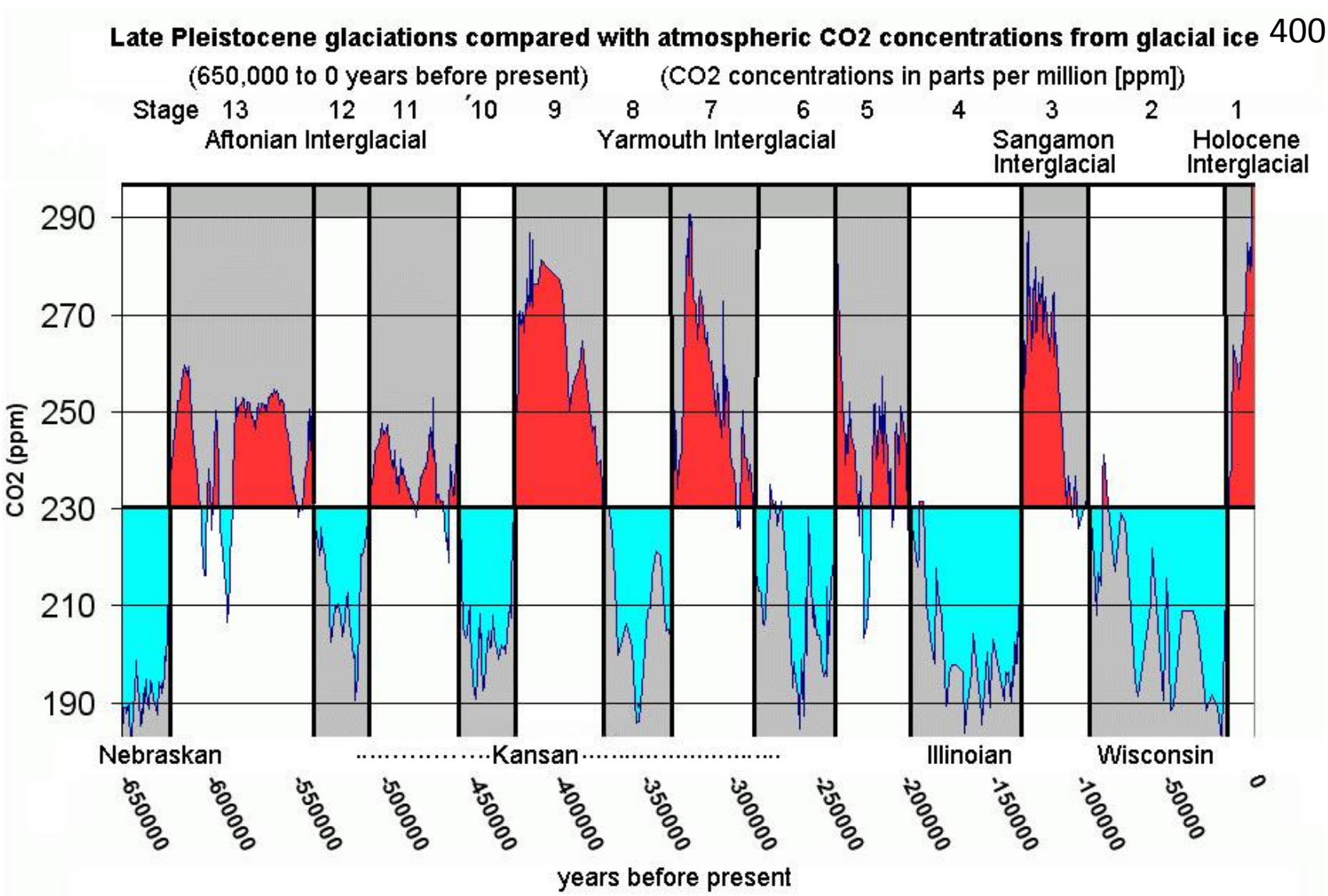


National Geographic, 2009



National Geographic, 2009

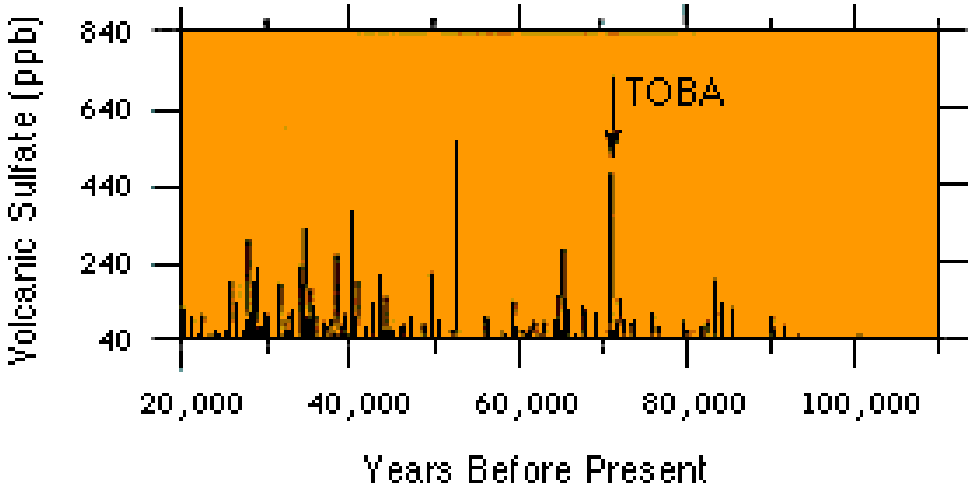

“Data! Data! Data!
I can't make bricks
without clay“
Sherlock Holmes



"The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions." IPCC AR5

How do we measure the gases that were in the atmosphere tens of thousands of years ago?

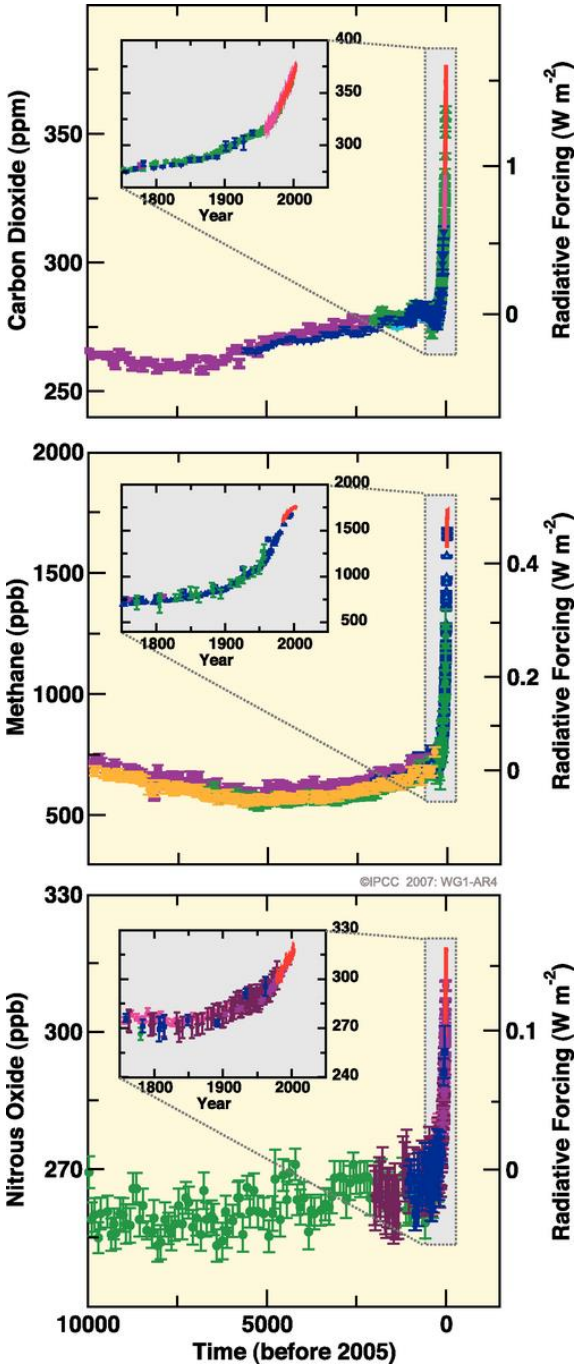
Ice cores can provide atmospheric gas/dust/aerosol data for approximately the past 1 million years – beyond that we depend on the geologic record to approximate climate (through geologic record and stable isotope data)



Evidence of past eruptions

(Toba was the largest eruption In the past 500,000 years)

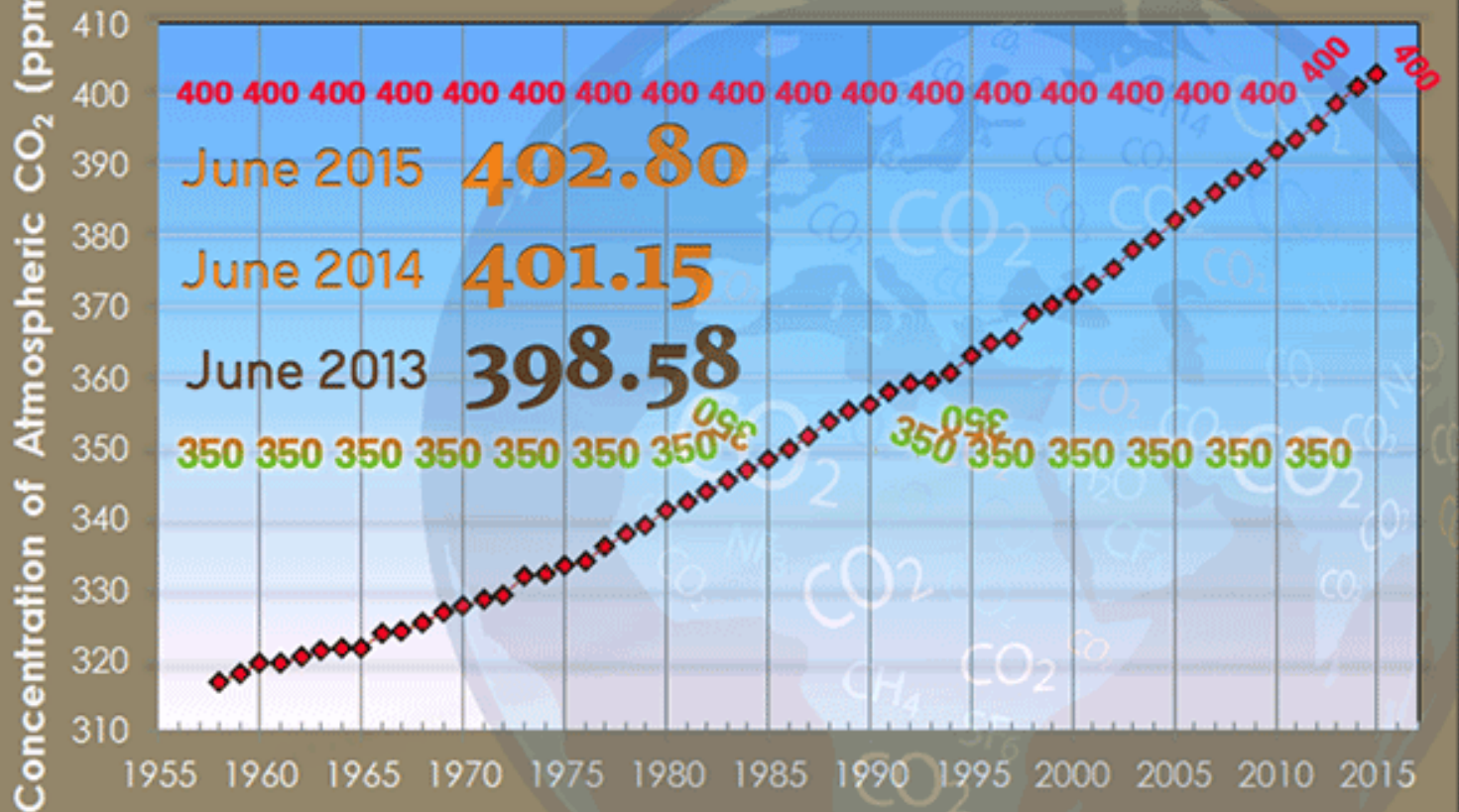
Gas data collected from ice cores



August 1958 – June 2015

Atmospheric CO2

June CO_2 | Year Over Year | Mauna Loa Observatory



CO2Now.org

Featuring NOAA-ESRL data of July 9, 2014

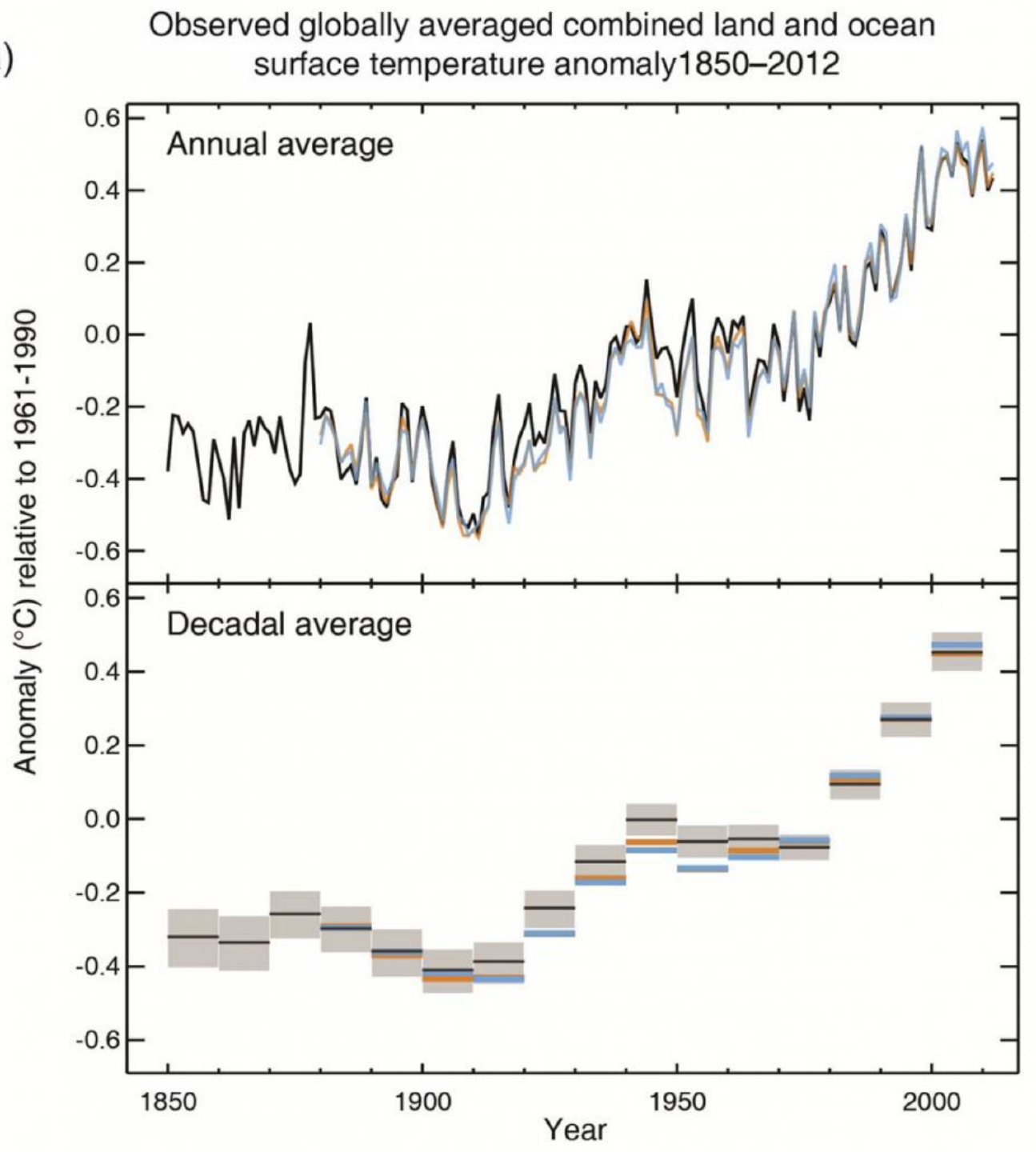
CO_2 Data Set: Original CO2 data files dated: **Wednesday July 8, 2015 (NOAA)**

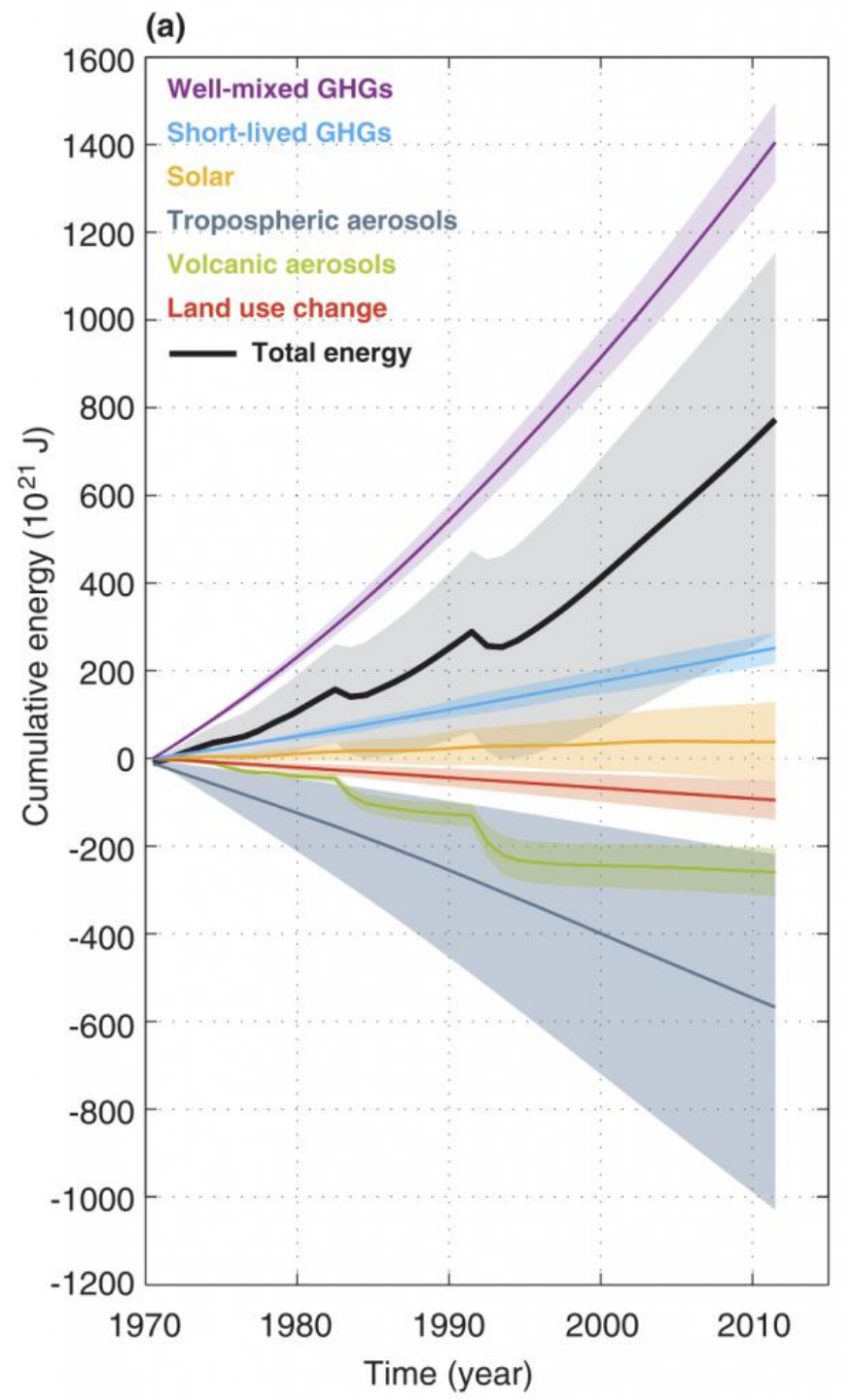
Field notes from a catastrophe

(title stolen from book by E. Kolbert)

The warming is unequivocal

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia."
IPCC AR5

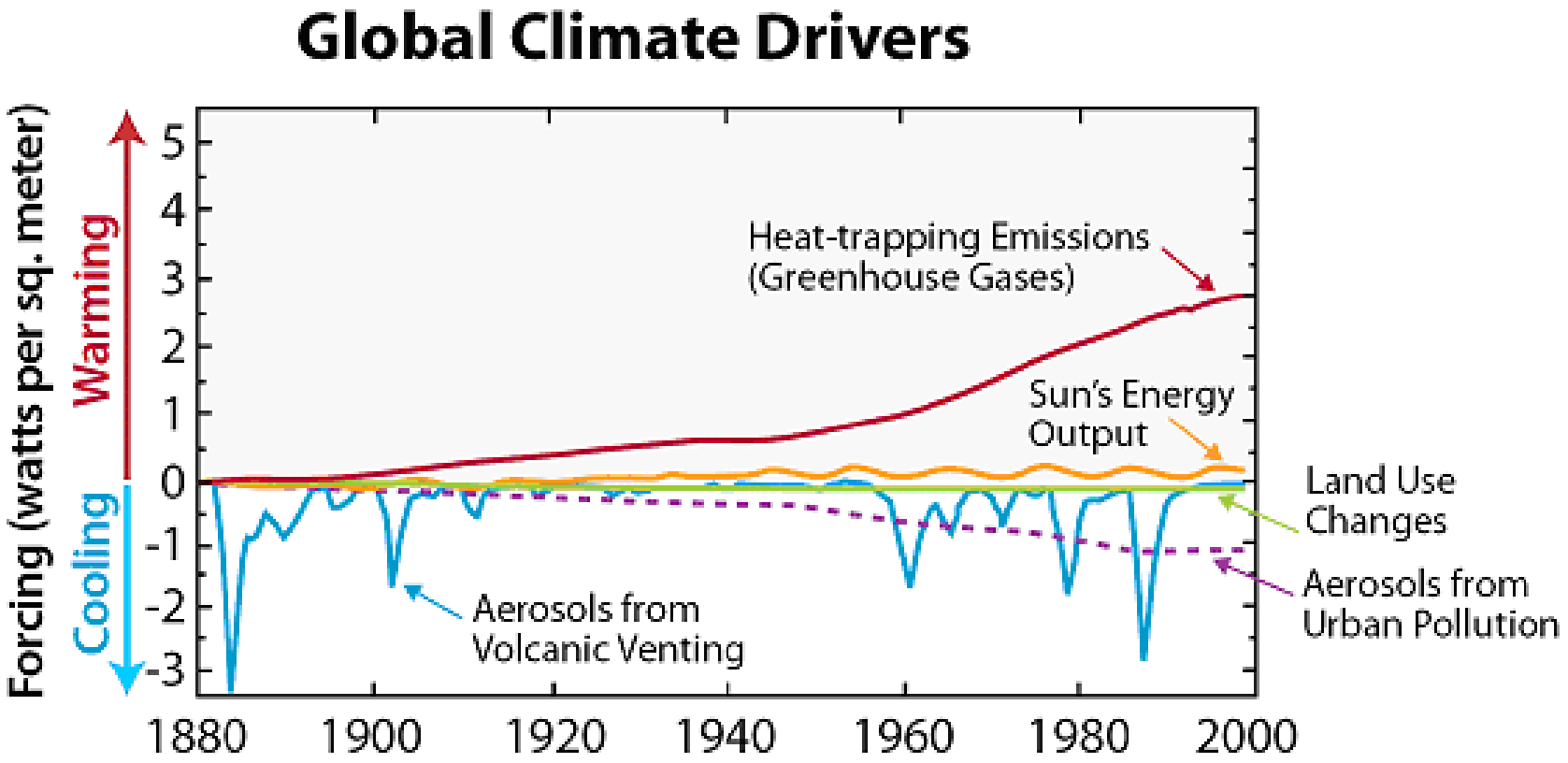




Humans caused the majority of it

"It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century".

IPCC AR5



Relative contribution of elements of radiative forcing

Hansen, J., L. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. Del Genio, D. Koch, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G.A. Schmidt, and N. Tausnev. 2005. Earth's energy imbalance: Confirmation and implications. Science 308:1431-1435.

MANY different scenarios of our future were modeled, IPCC chose four representative possibilities:

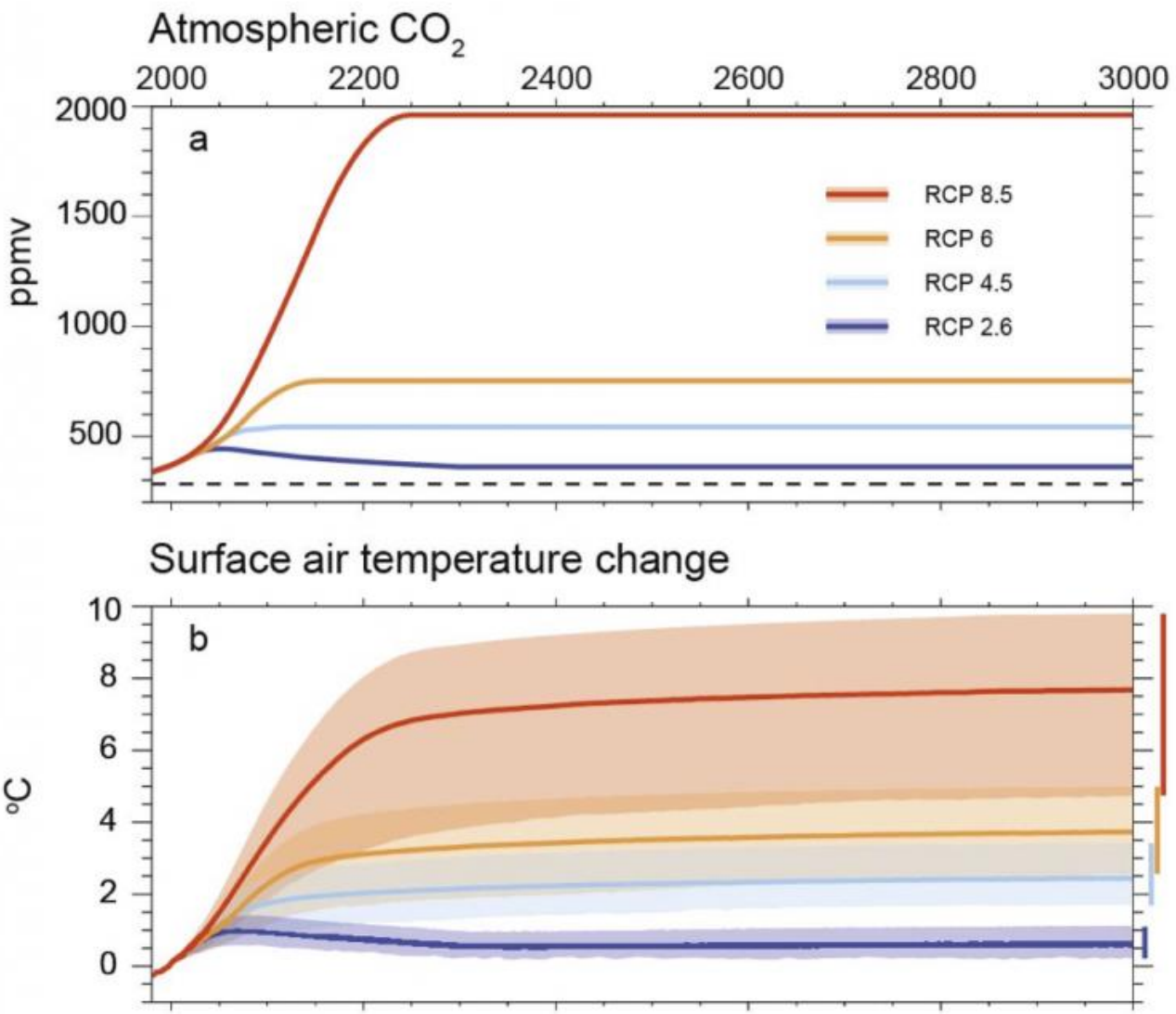
RCP8.5 represents 'business as usual' – strong economic development for the rest of this century, driven primarily by dependence on fossil fuels.

RCP6 represents a world with no global coordinated climate policy, but where lots of localized clean energy initiatives do manage to stabilize emissions by the latter half of the century.

RCP4.5 represents a world that implements strong limits on fossil fuel emissions, such that greenhouse gas emissions peak by mid-century and then start to fall.

RCP2.6 is a world in which emissions peak in the next few years, and then fall dramatically, so that the world becomes carbon neutral by about mid-century.

The warming is largely irreversible



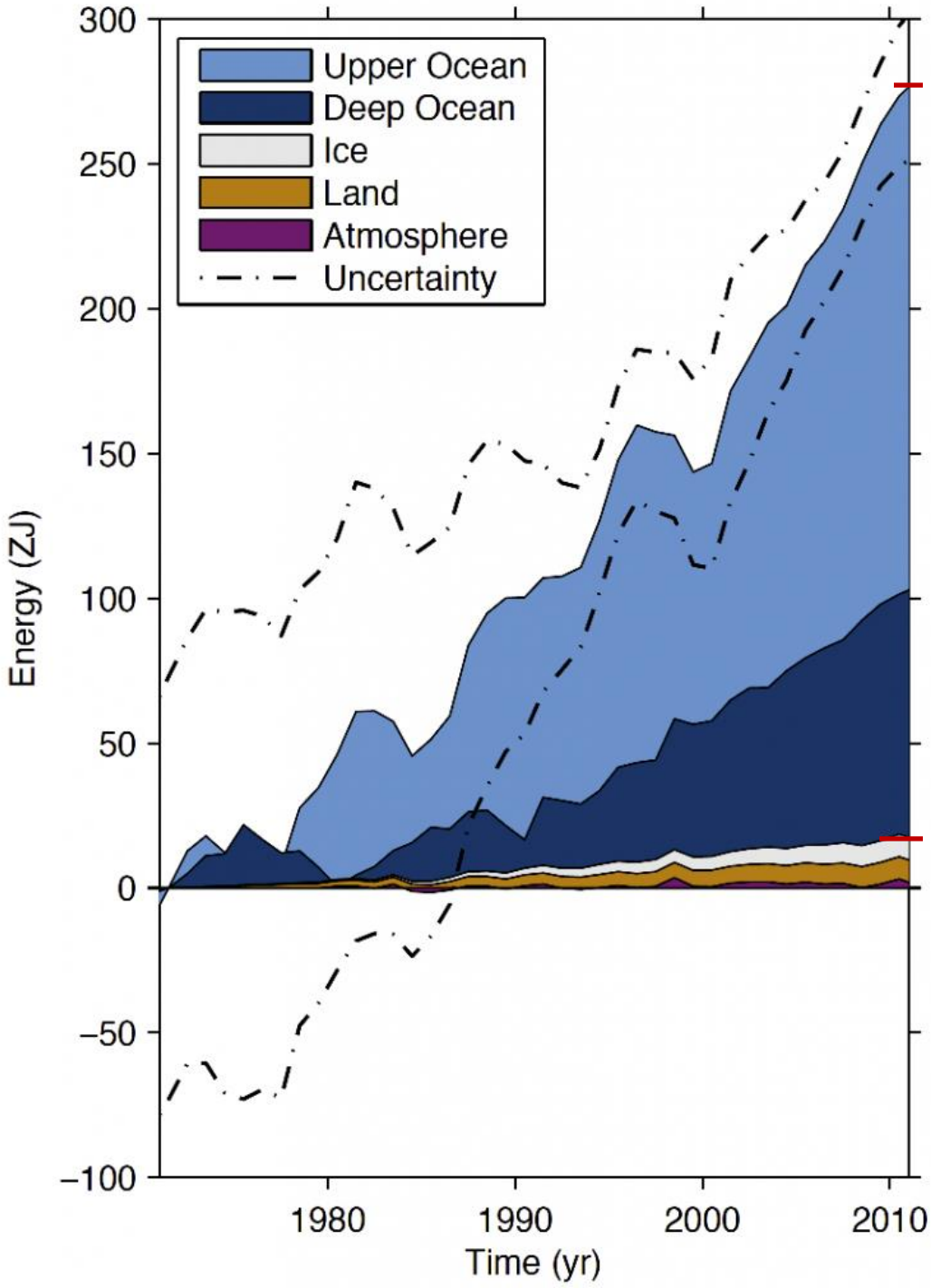
"A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions."

Much of this warming (energy) is stored in the ocean water

The oceans have a huge thermal mass compared to the atmosphere and land surface. They act as the planet's heat storage and transportation system, as the ocean currents redistribute the heat. This is important because if we look at the global surface temperature as an indication of warming, we're only getting some of the picture. The oceans act as a huge storage heater, and will continue to warm up the lower atmosphere (no matter what changes we make to the atmosphere in the future).

According to this figure, what percent of warming is stored by the oceans?

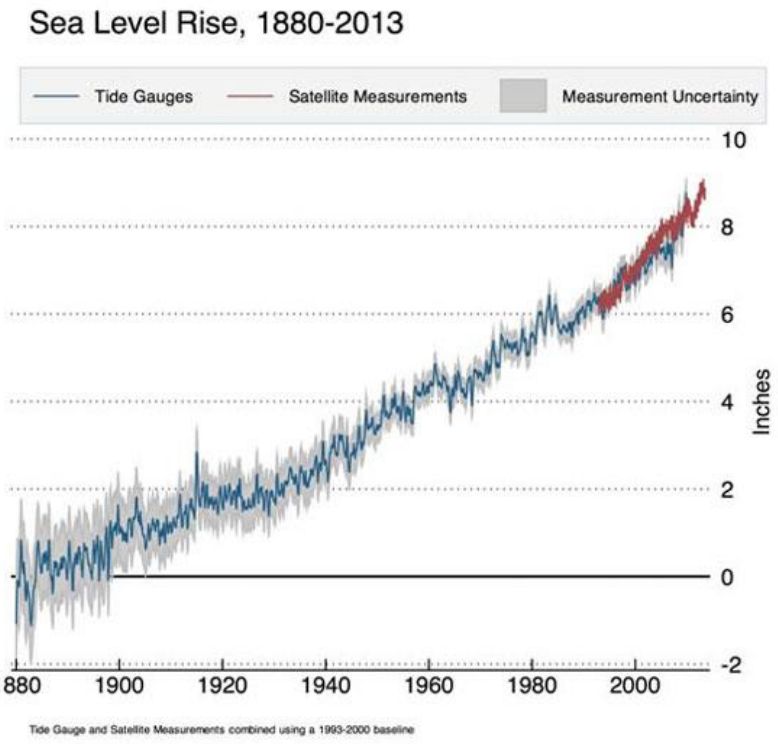
~85%

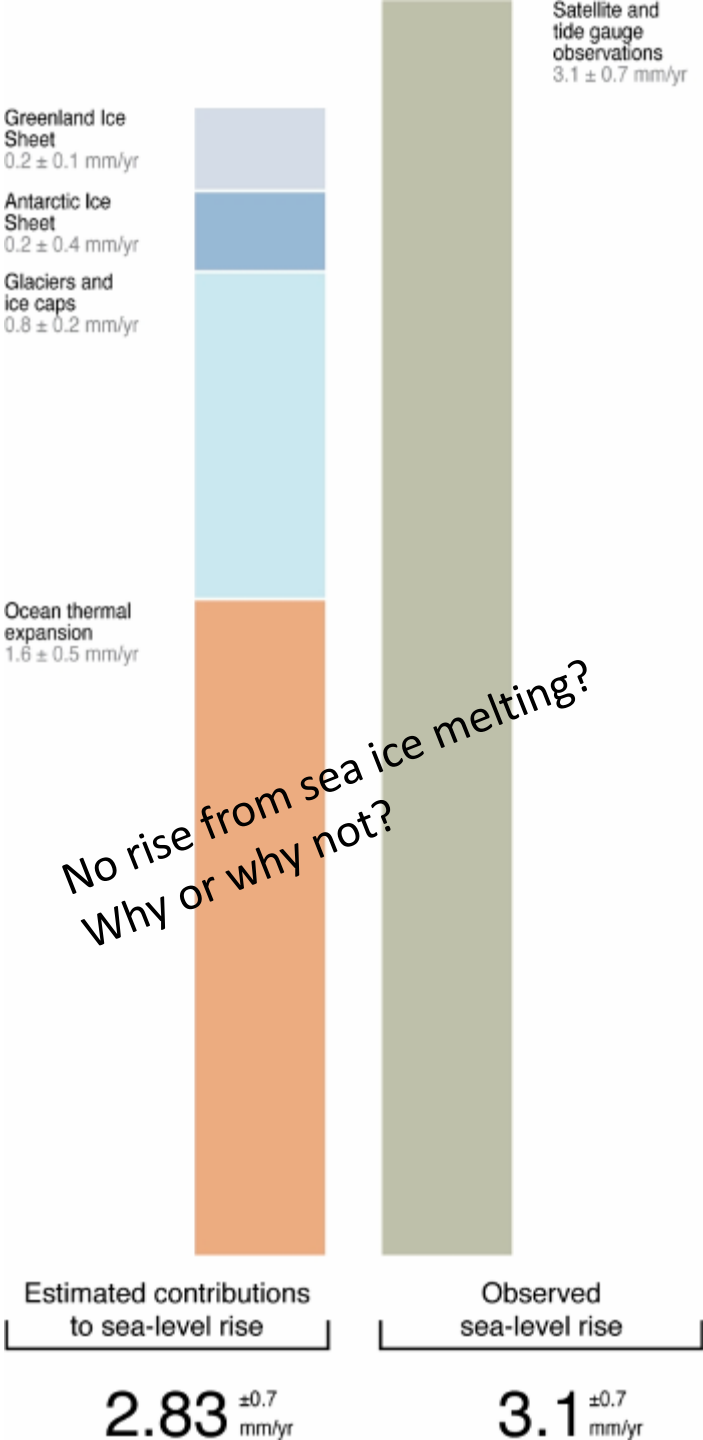


This stored heat/energy is also impacting average global sea level

Which of the following has the largest impact on sea level rise?

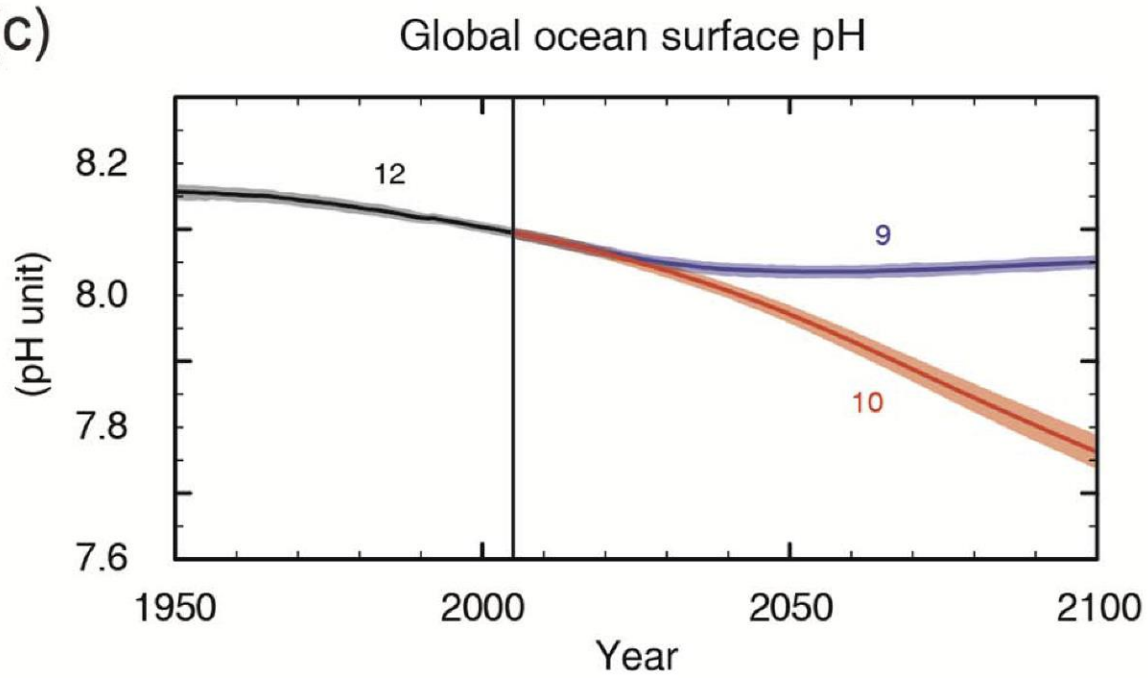
a. Melting of glaciers
b. Melting of ice sheets
c. Melting of sea ice
d. Thermal expansion of ocean





Current rates of ocean acidification are unprecedented.

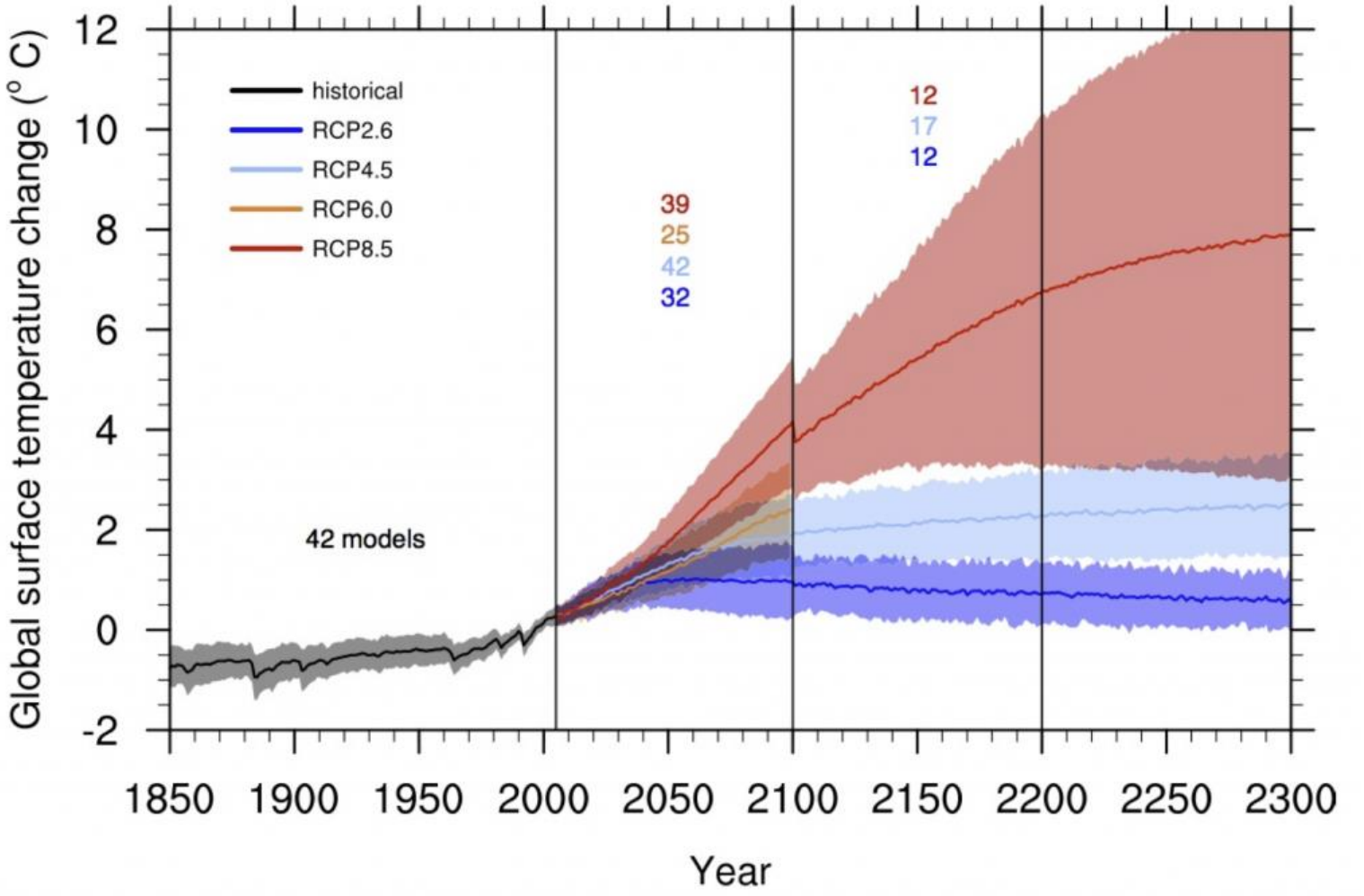
"The pH of seawater has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26% increase in hydrogen ion concentration. … It is virtually certain that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades. … Estimates of future atmospheric and oceanic carbon dioxide concentrations indicate that, ***by the end of this century, the average surface ocean pH could be lower than it has been for more than 50 million years****"*.



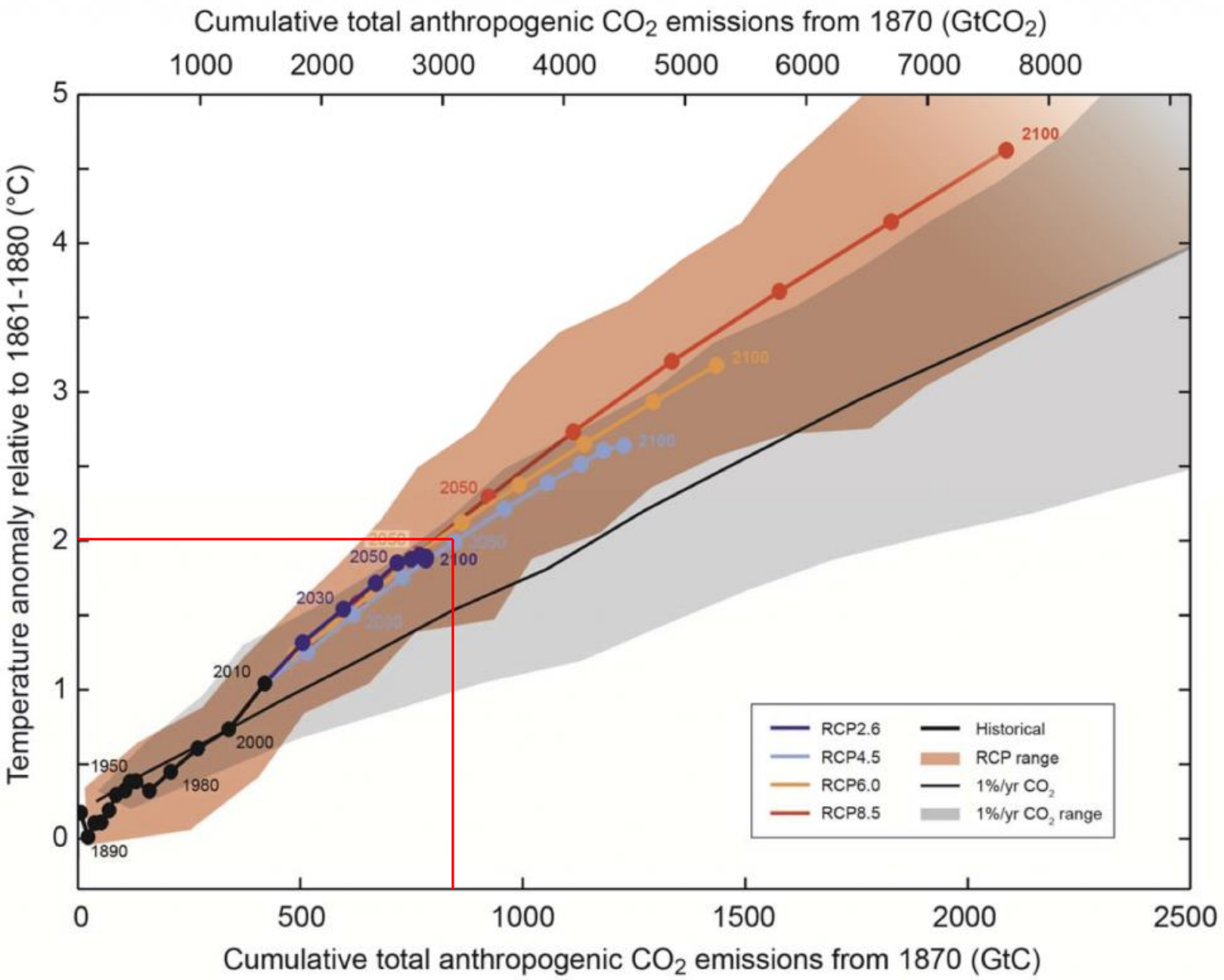
"We balance probabilities and choose the most likely. It is the scientific use of the imagination"

A. Conan Doyle. The Hound of the Baskervilles (1902)

The models are clear, 'business as usual' isn't pretty



To stay below 2°C of warming, most fossil fuels must stay buried in the ground.



To give us a 33% chance of staying below 2°C of warming over pre-industrial levels, we cannot ever emit more than 880 gigatonnes of Carbon.

To give us a 50% chance, we cannot ever emit more than 840 gigatonnes of Carbon.
To give us a 66% chance, we cannot ever emit more than 800 gigatonnes of Carbon.

HOW MUCH HAVE WE EMITTED SO FAR?

Since the beginning of industrialization, we have already emitted a little more than 500 GT. So our remaining budget is somewhere between 300 and 400 GT. Existing known fossil fuel reserves are enough to release at least 1000 GT!

New discoveries and unconventional sources will likely more than double this. That leads to one inescapable conclusion:

To stay below the agreed upon 2C warming target, most of the remaining fossil fuel reserves must stay buried in the ground.