

03-Emissions

ECEGR 4530
Renewable Energy Systems



Overview

- Solar Spectrum
- Atmospheric Effects
- Greenhouse Gases
- Global Warming
- CO₂ Emissions
- Emissions Calculations
- Other Emissions

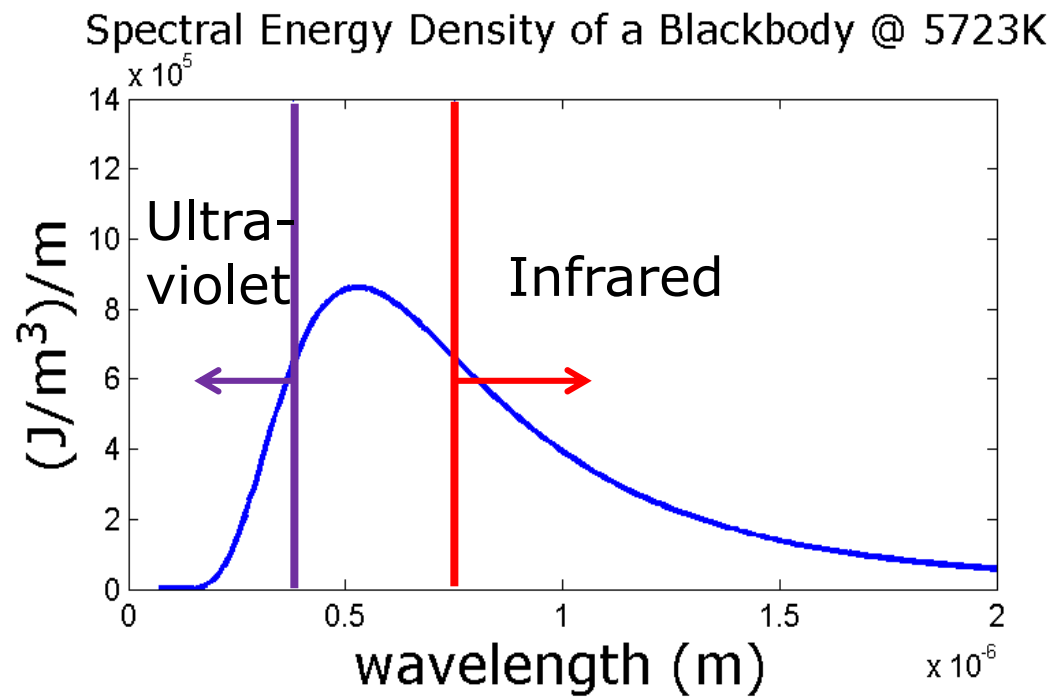


Solar Spectrum

- What is the frequency of solar radiation?
 - Determined by Planck's Law
 - Relates temperature to energy at each frequency



Solar Spectrum





Solar Spectrum

- Energy is distributed across a spectrum of frequencies (or wavelengths)

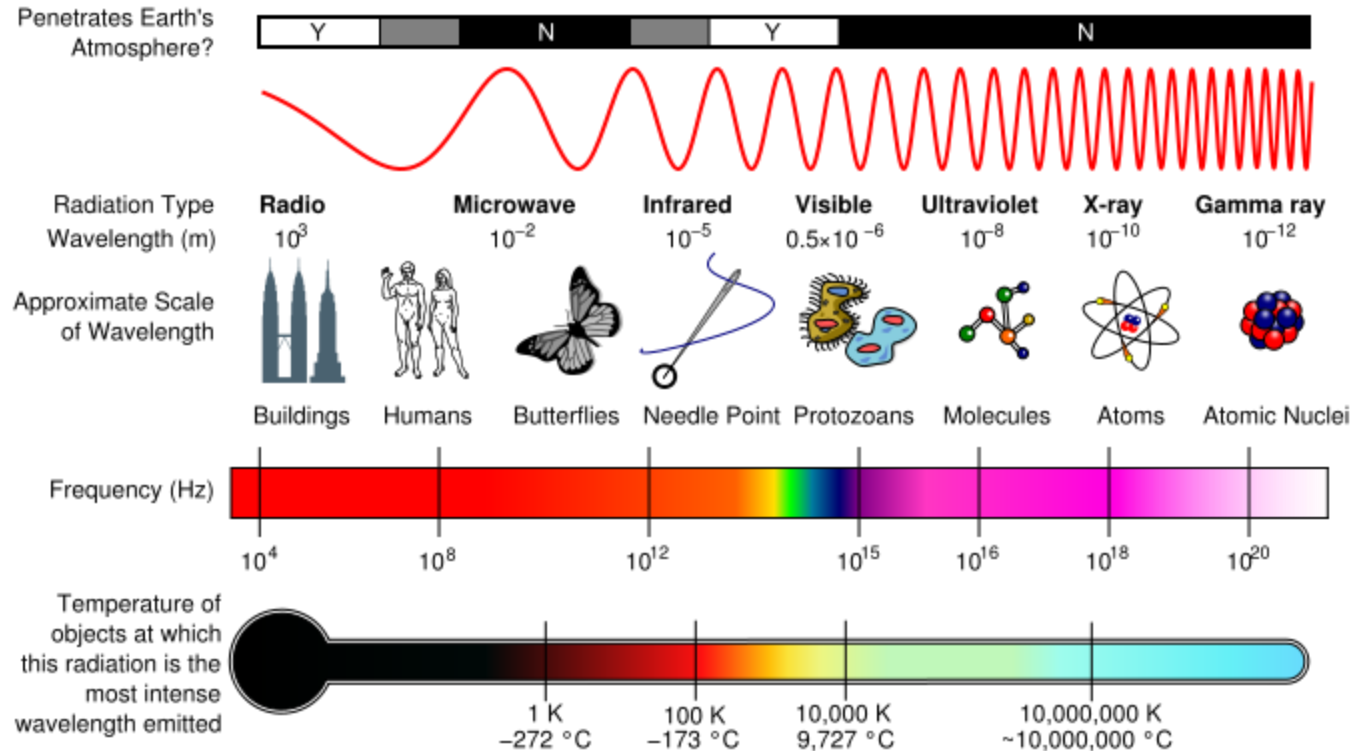
$$f = \frac{c}{\lambda}$$

← speed of light
← wavelength

- Higher frequency radiation contains more energy



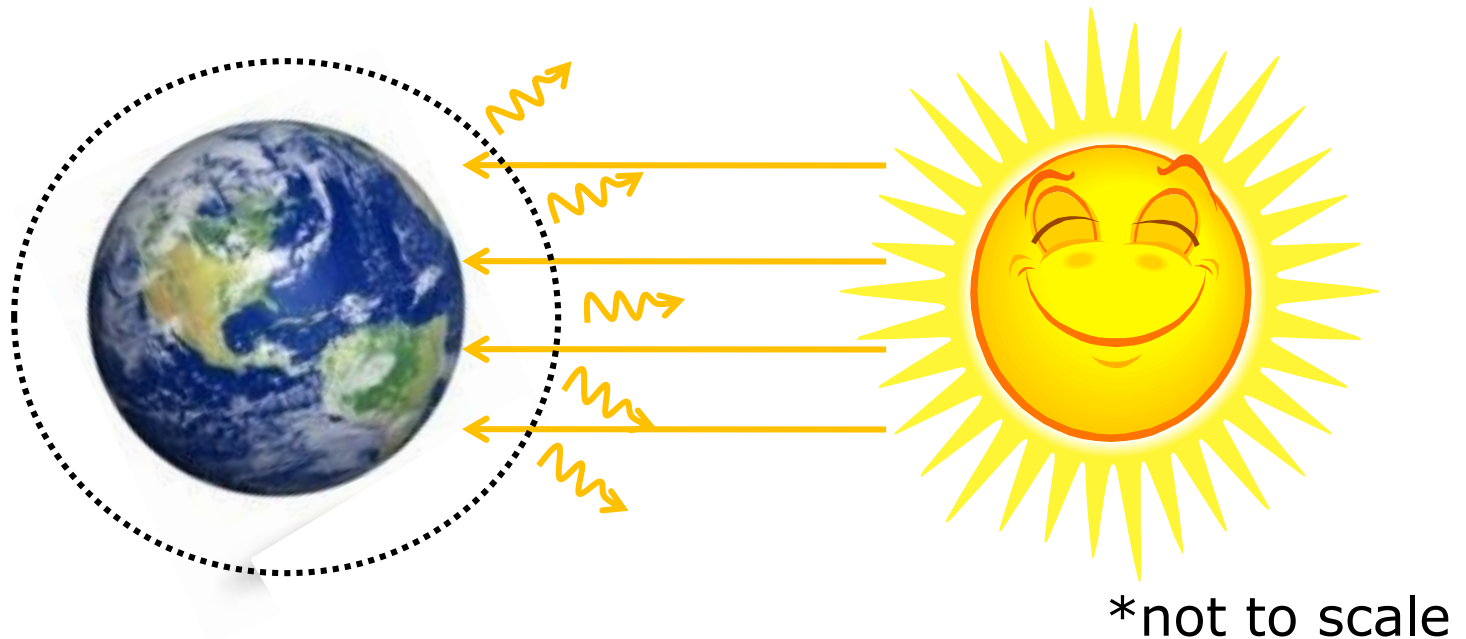
Solar Spectrum





Atmospheric Effects

- Earth receives radiation from the sun
 - Wide range of wave lengths: 250-5000 nm
- Atmosphere reflects about 30%
 - Not all wavelengths are reflected equally





Atmospheric Effects

top of the atmosphere

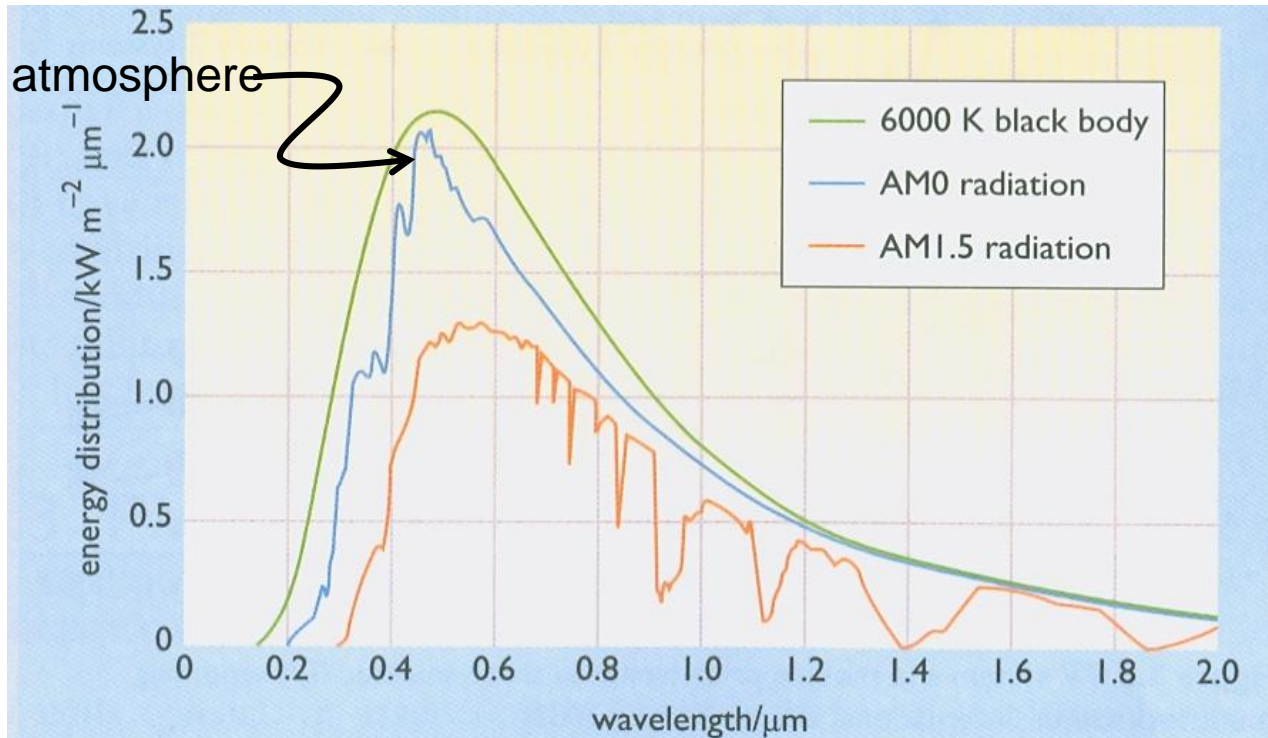


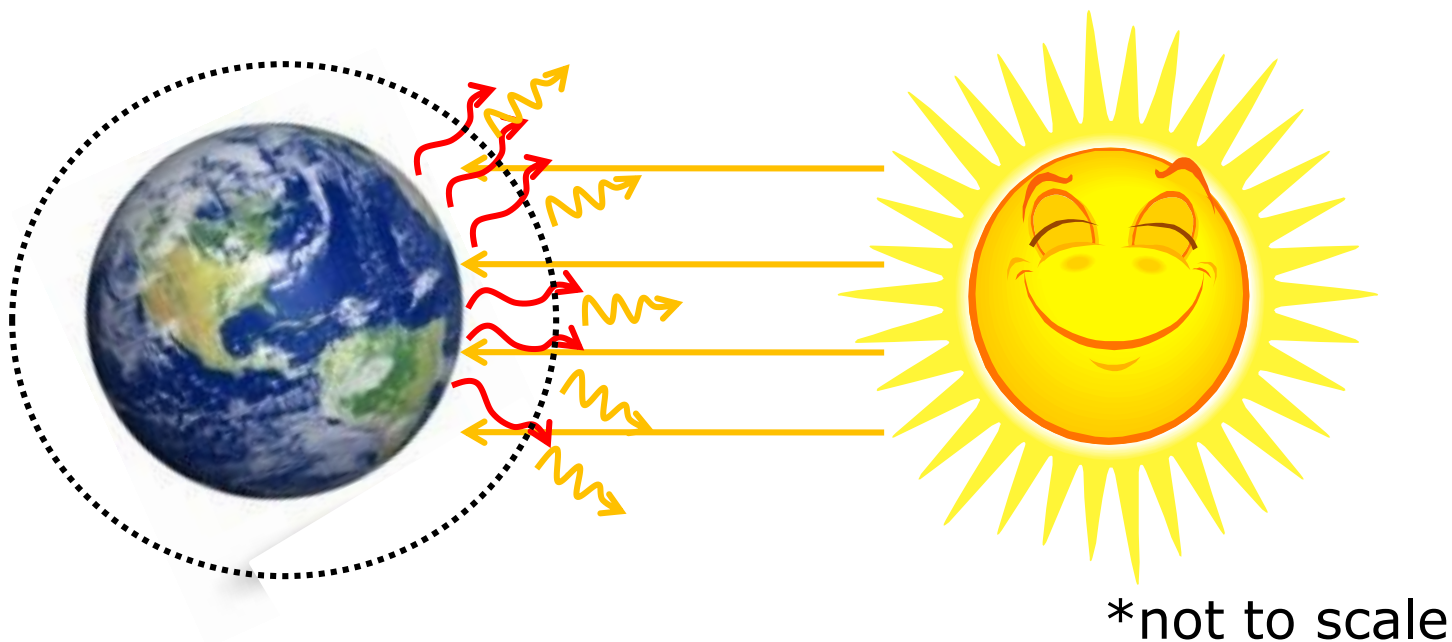
Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

Source: *Renewable Energy: Power for a Sustainable Future*, G. Boyle



Atmospheric Effects

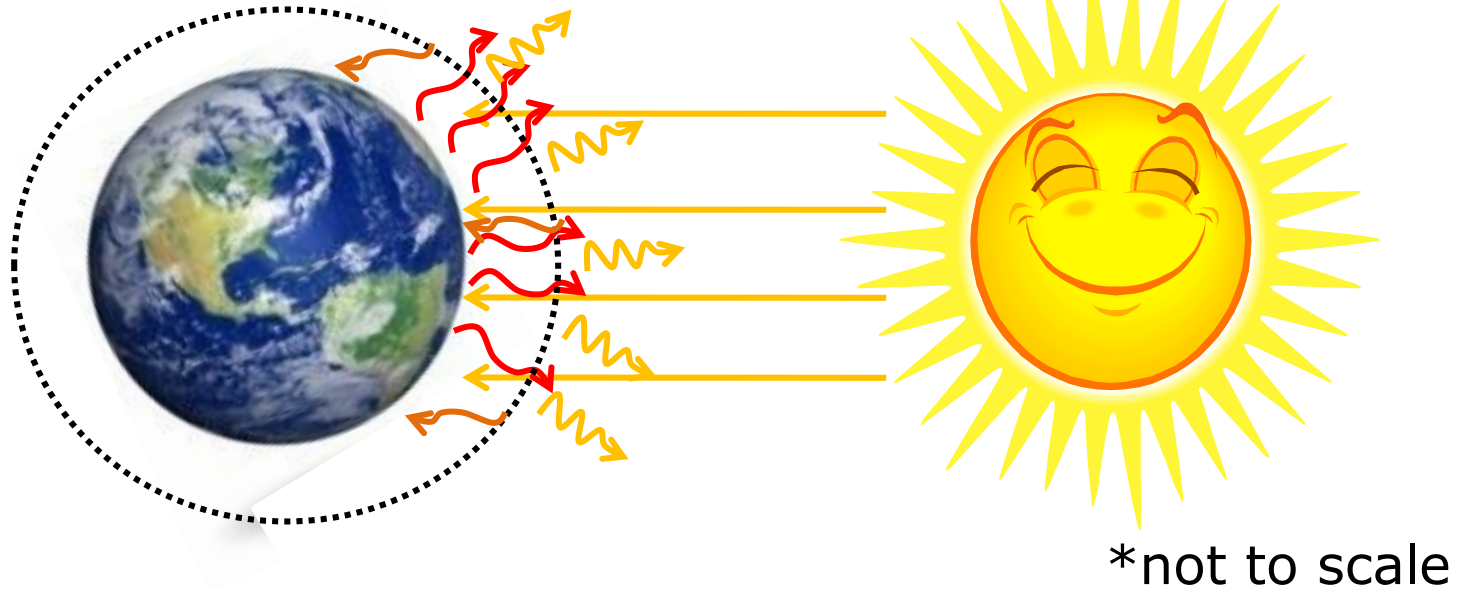
- Earth's surface heats and re-radiates heat back into space
 - Longwave infrared radiation





Atmospheric Effects

- Atmosphere blocks some of this radiation from being re-radiated back to space
- Average surface temperature
 - with atmosphere: 15 °C
 - without atmosphere: -18 °C





Greenhouse Gases

- Greenhouse gases: atmospheric gases that keep the longwave infrared radiation from escaping
- Common Greenhouse gases (GHG)
 - Water vapor (responsible for 60-80% of greenhouse effect)
 - Carbon dioxide (CO₂)
 - Methane
 - N₂O
 - Ozone



Greenhouse Gases

- Current CO₂ concentration ~ 400 ppm (parts per million)
 - increasing
 - 18th Century ~ 280 ppm
- Burning fossil fuels releases previously sequestered (buried) carbon into the atmosphere
 - Concentration of CO₂ increases



Global Warming

Global warming is a generalization in both space and time used to describe the rising trend in mean global temperature evident in many but not all analyses of near-surface temperature data-Timothy Casey



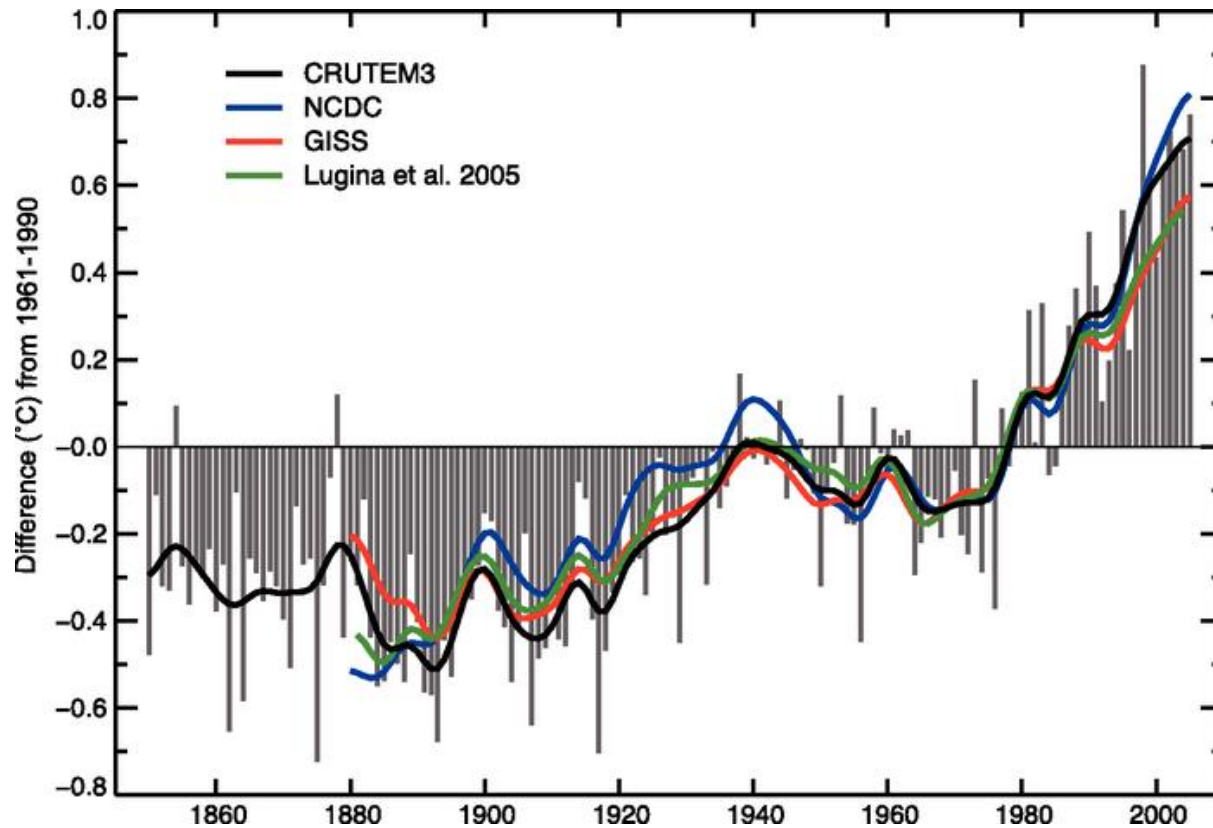


Global Warming

- Politically and scientifically contentious
- Is global warming happening?
 - How do you measure "warming"?
- What are the causes?
 - Anthropogenic?
 - Natural?
- What are the effects?
 - Desertification?
 - Rise in sea level?
 - Warmer in Seattle?
- What should be done?



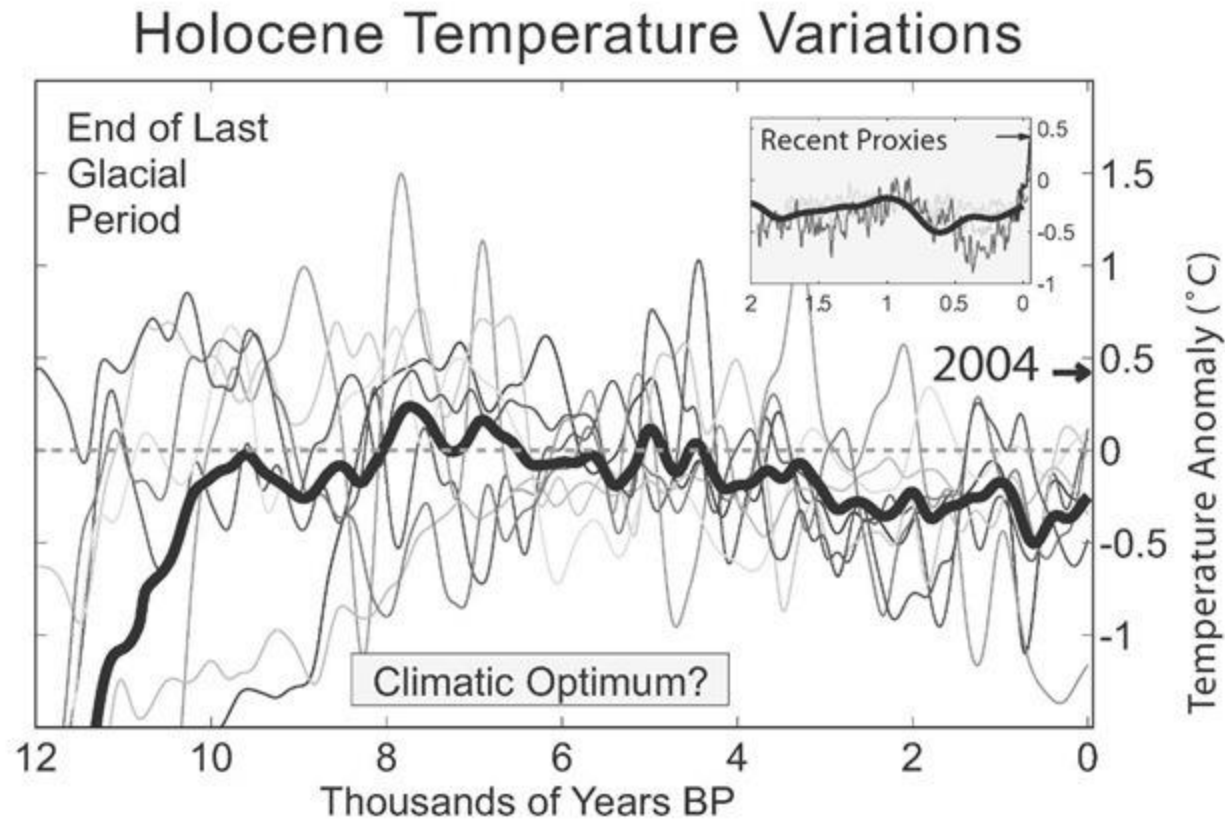
Global Temperature (Recent)



Source: IPCC Fourth Assessment Report

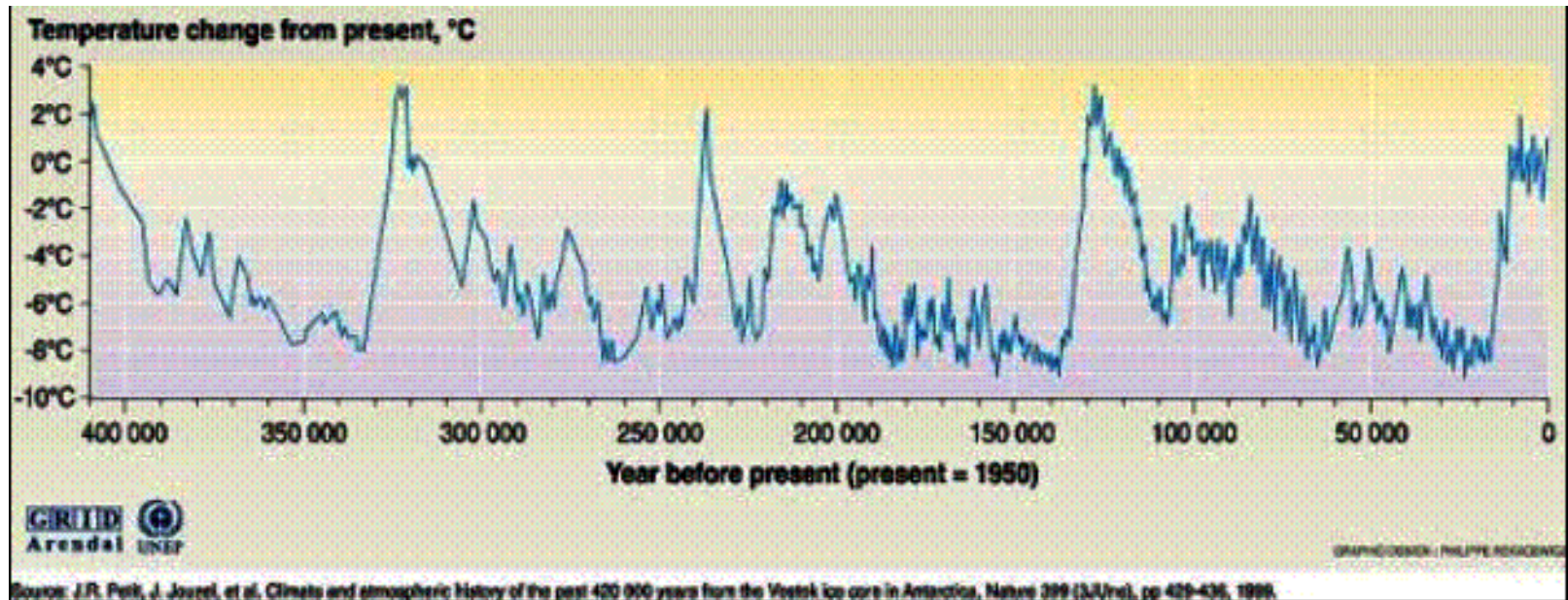


Global Temperature (Holocene)



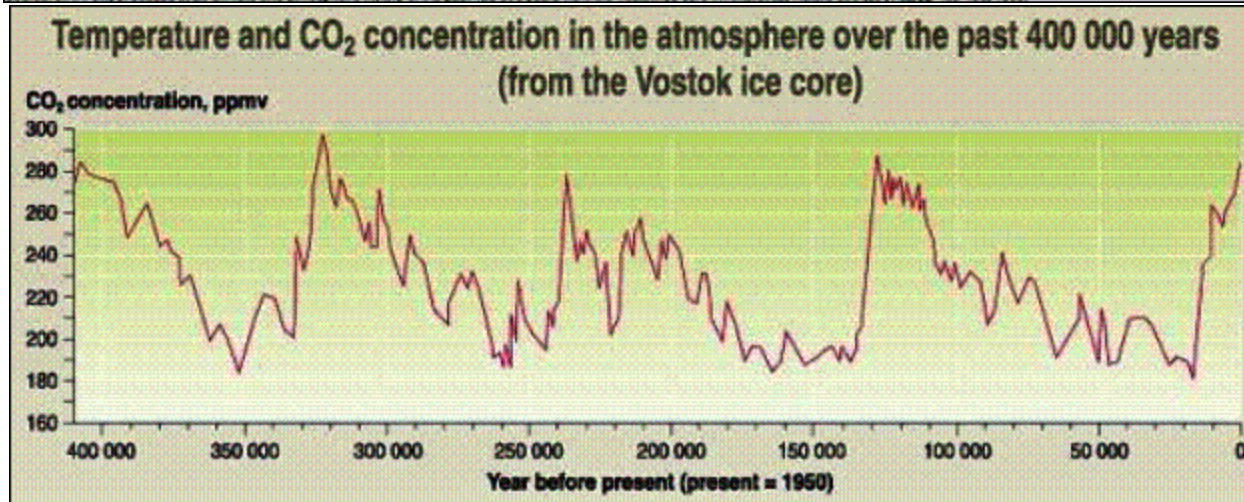
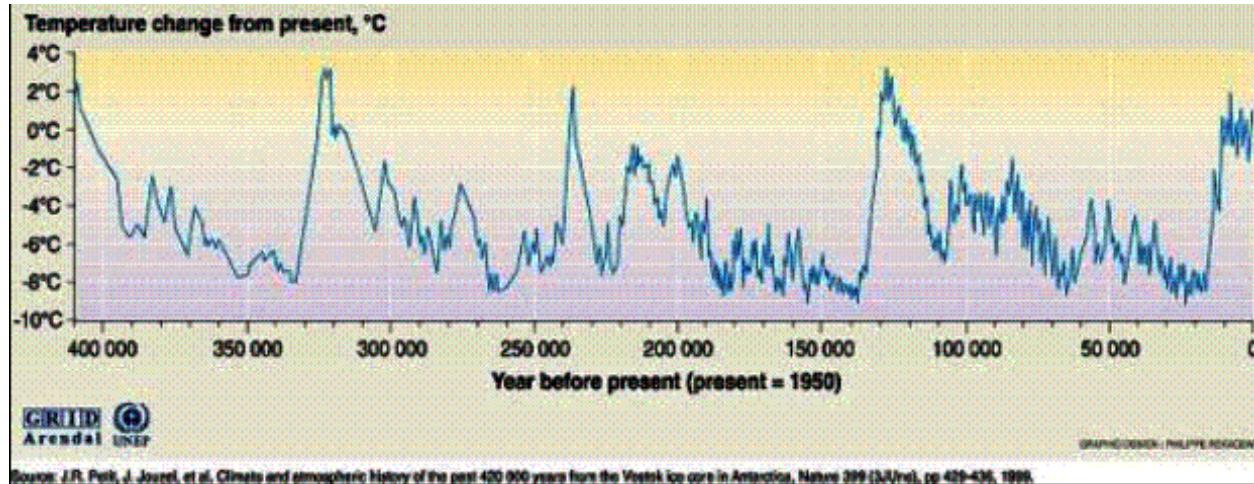


Global Temperature



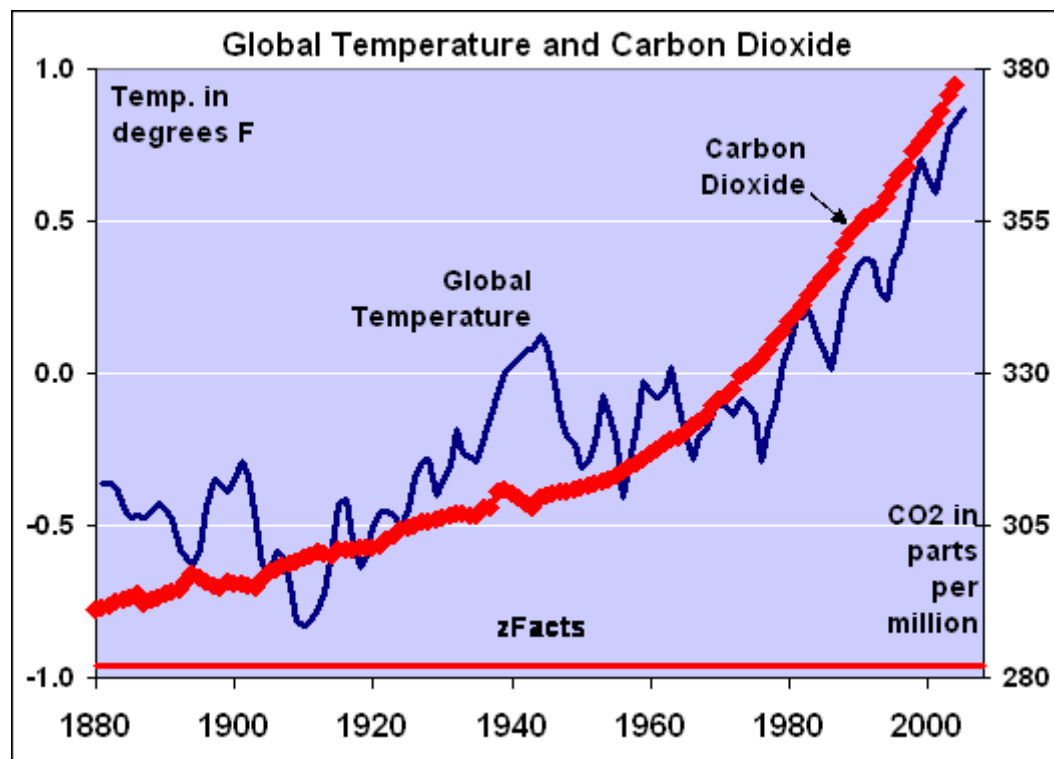


Global Temperature





Temperature and CO₂



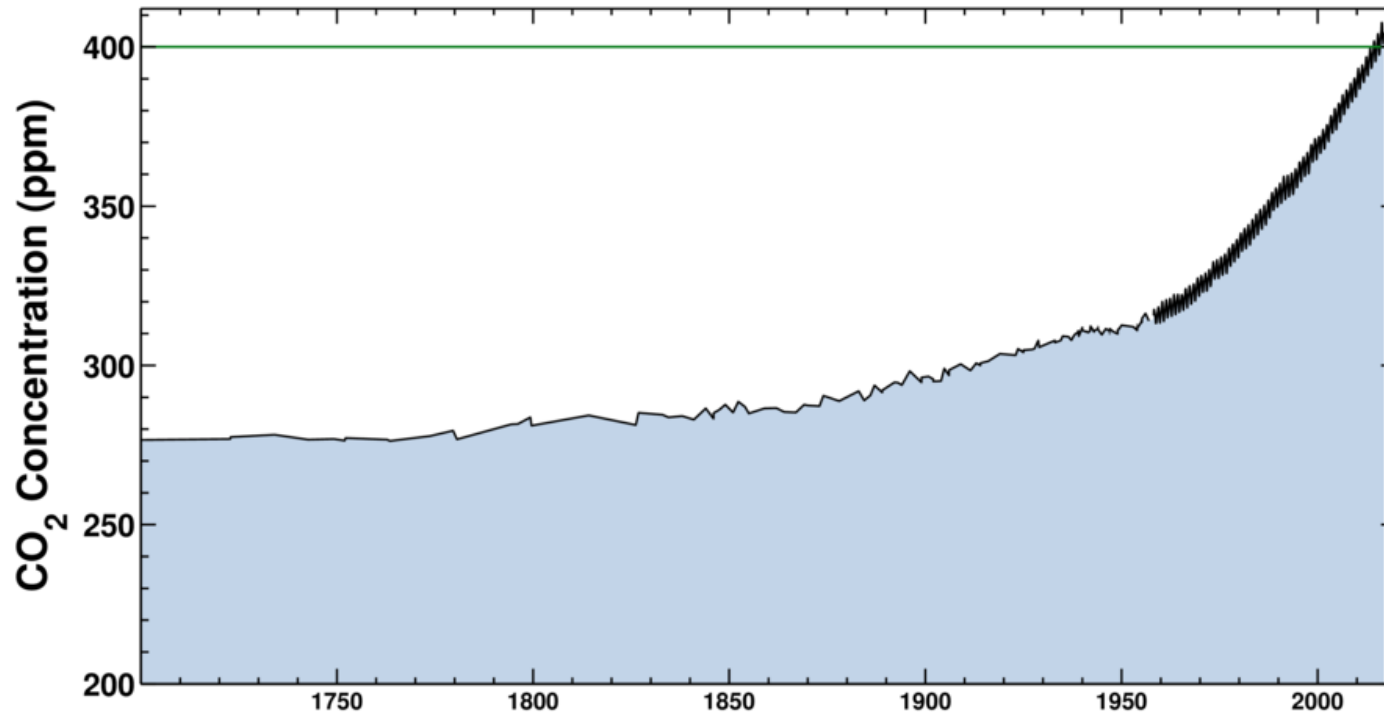
Beware of
simplified graphs!



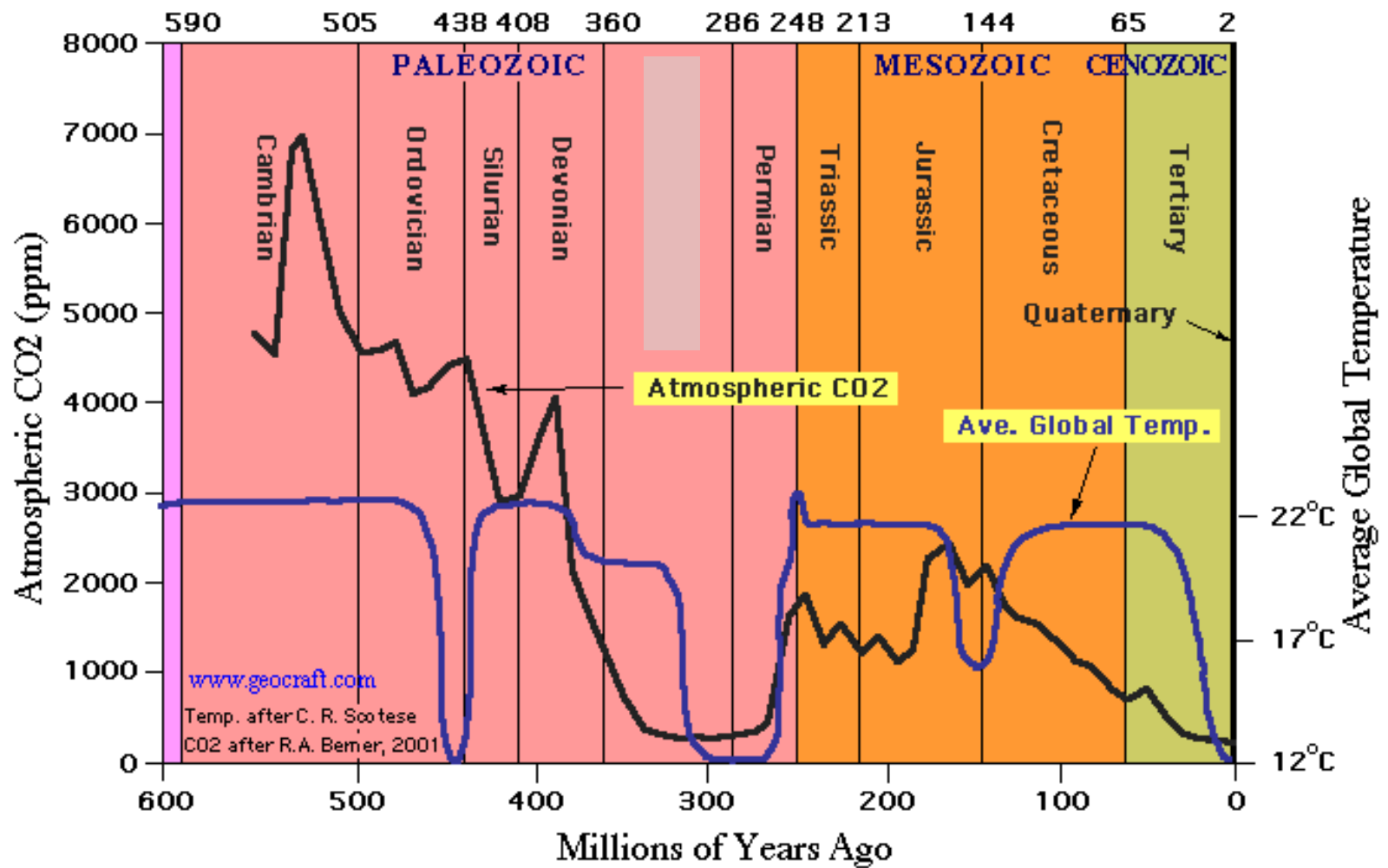
Latest CO₂ reading
January 01, 2017

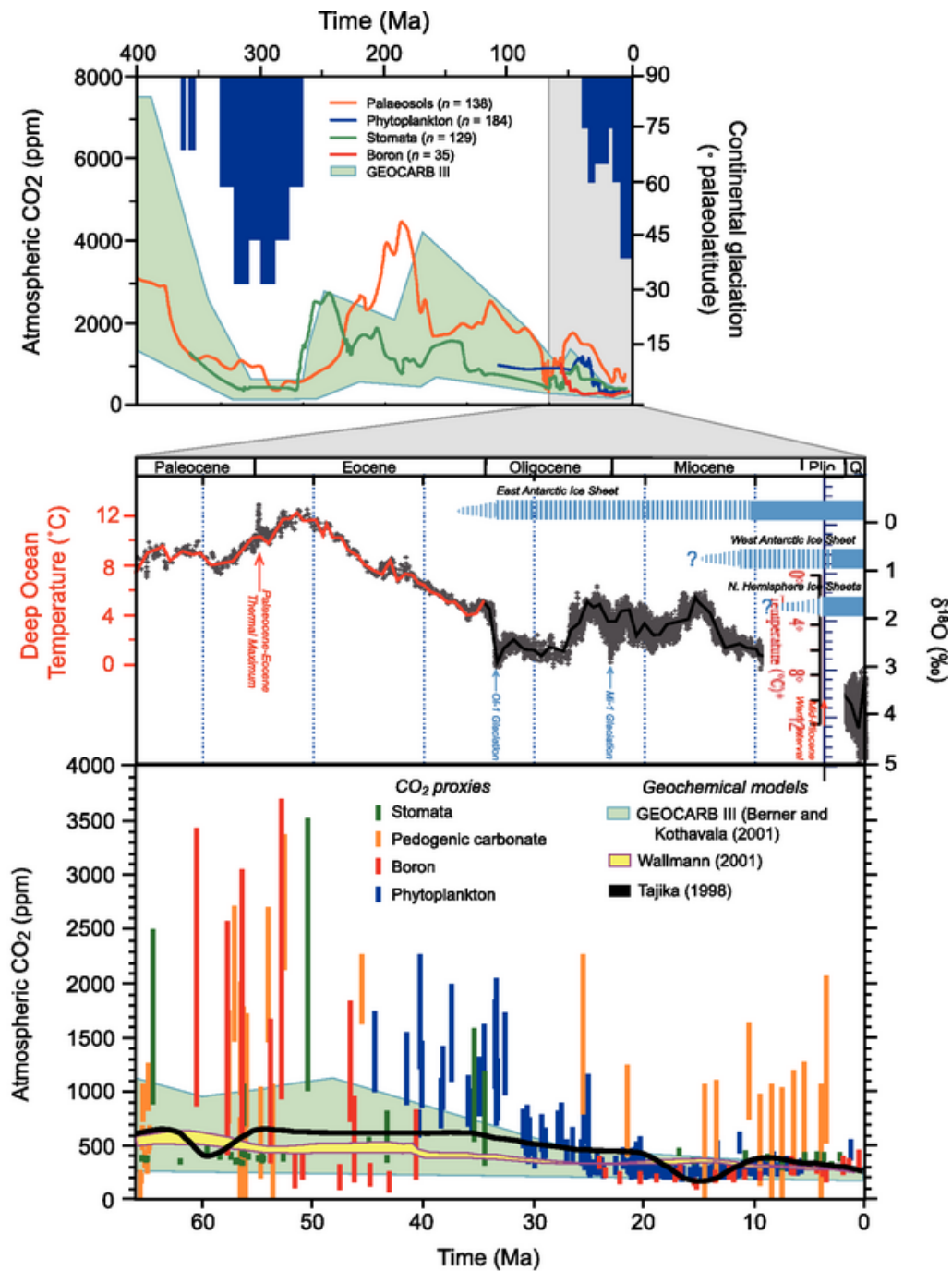
406.93 ppm

Ice-core data before 1958. Mauna Loa data after 1958.



Source: Scripps







Global Warming Effects

- *...equilibrium global mean SAT (surface air temperature) warming for a doubling of atmospheric carbon dioxide (CO_2), or 'equilibrium climate sensitivity', is likely to lie in the range 2°C to 4.5°C , with a most likely value of about 3°C*
- *It is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate.*
- *...give reductions in pH of between 0.14 and 0.35 units in the 21st century...*

Source: IPCC



World CO₂ emissions (kilotons)

million

35

10

1960

30

25

20

15

1965

1970

1975

1980

1985

1990

1995

2000

2005

2010

WORLD

Source: World Bank



U.S. Energy-related emissions have peaked

million

5.5

5.0

4.5

4.0

3.5

3

1960

1965

1970

1975

1980

1985

1990

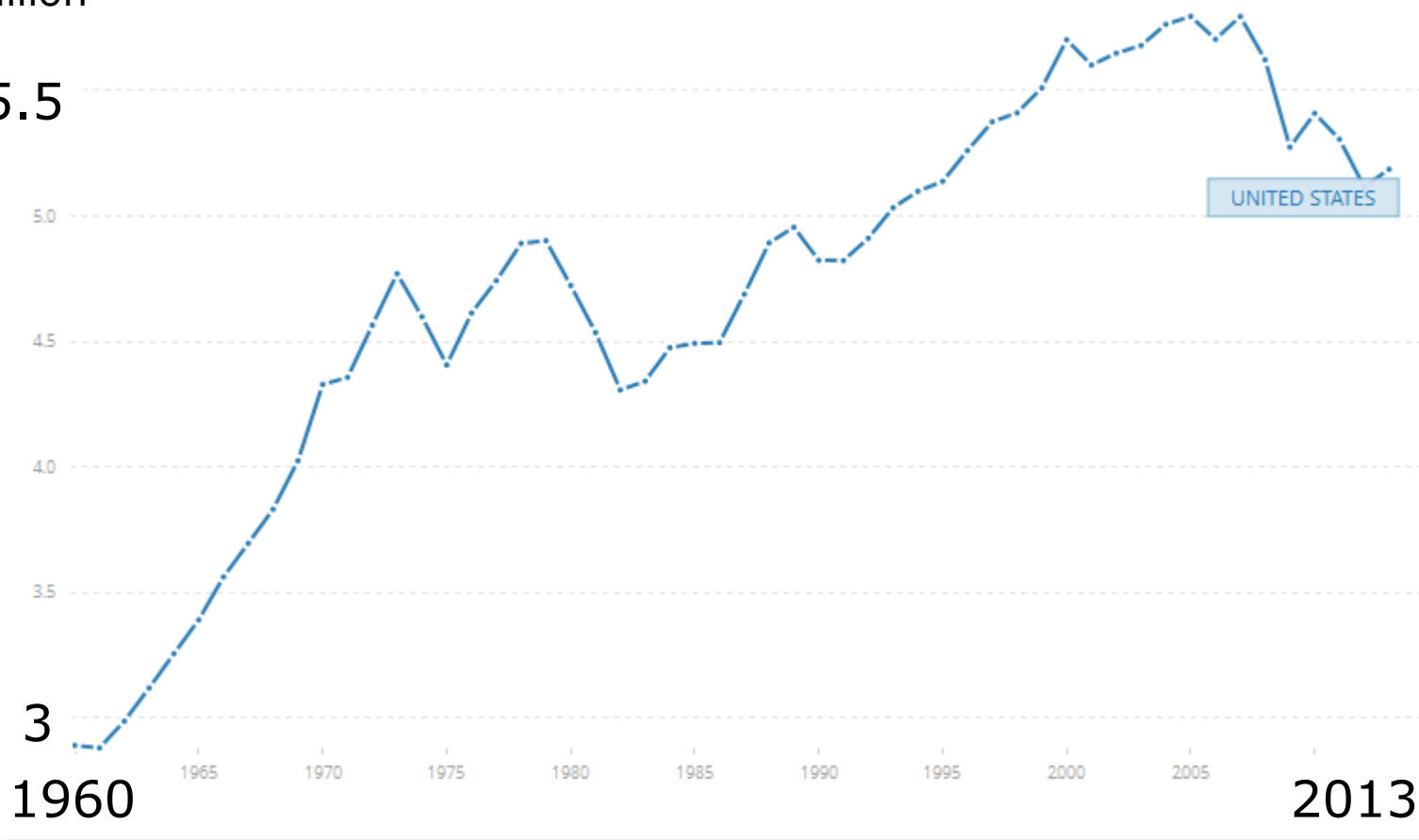
1995

2000

2005

2013


UNITED STATES

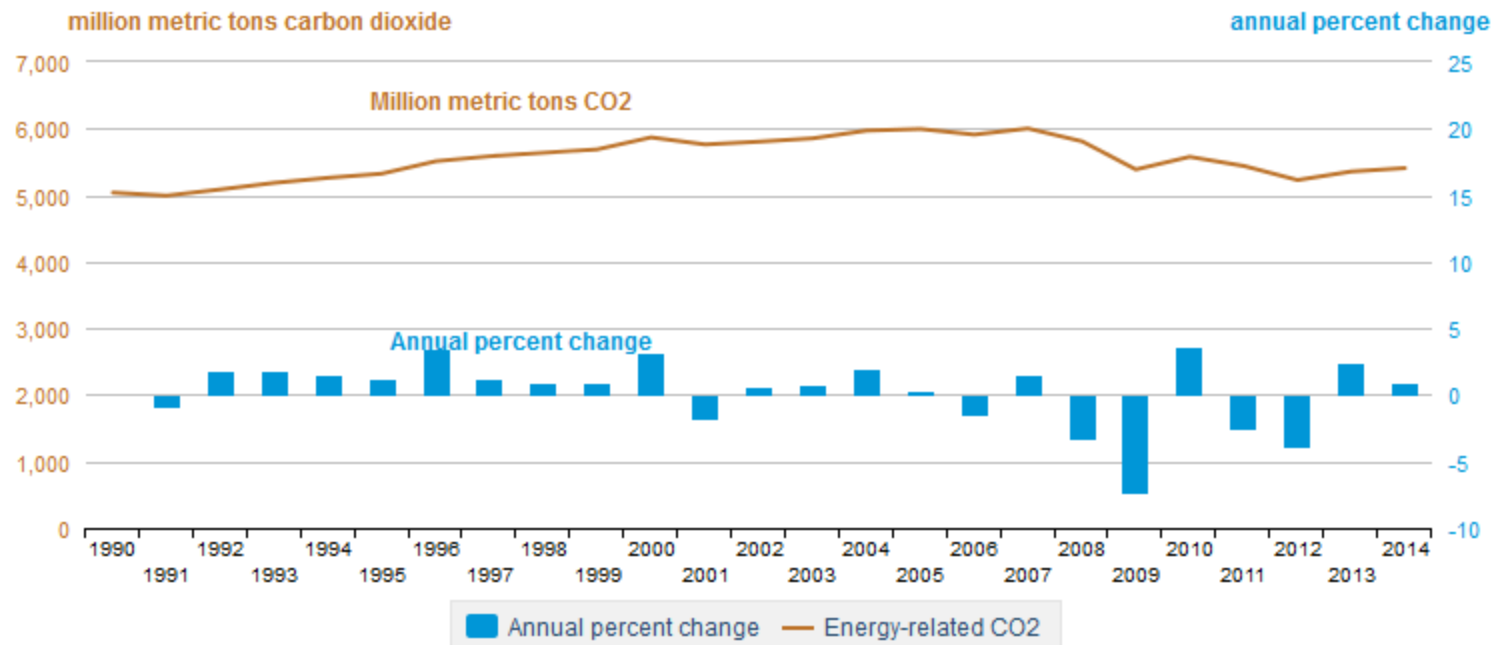




U.S. Energy-related CO₂ emissions

Figure 1. Energy-related carbon dioxide emissions, 1990-2014

 [DOWNLOAD](#)





China CO₂ emissions (kilotons)

million

10

9

8

7

6

5

4

3

2

1

1960

1965

1970

1975

1980

1985

1990

1995

2000

2005

2013

CHINA



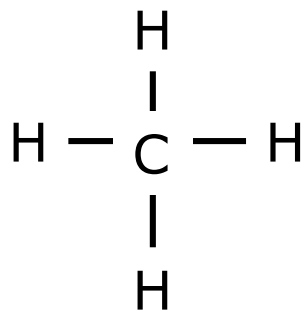
Greenhouse Gases

- Different GHG contribute differently to the greenhouse effect
- Global Warming Potential (GWP)
 - ratio of warming caused by a 1kg GHG to 1kg CO₂
- GWP of some GHG:
 - Carbon dioxide (CO₂): 1
 - Methane: 21
 - N₂O: 310



CO₂ Emissions

- How much CO₂ is released by burning a kg of Methane? Oil? Coal?
- First consider methane (CH₄)
 - 4 hydrogen
 - 1 carbon





CO₂ Emissions

- Atomic weights
 - Hydrogen: 1
 - Carbon: 12
- Total weight per Methane molecule:
 - $12 + 1 + 1 + 1 + 1 = 16$
- Carbon makes up 12/16 or 75% of the mass of methane
- 1kg of methane contains 0.75 kg of carbon



CO₂ Emissions

- Combustion reaction for methane:
 - $\text{CH}_4 + 2\text{O}_2 \Rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$
 - watervapor is a by-product
- Atomic weight of Oxygen is 16
- The carbon in CO₂ makes up 27.3% of its weight (12/(2 x 16 + 12))
- To put it another way: for every 1kg of carbon combusted, 3.67 kg of CO₂ is released
 - $1/0.27 = 367\%$



CO₂ Emissions

- If 1 kg of methane is combusted, how much CO₂ is released?
 - 1 kg of methane x 0.75(kg carbon/kg methane) = 0.75kg of carbon
 - 0.75 x 3.67 = 2.7 kg of CO₂
 - Note: more mass of CO₂ is released than there was of mass of methane



Emissions from Coal

- Coal contains
 - Carbon
 - Hydrogen
 - Sulfur
 - Nitrogen
 - others





Emissions from Coal

- Ratio of carbon mass to the molecular mass varies depending on type of coal
- A reasonable assumption range is 60-90%
 - Lignite on the lower end
 - Anthracite on the higher end



Emissions from Oil

- Emissions depend on the type of oil
- Consider $C_{16}H_{34}$
 - Ratio of carbon: $(16 \times 12)/(16 \times 12 + 34) = 85\%$
- How much CO_2 is released when 1 kg of $C_{16}H_{34}$ is combusted?



Emissions from Oil

- How much CO_2 is released when 1 kg of $\text{C}_{16}\text{H}_{34}$ is combusted?
 - 1kg of $\text{C}_{16}\text{H}_{34}$ contains 0.85 kg of carbon
 - 0.85 kg of carbon produces 3.11kg of CO_2 (0.85×3.67)



Emissions Calculations

- Usually we are interested in metrics such as kg of CO₂ emissions per kWh of energy or per gallon
- How many kg of CO₂ are released from one gallon of diesel fuel?
 - Assume 3 kg of diesel fuel per gallon



Emissions Calculations

- A back-of-the-envelope calculation:
 - Assume 3 kg of diesel fuel per gallon
 - $3 \times 0.85 \times 3.67 = 9.36$ kg of CO₂ /gallon
 - EPA value: 10.1 kg of CO₂ /gallon



Emissions Calculations

- Specific energy densities (approximate values shown)
 - Methane: 56 MJ/kg
 - Natural Gas: 53 MJ/kg
 - Coal: 15-30 MJ/kg
 - Diesel: 45 MJ/kg



Emissions Calculations

- Energy conversion efficiencies (approximate values shown)
 - Natural gas (Brayton cycle): ~25-35%
 - Coal (Rankine cycle): ~30-45%
 - Diesel (Diesel cycle): ~30-45%
- $E_{\text{out}} = \eta E_{\text{in}}$



Emissions Calculations

- What is the mass of the CO_2 released in order to generate 1kWh of electrical energy using:
 - Natural gas (Brayton cycle, $\eta = 30\%$)
 - Coal (Rankine cycle, $\eta = 40\%$)



Emissions Calculations

- First compute how many kg of fuel are used:
 - $1\text{kWh} = 3.6\text{MJ}$
 - Accounting for efficiency
 - $E_{\text{in}} = 3.6/0.3 = 12\text{ MJ}$
 - Using the specific energy density
 - $m_{\text{nat gas}} = 12/53 = 0.23\text{ kg}$



Emissions Calculations

- Compute the mass of carbon:
 - $m_C = 0.23 \times 0.75 = 0.17 \text{ kg}$
- Next compute how many kg of CO_2 are produced:
 - $m_{\text{CO}_2} = 0.17 \times 3.67 = \underline{0.62 \text{ kg}}$



Emissions Calculations

- Compute for coal assuming:
 - Anthracite: 90% carbon, 32 MJ/kg
 - Rankine efficiency: 40%



Emissions Calculations

- $E_{in} = 3.6/0.4 = 9 \text{ MJ}$
- $m_{coal} = 9/32 = 0.28 \text{ kg}$
- $m_c = 0.28 \times 0.9 = 0.25 \text{ kg}$
- $m_{CO_2} = 0.25 \times 3.67 = \underline{0.92 \text{ kg}}$



Emissions Calculations

- In this example:
 - Natural gas: 0.62 kg/kWh
 - Coal: 0.92 kg/kWh
- Actual values closer to
 - Natural gas: 0.50 kg/kWh
 - Coal: 1.00 kg/kWh



- Coal, Oil, natural gas contain impurities such as Sulfur and Nitrogen
- Sulfur Oxides cause acid rain, damage to plants, water supply and endanger respiratory health
 - $\text{S} + \text{O}_2 \Rightarrow \text{SO}_2$ (sulfur dioxide)
 - $2\text{SO}_2 + \text{O}_2 \Rightarrow \text{SO}_3$ (sulfur trioxide)
 - $3\text{SO}_3 + \text{H}_2\text{O} \Rightarrow \text{H}_2\text{SO}_4$ (sulfuric acid)
- Released on the order of
 - Coal: 7kg/MWh
 - Natural gas: 5kg/MWh



- NO_x causes
 - Smog
 - Acid rain
- Greenhouse gas
- Released on the order of 2kg/MWh



Questions

- How much money are you willing to pay to prevent all CO₂ from power plants from being emitted into the atmosphere?
- What happens if we do not reduce mankind's greenhouse gas emissions?
- Should the U.S. reduce its greenhouse gas emissions if China does not?



Reading

Mills, A. et al, "Dark Shadows," *Power and Energy Magazine, IEEE* , vol.9, no.3, pp.33-41, May-June 2011

- Accessible through the IEEEXplore database
- See: <http://libguides.seattleu.edu/ece>