03-Emissions

ECEGR 452

Renewable Energy Systems

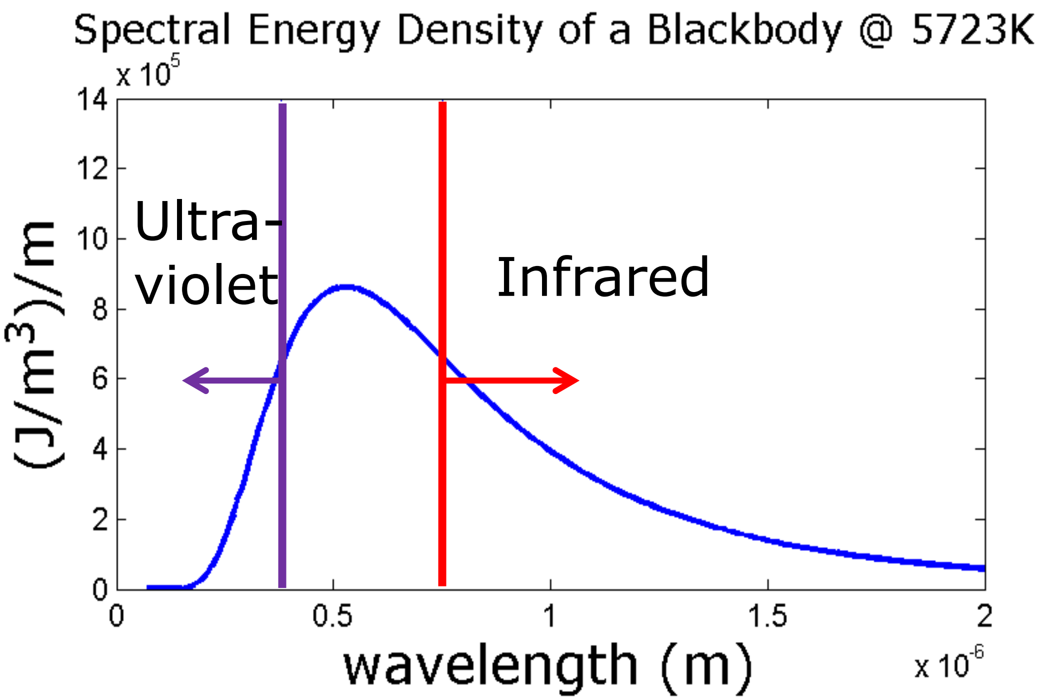
Overview

- Solar Spectrum
- Atmospheric Effects
- Greenhouse Gases
- Global Warming
- CO_2 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)

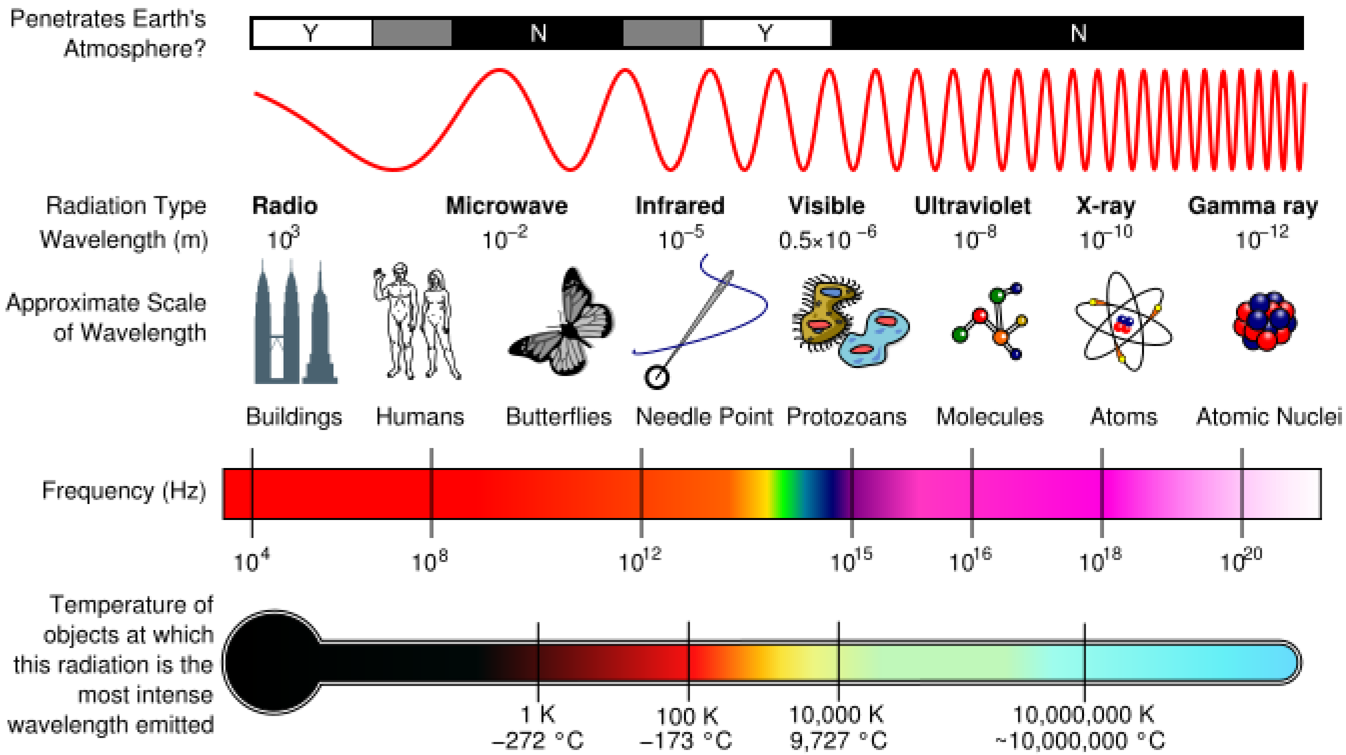
$$f = \frac{c}{\lambda}$$

c ⟵ speed of light

λ ⟵ wavelength

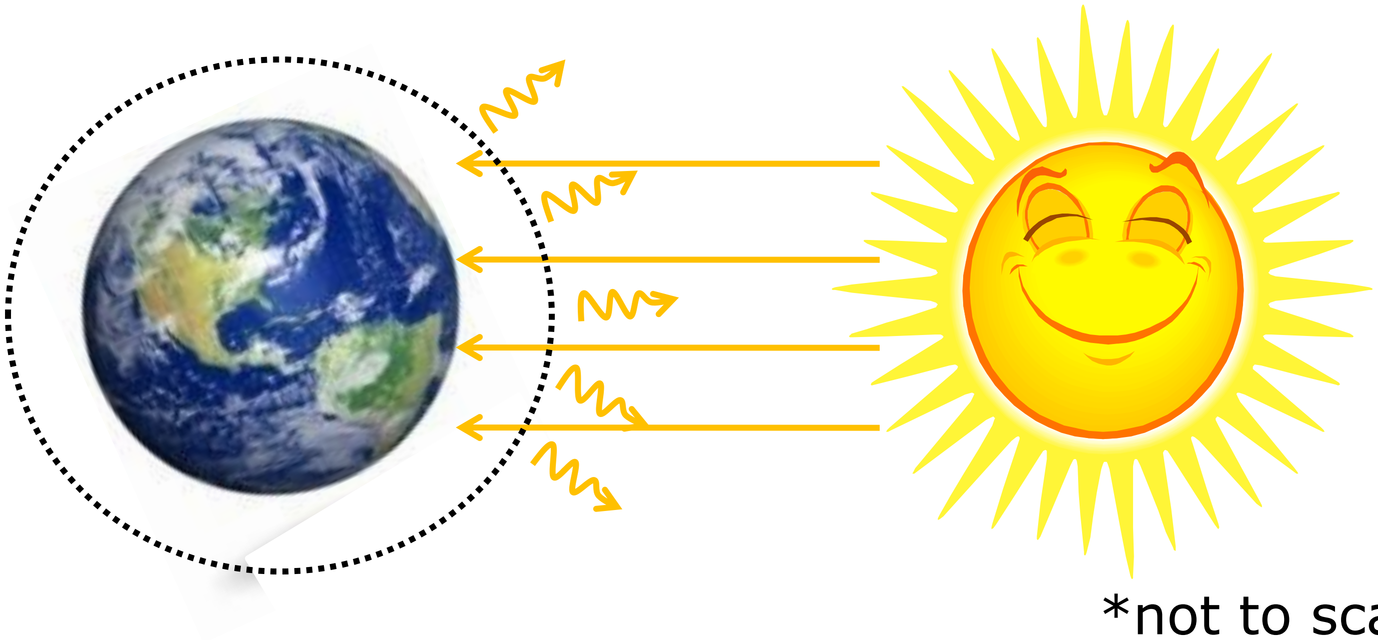
- Higher frequency radiation contains more energy

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



*not to scale

Atmospheric Effects

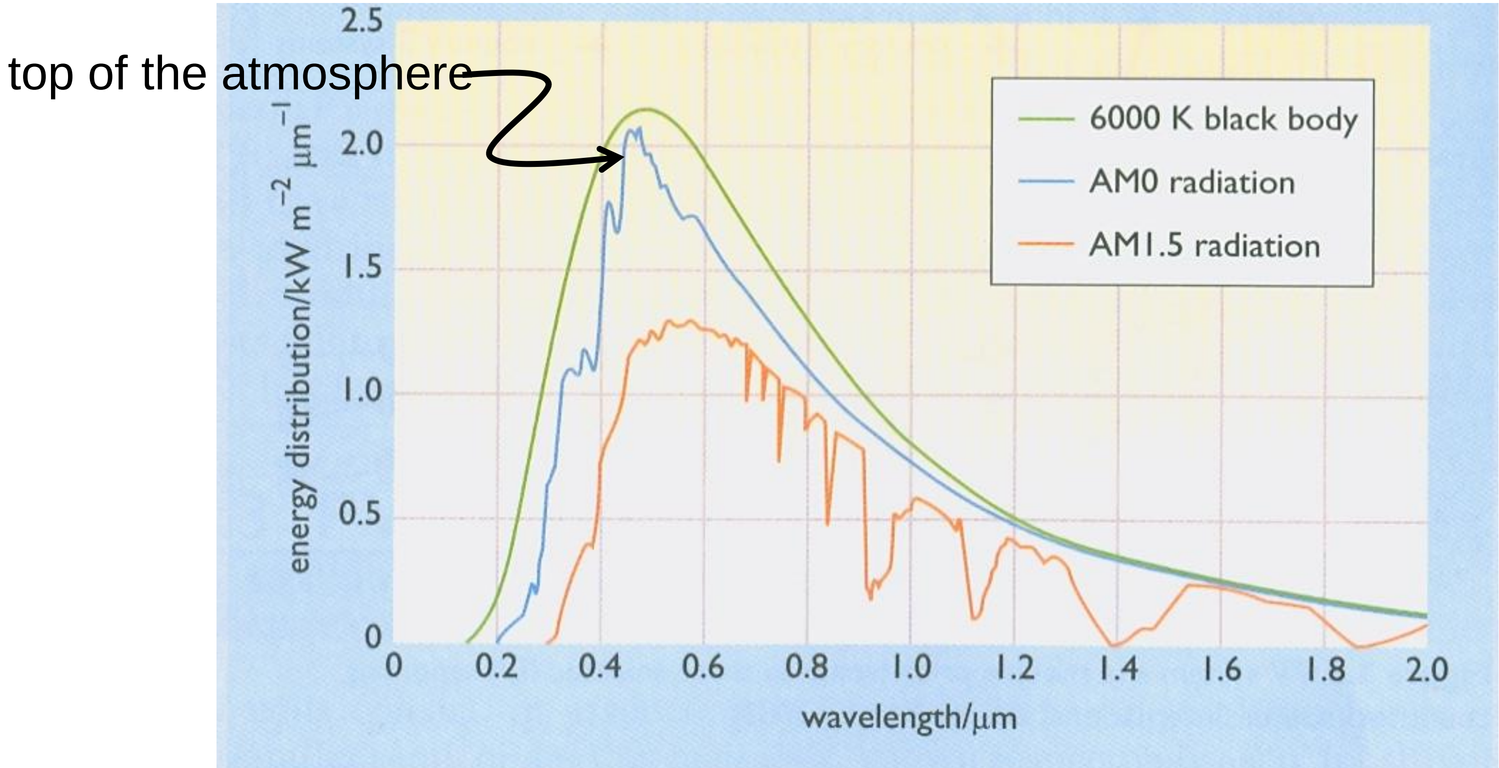
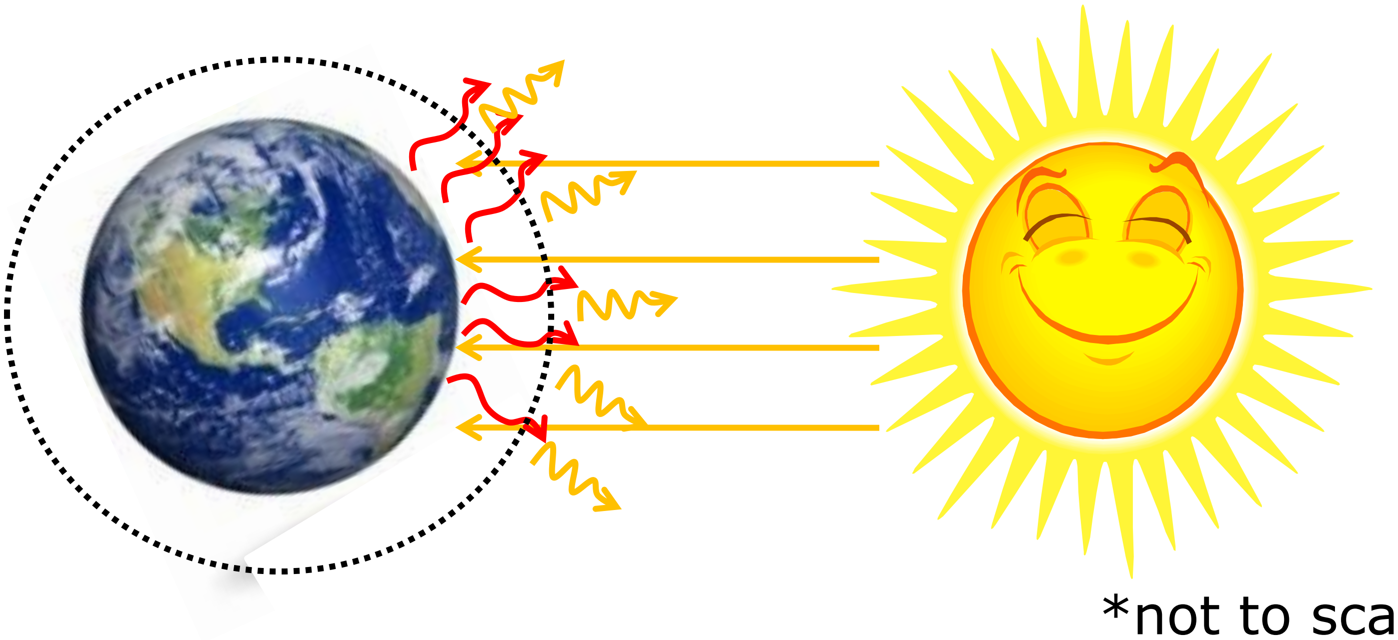


Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

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



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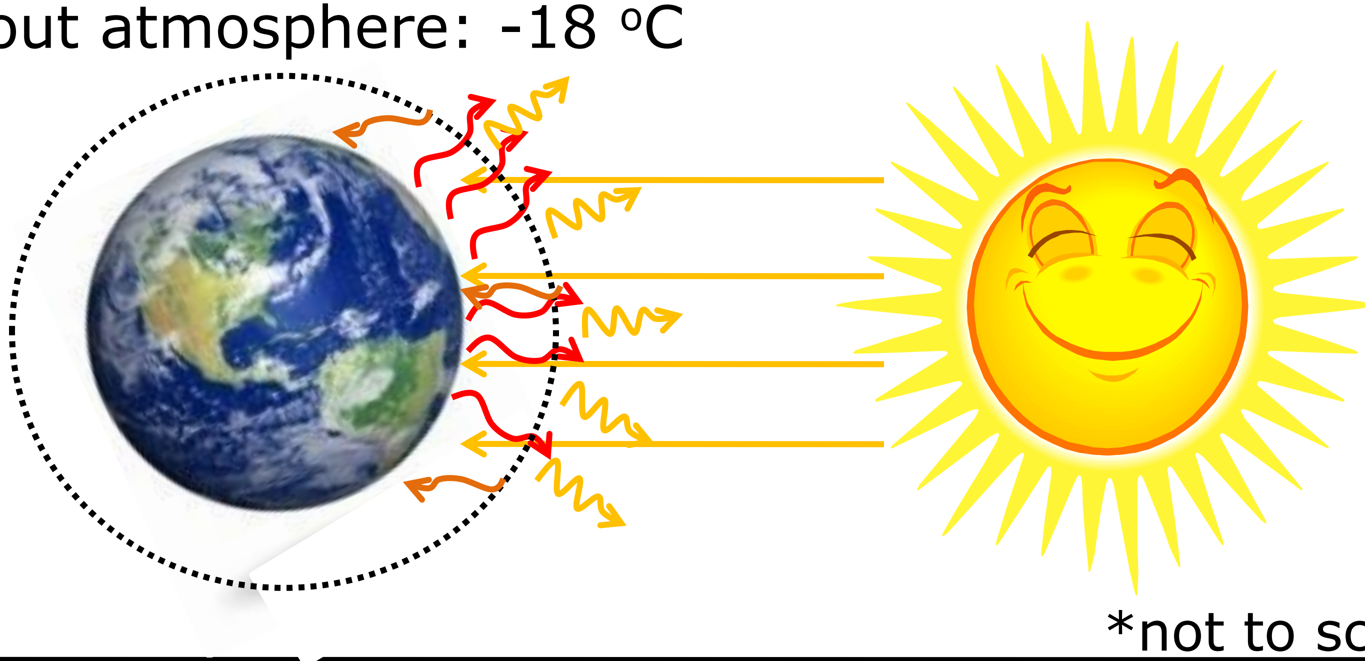
Atmospheric Effects

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



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Greenhouse Gases

- Greenhouse gases: atmospheric gases that keep the longwave infrared radiation from escaping

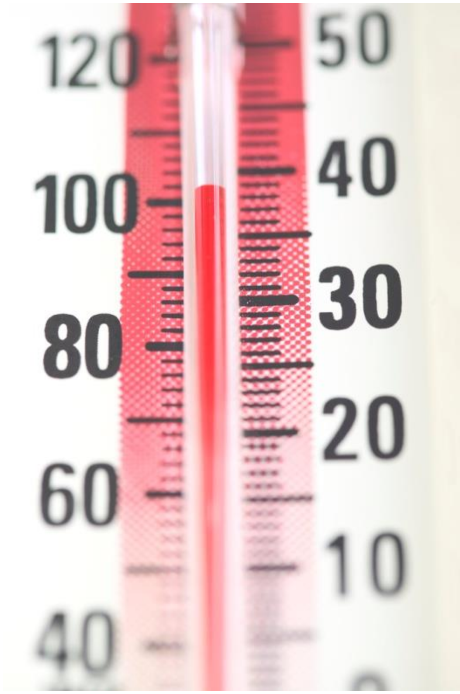
- Common Greenhouse gases (GHG)
  - Water vapor (responsible for 60-80% of greenhouse effect)
  - Carbon dioxide (CO_2)
  - Methane
  - N_2O
  - Ozone

Greenhouse Gases

- Current CO_2 concentration ~ 400 ppm (parts per million)
  - increasing
  - 18th Century ~ 280 ppm
- Burning fossil fuels releases previously sequestered (buried) carbon into the atmosphere
  - Concentration of CO_2 increases

Global Warming

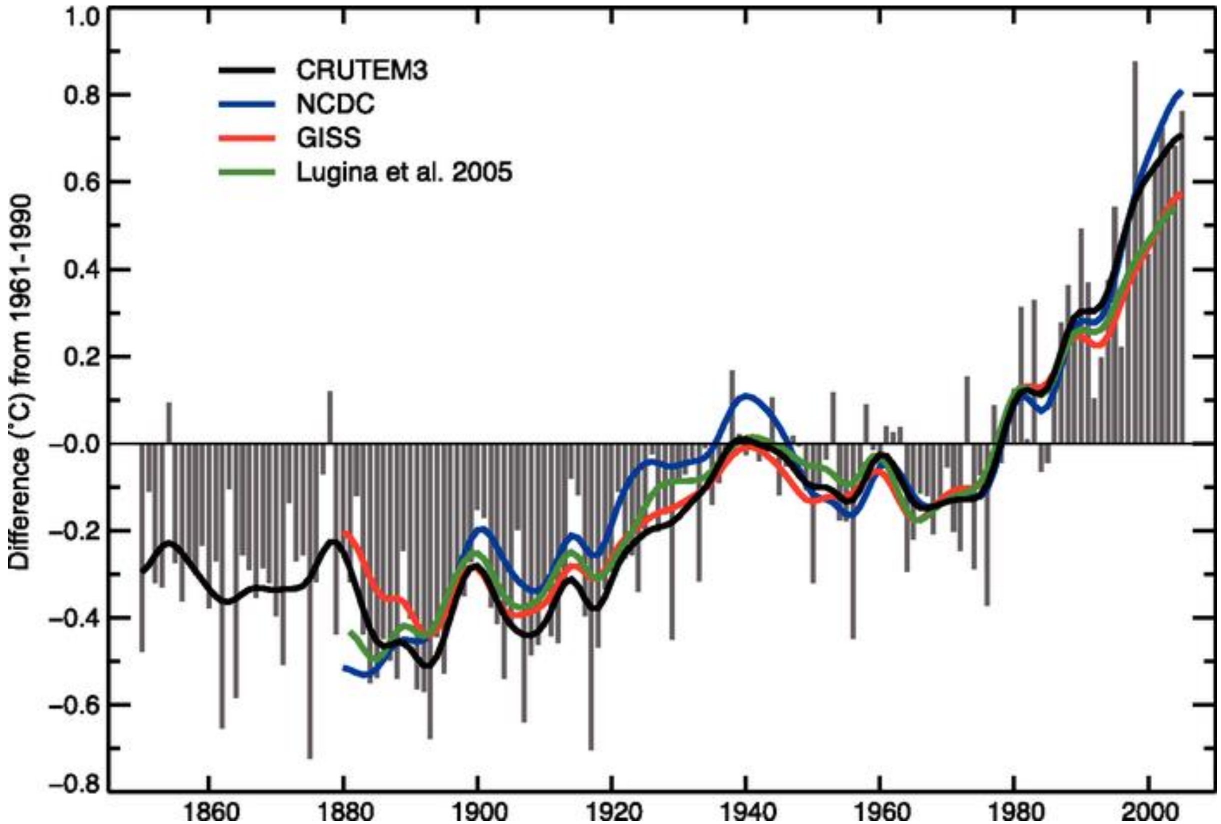
Global warming is a generalization in both space and time used to describe the rising trend in mean global temperature evident in many but not all analyses of near-surface temperature data-Timothy Casey



Global Warming

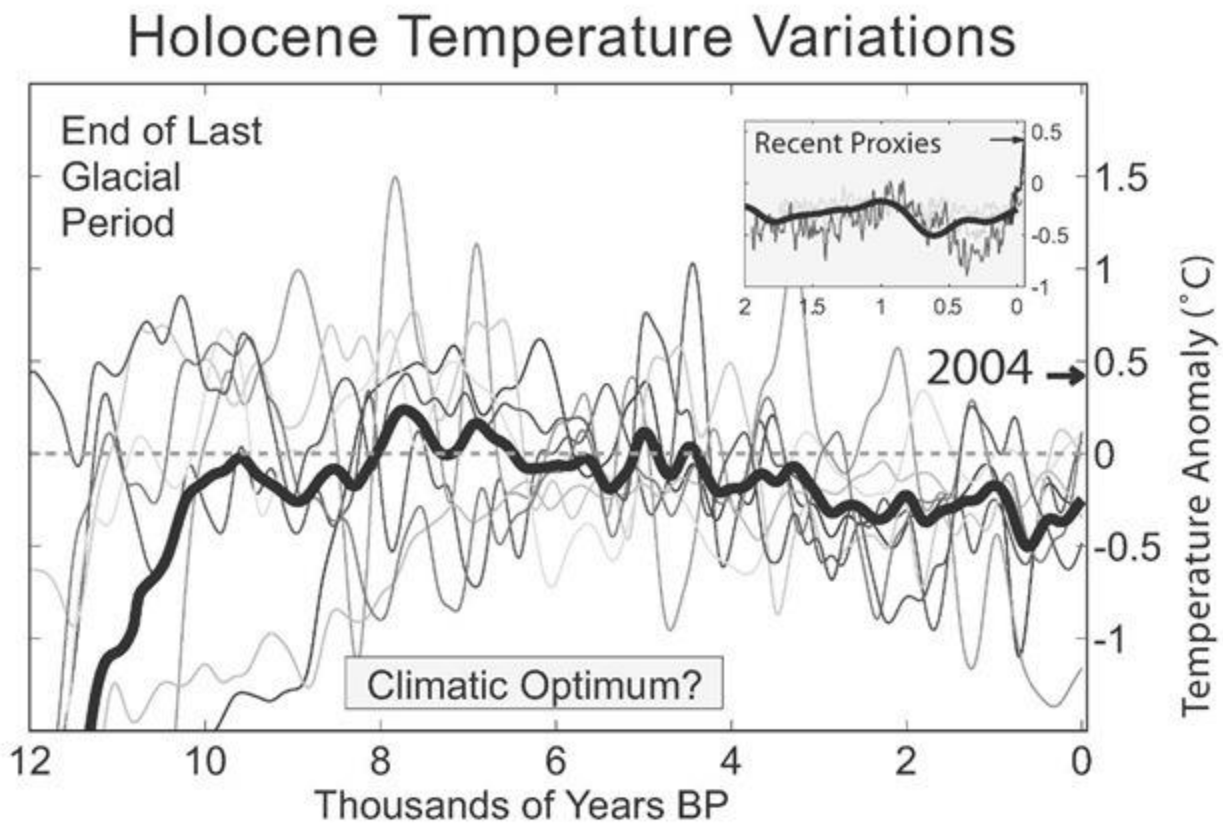
- Politically and scientifically contentious
- Is global warming happening?
  - How do you measure "warming"?
- What are the causes?
  - Anthropogenic?
  - Natural?
- What are the effects?
  - Desertification?
  - Rise in sea level?
  - Warmer in Seattle?
- What should be done?

Global Temperature (Recent)

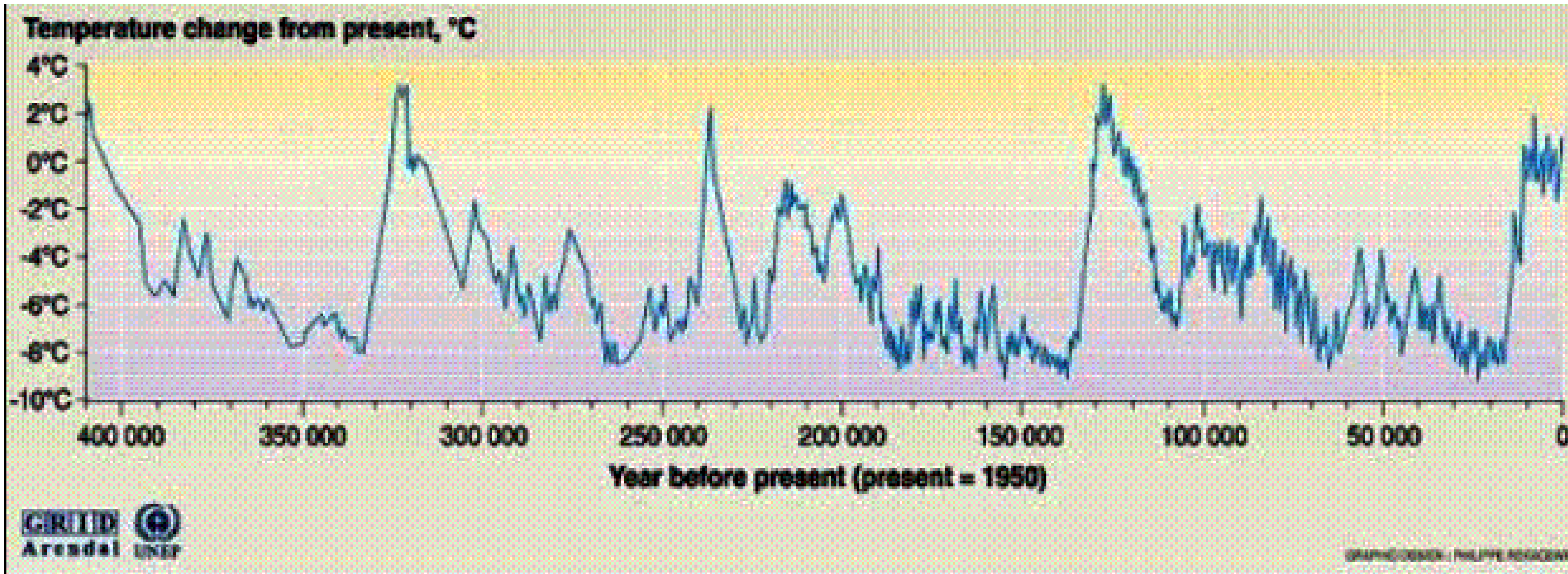


Source: IPCC Fourth Assessment Report

Global Temperature (Holocene)

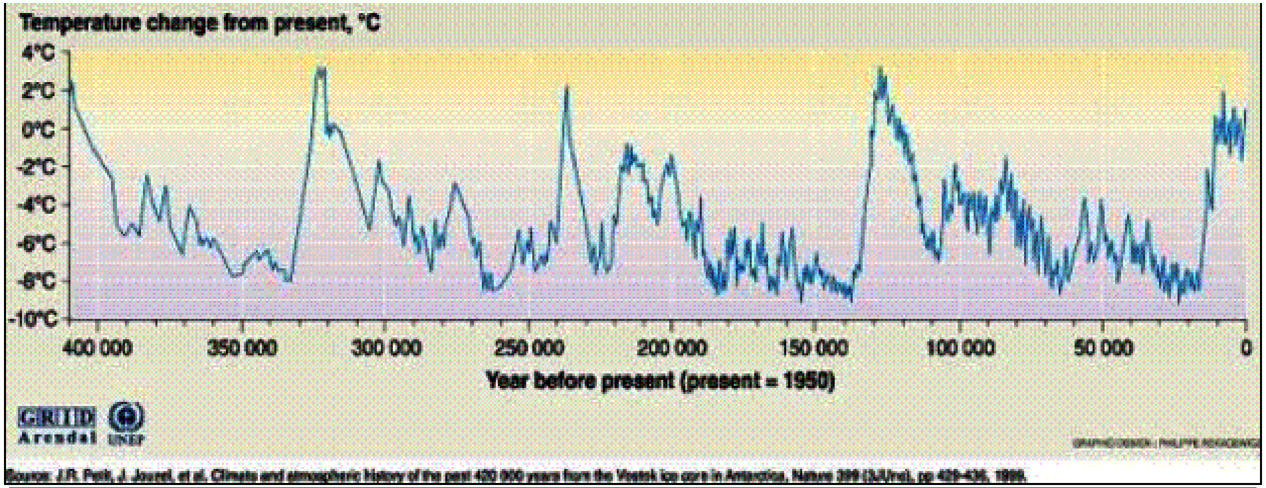


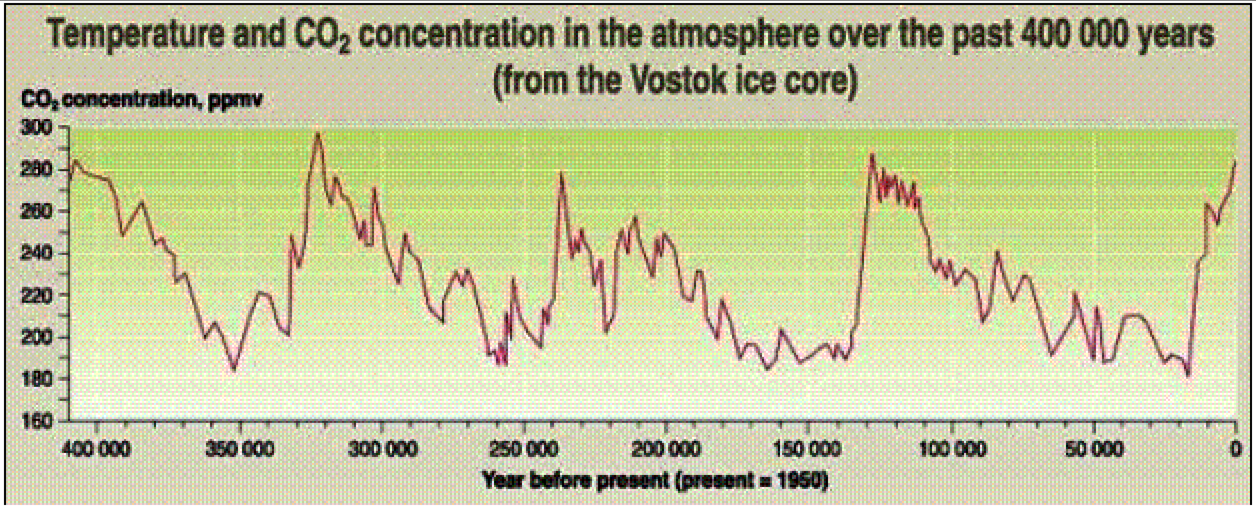
Global Temperature



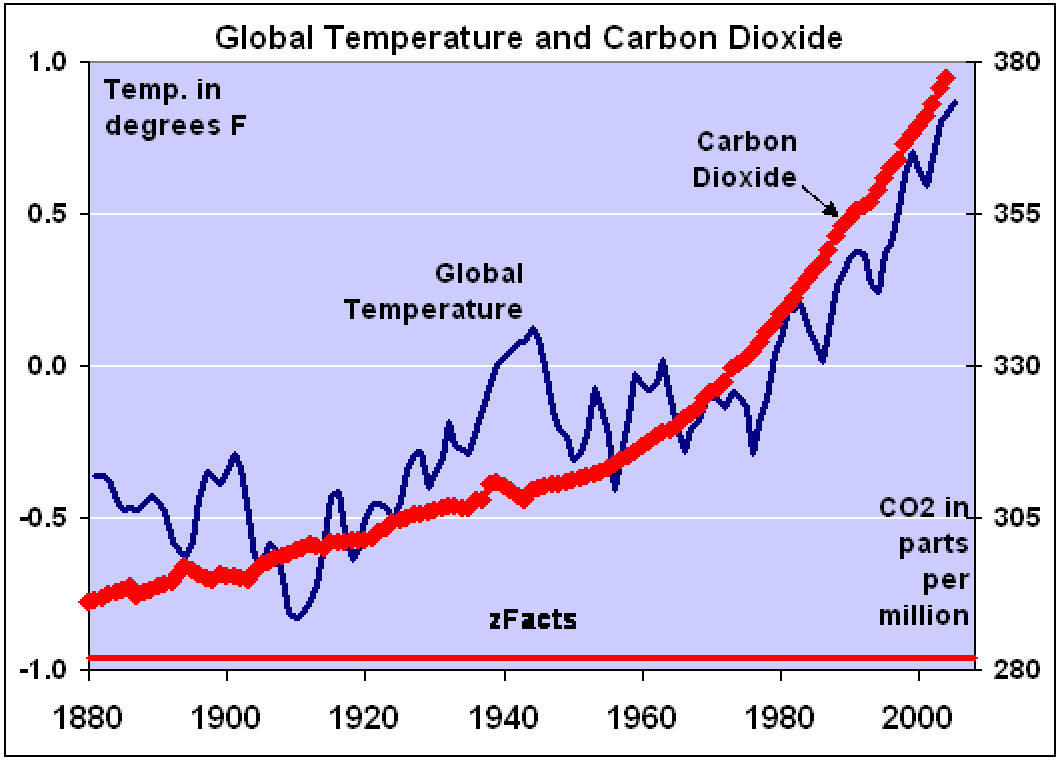
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3June), pp 429-436, 1999.

Global Temperature

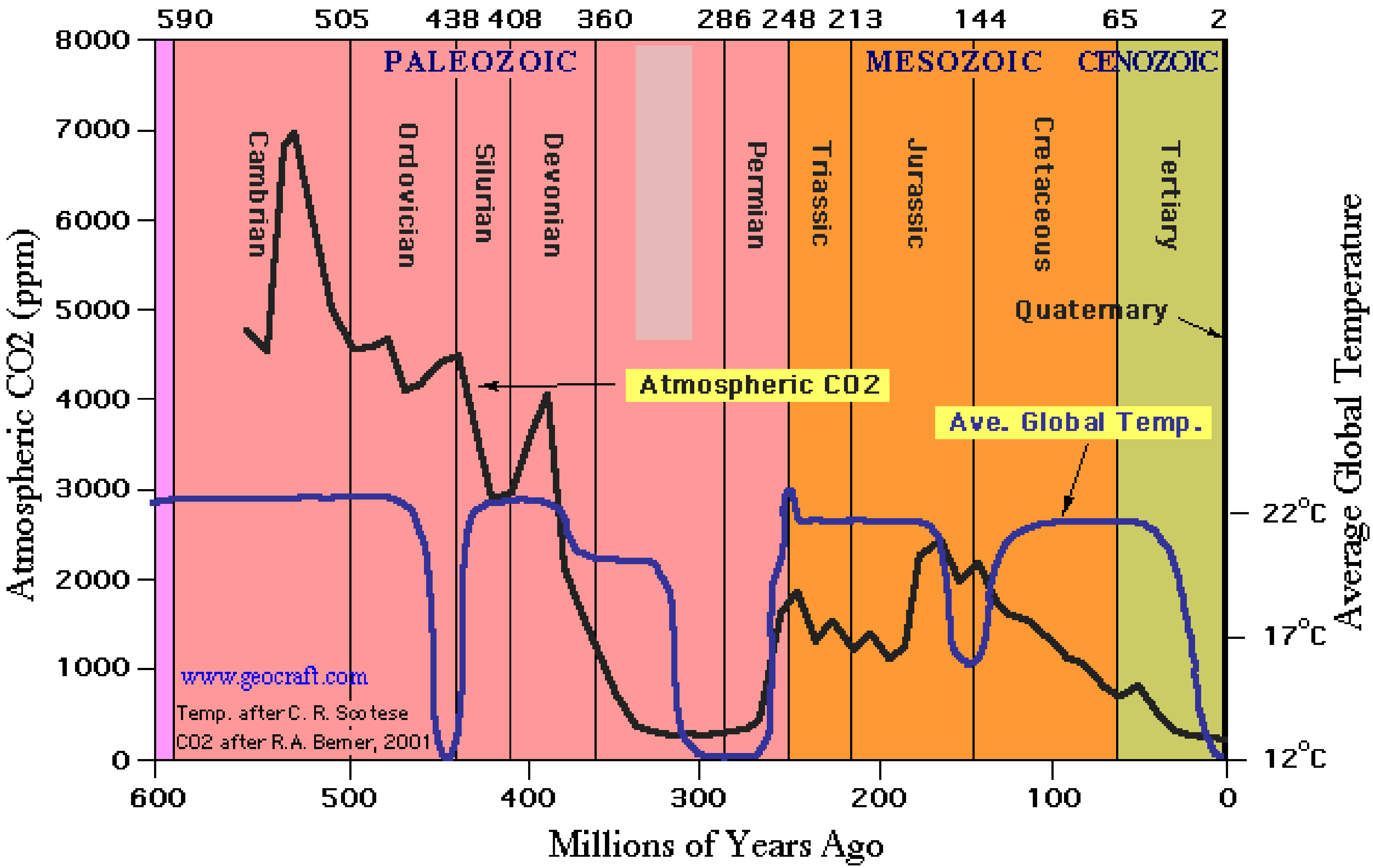




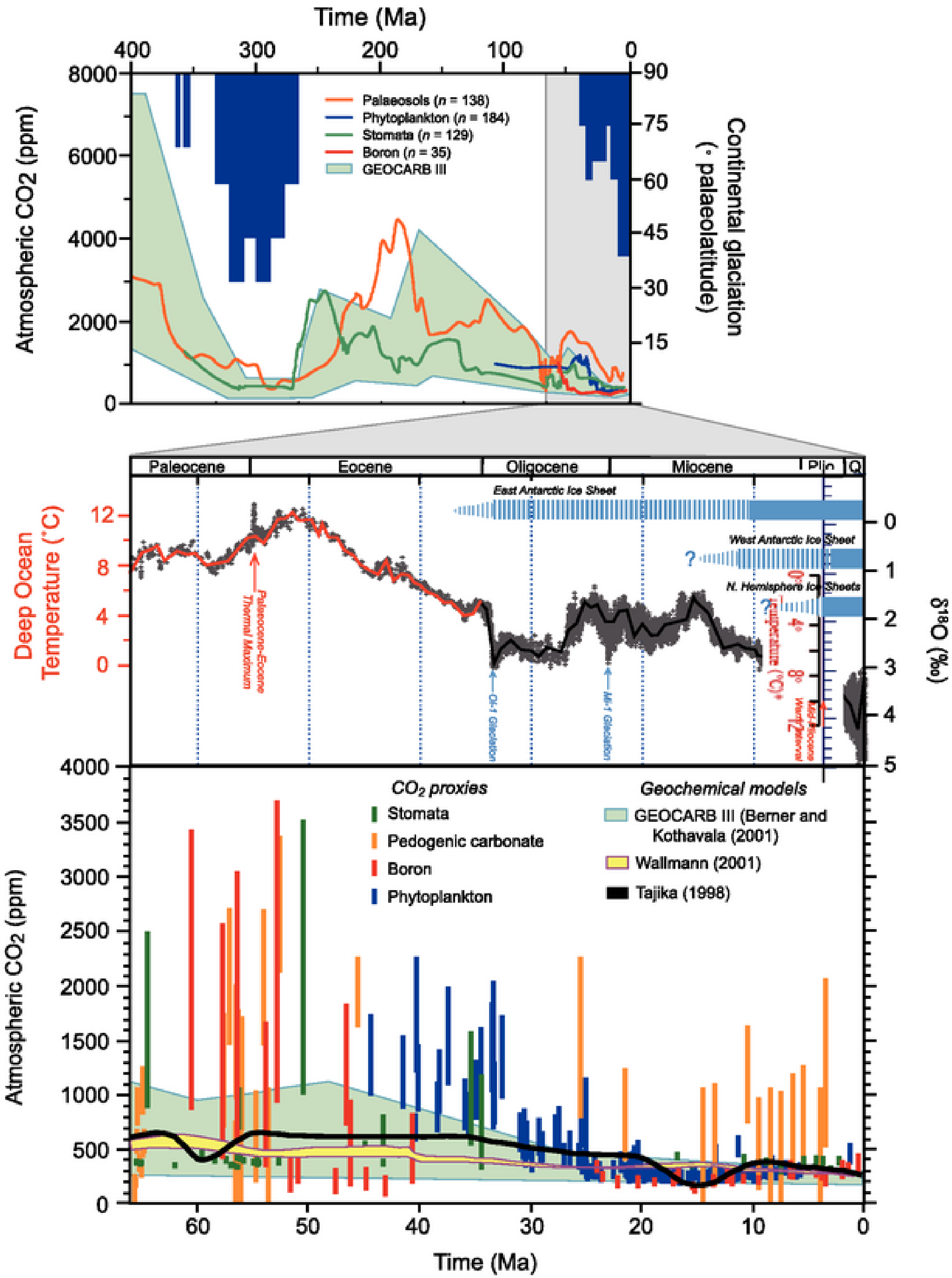
Temperature and CO_2



Beware of simplified graphs!



590
505
438 408
360
286 248 213
144
65
2
PALEOZOIC
MESOZOIC
CENOZOIC
Cambrian
Ordovician
Silurian
Devonian
Permian
Triassic
Jurassic
Cretaceous
Tertiary
Quaternary
Atmospheric CO2
Ave. Global Temp.
8000
7000
6000
5000
4000
3000
2000
1000
0
Atmospheric CO2 (ppm)
www.geocraft.com
Temp. after C. R. Scotese
CO2 after R.A. Berner, 2001
600
500
400
300
200
100
0
Millions of Years Ago
22°C
17°C
12°C
Average Global Temperature



Time (Ma)
400
300
200
100
0
8000
6000
4000
2000
0
Atmospheric CO2 (ppm)
90
75
60
45
30
15
Continental glaciation
(° palaeolatitude)
Palaeosols (n = 138)
Phytoplankton (n = 184)
Stomata (n = 129)
Boron (n = 35)
GEOCARB III
Paleocene
Eocene
Oligocene
Miocene
Plio
Q
Deep Ocean
Temperature (°C)
12
8
4
0
East Antarctic Ice Sheet
West Antarctic Ice Sheet
N. Hemisphere Ice Sheets
Palaeocene-Eocene
Thermal Maximum
Oi-1 Glaciation
Mi-1 Glaciation
δ18O (‰)
0
1
2
3
4
5
4000
3500
3000
2500
2000
1500
1000
500
0
Atmospheric CO2 (ppm)
CO2 proxies
Stomata
Pedogenic carbonate
Boron
Phytoplankton
Geochemical models
GEOCARB III (Berner and
Kothavala (2001)
Wallmann (2001)
Tajika (1998)
60
50
40
30
20
10
0
Time (Ma)

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…*

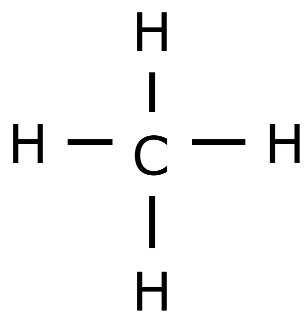
Source: IPCC

Greenhouse Gases

- Different GHG contribute differently to the greenhouse effect
- Global Warming Potential (GWP)
  - ratio of warming caused by a 1kg GHG to 1kg CO_2
- GWP of some GHG:
  - Carbon dioxide (CO_2): 1
  - Methane: 21
  - N_2O: 310

CO_2 Emissions

- How much CO_2 is released by burning a kg of Methane? Oil? Coal?
- First consider methane (CH_4)
  - 4 hydrogen
  - 1 carbon



CO_2 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

CO_2 Emissions

- Combustion reaction for methane:
  - $CH_4 + 2O_2 => CO_2 + 2H_2O$
    - watervapor is a by-product
- Atomic weight of Oxygen is 16
- The carbon in CO_2 makes up 27% of its weight (12/(2 x 16 + 12))
- To put it another way: for every 1kg of carbon combusted, 3.67 kg of CO_2 is released
  - 1/0.27 = 367%

CO_2 Emissions

- If 1 kg of methane is combusted, how much CO_2 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 CO_2
  - Note: more mass of CO_2 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 x 12)/(16 x 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 $C_{16}H_{34}$ is combusted?
  - 1kg of $C_{16}H_{34}$ contains 0.85 kg of carbon
  - 0.85 kg of carbon produces 3.11kg of CO_2 (0.85 x 3.67)

Emissions Calculations

- Usually we are interested in metrics such as kg of CO_2 emissions per kWh of energy or per gallon
- How many kg of CO_2 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 x 0.85 x 3.67 = 9.36 kg of CO_2 /gallon
  - EPA value: 10.1 kg of CO_2 /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%
- $E_{out} = \eta E_{in}$

Emissions Calculations

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

Emissions Calculations

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

Emissions Calculations

- Compute the mass of carbon:
  - $m_C = 0.23 \times 0.75 = 0.17$ kg
- Next compute how many kg of CO_2 are produced:
  - $m_{Co2} = 0.17 \times 3.67 = \underline{0.62\ kg}$

Emissions Calculations

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

Emissions Calculations

- $E_{in} = 3.6/0.4 = 9$ MJ
- $m_{coal} = 9/32 = 0.28$ kg
- $m_c = 0.28 \times 0.9 = 0.25$ kg
- $m_{CO2} = 0.25 \times 3.67 = \underline{0.92 \text{ kg}}$

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

SO_x

- 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
  - $S + O_2 => SO_2$ (sulfur dioxide)
  - $2SO_2 + O_2 => SO_3$ (sulfur trioxide)
  - $3SO_3 + H_2O => H_2SO_4$ (sulfuric acid)
- Released on the order of
  - Coal: 7kg/MWh
  - Natural gas: 5kg/MWh

NO_x

- 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 CO_2 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?