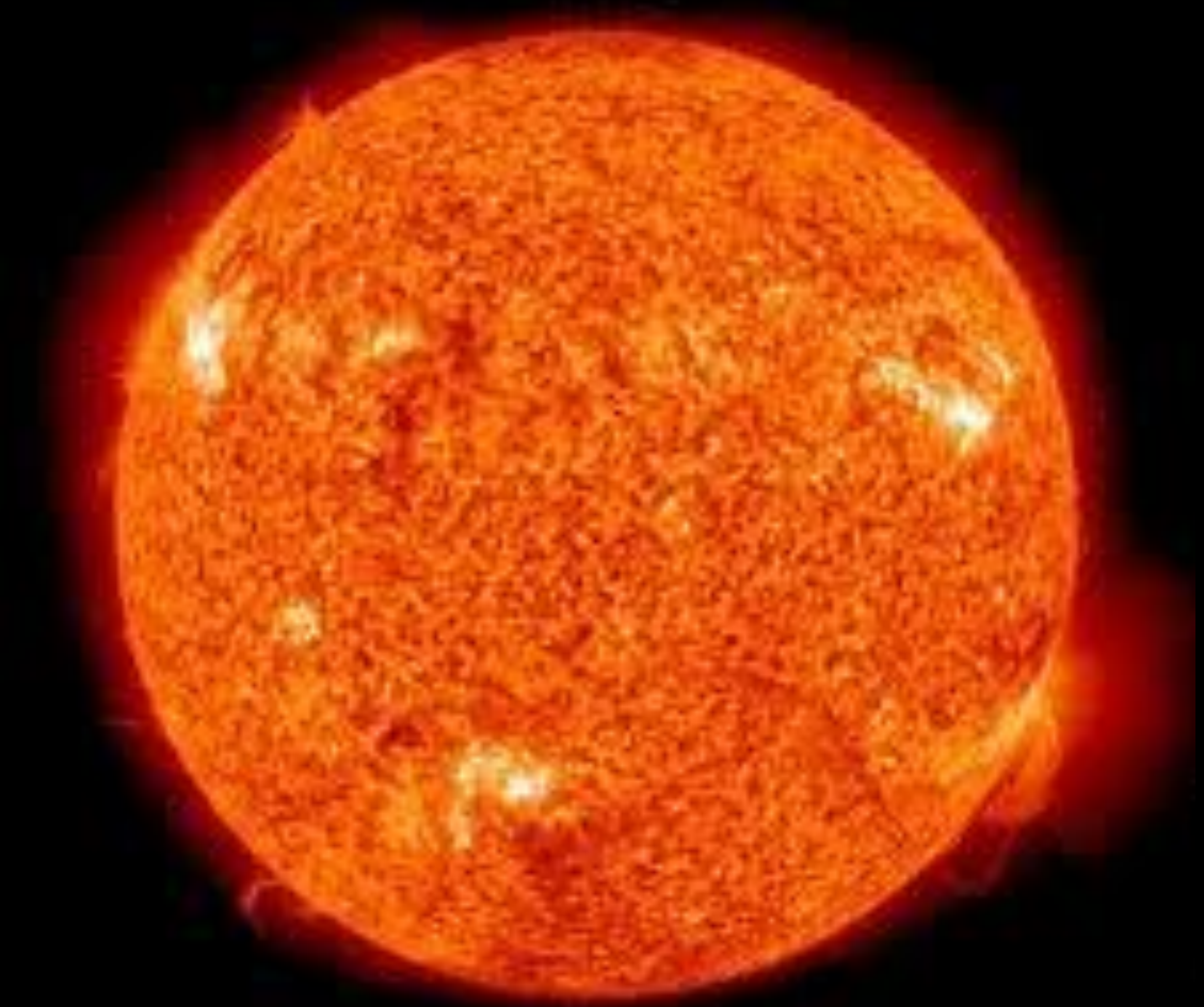
Solar Spectrum



Lecture - Learning Objectives

At the end of this lecture you should:

- Be able to calculate the solar constant.
- Understand variations in solar irradiance (locally and with respect to time).
- Understand climate/energy balances to a first order approximation.
- Understand how fossil fuels contribute to CO_2.

Why is the sun so important ?

- Comparison of renewable energy sources:
  - Geothermal: 0.3-2 TW
  - Hydro Power: 3-4 TW
  - Biomass: 2-6 TW
  - Wind Power: 25-70 TW
  - Solar Power: 23,000 to 177,000 TW ← Where does this number come from?
- Wind is basically caused by variations in temperature from non-uniform heating by the sun.
- Biomass is directly based off of solar.
- Hydrothermal is from water that has been evaporated by the sun.
- The sun is the source of the vast majority of our energy sources (nuclear reactions, and tidal waves are not.)

What is the sun ?

- The sun can be thought of as simply a source of blackbody radiation.
- Planck's law is: $I_E dE = \frac{2\pi v^3}{c^2} \frac{1}{\left(e^{hv/kT} - 1\right)} dE$

  Or equivalently: $I_\lambda d\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\left(e^{hc/\lambda kT} - 1\right)} d\lambda$

- However by using the speed of light equation: $c = \lambda v$

  And the Planck-Einstein relation: $E = hv$

  We can convert from energy to wavelength: $E(eV) = \frac{hc}{\lambda} = \frac{1240}{\lambda(\text{nm})}$

- Quickly converting from wavelength to energy is essential in any photo based energy field (e.g. photosynthesis, photovoltaics, photochemistry).

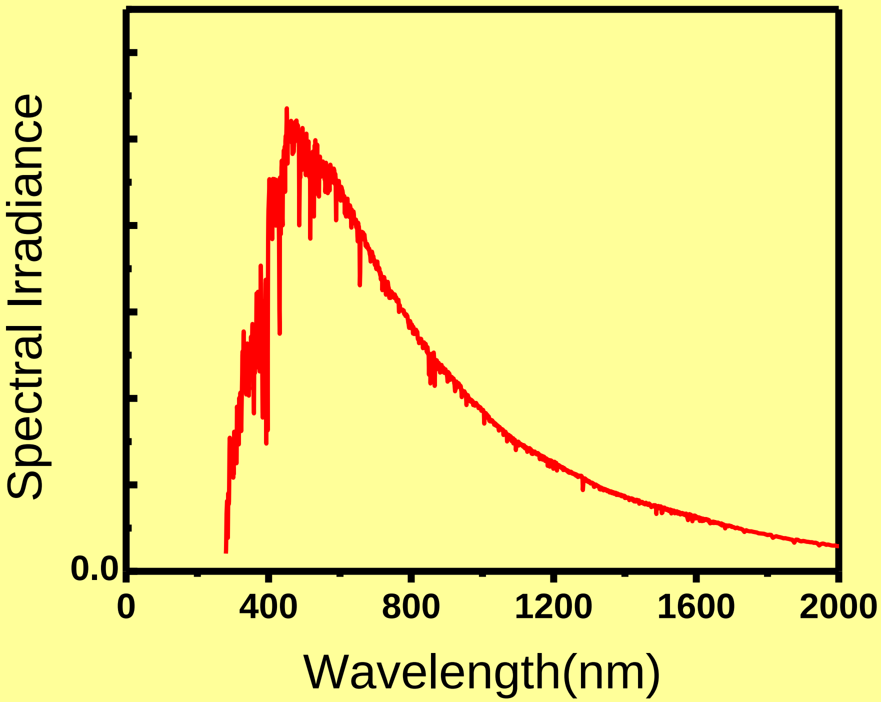
Planck's law- application

- Here is the Planck's law in convenient terms.

$$I_\lambda d\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{\left(e^{hc/\lambda kT}-1\right)}d\lambda$$

- Below is the spectrum from the sun. What is the sun's 'effective' temperature?

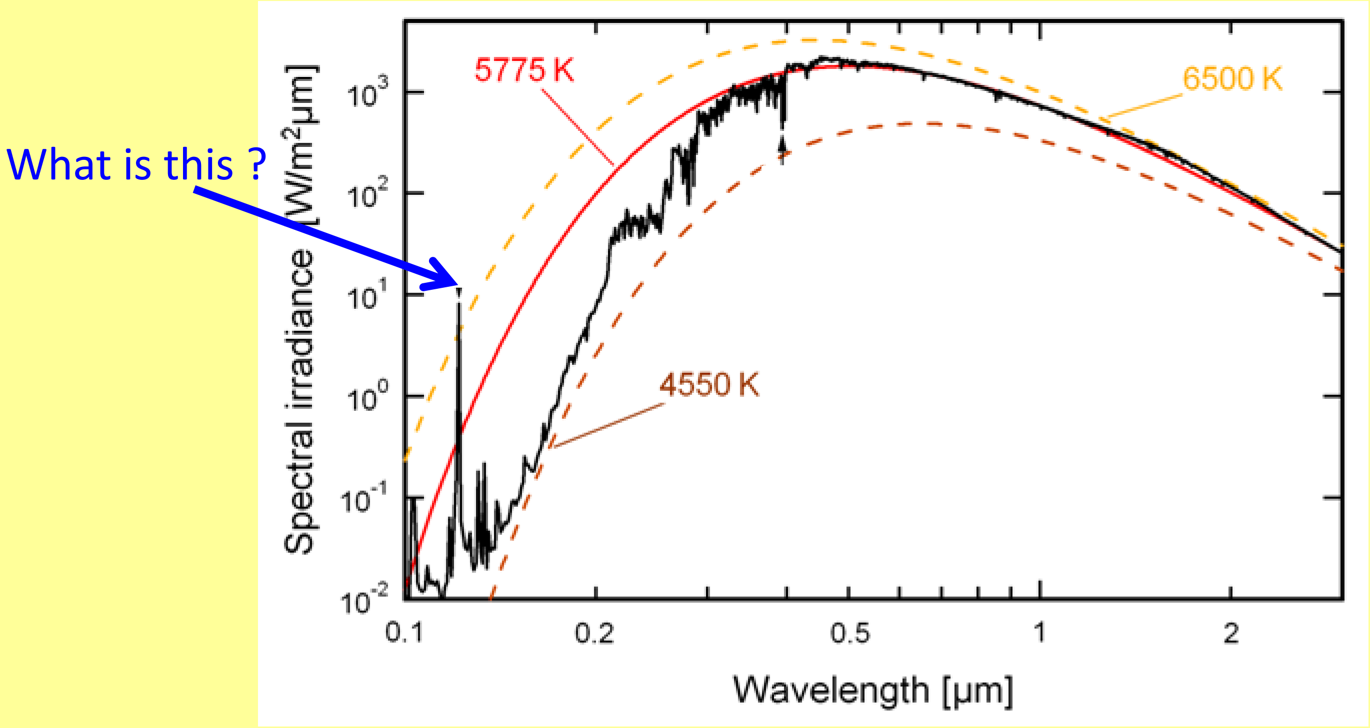
($k = 1.38 \times 10^{-23}\ m^2\ kg\ s^{-2}\ K^{-1}$ $c = 3 \times 10^{8}\ m/s$ $h = 6.6 \times 10^{-34}\ m^2\ kg\ s^{-1}$)



- The peak in radiation is simply where the derivative of this equation is zero.
- For ease in derivation, note the exponential is quite large, thus the '1' in the denominator can be ignored.

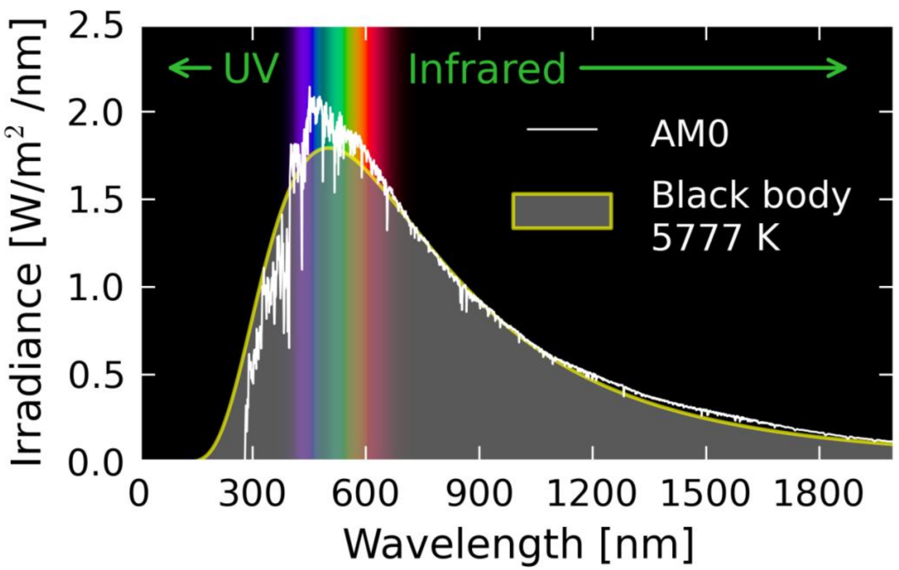
Blackbody approximation

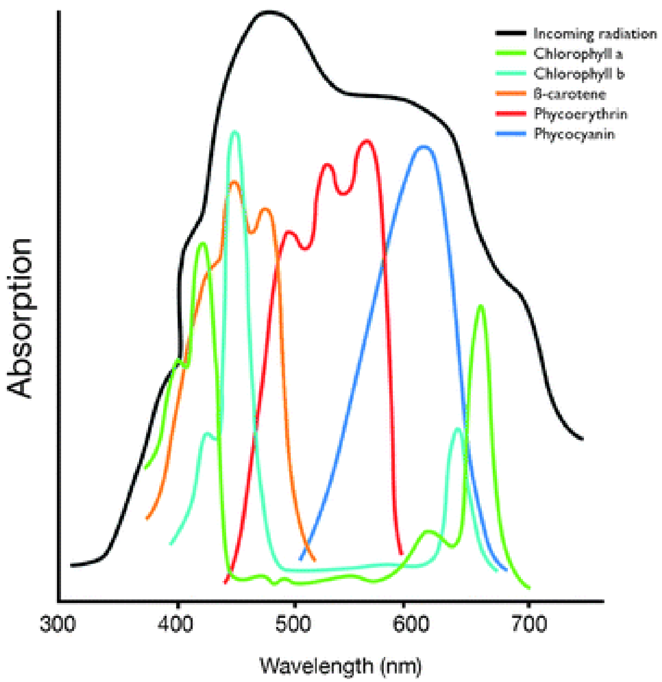
- The solar spectrum is very close to a pure black-body irradiator, but not exactly.
- Explain the differences.



Visible Light

- It is no coincidence that the visible spectrum matches that of the peak irradiance intensity.
- Evolution naturally led to producing molecules that would be in the most active spot of the solar spectrum.
- This is what allows us photosynthesis to produce about 70 TW worth of energy (little of this is feasible to capture though.)



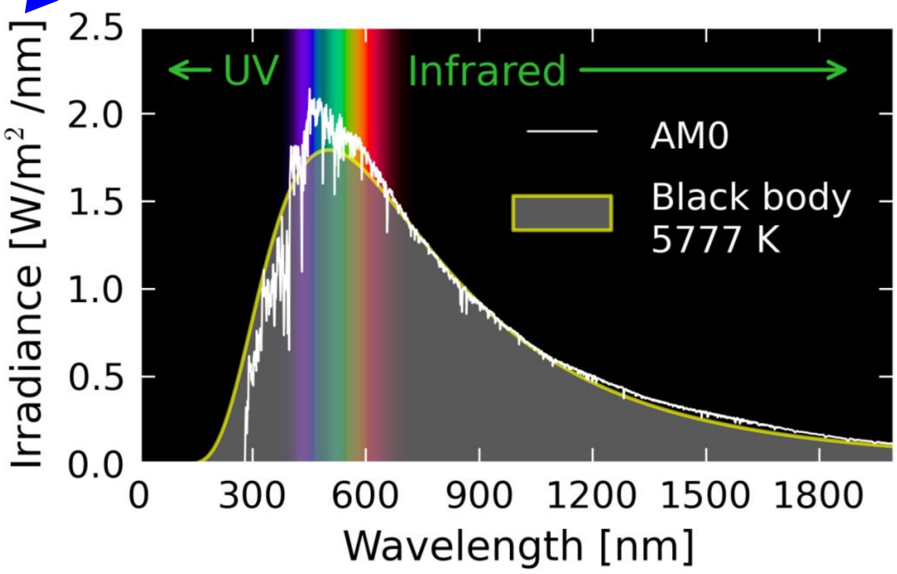


Visible Light

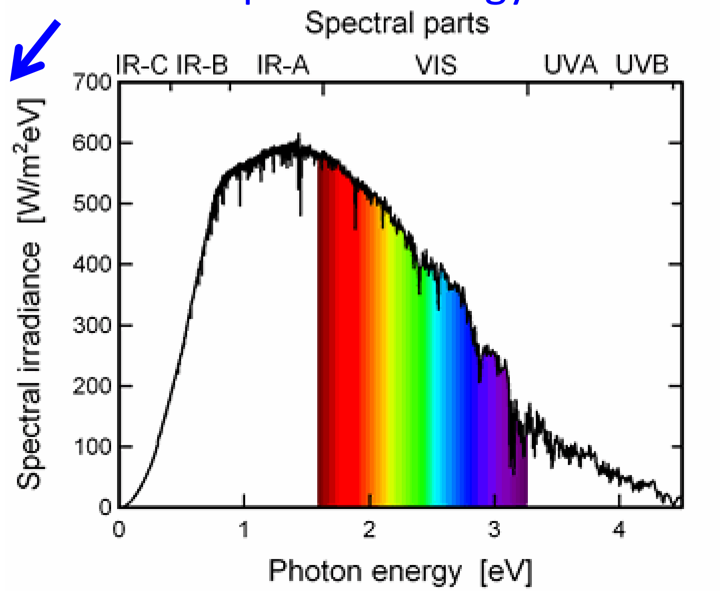
- While typically the plots are irradiance vs. wavelength, irradiance vs. photon energy can also be useful.
- We can convert these graphs using the following equation:

$$E(eV) = \frac{1240}{\lambda(\text{nm})}$$

Per nm of wavelength



Per eV of photon energy



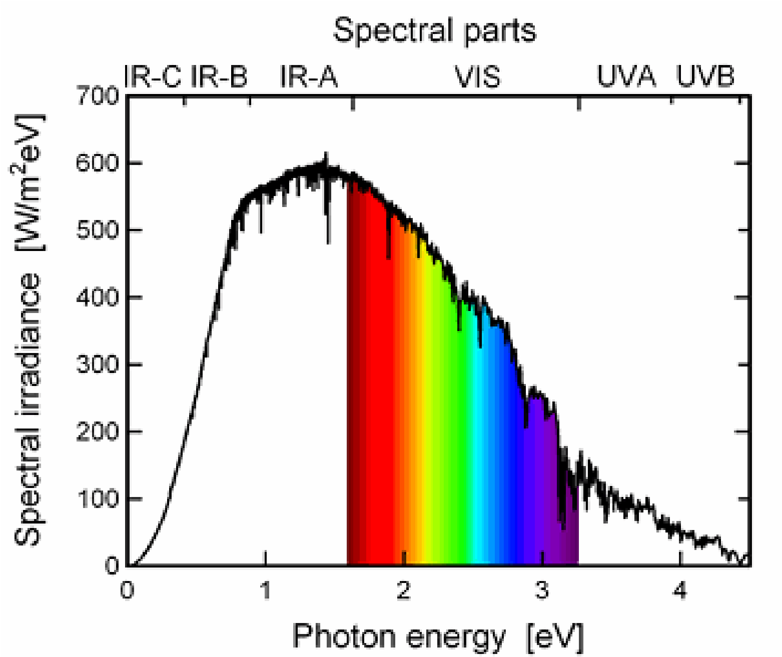
Irradiance vs. Photons

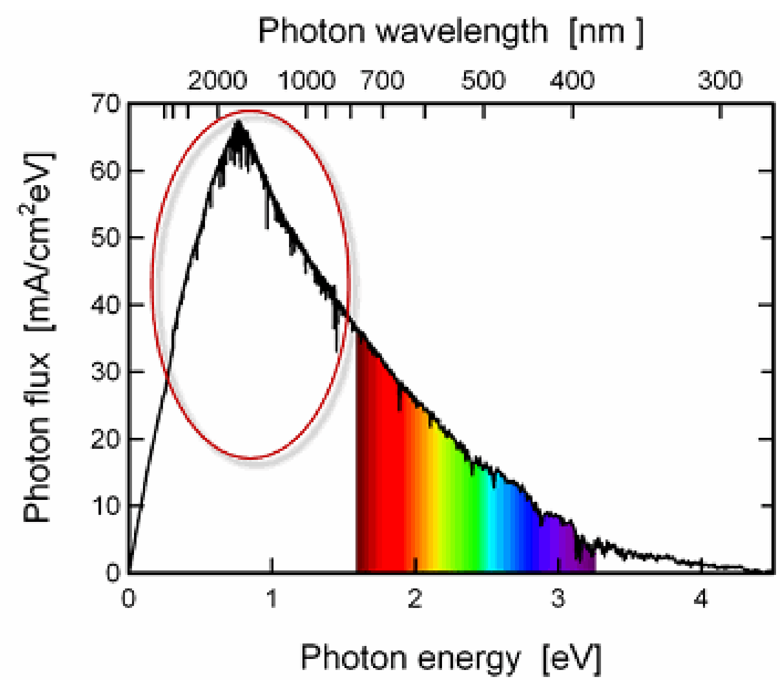
$$Total\ Power = \int_0^{\infty} n_{photons} \times E_{Photons} dE$$

Where n = number of photons / second

E = energy of photons

- Realize that the # of photons at a given wavelength is not the same as total power at a given wavelength (or given energy).





Total energy from the sun

- The total energy coming from the sun can be found be integrating the solar spectrum or, in effect, Planck's law.

Planck's law

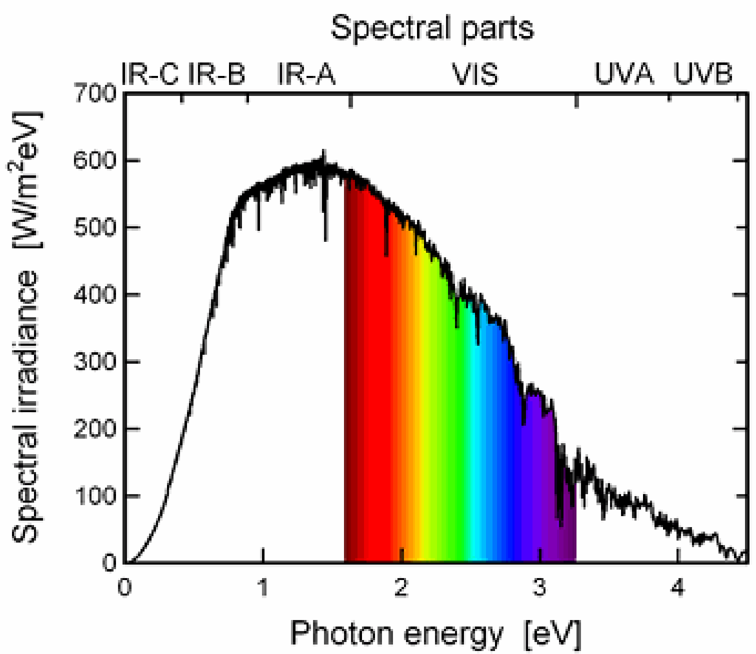
$$I_E dE = \frac{2\pi v^3}{c^2} \frac{1}{\left(e^{hv/kT} - 1\right)} dE$$

- Fortunately this yields a simple analytical solution.

- The Stefan-Boltzmann law:

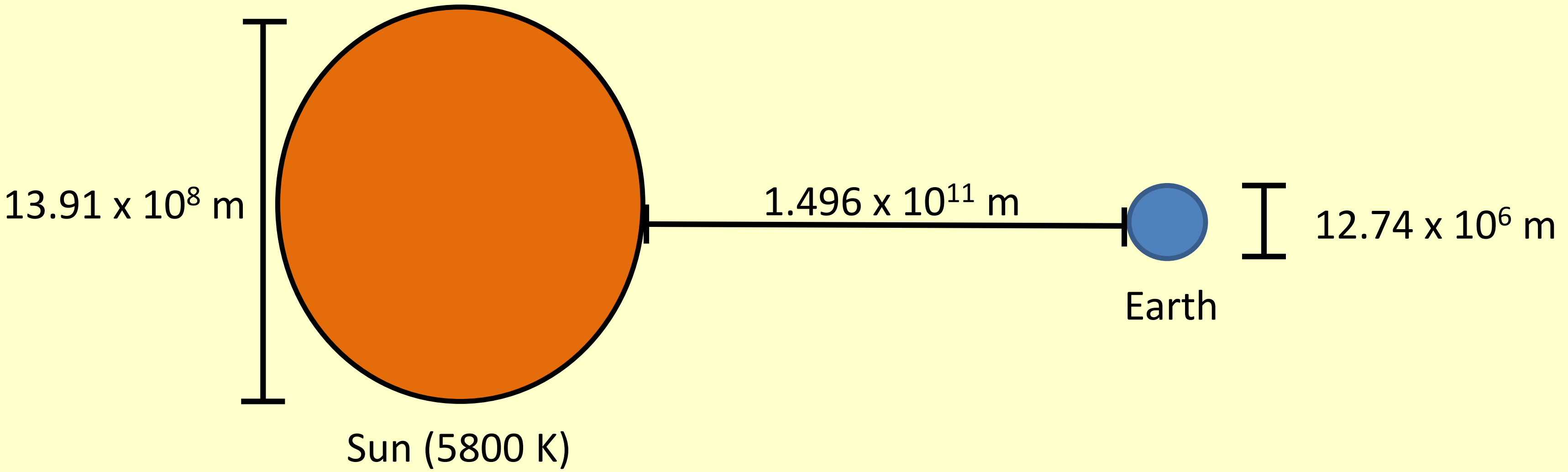
$$I = \sigma T^4$$

- Where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})



Irradiance striking earth

- First calculate the total power from the sun.
- Next, use geometric principles to calculate the earth's solar irradiance at the edge of earth's atmosphere in W/m^2.
- Also calculate the total amount of solar energy that strikes earth in W.



- Remember $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

Location specific irradiance

- Obviously the earth is round so different areas will have different illuminations.
- For a 1st order approximation we will assume no clouds or atmosphere.
- There are 3 main issues that will effect solar insolation.
  - Seasonal variations
  - Daily variations
  - Latitude on the globe

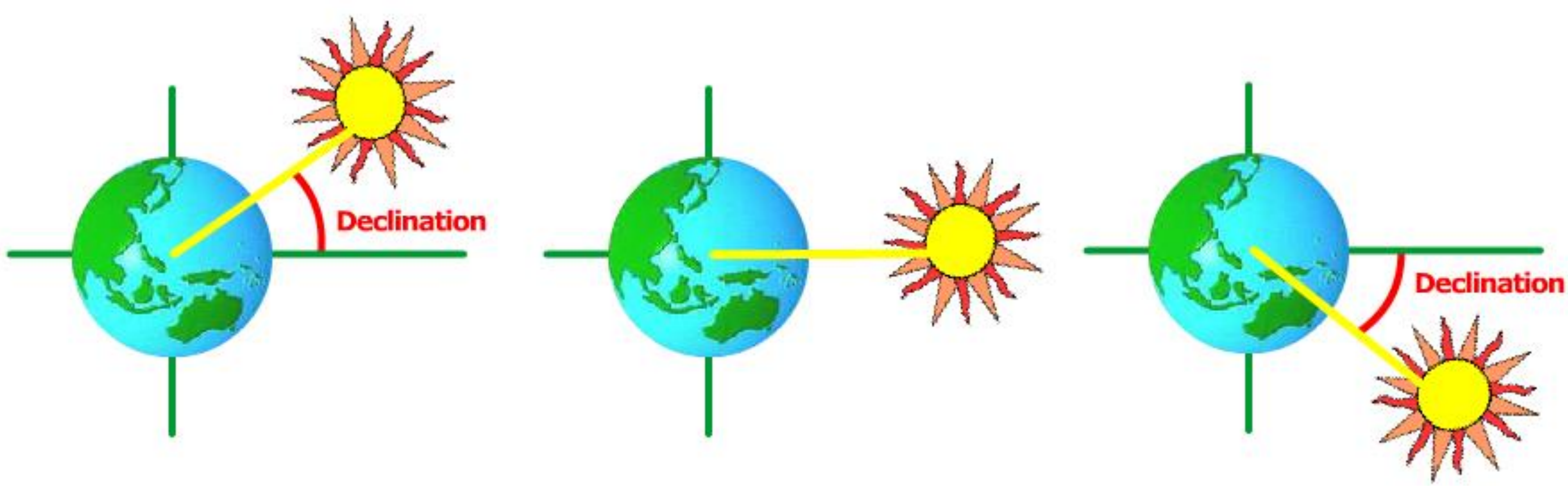
Seasonal variations in irradiance

- The easiest way to think about this is to think of the sun fluctuating and the earth staying still.
- The variation in angle (ε) reaches a maximum of 23.5°.
- This '*declination*' angle has been approximated to be:

$$\delta = sin^{-1}\left[sin(\varepsilon)sin\left(2\pi\frac{(N-81)}{365}\right)\right]$$

-where N stands for days with Jan 1st being d=1

- At noon at the equator the solar irradiance = S x cos (δ)



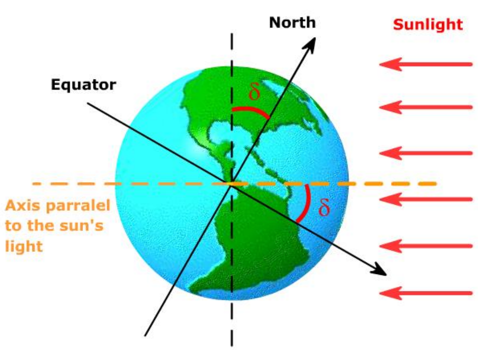
Daily and latitude variations in irradiance

- The daily variations and variations due to latitude become intertwined with seasonal variations.
- The zenith angle (β) can be calculated as followed:

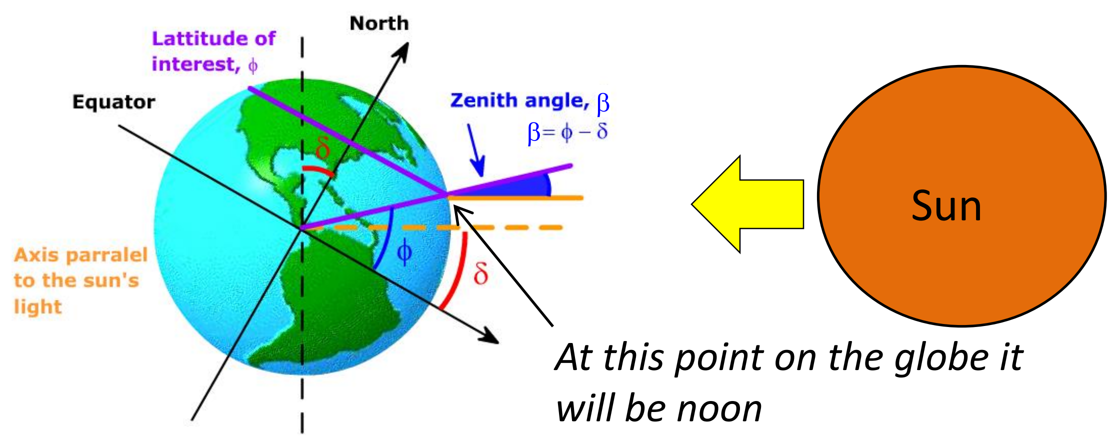
This is noon

$$\beta = cos^{-1}\left[\sin\delta\sin\phi + \cos\delta\, cos\,\phi\;\; cos\left(2\pi\frac{(t - 12hour)}{24\ hour}\right)\right]$$

- ϕ stands for the latitude (ϕ is conventional notation, but EP uses λ)
- *t* stands for time of the day in hours. This is the solar time, thus varies slightly throughout different time zones.



Just seasonal variations



Seasonal variations + latitude variations

Total irradiance

- The total irradiance then is:

$$\text{Irradiance} = S \times cos(\beta)$$

- Integrating this over time allows you to get how much energy strikes a certain location per hour, per day, per year….

- By setting cos β = 0, we can determine the time of sunrise and sunset.

$$\text{Cos}\,\beta = \sin\delta \sin\phi + \cos\delta\, cos\,\phi\;\; cos\left(\frac{2\pi}{24\ hour}(t - 12hour)\right)$$

Boring derivation

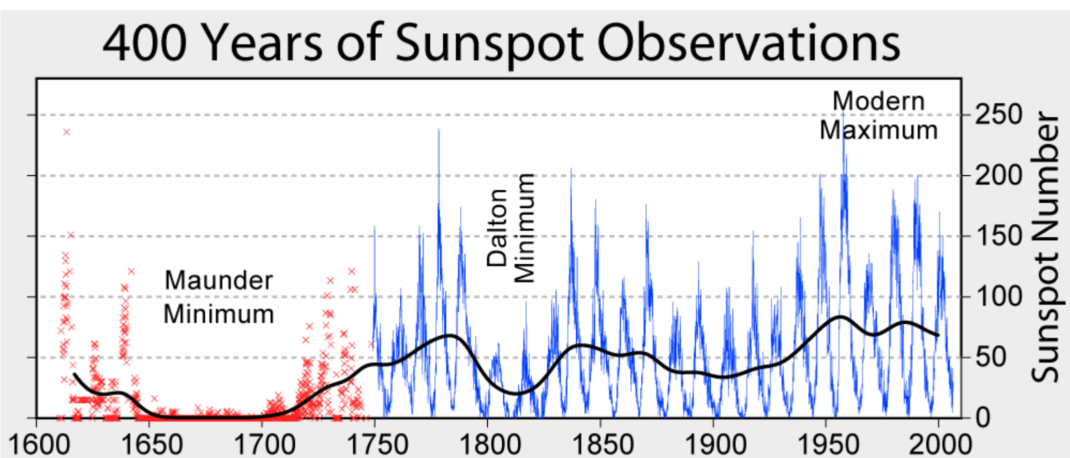
$$T = 12\ hour \pm \frac{24\ hour}{2\pi} cos^{-1}[-tan\,\phi \tan\delta]$$

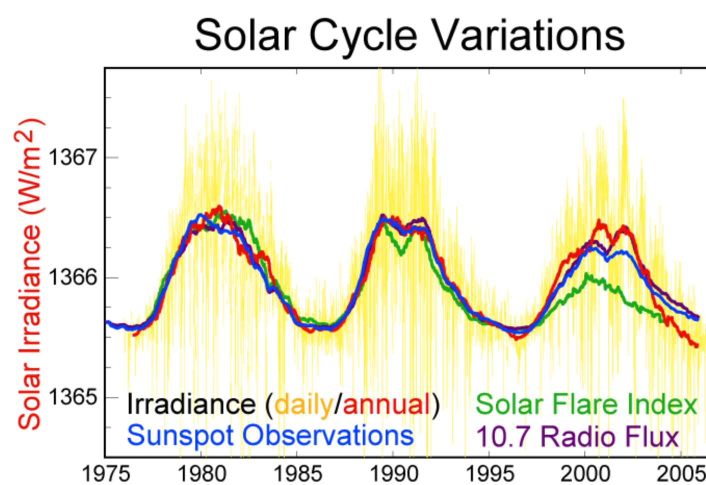
Long-term fluctuations in solar intensity

- There are multiple things that can change the solar irradiation:
  - The sun's temperature could fluctuate
    - Due to burning up all the fuel (Billion year time frame- irrelevent).
    - From convective mass transfer due to differences in heating between core and the outer edge of the sun.
  - The earth's tilt (for seasonal variations) actually varies over time.
  - The earth doesn't rotate perfectly around the sun due to:
    - Gyroscoptic effects from tidal forces
    - Relativity effects due to oblateness from the sun
    - Gravitational interactions with other planets

Solar fluctuations

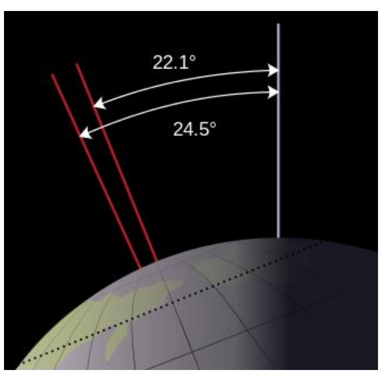
- The largest solar fluctuations are due to sunspots.
- Sunspots are basically a concentration of a magnetic field, that prohibits convection.
- This lowers the localized temperatures to 3000-4500 K, but actually increase the irradiance to Earth.
- These sun-spots are quite cyclical.
- They effect the solar constant (S) by about 1 W/m^2.



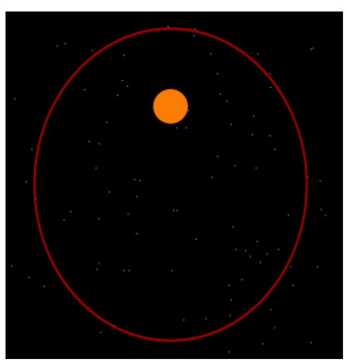


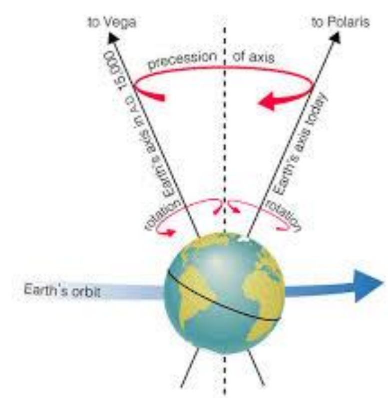
Variations in earth's rotation

- The earth's tilt varies from 22.1° to 24.5° every 41,000 years. Now it is at 23.44°.
- The earth's eccentricity (ε) varies from 0.000055 to 0.0679 over 413,000 years. Now it is at 0.017.
- The axial precession and apsidal precession also provide variation in the earth's rotation.

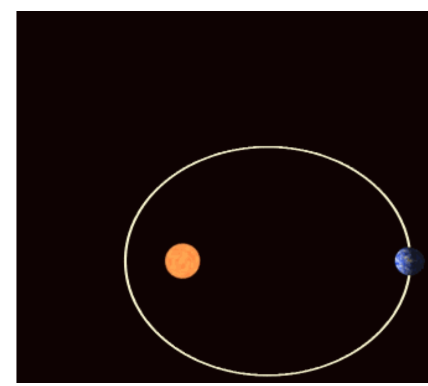


Tilt


Eccentricity (ε=0.5)

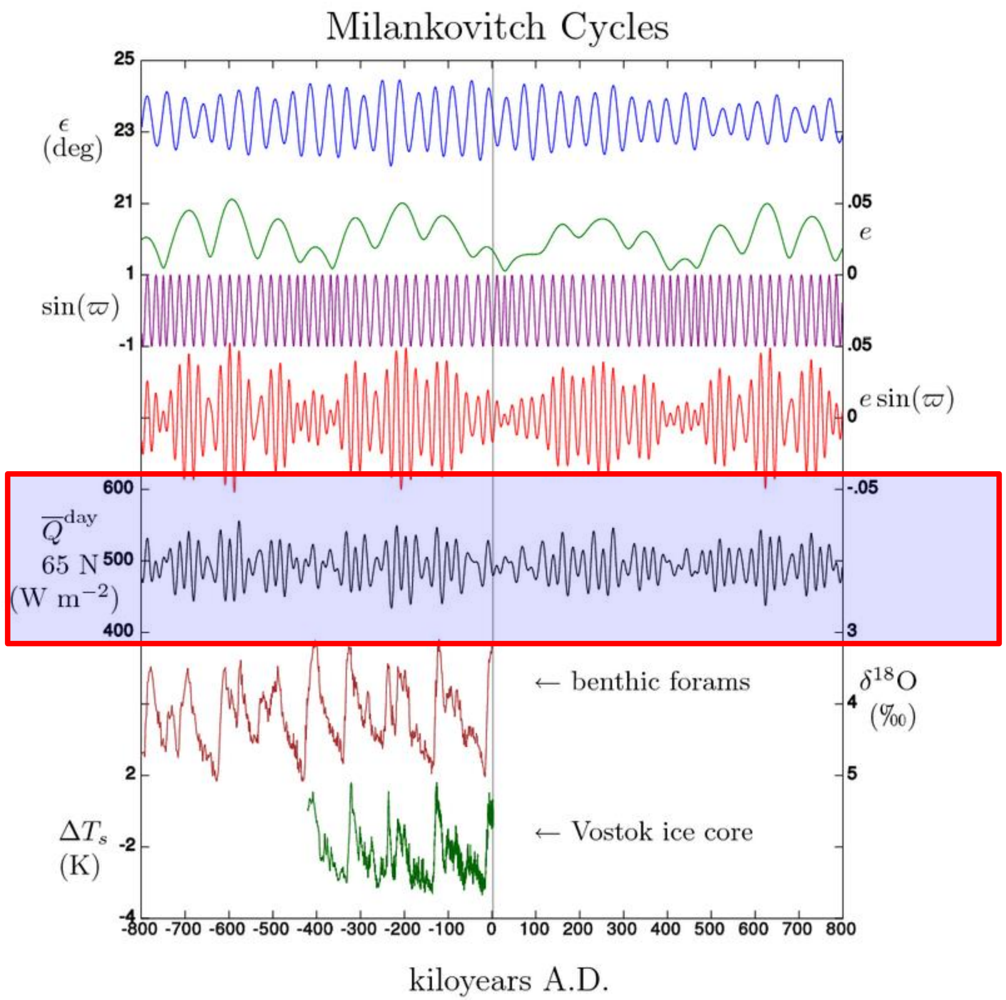


Axial Precession


Apsidal Precession

Variations in solar irradiation

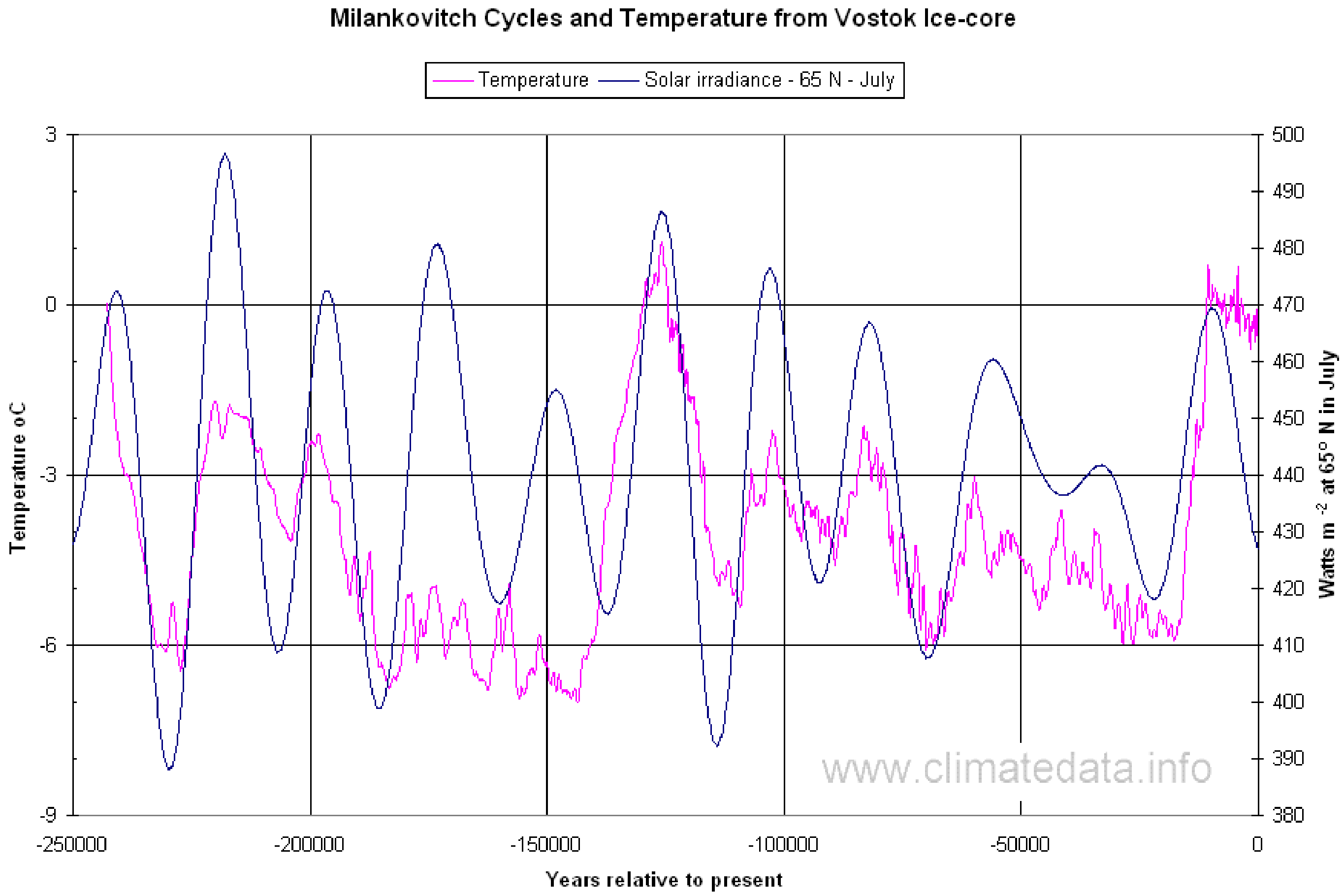
- While in a WW1 POW camp, Mulitin Milankovitch calculated all these effects.
- Due to tilt effects, global irradiation variations is felt most near the poles.
- There is a significant variation in solar flux.



— ε is obliquity (axial tilt).
— e is eccentricity.
— ϖ is longitude of perihelion.
— $e\sin(\varpi)$ is the precession index, which together with obliquity, controls the seasonal cycle of insolation.
— $\overline{Q}^{\text{day}}$ is the calculated daily-averaged insolation at the top of the atmosphere

Variations in solar irradiation

- It can be argued that solar cycles have some effect on the climate.



The solar spectrum- practical

- When discussing the solar spectrum, ‘air mass’ is used to account for the atmosphere

$$Air\ Mass = AM(x) = \frac{L}{L_0}\ 255\ \text{K}$$

- Where L = Path length through the atmosphere
  L_0 = Path length normal to the earth’s surface at sea level (i.e. the equator at noon on either the spring or autumn equinoxes)

- There are 2 standard spectrums that are used:
  - AM0- This is the solar spectrum at the edge of the atmosphere. The total irradiance= the solar constant
  - AM1.5- practically- average solar irradiation over the USA. Scientifically- 37^{o} tilt at 1976 US standard atmosphere, water vapor equivalent of 1.42 cm, ozone equivalent of 0.34 cm,….. other random minute details.

- American Society for Testing Materials (ASTM) has probably the most accurate spectrum. (http://rredc.nrel.gov/solar/spectra/am1.5/)

Break

What about Earth's irradiance

- Earth is also a black-body irradiance.
- What would be the black-body irradiance from earth (assuming no atmosphere).

$$\text{Energy In} = Energy\ Out$$

$$S \times \pi E^2 = \sigma T_{Earth}{}^4 \times 4\pi E^2$$

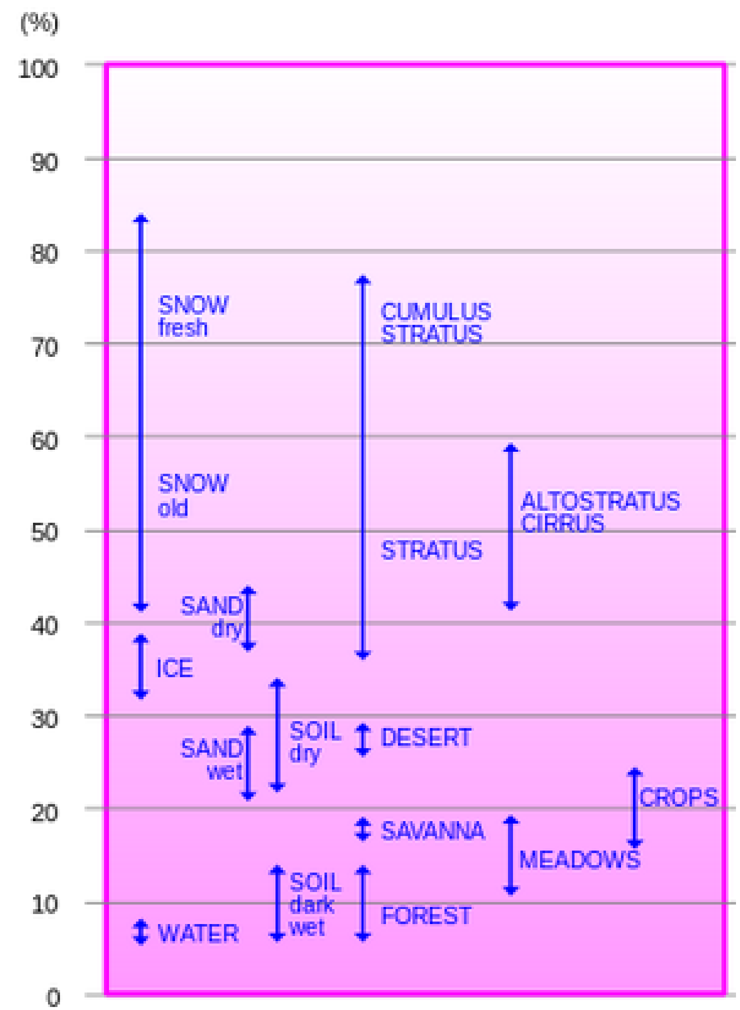
r= radius of earth

$$T_{earth} = \left(\frac{S}{4\sigma}\right)^{1/4}$$

- This would yield a temperature of 278 K (5° C), whereas the real temperature is 288 K.
- What will the atmosphere do?

Earth's albedo

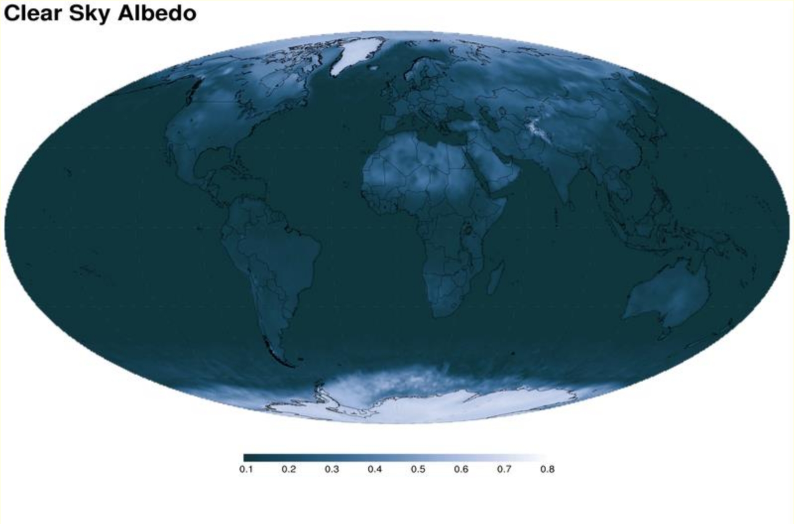
- Earth's albedo (*a*) is a value which is a fraction of how much solar irradiation gets reflected back into space.
- An albedo (*a*) of 100% means pure reflection of all light back into space.
- 0% means pure absorption.
- Note the difference between snow, ice and water.

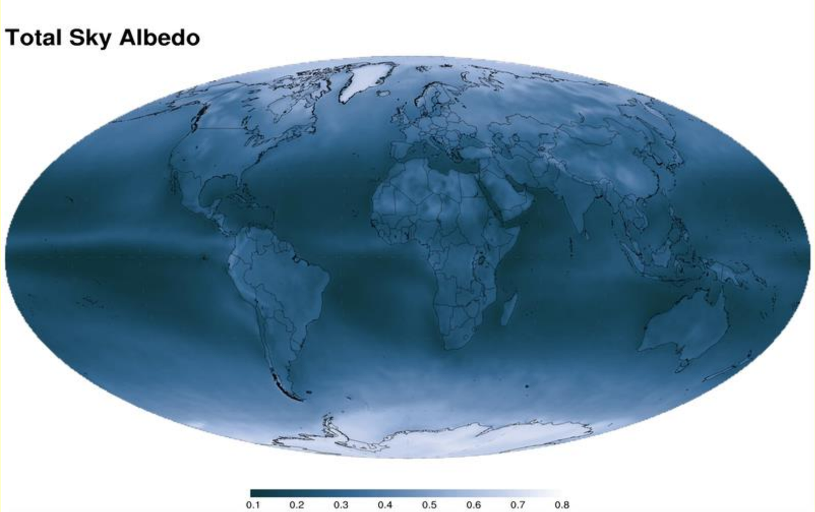


Percentage of diffusely reflected sunlight in relation to various surface conditions

Earth's albedo

- The albedo does vary with light wavelength, but it is relatively easy to average this out.
- Earth's average albedo is between 0.3-0.34.

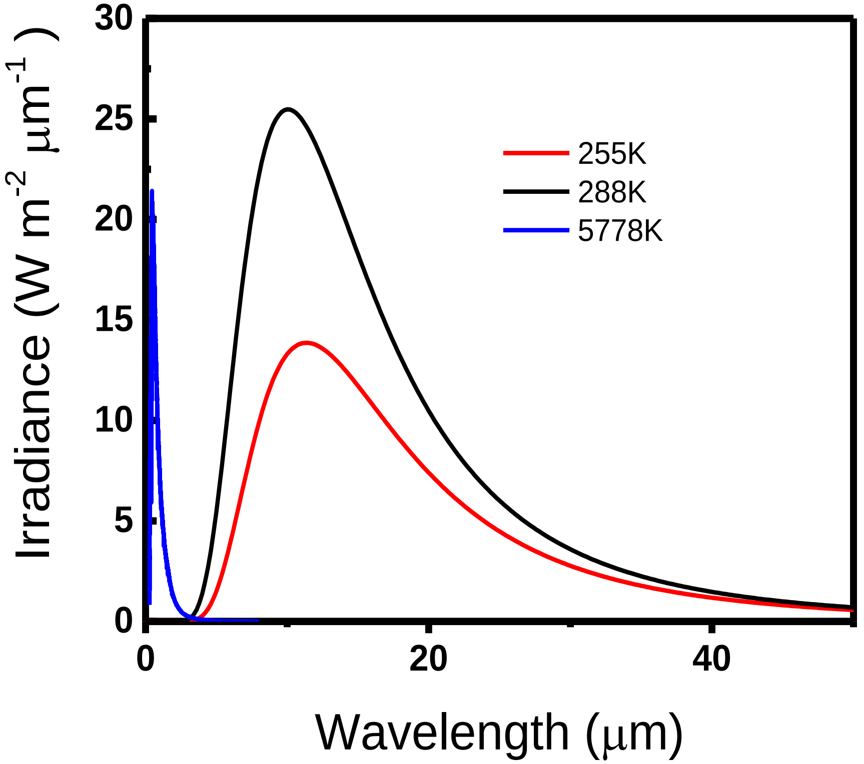


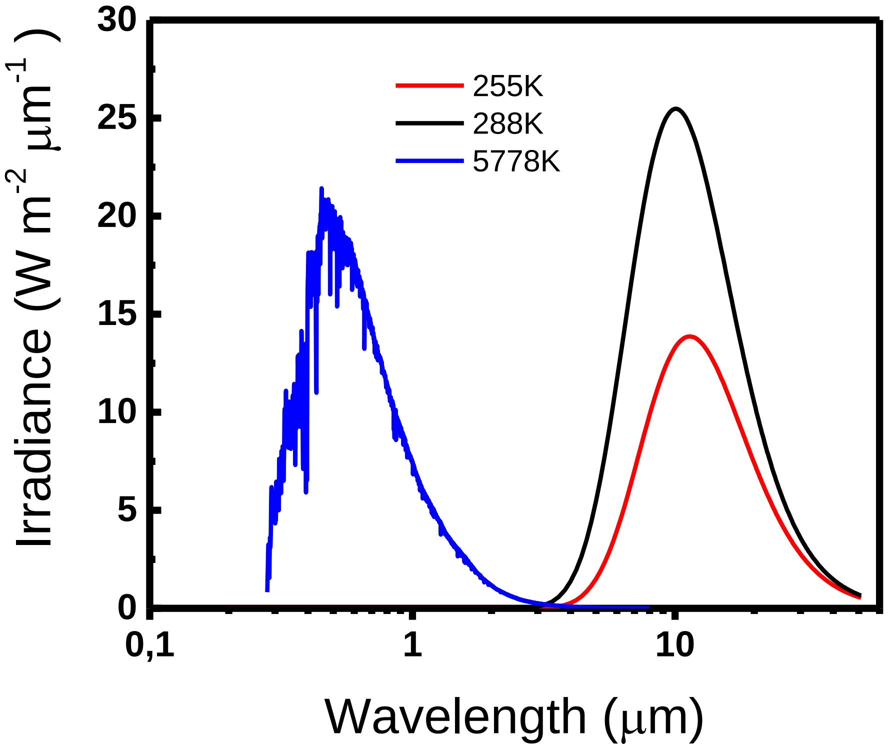


- Assuming an albedo of 0.3:
  - What is the amount (in TW) of photons that actually are absorbed, not reflected. Remember we calculated 177,000 TW irradiate the earth.
  - What is the Earth's temperature?

Emission spectra

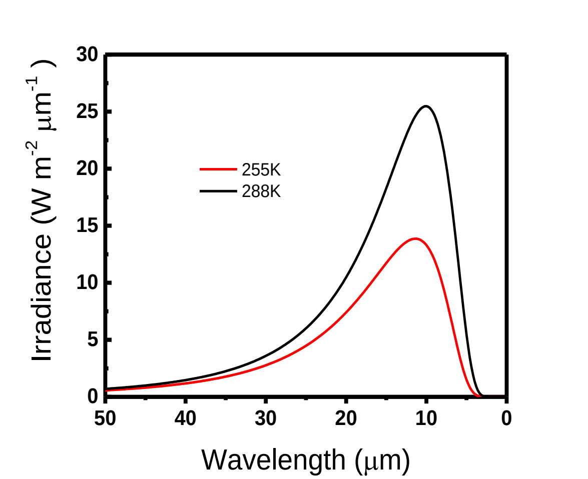
- 255 K emits over a broad range.
- There is not much variation between 255 K and 288 K.
- However compared to the sun there is a lot of variation.



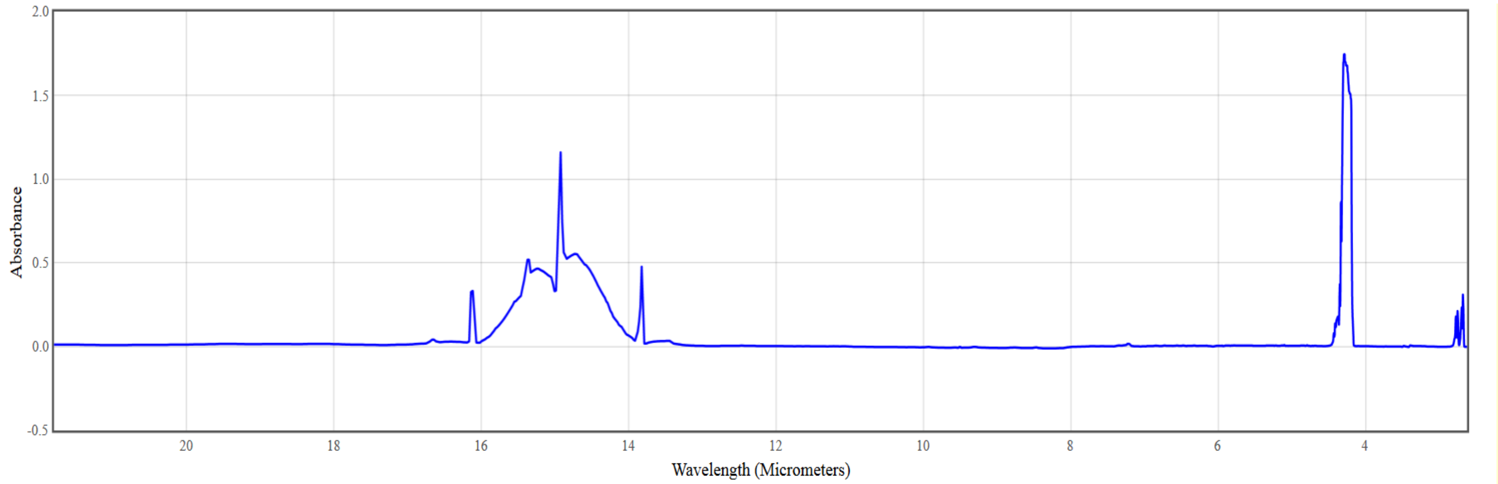


-Sun’s irrandiance power (at the sun) was scaled down by a factor of 100.

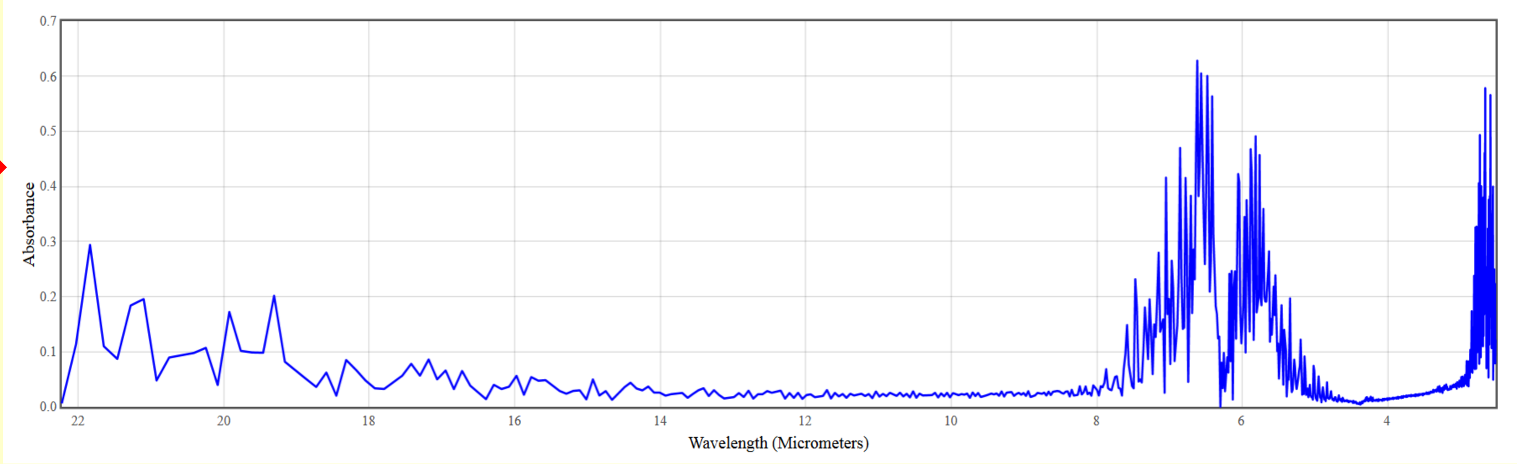
- Below is the absorption spectra for CO_2 and H_2O.
- Can you explain how these absorption spectra relate.



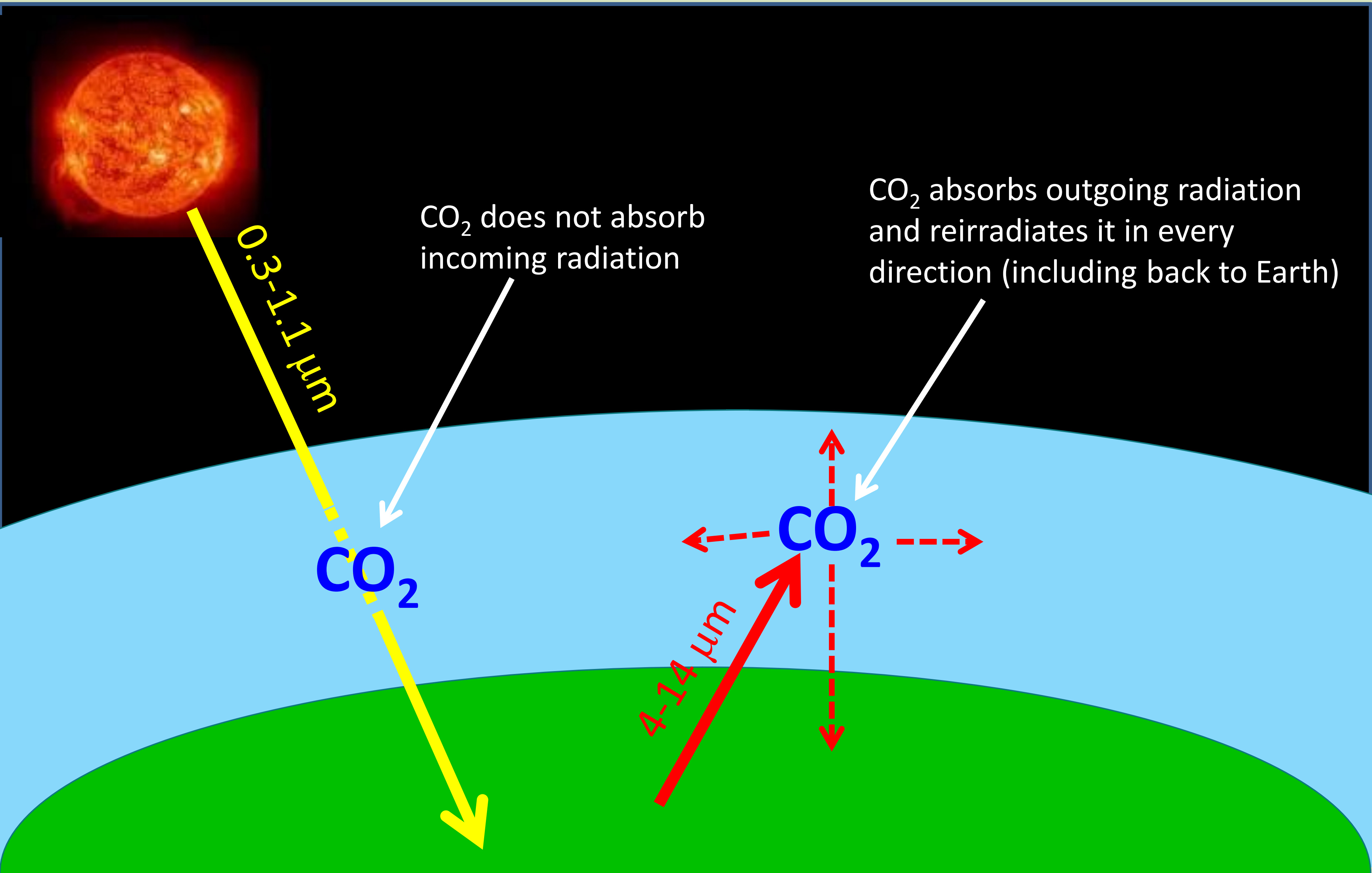
CO_2



H_2O

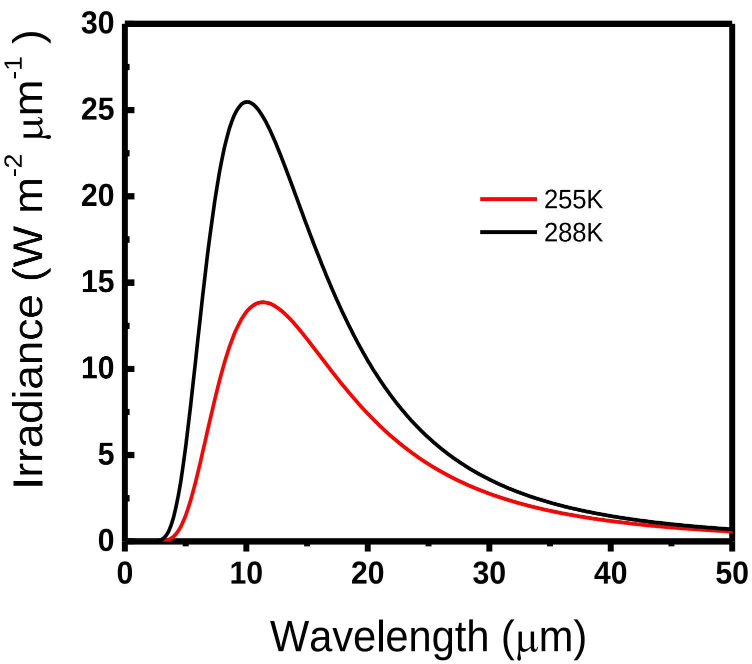


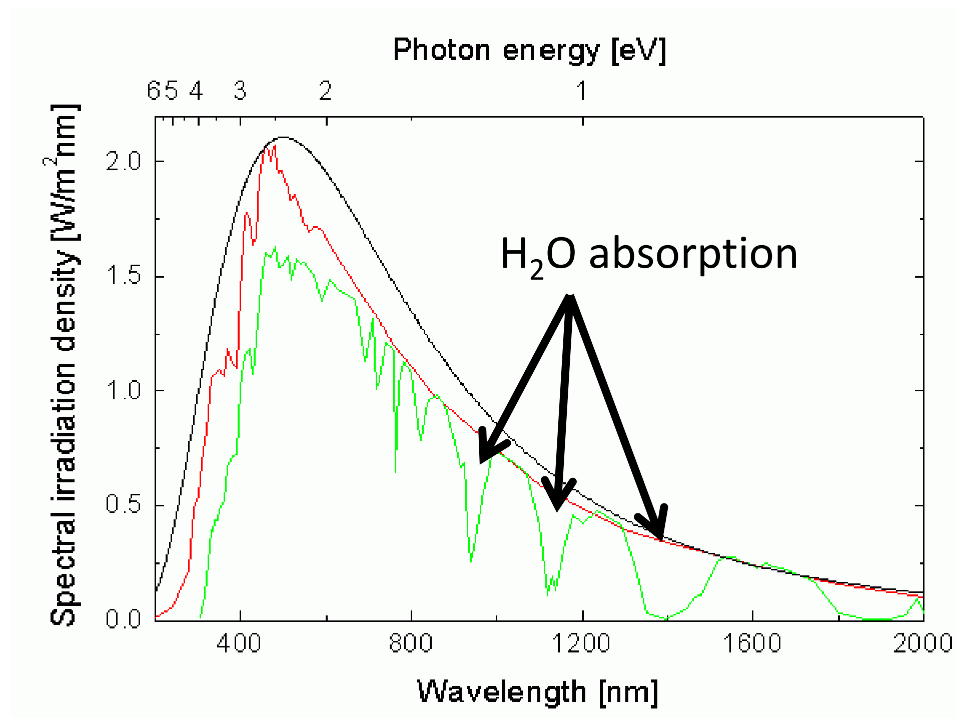
1st order climate modeling



Greenhouse effect

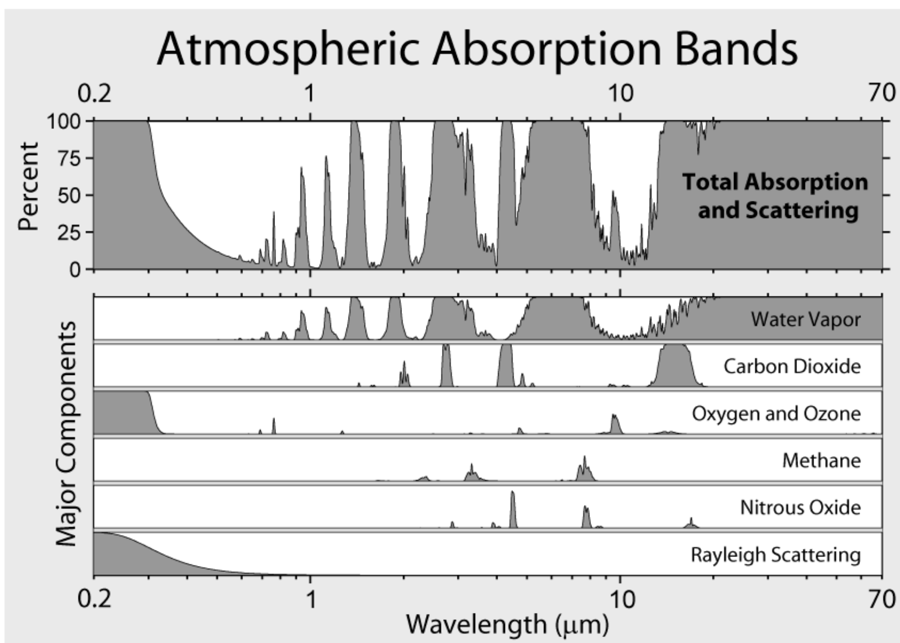
- The re-irradiation of greenhouse gases accounts for the temperature difference between 255 K and 288 K.
- A closer look at the solar irradiation spectra shows green houses gases (mostly water) also effects this spectra.
- Will water absorption have any effect on global warming?





It is not an 'Absolute' disaster, yet

- Water contributes to global warming, but it's effects are relatively consistent.
- CO_2 actually absorbs 100% at its peak wavelength … and always has.
- Increasing CO_2 is simply broadening the thickness in wavelengths of CO_2 absorption.



All greenhouse gasses

- CO_2 is not the only green house gas, it is just the largest contributor.
- The IPCC list of greenhouse gases consist of 6 major types of molecules

- While less common, other molecules have a greater impact on climate change.
- Water and ozone also are strong greenhouse gases.

Molecule	**CO_2 Equivalent**
Carbon dioxide (CO_2)	1
Methane (CH_4)	34h
Nitrous oxide (N_2O)	298
Hydrofluorocarbons (HFCs)	2,000-11,000
Perfluorocarbons (PFCs)	7,000-12,000
Sulphur hexafluoride (SF_6)	22,800

100 year global warming potential

All greenhouse gasses

- Breakdown of greenhouse gas by source

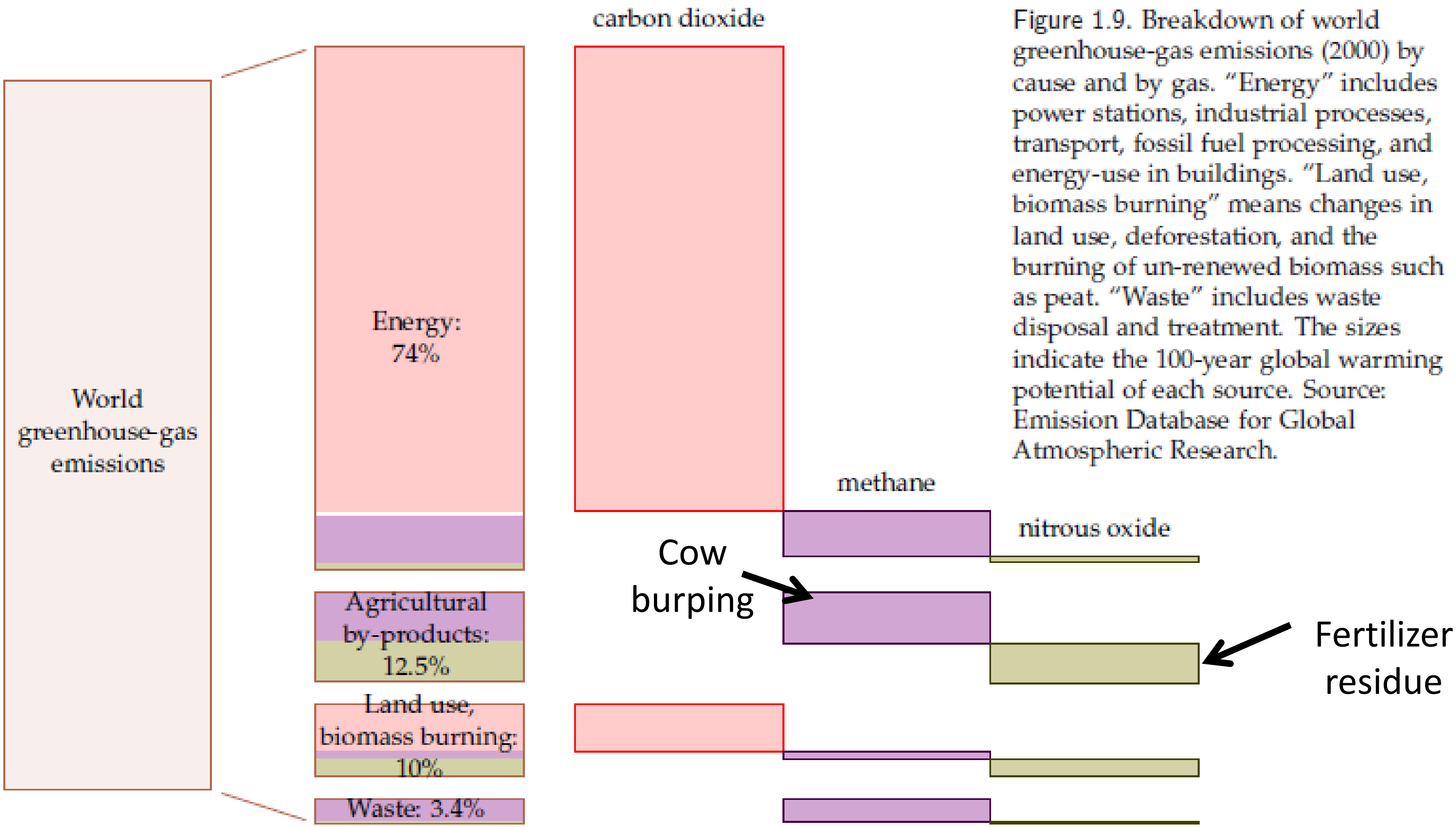
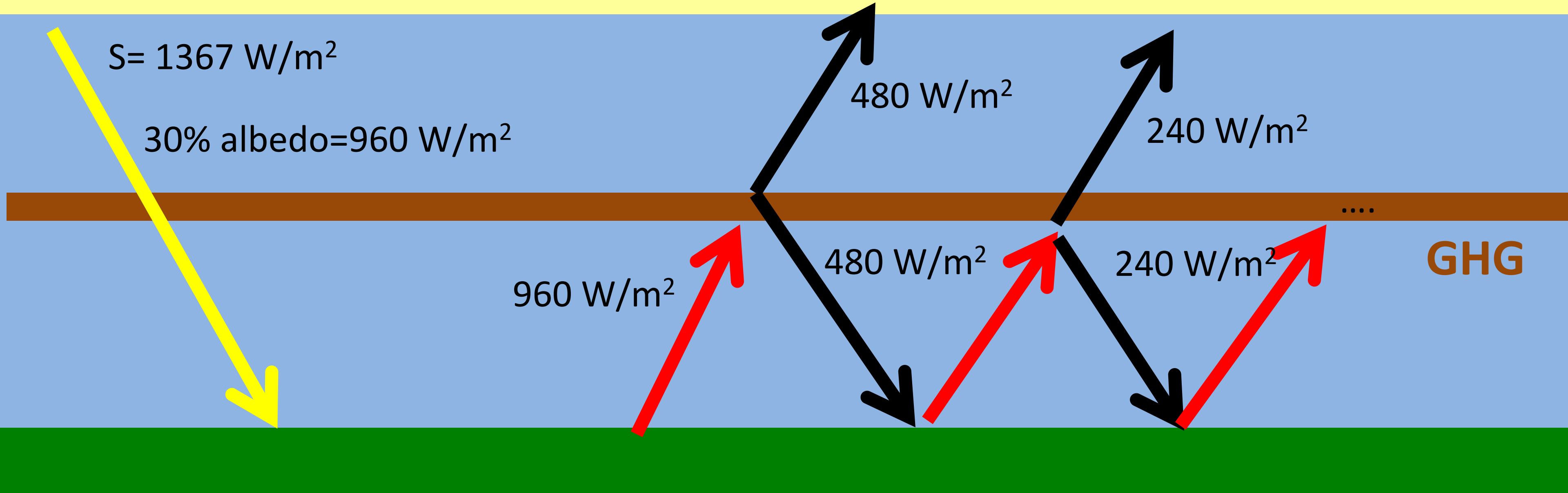


Figure 1.9. Breakdown of world greenhouse-gas emissions (2000) by cause and by gas. "Energy" includes power stations, industrial processes, transport, fossil fuel processing, and energy-use in buildings. "Land use, biomass burning" means changes in land use, deforestation, and the burning of un-renewed biomass such as peat. "Waste" includes waste disposal and treatment. The sizes indicate the 100-year global warming potential of each source. Source: Emission Database for Global Atmospheric Research.

1st order climate modeling

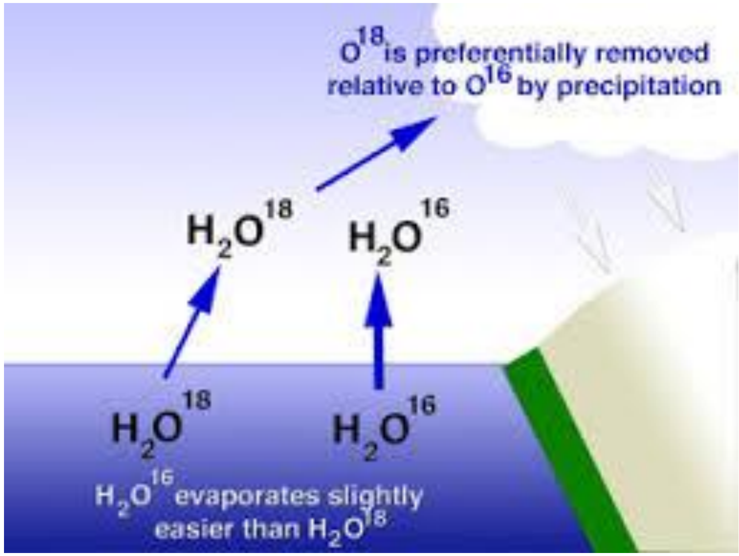
- Lets assume greenhouse gases (GHG) absorb 100% of Earth's outbound irradiation exactly at a set distance from earth.
- Assume 50% is irradiated out and 50% is irradiated back in (irradiation is uniform in all directions, so this is reasonable).
- What would be the temperature of Earth under these conditions?

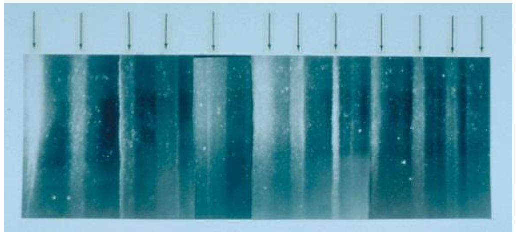


Break

Historical CO_2

- Atmospheric science is very complex and historical data is great for how CO_2 affects the environment.
- It is known that 2 different isotopes of water evaporate at different rates.
- The ratio between isotopes is a function of temperature.
- Comparing the water isotope ratio in ice cores allows to determine temperature for a given year´.
- Air bubbles then allow for researchers to determine the amount of CO_2 in the atmosphere.

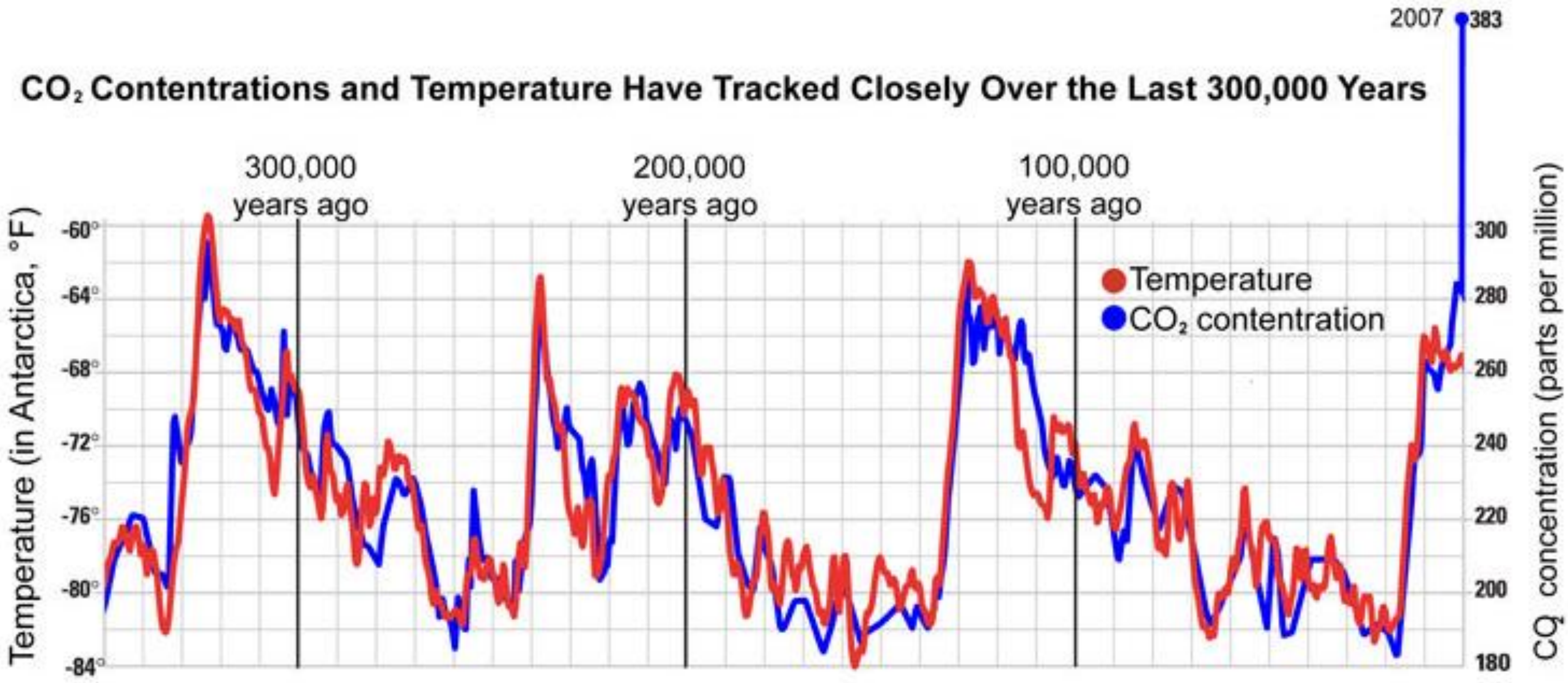




Ice Core

CO_2 relationship to temperature

- Ice core data is what led us to produce charts like the one below.
- Currently we are at a CO_2 concentration (411 ppm) that has never been seen before.



Vostok Ice Core

Fundamental physical laws in climate models (atmosphere)

Equation of state

$$p = \rho R T$$

Momentum equation

Coriolis Force

Viscous Force

$$\frac{D\boldsymbol{U}}{Dt} = -2\boldsymbol{\Omega} \times \boldsymbol{U} - \frac{1}{\rho}\nabla p + \boldsymbol{g} + \boldsymbol{F}_r,$$

Thermodynamic equation

$$J = c_v \frac{DT}{Dt} + p\frac{D\alpha}{Dt} = c_p \frac{DT}{Dt} - \alpha\frac{Dp}{Dt} \qquad \text{with } \alpha = \frac{1}{\rho}.$$

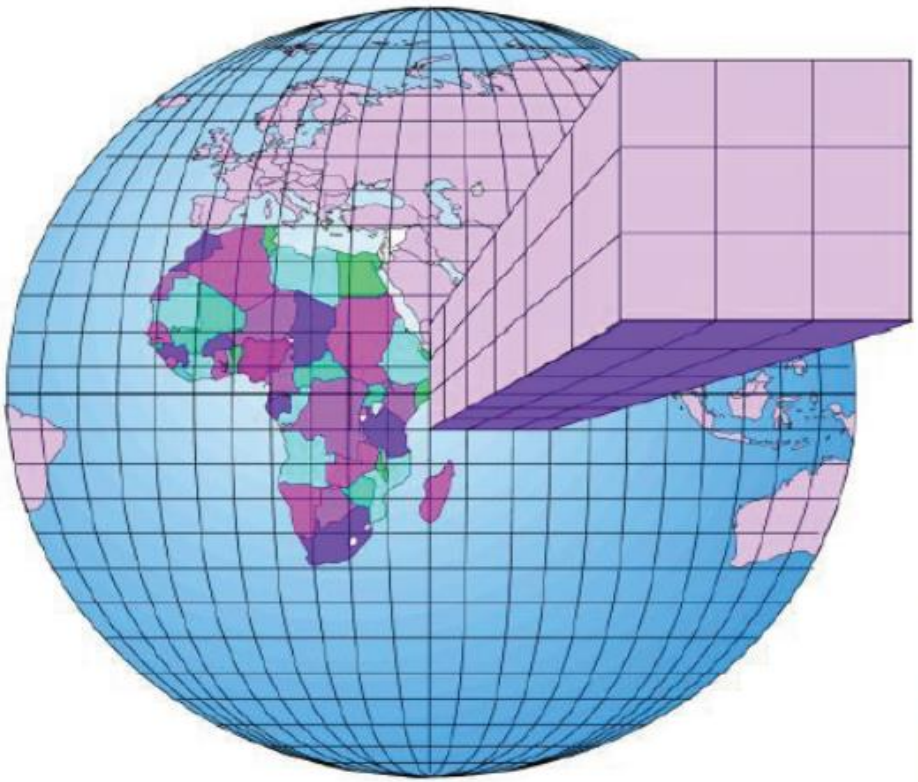
Continuity equation for dry air

$$\frac{D\rho_d}{Dt} = -\rho_d \nabla \cdot \boldsymbol{U} \quad ,$$

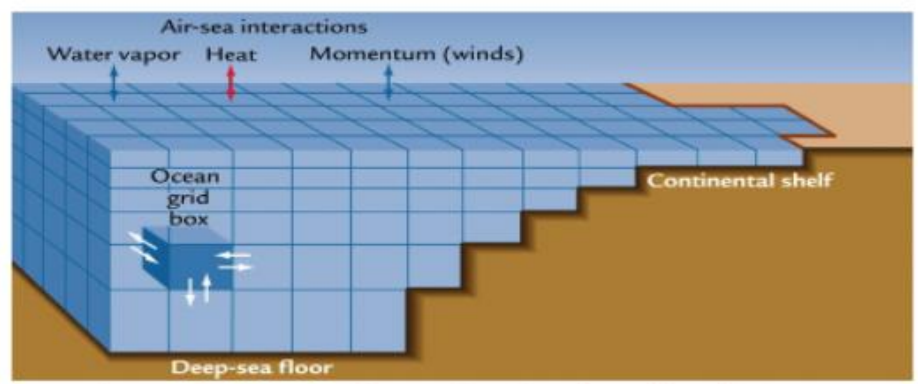
Continuity equations for atmospheric tracer no i

$$\frac{D\rho_i}{Dt} = -\rho_i \nabla \cdot \boldsymbol{U} + ss_i \quad \text{or} \quad \frac{Dq_i}{Dt} = SS_i \qquad \text{with } SS_i = ss_i/\rho_d.$$

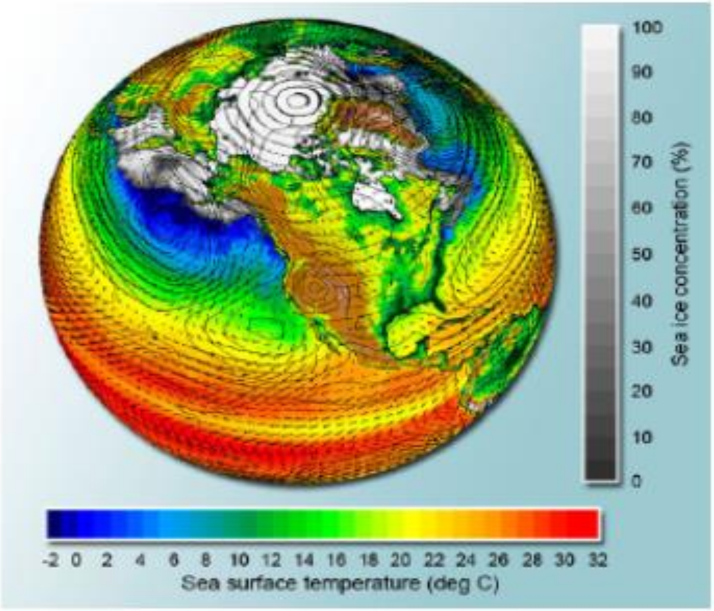
Numerical simulation

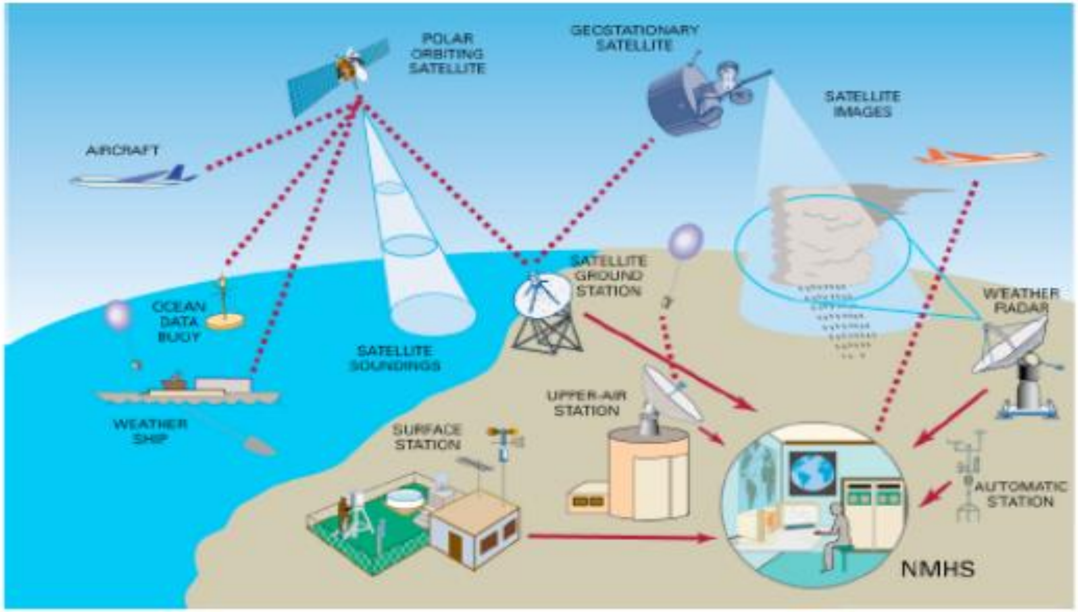


The atmosphere is devided into grid cells where the actual state of the atmosphere are known, i.e., all the variables are known at a given time step.



Initial conditions





To initiate a climate model or a numerical weather forecast model the three dimensional initial state of the atmosphere (and the oceans including sea ice) in all grid cells must be known. This can be obtained via a multitude of different observations. For climate models it may in fact also be obtained from the model itself.

The development of climate models, past, present and future

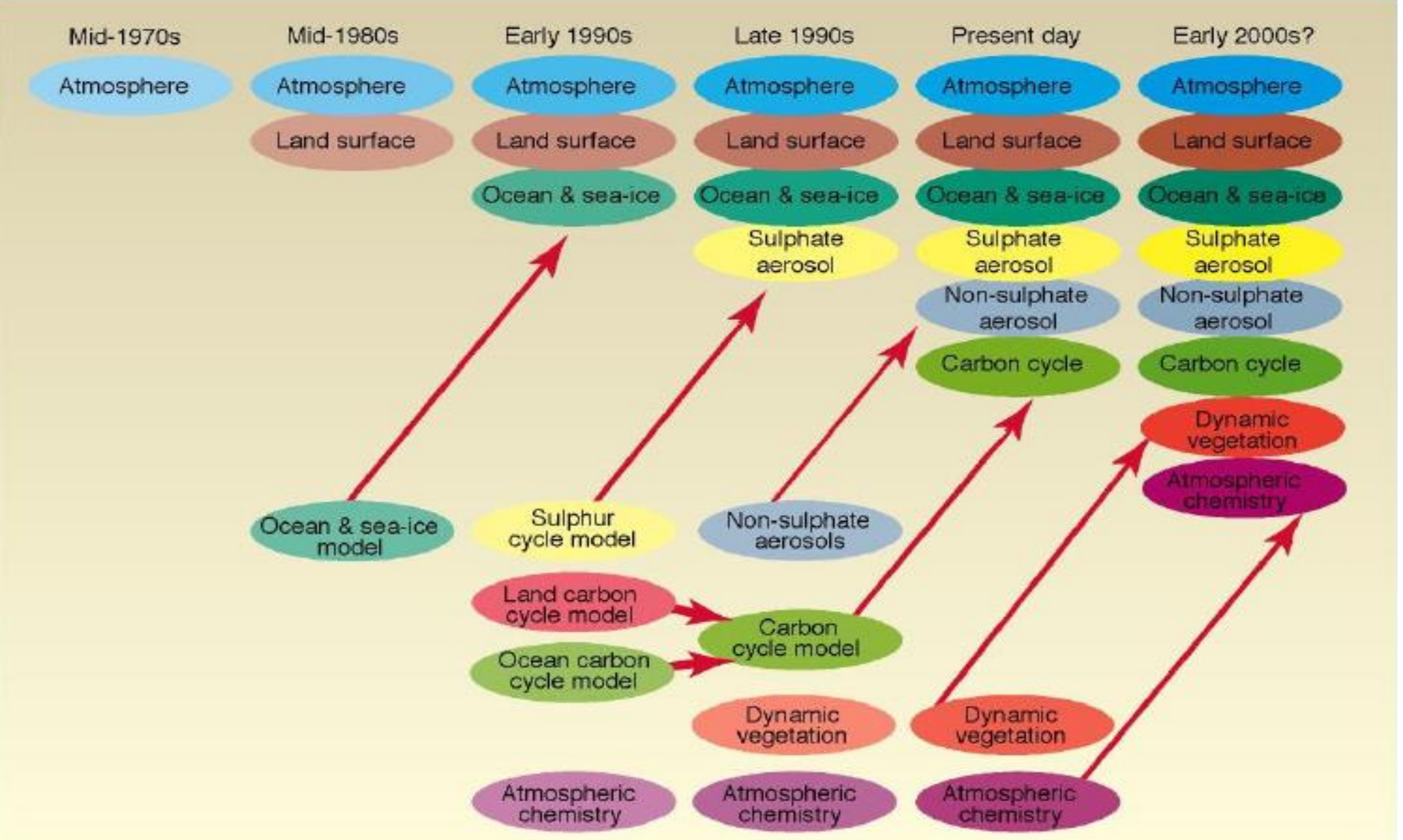


Figure 11: Evolution of model resolution and model complexity over time. The left panels illustrate the typical horizontal resolution at the time of the different IPCC assessment reports: First Assessment Report (FAR), Second Assessment Report (SAR), Third Assessment Report (TAR), and Assessment Report no. 4 (AR4. The spatial resolutions for the CMIP5 (Coupled Model Intercomparison Project phase 5) in AR5 are about the same as for AR4. It should be noted that the resolutions indicated in the figures (from AR4) are incorrect: e.g., T106 corresponds to a grid distance of ~185 km and not ~110 km.

Results- Temperature

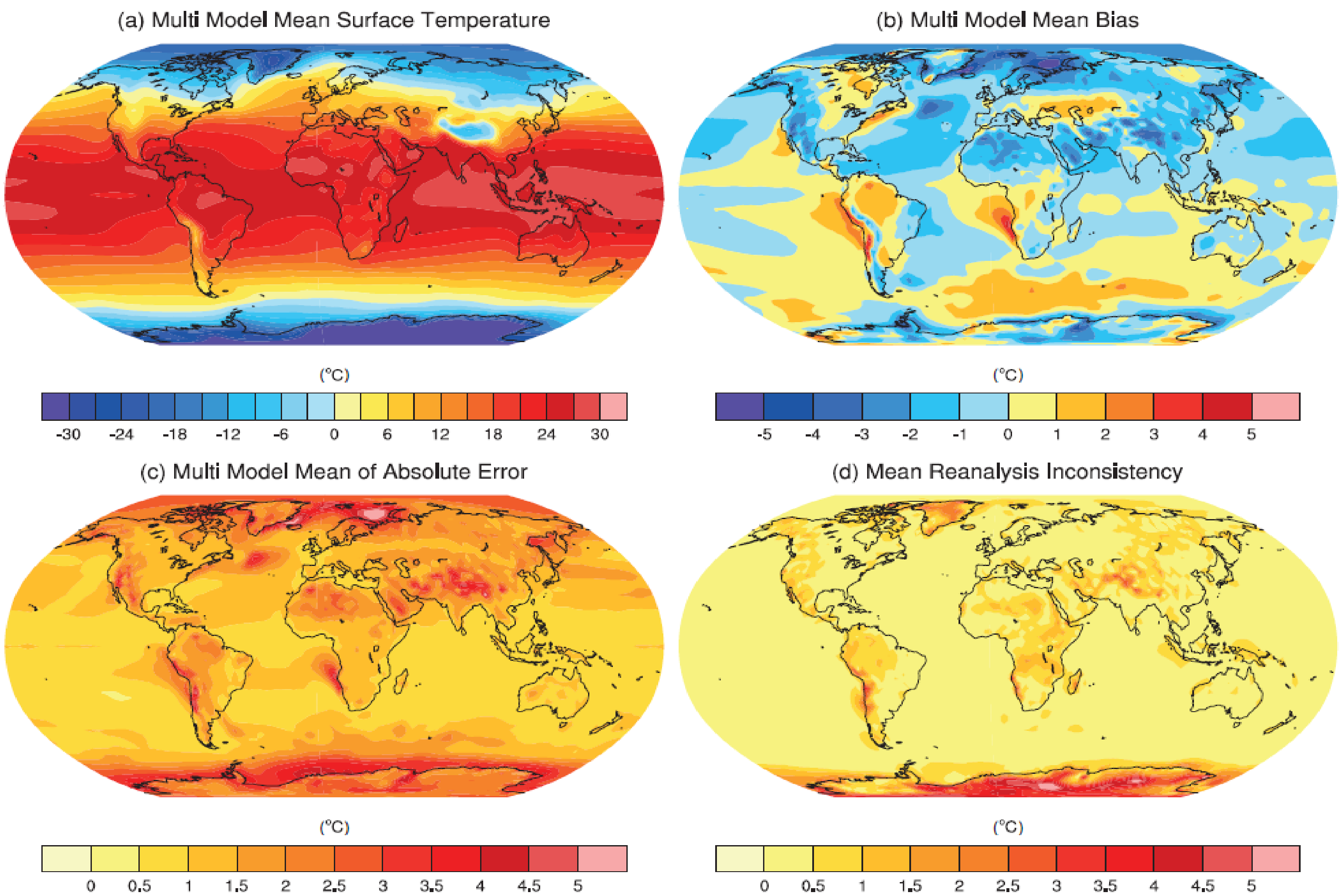


Figure 9.2 | Annual-mean surface (2 m) air temperature (°C) for the period 1980–2005. (a) Multi-model (ensemble) mean constructed with one realization of all available models used in the CMIP5 historical experiment. (b) Multi-model-mean bias as the difference between the CMIP5 multi-model mean and the climatology from ECMWF reanalysis of the global atmosphere and surface conditions (ERA)-Interim (Dee et al., 2011); see Table 9.3. (c) Mean absolute model error with respect to the climatology from ERA-Interim. (d) Mean inconsistency between ERA-Interim, ERA 40-year reanalysis (ERA40) and Japanese 25-year ReAnalysis (JRA-25) products as the mean of the absolute pairwise differences between those fields for their common period (1979–2001).

Taken from IPCC report (AR5, Chapter 9)

Results- Precipitation

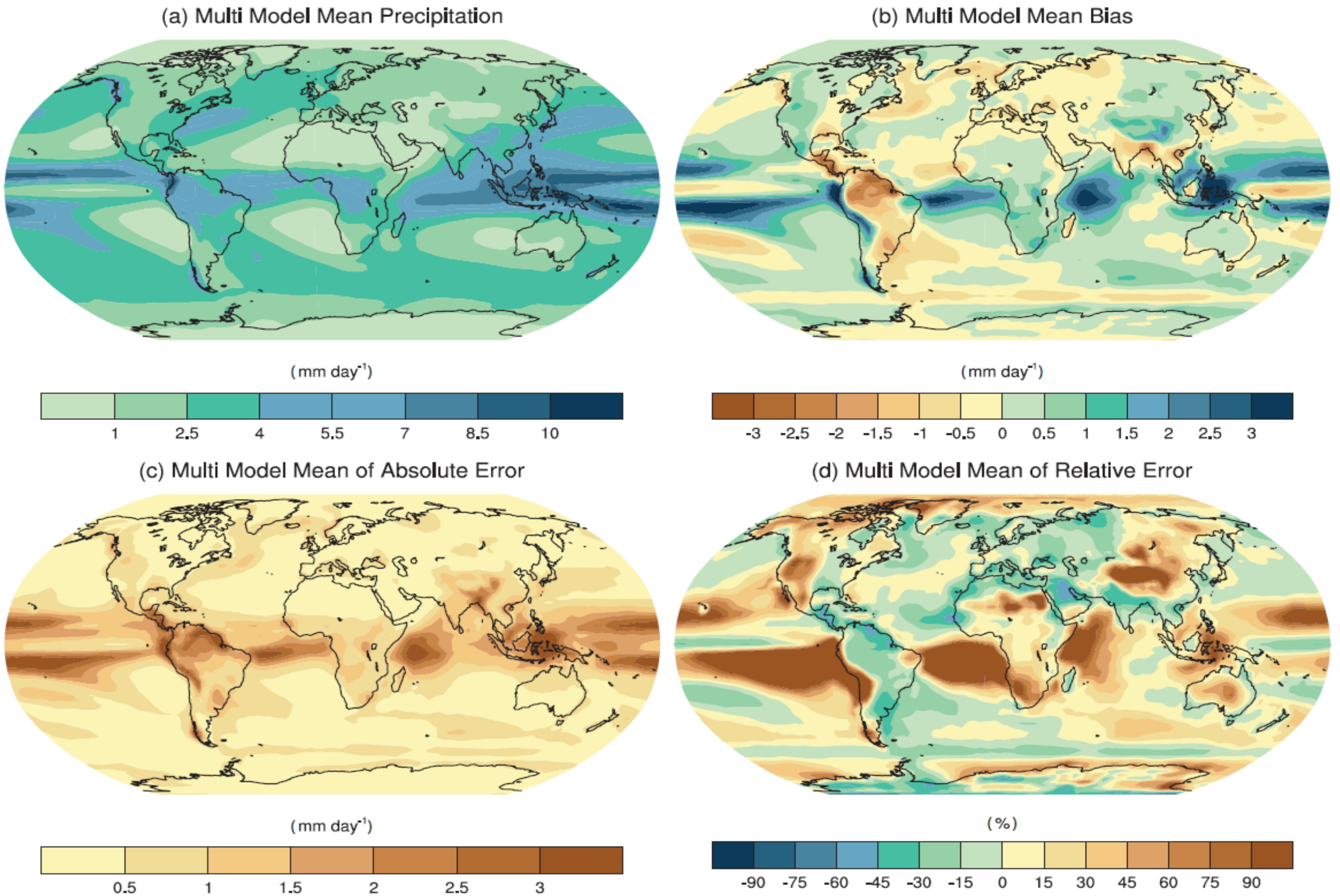
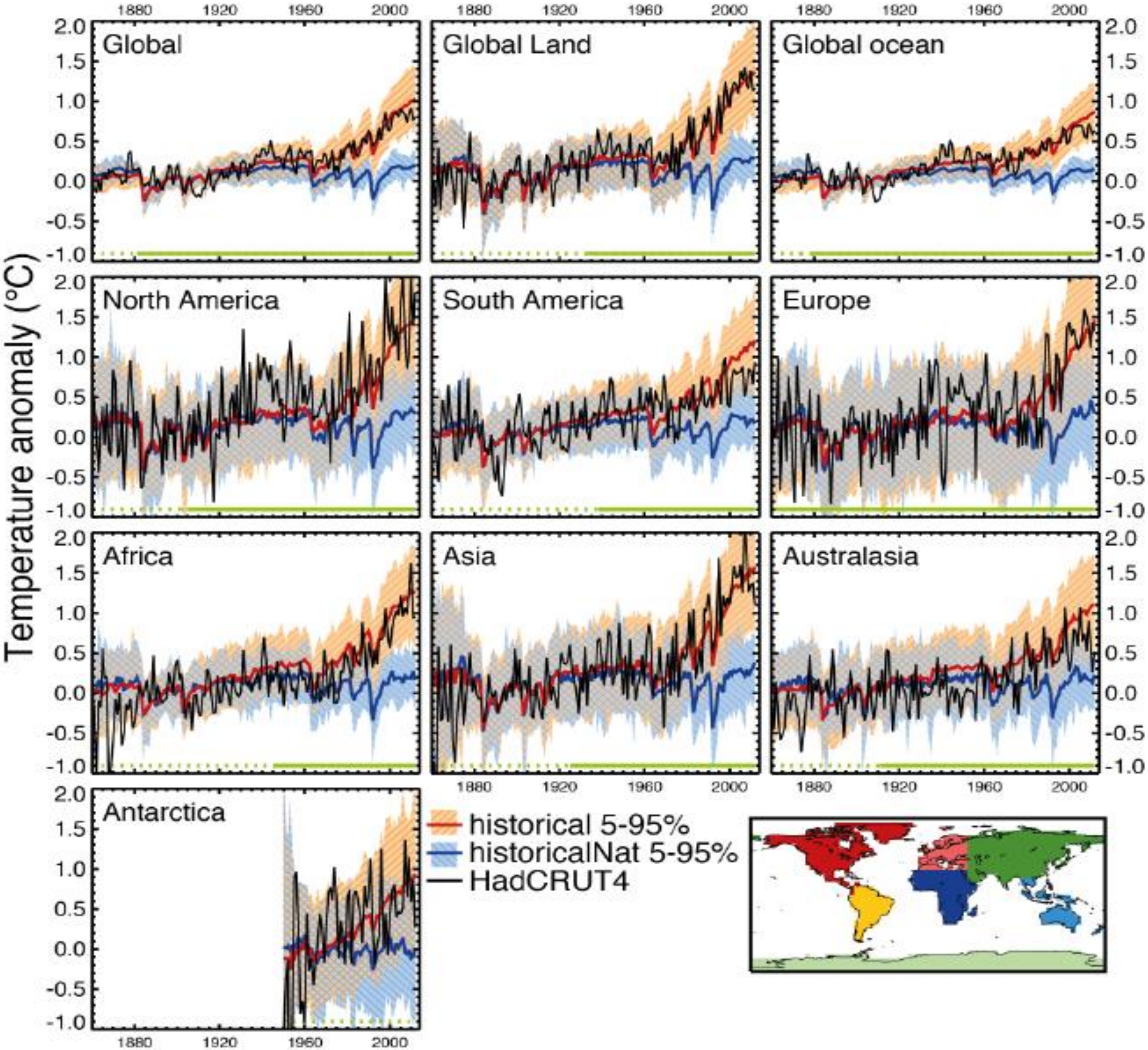


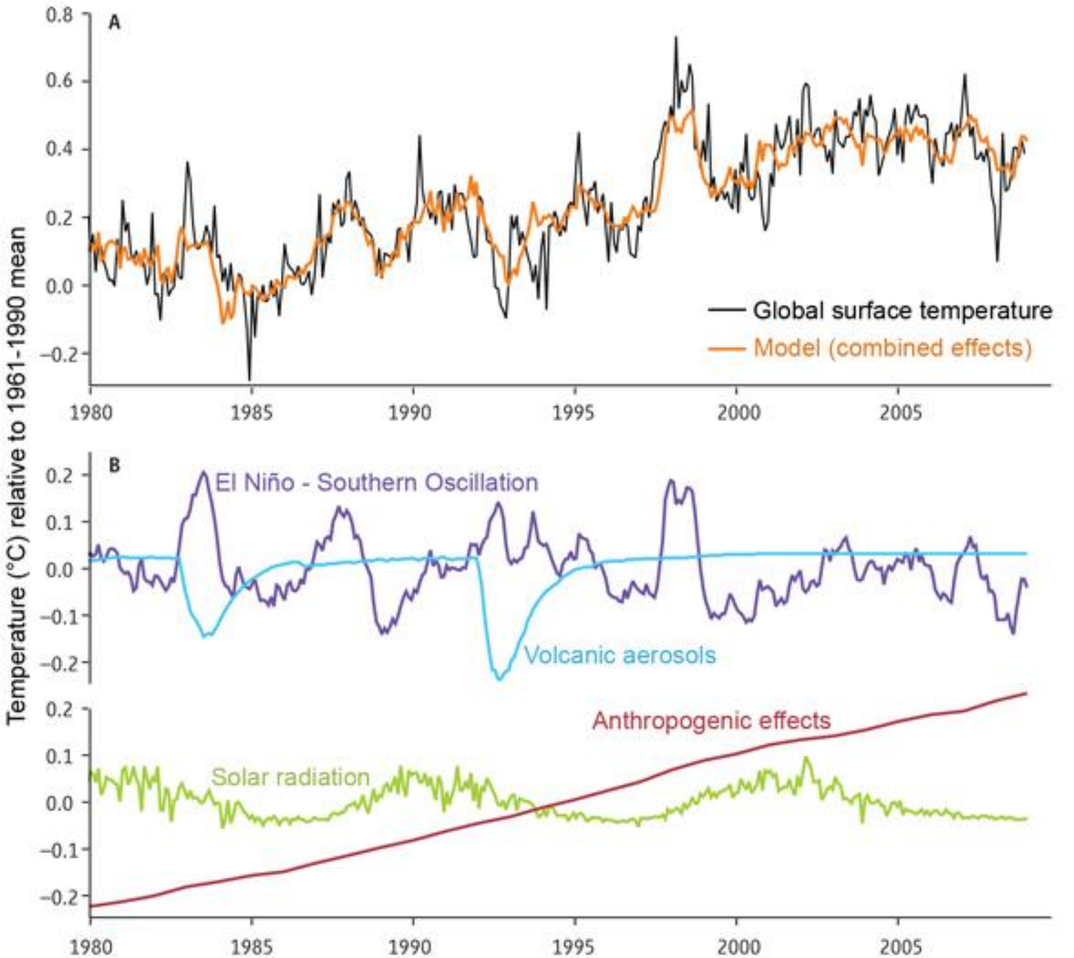
Figure 9.4 | Annual-mean precipitation rate (mm day^{-1}) for the period 1980–2005. (a) Multi-model-mean constructed with one realization of all available AOGCMs used in the CMIP5 historical experiment. (b) Difference between multi-model mean and precipitation analyses from the Global Precipitation Climatology Project (Adler et al., 2003). (c) Multi-model-mean absolute error with respect to observations. (d) Multi-model-mean error relative to the multi-model-mean precipitation itself.

Taken from IPCC report (AR5, Chapter 9)


Global
Global Land
Global ocean
North America
South America
Europe
Africa
Asia
Australasia
Antarctica
Temperature anomaly (°C)
historical 5-95%
historicalNat 5-95%
HadCRUT4
1880
1920
1960
2000
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0

Modelling climate change

- This figures break down the different effects affecting climate.



Adapted from Judith L. Lean and David H. Rind (2009), "How will Earth's surface temperature change in future decades?", *Geophysical Research Letters* **36**, L15708

Break

Slowing the global warming problem

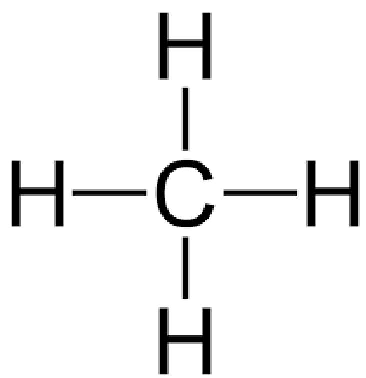
- We are only interested in energy, not CO_2.
- Do all hydrocarbons have the same CO_2/ energy?

$$C_xH_yO_z + O_2 \rightarrow \ CO_2 + H_2O$$

Generic hydrocarbon

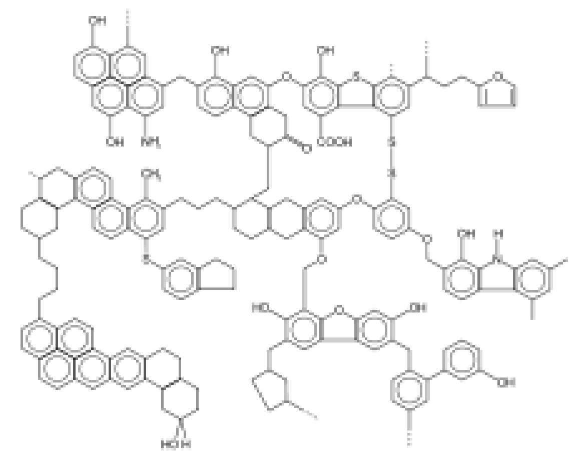
Differences in Fossil Fuels

- All fossil fuels are not created equal.
- Since they are different molecules, some will produce more energy/CO_2 than others.



Example chemical structure of natural gas

Example chemical structure of oil (octane)



Example chemical structure of coal

Fossil Fuels Emissions

- Fossil fuels with less oxygen in them have significant lower CO_2 production per kWh of energy.

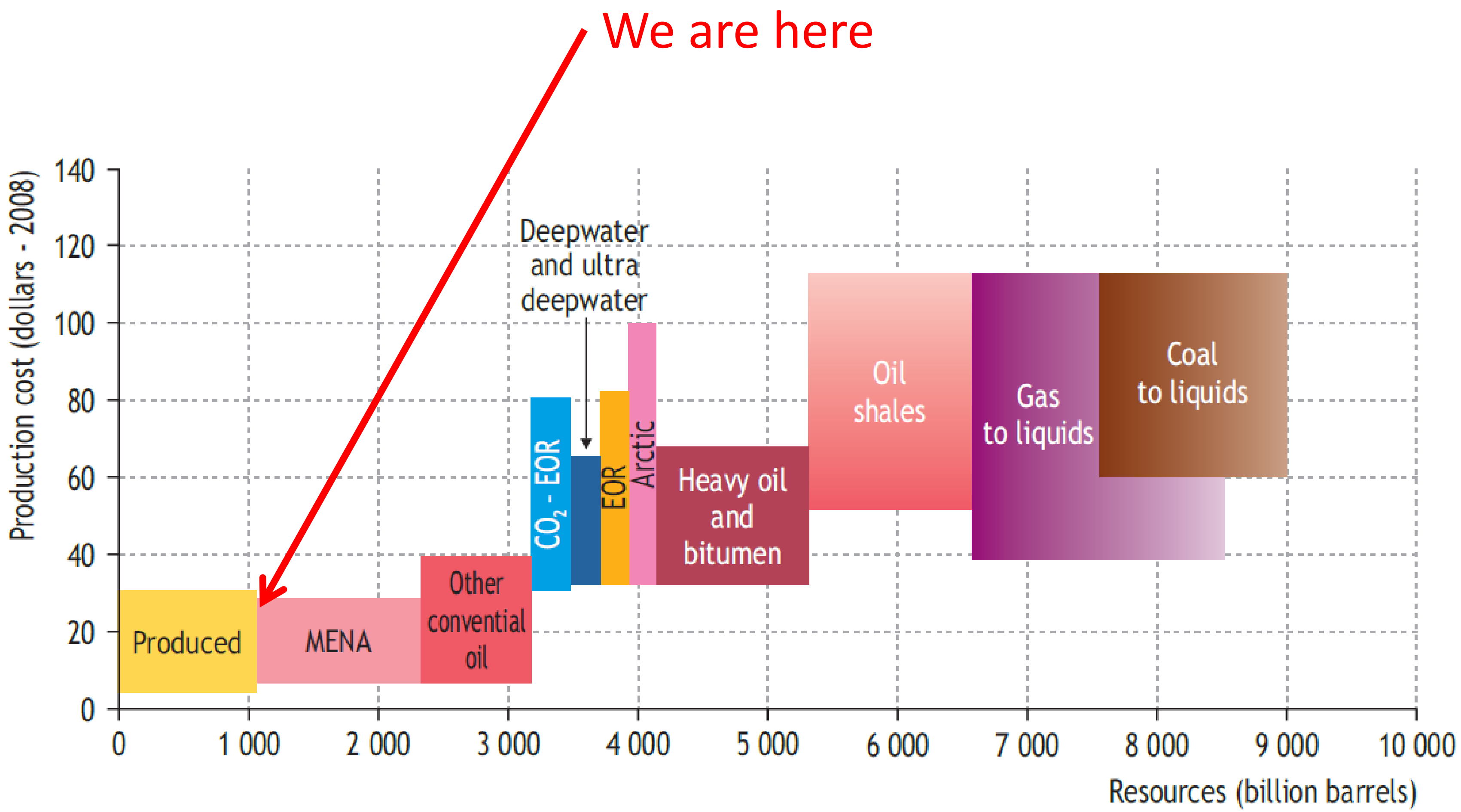
Fuel type	emissions ($g\,CO_2$ per kWh of chemical energy)
natural gas	190
refinery gas	200
ethane	200
LPG	210
jet kerosene	240
petrol	240
gas/diesel oil	250
heavy fuel oil	260
naptha	260
coking coal	300
coal	300
petroleum coke	340

Figure I.10. Emissions associated with fuel combustion. Source: DEFRA's Environmental Reporting Guidelines for Company Reporting on Greenhouse Gas Emissions.

- Short carbons have lower CO_2 / kWh than long carbon chains.

- There is a lot of oil left that has a high oxygen content, thus the CO_2 from these new sources will be more than traditional oil.

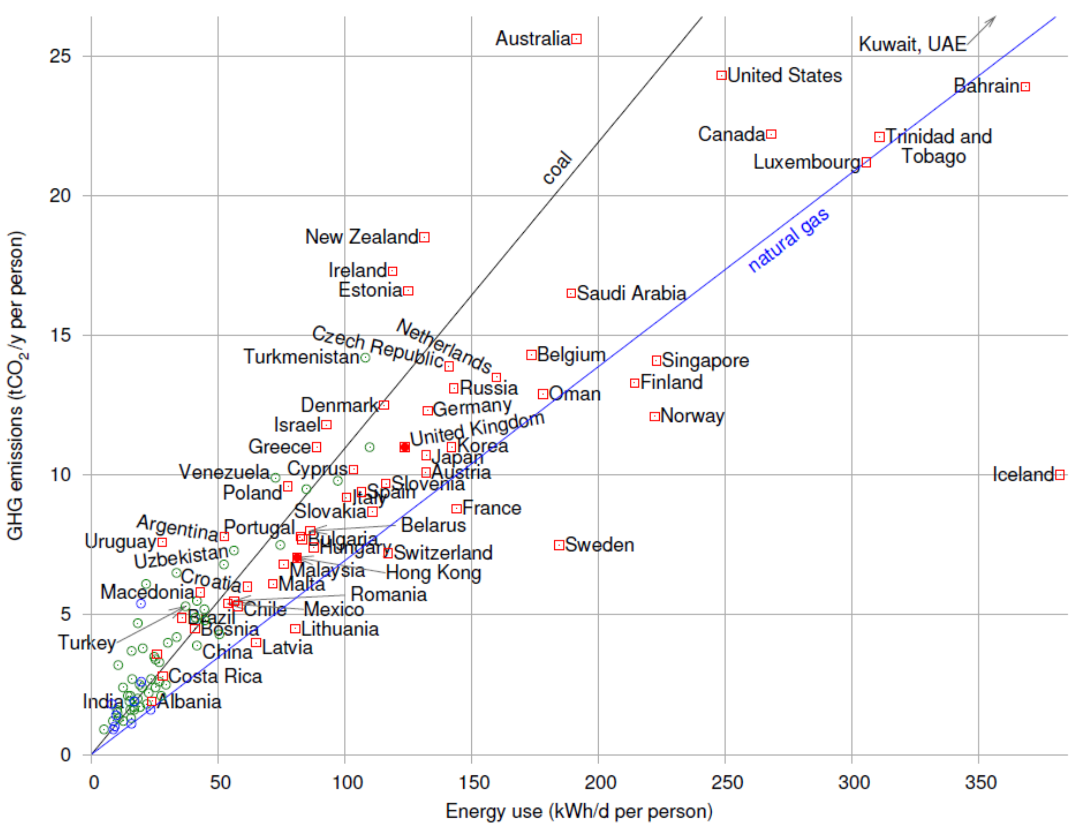
- Natural gas has the issue that we currently leaks 2% of it during extraction and production.

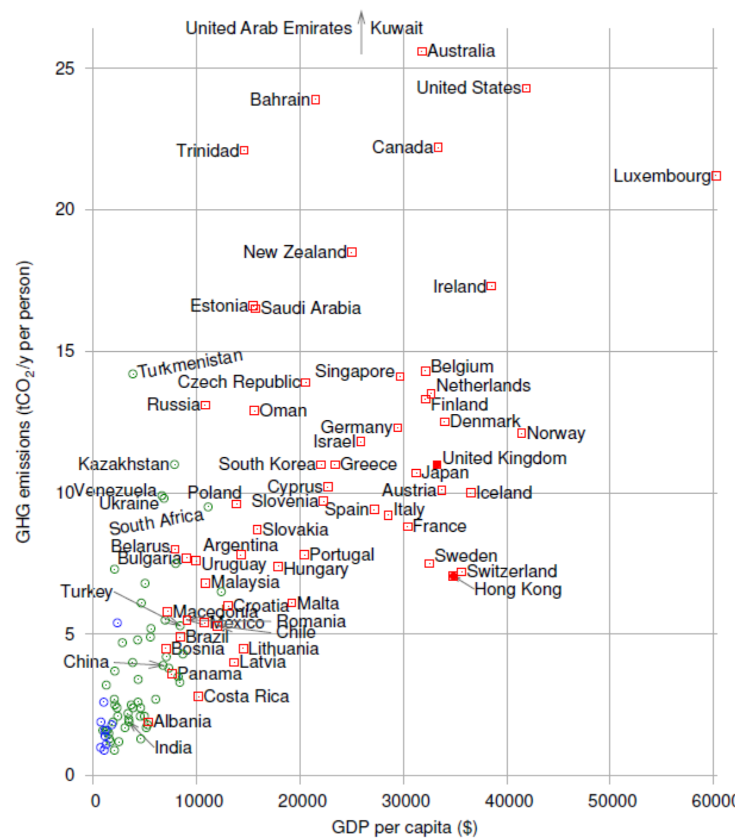


From 2008 IEA World Energy Outlook report (pg. 218)

Fossil Fuels Emissions

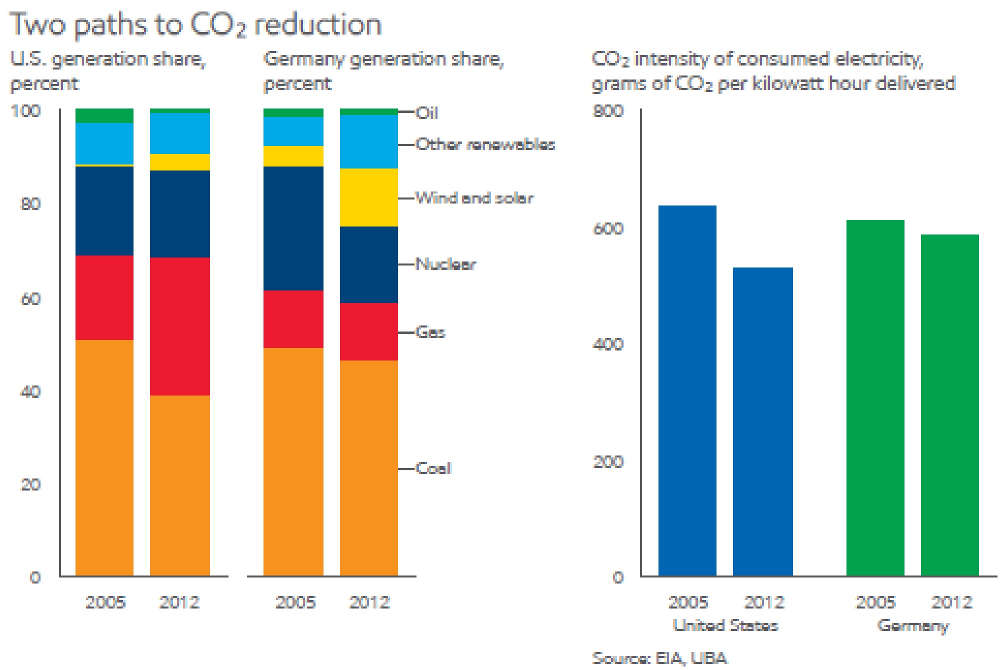
- The CO_2 emissions per energy use shows quite a variation among countries.





Weird, but true

- Germany has made focus on wind and solar, and mitigated nuclear for electricity.
- USA has switched from coal to natural gas.
- **USA has a smaller CO_2 per unit electricity than Germany.**
- Natural gas reduces our emissions now.
- Natural gas also does not fluctuate like wind and solar.



Exxon, 2016 Outlook for Energy

Lecture - Learning Objectives

At the end of this lecture you should understand:

- Be able to calculate the solar constant.
- Understand variations in solar irradiance (locally and with respect to time).
- Understand climate/energy balances to a first order approximation.

Exercises

- I am looking to buy light bulbs. The LED lights are rated in terms of illumination temperature. The 3000K light bulb costs 65DKK and the 2500K light bulb costs 50DKK. Which one gives me more photons/kroner in the visible range (390 nm to 700 nm)? Basically which is the better deal? (Assume electricity costs are free.)
- Calculate the solar constant for Mars. Mars has an albedo of 0.17. What should the temperature on Mars be (assuming no greenhouse effect)? Mars average temperature is 218 K. How much green house effect is there?
- Calculate the (atmosphere free) solar irradiation in W/m^2 for your hometown right now.

Concept Check

If the sun would heat up, its solar spectrum would:

a) not change

b) shift towards longer wavelengths

c) shift towards shorter wavelengths

d) come closer to normalizing over all wavelengths

Concept Check

Compared to Earth, the solar spectrum on Mars would:

a) not change

b) shift towards shorter wavelengths, and be less intense

c) shift towards longer wavelengths, and be less intense

d) would have the same spectrum, but be less intense

Concept Check

On a decade time scale the major fluctuations in the solar constant will be from:

a) Sunspots

b) Variation in axial tilt

c) Precession effects

d) A significant contribution from all of A, B, and C