Global warming and its implications for conservation.

2. How does it work? Part one: greenhouse gasses and blackbody radiation.

A quick review of:

- *Fossil fuels*
- *Carbon cycles*
- *Anthropogenic effects of fossil fuel oxidation on carbon cycles*

Fossil Fuels

The primary driver of anthropogenic climate change is CO_2. There are important other drivers:

- methane (contributes to warming, one molecule of CH_4 affects temperature more than one molecule of CO_2)
- particulates (contribute to cooling)
- water vapor (contributes to both, depending on altitude and type of cloud)

But CO_2 is the main driver (much more on this later). Can see this from data sets that relate temperature and atmospheric composition over time (e.g. ice core data)

Ohead: Archer Fig 8.3

The biggest source of anthropogenic CO_2 emission is from burning fossil fuels (coal, oil, natural gas) to produce energy. Almost all energy on earth ultimately comes from the sun. ***Plants capture that energy by photosynthesis***

CO_2 + H_20 + energy «-» CH_20 + O_2

- If this redox reaction proceed to the right, it is photosynthesis: storing energy by reducing a molecule of CO_2 to produce a carbohydrate.
- If it proceeds to the left, it is respiration: releasing energy by oxidizing a carbohydrate, consuming O_2 and releasing CO_2.

Over geological time, ***plant matter is converted to fossil fuels***, with high temperature, pressure and anaerobic conditions.

Coal: reduced ***terrestrial*** plants, mainly peat. Peat is organic matter that accumulates in soil when plant tissue accumulates (via photosynthesis) faster than it is decomposed to its inorganic components. As peat is geologically buried, the degree of compression determines the degree to which moisture is heated or squeezed out of the coal that forms:

lignite → brown coal → bituminous coal → anthracite coal
[-- 360 – 280 MYA --] [------ 140 – 60 MYA -----------]
High H_20 → Low H_20
Low energy (J/g) → High energy (J/g)

Oil and ***natural gas***: reduced ***aquatic*** plants (mainly algae) and animals that accumulated as ocean sediments, and were geologically subsumed and compressed. Oil is lighter than the water that saturates permeable or porous rock, so it works upwards. ***Oil deposits*** accumulate where porous rock is capped by impermeable rock. Most plankton do not end up in the sediments – they are consumed by other organisms. Consequently, only highly productive ocean waters produce enough organic sediment to allow oil to form – these are mainly ***nearshore***. Sediments that support oil formation also require waters to with low oxygen content (***anaerobic***).

Natural gas is mostly ***methane***, formed as a by product of the conversion of organic sediment into oil, so natural gas deposits usually are found in the same rock layers as oil.

The conditions for oil formation are narrow, so oil deposits are geographically restricted.

Ohead: Archer Fig 9.5, data from BP on proven oil deposits.

Fossil fuels (or ***hydrocarbons***) contain a lot of energy, because they are more fully reduced (have more hydrogens) than the carbohydrates that plants produce via photosynthesis. Hydrocarbons and carbohydrates together are called ***organic carbon.*** ***Inorganic carbon*** refers to oxidized forms, mainly CO_2 and calcium carbonate $CaCO_3$,

Natural gas (methane) is as fully reduced as possible, so its oxidation releases the most energy per molecule of CO2 emitted.
Oil is less fully reduced.
Coal is still less fully reduced, so its oxidation releases more CO_2 than the other hydrocarbons per W of energy produced

Ohead: Archer p. 86 table
Ohead: Archer Fig 9.2 & Common & Stagl p. 28
Ohead: Archer Fig 9.4

Coal is the most abundant of the fossil fuels. Oil is the most efficient (especially for transportation)

Ohead: Archer Figs 9.3 & 9.1

By oxidizing fossil fuel, we have energy at our disposal that allows us to do more work, in the physical sense. By increasing the amount of energy that a person can direct to a task, we effectively have '***energy slaves***' to increase economic productivity. More on this in a later lecture.

Fossil fuels are stored receipts of solar energy from the sun, but:

- Photosynthesis ***captures*** only a small fraction of incoming solar radiation (less than 0.1%)
- Of the plant matter produced, only a small fraction is ***converted*** to fossil fuel
- Coal (the most abundant FF) was deposited in two windows totaling 160 million years, a ***period*** less than 5% of the geological history of the earth. Similar temporal restriction on oil deposition.
- Consequently, it is clear that fossil fuels store only a tiny fraction of the energy available on earth: ***fossil fuels are a finite and rather small supply of energy, relative to the earth's total energy budget***.

    - Estimated ***total*** stock of fossil fuels prior to onset of human depeletion = 315,000 exajoules (exa = 10^{18})
    - Annual influx of solar energy at the earth's surface = 2,500,000 EJ
    - Annual total plant primary productivity = 1,200 EJ
    - Total fossil fuel stock = only 260 years of primary productivity, <1 year's worth of incoming solar radiation

The two points to consider:

1. The ***half empty glass***: even without concern about atmospheric CO_2, there are economically and politically important issues to do with the finite supply of fossil fuels. What is the cost of an oil war? We will return to this point - Hubbert Curves and 'peak oil'.
2. The ***half full glass***: The influx of energy from the sun is enormous in comparison to the supply from fossil fuels. We have made major energy transitions in the past (by exploiting animal power, then wood fire, then coal and oil). The transition from wood to coal was not made because coal was seen to be better… it was forced by deforestation in Europe. The transition from coal to non-fossil fuel sources might be forced by limited supply or by the greenhouse effect, but it will happen.

Carbon Cycles

Ohead: Archer fig 8.1 carbon cycles.

The unavoidable effect of oxidizing fossil fuel is to quickly release stored carbon as CO_2 (Currently it goes into the atmosphere, but ***carbon sequestration*** may change that).

CO_2 in the atmosphere is a small portion of the earth's total carbon. The ocean, land and sedimentary rocks all hold much more carbon: there are large ***carbon pools***, but relatively small ***carbon fluxes***, which are movements of carbon between pools.

The ***fast carbon cycle*** is the ***land-atmosphere flux***: CO2 moves between the atmosphere and terrestrial plants on an ***annual*** cycle. You can easily see the earth 'breathe' annually in measurements of atmospheric CO_2, as plants take up CO_2 in the growing season and then release it in the dry/cold season.

The ***slow carbon cycle*** is the ***ocean – atmosphere flux***: Time scale of ***100,000's of years*** Ocean holds far more CO2 than the atmosphere & land combined. CO2 moves both ways until the rates of exchange equilibrate. Equilibration is very slow (100s of years) because most of the ocean's water is subsurface and not in contact with the atmosphere.

Oheads: Archer Fig 8.3 & 8.4

As irregularities in the earth's orbit cause glacial and pluvial periods, ice sheets expand and contract. In pluvial periods (interglacials), reduction in the ice sheets increases oceanic CO_2 flux (mechanism not fully understood) and atmospheric CO_2 rises, to maximum values of 280 – 300 ppm over the last 800,000 years.

The ***very slow carbon cycle*** is the ***rock – atmosphere flux:*** Time scale of ***millions of years***, CO2 into atmosphere via volcanism (metamorphism) and back into rocks by weathering of silicate rocks to form carbonate rocks, taking up atmospheric CO2.

Ohead: Archer Fig 8.7

Extracting and oxidizing fossil fuels causes a shift in the carbon cycle. Carbon that took eons to move from the air to plants to hydrocarbons is instantaneously converted to atmospheric CO_2.

Combined effect of fossil fuel consumption and deforestation (hence reduced uptake of atmospheric CO_2) creates a new ***anthropogenic carbon flux of 9 GTon C/year***. The atmospheric pool of CO2 is only ***700 Gton***, so this represents an addition of 1.3% annually. That is a very significant imbalance to the equilibrium of the natural carbon cycle.

If something grows at 1.3% annually, it will double in 53 years. (Derive doubling time from the equation for exponential growth.

The atmospheric stock is not increasing by 9 Gton/year, it is only increasing by ***4 Gton/year,*** due to compensatory ***increases in uptake*** by the ***terrestrial and oceanic carbon sinks***. For example, experimental ***CO_2 fertilization*** can make plants grow faster.

4 Gton/year of anthropogenic CO_2 is ***0.6% of the 700 Gton atmospheric CO_2 pool.*** Growth at 0.6% annual increase takes ***116 years to double***.

The anthropogenically perturbed carbon cycle is causing atmospheric CO2 levels to increase:

Ohead: Keeling curve (Archer 8.2)
Ohead: the last millennium (Archer 10.1)
Ohead: geological timescale (Archer 8.3)

300 ppm CO_2 historically and 380 ppm CO_2 currently: atmospheric CO_2 is well outside the known range of variation, and rising at unprecedented rate.

Note that Figure 10.1 has a second Y-axis, ‘radiative forcing’ in units of W/m^2. More energy (W = J/s) is absorbed by each square meter (m^2) of the earth. ***The inevitable effect of increasing atmospheric CO_2 is an increase in temperature***. To understand this requires some ***physics*** and some ***atmospheric science***.

PHYSICS

Heat and light

Heat is the vibration of atoms within matter. Faster vibrations (more ***Brownian motion***) = more heat.

Heat can move by several mechanisms (conduction, convection, radiation, evaporation), but the simplest is conduction. ***Conduction*** is the transfer of vibrational energy by ***direct contact*** of two atoms. One bounces off the other and transfers its momentum, like pool balls.

Heat does can't be conducted through a vacuum, b/c there are no molecules present. A perfect vacuum is a perfect insulator (insulation is the opposite of conduction). A thermos is not a perfect vacuum, but its close enough to keep your coffee hot.

The earth is warmed mainly by energy from the sun.
But the ***earth and sun are separated by 150 million km of nearly perfect vacuum***.
WTF?!

Light (electromagnetic radiation) carries energy through space's ***vacuum*** that can be released as heat. All space, even a vacuum has an ***electric field*** and a ***magnetic field.*** ***Electromagnetic radiation*** is a wave that jointly oscillates the electric and magnetic fields as it radiates out from a source point. (Hence the name, electro – magnetic – radiation.

Different ***frequencies*** of light (= EM radiation) oscillate these fields at different rates, but they are all fundamentally the same thing.

Ohead: Archer Fig 2.1
Ohead: Archer Fig. 2.2

Can use the speed of light in a vacuum, c = 3 x 10^8 m/s (30,000 km/s or roughly 100 million km/h), to relate frequency (ν) to wavelength (λ):

$$\lambda\left(\frac{cm}{cycle}\right)=\frac{c\left(\frac{cm}{s}\right)}{\nu\left(\frac{cycle}{s}\right)}$$

For relatively long wavelengths like IR, sometimes refer to wave number, n, the inverse of wavelength

$$n\left(\frac{cycles}{cm}\right) = \frac{1}{\lambda\left(\frac{cm}{cycle}\right)}$$

We see visible light with wavelengths in the hundred of nanometers. This is of course no accident. Our eyes are adapted to this set of wavelengths because that is where much of the incoming radiation from the sun happens to fall (more later).

A side point: other species have eyes sensitive to other other frequencies

Ohead: Dugatkin pp 138-140, **UV:** a way to send signals to a small subset of species**.** People?
Ohead: Archer Fig 2.5, **IR**, which some cold-blooded species can sense. (Warm blooded species don't sense IR because they emit so much of it that your own emissions would garble incoming signals. Like listening through heavy static.)

Blackbody radiation

EM radiation interacts with matter. Molecules of matter have charged particles projecting out via bonds. Analogous to charged masses on springs.

Ohead: Archer Fig 2.3

Each bond (spring) oscillates at a given frequency. If an EM wave of that same frequency hits the molecule, the matter absorbs the radiation, taking up its energy as ***vibrational energy*** in the bond. Radiation of the correct frequency hitting a piece of matter will be absorbed, warming it.

- Transfer of energy between matter and EM radiation is a ***two-way street***.
- The ***vibrational energy*** of matter is ***heat***.
- Any matter above absolute zero has some vibrational energy.
- A vibrating bond has the potential to radiate EM waves.
    - The ***frequency*** of the radiated light depends on the ***molecular structure*** of the matter
    - The ***intensity*** of the radiated light depends on its ***temperature***.

Matter that absorbs and emits all frequencies is called a ***blackbody***. The light emitted is called ***blackbody radiation***. A plot of the intensity of light versus wave number (or wave length) is called a blackbody ***spectrum***.

Ohead: Archer Fig 2.4

There are ***two important points about blackbody spectra*** shown here:

1. ***As temperature of matter increases, the intensity of the radiated light increases (rapidly!)***. Hotter things radiate more energy. (Anyone who's sat on a stove or touched an incandescent light bulb knows this. One way you can tell that a compact fluoro is more efficient than an incandescent bulb is that you can easily unscrew a lit compact fluoro – compared to old bulbs, it loses little energy to heat.)

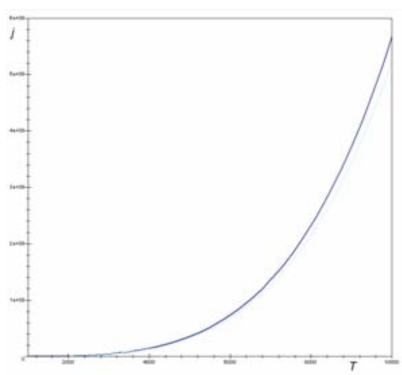
Graphically, the curves get higher as temperatures rise. The ***total area*** under the curve measures the ***total energy*** radiated.

Temperature – intensity relationship is described by the Stefan-Boltzmann equation from physics

$$I = \varepsilon\sigma T^4$$

I = intensity of radiated light, or the rate of incoming energy (W/m^2) (1 W = 1 J/s)
ε = emissivity, 0 – 1 a measures how good a blackbody is, 1 = perfect bb (dimensionless)
σ = Stefen – Boltzmann constant, a fundamental constant (= 5.67×10^{-8} W/m^2K^4)
T = temperature in Kelvins

Intensity



Temperature

2. ***As temperature of matter rises, the blackbody spectrum shifts*** to higher wave numbers, higher frequencies, shorter wavelengths.

The curves shift right (when x axis is expressed as wave number)

To get to the point (finally!), the sun is a great whacking ball of nuclear fission and fusion, so it is much hotter (5000^oK) than the earth (273^oK)

Consequently, the ***sun and the earth have very different blackbody spectra***.

(A) Sun is 10^5 times higher intensity. That is, the sun's curve has 10,000 times more area under it.

$$\left(\frac{5000K}{273K}\right)^4 \approx 112,520$$

(B) ***Sunshine*** is mainly ***visible light and UV***.
(C) ***Earthshine*** (terrestrial radiation) is ***infrared***.   An infrared camera pointed at the earth, even the dark side, would show it glowing, just as a visible light camera shows the sun glowing (though earthshine is much lower intensity).

These last two points are critical to understand the energy budget of the earth, i.e. inflows and outflows of energy, and how these affect the earth's temperature. To get there requires some atmospheric science, namely the ***layer model***.

HW: Archer problems 1.1 and 1.3