(1) Radiometer... How and why does it work???

An example of 'albedo' in action
Fundamental Controls on Atmospheric circulation

**Near Equator:**
More solar energy adsorbed than emitted

**Near Poles:**
More energy emitted than adsorbed

**Why?**

. Angle of incidence of solar radiation (Energy/area)

. Amt. of travel through atmosphere (particles, vapor, gases reflect solar energy)

. Tropics dominated by oceans (low albedo); Poles by ice (high albedo)
(Figs. on angle of incidence, albedo)
must go through more atmosphere

Figure 5-4: Effect of the Earth's shape and atmosphere on incoming radiation. In polar areas the sun's rays strike the Earth in an oblique manner (v) and therefore less energy than at equatorial locations.
Figure 9.4 (a) Earth-sun relationships. (b) Characteristics of the summer solstice (Northern Hemisphere).
Figure 5.5: Insolation at different latitudes during the year. The amount of solar energy is expressed as a percentage of the amount at the equator.

Total annual insolation

Percentage relative to equator

Latitude

0° 30° 60° 90°
Direct atmospheric circulation

18th c. English scientists Halley (of comet fame) and George Hadley first described atmospheric circulation:

Warm, moist air near the tropics rises.

Cool, dry air descends at the poles

Upward movement of air leaves less air; lower pressure; air must rush in horizontally to replace it= surface winds
"Hadley Cells"
(Schematic on direct circulation)
Constraints on "Hadley Cells"
  . Positions of continents
  . Coriolis Effect (rotation of Earth)

19th C. Frenchman Gaspard Coriolis realized why long-range gunnery shells landed to the right of their aimed target in N. hemisphere

Effect decreases near equator.

Force on moving particle is:
(1) perp. to direction of motion,
Figure 2.3 Diagrammatic illustration of the Coriolis Force. For explanation see text.
(2) proportional to its speed.
(3) to right in N. hemisphere, left in S. hemisphere.

Atmospheric cells: (cells figure)

(1) Hadley cell near equator:

. act like simple direct cell
. effect of Coriolis effect weak
. hot, moist air rises and cools, intense storms = tropics!
(Intertropical convergence zone, ITCZ)

. Cooler, dry air descends= band of deserts 15º to 30º lat N + S (e.g., Sahara, Kalahari)
Trace winds: Air sucked from north by ITCZ storms, turned right by Coriolis Effect=Easterlies (wind from east)

Polar Cell:
- high albedo and cool surfaces produce south-moving winds towards equator, away from poles.

Ferrel Cell:
More complicated motions in mid-latitudes--hurricanes, cyclones.
Figure 2.6 World patterns of precipitation (a) The distribution of precipitation throughout the world in mm per year: dark shading shows precipitation below 250 mm, light shading shows areas with precipitation above 2000 mm, and the diagonal shading shows areas above 3000 mm.
fig.
Let's talk about two important climate events that have received a great deal of study over the past decade and that provide insight into climate change and how we measure/reference it:

**Medieval Warm Period**

11th-14th c.

**Little Ice Age**

(16th) 17th -19th c.
Most of the historical accounts are from Europe and North America

Reading from Al Gore's *Earth in the Balance*
(1) **Impact on agriculture**

—During coldest periods of LIA, England's growing season 1-2 mos. shorter.

—Reflected in higher grain costs from ~1560.

—Particularly high in 1816/17 'year without a summer' due to Tambora Volcano, Sumbawa, Indonesia.

—1693 French famine in 1693; millions dead
—Switzerland... *Fusarium nivale* parasite (thrives under snow cover) devastated crops. Livestock starved to death.

—Norway 1665: grain harvest 67-70% of 1300 harvest.

—Series of famines in Scotland

—Wine production:

From 1100-1300 (MWP) wine grown in southern England, 300 mi further north than grown (Fr., Germ.) today
Starting 1400s, too cold, vineyards abandoned (still)
German wine production LIA decreased to 1/2 or less of pre-1300 production

(2) Impact on Forests:

After 1400, beech trees (warm-loving) replaced by oak and pine (note that tree population takes years to respond to climate change)

(3) Impact on human health
—Deaths of Vikings in Greenland, Iceland
—famine, illnesses kill millions in Europe
—Cool, wet summers lead to "St. Anthony's fire" due to ergot. (Salem witch trials???)

—malnutrition worsens epidemics.
—1557-8 England influenza epidemic.

—1500s deaths outnumbered births

—Black plague worsened by malnutrition

—Marshlands increase = malaria or 'ague' mentioned in 8 of Shakespeare's plays
Oliver Cromwell died of Ague, 1658

(4) Other economic impacts

—increasing grain prices, decreased wine production

—Many farmsteads destroyed = decreased tax revenues

—Cod move further south = decreased Scottish fishing

—glacier growth closed Austrian gold mines
—But, British fishermen benefit from southern migration of herring from Norway

(5) Social unrest
—1709 French famines
(reading)

—Many rebellions of the poor

—Huge increase in witch hunts during LIA (ergot and blame for bad weather)

—Famines of 1788-89, france "let them eat cake" French revolution
(6) Literature

1816 'year without a summer'
(Tambora volcano)—everyone indoors in summer.

—Mary Shelley Frankenstein

—Polidori

(7) Paintings

Neuberger==cloud cover and sky color (but Impressionism also important)

(8) Other climate problems
—increased flooding
—Glacier advances

Did the Medieval Warming Period and the Little Ice Age really happen???
Were they examples of Global Climate change???

(1) Timing of these periods varies globally.

(2) More local or hemispheric than global
(3) LIA a 'modest cooling of the Northern Hemisphere of <1°C relative to late 20th c. levels.

(4) However, changes more pronounced in some localized areas, due to changes in atmos. circulation.

What about the southern hemisphere???
No clear evidence of LIA, although 20th c. definitely warmer.

Medieval warm period also not necessarily hemispheric.

N. hemisphere Temp. from 11th to 14th c. 0.2 °C warmer than from 15th - 19th c., but below 20th c.
Many local variations. For example, Greenland particularly warm during MWP.

China probably cold during MWP. Southern hemisphere shows no evidence for MWP.

MWP mostly around north-Atlantic, hence probably related to ocean circulation.

Hence, the MWP was mostly localized to north Atlantic, and was not global as today's 'global warming.'
We have talked about the need to define what we meant by 'global' in 'global warming.' Let's look at a summary of observations:

(1) **Best estimate of global surface temp. change** 0.6°C since late 19th century.

—most of this happened from 1910-1945, post 1976.

—magnitude of 20th century warming greatest of any period during the last 1000 years.

—most recent warming more over land than oceans.

—1990s warmest decade of the millennium.
(2) Compare different parts of the Earth surface:

20th c. shows broad pattern of tropical warming, other zones more variable.

—1976-2000 trend globally synchronous, but emphasized N. hemisphere during winter and spring.

—some year-round cooling parts of S. hemisphere/Antarctica

(3) Warming of global ocean... more than half of increase occurred in upper 300m, mainly since late 1950s, ave. temp. increase 0.037°C/decade
—Warming of the oceans has been increasing greatly over the last 5 years, affecting European climate.
(4) **Change in temperature ranges:**

—Night minimum temperatures are increasing--this is a major part of 'global warming.'

—Hence, difference in min/max decreasing

—Reduction in extreme low temperature events but no change in extreme high temp. events.

(5) **Changes in temp. related variables:**

—retreat of alpine glaciers except in a few maritime regions (due to precip.)

—~ 2 weeks fewer/year lake and river ice in N. hemisphere.
—decline in Arctic sea-ice extent in summer but no change in winter.

—Antarctic sea ice almost stable since 1978.

(6) Changes in temp. above surface layer:

—Since 1958, low to mid-troposphere warming similar to surface, 0.1°C/decade.
—Since early 1960s no significant trends for global mean temp. in upper troposphere.
—Satellites suggest lower rate of warming in troposphere than surface air.
—Satellites suggest stratosphere cooling.
(7) Pre-instrumental period temp. changes:

—magnitude N. hemisphere warming in 20th c. largest of any century past 1,000 yrs.

—1900s warmest decade of the millennium, N. hemisphere.

—Evidence does not suggest a globally synchronous LIA, MWP; but evidence in N. hemisphere
(8) **Precipitation**
— Has increased in most of N. hemisphere mid to high lat., except Russia.

— Decrease in sub-tropical ppt.

— More frequent ENSO S. Pacific

— Regions where total ppt. increased more extreme ppt. events, and converse.

— Widespread increases in the proportion of total ppt. derived from heavy and extreme ppt events over land in mid- and high-latitudes of Northern Hemisphere.

— Maybe more extreme events????
An example of how precipitation changes may be affecting ecosystems in the midwest:

It has been proposed that 'global warming' will result in more summer droughts in the American midwest.

Summer droughts mean less flushing of soil and wetlands into streams and lakes.

Soils and wetlands are both sources of natural organic matter to surface waters and shallow ground waters.
Natural organic matter acts as a 'natural sun block' against damaging UV radiation.

Hence, during summer droughts, the streamflow will decrease, lake levels will decrease, and concentration of natural organic matter will also decrease.

If the conc. of NOM decreases into single digits, damaging UV light penetration increases = more damage to aquatic ecosystems.

Study with Drs. Bridgham, Lamberti, and Lodge at Notre Dame's UNDERC. May be looking for summer students to work on this and similar projects.
The Global Carbon Cycle:

Why does CO₂ cause the green house effect and global warming???

CO₂ allows short-wave, higher energy UV radiation to pass through, but traps longer-wave, IR radiation.

Why is CO₂ IR active???

Multiple-atom molecule with asymmetric stretch, plus degenerate bending that allows IR to be absorbed... see www site.

http://science.widener.edu/svb/ftir/ir_co2.html

To understand the C cycle, it is important first to look at the Hydrologic Cycle, because the two cycles are closely related
How much has atmospheric \( \text{CO}_2 \) increased during industrial times?

1800: 280 ppm

1999: 367 ppm

How do we know this?

- air bubbles in Antarctic Ice
- Since 1957, direct measurements
- Two methods agree (post-1957)
How do we know that the increase is primarily due to anthropogenic CO$_2$ emissions?? 

. Combustion consumes O$_2$, and atmospheric O$_2$ is decreasing at a rate of fossil fuel emissions of CO$_2$. 
. Isotopic signature: fossil fuels do not have $^{14}$C, depleted in $^{13}$C relative to $^{12}$C 
. Increase in CO$_2$ more in N. hemisphere (most fossil fuel burning here!)
Atmospheric CO$_2$ increasing ~1/2 rate of fossil fuel emissions. What happens to the rest?

. Some dissolves in sea water (see CO$_2$ problem)
  limited by ocean circulation
  and carbonate chemistry
  (finite buffering)

. Uptake by terrestrial ecosystems

  . Excess primary production
    (photosynthesis) over respiration
    and other O$_2$ consuming processes.

Photosynthesis:

$$\text{CO}_2 + \text{H}_2\text{O} \xrightarrow{-hv} \text{CH}_2\text{O} + \text{O}_2$$
. Note that terrestrial ecosystems can also be source of anthropogenic CO$_2$ due to land-use changes.
We can calculate how much \( \text{CO}_2 \) taken up by land versus oceans:

- Terrestrial process involves \( \text{O}_2 \) exchange; ocean does not.

**Terrestrial, Photosynthesis:**

\[
\text{CO}_2 + \text{H}_2\text{O} - h\nu \rightarrow \text{CH}_2\text{O} + \text{O}_2
\]

**Ocean, \( \text{CO}_2 \) dissolution:**

\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3
\]

Global Carbon budgets based on \( \text{CO}_2, \text{O}_2 \) shown in Table 3.1 of text.
See Figures on the natural C cycle and the anthropogenic perturbations.

Terrestrial uptake of CO\textsubscript{2} governed by net biome production (NBP):

Balance of:
net primary production, NPP and carbon losses due to heterotrophic respiration (decomposition, herbivory) and fire (rainforest destruction)

NPP increases with atm. CO\textsubscript{2} = 'fertilization effect' up to a point. Effectiveness of terrestrial uptake depends on residence time
Carbonate equilibria

Today, we shall look at how atmospheric CO\textsubscript{2} affects the pH of the ocean. To model this, we shall use a system of calcium carbonate (CaCO\textsubscript{3}) in equilibrium with water open to the atmosphere, such that the atmosphere serves as an infinite reservoir with a fixed partial pressure of carbon dioxide, pCO\textsubscript{2}.

\[
\text{CO}_2 (g) + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3
\]

\[
\text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^-
\]

\[
\text{HCO}_3^- \rightleftharpoons \text{H}^+ + \text{CO}_3^{2-}
\]

\[
\text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{OH}^-
\]

\[
\text{CaCO}_3 (s) \rightleftharpoons \text{Ca}^{2+} + \text{CO}_3^{2-}
\]

Our unknowns are: [Ca], [CO\textsubscript{3}], [HCO\textsubscript{3}], [OH], [H], [H\textsubscript{2}CO\textsubscript{3}]; the concentration of H\textsubscript{2}O in itself is always taken to be 1.

We can solve for our species concentrations, including pH (= -log\textsubscript{10} [H\textsuperscript{+}] by coming up with 6 equations (to match the 6 unknowns) and solving them simultaneously.

We shall simplify by not taking into consideration the various ocean salts such as Na\textsuperscript{+}, Cl\textsuperscript{-}, and not correcting for the ionic strength of the solution. For those of you who know aqueous
chemistry, this means that we are setting concentration = activity.

Remember that for any generic chemical equation,

\[ aA + bB \rightleftharpoons cC + dD, \]

we can write a mass action equation:

\[ K_{eq} = \frac{[C]^c[D]^d}{[A]^a[B]^b} \]

Using the known equilibrium constants for the reactions above, we can write them in terms of mass action equations.

Our equations are:

1. \[ [Ca^{2+}][CO_3^{2-}]/[CaCO_3 (s)] = K_{CaCO_3} = 10^{-8.3} = [Ca^{2+}][CO_3^{2-}] \]

The concentration of any solid (CaCO_3) in itself is 1.

2. \[ K_{H_2CO_3} = [HCO_3^-][H^+]/[H_2CO_3] = 10^{-6.4} \]

3. \[ K_{HCO_3} = [CO_3^{2-}][H^+]/[HCO_3^-] = 10^{-10.3} \]
(4) \( K_{\text{CO}_2} = \frac{[\text{H}_2\text{CO}_3]}{P_{\text{CO}_2g}} = 10^{-1.5} \)

(5) \([\text{OH}^-][\text{H}^+] = K_w = 10^{-14}\)

Let's take \(p\text{CO}_2\) to be \(10^{-3.5}\)

\(p\text{CO}_2 = 10^{-3.5}\ \text{atm.}\)

Note that 1 ppm = \(10^{-6}\) atm.

Now, this is only 5 equations, and we need 6. We can recall that any solution has to be charge balanced, and write an equation for charge balance:

If we want to solve for the pH, we have

charge balance:

\[2[\text{Ca}^{2+}] + [\text{H}^+] = 2[\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{OH}^-]\]

Now, we start substituting into the various equations, solving for \([\text{H}^+]\). The goal will be to put all of the unknowns in terms of constants and/or \([\text{H}^+]\)

\([\text{H}_2\text{CO}_3] = 10^{-1.5} \times 10^{-3.5} = 10^{-5}\)

\(K_{\text{H}_2\text{CO}_3} = \frac{[\text{HCO}_3^-][\text{H}^+]}{[\text{H}_2\text{CO}_3]} = 10^{-6.4}\)
Rearrange and substitute in [H$_2$CO$_3$] to get:

\[ [\text{HCO}_3^-] = 10^{-6.4} \times 10^{-5}/[\text{H}^+] \]

\[ = 10^{-11.4}/[\text{H}^+] \]

\[ K_{\text{HCO}_3} = [\text{CO}_3^{2-}][\text{H}^+] / [\text{HCO}_3^-] = 10^{-10.3} \]

\[ [\text{CO}_3^{2-}] = 10^{-10.3} \times 10^{-11.4}/[\text{H}^+]^2 \]

\[ = 10^{-21.7}/[\text{H}^+]^2 \]

\[ [\text{OH}^-] = 10^{-14}/[\text{H}^+] \]

\[ [\text{Ca}^{2+}] = 10^{-8.3}/[\text{CO}_3^{2-}] = 10^{13.4} [\text{H}^+]^2 \]

Substitute these into the charge balance:

\[ 2 \times 10^{-13}[\text{H}^+]^2 + [\text{H}^+] = 2 \times 10^{-21.7}/[\text{H}^+]^2 + 10^{-11.4}/[\text{H}^+] + 10^{-14}/[\text{H}^+] \]

This will give us a messy equation with $[\text{H}^+]^2$ and $[\text{H}^+]^4$. Solved by trial and error, it will give a pH $= 8.4$.

To solve by trial and error, start with an estimate for $[\text{H}^+]$ and see how close you come to balancing the two sides of the equations, and then try a higher or lower concentration until you converge.
Even better, write a computer macro. to solve the equation for you!

\[
\begin{align*}
\text{open system} & \\
[\text{Ca}^{2+}] &= 10^{-3.4} \\
[\text{CO}_3^{2-}] &= 10^{-4.9} \\
[\text{HCO}_3^{-}] &= 10^{-3.0} \\
[\text{OH}^{-}] &= 10^{-5.6} \\
[\text{H}_2\text{CO}_3] &= 10^{-5.0}
\end{align*}
\]

Does anyone know what the pH of the surface of the ocean is? 8.2 We can see that calcium carbonate equilibrium exerts an important control on the ocean pH. The presence of other cations and anions does shift the pH of the ocean, but it does this primarily through effects on the charge balance equation. Most of what is in the ocean is neutral salts (NaCl, for example!)

Calculate how the pH of the ocean would change if the atmospheric concentration of CO2 changed from (a)
280 ppm to (b) 370 ppm to (c) 700 ppm to (d) 1000 ppm.

How do the concentrations of all of the unknowns vary with pCO$_2$??

Due Thursday, Feb. 14th, in class.