Part II: Past climates

This week

Solid Earth - excerpts of Ch 7

Carbon cycle - Ch 8

Next week

Guest lectures - Monday and Tuesday

Reduced reading assignments - see schedule
Early unexplainable things about the Earth...

**Continental Drift (Alfred Wegener, 1920s)**

- Ocean basins: trenches and mid-ocean ridges
- Mountains = evidence of shortening. Why?
- Distribution of earthquakes and volcanoes -- association with mountains and trenches.
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Magnetic stripes on the ocean floor -- creation of ocean crust at mid-ocean ridges

Subduction of ocean crust at oceanic trenches

The oceanic crust is a thin layer on top of a convecting mantle

Continents as rafts of lighter material -- ‘bump’ into each other, forming compressional mountain ranges and adding new material to continents

Pattern created by magnetic stripes along the Mid-Atlantic Ridge south of Iceland.
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The summary:

Continents ride on a mobile crust that is continually created at mid-ocean ridges and destroyed in subduction zones.

The driving force: convective currents in the mantle.

The result: the size, shape, and distribution of continents, mountain ranges, and oceans changes through time.
Climate consequences of plate tectonics...

Location of continents near the poles, or not -- this affects whether or not large ice sheets can exist.

Location of mountain ranges -- interruptions to atmospheric circulation.

Shape of ocean basins -- can ocean currents circulate zonally, or are they forced to move warm water from the equator to the poles -- affects the ocean’s ability to transport heat.
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No connection between Arctic and Atlantic

No circumpolar current
Seafloor Spreading and Plate Boundaries
The Rock Cycle takes 100+ million years
Weathering - rock to sediments

- thermal expansion
- freezing fractures and glaciers pulverize
- plant/tree roots break rock
- chemical (removes CO$_2$ from air)

Erosion - transport of sediments to ocean
Mountains - hotbeds of erosion

Uplift minus erosion determines elevation

Precipitation causes erosion

So precipitation shapes mountains (and vice versa)
Home subduction zone

From Wikipedia - Subduction Zone
Melting of solid rock at Subduction Zone

I said Friction, which is not the main cause

Instead

Temperature increases with depth 25deg/km

Pressure melting and decompression melting (don’t confuse with air parcels, which cooling by decompressing!)
We use box diagrams to describe reservoir and flow or matter.
An example

Source - flow from tap

Sink - drain

When the flow in equals the flow out, the water level (reservoir) does not change

Input = Output
Source = Sink
Residence Time

The average length of time matter spends in a reservoir

Residence Time (RT) = \( \frac{\text{Reservoir Size}}{\text{Outflow Rate}} \)

\[ RT = \frac{100}{5} = 20 \text{ minutes} \]
Carbon Cycle Example:
Vegetation and atmosphere only Fig 8-5

Gt C = “gigaton” = 1 billion X 1000kg of Carbon

Typically only count weight of carbon itself, although not always!
Residence Time (RT) = \frac{\text{Reservoir Size}}{\text{Outflow Rate}}

= \frac{760 \text{ Gt}}{60 \text{ Gt/yr}} = 12.7 \text{ yr}

So is atm in Equilibrium (ie Steady State) ???
Why is C so special?

- Carbon atom has 6 electrons - 2 in the lowest energy level and 4 in the second (second level is complete with 8)

- Makes covalent bonds - Carbon fills its second level by sharing electrons with other atoms

- Can form large chains or rings of molecules by bonding with itself, oxygen, nitrogen, phosphorus, and sulfur
Organic = association with living organism
C-C or C-H bonds

Inorganic = not organic. All CO$_2$ in atm, also shells and rocks

大多数
Organic carbon cycle: Short term 1

**vegetation:**

**photosynthesis** \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \]

**respiration/burning/decomposition** \[ \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \]
$\text{CO}_2 + \text{H}_2\text{O}$

Energy out
Respiration/burning/decay

Energy in
Photosynthesis

$\text{CH}_2\text{O} + \text{O}_2$
Atm CO$_2$

Photosynthesis 60Gt

Plants

Consumers

Respiration 30Gt

Cycle is incomplete
Primary Production = amount of organic matter produced by photosynthesis

Biomass = organic matter in a reservoir includes primary producers and consumers (like us)
"Breathing of the Biosphere"

Fig 8-4  Annual cycle of CO2 at Mauna Loa
A Brief Segue on Forests

Largest component of terrestrial biomass

Store CO2 in tree trunks, roots, litter and soil

Mature forests are a carbon reservoir
NOT a sink
In class activity - Graded

Consider three land owners, each with a mature forest containing carbon locked up in the biomass of the trees.

#1: leaves it alone

#2: burns it down and starts a farm

#3: logs it and replants with trees

Which one removes or adds the most CO2 to the atmosphere? EXPLAIN WHY
(a) In 1 year? (b) after 200 years?
Announcements

Slides for today were revised, re-posted later today.

No office hours Tuesday. See Clark on Monday or schedule time with him or me after Tuesday.

Guest lectures Monday and Tuesday. Turn in at end of class: One new and interesting thing you learned. Also note questions you have about the lecture.

Sections Friday, exams returned and more on carbon cycle.

Read Ch 11 & 12 for next week.
Breathing in Keeling curve reflects larger biomass in NH, but also the measurement is from the NH!
Plankton = free-floating marine biology:

Primary Producers - Phytoplankton (diatoms, coccolithophoreolds, etc)

Consumers - Zooplankton (foraminifera, radiolarians, copepods, etc)

“hard parts” are inorganic shells made from dissolved CO₂ and bi-products of weathering-erosion

“soft parts” are organic made from photosynthesis and consumption
Plankton continued:

Both types remove CO$_2$ and nutrients from surface waters either by photosynthesis or growing shells.
Biological Pump (downward) fecal pellets and dead bodies sink and decompose to CO$_2$, nutrients

- Soft parts (organic) decay quickly, only about 1% buried in sea-floor sediments
- Hard parts (inorganic) mostly sink (not part of the “bio pump”), more later...

Upwelling and mixing returns CO$_2$ and nutrients to surface

By the thermohaline circulation and Ekman pumping
Processes: Photosynthesis
  Fecal-pellet production
  Oxygen production

\[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{“CH}_2\text{O”} + \text{O}_2 \]

Surface ocean

Depletes \text{CO}_2
But adds \text{O}_2

Settling of organic matter

Upwelling of nutrients

\[ \text{“CH}_2\text{O”} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \]

Depletes \text{O}_2
But adds \text{CO}_2

Same mass of water
Different properties

Mostly just shells settle to sea floor, as inorganic carbon
Deep ocean

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A river flowing at 1km high on Greenland is thought to reach the base of the glacier and speed up flow during summer. What if such a river causes a catastrophic collapse of Greenland dumping salt-free low density water where deep water once formed, shutting off mixing and the thermohaline circulation (THC)...

What would happen to the CO$_2$ and O$_2$ in the global ocean without the THC?

What if instead the ocean biology died but the THC remained?
Sedimentary rock:

- Transport of organic sediments to the sea floor
- Pressure makes rocks with “organic” carbon*
- Occasionally conditions are right to make coal or petroleum
- Ultimately rock cycle returns rocks to surface where they weather

*Considered a reservoir of “organic” carbon because of its former source and the C-C and C-H bonds
Recall:

photosynthesis: \[ \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2 \]

respiration/burning/decomposition: \[ \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \]

Erosion of \( \text{CH}_2\text{O} \) causes a leak in this cycle.

Which supplies \( \text{O}_2 \) to atmosphere, replenishing \( \text{O}_2 \) lost by non-carbon cycle oxidation.
Sedimentary rock Cont:

Overall process takes C from atm via photosynthesis, erosion, etc. and stores it in rocks or fossil fuels for a long time.

Eventually the rocks are weathered via a “respiration” like reaction (uses O to make CO2)

Or the fossil fuels are burned
Inorganic carbon cycle: Short term 1

Remember CO$_2$ in atmosphere is inorganic

Gas exchange between atmosphere and ocean

CO$_2$ uptake by ocn from atm where primary productivity is high. Why?

CO$_2$ expelled by ocn to atm where ocn upwells

“diffusion” = uptake or expelled
Continued

Inorganic CO$_2$ gas in ocean can be converted to carbonic acid *(skim chap 8, p 162-163)* altering ocean ph but ultimately allowing more uptake

Anthropogenic increase in CO$_2$ in atm causes net diffusion to ocn - *to a point*

But also acidifies the ocean.
Continued What is p162-164 really about?

1) When CO$_2$ dissolves in water, it may hydrate to form carbonic acid. Reaction goes both ways, depending on the concentration of molecules

\[
\text{CO}_2 \text{ (aq)} + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_2
\]

2) Acid dissociate into ions, including carbonate ion CO$_3^{2-}$

3) CO$_2$ can in turn react with CO$_3^{2-}$, thus making room for ocn to take up another CO$_2$ molecule!

\[
\text{CO}_2 \text{ (aq)} + \text{CO}_3^{2-} + \text{H}_2\text{O} \leftrightarrow 2\text{HCO}_3^{-}
\]
Continued What is p162-164 really about?

Good thing: ocn can take up anthropogenic CO$_2$

Bad thing: ocn acidifies (ie increase H$^+$)

Why is this bad?

Ask a plankton! Their shells tend to dissolve.
(Currently plankton shells dissolve very little in the upper ocn, but we worry about the future)
Prediction of change in ocean pH, showing it becoming more acidic.

Current pH is about 8

Caldiera and Wicket 2003
weathering

$\text{CO}_2$ dissolves in raindrops to form carbonic acid $\text{H}_2\text{CO}_3$

This acid dissolves carbonates and silicates - the main composition of lithosphere

Is climate a factor?

Is making fresh rock a factor?
Weathering bi-products (sediments) reach the ocean and some Ca and Si is taken up by plankton.

**Example of carbonate cycle**

Weathering: \( \text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \)

Plankton uptake: \( \text{Ca}^{2+} + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{CO}_3 \)

Sinking dead plankton (shells) transfers Ca to sediments or deep water (more about this soon)

Oops forgot the raindrop.
Carbonate cycle cont:

Weathering: \[ \text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \]

Plankton uptake: \[ \text{Ca}^{2+} + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{CO}_3 \]

In large reservoirs with no direct flux to atmosphere:
C is moved from rock at surface to deep ocean, but rocks are plentiful (now)

Either in the atmosphere or in modest ocean reservoir with large direct flux to atmosphere:
Weathering step here hides the role of plankton and carbonic acid

Carbonate metamorphism in the mantle is the other half

**Simplified silicate cycle**

weathering \[ \text{CaSiO}_3 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{SiO}_2 \]

metamorphosis \[ \text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \text{CO}_2 \]
Continued

The time it takes for weathering bi-products $\text{CaCO}_3 + \text{SiO}_2$ to re-release CO2 is millions of years, as determined by plate tectonics.
What is the RT of CO2 in sedimentary rock?

Reservoir is 40,000,000 Gt/yr

Sedimentation and burial rate is 0.2 Gt C/yr

RT = ?
The text attempts to discuss the fate of plankton shells as they sink. Says that they only dissolve below “carbonate compensation depth” p165. The explanation is cryptic.

The bottom line is the deep ocean is depleted in carbonate ion, so shells dissolve.

Can’t think of why you need to know this.
**Upper Ocean** is rich in CO$_2$, especially where primary productivity is high.

Dead plankton rain downward. Organic carbon dissolves quickly but plankton shells (CaCO$_3$ and SiO$_2$) last longer and accumulate in sediments at mid-depth.

**Deep Ocean** is devoid of plankton shells - Why?
Lack of carbonate ion.
Weathering Feedback Loop

As temperature goes up, weathering rates increase (more rainfall)
Weathering Feedback Loop

Weathering removes CO$_2$ and as CO$_2$ declines the planet cools.
Key control on making climate stable on long time scales - millions of years
Carbon cycle: Methane

**Soil:**

Methanogenesis = anaerobic decomposition in soils

\[ 2\text{CH}_2\text{O} \rightarrow \text{CO}_2 + \text{CH}_4 \]
Carbon cycle: Methane

\[ \text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \]

Reservoir of methane in the atmosphere is 5-10 Gt C

rate of decomposition is 0.5 Gt C/yr

\[ \text{RT} = ? \]

Does anyone know the major sources of methane?
Anthro sources are cows, rice patties, industry
Carbon cycle: reservoirs

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Size (Gt C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>760</td>
</tr>
<tr>
<td>Land</td>
<td>2190</td>
</tr>
<tr>
<td>Ocean Mixed Layer</td>
<td>1023</td>
</tr>
<tr>
<td>Deep Ocean</td>
<td>38,100</td>
</tr>
<tr>
<td>Carbonate Rock</td>
<td>40,000,000</td>
</tr>
</tbody>
</table>

1. Coupled by biological processes and CO2 solubility - fast
2. Coupled by thermohaline circulation (and other mixing, upwelling processes) - slow
3. Coupled by geological processes - very slow
Basic unit of measure:

Gt C: Gigatons of carbon atom
Gt = $10^9$ metric tons (or $10^{15}$ g or 1 "petagram")
metric ton = 1000 kg ~ 2000 lbs or 1 English ton

Biological reservoirs

- land biomass is a large reservoir: ~600 Gton C
- ocean biomass is a tiny reservoir: ~3 Gton C

Biological fluxes

- very large fluxes with atmosphere, but no net change in atmospheric CO2 unless...
  1. land biomass changes (fast, temporary)
  2. ocean biological pump changes (longer lasting)
- ocean biological pump
- hard shells sink to deep ocean or ocean bottom
The land-ocean-atmosphere (LOA):
• atmosphere reservoir (760 Gton) small but tightly coupled to:
  1 land biota (2200 Gton) via photosynthesis and respiration/burning
  2 surface ocean (1020 Gton) via dissolution (uptake/release)
• thus, it is appropriate to consider the LOA as a single reservoir on timescales of a few years to a few decades

Removal from the atmosphere
• grow trees: temporary
• dissolved into surface: can be longterm, but acidifies ocn
• mix with deep ocean: 1000's of years (still temporary)
• carbonate weathering:
  • moves C from air to upper ocn: can be longterm, but acidifies the ocn
  • also moves C from surface rock to deep ocn: so what, rocks are plentiful
• form new carbonate sediments via silicate weathering:
  PERMANENT (for our purposes)