INTRODUCTION TO CARBON CYCLING

$\text{CO}_2$ greenhouse gas - necessary to keep planet warm

\[ \text{vibrational modes sensitive to infrared} \]

Energy balance

Incoming solar radiation

\[ \text{without CO}_2, \text{ Earth's surface T would be } \sim 25^\circ C \]

Incoming solar radiation \( \sim 300 \text{ W/m}^2 \)

Compare to geothermal heat flow \( 80 \text{ mW/m}^2 \)

WHAT CONTROLS CO$_2$ THROUGH TIME?
Carbon comes in different forms (oxidation states)

- C\textsuperscript{-4}  methane
- C\textsuperscript{0}  graphite, diamond, [CH\textsubscript{2}O]
- C\textsuperscript{+2}  carbon monoxide
- C\textsuperscript{+4}  CO\textsubscript{2}, CaCO\textsubscript{3}

Increase oxidation state + oxygen

\[
C + \frac{1}{2}O\textsubscript{2} = \text{CO}_2
\]
\[
\text{CH}_2\text{O} + O\textsubscript{2} = \text{CO}_2 + H_2O
\]
\[
\text{CH}_4 + 2O\textsubscript{2} = \text{CO}_2 + 2H_2O
\]

Today's Earth

\[
\text{CO}_2 \quad \text{ mantle} \quad \text{CH}_2\text{O} \quad \text{CaCO}_3
\]

Photosynthesis  \[
\text{CO}_2 + H_2O + \text{sun} = \text{CH}_2\text{O} + O_2
\]  
Free oxygen is produced

Carbonate precipitation  

organic C  

organic C
Carbonate Precipitation

\[ \text{CO}_2(g) \rightarrow \text{CO}_2(l) \]
\[ \text{CO}_2 + \text{H}_2\text{O} = \text{H}_2\text{CO}_3 \]
\[ \text{H}_2\text{CO}_3 = \text{H}^+ + \text{HCO}_3^- \]

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

or
\[ \text{Ca}^{2+} + \text{CO}_2 + \text{H}_2\text{O} = \text{CaCO}_3 + 2\text{H}^+ \]

\[ \text{Ca}^{2+} \text{ exists} \]

\[ \text{f}_{\text{org}} = 20\% \]

organic C

\[ \rightarrow \text{production of O}_2 \]

changes N, S, P, Fe cycling

\[ \text{CO}_2 \]

\[ \rightarrow \text{Carbonate CaCO}_3 \]

80%
\[
\frac{dM}{dt} = P - J_{out}
\]

\(J_{out}\) should be proportional to mass of C in ocean/atmosphere M

\(J_{out} \propto M\)

\(J_{out} = kM\)

\[
\frac{1}{k} = \text{residence time}
\]

\[
\tau = \frac{M}{J_{out} J_{in}}
\]

at steady state \(M = \frac{P}{k} \]

\[
M = \frac{P}{k} (1 - e^{-kt}) + M_0 e^{-kt}
\]
\[
\frac{dM}{dt} = P - kM
\]

- negative feedback

\[k\] is a measure of efficiency of C build

negative feedback which buffers system.

\[k\] is often called the weathering feedback

\[CaSiO_3 + CO_2 = CaCO_3 + SiO_2\] (net rxn)

\[\uparrow\]

\[CO_2\] in form of acid rain

dissolves calcisilicates

\[P\] is production of volcanic gases or any

other origin

Negative feedback prevents runaway

\[T_{out} = kM\]

- in a linear system

increase \[M\] by increasing \[P\] or by changing \[k\]
\[ \text{increase } P \text{ to increase } M \]

\[ P \text{ constant} \]
- change efficiency of \( k \)
  - if \( k_1 \) decreases to \( k_2 \)
    - \( M_1 \) increases to \( M_2 \)

\( P \) controlled by degassing from mantle

\( k \) - silicate weathering \( \rightarrow \) carbonate precipitation
  - more orogeny \( \uparrow k \)
  - higher \( T \) \( \uparrow k \)
  - more basalt \( \uparrow k \)
  - cooler \( \downarrow k \)
  - more rain \( \uparrow k \)
Runaway

Jout is not linear

- transport limited
- threshold limited

For example, if erosion rates are too fast compared to chemical dissolution rates, weathering feedback decreases

If weathering stops because kinetics freeze up...

E.g. if \( T \) is too low, or water too low then \( k \) decreases

\[ J \]

\[ \text{kinetic limited} \]

\[ M \]

- perhaps \( \text{CO}_2 \) \( \downarrow \), then \( T \) \( \downarrow \) and precipitation \( \downarrow \)

\[ M_0 \]

\[ M \text{ steady state} \]

\[ \text{snowball} \]

Runaway greenhouse
Deep Earth

\[ \text{Subduction} \rightarrow 2 \times 10^{-2} \text{ Gt} \rightarrow \text{Arc} \rightarrow 5 \times 10^{-2} \text{ Gton/y} \]

Mantle

1-10 \times 10^8 \text{ Gt C}

C. in mantle \sim 4 \text{ Gt} \text{ or more}
\[ \text{Fluxes } G+C \quad \text{mass } G+C \]

\[ \begin{align*}
\text{Atmosphere} & \quad 615 \\
\text{Biosphere} & \quad 731 \\
\text{Soil} & \quad 1238 \\
\text{Surface Ocean} & \quad 842 \\
\text{Intermediate} & \quad 9744 \\
\text{Deep Ocean} & \quad 26,280 \\
\text{Sediments} & \quad 9,000,000 \\
\end{align*} \]

- for ocean, atmosphere, biosphere = 170,000 y
- for soils = 20 y
- for total ocean = 614 y
- for surface ocean \sim 10 \text{ years}
- for surface + intermediate \sim 10 \text{ years}
- for biosphere 10 years

* Modern anthropogenic emission 10 Gtons C/yr
Questions

* What is response time, residence time?
* What controls steady state?

$> My \text{ timescale}$

$P(t) - \text{ tectonics}$

$K - \text{ weathering}$

$< 100 \text{ ky timescales}$

$P(t) - \text{ ocean degassing}$

$K - \text{ biosphere and ocean uptake}$

'Solar insolation'

$< 1000 \text{ y}$

$P(t) - \text{ biosphere, anthropogenic}$

$K - \text{ biosphere + ocean uptake}$