XIII. natural variation of CO$_2$ and climate
Which has the longest time scale for carbon exchange with the atmosphere?

A. above ground terrestrial biosphere (tree trunks, leaves)
B. below ground terrestrial biosphere (soil/plant litter)
C. upper ocean
D. deep ocean
E. carbon in rocks
The ocean’s biological pump
• a) describes the photosynthetic uptake and downward settling of carbon in the ocean
• b) describes the removal carbon from the sunlit surface by respiration
• c) quickly returns carbon from the deep ocean to the ocean surface and atmosphere
• d) all of the above
• e) none of the above
clicker question

Organic carbon stored as fossil fuels can be oxidized to produce CO$_2$ and

• a) this happens naturally as a consequence of weathering

• b) this happens during combustion of fossil fuels by humans

• c) a) and b) are both true but a) happens faster

• d) a) and b) are both true but b) happens faster

• e) neither a) or b) are true
• carbon cycle includes the atmosphere, ocean, terrestrial biosphere and rock reservoirs
• each of the reservoirs influences the atmosphere on different time scales, depending on size of exchange and size of reservoir
• the terrestrial biosphere is responsible for seasonal variations in CO$_2$
• other reservoirs must be responsible for longer time scale changes in CO$_2$
• **human activity and burning of fossil fuels connects the very long time scale of the “rock cycle” with the much shorter time scales of the atmosphere, ocean and biosphere**
• emissions of CO$_2$ due to burning of fossil fuels have totaled ~250 GTC (by 1994) for since the 1800’s
• a bit more than half has remained in the atmosphere
• about half has been taken up by the oceans (this is good!)
• closing the C budget suggests that the terrestrial biosphere has been a net source of C to the atmosphere
• the uptake of fossil fuel derived CO$_2$ into the oceans has led to ocean acidification (the dissolution of CO$_2$ into water produces carbonic acid) which impacts carbonate-shelled organisms (bad!)
outline

• overview of Phanerozoic climate (last ~540 My)
• a mechanistic model of the long-term C-cyle
  - controls on C flows into and out of surface reservoirs
• modeled CO$_2$ vs. geologic observations
• CO$_2$ and climate in deep time
  – Mesozoic warmth
  – Cenozoic cooling
  – onset of Antarctic Glaciation (CO$_2$ threshold?)
• CO$_2$ and sea level
• the “Paleocene Thermal Maximum”
Earth temp. from geochem & fossils

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**major periods of glaciation**
Earth temp. from geochem & fossils

Mesozoic and early Cenozoic warmth, +2 to +6°C at equator & +20 °C or more at poles!

Mega-glaciations

Present Ice Age
Earth temp. from geochem & fossils

progressive Cenozoic cooling to Ice Age temperatures (0 to -6 °C)

Mesozoic and early Cenozoic warmth, +2 to +6°C at equator & +20 °C or more at poles!

mega-glaciations

(temperature estimates are given as departures from present)
Phanerozoic climate change

• what factors might have contributed to long-term changes in Phanerozoic climate?
  – tectonics, paleo-geography
  – solar luminosity (~ +1%/100 my)
  – atmospheric CO₂
  – other (galactic cosmic ray fluxes?)

• changes in average latitude of continents and land-sea configuration important but not sufficient

• change in solar luminosity largely unidirectional

• CO₂ influences climate, but 4x changes or more (v. present) would be required
  – need data or highly educated guess
the long-term C-cycle

\[
\text{organic} \quad \text{inorganic}
\]

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

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

Berner '03
the organic carbon cycle

photosynthesis

atm. CO$_2$
700 GTC

respiration

plants
600 GTC

decay

sedimentation and sediments
1,600 GTC

~0.1 burial

sedimentary rocks
10,000,000 GTC

weathering
~0.1 GTC/yr

~0.1 recall leak in organic C-cycle to seds (balanced by Wx)
mechanistic model of C-cycle...

what changes to flows might influence CO₂ in surface reservoir?
mechanistic model of C-cycle...

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

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

- **tectonics**
  - continental relief/position
  - sea-floor spreading/subduction/volg.

- **climate**
  - \( T, P \)

- **plants**
  - abundance, type

Factors influencing key flows (\( Wx, \) burial, subduction, volc.)
GEOCARB model

• Yale’s Bob Berner considered the evolution (based on independent geologic observations) of these various factors over time in a mechanistic model of the long-term C-cycle

• this enabled Berner to estimate changes in CO$_2$ across the Phanerozoic (last 540 MY)

• what did he find?
GEOCARB model

\[ \text{RCO}_2 = \frac{\text{model CO}_2}{"\text{present}" \ (300 \text{ ppm})} \]

Paleozoic
Mesozoic
Cen.

Time (my)

RCO_2 = \text{model CO}_2/"\text{present}" \ (300 \text{ ppm})
the decline in modeled CO\textsubscript{2} accelerated \(~350\) MY ago and some driving factors might be.....

a) appearance/expansion of vascular (woody) plants, b) formation and burial of organic C in poorly oxygenated swamps, c) increased silicate weathering, d) increased volcanism, e) all but d)
answer

• woody plants appeared, expanded 350 - 300 MY ago
  – plants promote silicate weathering (via root respiration)
  – woody plant tissue resistant to oxidation, more likely to survive ‘til burial

• continental position, low relief and warm, humid climate led to development of large inland swamps
  – swamps allow growth and then preservation (due to low oxygen levels) of organic matter

• increased formation, preservation and burial of plant remains led to formation of massive “Carboniferous” coal beds (300-250 MY)
CO$_2$ estimates

estimates from various proxies (colored lines)

all estimates (grey) and their 10 MY average (black)

substantial data - model agreement suggests reconstructions reliable despite uncertainties in both

Royer et al., ‘04
Phanerozoic climate & CO$_2$

$^{18}$O geo-thermometer corrected for geo-chemical effects

CO$_2$ estimated from various proxies and model (pink)

major glaciations (assoc. w/ low CO$_2$)

after Royer et al., '04
Phanerozoic climate & \( \text{CO}_2 \)

\( ^{18} \text{O} \) geo-thermometer corrected for geo-chemical effects

\( \text{CO}_2 \) estimated from various proxies and model (pink)

major glaciations (assoc. w/ low \( \text{CO}_2 \))

after Royer et al., ‘04
Mesozoic

increased sea-floor spreading rates:

= increased subduction of C in seds (yellow) ➞ increased metamorphosis & volcanism (stronger CO₂ source)

= decreased land area (more ocean crust, black) ➞ decreased silicate weathering (weaker CO₂ sink)
Cenozoic

decreased sea-floor spreading rates (early Cenozoic):
= decreased metamorphosis & volcanism of C (weaker CO₂ source)

increased mountain uplift (late Cenozoic):
= increased silicate weathering (stronger CO₂ sink)
summary points (so far)

• *major changes of Phanerozoic climate and CO$_2$ appear related*

• *magnitude of CO$_2$ changes (>>4X “modern”) consistent with role as major climate forcing agent*

• “*observed*” CO$_2$ from proxies well explained by mechanistic / process model of the long-term C-cycle
Cenozoic T

from relative abundance of a heavy isotope of oxygen ($^{18}$O) in benthic (ocean bottom) carbonate shells

Zachos et al. '01
Colder more

18O reduction of CO₂ to ~2.5X modern permits expansion of glaciers in Antarctica ("system threshold")

CO₂ estimated from carbon isotope measurements in phytoplankton

inception of continental-scale glaciation in Antarctica

Pagani et al.
Cenozoic T

ice house

hot house

more $^{18}$O

colder

Zachos et al. ‘01
Cenozoic sea level & CO$_2$

- >35 million yrs ago: no permanent ice
- ~32 million yrs ago: onset of ANT glaciation
- Recent pre-industrial period
- Last glaciation: 21 kyr ago
Paleocene Thermal Maximum

• an abrupt perturbation of the C-cycle and $T$
• $\sim 5000$ GTC released in a few 1000 years*
• deep ocean warmed by 5 °C
• lead to severe ocean acidification (marine carbonate dissolved)
• and, extinction of benthic organisms
• recovery of $T$ and ocean chemistry takes $\sim 100,000$ years

*based on $^{13}$C proxy ($^{13}$C discriminated against during photosynthesis and methanogenesis, so organic matter is low in $^{13}$C- low values in carbonates indicate addition of organic C as $CO_2$ to ocean & atmosphere
Paleocene Thermal Maximum

$\delta^{18}O$ (‰)

Paleocene

more $^{18}O$
colder

$\delta^{13}C$ (‰)

5 °C warming of deep sea

$\sim 5000$ GTC released

$\delta^{18}O$, $\delta^{13}C$, $T$, $CO_2$

Zachos et al. '01
Paleocene Thermal Maximum

is the implied rate of C release consistent with a source in the hard rock reservoir?
methane hydrate

methane held in water ice by high pressure and low temperature beneath sea floor

possible source of low $^{13}$C carbon during LPTM
recall

• current inventory of fossil fuels is ~5000 GTC
• at current rates of consumption it would take ~500 years to burn it all
• the LPTM is a strong indication from the geologic record that it would be a mistake to do so
• consequences (?):
summary

• flows of inorganic and organic C into and out of the “rock reservoir” control atmospheric CO$_2$ on long time scales
• these flows are influenced by tectonic forces, climate, and biology
• changes in these factors can be used to estimate CO$_2$ variations in deep time
• such estimates are largely consistent w/ geologic “proxy” evidence of past CO$_2$ amount
• variations of CO$_2$, climate, glaciation and sea level during the Phanerozoic appear to be causally related
• at the end of the Paleocene a marked perturbation of CO$_2$ and climate occurred that appears to be unique in the Cenozoic
learning goals

• be able to describe the primary flow paths of C in the long-term (“rock”) C-cycle and some of the factors that influence the strength of these flows
• use your understanding of the above to explain or “predict” the evolution of CO$_2$ through the Phanerozoic (last 540 MY)
• describe the relationship between Cenozoic cooling, CO$_2$ change and continental scale glaciation in the N and S Hemispheres
• outline the events of the PTM and consider how they might inform our understanding of the timescales of recovery from a large release of C
• establish your own summary view of the overall relationship between CO$_2$, climate and sea level in deep time