Geological history of atmospheric CO2 variations and Earth’s climate

David L. Fox
Dept. of Earth and Environmental Sciences
University of Minnesota

Outline
1. The global carbon cycle and climate
2. The Faint Young Sun and Precambrian CO₂
3. Snowball Earth
4. CO₂ over the last 400 million years
5. The Paleocene-Eocene Thermal Maximum 56 million years ago
6. Glacial-interglacial cycles of the last 2.6 million years
7. Rapid climate changes of the last 50,000 years
Earth’s energy balance

At steady state:

Energy emitted by Earth = Energy absorbed by Earth

\[ \sigma T_e^4 = \frac{S}{4} (1 - A) \]

Surface temperature depends on:

1) \( S \), solar flux at 1 AU (inverse-square law)
2) \( A \), albedo
3) Warming provided by the atmosphere (greenhouse effect)

Ice-albedo feedback: increasing average albedo leads to cooling, which will increase snow and ice, increasing average albedo, decreasing energy from Sun, increasing albedo...

Runaway ice albedo: theoretically may occur if sea ice extends into tropics (30° N and S latitude)
Earth’s thermostat: chemical weathering of silicate rocks
(igneous, most metamorphic, and siliciclastic sedimentary rocks)

**Basic reactions**

\[
\begin{align*}
\text{CO}_2 + \text{H}_2\text{O} & \rightarrow \text{H}_2\text{CO}_3 \\
\text{CaSiO}_3 + 2\text{H}_2\text{CO}_3 & \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- + \text{SiO}_2 \\
\text{CaCO}_3 + \text{H}_2\text{CO}_3 & \rightarrow \text{Ca}^{2+} + \text{HCO}_3^- \\
\text{Ca}^{2+} + 2\text{HCO}_3^- & \rightarrow \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O}
\end{align*}
\]

Chemical weathering of silicate rocks consumes atmospheric CO\(_2\)

If rate of CO\(_2\) consumption is greater than rate of CO\(_2\) supply by outgassing from volcanoes (really from mantle), CO\(_2\) levels in the atmosphere will decrease
Marine sediments and crust: 100,000,000

1 Gigaton = 1,000,000,000 tons
Tectonics and the planetary carbon cycle

Basic components of Earth’s plate tectonics

- volcanic arc
- accretionary wedge
- mid-ocean ridge
- deep and shallow marine sediments
- intrusions
- continental collision (dynamothermal meta)
- cont crust
- litho mantle
- subduction zone
- lithospheric mantle
- asthenosphere
Chemical weathering of rocks consumes (reduces) atmospheric CO$_2$.

Chemical and mechanical weathering of rocks delivers CO$_3$ and organic C to oceans.

Tectonics and the planetary carbon cycle
Tectonics and the planetary carbon cycle

Deposition of carbon on continental shelves and deep ocean floor as CaCO$_3$ and organic matter
The Biological Pump moves CO\(_2\) from the atmosphere to ocean sediment as CaCO\(_3\) and organic matter.
Tectonics and the planetary carbon cycle

Subduction of oceanic lithosphere (plates) moves carbon into the geosphere
Tectonics and the planetary carbon cycle

Heat and pressure in subduction zone alters rocks and releases some of the CO$_2$ to the atmosphere
Tectonics and the planetary carbon cycle

Heat and pressure in subduction zone alters rocks and releases some of the CO\textsubscript{2} to the atmosphere.

Volcanoes above the subducted plate release more CO\textsubscript{2} during eruptions.
The subducted plate and its remaining carbon mixes into the convecting mantle
Tectonics and the planetary carbon cycle

The subducted plate and its remaining carbon mixes into the convecting mantle

Volcanoes of the mid-ocean ridges release carbon to atmosphere during eruptions as ocean basins grow wider
The Faint Young Sun Paradox
Young Main Sequence stars increase in luminosity over billions of years.
Ice ages in Earth history

Glacial Ages

Billion Years Ago

http://www.internetlooks.com/globaltempchange.html
Much higher $p\text{CO}_2$ as solution to FYS?

Moodies Group, Barberton Greenstone Belt, South Africa

3.2 Ga siliciclastic alluvial fan and braided fluvial deposits
Oldest known non-marine deposits

Pebbles with Fe$^{2+}$CO$_3$ siderite in weathering rinds
Implies anoxic surface environment

Hessler et al., 2004
Thermodynamics of weathering reactions require minimum pCO$_2$ higher than modern over range of T and pCO$_2$

Reaction 2 is most like weathering rinds and requires pCO2 higher than modern
Thermodynamics of weathering reactions require minimum \( p\text{CO}_2 \) higher than modern over range of \( T \) and \( p\text{CO}_2 \).

Kasting, 2018

Kasting, 2018

Kanzaki & Murakami (2015)

Kasting (1987)

Kah & Riding (2007)

Driese et al. (2011)

Sheldon (2006)

Age (Ga ago)

\( p\text{CO}_2 \) (PAL)
Older Cryogenian ('Sturtian') glacials

730 - 700 Ma

http://www.snowballearth.org/week1.html
Younger Cryogenian ('Marinoan') glacials
(665 - 635 Ma)

http://www.snowballearth.org/week1.html
Paleogeography of Rodinia during Neoproterozoic

SWEAT: SouthWest US-East Antarctica

http://www.scotese.com/rodinia.jpg
Low latitude Neoproterozoic global glaciations

Hoffman and Schrag, 2002
400 million year record of atmospheric CO₂ and climate

CO₂ record based on:
- fossil leaf anatomy
- chemistry of fossil soils
- chemistry of fossil plankton
- chemistry of fossil liverworts

Ice extent based on:
- geology
- paleogeography from paleomagnetic record

Foster et al., 2017. Nature Communications
Atmospheric CO$_2$ estimated by GEOCARBSULF

Royer et al., 2014
Atmospheric $O_2$ estimated by GEOCARBSULF

Royer et al., 2014
Major coal deposits in the United States

Western: Cretaceous and Paleogene
Central and eastern: Pennsylvanian

Monroe and Wicander, 2001  21.30  p. 623
Carboniferous coal deposits globally
400 million year record of atmospheric CO₂ and climate

Foster et al., 2017. *Nature Communications*
65 million year record of atmospheric CO$_2$ and climate

Beerling and Royer, 2011. *Nature Geoscience*
$^{13}$C/$^{12}$C and $^{18}$O/$^{16}$O ratios of benthic microfossils (foraminifera) record changes in the global carbon cycle and water temperature ($\pm$ changes in ice volume)
Global compilation of benthic foraminifera oxygen and carbon isotope compositions

Zachos et al., 2008
Stable isotope composition of benthic foraminifera across the Paleocene-Eocene boundary (global compilation)
Paleogeographic map for 56 Ma with P-E boundary sites

McInerney and Wing, 2011
Bighorn Basin, north central Wyoming
Stable isotope composition of paleosol carbonates at the Paleocene-Eocene boundary, Bighorn Basin, Wyoming

Bowen et al., 2001
Isotopic signal of CIE and PETM in mammalian tooth enamel

Secord et al., 2012
Carbon isotope excursion in the linked ocean-atmosphere-terrestrial biosphere system
Biome shifts across the PETM, Bighorn Basin, WY

McInerney and Wing, 2011
Mass balance and the amount of carbon added

\[
(M_{\text{final}}) \times (\delta^{13} C_{\text{final}}) = (M_{\text{initial}}) \times (\delta^{13} C_{\text{initial}}) + (M_{\text{added}}) \times (\delta^{13} C_{\text{added}}).
\]

\[
M_{\text{final}} = M_{\text{initial}} + M_{\text{added}},
\]

\[
\text{CIE} = \delta^{13} C_{\text{final}} - \delta^{13} C_{\text{initial}}.
\]

\[
M_{\text{added}} = -\text{CIE} \times M_{\text{initial}} / (\delta^{13} C_{\text{final}} - \delta^{13} C_{\text{added}}).
\]

McInerney and Wing, 2011
Climate sensitivity and the PETM CIE

C input to atmosphere to explain 5°C warming depends on...

Pre-PETM conditions

5°C warmer than recent pre-industrial pCO₂ = 280 ppm

Climate sensitivity to doubling of CO₂

Source and isotope composition of C

Pagani et al., 2006
Duration of CO$_2$ release during PETM

Zeebe et al., 2016
Anthropogenic carbon release rate unprecedented during the past 66 million years

Richard E. Zeebe\textsuperscript{1*}, Andy Ridgwell\textsuperscript{2,3} and James C. Zachos\textsuperscript{4}

Carbon release rates from anthropogenic sources reached a record high of $\sim10$ Pg C yr$^{-1}$ in 2014. Geologic analogues from past transient climate changes could provide invaluable constraints on the response of the climate system to such perturbations, but only if the associated carbon release rates can be reliably reconstructed. The Palaeocene–Eocene Thermal Maximum (PETM) is known at present to have the highest carbon release rates of the past 66 million years, but robust estimates of the initial rate and onset duration are hindered by uncertainties in age models. Here we introduce a new method to extract rates of change from a sedimentary record based on the relative timing of climate and carbon cycle changes, without the need for an age model. We apply this method to stable carbon and oxygen isotope records from the New Jersey shelf using time-series analysis and carbon cycle–climate modelling. We calculate that the initial carbon release during the onset of the PETM occurred over at least 4,000 years. This constrains the maximum sustained PETM carbon release rate to less than 1.1 Pg C yr$^{-1}$. We conclude that, given currently available records, the present anthropogenic carbon release rate is unprecedented during the past 66 million years. We suggest that such a ‘no-analogue’ state represents a fundamental challenge in constraining future climate projections. Also, future ecosystem disruptions are likely to exceed the relatively limited extinctions observed at the PETM.
$^{18}\text{O}/^{16}\text{O}$ ratios of benthic microfossils (foraminifera)

Repeated, periodic ice ages over the last 2.6 Ma

Globigerinoides sacculifer
Orbulina universa

Ruddiman, 2000
Energy at the surface varies with changes in...

Earth’s orbit around the sun
orientation of the spin axis relative to the plane of the orbit

Three major frequencies:

Eccentricity (100 ka): shape of orbit varies from more elliptical to more circular

Obliquity (41 ka): tilt of rotational axis varies from 24-21° from plane of orbit around Sun

Precession (ca. 20 ka): rotational axis wobbles like a spinning top so that seasons change in relation to position in orbit around Sun
Antarctic ice sheet drilling sites

http://cdiac.ornl.gov/trends/co2/ice_core_co2.html
Vostok Ice Core, Antarctica


- Glacial ice disrupted by bedrock deformation (227 m thick)
- "Muddy" Ice: Formed by repeated freezing and thawing along the lake margin (70 m thick)
- Core "3590" (~153 m above lake)
- Accretion Ice (~205 m thick): Large ice crystals, low EC, constant isotope and gases
- Clear Ice: Accreted as ice flowed over Lake Vostok proper (~135 m thick)
- Ice/Water Interface

3311 m
3538 m
3608 m
3623 m (maximum core depth)
~3743 m
Dome C ice temperature ($\delta^D$) and ocean temperature/ice volume ($\delta^{18}O$)

Jouzel et al., 2007

warmer

colder
Dome C ice temperature and atmospheric CO$_2$ trapped in ice bubbles

Luthil et al., 2008

![Diagram showing ice temperature and atmospheric CO$_2$ variations over time.](image-url)
Dome C ice temperature and atmospheric CO$_2$ trapped in ice bubbles

408.5 ppmV, Oct. 2019

Luthil et al., 2008
Comparison of Antarctic and Greenland ice core records

EPICA, 2006
Abrupt climate changes in the last 15,000 years

**Younger Dryas**
- 11.5-13 ka
- widespread, rapid global cooling during deglaciation
- followed by rapid warming

**8200 event**
- 8.2 ka
- very brief, widespread cooling
- not as prominent as YD

Alley et al., 2003