Paleoclimate:
What can the past tell us about
the present and future?

12.340 Global Warming Science
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Recent observed trends: Greenhouse gases

Global Trends in Major Greenhouse Gases to 1/2003

Global trends in major long-lived greenhouse gases through the year 2002. These five gases account for about 97% of the direct climate forcing by long-lived greenhouse gas increases since 1750. The remaining 3% is contributed by an assortment of 10 minor halogen gases, mainly HCFC-22, CFC-113 and CCL4.

Image courtesy of NOAA.
Recent observations:
Land surface temperature

Recent observations:

Sea surface temperature

Recent observations:
Drought

Recent observations:

Sea ice

Public domain image courtesy of National Snow and Ice Data Center, University of Colorado, Boulder.
Recent observed trends:

Glacier extent

Muir Glacier, Alaska

Public domain image courtesy of National Snow and Ice Data Center, University of Colorado, Boulder.
Recent observed trends:
Glacier extent

Public domain image courtesy of National Snow and Ice Data Center, University of Colorado, Boulder.
Recent observed trends:

Ice sheet mass loss

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Please see Figure 2 on http://onlinelibrary.wiley.com/doi/10.1029/2011GL046583/full.
Recent observed trends:

Sea level rise

Given these observations, what questions do you have that records of the pre-instrumental past could help answer?
How do we get information about past climates?

Climate archives
• ice cores
• tree rings
• ocean and lake sediments
• corals
• fossils
• glacial features
• boreholes
• stalagmites

Image courtesy of NASA.
A paleoclimatic tour from 400 to 1 Myr ago (with a few interruptions)

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Please see the photo on http://www.raleighite.com/2013/hs-76-the-tour-guide.
Climate and $\text{CO}_2$ over the last 400 Myr

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Oxygen isotopes: Versatile recorders of paleoclimatic conditions

\[ \delta (\%) = \left( \frac{R_{\text{sample}}}{R_{\text{std}}} - 1 \right) \cdot 10^3, \quad R = \frac{^{18}O}{^{16}O}, \frac{^{13}C}{^{12}C}, \frac{D}{H}, \text{etc.} \]

For oxygen, the \( \delta \) notation would be \( \delta^{18}O \); the convention is to put the mass of minor isotope after the symbol \( \delta \).
Oxygen isotope fractionation

As a general rule of thumb, $^{18}$O tends to be enriched relative to $^{16}$O in the most “immobile” state involved in a reaction or transformation.

Figure: more energy is needed to break bonds involving heavier isotopes (in this case, H-H vs. H-D vs. D-D, where D=$^2$H, H=$^1$H)

Figure by MIT OpenCourseWare.
Oxygen isotope fractionation

Fractionation increases with decreasing temperature

Figure: δ\(^{18}\)O enrichment in cultured foraminifera vs. temperature

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Figure by MIT OpenCourseWare., after Erez et al., 1983
Climate over the last 65 Myr
(beware the flipping x-axis…)

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Please see Figure 2 in
Oxygen isotope fractionation

Water vapor is depleted in $^{18}O$ relative to liquid water due to the greater mass of $H_2^{18}O$ vs. $H_2^{16}O$.

Air masses become more $^{18}O$-depleted with increasing rain-out and decreasing temperatures.

Image courtesy of NASA.
Oxygen isotope fractionation

Because ice sheets are made with $^{18}$O-depleted precipitation, ice sheet growth causes global oceans to be enriched in $^{18}$O.

As a result, global oceans at the peak of the last glacial period had $\delta^{18}$O $\sim 1\%$ more positive than at present.
Climate over the last 65 Myr
(beware the flipping x-axis…)

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Please see Figure 2 on https://pangea.stanford.edu/research/Oceans/GES206/readings/Zachos2001.pdf
Climate and CO$_2$ over the last 65 Myr

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The Pliocene, 5.3-2.6 Myr ago

- $pCO_2$ likely $\sim 400$ ppmv
- Continents near present positions
- Abundant marine and terrestrial sediments available for study
The Pliocene, 5.3-2.6 Myr ago

Reconstructed global average temperature ~2-3 °C warmer than at present

Image courtesy of USGS.
Models appear to underestimate high latitude warming in the Pliocene

Annual average reconstructed SST-modeled SST

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Please see: Figure 3 on page, http://www.nature.com/ngeo/journal/v3/n1/full/ngeo706.html

Map view (squares = faunal SST estimates; stars = Mg/Ca or alkenone SST estimates)

Zonal average (solid line)

What are models missing?
Pliocene sea levels

~20-30 m above modern

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Please see Figure 2 on http://www.moraymo.us/2011_Raymoetal.pdf

Modern elevation above sea level of a Pliocene shoreline reflecting 14m higher sea level (i.e., full deglaciation of Greenland and West Antarctica) – note that isostatic adjustments to Plio-Pleistocene ice sheet growth and recent deglaciation causes significant deviations from the “real” (eustatic) sea level difference
Problem:
Equilibrium vs. transient response to high pCO$_2$
The Paleocene-Eocene Thermal Maximum (PETM), 55 Myr ago

Temperature rise

Addition of low-$^{13}$C carbon to the atmosphere and ocean

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Please see Figure 5 on

Temperature rise
The Paleocene-Eocene Thermal Maximum (PETM), 55 Myr ago

Global temps rose ~5-9°C in 1-10 kyr

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Please see Figure 2 on http://www.sciencemag.org/content/302/5650/1551.full
PETM ocean acidification consistent with large pCO$_2$ increase

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Please see Figure 1 on http://www.sciencemag.org/content/308/5728/1611.full
How much carbon was added to the atmosphere?

**Method 1:** use $d^{13}C$ of source and $d^{13}C$ anomaly to estimate

**Problem:** $d^{13}C$ of potential sources very different (-5 to -60 per mil)

**Estimates:** mostly 3000-8000 GtC (order 1-10 GtC/yr)

**Method 2:** use amount of carbonate dissolution in ocean sediment cores to estimate how much ocean pH was lowered

**Problem:** requires good spatial coverage of cores, accurate ocean model, and estimate of ocean alkalinity

**Estimates:** $\leq 3000$ GtC, or an increase in atmospheric pCO$_2$ by factor of $\approx 1.7$.

**New problem:** not enough to explain 5-9°C warming! (Zeebe et al., Nat. Geosci. 2009)
Duration of perturbation $\sim 200$ kyr

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Please see Figure 5 on
A few questions for paleo-records

• Are modern conditions and rates of change exceptional?

• What the links between GHGs and climate?
  – $\text{CO}_2$-temperature sensitivity ($^\circ\text{C}$/doubling of $\text{CO}_2$)
  – Natural controls on atmospheric GHG levels

• What were conditions during past warm climates and warmings?
  – Temp gradients, droughts, sea level, ice sheet stability in past warm climates
  – Climate model performance
  – Potential for nonlinear responses
References


