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

12.340 Global Warming Science

February 14, 2012

David McGee

Recent observed trends: Greenhouse gases

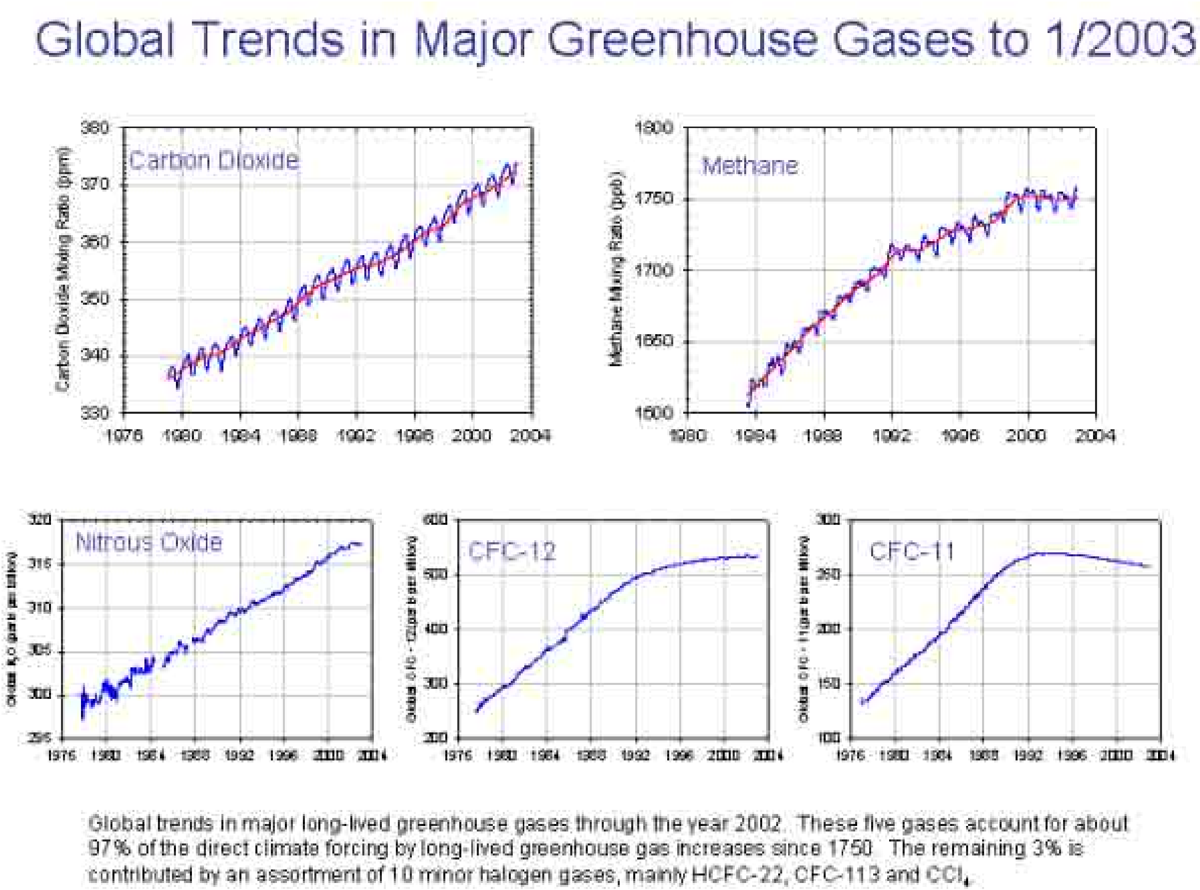
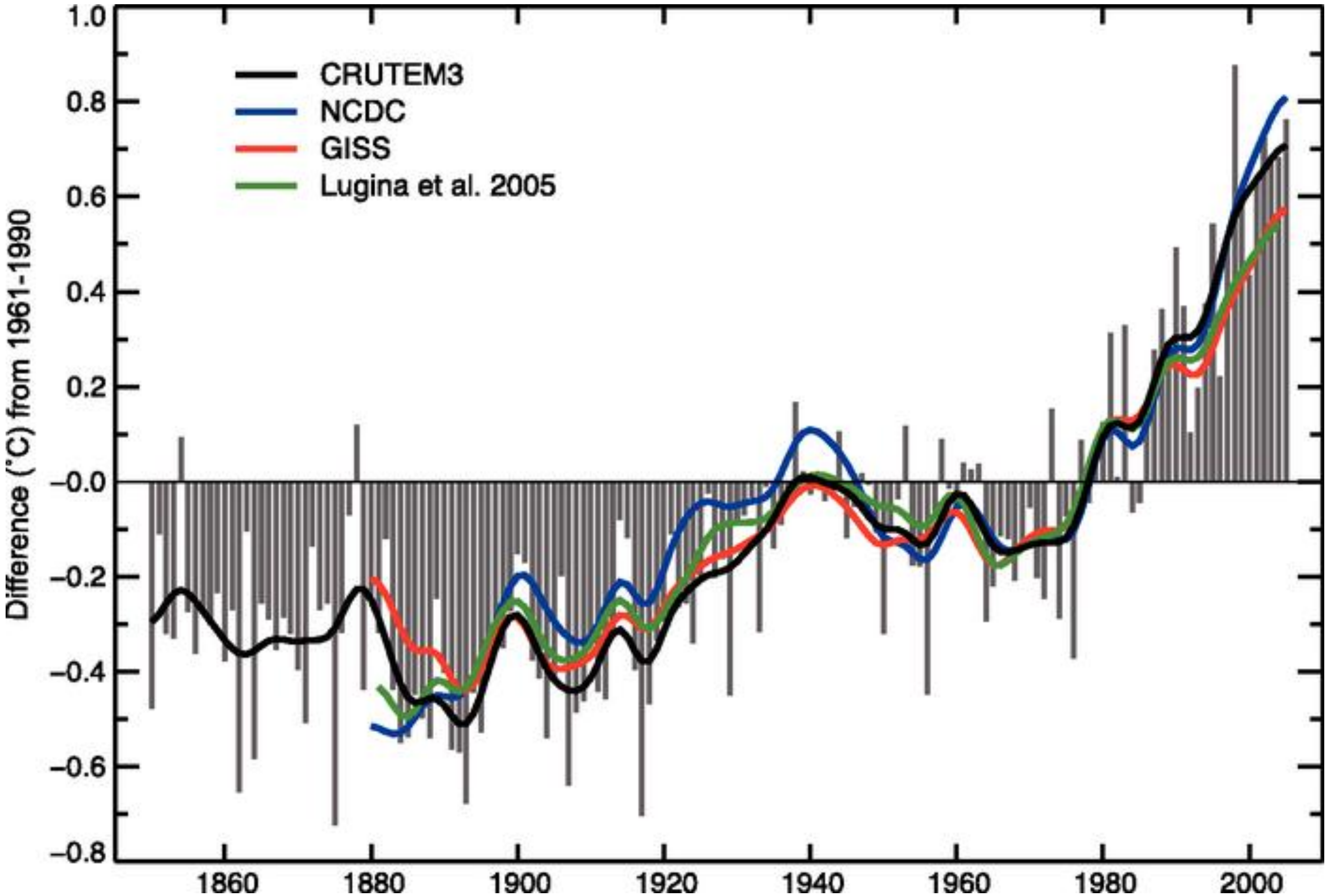


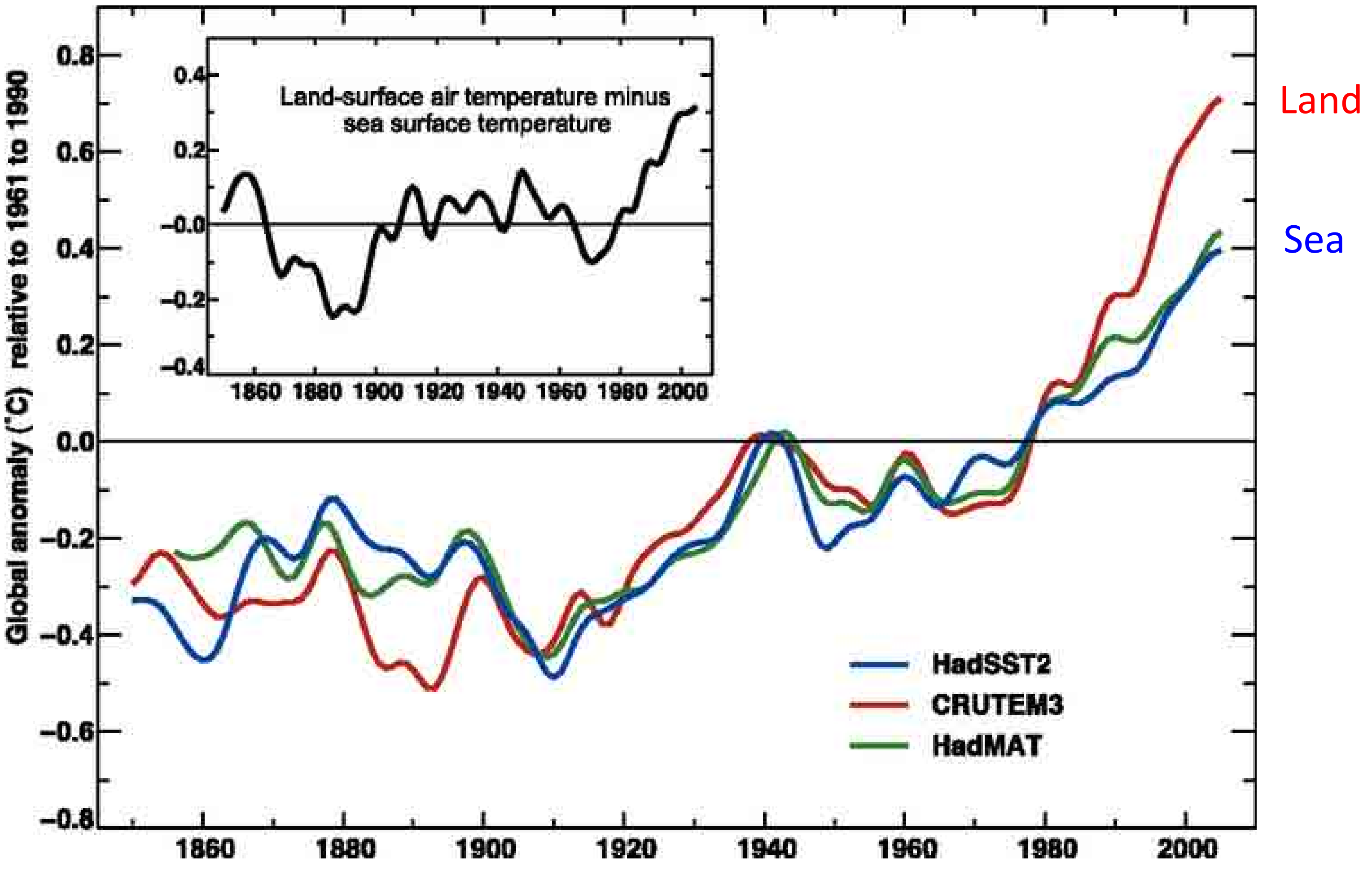
Image courtesy of NOAA.

Recent observations:
Land surface temperature



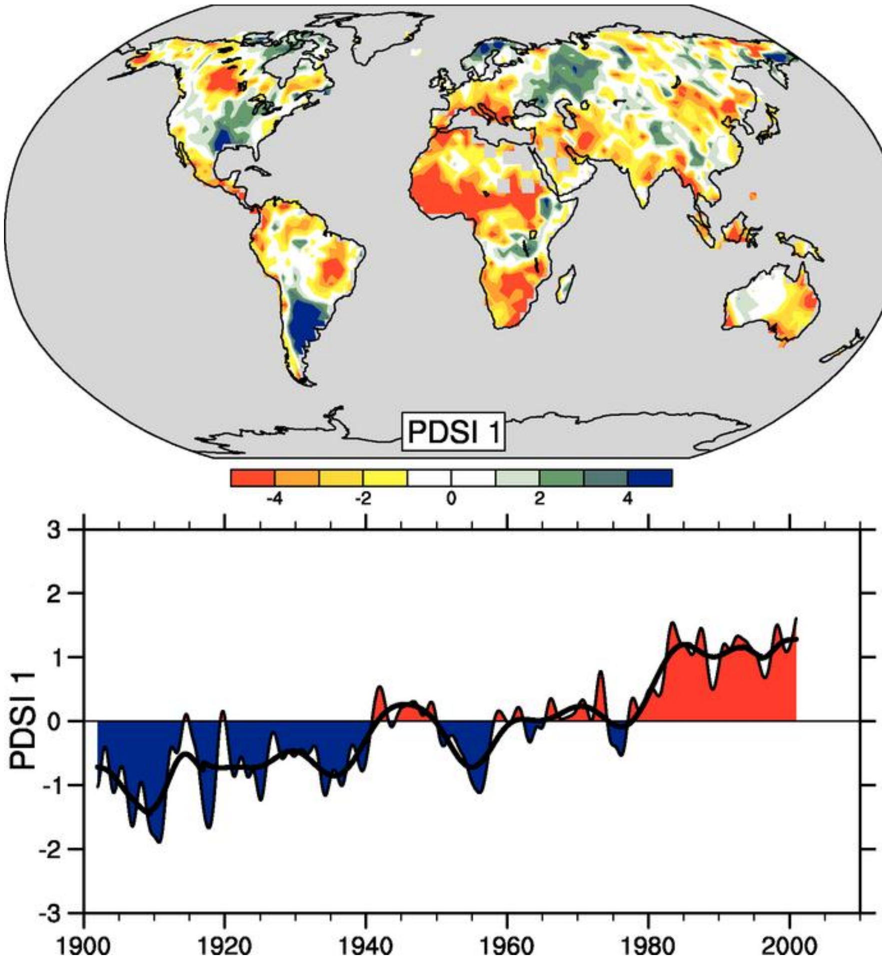
Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 3.1. Cambridge University Press. Used with permission.

Recent observations:
Sea surface temperature



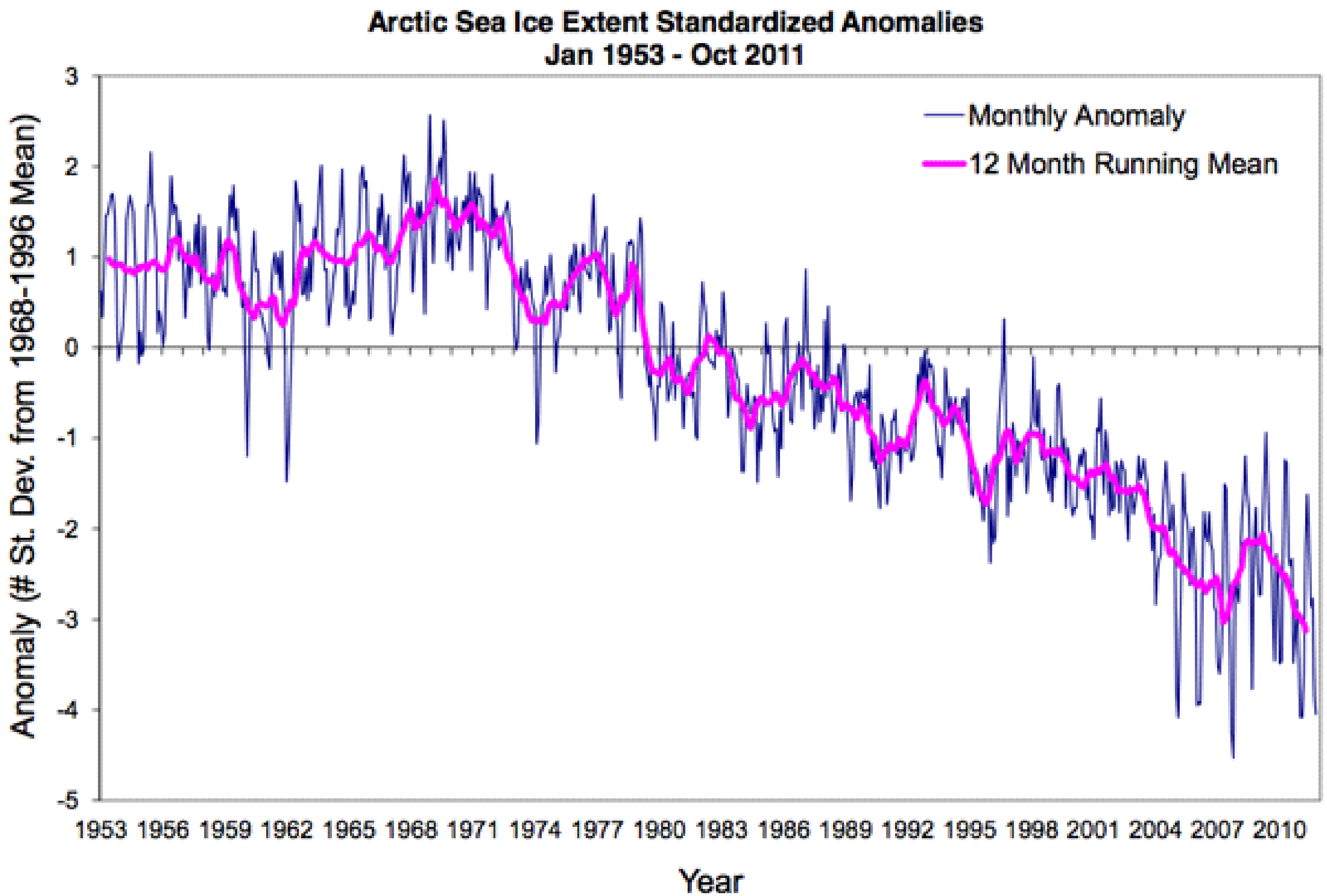
Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 3.8. Cambridge University Press. Used with permission.

Recent observations: Drought



Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, FAQ 3.2, Figure 1. Cambridge University Press. Used with permission.

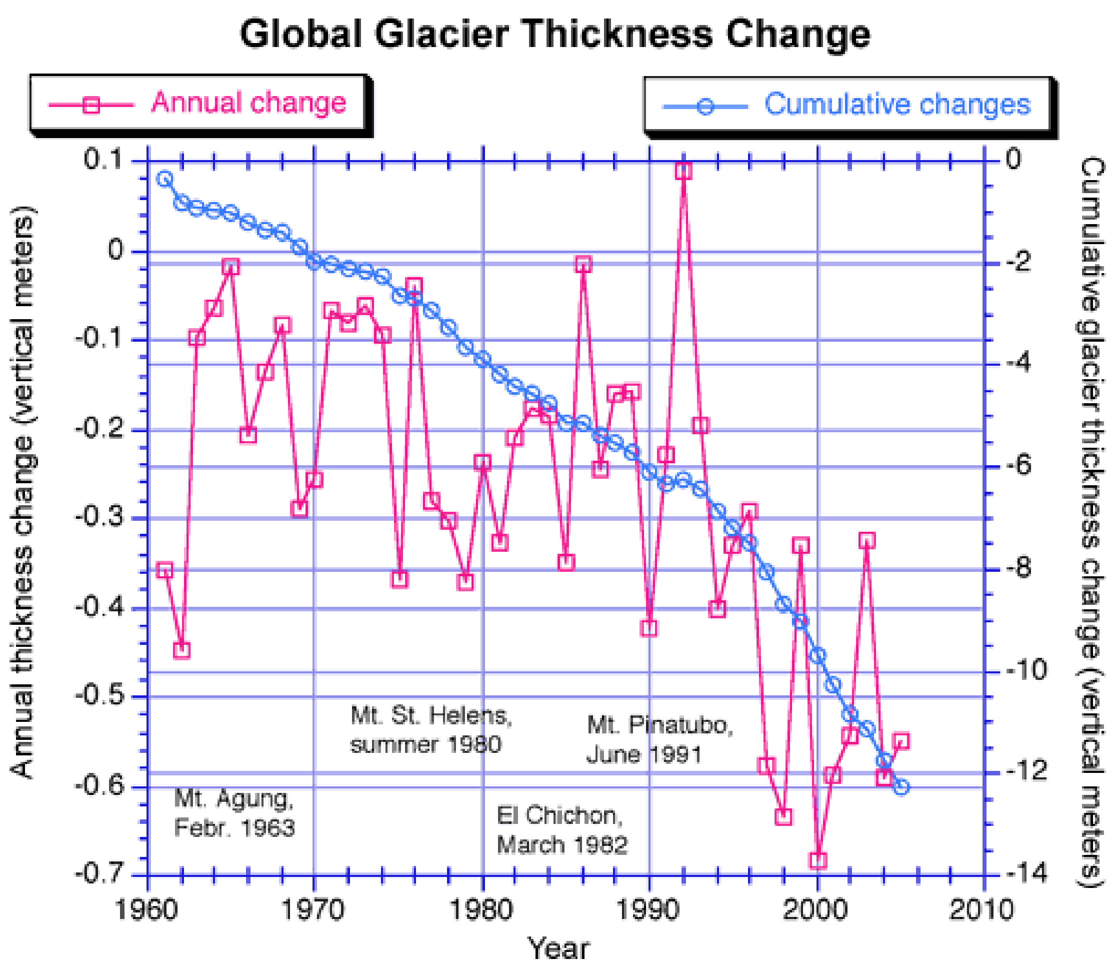
Recent observations:
Sea ice



Recent observed trends: Glacier extent

Muir Glacier, Alaska

Recent observed trends: Glacier extent



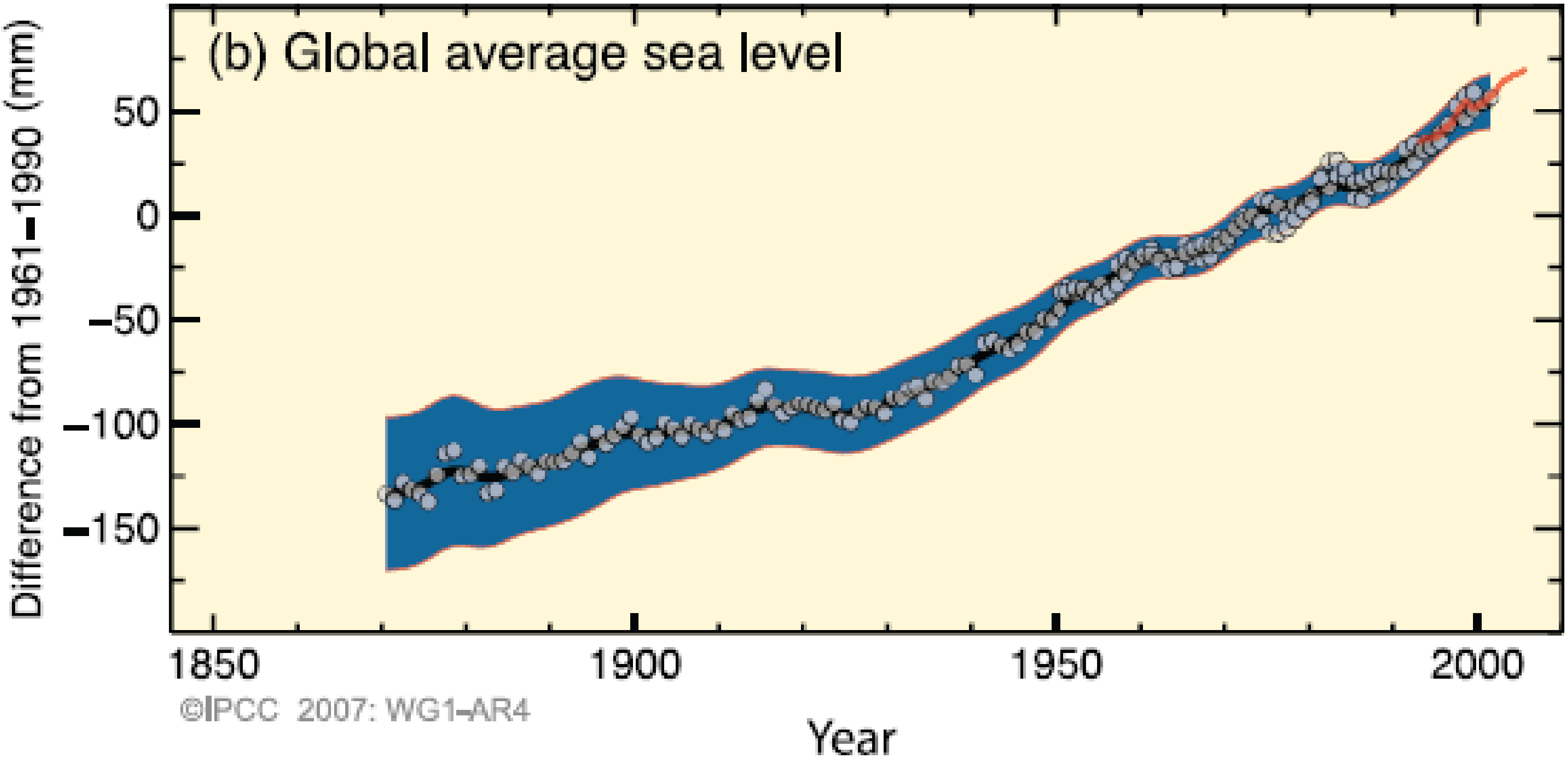
Public domain image courtesy of National Snow and Ice Data Center, University of Colorado, Boulder.

Recent observed trends:
Ice sheet mass loss

This image has been removed due to copyright restrictions.

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

Recent observed trends:
Sea level rise



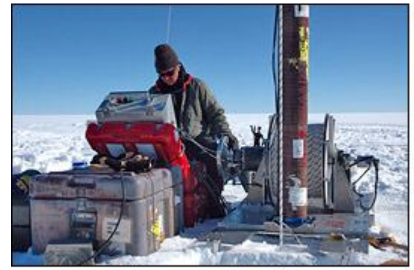
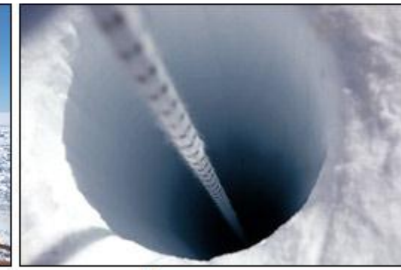
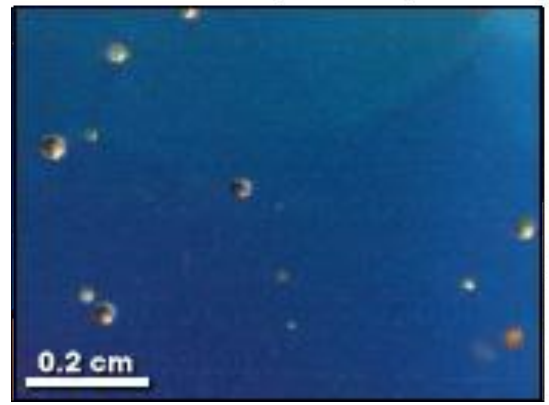
Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.3. Cambridge University Press. Used with permission.

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



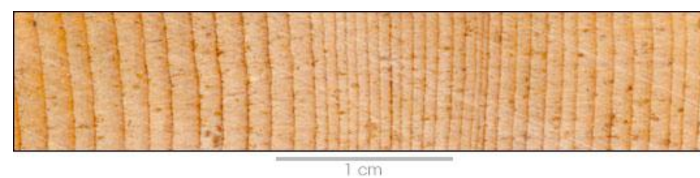



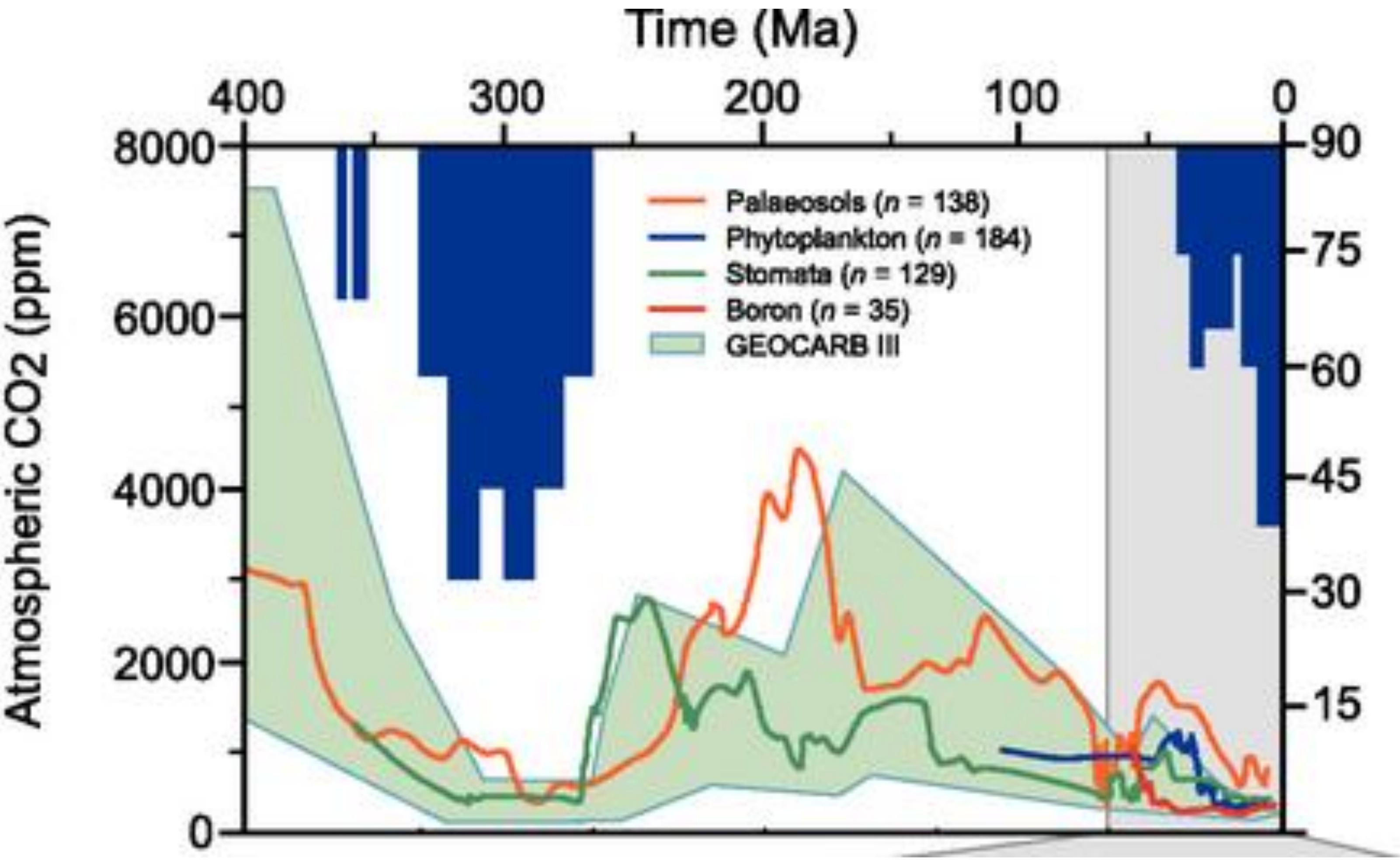
Image courtesy of NASA.

A paleoclimatic tour from 400 to 1 Myr ago (with a few interruptions)

This image has been removed due to copyright restrictions.

Please see the photo on
http://www.raleighite.com/2013/hs-76-the-tour-guide.

Climate and CO_2 over the last 400 Myr



Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 6.1. Cambridge University Press. Used with permission.

This image has been removed due to copyright restrictions.

Please see: Figure 2. Beerling, D. J., & Royer, D. L. (2011). Convergent Cenozoic CO2 history. Nature Geoscience, 4(7), 418–420. doi:10.1038/ngeo1186

Oxygen isotopes: Versatile recorders of paleoclimatic conditions

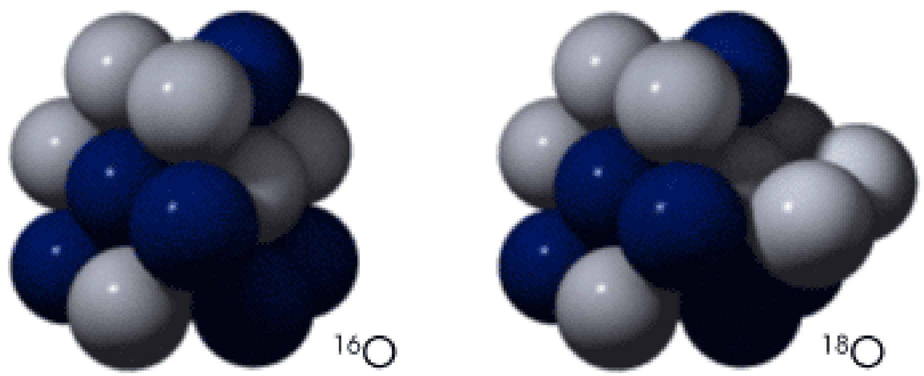


Image courtesy of NASA.

$$\delta\,(‰) = \left(\frac{R_{sample}}{R_{std}} - 1\right) \cdot 10^3,\ \ R = {}^{18}O/{}^{16}O,\ {}^{13}C/{}^{12}C,\ D/H,\ etc.,$$

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

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 $D={}^{2}H$, $H={}^{1}H$)

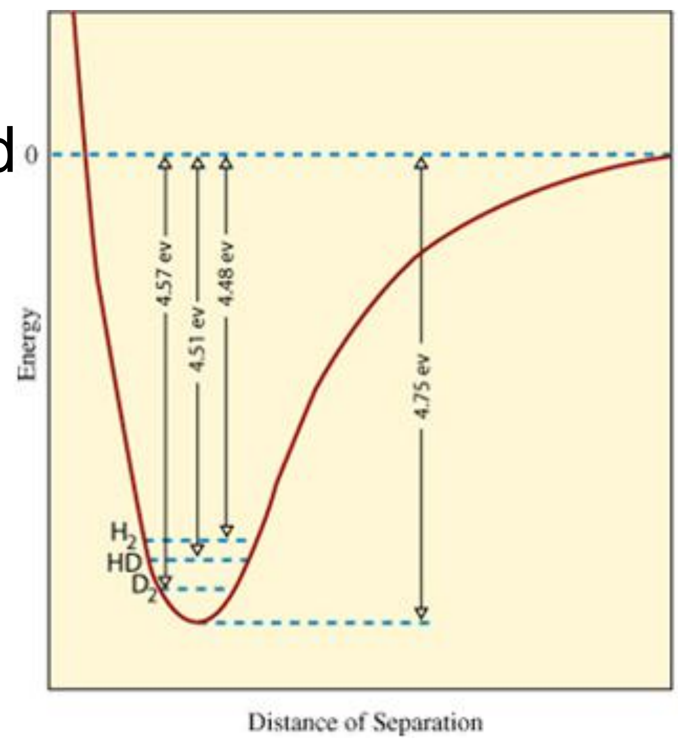


Figure by MIT OpenCourseWare.

Oxygen isotope fractionation

Fractionation increases with decreasing temperature

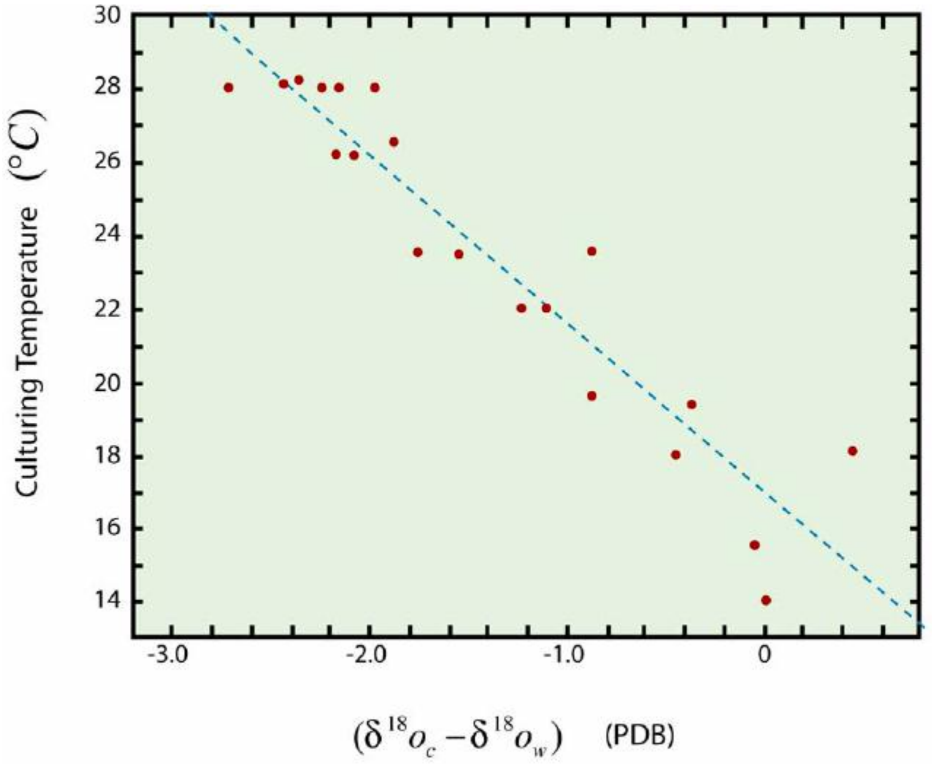


Figure: δ^{18}O enrichment in cultured foraminifera vs. temperature

This image has been removed due to copyright restrictions.

Figure by MIT OpenCourseWare., after Erez et al., 1983

Climate over the last 65 Myr

(beware the flipping x-axis…)

This image has been removed due to copyright restrictions.

Please see Figure 2 in
https://pangea.stanford.edu/research/Oceans/GES206/readings/Zachos2001.pdf

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

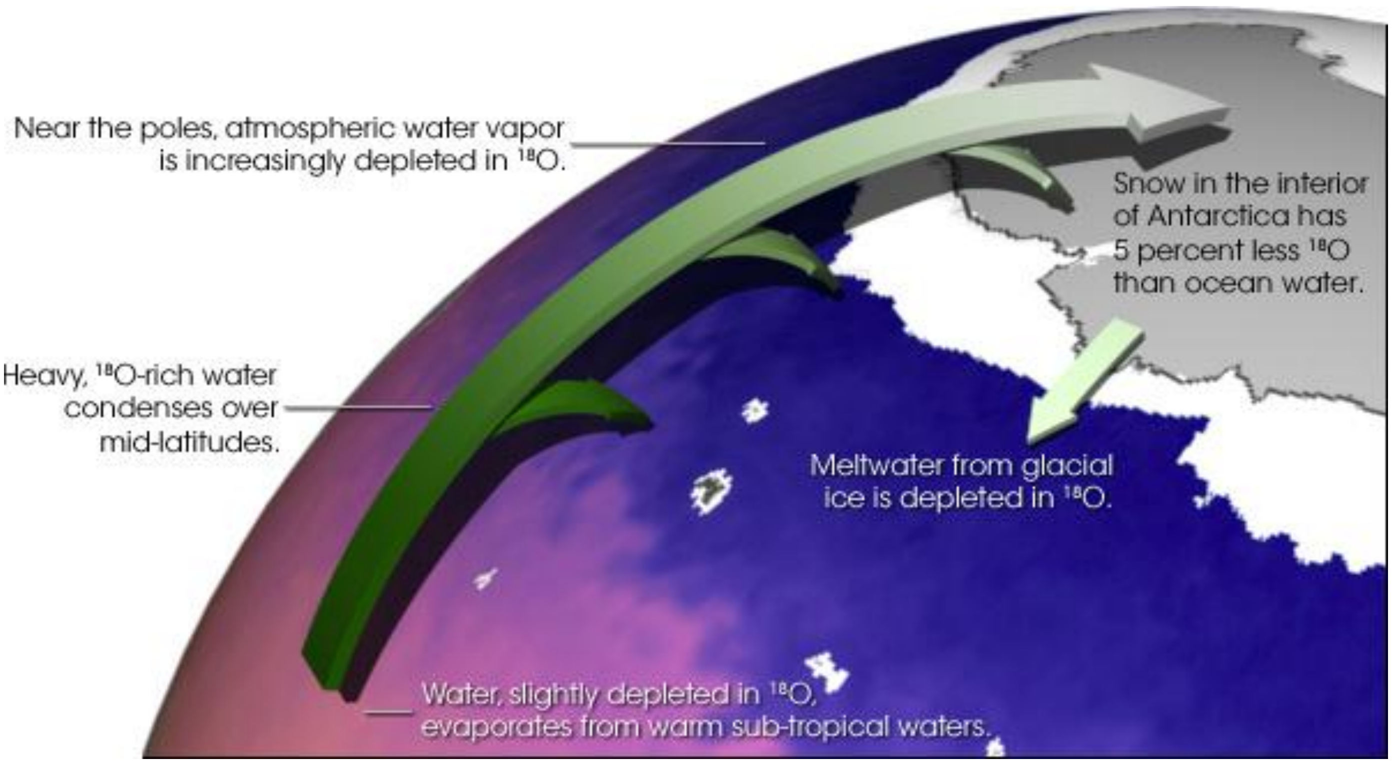


Image courtesy of NASA.

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 $\delta^{18}O$ ~1‰ more positive than at present

Climate over the last 65 Myr

(beware the flipping x-axis…)

This image has been removed due to copyright restrictions.

Please see Figure 2 on https://pangea.stanford.edu/research/Oceans/GES206/readings/Zachos2001.pdf

Climate and CO_2 over the last 65 Myr

This image has been removed due to copyright restrictions.

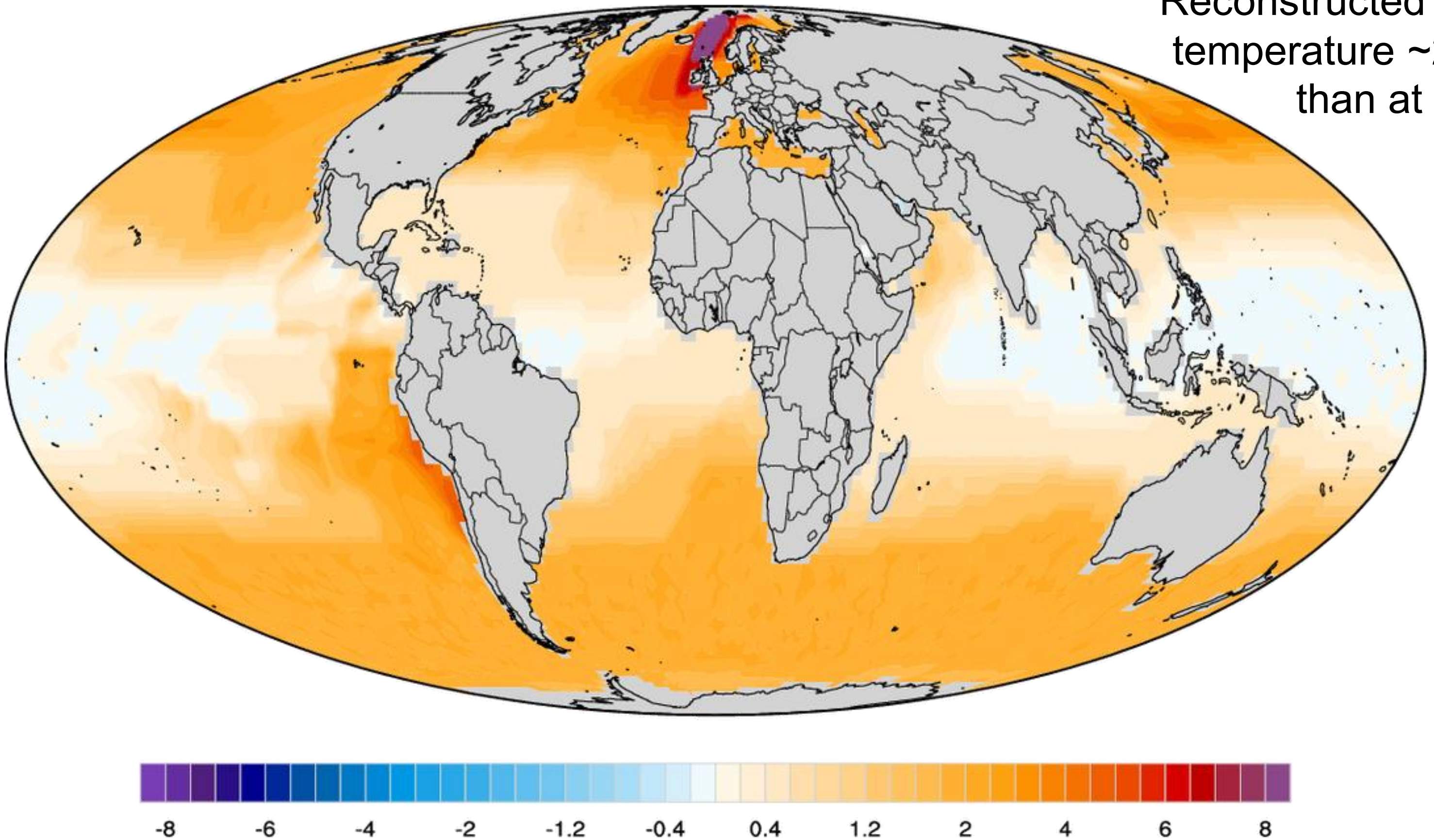
Please see: Figure 1. Beerling, D. J., & Royer, D. L. (2011). Convergent Cenozoic CO2 history. *Nature Geoscience*, 4(7), 418–420. doi:10.1038/ngeo1186.

The Pliocene, 5.3-2.6 Myr ago

- pCO_2 likely ~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



Annual average SST anomaly

USGS PRISM3 project

Image courtesy of USGS.

Models appear to underestimate high latitude warming in the Pliocene

Annual average reconstructed SST-modeled SST

This image has been removed due to copyright restrictions.

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

This image has been removed due to copyright restrictions.

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

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

This image has been removed due to copyright restrictions.

Please see Figure 5 on https://pangea.stanford.edu/research/Oceans/GES206/readings/Zachos2001.pdf

Temperature rise

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

Global temps rose ~5-9˚C in 1-10 kyr

This image has been removed due to copyright restrictions.

Please see Figure 2 on http://www.sciencemag.org/content/302/5650/1551.full

PETM ocean acidification consistent with large pCO_2 increase

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 d13C 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: <=3000 GtC, or an increase in atmospheric pCO_2 by factor of ~1.7.
New problem: not enough to explain 5-9˚C warming! (Zeebe et al., Nat. Geosci. 2009)

Duration of perturbation ~200 kyr

Please see Figure 5 on
https://pangea.stanford.edu/research/Oceans/GES206/readings/Zachos2001.pdf

A few questions for paleo-records

- Are modern conditions and rates of change exceptional?
- What the links between GHGs and climate?
  - CO_2-temperature sensitivity (˚C/doubling of 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

Beerling, D. J., & Royer, D. L. (2011). Convergent Cenozoic CO2 history. *Nature Geoscience*, *4*(7), 418–420. Nature Publishing Group. doi:10.1038/ngeo1186

Lunt, D. J., Haywood, A. M., Schmidt, G. A., Salzmann, U., Valdes, P. J., & Dowsett, H. J. (2009). Earth system sensitivity inferred from Pliocene modelling and data. *Nature Geoscience*, *3*(1), 60–64. Nature Publishing Group. doi:10.1038/ngeo706

Zachos, J., Pagani, M., Sloan, L., Thomas, E., & Billups, K. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science*, *292*(5517), 686–693. doi:10.1126/science.1059412

Zachos, J. C. (2003). A Transient Rise in Tropical Sea Surface Temperature During the Paleocene-Eocene Thermal Maximum. *Science*, *302*(5650), 1551–1554. doi:10.1126/science.1090110

Zachos, J. C. (2005). Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum. *Science*, *308*(5728), 1611–1615. doi:10.1126/science.1109004

Zeebe, R. E., Zachos, J. C., & Dickens, G. R. (2009). Carbon dioxide forcing alone insufficient to explain Palaeocene--Eocene Thermal Maximum warming. *Nature Geoscience*, *2*(8), 576–580. Nature Publishing Group. doi:10.1038/ngeo578