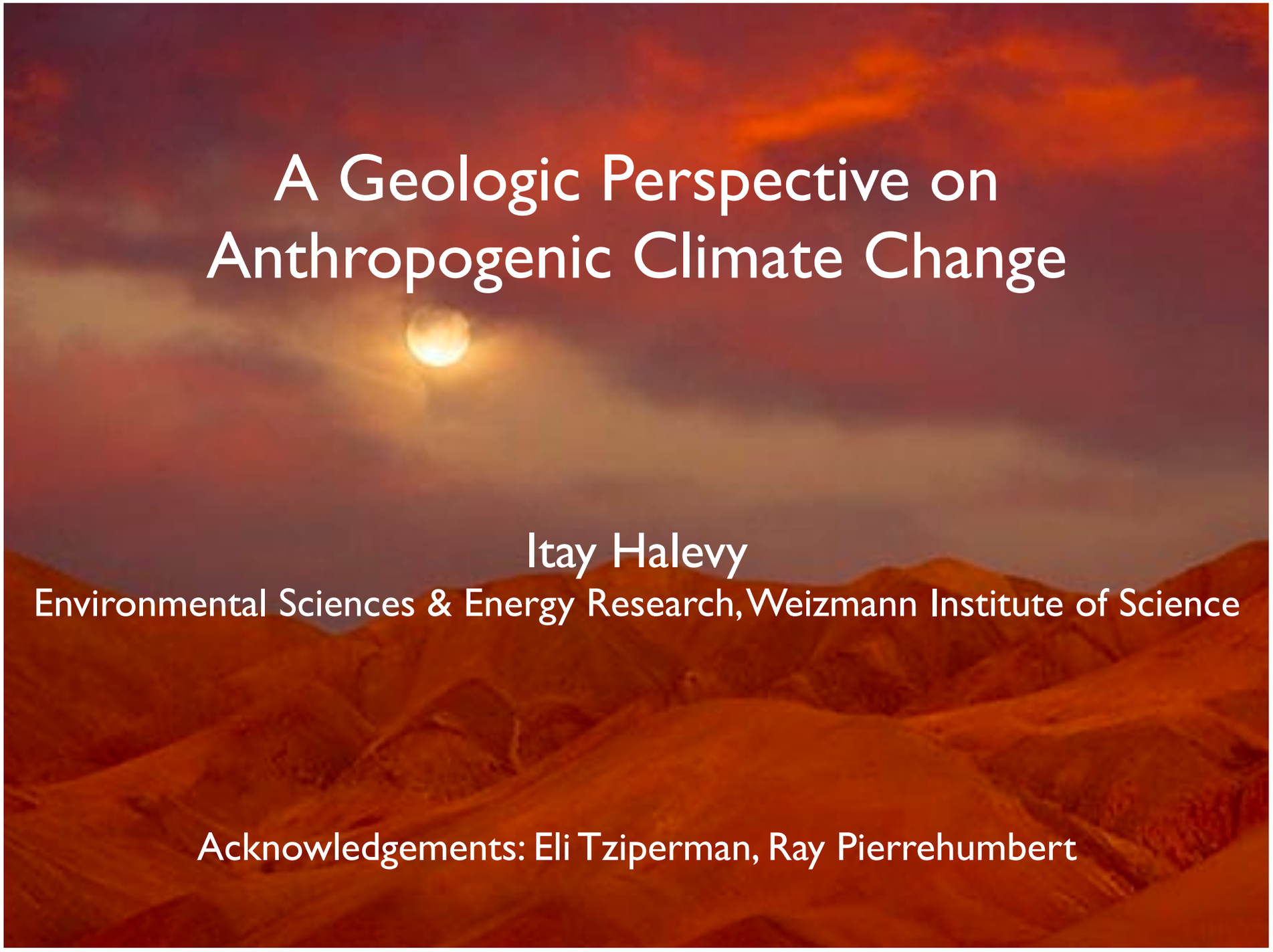


A Geologic Perspective on Anthropogenic Climate Change

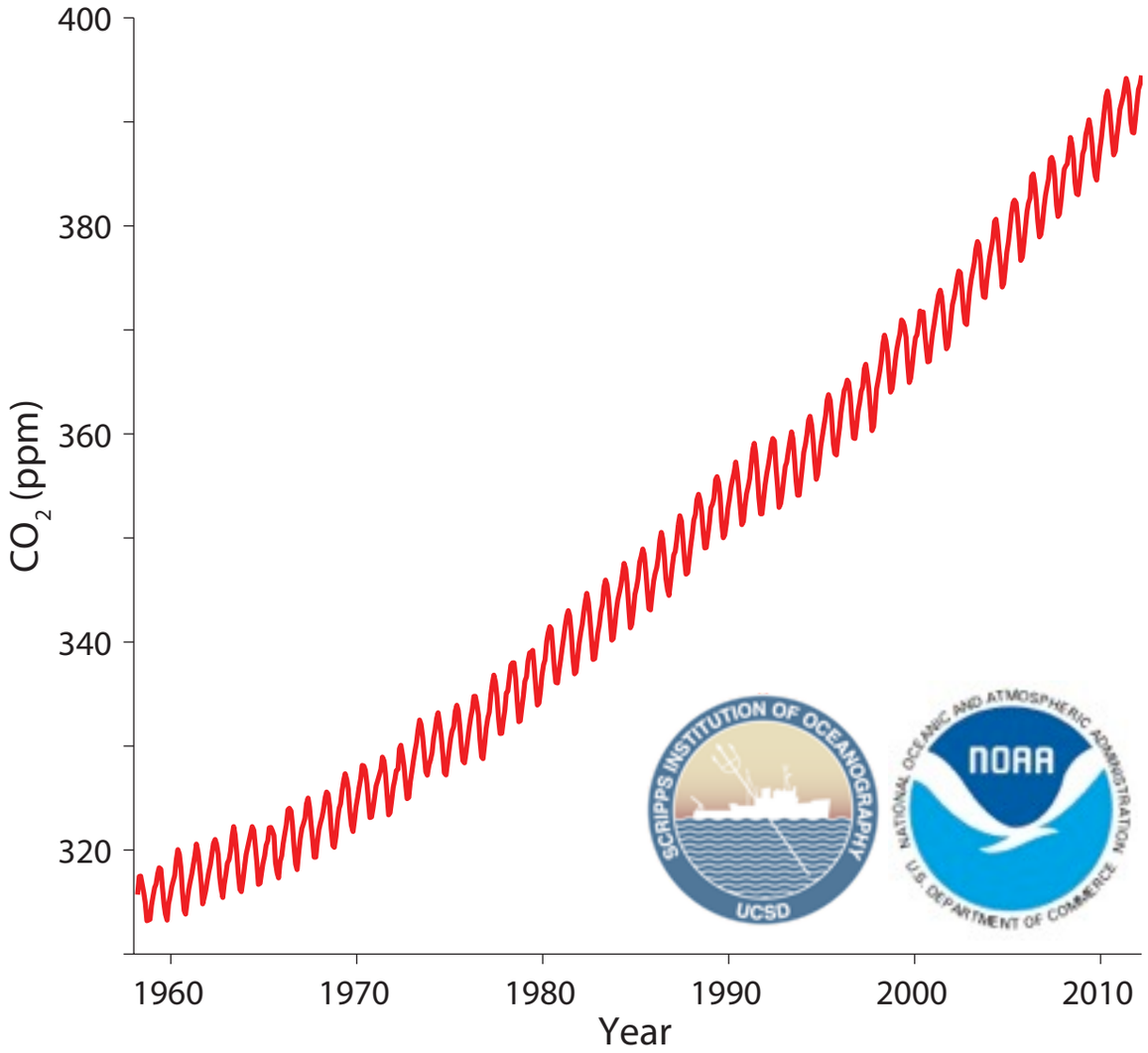
Itay Halevy
Environmental Sciences & Energy Research, Weizmann Institute of Science

Acknowledgements: Eli Tziperman, Ray Pierrehumbert

AERI Seminar
April 29, 2012

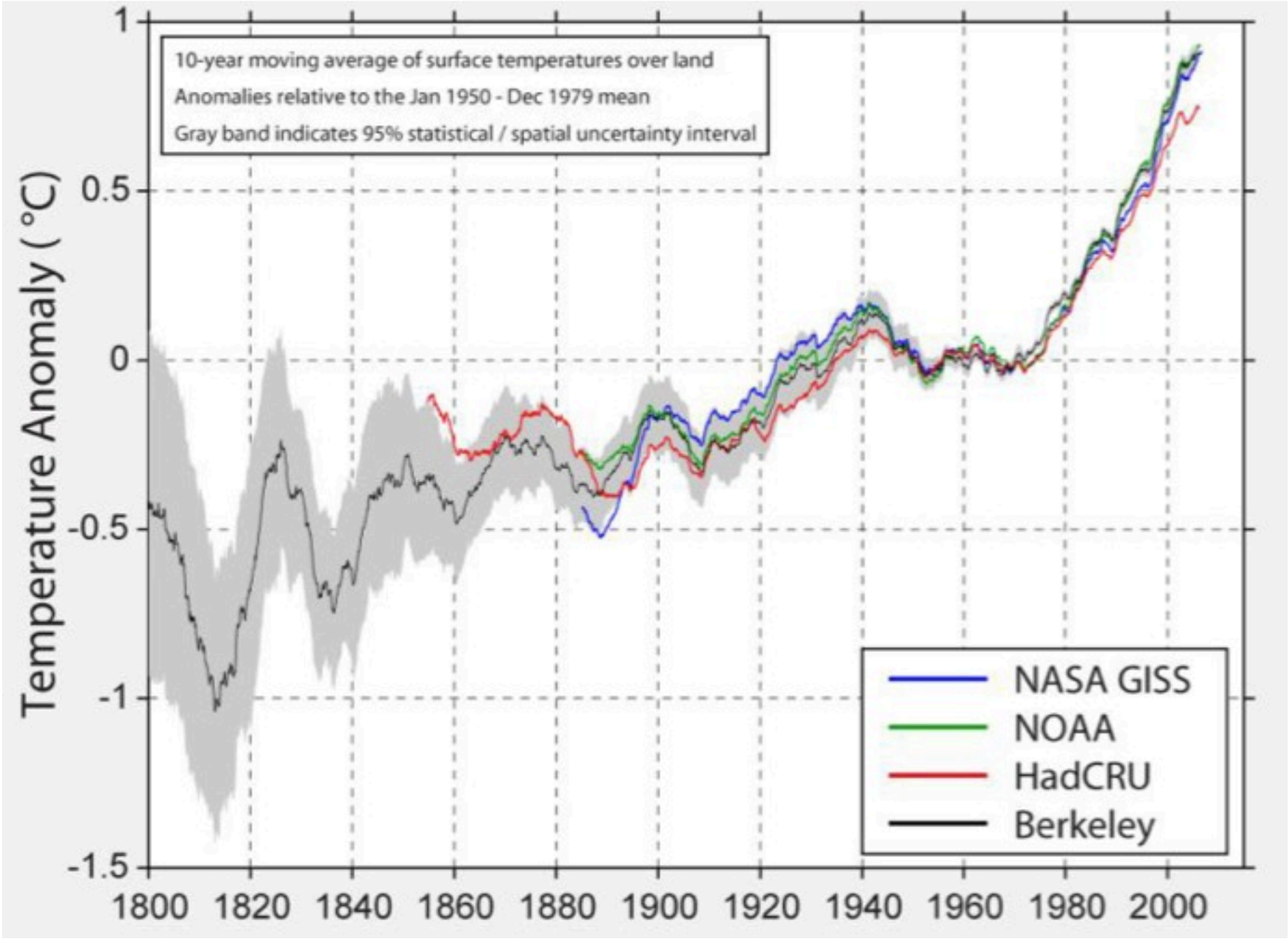
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

The rise of atmospheric CO_2



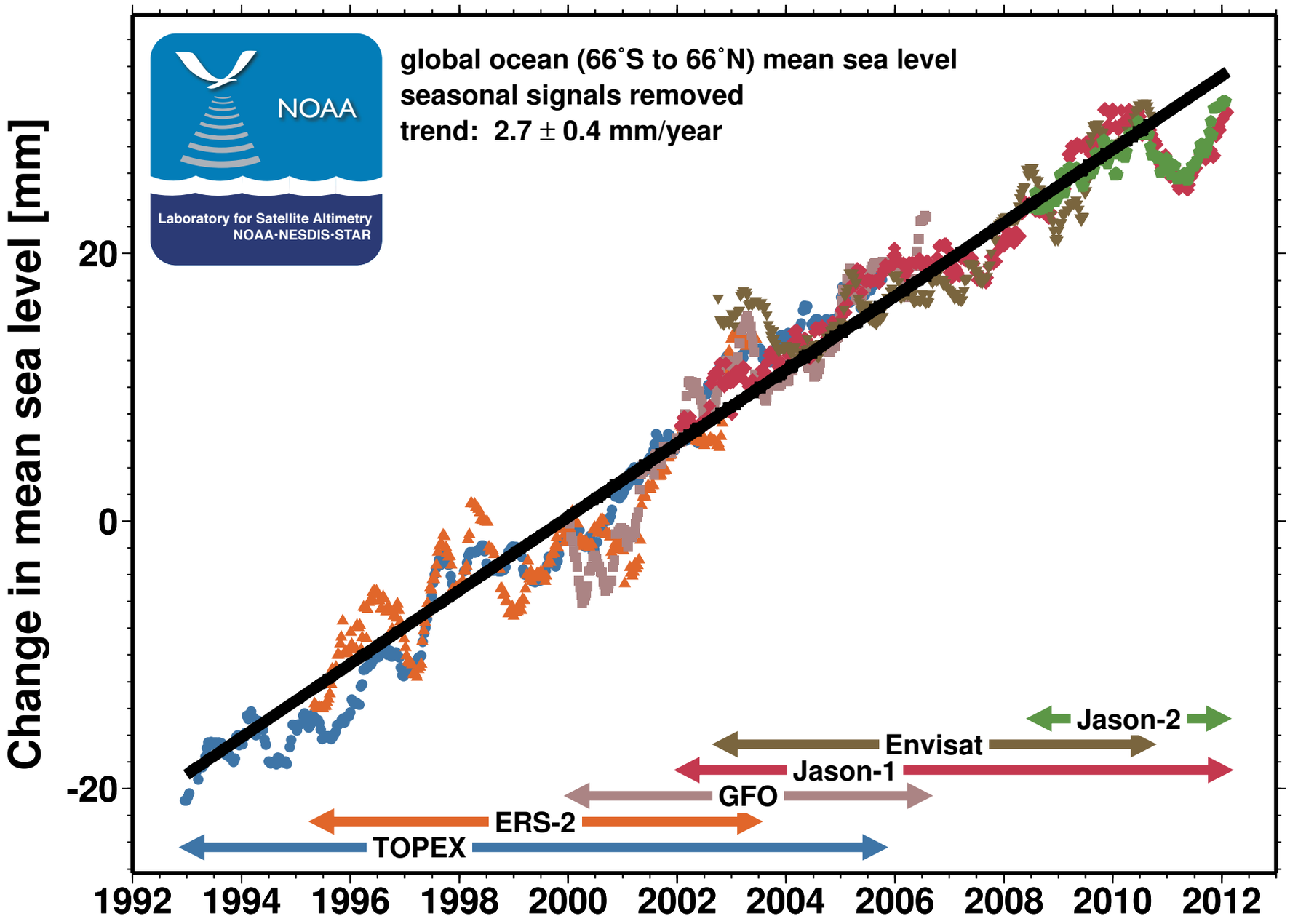
Charles (Dave) and Ralph Keeling (1989)

The rise of surface temperature

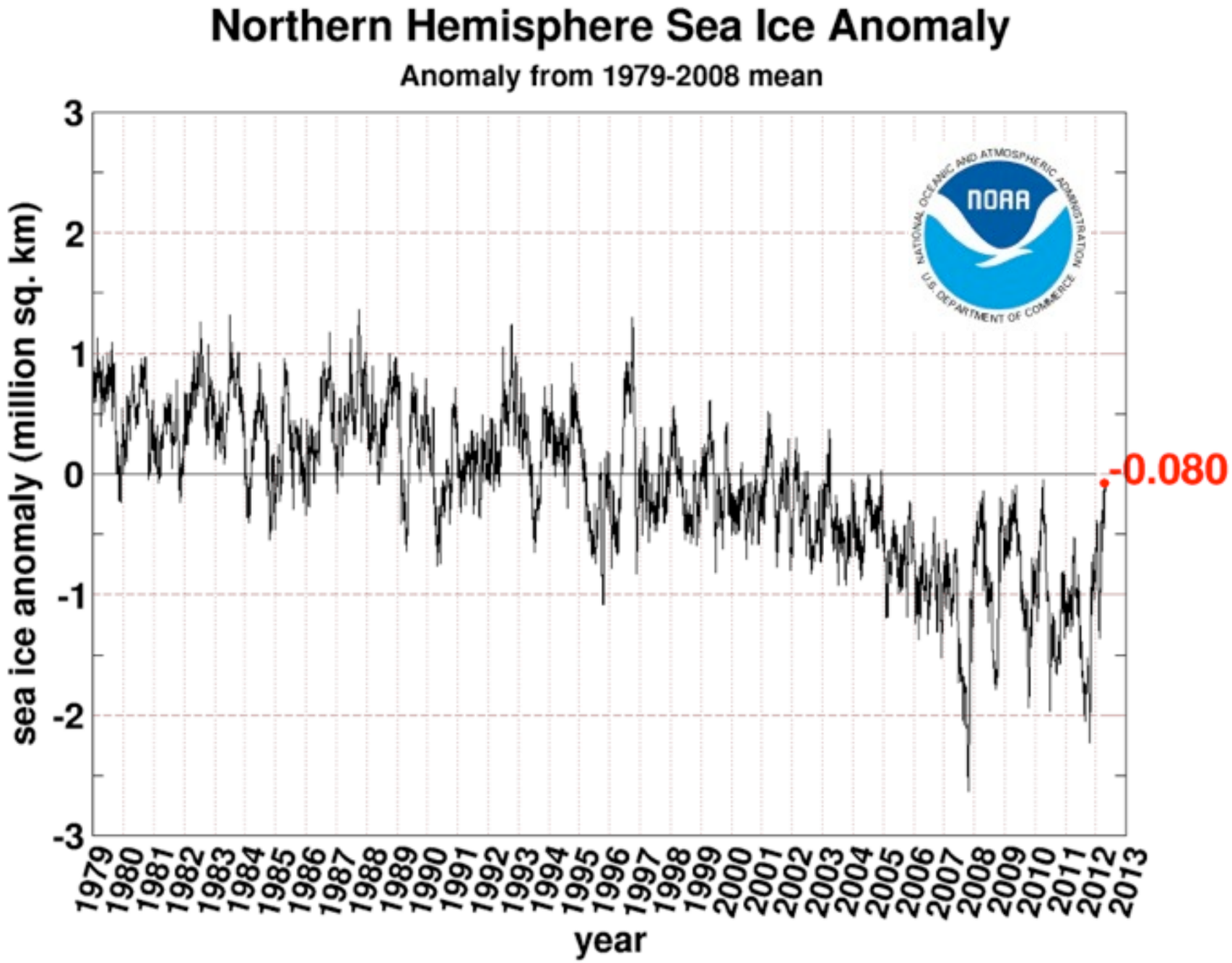


www.BerkeleyEarth.org

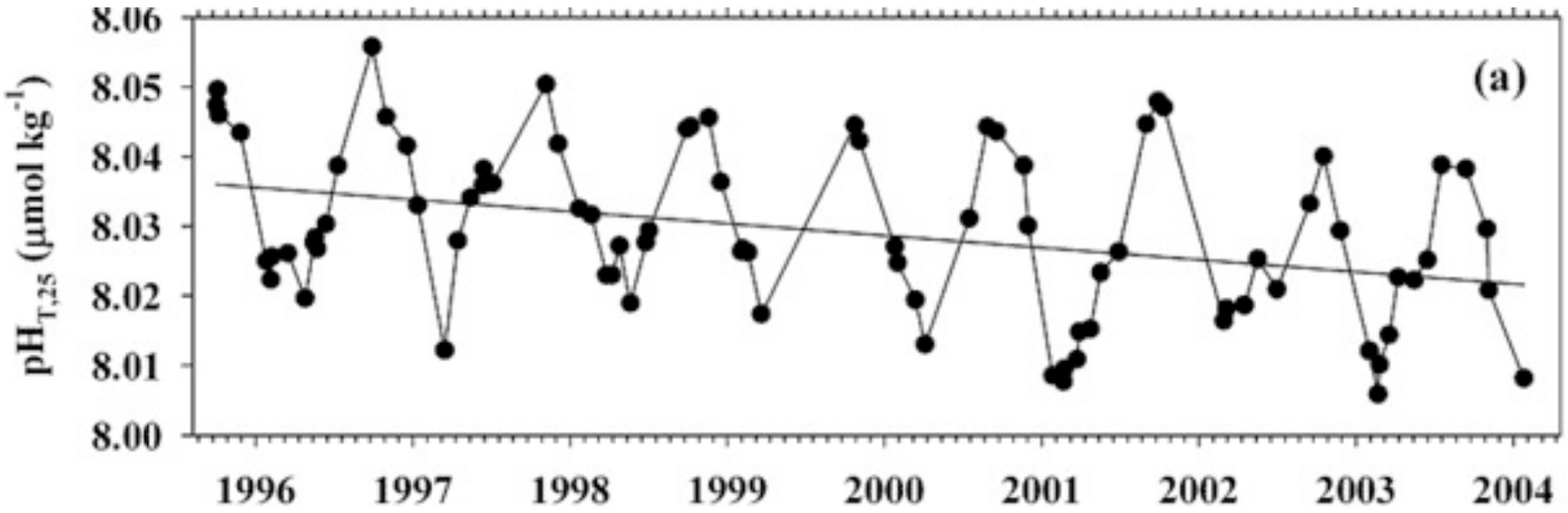
The rise of sea level



The decrease of sea ice extent

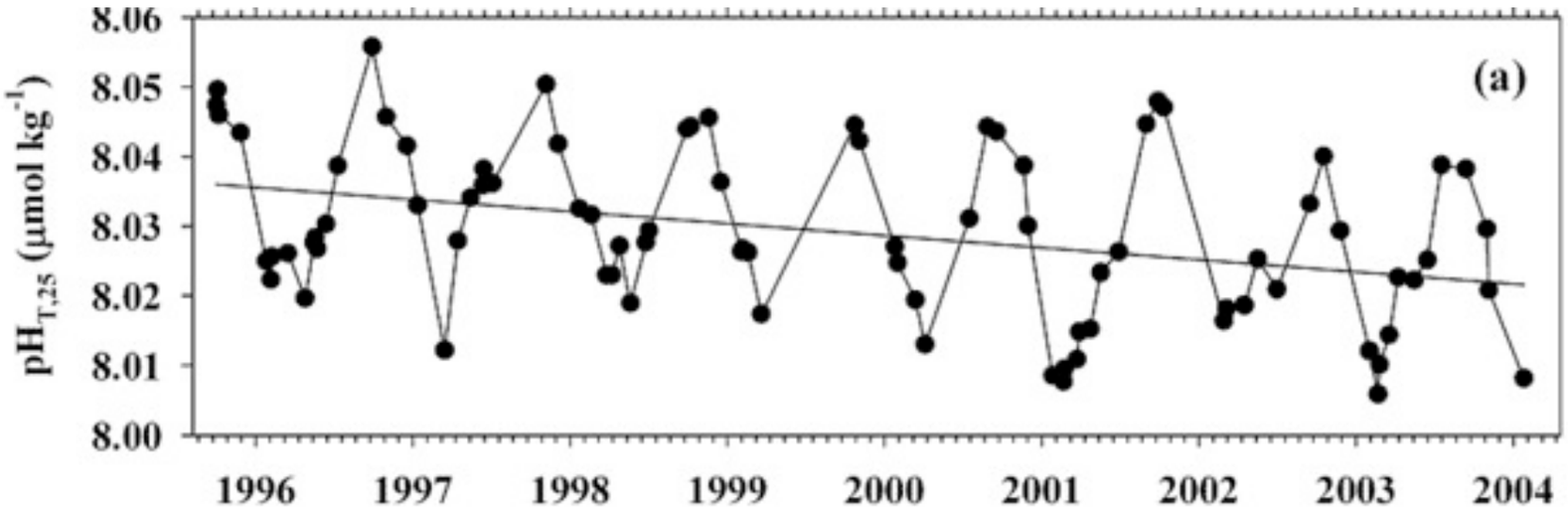


The decrease of ocean pH



Santana-Casiano *et al.*, *Global Biogeochemical Cycles*, 2007

The decrease of ocean pH



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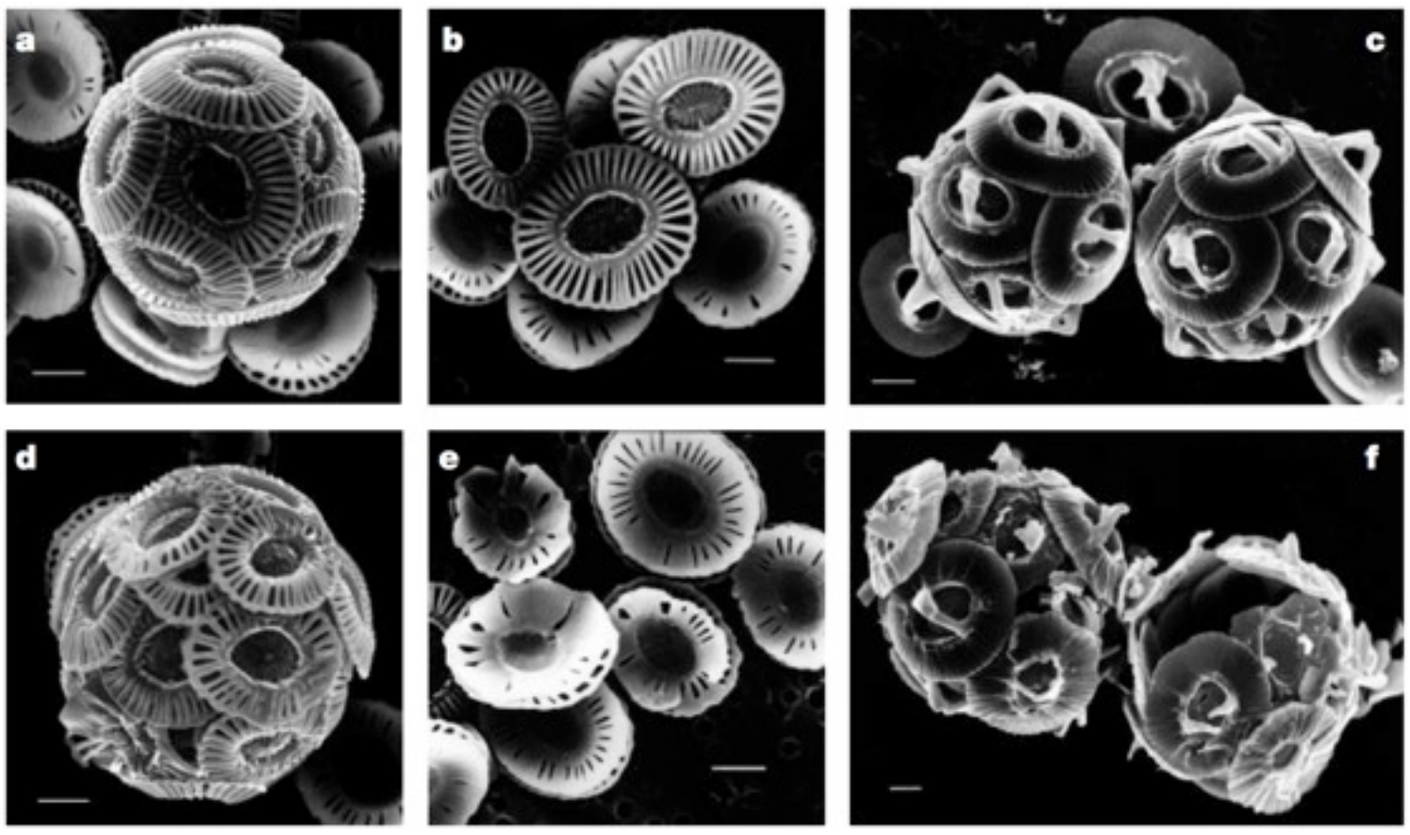
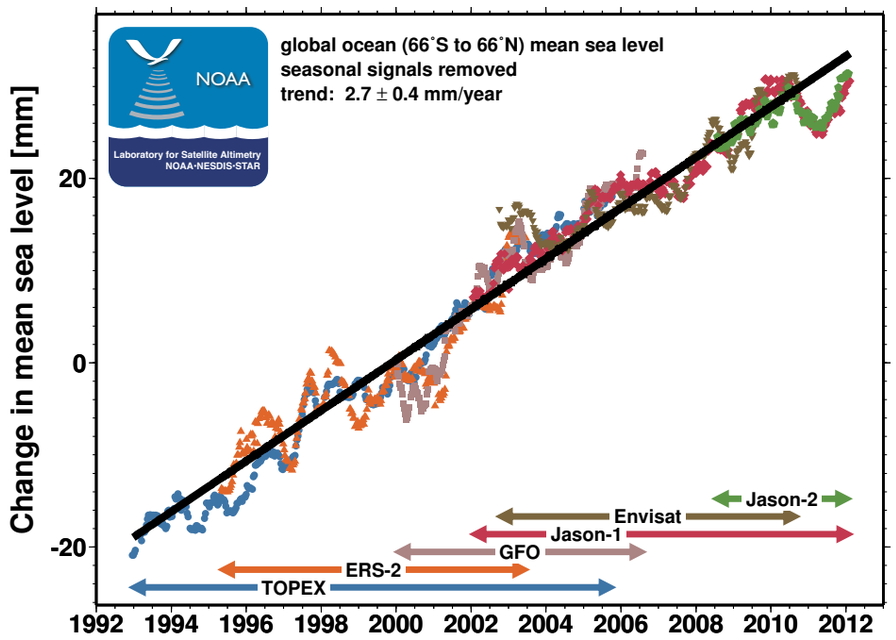
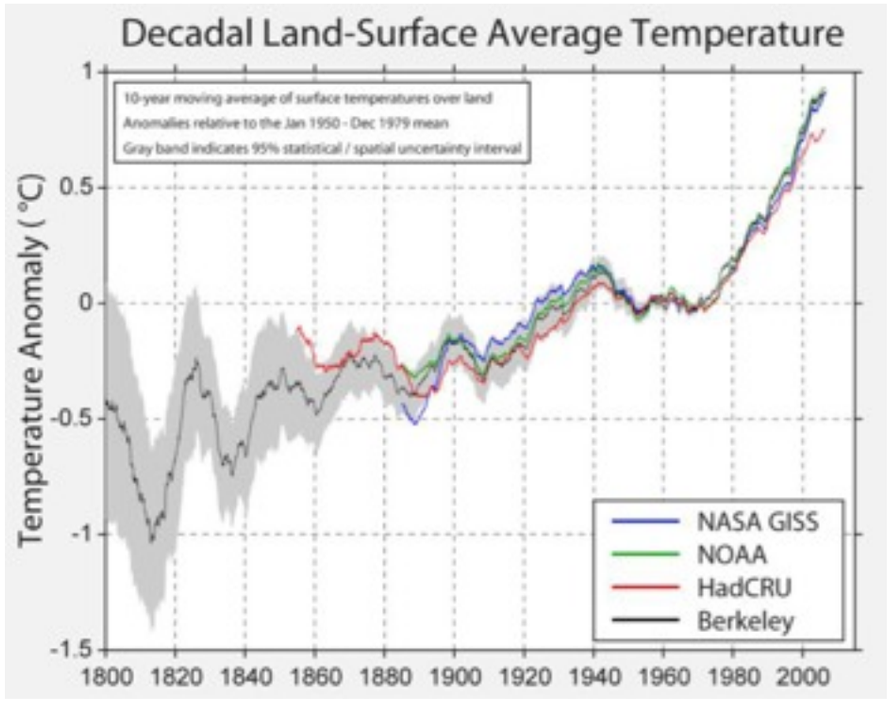
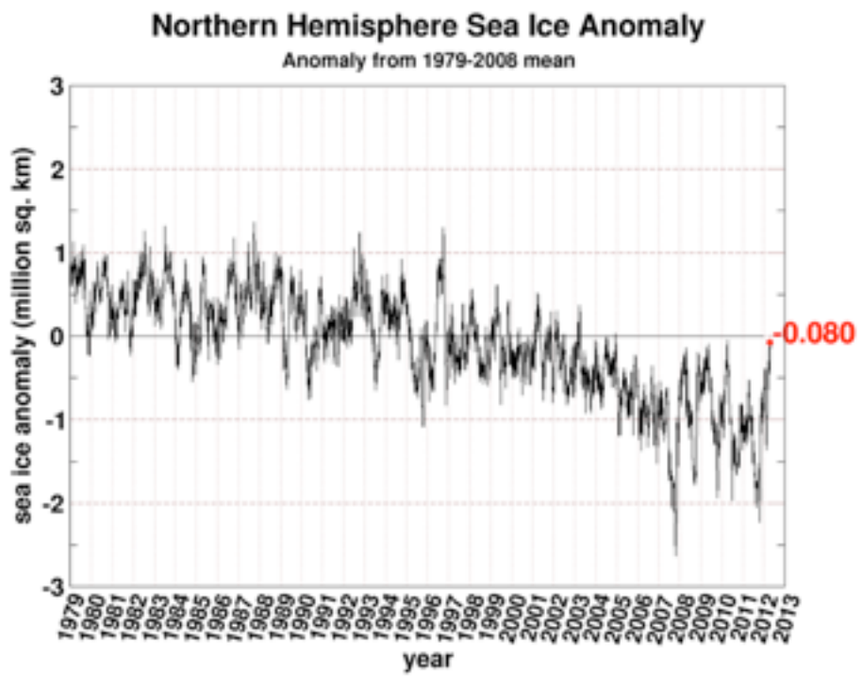


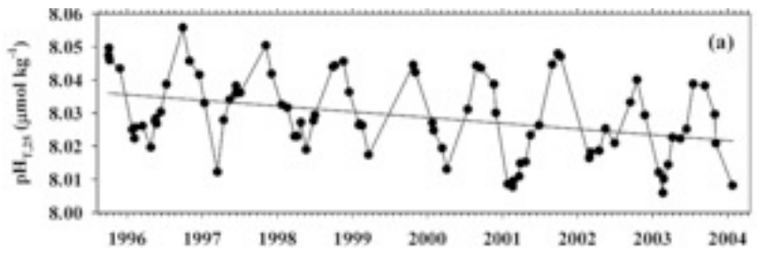
Riebesell *et al.*, *Nature*, 2000

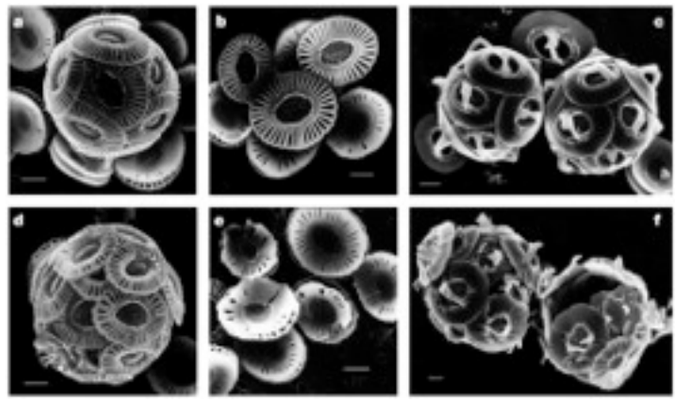
How is CO_2 responsible for all of this?



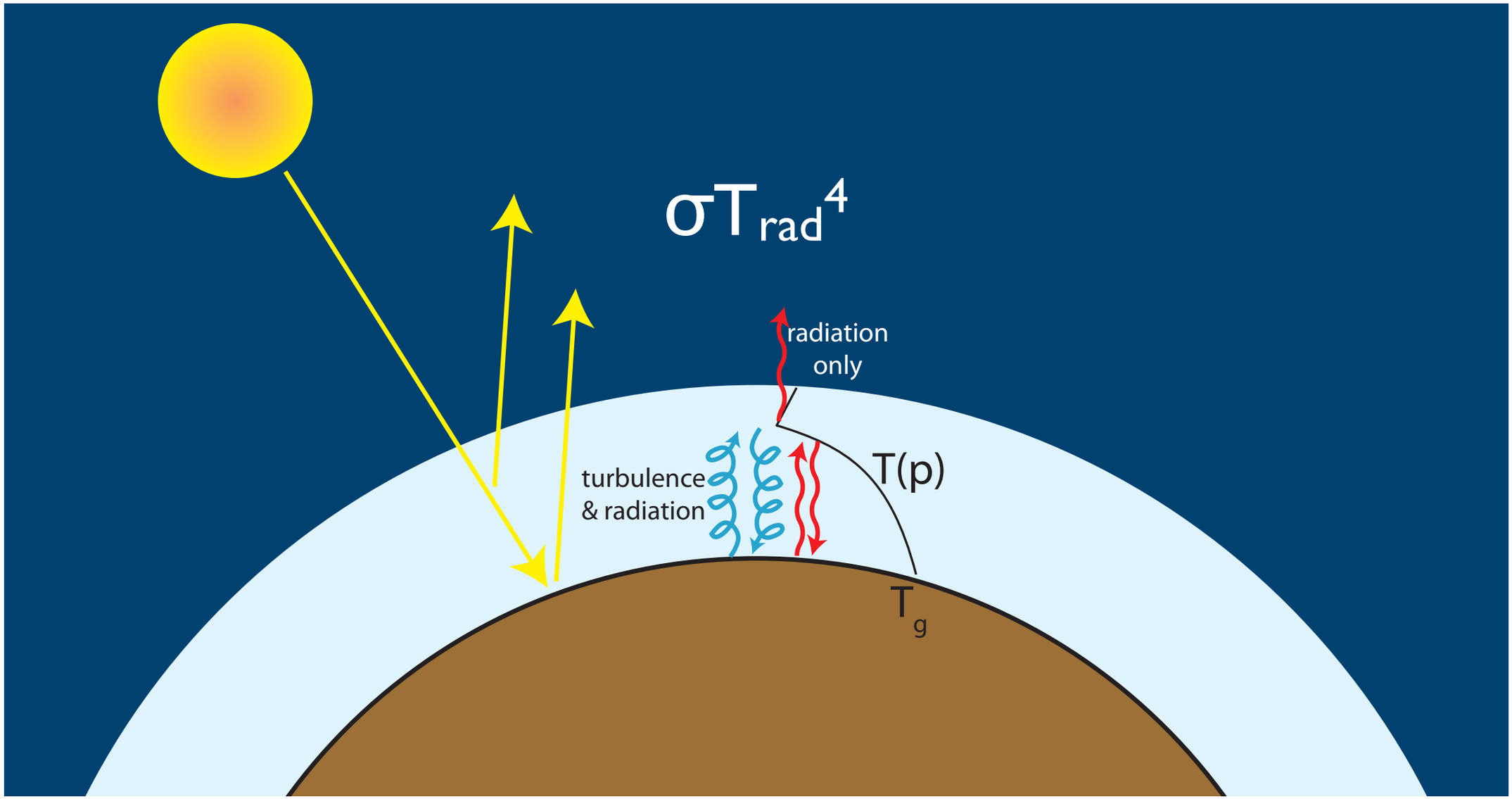








The planetary energy budget



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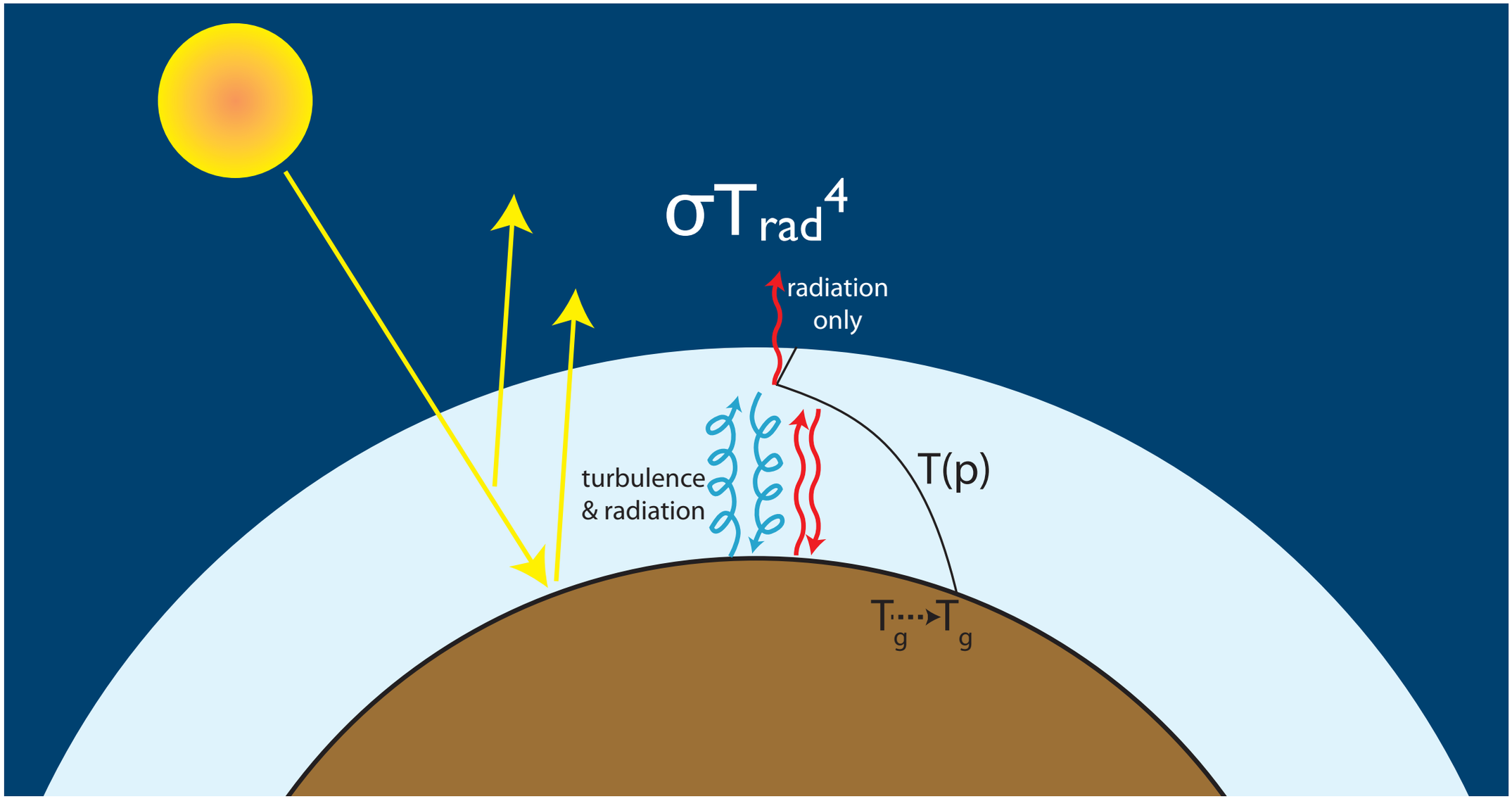
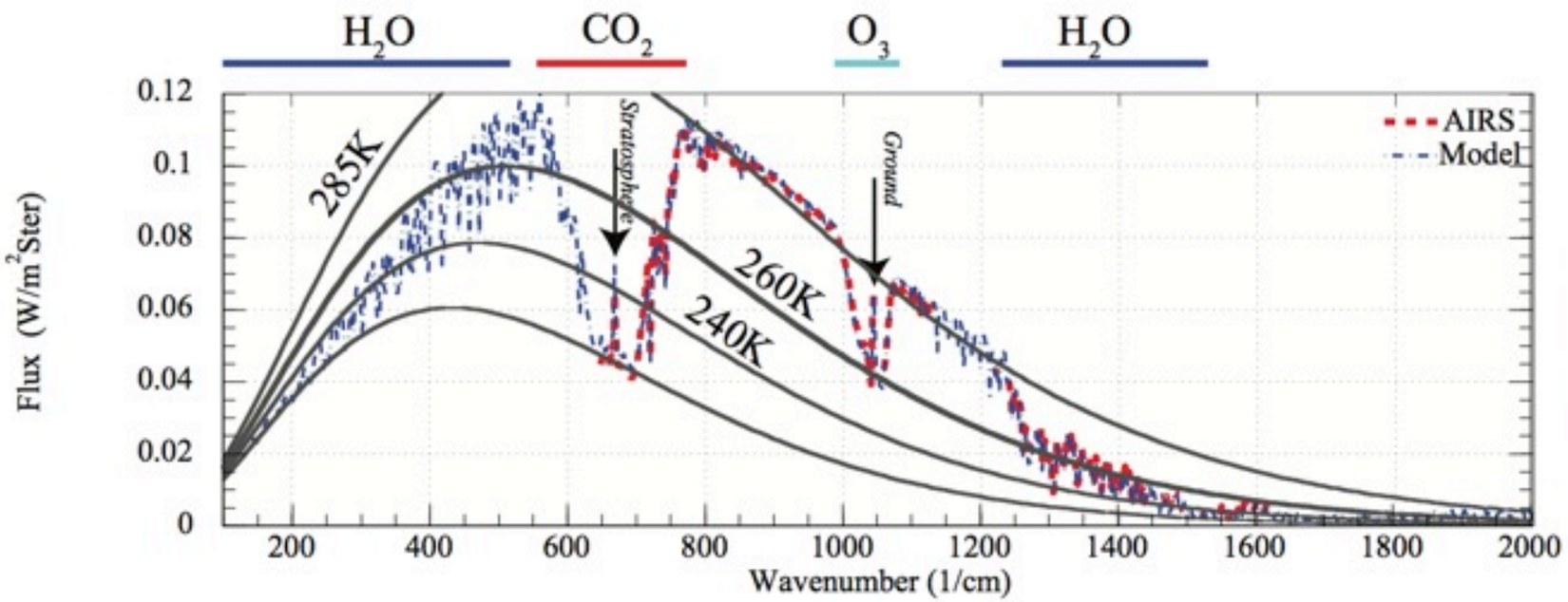
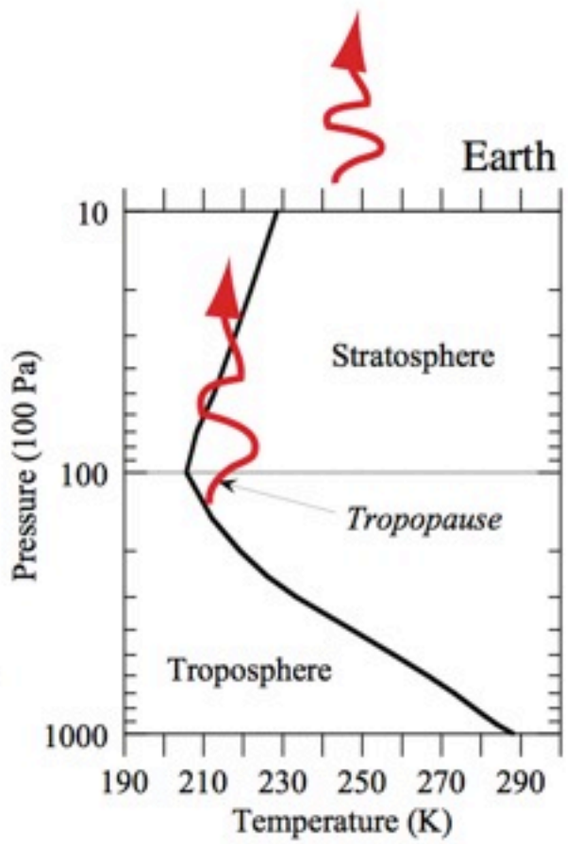


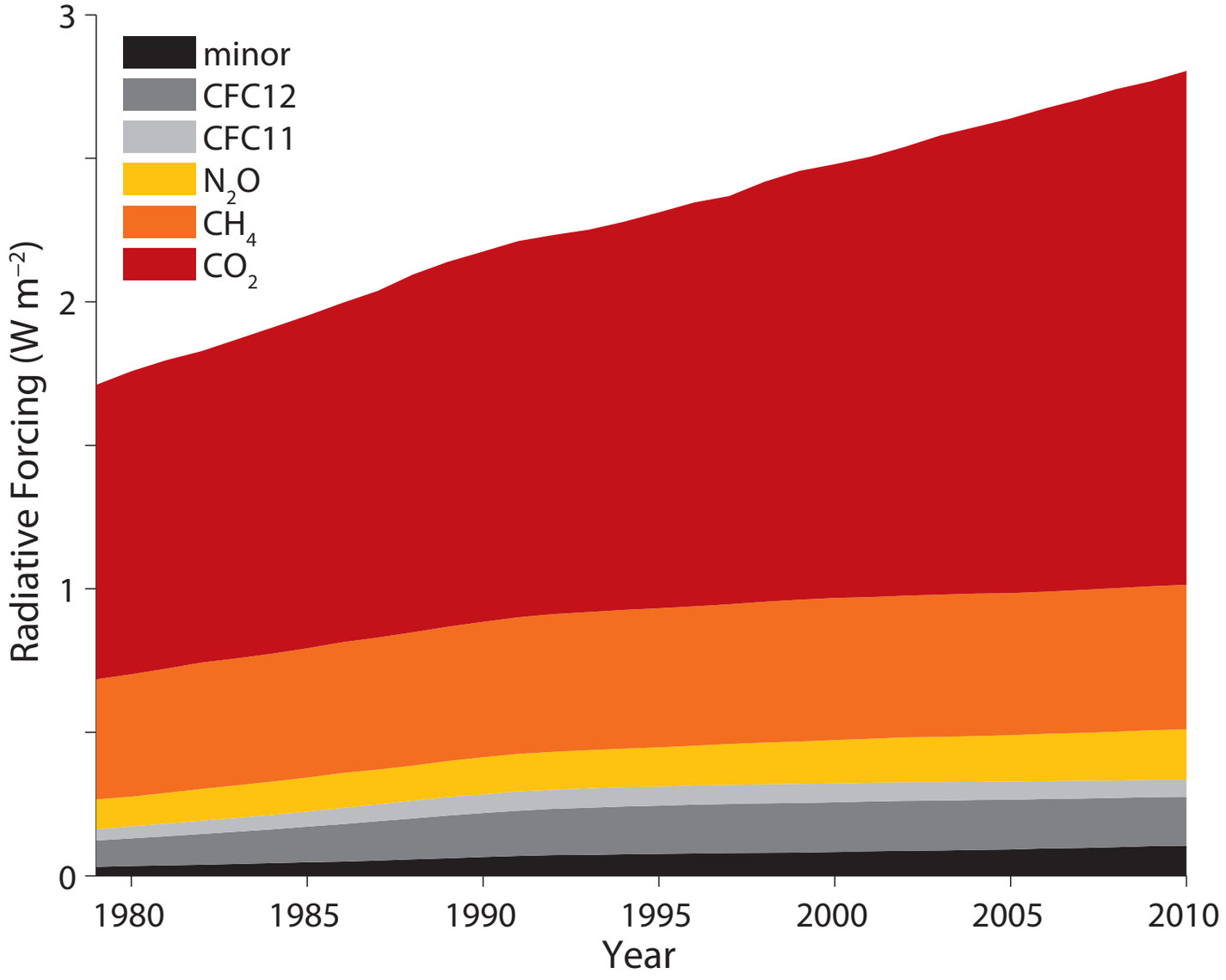
Greenhouse from space





Courtesy of Ray Pierrehumbert, U. Chicago

CO_2 is not the only culprit



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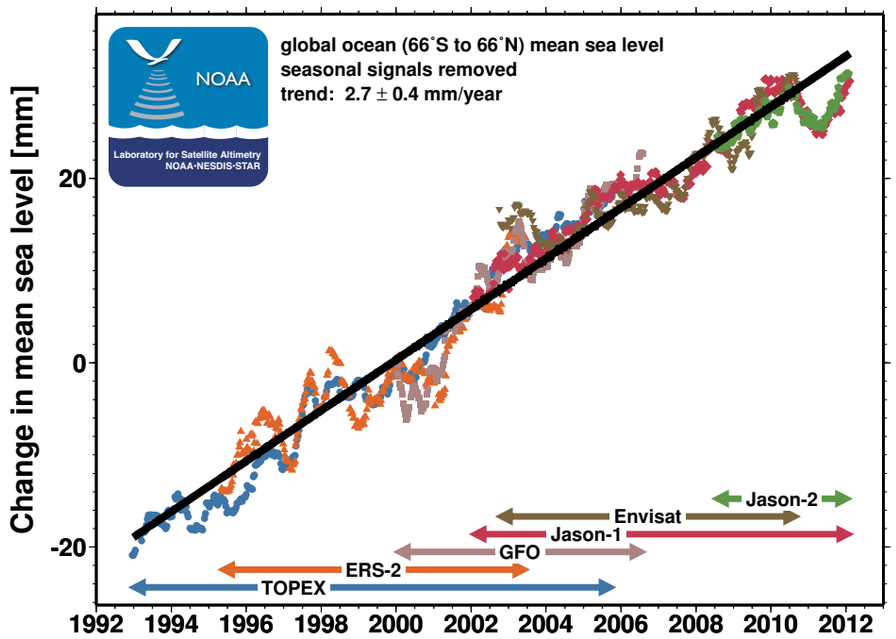
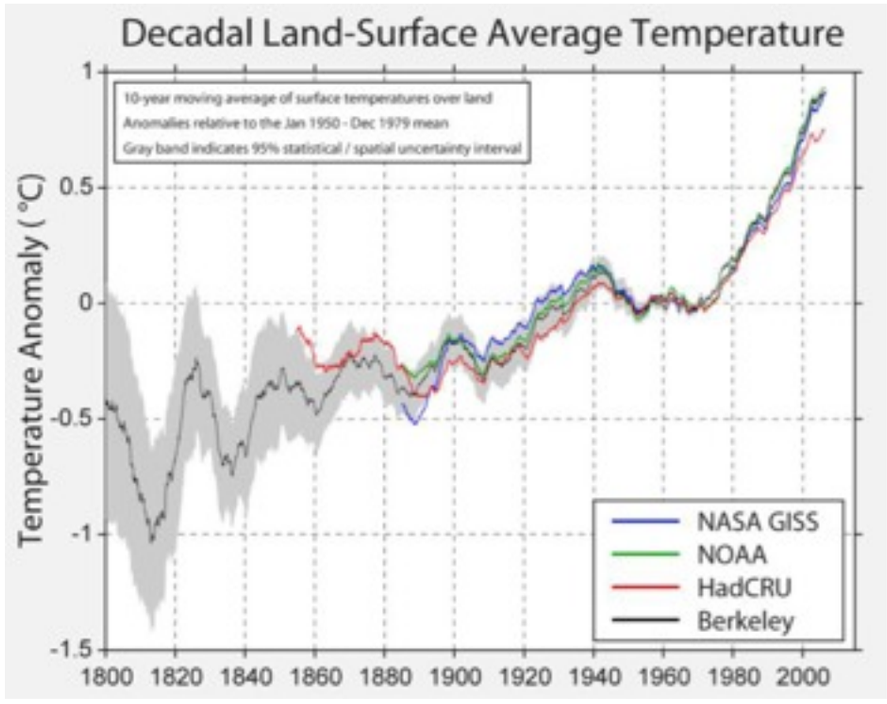
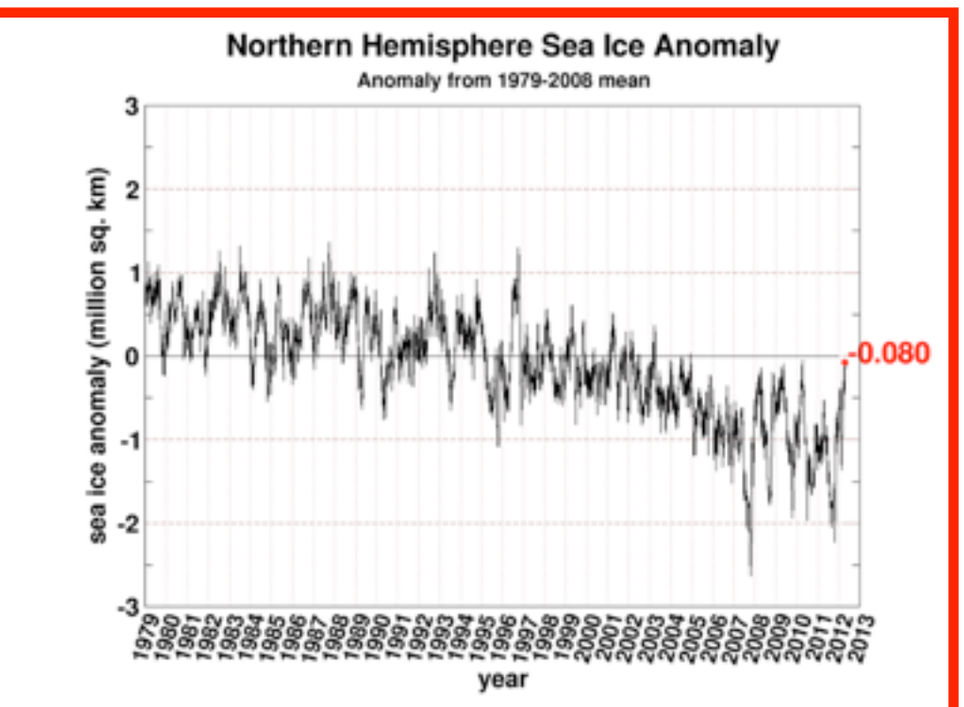
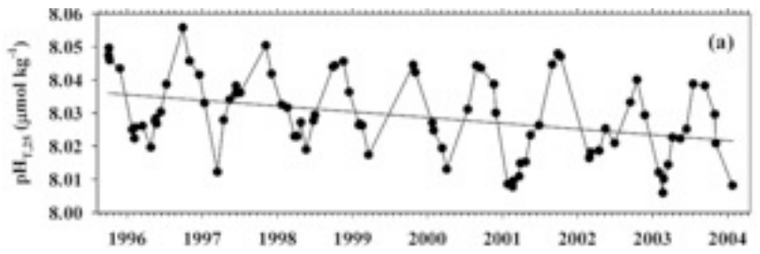
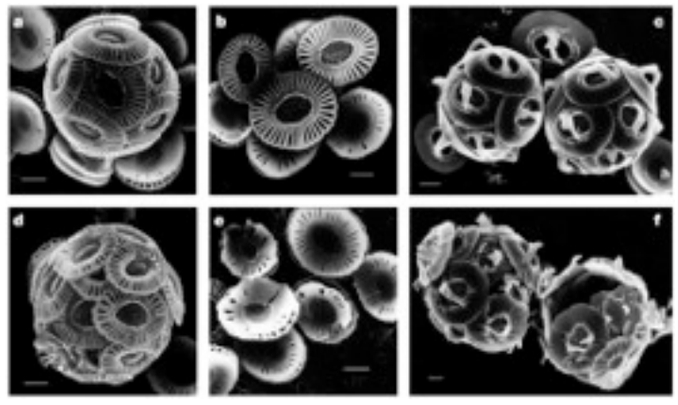


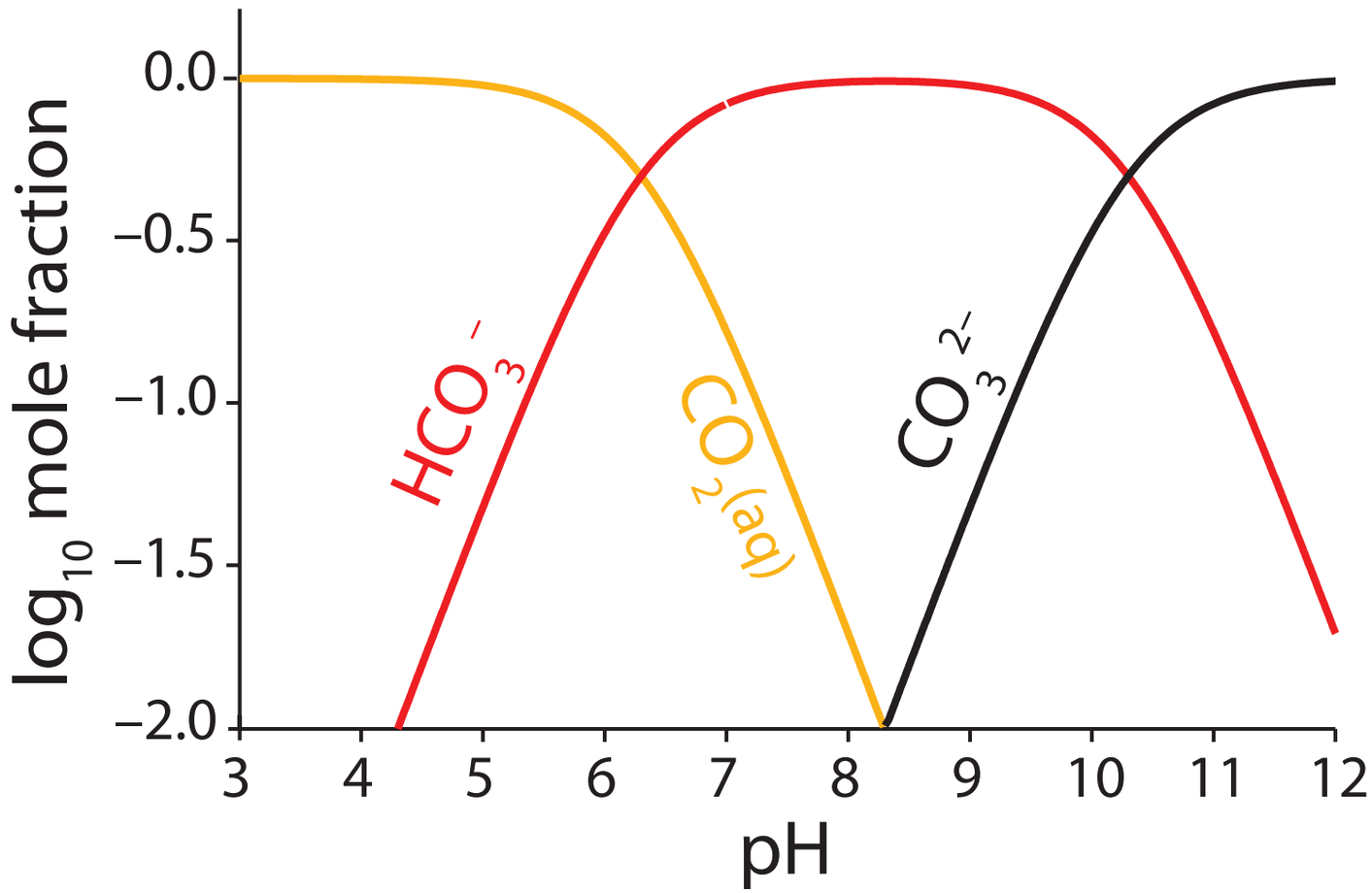








CO_2 and ocean acidification



$$CO_{2(g)} \rightleftharpoons CO_{2(aq)} \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + 2H^+$$

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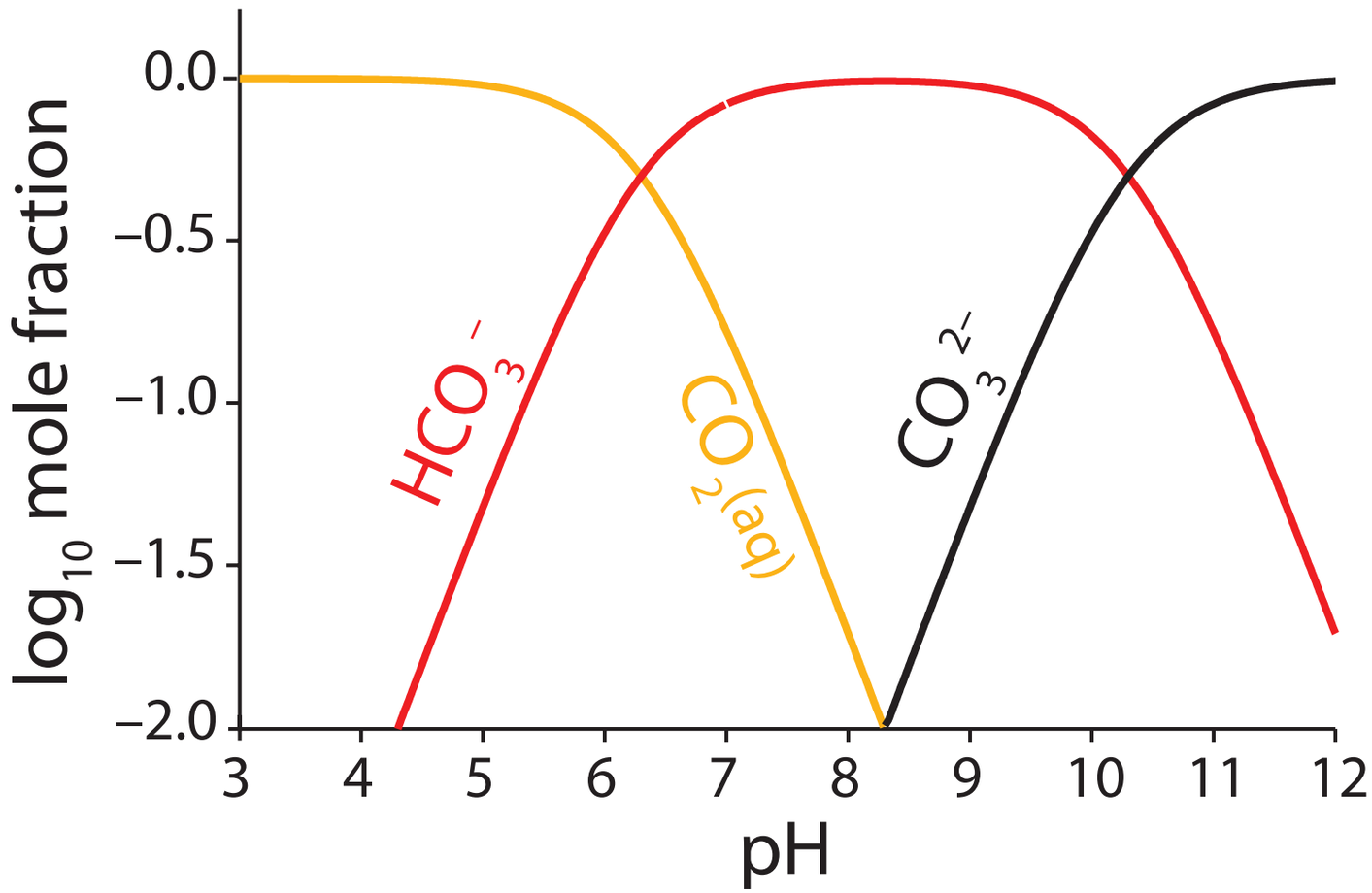

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$pCO_2 \uparrow$

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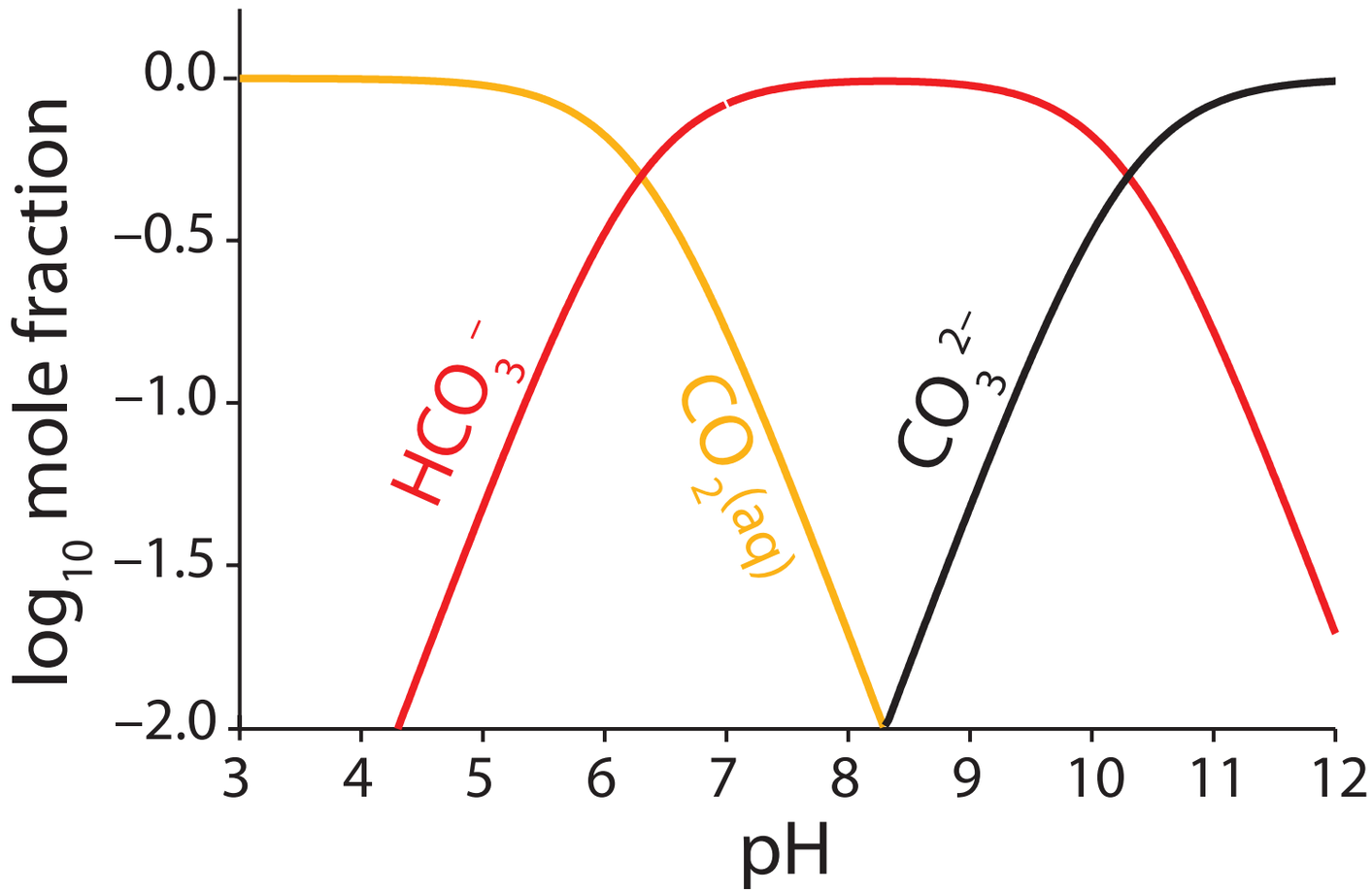

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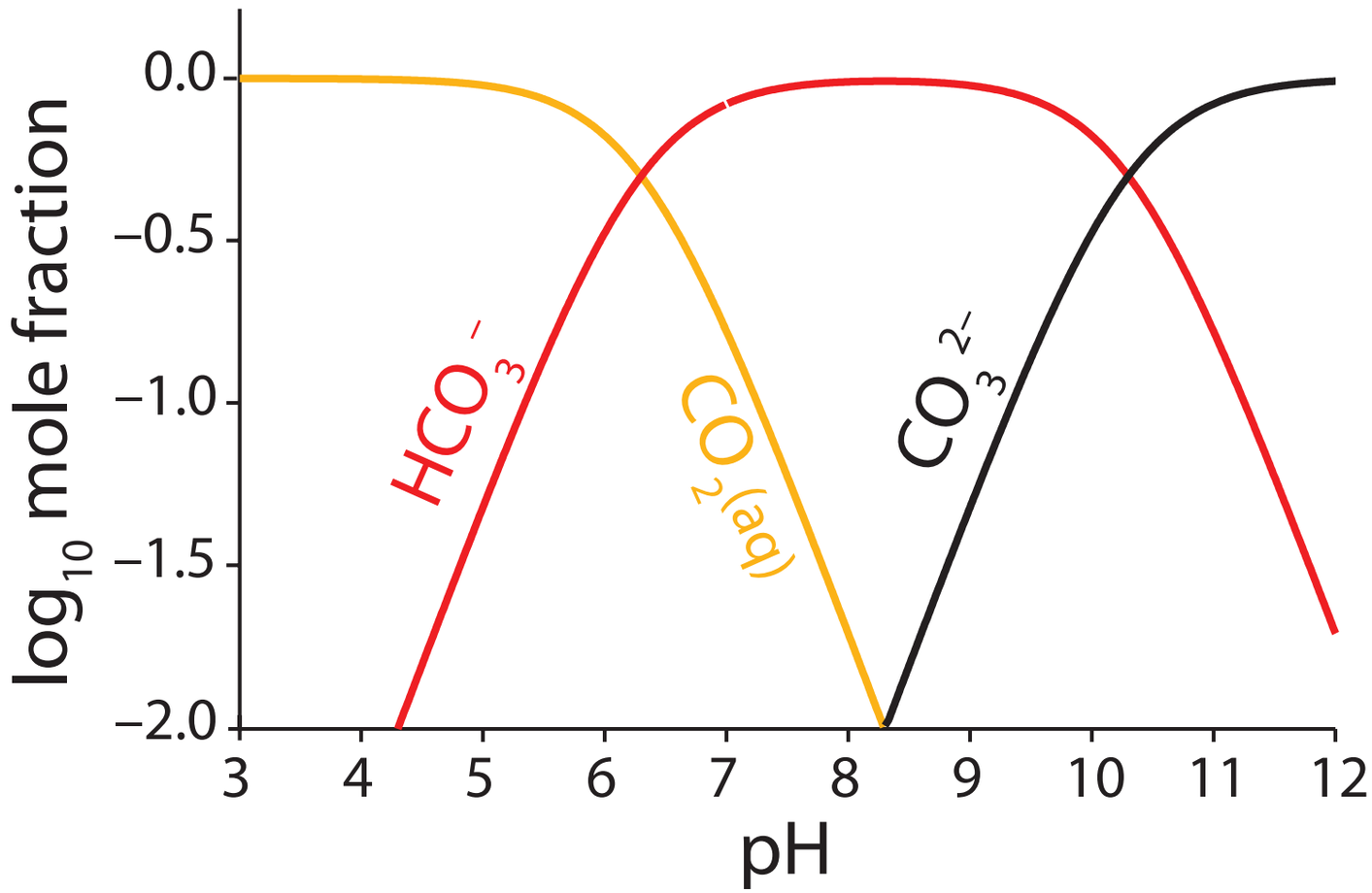

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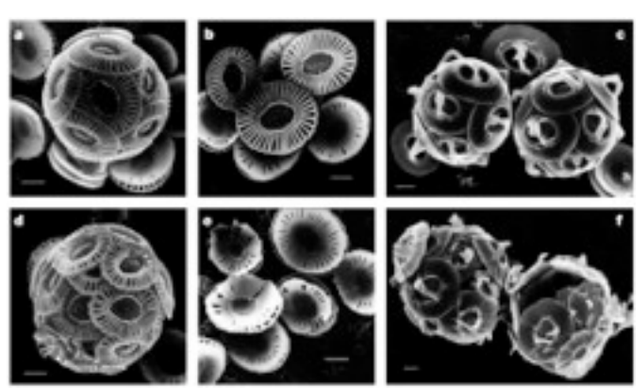
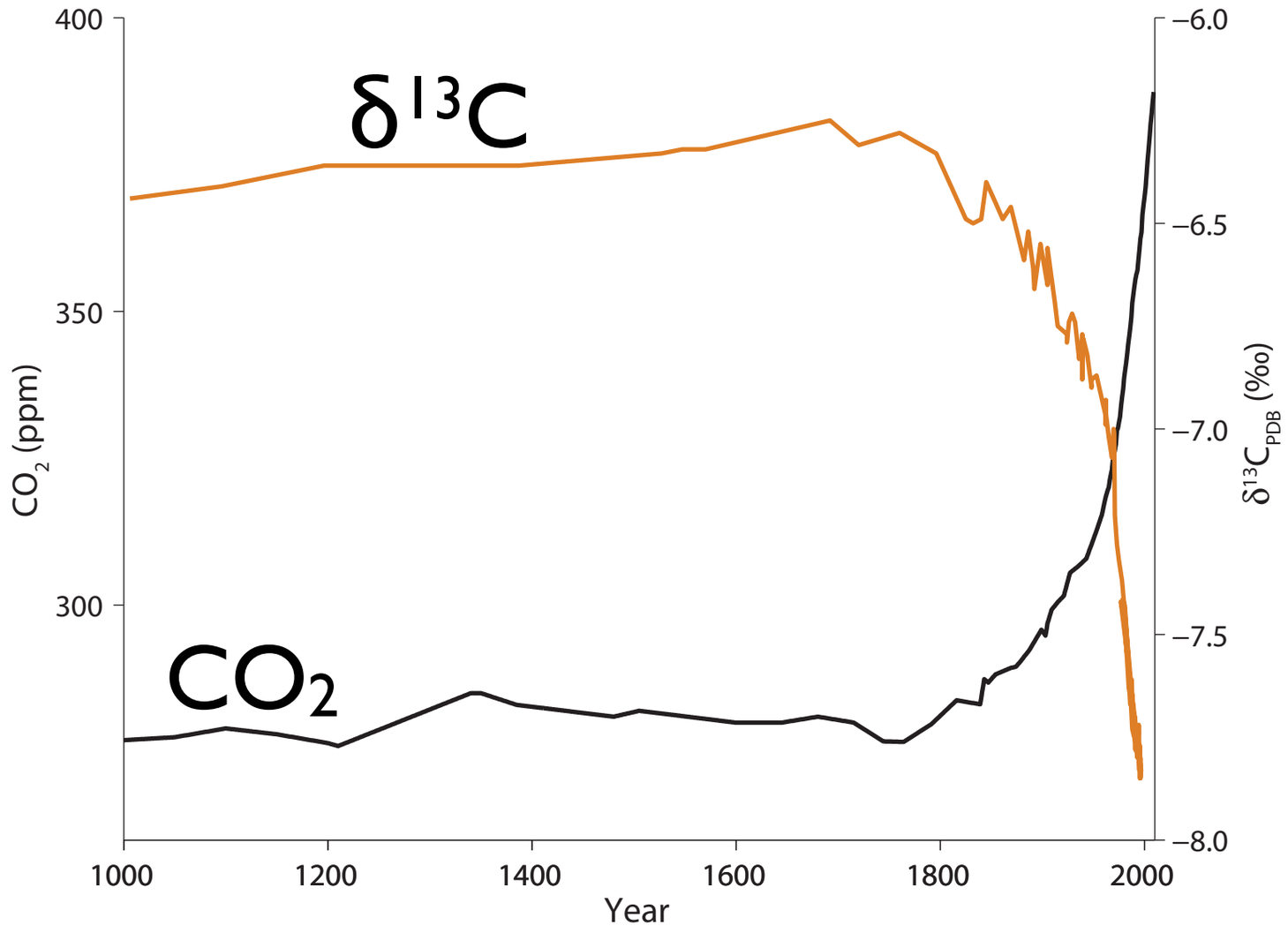


Fossil fuel burning is implicated



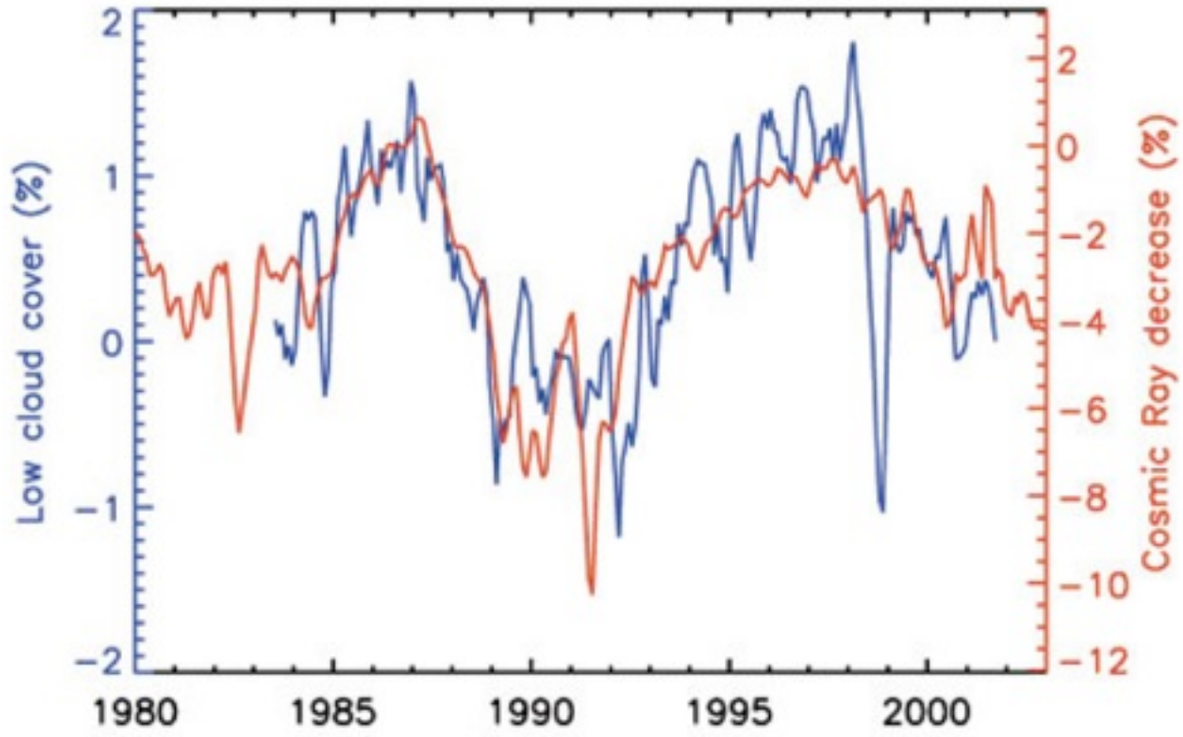
$$\delta^{13}C\ (‰) = [(^{13}C/^{12}C)_s/(^{13}C/^{12}C)_r - 1]\times 1000$$

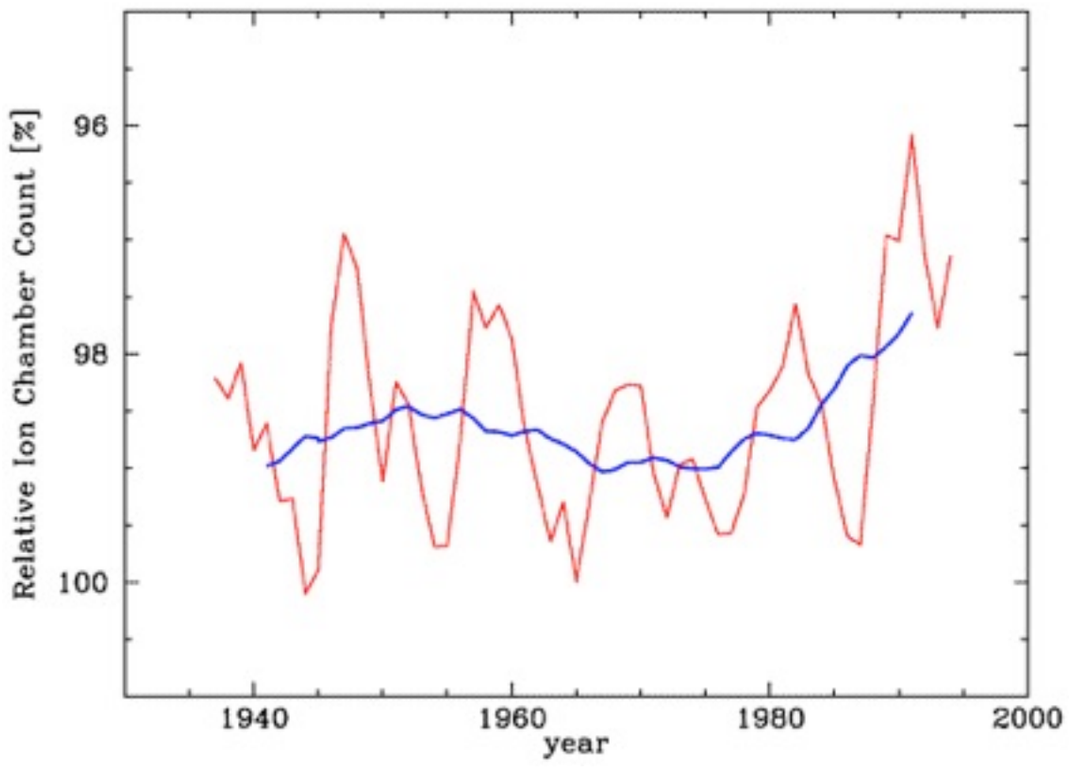
Cosmic rays as an explanation?

- **Hypothesis**: An active solar magnetic field shields Earth from cosmic rays, causes less tropospheric ionization, generation of fewer condensation nuclei and warming.
  Question: Are these simply covarying time series that are being affected by the same cause (sun spot activity)?

- **Evidence**: 20th century warming looks like the cosmic ray record with the 11 year cycle averaged out.

From Nir Shaviv's webpage





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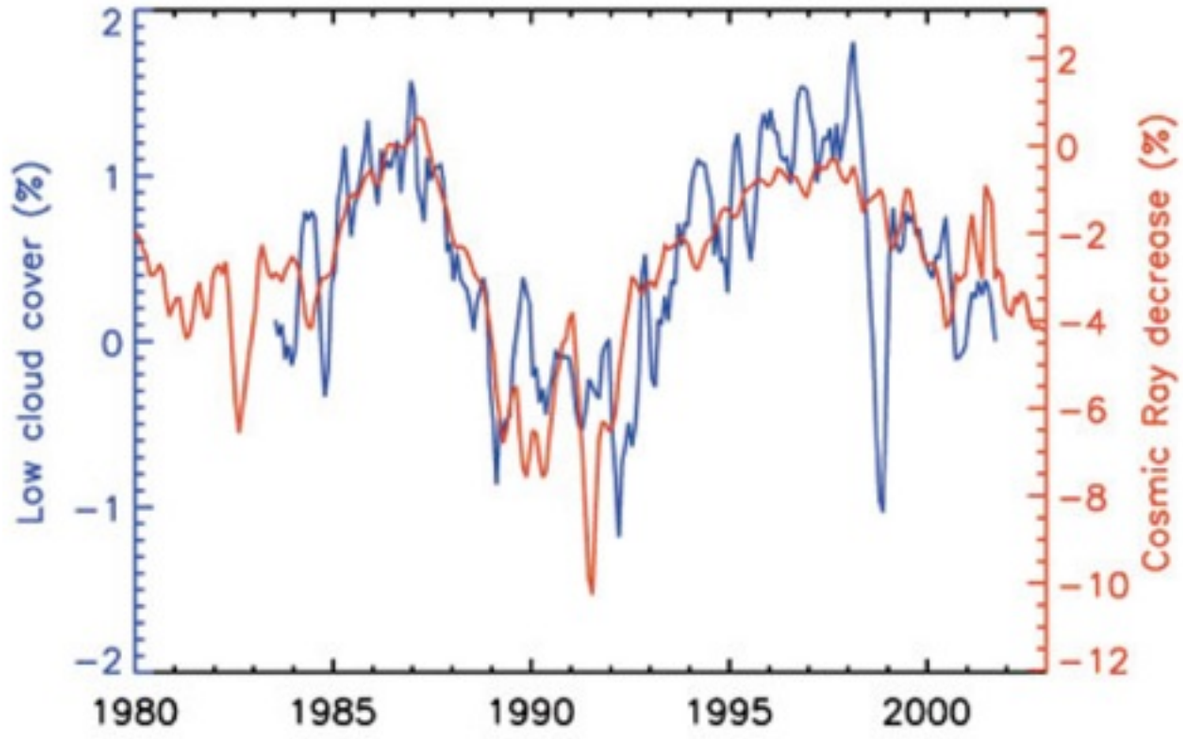

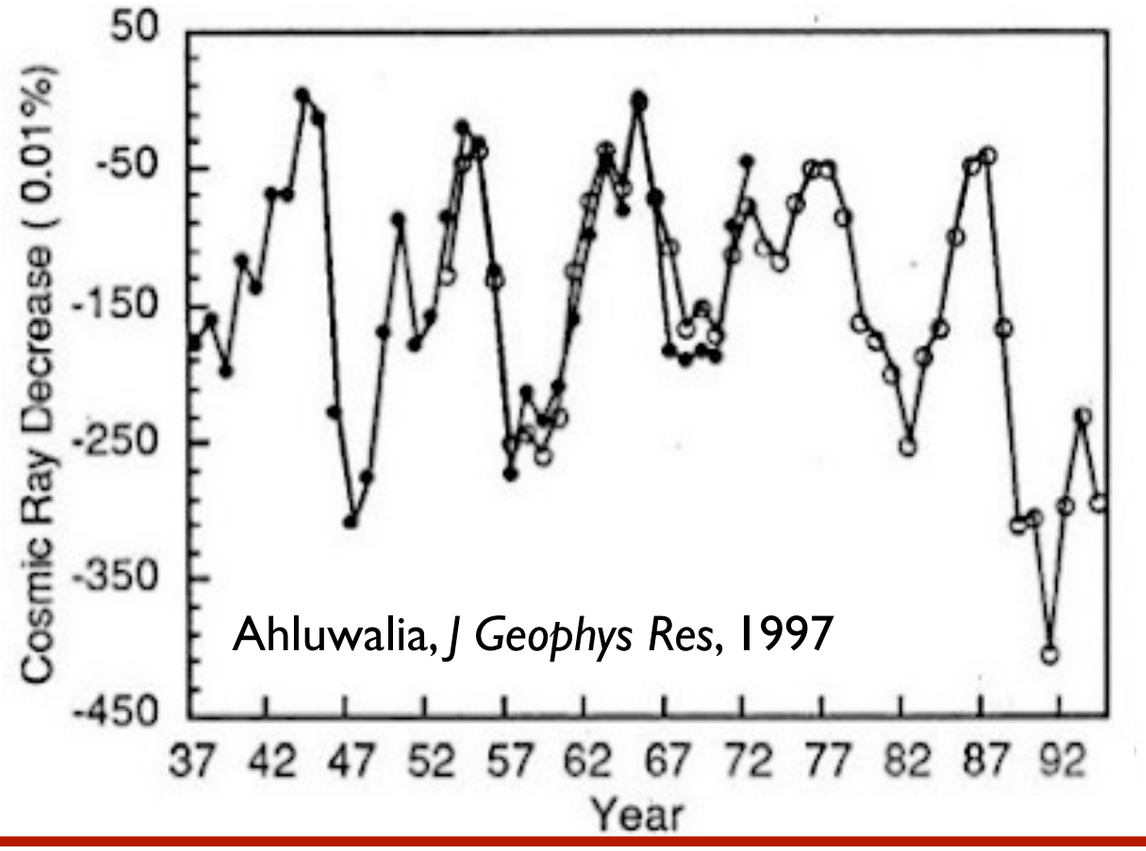

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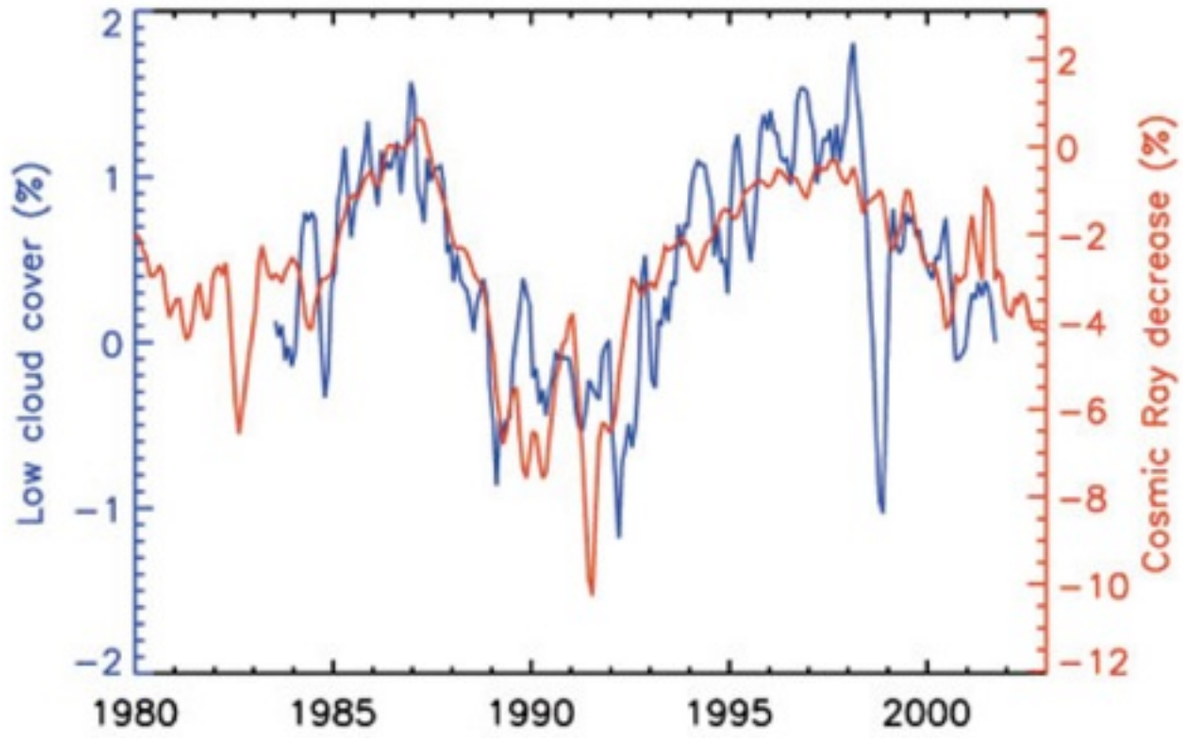

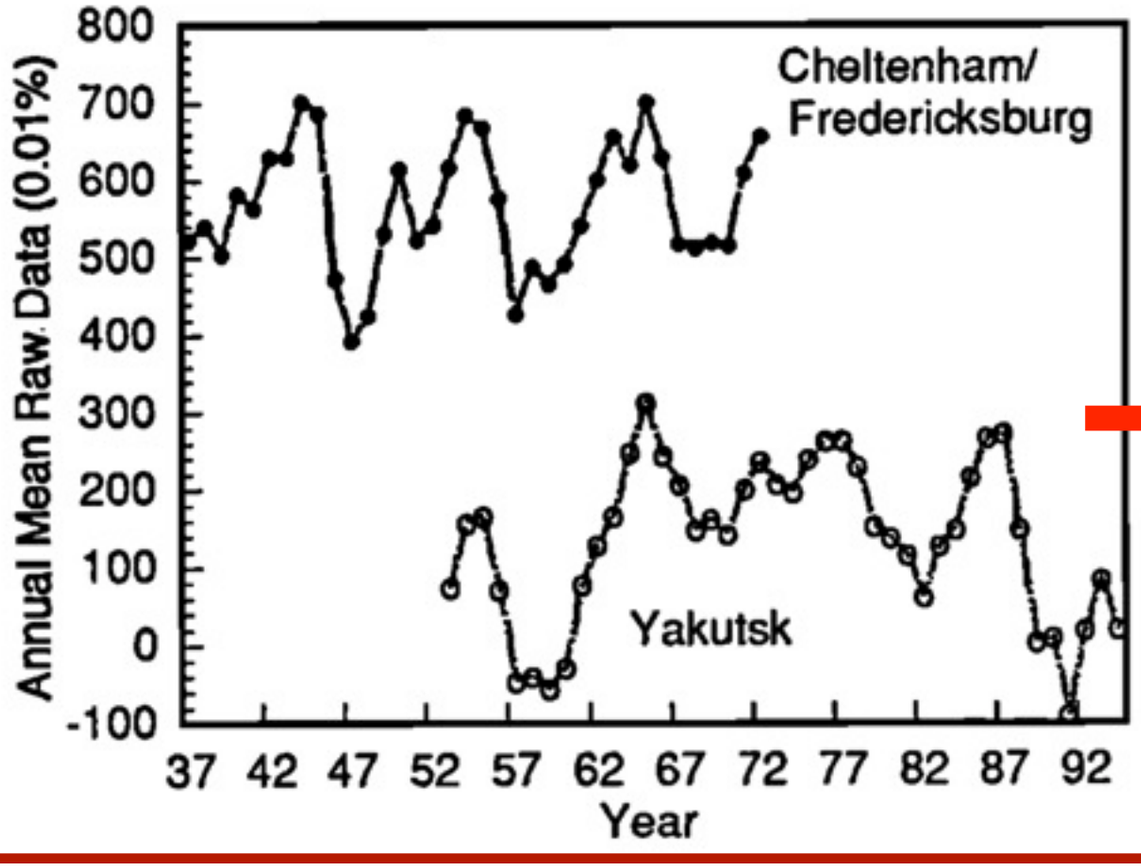

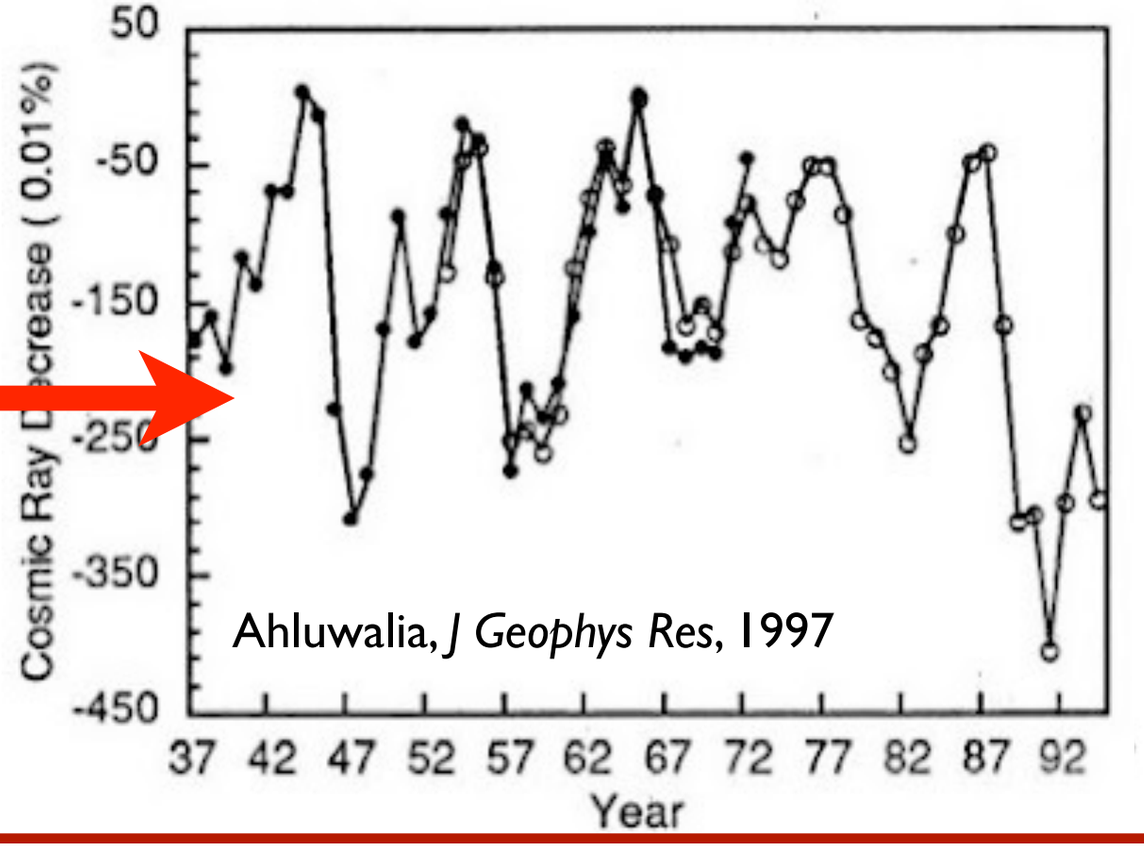

Ahluwalia, *J Geophys Res*, 1997

Cosmic rays as an explanation?

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PROCEEDINGS OF THE ROYAL SOCIETY A

Proc. R. Soc. A (2007) **463**, 2447–2460
doi:10.1098/rspa.2007.1880
Published online 10 July 2007

Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature

By Mike Lockwood[1,2,*] and Claus Fröhlich[3]

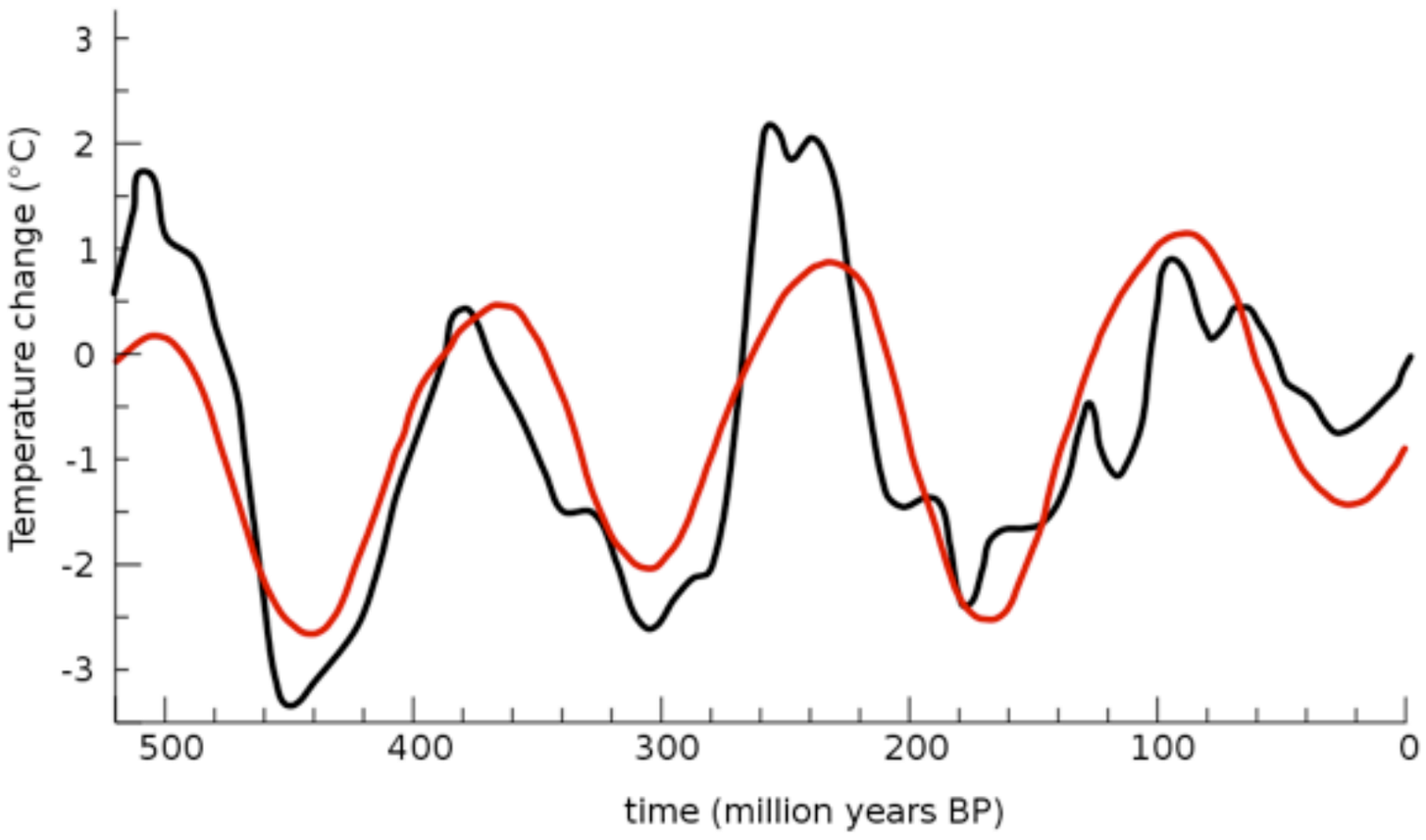
[1]*Rutherford Appleton Laboratory, Chilton, Oxfordshire OX11 0QX, UK*
[2]*Space Environment Physics Group, School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK*
[3]*Physikalisch–Meteorologisches Observatorium Davos, World Radiation Center, 7260 Davos Dorf, Switzerland*

There is considerable evidence for solar influence on the Earth's pre-industrial climate and the Sun may well have been a factor in post-industrial climate change in the first half of the last century. Here we show that over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures.

Keywords: solar variability and climate; solar–terrestrial physics; anthropogenic climate change

Cosmic rays as an explanation?

- **Evidence**: Cosmic rays and global average temperature are correlated over the past 500 million years.
  Problem: Severe data processing required to reach agreement with cosmic ray record.



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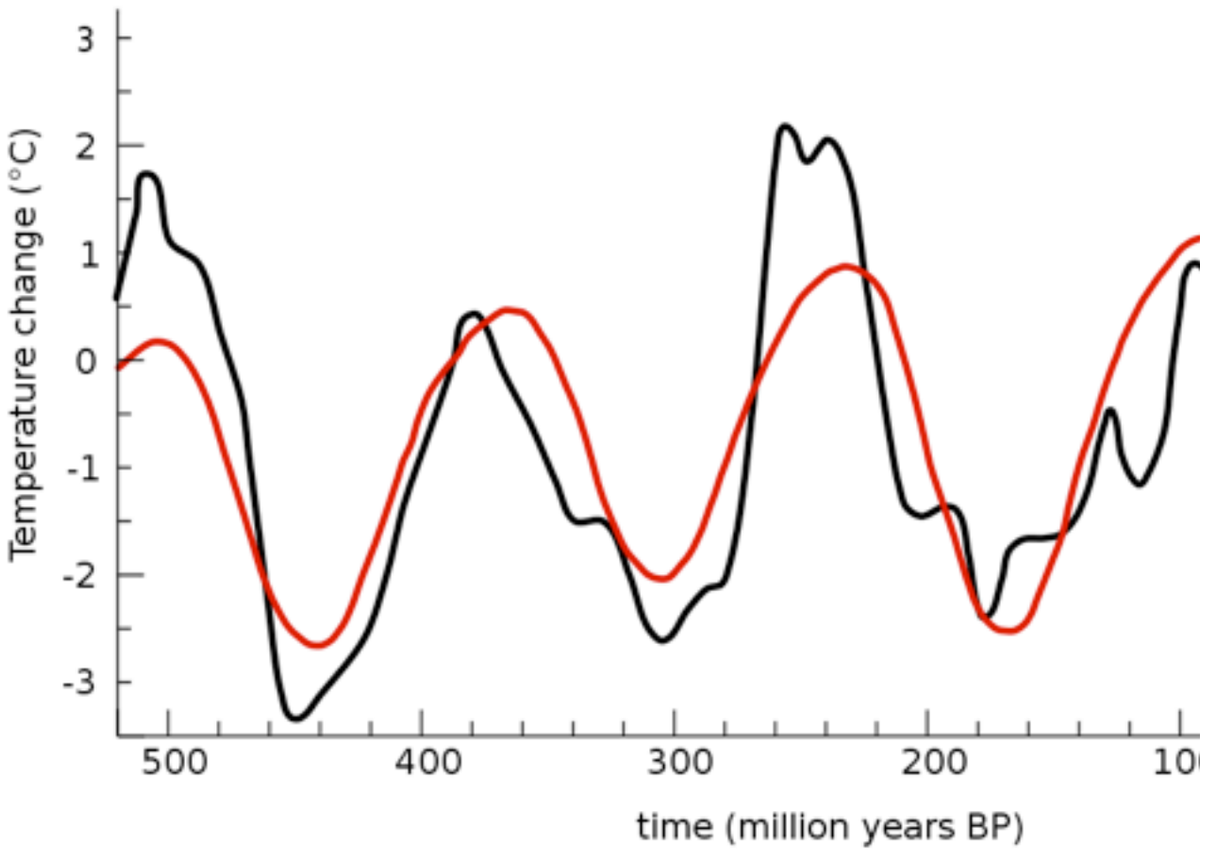
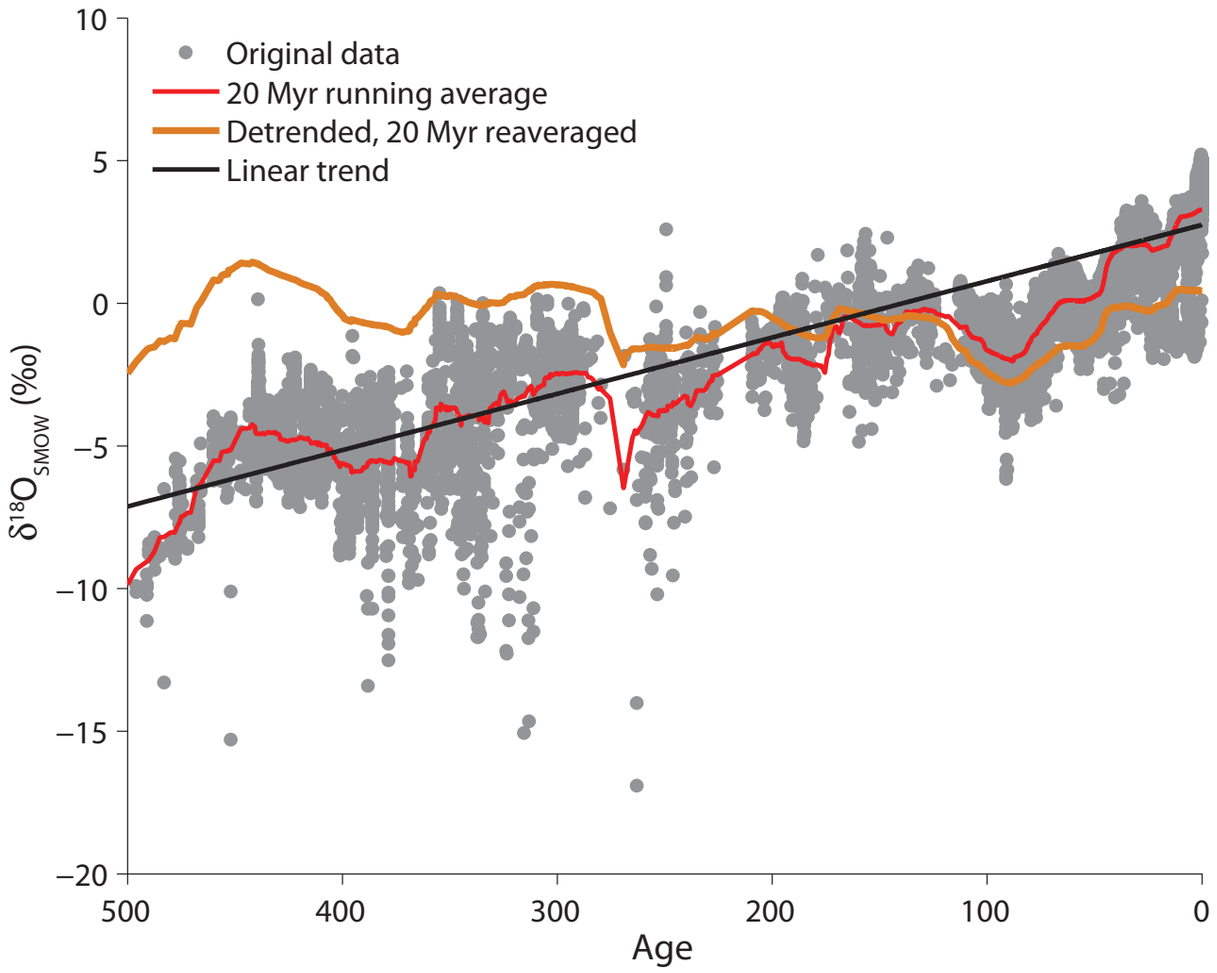
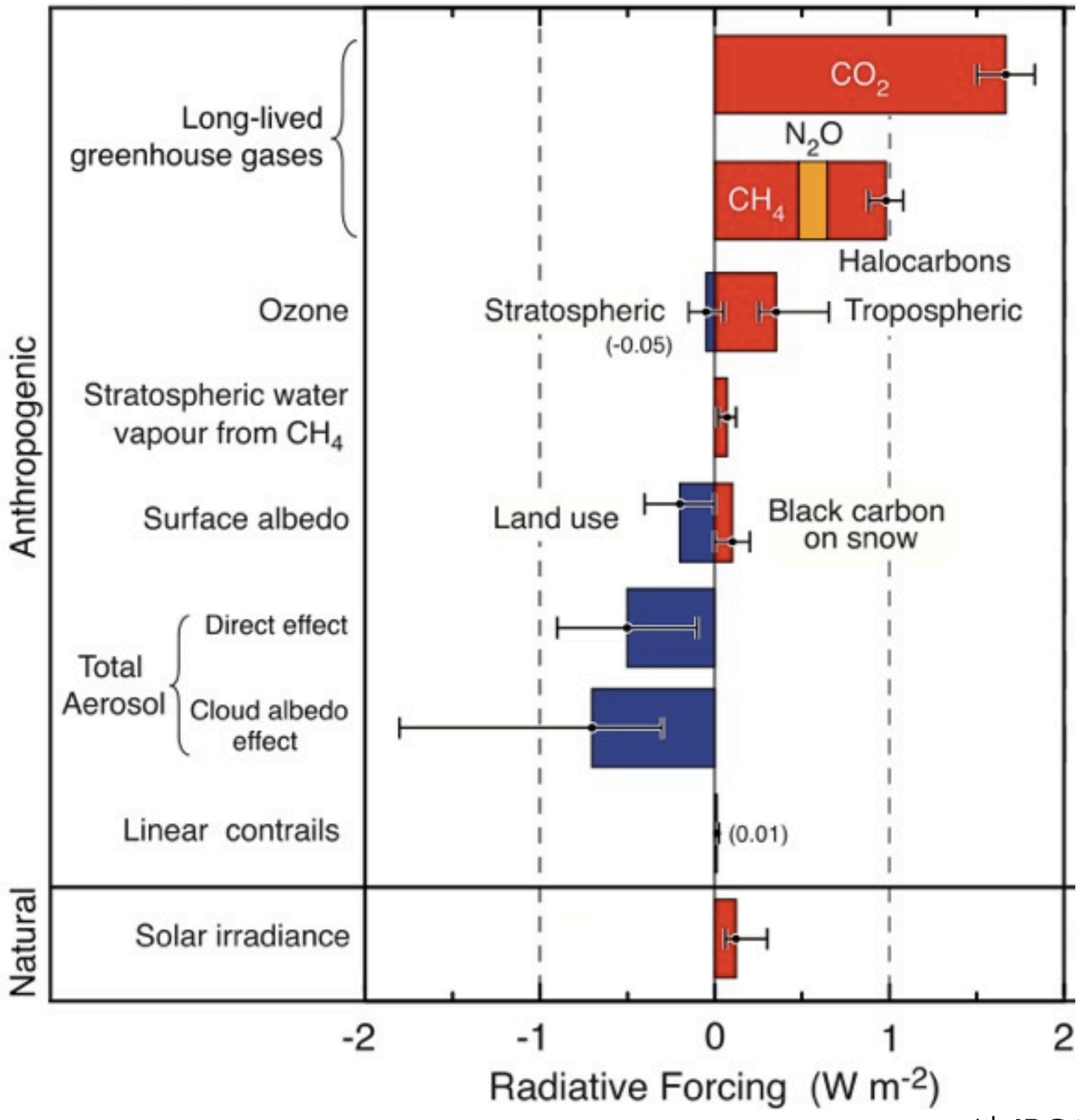




Sources of uncertainty

- Anthropogenic radiative forcing is uncertain
- Various stabilizing and destabilizing feedbacks add uncertainty:
  - Ice albedo
  - Water vapor
  - Terrestrial biosphere
  - Biomineralization
  - **Clouds**



4th IPCC

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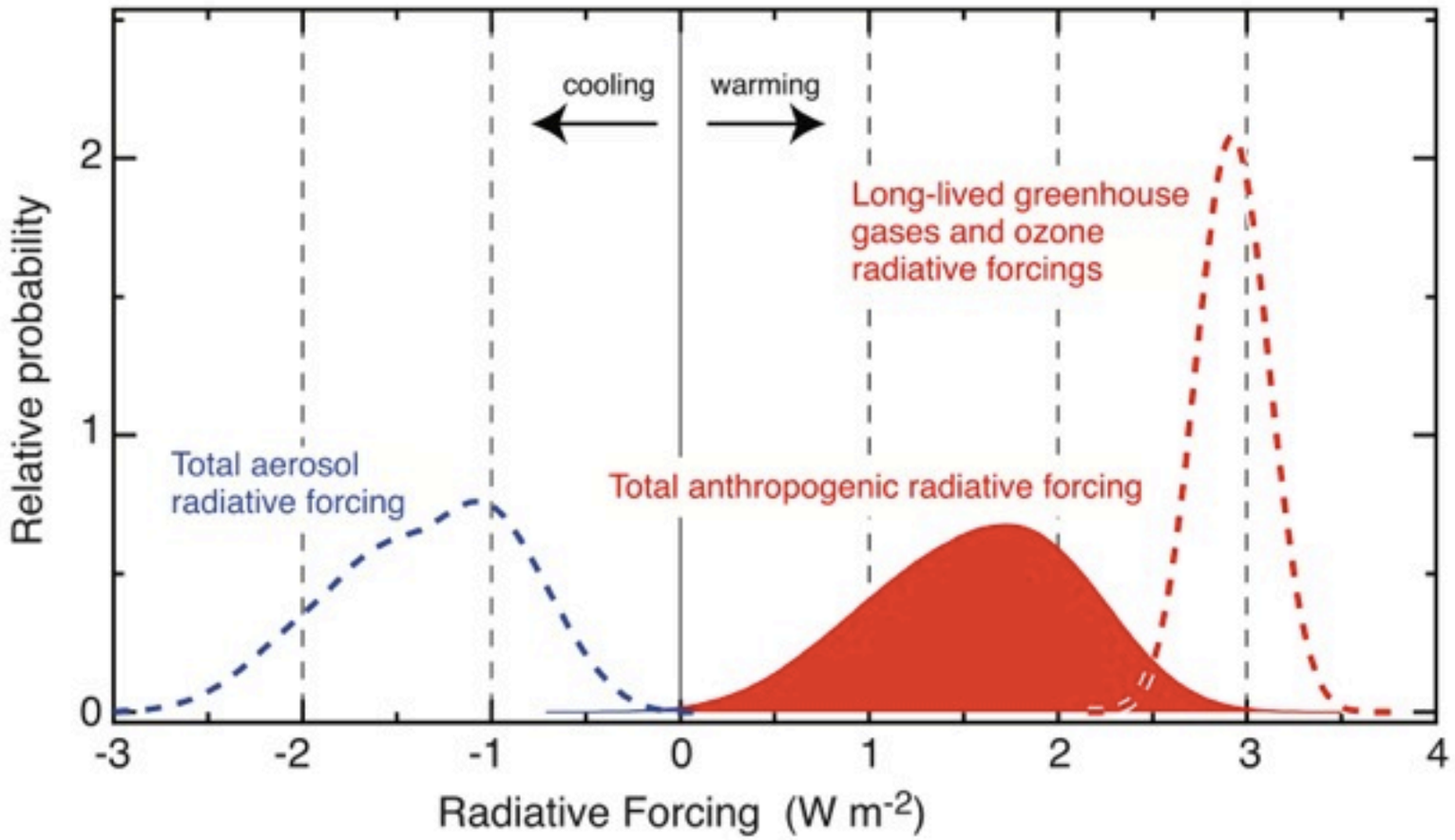

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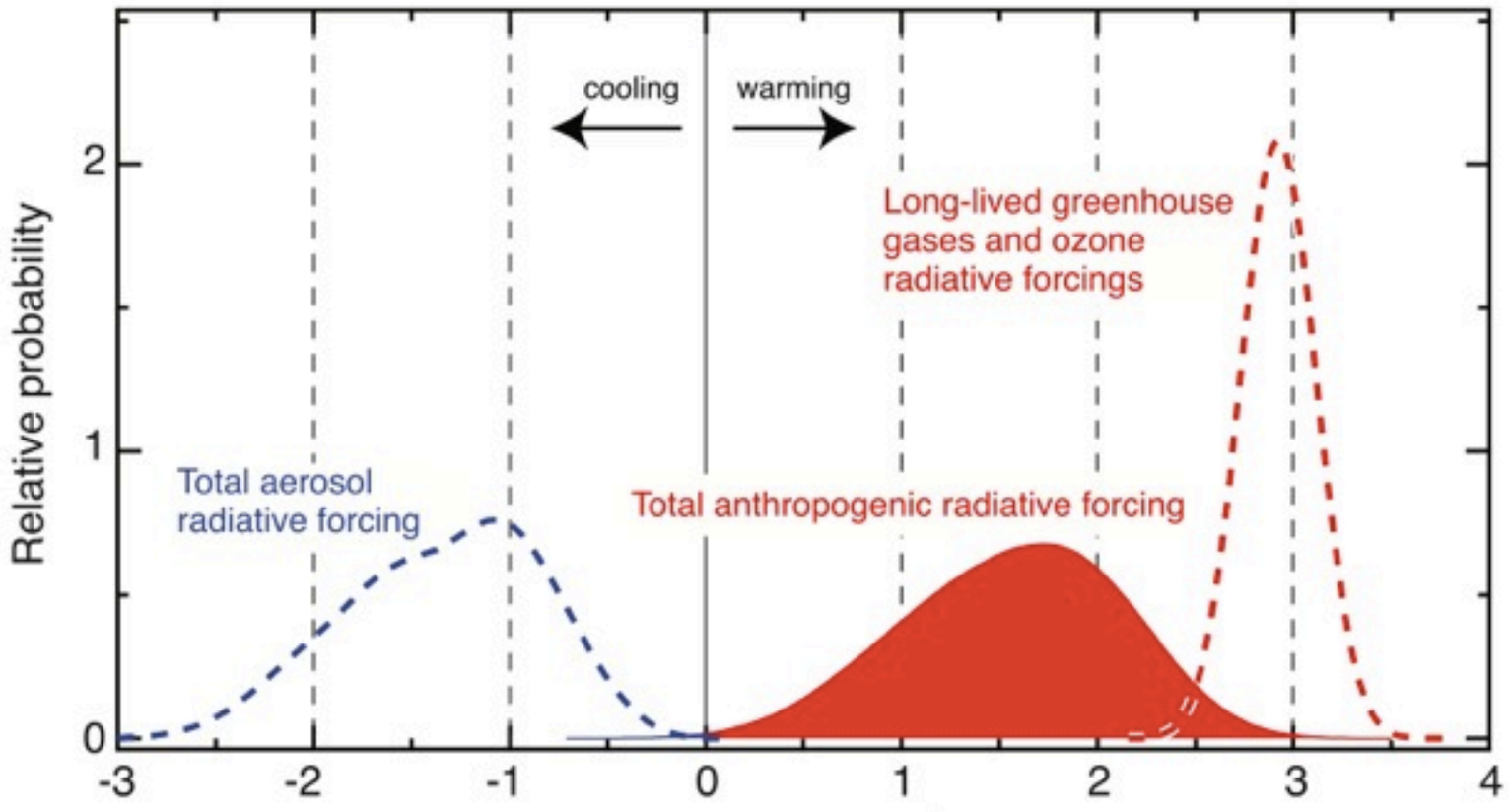

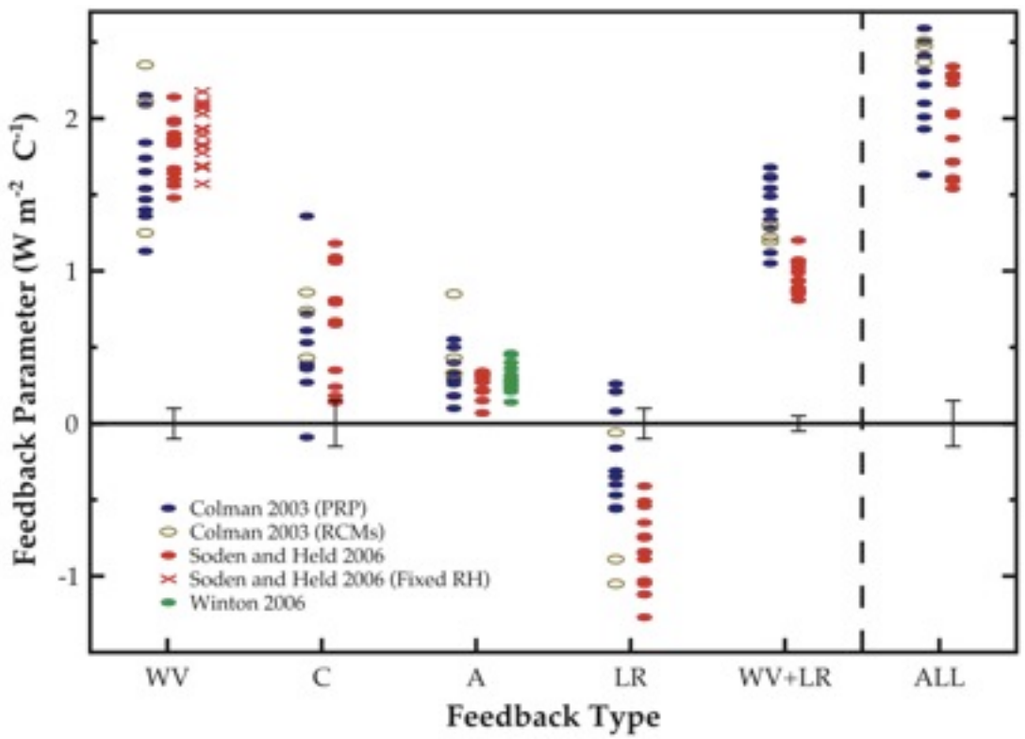

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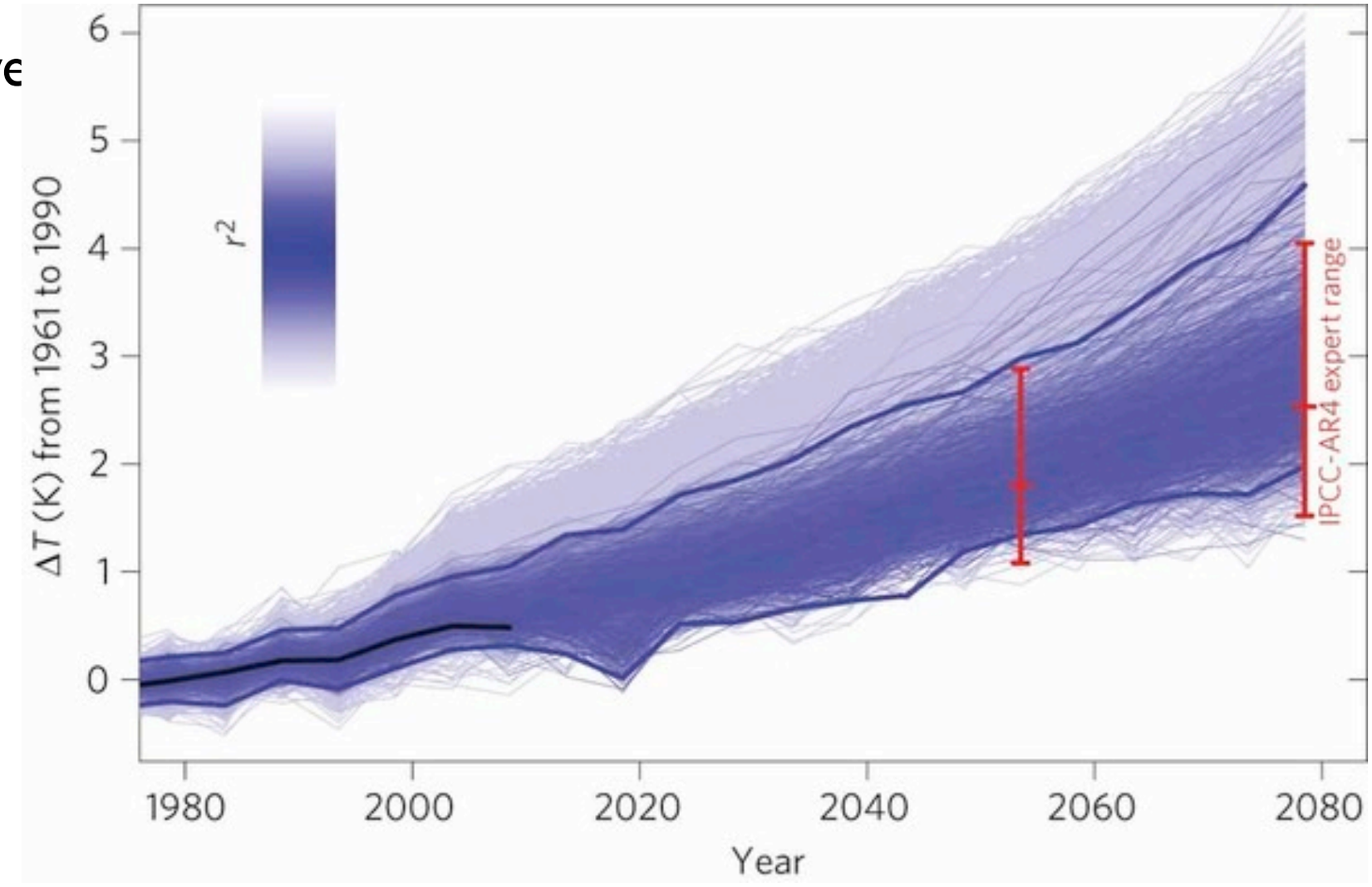
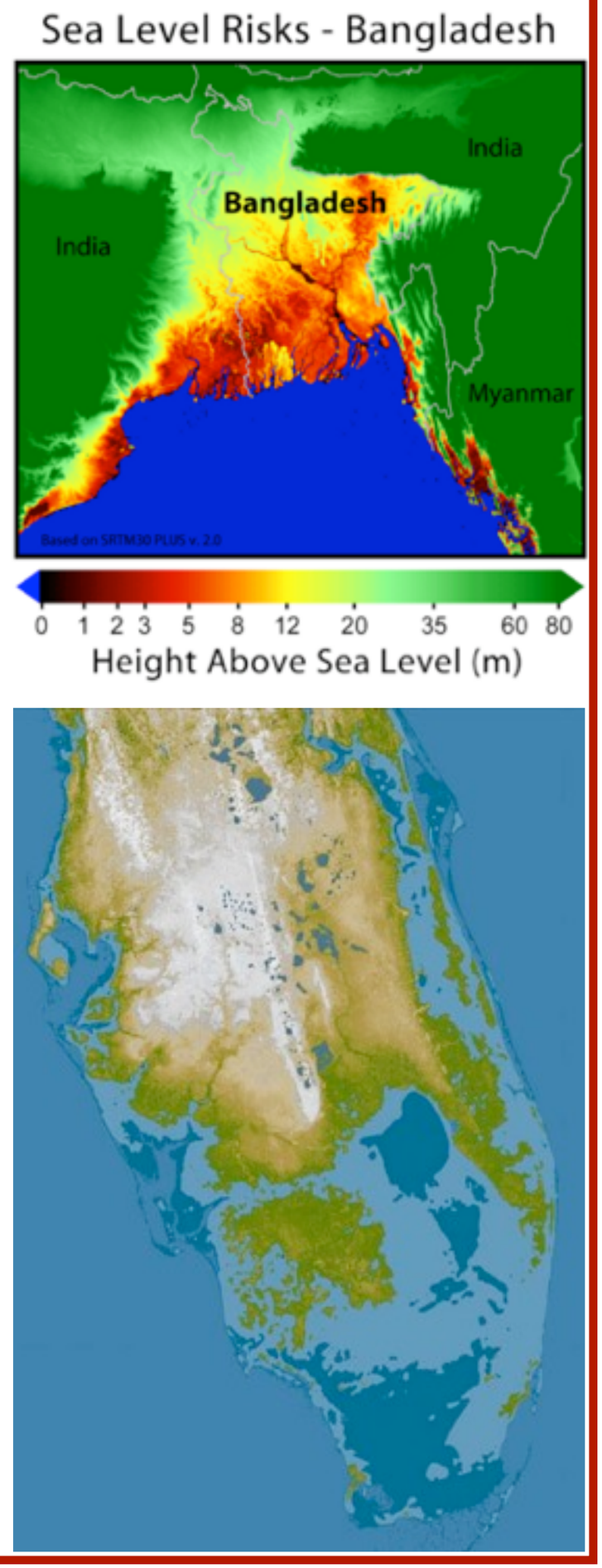


Rowlands *et al.*, *Nature Geoscience*, 2012

The problem

- Anthropogenic (and natural) radiative forcing is uncertain
- The magnitude and even sign of some feedbacks is uncertain
- These uncertainties lead to a wide range of model responses
- The effects on properties of societal interest is uncertain (e.g., sea level, precipitation)



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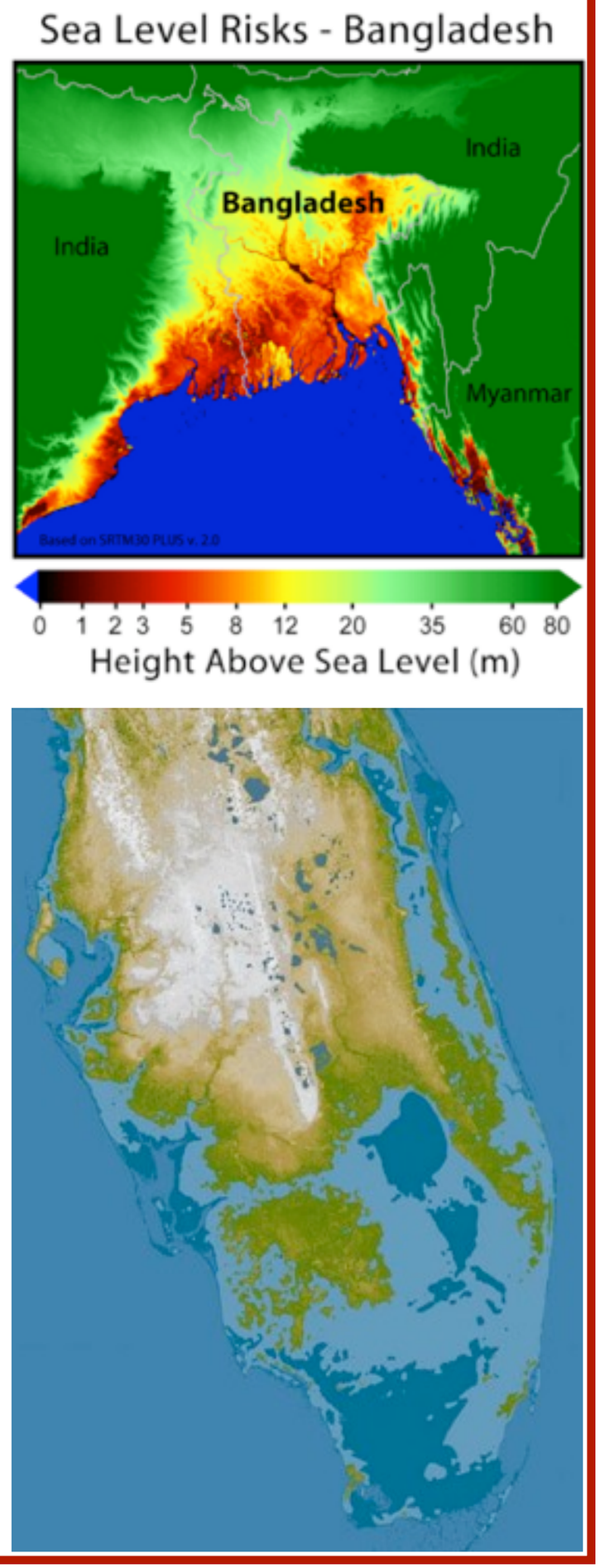
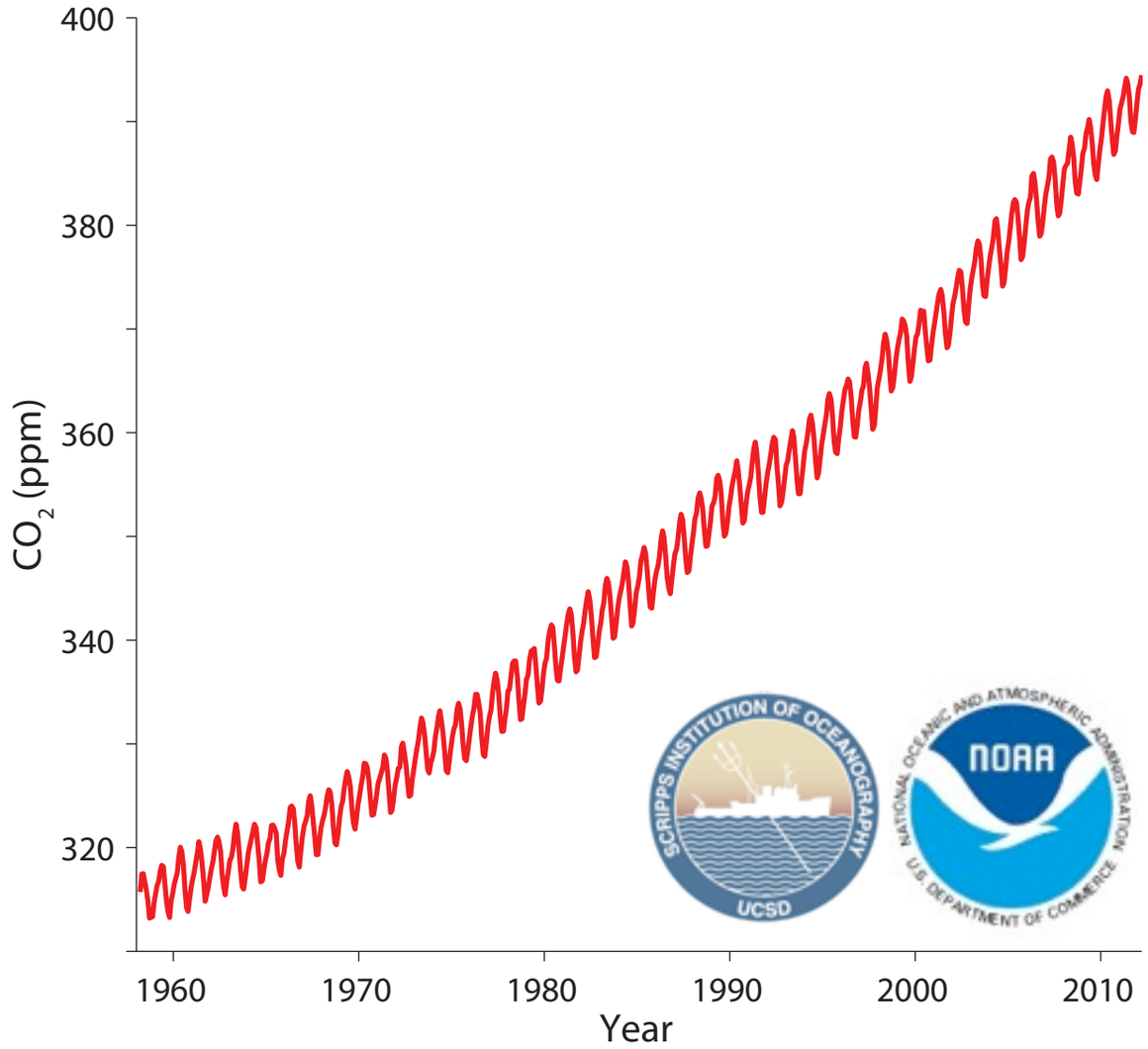
Can the geologic record help here?



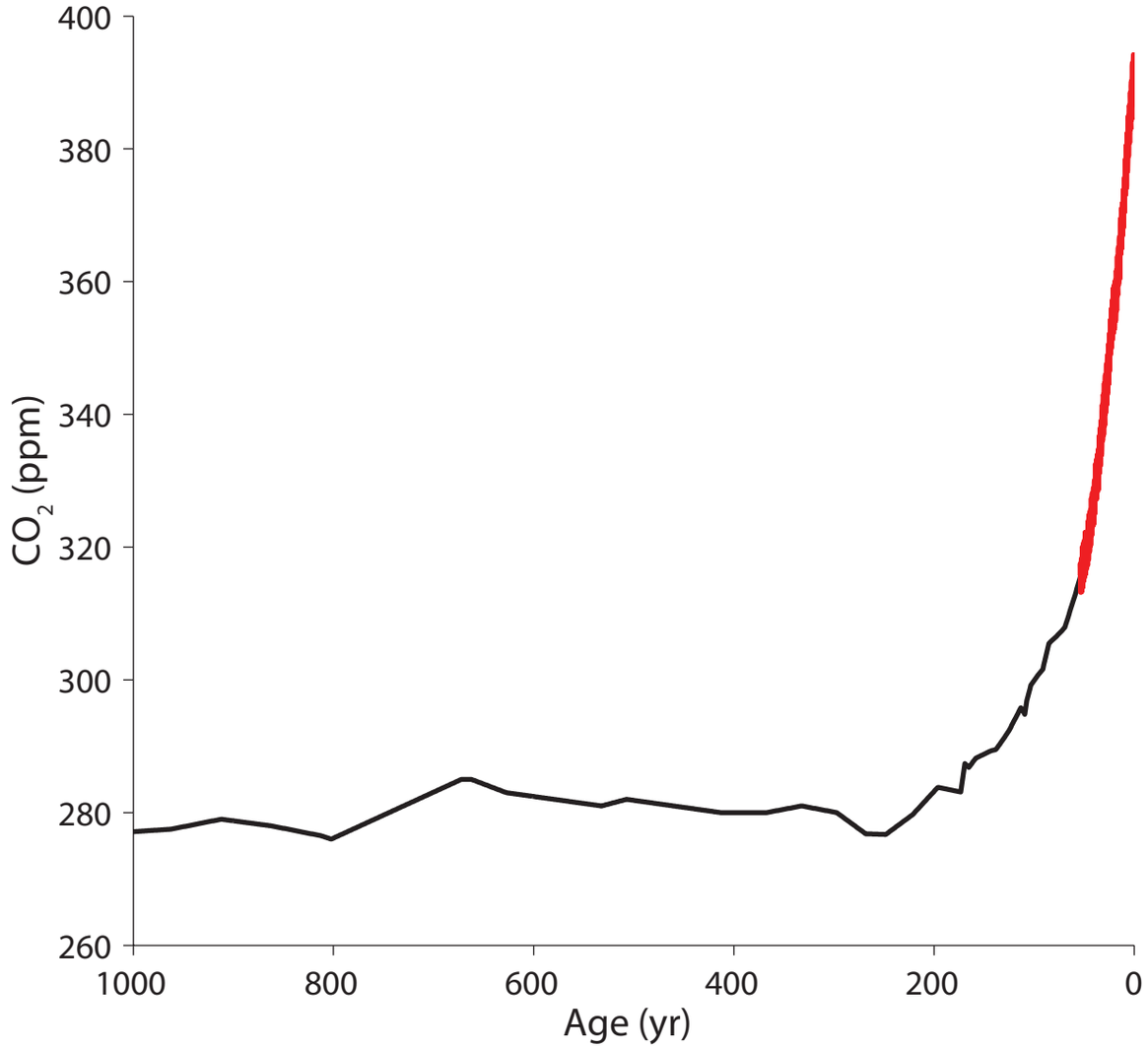
The record of atmospheric CO_2

20th century



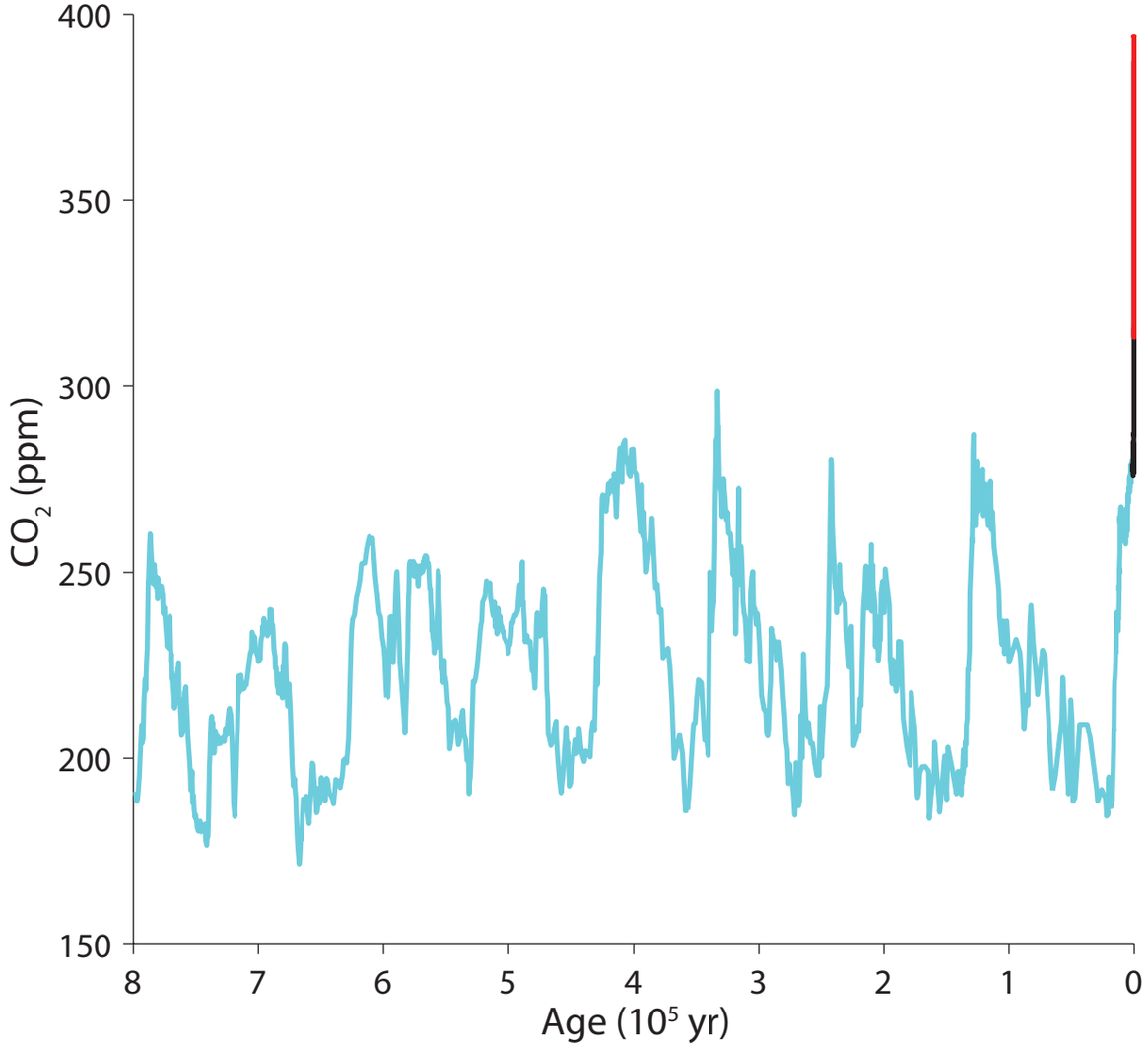
The record of atmospheric CO_2

Last millennium



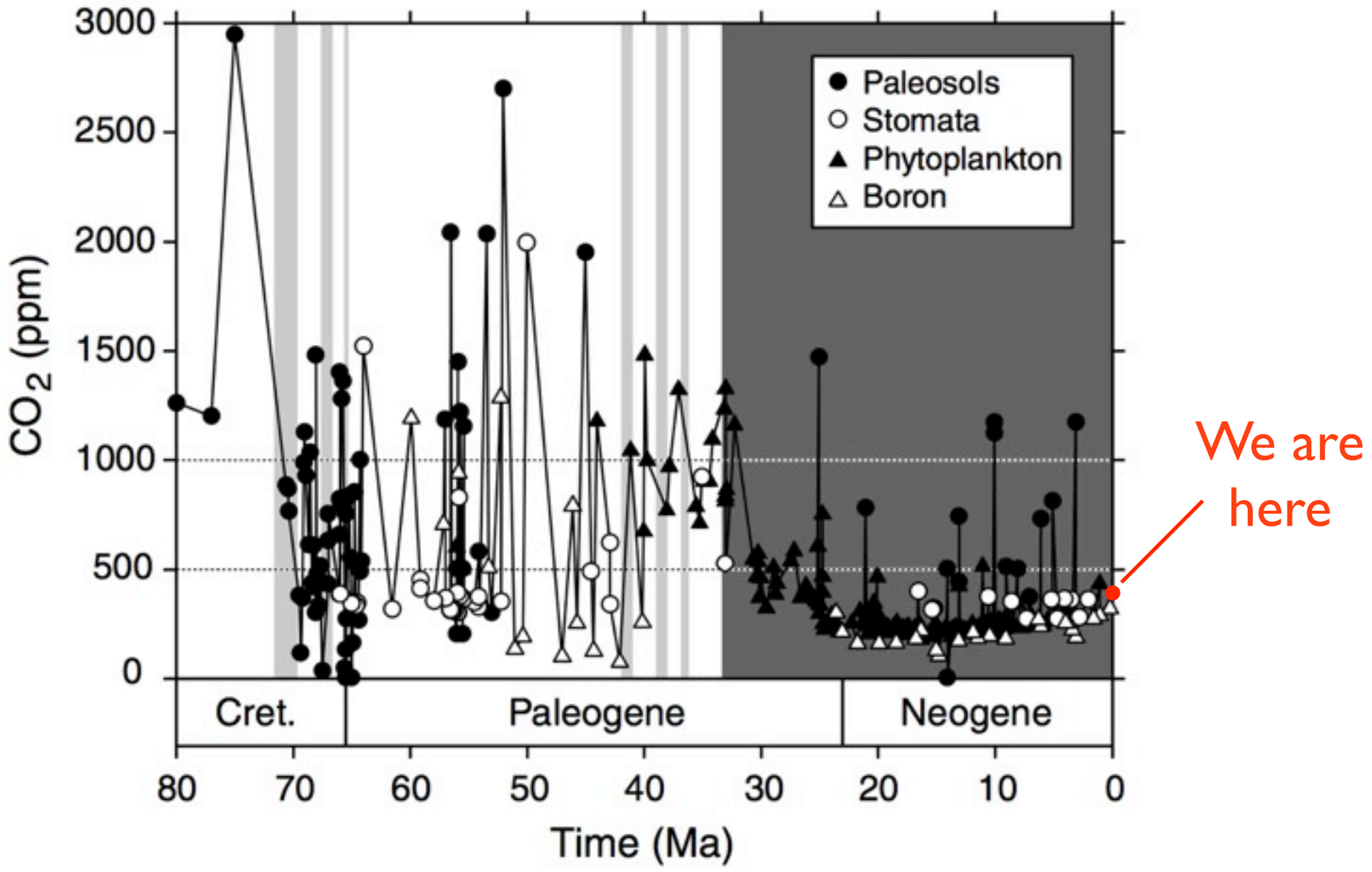
The record of atmospheric CO_2

Last 800 kyr



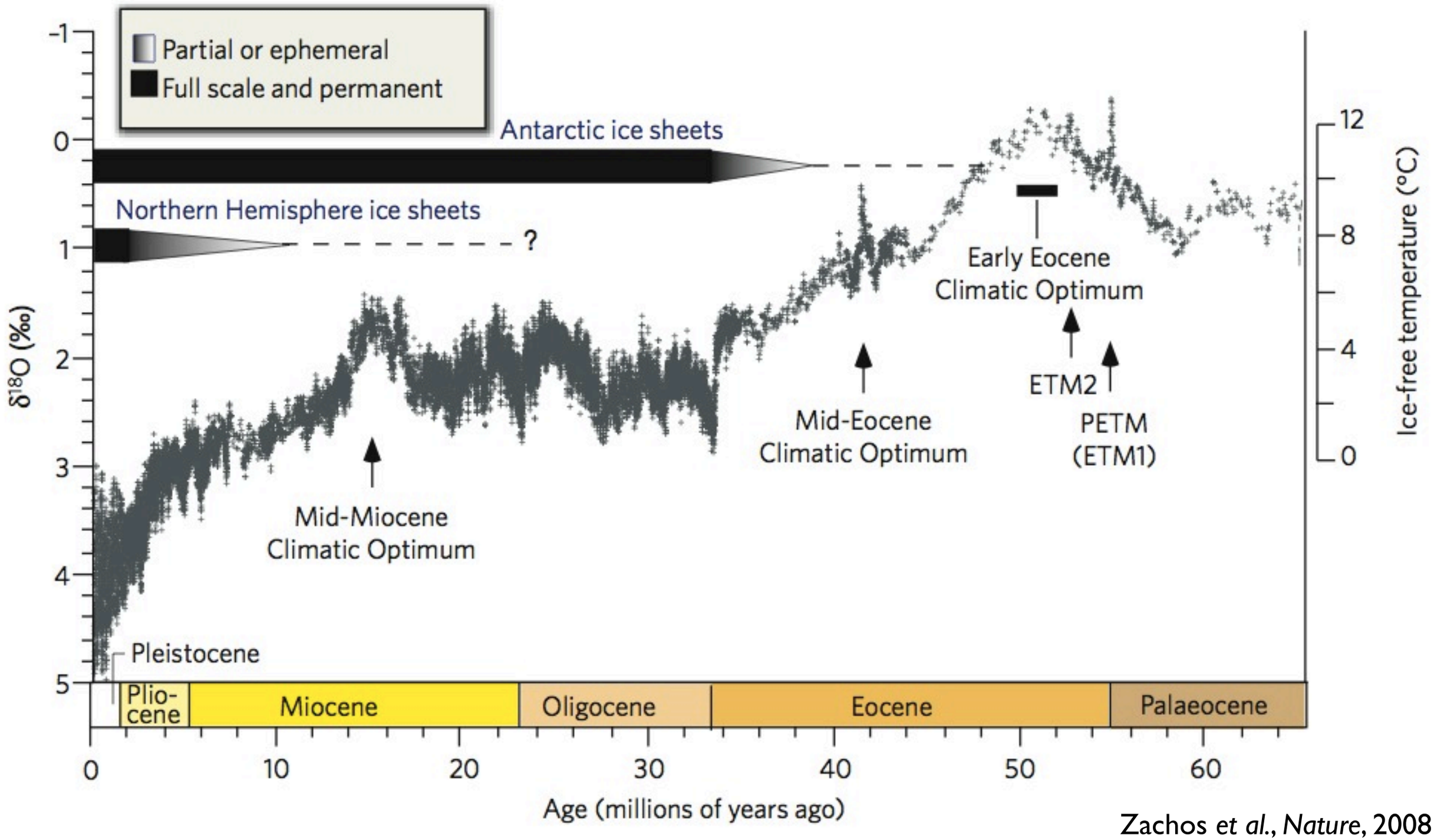
The record of atmospheric CO_2

Last 80 Myr



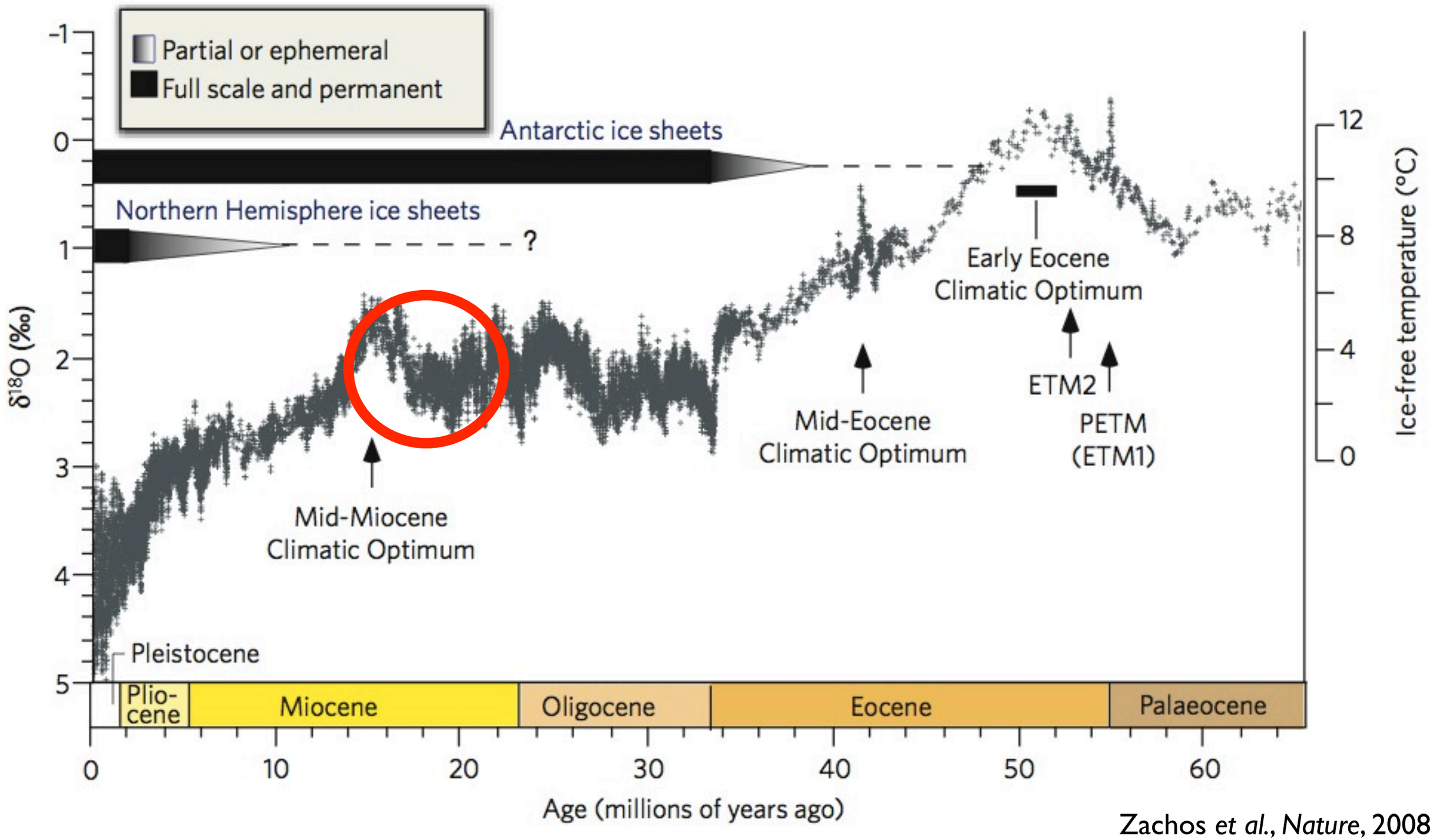
Royer, *Geochimica et Cosmochimica Acta*, 2006

Cenozoic (last 65 Myr) climate change



Zachos *et al.*, *Nature*, 2008

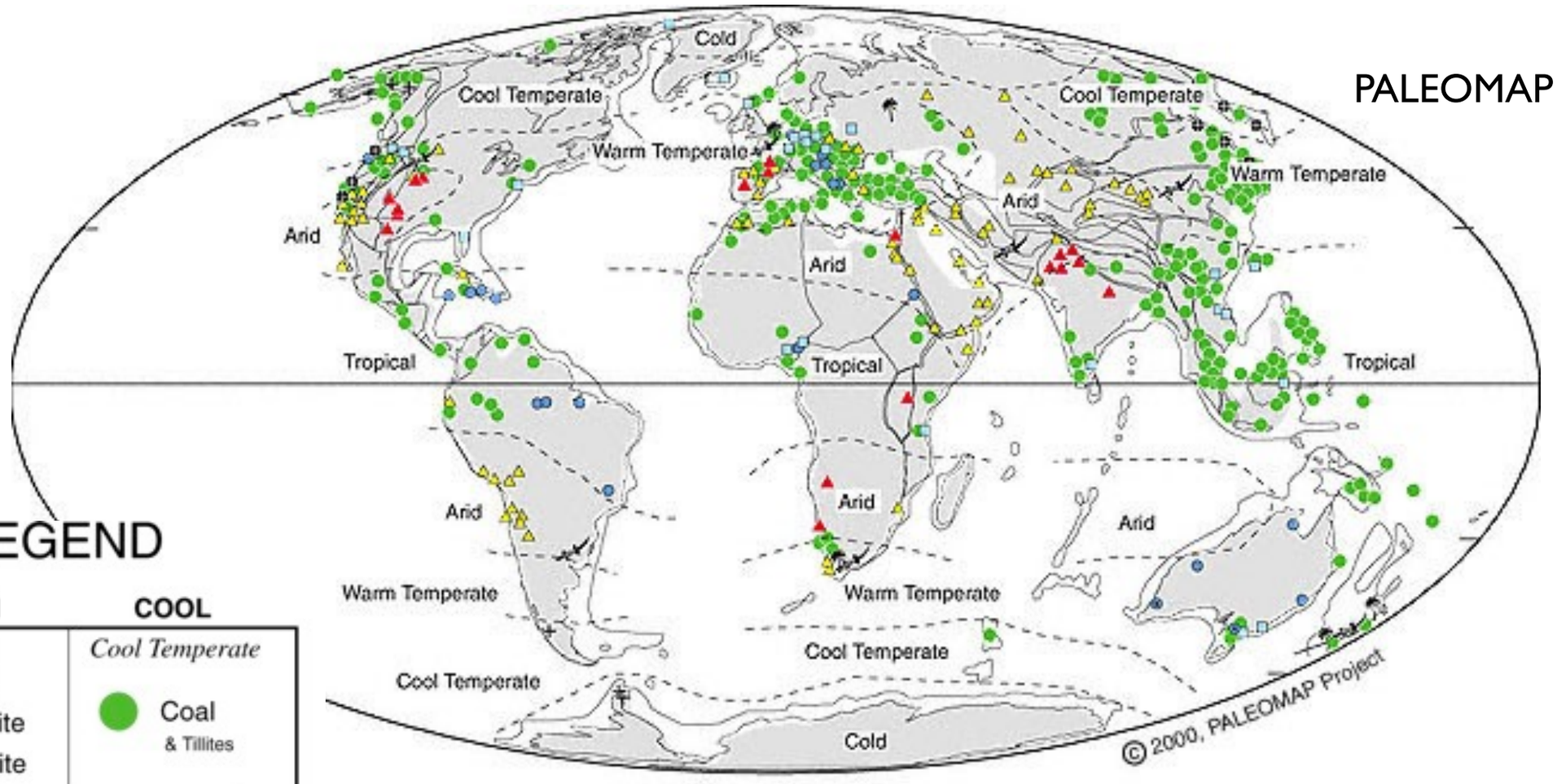
Cenozoic (last 65 Myr) climate change



Zachos *et al.*, *Nature*, 2008

Early-middle Miocene climate: Constraints on equilibrium climate

PALEOMAP Project



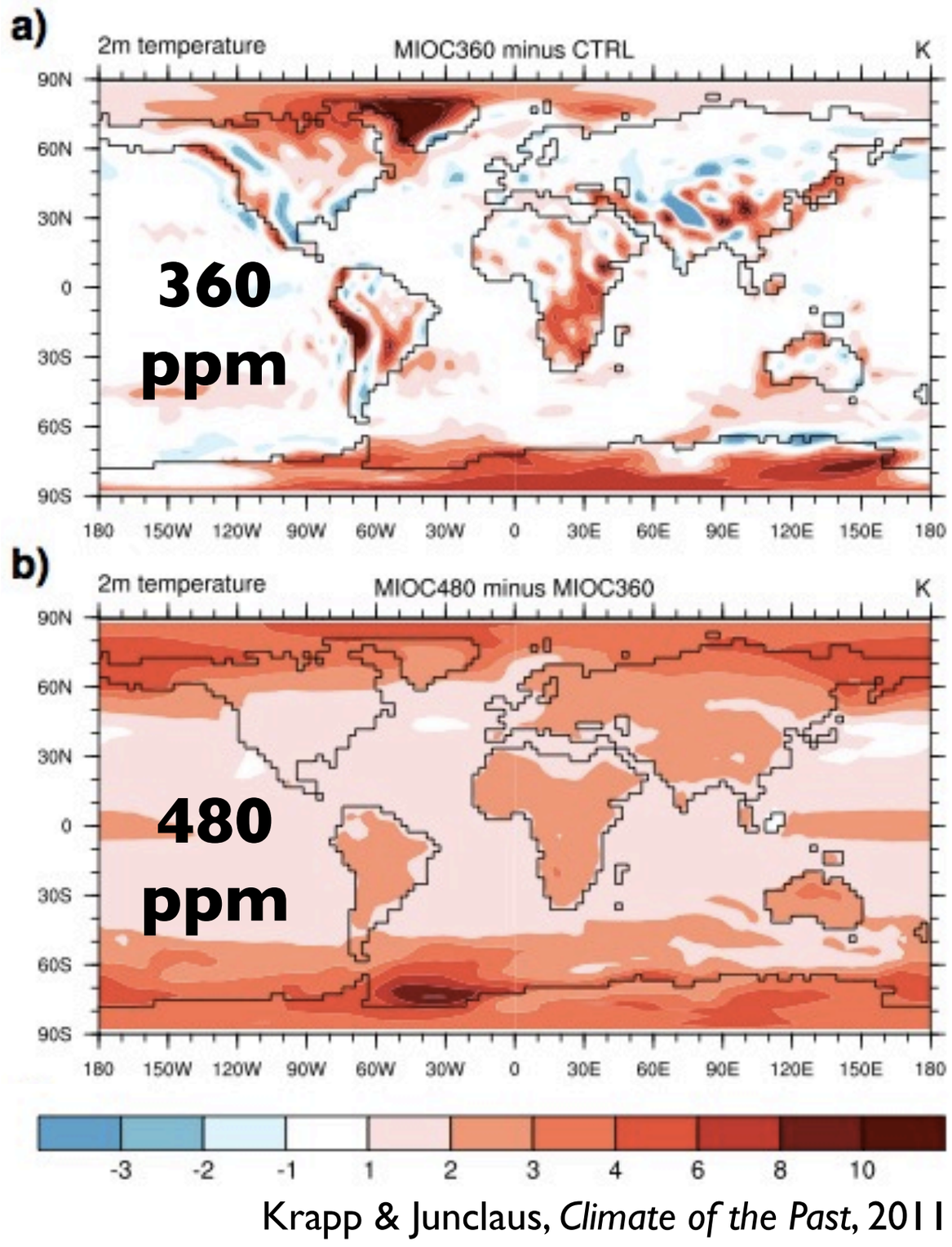
Miocene

LEGEND

	WARM	COOL
WET	*Tropical*: Coal, Bauxite, Laterite	*Cool Temperate*: Coal & Tillites
	Warm Temperate: Kaolinite (& coal & evaporite), Crocodiles, Palms & Mangroves	
DRY	*Arid*: Evaporite, Calcrete	*Cold*: Tillite, Dropstone, Glendonite

"Paratropical" = High Latitude Bauxites

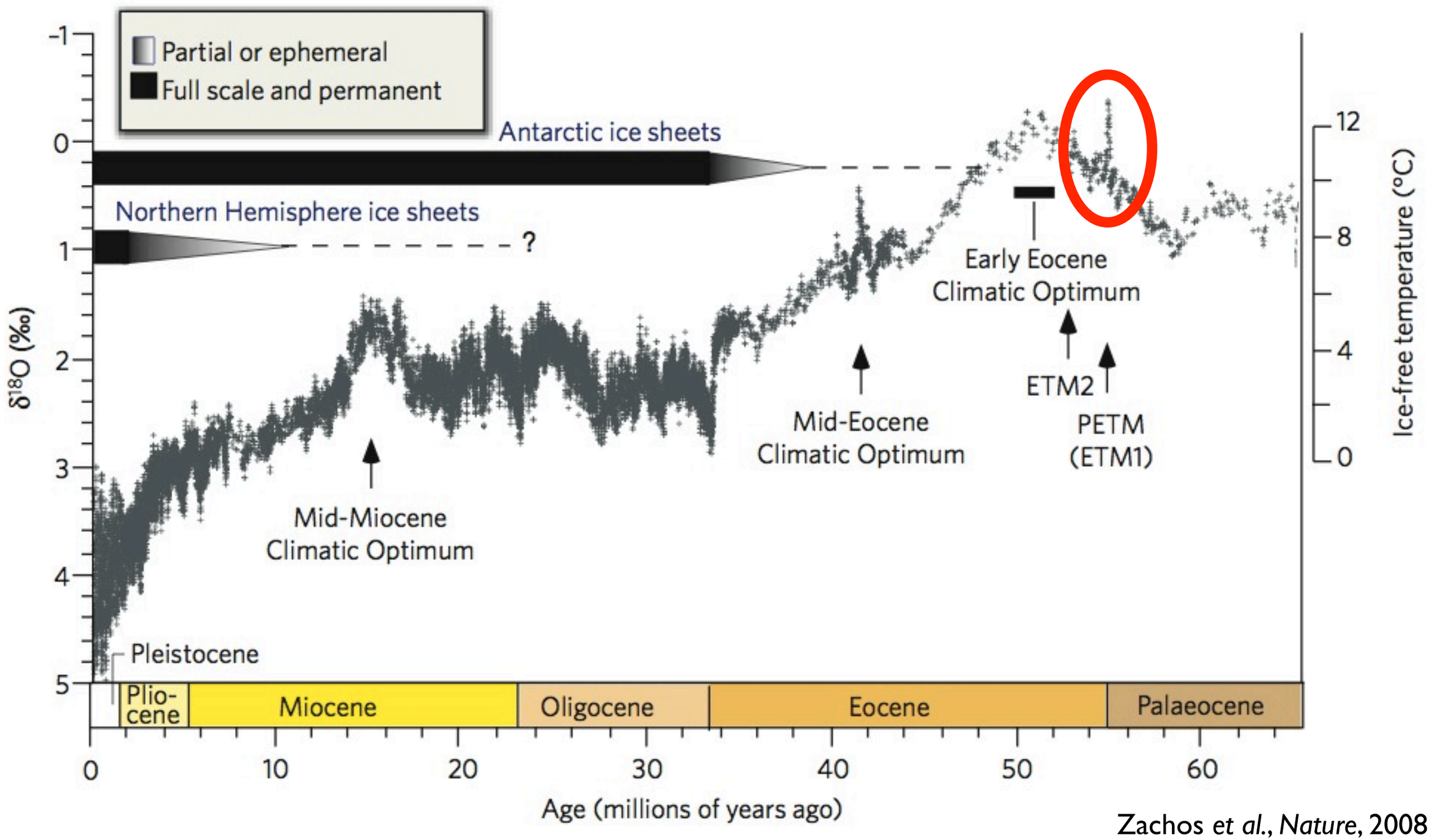
Early-middle Miocene climate: Constraints on equilibrium climate



Krapp & Junclaus, *Climate of the Past*, 2011

- CO_2 estimates: ~350–700 ppm
- We have exceeded the lower end and will exceed the upper end, even with moderate growth
- No Northern Hemisphere ice
- Palm trees near Moscow, crocs east of the Canadian Rockies
- Global average T: +3°C
  Land average T: +4°C
  High latitude T: up to +15°C
- Sea level ~100 m higher than present

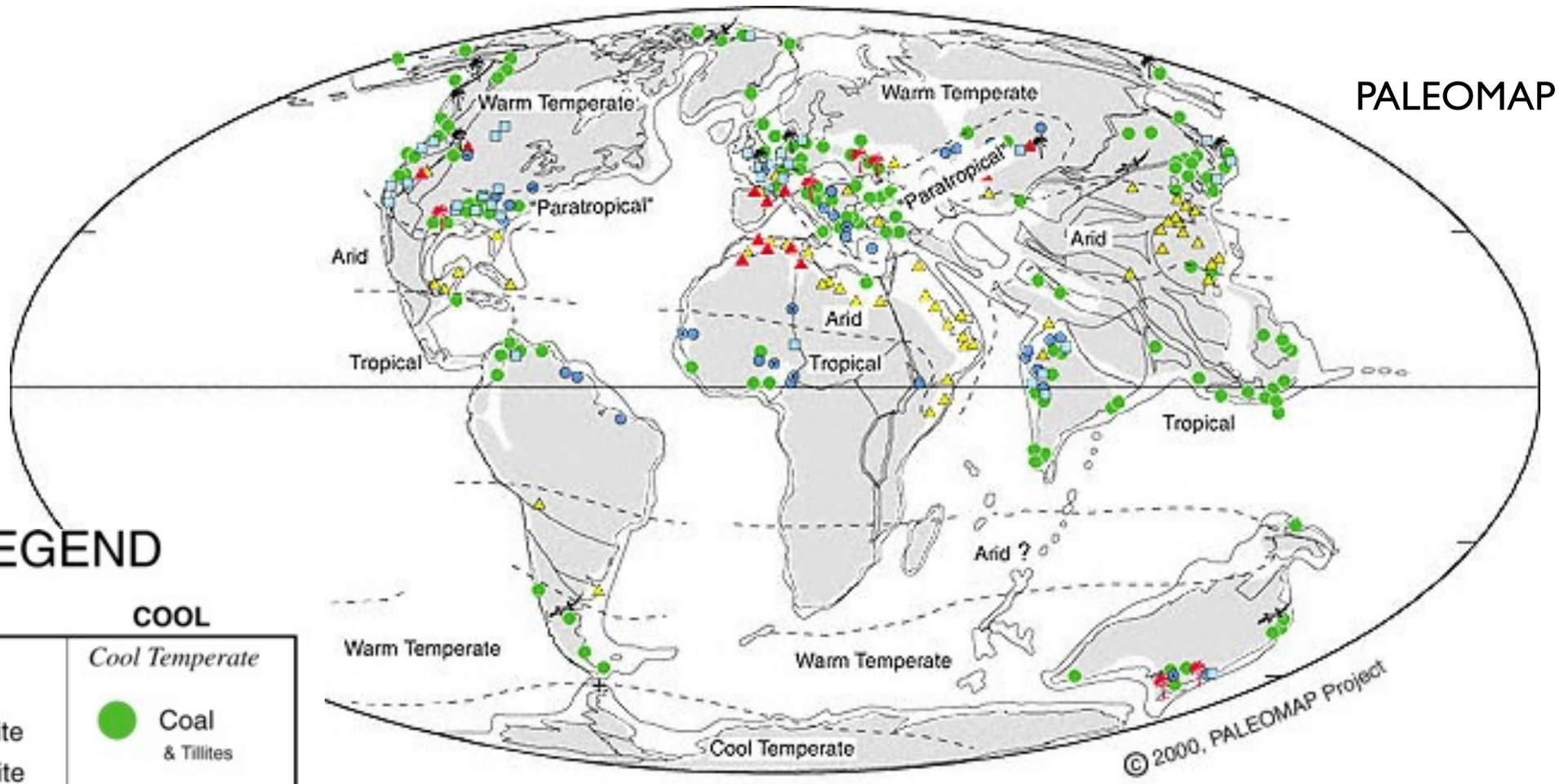
Paleocene-Eocene Thermal Maximum (PETM)



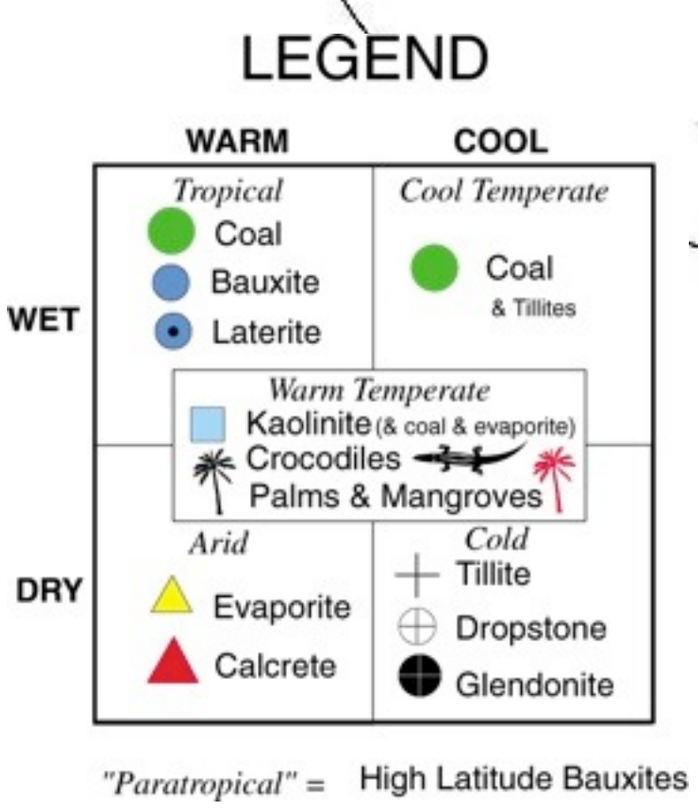
Zachos *et al.*, *Nature*, 2008

Early Eocene climate: Constraints on short-timescale response

PALEOMAP Project



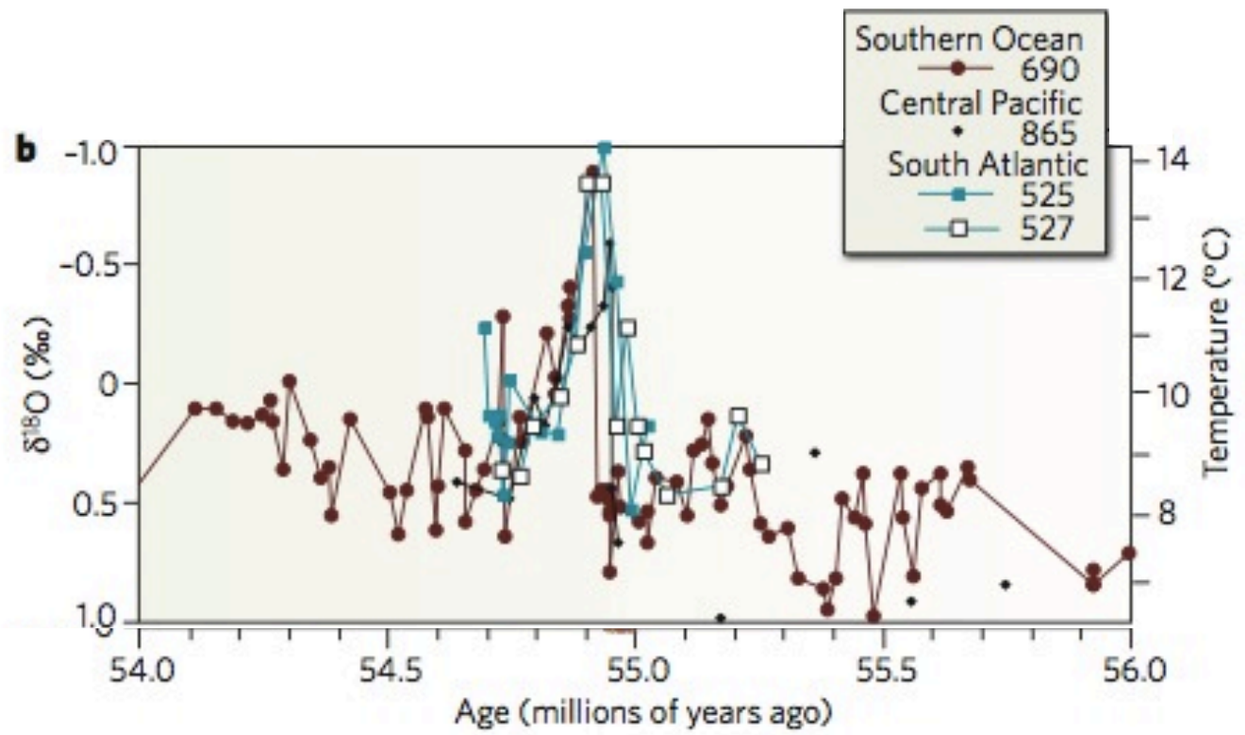
Lower Eocene



Alligators near N. Pole, palm trees in Alaska

PETM: Response to rapid CO_2 injection

Temperature

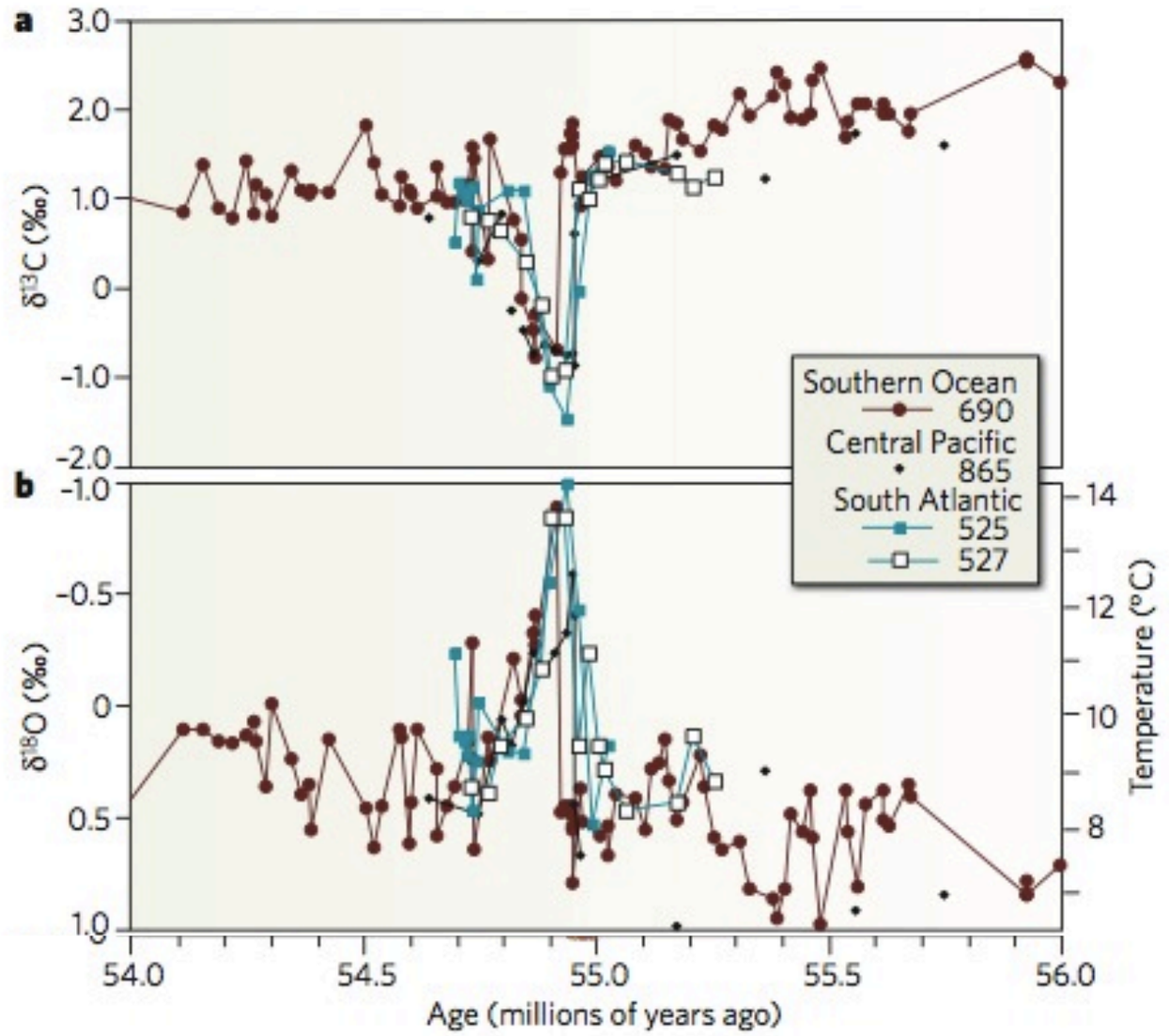


Zachos *et al.*, *Nature*, 2008

PETM: Response to rapid CO_2 injection

$\delta^{13}C$

Temperature



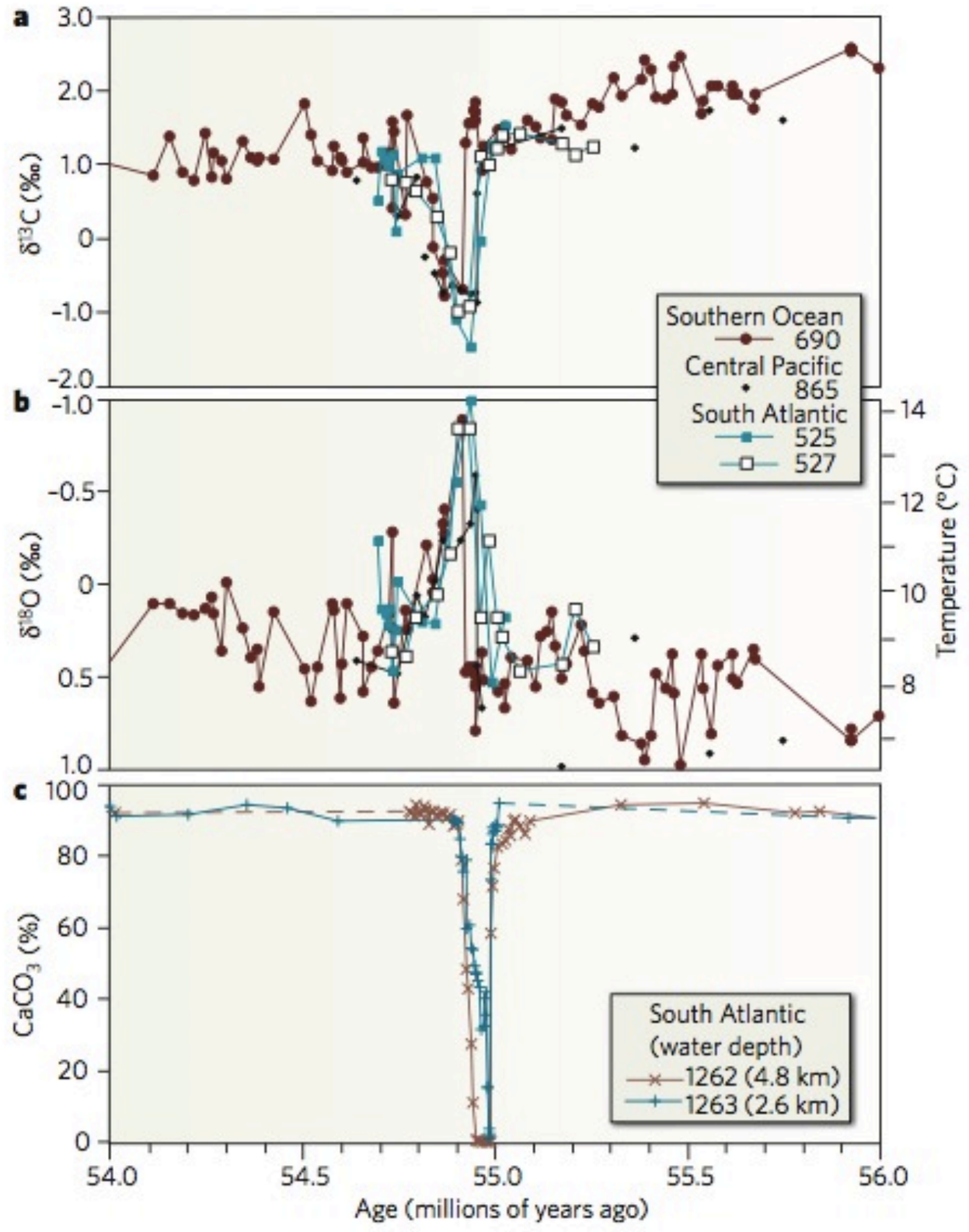
Zachos *et al.*, *Nature*, 2008

PETM: Response to rapid CO_2 injection

$\delta^{13}C$

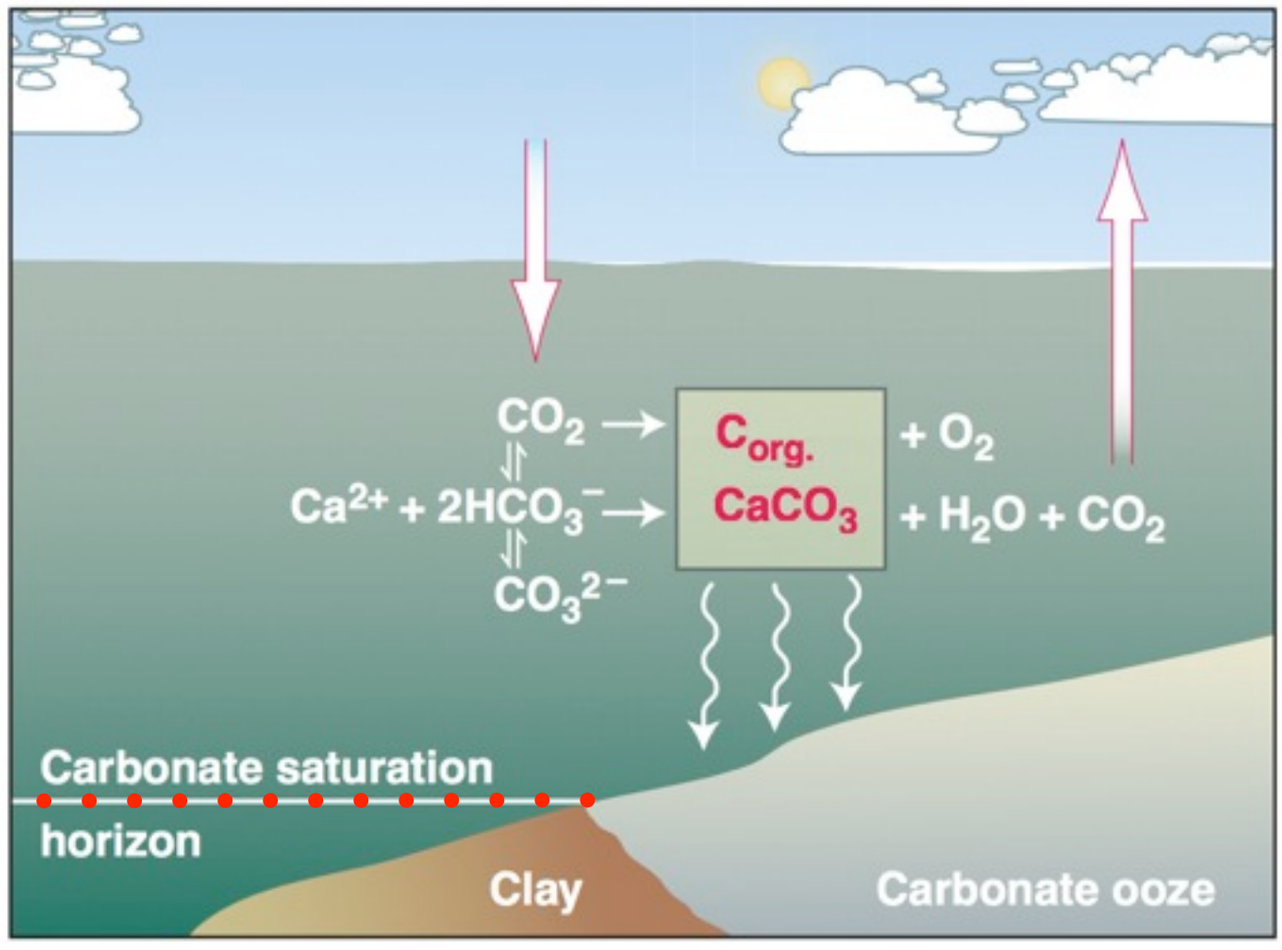
Temperature

% carbonate



Zachos *et al.*, *Nature*, 2008

Shoaling of the carbonate saturation horizon



Elderfield, *Science*, 2000

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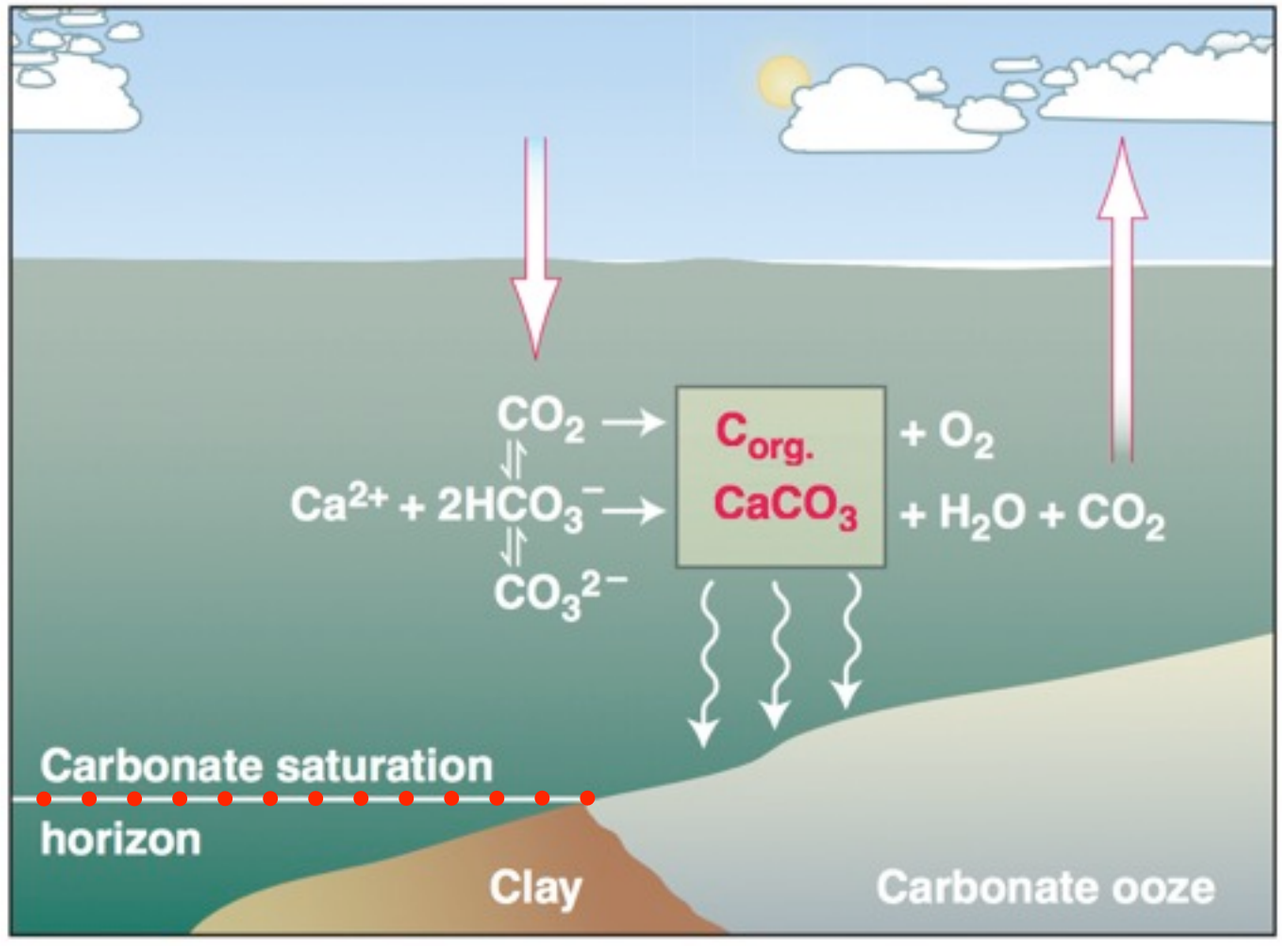

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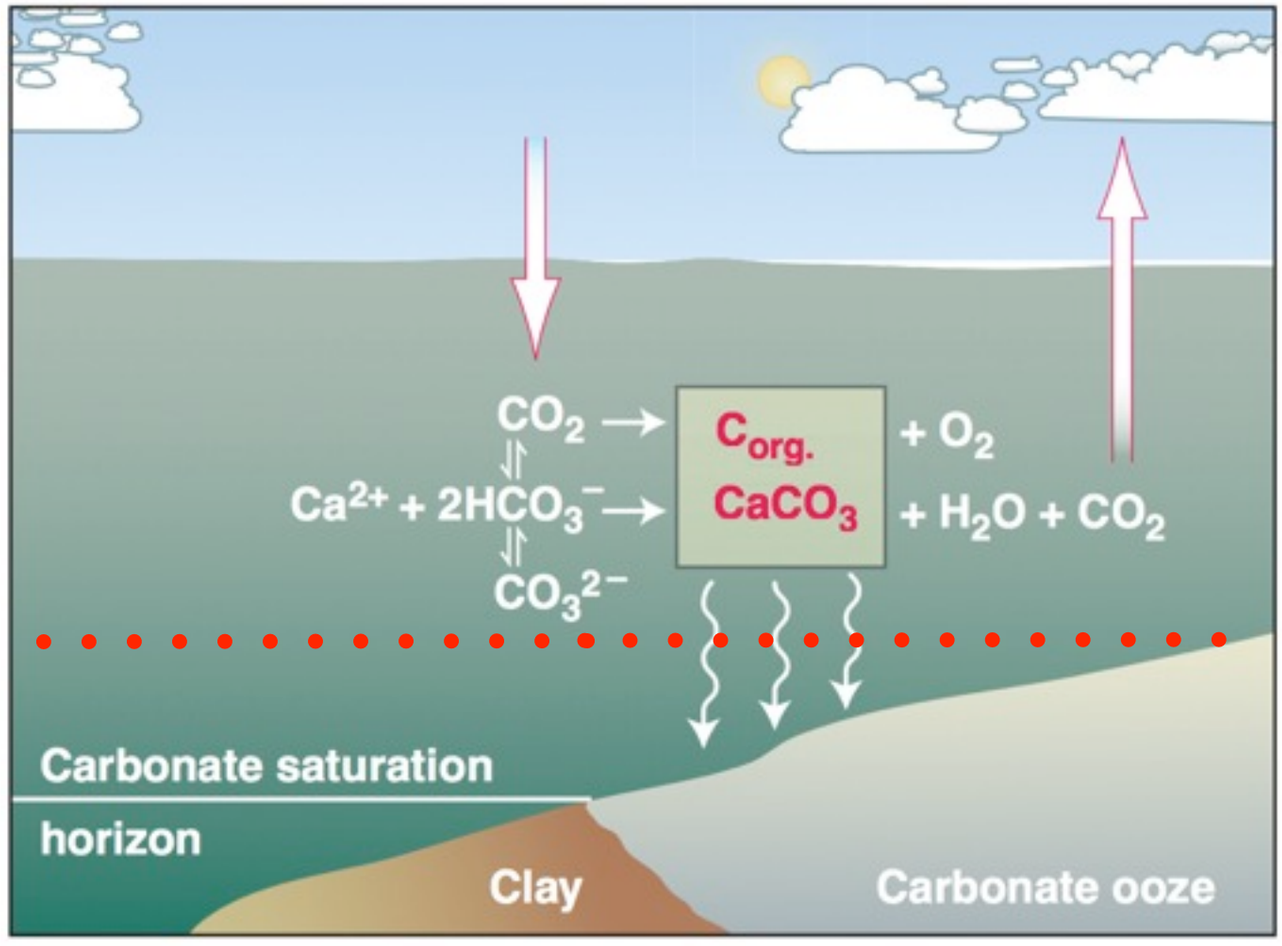

Elderfield, *Science*, 2000

PETM: Response to rapid CO_2 injection

$\delta^{13}C$

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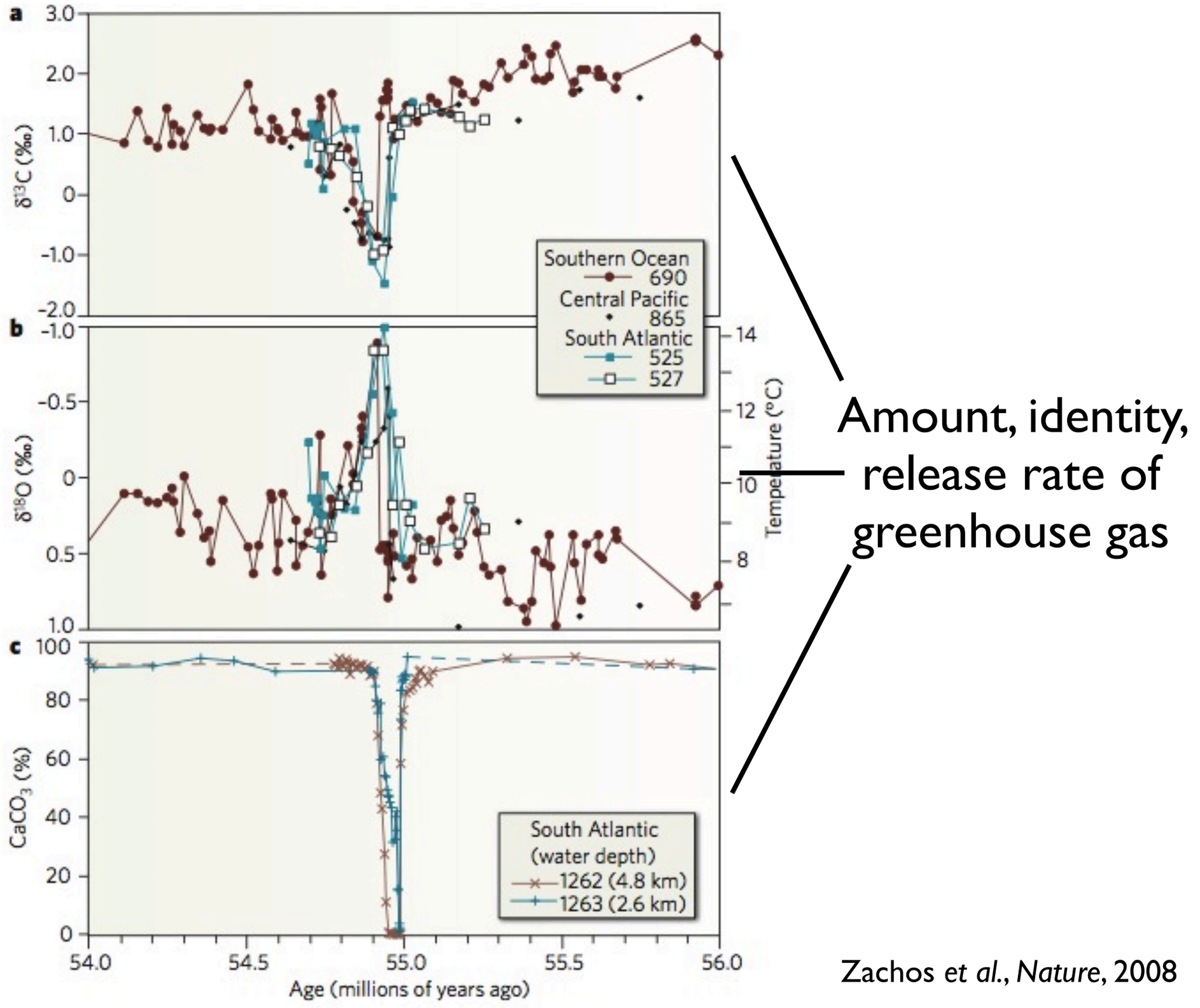


Amount, identity, release rate of greenhouse gas

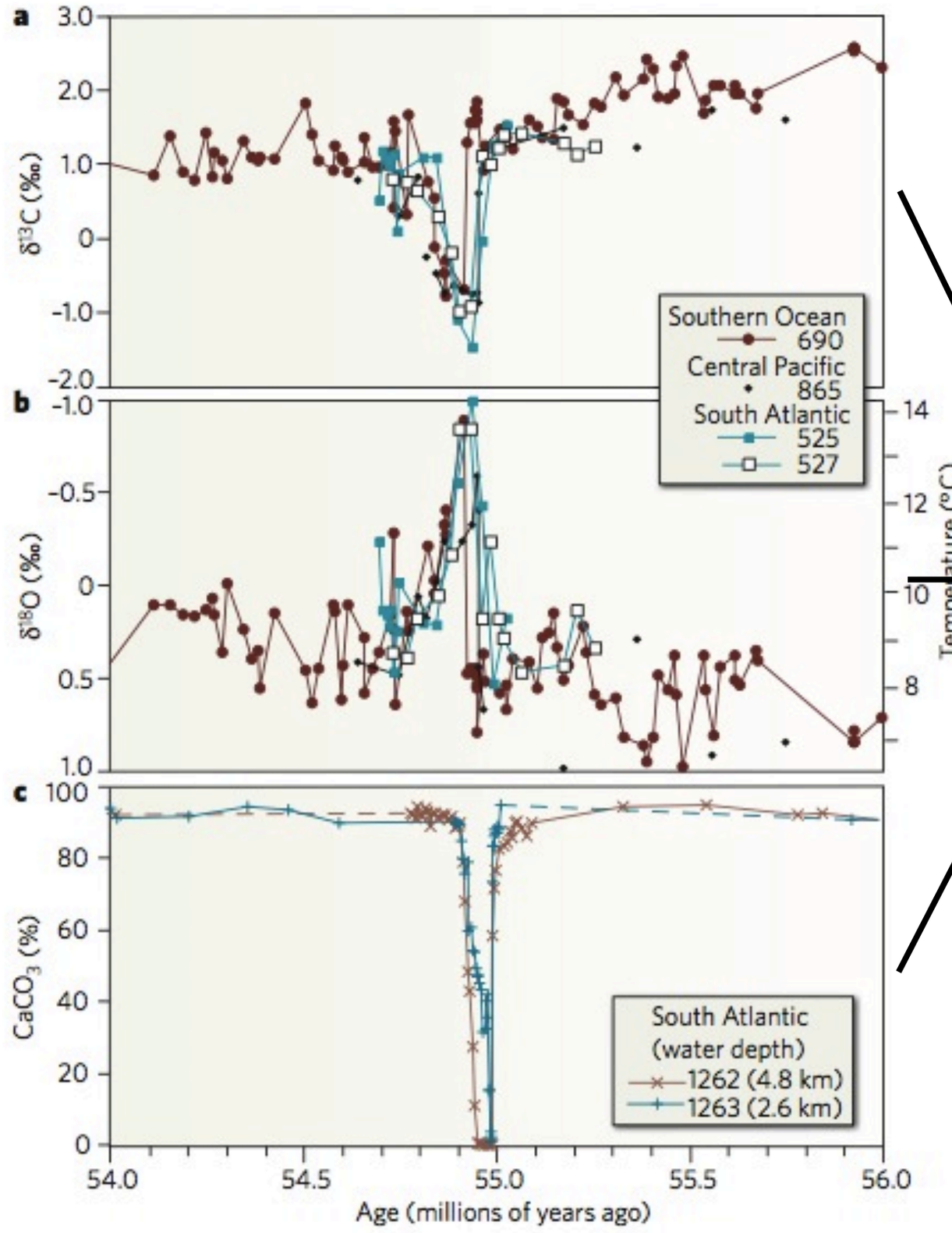
Zachos *et al.*, *Nature*, 2008

PETM: Response to rapid CO_2 injection

$\delta^{13}C$

Temperature

% carbonate



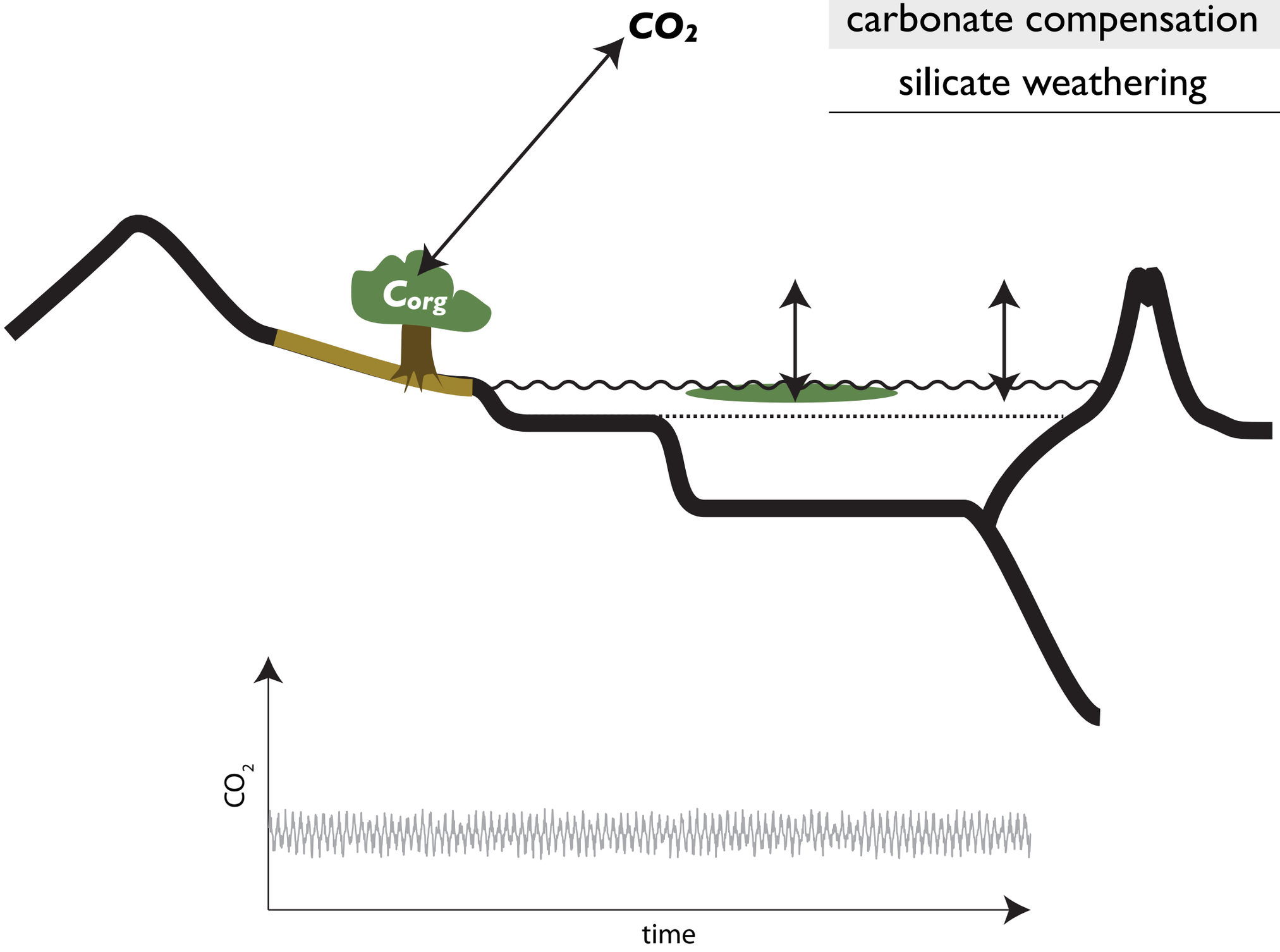
Amount, identity, release rate of greenhouse gas

⇓

~5,000 Gt C
as CO_2 + CH_4
over ~10,000 years

C cycle timescales

process	τ (kyr)
atm-biosphere	**0.1**
atm-ocean	1
carbonate compensation	10
silicate weathering	200



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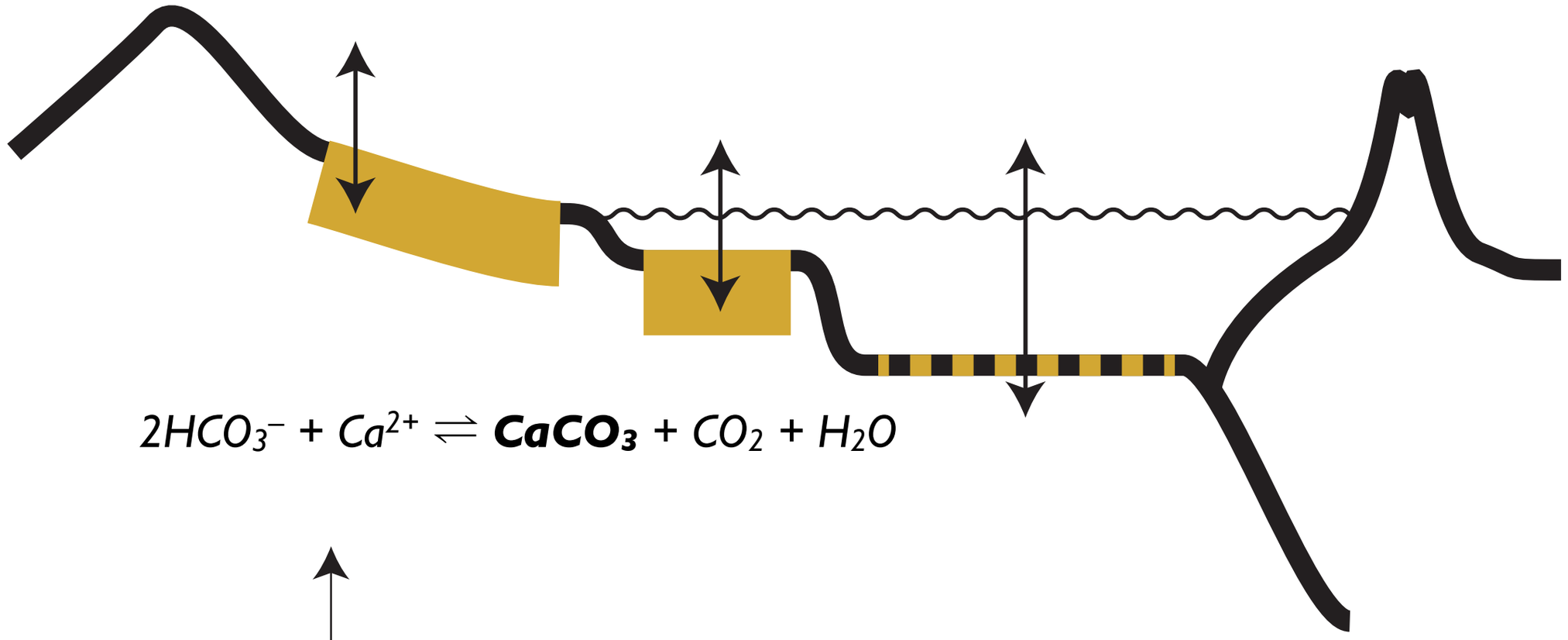
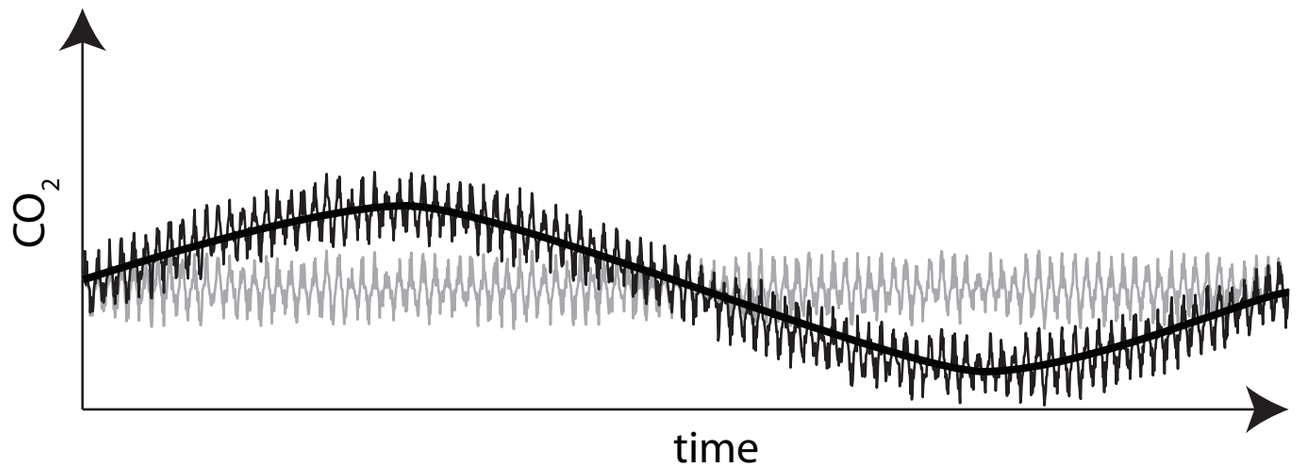


$$2HCO_3^- + Ca^{2+} \rightleftharpoons \mathbf{CaCO_3} + CO_2 + H_2O$$



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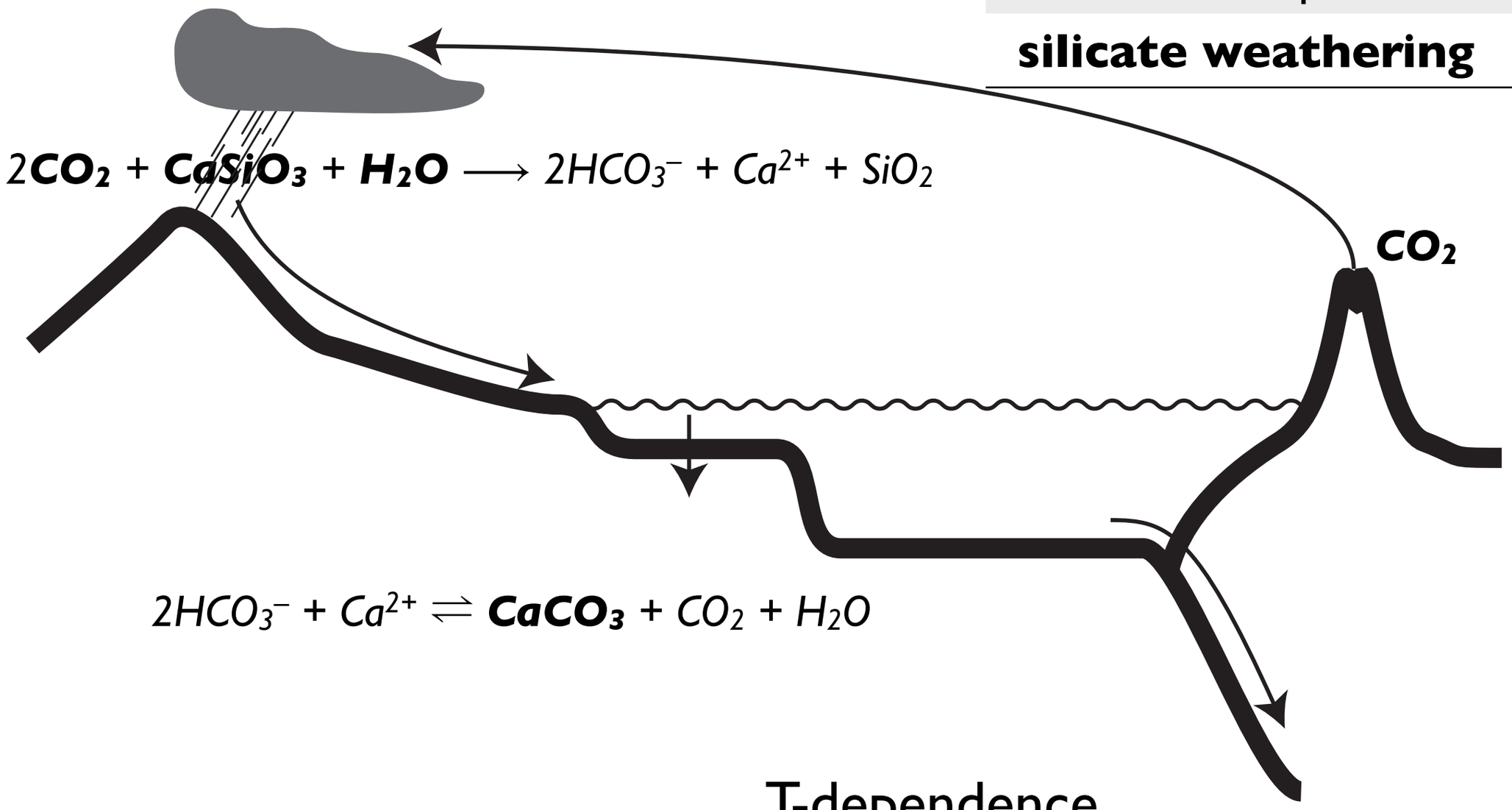


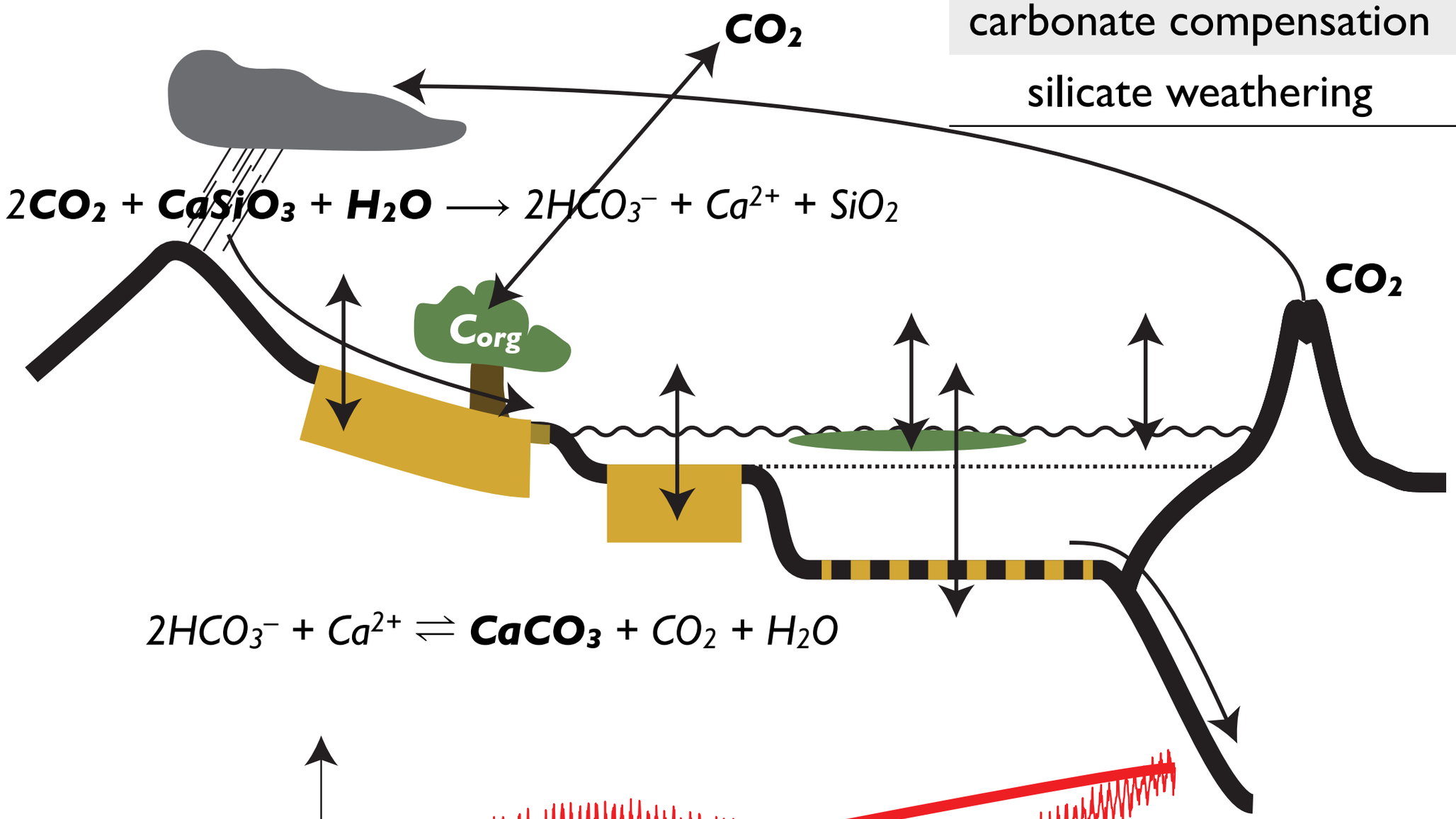
T-dependence

↓

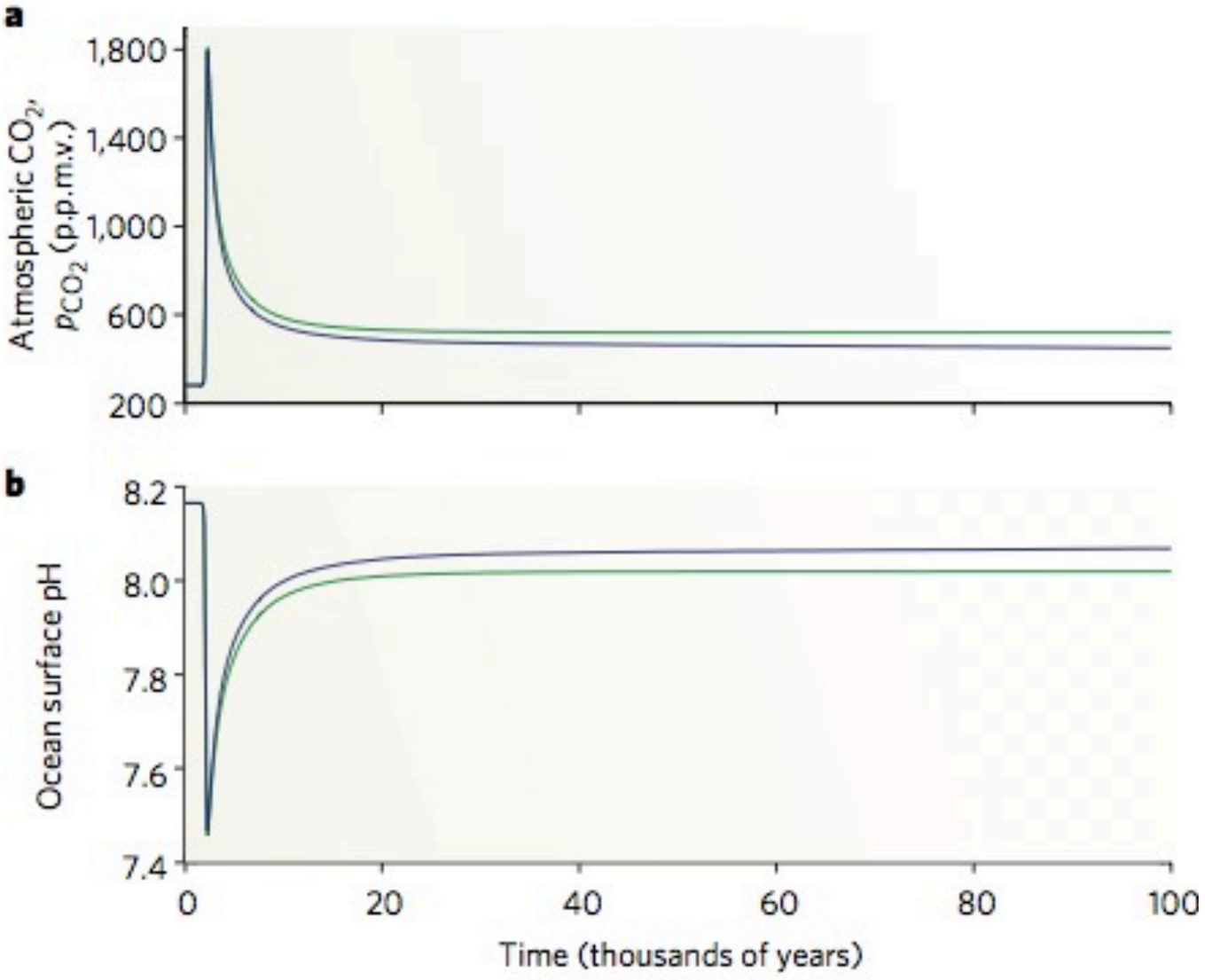
Net reaction: $CO_2 + CaSiO_3 \longrightarrow CaCO_3 + SiO_2$

C cycle timescales

process	τ (kyr)
atm-biosphere	0.1
atm-ocean	1
carbonate compensation	10
silicate weathering	200



Model response to PETM-like CO_2 injection



Zachos *et al.*, *Nature*, 2008

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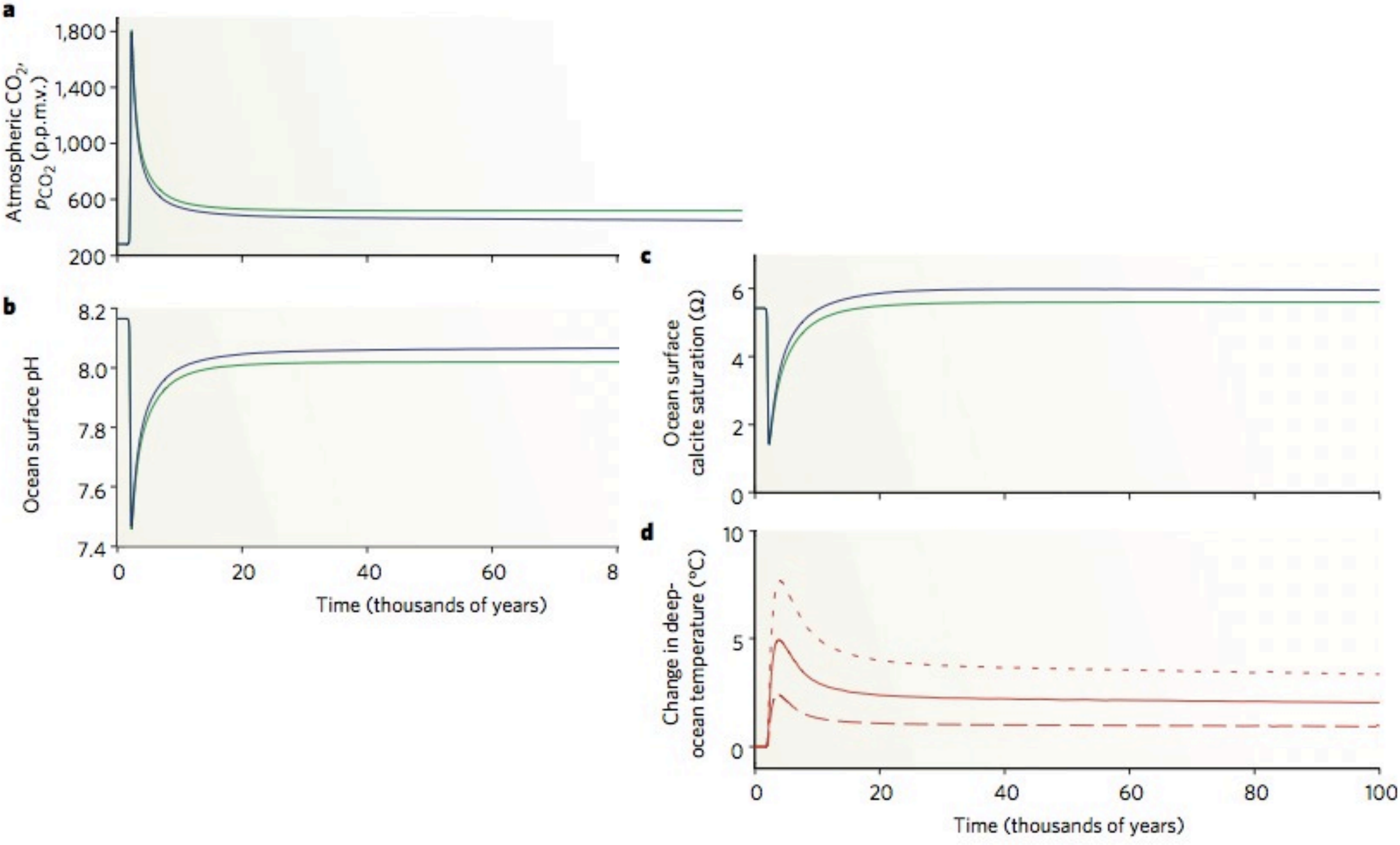
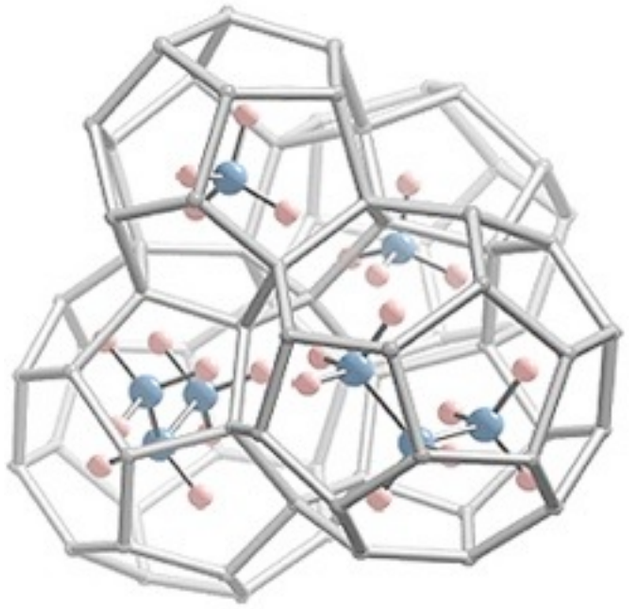
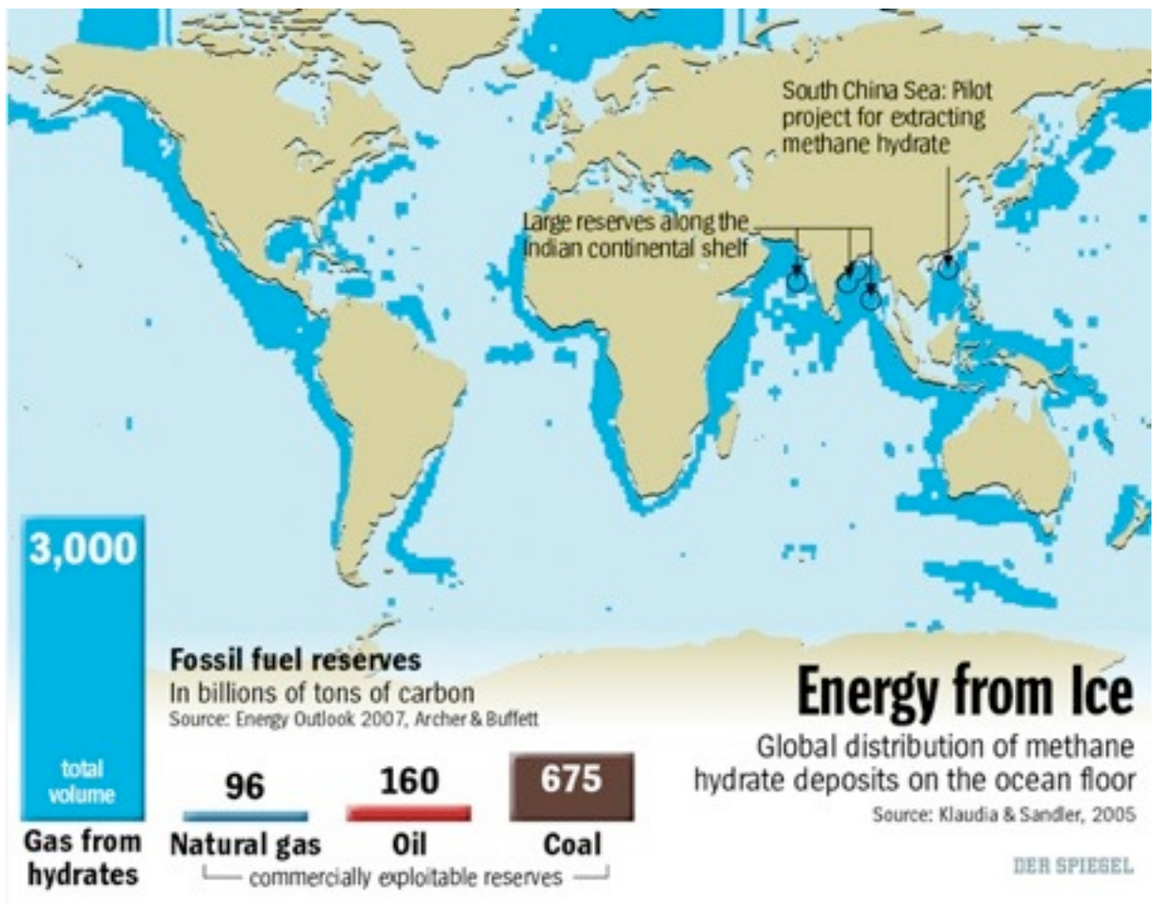


Zachos *et al.*, *Nature*, 2008

Positive feedbacks: CH_4 hydrates





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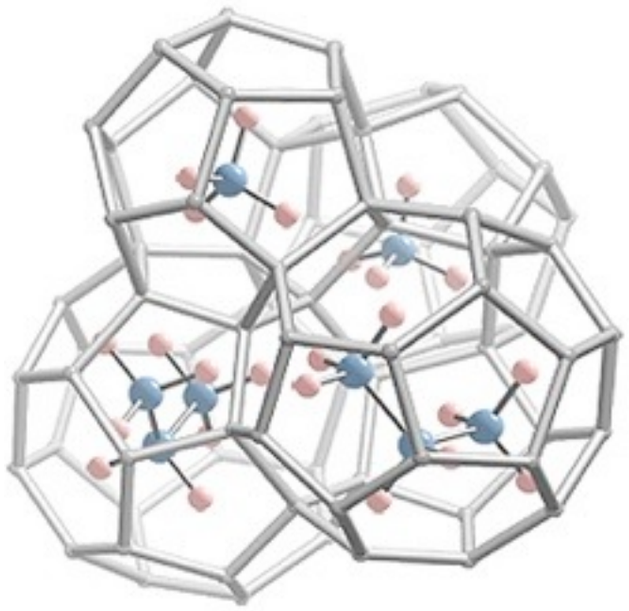
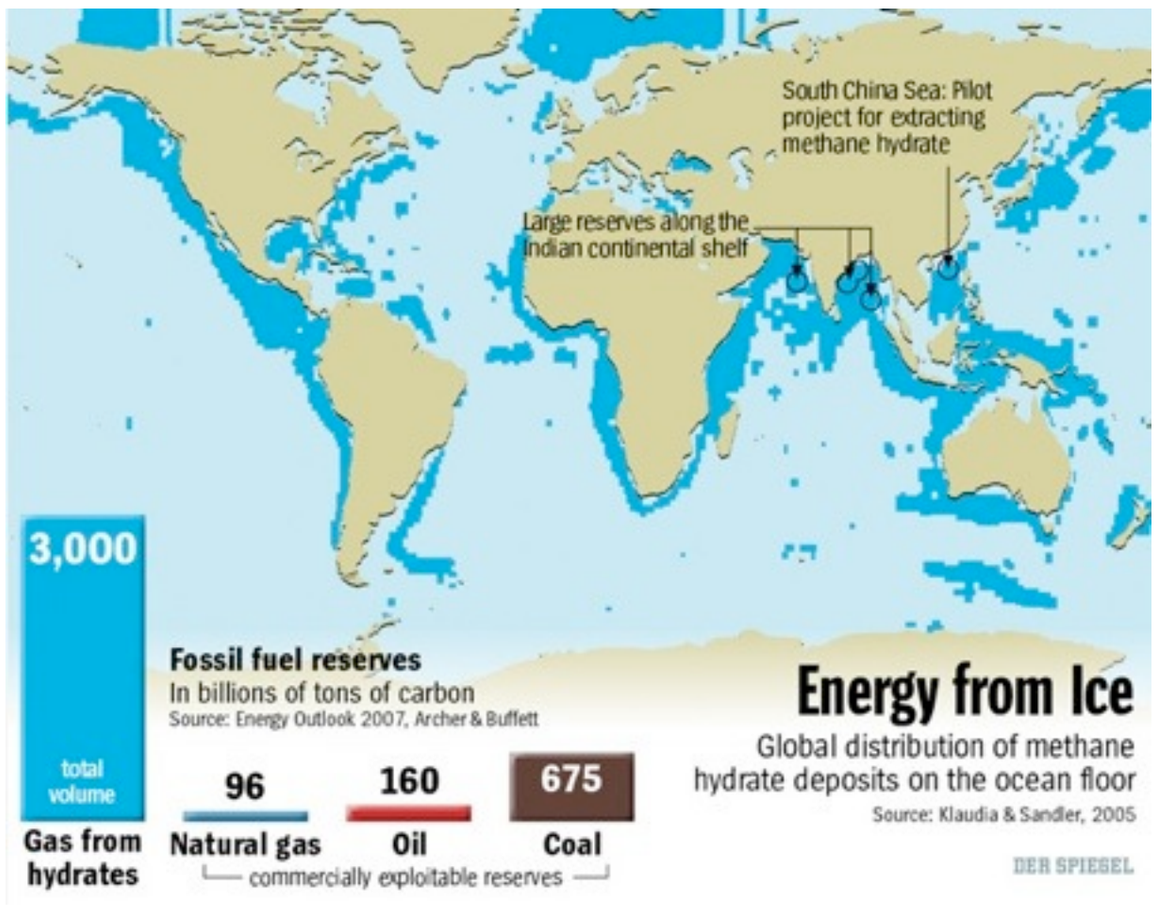
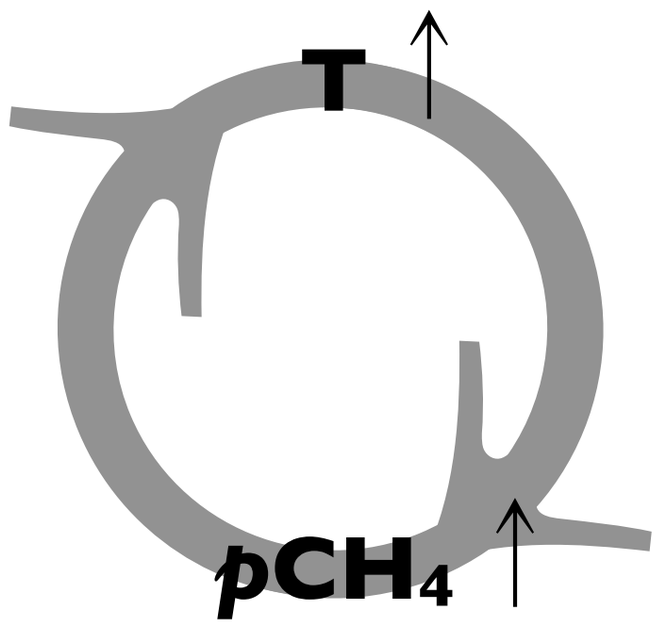
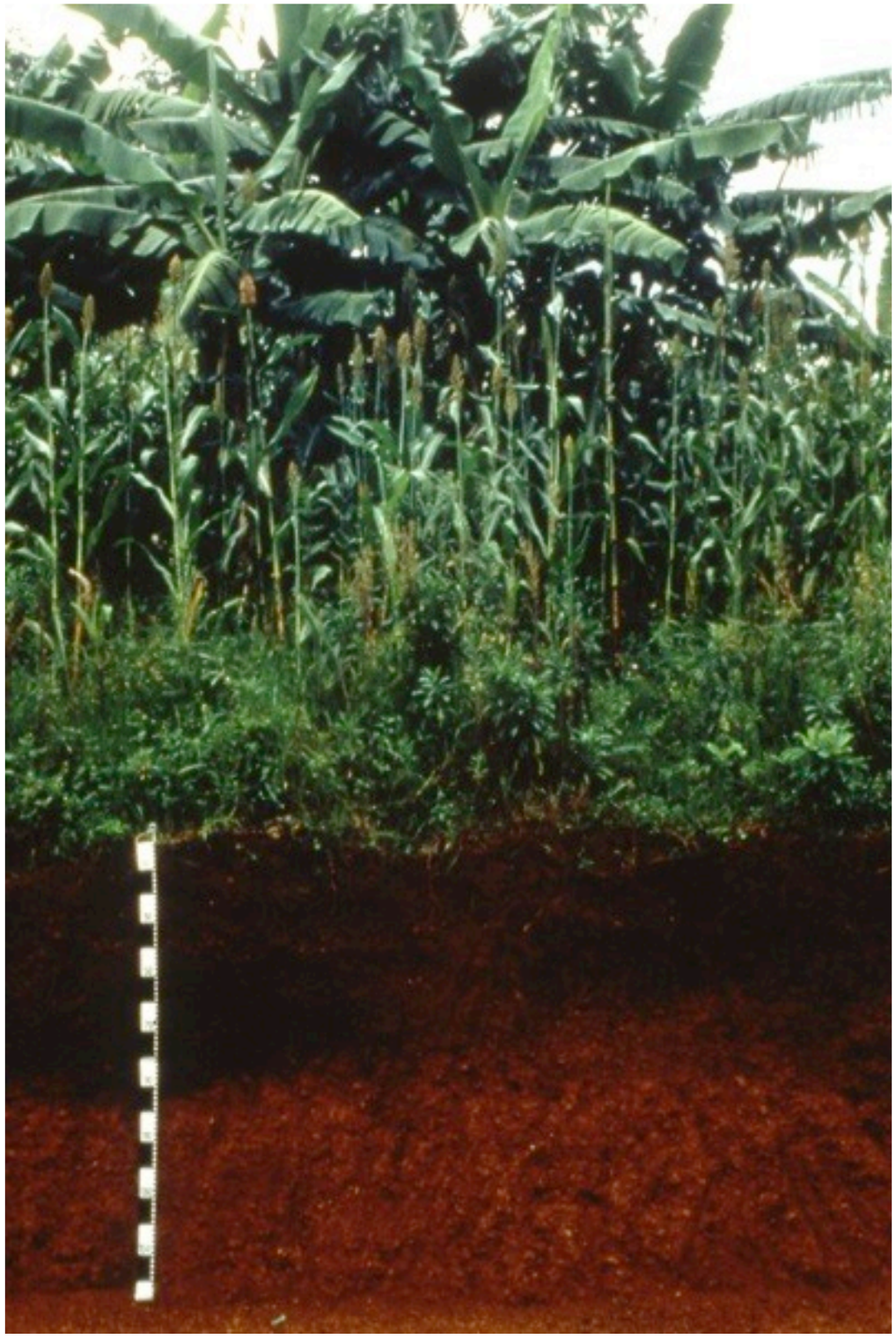






Positive feedbacks: Soil organic C



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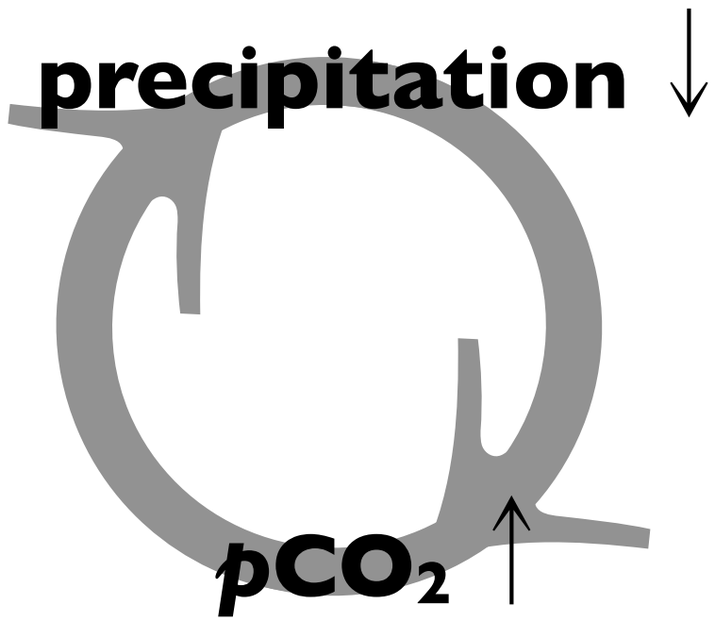

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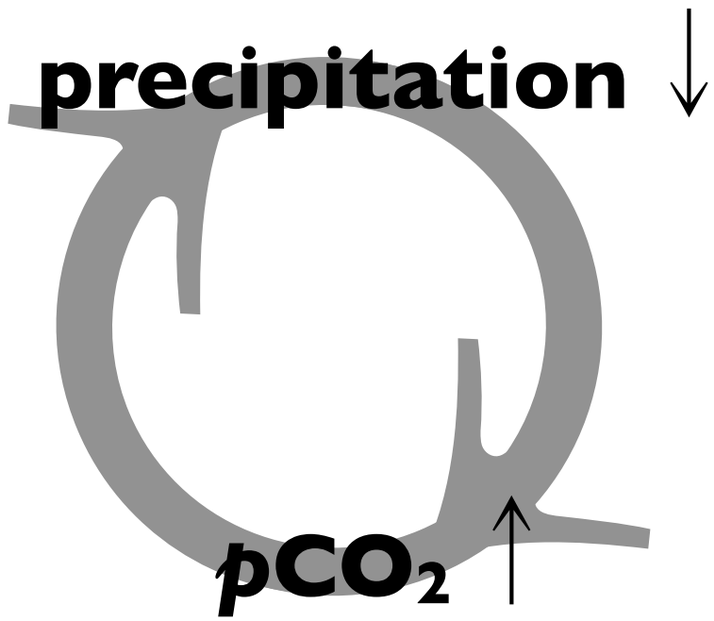
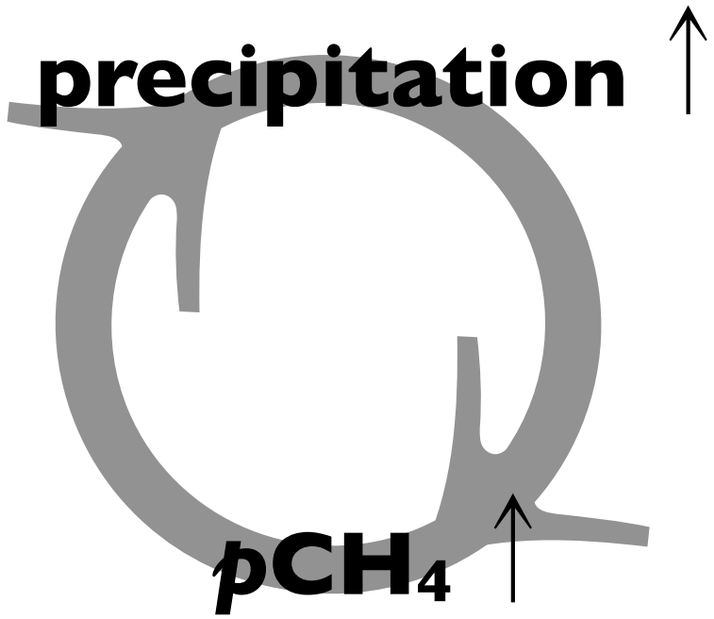
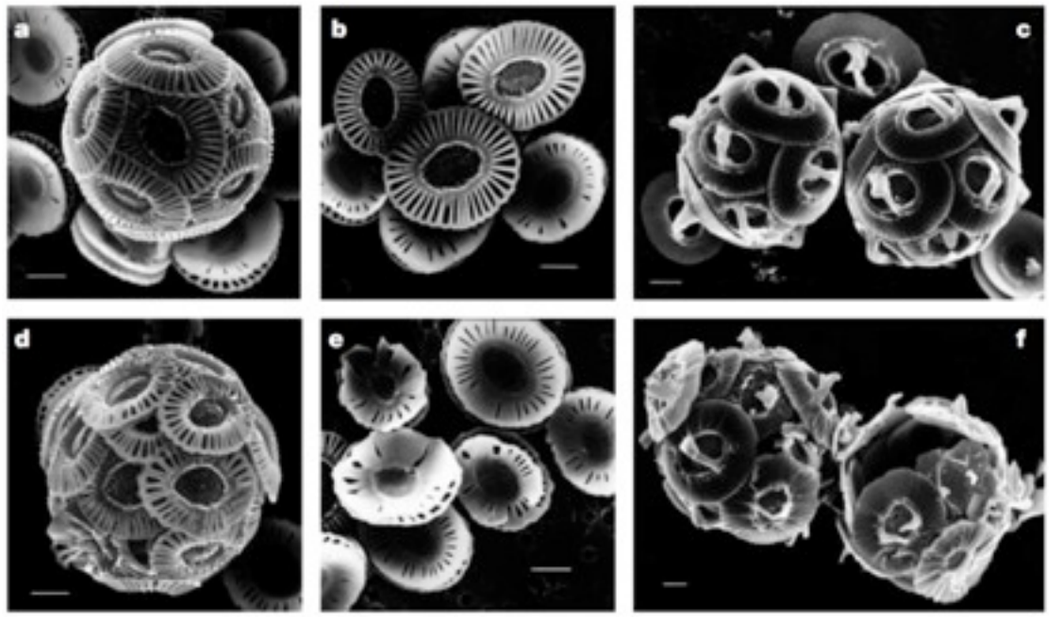
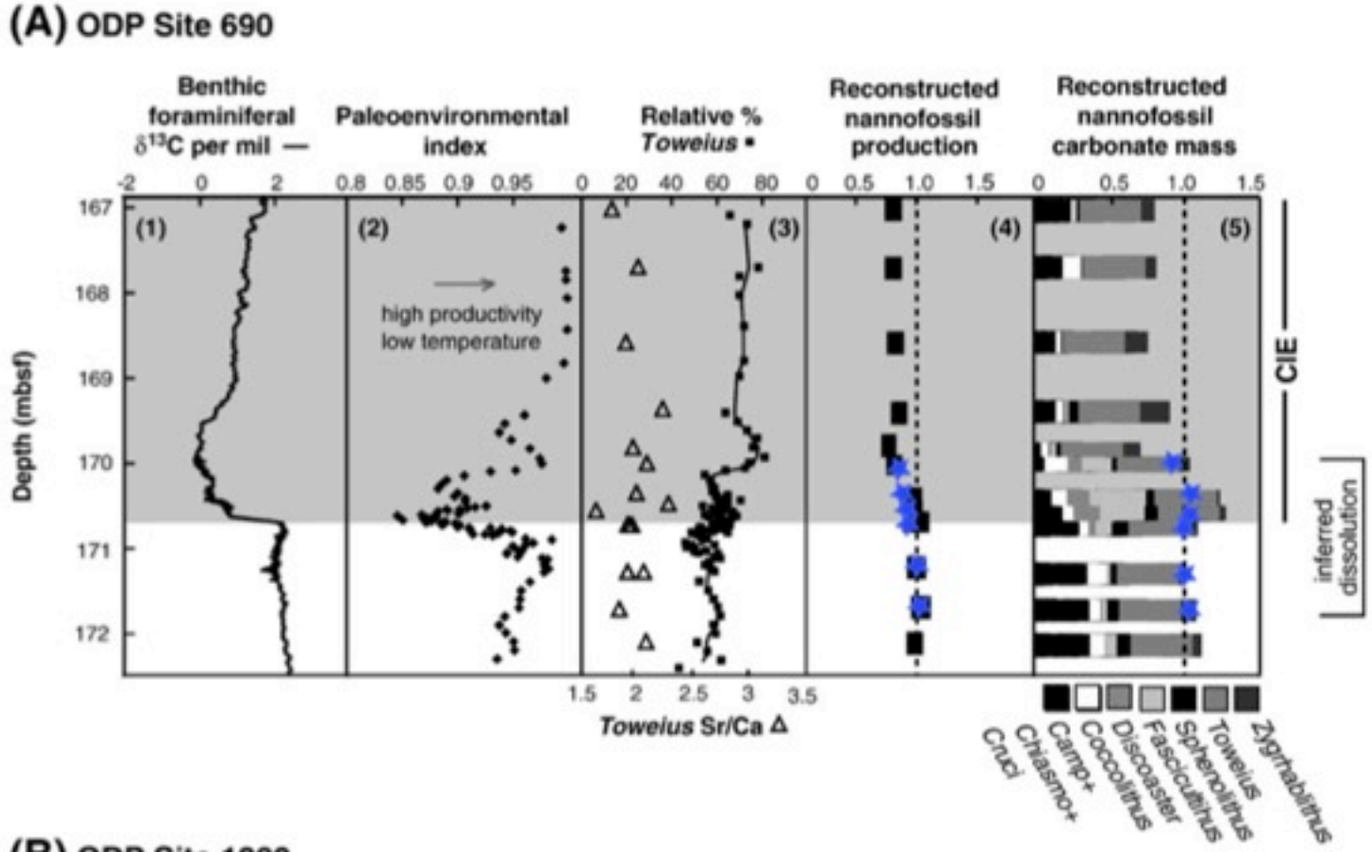


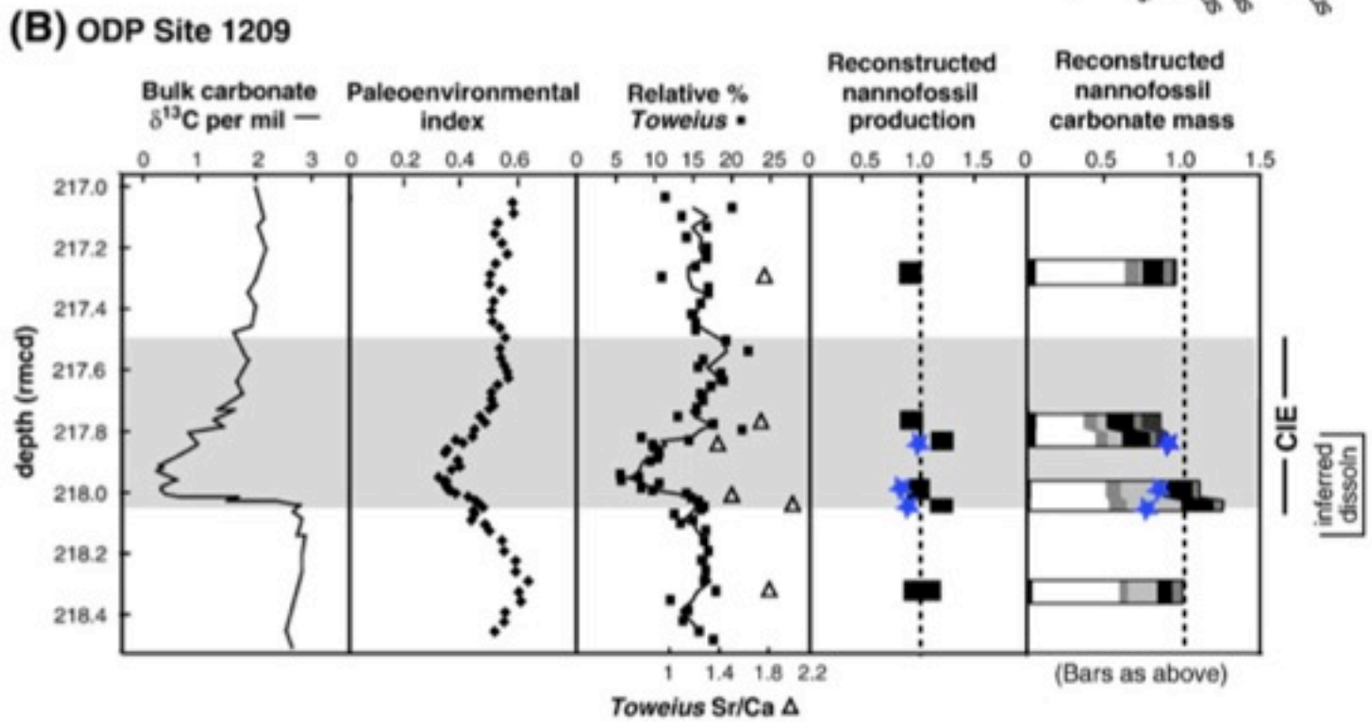


Effect on biomineralization?



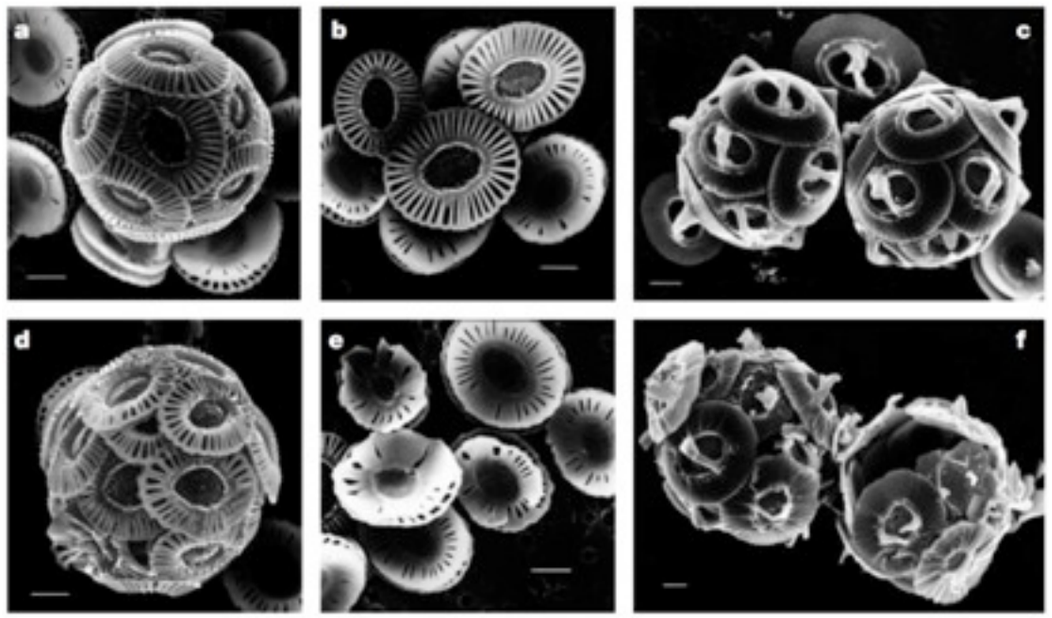
Riebesell *et al.*, *Nature*, 2000





Gibbs *et al.*, *Earth & Planetary Science Letters*, 2010

Effect on biomineralization?



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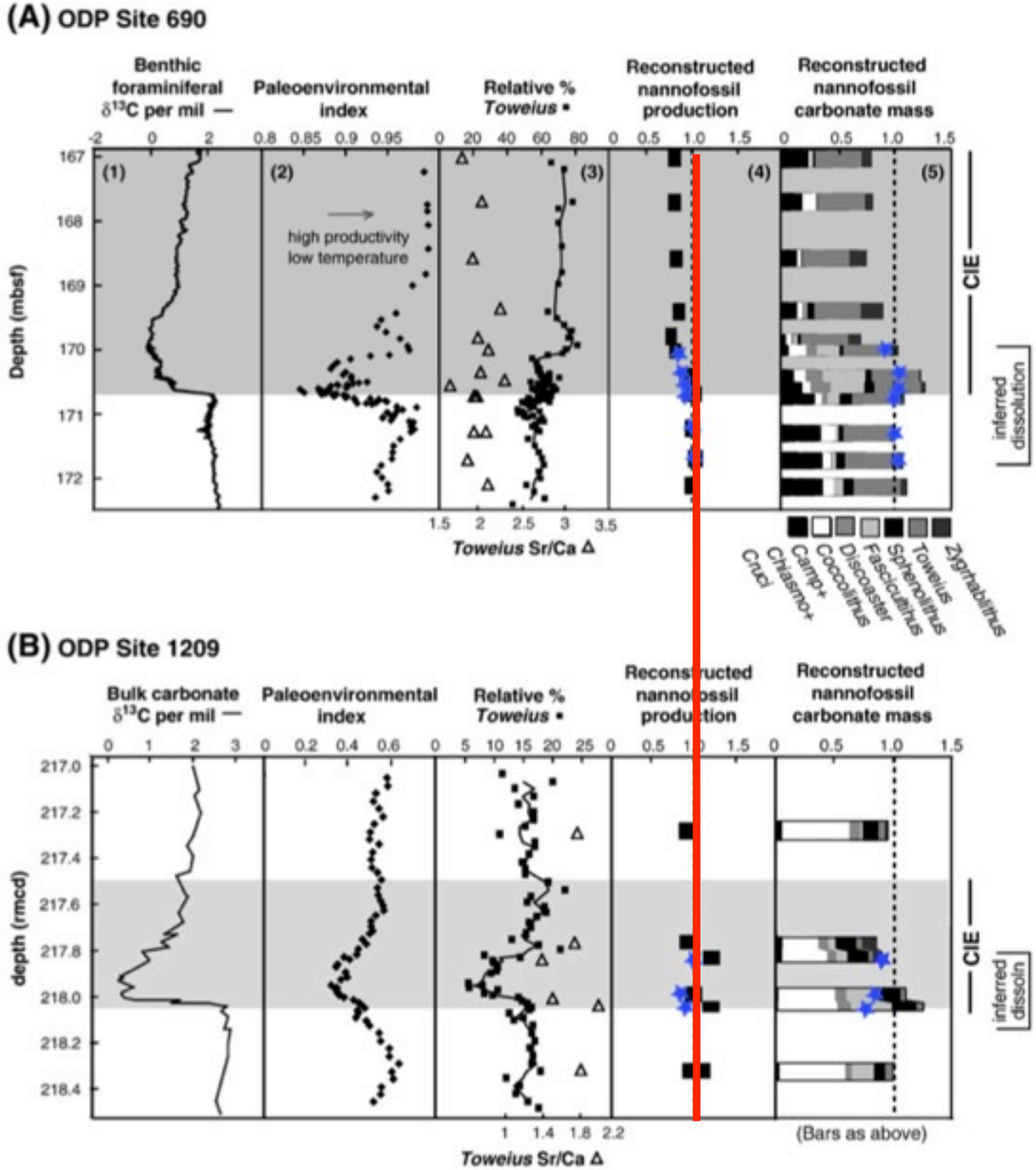


Gibbs *et al.*, *Earth & Planetary Science Letters*, 2010

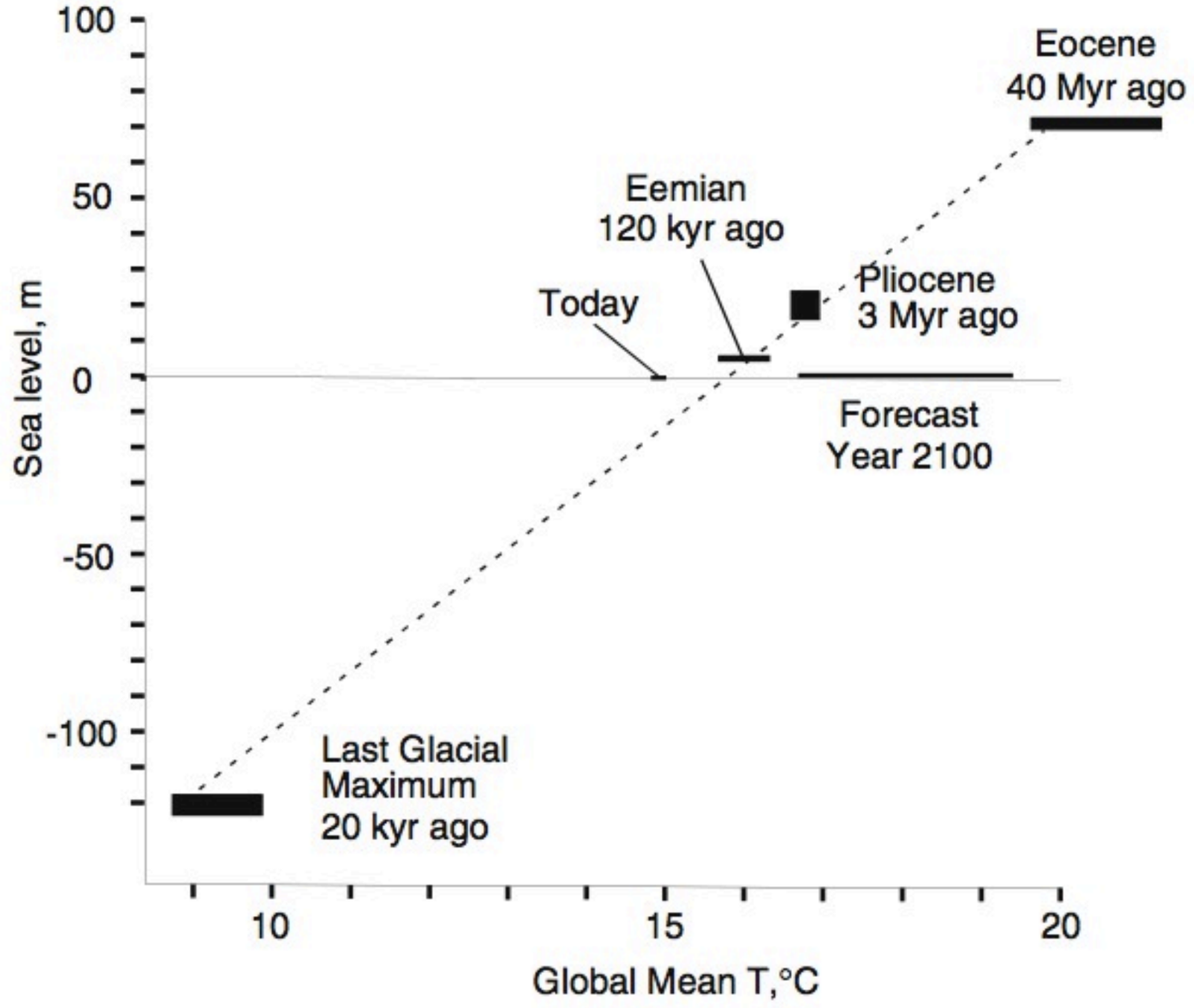
On geologic timescales, no effect on calcification apparent

PETM summary

- 5,000 Gt C released as CO_2 and CH_4 over ~10,000 years
- Deep ocean T warmed by ~5°C despite warm background climate
- Climate sensitivity ~3°C per CO_2 doubling
- The carbonate saturation horizon shoaled by >2 km
- Extinction of benthic organisms, but planktonic organisms apparently unaffected

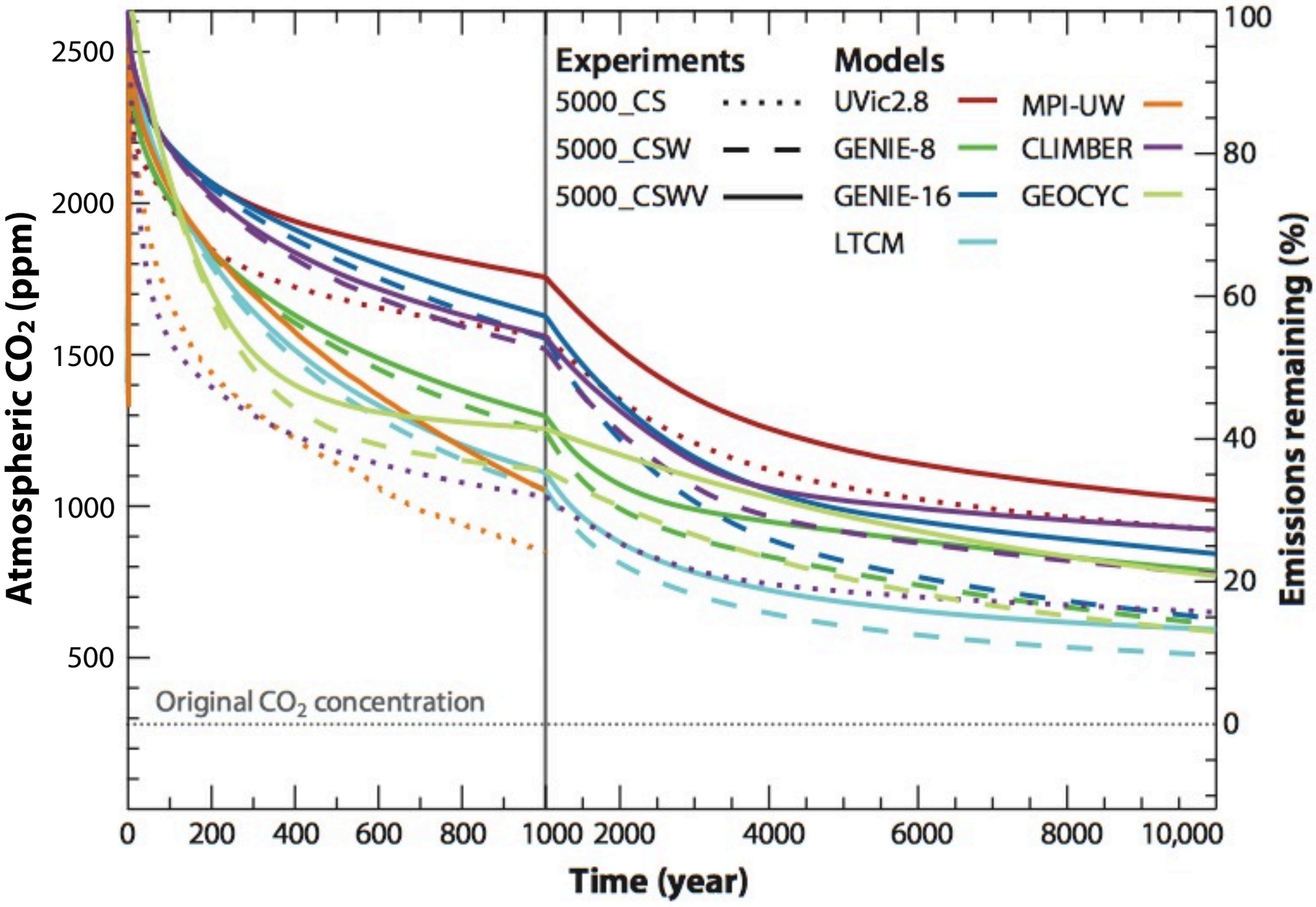
At moderate growth scenarios, we will release this amount of CO_2 by the year 2,400 (~500 years)

A perspective on sea level



Archer & Brovkin, *Climatic Change*, 2008

Model response to PETM-like CO_2 injection



Archer *et al.*, *Ann Rev Earth Planet Sci*, 2009

Summary

- Anthropogenic emission of CO_2 and other greenhouse gases is warming Earth, melting ice, raising sea level and decreasing ocean pH.

- Uncertainty in radiative forcing and feedback sign and magnitude translates into uncertainty in climate sensitivity and impact severity.

- The geologic record of climate change can help constrain both the equilibrium climate and the short-term response.

- The equilibrium climate at present-day CO_2 levels is ~4°C warmer and ice-free in the N. Hemispere.

- By 2,400 we will have emitted ~5,000 Gt C into the atmosphere. Similar amounts released much more slowly during the PETM warmed the oceans by ~5°C, decreased surface ocean pH by ~1 unit, caused a global carbonate dissolution event.

- The effects of anthropogenic climate change will linger for multiple millennia.