Climate change and geodynamics

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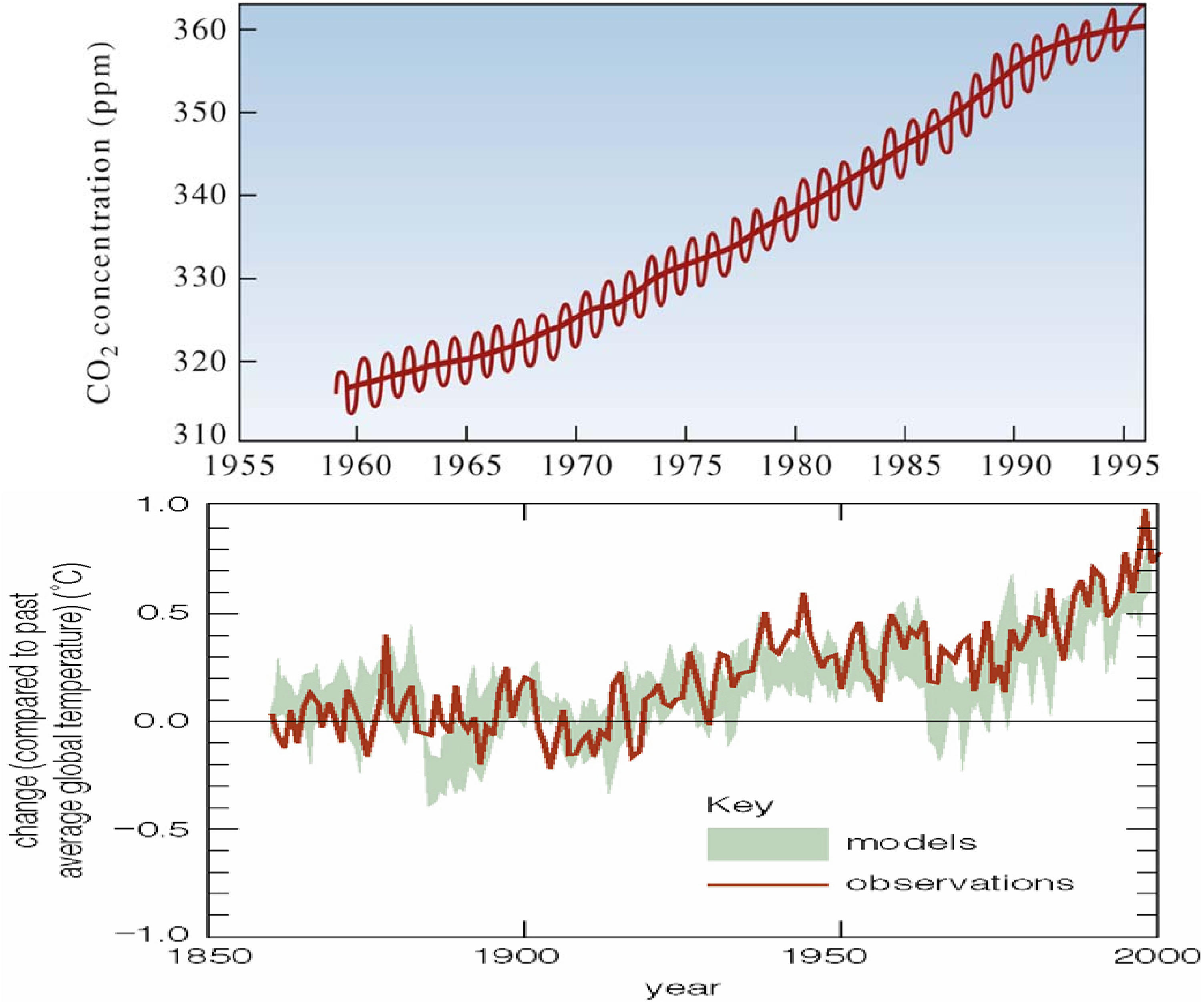
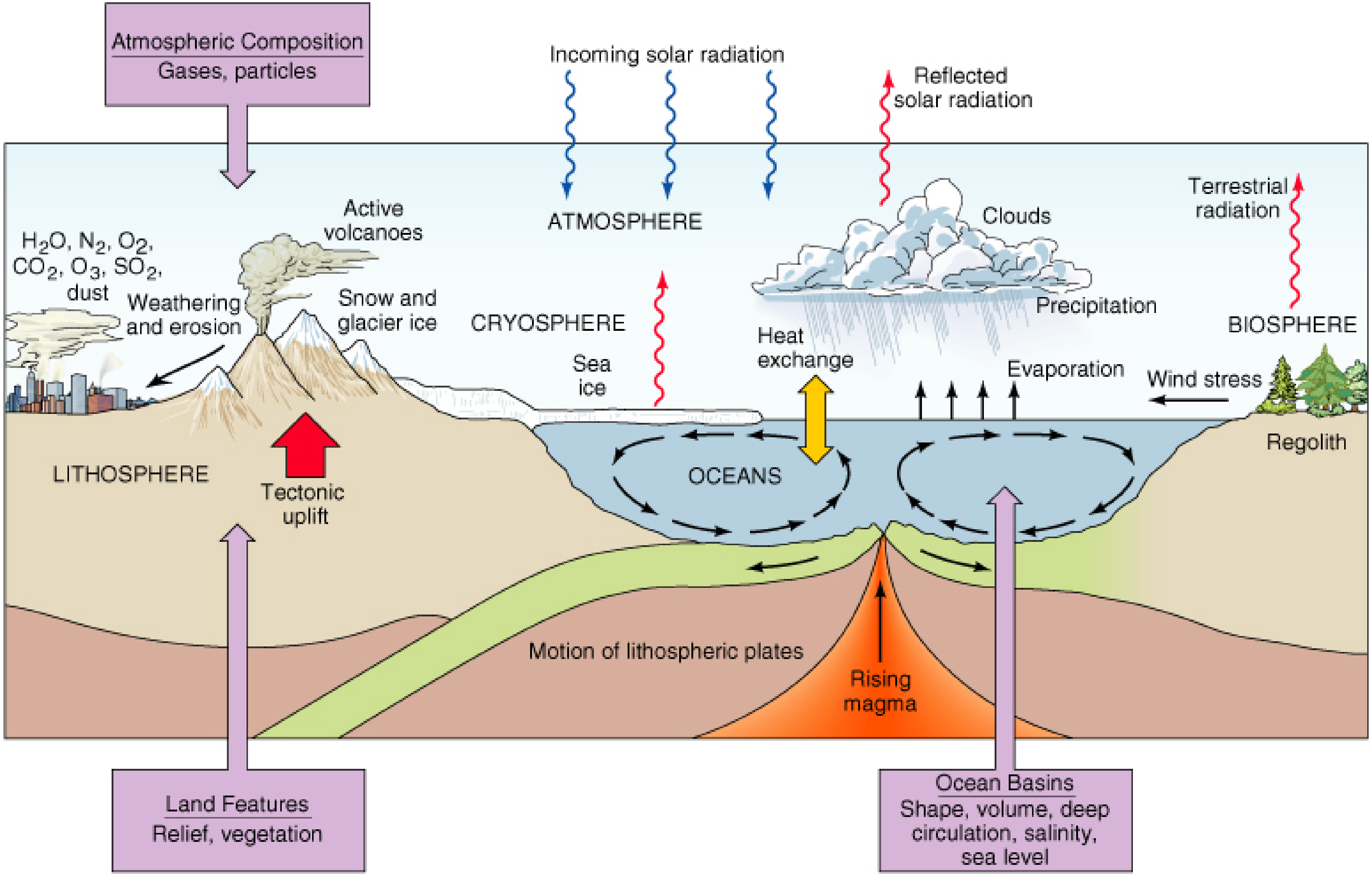
Outline

- Climate modeling and their challenges
- What can we learn from the deep past
- Snowball Earth
- Permian-Triassic mass extinction
- Cenozoic cooling
- Onset of Quaternary
- Conclusions

Atmospheric CO_2 and global surface temperature



The Earth's Climate System



„Primitive equations“

$$\frac{d\rho}{dt} = -\rho \operatorname{div} \mathbf{c};$$

$$\frac{du}{dt} = \frac{\tan\phi}{R} uv - \frac{uw}{R} + fv - f'w - \frac{1}{\rho}\frac{\partial p}{R\cos\phi\partial\lambda} + F_\lambda;$$

$$\frac{dv}{dt} = -\frac{\tan\phi}{R} u^2 - \frac{vw}{R} - fu - \frac{1}{\rho}\frac{\partial p}{R\partial\phi} + F_\phi;$$

$$\frac{dw}{dt} = \frac{u^2}{R} + \frac{v^2}{R} + f'u - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + F_z;$$

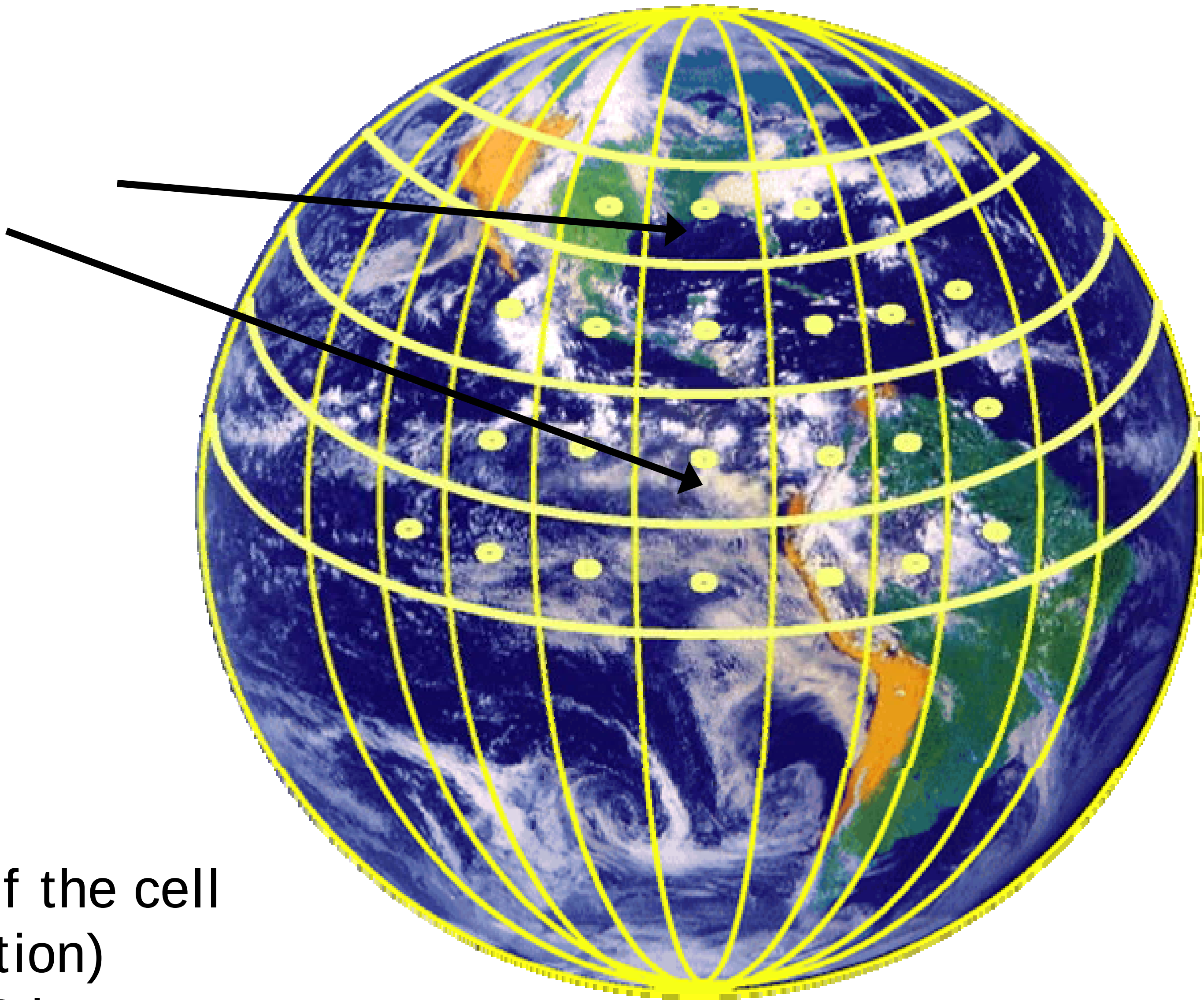
$$c_p\frac{dT}{dt} = Q + \alpha\frac{dp}{dt};$$

$$\frac{dq}{dt} = s(q) + D;$$

$$p = \rho RT(1 + 0.61q).$$

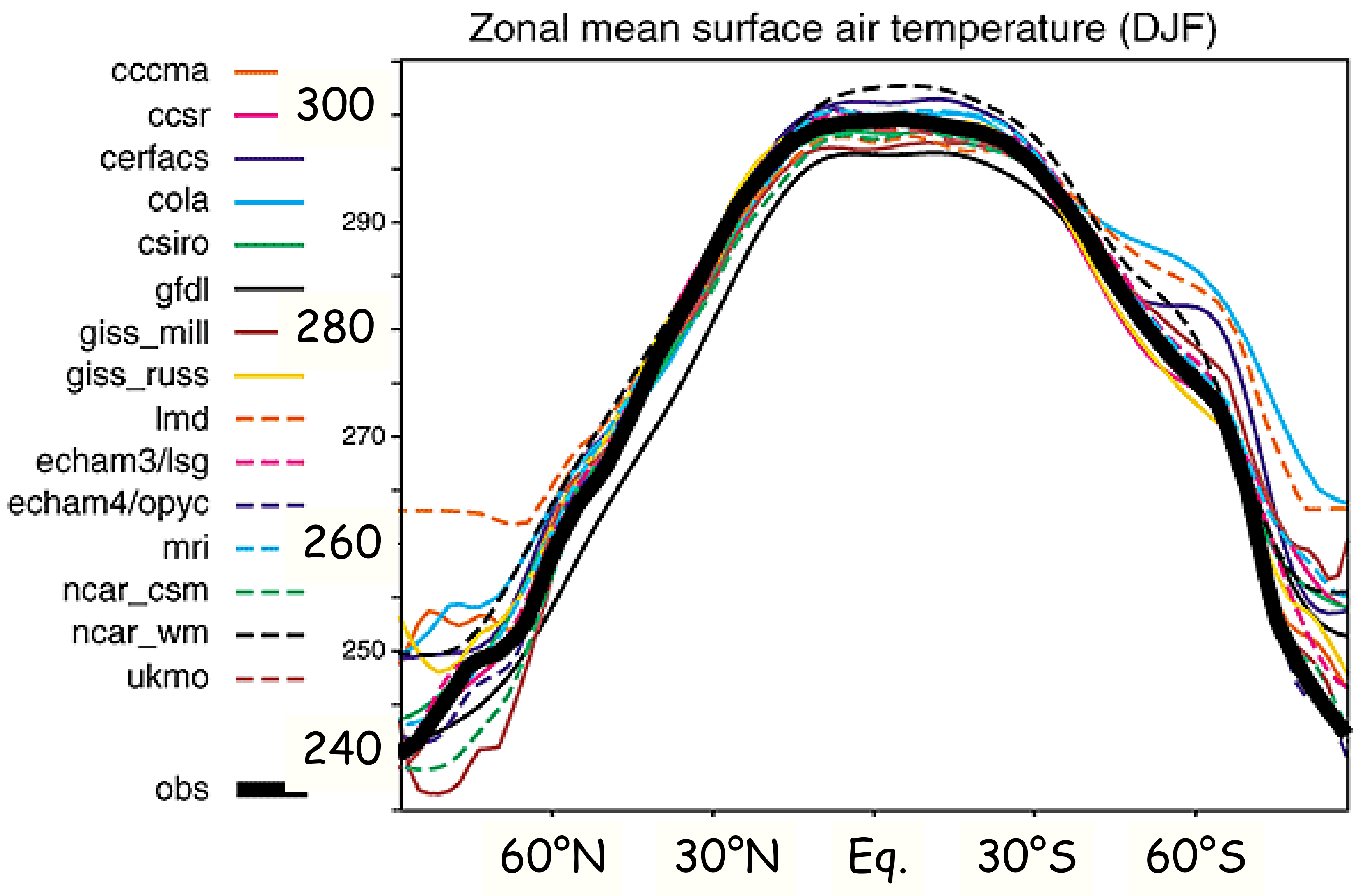
Discretization methods

The atmosphere and the ocean are divided in computational cells both horizontally and vertically.

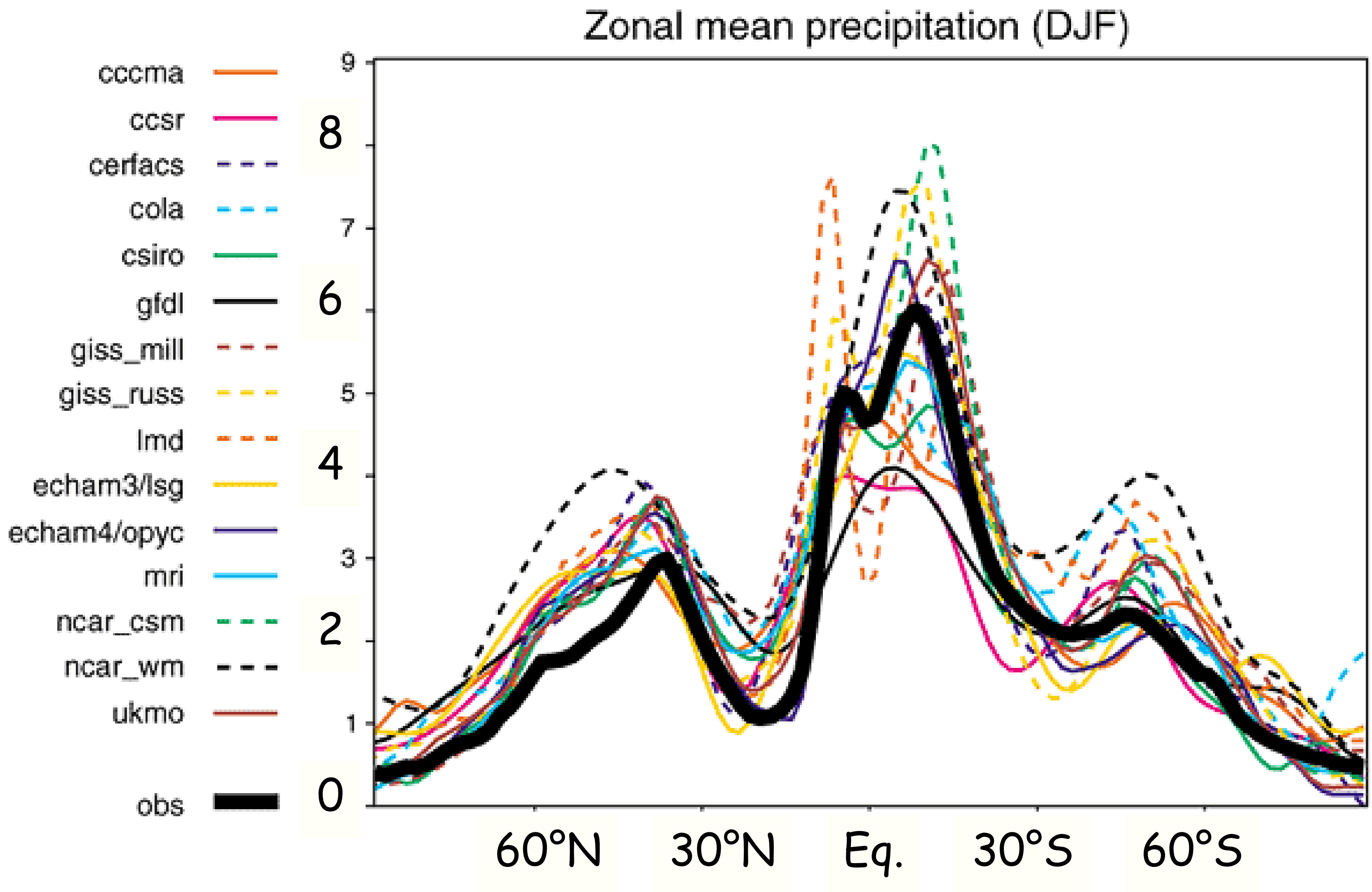


Dimension of the cell
(resolution)
100-200 km

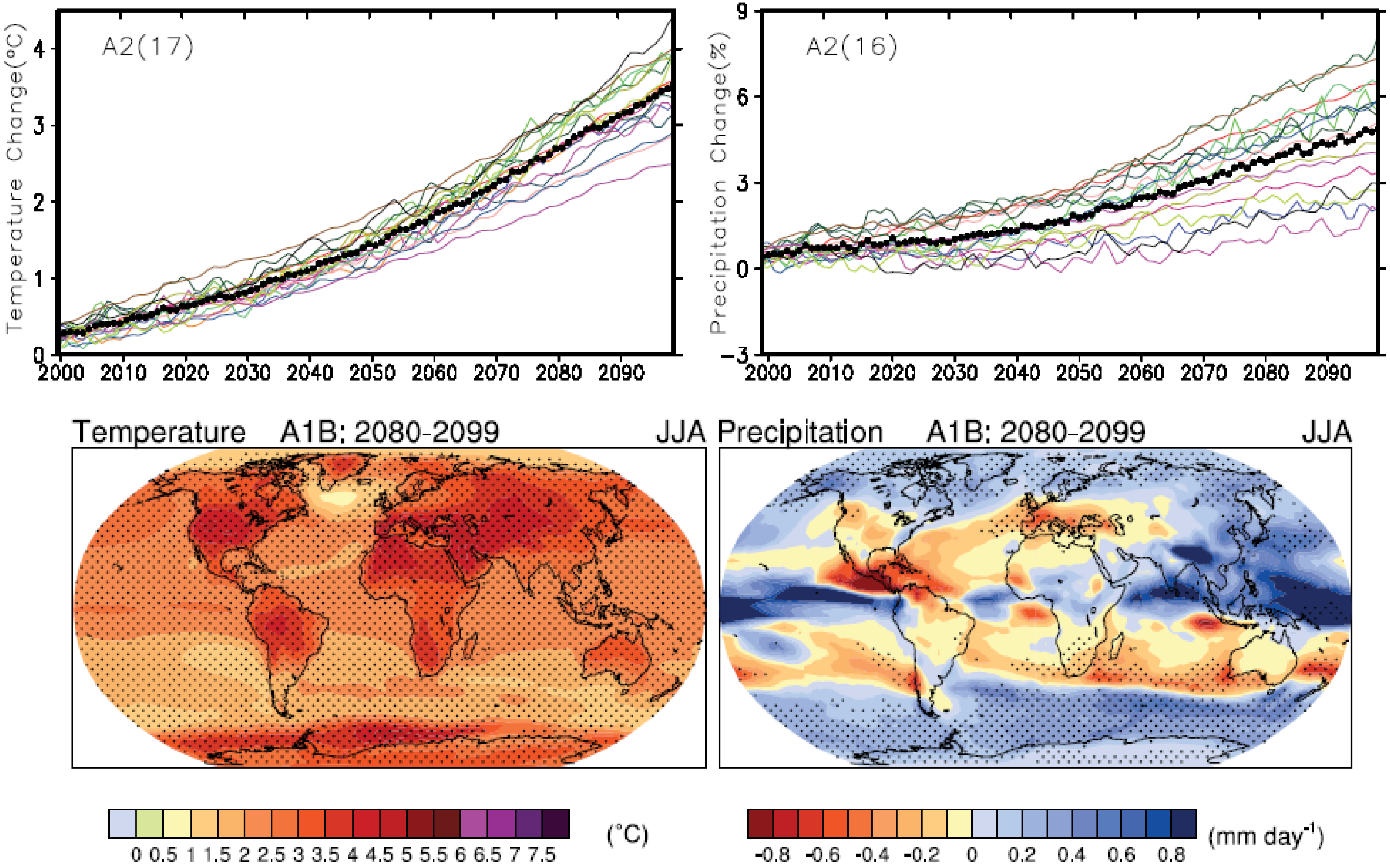
Model performance - Temperature



Model performance - Precipitation

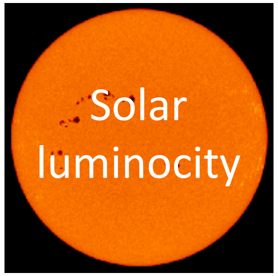


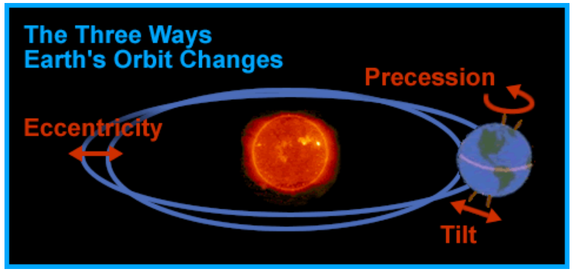
Global climate model projections for 21st century



External causes of climate change

Astronomical factors

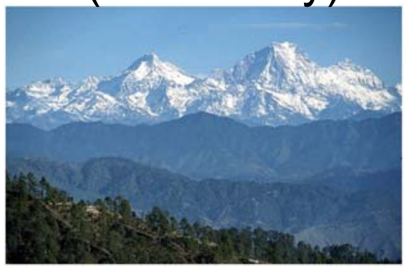




Volcanic Activity

Geography

Topography
(bathimetry)



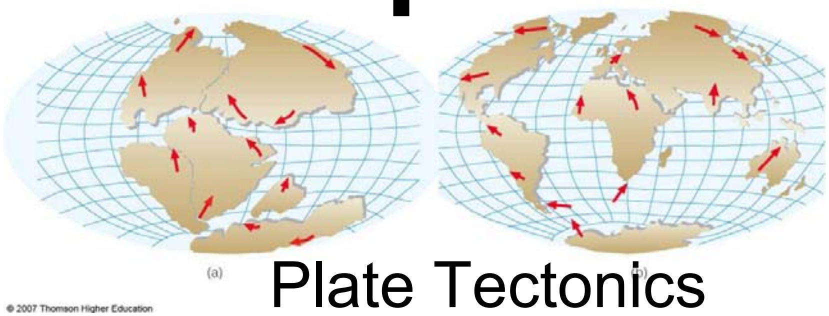
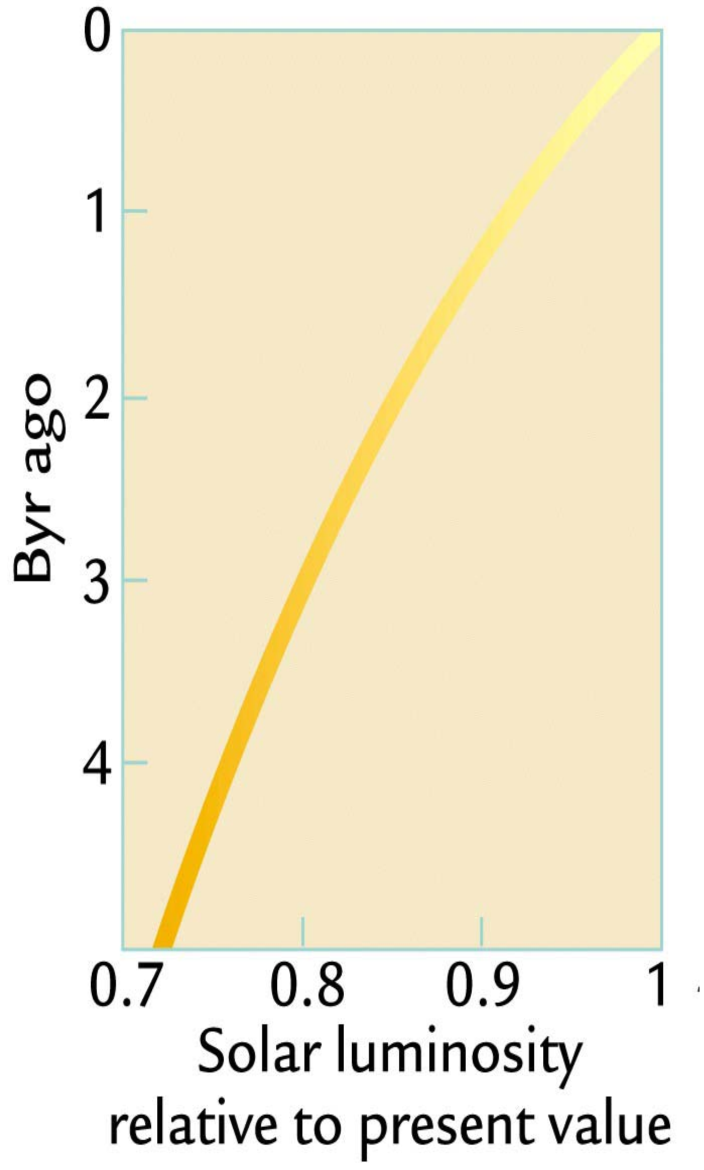


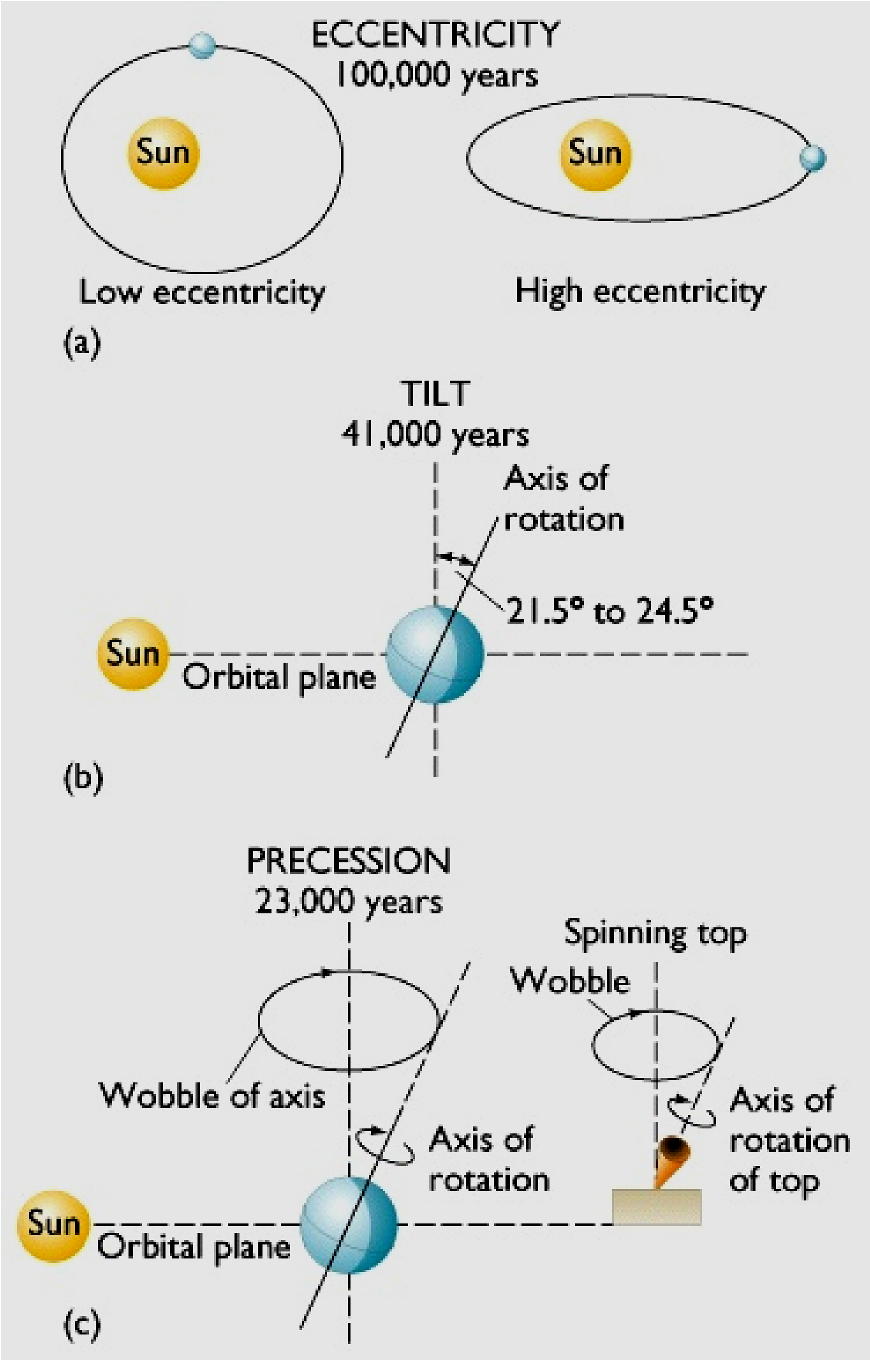
Plate Tectonics

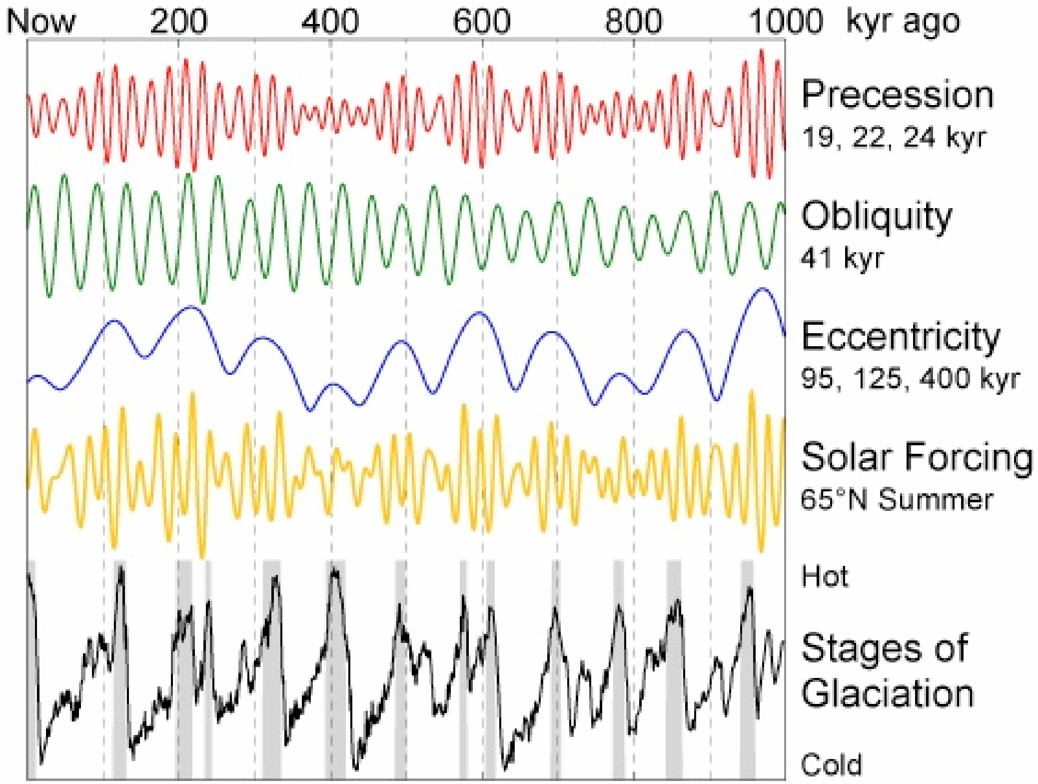
Early Earth: Faint Young Sun paradox

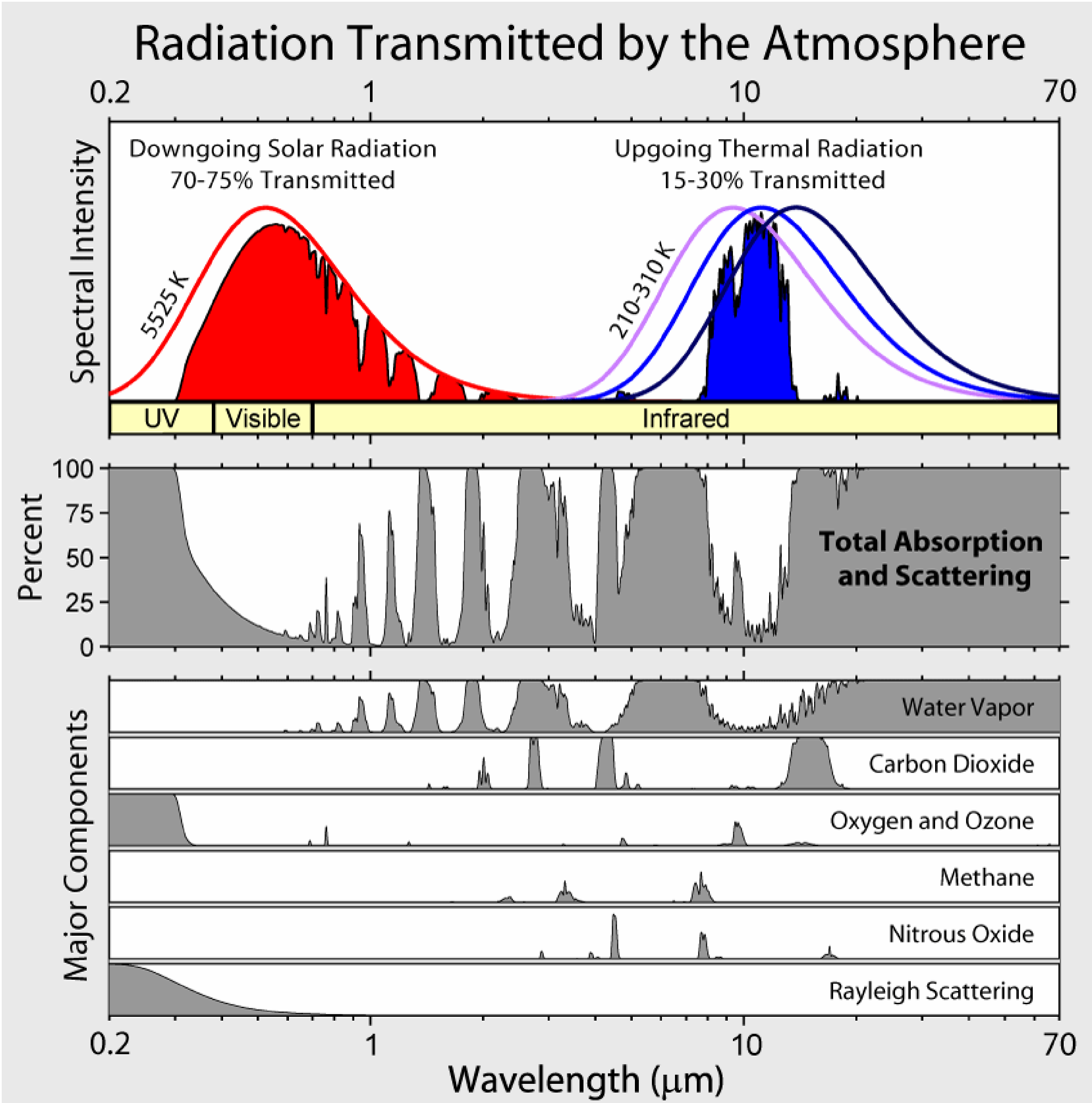
Solar luminosity 4.55 Ba was 25% lower than today



Milankovitch Cycles







Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (μm)

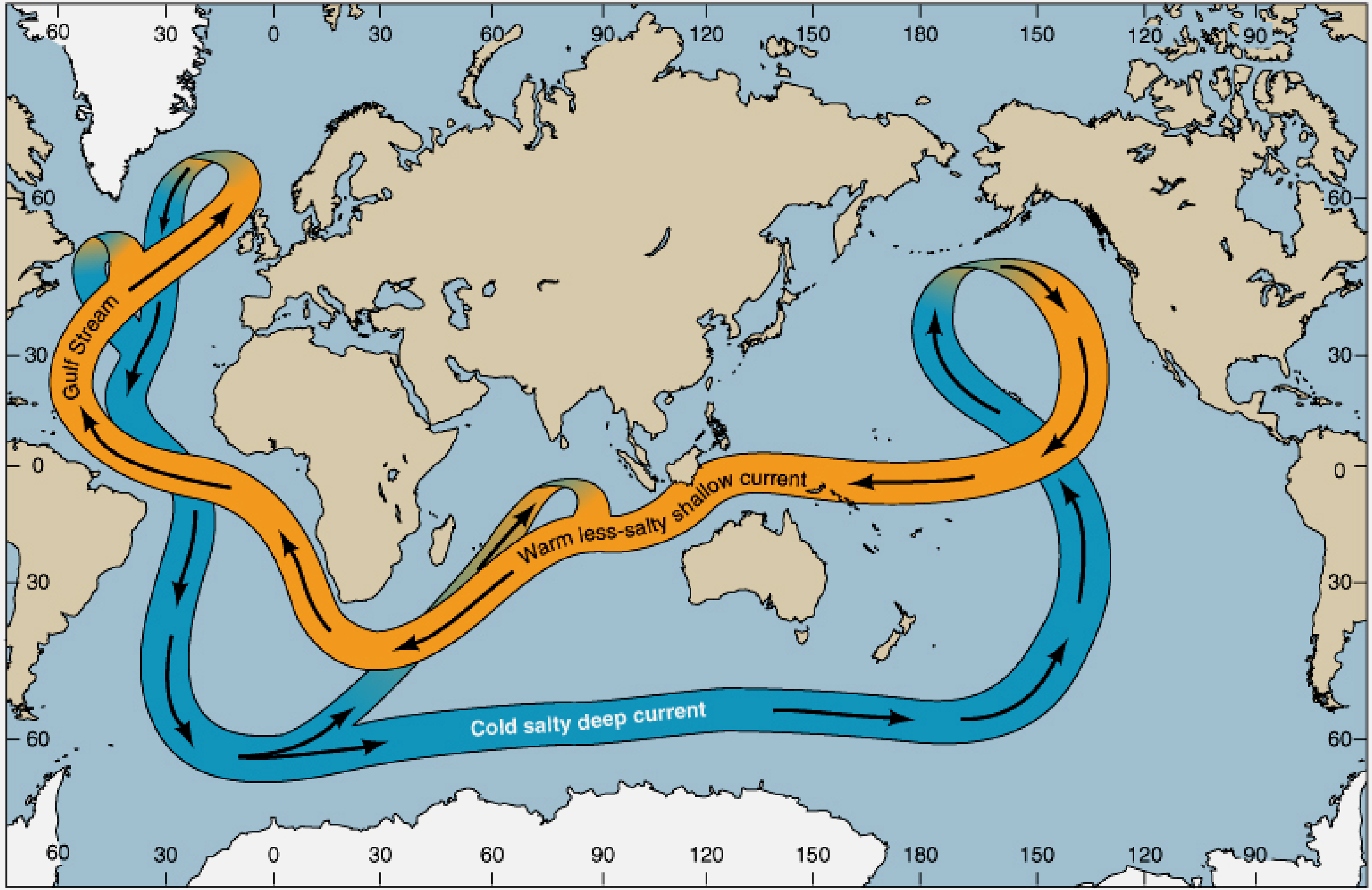
Table 11.2. The Greenhouse Effect on the Terrestrial Worlds

World	Average Distance from Sun (AU)	Reflectivity	"No Greenhouse" Average Surface Temperature*	Actual Average Surface Temperature	Greenhouse Warming (actual temperature minus "no greenhouse" temperature)
Mercury	0.387	11%	164°C	425°C (day), −175°C (night)	—
Venus	0.723	72%	−43°C	470°C	513°C
Earth	1.00	36%	−17°C	15°C	32°C
Moon	1.00	7%	0°C	125°C (day), −175°C (night)	—
Mars	1.52	25%	−55°C	−50°C	5°C

*The "no greenhouse" temperature is calculated by assuming no change to the atmosphere other than lack of greenhouse warming. Thus, for example, Venus ends up with a lower "no greenhouse" temperature than Earth even though it is closer to the Sun, because the high reflectivity of its bright clouds means that it absorbs less sunlight than Earth.

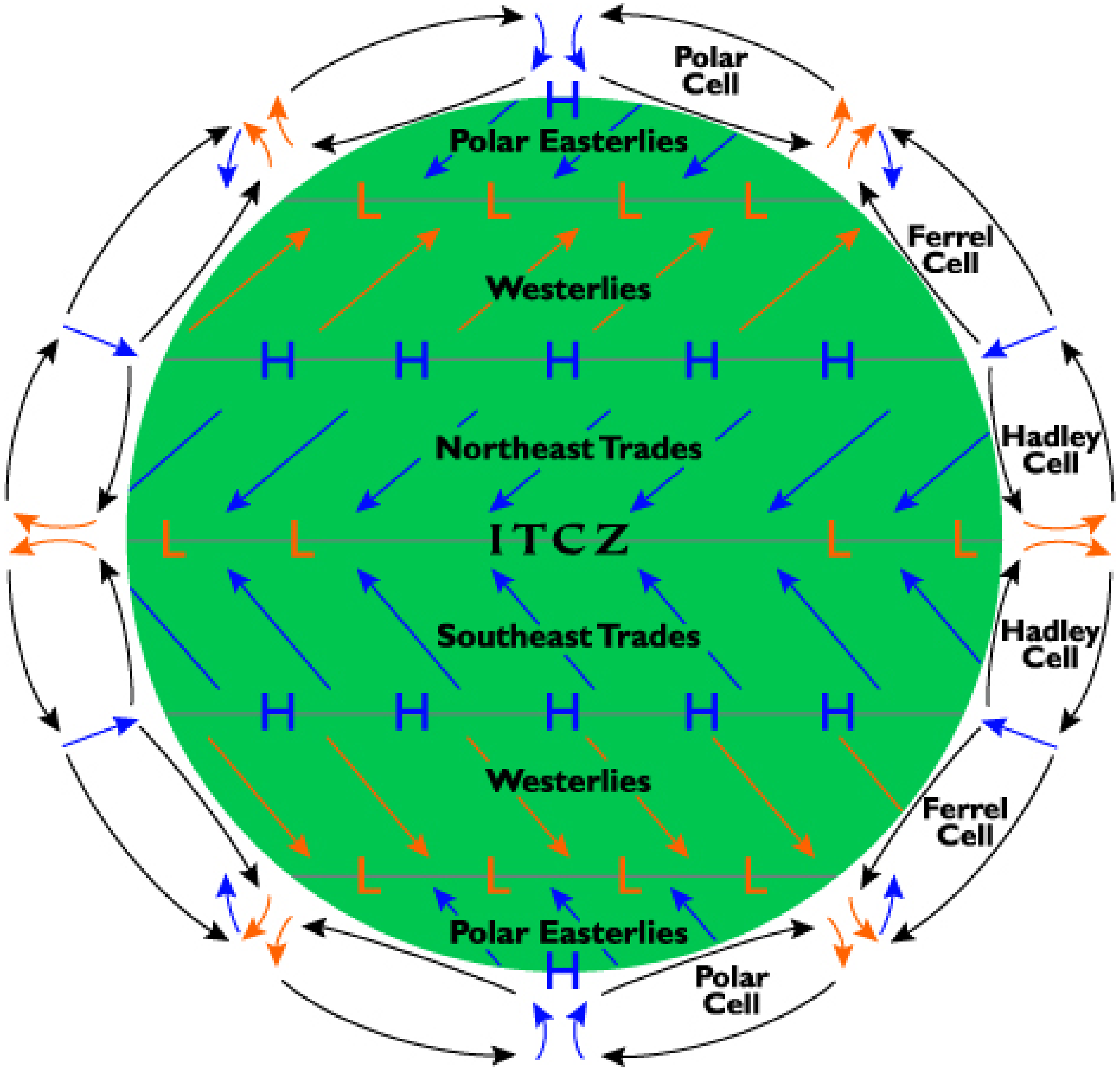
Greenhouse effect gives +32°C warming and allows for liquid H_2O to exist on the planet

Present global ocean circulation



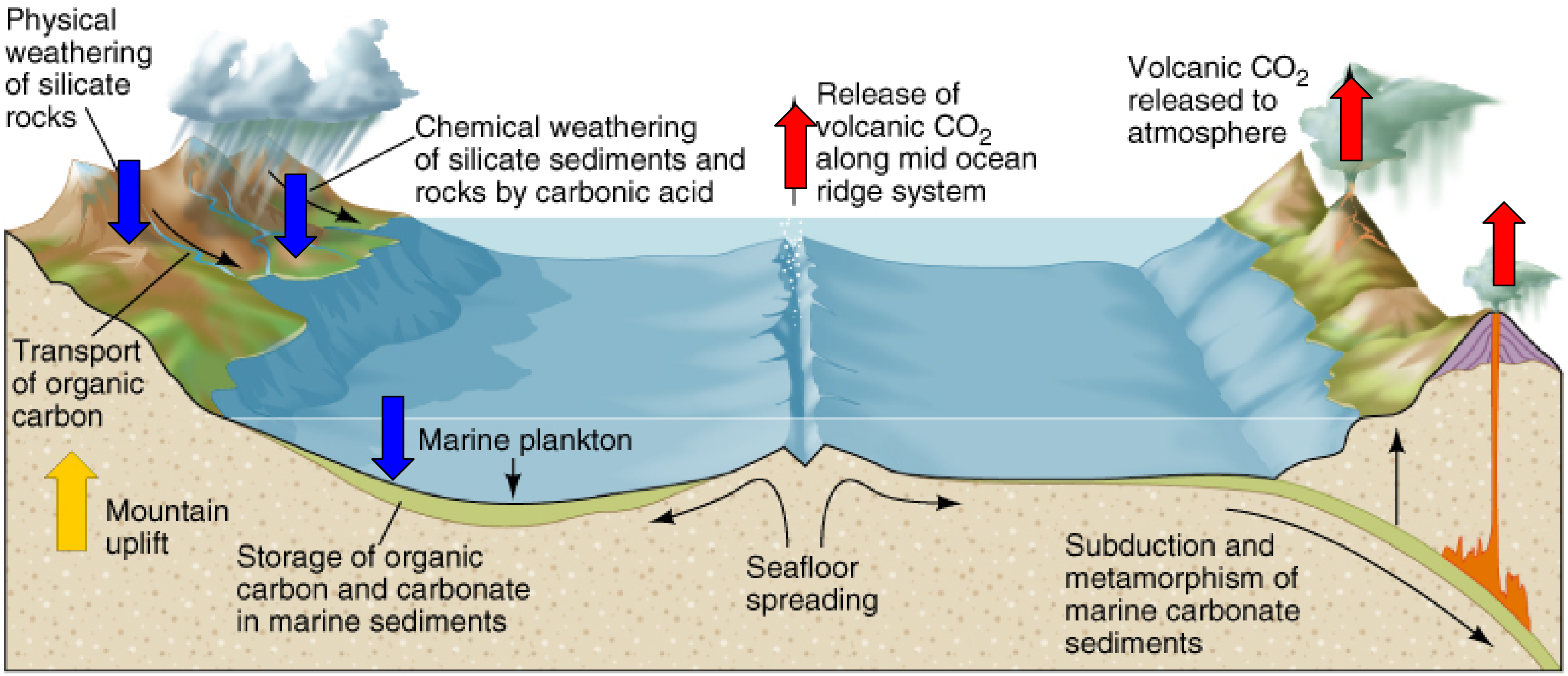
Based on information from Lamont-Doherty Geological Observatory (Columbia University) Report 1990/91, Fig. 4, p. 50; J. Imbrie et al. (1992). On the structure and origin of major glaciation cycles, 1: Linear responses to Milankovitch forcing *Paleoceanography* 7, Fig. 1b, p. 704, published by the American Geophysical Union.

Global atmosphere circulation



The CO_2 Cycle as Earth's Thermostat

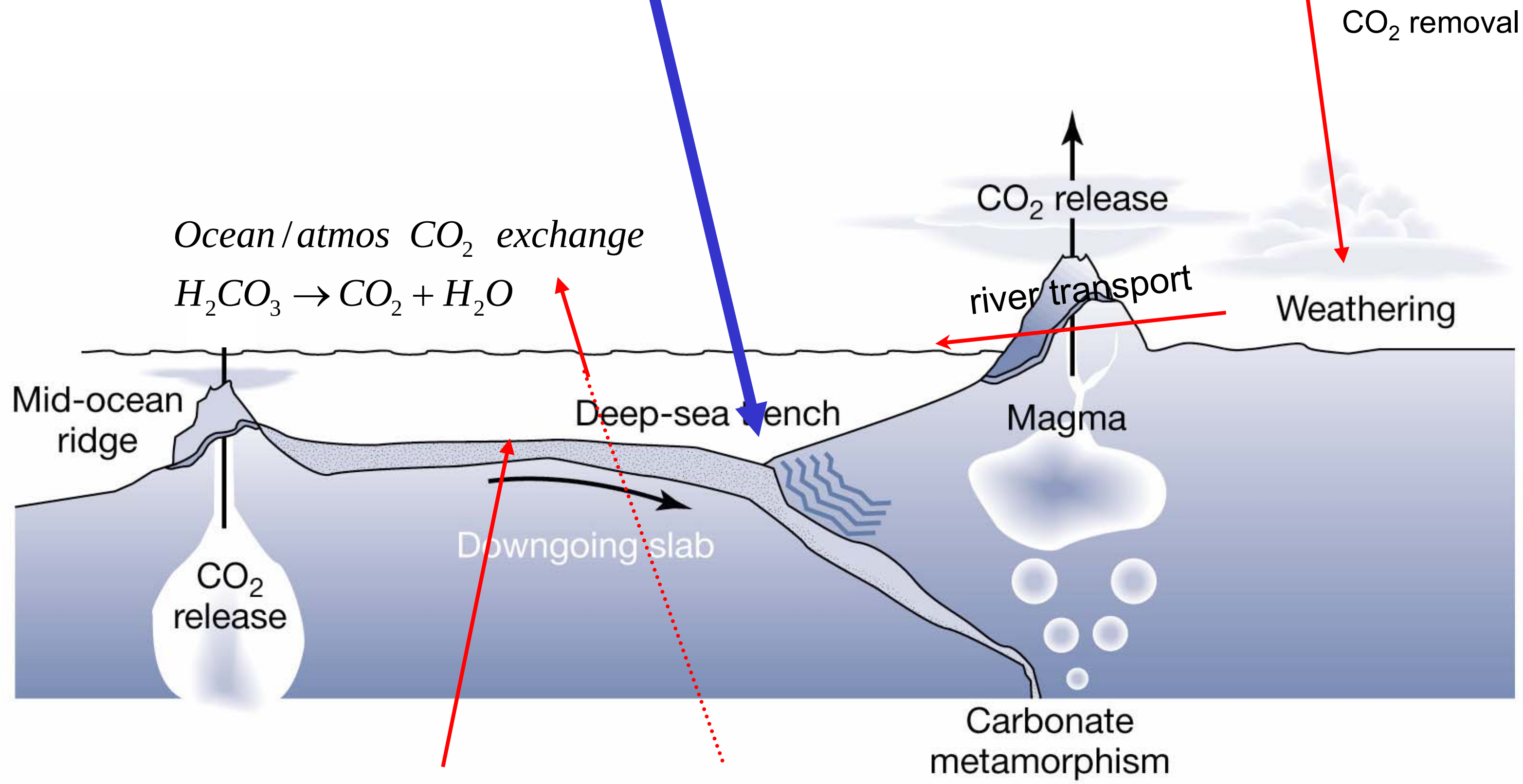
Increased volcanism inputs of CO_2 into the atmosphere causes increased chemical weathering and marine carbonate deposition which lowers atmospheric CO_2



Net result (of weathering and biol. ppt in the ocean)

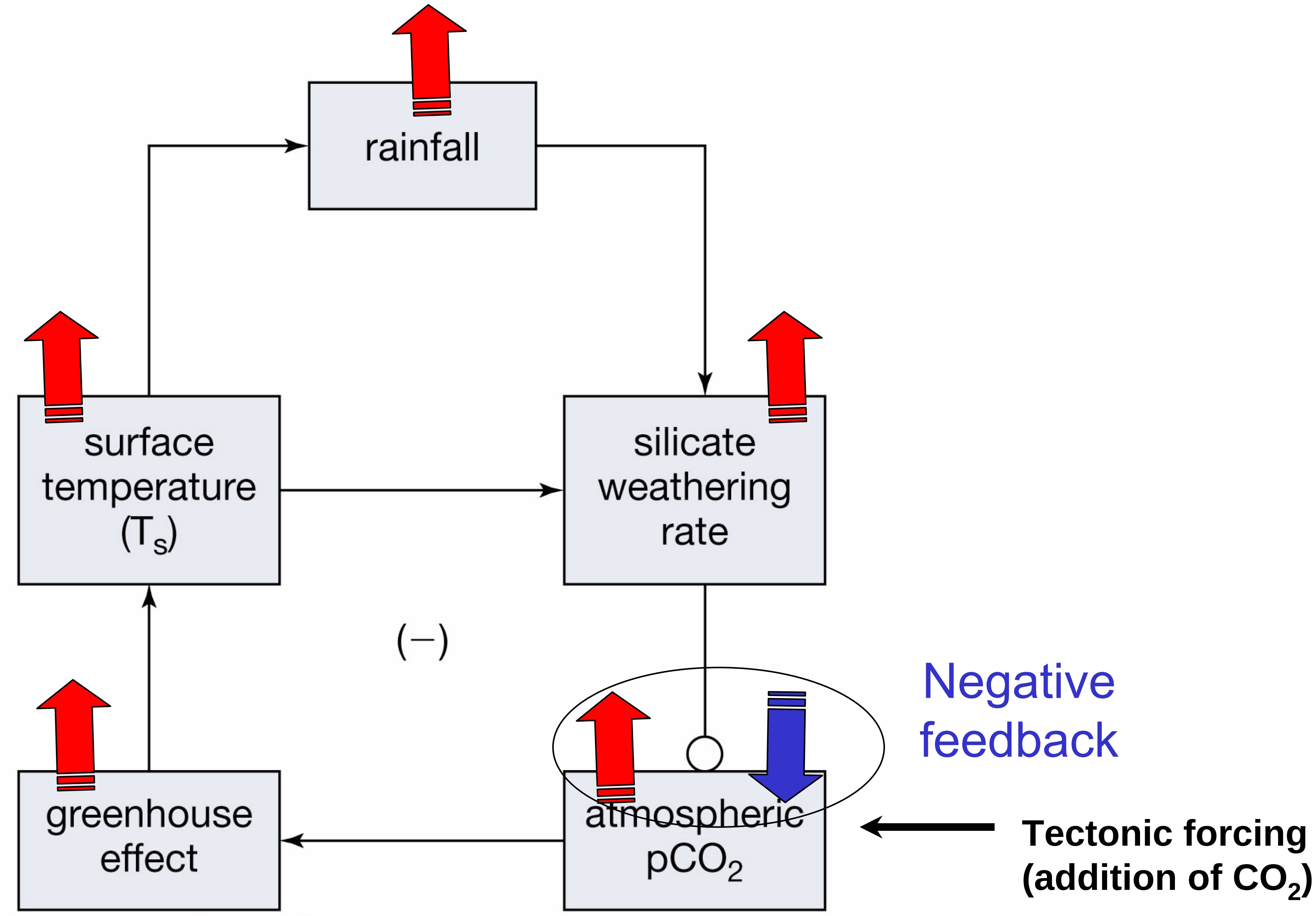
$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

$$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2 + H_2O$$



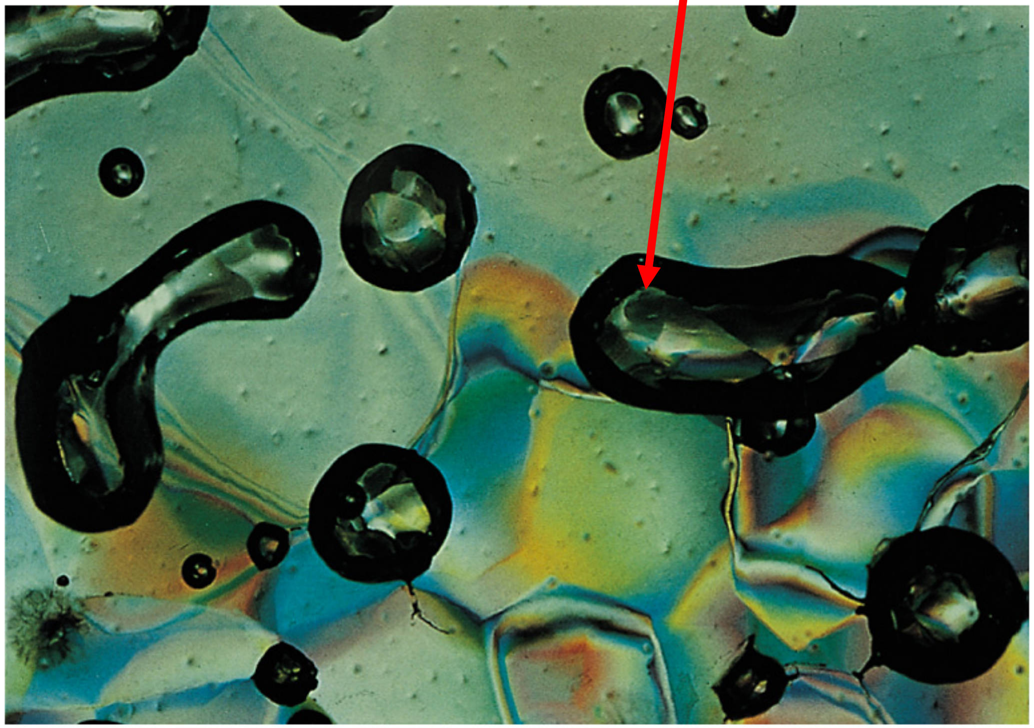
$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2CO_3$$

Carbonate ppt. (dissolved silica also precipitates out)


rainfall
surface temperature (T_s)
silicate weathering rate
(−)
greenhouse effect
atmospheric pCO_2
Negative feedback
Tectonic forcing (addition of CO_2)

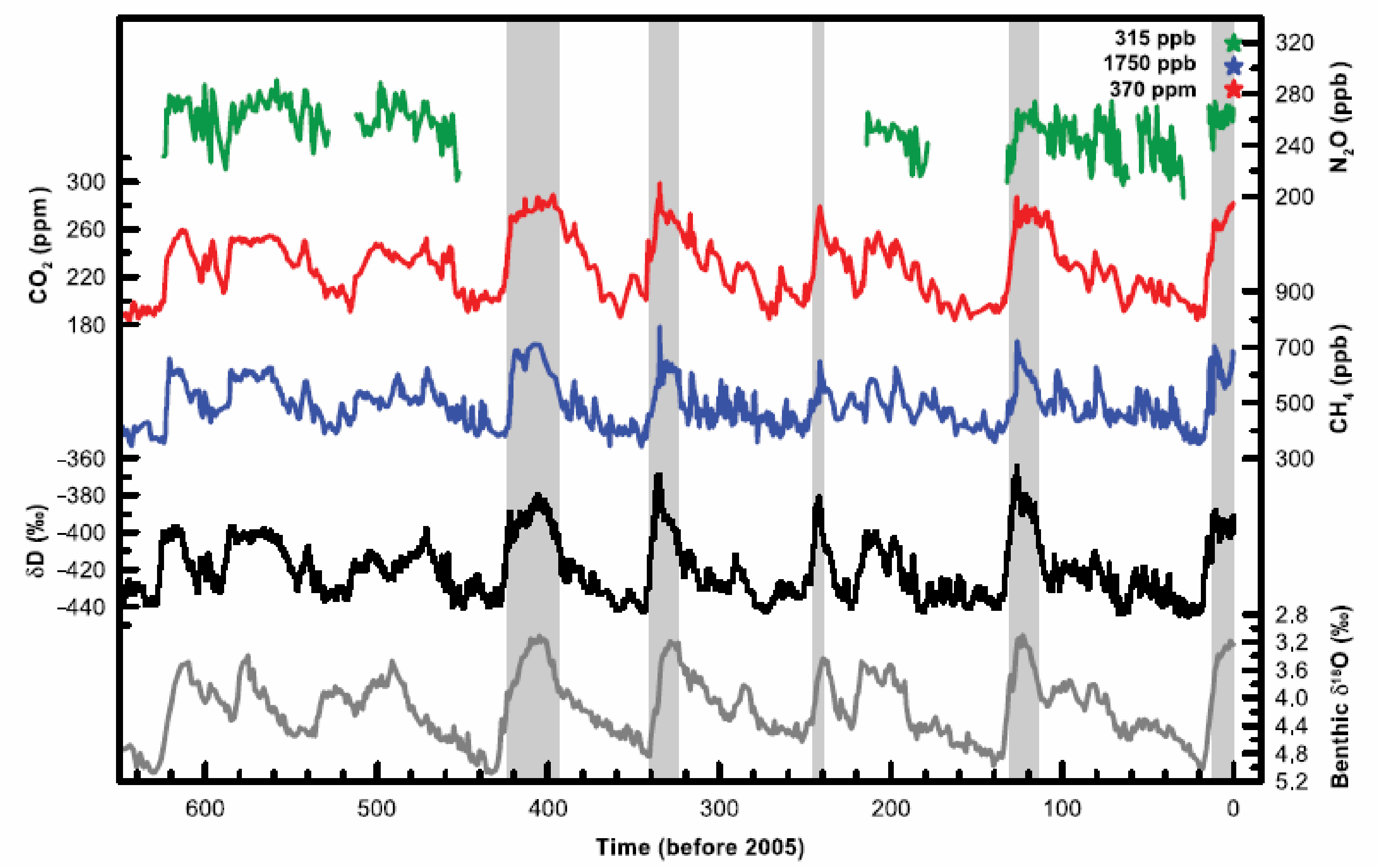
Antarctic/Greenland ice core records

1. Oxygen isotopes of the ice (temperature proxy)
2. CO_2 trapped in air bubbles

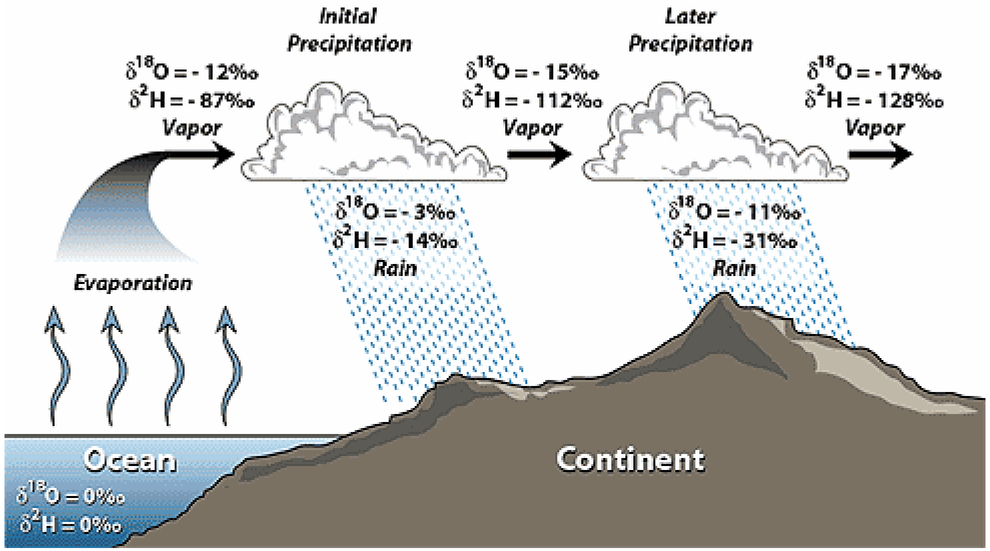


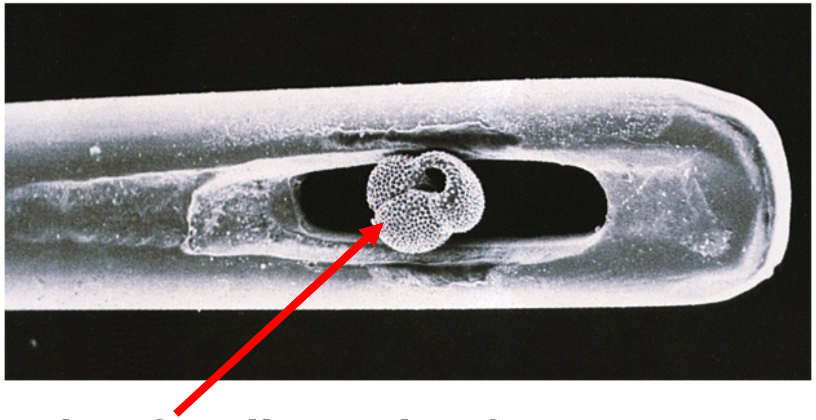
S. C. Porter.

Climate evolution over the past 600,000 yrs



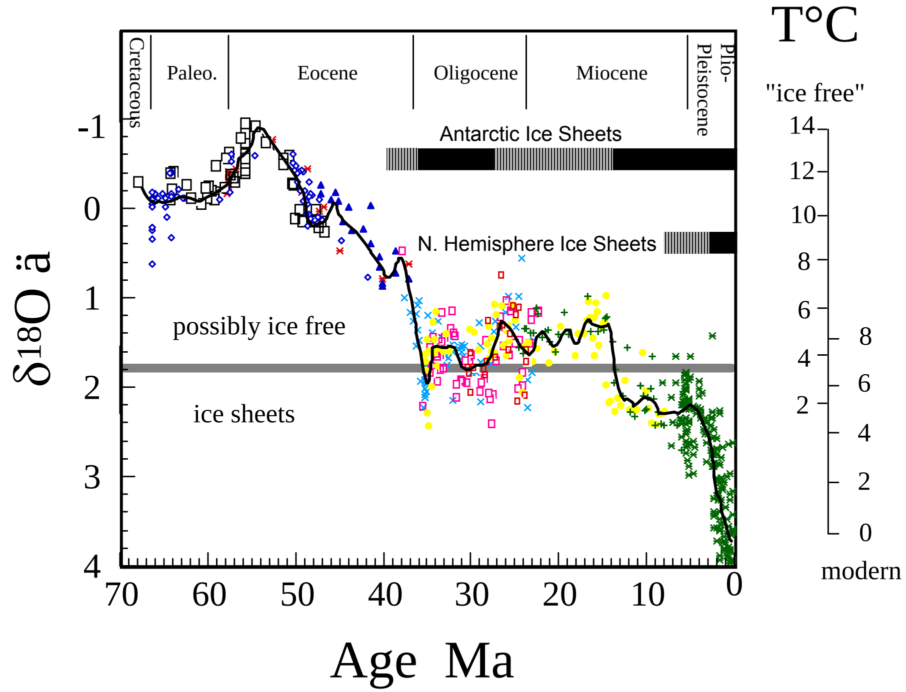
Marine oxygen isotope records



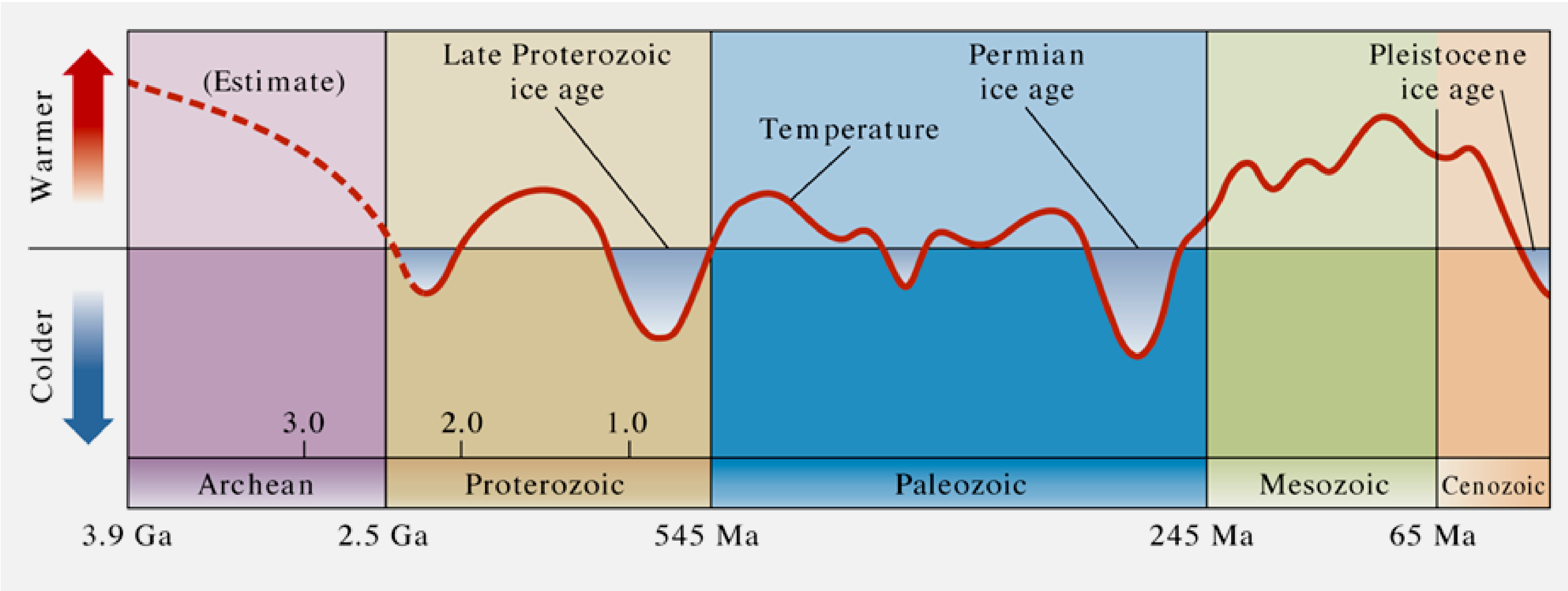


Microfossils made of $CaCO_3$

$^{18}O/^{16}O$ is a function of ice volume and ambient ocean temperatures



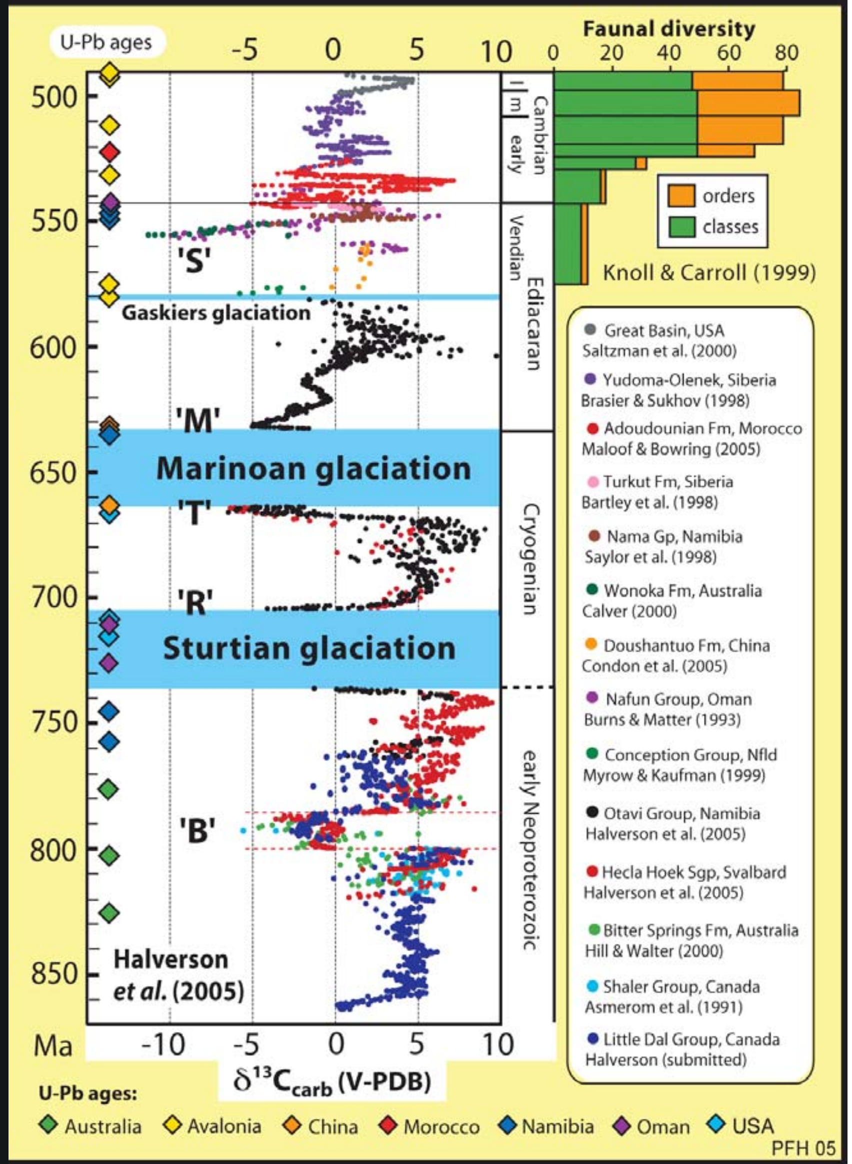
Climate evolution during past 4 Ga



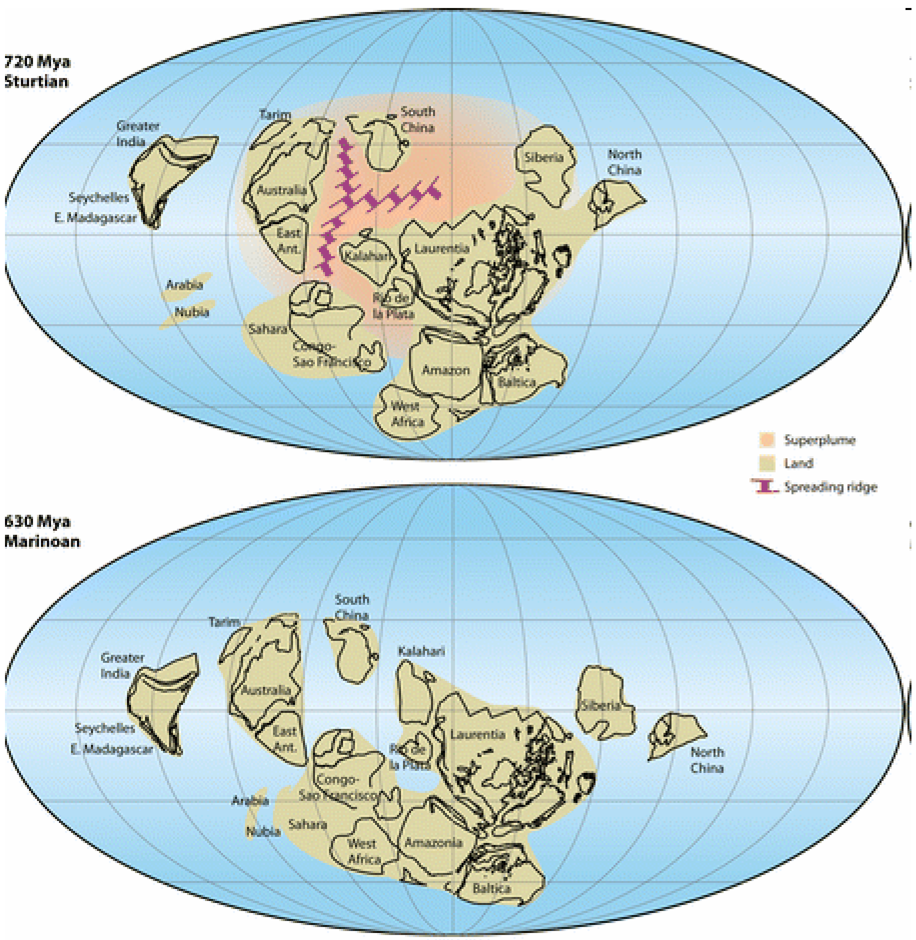
What can we learn from the deep past:

- Climate sensitivity under high CO_2
- Life time of the atmospheric CO_2
- Stability of methane hydrates
- Impacts:
  - ocean acidification
  - ocean anoxia
  - mass extinction (biodiversity)

THE SNOWBALL EARTH

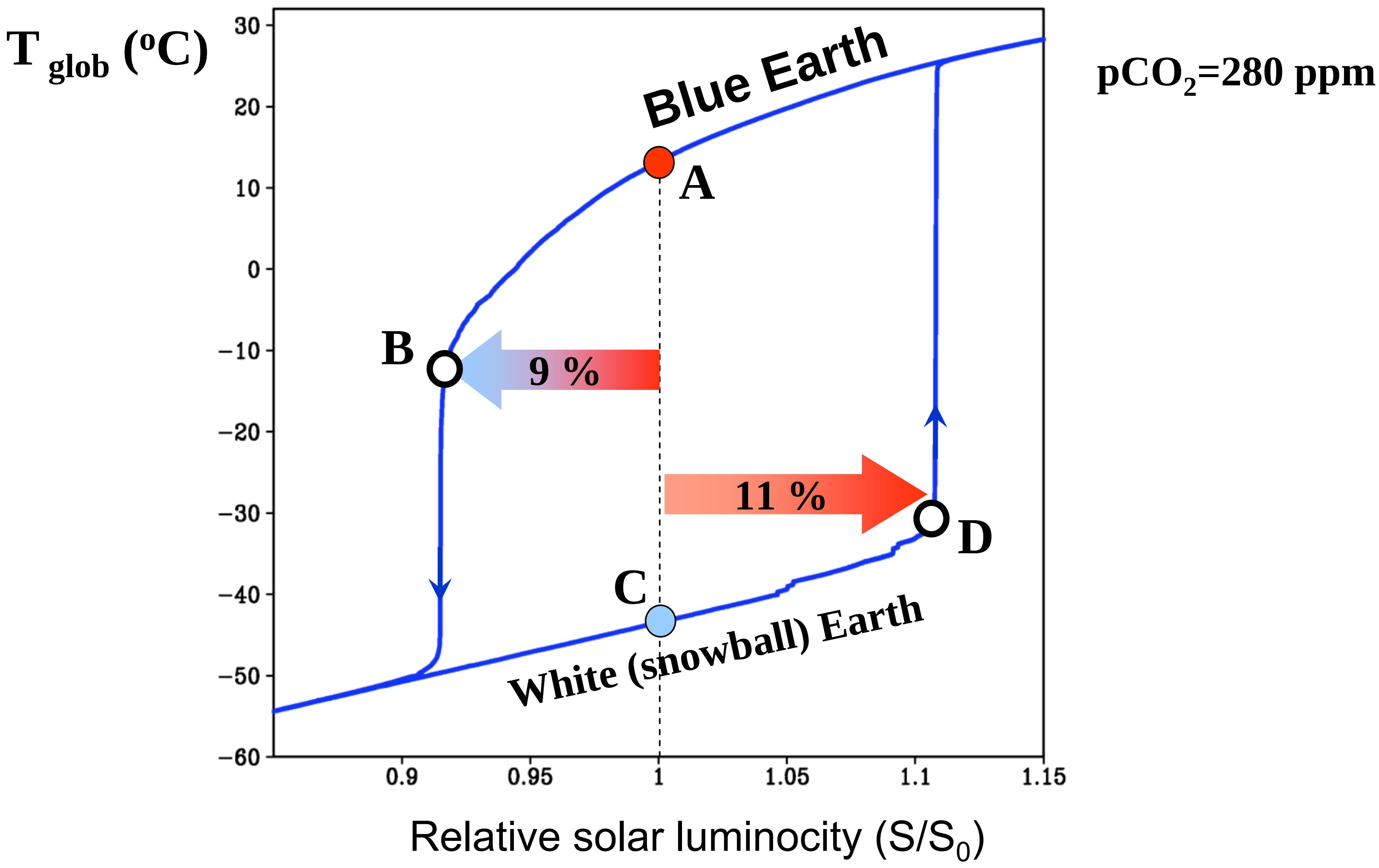


Proterozoic Earth geography

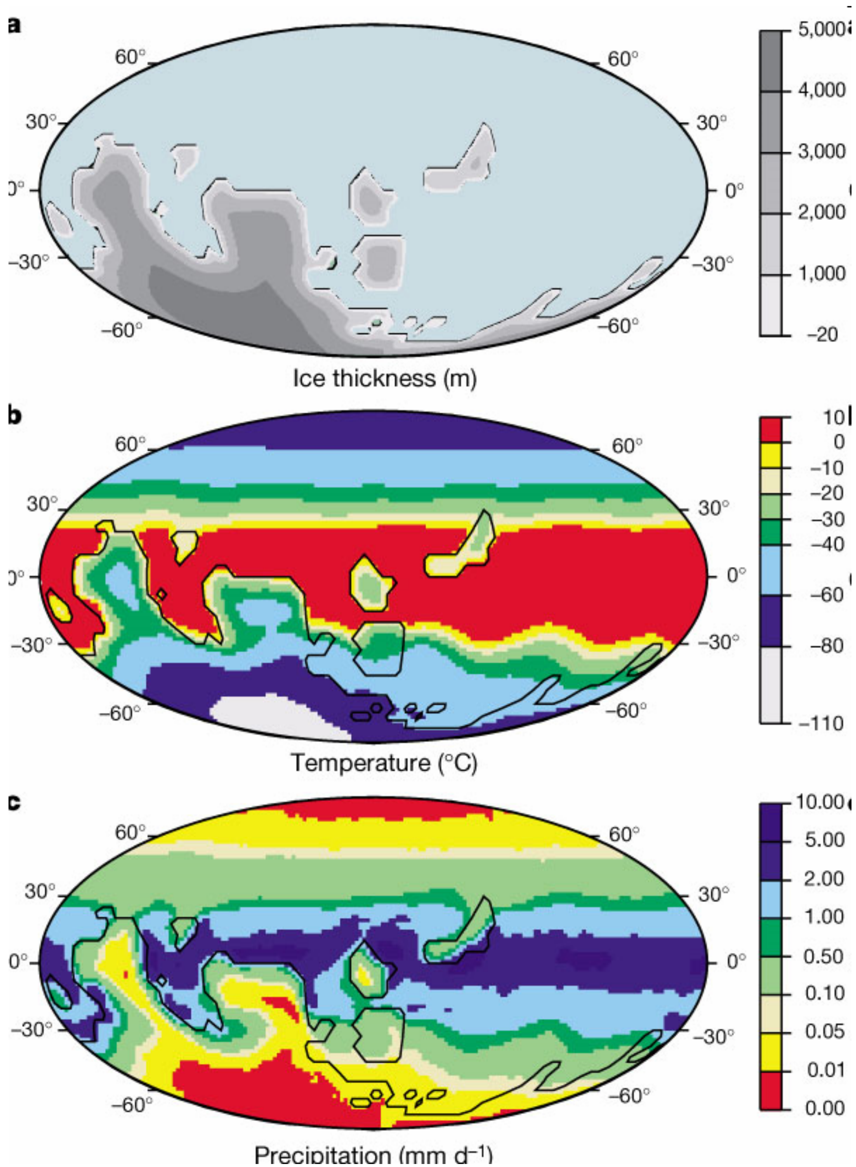


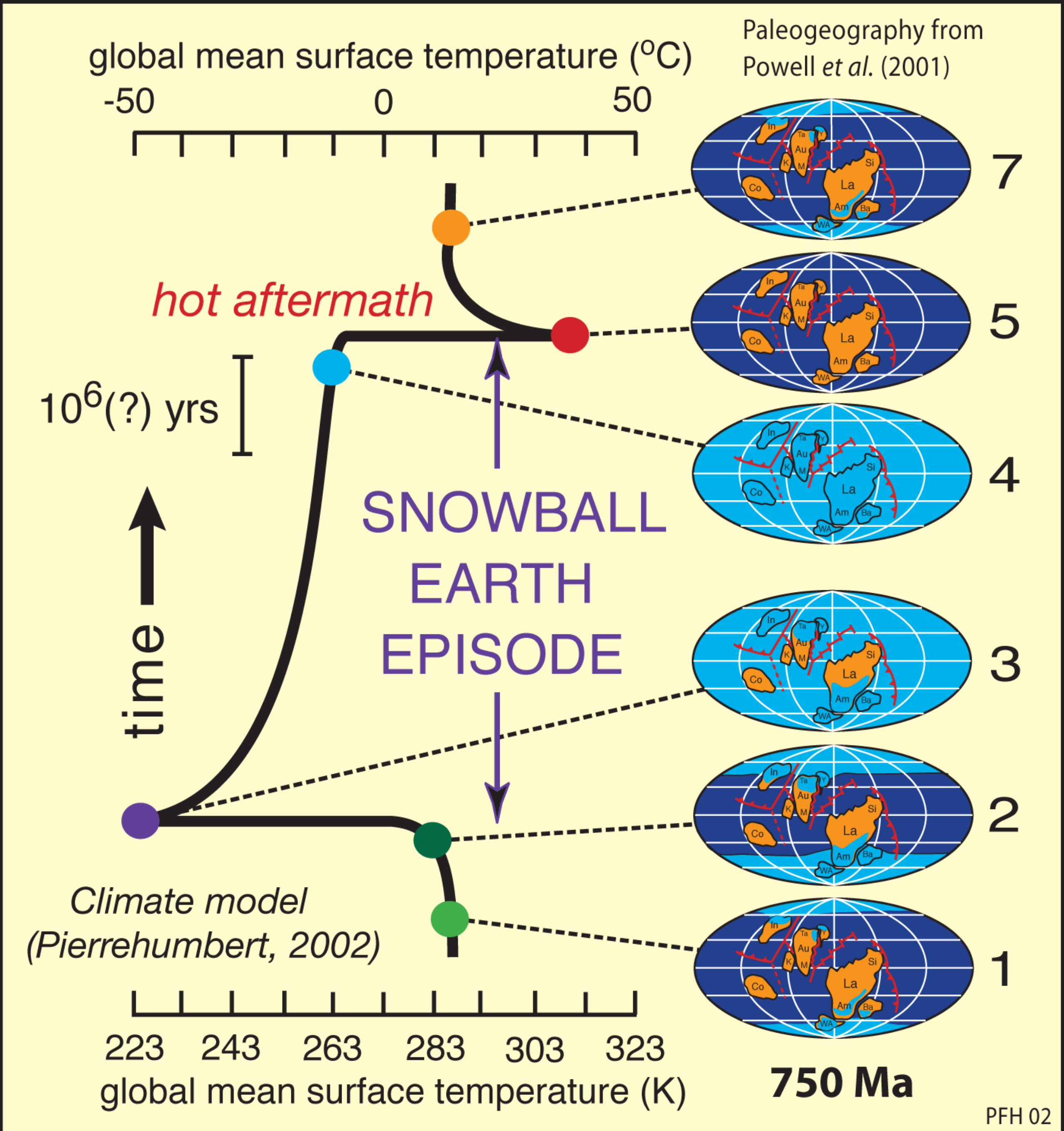
Pierrehumbert RT, et al. 2011.
Annu. Rev. Earth Planet. Sci. 39:417–60

Earth temperature hysteresis



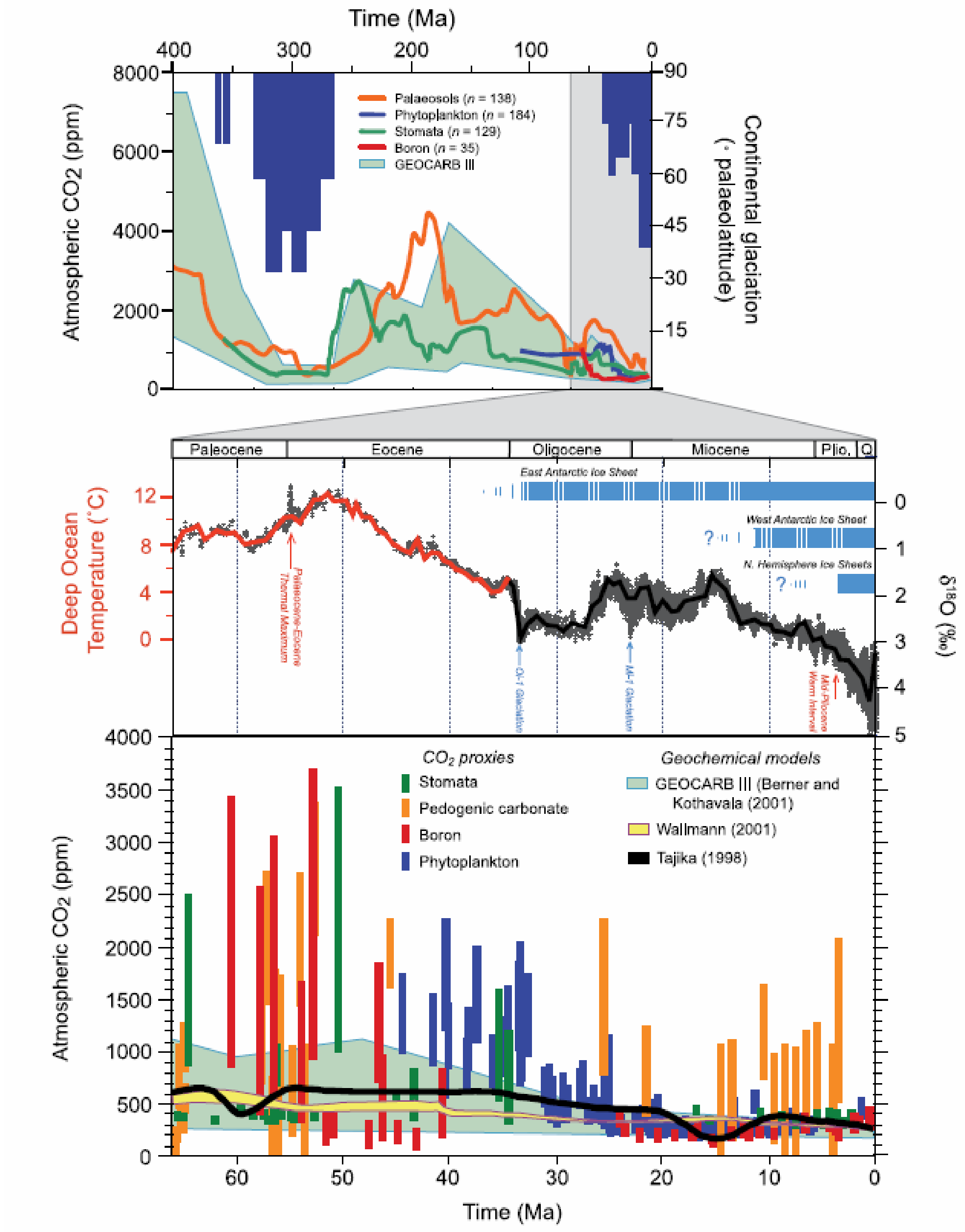
Modeling of snowball earth





global mean surface temperature (°C)
-50
0
50
Paleogeography from
Powell *et al.* (2001)
hot aftermath
10⁶(?) yrs
time
SNOWBALL
EARTH
EPISODE
7
5
4
3
2
1
Climate model
(Pierrehumbert, 2002)
223
243
263
283
303
323
global mean surface temperature (K)
750 Ma
PFH 02

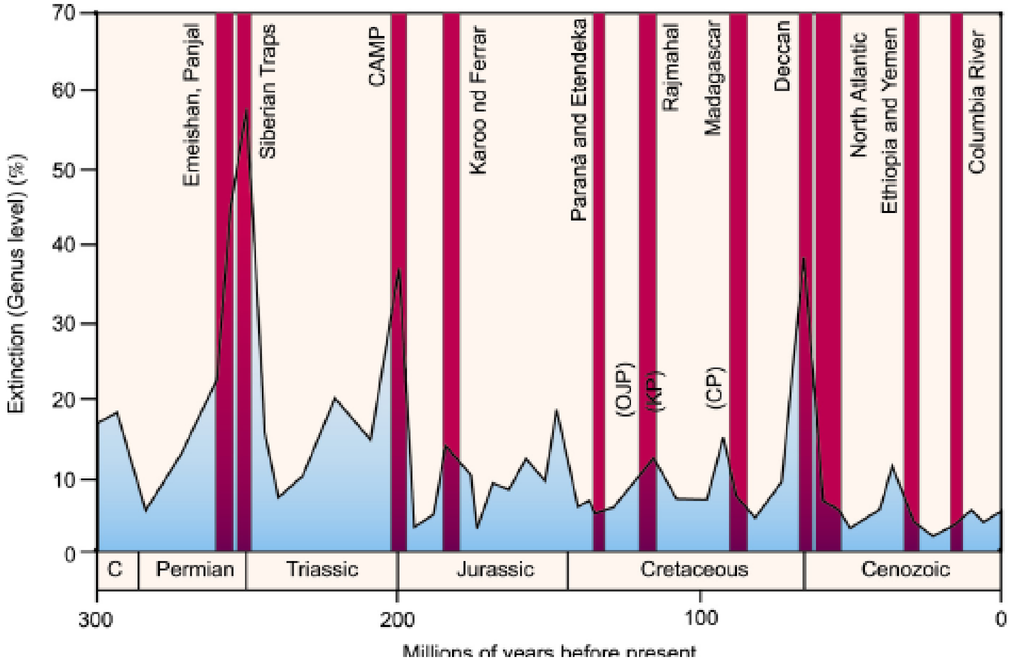
Palecolimate reconstructions



Causes of Permian Ice Age (ca. 300 MaBP):

- large land mass over the south pole
- weak oceanic circulation?

Permian-Triassic mass instinction event



At 251 (MaBP) about 90% of marine species and 70% of land vertebrate families disappear and there were large changes in land plant species abundance and community structure

Causes of Permian-Triassic mass instinction

Due to synchronicity with the Siberian Traps a number of proposed causes are related to extensive volcanism:

- mantle mega-plumes inducing the release of methane along continental margins
- ocean acidification caused by high atmospheric CO_2 concentrations
- acid rain and global cooling
- widespread deep ocean anoxia due to global warming induced by the release of CO_2 and CH_4 by volcanic activity
- escape of hydrogen sulfide from the ocean, which would cause both direct poisoning and damage to the ozone layer

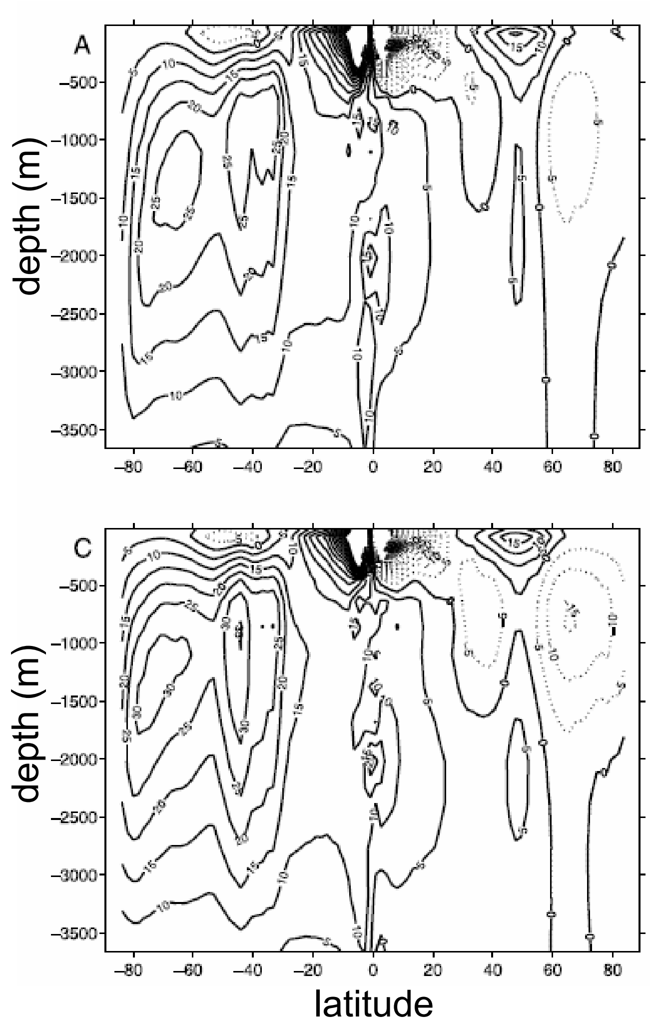
Modeling of Permian-Triassic instinction event: Ocean anoxia (negative)

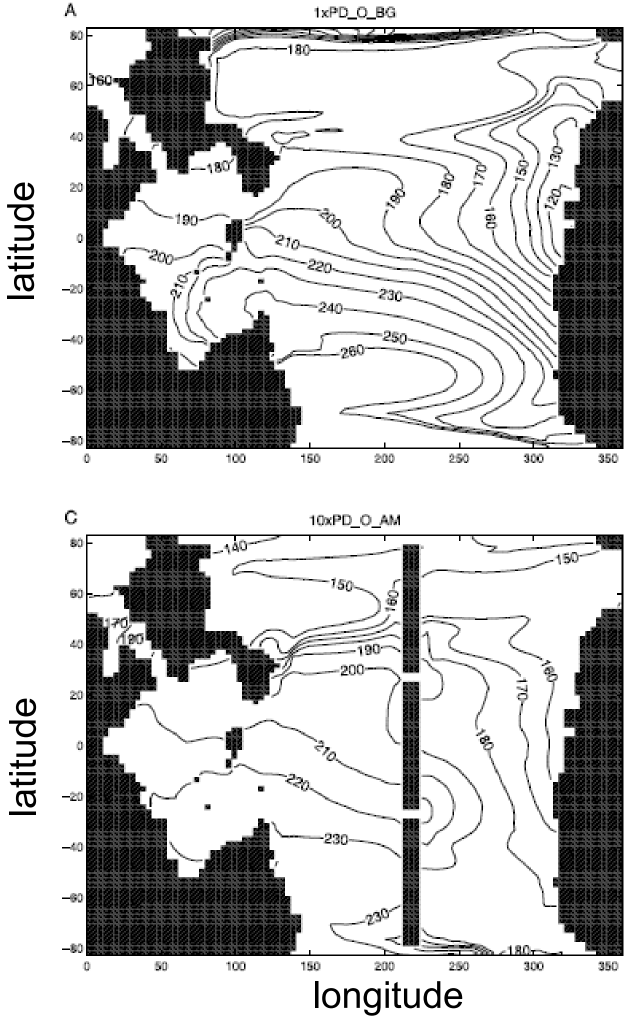
Meridional overturning circulation

Deep ocean O concentration

1xCO_2

10xCO_2

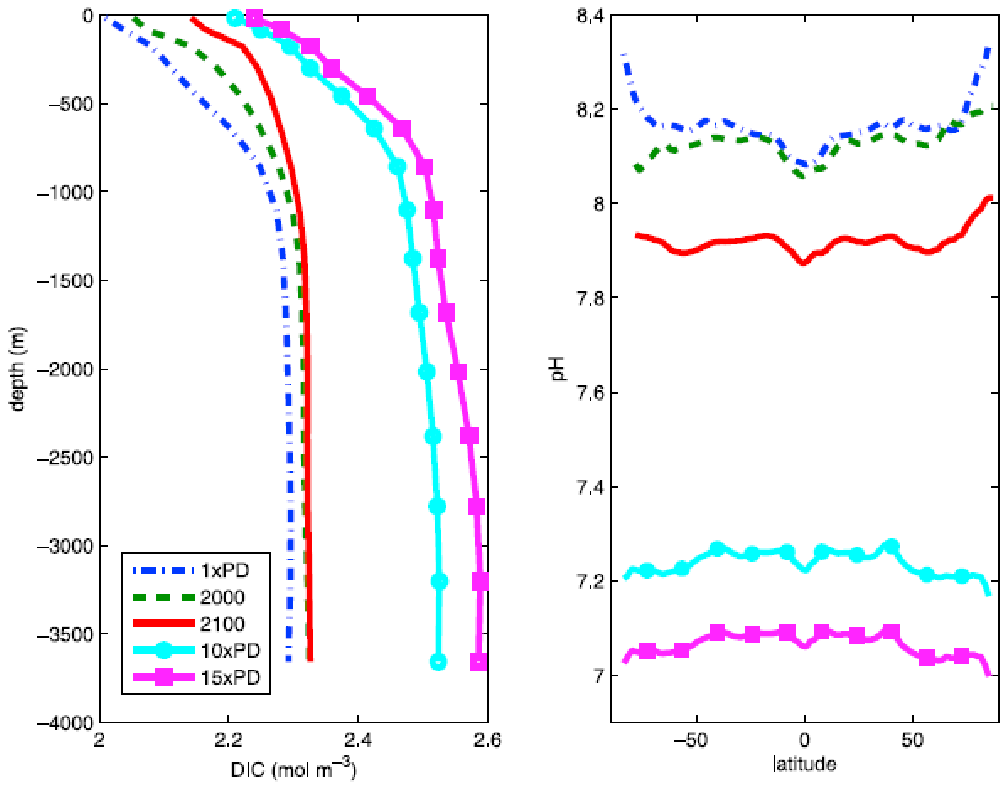




Montenegro et al. (2011)

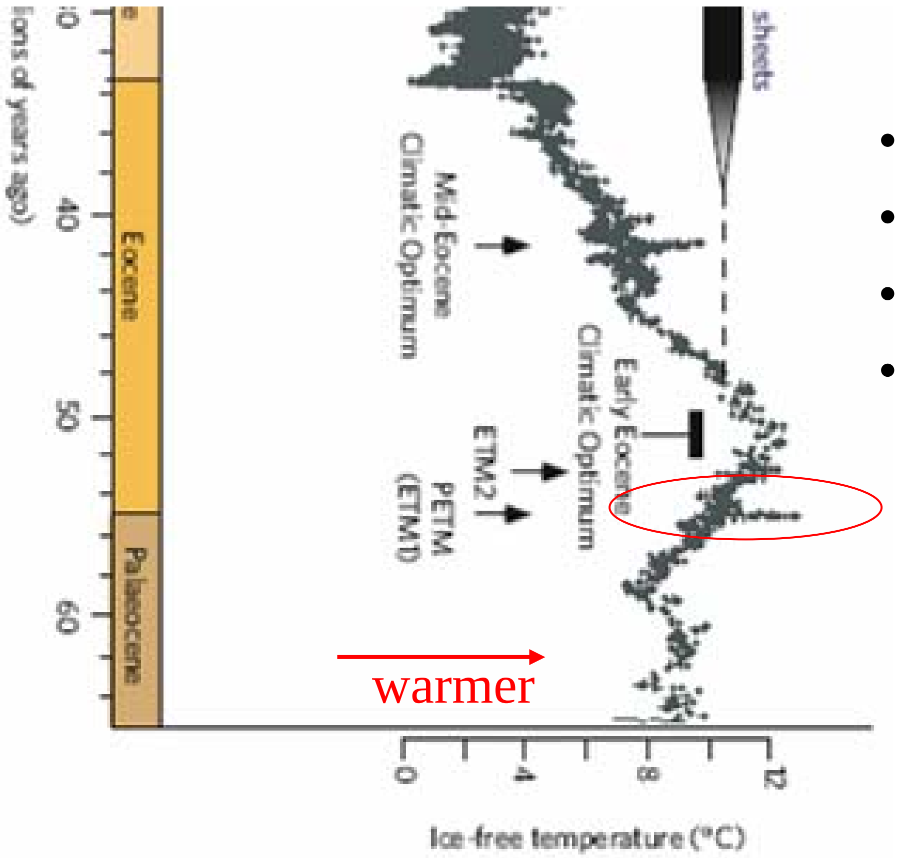
Modeling of Permian-Triassic instinction event:
Ocean acidification

Reduction in ocean pH is biologically significant:
• the whole ocean unsuitable to aragonitic species
• large areas of the ocean unsaturated in relationship to calcite



Montenegro et al. (2011)

Paleocene Eocene Thermal Maximum (PETM) 55 MaBP



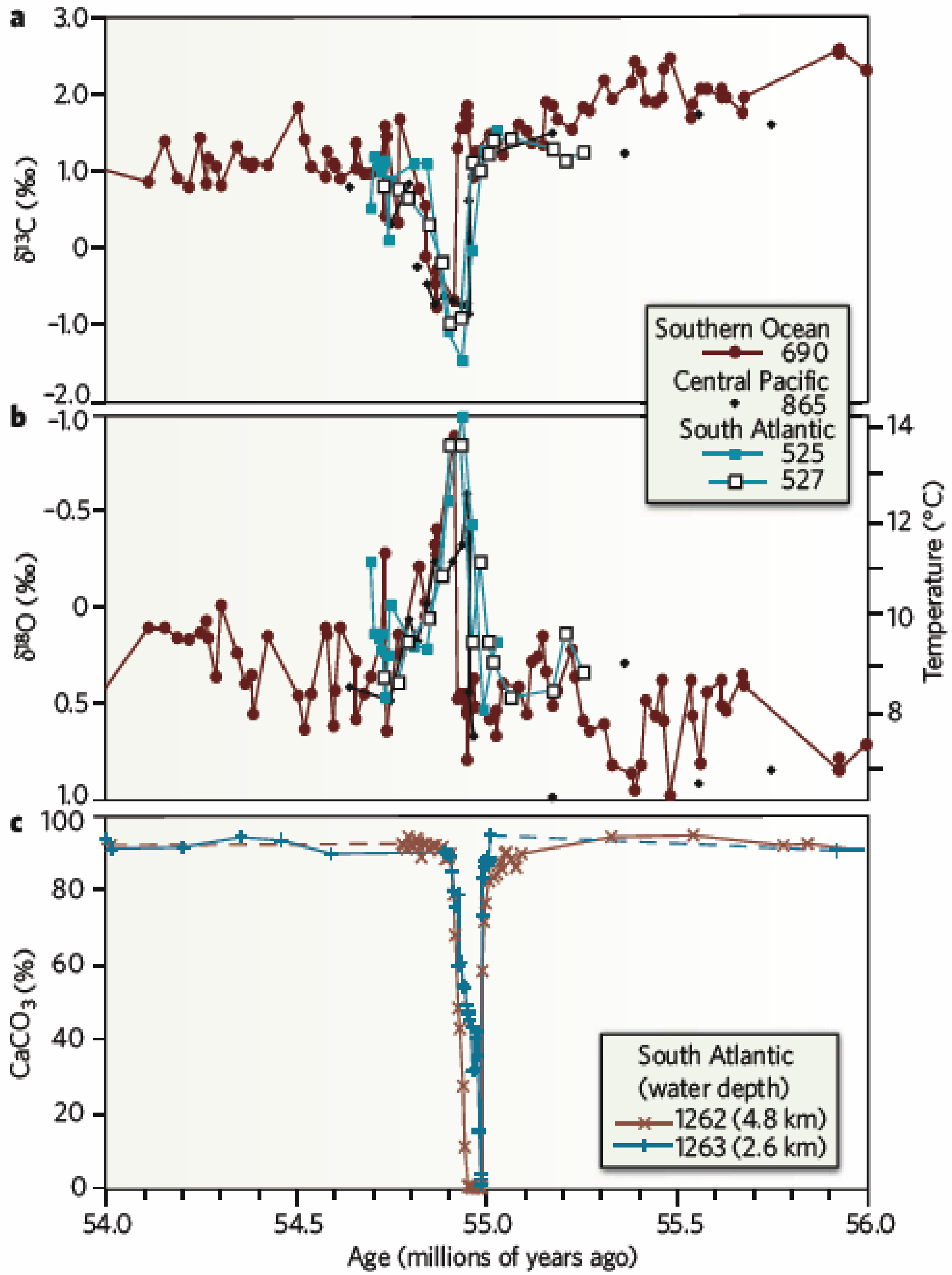
- Globally: +5°C in <10,000 yrs
- High latitude surface waters: +6…8°C
- Bottom waters: +4…5°C
- Tropical waters: +4…5°C

Negative $\delta^{13}C$ excursion ~ -3‰ suggests a release into the atmosphere >1200 gigatons of ^{13}C depleted carbon CO_2 (or/and CH_4)

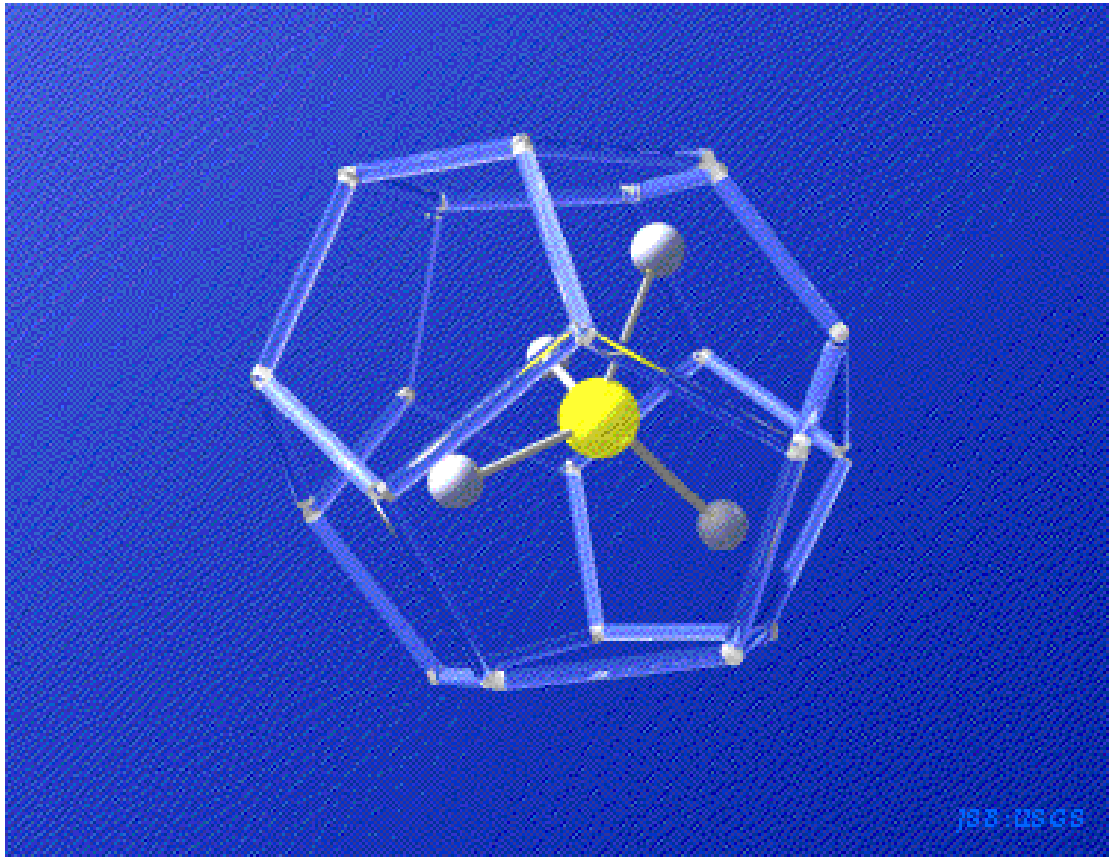
The oxygen isotope records based on benthic foraminiferal indicates abrupt (< 10,000 yrs) warming

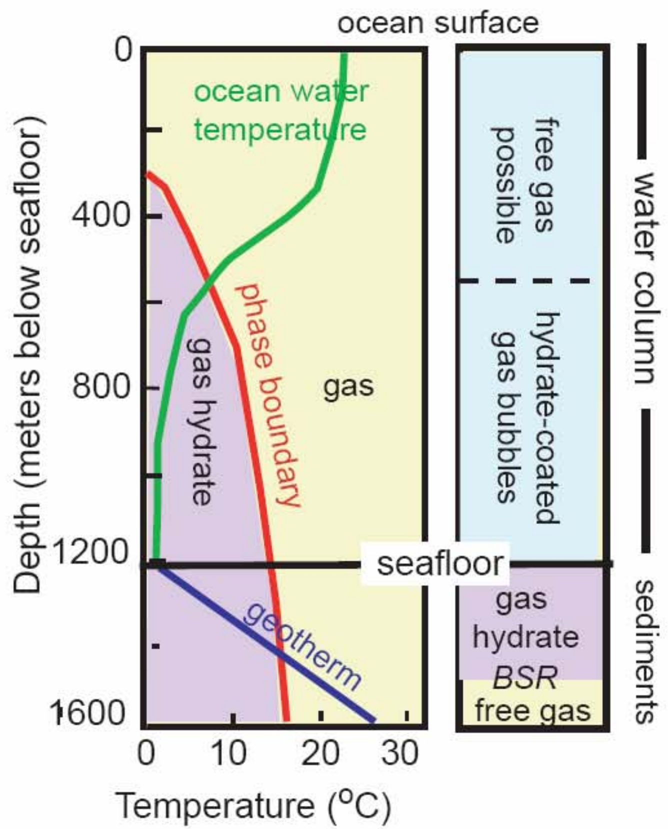
The decrease in sedimentary $CaCO_3$ reflects increased dissolution and indicates a severe decrease in seawater pH (ocean acidification).

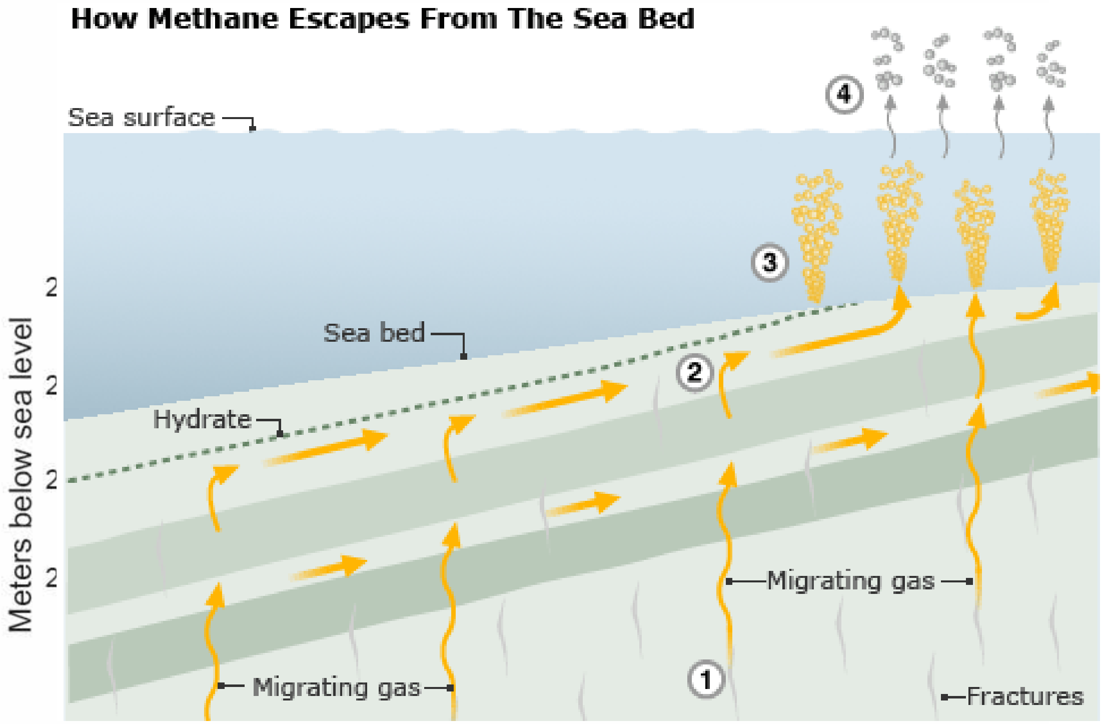
From Zachos et al. Nature, 2008



Methane Clathrates Gas Hydrates

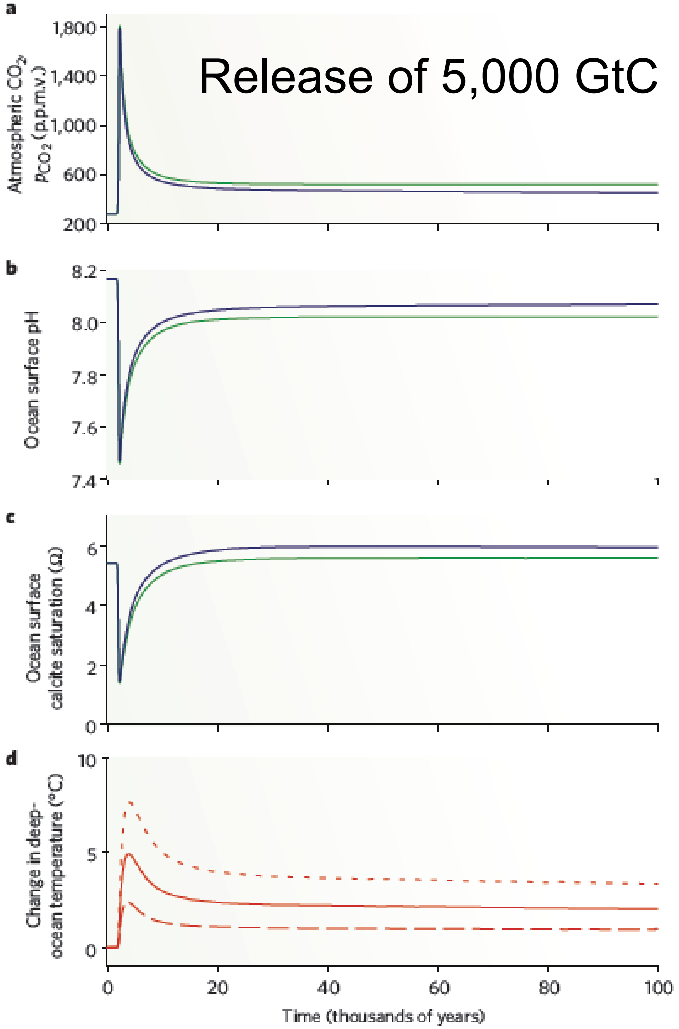




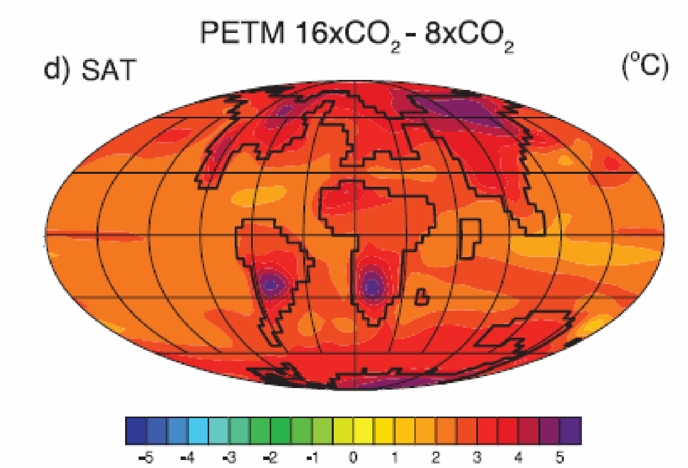


As seawater warms, the solid lid decomposes, and the methane escapes as bubbles.

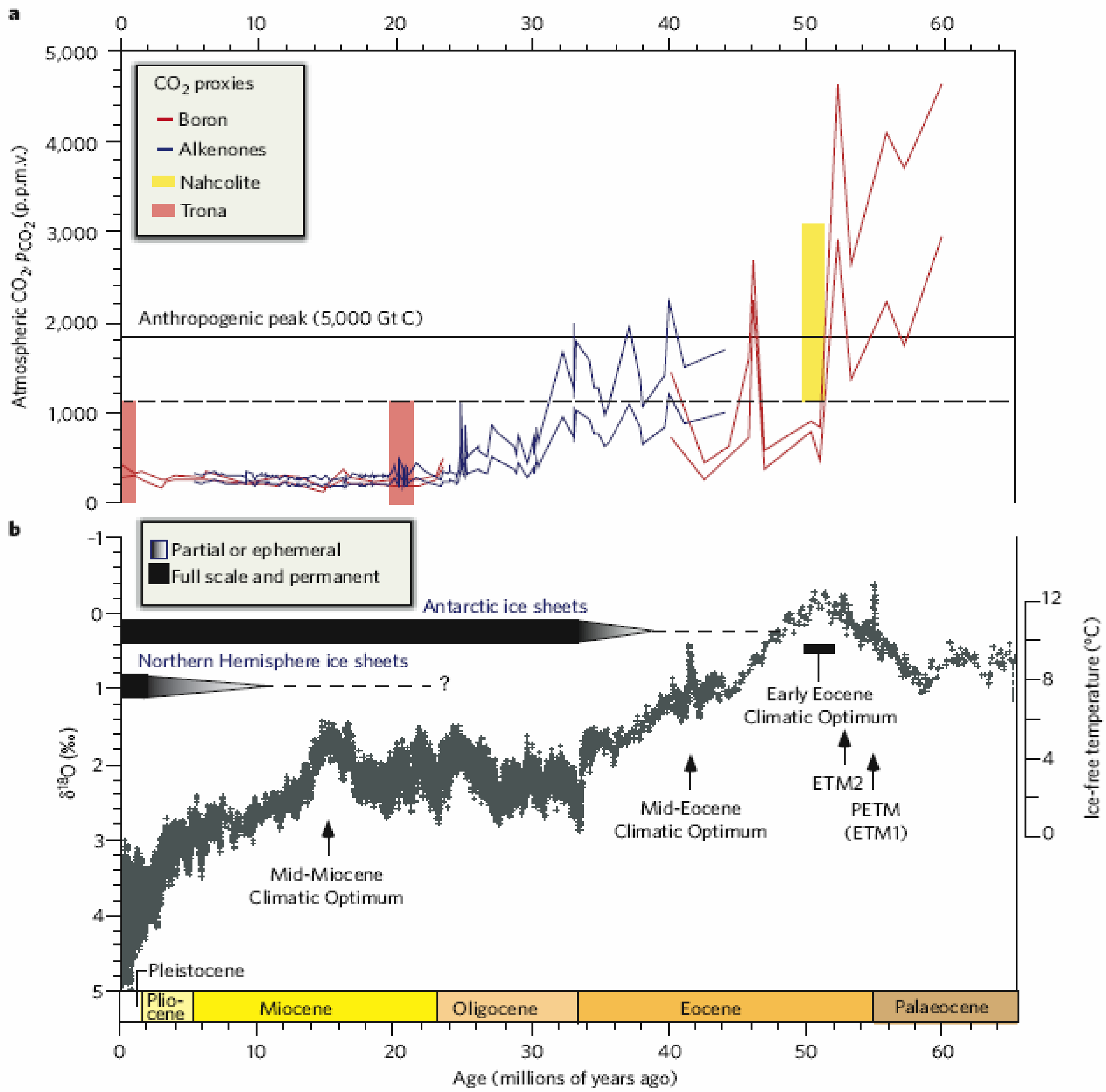
PETM Modeling



Temperature change

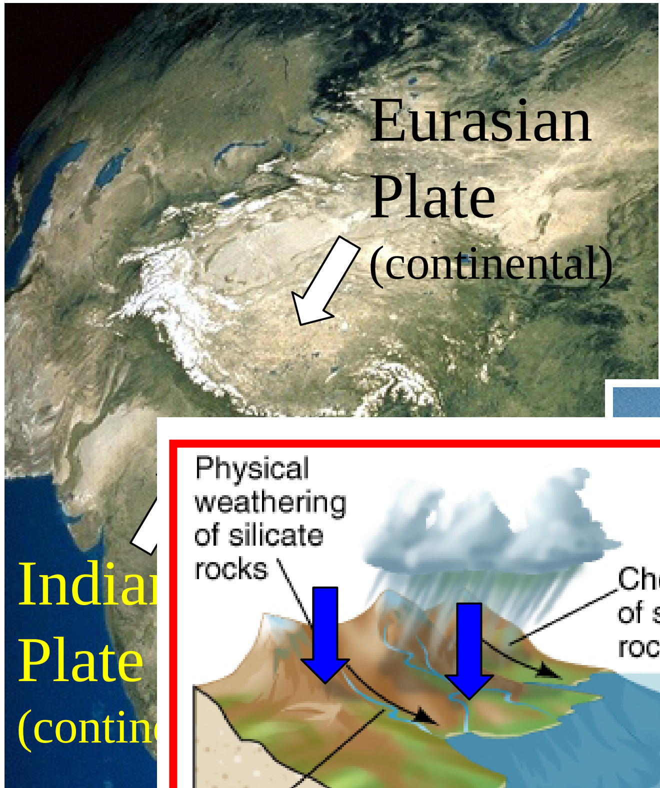


Cenozoic cooling and CO_2

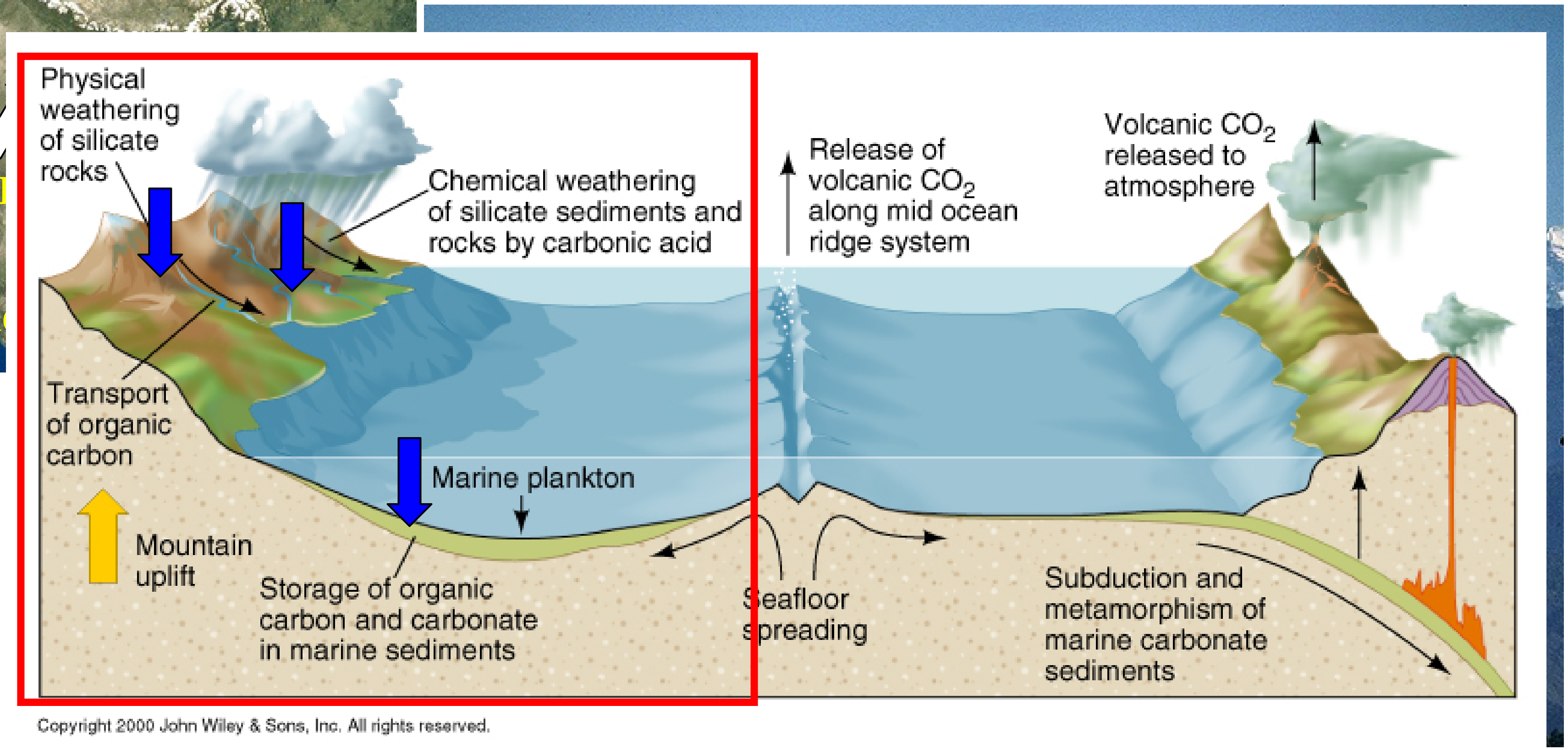


Zachos et al. (2007)

Uplift of Himalaya Mtns and Tibetan Plateau



Exposure of large volume of crust increases chemical weathering and lowers atmospheric CO_2



Uplift Weathering Hypothesis

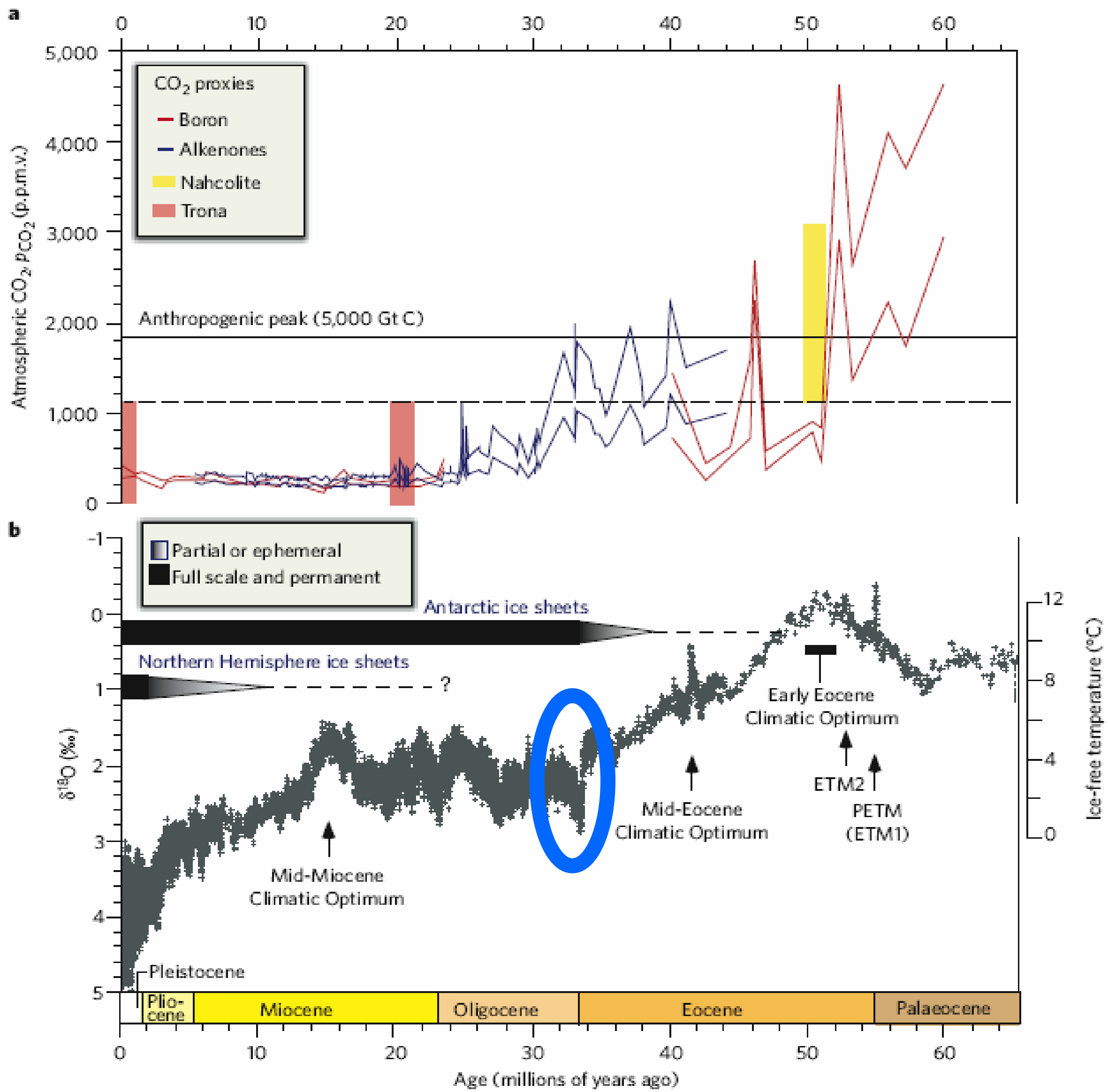
- More rocks exposed to weathering (availability)
- Steep slopes
- Change in rain patterns- orographic effects

→ enhance continental silicate weathering

→ draw-down atmospheric CO_2

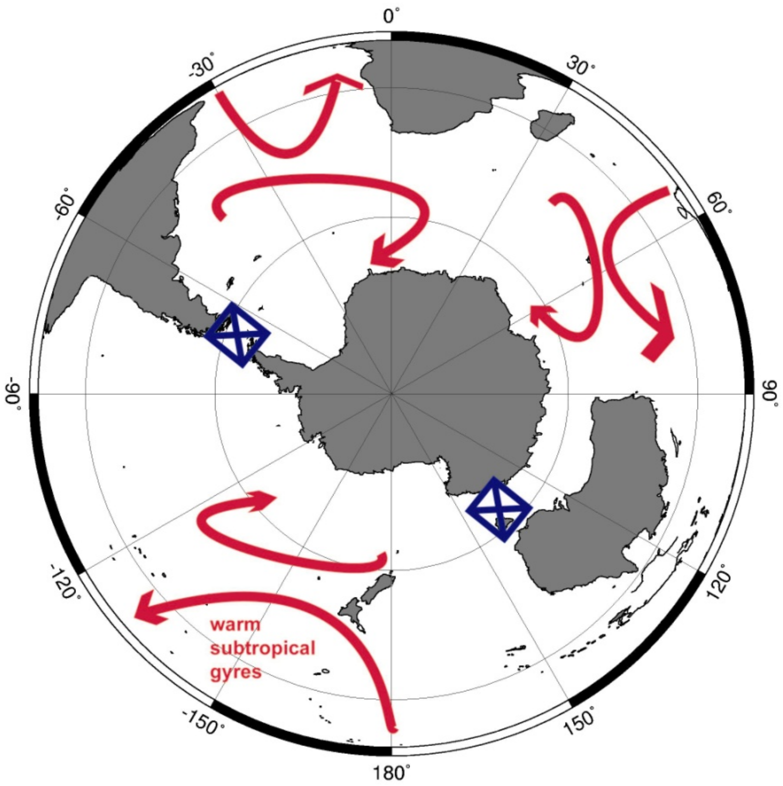
Raymo and Ruddiman (1994)

Cenozoic cooling and CO_2

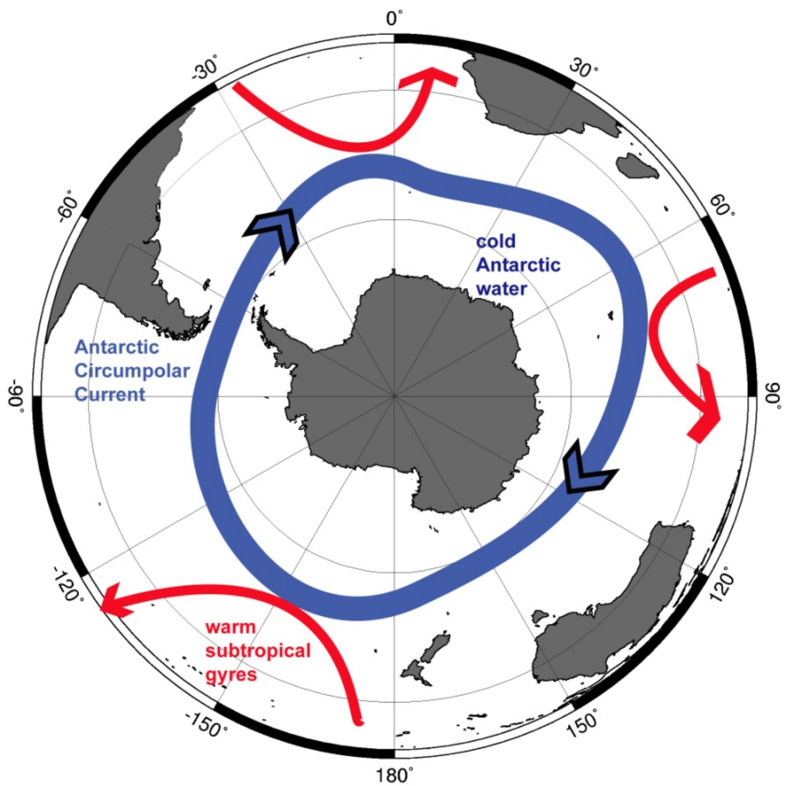


Zachos et al. (2007)

Drake passage opening ca. 40-30 MaBP

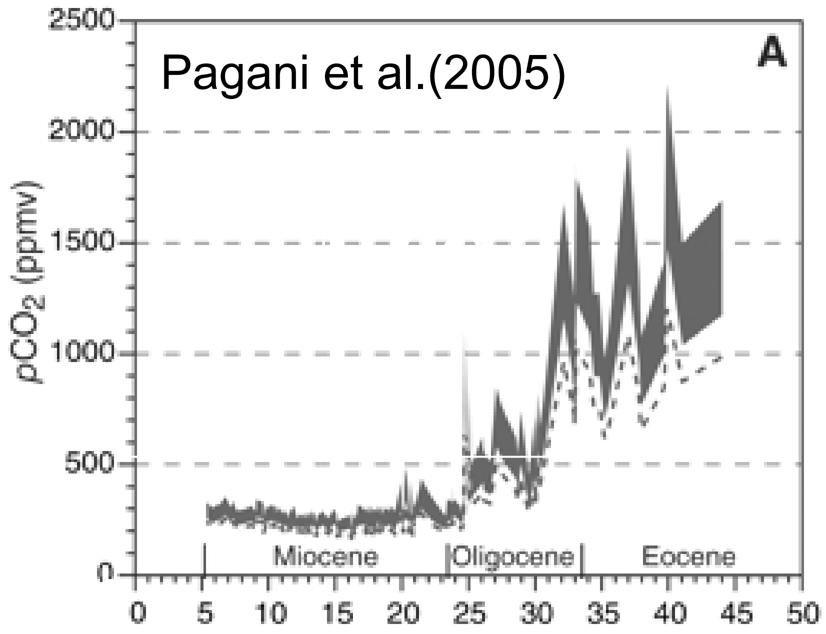


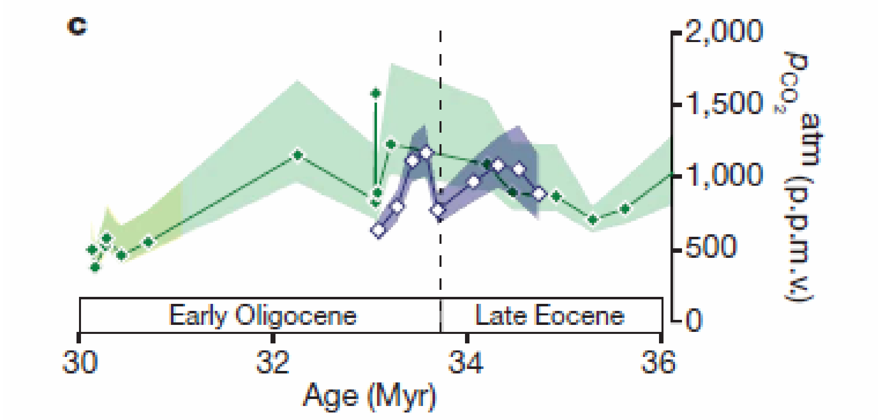
Eocene



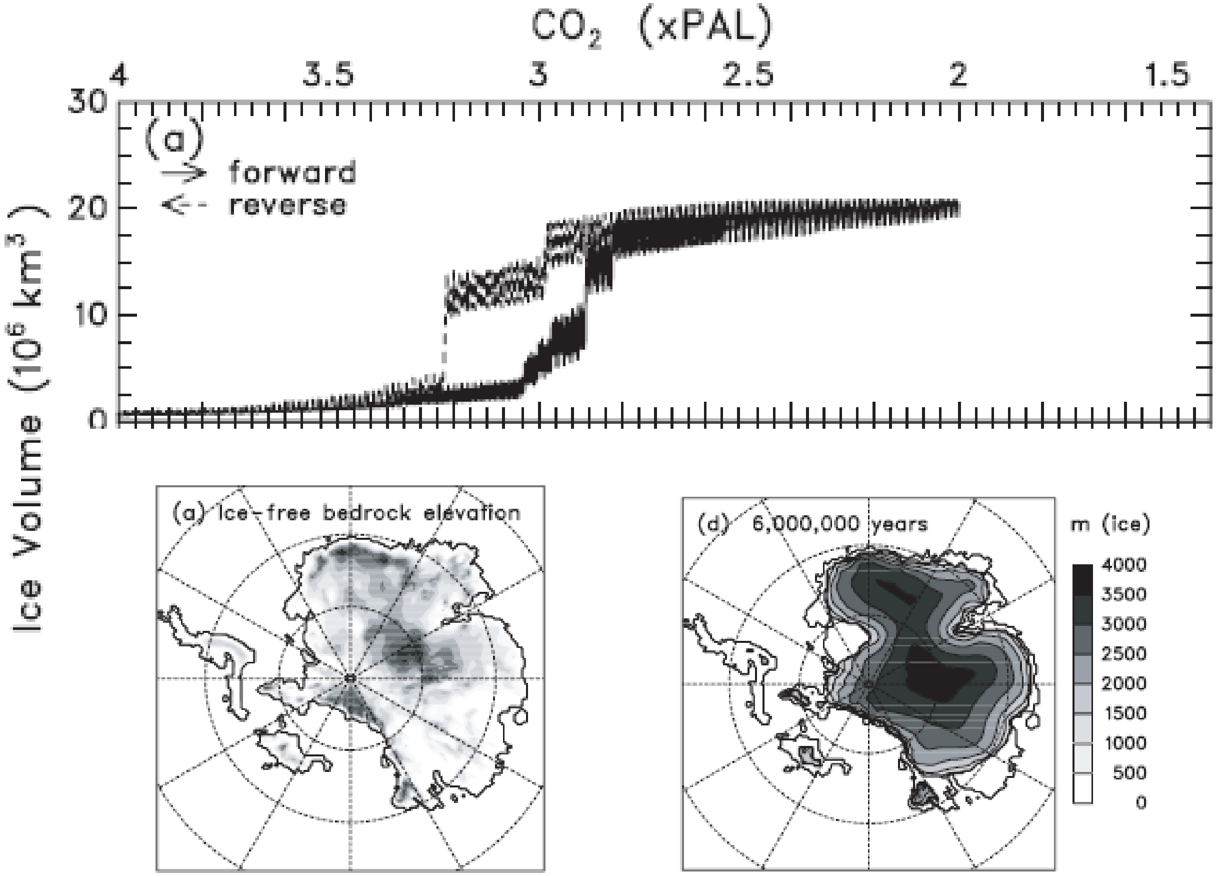
Modern

Paleogene CO_2



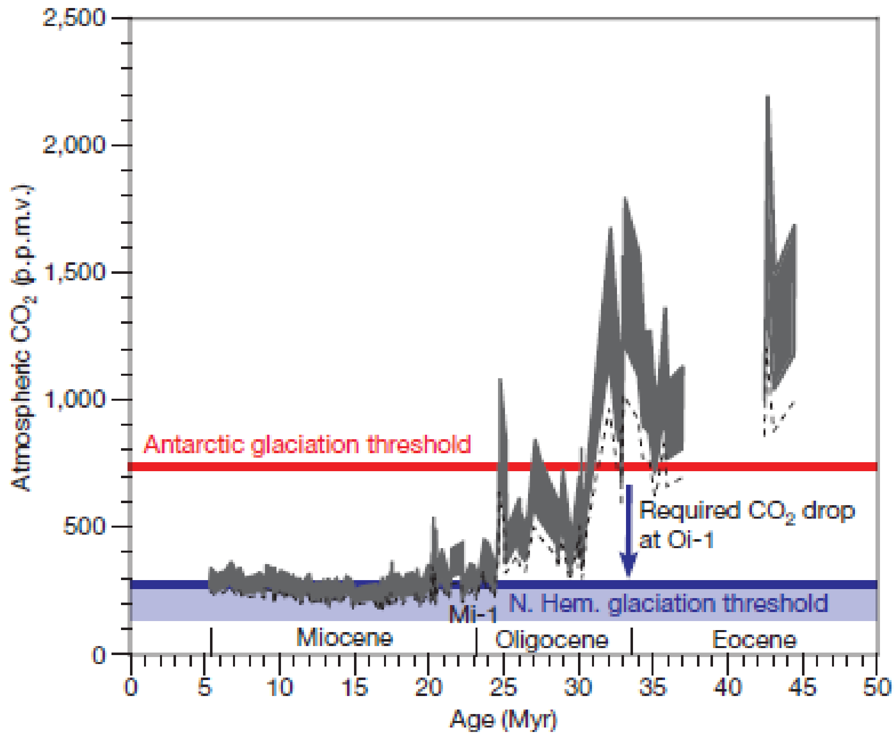


Antarctic glaciation 35 MaBP



DeConto and Pollard (2005)

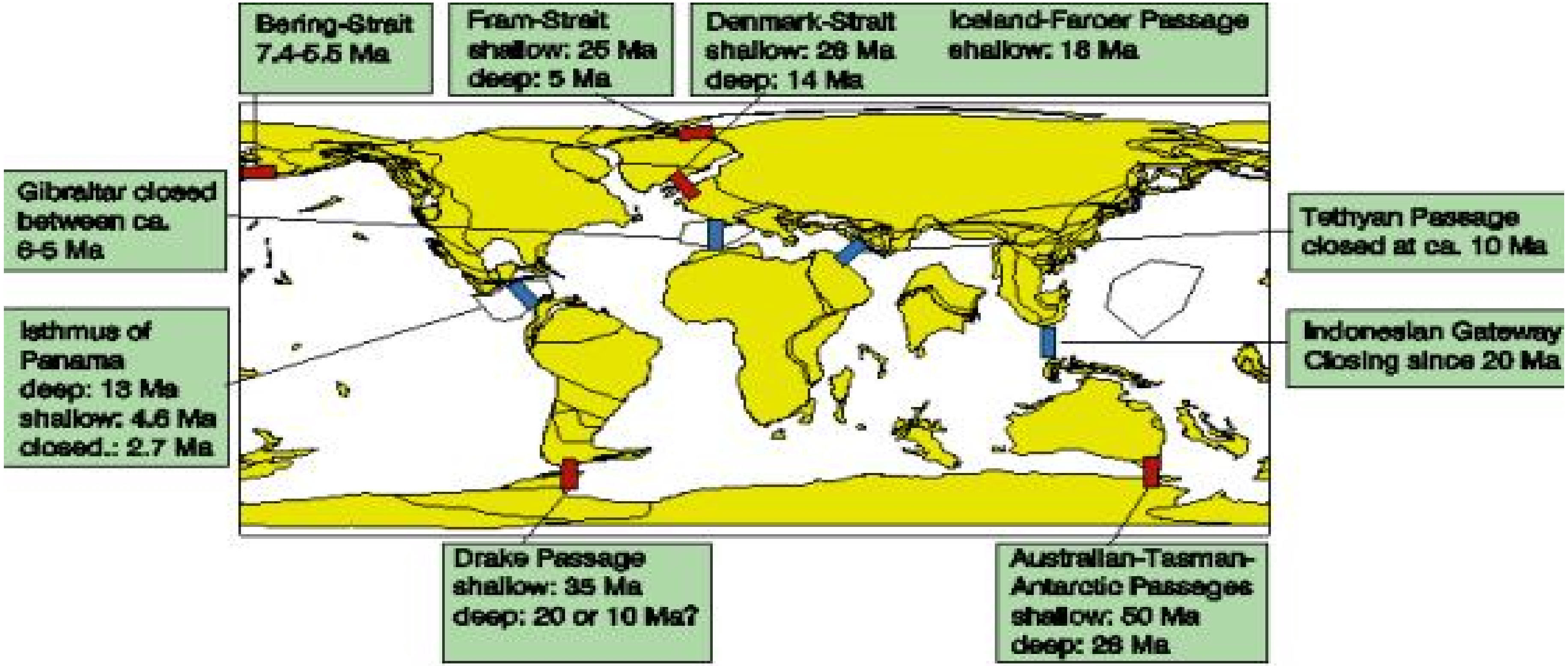
Antarctic glaciation 35 MaBP



Causes of Quaternary glaciation (2.7 MaBP)

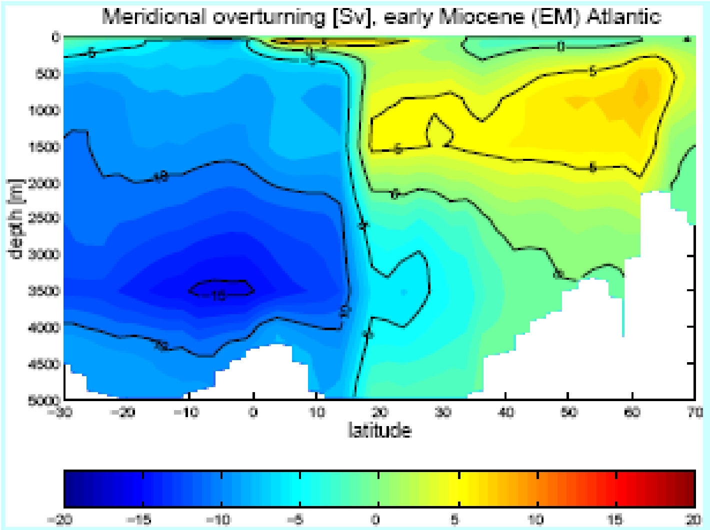
- lowering of atmospheric CO_2 concentration
- uplift of Rocky Mountains
- Isthmus of Panama closure
- onset of permanent stratification in the North Pacific
- change in ENSO regime

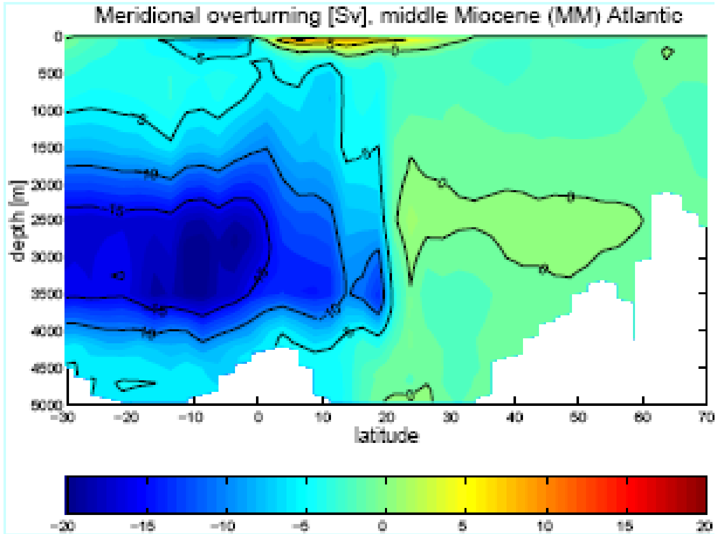
Gateways and Ocean Circulation

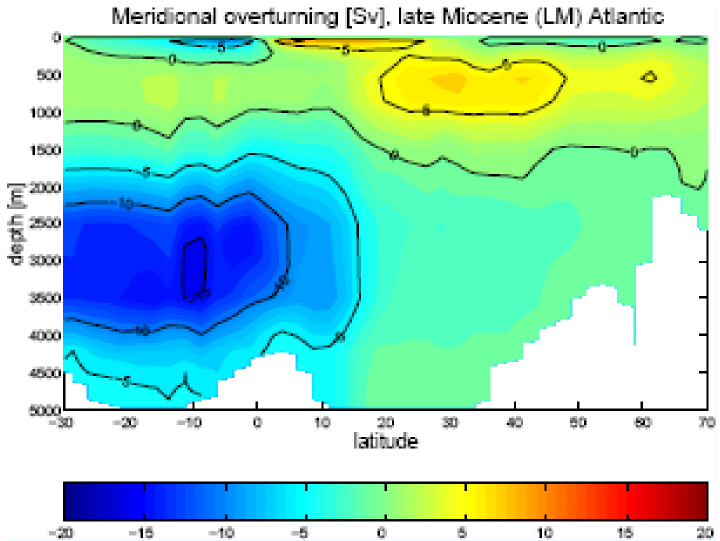


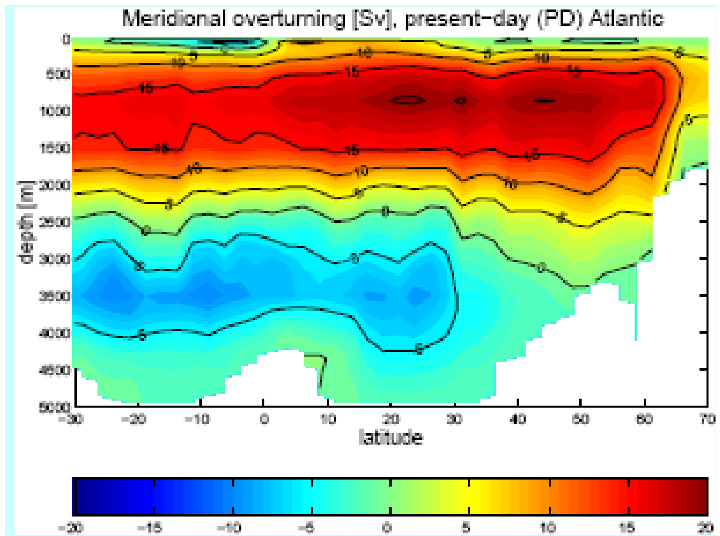
Evolution of major ocean gateways since the Eocene. Figure courtesy of Bill Hay, GEOMAR).

Gateways and Ocean Circulation

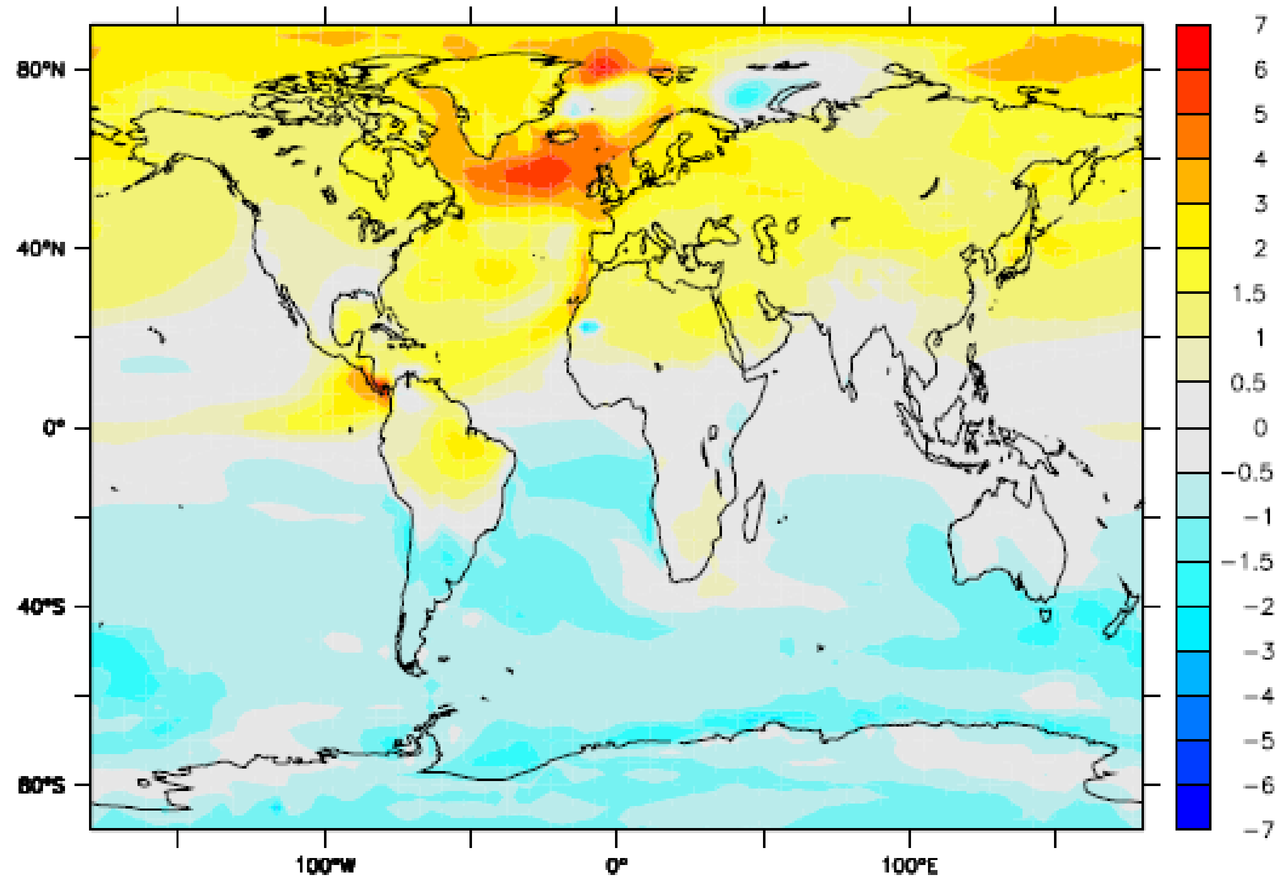






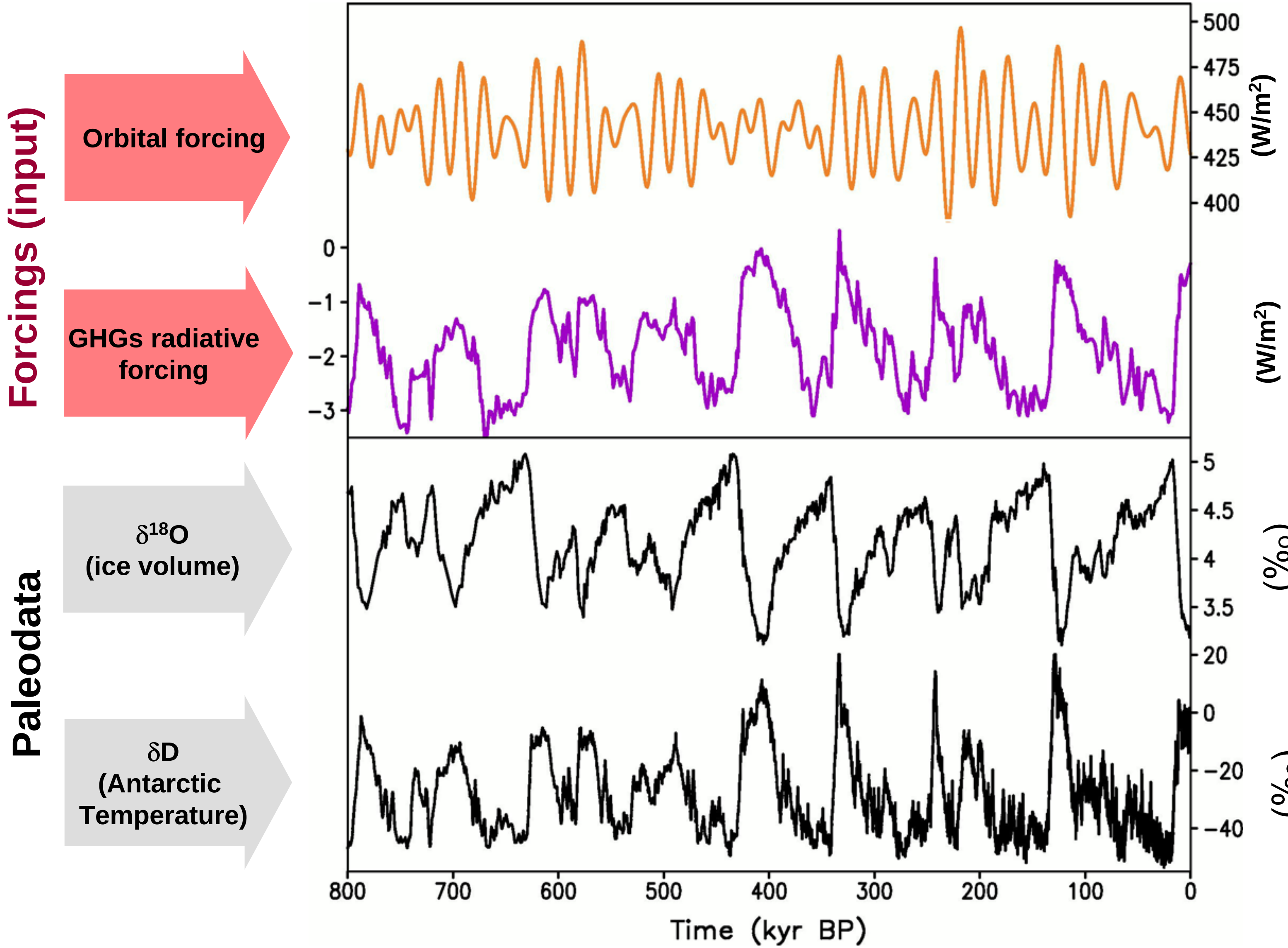


Effect of Panama closure on global climate



Simulation of the last 800 Kyr

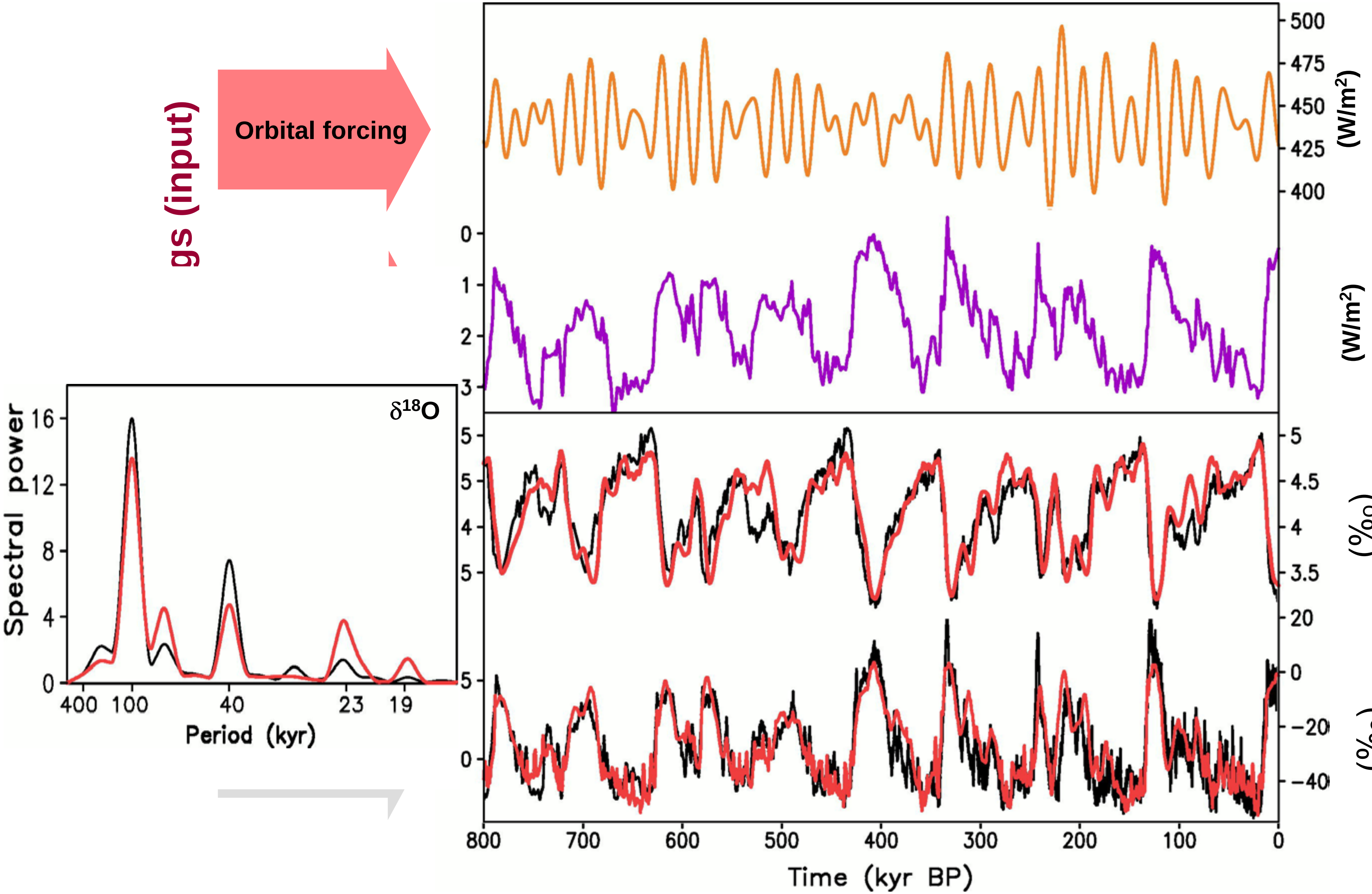
(orbital forcing + GHGs)



Ganopolski & Calov (*2011*)

Simulation of the last 800 Kyr

(orbital forcing + GHGs)



Ganopolski & Calov (2011)

Conclusions

Climate evolution over geological time scales is closely linked to geodynamics

Climate models are useful for testing hypothesis on the mechanisms of major climate transitions and mass extinction events

Large uncertainties remain in past climate focings and paleoclimate reconstructions

Simulations of the last 400 Kyr

orbital forcing + GHGs