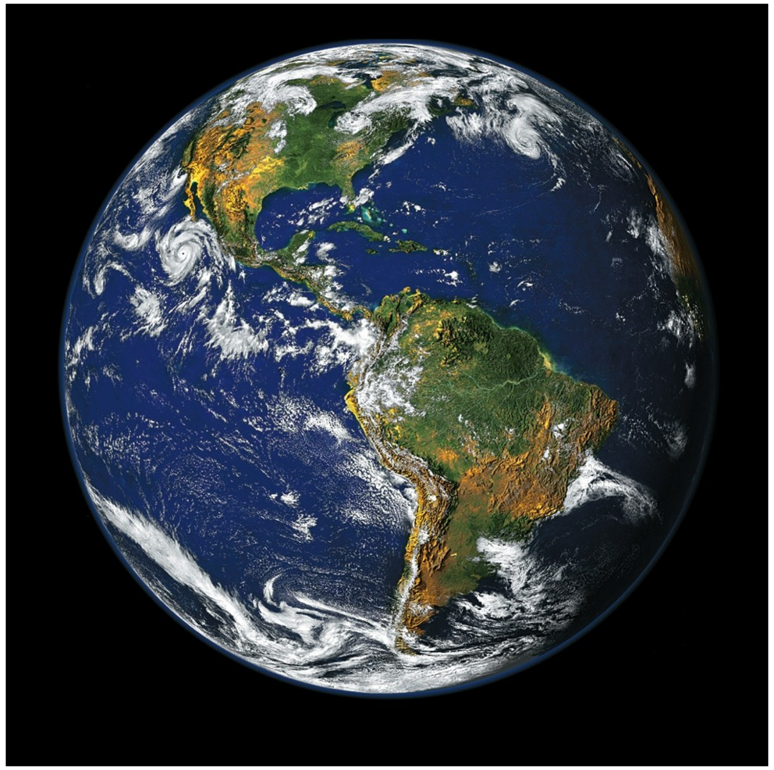


Lecture 4: Ice cores and climate

Learners: Climate Redux

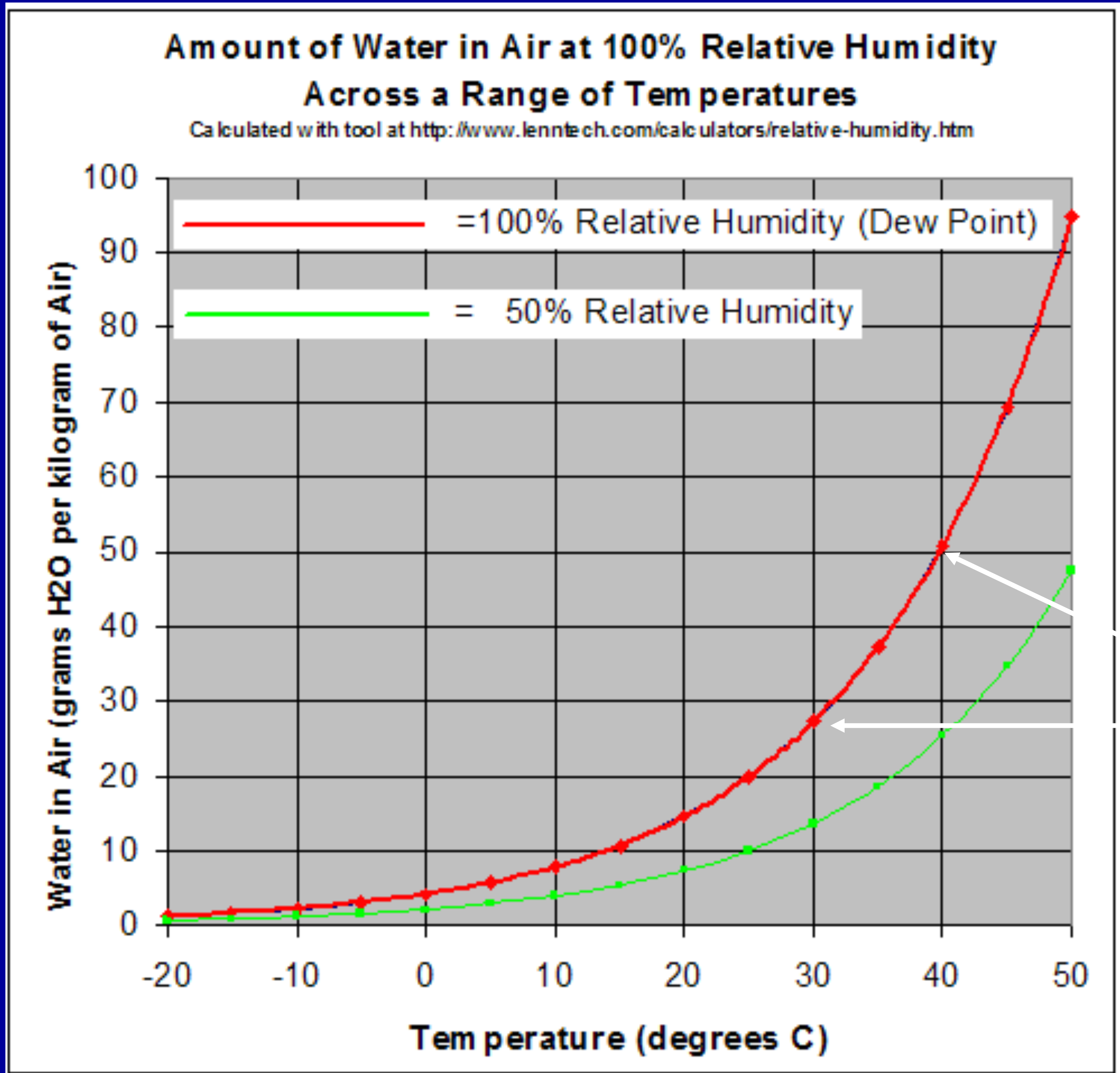
February 26, 2021

Jonathan F. Ormes
JFOrmes@gmail.com

Forest health: Dick Erdmann

- Deforestation
- Bark beetles and other pests
- Fire – for good and bad
  - Forest health
  - Forest destruction
- Overgrowth and poor age distribution
- Invasive species

Vital for fresh air, clean water, wildlife habitat and recreation, to say nothing about aesthetics.



Why are there more severe rainstorms and flooding?

Warmer air holds more H_2O

40^{o}C is 104^{o}F

30^{o}C is 86^{o}F

40^{o}C air holds twice more water vapor than 30^{o}C air

What I'm going to discuss today

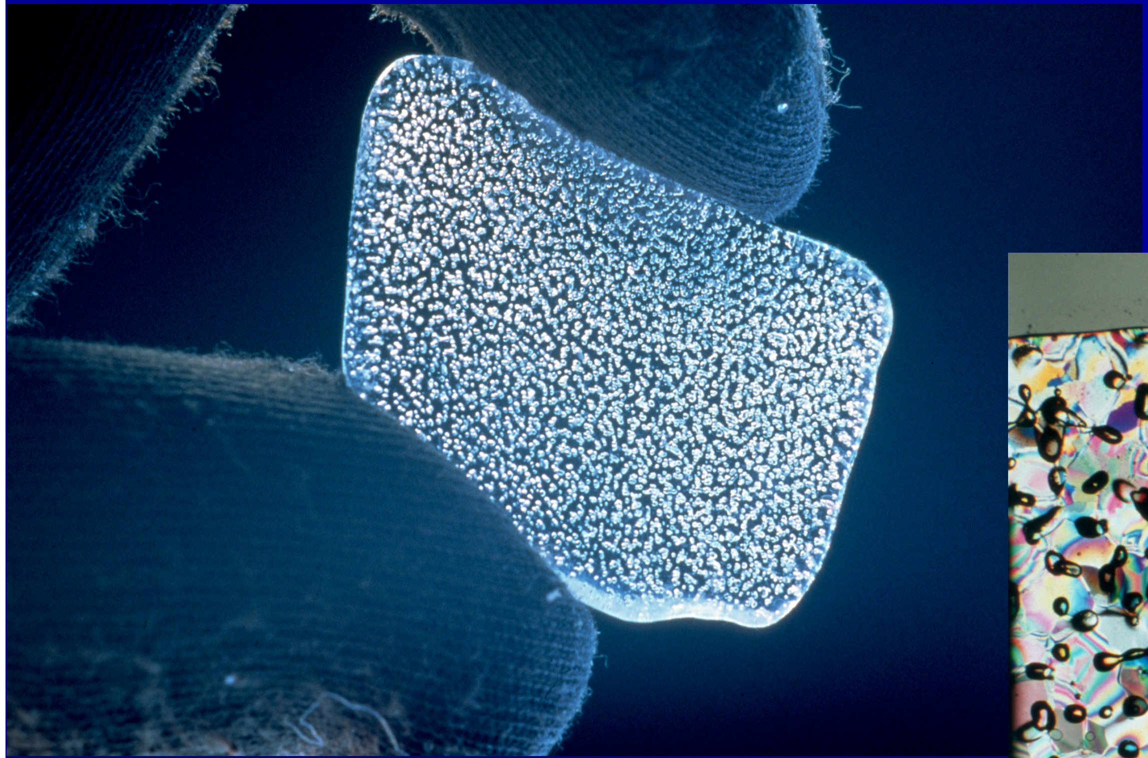
- Ice cores & ice ages
- Solar irradiance variations
- Paleo temperature record
- Weathering
- Paleo variations of Temperature & CO_2
- Oceanic and atmospheric circulations
- Climate feedbacks

National Ice Core Laboratory, Denver Federal Center

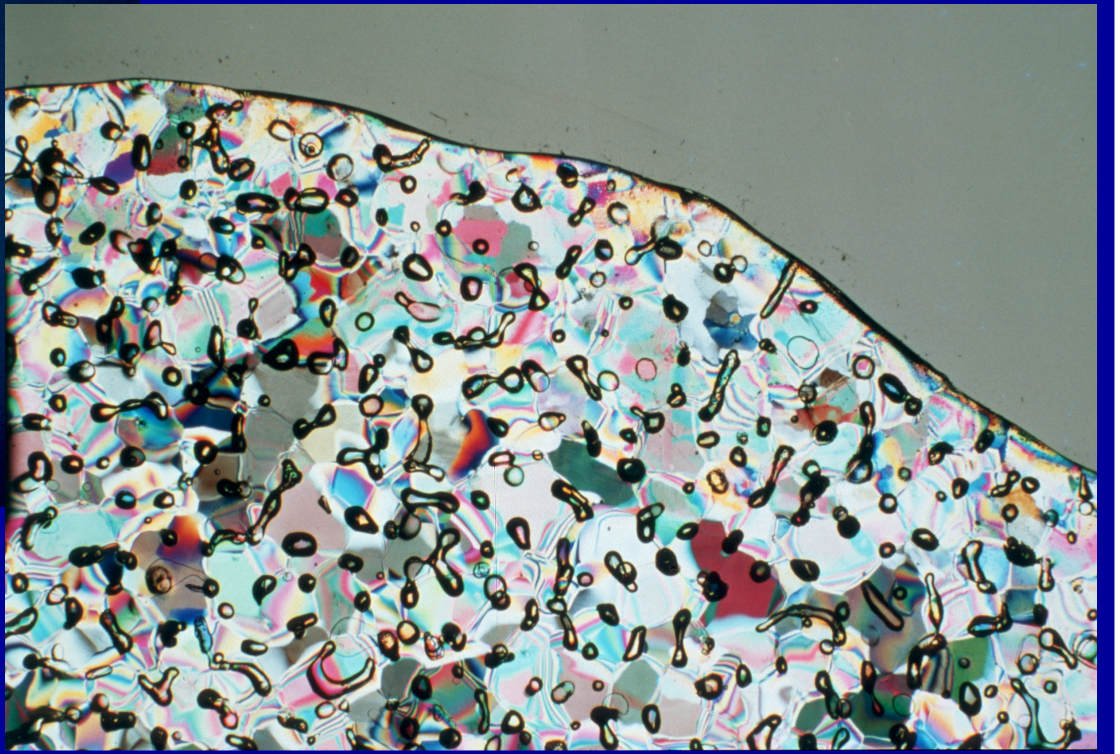

A picture of an ice core at the
National Ice Core Laboratory (NICL)
here in Denver, Colorado

Ice core data
Greenland: 130k year record
Antarctica: 440k & 800k yr records

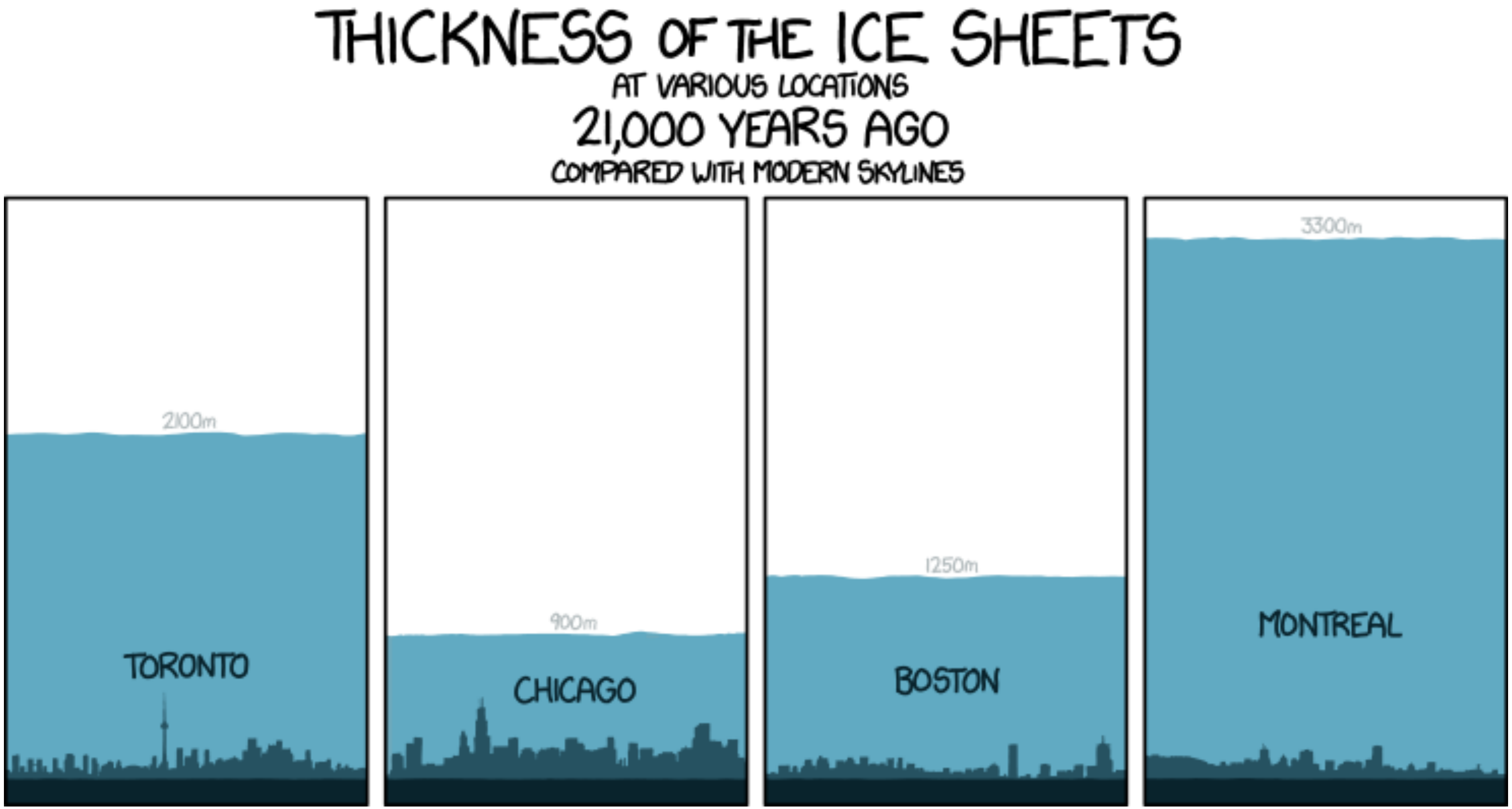
See the trapped bubbles of air



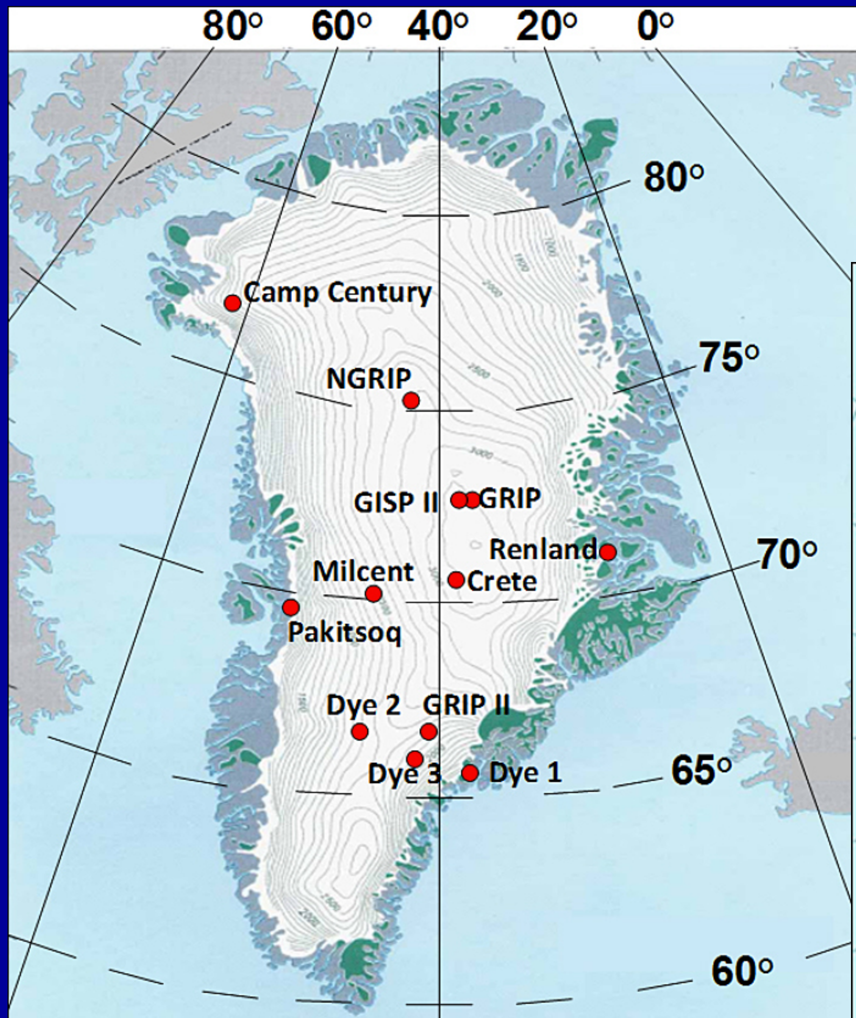
A thin section in polarized light




Sid hanging onto Diego’s leg


THICKNESS OF THE ICE SHEETS
AT VARIOUS LOCATIONS
21,000 YEARS AGO
COMPARED WITH MODERN SKYLINES
2100m
TORONTO
900m
CHICAGO
1250m
BOSTON
3300m
MONTREAL

Location of cores

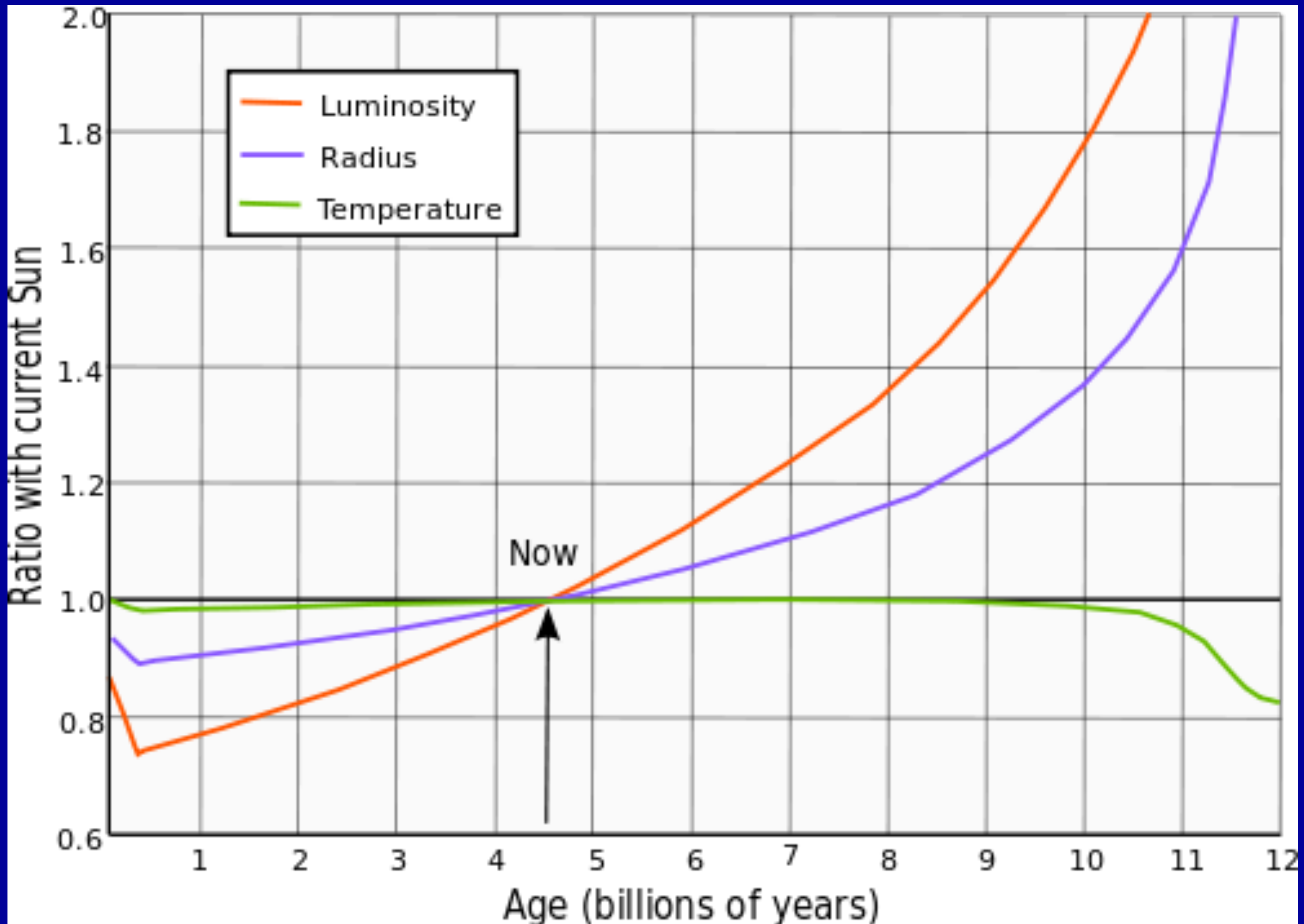


Climate changes with changes in the radiation balance

1. changing the incoming solar radiation (e.g., by changes in the Earth's orbit or in the Sun itself),
2. changing the fraction of solar radiation that is reflected (the albedo can be changed, for example, by changes in ice coverage, aerosols or land cover),
3. altering the energy radiated back to space (e.g., by changes in greenhouse gas concentrations).

Local climate also depends on how heat is distributed by winds and ocean currents. All of these factors have played a role in past climate changes.

The sun evolves

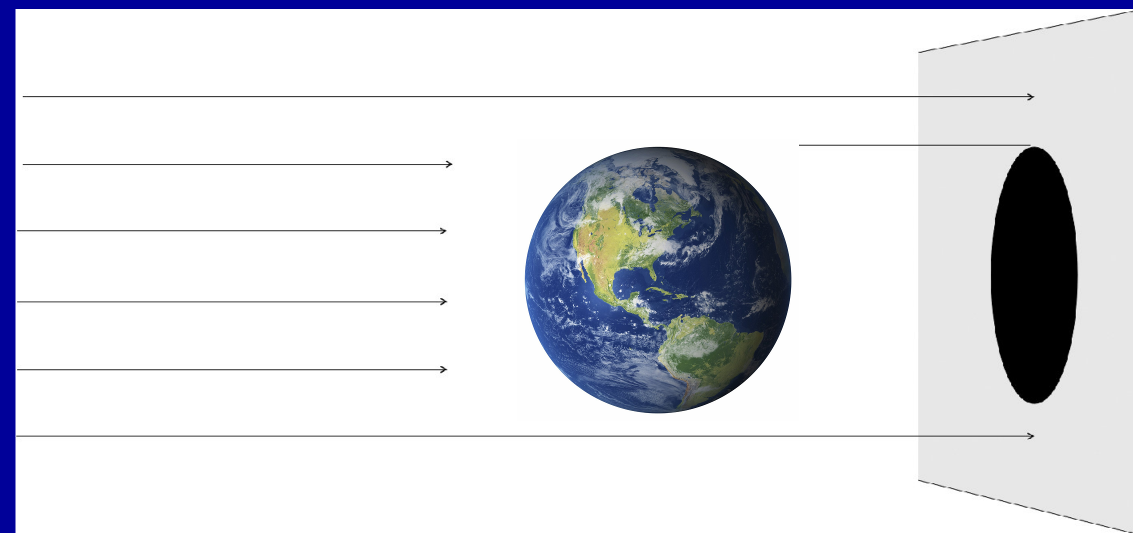


Solar luminosity (red curve) is the one that concerns climate.

Current rate is just under 10%/billion years = 0.000005%/100 years

Solar insolation: Energy flux
Energy per unit time and area

⟵ $R_{S\text{-}E} = 1.50 \times 10^8$ km ⟶



$A\sigma T^4$

Insolation at Earth's orbit
=1362 W m^{-2}

Area of circle is
¼ area of sphere

πR_E^2

=340.5 W m^{-2}

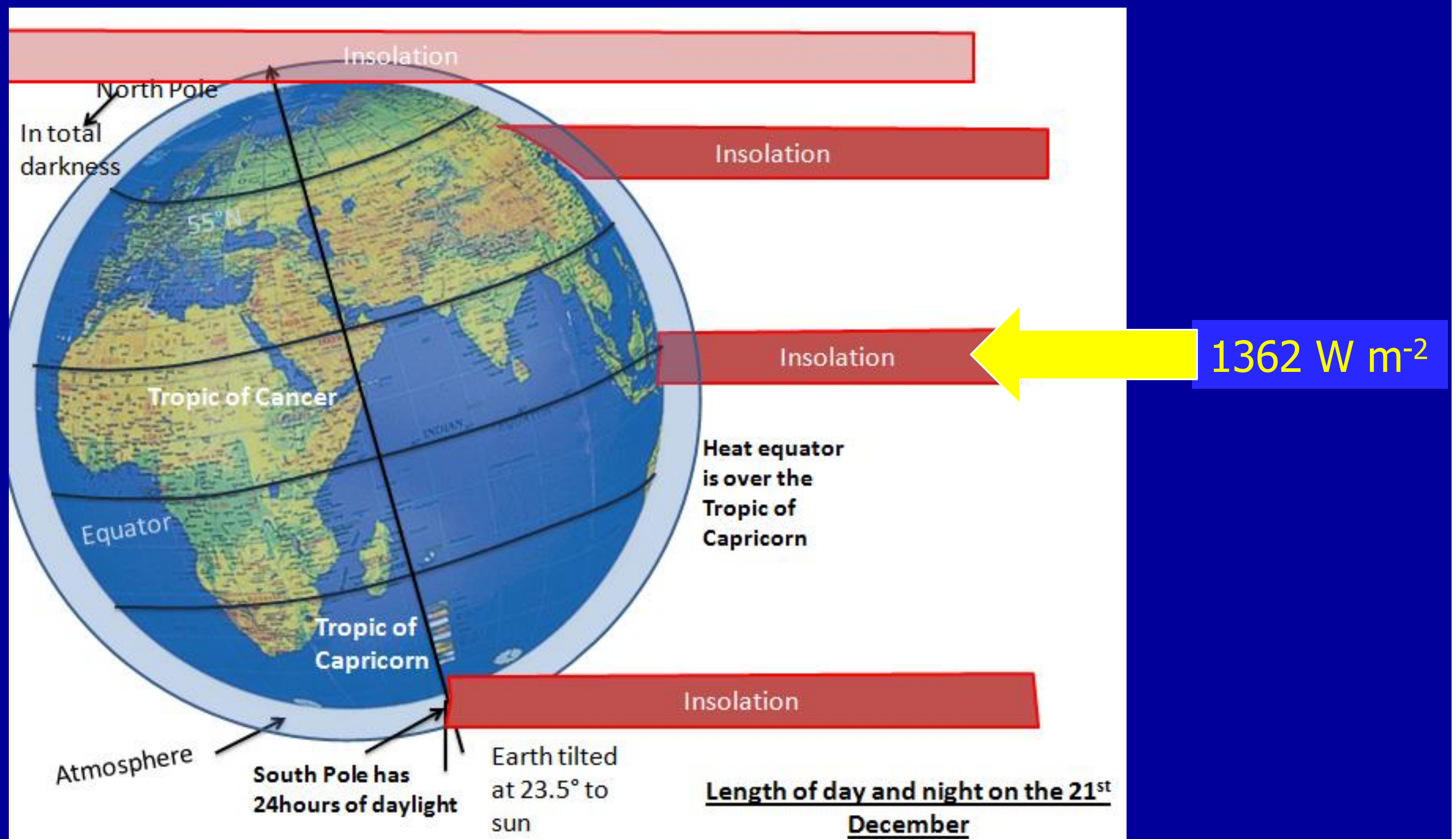
Average albedo of Earth = 0.31
Includes atmosphere, clouds, aerosols and surface
$(1-\alpha) = 0.69$

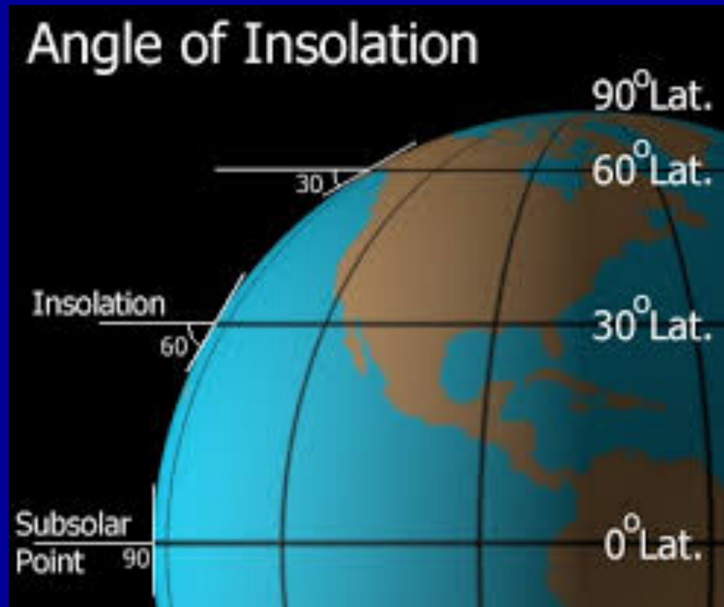
$(1-\alpha)\pi R_E^2$

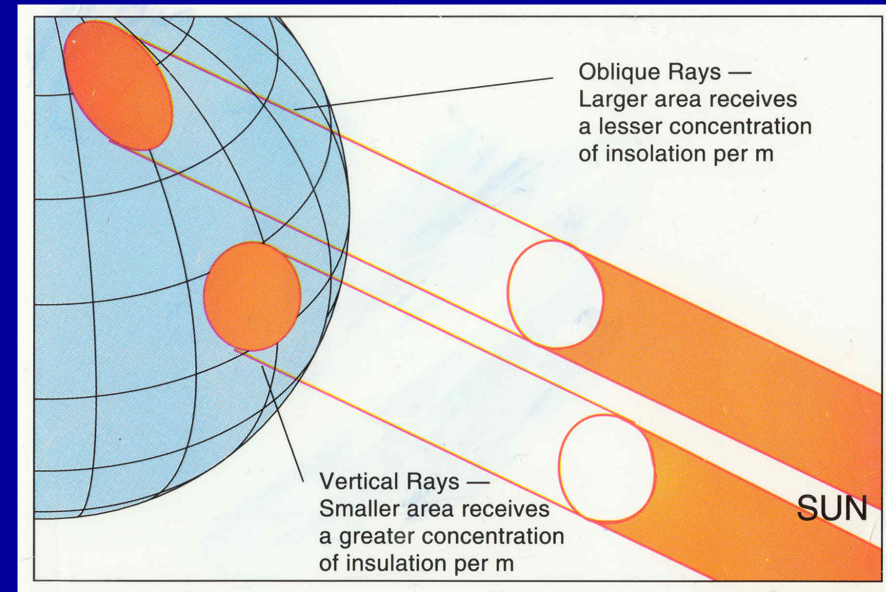
Energy absorbed by Earth=235 W m^{-2}

Sensitivity zone

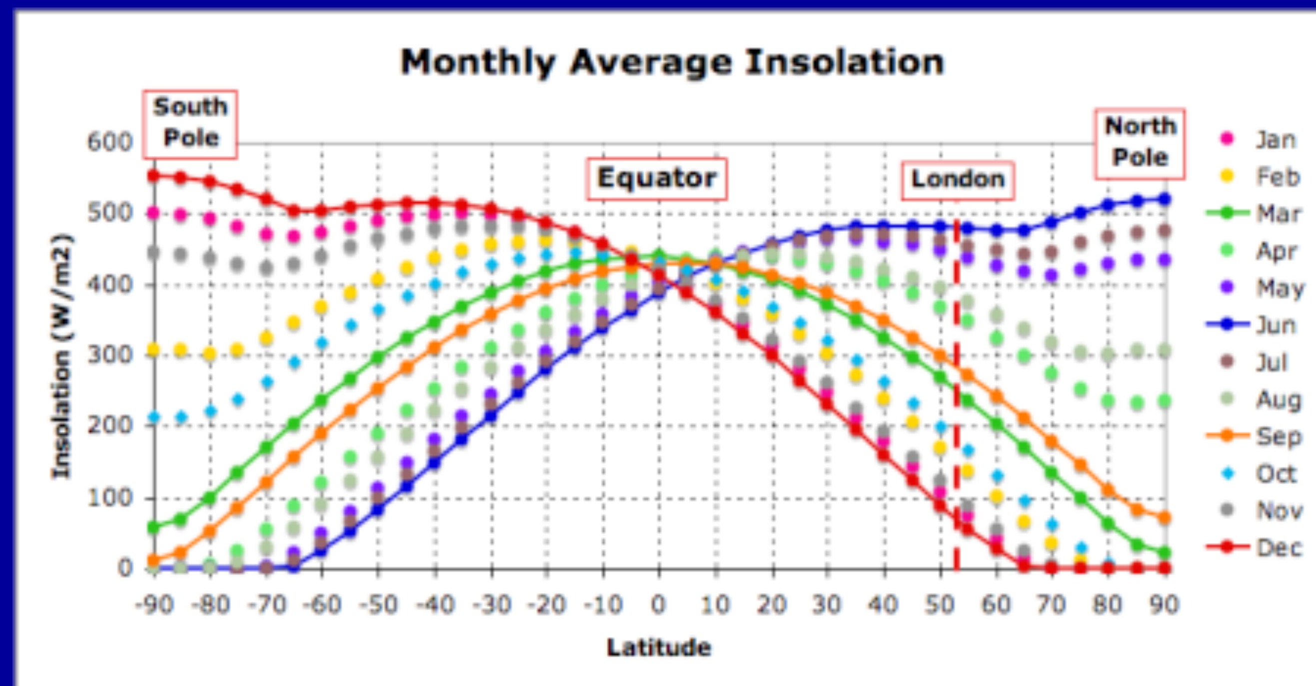
Planet sensitive to the solar irradiance at 65 degrees north latitude.







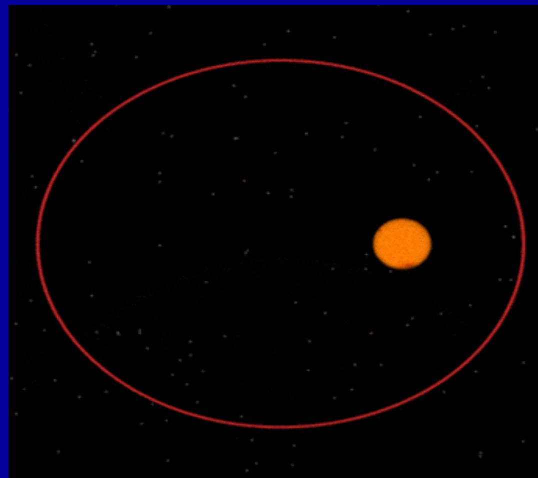
Denver 40 °NLat

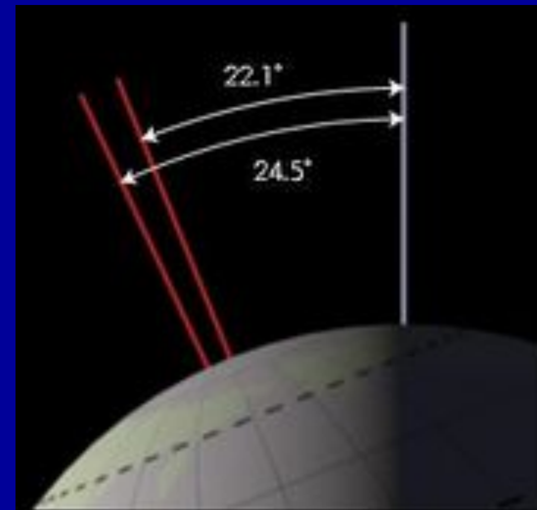


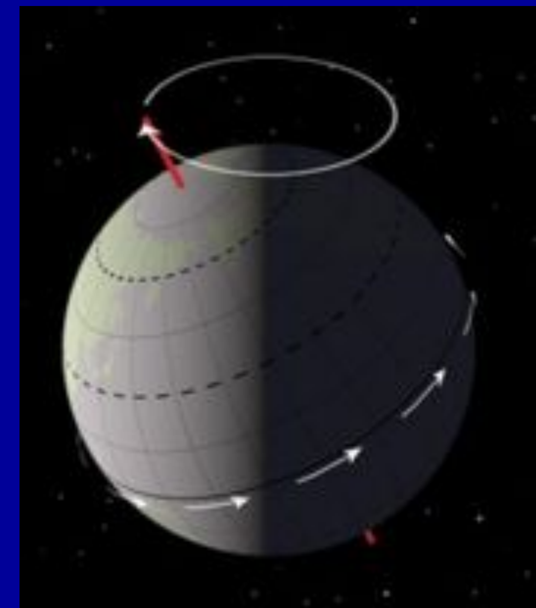
Solar insolation

The term insolation comes from 'incident solar radiation'.

Milankovitch cycles



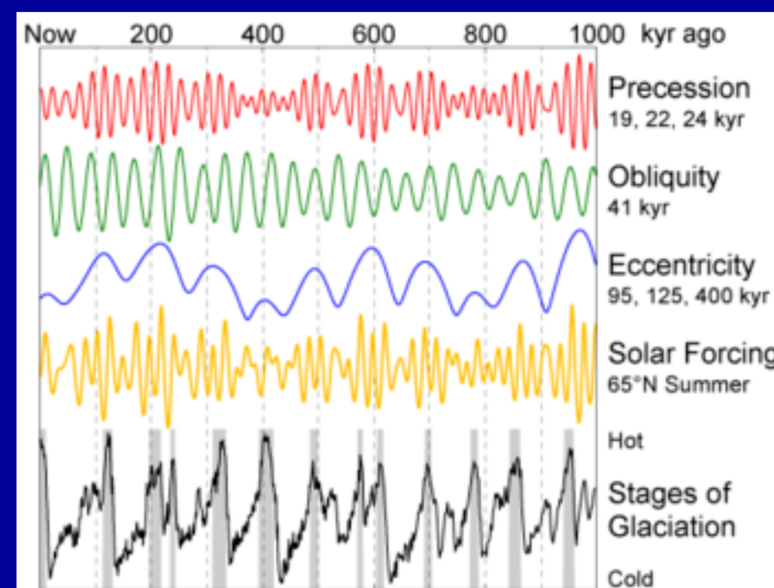




Precession:
19, 22 and 24 kyr

Eccentricity: $R_{sun\text{-}E}$ changes by 3.4% over the year and currently is furthest in the summer (around July 4).
95, 125 and 400 kyr

Obliquity: 21.5°-24.5°
now 23.44°
41 kyr



Motions are complex, and driven by solar and lunar tidal forces, and by gravitational effects of Saturn and Jupiter.
Periods: 20,000-260,000 years.

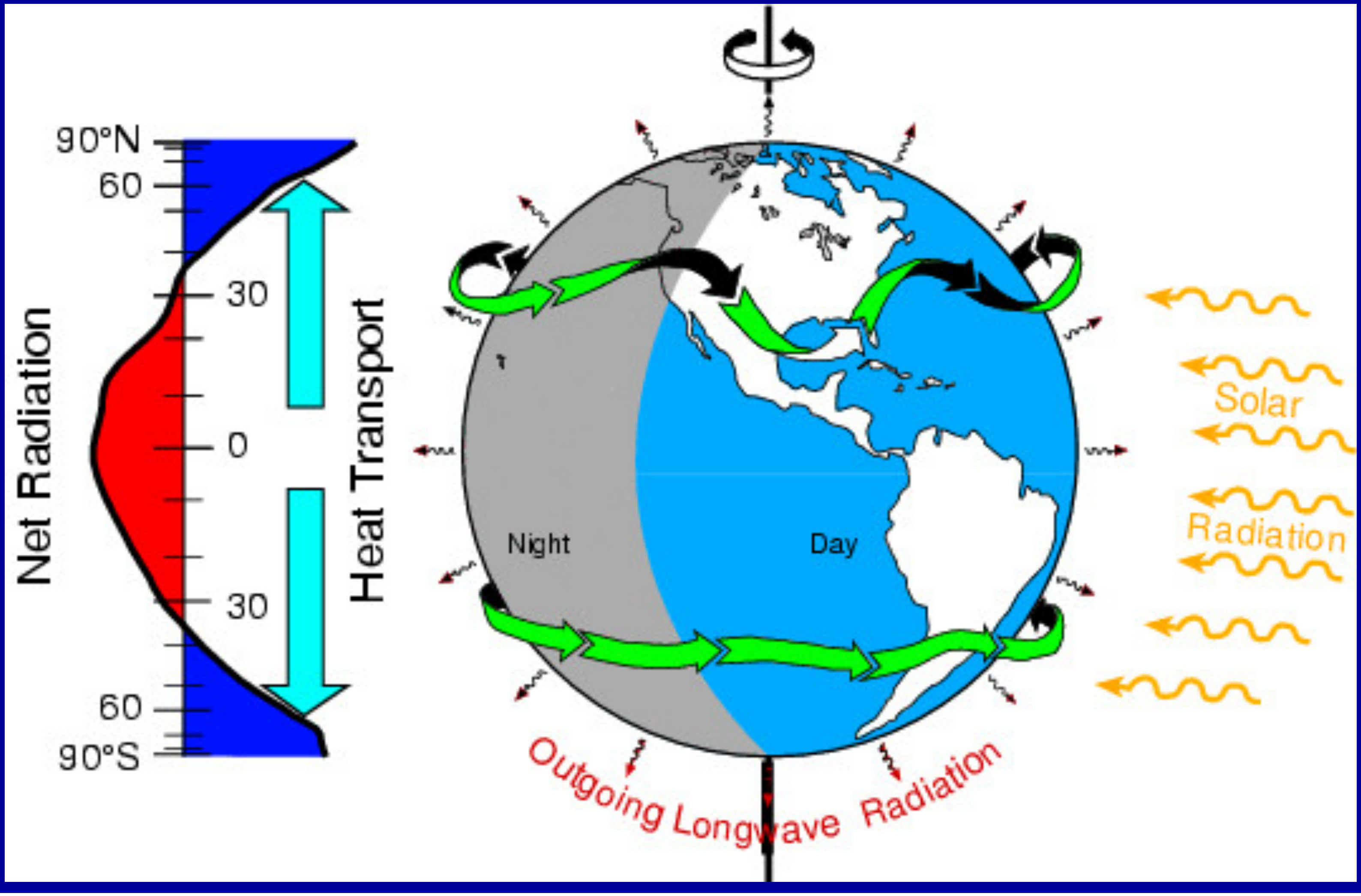
How the heck do you know the temperature back then?

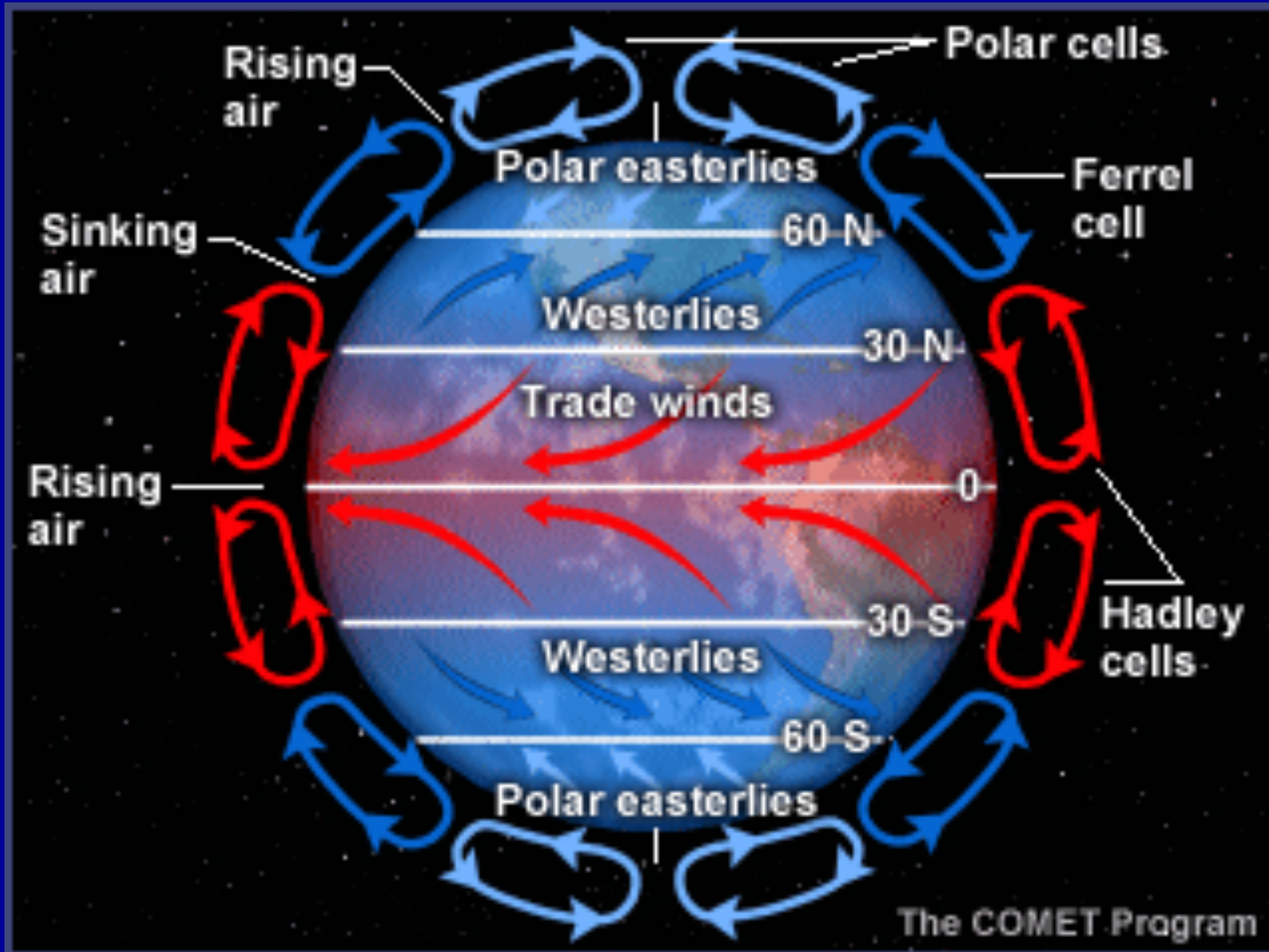
Energy Distribution

Incoming solar radiation is unevenly distributed

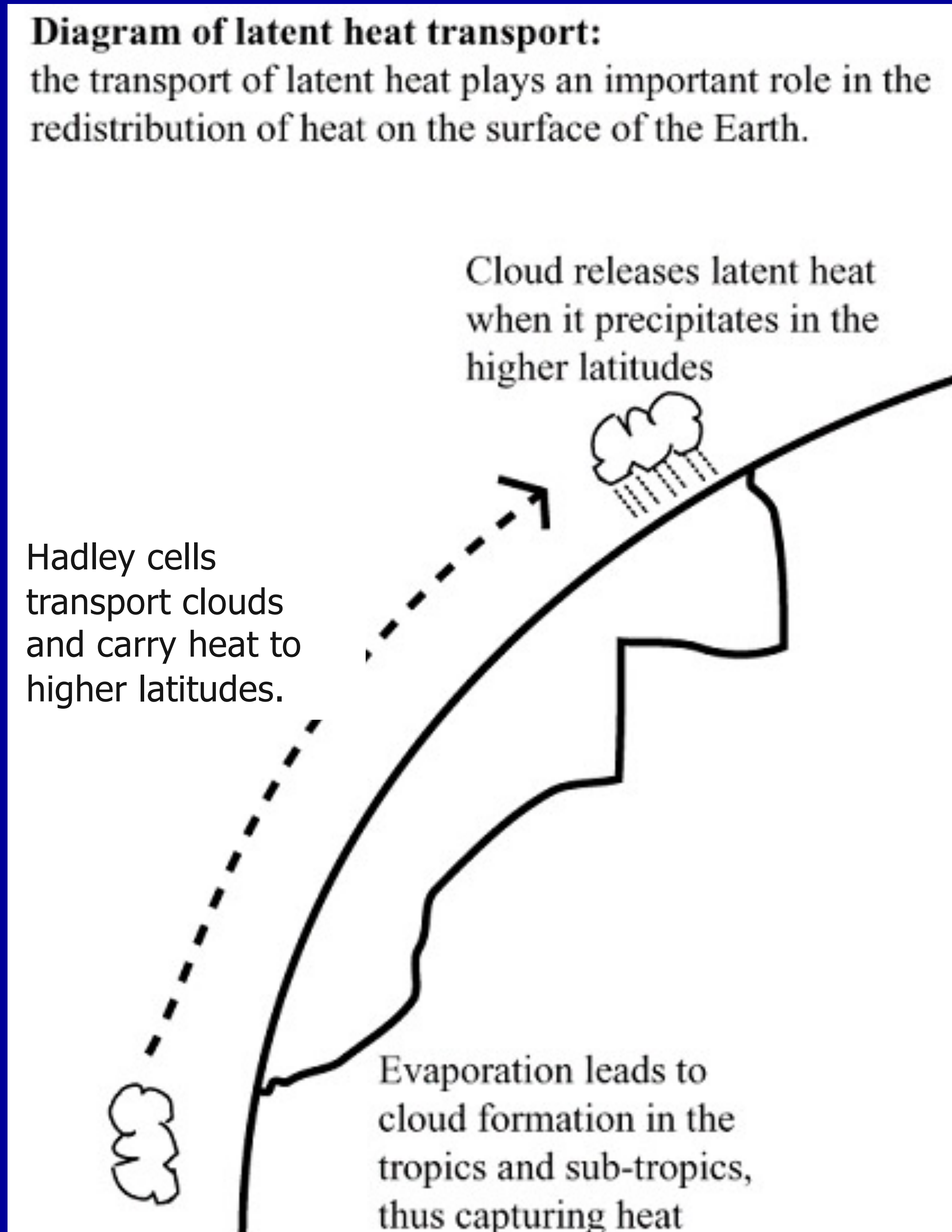
the Earth is a sphere.

Outgoing infrared heat radiation is more uniform.





Polar cells
Rising air
Polar easterlies
Ferrel cell
Sinking air
60 N
Westerlies
30 N
Trade winds
Rising air
0
Hadley cells
30 S
Westerlies
60 S
Polar easterlies
The COMET Program



Heat transport

Transport by Hadley cells:

Latent heat is the heat energy required to change ice to liquid and liquid to gas.

Latent *heat flux* is the global movement of heat energy through circulations of air and water.

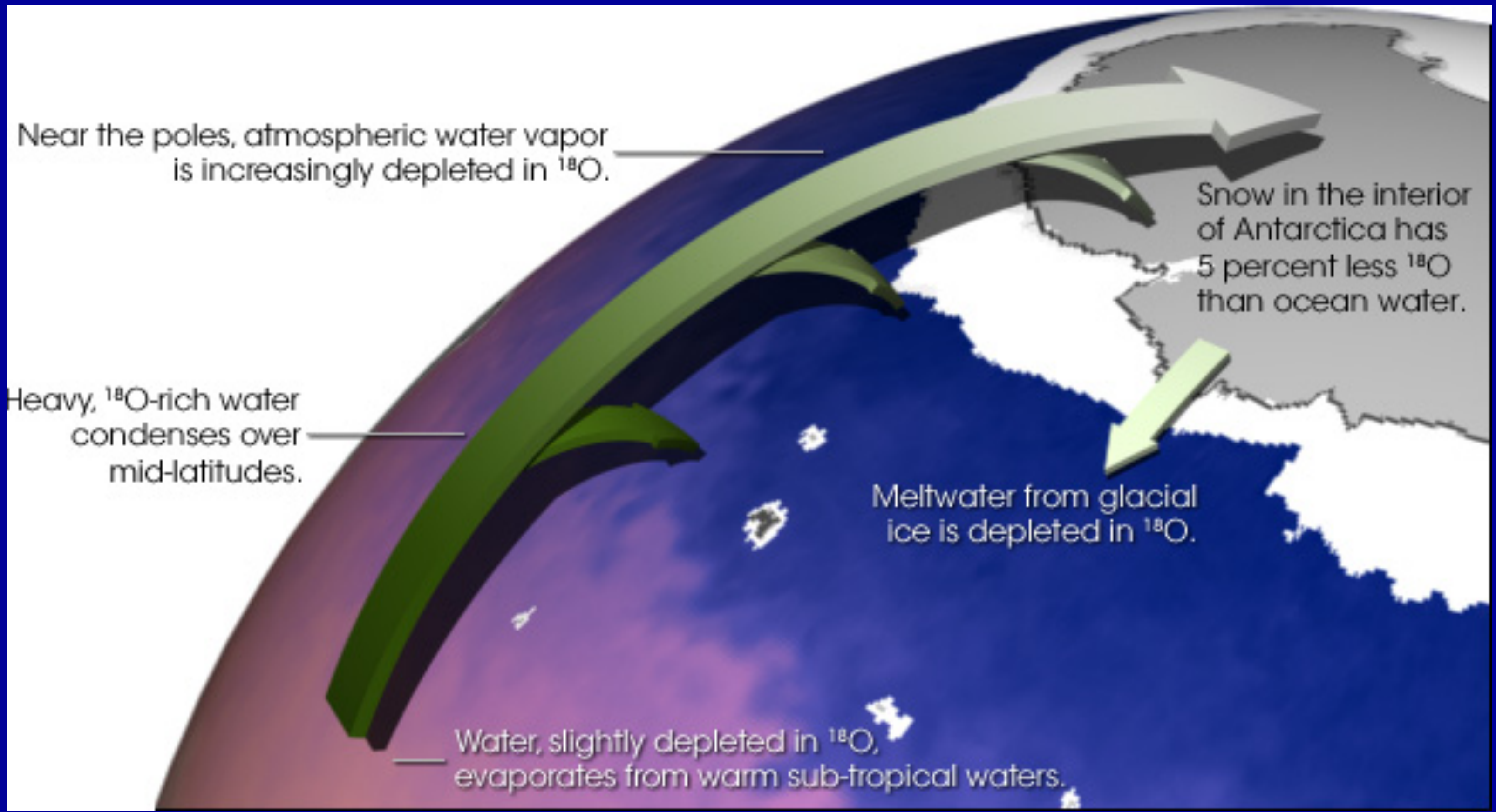
Atmospheric circulation moves heat energy from the tropics to cooler locations where it is condensed as rain or is deposited as snow releasing the latent heat energy.

http://earthguide.ucsd.edu/virtualmuseum/images/LatentHeatFlux.html

^{18}O as a temperature proxy

Evaporation and condensation influence the abundance ratio [$^{18}O/^{16}O$].
^{18}O is 12.5% heavier than ^{16}O.
$H_2{}^{16}O$ evaporates more easily than $H_2{}^{18}O$.
$H_2{}^{18}O$ condenses more easily than $H_2{}^{16}O$.

Heavy hydrogen (deuterium) can be used in the same way.

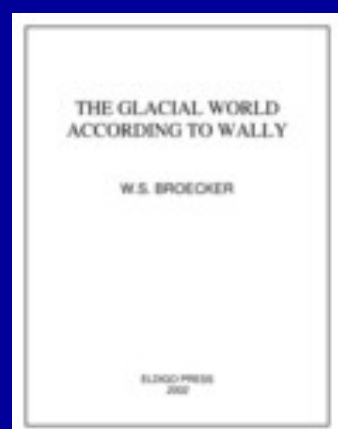


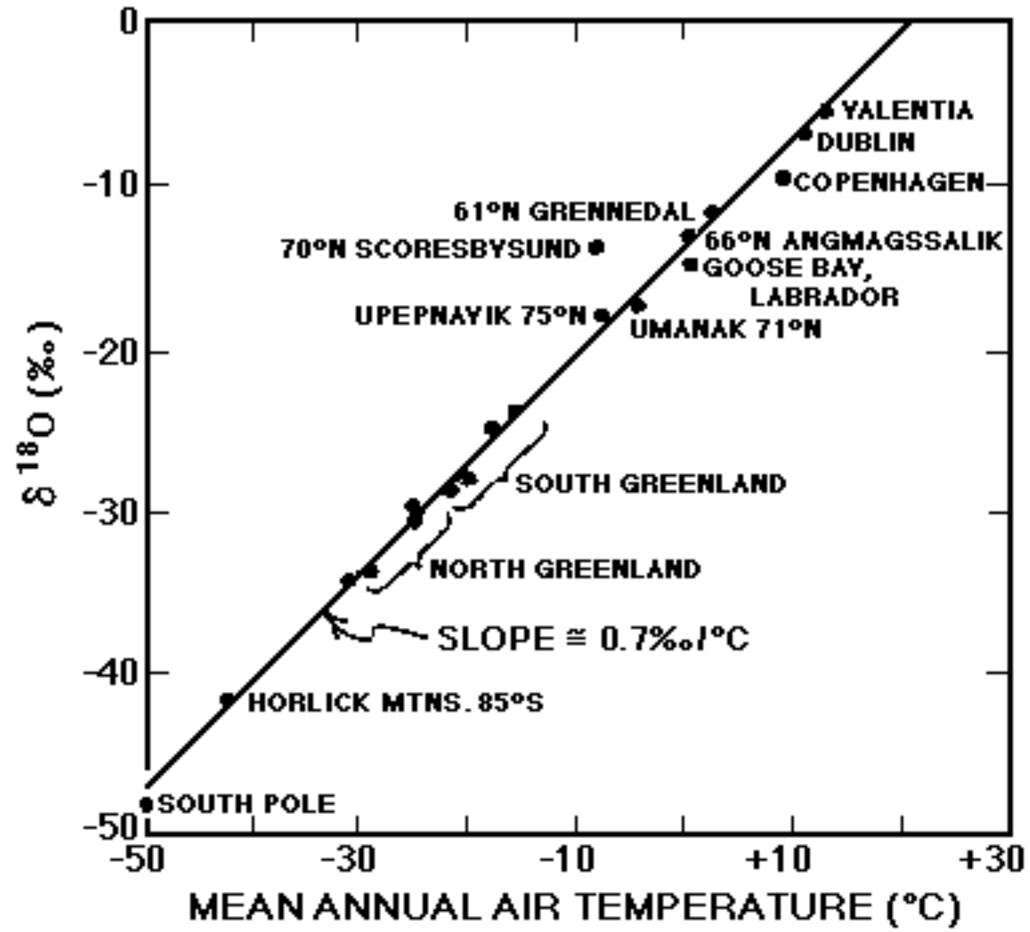
The $^{18}O/^{16}O$ temperature proxy.

Measure $\delta^{18}O$ along an ice core and get out a record of temperature vs. time.

Also, with sea floor cores.

Wallace S. Broecker





Observed $\delta^{18}O$ in average annual precipitation as a function of mean annual air tamperature (Dansgaard, 1964). Note that all the points on this graph are for high latitudes (>45°). The $\delta^{18}O$ values are calculated as follows:

$$\delta^{18}O = \frac{\left[\left(\frac{^{18}O}{^{16}O}\right)_{\text{sample}} - \left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}\right]}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{standard}}} * 1000\%$$

Natural CO_2 weathering

Carbonate Rocks

1. CO_2 is removed from the atmosphere by dissolving in water, forming carbonic acid and precipitating as rain
   - $CO_2 + H_2O \rightarrow H_2CO_3$ (carbonic acid)
2. Carbonic acid rain interacts with rocks, yielding bicarbonate ions and other ions, making clays (soils)

$H_2CO_3 + H_2O$ + minerals in rocks ->
HCO_3^- + ions (Ca^{++}, Fe^{++}, Na^+, etc.) + clays

3. Bicarbonate and the other ions dissolve in rain and wash to the ocean and are used by sea creatures.

Weathering is the process whereby CO_2 is slowly removed from the atmosphere by these reactions.

Reaction rates for weathering

- Increase with temperature (typically)
- Increase with humidity

- Most effective in the tropical latitudes

- Weathering time scales are geologic
  - 0.5 to millions of years

Chemical Weathering

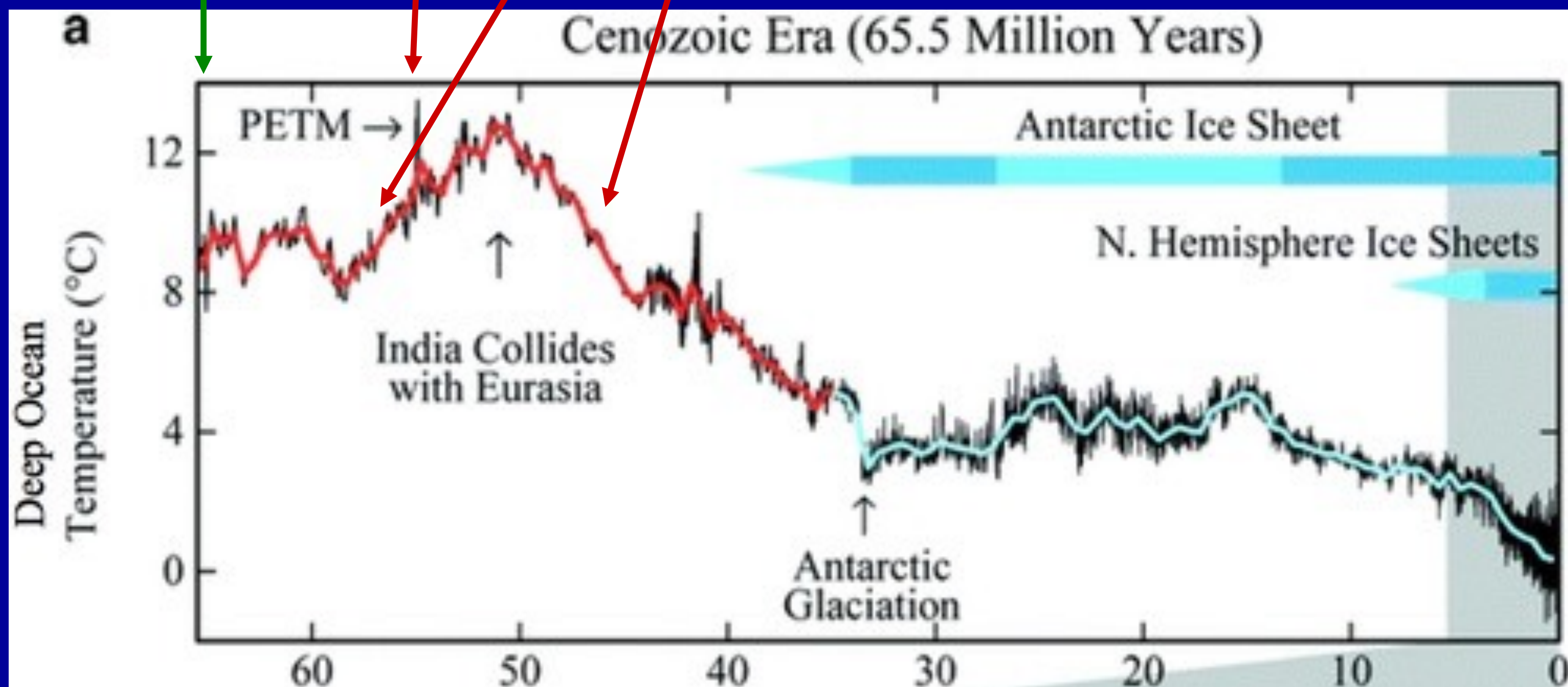
65.5 Million years of climate change

PETM: Paleocene-Eocene Thermal Maximum
What happened to make the climate warm suddenly?

Temperature rising due to buildup of CO_2 in atmosphere.

India-Eurasian collision exposes fresh rock
increasing rate of CO_2 drawdown by weathering.

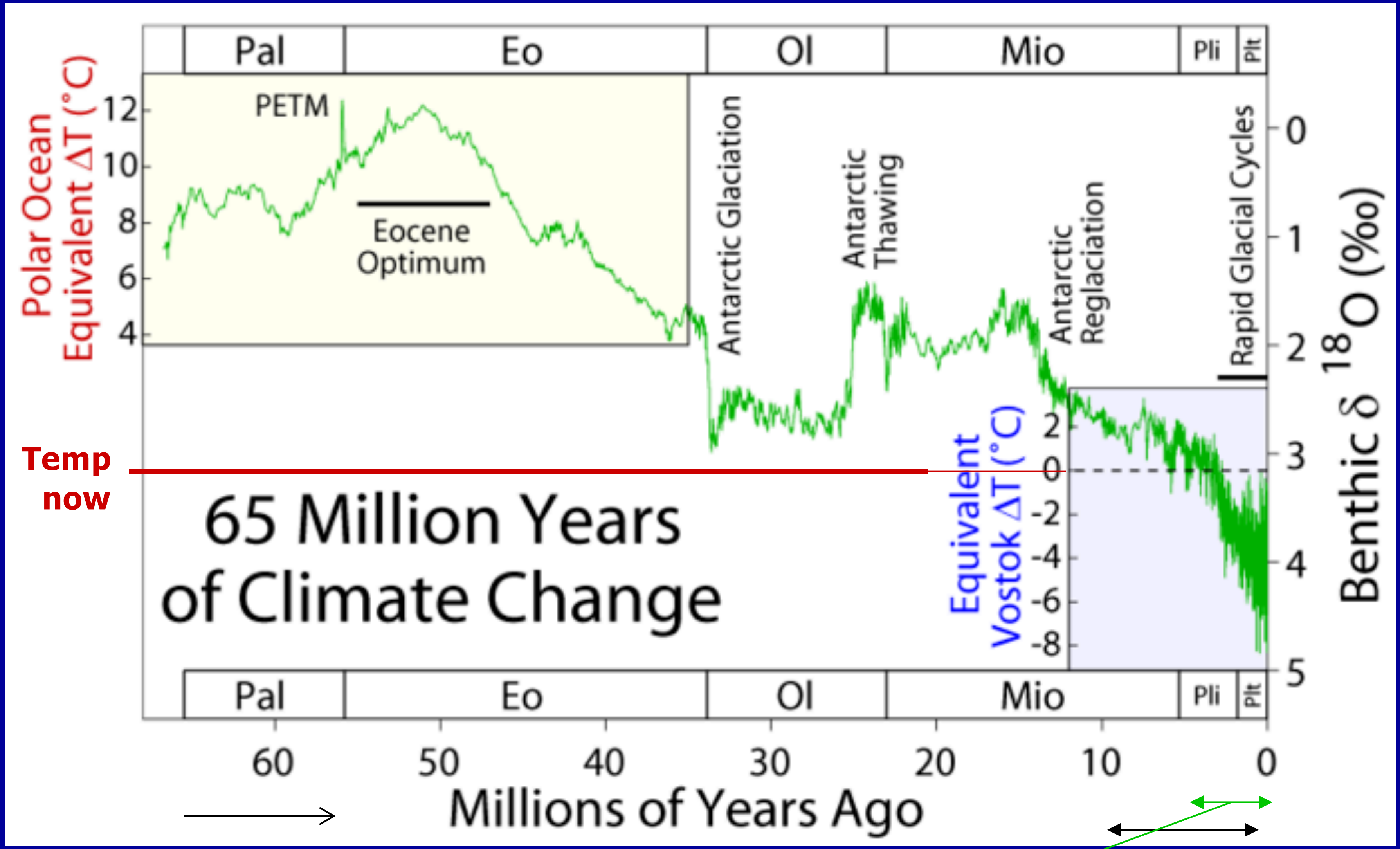
Big meteor hits Yucatan
Bye-bye dinosaurs



Millions of years

Since the dinosaurs

PETM: Paleocene Eocene Thermal Maximum



birds and mammals

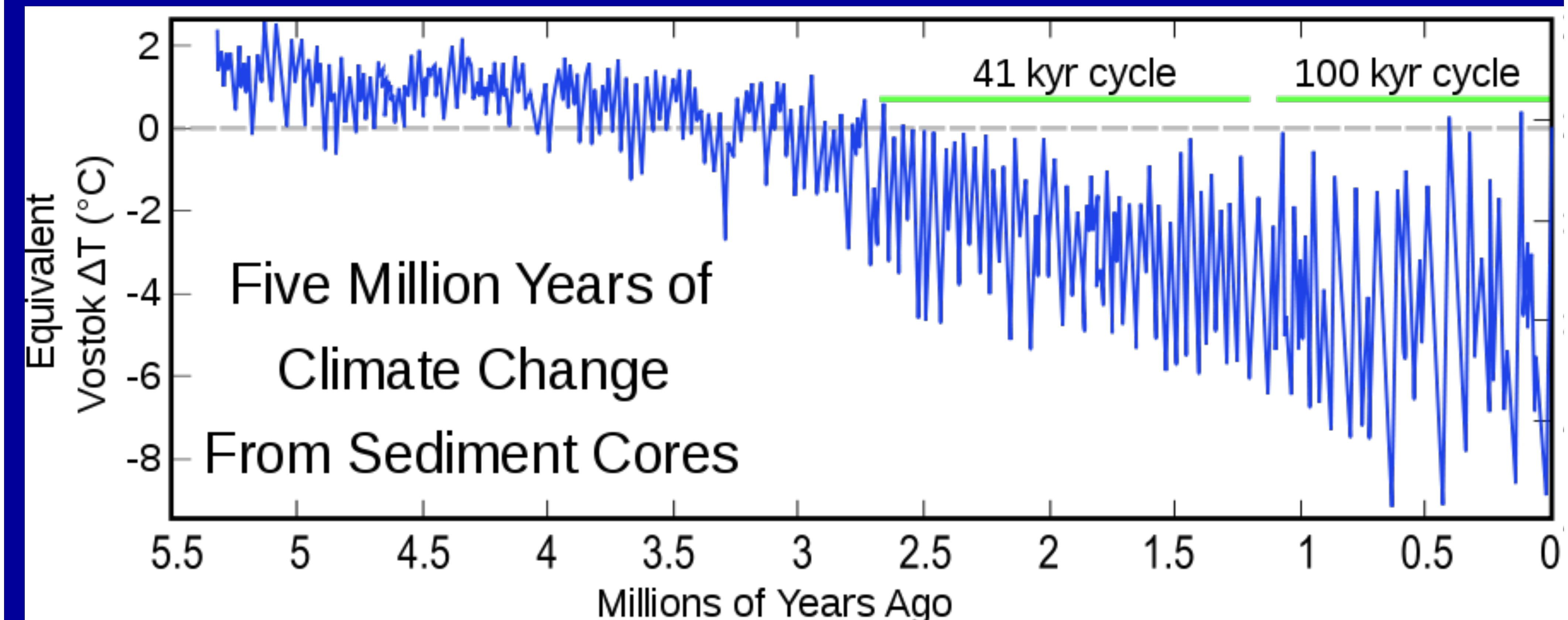
Genus homo

Next slide

δO^{18} benthic temperature for the past 5 M years

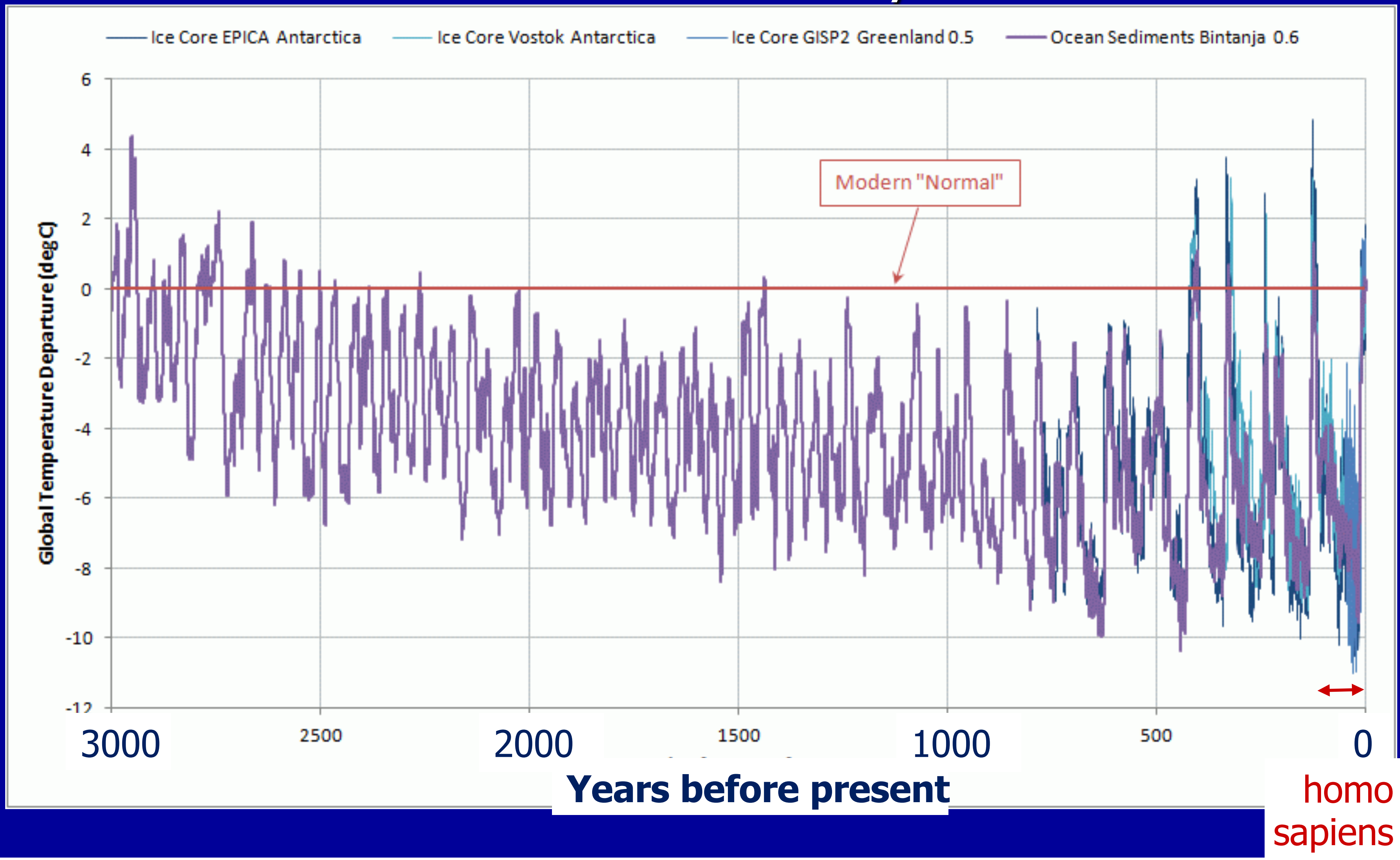
Temperature inferred from sea floor sediment measurements converted to Vostok/Antarctica ice core temperatures.

41 kyr cycle obliquity 100 kyr eccentricity

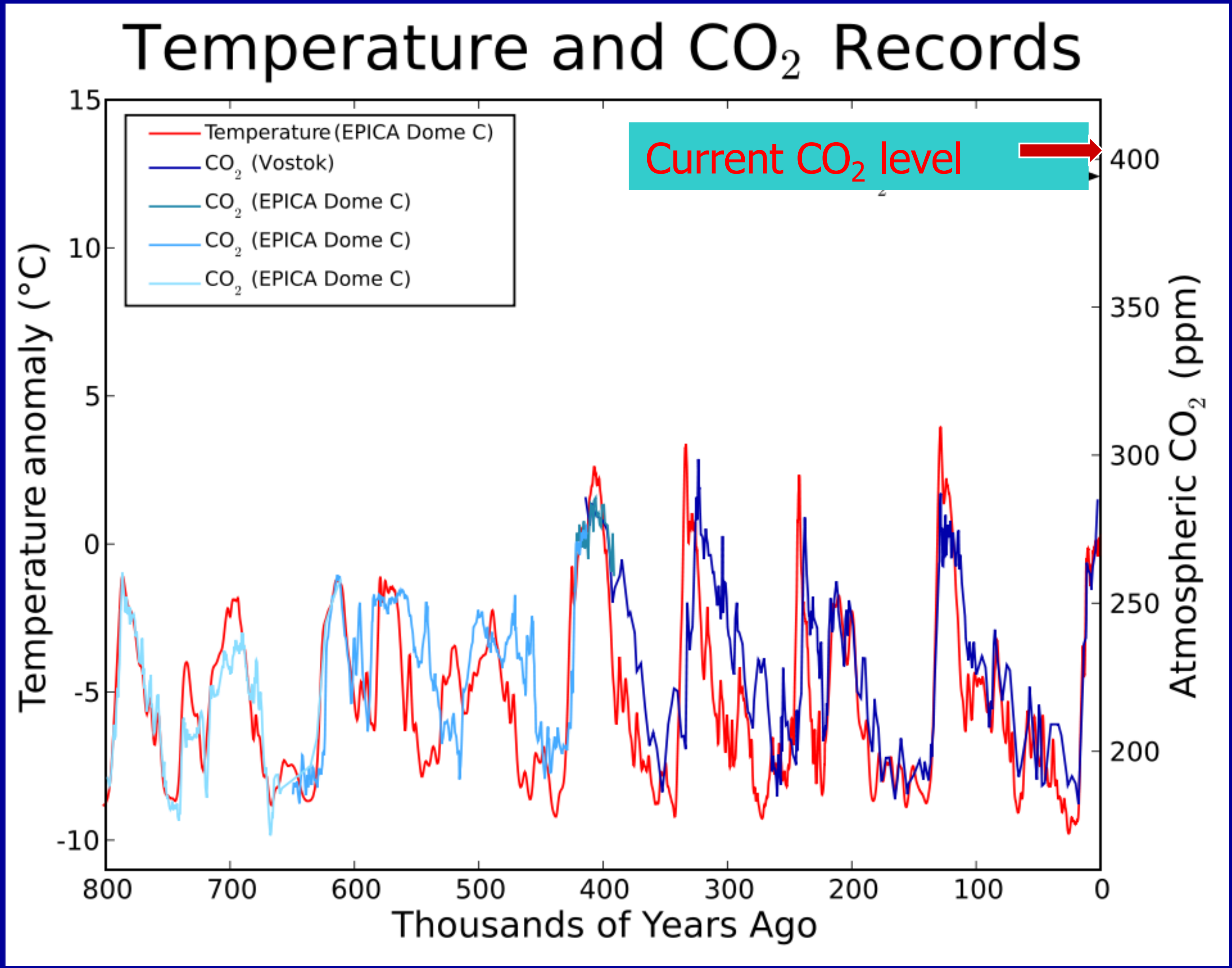


The climate changes all the time.

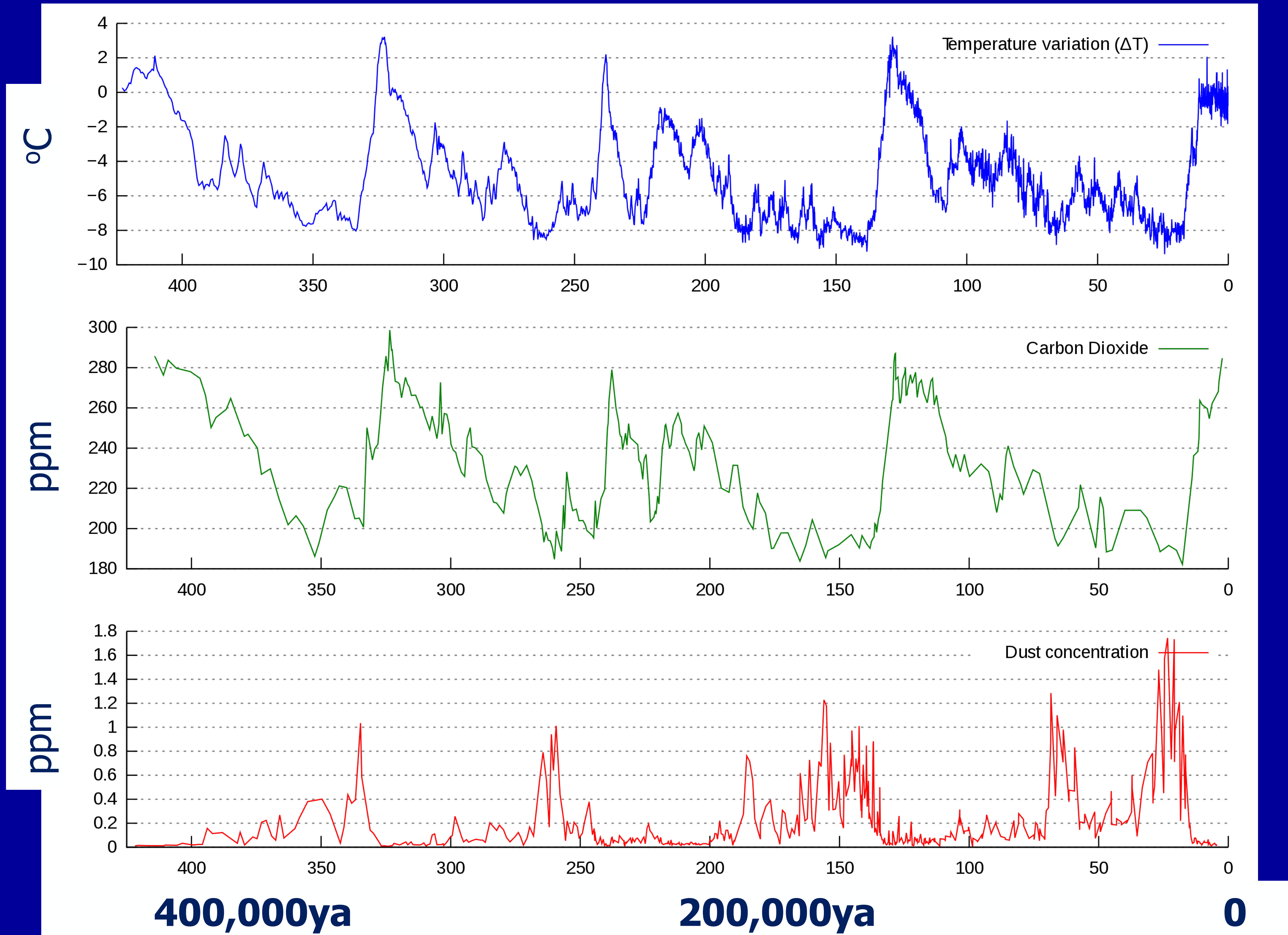
The plot shows average planetary temperature for the last 3 million years.



Now we can see CO_2 data, too, in ice cores going back 800k years.



Temperature, CO_2 and dust history (Vostoc/Antarctica)



Dansgaard-Oeschger (D-O) events (quasi periodic 1500 years)

Sudden warming episodes (8°C over 40 years)

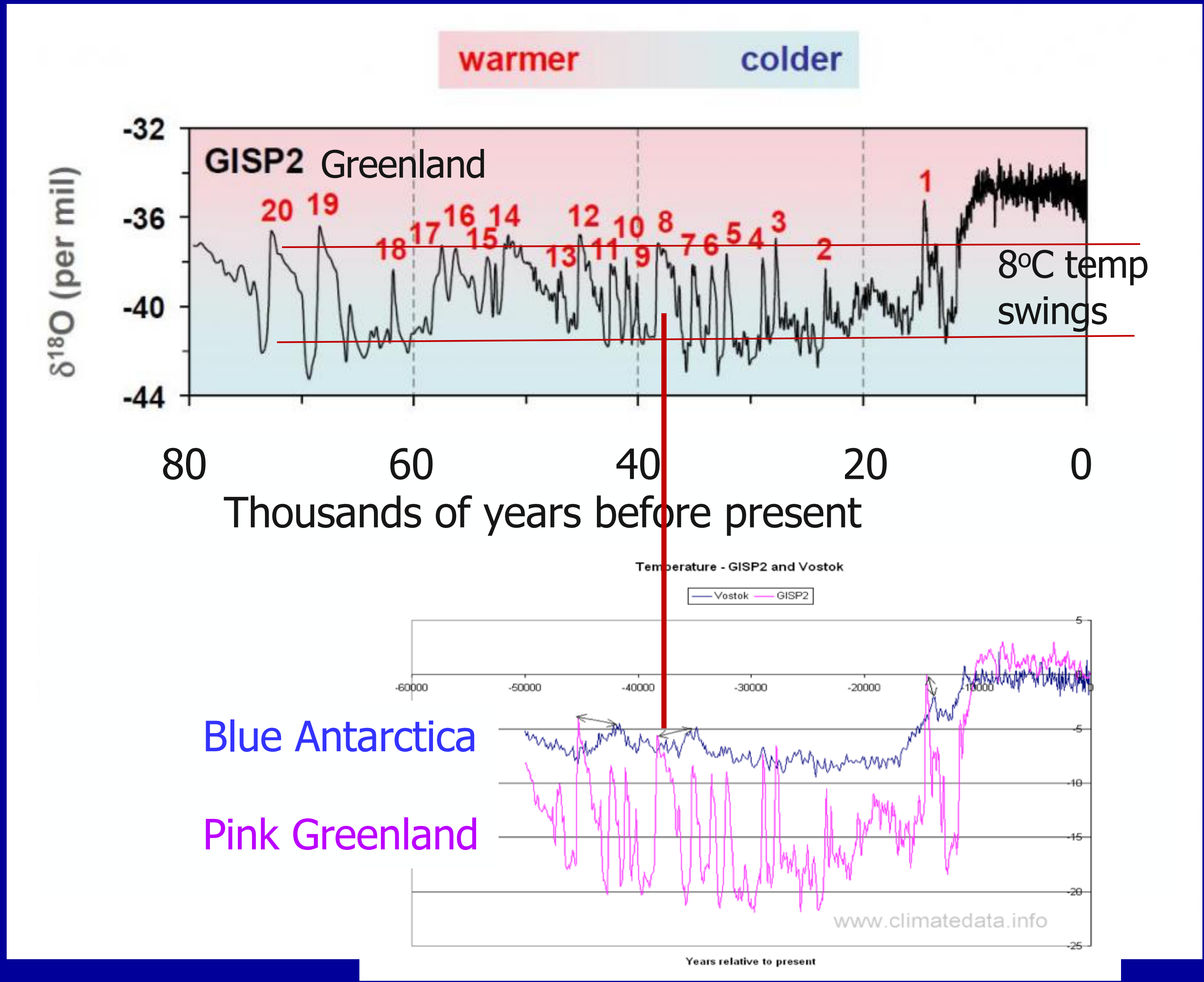
Gradual cooling

Binge-purge cycling of ice sheets

Changes in the Atlantic ocean current pumps

Bi-polar seesaw – a natural oscillation of the system??

North leads: 200 years



Heinrich events (iceberg stones in Atlantic)

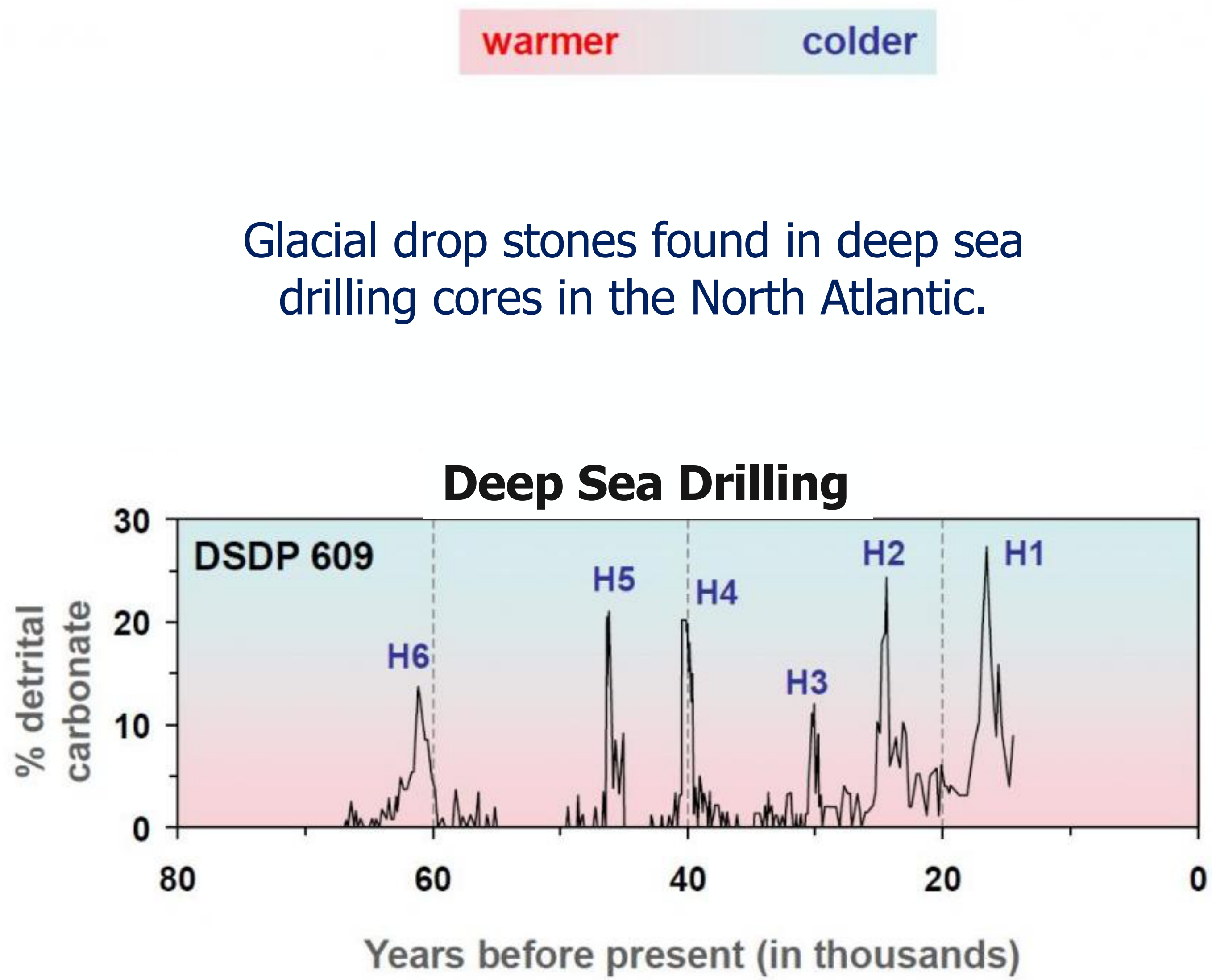
Ice sheet breakup (trigger unknown)

Freshwater dumps -> reduced salinity

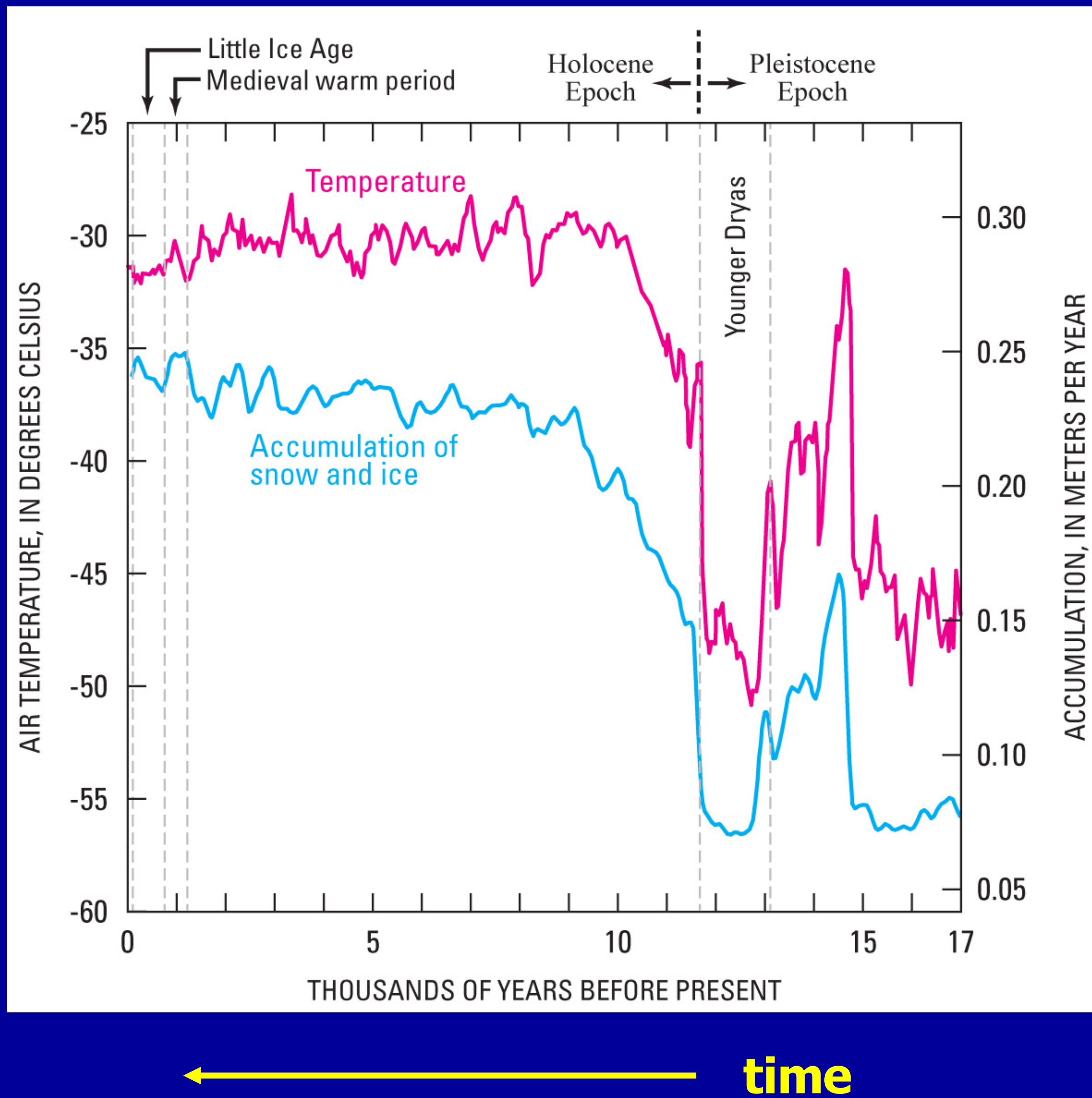
Cutting off the Atlantic ocean current pumps

Cooling North Atlantic, Eastern North America and Europe

Glacial drop stones found in deep sea drilling cores in the North Atlantic.



Younger Dryas



Why did we suddenly go back into a cold period? Turn-off on the circulation caused by sudden freshwater release or a meteoritic impact (or comet or VELA supernova).

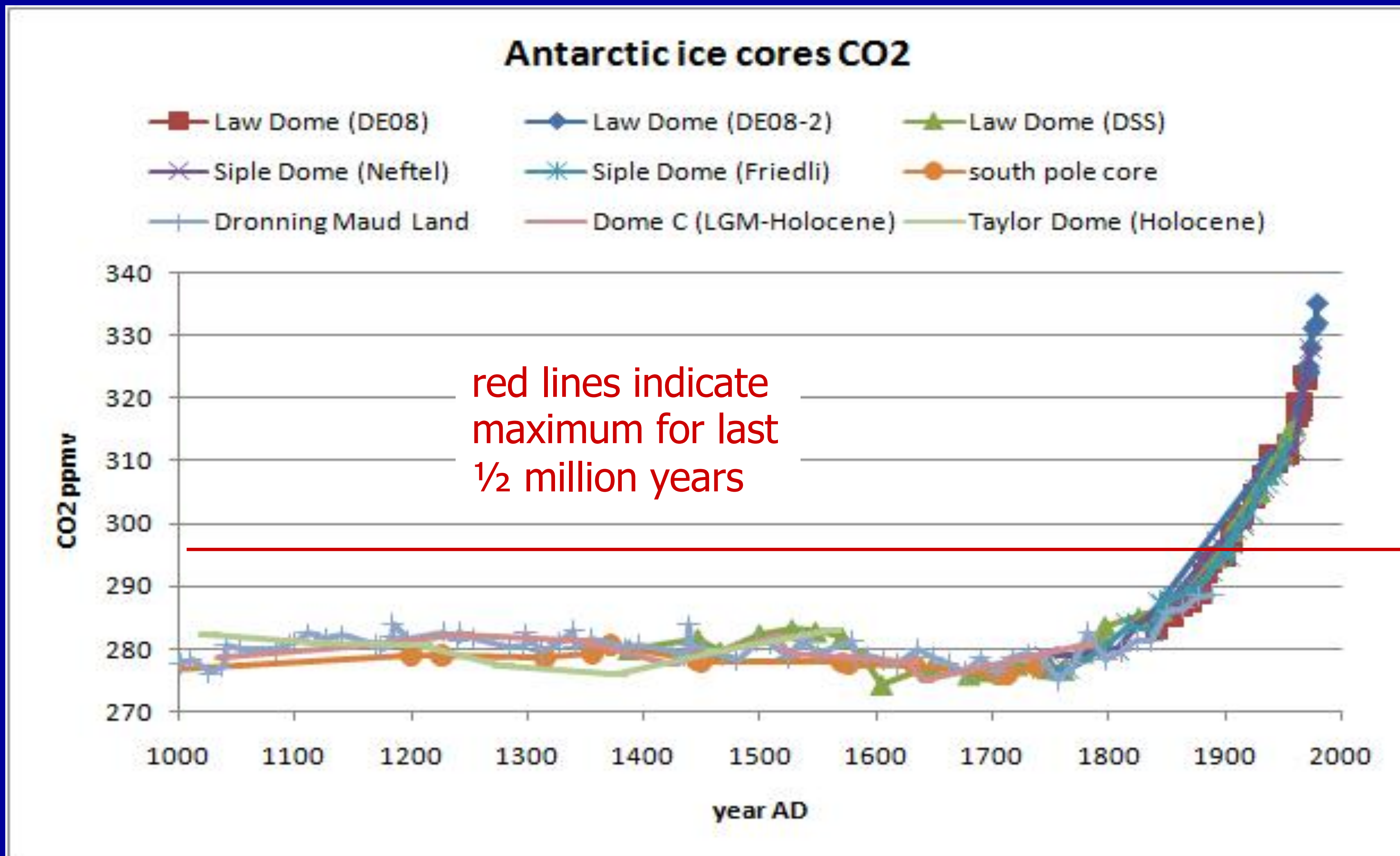
The bigger mystery is why we warmed so quickly. Temperature increase caused by the sudden (few to 50 years) turn-on of the North Atlantic circulation and a change in the atmospheric circulation?

Glacial intervals

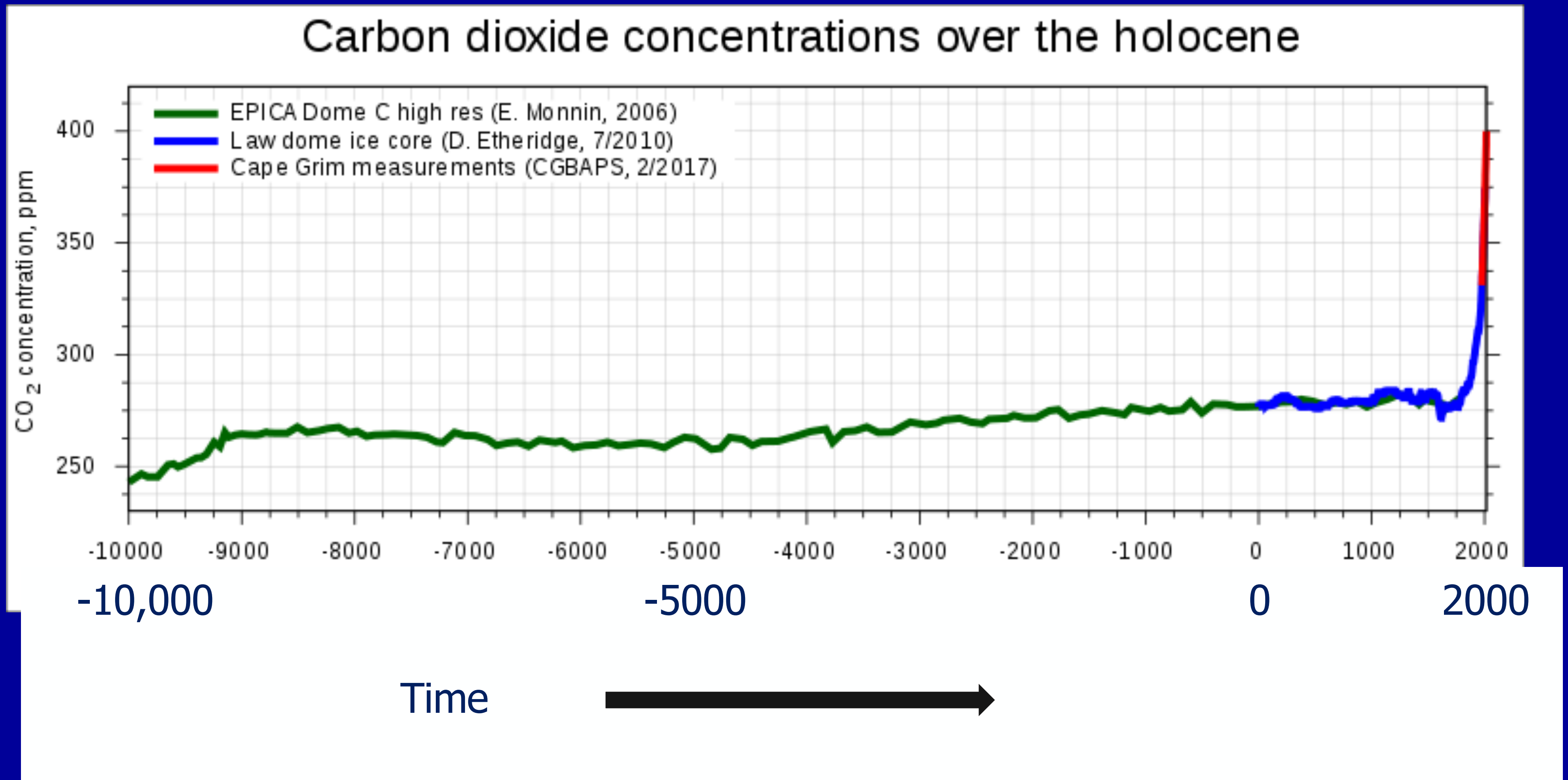
- Previous interglacial 100,000 years ago
- Current warm for the past 10,000 years
- Glacial interval 10kya – 100kya
  - kya = thousand years ago
- Glacial oscillations
  - Younger Dryas 11.8kya -13.1kya
  - N-S differences/oscillations 10kya-50kya
  - D-O events 10kya- 80kya
  - Heinrich Events 10kya-80kya

Current 415 ppm

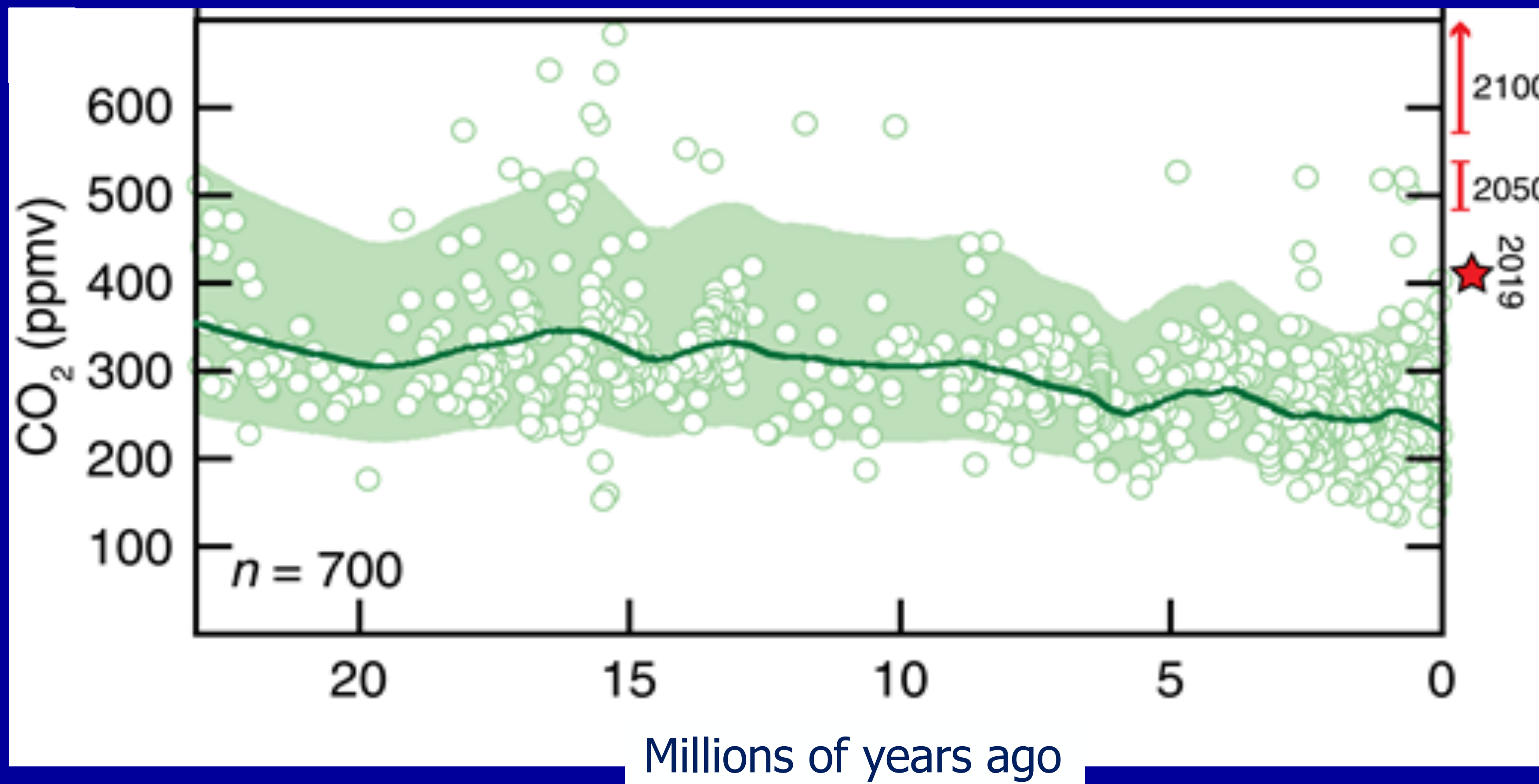
1/3 of CO_2 in air added since 1800



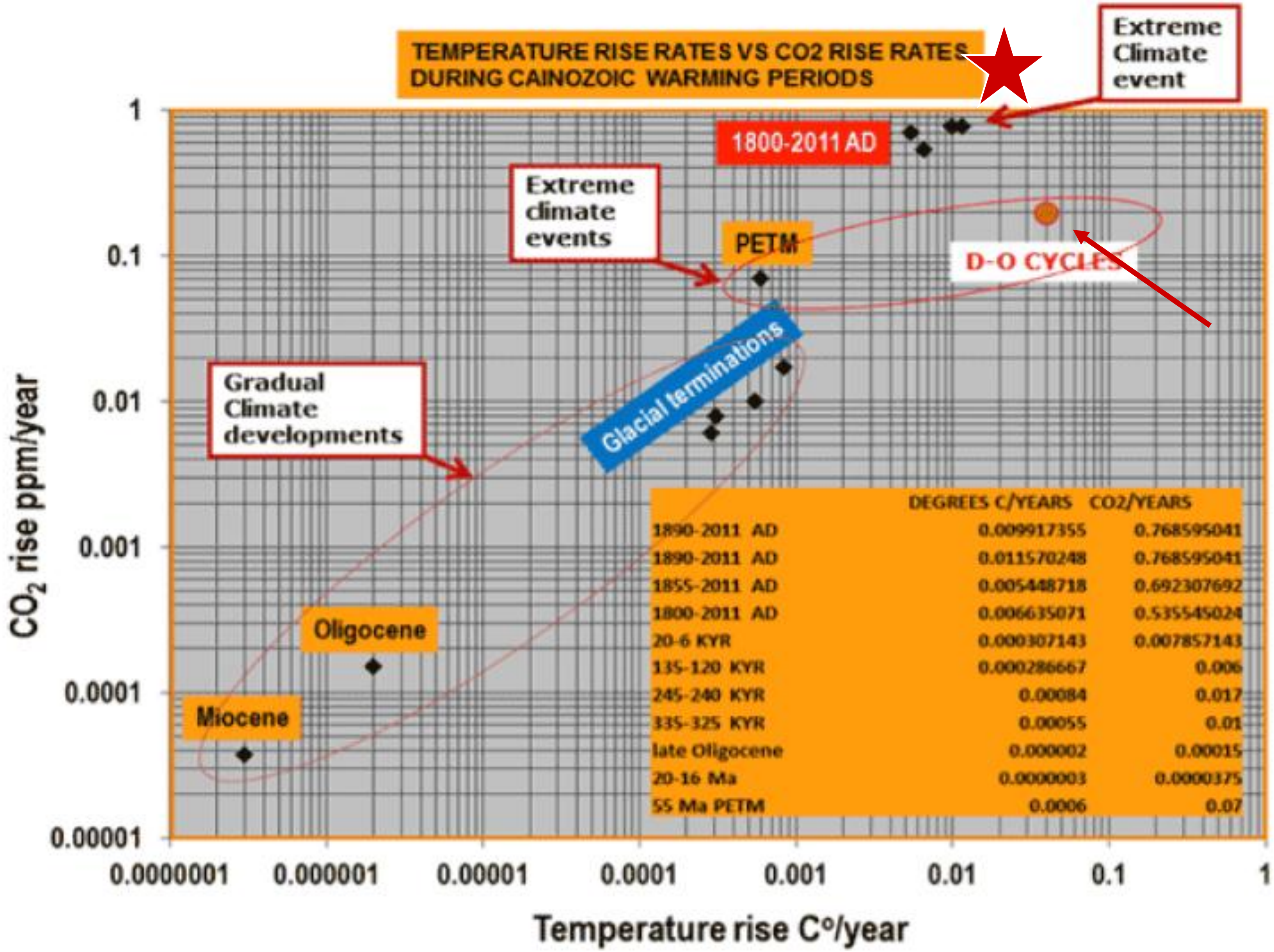
CO_2 during the current warm period



CO_2 from fossil plants: a 25 million year record



Cui et al., 2020, Geology, **48**(9), 888.



	DEGREES C/YEARS	CO2/YEARS
1890-2011 AD	0.009917355	0.768595041
1890-2011 AD	0.011570248	0.768595041
1855-2011 AD	0.005448718	0.692307692
1800-2011 AD	0.006635071	0.535545024
20-6 KYR	0.000307143	0.007857143
135-120 KYR	0.000286667	0.006
245-240 KYR	0.00084	0.017
335-325 KYR	0.00055	0.01
late Oligocene	0.000002	0.00015
20-16 Ma	0.0000003	0.0000375
55 Ma PETM	0.0006	0.07

Last 40 yrs
0.02 °C/yr
2 ppm CO_2/yr

D-O cycles
0.04 °C/yr
0.2 ppm CO_2/yr

Figure 2: *Relations between CO_2 rise rates and mean global temperature rise rates during warming periods*, including the Paleocene-Eocene Thermal Maximum, Oligocene, Miocene, glacial terminations, Dansgaard-Oeschger cycles and the post-1750 period.

What is the message?

- Climate changes all the time on geologic time scales
- Humans evolved during an unusually stable climate for the past 10,000 years
- We are adding CO_2 at 100 times faster than volcanoes and 10,000 times faster than weathering can remove it.