Earth's Past climate (Paleoclimate)

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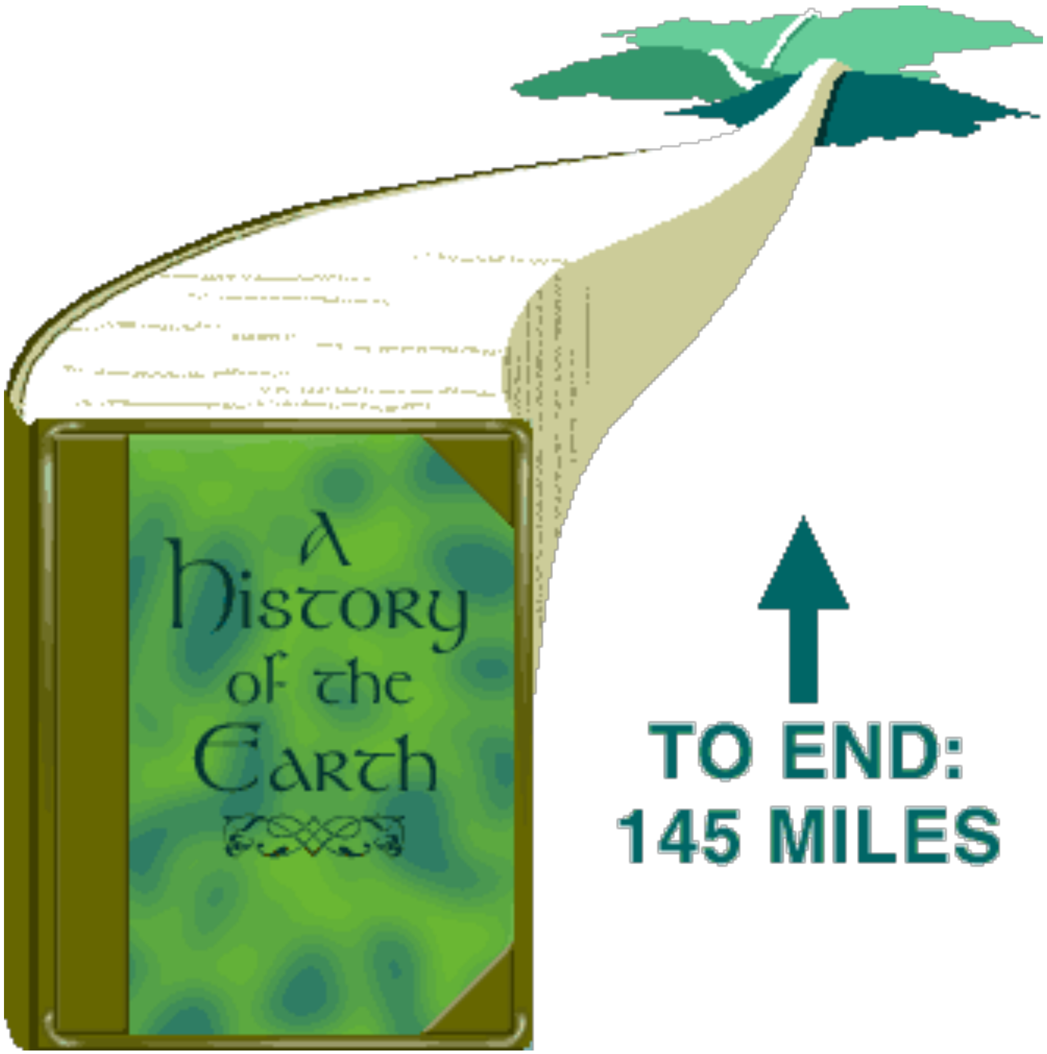
Outline

- Geological time
- How can earth's climate change?
- How do we know about earth's past climate?
- How has earth's climate changed?
    - Focus on mass extinctions, glaciations, and glacial-interglacial cycles of past 800,000 years
- How does past climate change compare to current climate change?

History of Earth: Geological time



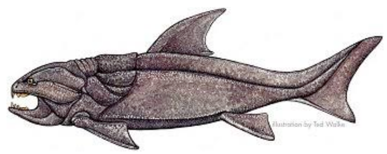
- Earth is 4.54 billion years old
- If you were to write a history of Earth, allowing just one page per year, your book would be 4,540,000,000 pages long.
- That's a very thick book ***145 miles thick!***
- Climate has changed a lot over 4.54 billion years

Geologic time scale:

Units billions of years ago (bya)

First humans

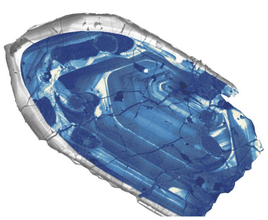
First dinosaurs



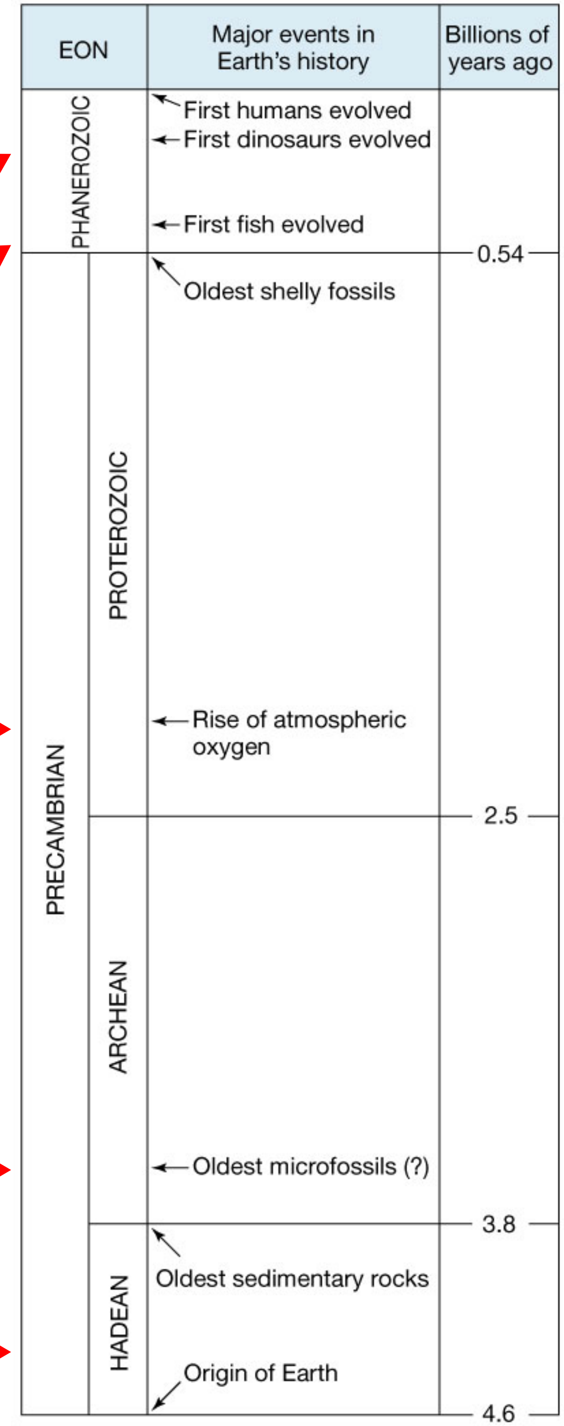
First fish

Rise in Atmospheric Oxygen

Oldest microfossils

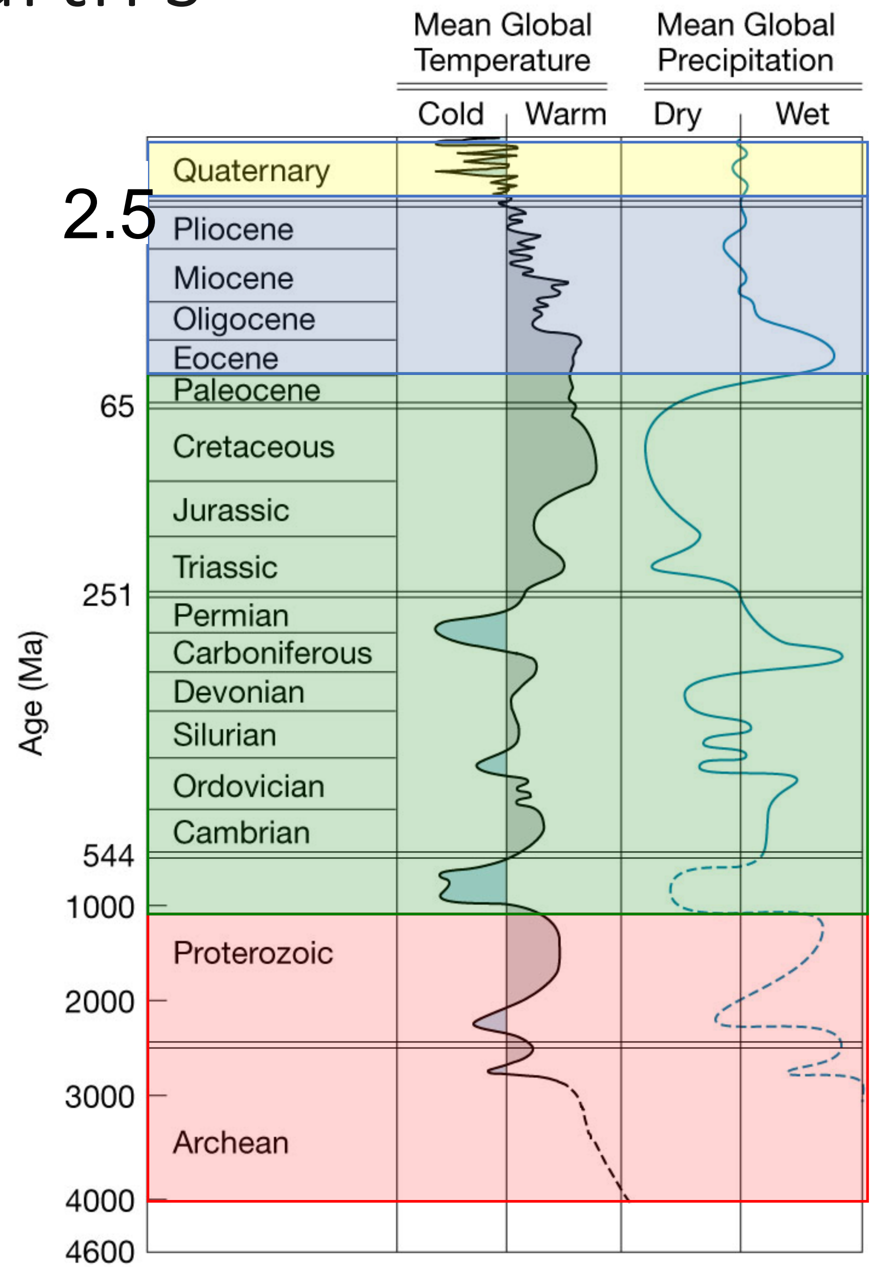


Oldest rock found on earth



Climate change over earth's history

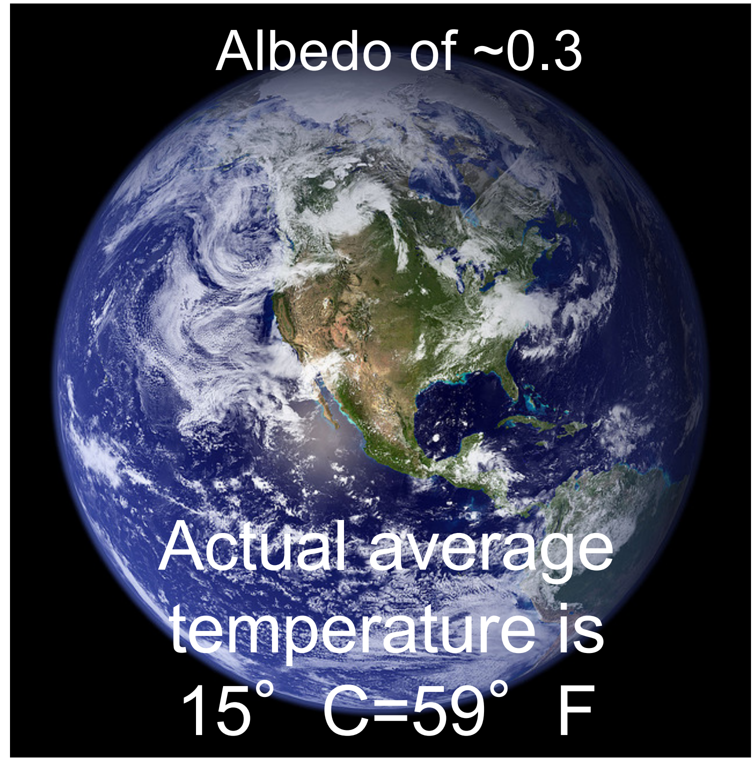
- **Early earth, the Archean and Proterozoic (4,000 million years ago to 1000 million years ago – a span of 3000 million years)**
- **Icehouses and hothouses: From the late Proterozoic to the Paleocene**
- **Eocene to the Pliocene**
- **The Quaternary**



What determines Earth's average temperature?

The average temperature of a planet depends on:

1. The amount of incoming radiation from the sun
2. The amount of that radiation that is reflected by the surface back to space (albedo)
3. The amount of radiation that is retained in the atmosphere



For earth:

1. At the top of the atmosphere, we receive 1361 Wm^{-2} from the sun
2. 30% of radiation from the sun is reflected back to space

→ Without any heat captured in the atmosphere (point 3), that would mean earth's global mean temperature would be -18° C= -0.4° F → not habitable!

Earth’s average temperature

- Without clouds, Earths albedo would be ~0.1, which means a lot more of sun’s radiation would be absorbed (90%).
- That would raise the equilibrium temperature by 16 degrees K, to -2° C =28° F!

→ But even without clouds, still below freezing

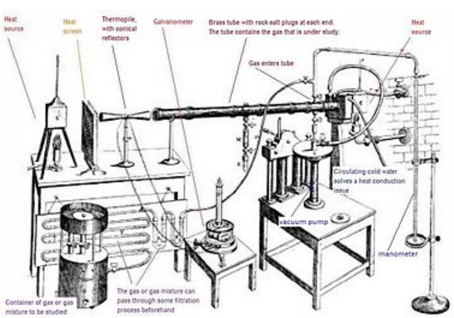
So what could raise the global mean temperature to the observed 15° C?

The greenhouse effect

- Joseph Fourier first did this calculation of the expected temperature of earth in 1827, and also wondered why earth was much warmer
- He hypothesized that there had to be another process occurring in the atmosphere — something similar to the way a greenhouse retains heat → **hence the name "greenhouse effect" we still use today!**

Greenhouse effect

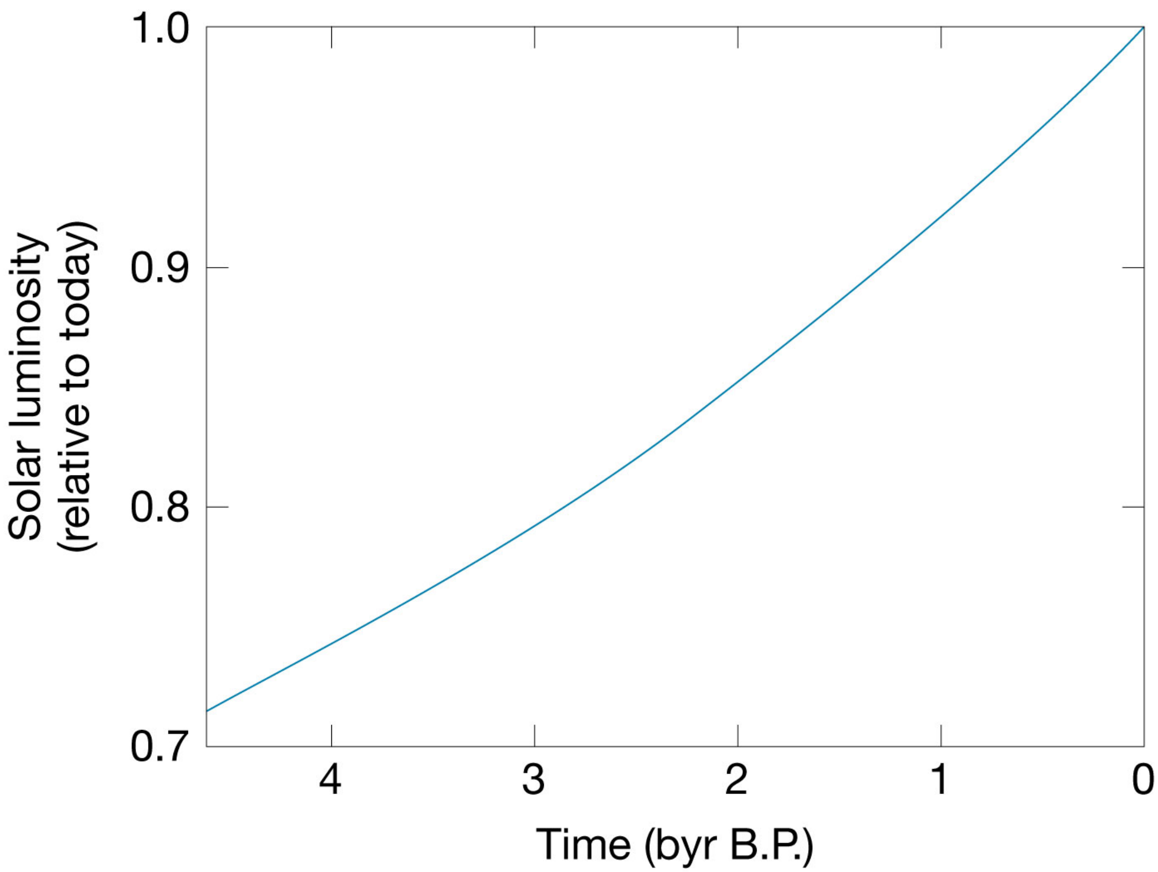
- John Tyndall followed up on Fourier's greenhouse effect hypothesis in the 1850s, to understand <u>how earth's atmosphere acted as a greenhouse</u>
- He began a series of experiments to measure the amount of radiant heat (infrared radiation) that the gases present in the atmosphere could absorb
- Tyndall found that water vapor and carbon dioxide were good absorbers and emitters of infrared radiation, and were abundant in the atmosphere.
- **He was the first to proof the existence of the greenhouse effect**
- He was also the first to hypothesize on how climate would change if the abundance of water vapor and carbon dioxide was changed, due to the greenhouse effect



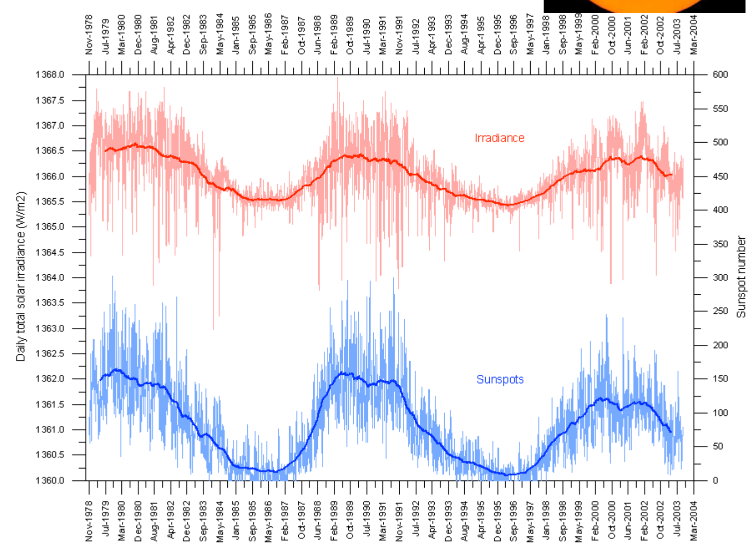
Why can earth's climate change?

- Changes in the amount of radiation received from the sun
  - Due to changes in the sun's output
  - Due to changes in the orbit of earth (Milankovitch cycles)
- Changes in the amount of radiation retained in the atmosphere-earth system
  - Through changes in the reflectivity of the surface (change from ice covered to dark surfaces, position and size of continents)
  - Through changes in the composition of the atmosphere (e.g., greenhouse gases, volcanic eruptions, meteorite impacts)
- Through changes in the atmospheric and oceanic circulation

Changes in the amount of radiation emitted from the sun



Radiation output from the sun has increased over the history of earth

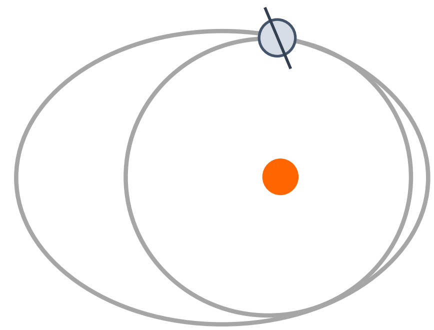


Short term fluctuations due to sun spots (11 year cycle)

Changes in the amount of radiation received from the sun due to the orbit of earth: Milankovitch cycles

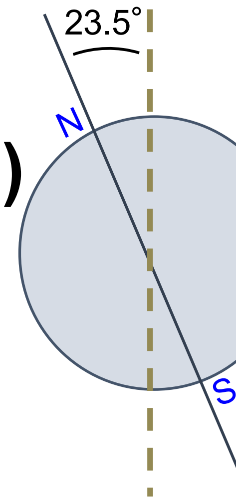
1) Eccentricity (100,000 years)

How circular is the Earth's orbit around the sun?



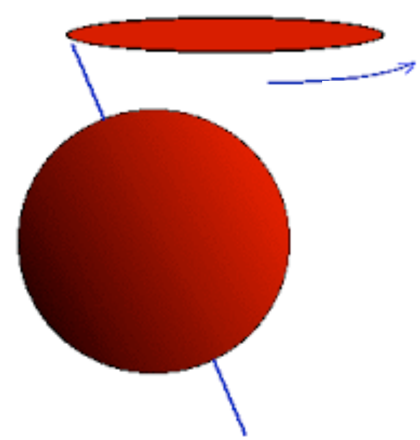
2) Obliquity (41,000 years)

How tilted is the Earth axis?



3) Precession (~21,000 years)

In which direction does the earth axis point?



Milankovitch cycles

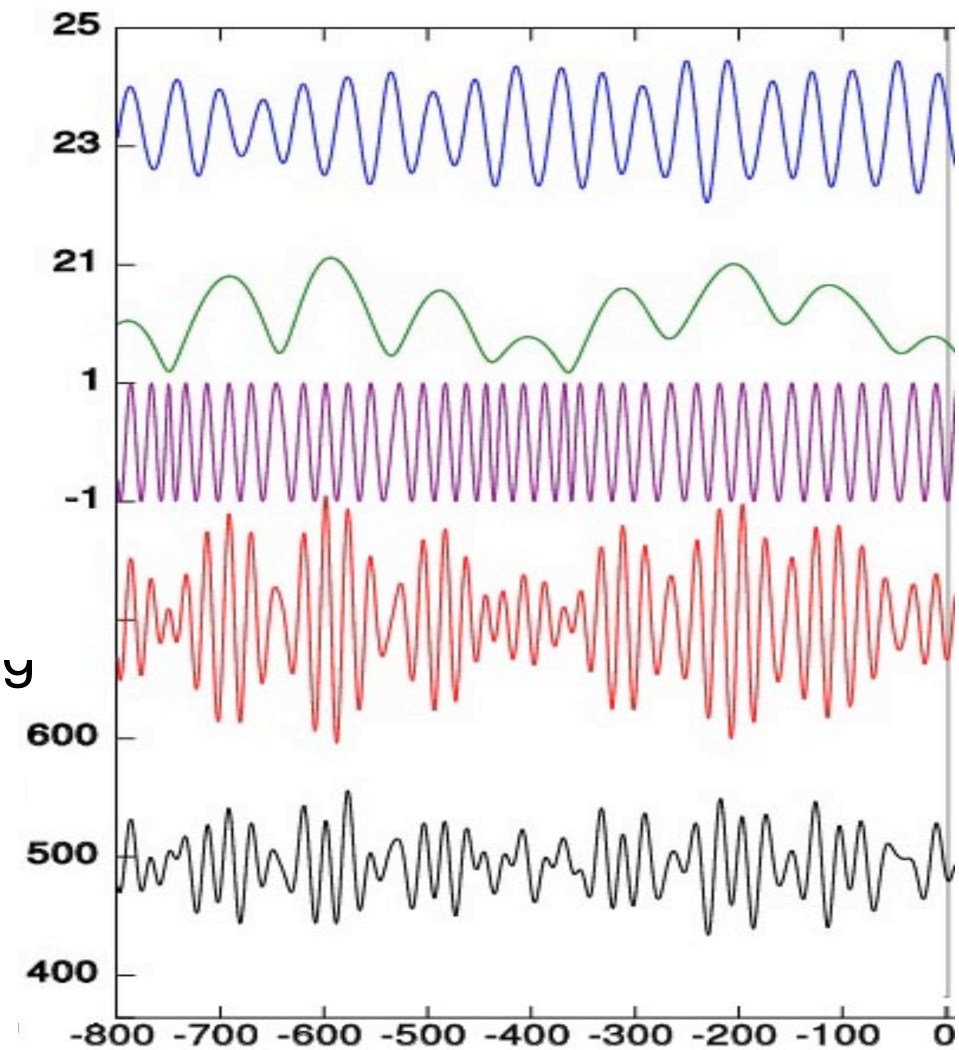
Obliquity

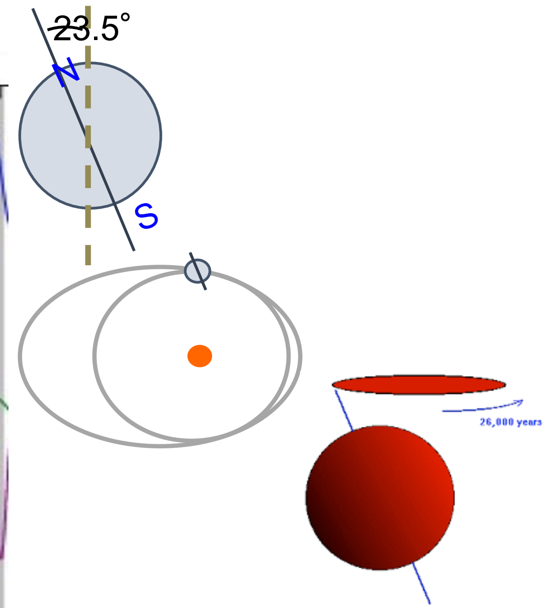
Eccentricity

Precession

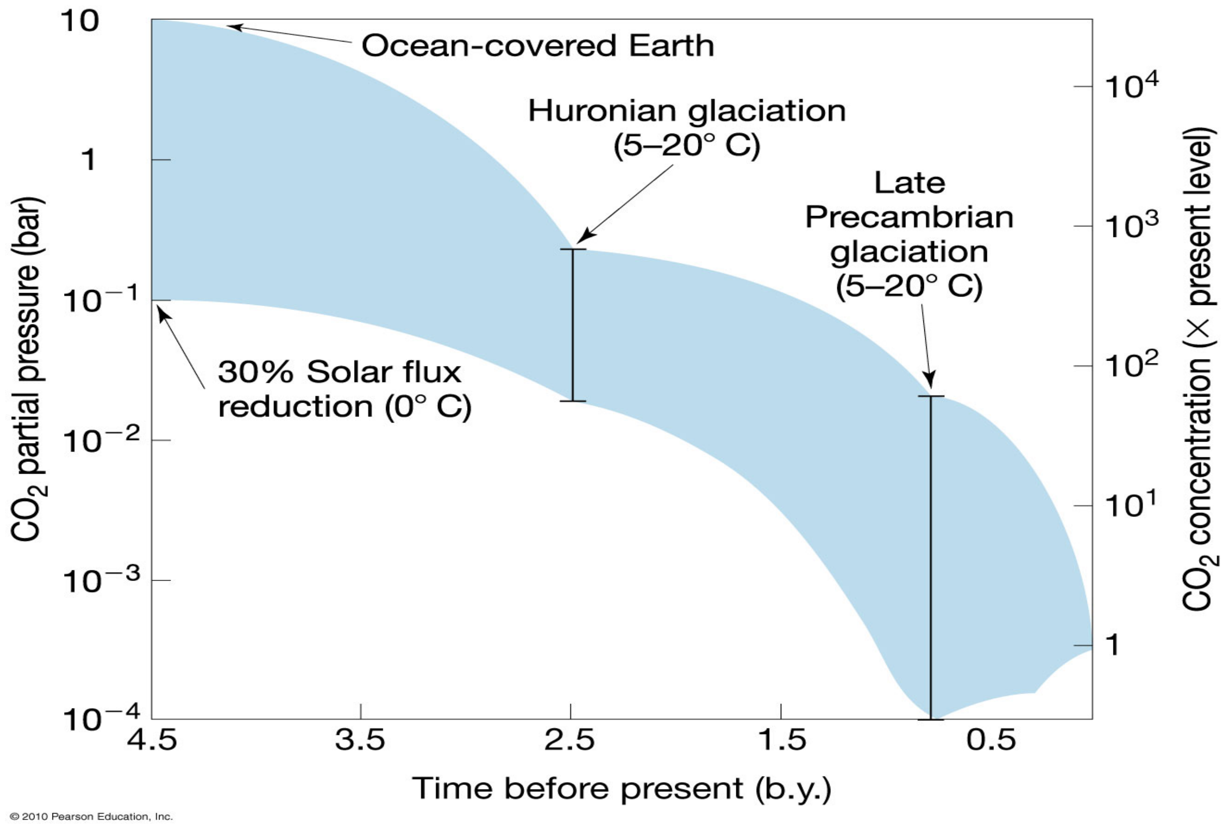
Combined orbital forcing

Solar forcing at 65N



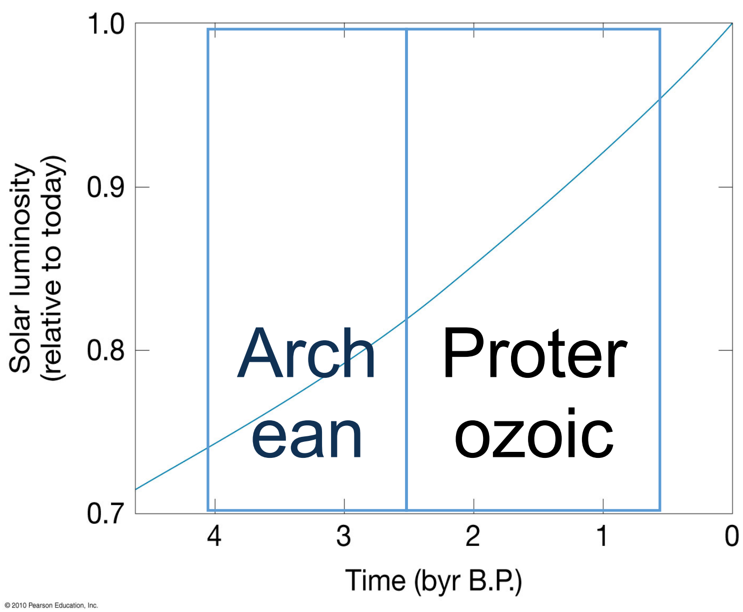


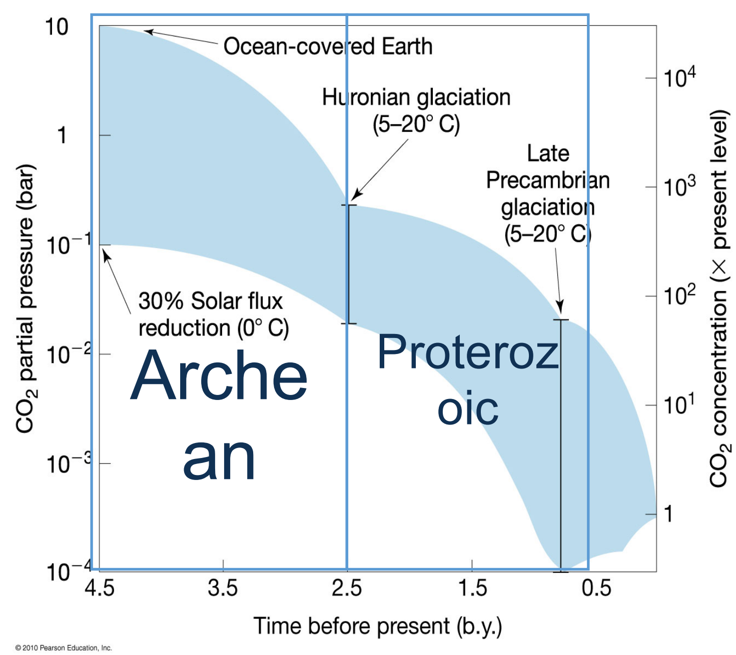
Changes in the greenhouse effect

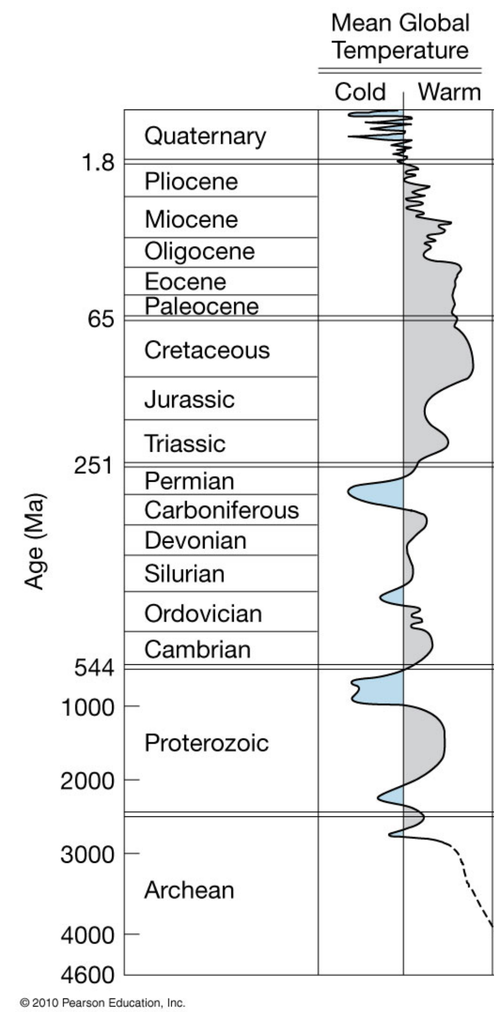


Much higher CO_2 levels () and Methane levels in the early earth's atmosphere than today (over ~1000 x today's levels).

Solar intensity and Atmospheric CO_2 over earth's history



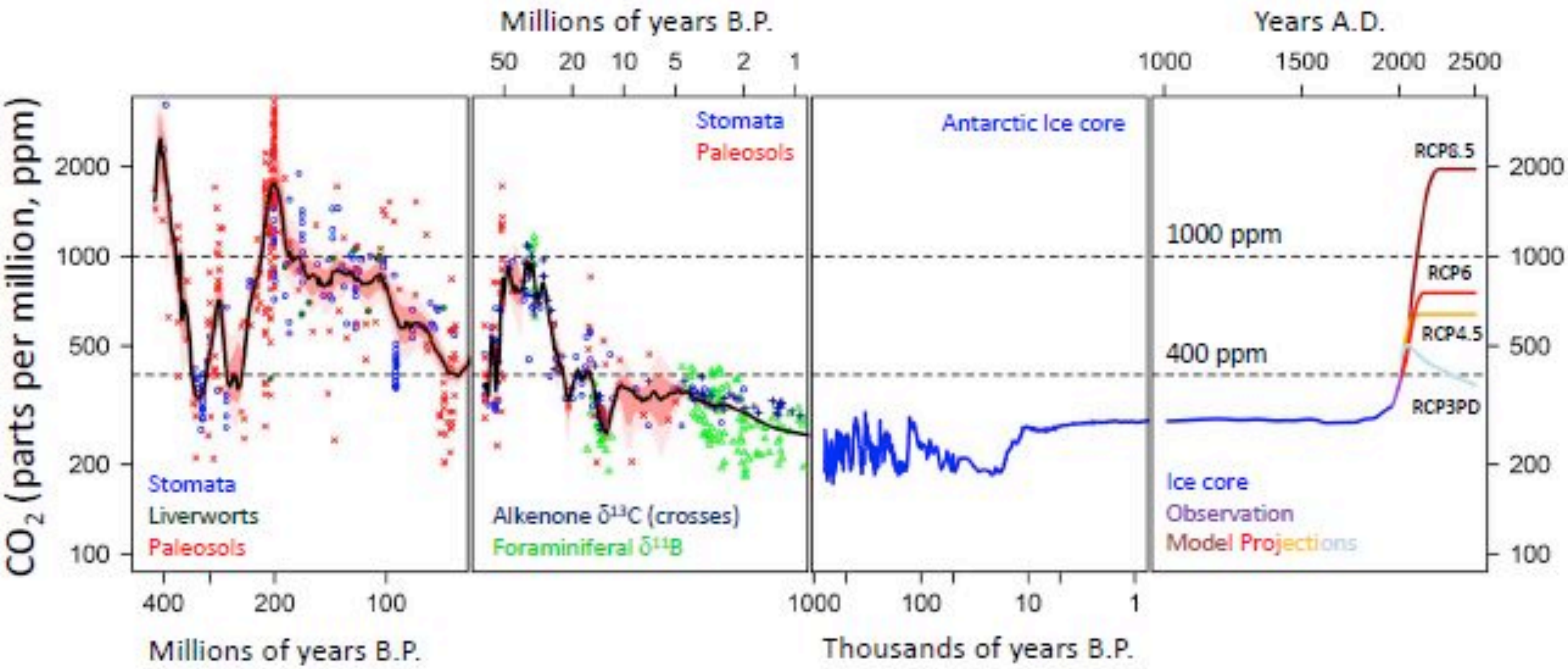




Much higher CO_2 levels warmed early earth despite lower sun luminosity (faint early sun paradox)

How do we know about earth's past climate?

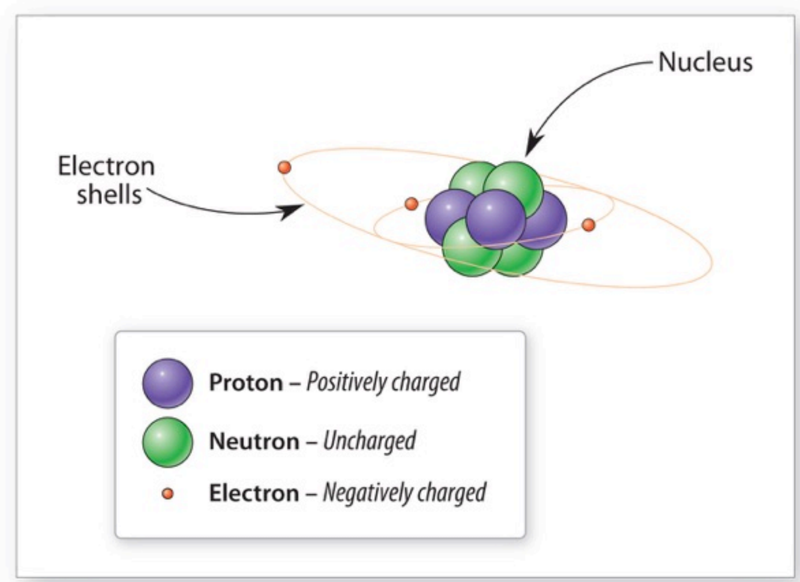
Paleo proxies: Many of them use isotopes

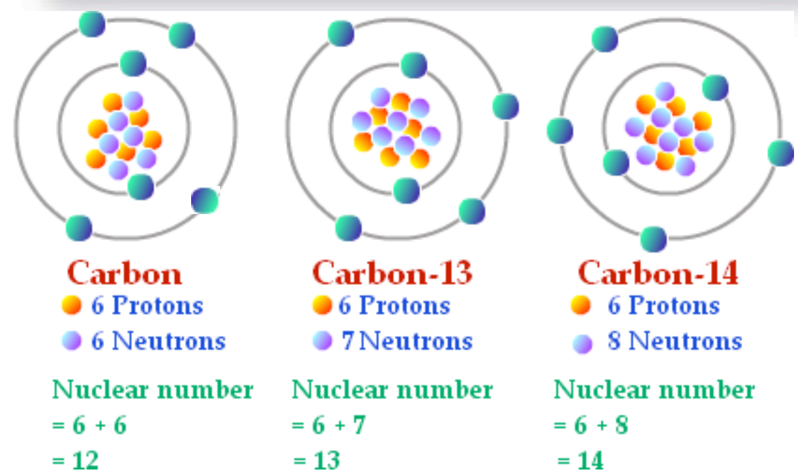


What are isotopes?

- Isotopes are variants of an element with additional neutrons → these lead to small differences in the physical properties of the element

- Unstable isotopes break down by radioactive decay at a constant rate → can be used for dating



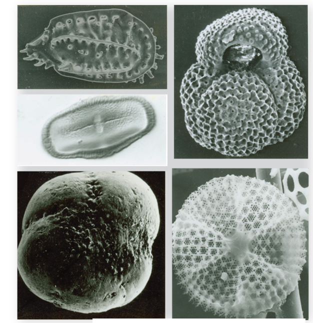


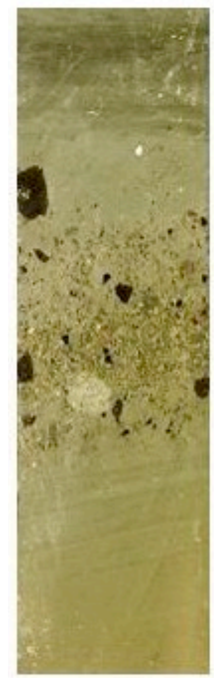
Fractionation

- The small differences in the physical properties of each isotope affect how isotopes are partioned between different parts of the climate system → this is called "fractionation"
- Due to fractionation, isotopes can be used to measure environmental changes
  - Oxygen and hydrogen isotopes help us reconstruct temperature, ice volume, precipitation pathways
  - Carbon isotopes help us infer changes in the ocean circulation and in the biological productivity

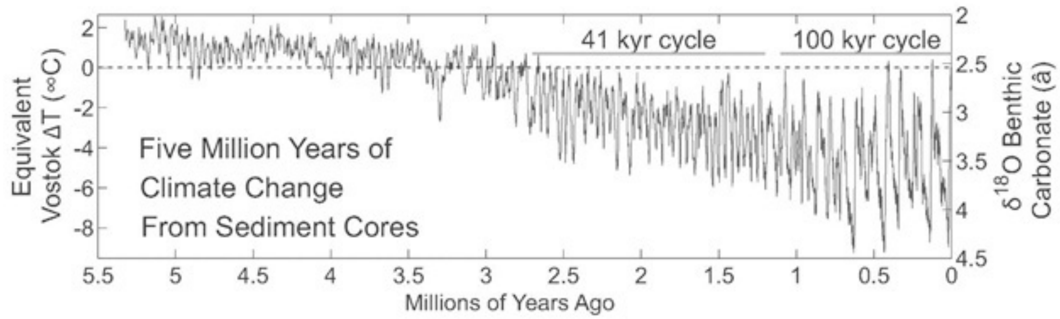
Sediment cores

- Sediment cores are recovered from ocean and lake beds
- They can provide a very long (several million) record of climate
- Often lack clear annual layers, as sedimentation does not necessarily have an annual cycle. Also, activity of invertebrates mixes the upper layers of sediment in most shallow environments
- Can analyze geochemistry, isotopes, microfauna and microflora, rocks





Ocean sediment core drill ship

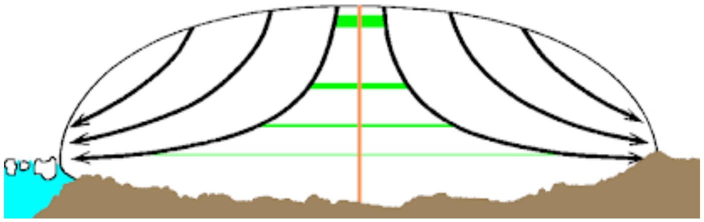


Combined sediment core record of $\delta^{18}O$ from benthic foraminifera from 57 globally distributed deep-sea sediment cores

Ice cores

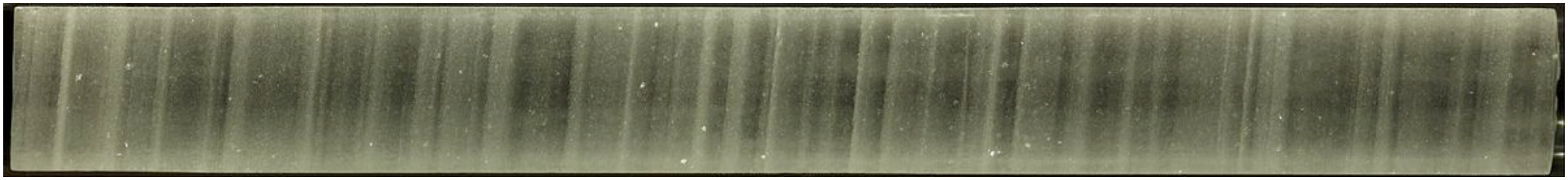
- Can reach back 800,000 years
- Oxygen and hydrogen isotopes allows reconstruction of the temperature at which ice formed
- Thickness of annual layers tell scientists about precipitation changes. As depth increases, annual layers are lost due to compression
- Volcanic ash layers can be used to date and match ice cores to other cores

Ice core drill bit with ice core



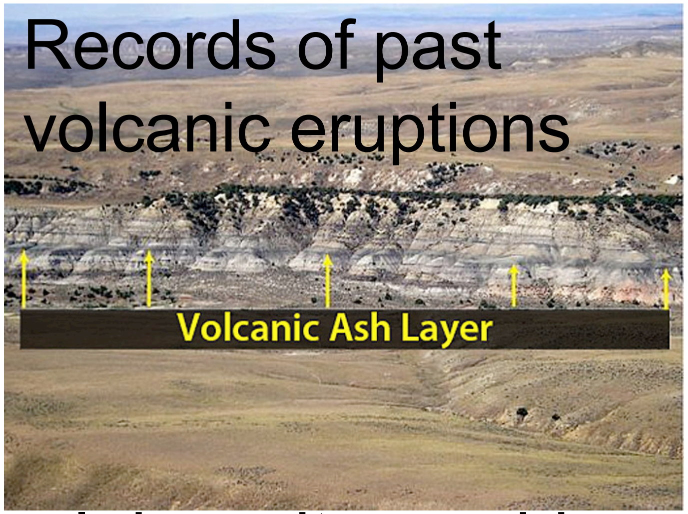
Location of ice core drilling site

Ice core



GISP2 ice core at 1837 meters depth with clearly visible annual layers.

Landscape and fossils



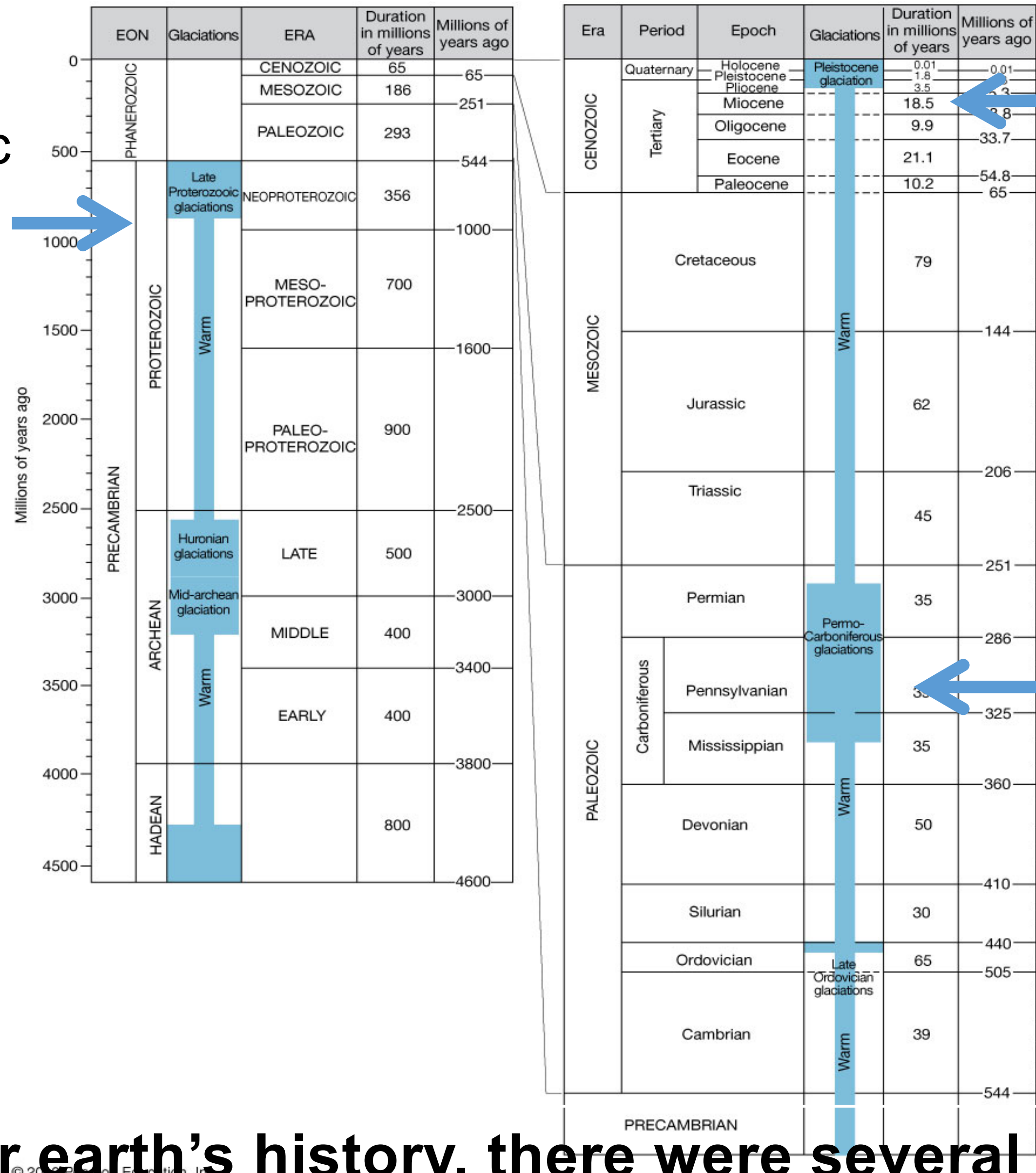
Coal deposits provide evidence of past dense vegetation

Alluvian fans: Evidence of past rivers

Ripple marks in rock (evidence of past running water)

Glaciations in earth's history

Proterozoic Snowball earth glaciation



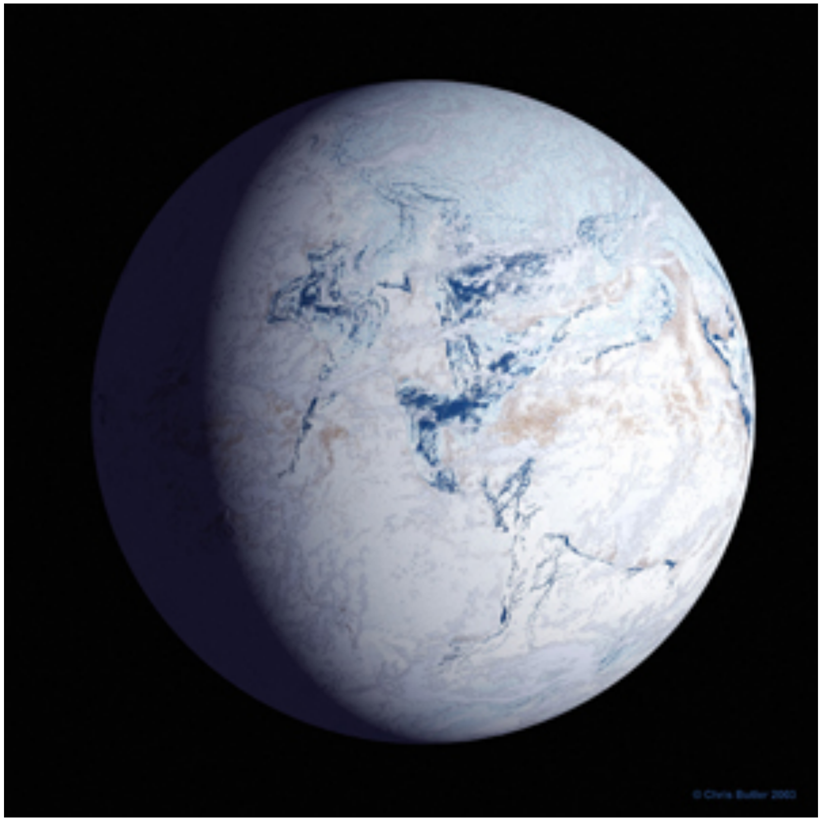
Pleistocene glaciations

Permo-Carboniferous glaciation

Over earth's history, there were several major periods of glaciations

Proterozoic: Snowball earth glaciation

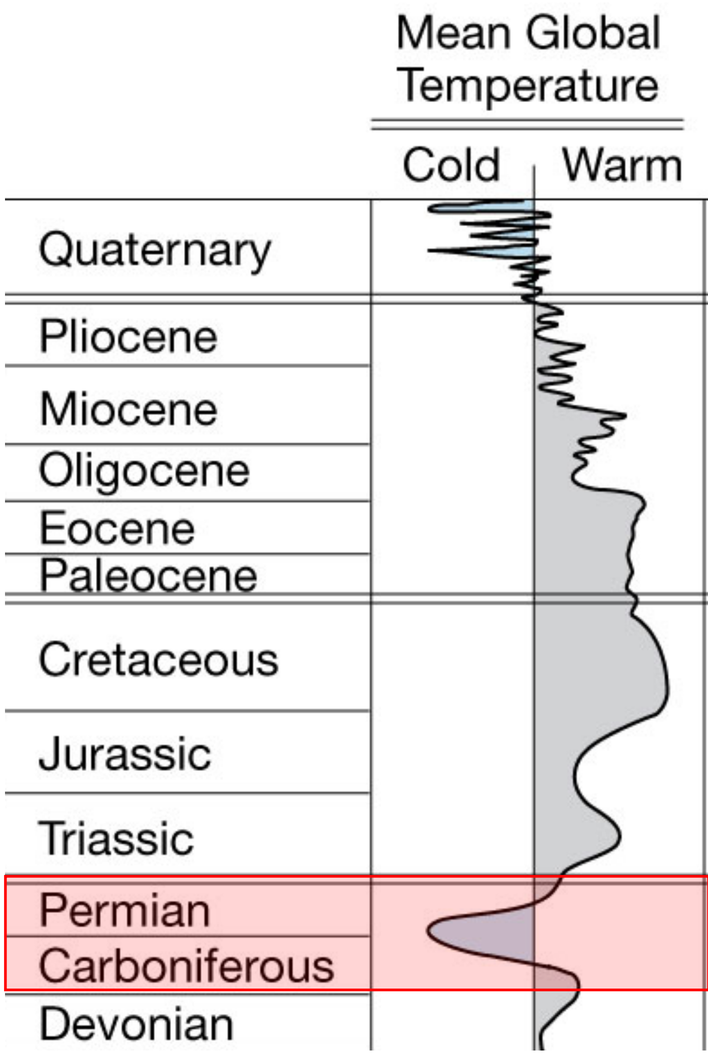
- Glacial sediments and dropstones from 750 to 630 million years ago indicate a significant glaciation even at low latitudes
- It was caused by Albedo exceeding a critical threshold that lead to glaciations past the mid latitudes into the tropics and to the equator → snowball earth



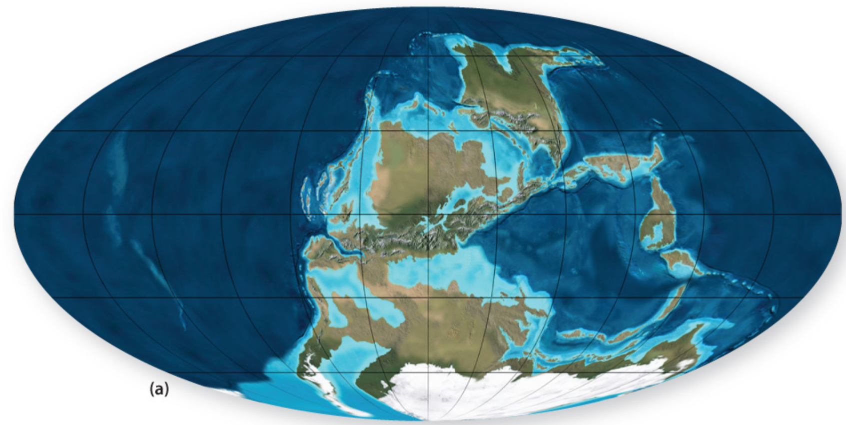
Snowball Earth!

Permo-Carboniferous glaciation

- 310-290 million years ago



Supercontinent Pangaea

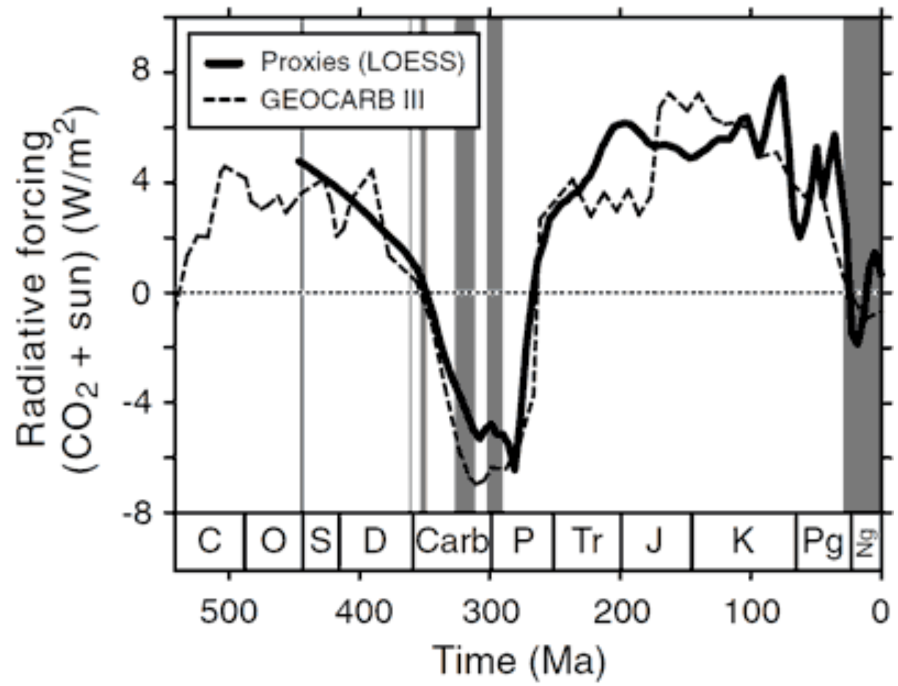


- Continents surrounded South Pole → as heat is lost faster from land than oceans (heat capacity), land at high latitudes leads to large cooling
- Atmospheric CO_2 dropped from 1500 ppm to around 300-400 ppm
- Coldest period on earth during the last 500 million years

The Permo-Carboniferous glaciation CO_2 drop

Causes of atmospheric CO_2 drop from 1500 ppm to around 300-400 ppm:

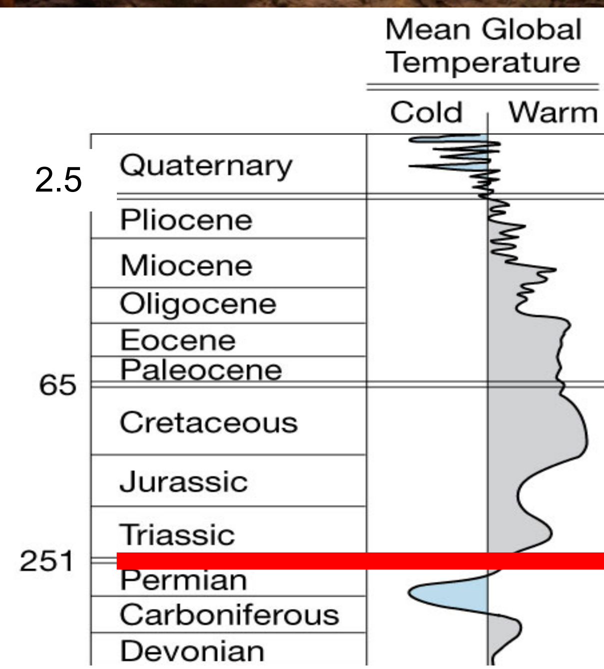
- Cooling ocean absorbed more CO_2, decreasing atmospheric CO_2 levels → further cooling



→Glaciation only ended when the continents moved away from the south pole during the Permian to early Jurassic and increased volcanism added CO_2 to the atmosphere

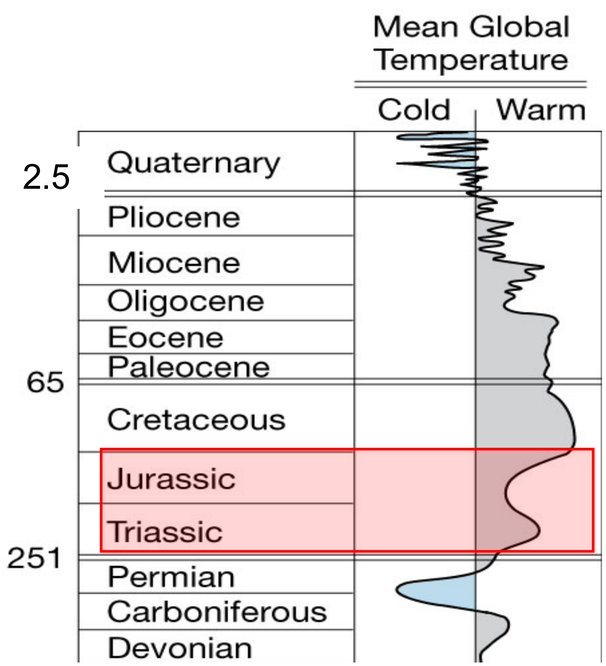
Permian Mass extinction

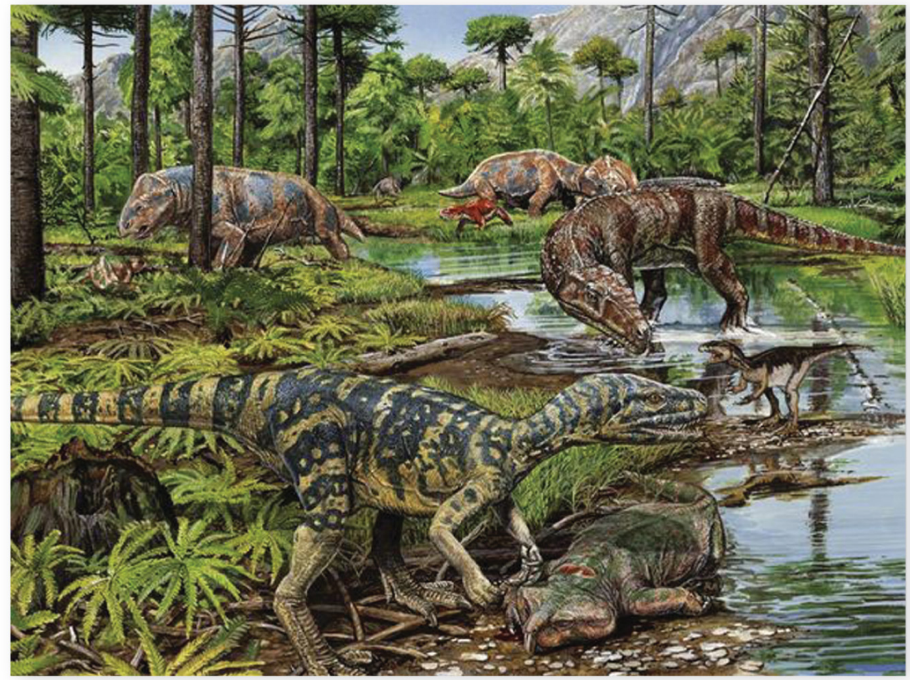
- Major extinction at end of Permian: 95% of all marine species and 70% of land vertebrates went extinct over a period of 10 million years
- Scientists think this was due to poisonous hydrogen sulfide produced in ocean dead zones, which lead to very acidic oceans and rain (as acidic as lemon juice!), along with reduced atmospheric Oxygen
- Most extreme extinction event in last 600 million years



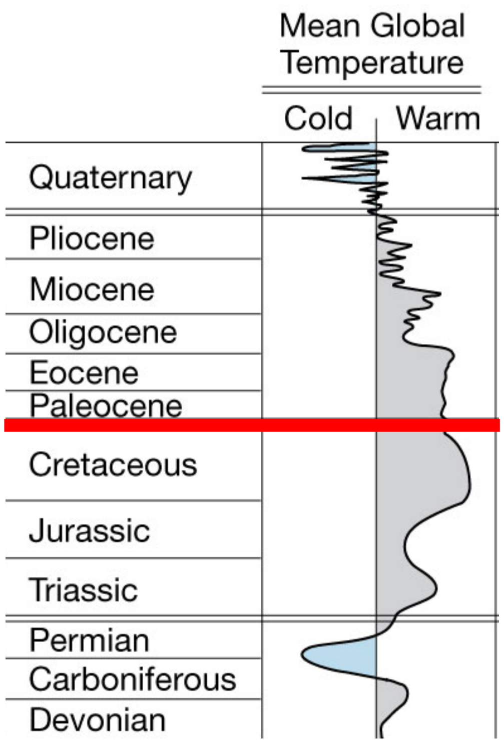
Triassic, Jurassic, Cretaceous (age of the dinosaurs)

- Early dinosaurs were well adapted to lower oxygen content and warmer climate, and began to thrive during the Triassic and Jurassic

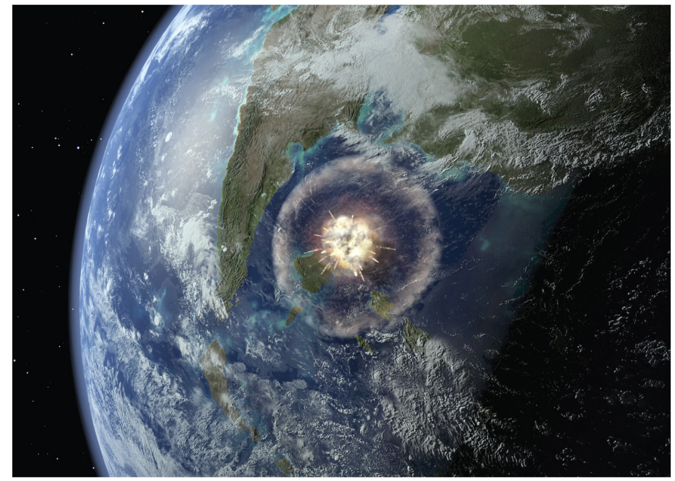




K-T extinction (Cretaceous-Tertiary)

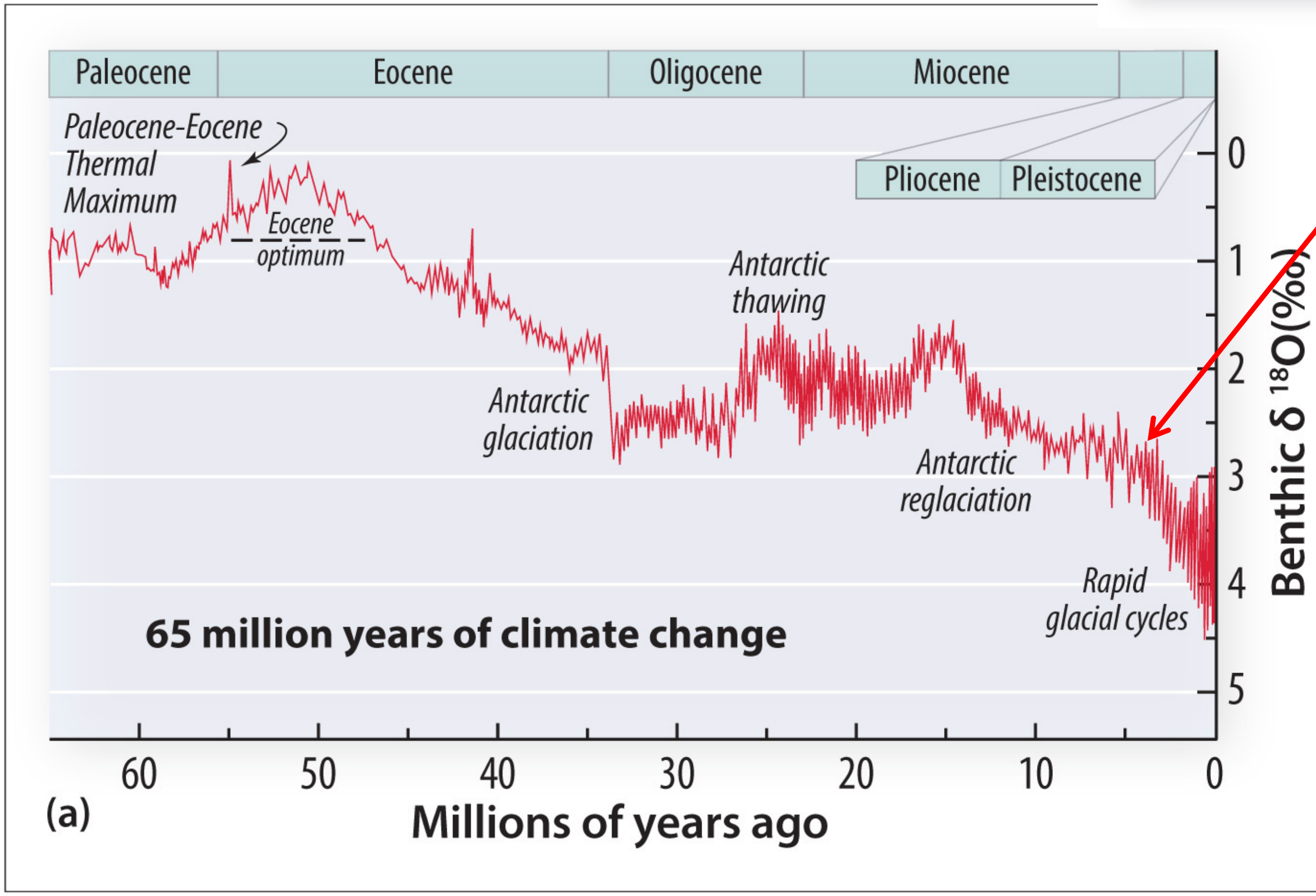


- Cretaceous ended abruptly 65 million years ago, as dinosaurs and 60% of other species became extinct
- Scientists hypothesize that this was due to a large (>10 km diameter) meteorite impact in northern Mexico



Climate overview, 65 million years ago to today – the age of the mammals

Eon	Era	Period		Epoch	Start date (*mya*)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	2.58
		Tertiary	Neogene	Pliocene	2.58
				Miocene	23.3
			Paleogene	Oligocene	35.4
				Eocene	56.5
				Paleocene	65



Last time CO_2 was as high as today (~400 ppm) was during the Pliocene (~2.5 million years ago)

Continuous cooling from 50 million years ago, with increasing ice volume.

The Quaternary

- The Quaternary includes the Pleistocene and the Holocene, our current climate Epoch
- The continents are in about the same position as today, with small differences

Eon	Era	Period		Epoch	Start date (*mya*)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.01
				Pleistocene	2.58
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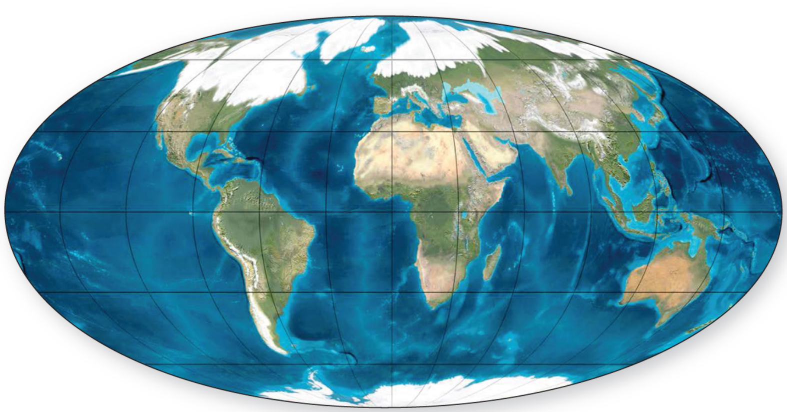
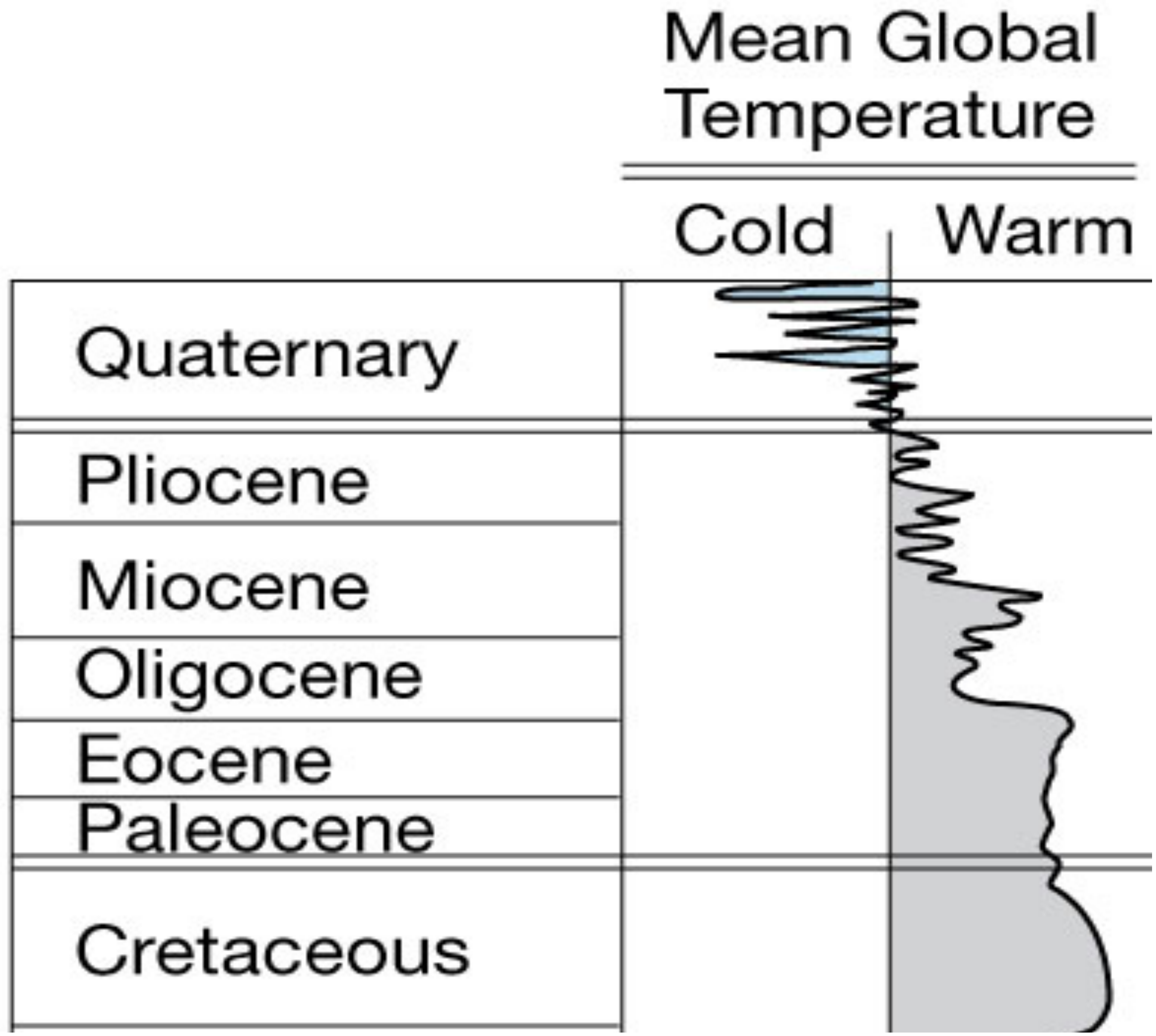
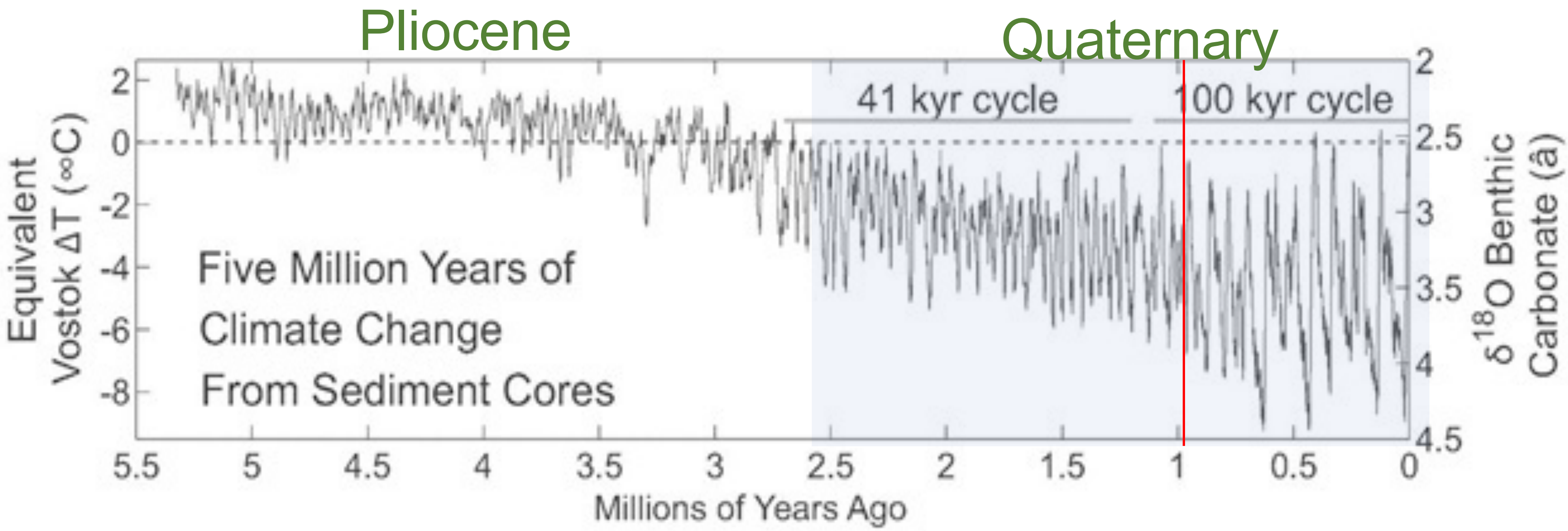


Quaternary Glaciations

- In the last ~2.5 million years, geologically "quick" transitions from glacial to interglacial conditions
- "geological quick" ~ hundred of thousands of years
- Driven by changes in earth's orbit (Milankovitch cycles)

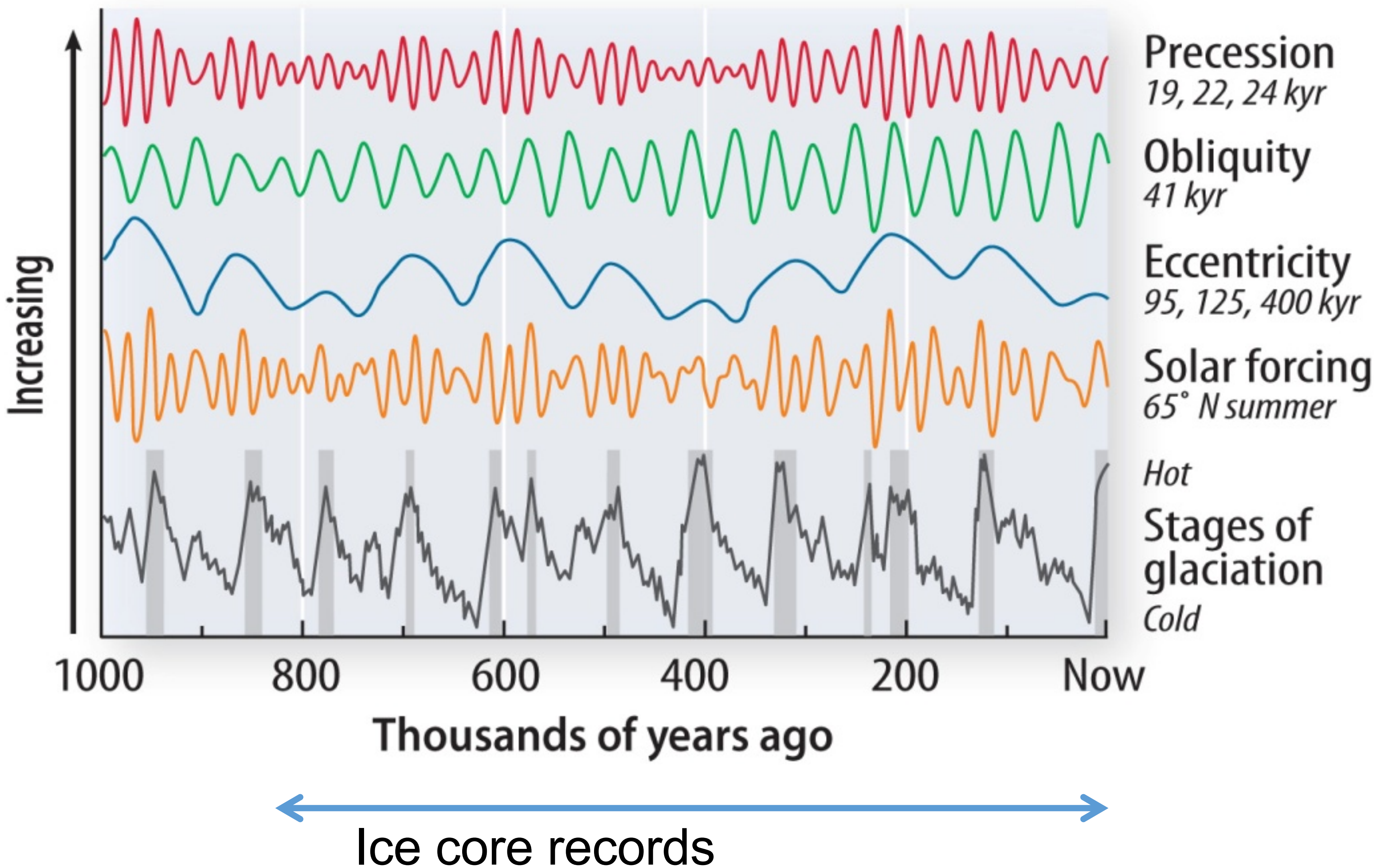


Ice sheets during the Quaternary

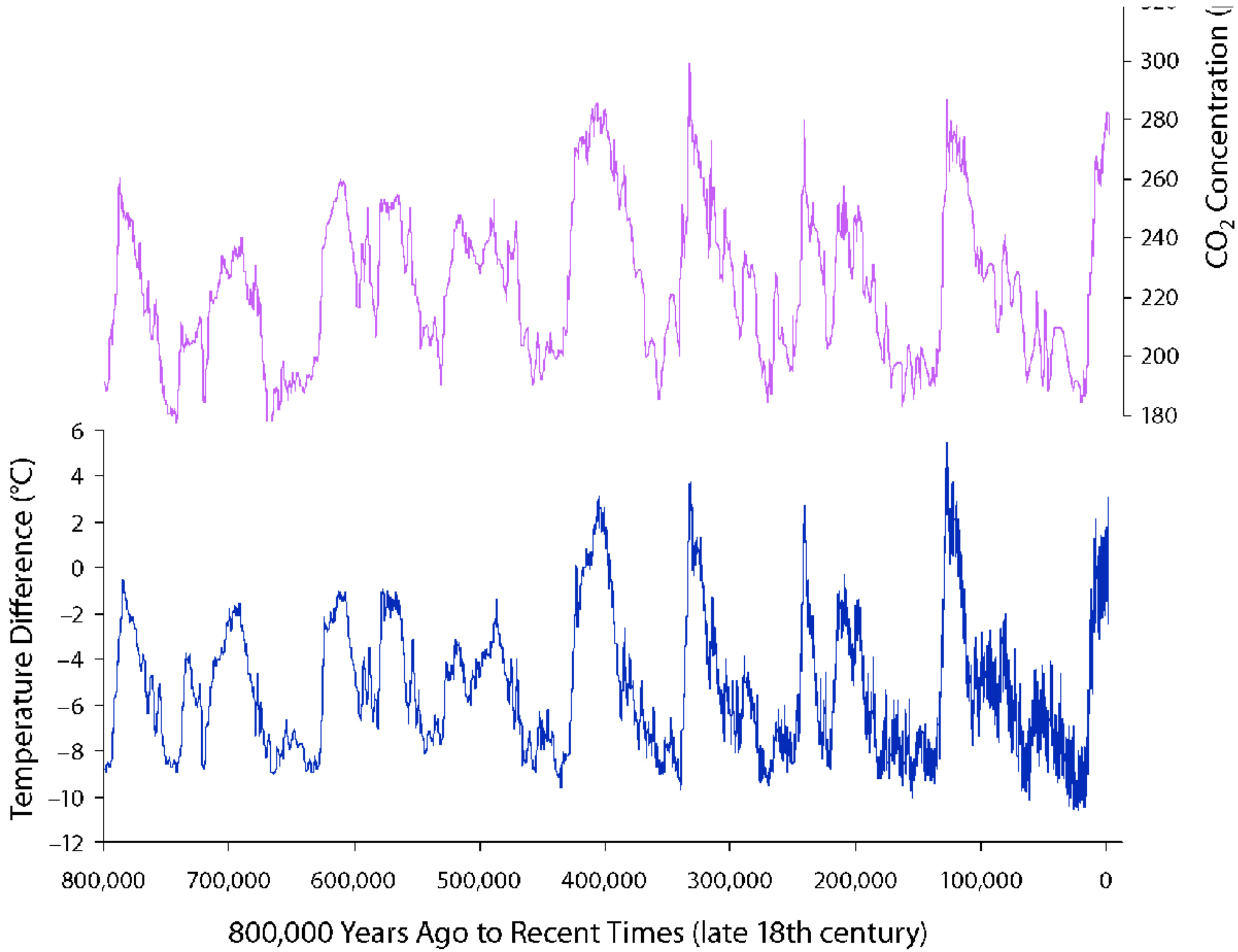


- Increasingly large amplitude of ice volume changes during the Quaternary compared to the prior 2.5 million years
- Change in length of glacial-interglacial cycles during the Quaternary 1.2-0.7 million years ago (**Mid Pleistocene transition**), from 41 kyr to 100 kyr → **change from obliquity dominated (41 kyr) to eccentricity dominated (100 kyr) glacial cycles**
- **Cause for this change is unknown so far, several theories**

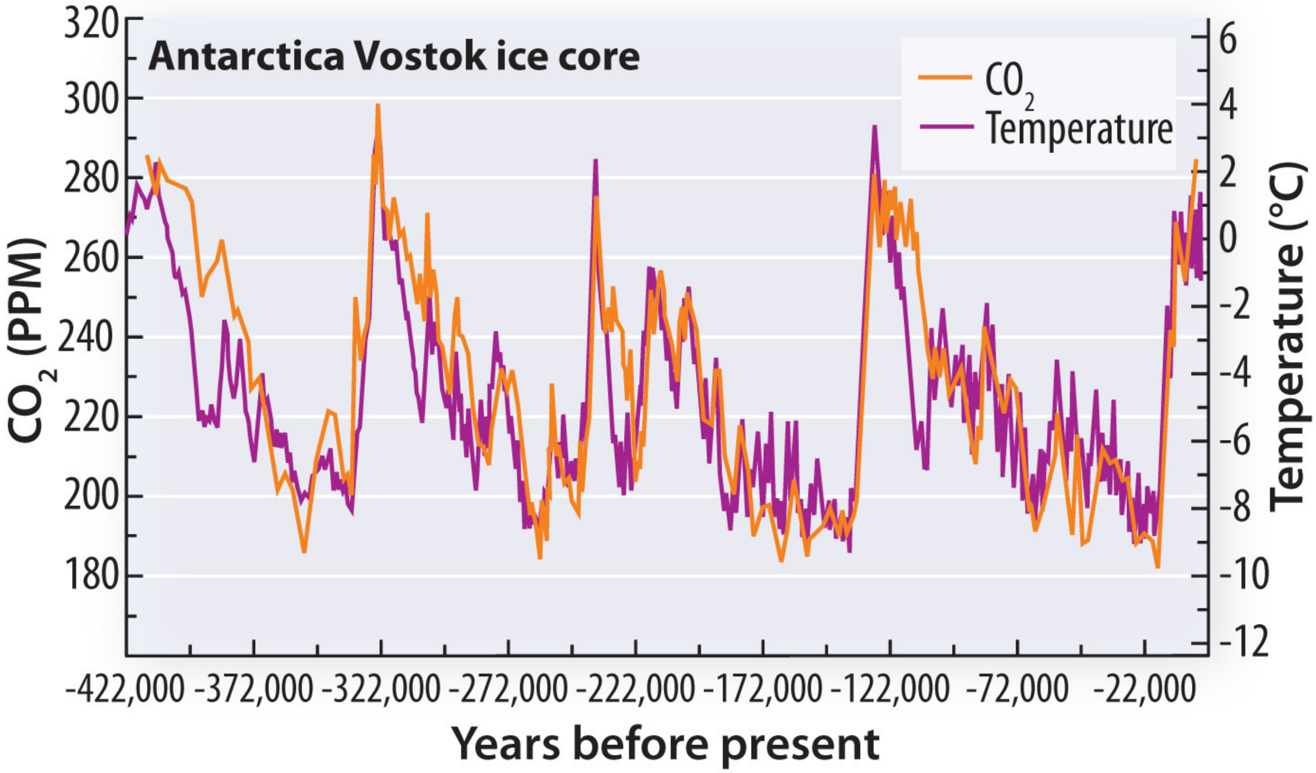
Glacial-interglacial cycles driven by Milankovitch cycles



Temperature and carbon dioxide track each other over last 800,000 years



Temperature-CO_2 relationship

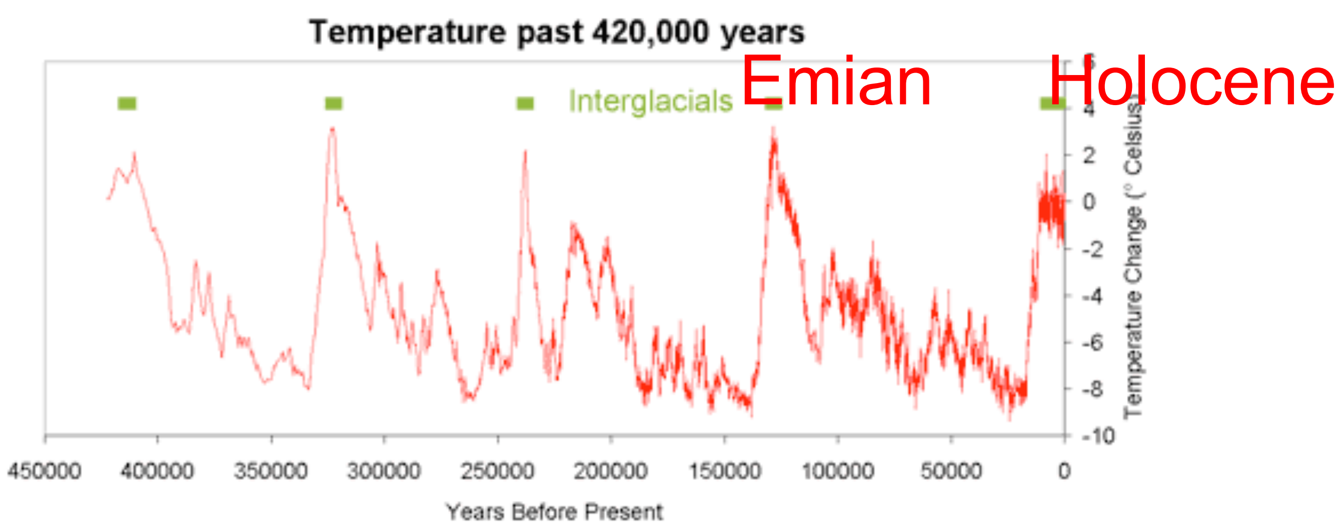


During the glacial-interglacial cycles, temperature begins to change before CO_2 changes

→ The initial warming/cooling comes from the orbital cycles (Milankovitch), and is amplified by feedbacks, including the ocean solubility feedback, leading to CO_2 changes than amplify the initial temperature change

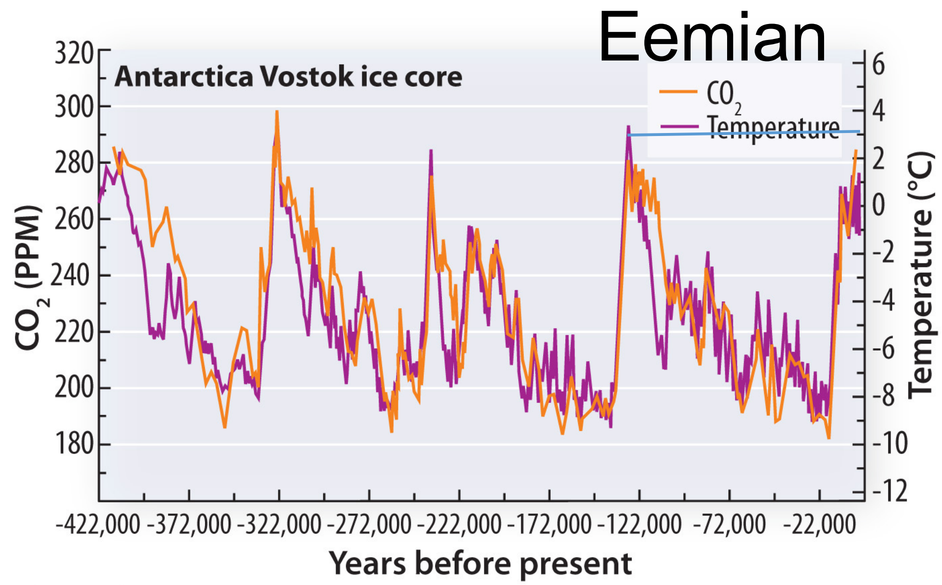
Glacial interglacial cycles after the mid- Pleistocene transition

- Detailed record from Antarctic ice cores, reaching back 800,000 years, even longer records from sediment cores (with less detail)
- Note: Glacials are longer than interglacials
- Since the mid-Pleistocene transition, glacials are between 80,000–100,000 years long and interglacials 10,000–20,000 years



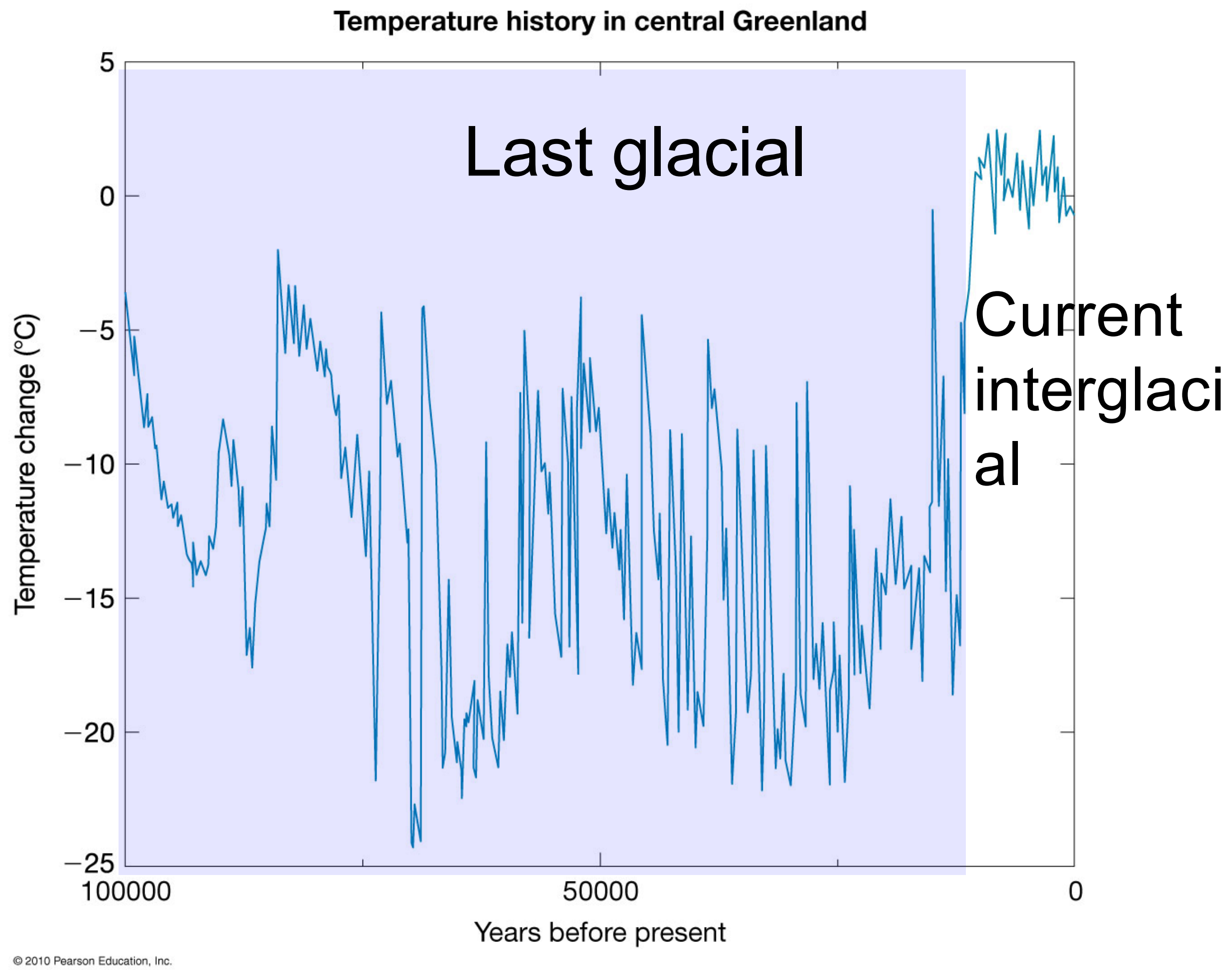
The last interglacial: The Eemian (130,000 to 114,000 years ago)

- The Eemian was the last interglacial before our present interglacial (Holocene)
- The last time the world was at least as warm as during the Holocene
- The obliquity was higher than it is today during the Eemian (more radiation during NH summer at 65 N), making the Eemian warmer than today and sea level about 4-6 m higher than today, at a CO_2 level of about 280 ppm

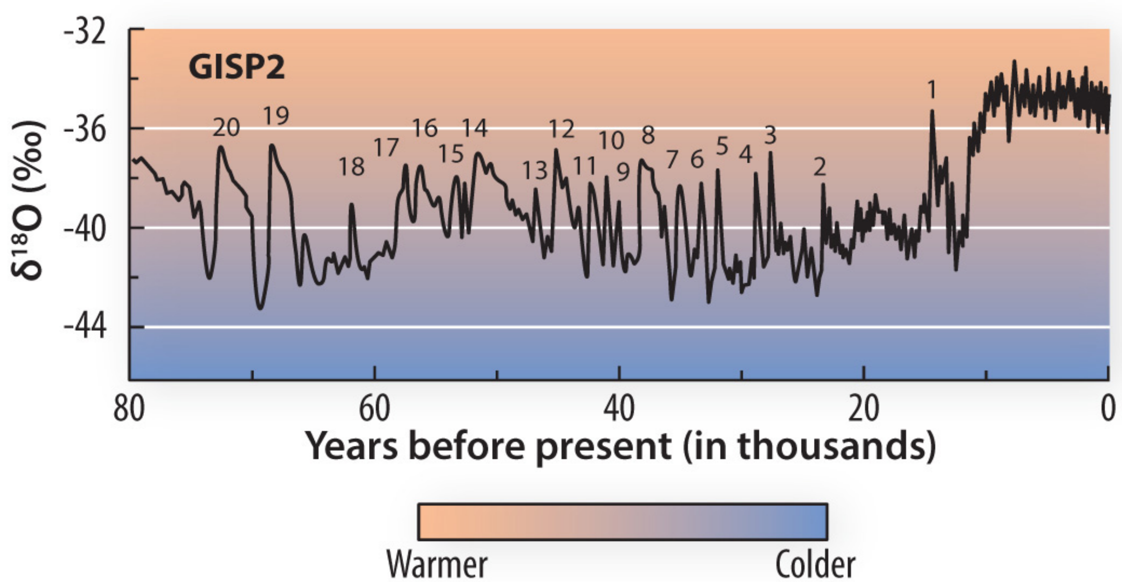


The last glacial

- Relatively unstable climate during last glacial period
- Much more stable climate during current interglacial



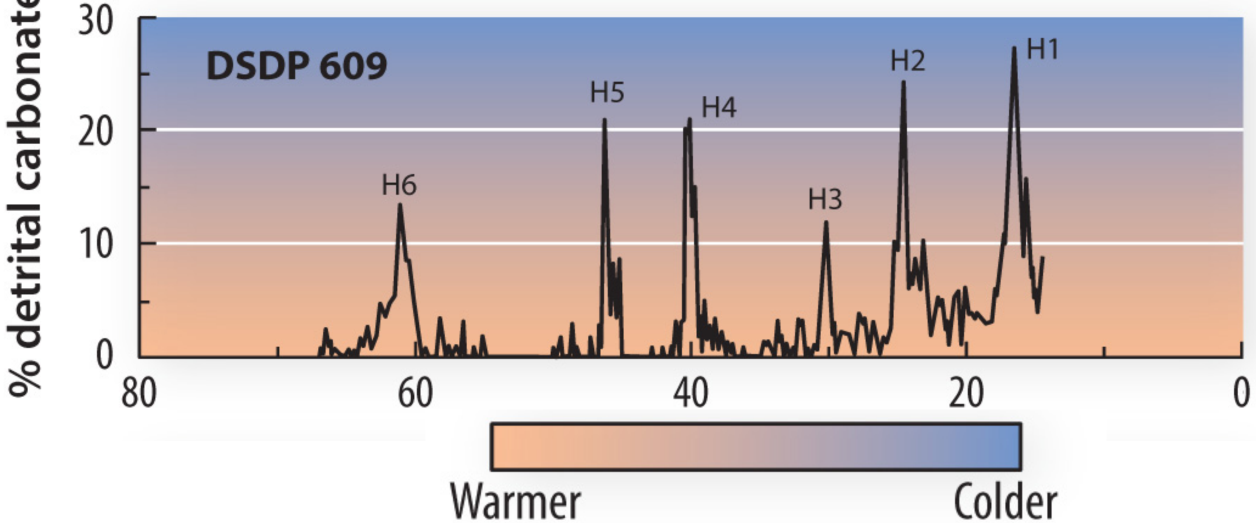
Rapid climate change: D-O events



- Rapid Warming of 8-10C in as little as 20 years in Greenland
- Lasted 500-2000 years, then temperature fell again, first slowly then rapidly
- They are though to have been caused by changes ocean circulation, probably related to ice-sheet instability and/or atmospheric changes related to ice sheet changes
- Cause for timing is still unclear and active area of research

Rapid climate change: Heinrich events

Detrital carbonate in ocean sediments are indications of ice-rafted debris

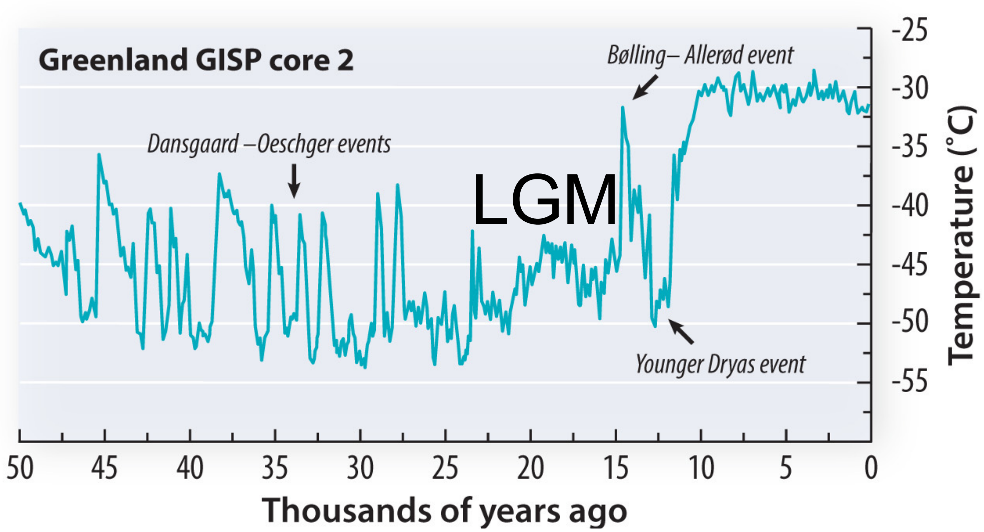


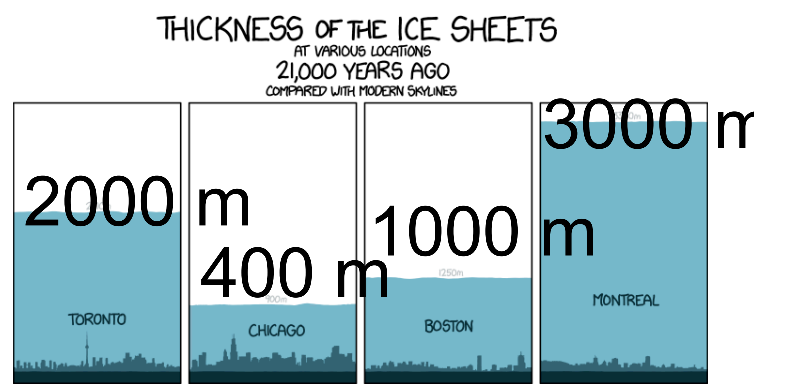
Frequency of Heinrich events during last glacial: every 7,000-10,000 years

- Rapid cooling events, due to lots of icebergs flooding the North Atlantic (as we know from dropstones on the ocean bottom in sediment cores), as the Laurentide (North American) ice sheet became unstable under its own mass
- This lead to a shut-down of deep convection due to surface ocean freshening, global sea level rise of up to 15 m, and a dramatic drop in temperatures in Greenland

Last Glacial Maximum (LGM), ~21,000 years ago

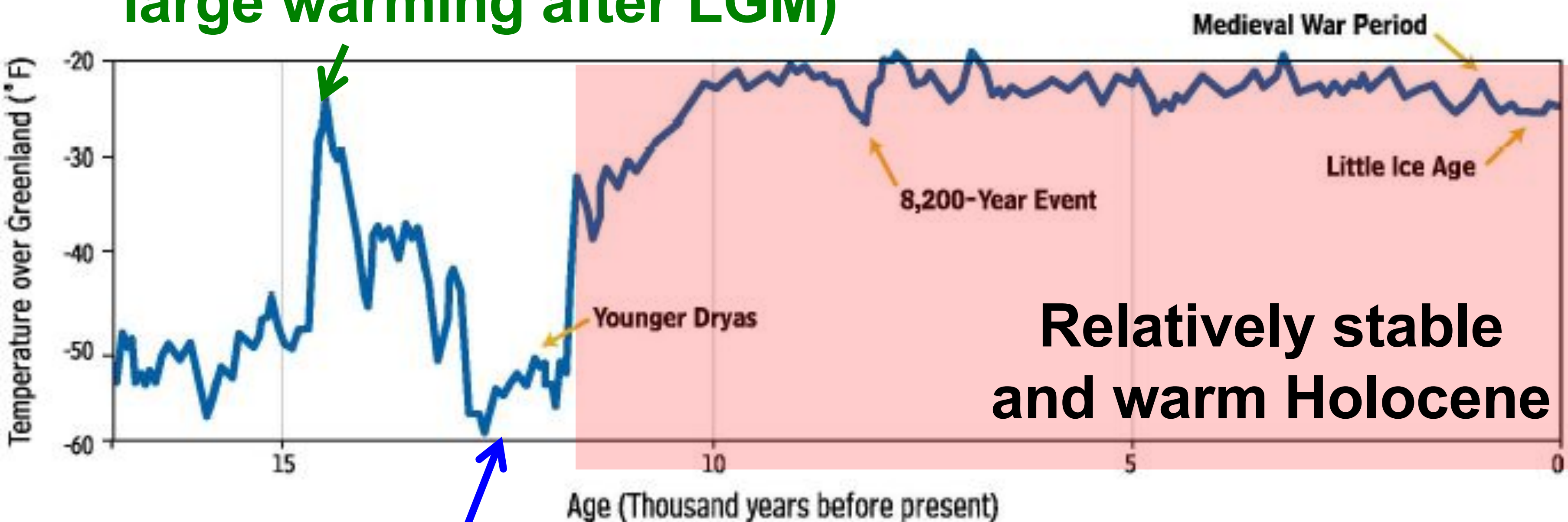
- Atmospheric CO_2 was at 180 ppm
- Globally 5-7° C colder than today
- Up to 30% of the global land mass was covered by ice, mainly on Northern Hemisphere
- Ice sheets were as thick as 3000 m (10,000 feet)
- Global sea level was 120 m lower





After the Last Glacial Maximum

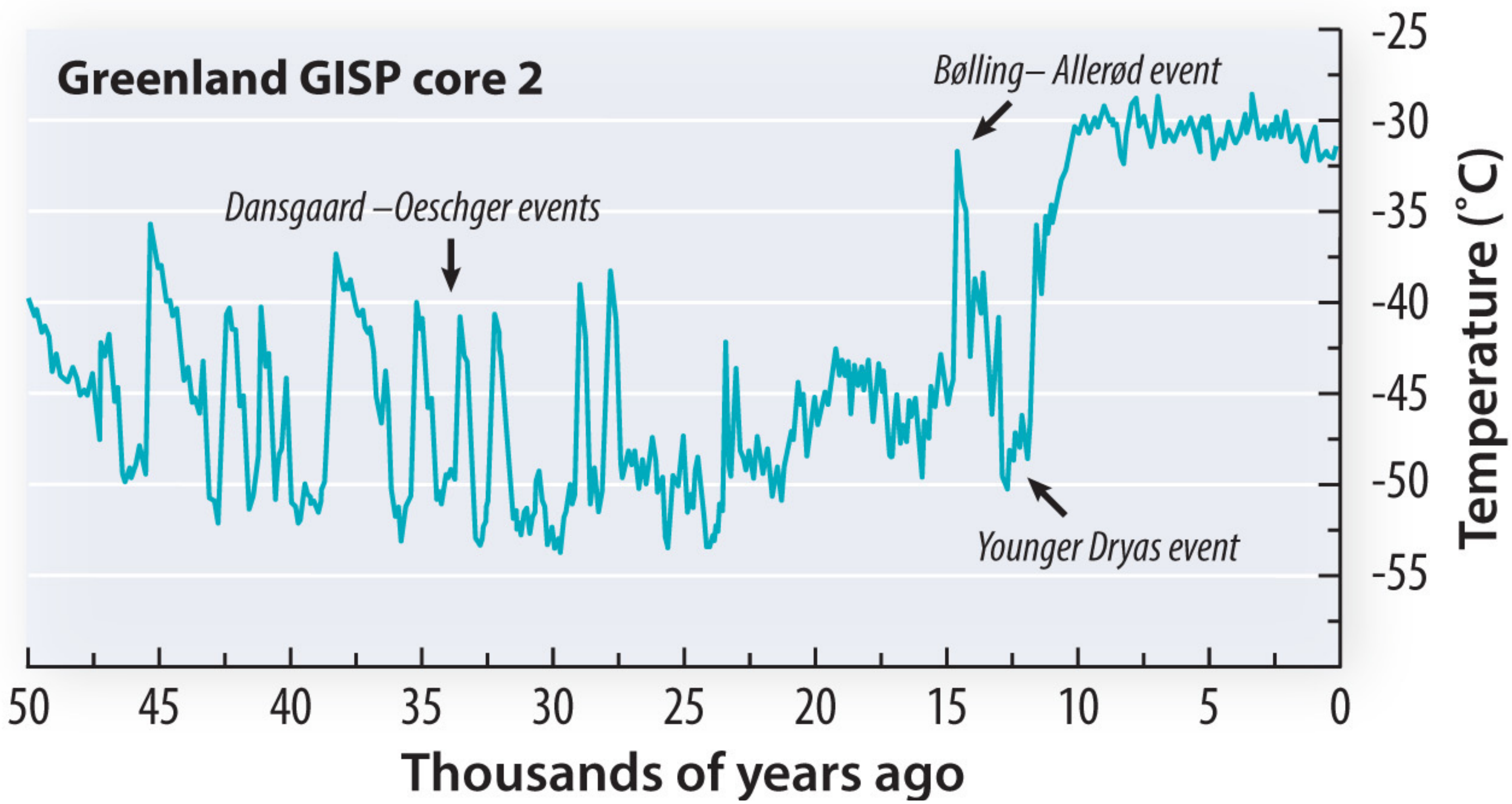
Bølling-Allerød (first large warming after LGM)



Younger Dryas: Last rapid cooling/temperature swing of the glacial

Bølling-Allerød (14,700-12,700)

- Rapid warming as Milankovitch cycles provided more energy to the NH summer
- Lead to rapid ice sheet melt, which might have contributed to Younger Dryas cooling

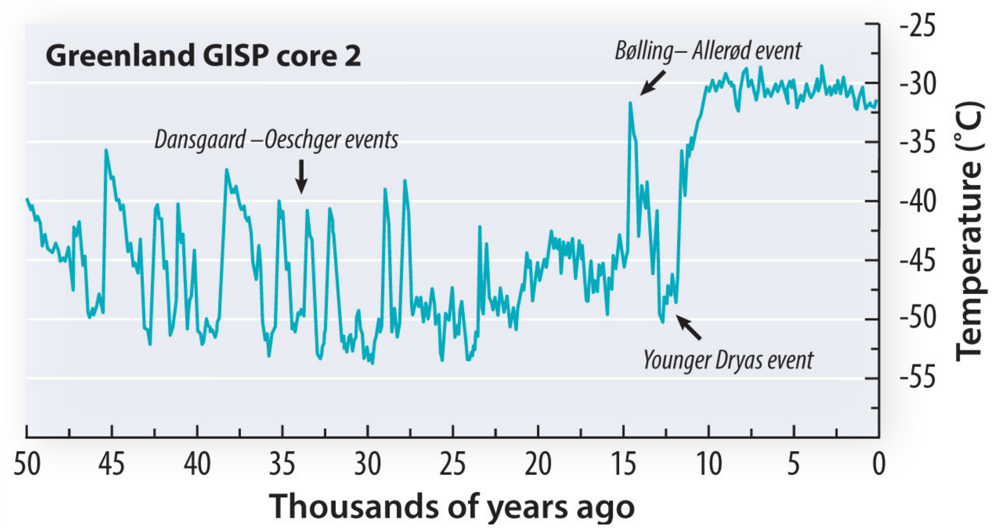


Younger Dryas (12,800 and 11,500 years ag0)

- Brief return to cold conditions
- Thought to be caused by a shut-down of the overturning circulation (similar to Heinrich events), but caused by the breaking of an ice dam and the draining of **Lake Agassiz**, and potentially pre-conditioned by ice melt from Bølling-Allerød
- Younger Dryas ended when the cooling in the North Atlantic lead to very dense water, starting up the formation of deep water again

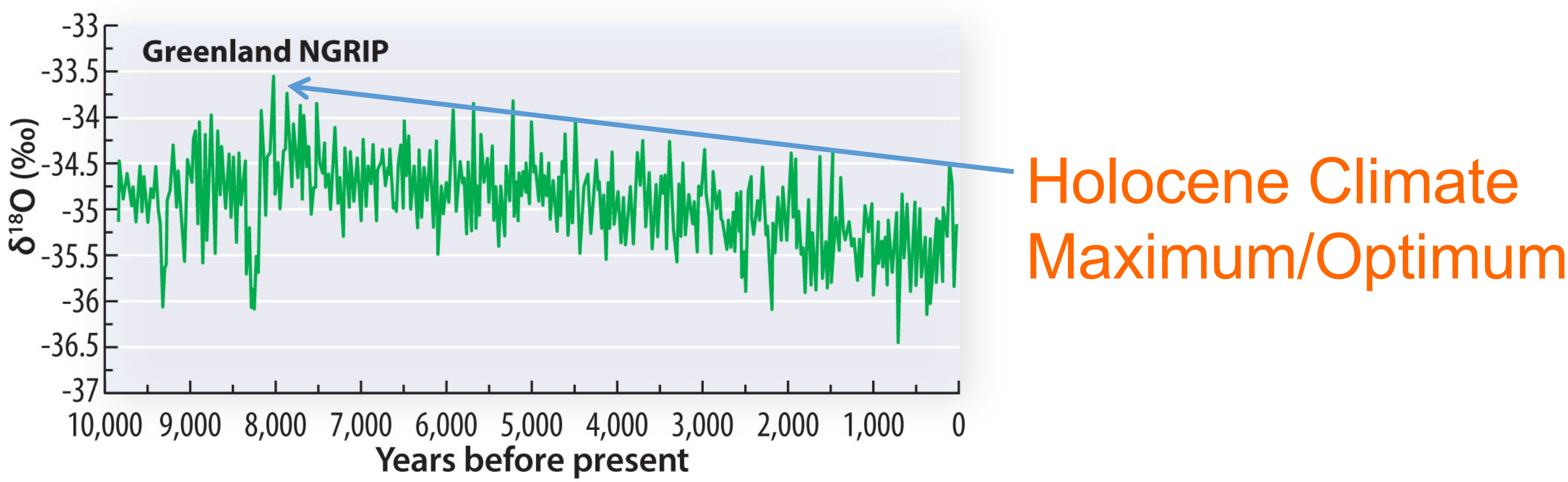
The Holocene (11,000 to today)

- The return to warm conditions after the Younger Dryas marks the beginning of the Holocene, the current interglacial
- Very stable climate in the Holocene (and in general in interglacials) compared to glacial periods → due to much smaller and stable ice sheets

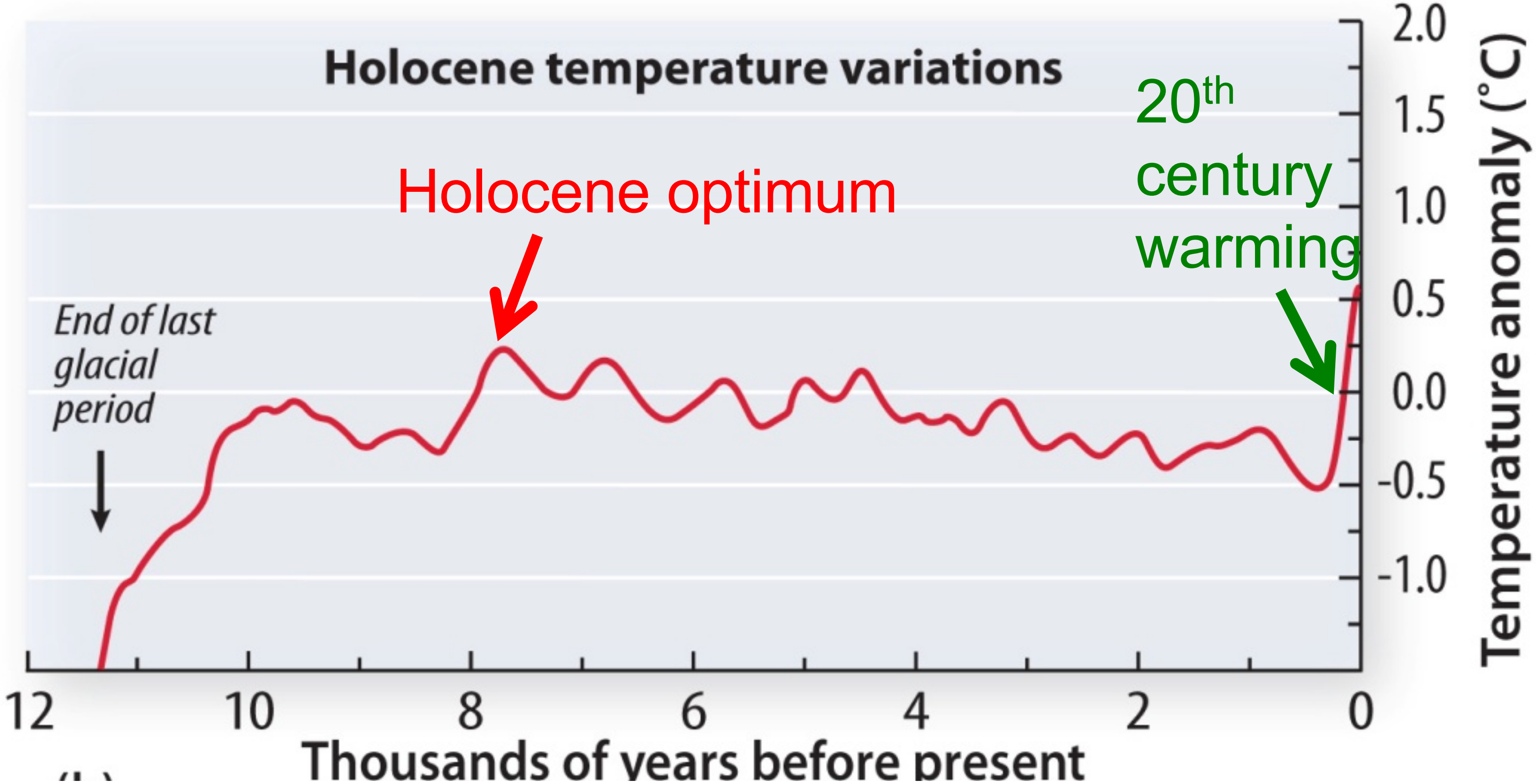


Holocene climate Maximum/Optimum

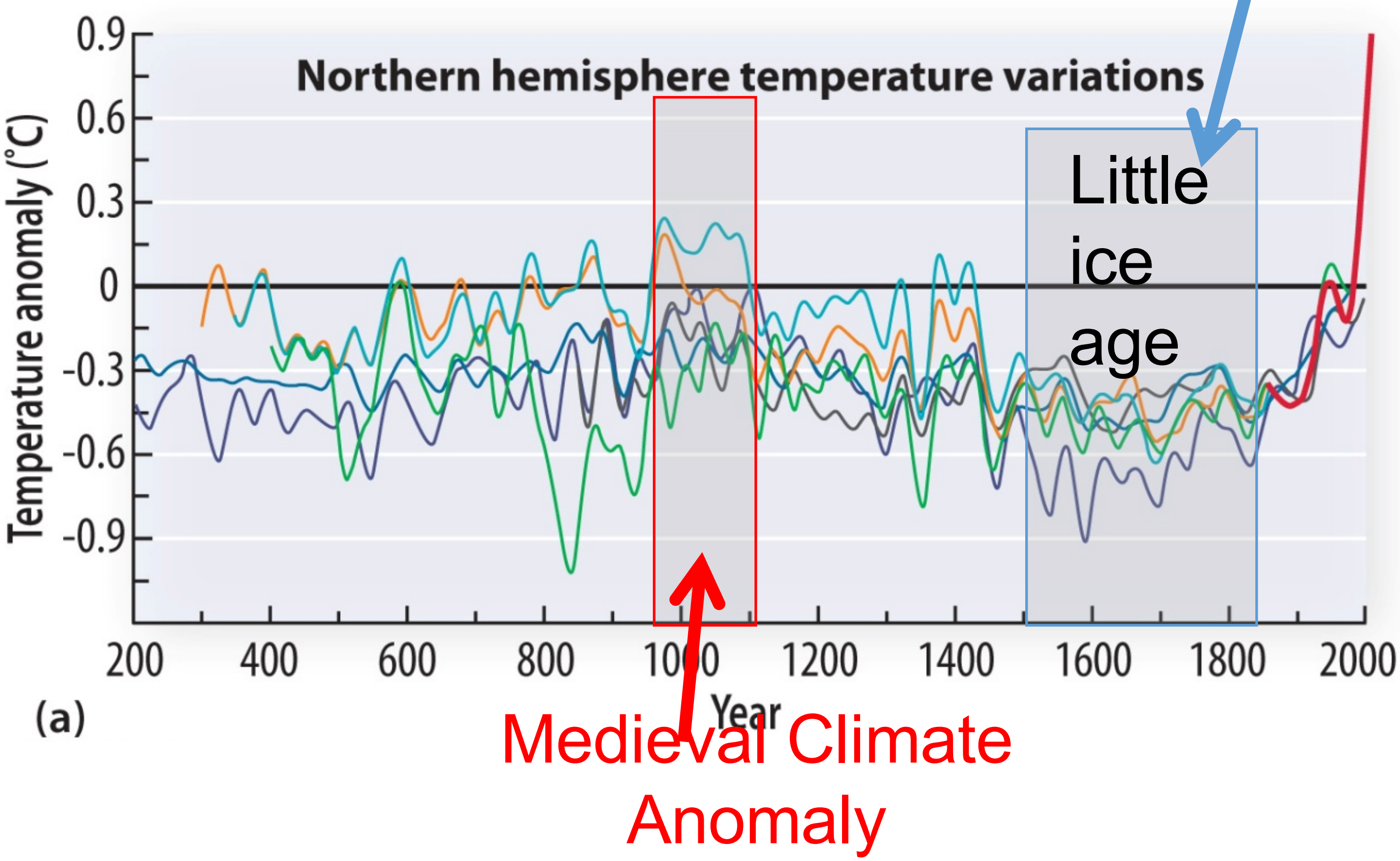
- The Holocene was warmest around 8000 years ago (right after the 8200 year cold event), and global temperatures have decreased slowly since then (until the 20th century)
- At the Holocene climate Optimum, insolation reached its maximum during summer at 65°N, and has declined since then (it was 7% higher then than it is today)



Holocene temperature evaluation



Historical climate change



Want to know more about the little ice age?

RSVP here: https://goo.gl/YEztQ7

The Coldest Centuries in 8000 Years: The Little Ice Age: Causes and Human Consequences

Friday-Saturday | November 3-4, 2017
Benson Earth Sciences Rm 180 | Free and Open to the Public

The Little Ice Age (LIA) is broadly defined as the time period from about 1250 to 1900 CE, the coldest centuries of the past 8000 years. The causes of this cold interval are the subject of increasing interest to scientists, yet its effects on the people who lived through it are only beginning to be fully assessed. This conference brings together scholars who study climate forcings and climate change, as well as historians, archaeologists, and others who explore the human impact of the LIA. We hope to advance understanding of both the environmental and cultural effects of this global event.

Even art, such as this painting of skaters in the Netherland by Hendrick Avercamp, reflects the cold conditions in the 16th century

Keynote Address, Friday 7pm:
Alan Robock: Climate Impacts of Explosive Volcanism

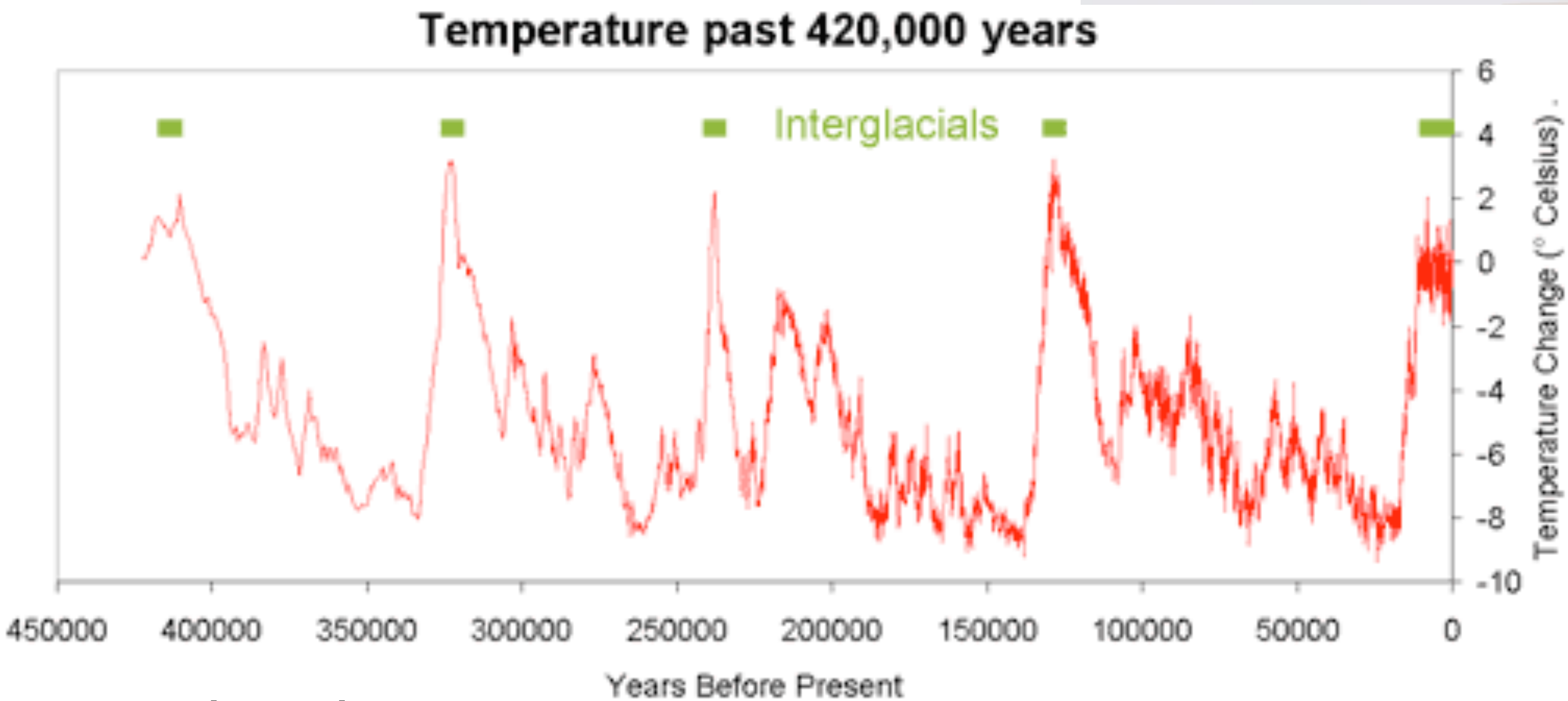
Saturday Speakers, 8:45AM - 5:30PM:
Gifford Miller: Glaciers record onset of persistent LIA cold
Raymond Bradley: Climate of the Little Ice Age
Alexandra Jahn: Positive feedbacks from Arctic Ocean Sea Ice
Sam White: Cultural Impact of LIA cooling in Europe
Charles Cobb: Cultural impact of LIA cooling in SE USA
Scott Ortman: Mesa Verde at the start of the LIA
Aun Ali: Cultural impact of LIA cooling in Asia
Bette Otto-Bliesner: Explosive volcanism in a warming world

Event Details: **https://goo.gl/YEztQ7**

Center for the Study of Origins
UNIVERSITY OF COLORADO **BOULDER**

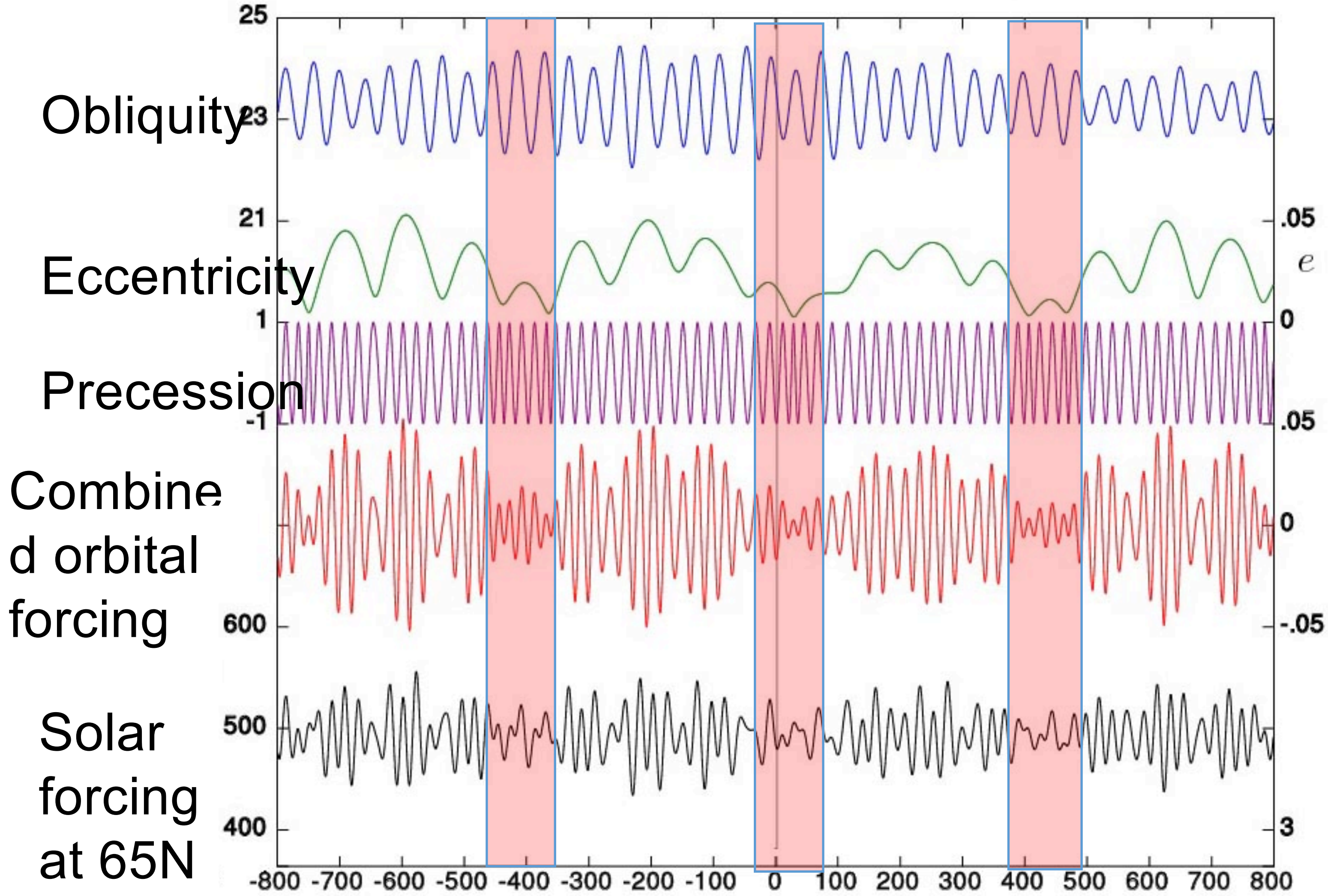
Center for the Study of Origins

When will we go into the next glacial?



- Last Glacial maximum 20,000 years ago
- Start of current interglacial 11,000 years ago, average length of interglacials 10,000 to 20,000 years → any time now to in 10,000 years?

Milankovitch cycles for the past and future

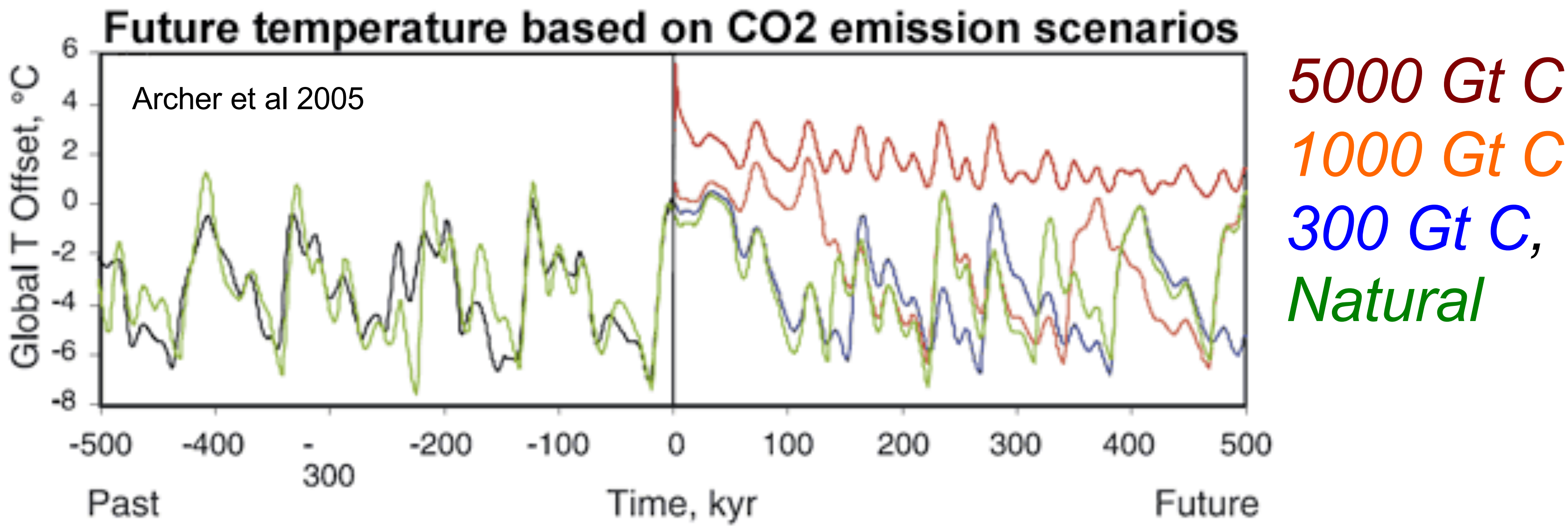


Eccentricity has secondary 400,000 year cycle, which leads to small insolation changes every 400,000 years, which leads to long interglacials (~40,000 years)

→ We happen to live in one of these periods

So when will we go into the next glacial?

Without any anthropogenic greenhouse forcing, the next glacial wont begin for another ~30,000 years (started 11,000 years ago, will be ~40,000 years long)

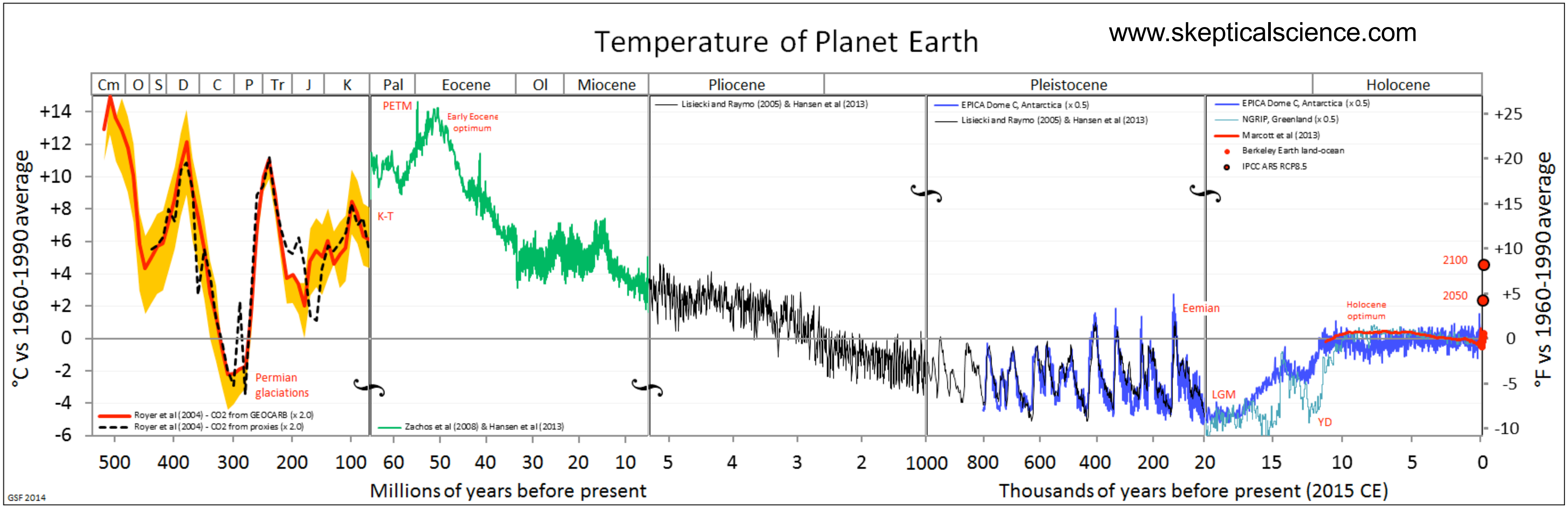


Depending on future CO_2 emissions, we could delay (~1000 Gt C) or prevent (>2500 GtC) the start of the next glacial

We are currently at ~580 Gt C cumulative emissions, and under RCP8.5 could pass 2500 Gt C by 2100

Staying below 1.5C means staying below 1000 GtC

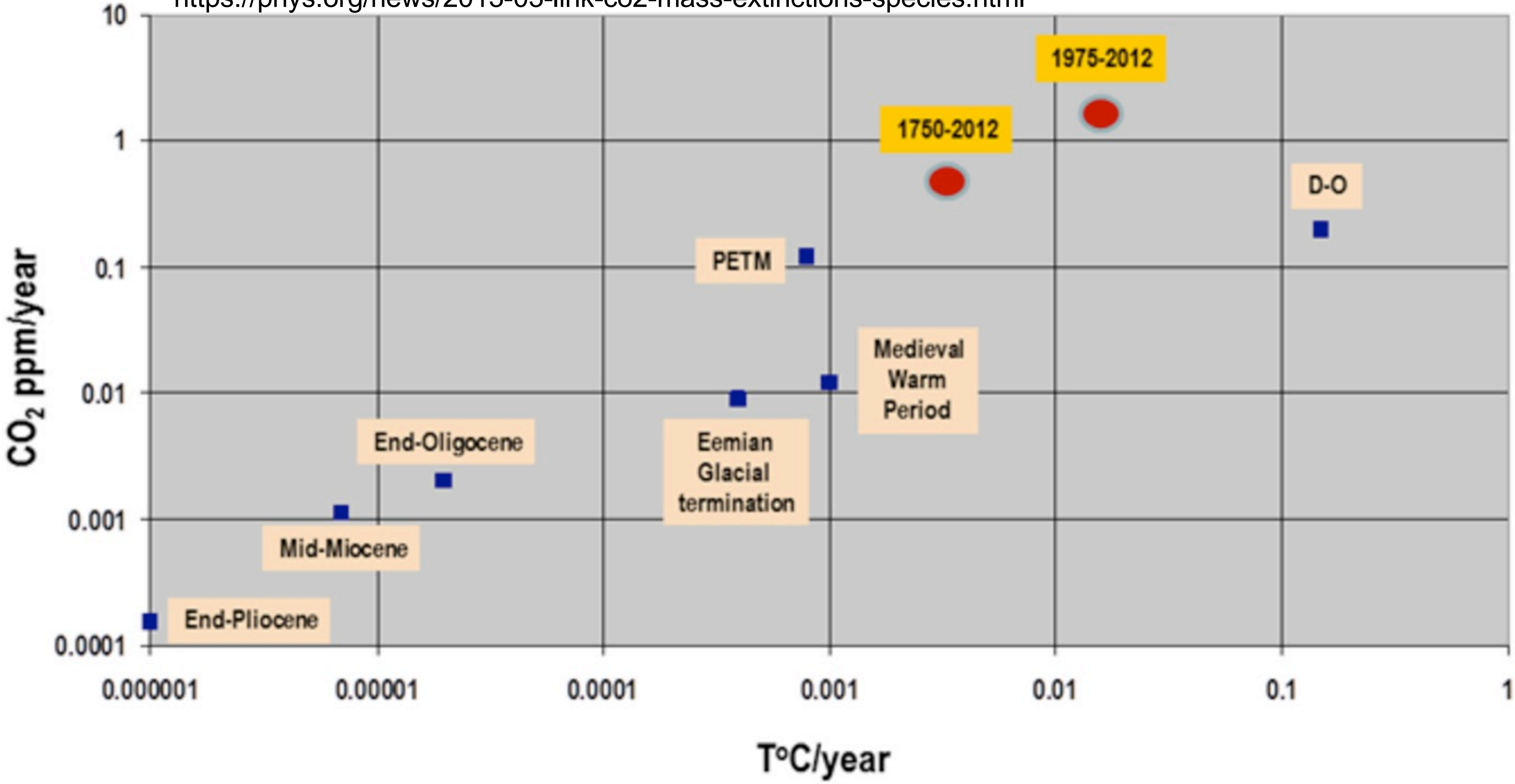
How does past climate change compare to current climate change?



- Observed and projected warmth is not unprecedented in earth’s history

How does past climate change compare to current climate change?

https://phys.org/news/2013-03-link-co2-mass-extinctions-species.html



- The rate of warming and CO_2 rise is very rapid, not normally seen in interglacials
- Past rapid climate change has lead to mass extinction events

Thank you!