ATM S 111, Global Warming: Paleoclimate

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Day 26: July 27, 2010

Next Topic: Paleoclimate

- Climate of the past
  - The first three eons & the rise of oxygen
  - Snowball Earth
  - Continental drift
  - Ice ages
  - Relevance to global warming

What Sets the Climate Over Earth's History?

- The Sun
  - It's changed in magnitude over its lifespan
    - Initially 75% as strong as it is now
    - Over last billion years, increased 10%

What Sets the Climate Over Earth's History?

- The orbit of the Earth around the Sun
  - If it was just the Earth & the Sun, the orbit would be a perfect **ellipse** that never changed
  - However, there are other planets/moons in the solar system, whose gravitational pull makes the orbit change with time.

What Sets the Climate Over Earth's History?

- Location of the continents
  - These have shifted with time
  - Mountain ranges appear, sometimes high latitude ice sheets aren't possible, etc

What Sets the Climate Over Earth's History?

- Location of the continents
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Exact representation of continental drift… → →

What Sets the Climate Over Earth's History?

- Volcanoes
  - On short timescales, cause cooling
  - Over long timescales, can add significant CO_2 to the atmosphere
    - We'll discuss exchange between the solid Earth and the atmosphere

How Do We Know About Paleoclimate?

- **Proxy** data: tells us about temperature, precipitation, etc through other indicators
  - **Biological data**
    - Tree rings, pollen, corals, fossils
    - Ex: Alligator skeletons at relatively high latitudes tell us the Eocene winter temperatures must have been very mild

How Do We Know About Paleoclimate?

- **Proxy** data: tells us about temperature, precipitation, etc through other indicators
  - **Cryological data:** from **ice cores**
    - Ice at the bottom of Greenland/Antarctica is hundreds of thousands years old
    - Ex: Ice cores have **tiny bubbles of air** trapped inside that reveal past atmospheric composition

How Do We Know About Paleoclimate?

- **Proxy** data: tells us about temperature, precipitation, etc through other indicators
  - **Geological data**:
    - Rocks, sediments, shape of the land, etc
    - Ex: land in the Seattle area is cut out by glacier flows from when ice sheets used to have a much larger extent

How Do We Know About Paleoclimate?

- **Proxy** data: tells us about temperature, precipitation, etc through other indicators
  - **Isotopic data**:
    - Many of the previously mentioned datasets can be dated using **carbon dating** or other radiometric dating techniques
    - Also isotopes can tell us about **precipitation** as we'll see

History of the World, Part I

- We'll look at this timeline:
  - Lifetime of Earth (4.5 billion years)
  - Past 100 million years
  - Past million years
  - Past 20,000 years
- Equivalent timeline for 20 yr old student:
  - Whole life
  - 100 million yrs = last 5 months
  - 1 million yrs = last 2 days
  - 20,000 yrs = last 45 minutes

In the region of the Earth less than a million years after the sun formed. Small grains of dust are aggregating into "planetesimals." Planets grew by collisional aggregation of these objects.

Hadean eon (4.6-3.8 billion ybp)

One catastrophe after another: constant bombardment with asteroids

End of the Hadean Eon

- Most bombardment ended around 3.8 billion ybp (years before present)
  - These obviously still happen
- Oceans had formed by this time
  - Atmosphere likely had water vapor, carbon dioxide, nitrogen
  - "Faint young Sun paradox": how was the early Earth **warm** when the Sun was so much **dimmer**
    - Greenhouse effect was likely the key
- **No oxygen** in the atmosphere yet though!
  - We'll come back to this shortly…

Controls on Carbon Dioxide Over Time

- **Release by volcanoes** is a relatively efficient way of getting CO_2 into the atmosphere
  - Remember this is small as compared to **current** human emissions
  - Volcanoes are very important over hundred thousand year timescales
- How does CO_2 get **removed** from the atmosphere over long times?
  - **Land masses** are key in a process called **chemical weathering**
  - When rain/snow falls on silicate rocks, it reacts and takes CO_2 **out of the atmosphere**

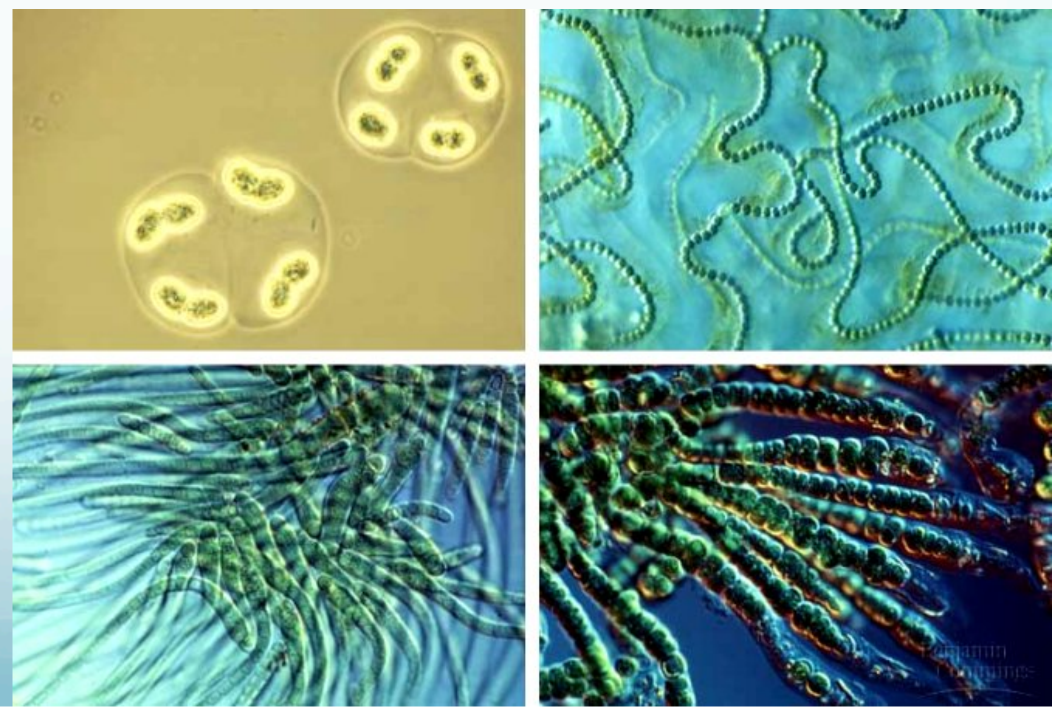
Chemical Weathering

- Chemical weathering is a **negative feedback**
  - When climate is hotter, it's easier for weathering to take CO_2 out of the atmosphere
  - Likely key for **stabilization** of climate over millions of years

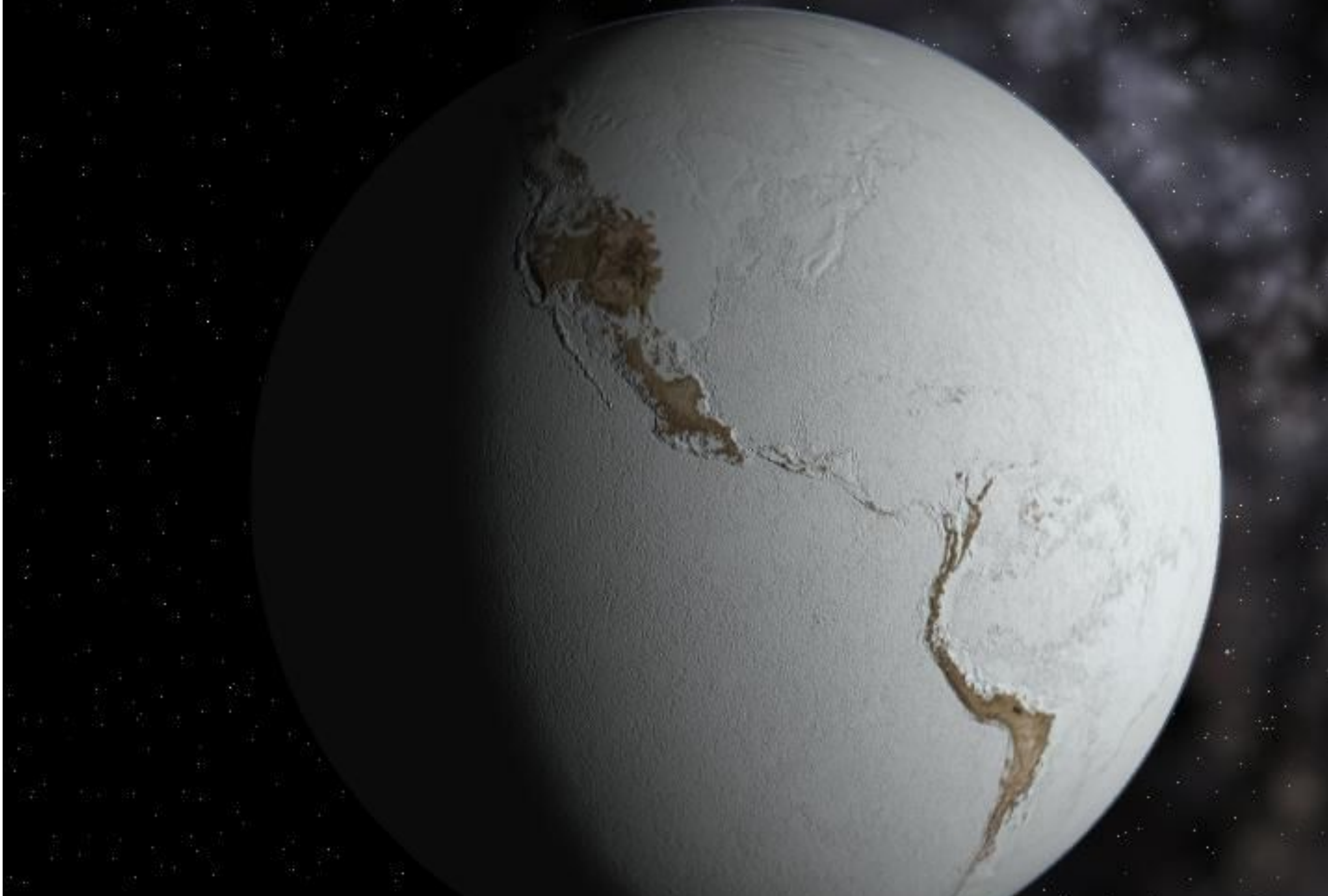
Rise of Oxygen

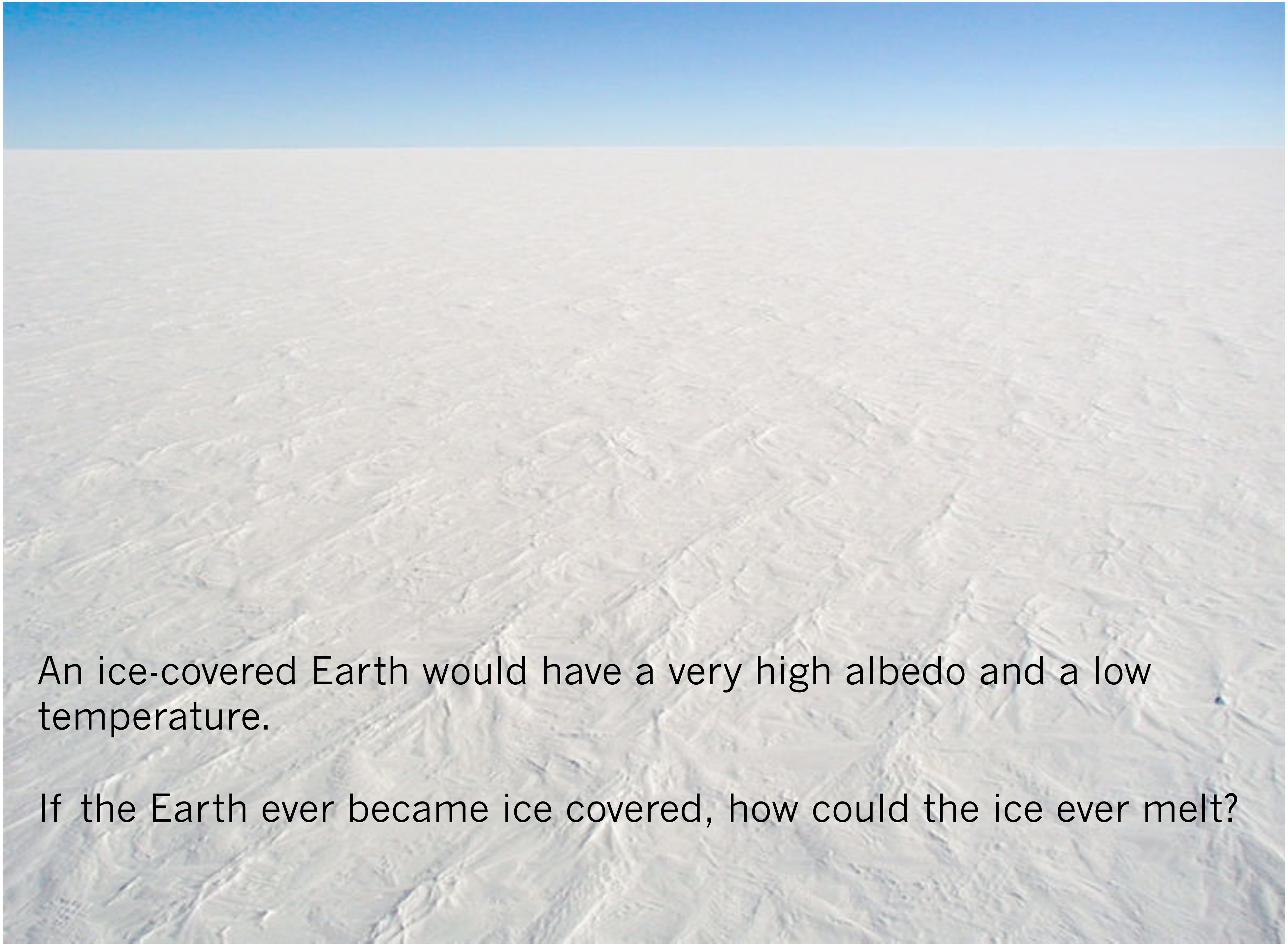
- Oxygen appeared due to life!
  - **Blue-green algae photosynthesis** created oxygen
- This oxygen also led to the ozone layer, which protects us from UV radiation

Life allowed other life to exist!



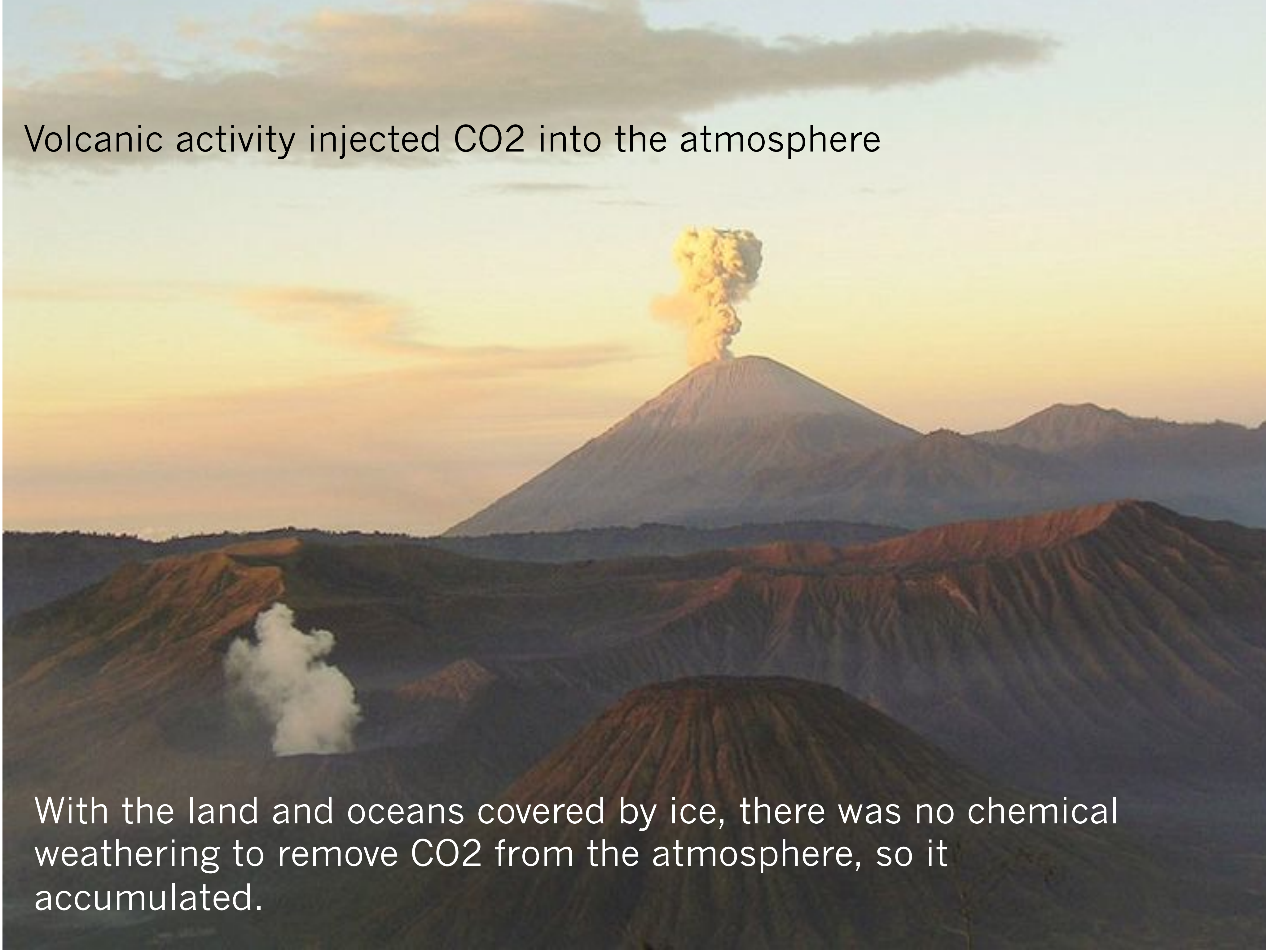
Snowball Earth– occurred several times in the last billion years when ice-albedo feedback spiraled out of control

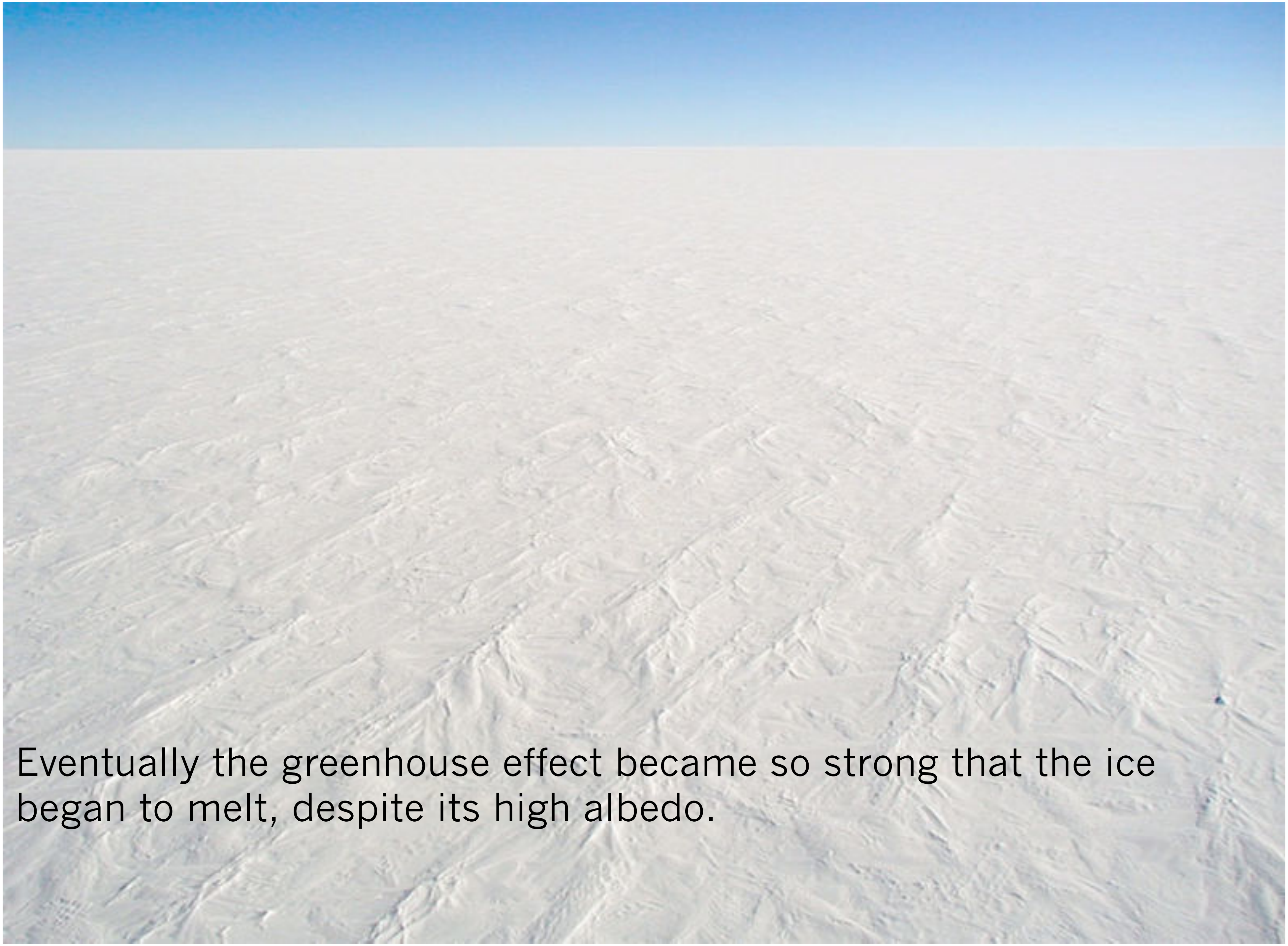




An ice-covered Earth would have a very high albedo and a low temperature.

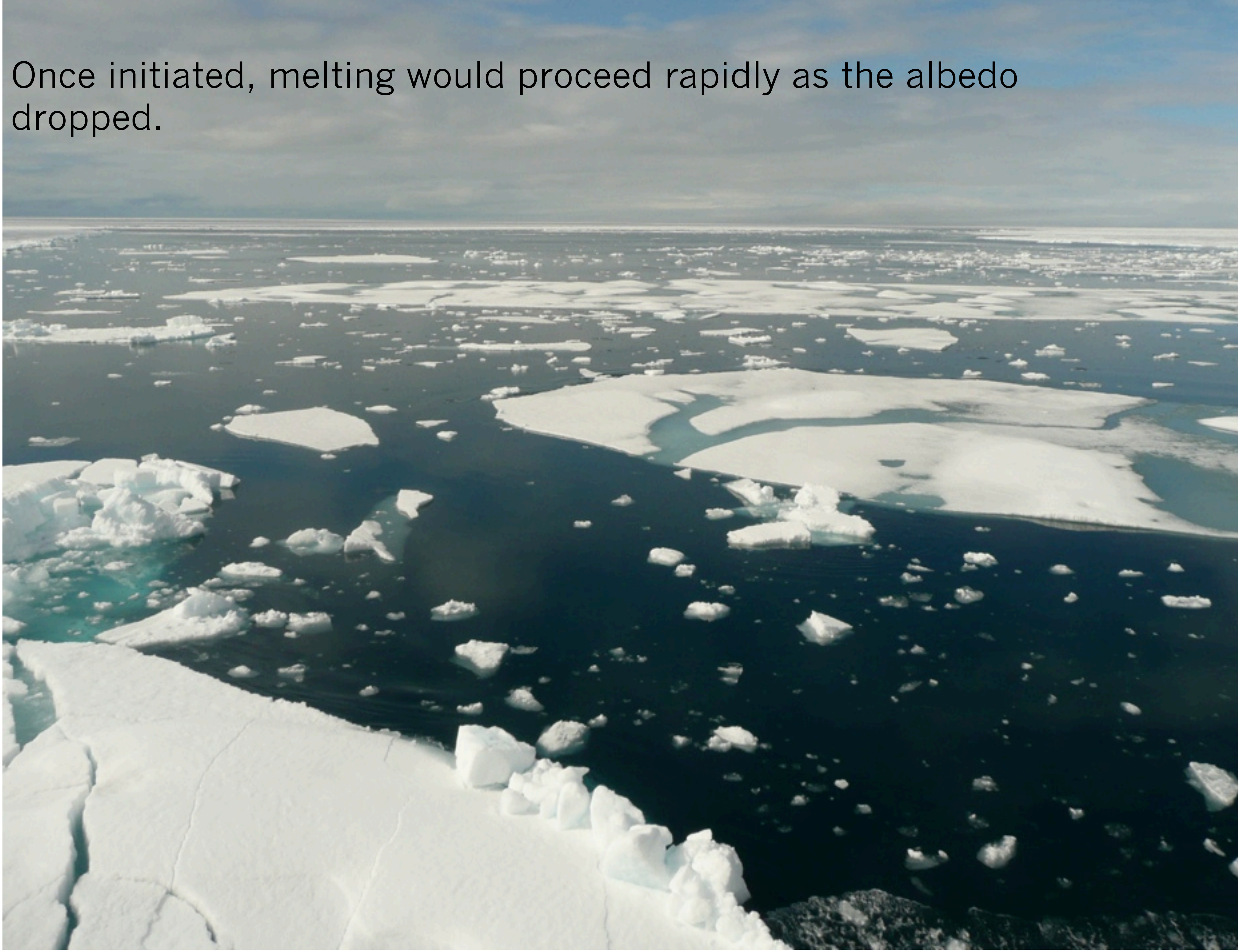
If the Earth ever became ice covered, how could the ice ever melt?


Volcanic activity injected CO2 into the atmosphere
With the land and oceans covered by ice, there was no chemical weathering to remove CO2 from the atmosphere, so it accumulated.

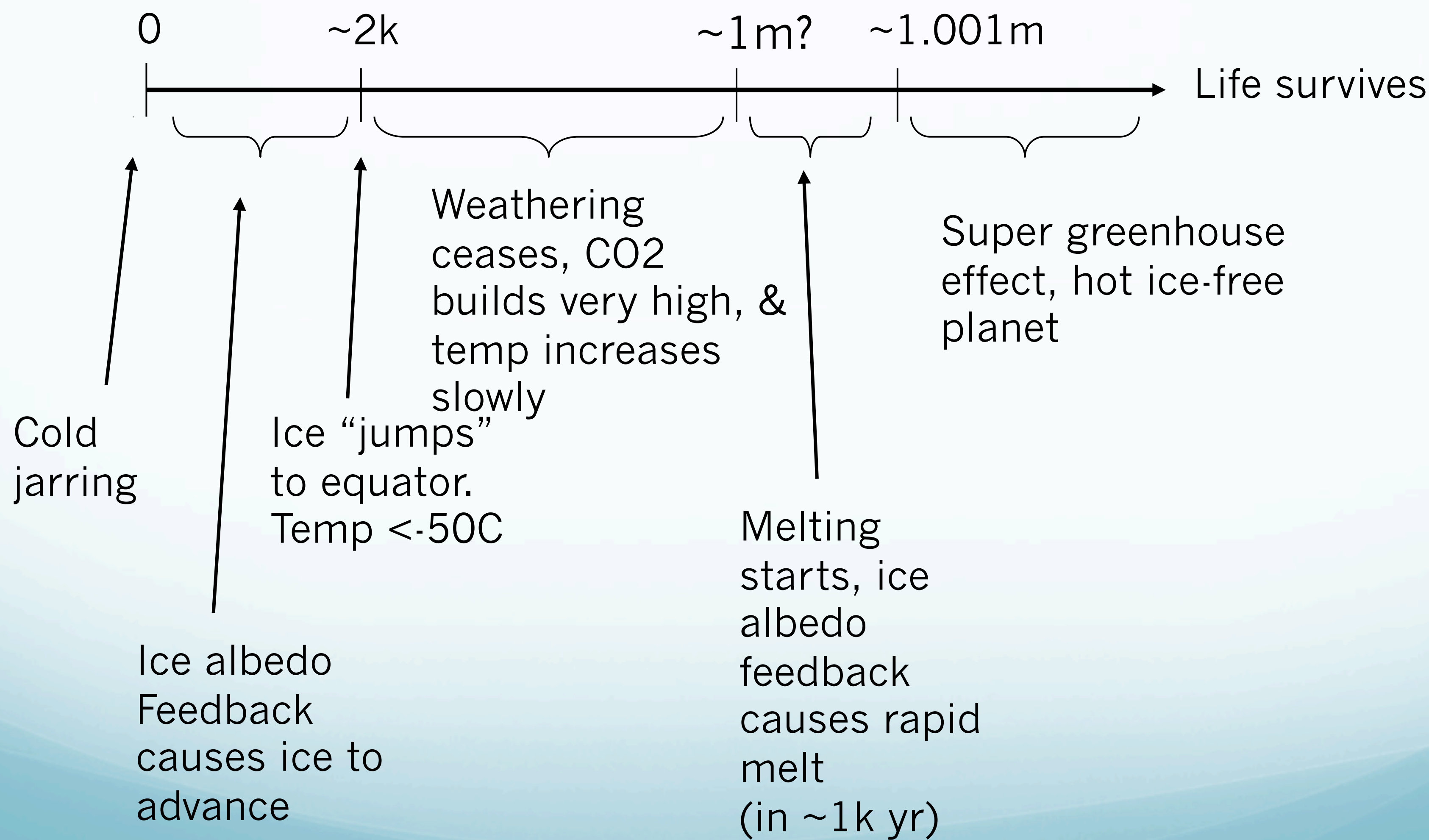


Eventually the greenhouse effect became so strong that the ice began to melt, despite its high albedo.

Once initiated, melting would proceed rapidly as the albedo dropped.



Snowball Earth Timeline

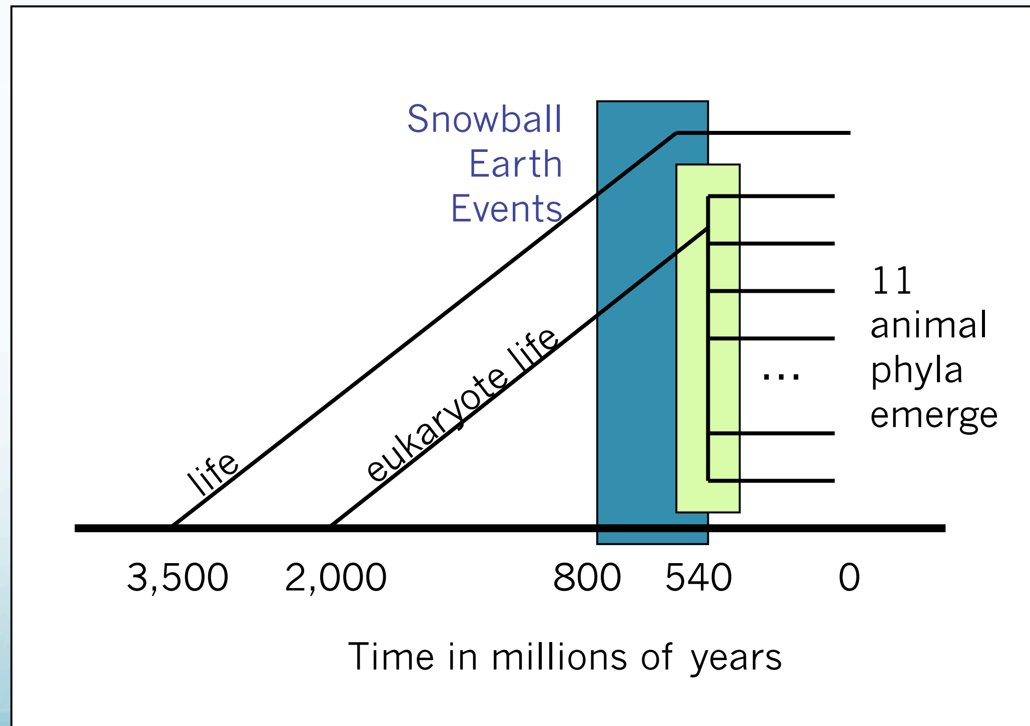


So what?

Ice covering the planet is cool

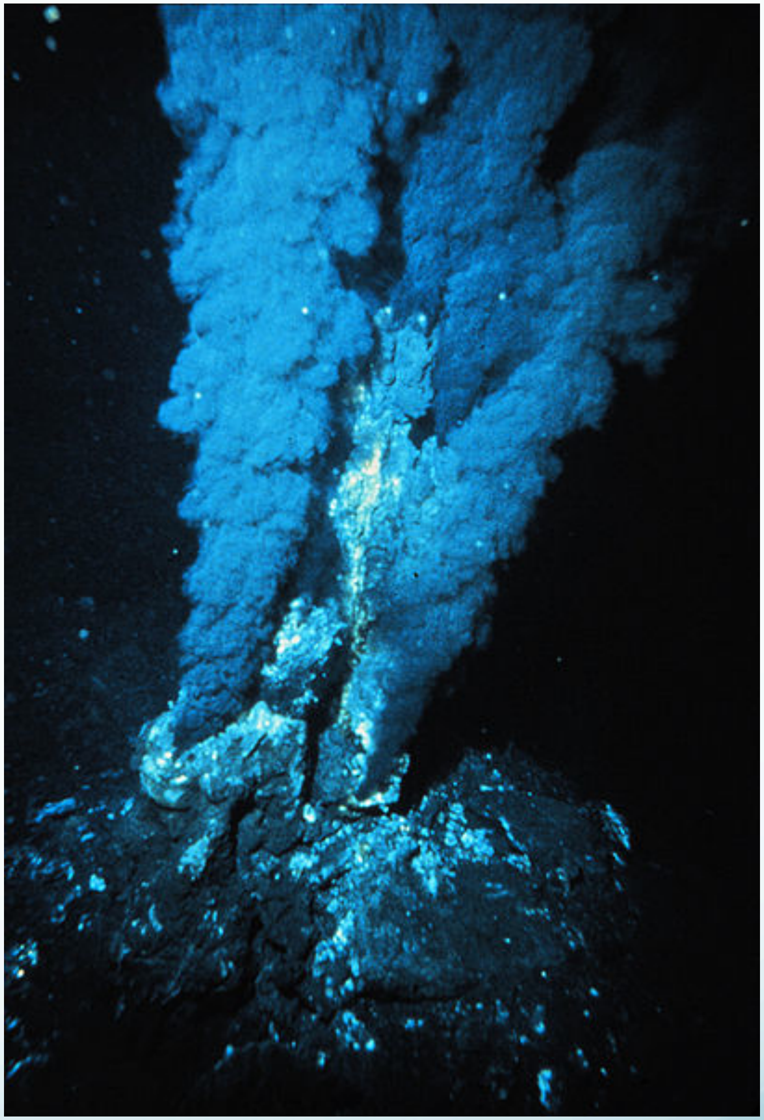
Rapid melt warmed Earth ~100^{o} C in a thousand years

How did life survived these events?



How did life survive snowball Earth?

Cracks in the ice?

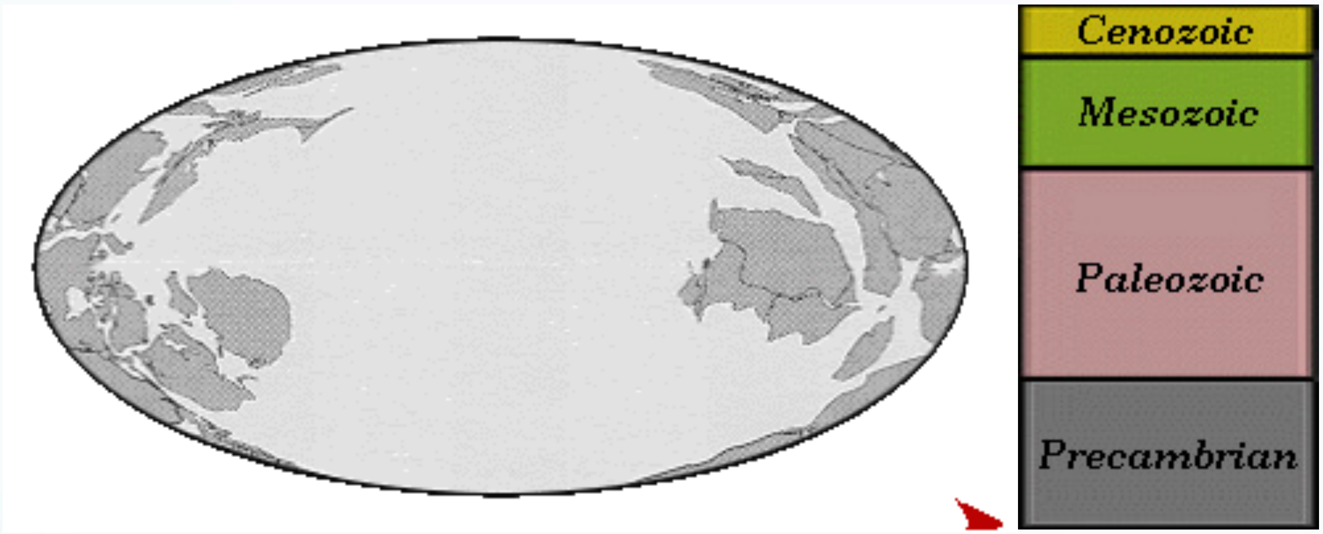


Hydrothermal vents?

Once thawed, the Earth would be very warm because of the high atmospheric concentrations of GHG.

But these high GHG concentrations would gradually decline due to massive weathering

Next Time Period: Last 100 Million Years



Continental Drift (Alfred Wegener, 1920s)

Another major factor in the history of climate change

Plate tectonics and climate – some examples

Decline in atmospheric CO_2 starting 60 million years ago

rise of **Himalayas** and **Rockies**– more weathering as fresh rock exposed

slowdown in continental drift– less volcanism– less CO_2

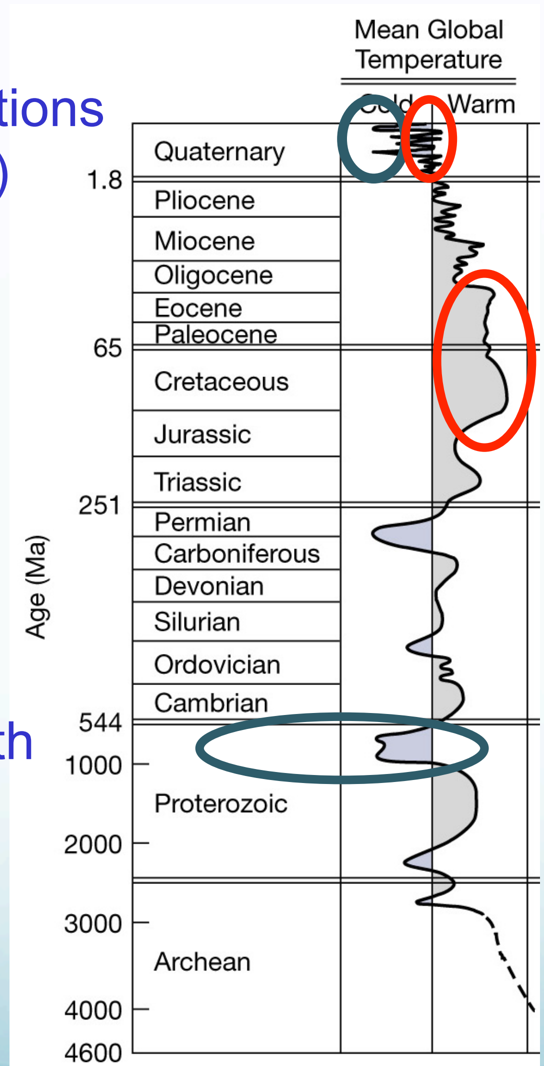
Movement of Antarctica over the South Pole– glaciation– higher albedo

Closing of the **isthmus of Panama** was the last major change to the land distribution (about 4 million years ago)

Temperature through Time

Glacial Conditions (ice-ages)

Inter-glacial Conditions (e.g. the present)



Mesozoic/Early Cenozoic Warm Period

Snowball Earth Events

deep past was mostly warmer than today

Kasting et al

Warm Mesozoic (250 - 65 million years)
Dinosaurs - 2-6 deg C warmer globally
Poles were especially warm - mystery

Evidence:
   Lush ferns and alligators in Siberia

Cretaceous sea levels were 200 m higher than today!

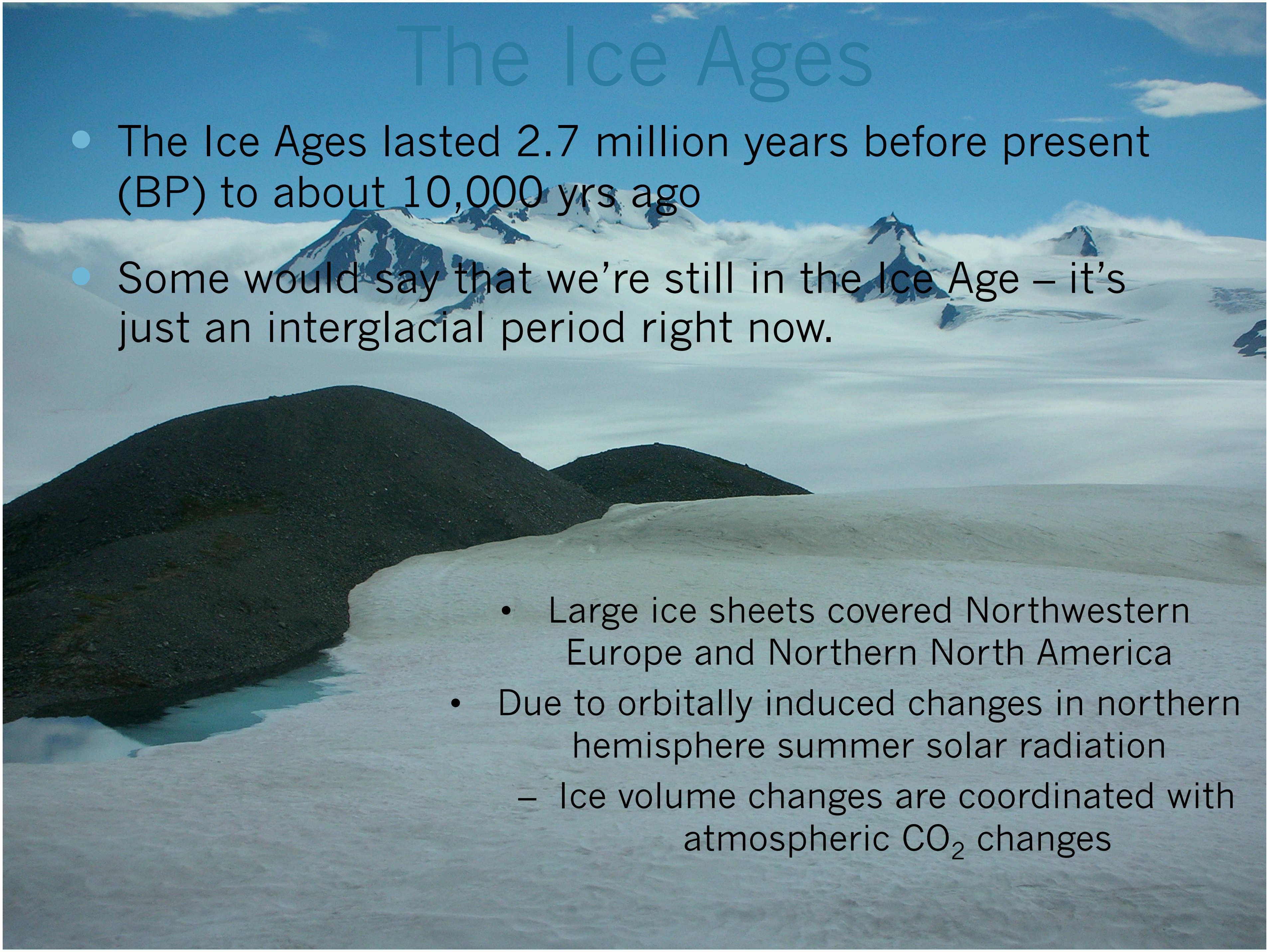
The entire middle of North America was a giant seaway

Cenozoic - 65 million years to present

- Earth slowly cooling
- Life retreats from poles
- Polar ice caps established
- Most recent ice-ages begin ~3 million years ago

Cause of decline in CO_2?

Himalayas form when India collides with Asia and the fresh rock and high precipitation around mountains increased weathering (maybe)



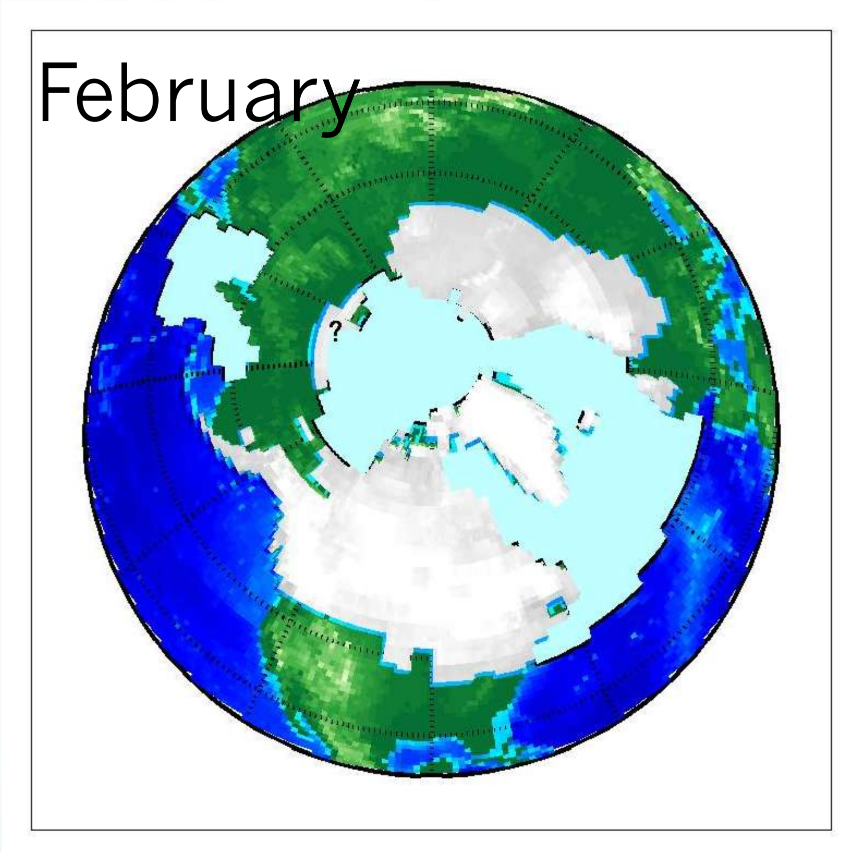
The Ice Ages

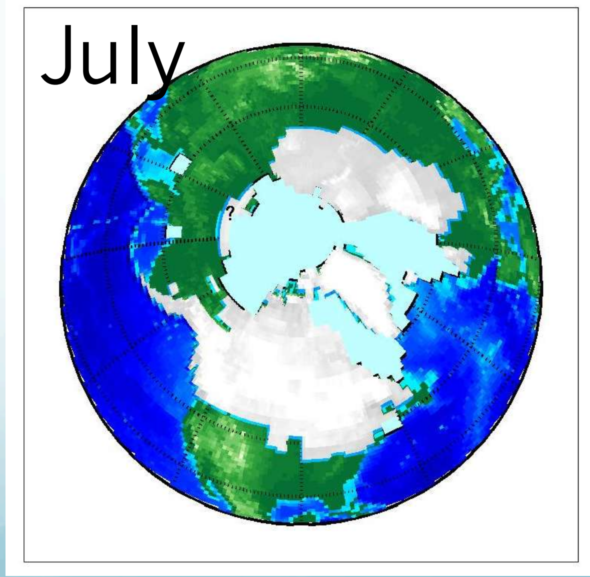
- The Ice Ages lasted 2.7 million years before present (BP) to about 10,000 yrs ago
- Some would say that we're still in the Ice Age – it's just an interglacial period right now.

- Large ice sheets covered Northwestern Europe and Northern North America
- Due to orbitally induced changes in northern hemisphere summer solar radiation
  - Ice volume changes are coordinated with atmospheric CO_2 changes

What does an ice age look like?

- Reconstruction of land and sea ice 21,000 years ago

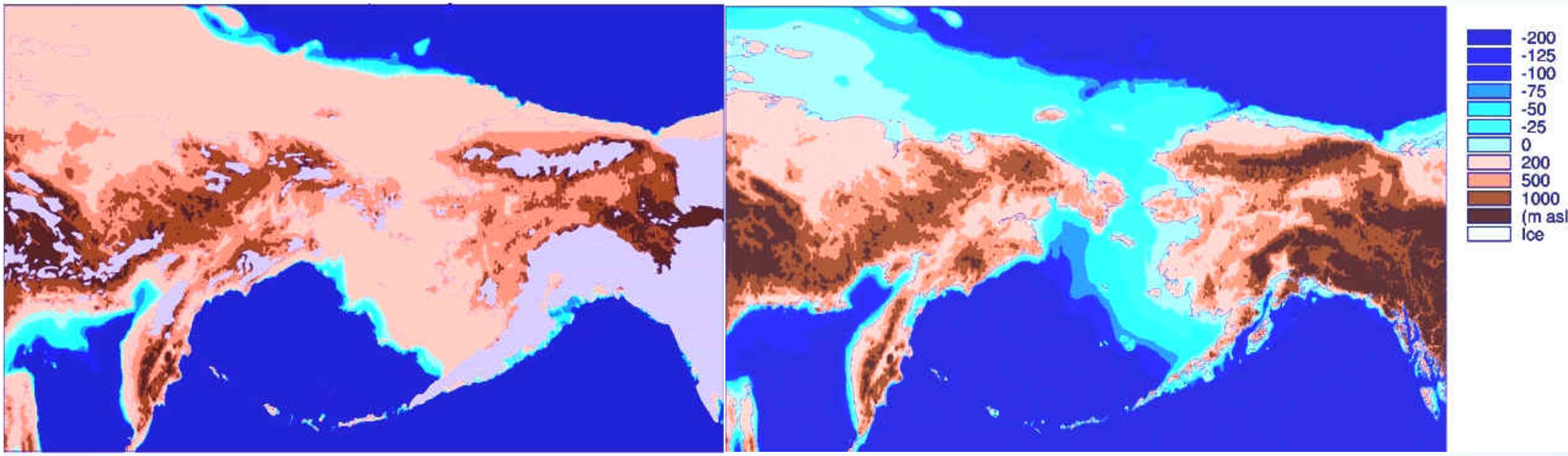




CLIMAP reconstruction

The last glacial maximum (LGM) occurred around 20,000 years ago.

Sea level was lower by ~120 m at the time of the LGM because of the storage of water in the continental ice sheets



20,000 ybp

today

The land bridge

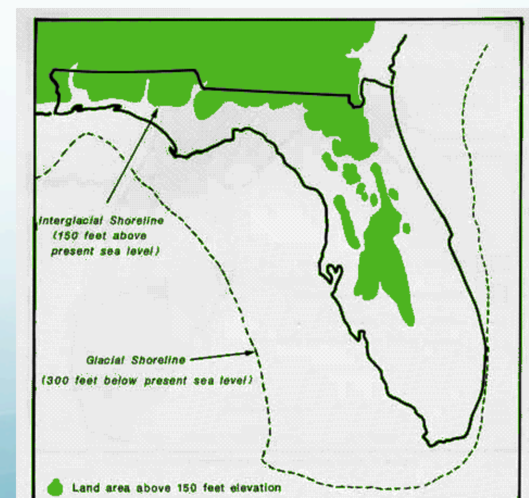


Figure 16. Pleistocene shorelines in Florida. Illustration by Frank R. Rupert.

The home ice sheet ~20kbp

Cordilleran Ice Sheet

Lake Missoula

Spokane Floods (from Lake Missoula)

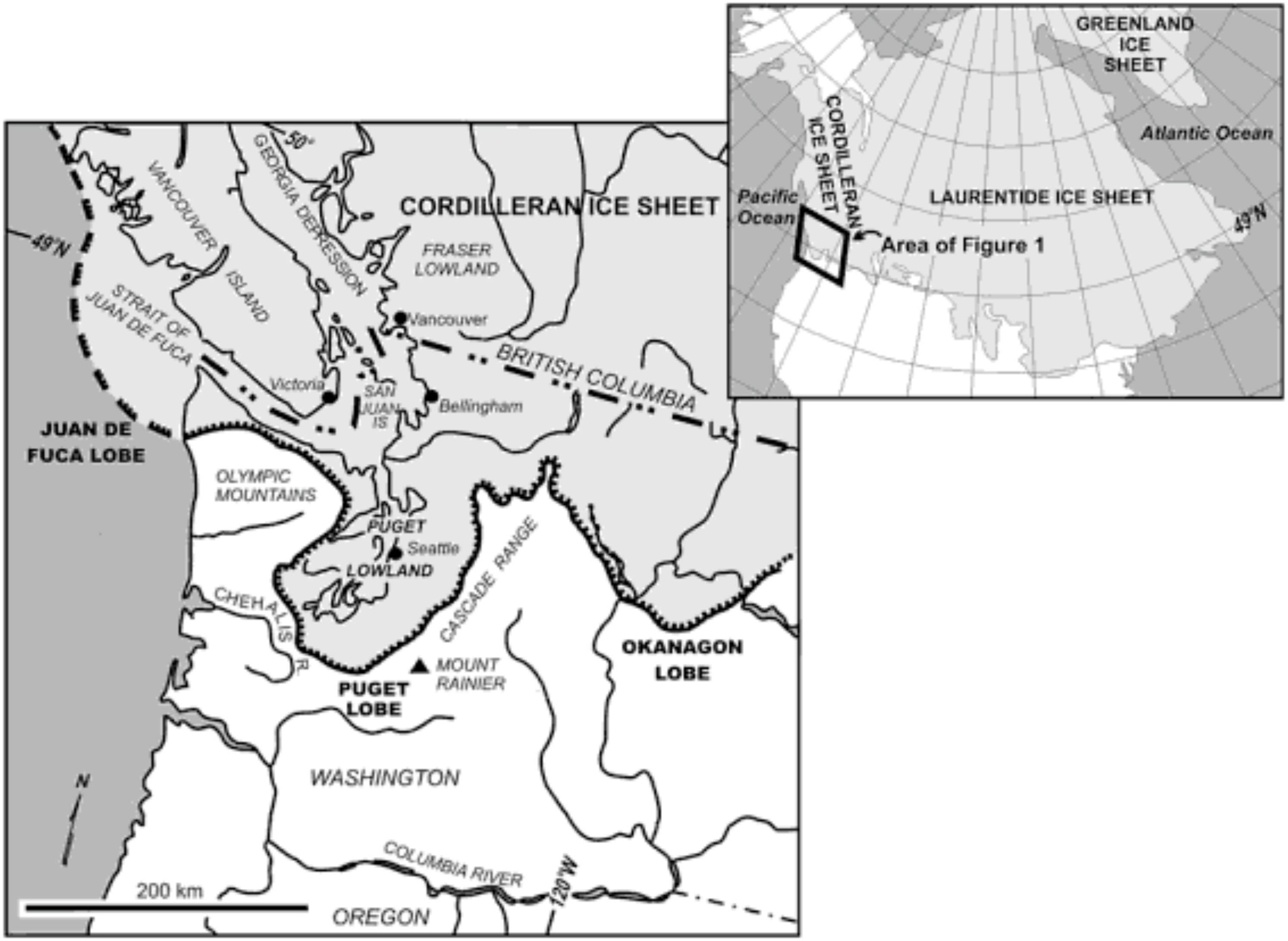
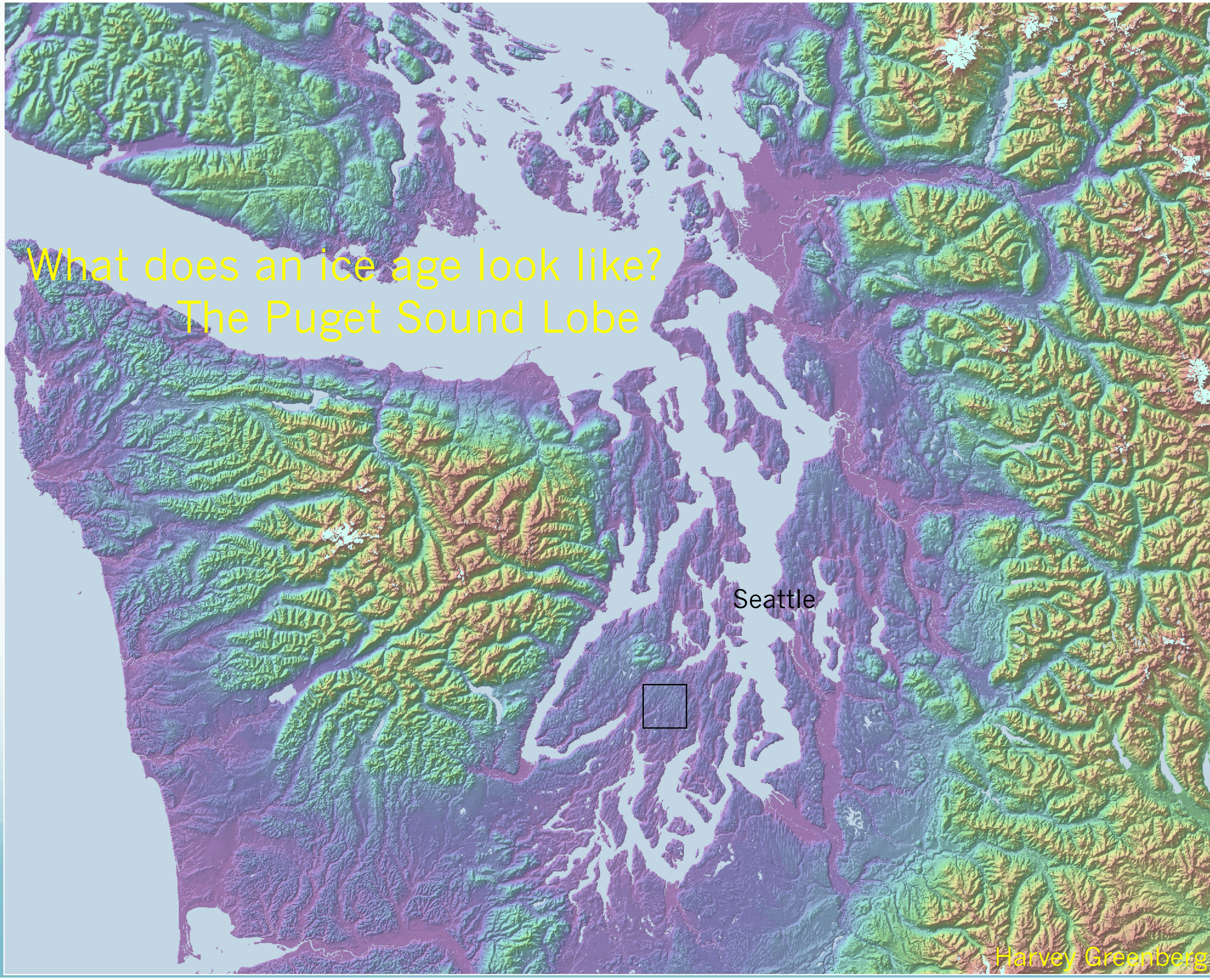
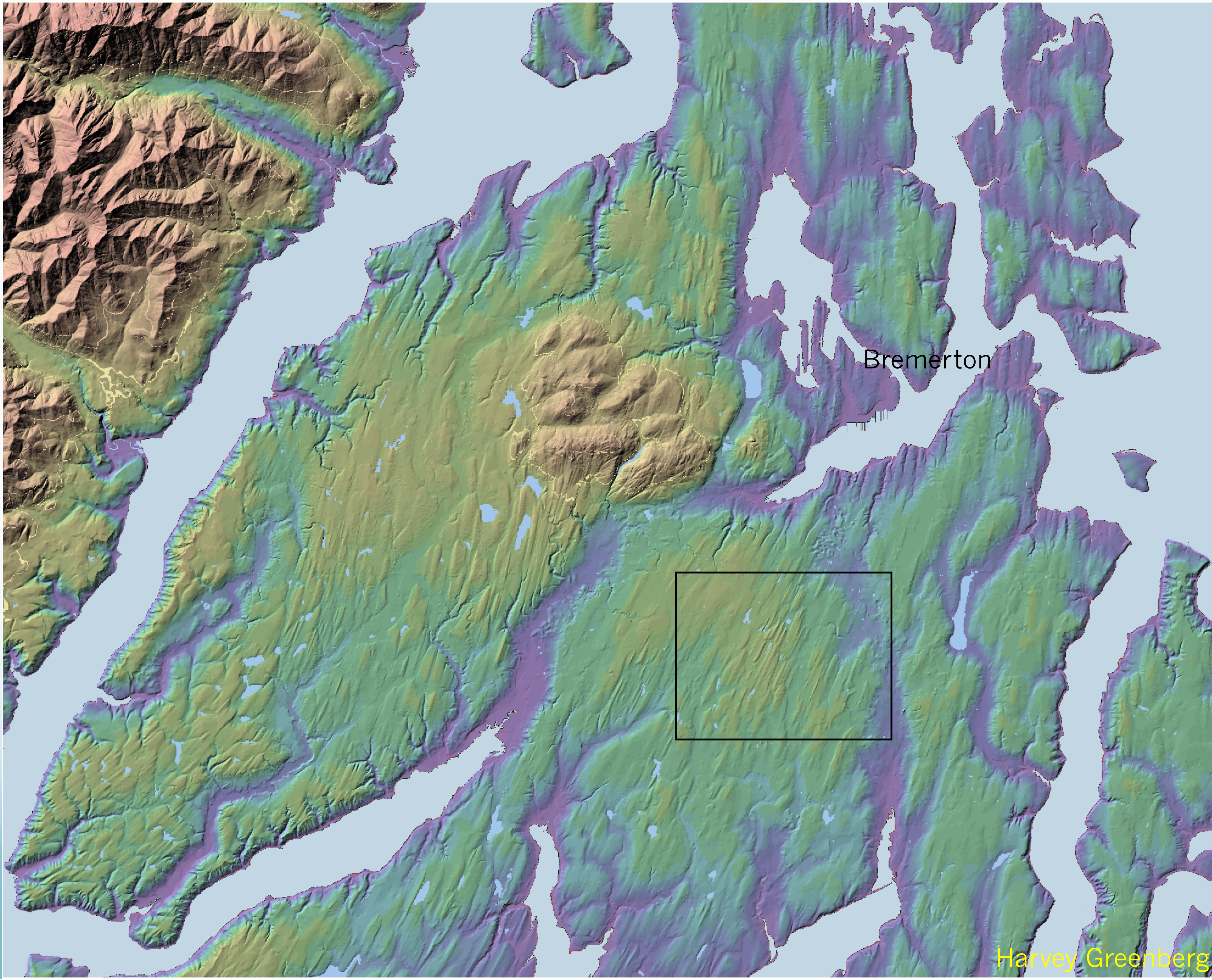
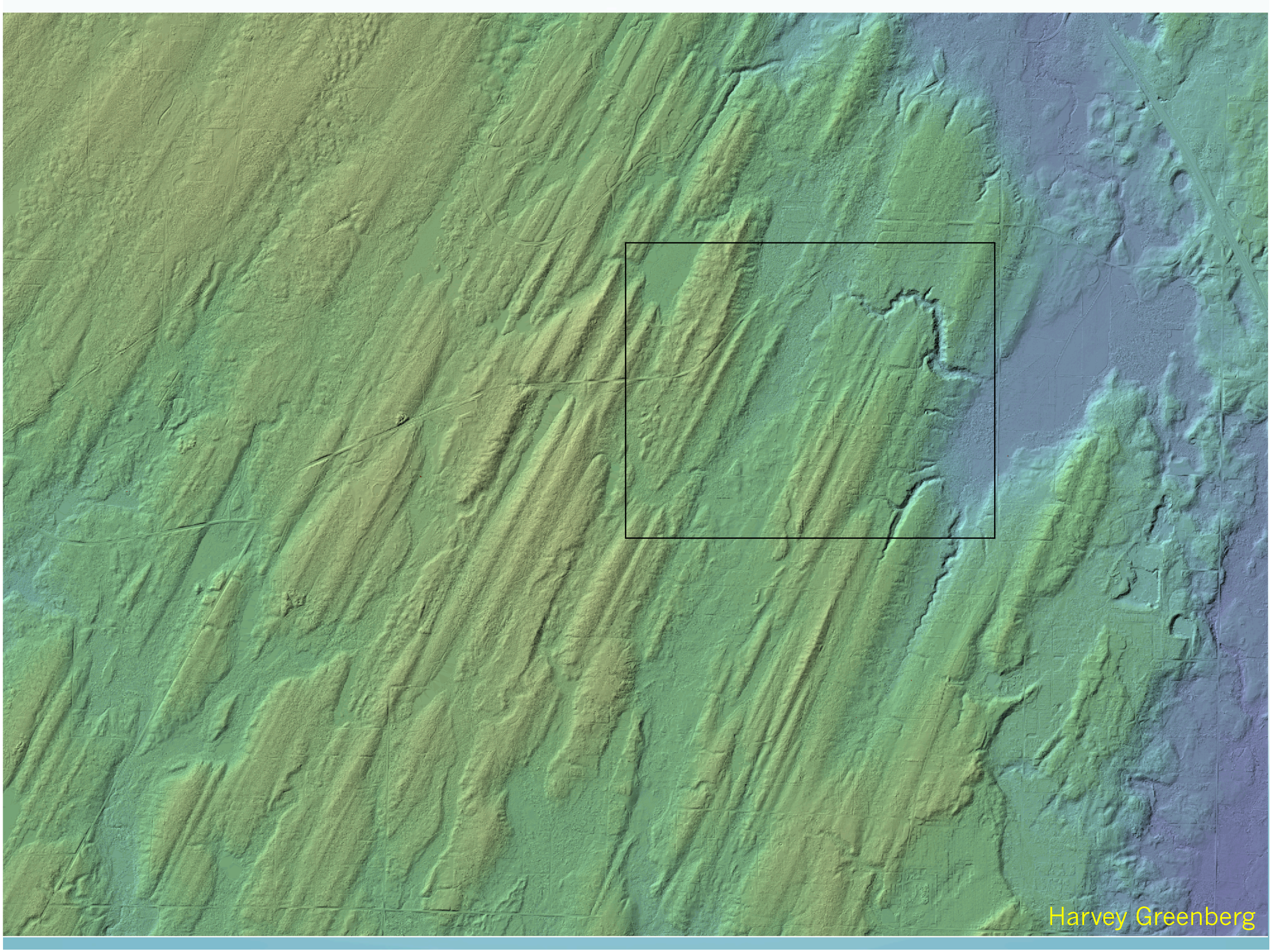


Figure 1. Location of Seattle, Puget Lowland, and most recent ice limit (shown by hachure marks) in Washington State (modified from Booth et al., 2004b).

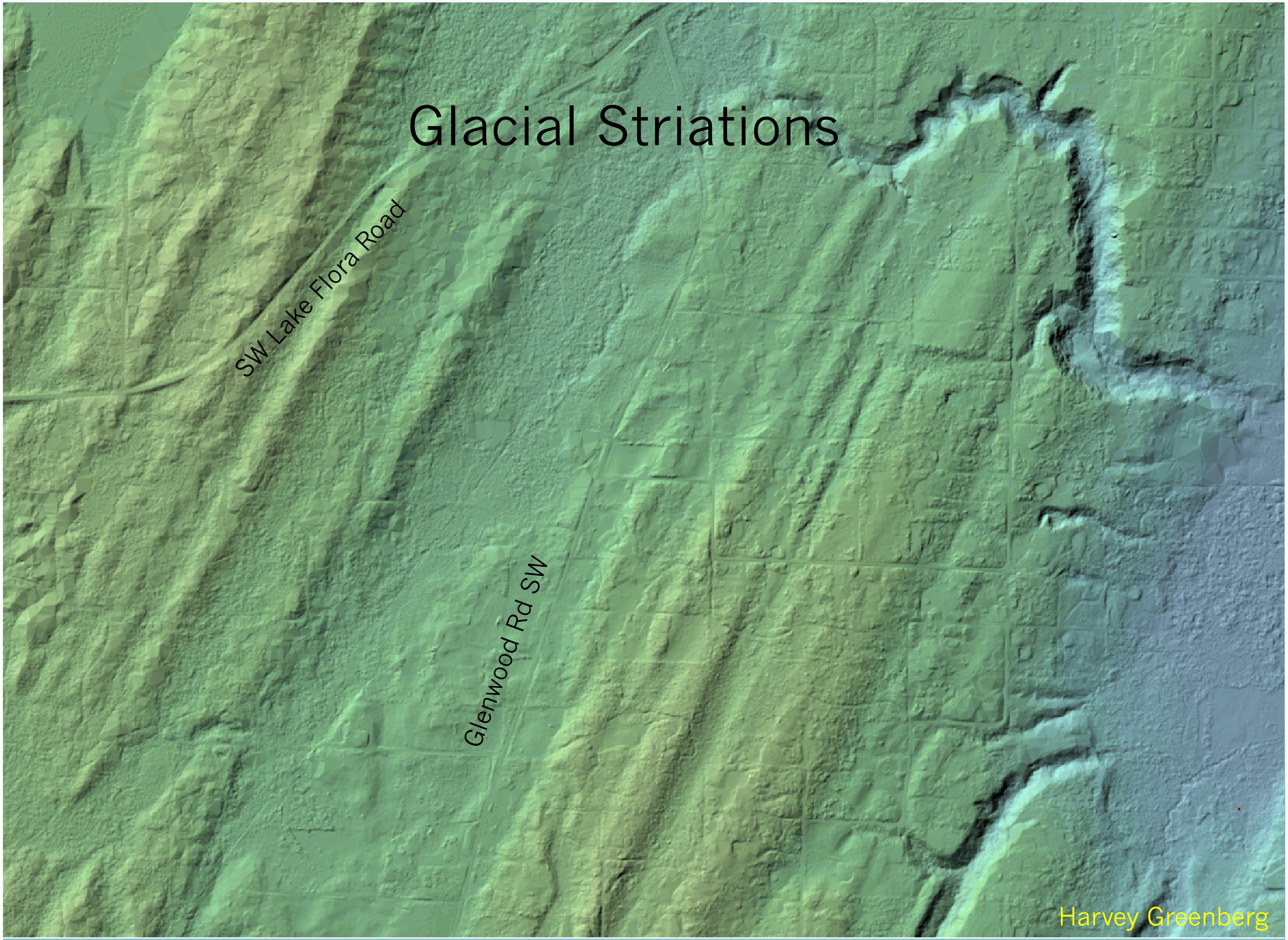
From Troost & Booth 2008


What does an ice age look like?
The Puget Sound Lobe
Seattle
Harvey Greenberg

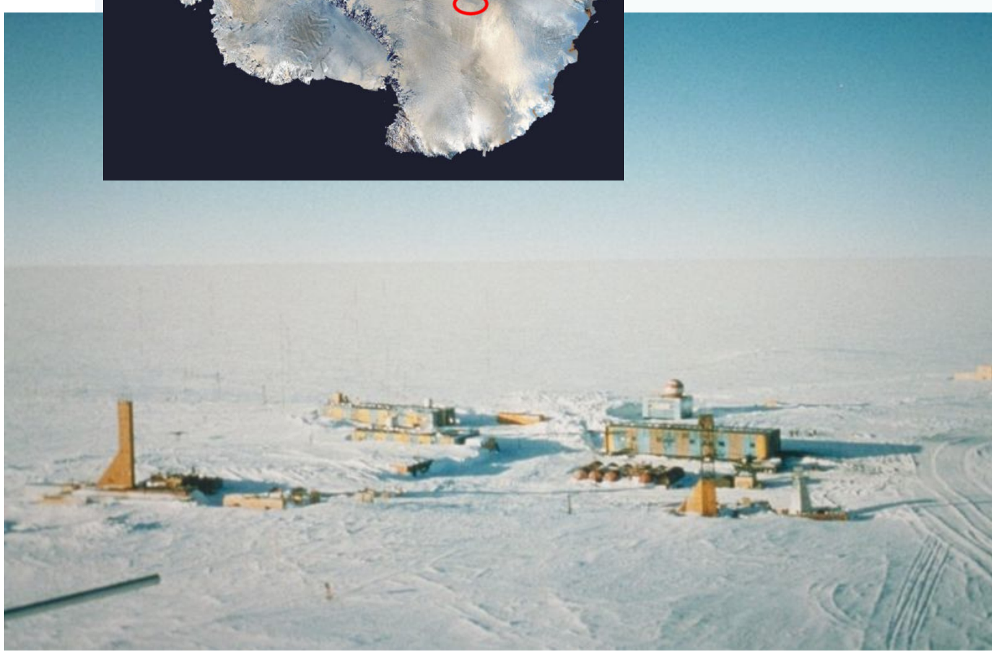

Bremerton
Harvey Greenberg

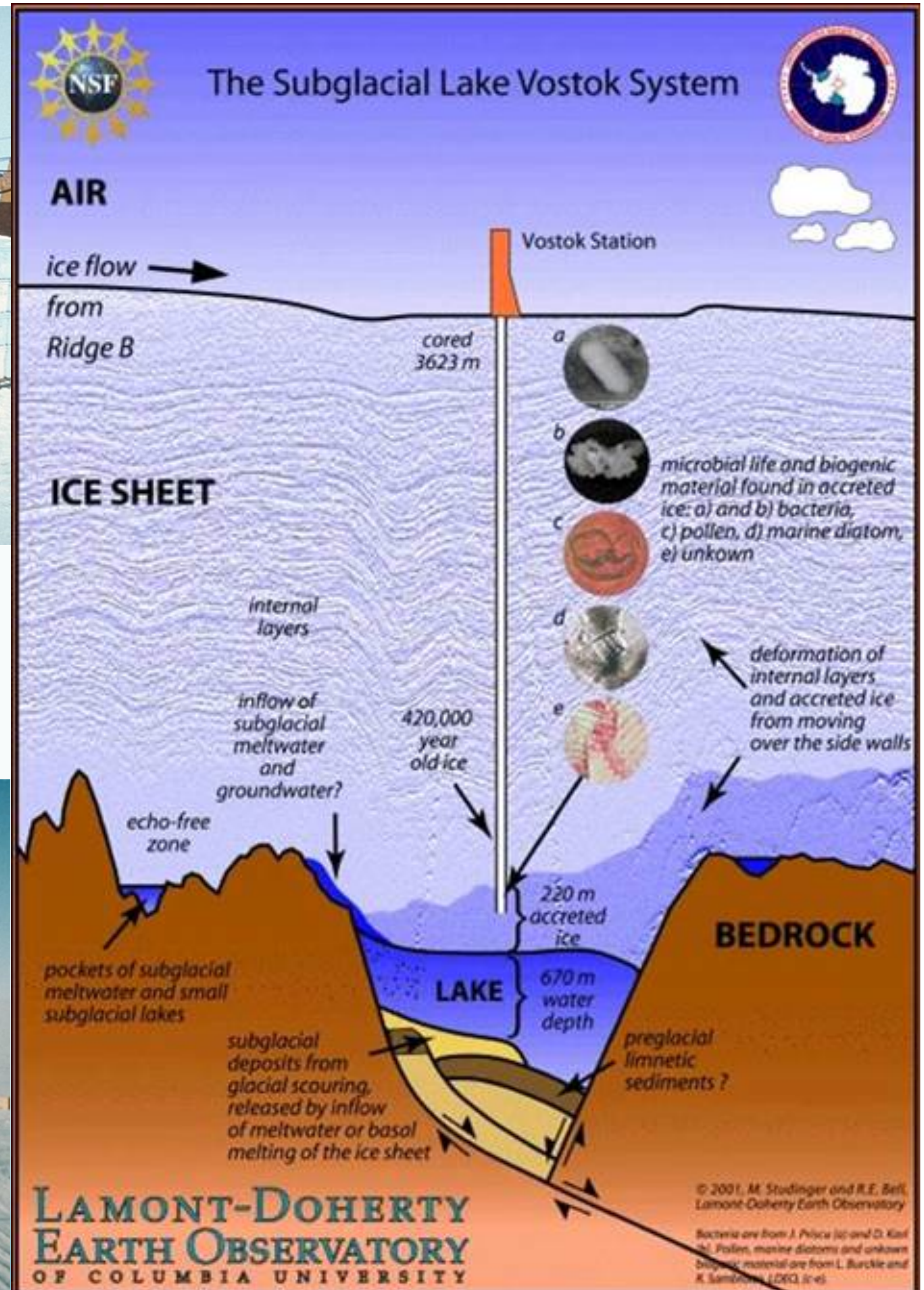

Harvey Greenberg

Glacial Striations

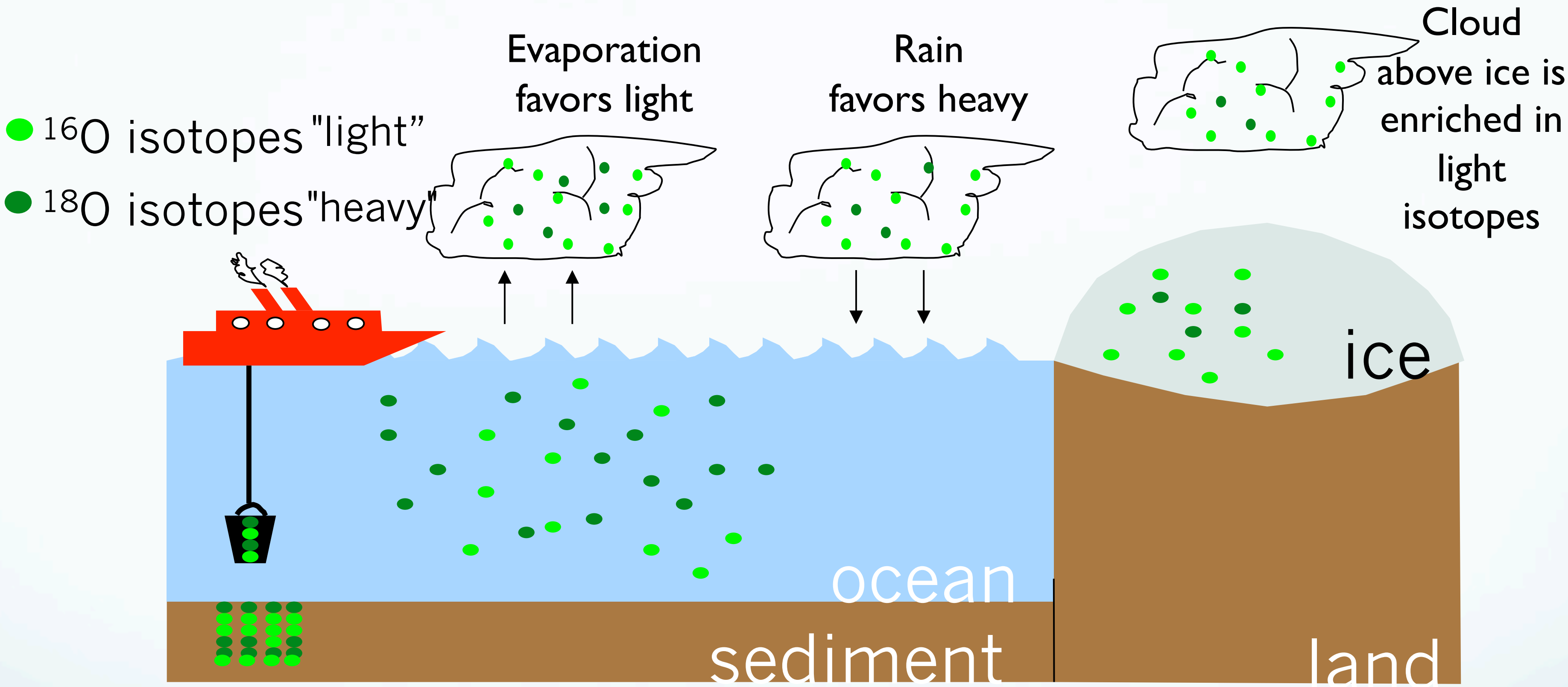


Vostok Station





Isotopic Evidence

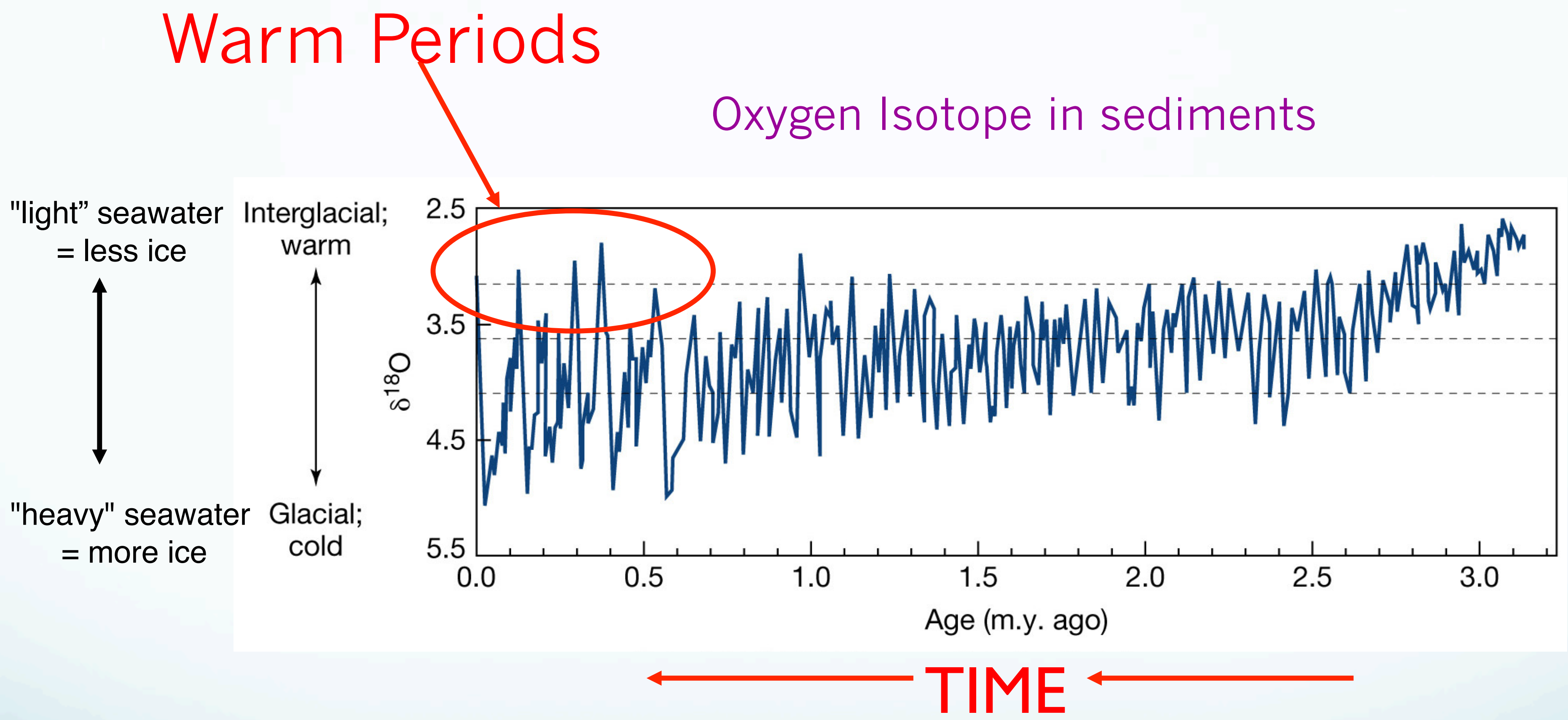


Two immensely valuable consequences:

Isotopes in ocean sediments records glacial ice volume

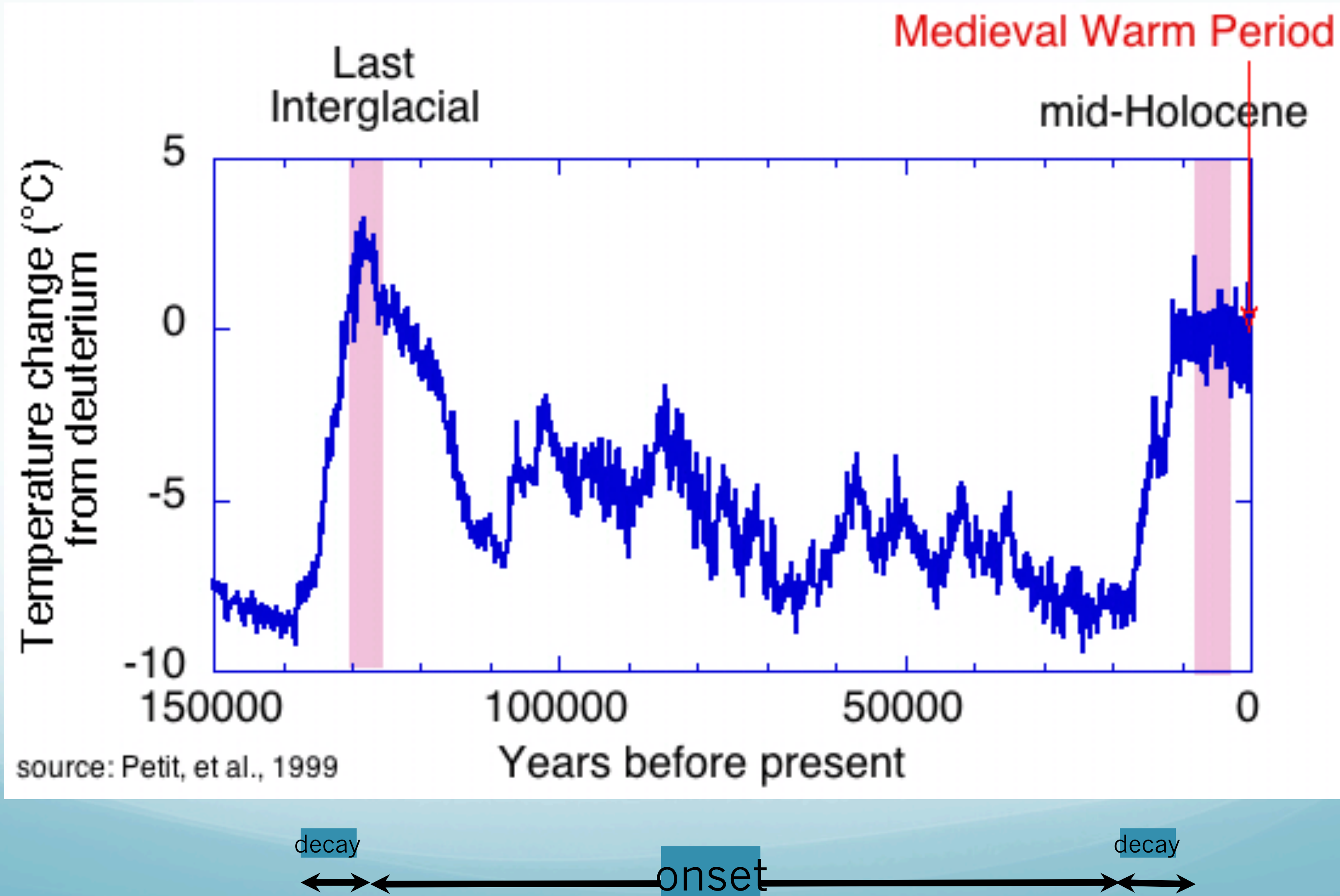
Isotopes in ice-cores indicates local temperature

3 Million Year Record of Global Ice Volume



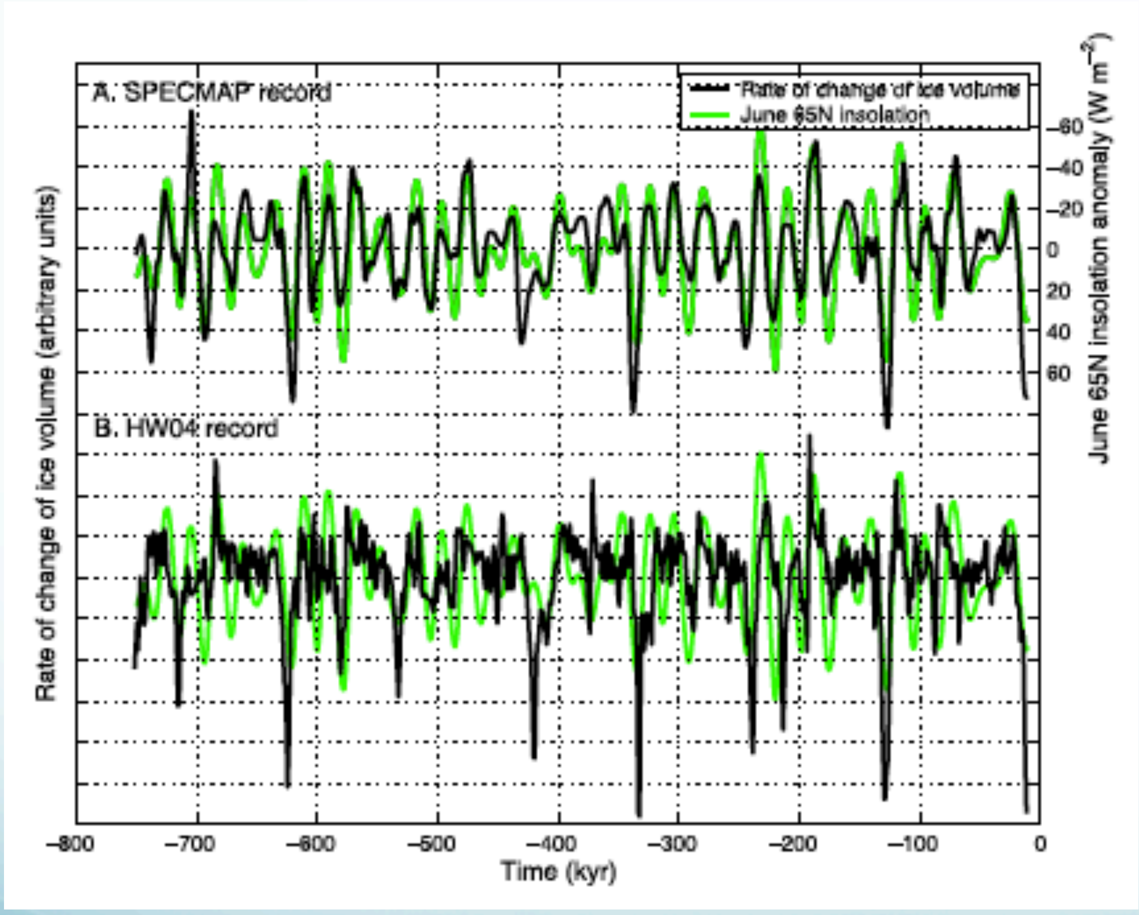
Kasting et al

Glacial epochs have a slow onset and a **rapid decay**, suggesting that ice dynamics may play a role in the decay process. That's one reason scientists are closely watching the behavior of the Greenland ice sheet



Theory of the Ice Ages:

Orbital induced solar radiation changes and global ice volume



Most continents that can grow ice sheets are in the Northern Hemisphere.

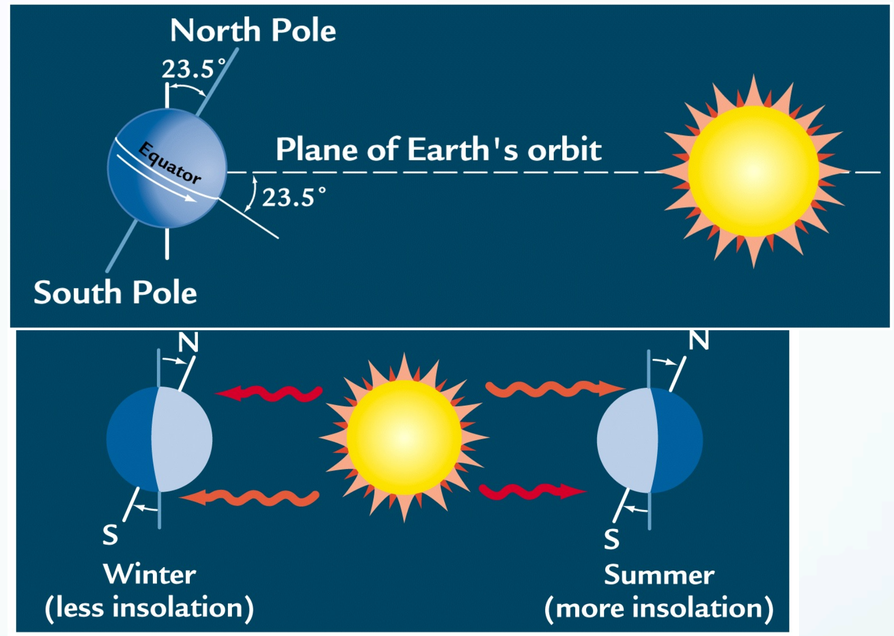
But if summers are too warm, the ice will melt back; ice sheets are hard to grow.

Hence, the amount of sunlight in Northern Hemisphere summers is key.

Orbital Variations and Sunlight

Obliquity or Tilt

- Tilt angle is presently 23.44°
- Tilt is the main reason why we have seasons

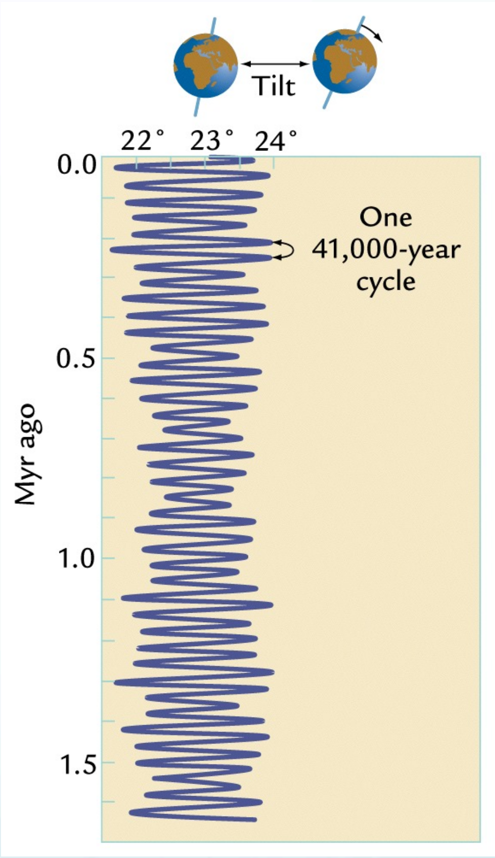


If tilt increases would our summers be warmer or cooler?

Orbital Variations and Insolation

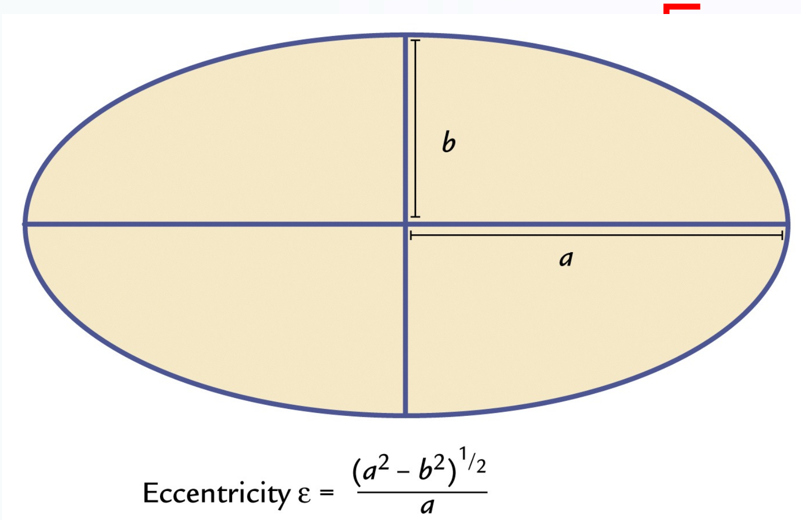
Obliquity or Tilt

- Tilt of axis of rotation varies from 22.5 ° and 24.5 °.
  - Dominant period of 41 kyr
- Higher tilt makes summers hotter and winters colder, especially in high latitudes
- We are currently in the middle at the road, but tilt is decreasing and will reach its minimum in ~8,000 yrs



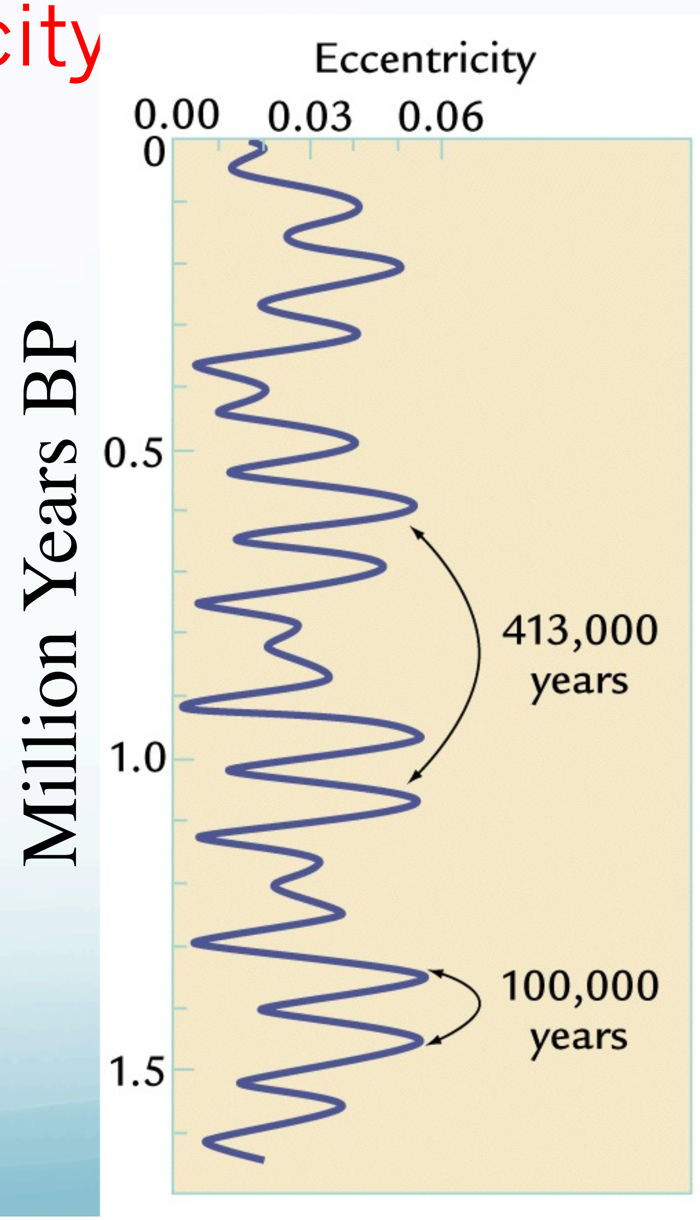
Orbital Variations and Insolation

Eccentricity

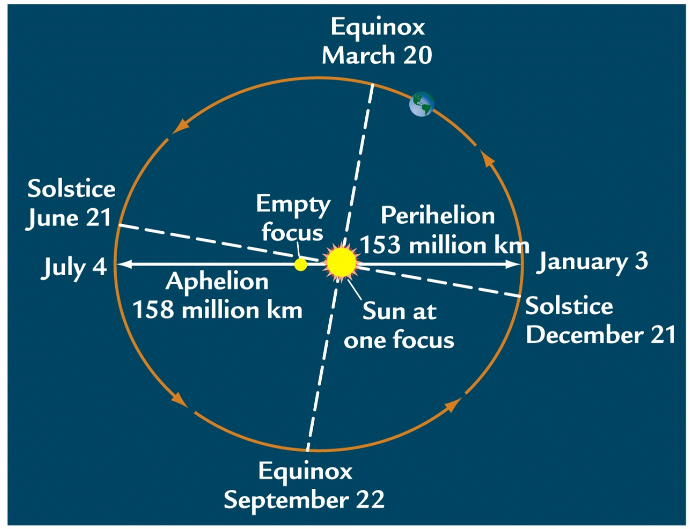


- Eccentricity: Lower is more circular and higher is a more elongated ellipse

- Varies on long timescales, primarily 100k and 413k years

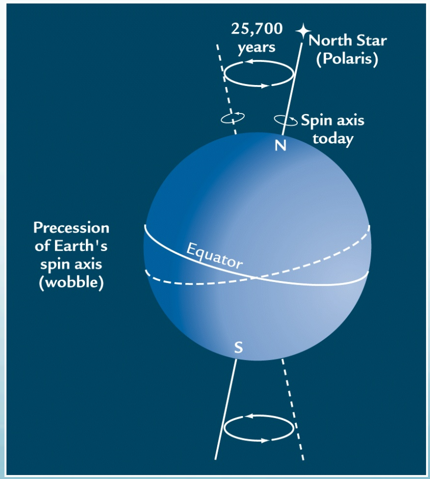


Orbital Variations and Insolation:
Precession

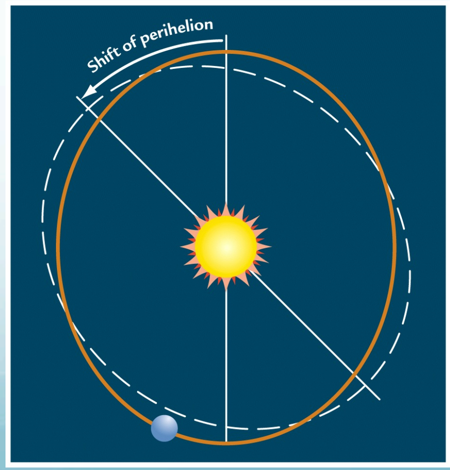


Presently Earth is closest to the sun during NH winter, which makes the NH seasons slightly less extreme.

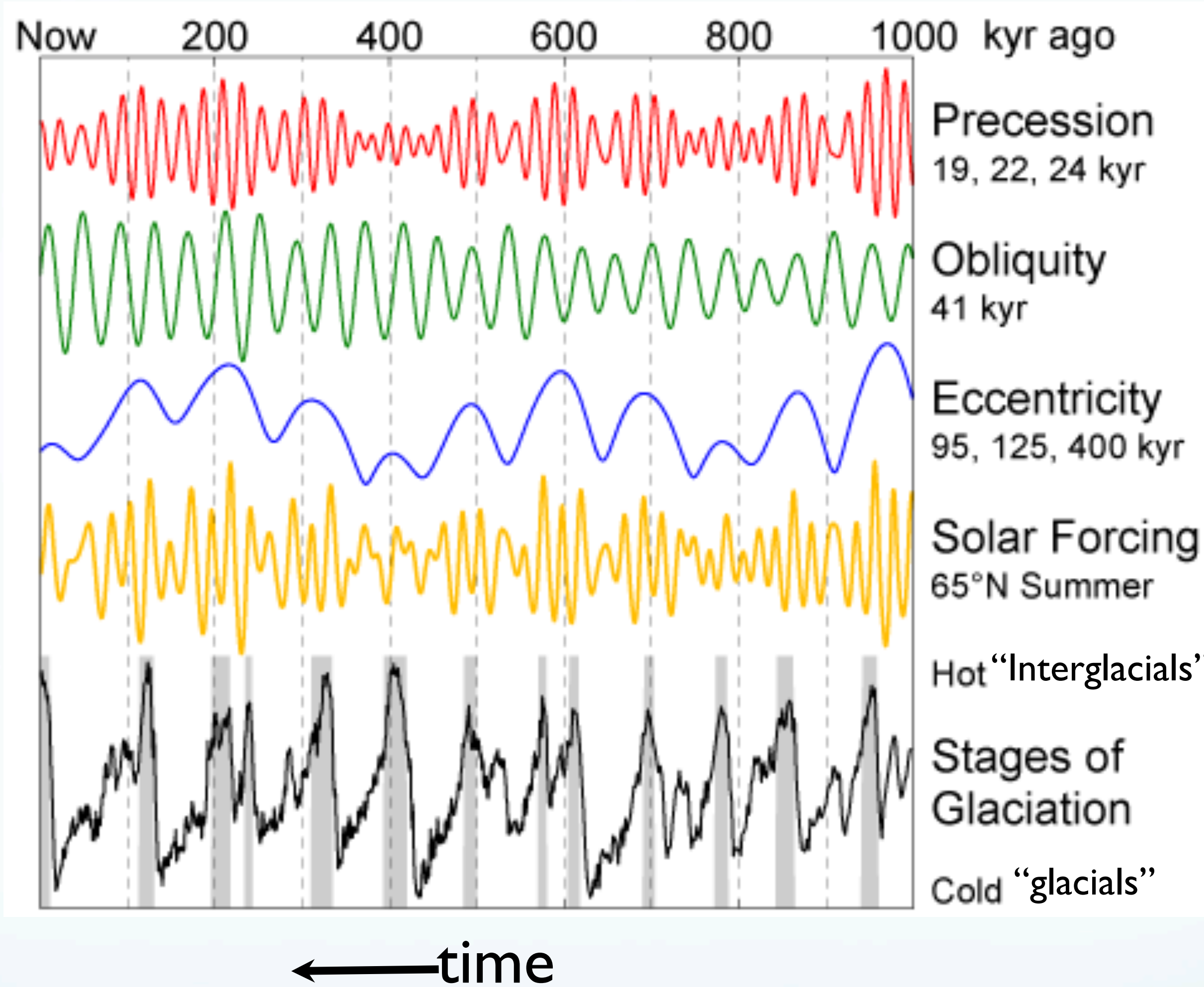
Wobble



Precession of Ellipse



Is Earth's current precession state favorable for glaciation?

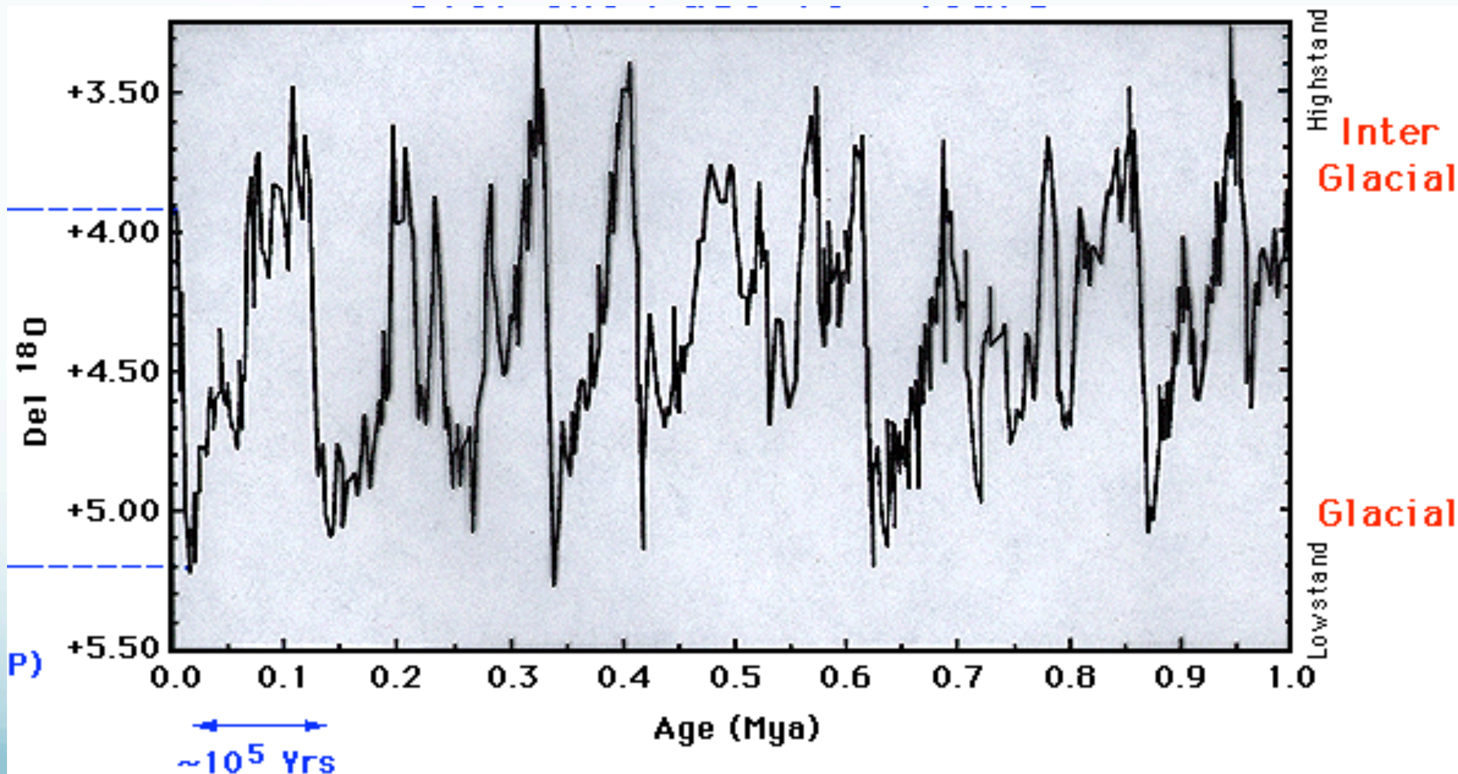


The colored curves represent the strength of the radiation incident on high latitudes of the NH during summer due to each of the three kinds of orbital variations. When the combined effect is such that the radiation is weak, winter snow can remain unmelted through the summer, building a continental ice sheet.

Summary: orbital changes on insolation

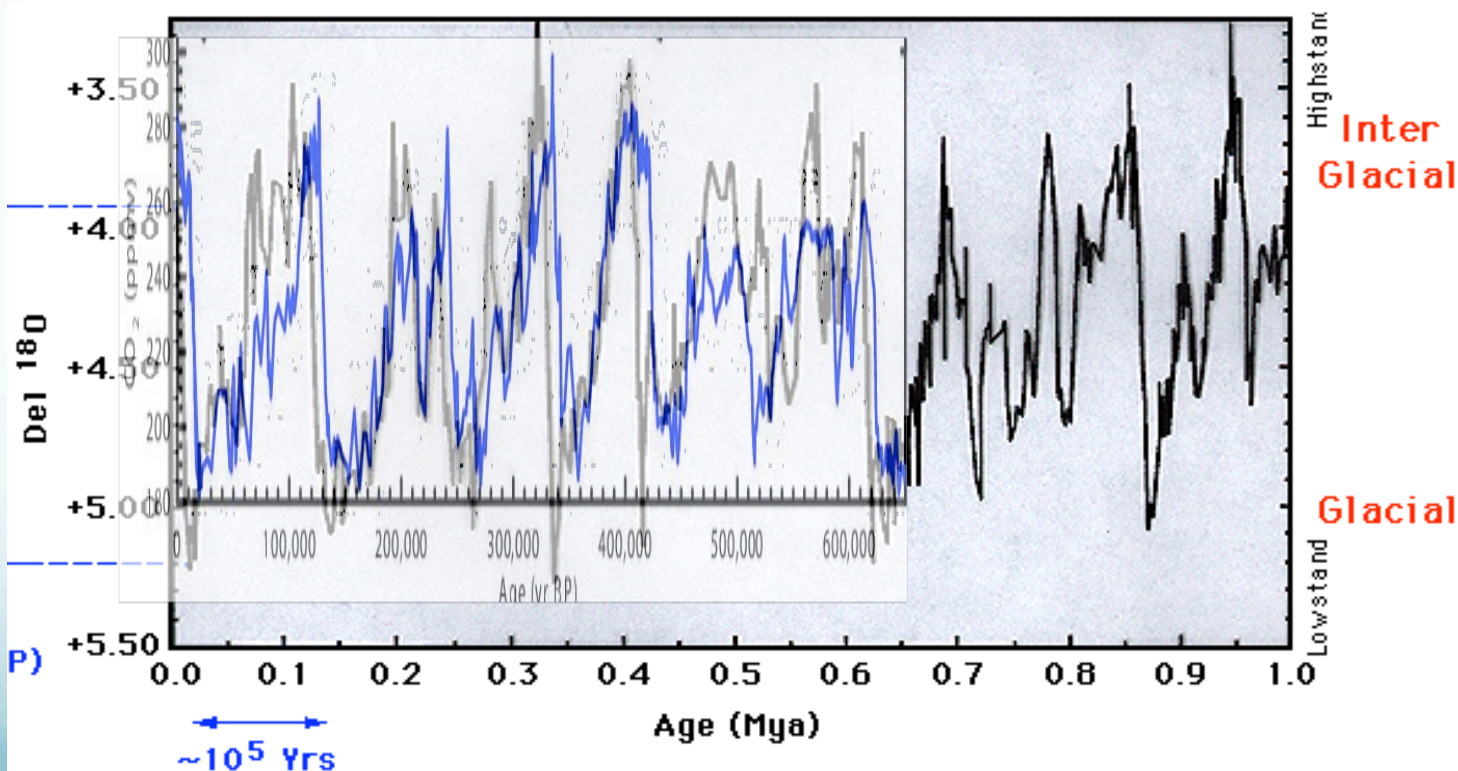
- Tilt and precession can act together to reduce northern hemisphere summer sunlight and make conditions favorable for glaciation (double whammy on ice volume).
- For example, right now the precession cycle makes cool summers in the NH, which favors glaciation. Tilt is in between extremes but it is declining, but will eventually favor glaciation in ~8,000 yrs.
- Only eccentricity can change the global, annual average insolation by about .18%, or 5 Wm^{-2}.
- Compare this to ~2.5 Wm^{-2} for the radiative punch from anthropogenic GHG to date.
- By the end of this century, will humans totally dominate the signal from orbital changes?

The Ice Age Cycles:
Some big unsolved questions

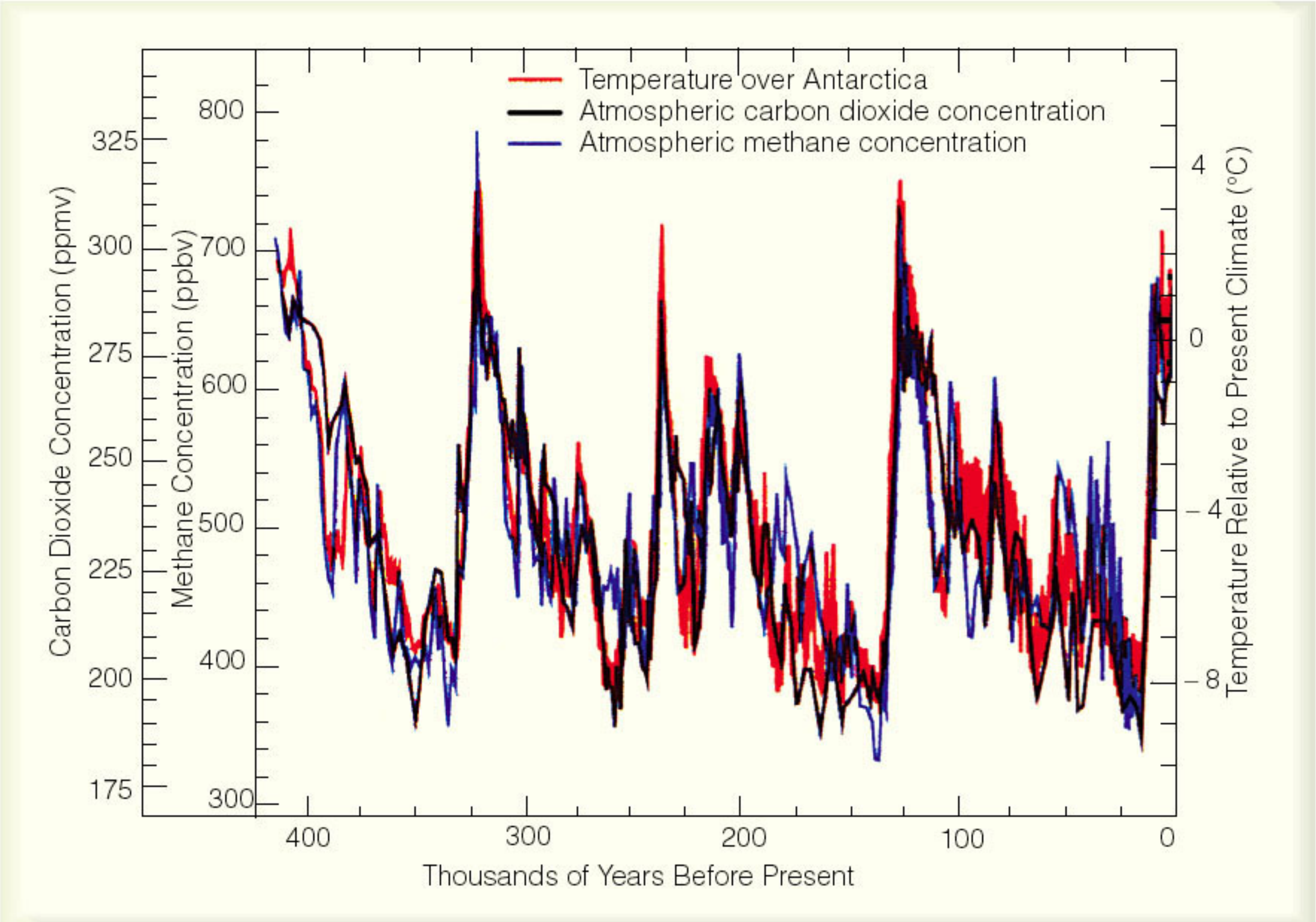


The Ice Age Cycles:
Some big unsolved questions

Why is CO_2 so highly correlated with ice volume?



Why is CO_2 even more highly correlated with Antarctic temperature?



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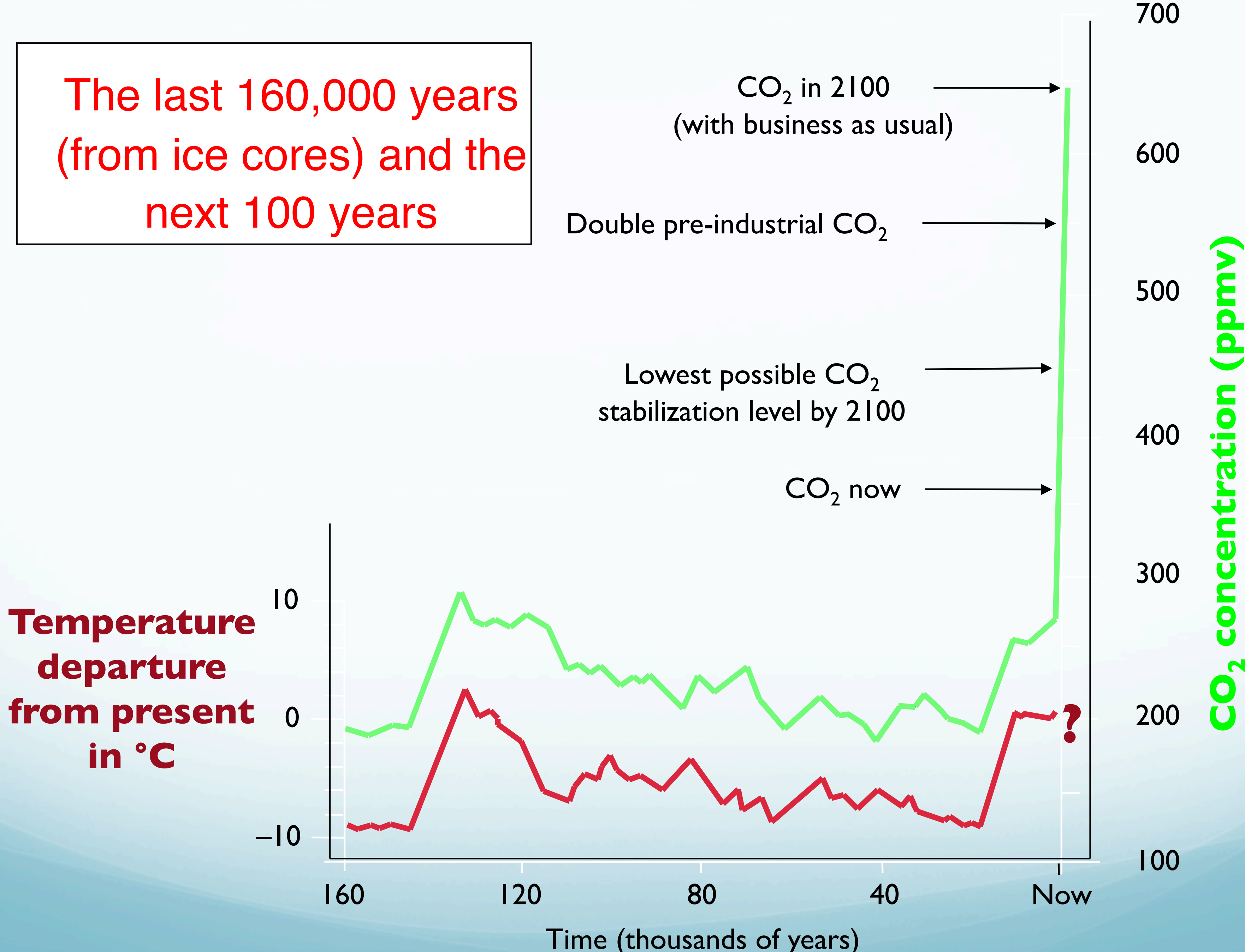
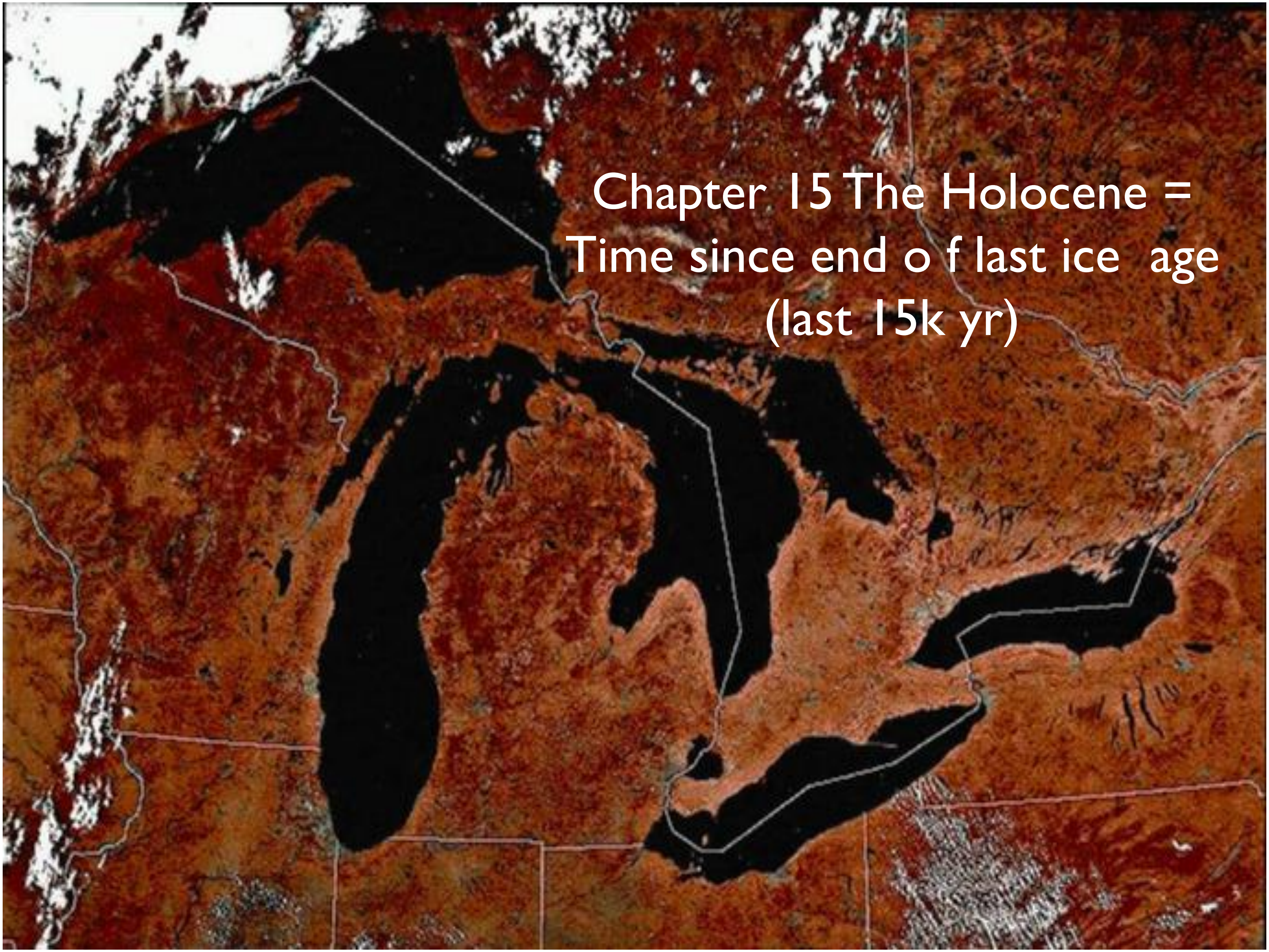
A simple (but incomplete) answer:

Colder oceans can dissolve more atmospheric CO_2

The last 160,000 years (from ice cores) and the next 100 years



Chapter 15 The Holocene = Time since end o f last ice age (last 15k yr)



The Holocene Epoch

About 15,000 years ago, the earth began to warm* and the huge ice sheets began to melt. This had a number of impacts:

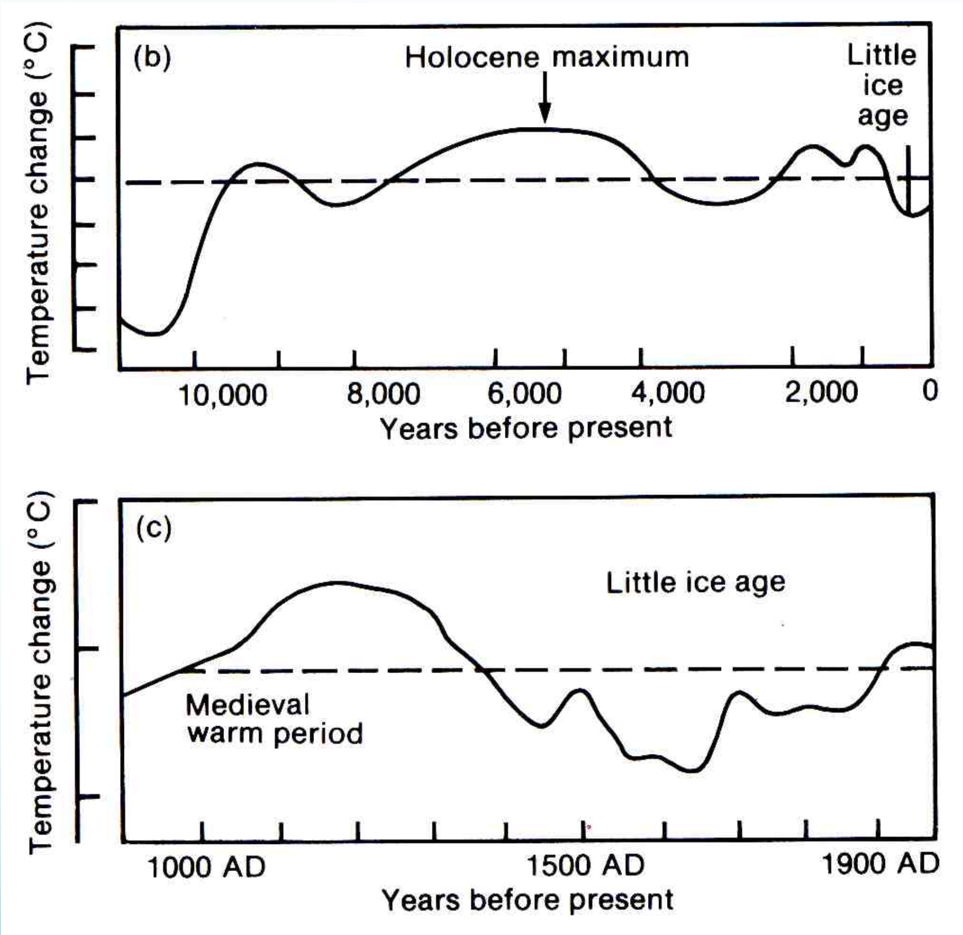
(1) lake formation in regions left behind by glaciers

(2) sea level rise

(3) Vegetation expanded

*warming leads CO2 rise

IPCC 1990



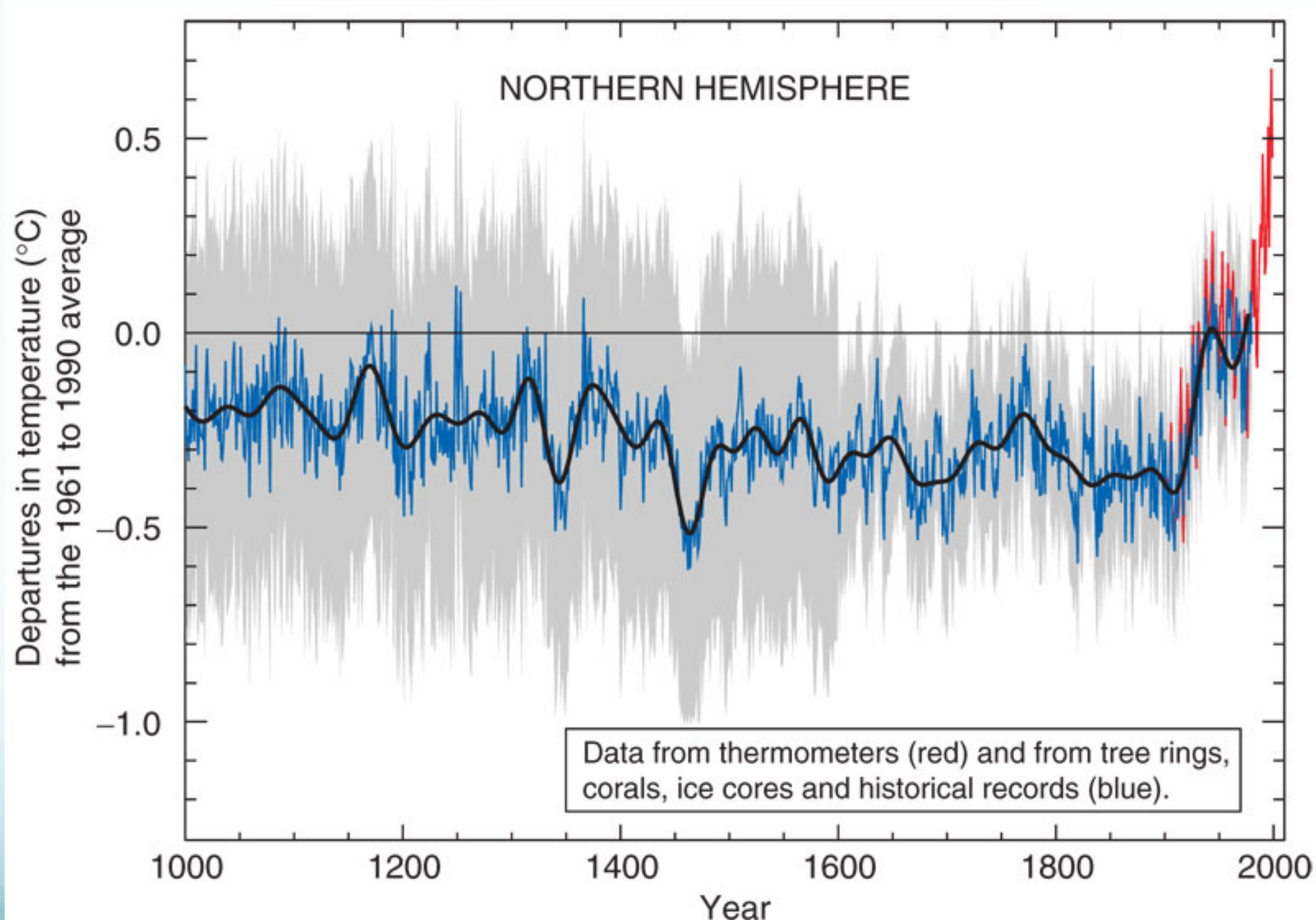
looking back at the history of global temperature

Note that there are no numbers on the temperature scales (these are just schematics)

Little Ice Age: 1600 AD
Medieval Warm Period: 1200 AD

These were probably due to changes in solar intensity (sunspot cycle) and volcanic activity. However, it is not certain how global these recent climate changes were.

IPCC 2001


NORTHERN HEMISPHERE
0.5
0.0
–0.5
–1.0
Departures in temperature (°C) from the 1961 to 1990 average
Data from thermometers (red) and from tree rings, corals, ice cores and historical records (blue).
1000
1200
1400
1600
1800
2000
Year

Summary

- May have been multiple snowball Earth events over 500 million years ago.
- After this, the Earth was generally warmer than it is today. High volcanism may have put more CO_2 in the atmosphere than is naturally there today.
- Rapid warming may have caused many of the extinctions at the end of the Permian 250 million years ago.
- 60 million years ago, high latitudes were warm enough that alligators could live on Ellesmere Island (80° N).

Summary

- About 3 million years ago, Earth began to cool, possibly due to removal of CO_2 by weathering of Himalayas
- The Ice Age is characterized by glacial periods, with large continental ice sheets, and interglacial periods with fewer ice sheets (right now).
- Changes in Northern Hemisphere sunlight is key to the ice ages.
- CO_2 provides a positive feedback – colder oceans dissolve less CO_2, enhancing the cooling.

Summary

- Since the last glacial maximum, the Holocene has been relatively stable climatically.
- Variability in solar intensity and volcanic activity could have created the Medieval Warm Period and the Little Ice Age.
- The expected warming by 2100 due to anthropogenic greenhouse gases is as large in amplitude as the difference between a glacial and interglacial time.