Isotopes

EES 2110

Introduction to Climate Change

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Wrapping Up Carbon Cycle

CO_2 vs. Methane

- CO_2:
  - After 1000 years, around 30% of excess CO_2 remains in atmosphere
  - After 10,000 years, 13% remains
  - After 100,000 years, 6% remains
- Methane (CH_4):
  - 31 times more powerful (molecule-for-molecule) than CO_2
  - Reacts with OH^- (hydoxyl radicals) and oxidizes into H_2O and CO_2.
  - Atmospheric lifetime: 9.6 years:
    - After 25 years, 7% remains.
    - After 100 years, 0.003% remains.

- When we reduce methane emissions, atmospheric methane drops quickly
- When we reduce CO_2 emissions, CO_2 continues rising, but more slowly
- When we stop CO_2 emissions altogether, CO_2 only drops slowly.

Weathering as Thermostat

Weathering as Thermostat

CO_2 is balance of volcanic outgassing and chemical weathering

- **Higher temperatures:**
  - More rain, faster chemical reactions
  - Faster weathering
  - Atmospheric CO_2 falls
- **Lower temperatures**
  - Less rain, slower chemical reactions
  - Slower weathering
  - Atmospheric CO_2 rises
- Net effect:
  - Keeps temperature stable near some “set point”
  - Set-point is determined by geology

Temperature of Earth

- Weathering acts as thermostat.
- Earth’s temperature has been remarkably stable over time.
  - 4 billion years ago, sun was 30% dimmer…
  - But there has constantly been liquid water.
- Geologic change alters thermostat “setting”:
  - Volcanic outgassing
  - Land surface (e.g., mountain ranges)
  - Vascular plants
- In the long run, silicate thermostat will fix global warming…
  - …but it will take tens to hundreds of thousands of years.

What's Causing CO_2 to Rise?

Carbon Isotopes:

Stable Isotopes: ^{12}C and ^{13}C

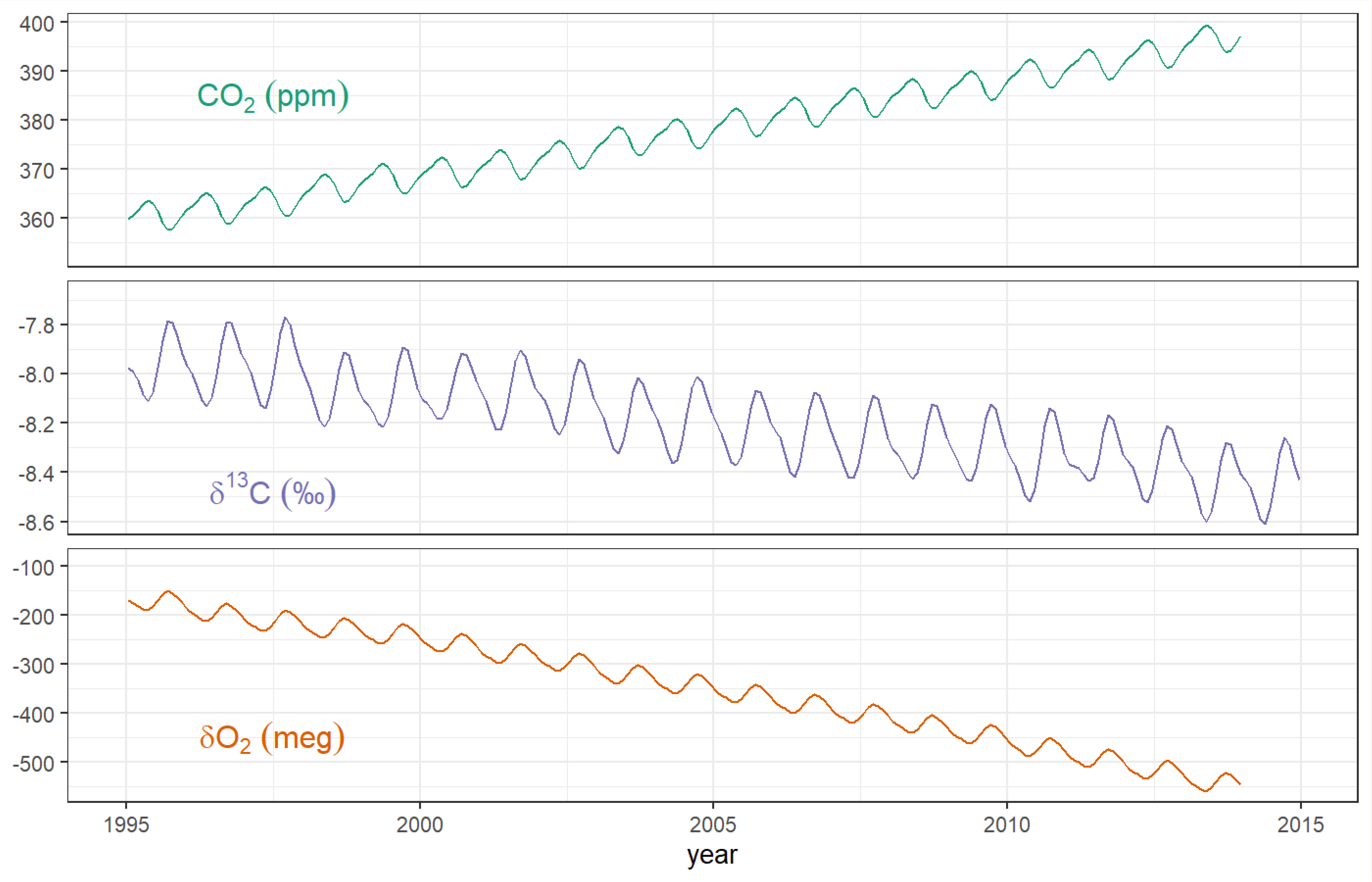
- ^{12}C: 99% of all carbon on earth
- ^{13}C: About 1%. Just like ^{12}C, but slightly heavier
  - Greater mass → slower chemical reactions
  - Molecules produced by photosynthesis have slightly less ^{13}C, more ^{12}C than the atmosphere.
- Notation:

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{\text{specimen}} - \left(\frac{^{13}C}{^{12}C}\right)_{\text{reference}}}{\left(\frac{^{13}C}{^{12}C}\right)_{\text{reference}}} \right)$$

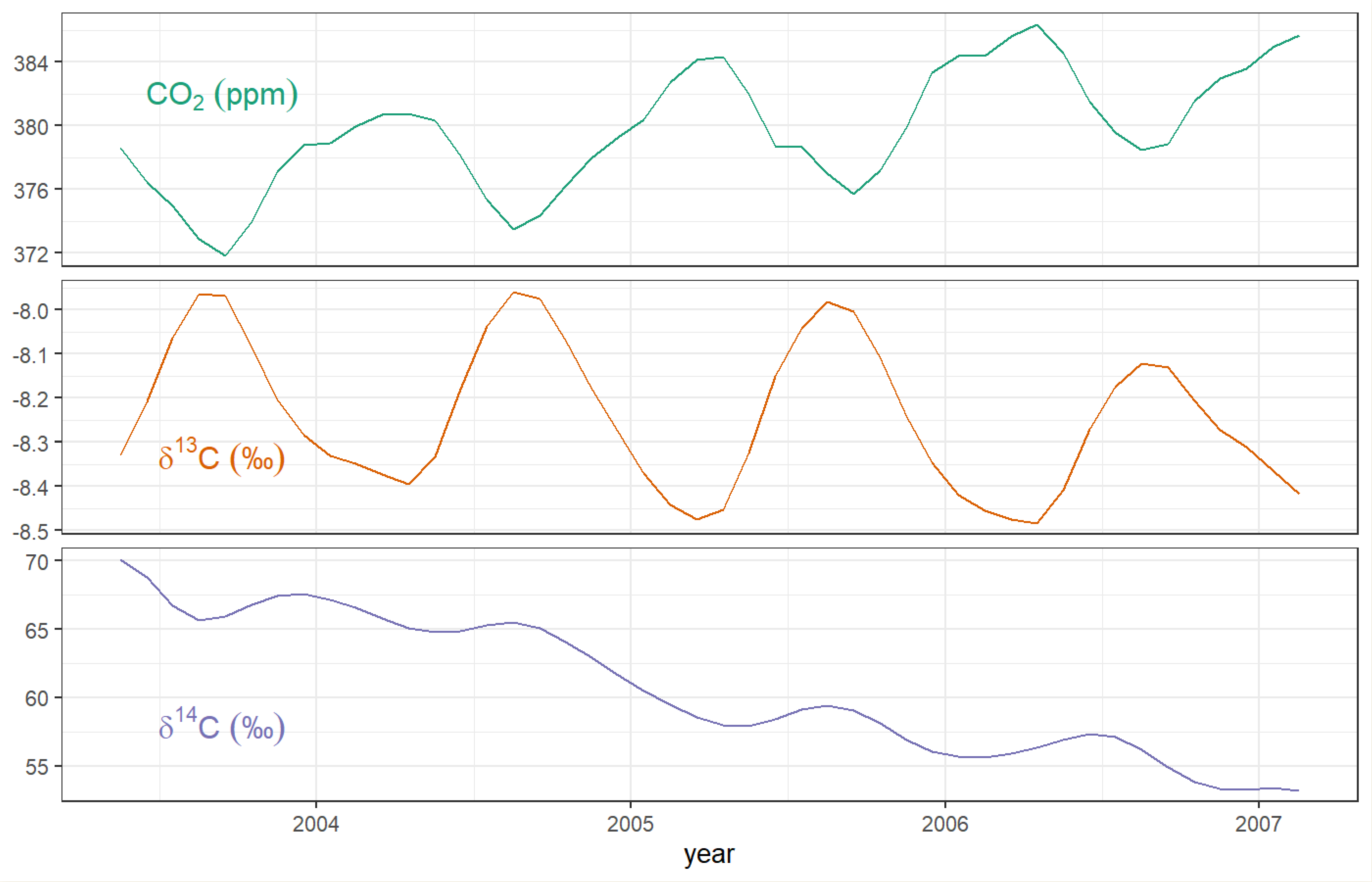
Unstable Isotopes: ^{14}C

- ^{14}C: Radioactive, unstable
  - Produced in the atmosphere by cosmic rays hitting nitrogen atoms
  - Decays from ^{14}C to ^{14}N over thousands of years
  - Every 5,500 years, half of the ^{14}C turns into ^{14}N
  - Measuring the amount of ^{14}C relative to ^{12}C in animal or plant matter tells you about the age since it died.

Evidence: O_2 and ^{13}C



Evidence: ^{13}C and ^{14}C



Fossil Fuels vs. CO_2

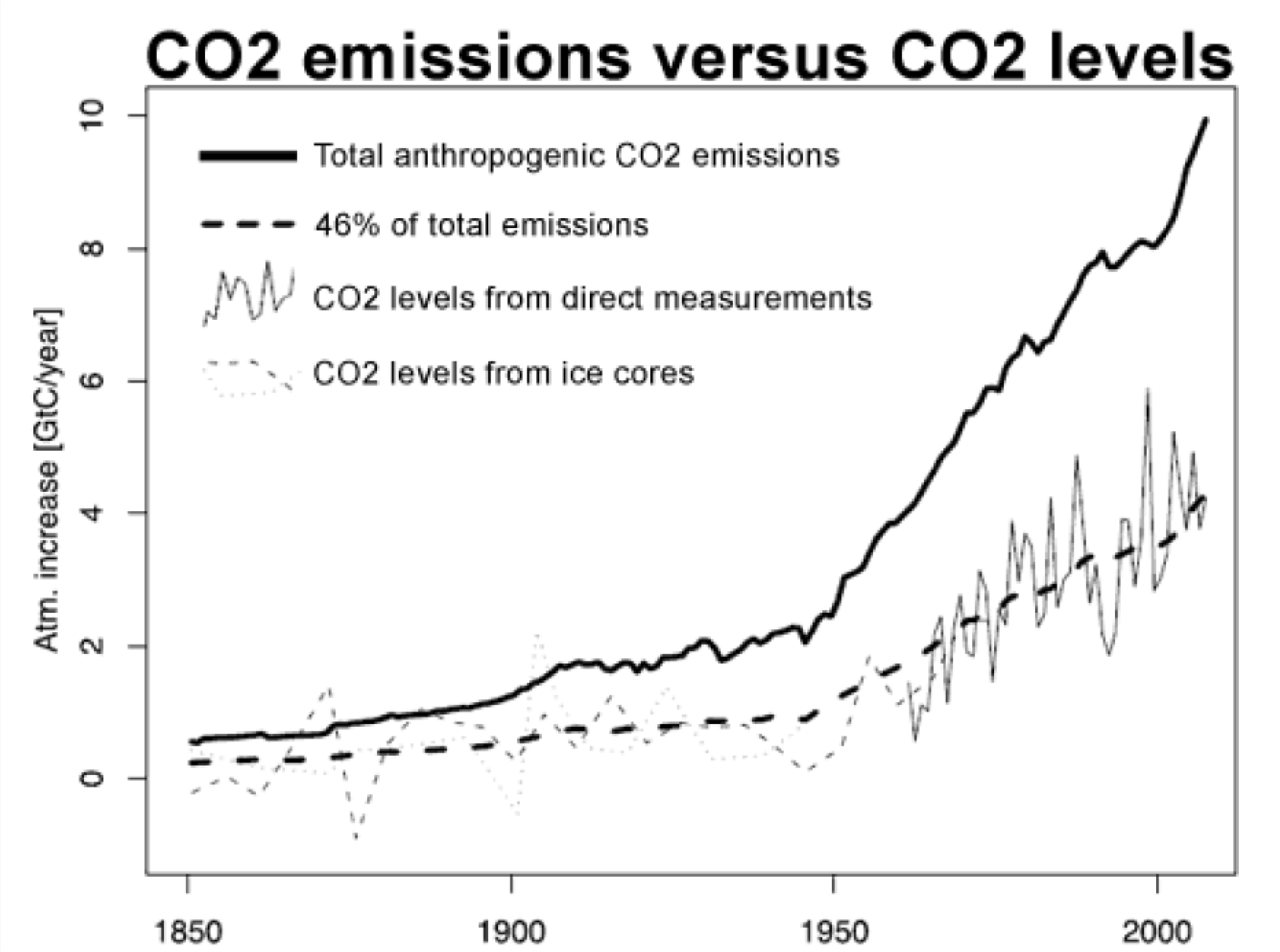


Image credit: W. Knorr, Geophys. Res. Lett. **36**, L21710 (2009) doi: 10.1029/2009GL040613

- Concentrations match 46% of fossil fuel consumption

Assessing the Evidence

- Decreasing O_2: CO_2 produced by burning or oxidizing.
  - Not a mineral source (volcanoes).
- Decreasing $\delta^{13}C$: CO_2 must have biological origin.
- Decreasing $\delta^{14}C$: The fuel must be thousands of years old.
- Possible sources:
  - Where are billions of tons per year of very old organic matter being burned or oxidized?
- Rate of rise matches fossil fuel consumption.
- **Therefore: Dominant source must be fossil fuels.**

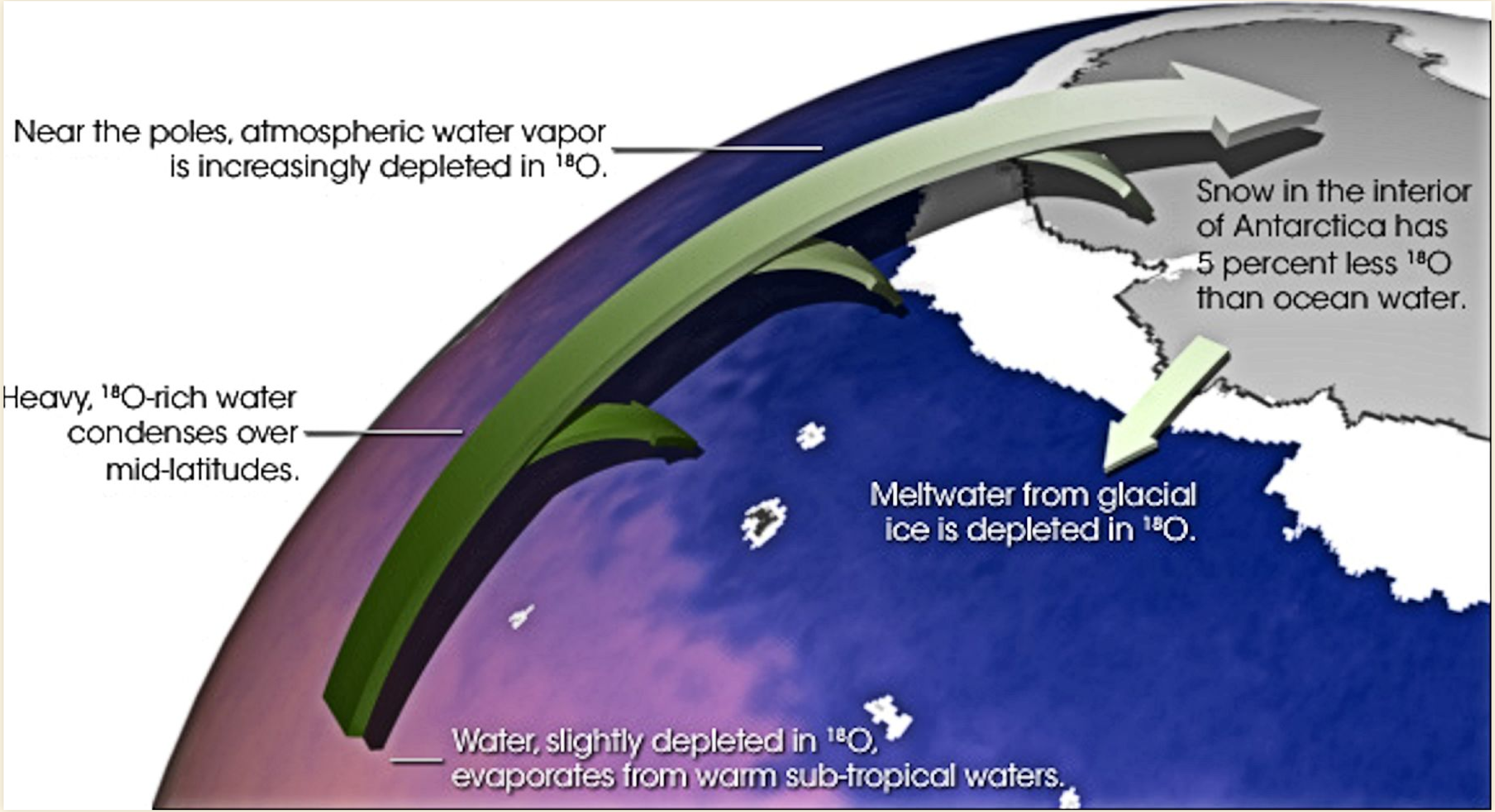
Oxygen & Hydrogen Isotopes and Past Climates

Oxygen & Hydrogen Isotopes

$$\delta^{18}\mathrm{O} = \left(\frac{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{sample}} - \left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{ref}}}{\left(\frac{^{18}\mathrm{O}}{^{16}\mathrm{O}}\right)_{\mathrm{ref}}} \right) \times 1000‰$$

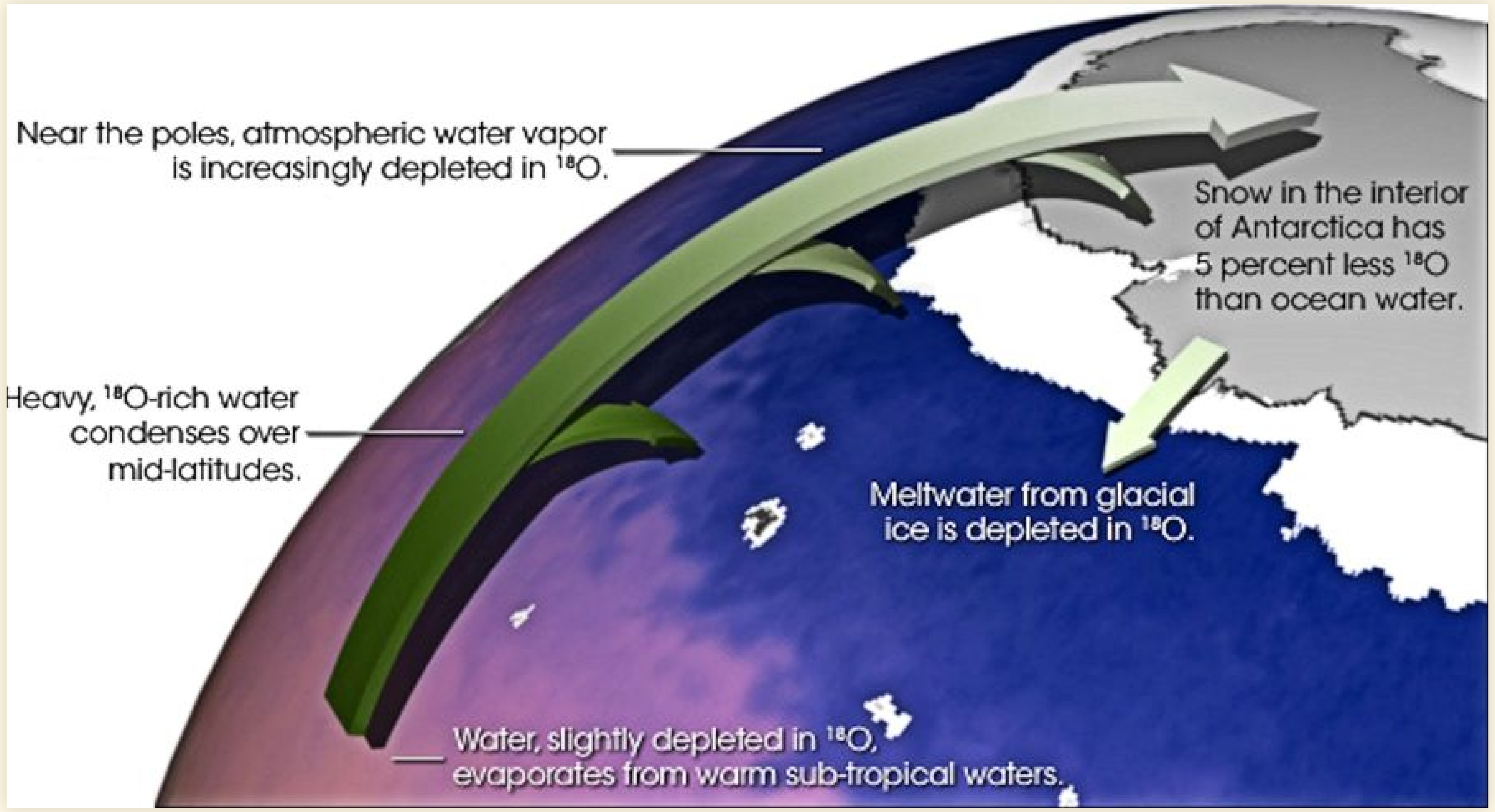
- δ^{18}O compares measured concentration of ^{18}O to the concentration in a reference sample.
- Lighter isotopes (^{1}H and ^{16}O) evaporate faster
  - Vapor has less of heavier isotopes (smaller δ^{18}O, $\delta^{2}\mathrm{H} = \delta\mathrm{D}$)
  - Ocean is richer in heavier isotopes (greater δ^{18}O, δD)
  - Warmer $\rightarrow$ greater δ^{18}O, δD in vapor

Rain, Snow, Ice



Rain, Snow, Ice

- Rain, snow are richer in heavier isotopes
  - More precipitation $\rightarrow$ less deuterium (D, ^{2}H) and ^{18}O left in vapor
  - Farther from source region $\rightarrow$ smaller δD and δ^{18}O.
- Reduction in δD and δ^{18}O depends on air temperature.
  - Different for H and O.
- Comparing δD and δ^{18}O can tell us about both sea-surface temperature and air temperature over glaciers.
- **Higher air temperature over glacier $\rightarrow$ greater δD and δ^{18}O in glacier snow/ice.**



Glacial Ice

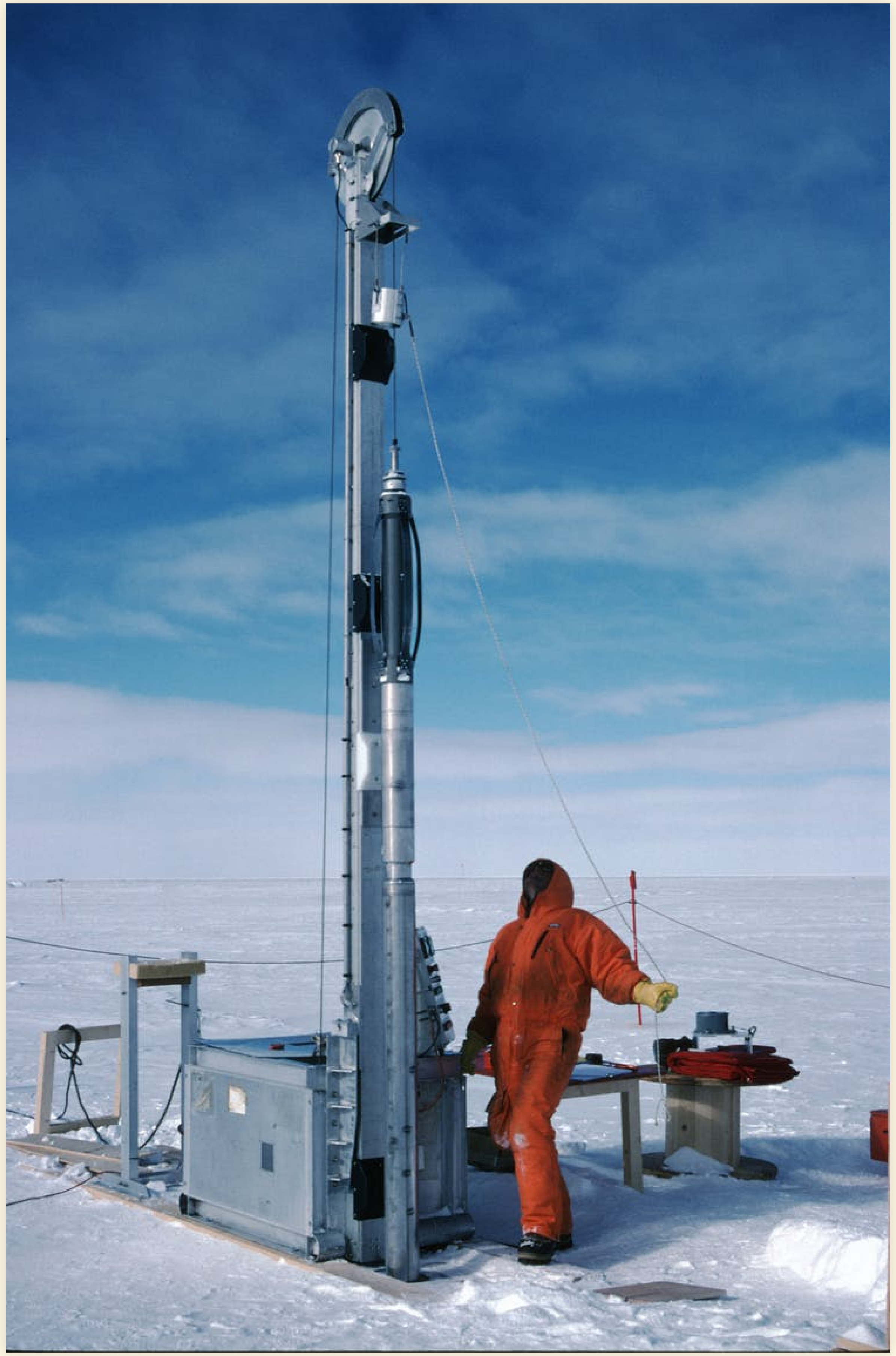


Image Credit: R Mulvaney/British Antarctic Survey

Ice Cores

Image credits: Pete Bucktrout/British Antarctic Survey

Inside the Ice Core

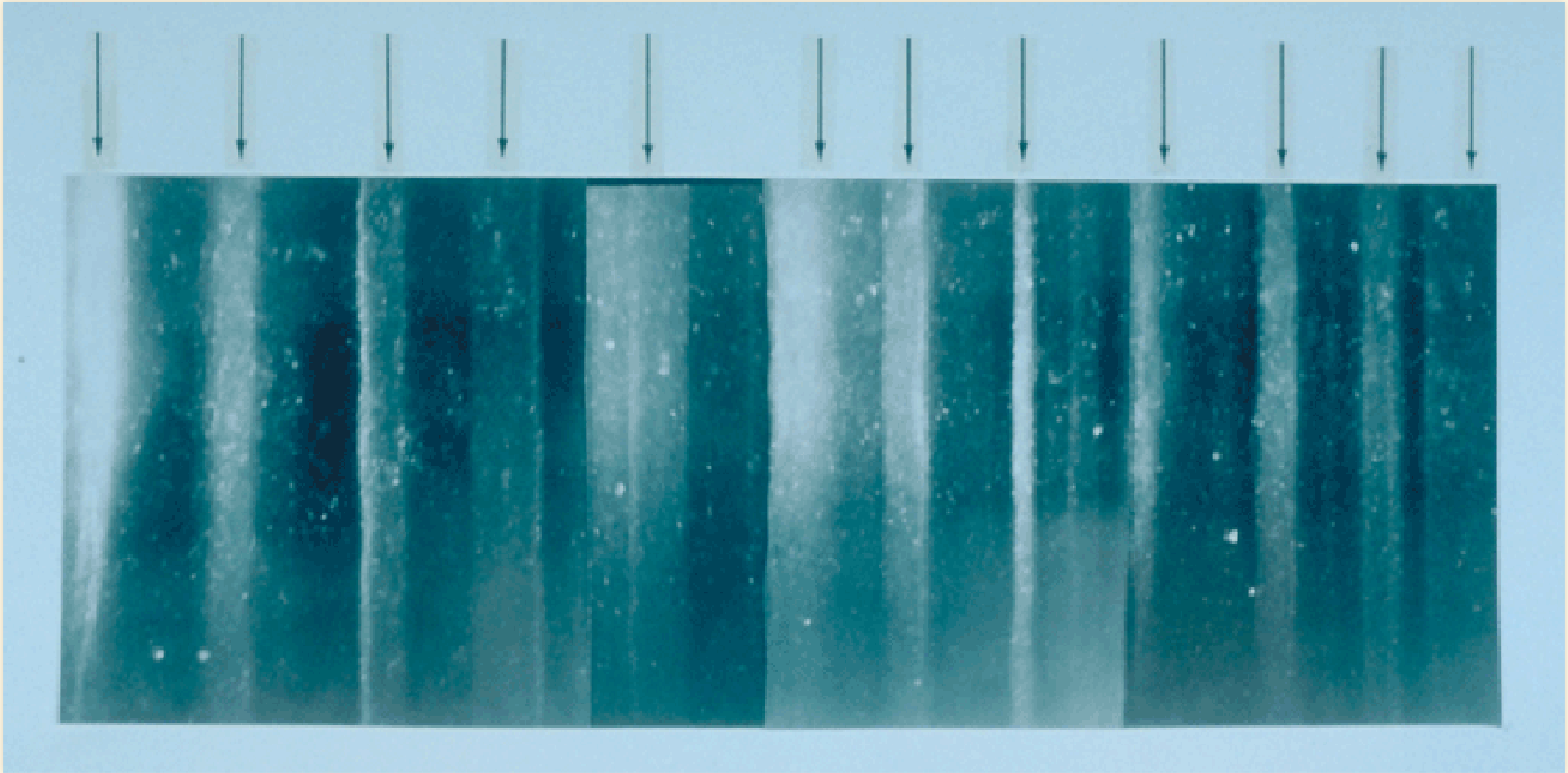
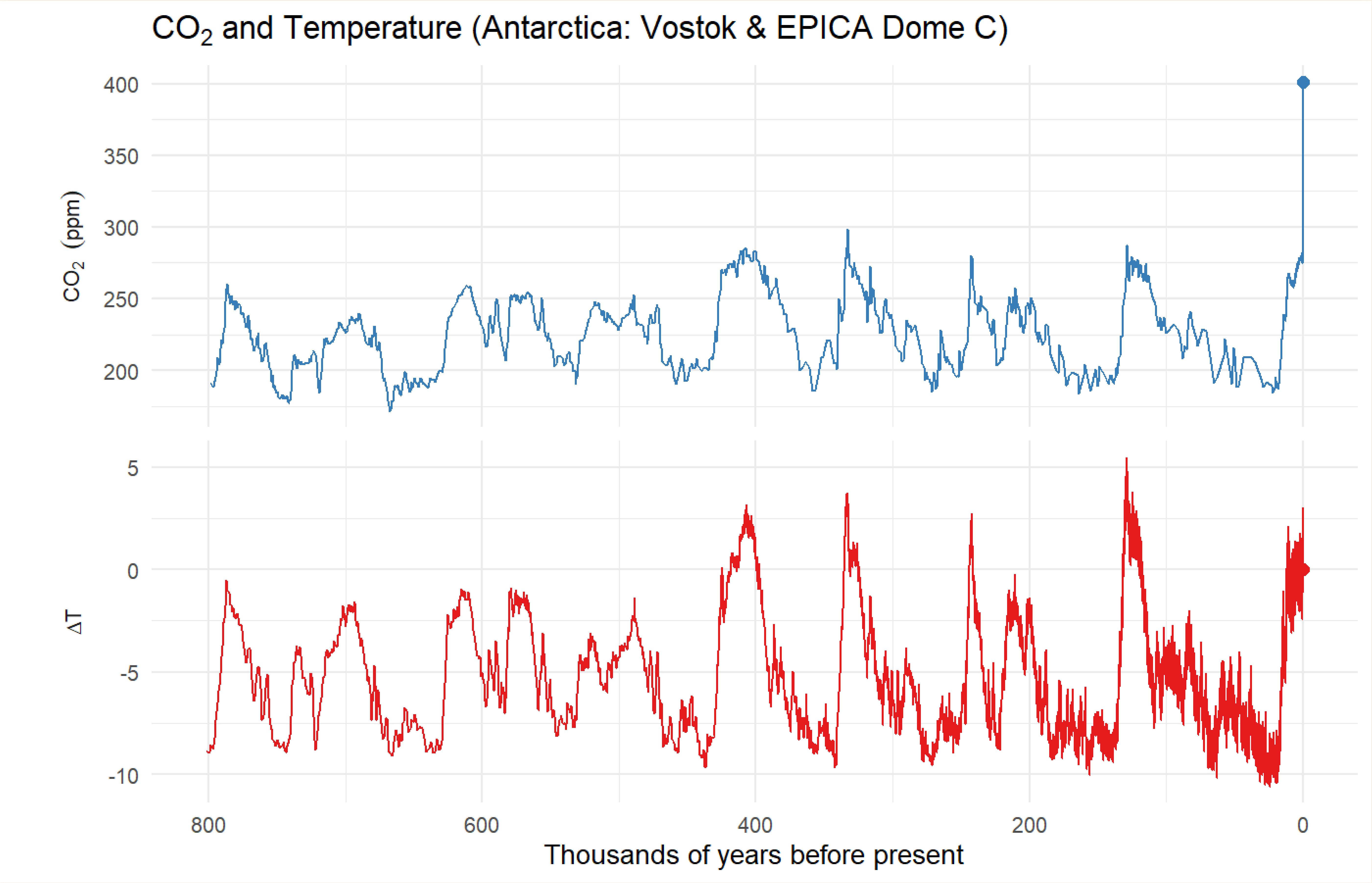
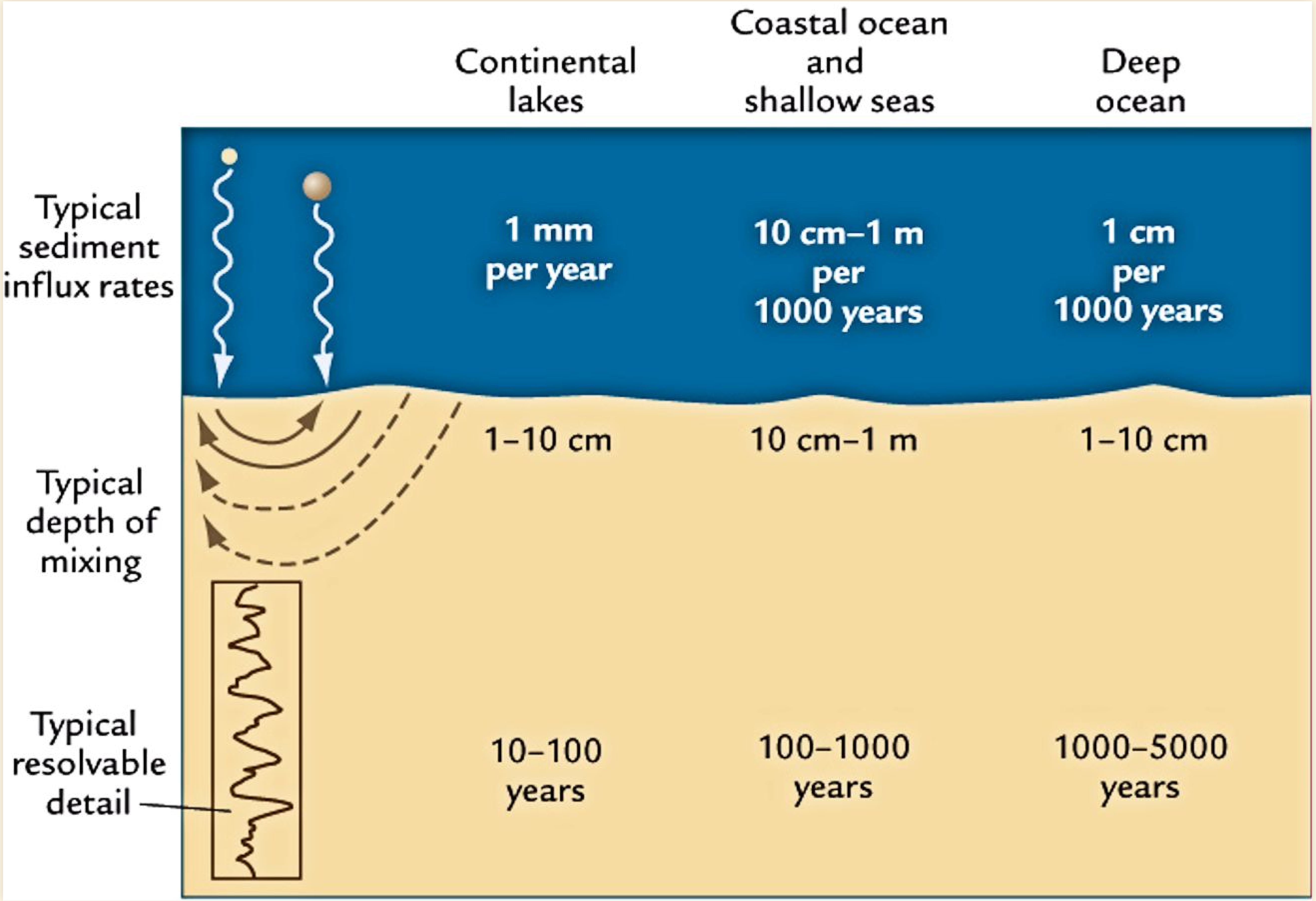


Image credit: National Ice Core Laboratory

800,000 years of CO_2 and Temperature

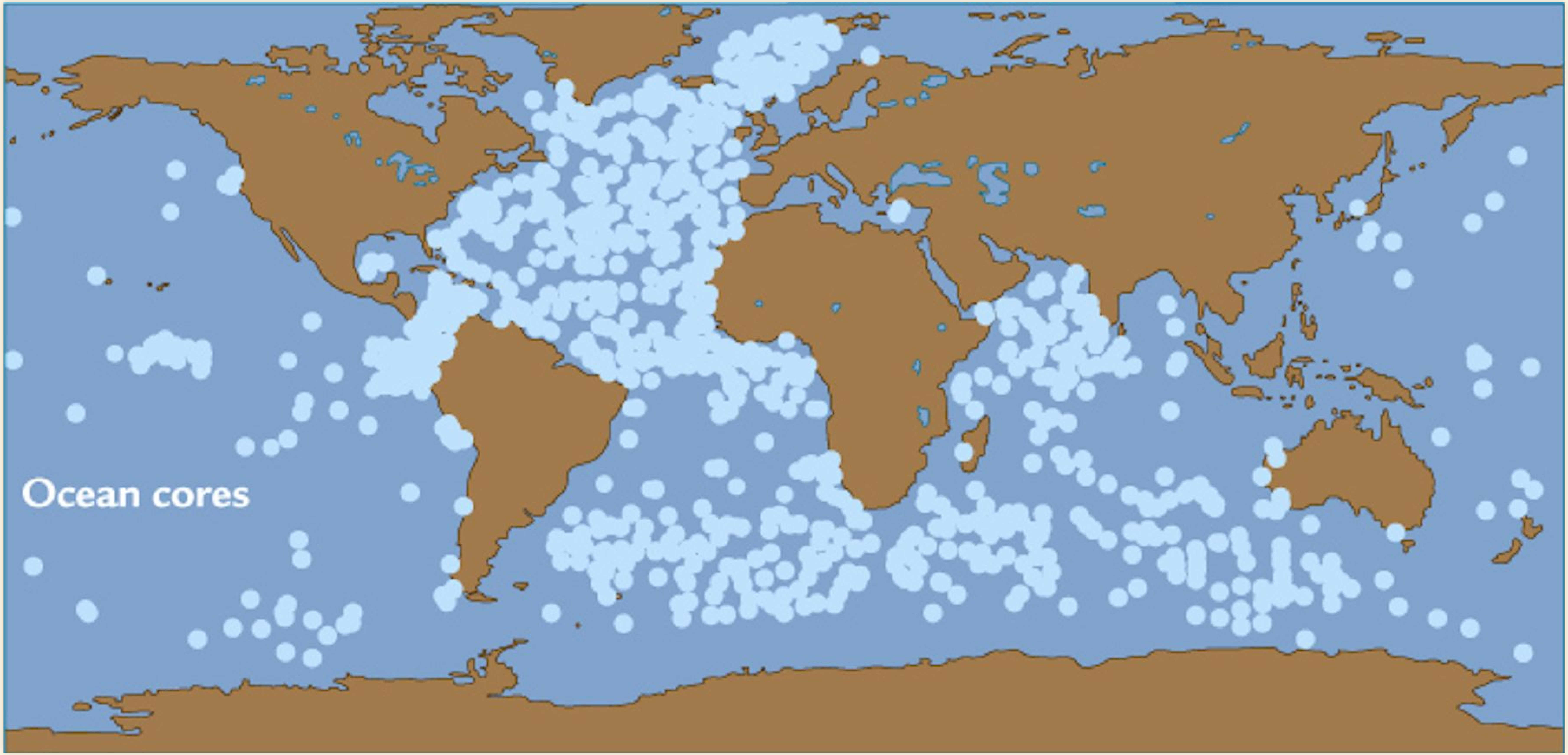


Sediments and History

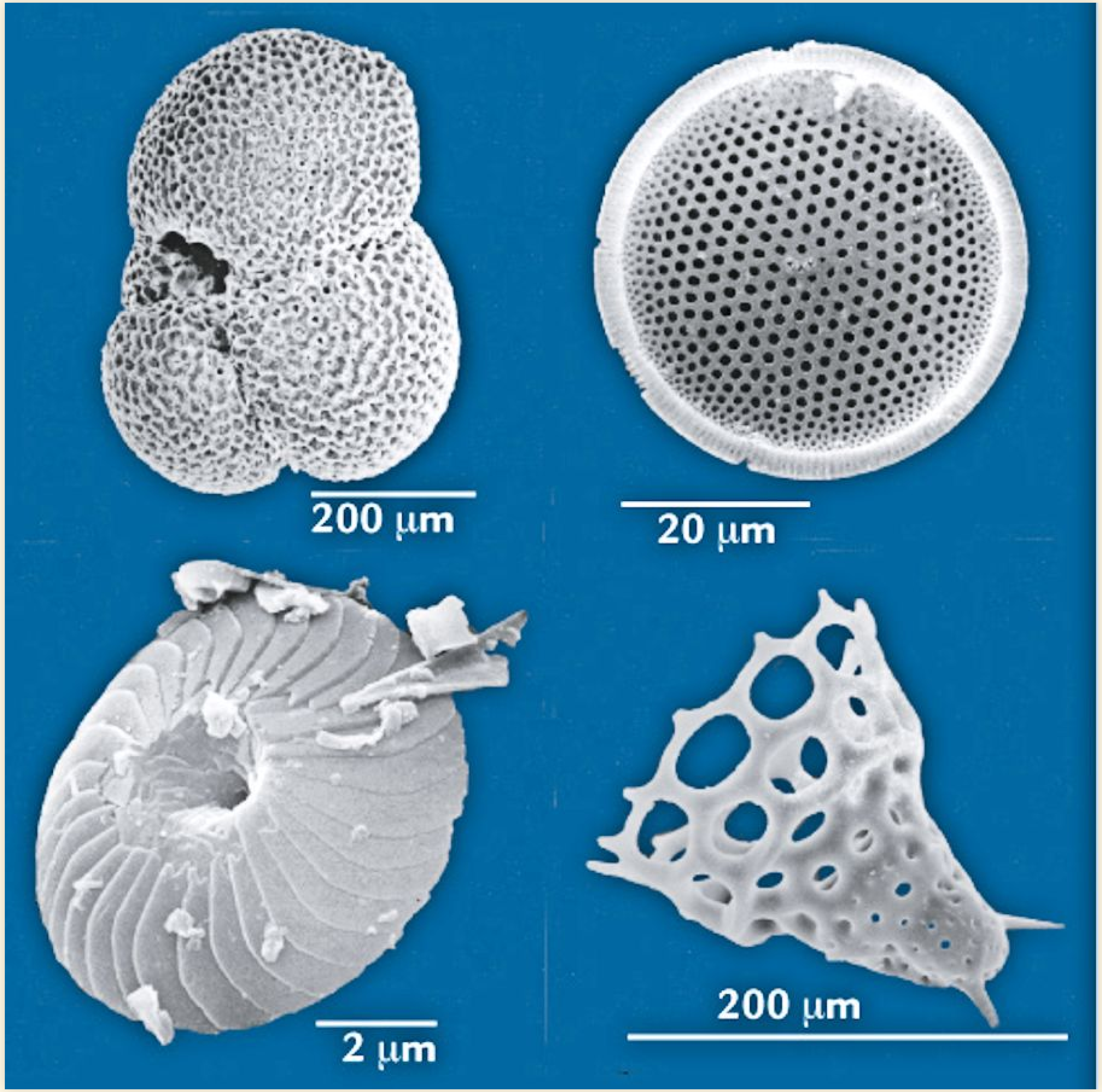


Bottom $\rightarrow$ top = oldest $\rightarrow$ youngest

Ocean Cores for Past Climates

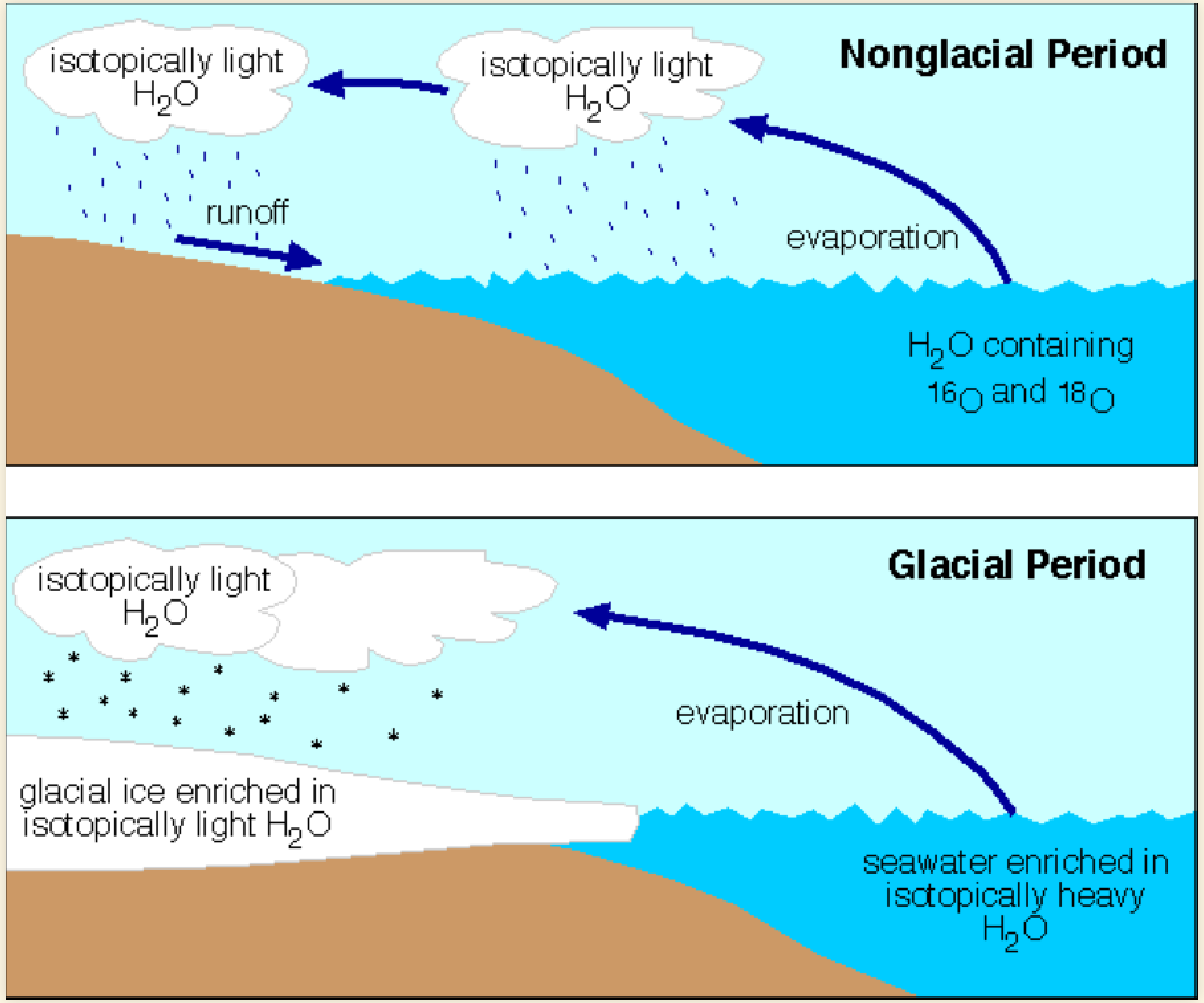


Deep-Sea Sediments

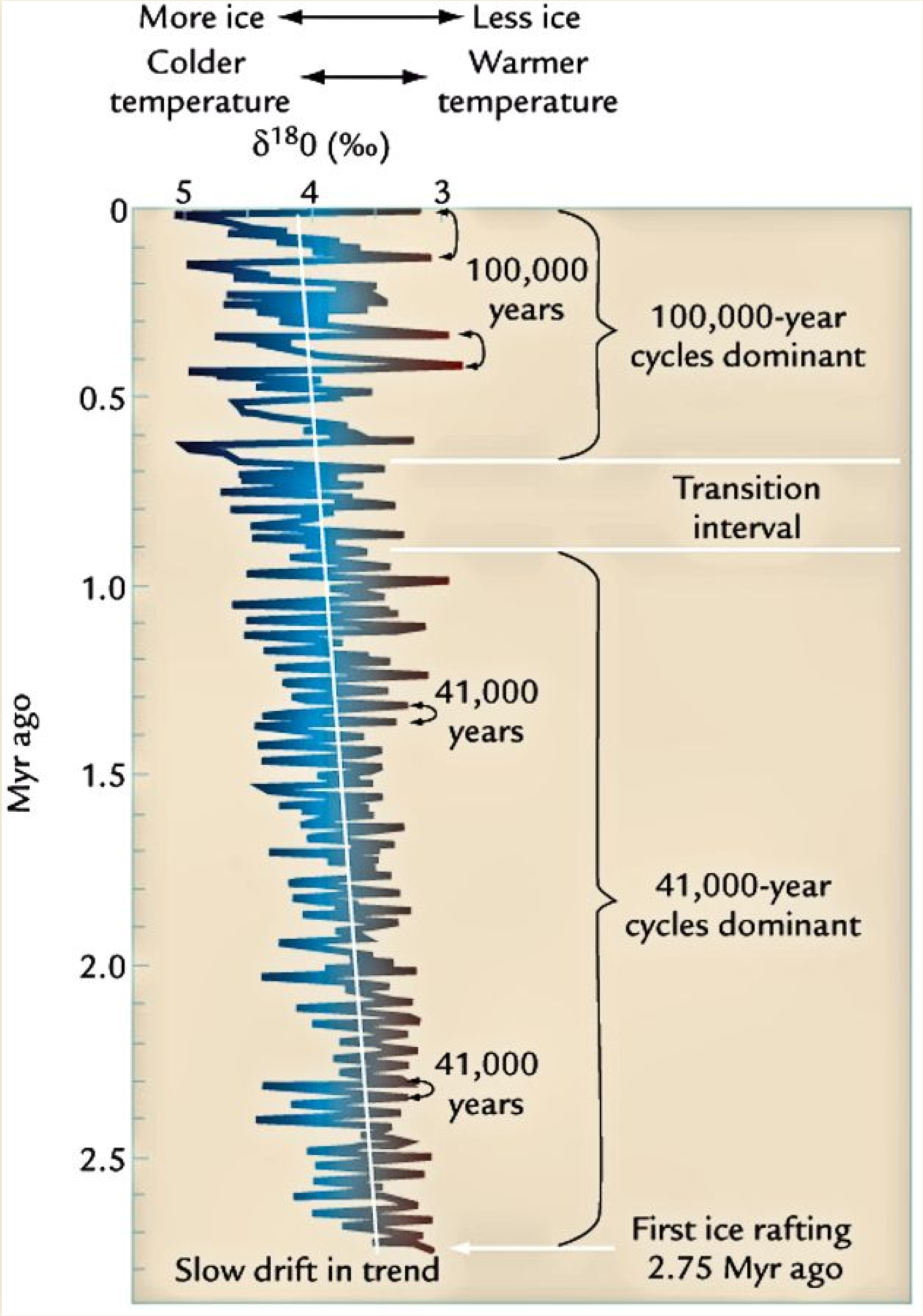


Past Sea Levels

- Water vapor, rain, snow is always isotopically lighter than sea water
- Snow, ice on land remove light isotopes from ocean
- Bigger glaciers:
  - Lower sea-level
  - Greater (positive) $\delta^{18}O$ in ocean sediments
- Smaller glaciers:
  - Higher sea-level
  - Smaller $\delta^{18}O$ in ocean sediments



Sediment Climate Record



Summary of Oxygen Isotopes

- Two different uses:
  - δ^{18}O in **glacial ice** tells us about **air temperature**:
    - Greater δ^{18}O means warmer temperature.
  - δ^{18}O in **sea-floor sediments** (skeletons of deep-sea organisms) tells us about **sea level**:
    - Greater δ^{18}O means lower sea-level.
- During ice-age cycles:
  - ***cold temperatures*** go with ***low sea-level***
    - δ^{18}O is *lower* than usual in glaciers, *greater* in sea-floor sediments.
  - ***warm temperatures*** go with ***high sea-level***:
    - δ^{18}O is *greater* than usual in glaciers, *lower* in sea-floor sediments.
  - But sea-level changes more slowly than temperature, so changes in sediments usually lag behind changes in glaciers.

Review

Review

- What do we learn from studying δ^{13}C in the atmosphere?
- What do we learn from studying δ^{14}C in the atmosphere?
- How do we know that the rise in CO_2 comes from burning fossil fuels?
- What do δ^{18}O and δD in glacial ice tell us about the past?
- What is different between what we learn from δ^{18}O in ice and δ^{18}O in sea-floor sediments?
- How does the silicate weathering cycle act as a thermostat to keep earth's temperature stable?
- How do the lifetimes of CO_2 and CH_4 compare? Why is this important?