Paleoclimate

Understanding past climate through the cryosphere

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Overview

- Introduction to paleoclimatology
  - Brief overview of history of Earth's climate
- Introduction to temperature proxy records
- Glaciology-specific temperature proxy records
  - Glacial geomorphology
  - Ice core reconstructions

Paleoclimatology

- Study of the climate (temperature, moisture, wind vectors, etc.) prior to direct, quantitative observations of climatological variables
- Why would we want to know about climate in the past?

Paleoclimate

- What’s the difference between climatology and paleoclimatology
- How do we measure temperature?

Paleoclimate

- How do we measure temperature?
  - Mercury displacement (traditional thermometers)
  - Changes in electrical properties (digital thermometers)
  - Emission spectrum (satellites, infrared sensors)

Paleoclimate

- Direct temperature measurements only go back a few hundred years
- How can we estimate temperature before thermometers?

Paleoclimate proxies

- An indirect measurement of a variable (i.e. the proxy) that is correlated with some other variable of interest (e.g. temperature)
- Percentage of people wearing a coat

Paleoclimate proxies

- Examples of temperature proxies:
  - Coral distributions
  - Tree ring widths
  - Types and fequency of vegetation/pollen
  - Fossil assemblages
  - Marine sediment records
  - Geologic units and transitions

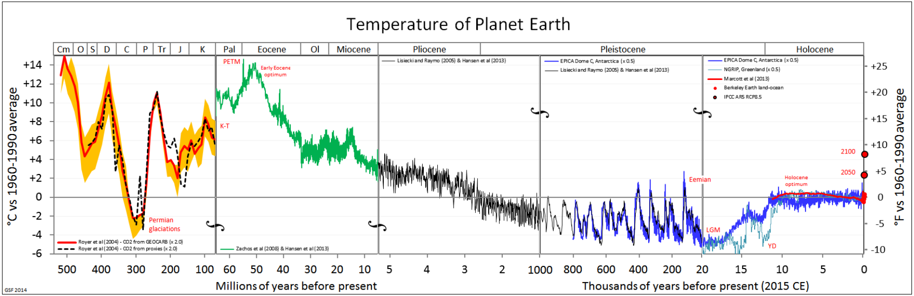


Figure 1: Mean global Earth temperature 540 Ma to present. (Source: https://commons.wikimedia.org/wiki/File:All_palaeotemps.png)

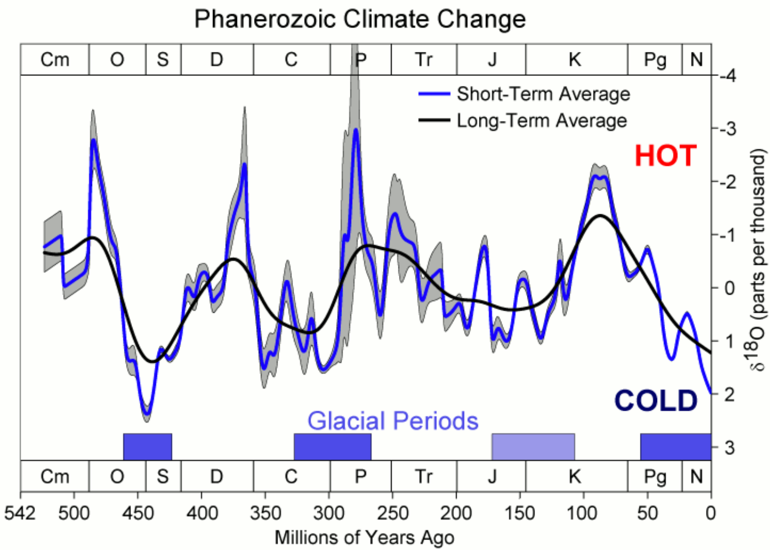

Phanerozoic Climate Change
Cm
O
S
D
C
P
Tr
J
K
Pg
N
Short-Term Average
Long-Term Average
HOT
COLD
Glacial Periods
-4
-3
-2
-1
0
1
2
3
δ18O (parts per thousand)
542
500
450
400
350
300
250
200
150
100
50
0
Millions of Years Ago

Figure 2

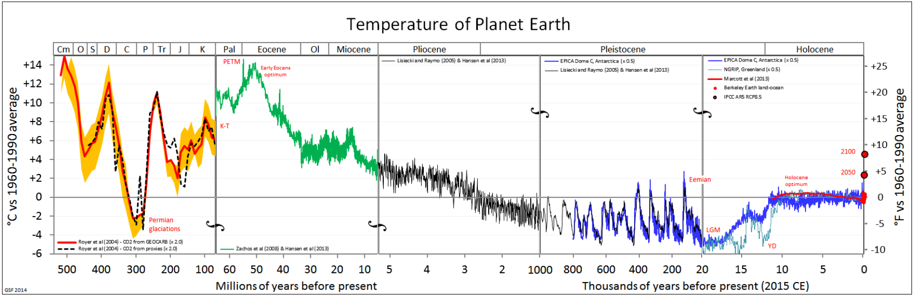


Figure 3: Mean global Earth temperature 540 Ma to present. (Source: https://commons.wikimedia.org/wiki/File:All_palaeotemps.png)

- Focus on two specific temperature proxies
  - What are they
  - How they work
  - Advantages and limitations
- Glacial geomorphology
- Isotopes in ice cores

Glacial geomorphology

Figure 4

Review of glacier mass balance

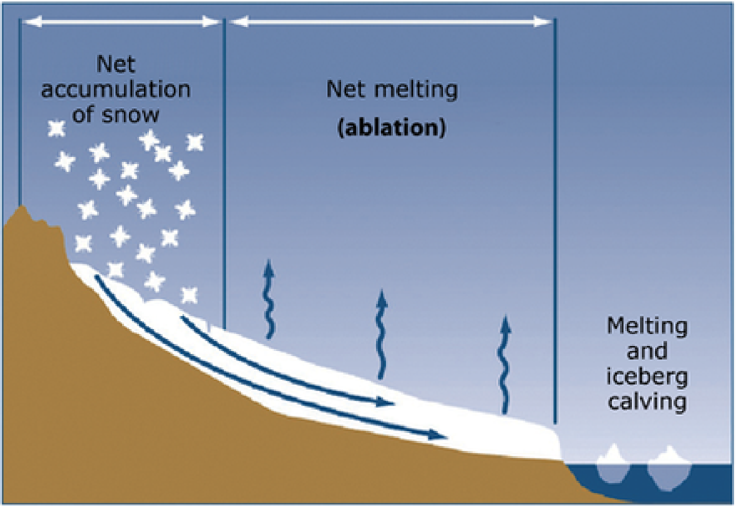


Figure 5

$$\dot{b} = accumulation - ablation$$

- What happens if temperatures increase?
- What happens if more snow falls?

$\dot{b} = accumulation - ablation$

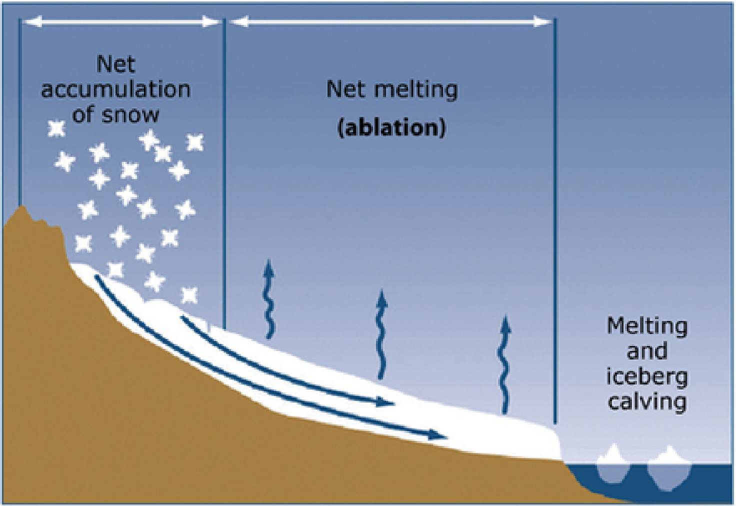


Figure 6

Glacial geomorphology

- Changes in landscape due to presence of or changes in nearby glaciers
  - Glacier valleys
  - Moraines
  - Meltwater planes
  - Glacial scouring
  - Glacial erratics

Example of glacial erratic

Figure 7

Example of glacial scour

Figure 8

Moraines

- Mass of rock and debris pushed by movement of glacier (best preserved in equilibrium)
- Records the extent of a glacier at a specific point in time
- Three types of moraines:
  - Lateral
  - Medial
  - Terminal

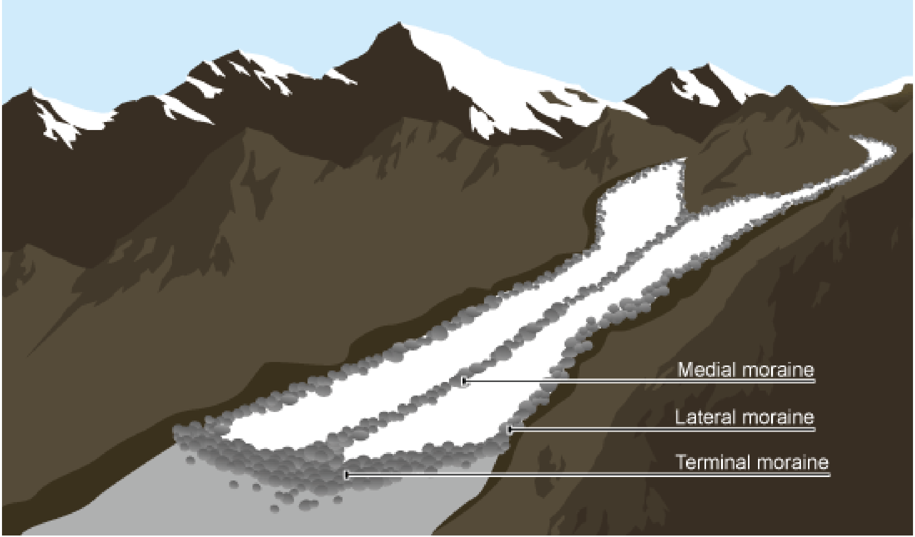


Figure 9

Moraines

- We can use moraine positions to reconstruct glacier growth/retreat over time
- We can then make inferences about the changes in climate driving those glacial changes

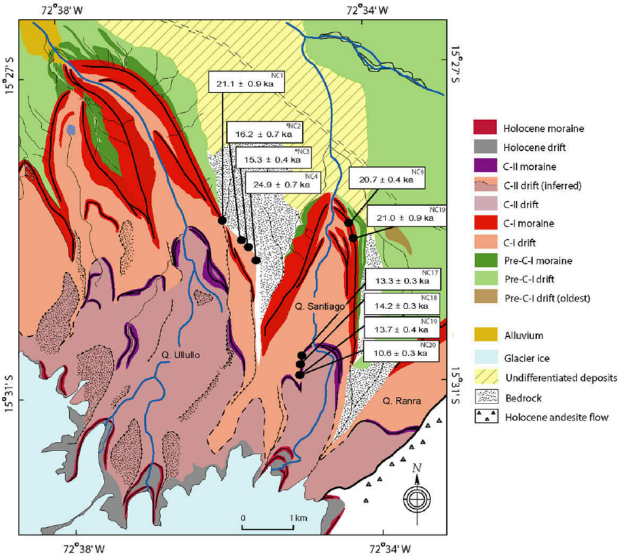

72°38' W
72°34' W
15°27' S
15°31' S
21.1 ± 0.9 ka
NC1
16.2 ± 0.7 ka
NC2
15.3 ± 0.4 ka
NC3
24.9 ± 0.7 ka
NC4
20.7 ± 0.4 ka
NC9
21.0 ± 0.9 ka
NC10
13.3 ± 0.3 ka
NC17
14.2 ± 0.3 ka
NC18
13.7 ± 0.4 ka
NC19
10.6 ± 0.3 ka
NC20
Q. Santiago
Q. Ullullo
Q. Ranra
0
1 km
N
Holocene moraine
Holocene drift
C-II moraine
C-II drift (inferred)
C-II drift
C-I moraine
C-I drift
Pre-C-I moraine
Pre-C-I drift
Pre-C-I drift (oldest)
Alluvium
Glacier ice
Undifferentiated deposits
Bedrock
Holocene andesite flow

Figure 10

- Glacial geomorphology used to determine relative age/magnitudes of the glacial advances
- Our earliest understanding of ice ages came largely from studies of glacial geomorphology

Timeline of ice ages

Glaciation stadial	Time
Last Glacial Period (Wisconsinan Stage)	~115 ka to 11.7 ka
Penultimate Glacial Period (Illinoian Stage)	~194 ka to ~135 ka

- Any ideas on how they got those names?
- Locations of major moraine sets used to determine the ice age!

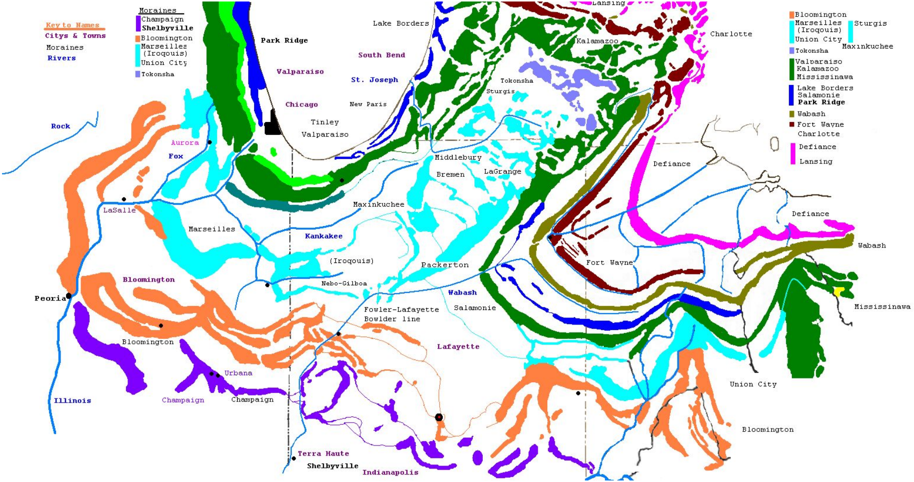

Key to Names
Citys & Towns
Moraines
Rivers
Moraines
Champaign
Shelbyville
Bloomington
Marseilles
(Iroquois)
Union City
Tokonsha
Park Ridge
Lake Borders
South Bend
Valparaiso
St. Joseph
Chicago
New Paris
Tinley
Valparaiso
Lansing
Kalamazoo
Charlotte
Tokonsha
Sturgis
Rock
Aurora
Fox
LaSalle
Marseilles
Middlebury
Bremen
LaGrange
Maxinkuchee
Kankakee
(Iroquois)
Nebo-Gilboa
Packerton
Defiance
Fort Wayne
Defiance
Wabash
Peoria
Bloomington
Bloomington
Wabash
Salamonie
Fowler-Lafayette
Bowlder line
Lafayette
Mississinawa
Urbana
Illinois
Champaign
Champaign
Union City
Bloomington
Terra Haute
Shelbyville
Indianapolis
Bloomington
Marseilles
(Iroquois)
Union City
Sturgis
Maxinkuchee
Tokonsha
Valparaiso
Kalamazoo
Mississinawa
Lake Borders
Salamonie
Park Ridge
Wabash
Fort Wayne
Charlotte
Defiance
Lansing

Figure 11

Complications

- Different glaciers respond to climate differently
- Features can erode naturallly, or overridden by later glacial events
- Difficult to seperate effects of different climatic variables (e.g. temperature or preciptation?)
- Can be difficult to place a specific moraine set to an absolute point in time

Ice cores

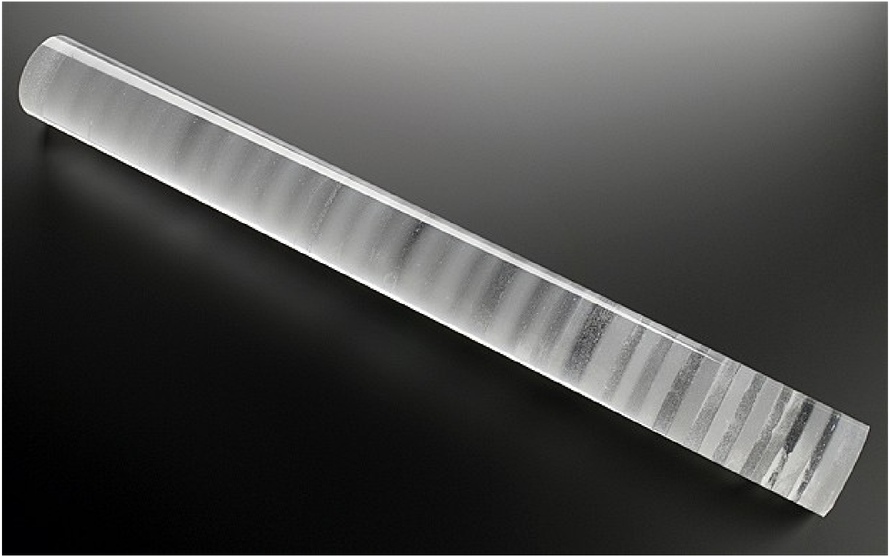


Figure 12

Ice cores

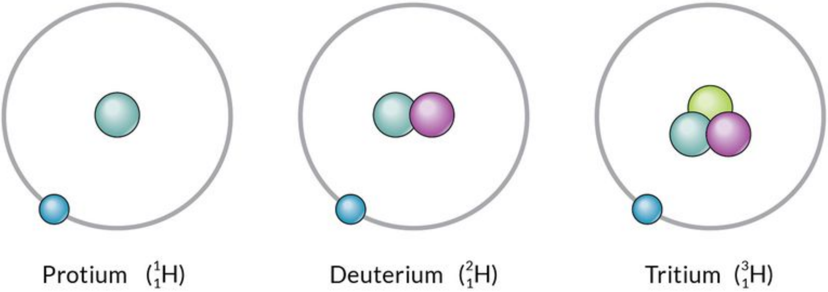
Figure 13

Stable water isotopes

- Focus specifically on two isotope species
  - Deuterium (^2H) and oxygen-18 (^{18}O)
- Stable isotopes (i.e. they do not decay over time)
- Naturally occurring, but in much lower abundance
- Isotopes behave chemically similar to more abundant variety
  - Forms water molecules (e.g. $H_2^{18}O$ and $^1H^2H^{18}O$)

Isotope review

- Same element with differing number of neutrons in the nucleus



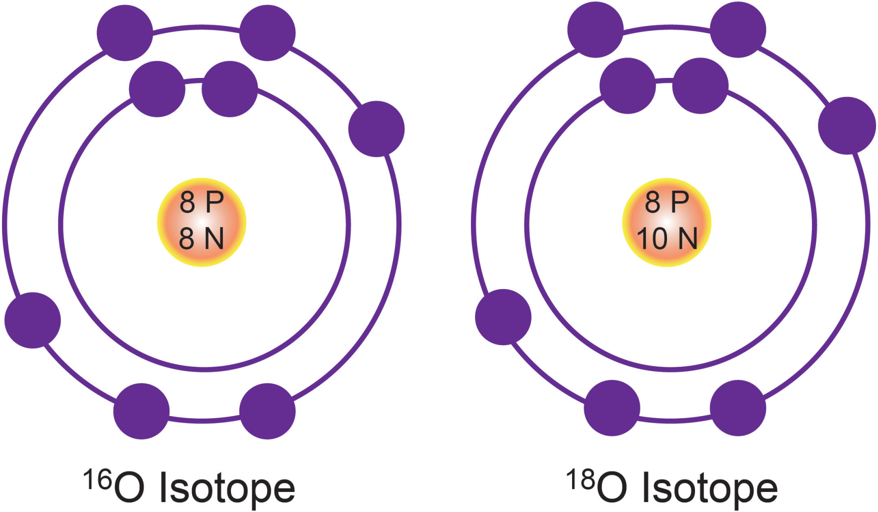


Figure 15

Fractionation physics

- Although chemically similar, isotopes respond slightly differently due to differences in bond strength and diffusion velocity
- Heavier isotopes (e.g. ^{2}H and ^{18}O) vibrate at a lower frequency and diffuse more slowly (conservation of momentum)
    - Energetically more favorable in lower energy states
- This leads to a fractionation effect i.e. a preference of heavier isotopes go into/remain in lower energy phases
    - Isotopic ratio changes during a phase change

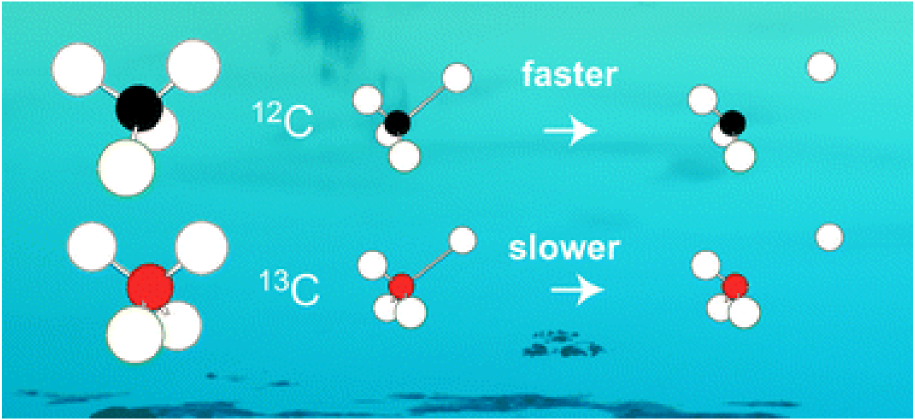


Figure 16

Table 2.1: Natural abundances of oxygen and hydrogen isotopes. After Mook (2001).

Oxygen		Hydrogen	
Isotope	Abundance (%)	Isotope	Abundance (%)
^{16}O	99.76	^{1}H	99.985
^{17}O	0.038	$^{2}H(D)$	0.015
^{18}O	0.200	$^{3}H(T)^{*}$	$< 10^{-15}$

*radioactive isotope

Figure 17: Stable water isotope abundances

- Measure isotopic values as a ratio between the rare isotope and the more common form
  - E.g. $^{18}R = \frac{[H_2^{18}O]}{[H_2^{16}O]}$
- More informative when we express these ratios relative to a standard (V-SMOW)
  - $\delta^{18}O = \frac{^{18}R_{sample} - ^{18}R_{std}}{^{18}R_{std}} x1000$

- Evaporation leads to a water vapor depleted in heavier isotopes, and remnant liquid water enriched

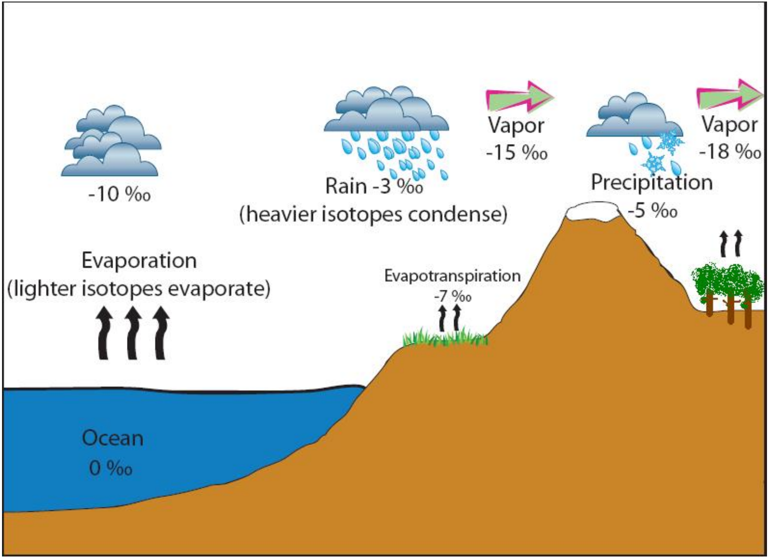


Figure 18: Fractionation and transport

Equilibrium fractionation

- Equilibrium and kinetic fractionation influence final δ values
- In regards to precipitation cycles, most of the isotopic fractionation is governed by equilibrium effects
- Vapor transport gives sufficient time for liquid/vapor constituents to remain in equilibrium
- The amount of equilibrium fractionation is governed by a reaction constant (the 'fractionation factor' α)

$$\alpha^{18}O_{water-vapor} = \frac{(^{18}O/^{16}O)_{water}}{(^{18}O/^{16}O)_{vapor}}$$

- At lower temperatures, this fractionation constant is highly temperature-dependent

$$10^3 \cdot ln(\alpha_b^a) = \frac{A \cdot 10^6}{T^2} + B$$

- (A and B are constants unique to the substances in exchange)

$$10^3 ln(\alpha_b^a) \approx \delta_a - \delta_b = \Delta_b^a$$

- Dansgaard determined an empirical estimate of temperature from $\delta^{18}O$ values:

$$\delta^{18}O \approx 0.62 \cdot T - 15.25$$

- Can be subject to localized variation as well

Paleoclimate reconstruction

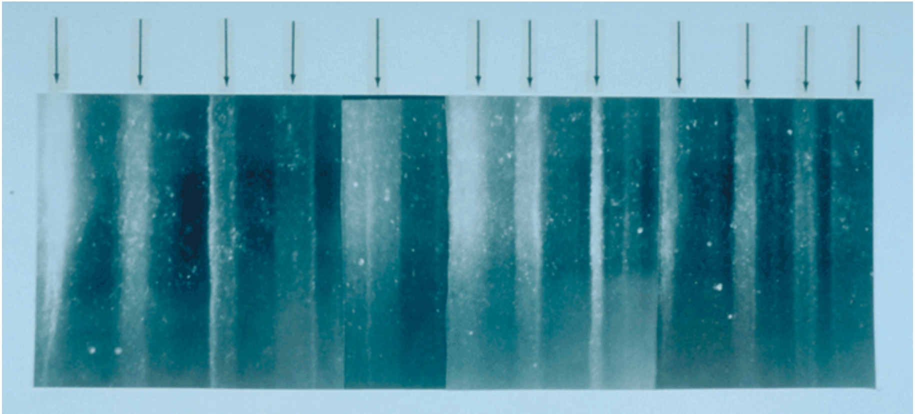


Figure 19

Paleoclimate reconstruction

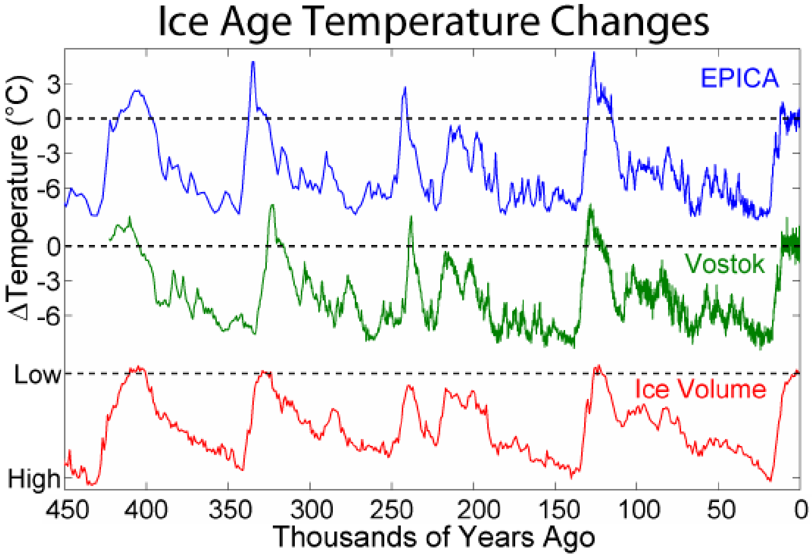


Figure 20

Advantages of ice core reconstructions

- Very high resolution (annually resolved for 10s of 100s of thousands of years)
- Highly correlated with temperature (very good proxy)
- Many other records can be extracted as well
  - Dust content
  - Aerosals
  - Atmospheric composition

Complications

- Mostly limited to polar regions
- Complications in flowing ice
- Limited to ∼1 Ma or later
- Other chemical interactions can affect isotope values
- Subject to high frequency variability (not always regionally representative)

Future climate scenarios

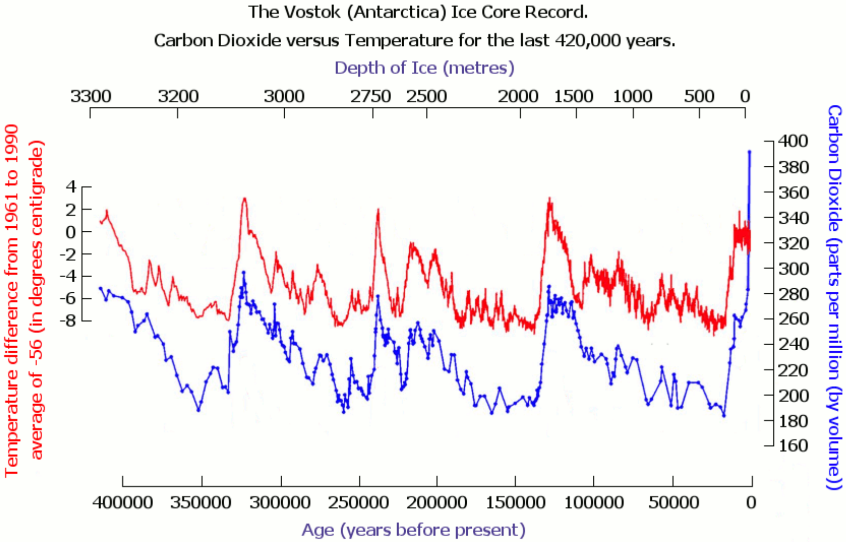


Figure 21

Summary