Climate II

(Winter 2020/2021)

2nd lecture:

The Global Water Cycle

(water cycle, stable water isotopes, ice core records)

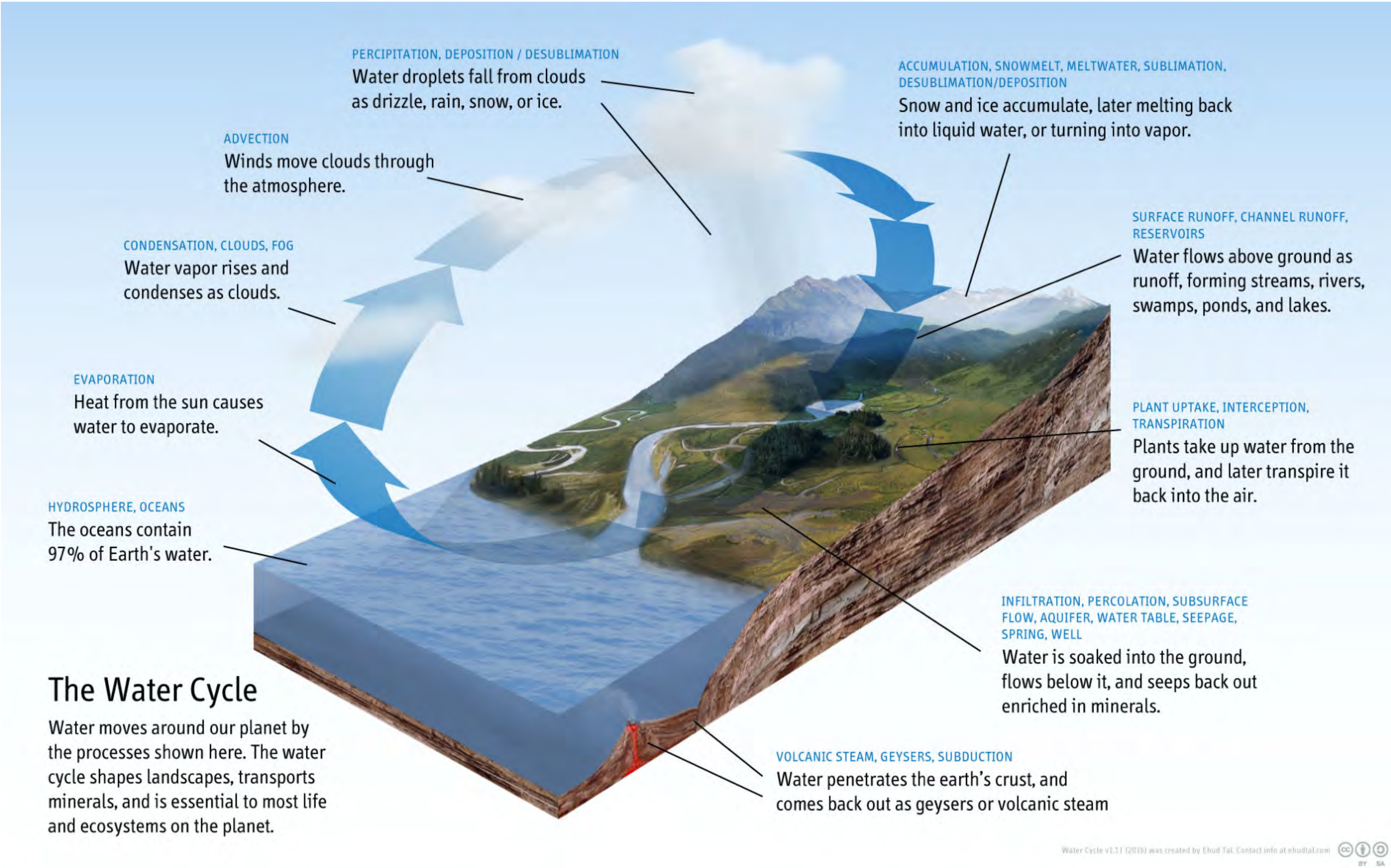
Gerrit Lohmann, Martin Werner

Tuesday, 10:00-11:45

(sometimes shorter, but with some exercises)

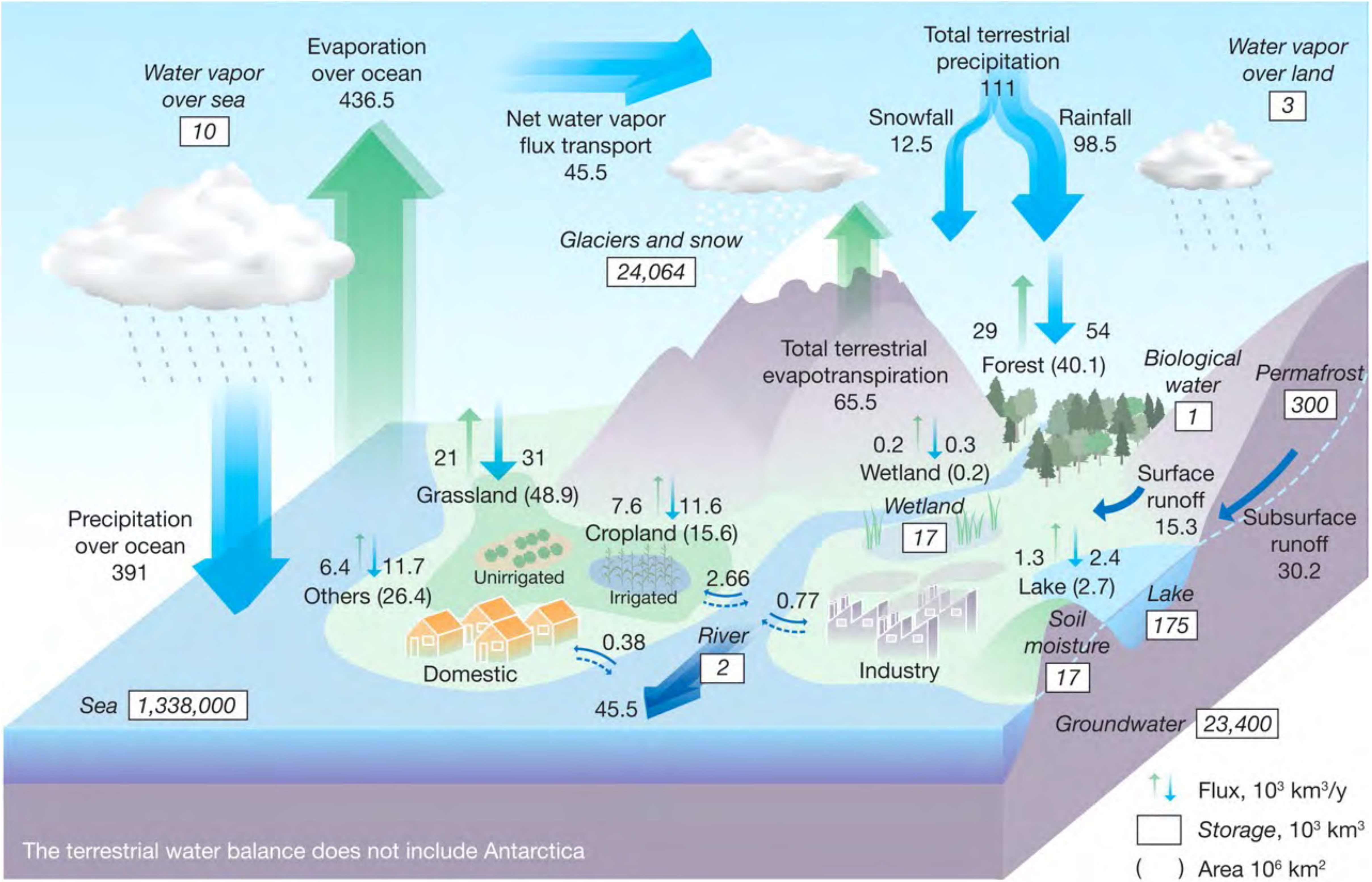
https://paleodyn.uni-bremen.de/study/climate2020_21.html

The global water cycle



https://en.wikipedia.org/wiki/Water_cycle

The global water cycle



Taikan Oki, and Shinjiro Kanae Science 2006;313:1068-1072

Fig. 1. Global hydrological fluxes (1000 km3/year) and storages (1000 km3) with natural and anthropogenic cycles are synthesized from various sources (1, 3–5).

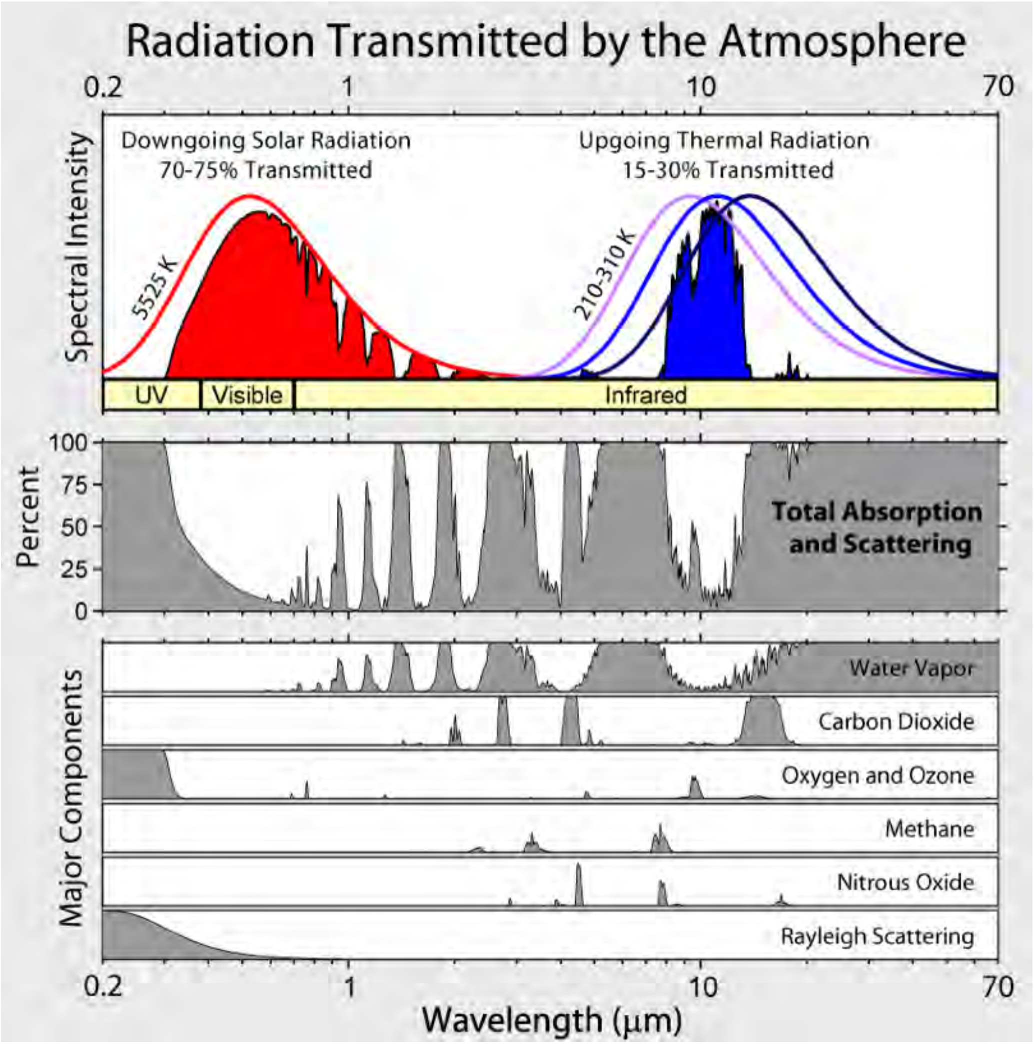
The global water cycle

- absolute water amount:
  (i) in the atmosphere: 0.013 $10^6 m^3$
  (ii) in the oceans: 1,350·$10^6 m^3$

- 97.3% of all available water (liquid equivalent) is stored in the oceans

- mean residence time of water molecules can range between a few days (in the atmosphere) to thousands of years (in the large glaciers and ocean)

- water is the most important greenhouse gas



https://en.wikipedia.org/wiki/Greenhouse_gas

The global water cycle

Quizz - Questions #1:

1. How many oceans do exist on Earth?

2. Assume all water vapour in the atmosphere is liquid and distributed as a water layer on the Earth’s surface.

   => How high would such a water layer be?

The global water cycle

- absolute water amount:
  (i) in the atmosphere: 0.013 $10^6 m^3$
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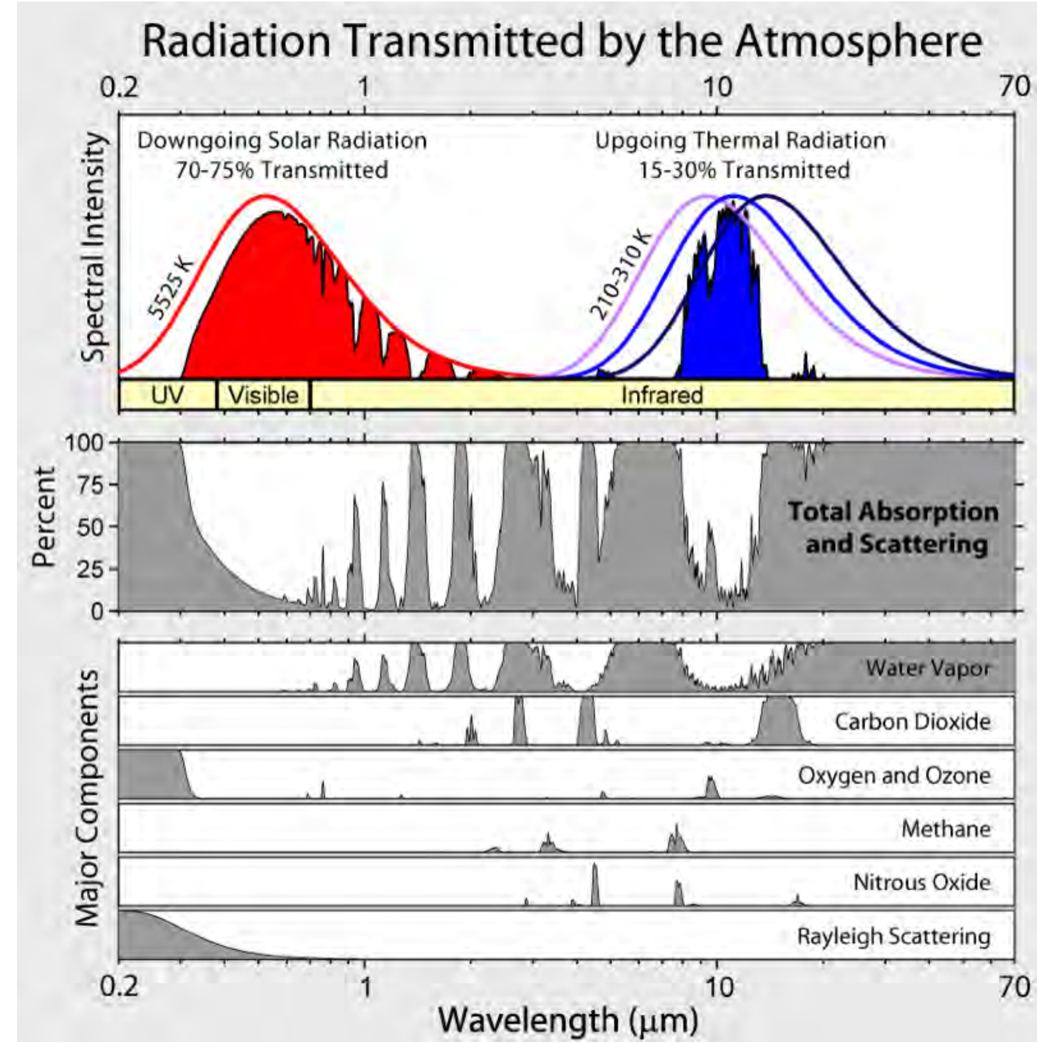
- 97.3% of all available water (liquid equivalent) is stored in the oceans

- mean residence time of water molecules can range between a few days (in the atmosphere) to thousands of years (in the large glaciers and ocean)

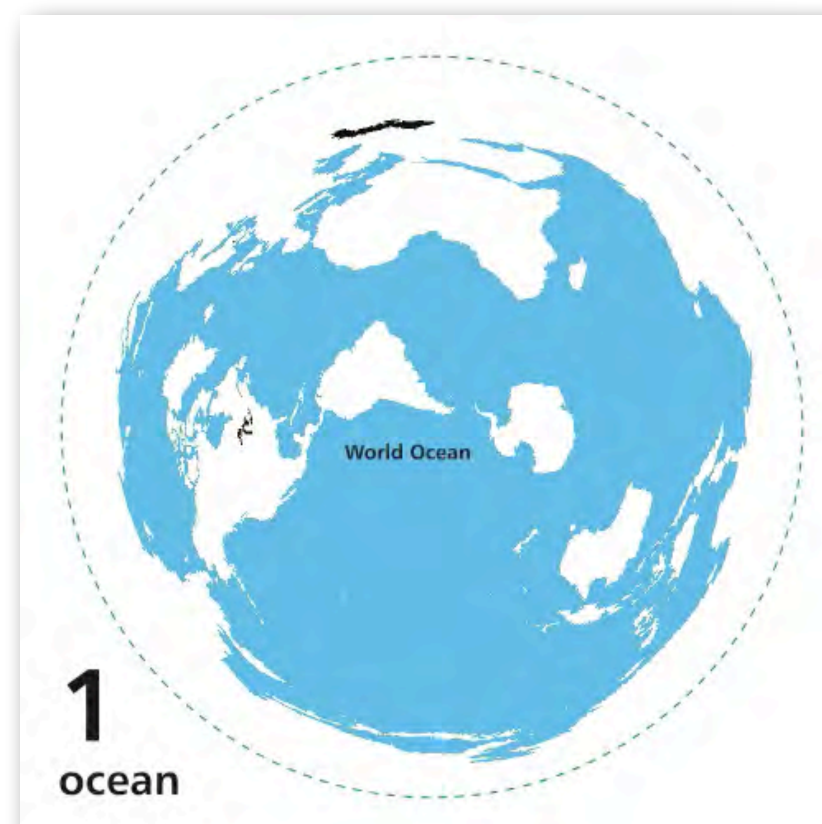
- water is the most important greenhouse gas

- how many oceans do exist on Earth
  => the answer depends whom you ask…

- vapour as a liquid layer: approx. 2.5cm high

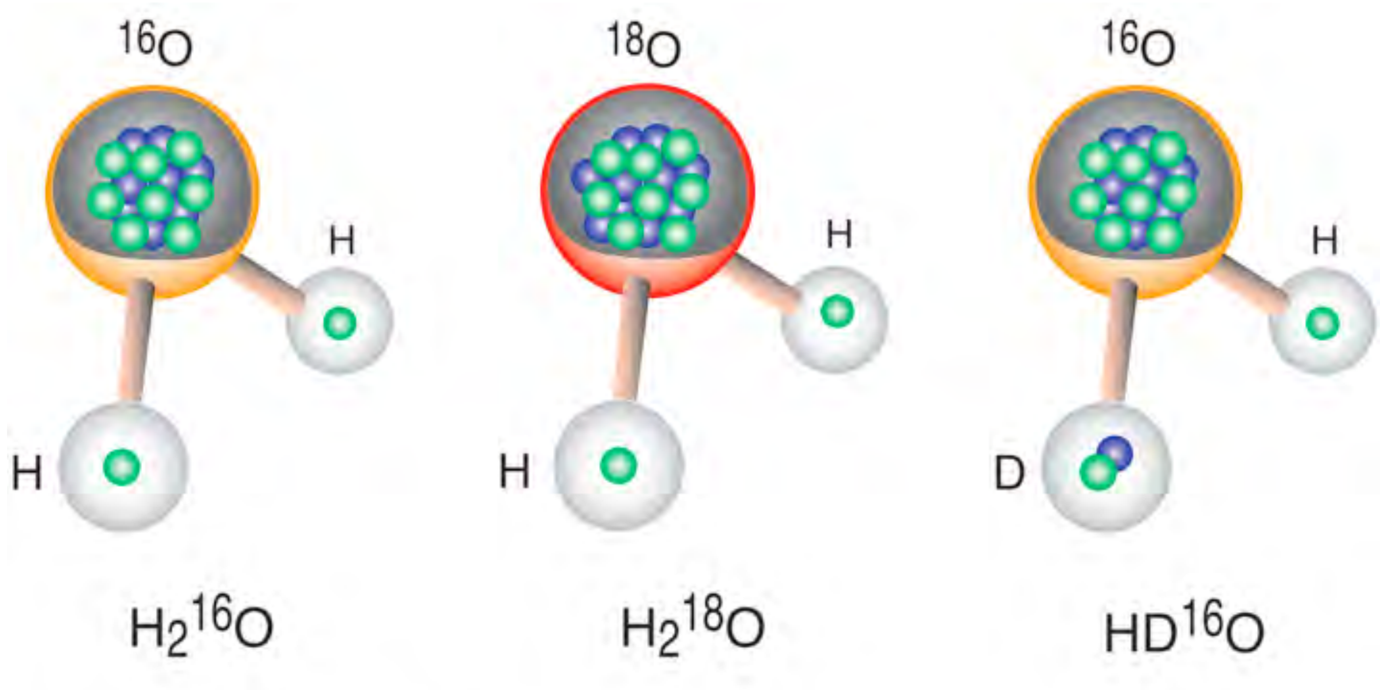


https://en.wikipedia.org/wiki/Greenhouse_gas



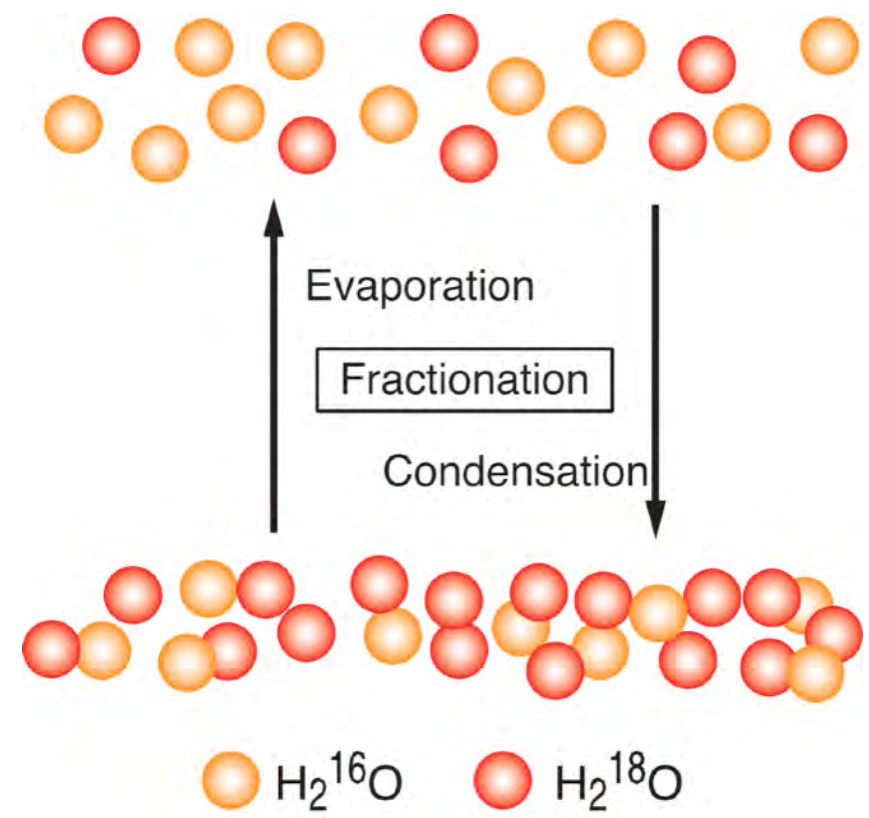
http://en.wikipedia.org/wiki/File:World_ocean_map.gif

Natural abundance of stable water isotopes



1,000,000 2005.2 311.52

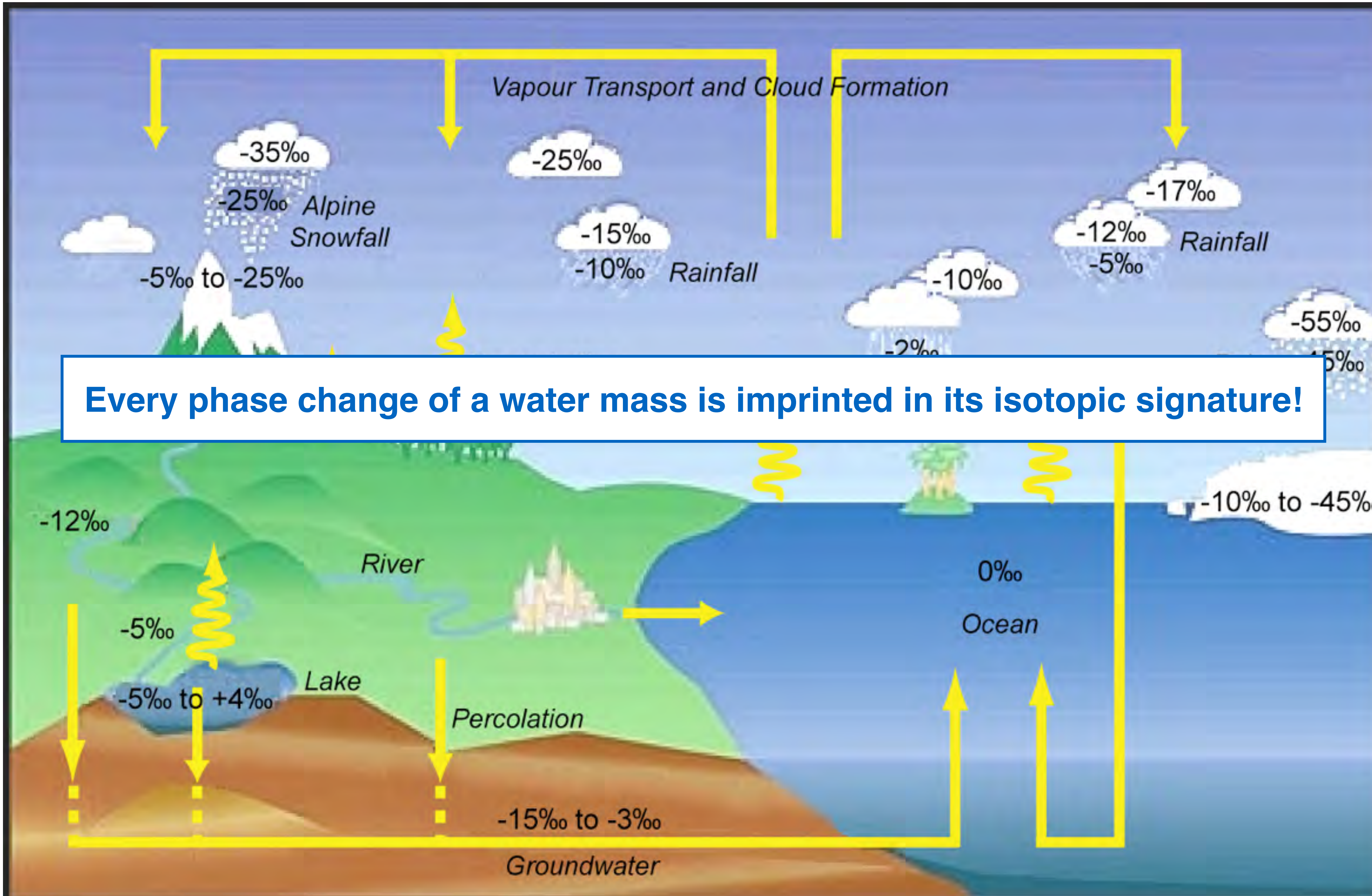
approx. number of molecules in ocean water



- **different isotopes have a different molecular weight and a different molecular symmetry** ***(both effects change the vapour pressure of the water isotopes)***
- **fractionation: light isotopes evaporate more easily while heavy isotopes prefer to stay in the liquid (or solid) phase**
- **the strength of the fractionation is temperature-dependent and expressed in a delta-notation (typically given in ‰)**

$$\delta^{18}O_{sample} = \left(\frac{\left[\frac{H_2^{18}O}{H_2^{16}O}\right]_{sample}}{\left[\frac{H_2^{18}O}{H_2^{16}O}\right]_{standard}} - 1 . \right) * 1000 .$$

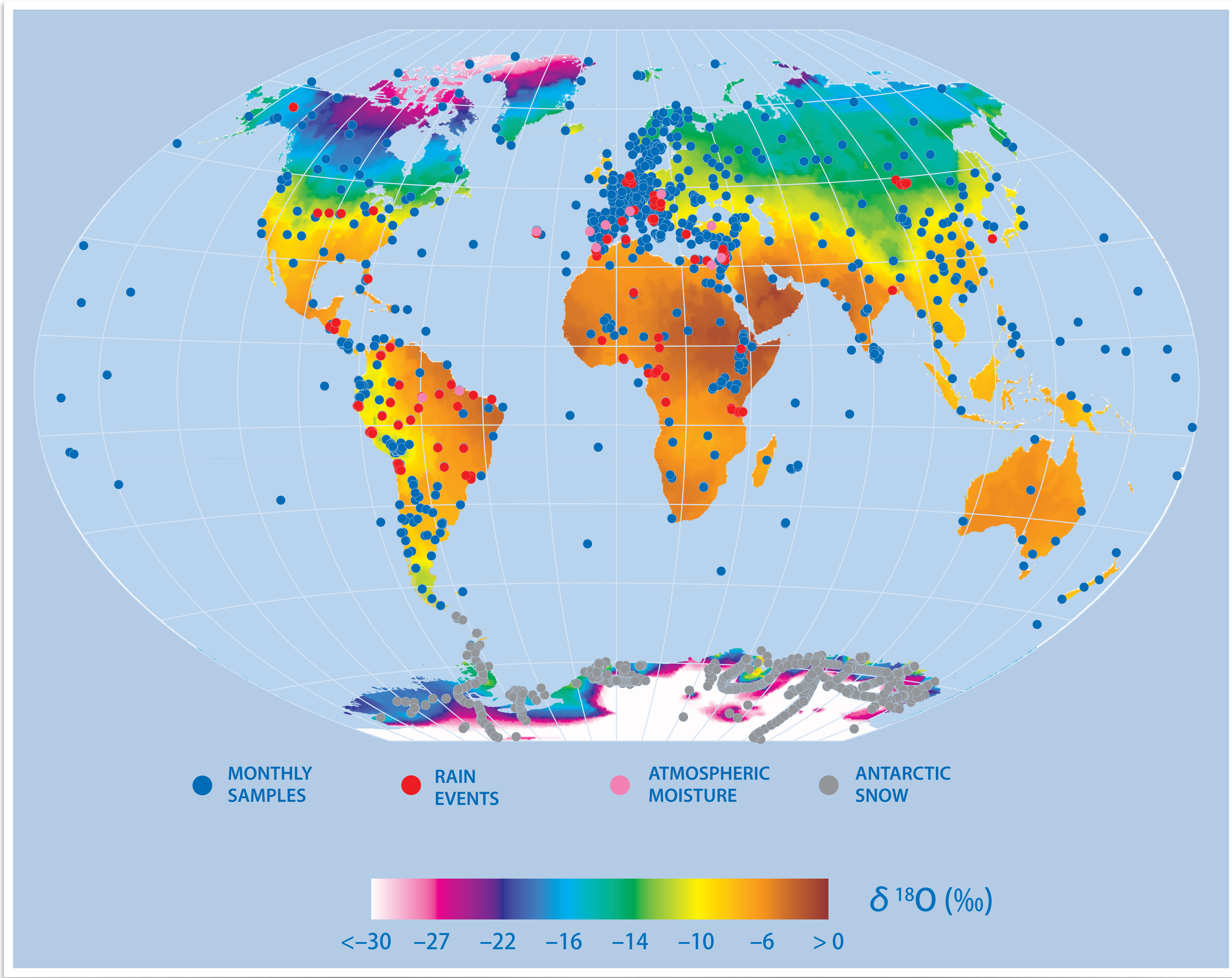
Global distribution of $\delta^{18}O$ in the hydrological cycle



Every phase change of a water mass is imprinted in its isotopic signature!

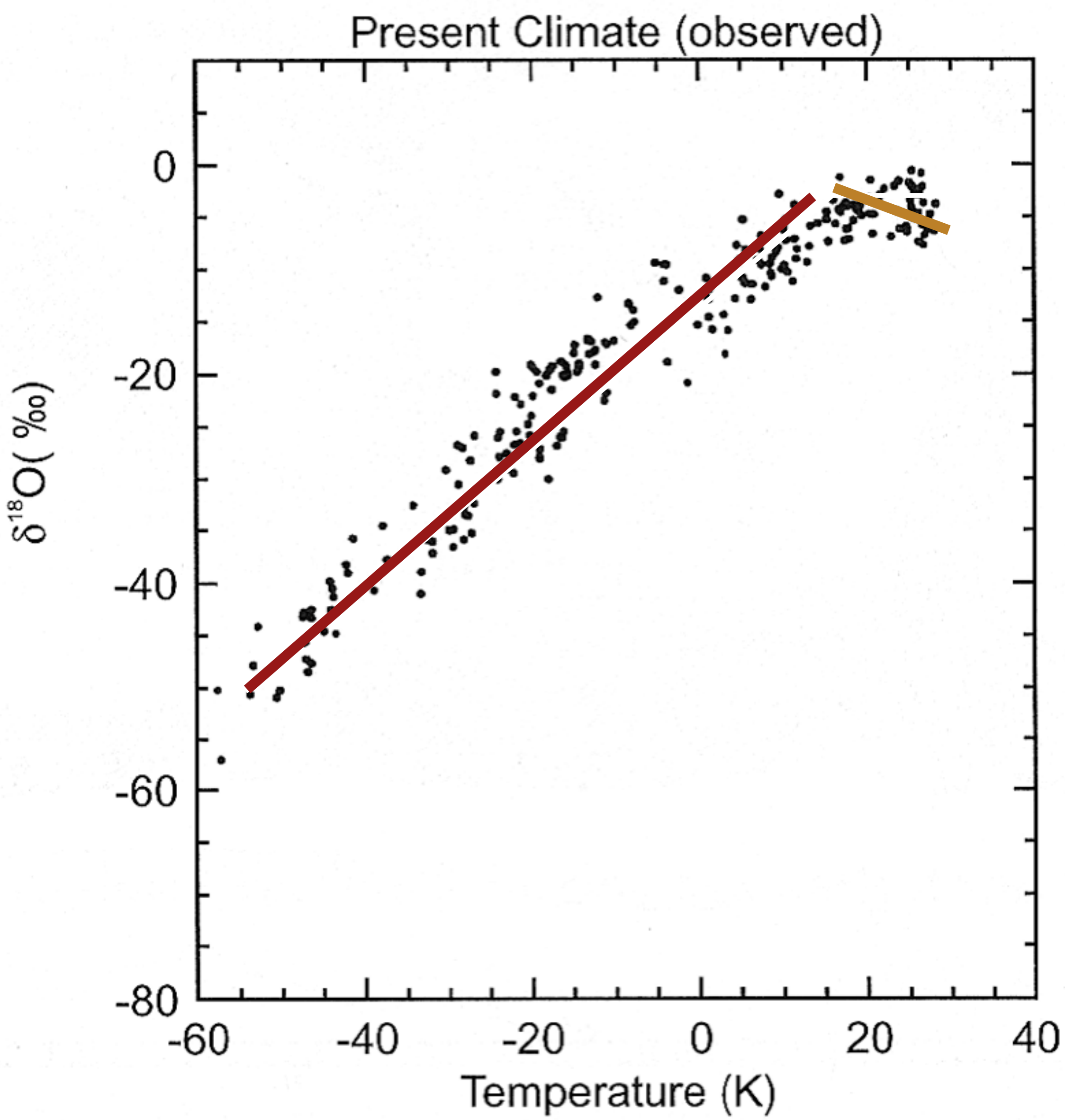
[plot adapted from the GNIP brochure, IAEA, 1996]

Global Network of Isotopes in Precipitation (GNIP)



(GNIP brochure: http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html)

Stable water isotopes as a temperature or precipitation proxy

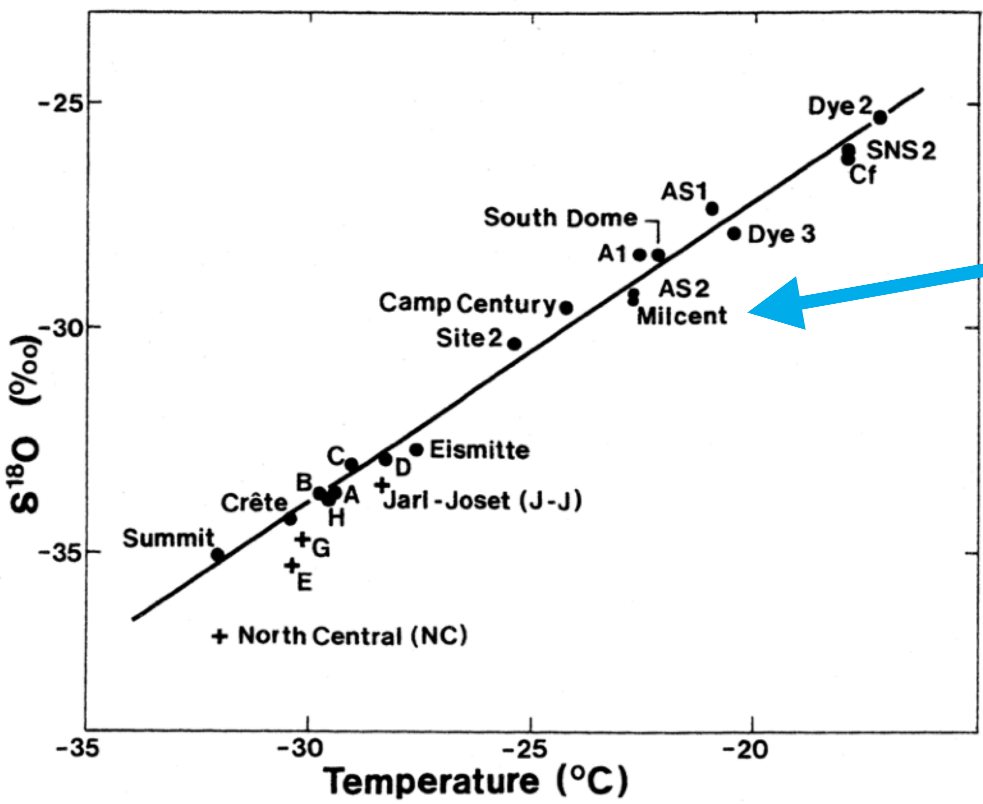


Annual $\delta^{18}O$ in precipitation in relation to mean annual temperature at the same site, based on data from the International Atomic Energy Agency.

(from: Jouzel et al., 1994)

- **$\delta^{18}O$ signal is influenced by environmental conditions during evaporation and condensation**
- **the exact fractionation processes can be very complex to describe**
- **on a global scale, two effects dominate:**
  - ***the temperature effect: linear relationship between $\delta^{18}O$ and surface temperature for mid- to high latitudes***
  - ***the precipitation effect: linear relationship between $\delta^{18}O$ and rainfall amount, mainly in tropical regions with strong precipitation events and (almost) constant surface temperatures***
- **for paleoclimate studies, $\delta^{18}O$ and δD are used (among others) for two purposes:**
  - ***measurement of δ-signals in ice cores and terrestrial records are used for temperature or rainfall amount reconstructions***
  - ***$\delta^{18}O$-variations in marine sediments indicate changes in global ice volume***

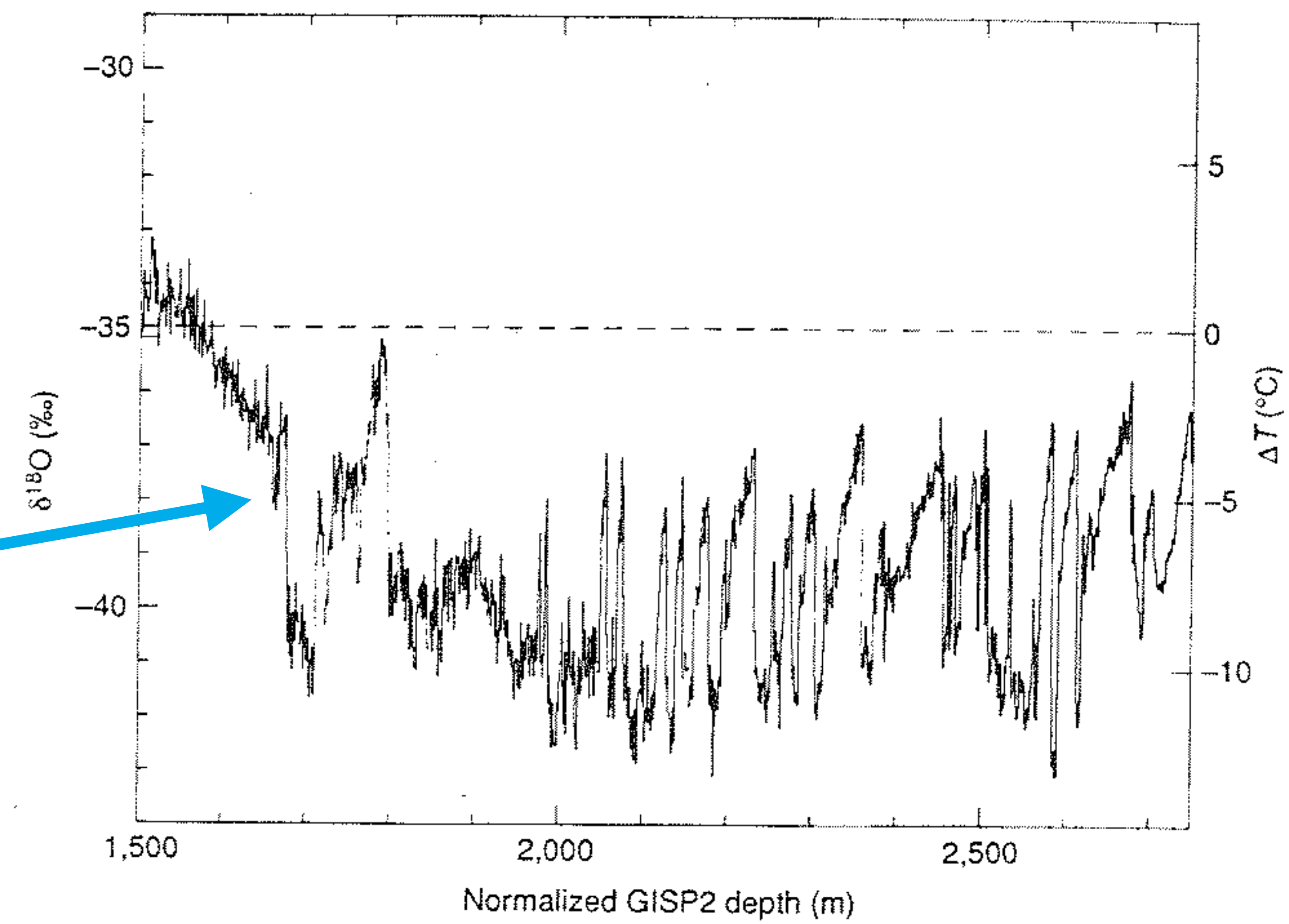
The use of of $\delta^{18}O$ in precipitation as a temperature proxy



[Johnsen et al., Tellus, 1989]

Modern spatial relation between $\delta^{18}O$ and surface temperature (on Greenland):

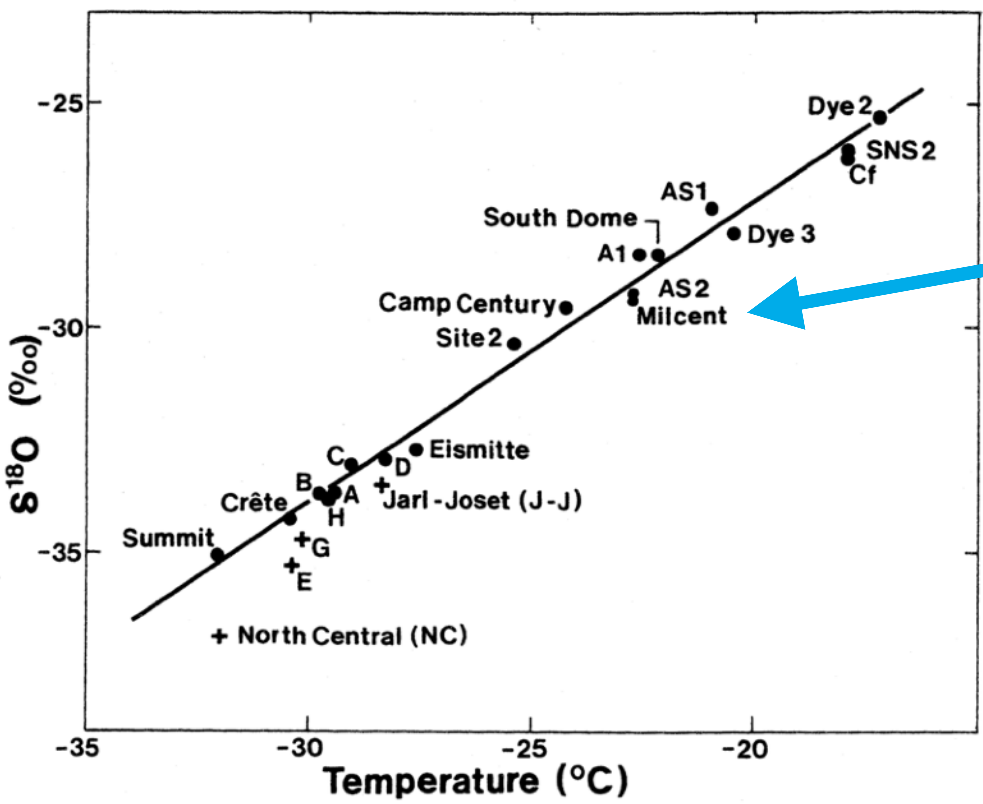
$$\delta^{18}O = 0.67 \cdot T_{surf}$$



Converting temporal changes of $\delta^{18}O$ into past temperature changes

[Grootes et al., Nature, 1993]

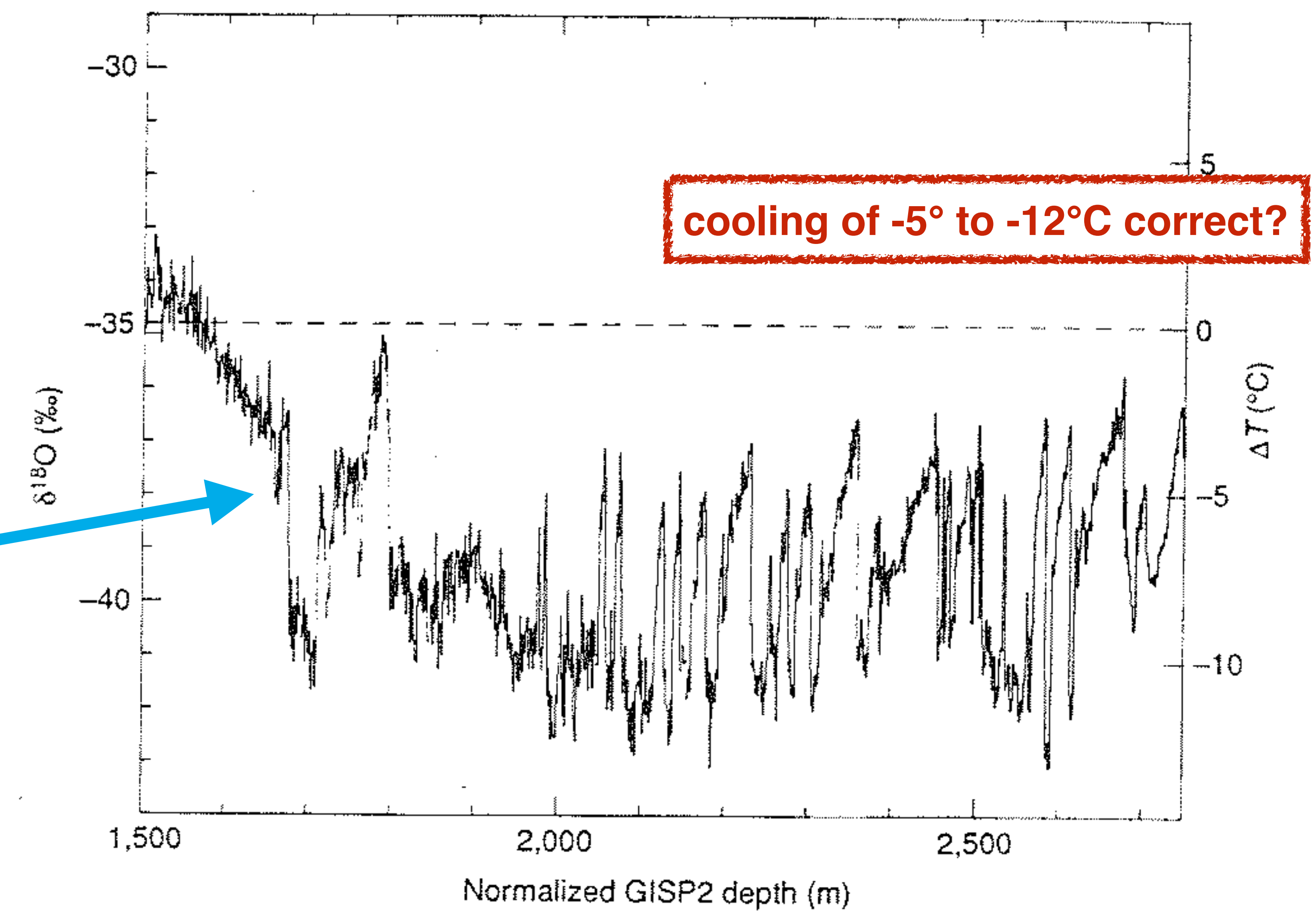
The use of of δ¹⁸O in precipitation as a temperature proxy



[Johnsen et al., Tellus, 1989]

Modern spatial relation between δ¹⁸O and surface temperature (on Greenland):

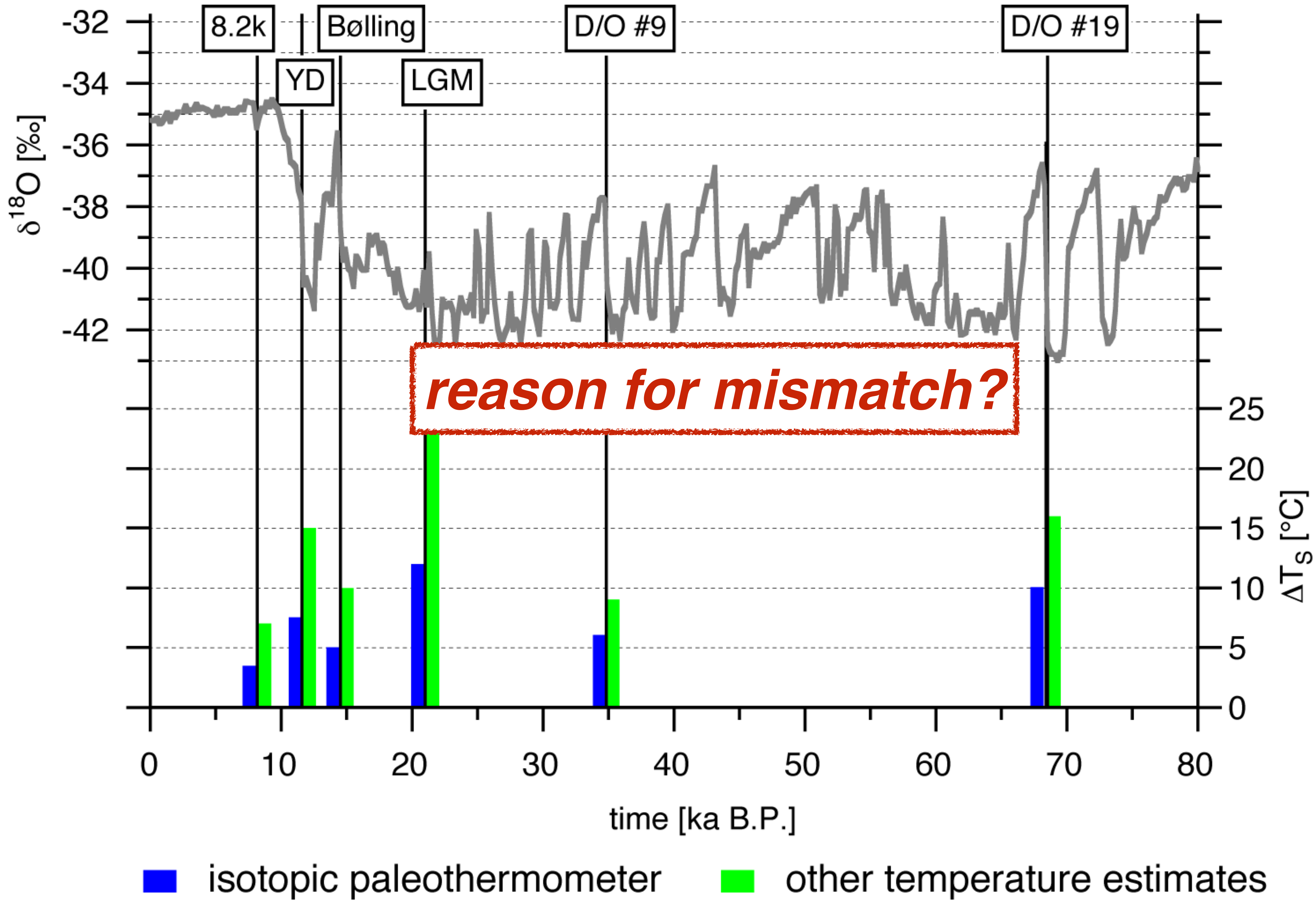
$$\delta^{18}O = 0.67 \cdot T_{surf}$$



Converting temporal changes of δ¹⁸O into past temperature changes

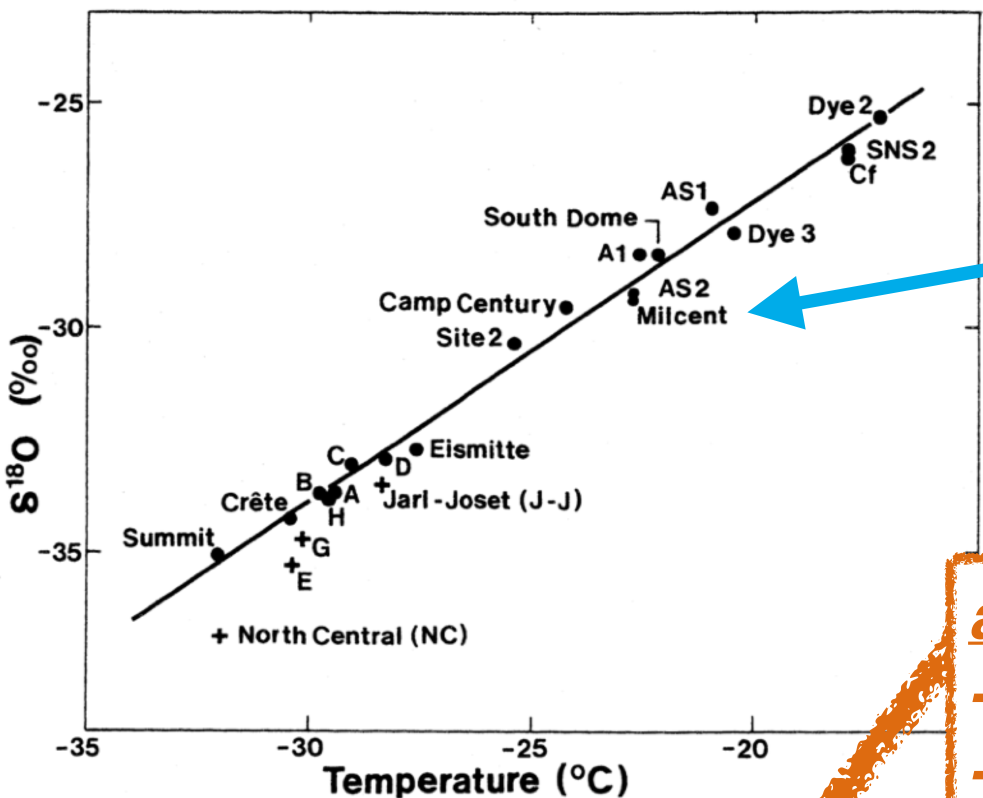
[Grootes et al., Nature, 1993]

Different past temperature estimates for Greenland



[adapted from: J. Jouzel, Science, 1999]

The use of of δ¹⁸O in precipitation as a temperature proxy



[Johnsen et al., Tellus, 1989]

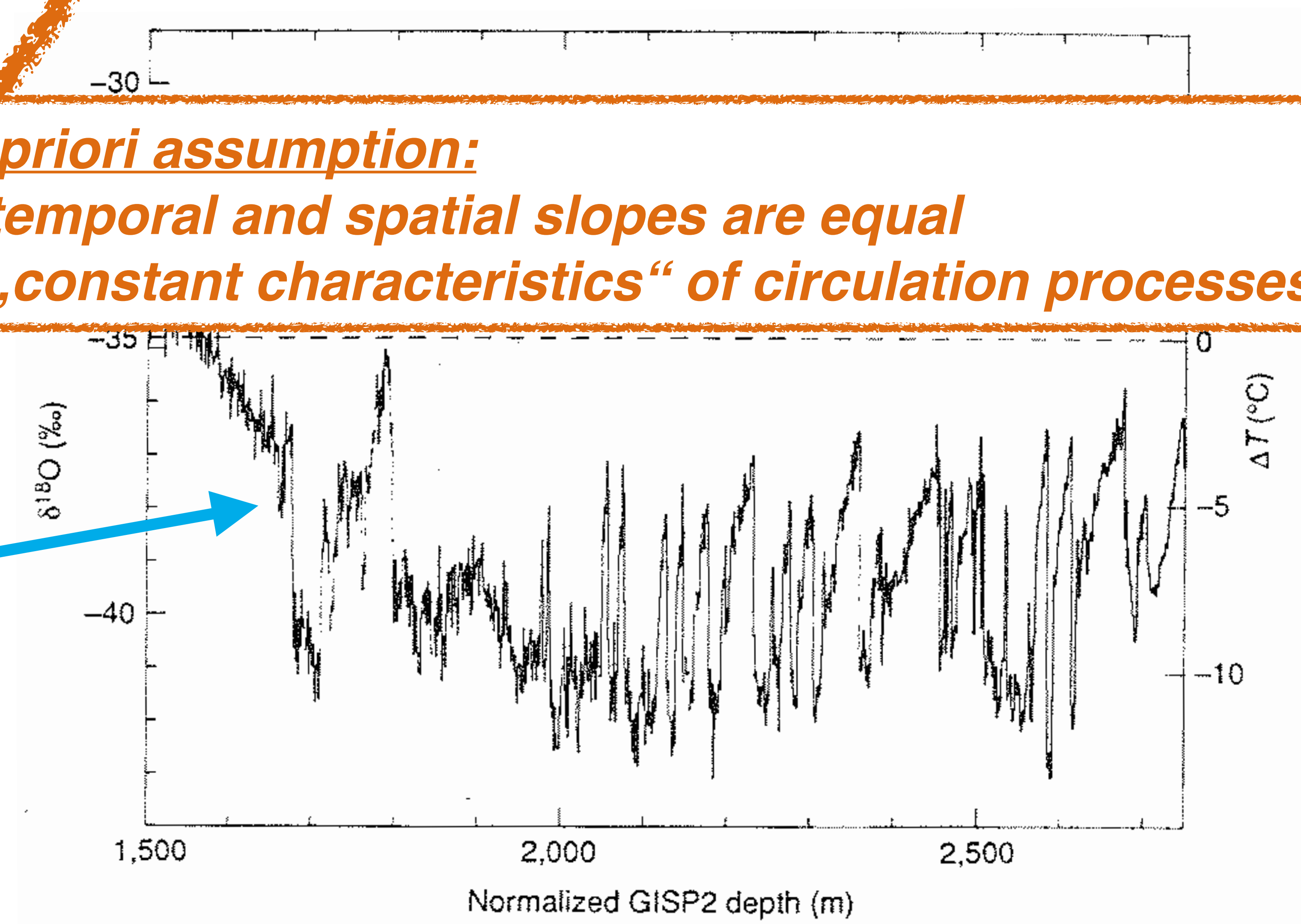
Modern spatial relation between δ¹⁸O and surface temperature (on Greenland):

$$\delta^{18}O = 0.67 \cdot T_{surf}$$

a priori assumption:

- temporal and spatial slopes are equal

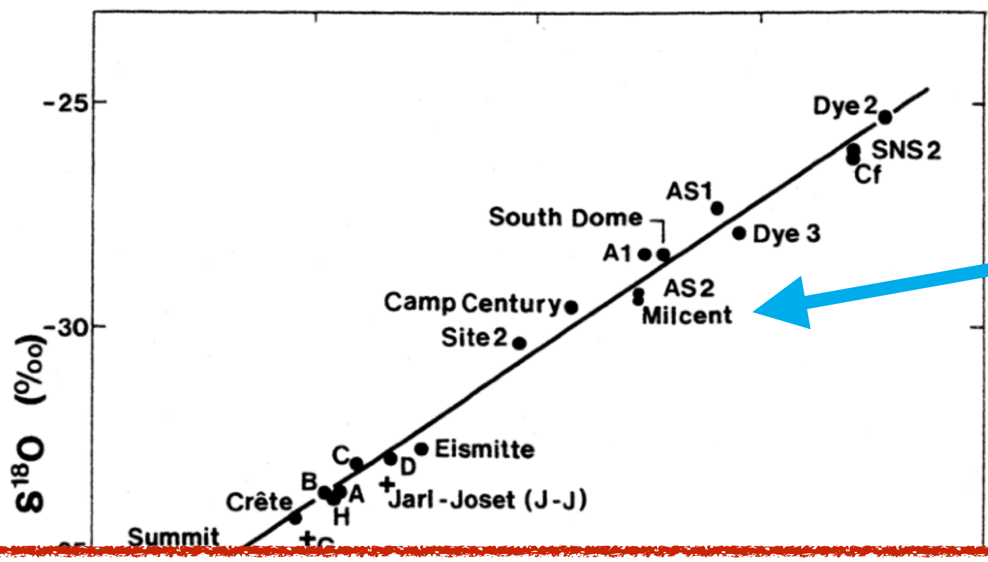
- „constant characteristics“ of circulation processes



[Grootes et al., Nature, 1993]

Converting temporal changes of δ¹⁸O into past temperature changes

The use of of δ18O in precipitation as a temperature proxy

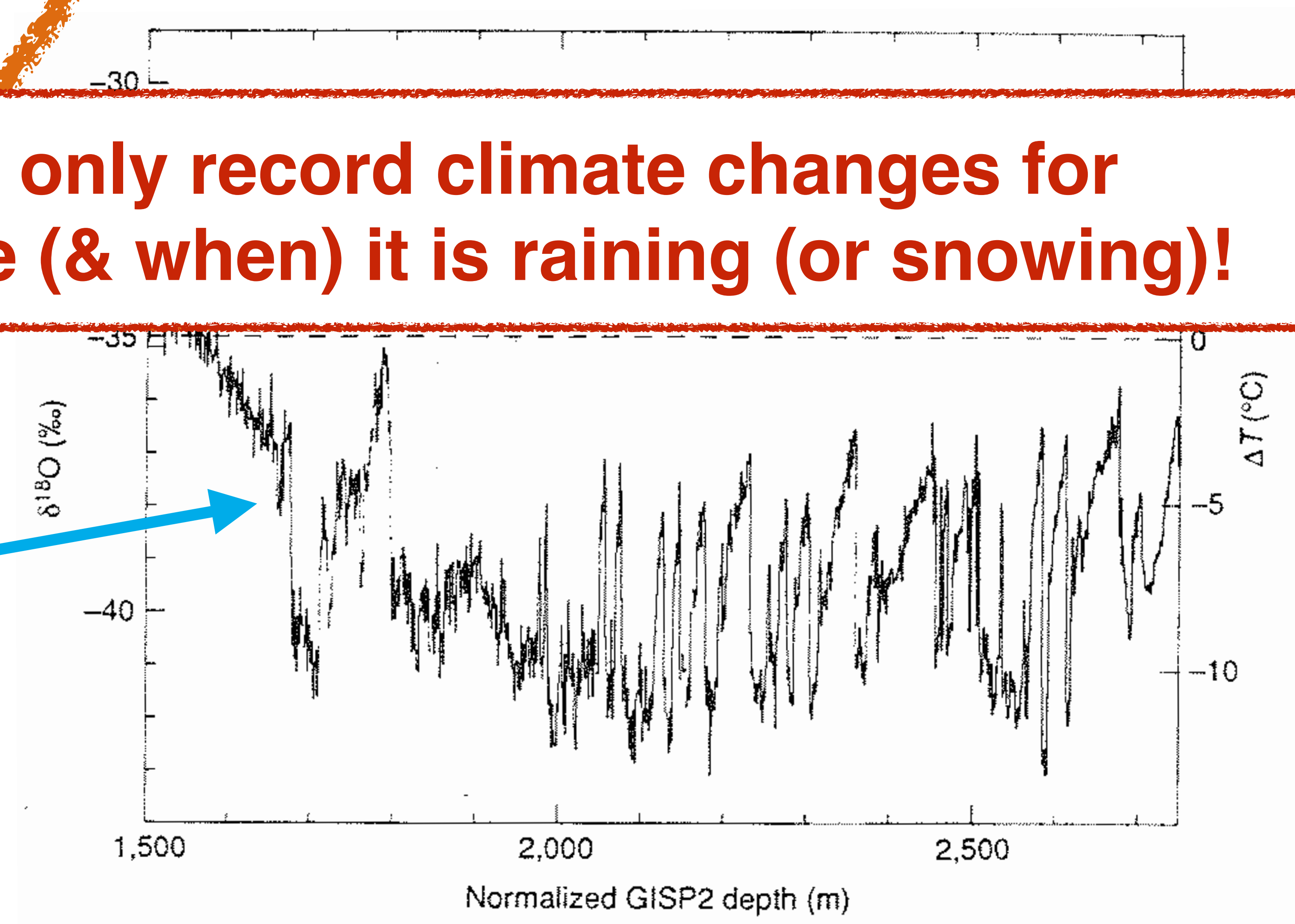


Modern spatial relation between δ18O and surface temperature (on Greenland):

$$\delta^{18}O = 0.67 \cdot T_{surf}$$

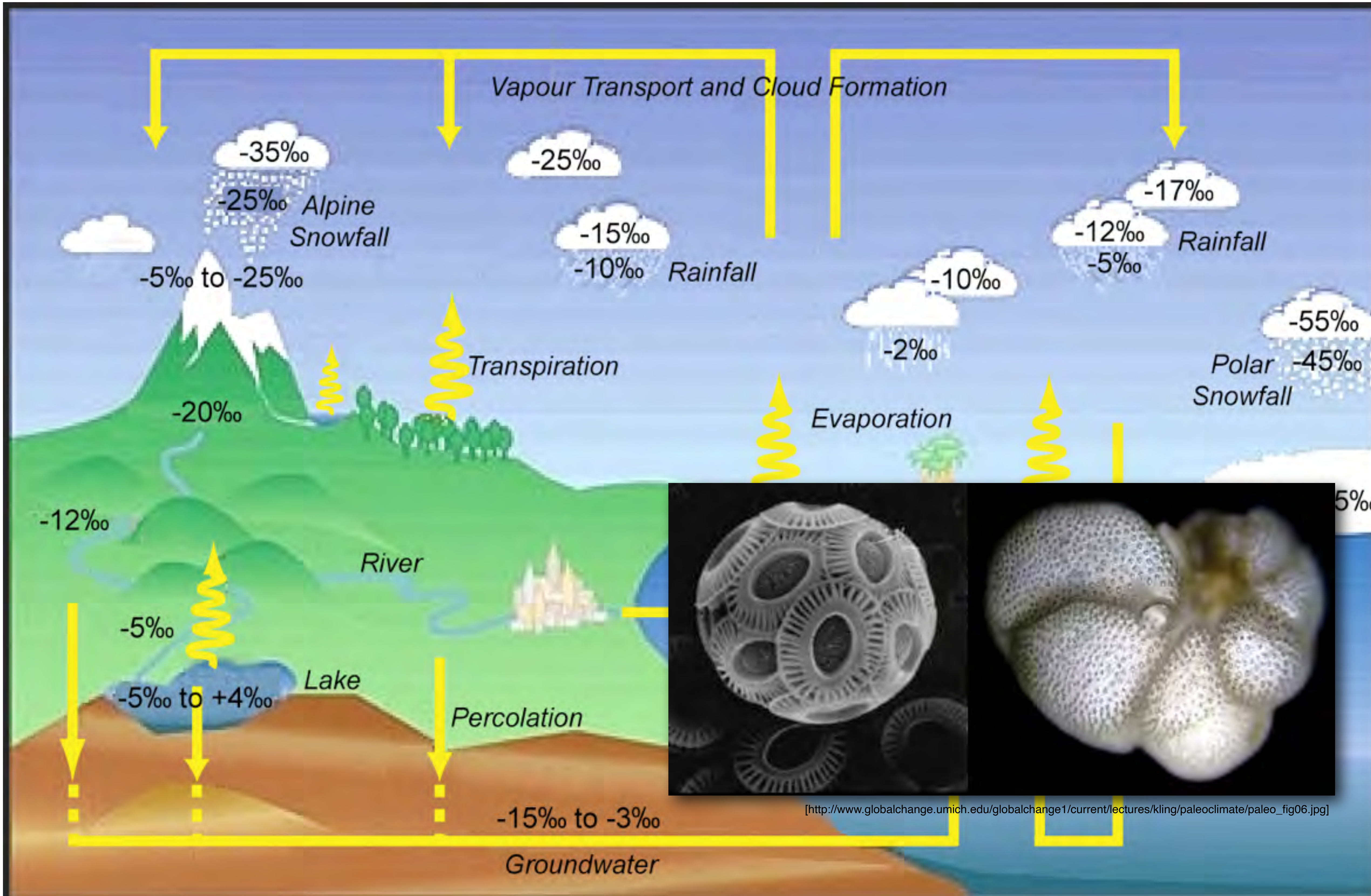
Stable water isotopes only record climate changes for places (& periods), where (& when) it is raining (or snowing)!

Converting temporal changes of δ18O into past temperature changes



[Grootes et al., Nature, 1993]

The $\delta^{18}O$ signal in marine sediment cores



[plot adapted from the GNIP brochure, IAEA, 1996]

The $\delta^{18}O$ signal in marine sediment cores

- **during the formation of calcium-carbonate ($CaCO_3$), ^{18}O gets enriched in the carbonate**
  - *this fractionation effect occurs in different marine species, e.g. foraminifera*
  - *the fractionation strength is temperature-dependent (less fractionation with warmer temperatures)*
- **when large ice sheets (depleted in ^{18}O) existed in the past, $\delta^{18}O$ of sea water must have been enriched**
  - *changes of ^{18}O of the sea water influences the ^{18}O signal in $CaCO_3$*
- *the ^{18}O signal in $CaCO_3$ contains both a local component (temperature) and a global component (ice volume)*
  - *an empirical global relationship was determined from a multi-core analysis:*

$$T = 16.9 - 4.2\,(\delta_c - \delta_w) + 0.13\,(\delta_c - \delta_w)^2$$

(with $\delta_c = \delta^{18}O_{CaCO3}$ and $\delta_w = \delta^{18}O_{Ocean}$)

The $\delta^{18}O$ signal in marine sediment cores

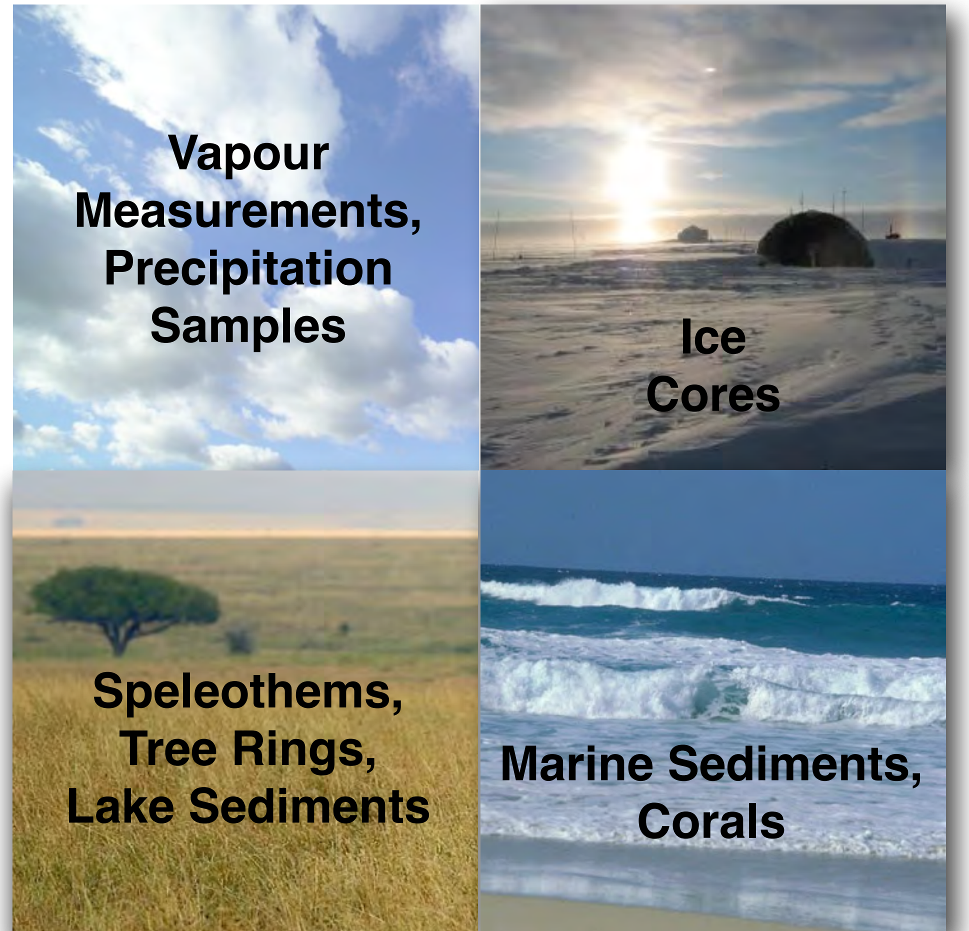
- for a correct interpretation of the $\delta^{18}O$ signal in $CaCO_3$, **temperature effect** and **ice volume effect** have to be separated

$$T = 16.9 - 4.2\,(\delta_c - \delta_w) + 0.13\,(\delta_c - \delta_w)^2$$

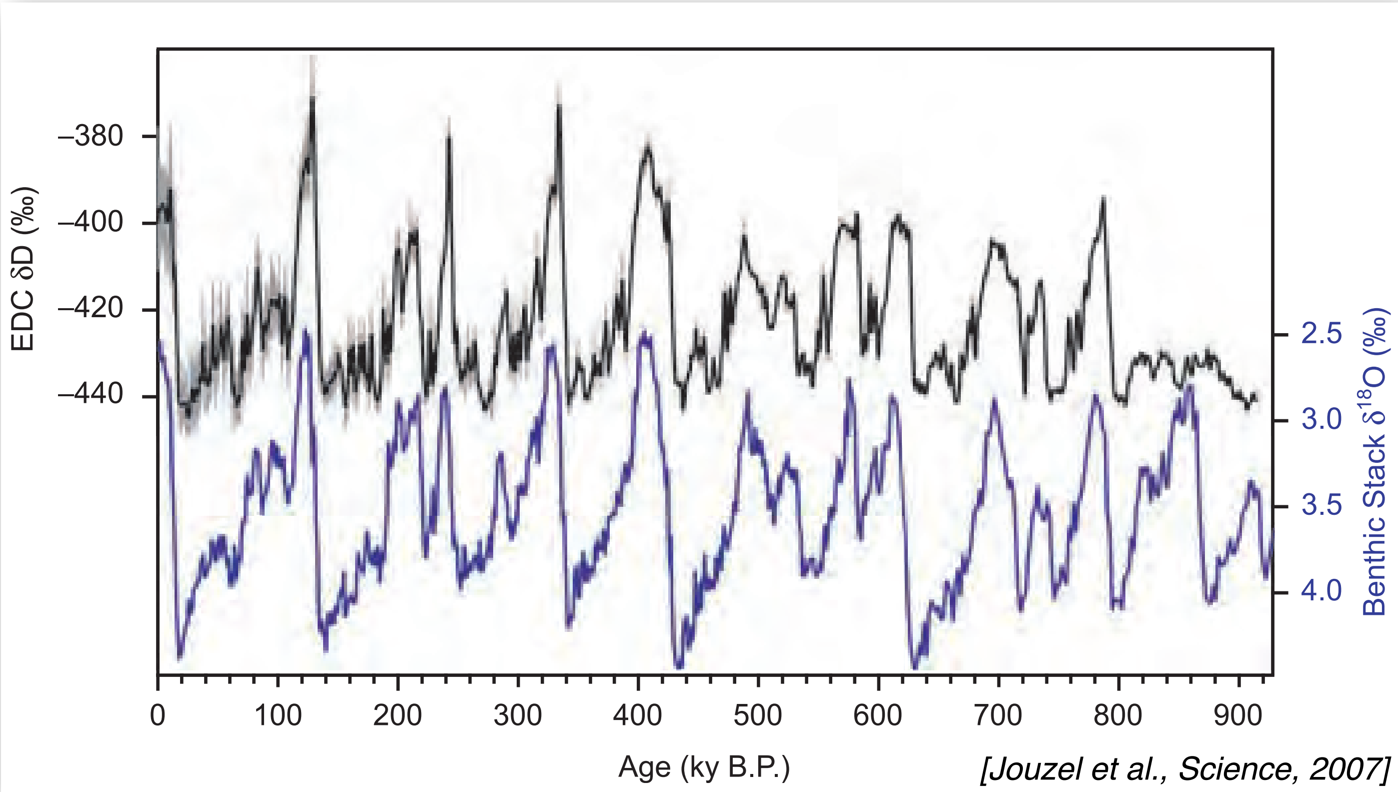
(with $\delta_c = \delta^{18}O_{CaCO3}$ and $\delta_w = \delta^{18}O_{Ocean}$)

- *$\delta^{18}O_w$ might be determined by **porewater analyses** contained in the core*
- *$\delta^{18}O_c$ changes of **benthic foraminifers** living at the sea floor are mainly an **ice volume signal** (as temperatures does not change much at the sea floor)*

The use of δ¹⁸O and δD as a climate proxy in paleo archives

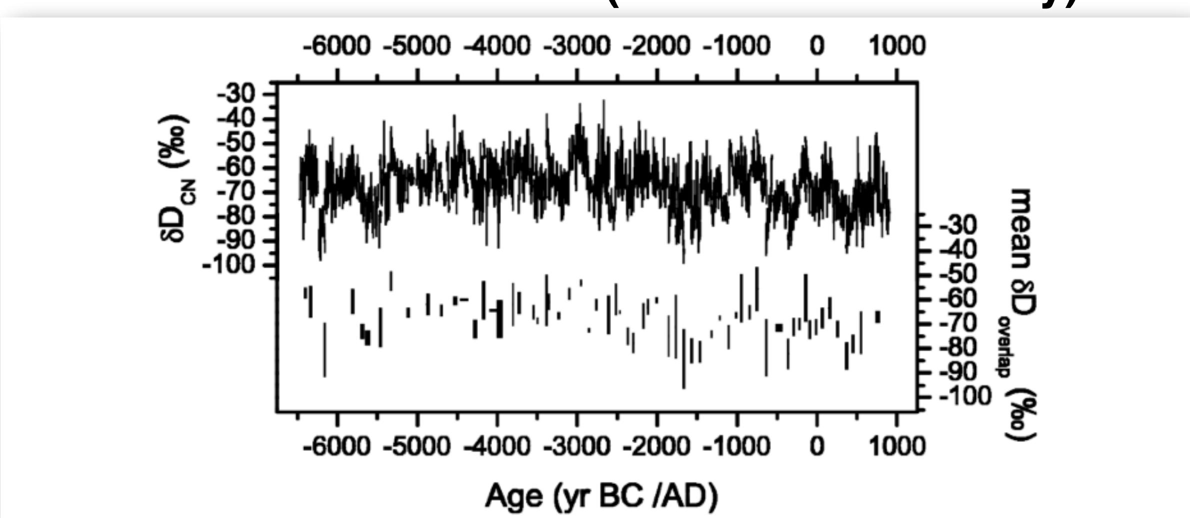


EPICA Dome C and Benthic Oxygen-18 Records



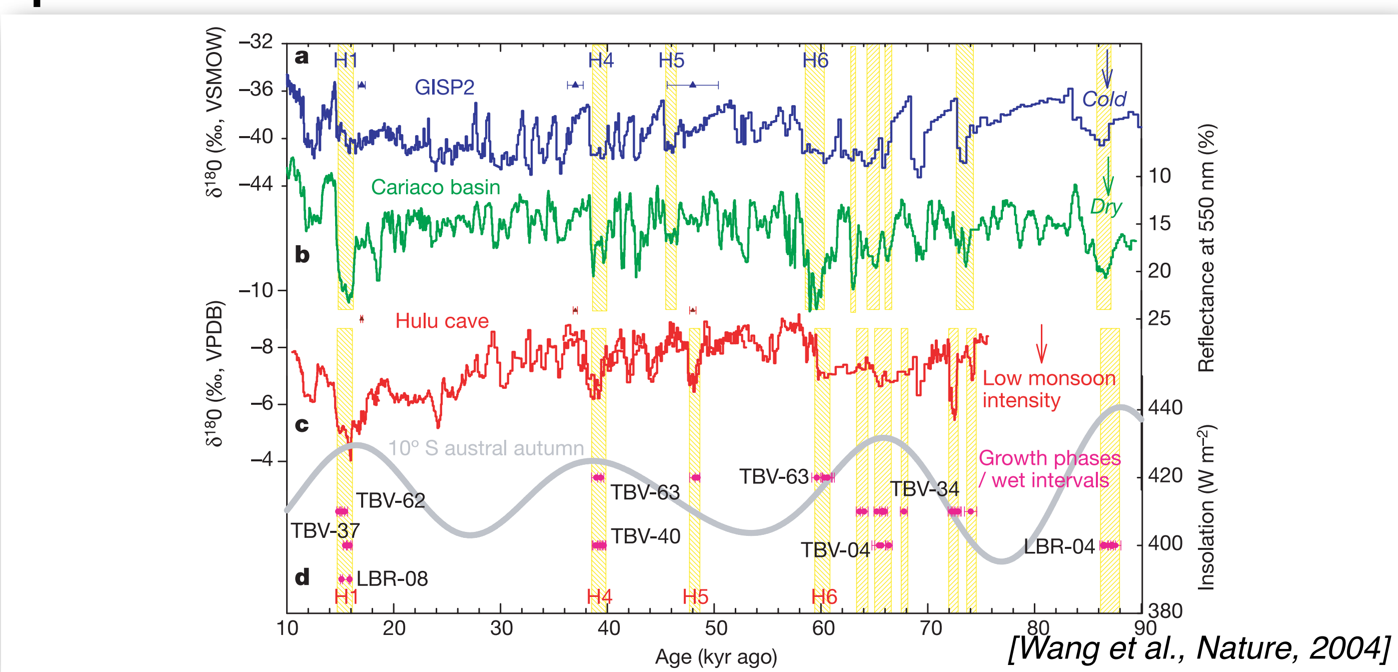
[Jouzel et al., Science, 2007]

Subfossil Holocene Oaks (Southern Germany)



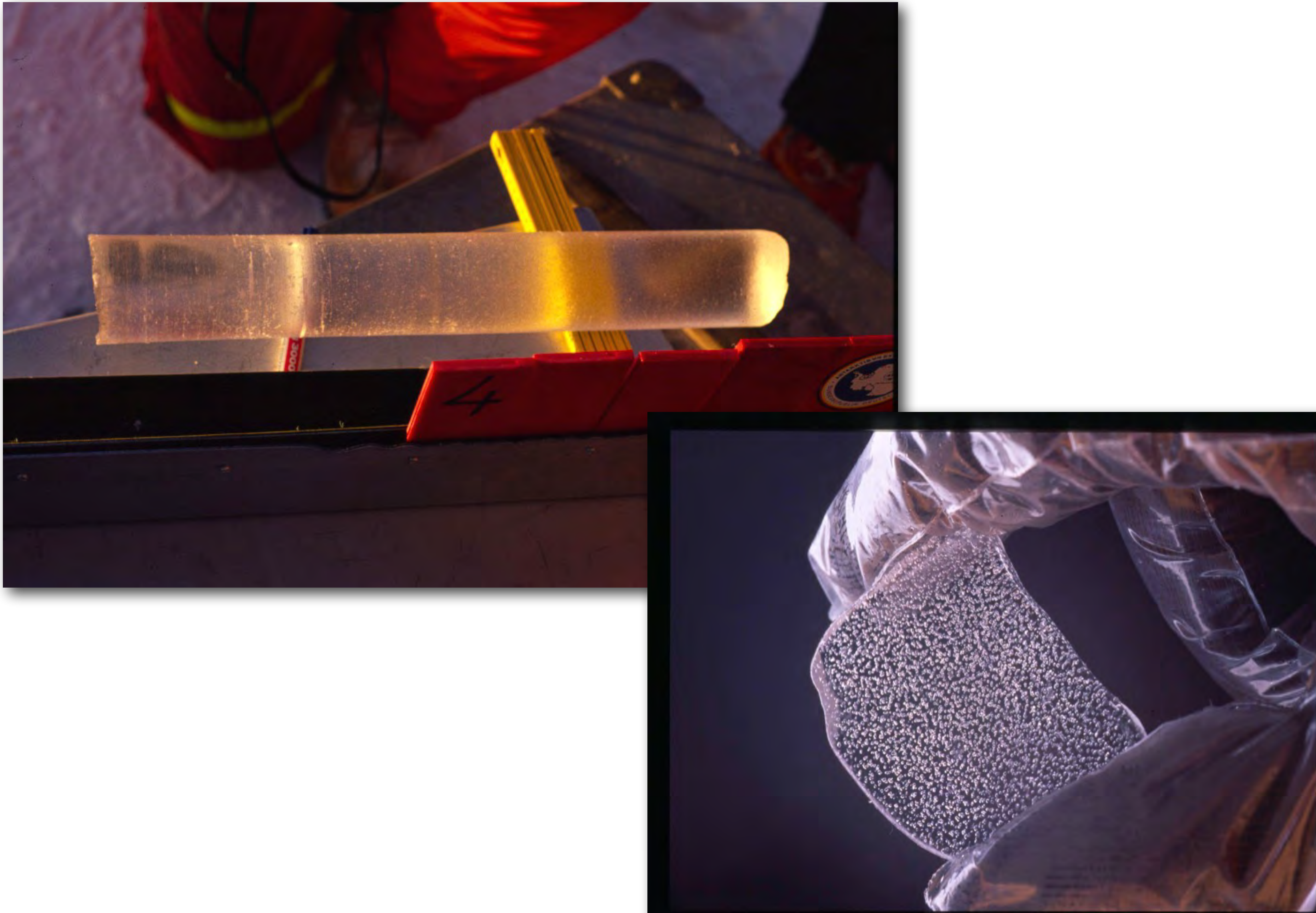
[Mayr et al., The Holocene, 2003]

Speleothem Records from Eastern China and Southern Brasil



[Wang et al., Nature, 2004]

Ice cores - a key climate archive



Cross section of an ice sheet

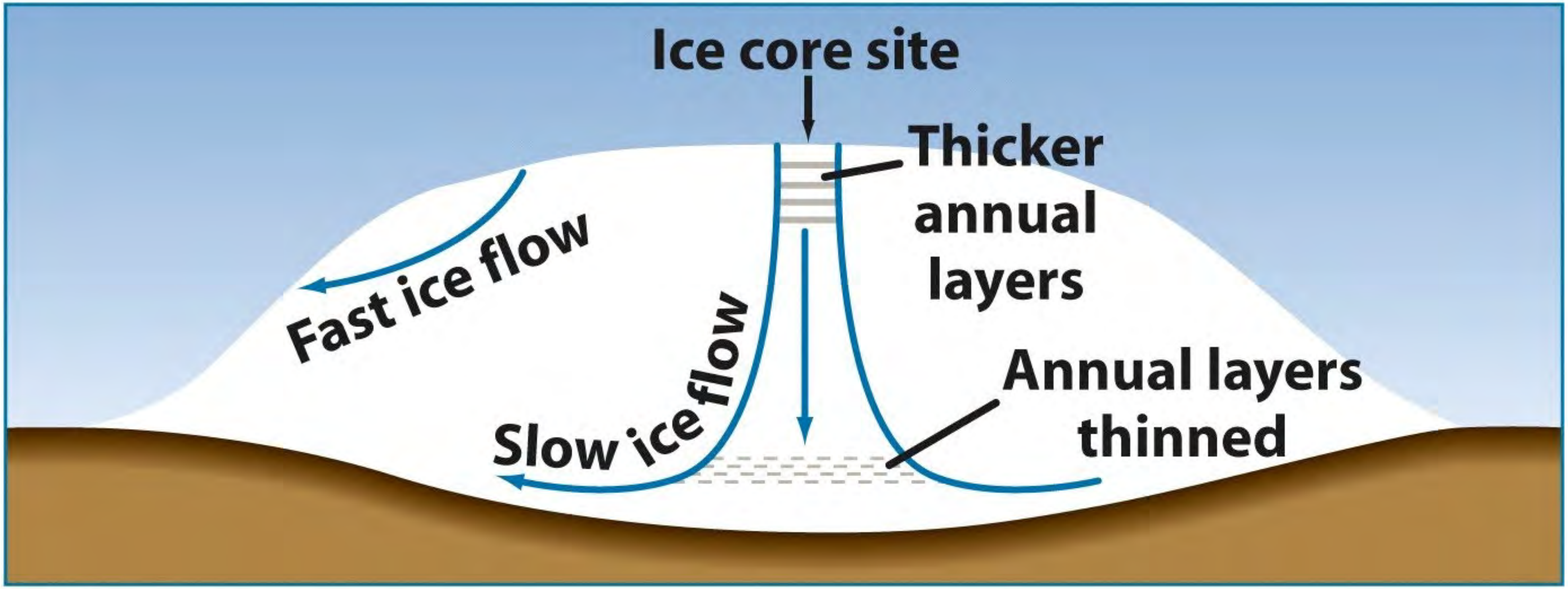
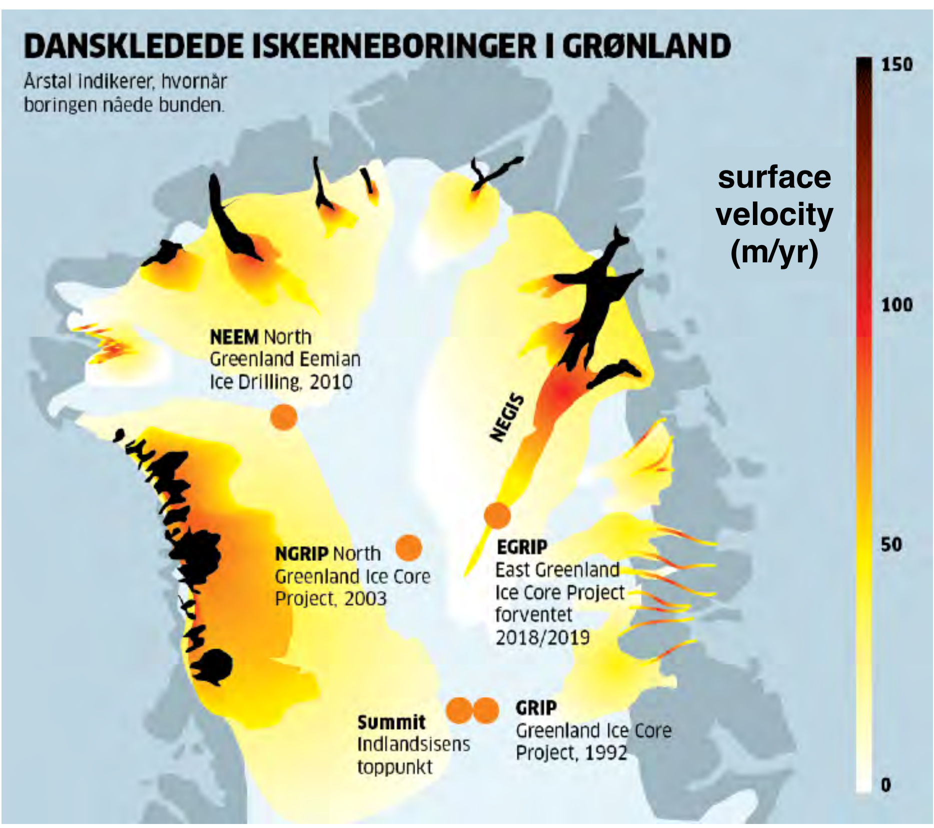
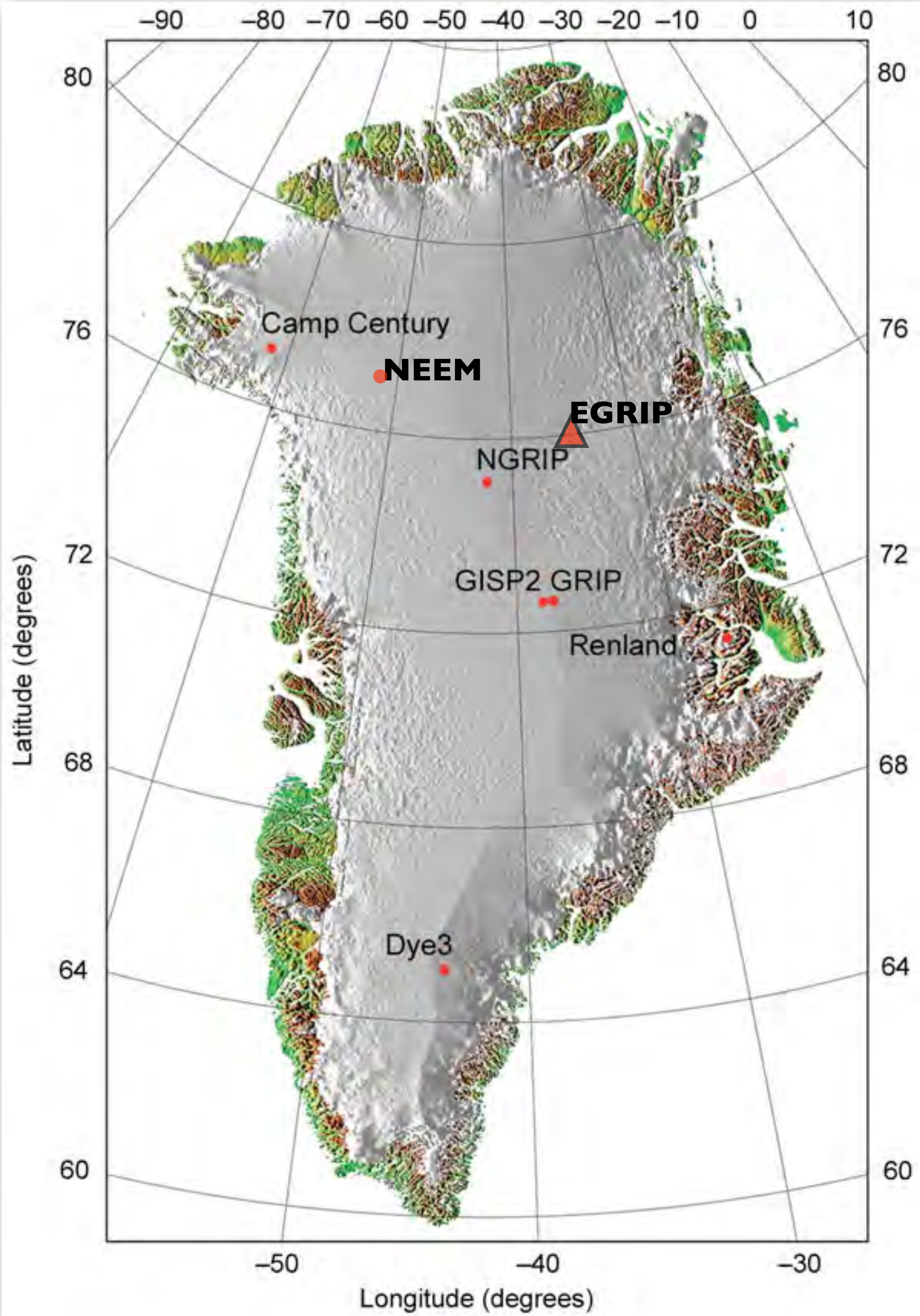


Figure 10-1
Earth's Climate: Past and Future, Second Edition

Greenland ice cores

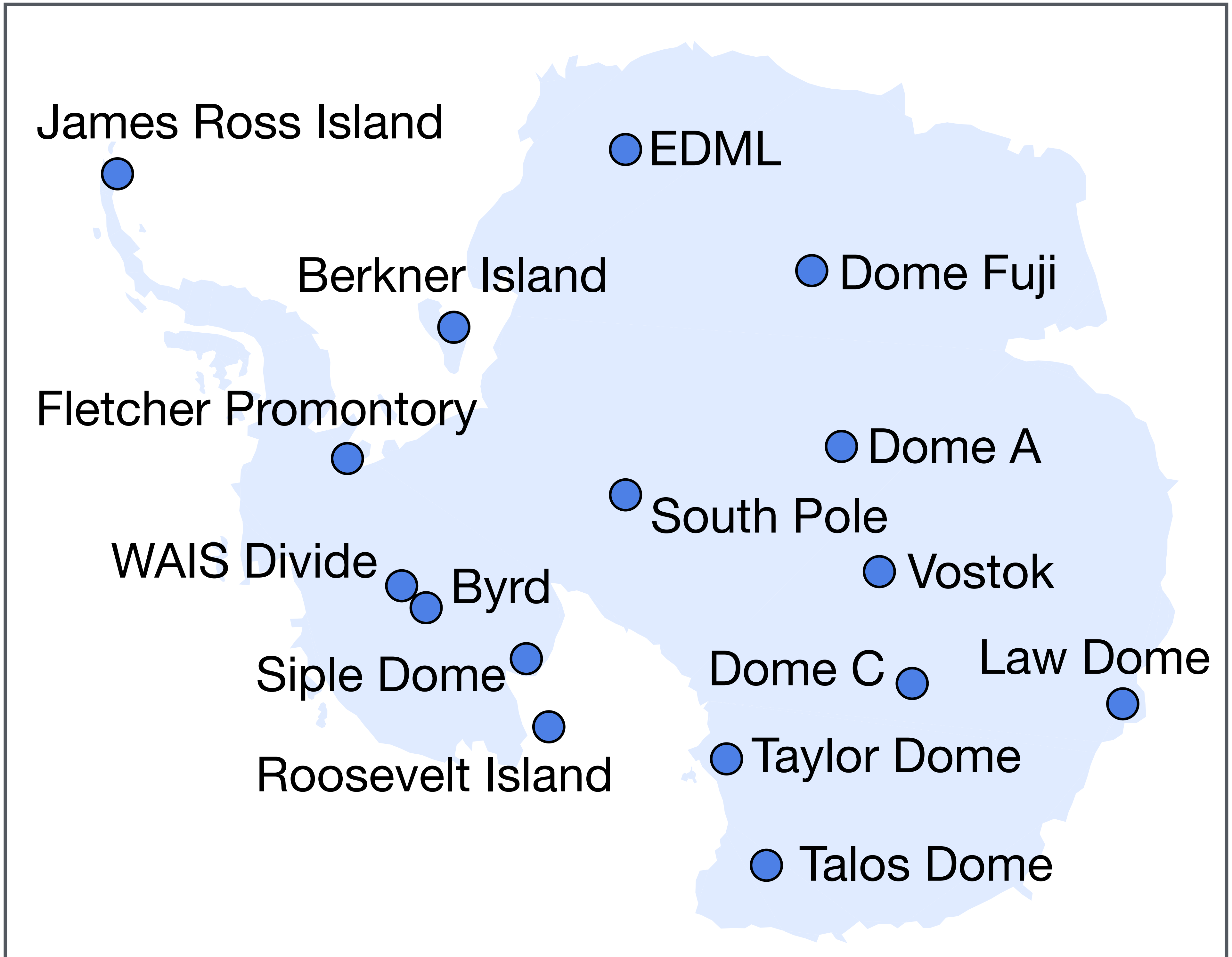


https://ing.dk/artikel/dynamikken-gronlands-isstromme-joker-klimaet-197376



http://www.nature.com/nature/journal/v431/n7005/fig_tab/nature02805_F1.html

Antarctic ice cores



[Brook and Buizert, Nature, 2018]

Ice core sites in (sub)tropical regions

Location of the most important stable isotope records from tropical ice cores:

❶ Chimborazo (Francou, 2000, pers. comm.) ❷ Huascarán (Thompson et al., 1995)
❸ Quelccaya (Thompson et al., 1984) ❹ Illimani (Hoffmann et al., 2002)
❺ Sajama (Thompson et al., 1998) ❻ Kilimanjaro (Thompson et al., 2002)
❼ Dasuopu (Thompson et al., 2000b) ❽ Guliya (Thompson et al., 1997)
❾ Dunde (Thompson et al., 1989).

(from: M. Vuille, pers. comm.)

Ice cores

Quizz - Questions #2:

1. In which region can we find the oldest ice cores?

=> Antarctica

(most parts of Greenland melted approx. 130-125,000 B.P.)

2. How old is the oldest ice core retrieved so far?

=> approx. 800,000 years

Ice core drilling

Ice core drilling

Ice core drilling

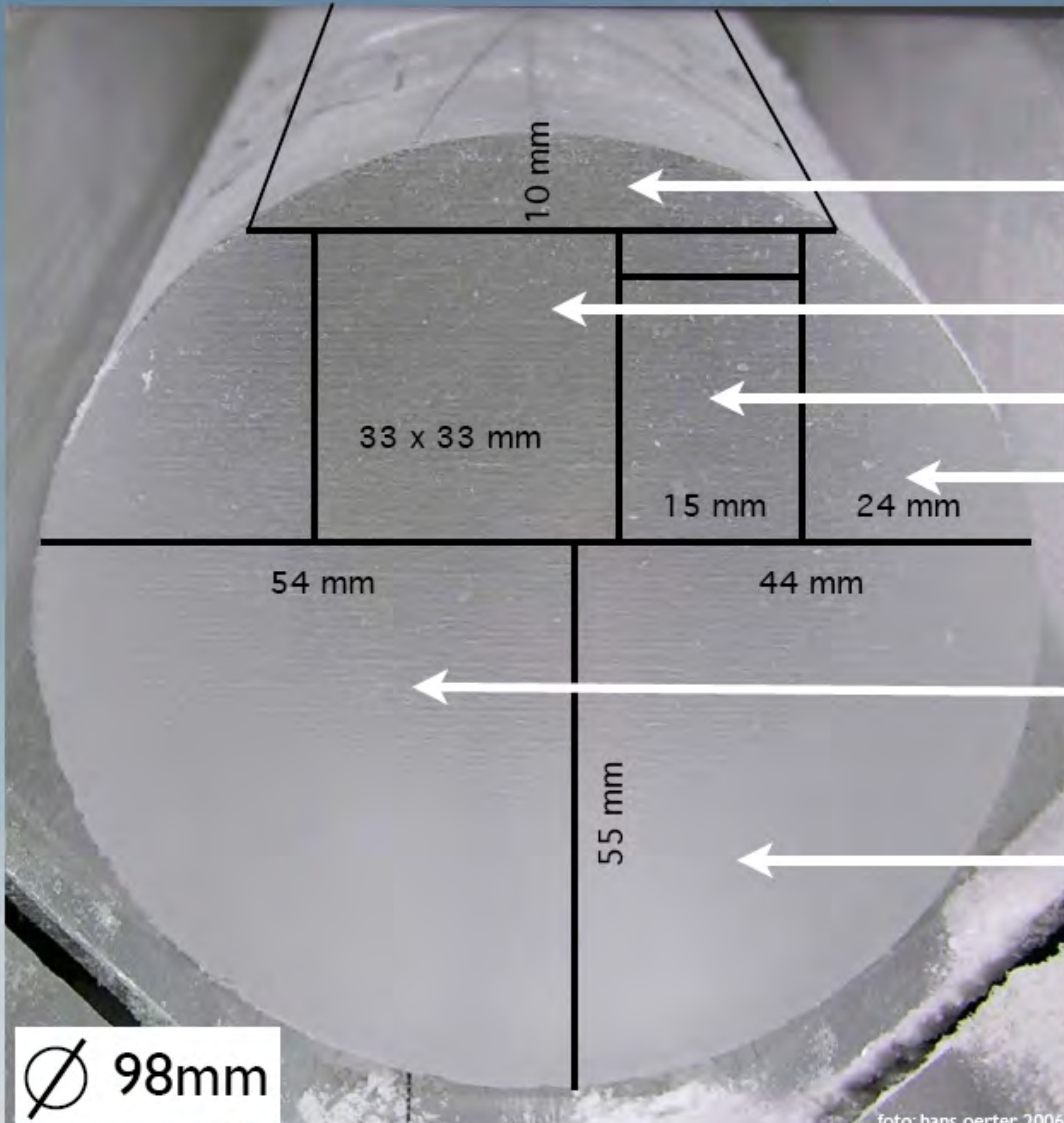
Ice core drilling

Ice core drilling

Ice core drilling

Ice Core Laboratory, AWI Bremerhaven

Ice core drilling



Optical Analyses

Chemical Analyses

$\delta^{18}O$

^{10}Be

Archive

Gas & Dust Analyses

Hans Oerter, AWI

Dating methods

- relevance of dating methods
  - an exact dating is the Achilles‘ heel of all paleoclimate data series!!
  - even the most exact measurements and/or reconstructions of climate change (e.g., temperature change, precipitation pattern) are useless, if the timing of the change is not known well enough

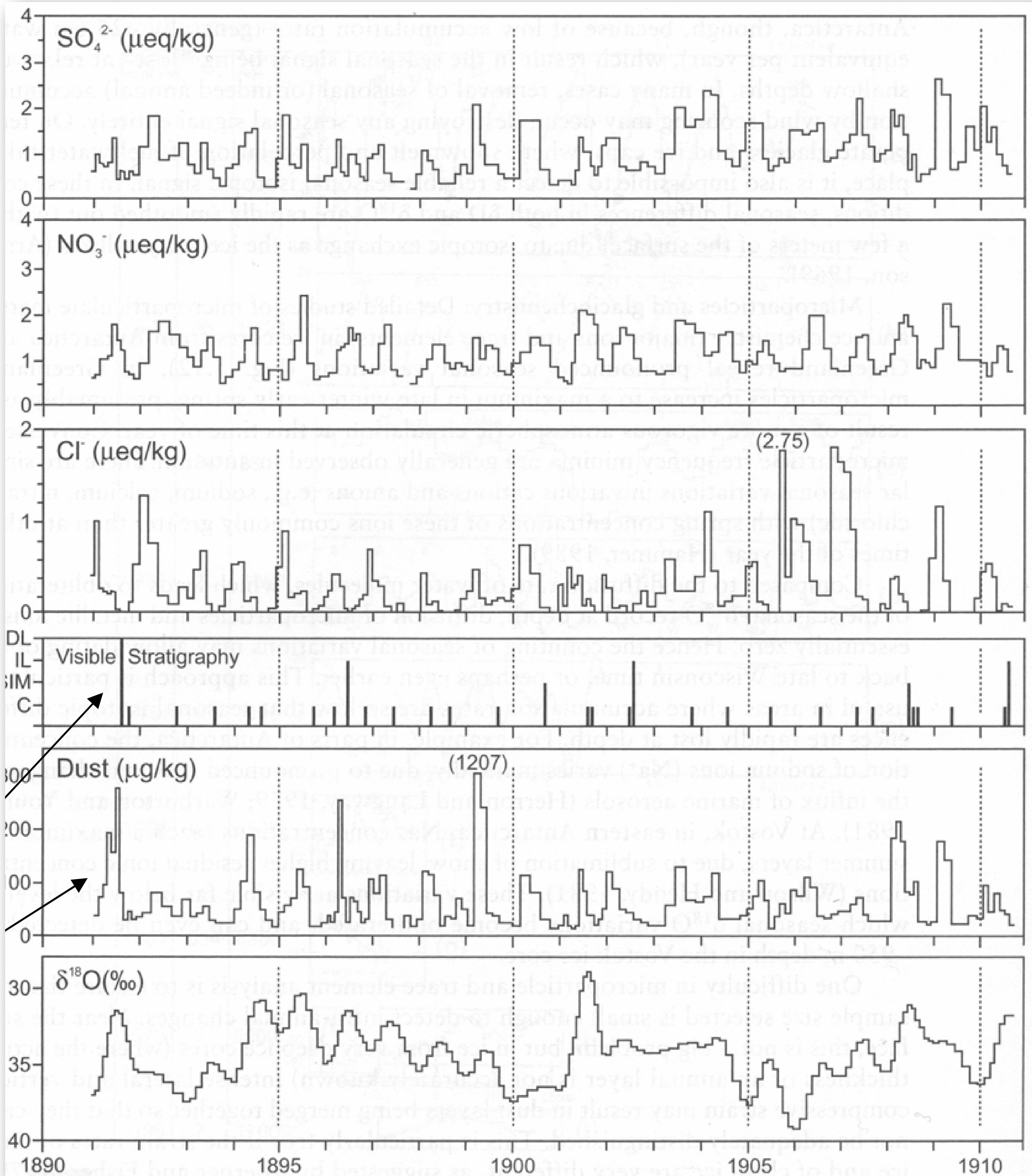
- difference in dating methods
  - absolute dating:
    climate events can be attributed to a specific calendar year (or duration of years)
  - relative dating:
    the temporal order of several climate events can be determined, but not the absolute timing of these events

Dating methods

Quizz - Questions #3:

- **Which dating methods could be used for ice cores?**
  - ***counting annual layers***
  - ***identifying individual time horizons (e.g. volcanic events)***
  - ***radioisotope dating (but no ^{14}C dating, so far)***
  - ***modelling of ice flow dynamics***
  - ***synchronising different ice cores (e.g. via CH_4 concentrations) and/or synchronising ice cores with marine & terrestrial records („wiggle matching“)***

Example: dating of ice cores - annual layer counting



Bradley, Abb. 5.12

<u>Example:</u> ice core synchronising via methane records

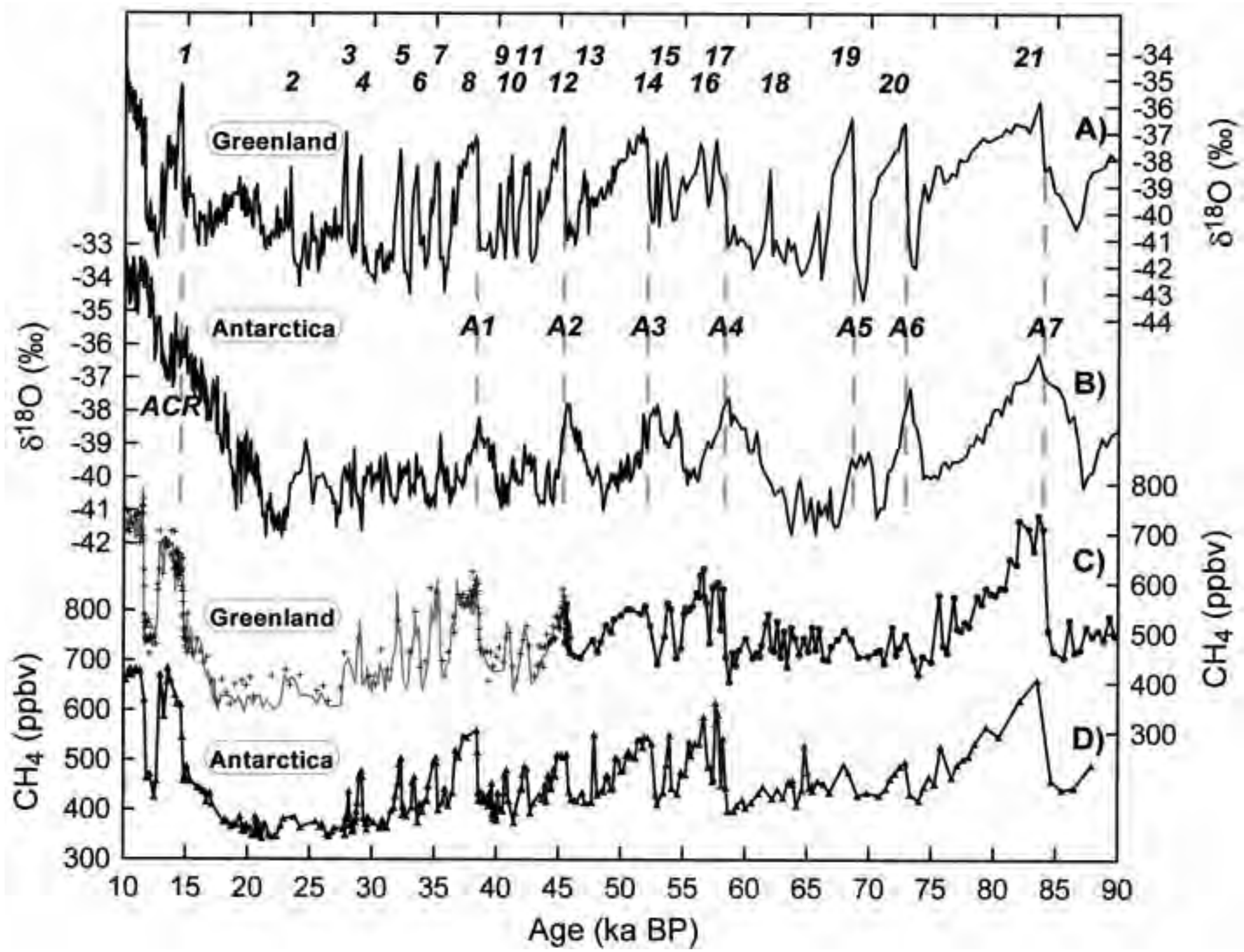


Fig. 1. Isotopic and CH_4 data from Greenland and Antarctica on the GISP2 time scale. Dashed lines indicate the onset of major D-O events. (**A**) $\delta^{18}O_{ice}$ from GISP2, Greenland (*16*). (**B**) $\delta^{18}O_{ice}$ from Byrd station, West Antarctica (*23*). (**C**) CH_4 data from GISP2 and GRIP. Crosses and dots are from GISP2 [(*4*) and new data]; the solid gray line is from GRIP (*2*, *8*). The solid line runs through the data used for the synchronization: GISP2 (black line) up to 45.5 ka and GRIP data (gray line) from 45.5 ka to the Holocene. (**D**) CH_4 data from Byrd station [(*2*) and new data]. Data are available as supplemental information on *Science* Online (*10*) and at the NOAA Geophysical Data Center (*5*).

Blunier & Brook, Science, 2001

Ice cores - a key climate archive

- <u>ice cores</u>
  - where are they drilled?
  - how are they drilled?
  - how are they dated?

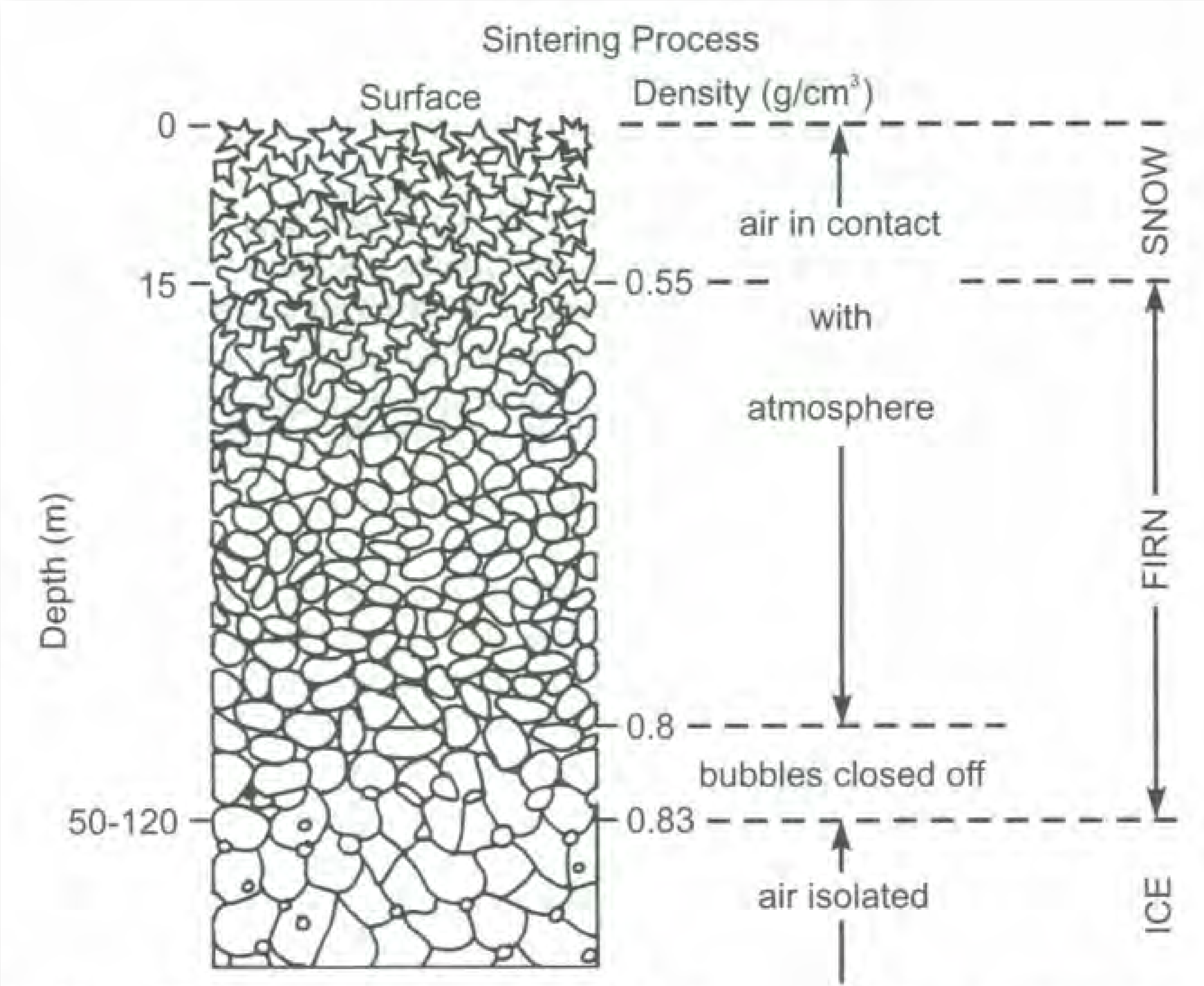
- <u>key analyses</u>
  - temperature reconstruction by stable water isotopes
  - *gas analyses - the composition of the past atmosphere*

Ice cores are currently the only archive

which allow to directly measure

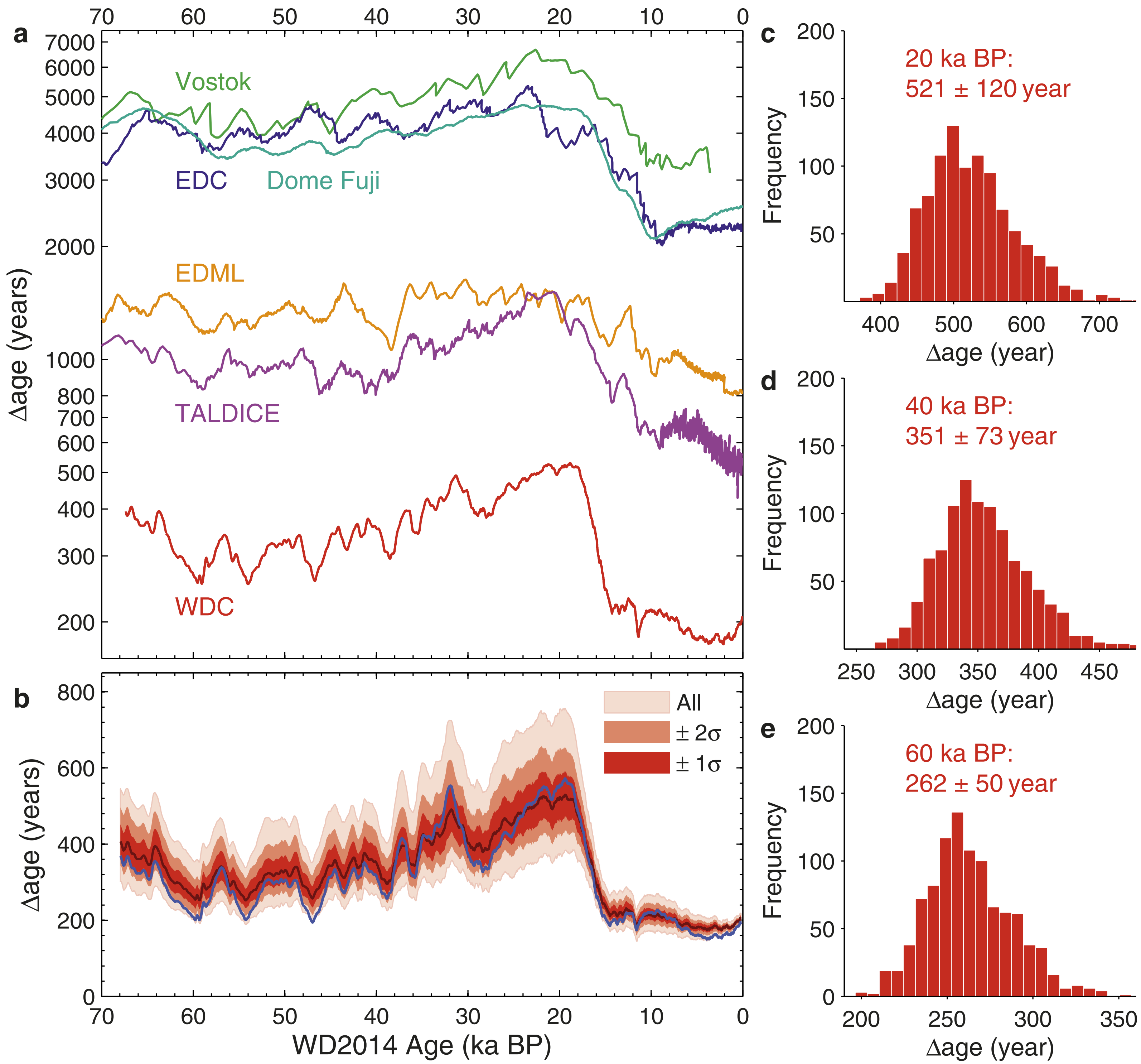
the past atmospheric composition!

Transformation of snow to ice



Bradley, Abb. 5.30

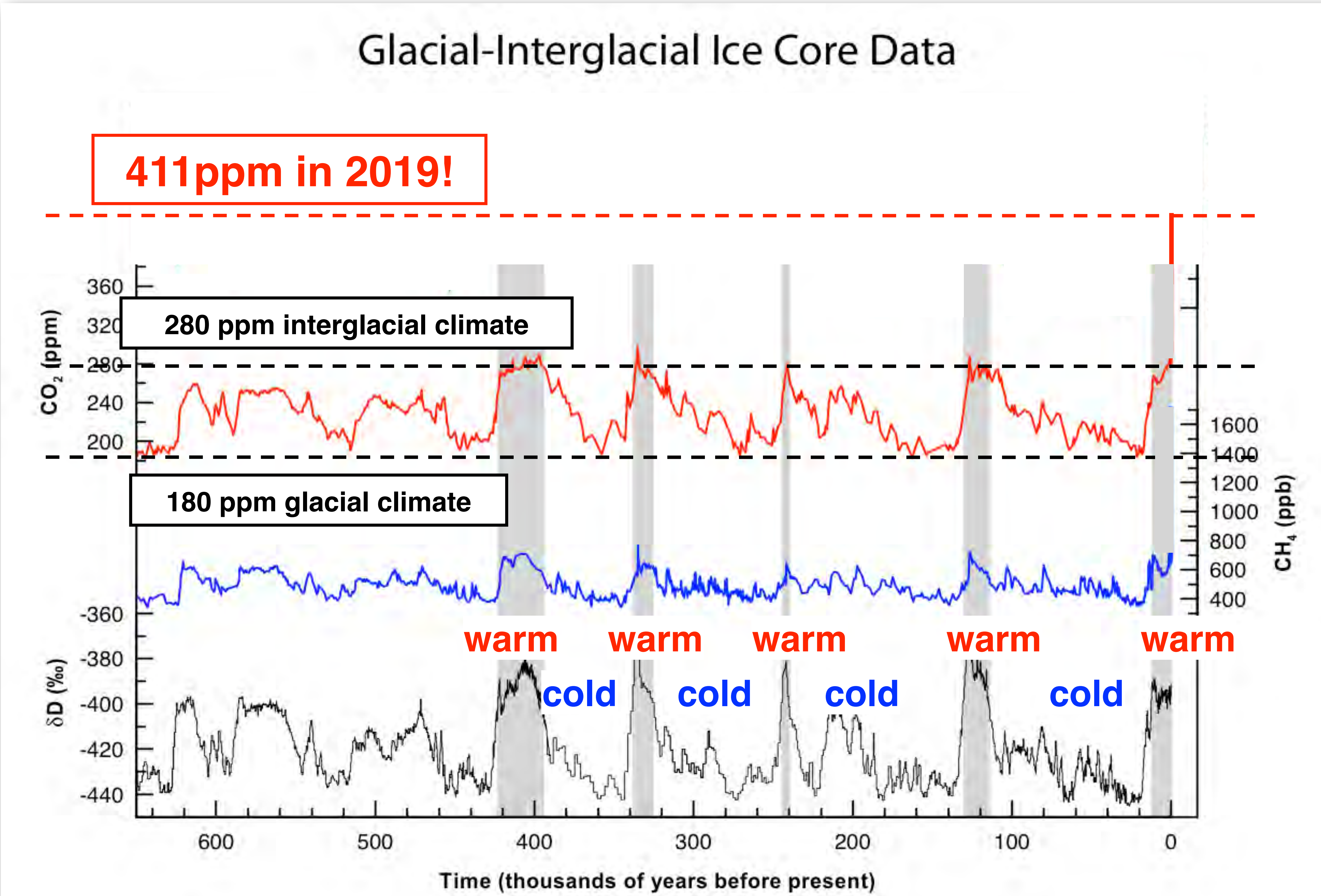
Example: difference between ice age and gas age



Extended Data Figure 1 | Difference between gas age and ice age (Δage) at WAIS Divide. **a**, Comparison of WDC Δage with other Antarctic cores. Ice core abbreviations: EDC, EPICA Dome Concordia; EDML, EPICA Dronning Maud Land; TALDICE, Talos Dome; WDC, WAIS Divide. Δage values are taken from refs 23, 63–65. The vertical axis is on a logarithmic scale. **b**, Δage uncertainty bounds obtained from an ensemble of 1,000 alternative Δage scenarios; details are given elsewhere[23]. A Δage scenario obtained with an alternative densification model (ref. 39 instead of ref. 38) is shown in blue. **c**–**e**, Histograms of the 1,000 Δage scenarios at 20 kyr BP (**c**), 40 kyr BP (**d**) and 60 kyr BP (**e**); stated values give the distribution mean ± the 2σ standard deviation.

WAIS Divide Project Members, Nature, 2015

Orbital-scale changes of greenhouse gases



Climate II

(Winter 2020/2021)

2nd lecture:

The Global Water Cycle

(water cycle, stable water isotopes, ice core records)

End of lecture.

Slides available at:

https://paleodyn.uni-bremen.de/study/climate2020_21.html