Climate System II

(Winter 2022/2023)

5th lecture:

The global water cycle

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

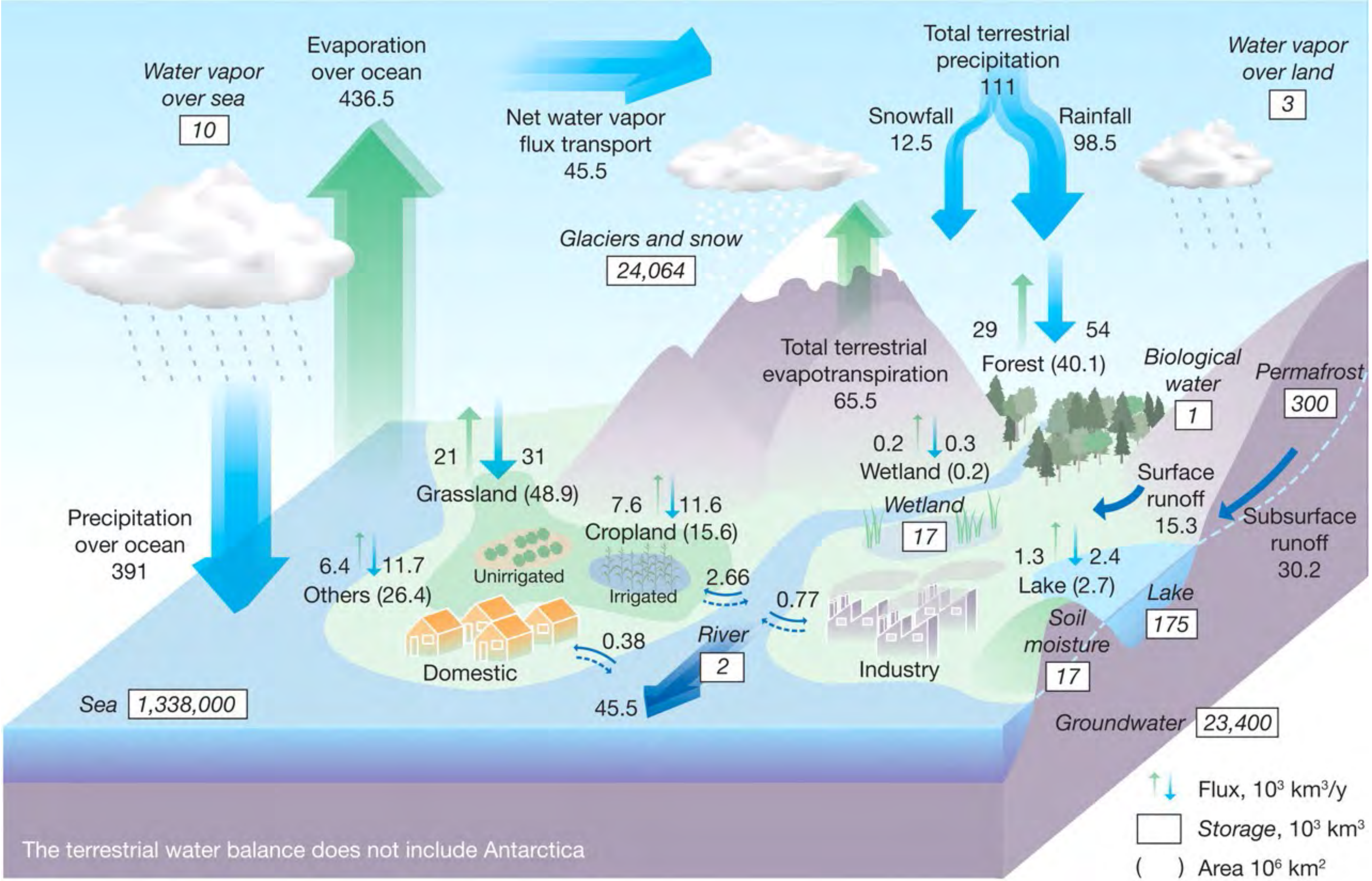
Gerrit Lohmann, Martin Werner

Tuesday, 10:00-11:45

(sometimes shorter, but then with some exercises)

https://paleodyn.uni-bremen.de/study/climate2022_23.html

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).

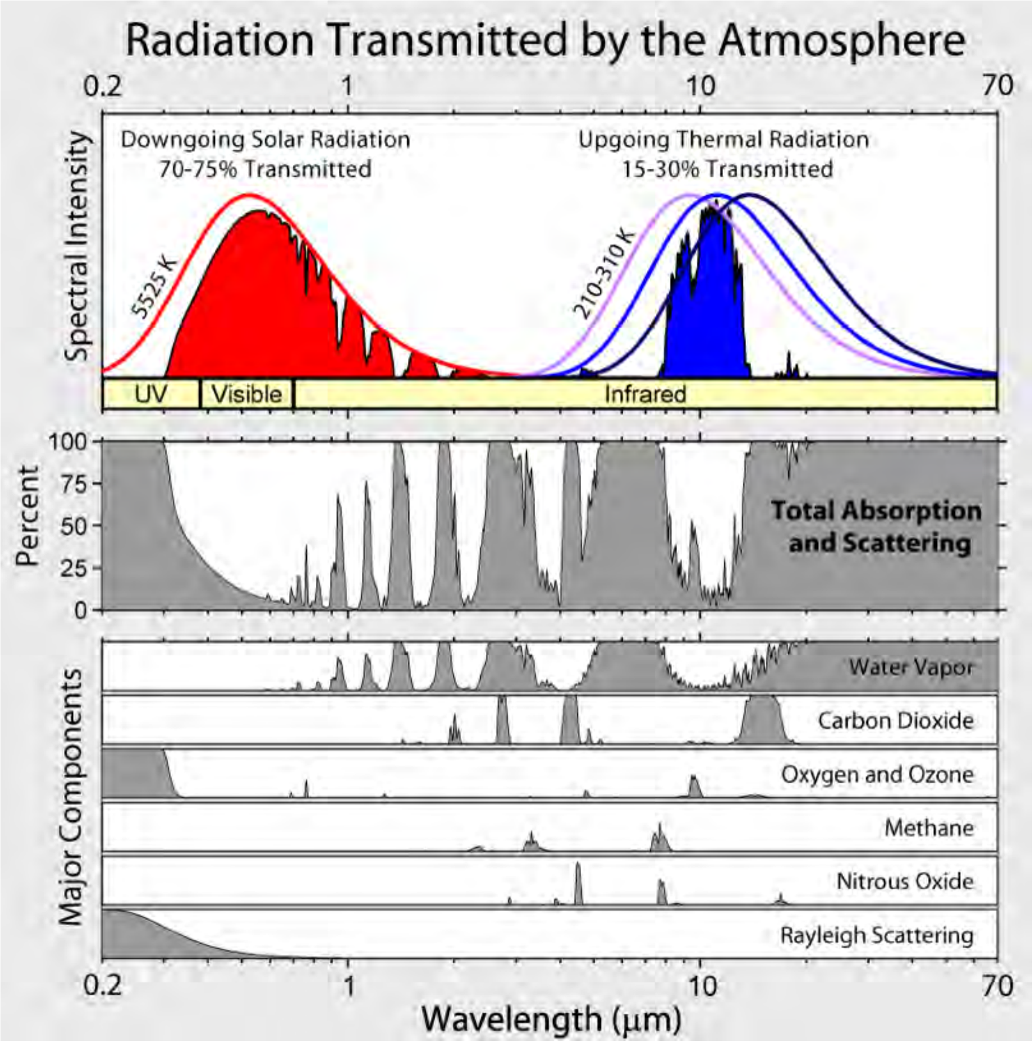
The global water cycle

- absolute water amount:
  (i) in the atmosphere: 0.013 $10^6 km^3$
  (ii) in the oceans: 1,338·$10^6 km^3$

- 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:

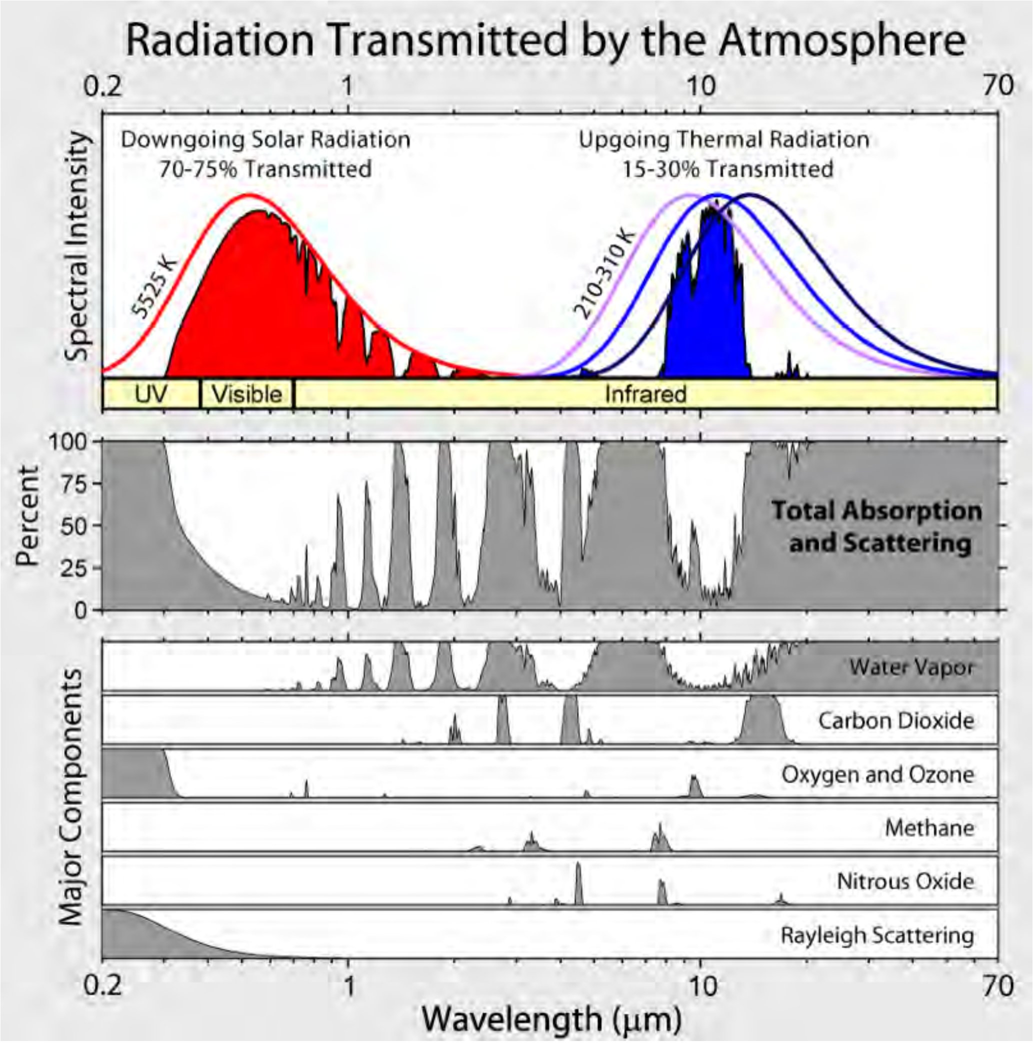
1. How many oceans do exist on Earth?

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

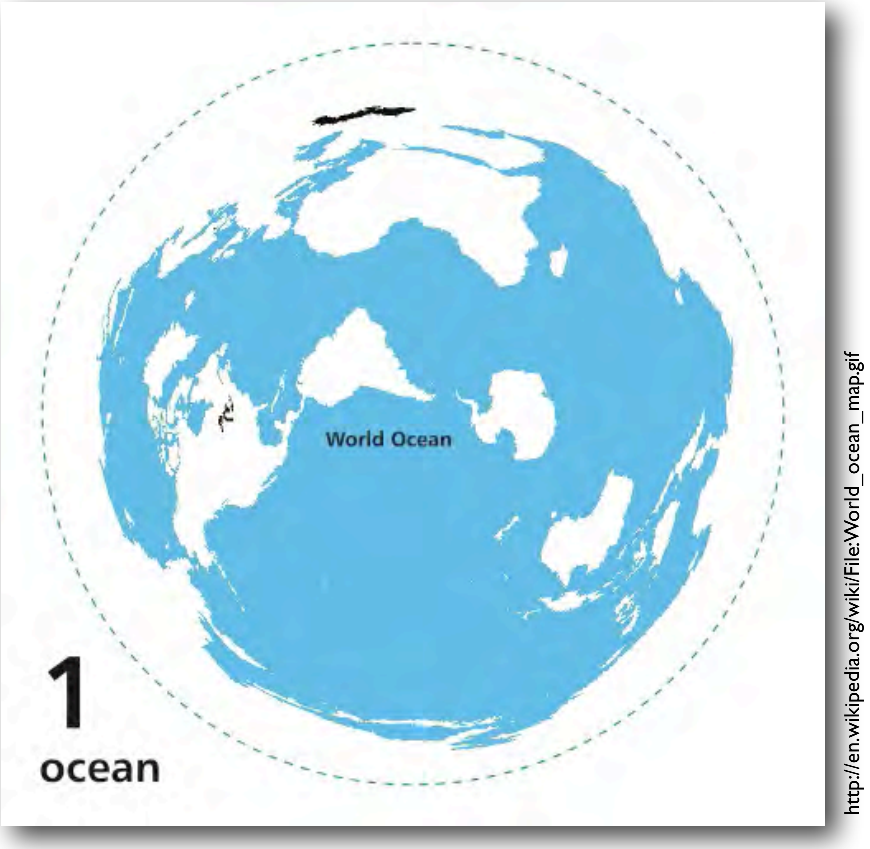
   => How high would such a water layer be?

The global water cycle

- absolute water amount:
  (i) in the atmosphere: 0.013 10^6km^3
  (ii) in the oceans: 1,338·10^6km^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
- how many oceans do exist on Earth
  => the answer depends whom you ask…
- all vapour condensed as a liquid layer
  => layer would be approx. 2.5cm high

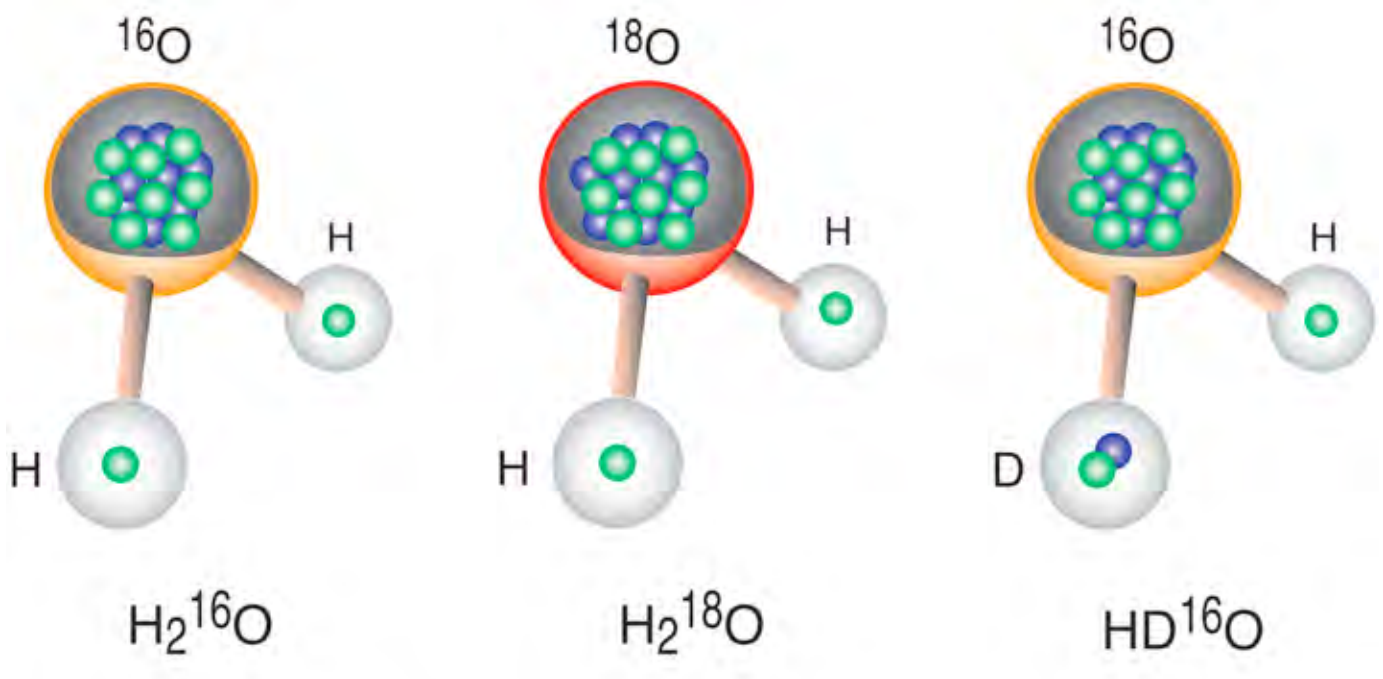


https://en.wikipedia.org/wiki/Greenhouse_gas



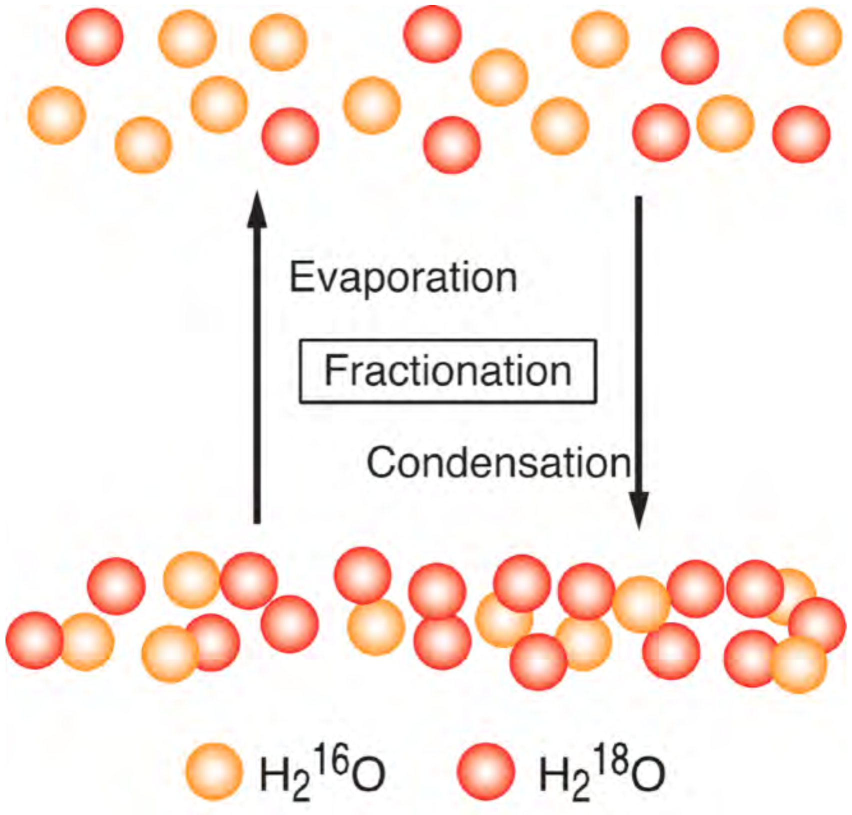
http://en.wikipedia.org/wiki/File:World_ocean_map.gif

Natural abundance of stable water isotopes



1,000,000 2005.2 311.52

approx. number of molecules in ocean water



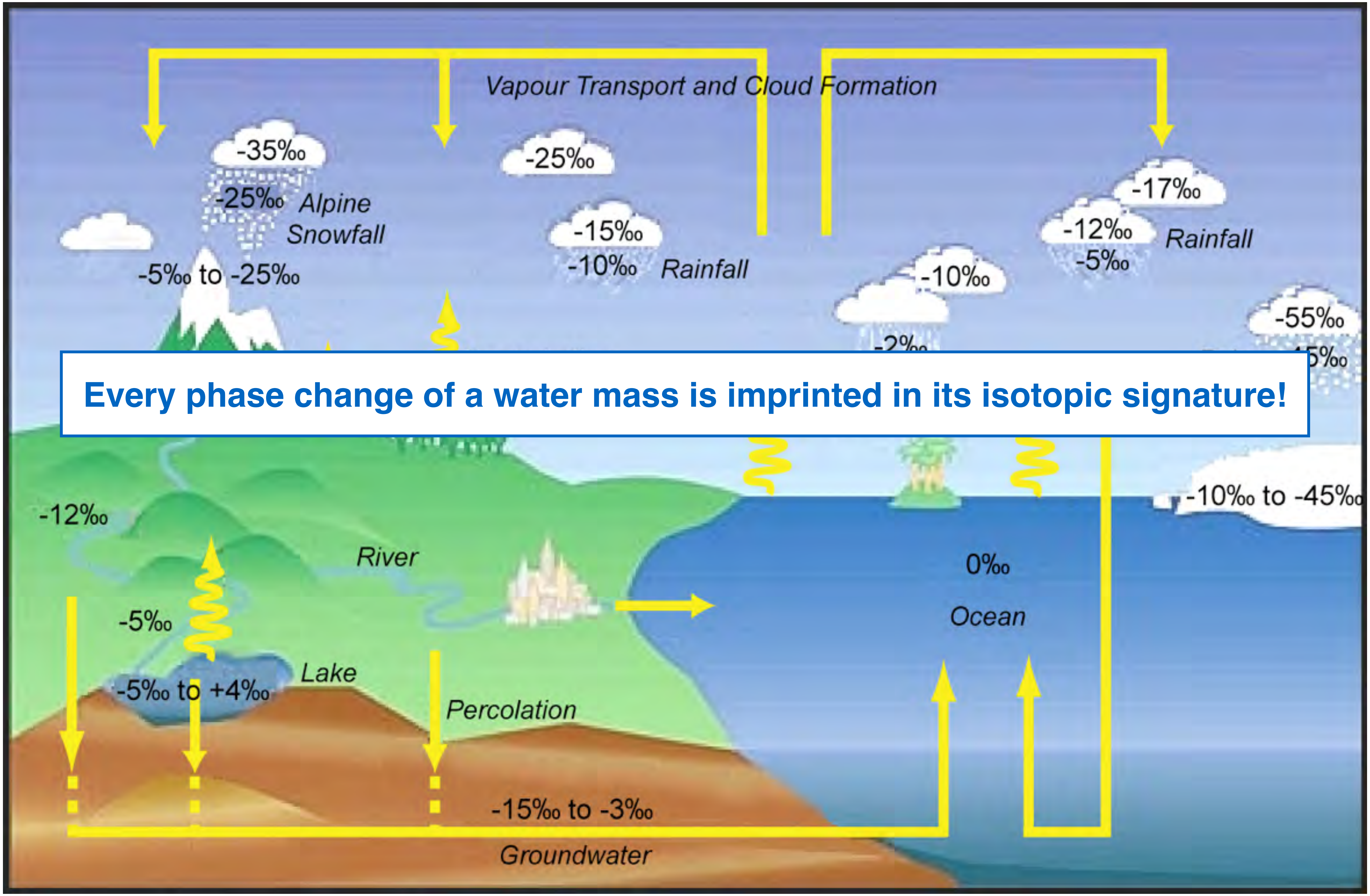
- **different isotopes have a different molecular weight and a different molecular symmetry** *(both effects change the vapour pressure of the water isotopes)*

- **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 ‰)**

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

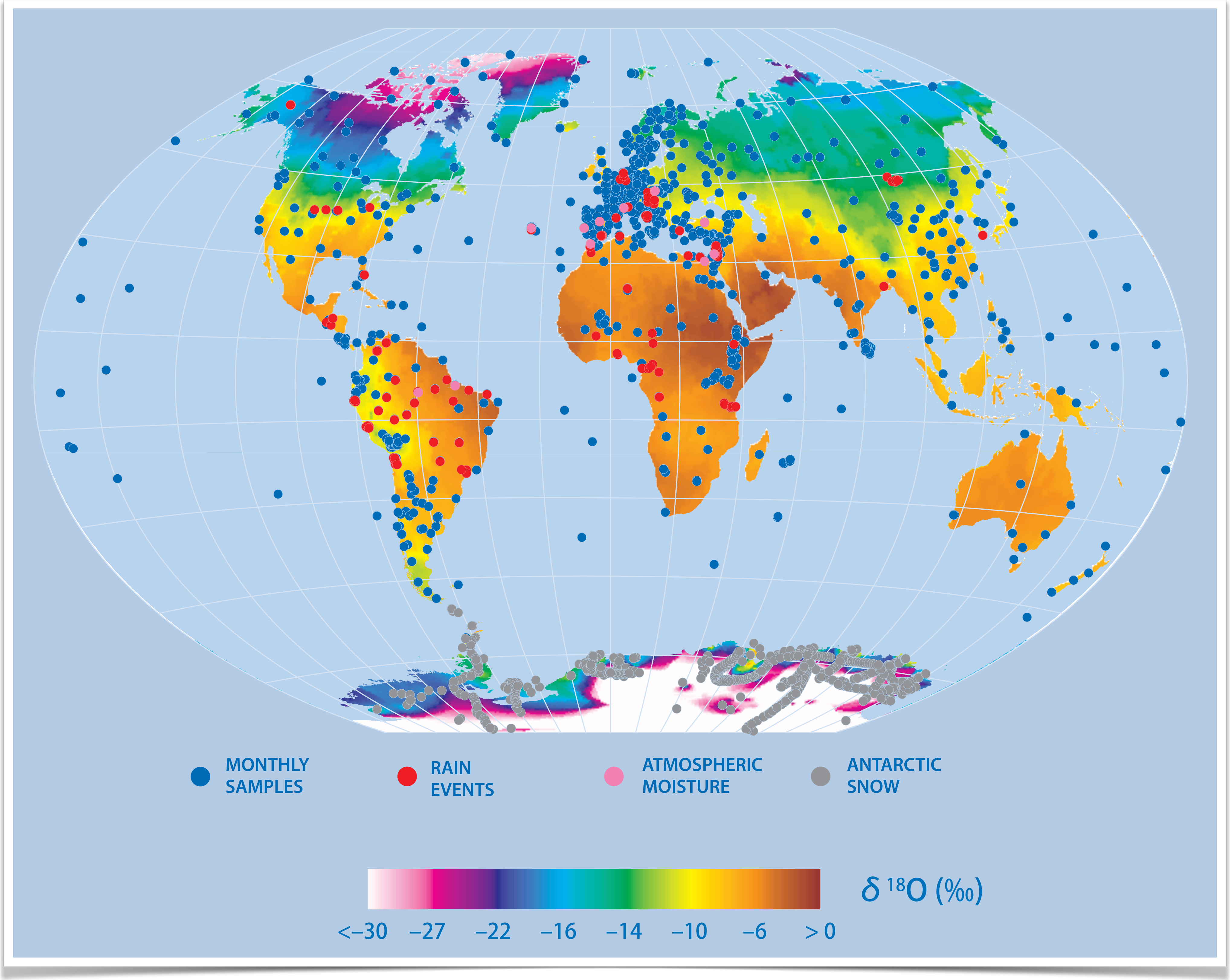
Global distribution of $\delta^{18}O$ in the hydrological cycle



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

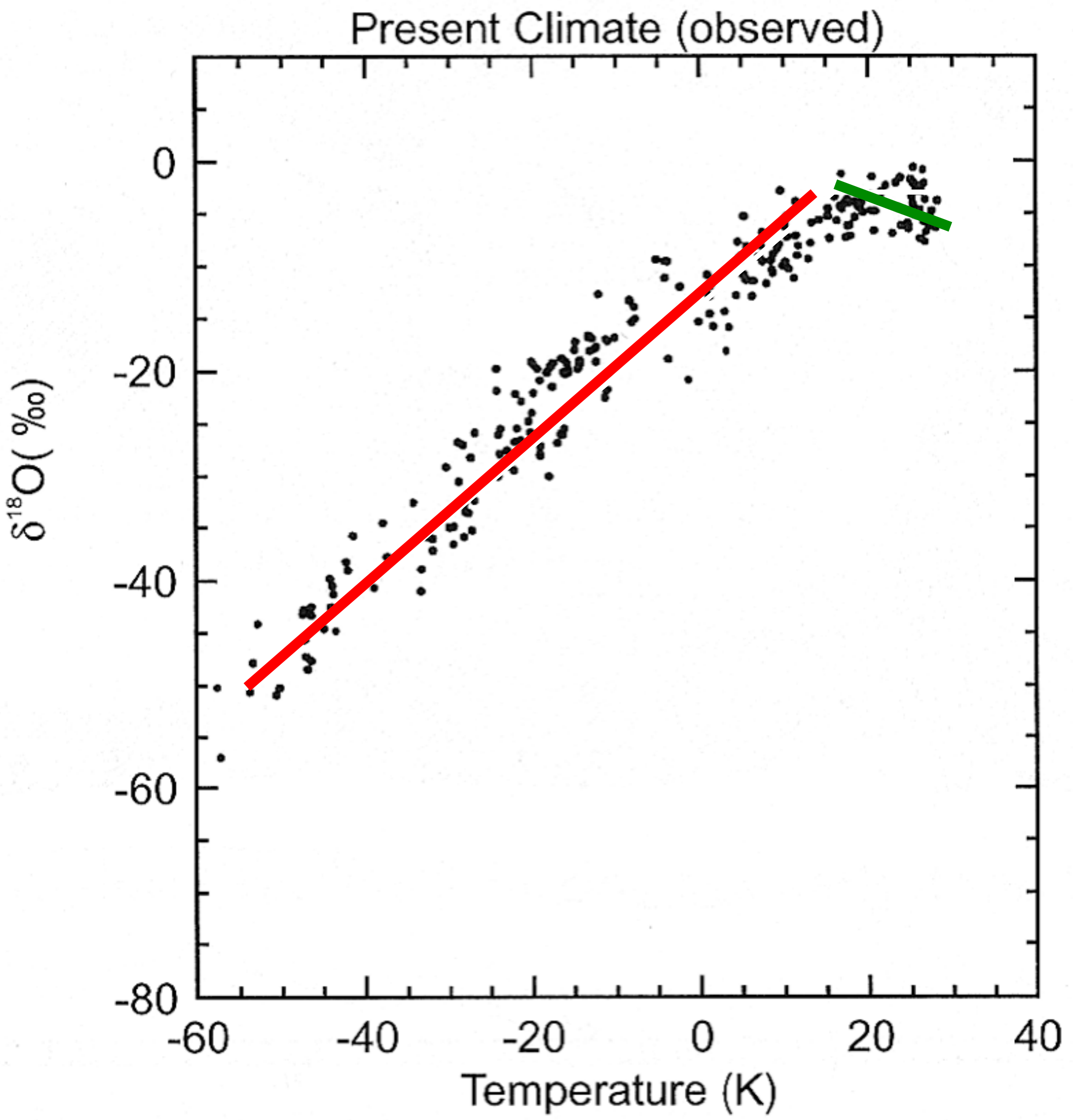
[plot adapted from the GNIP brochure, IAEA, 1996]

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

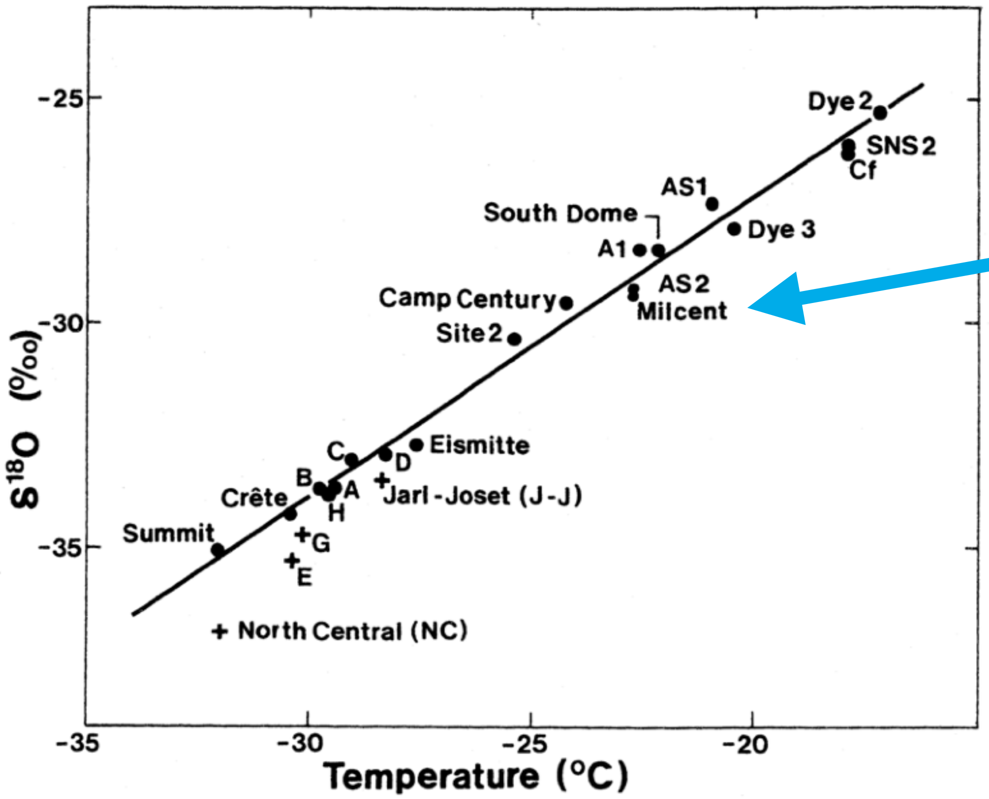


Annual $\delta^{18}O$ in precipitation in relation to mean annual temperature at the same site, based on data from the International Atomic Energy Agency.

(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 δ^{18}O in precipitation as a temperature proxy

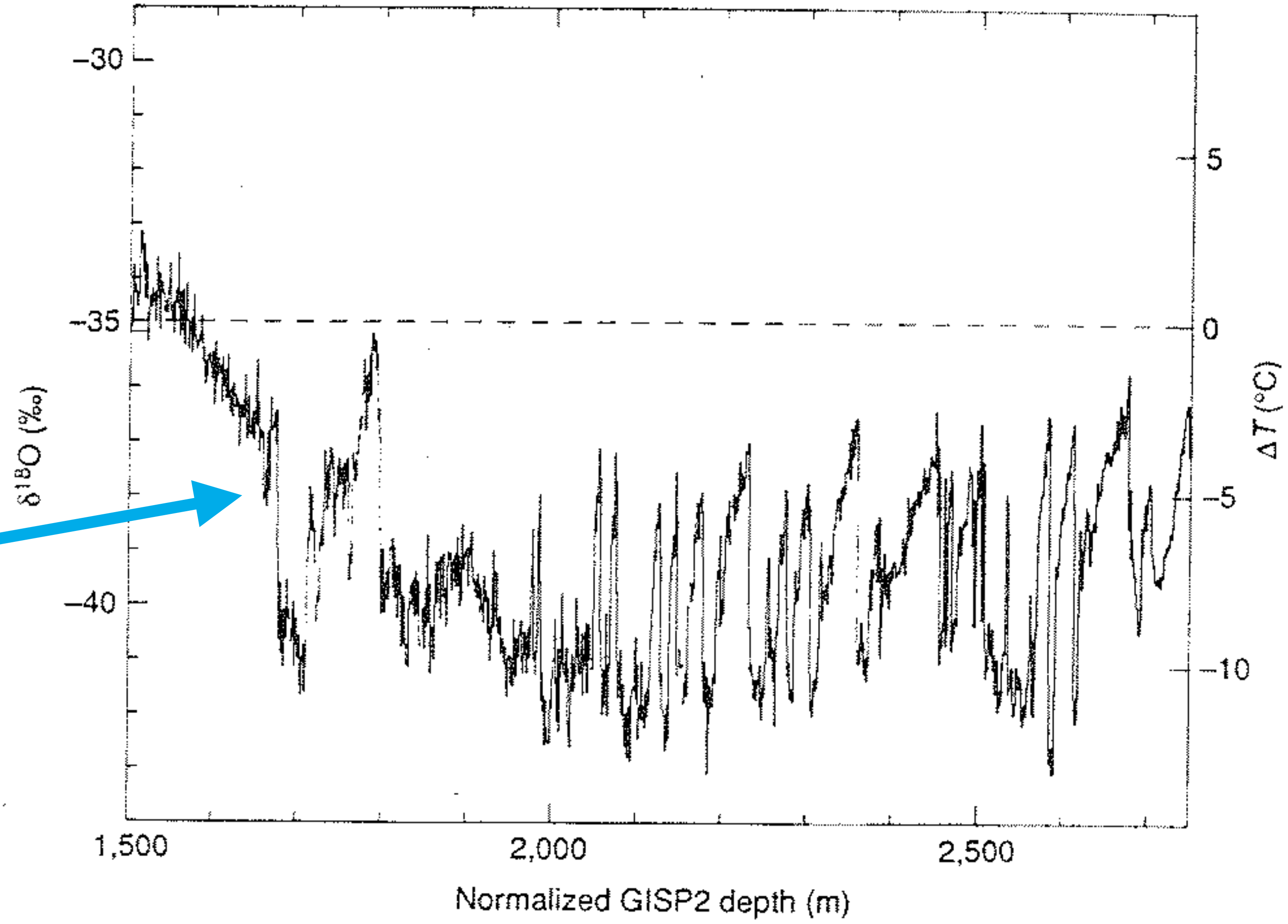


[Johnsen et al., Tellus, 1989]

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

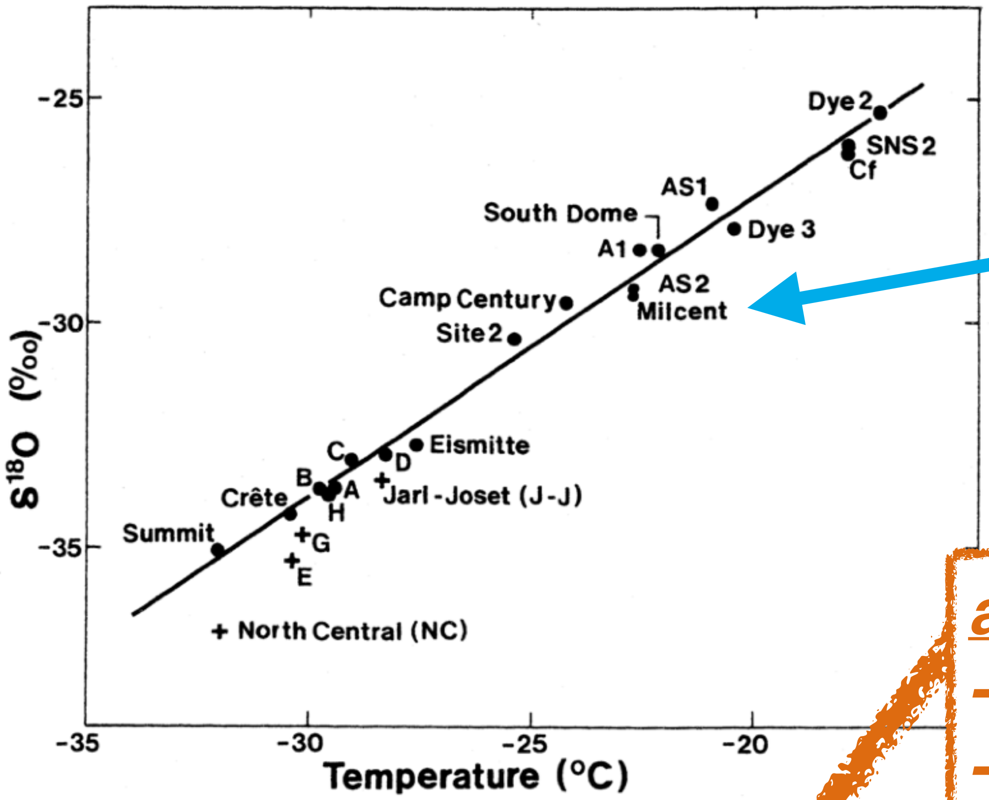
$$\delta^{18}O = 0.67 \cdot T_{surf}$$

Converting temporal changes
of δ^{18}O into past temperature
changes



[Grootes et al., Nature, 1993]

The use of of δ18O in precipitation as a temperature proxy



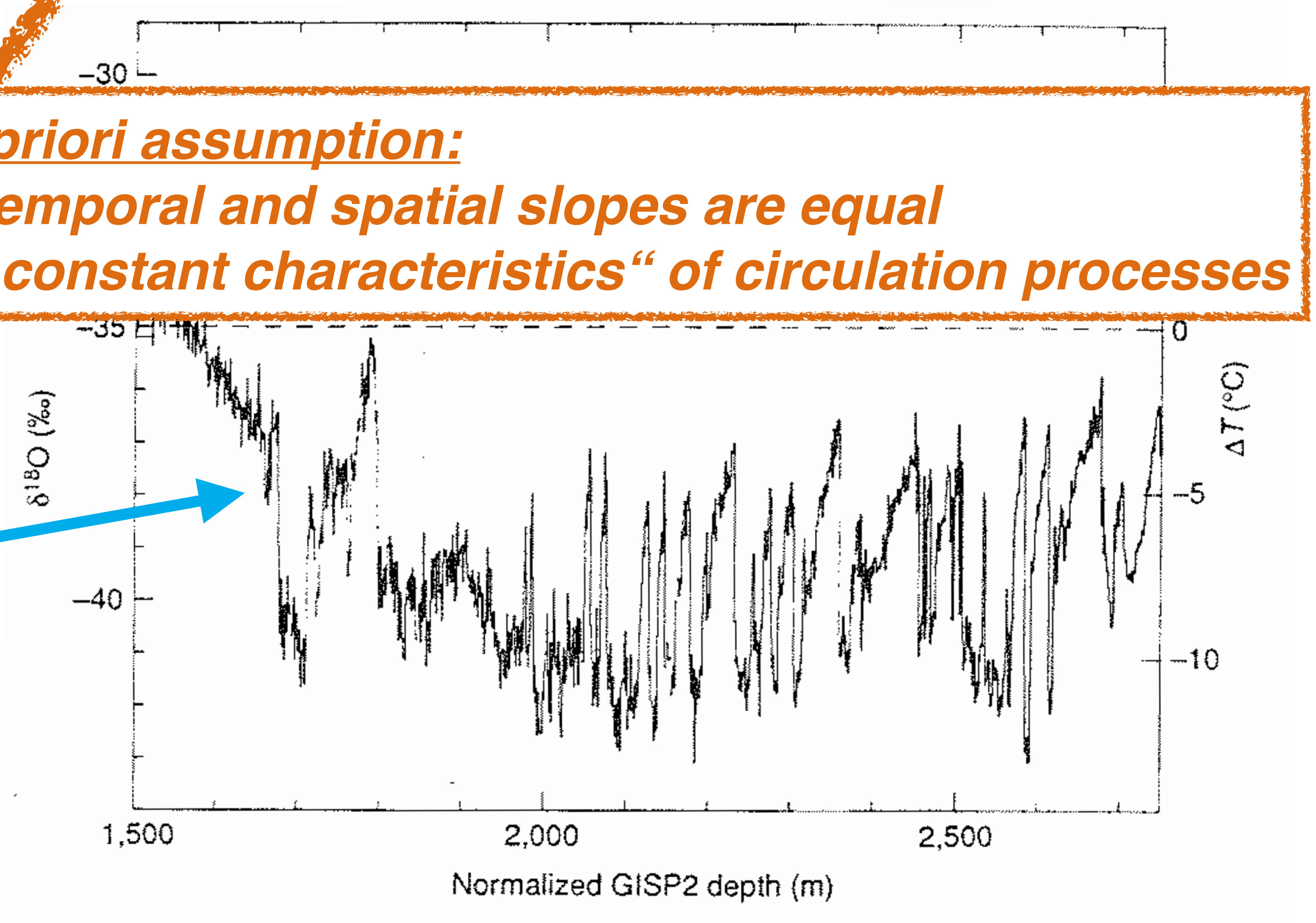
[Johnsen et al., Tellus, 1989]

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

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

a priori assumption:

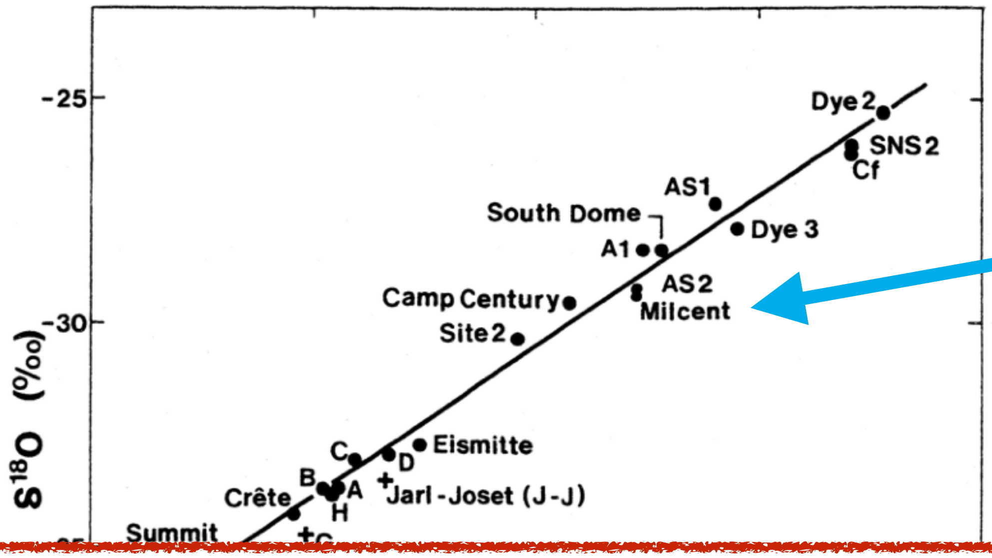
- ***temporal and spatial slopes are equal***
- ***„constant characteristics" of circulation processes***



Converting temporal changes of δ18O into past temperature changes

[Grootes et al., Nature, 1993]

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

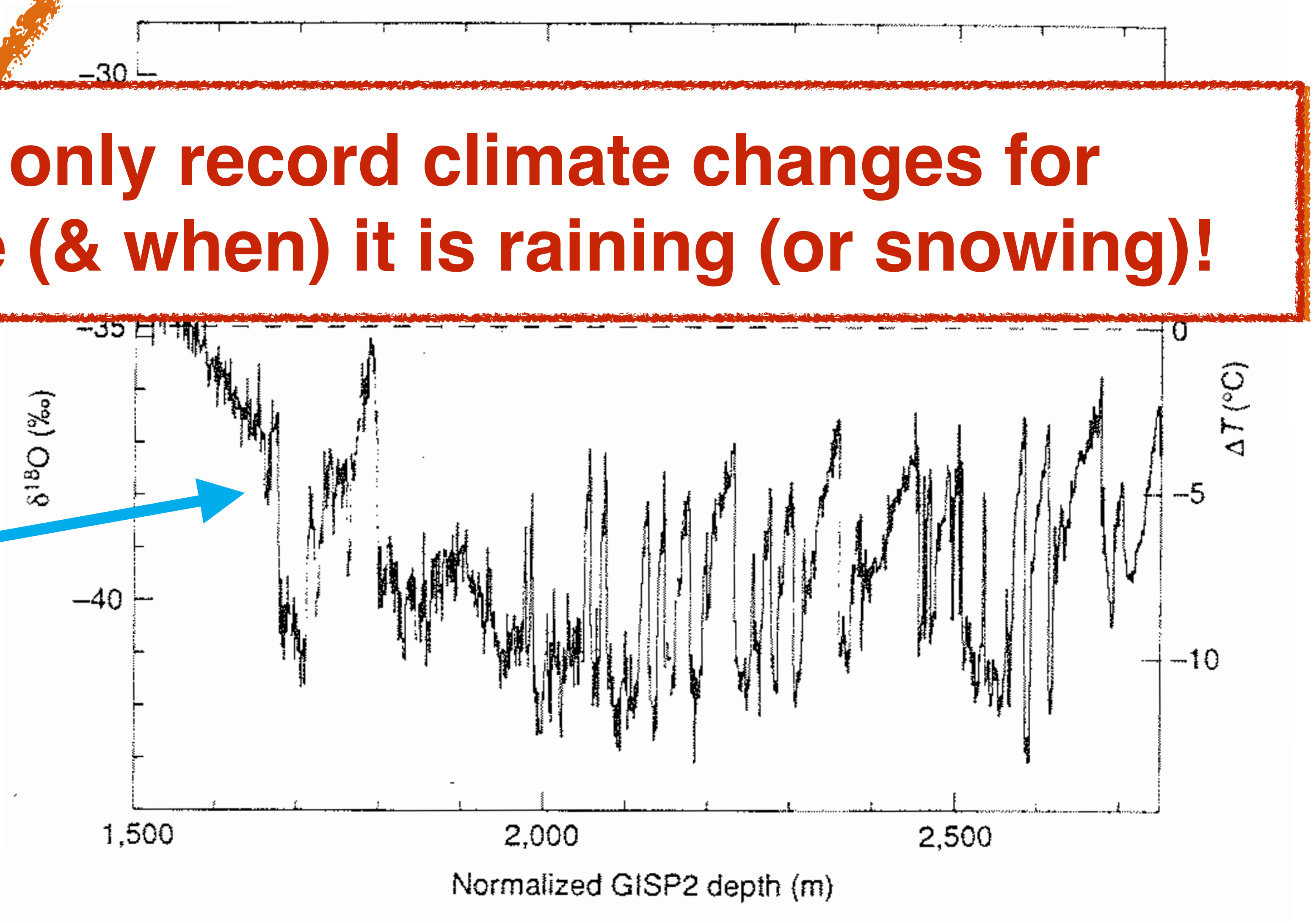


Modern spatial relation between $\delta^{18}O$ and surface temperature (on Greenland):

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

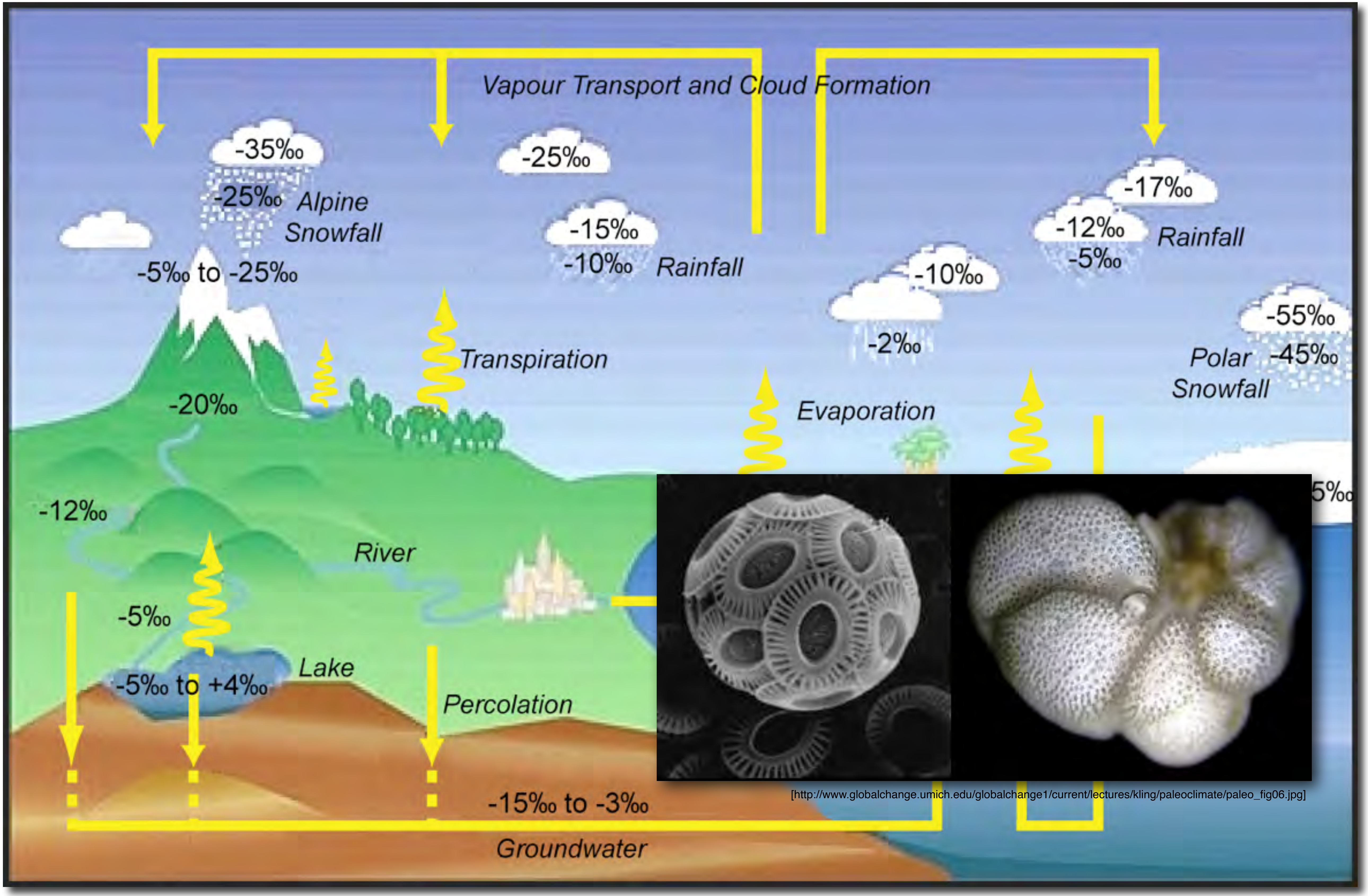
Stable water isotopes only record climate changes for places (& periods), where (& when) it is raining (or snowing)!

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



[Grootes et al., Nature, 1993]

The δ^{18}O signal in marine sediment cores



[http://www.globalchange.umich.edu/globalchange1/current/lectures/kling/paleoclimate/paleo_fig06.jpg]

[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

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

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

- *$\delta^{18}O_w$ 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

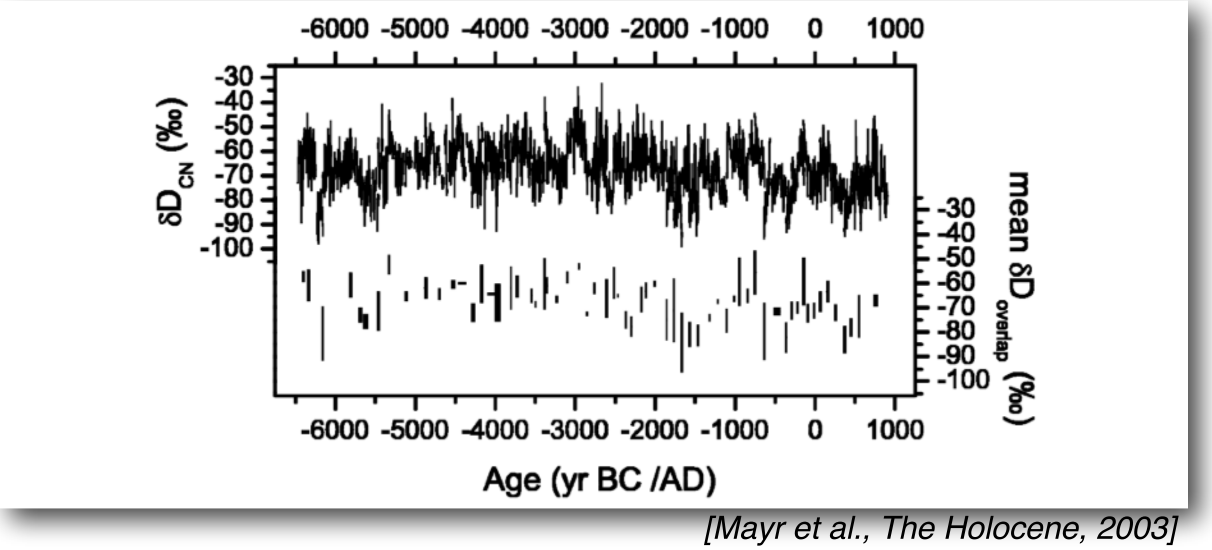
Vapour Measurements, Precipitation Samples

Ice Cores

Speleothems, Tree Rings, Lake Sediments

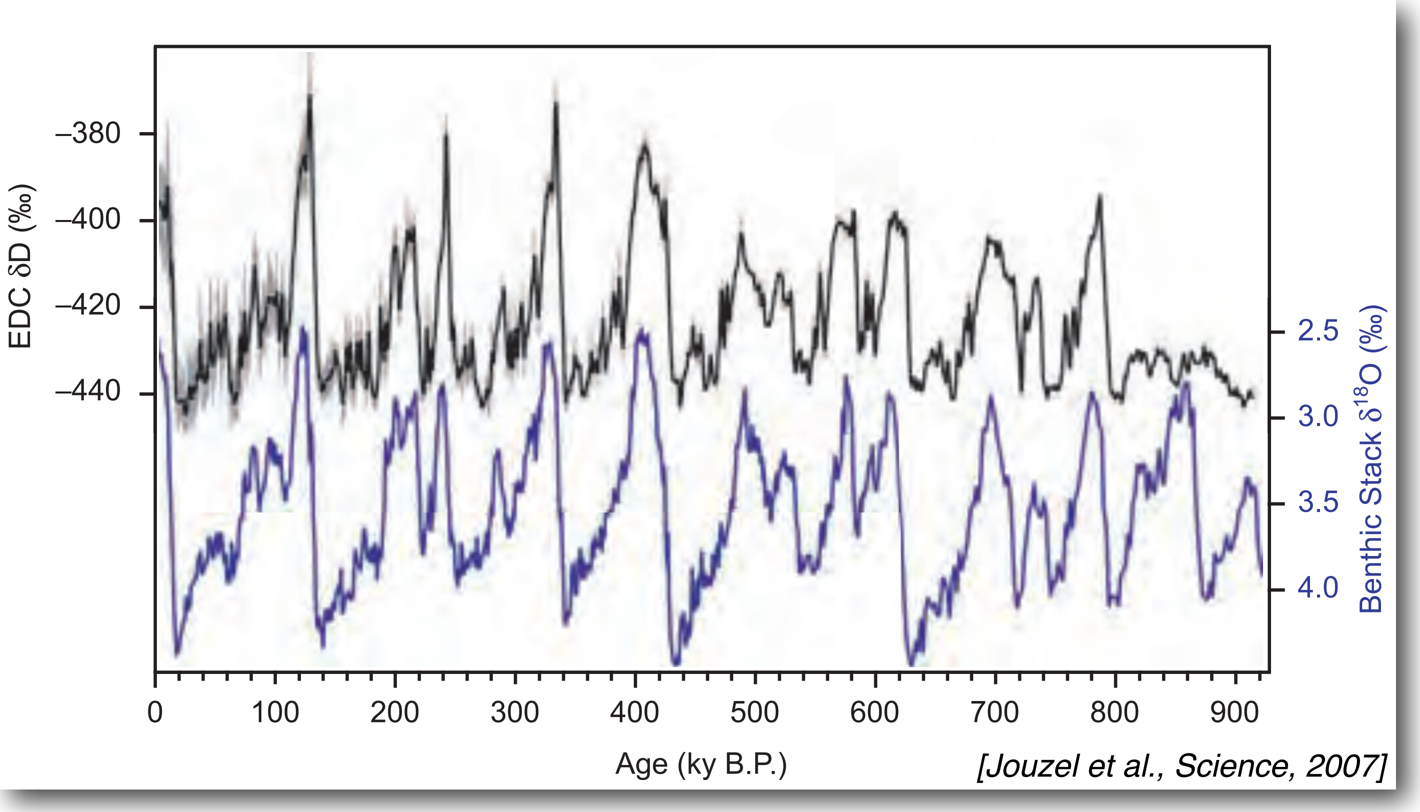
Marine Sediments, Corals

Subfossil Holocene Oaks (Southern Germany)



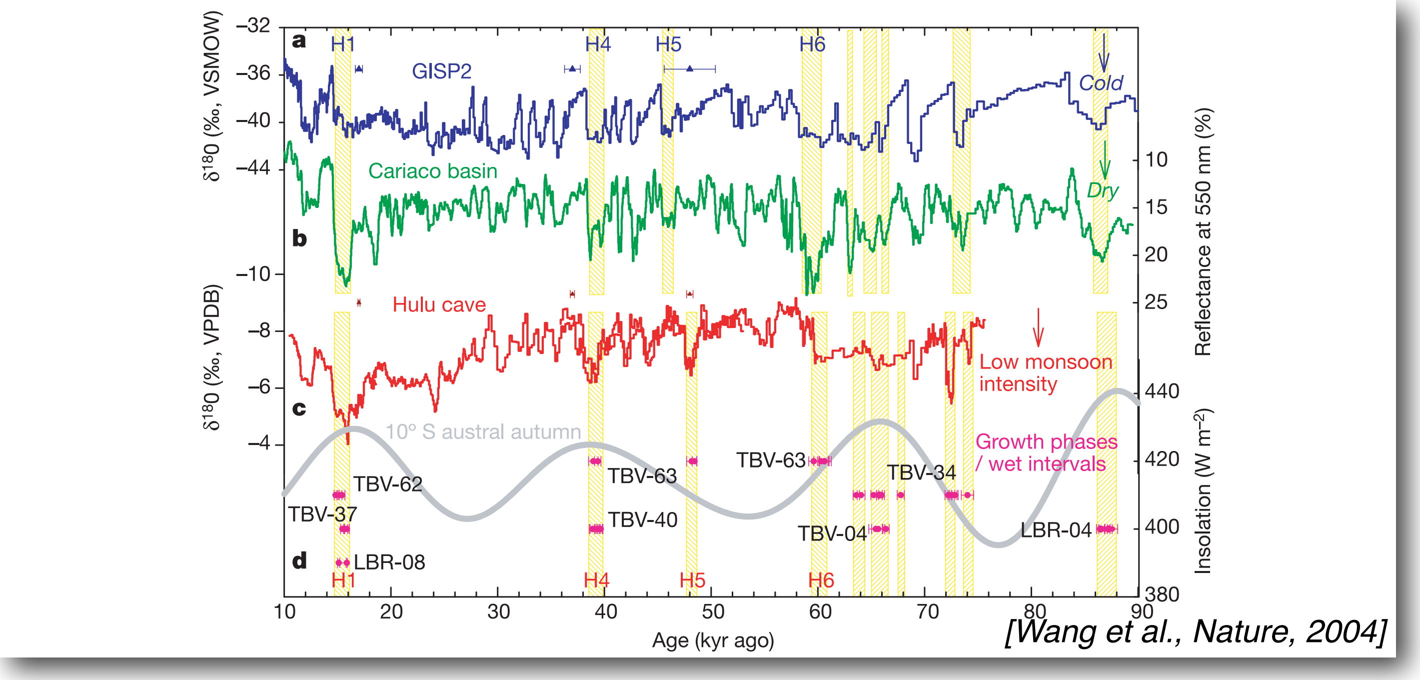
[Mayr et al., The Holocene, 2003]

EPICA Dome C and Benthic Oxygen-18 Records



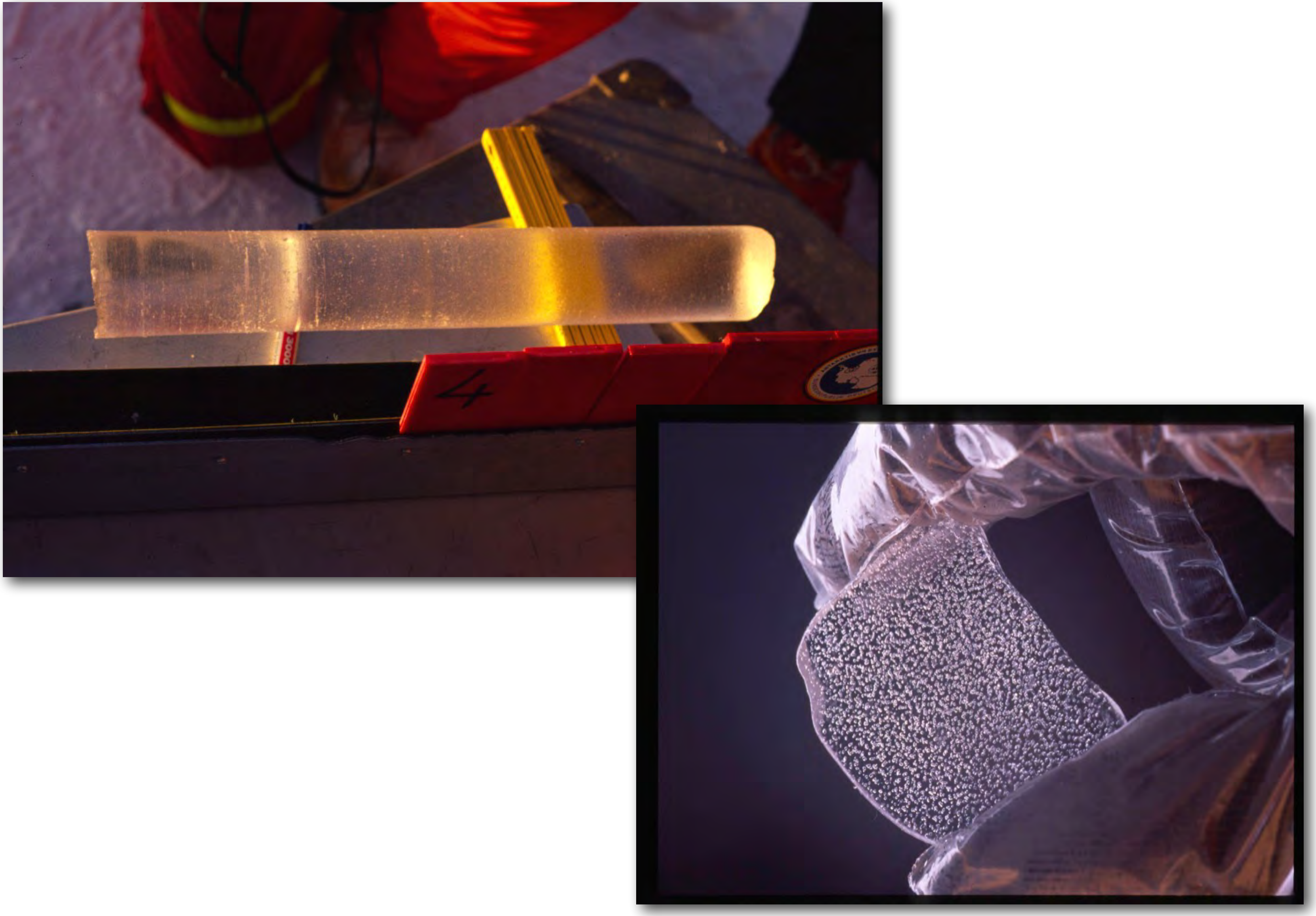
[Jouzel et al., Science, 2007]

Speleothem Records from Eastern China and Southern Brasil



[Wang et al., Nature, 2004]

Ice cores - a key climate archive



Ice cores - a key climate archive

- ice cores
  - *where are they drilled?*
  - how are they drilled?
  - how are they dated?

- key analyses
  - temperature reconstruction by stable water isotopes
  - gas analyses - the composition of the past atmosphere

Cross section of an ice sheet

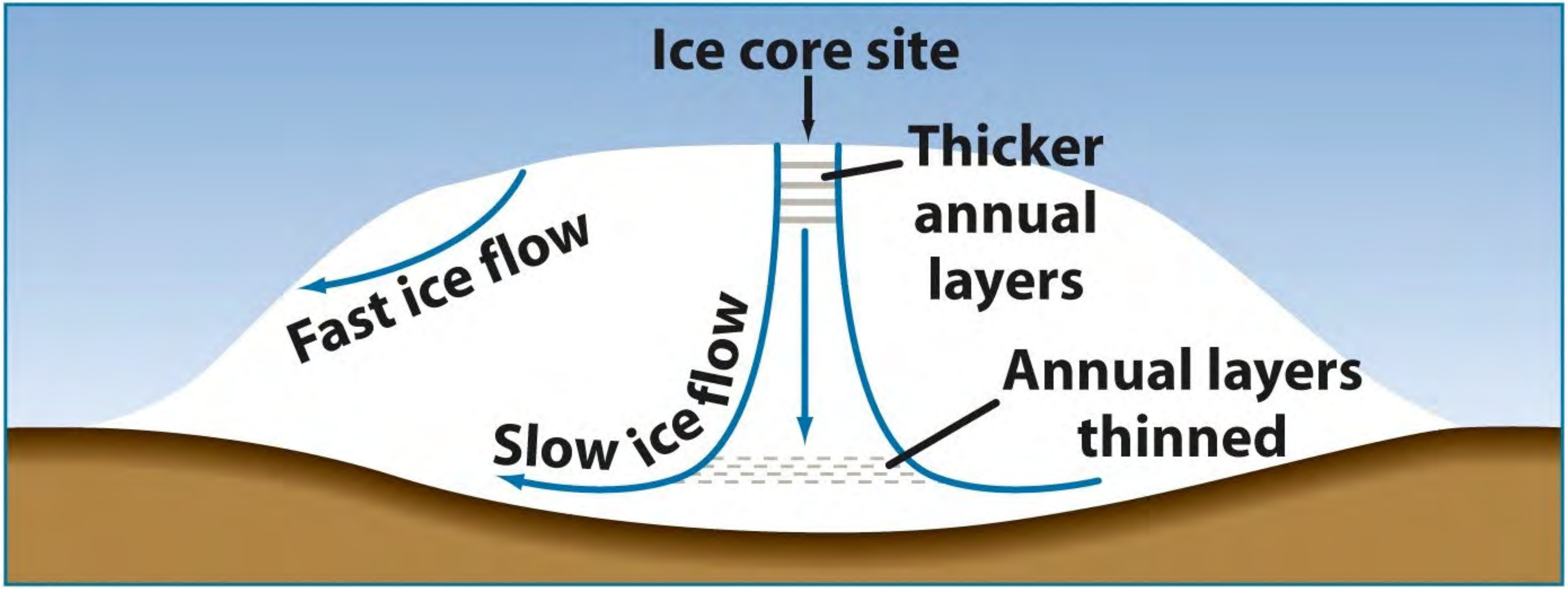
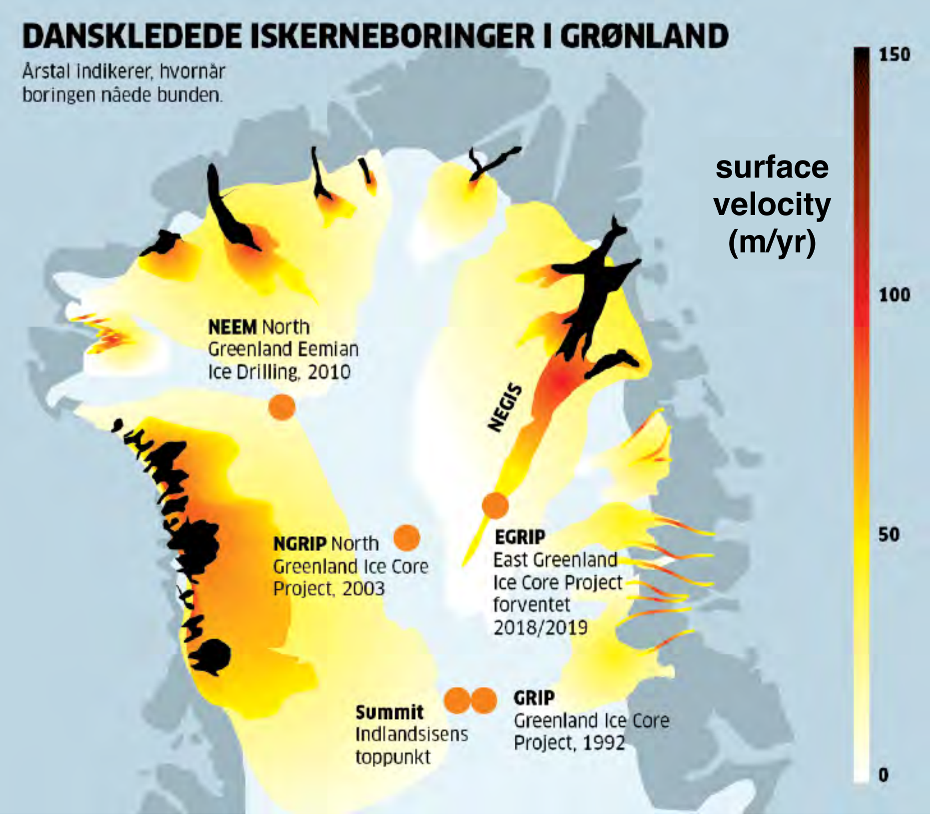
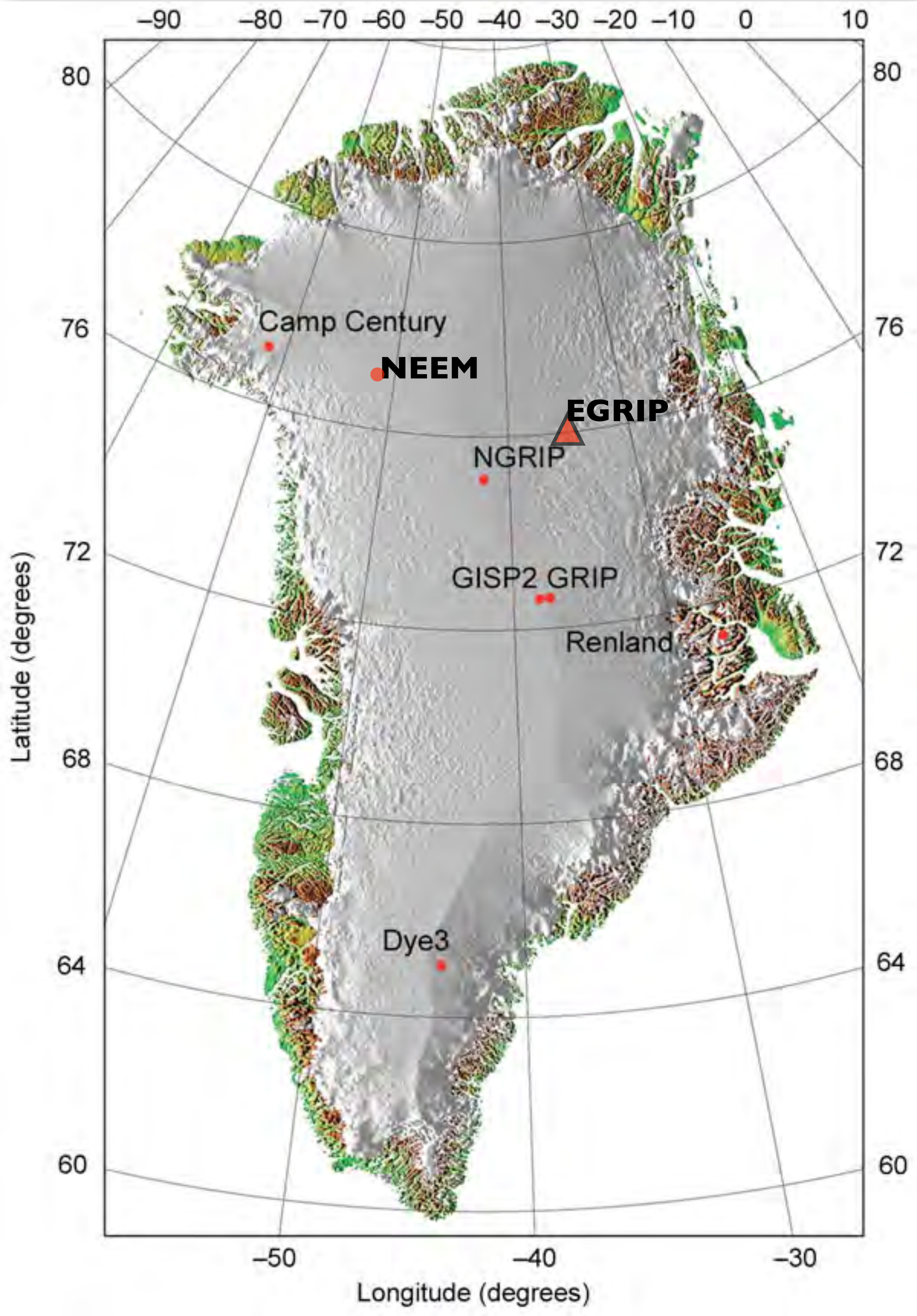


Figure 10-1
Earth's Climate: Past and Future, Second Edition

Greenland ice cores

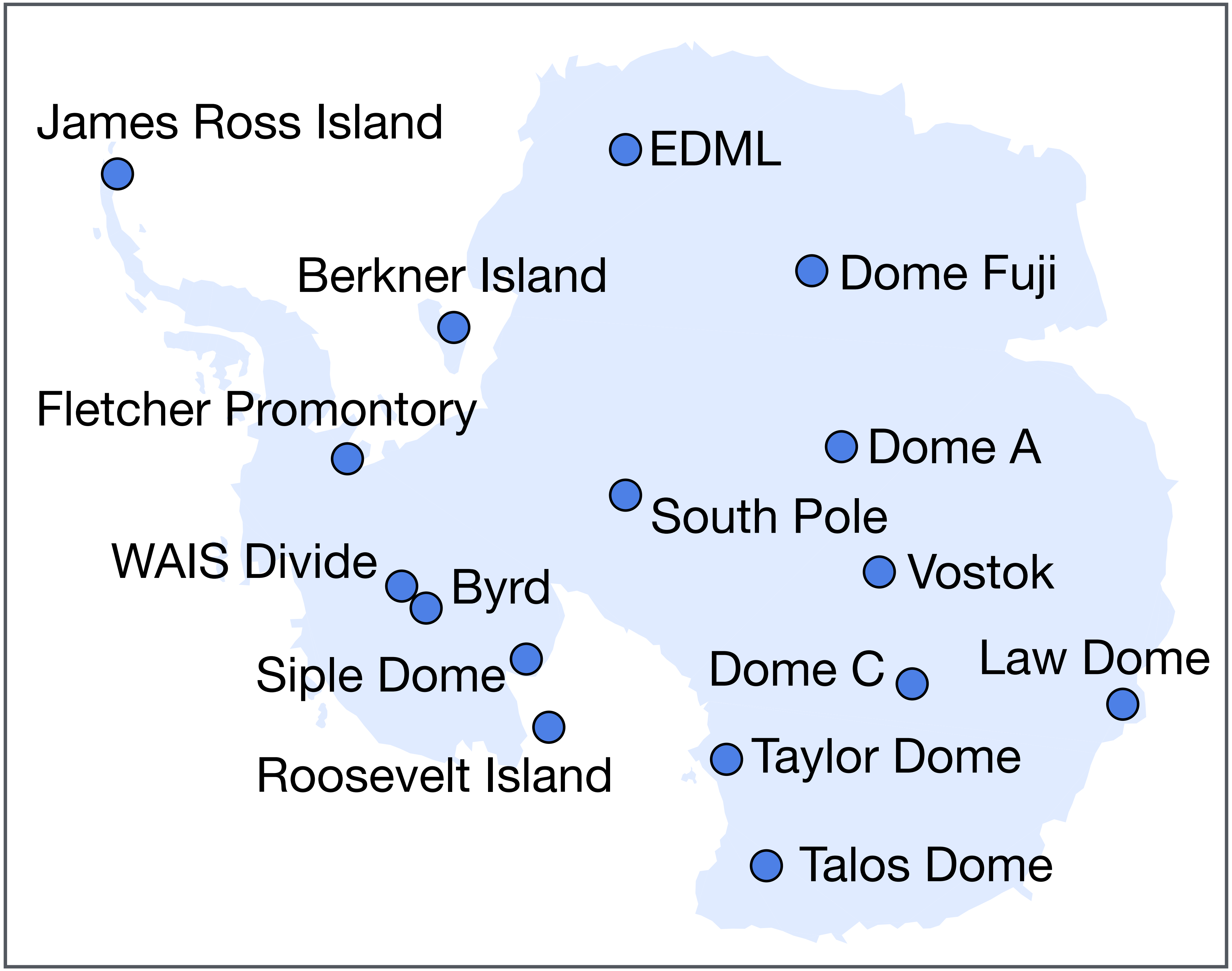


https://ing.dk/artikel/dynamikken-gronlands-isstromme-joker-klimaet-197376



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. 130,000-125,000 B.P.)

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

=> approx. 800,000 years

Future ice core sites in Antarctica

(where to find and drill the oldest ice?)

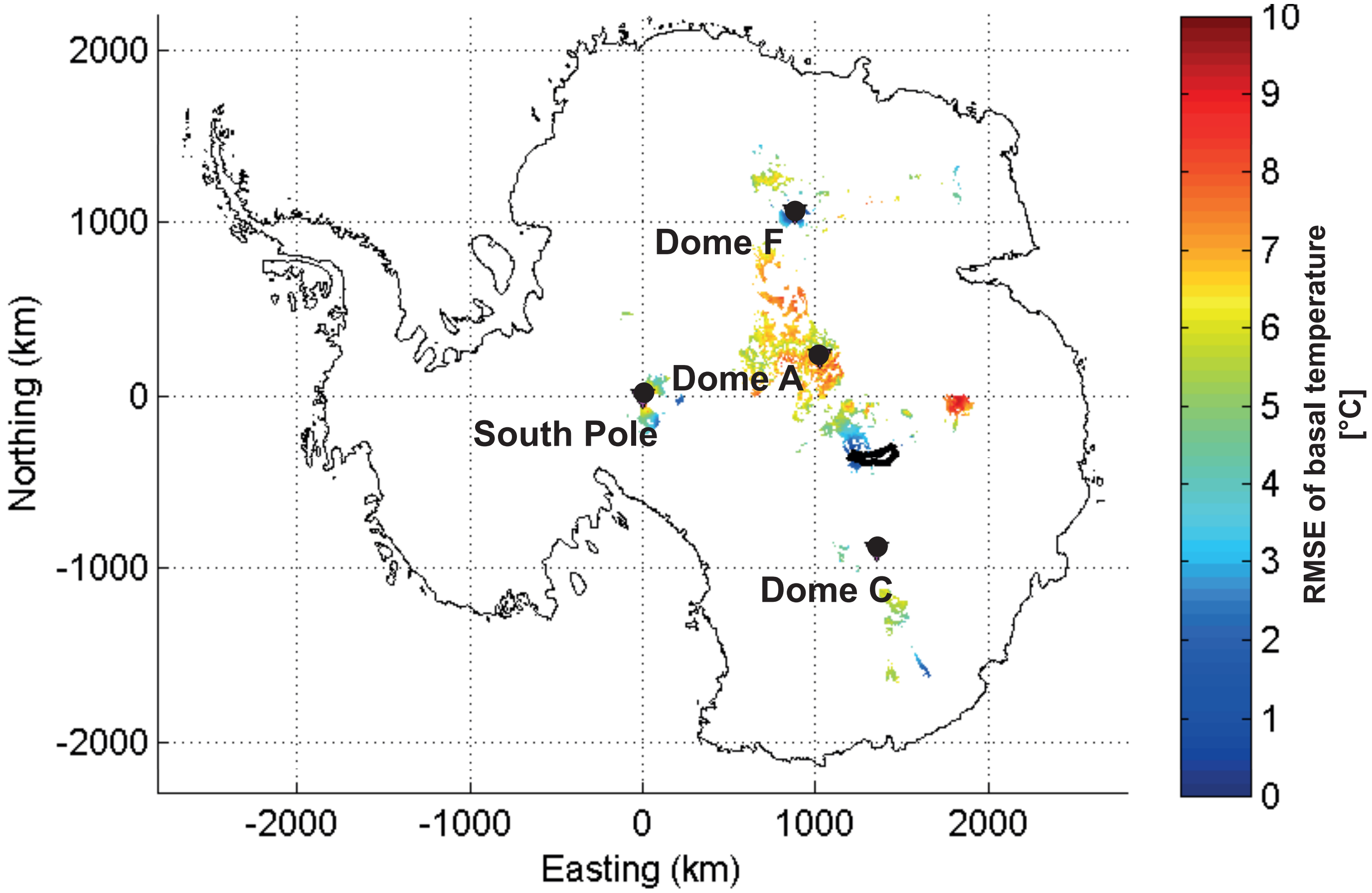


Fig. 11. Potential Oldest-Ice study areas, where horizontal flow is smaller than $2\,\mathrm{m\,yr}^{-1}$, mean ice thickness larger than 2000 m and the bottom temperature below $-5\,^{\circ}\mathrm{C}$. The color bar indicates the root mean square error of the basal temperature derived from a mode ensemble (van Liefferinge and Pattyn, 2013).

(H. Fischer et al., Where to find 1.5 million yr old ice for the IPICS “Oldest-Ice” ice core, Climate of the Past, 2013)

Future ice core sites in Antarctica

(where to find and drill the oldest ice?)

for more information: https://www.beyondepica.eu/en/

Ice cores - a key climate archive

- ice cores
  - where are they drilled?
  - *how are they drilled?*
  - how are they dated?

- key analyses
  - temperature reconstruction by stable water isotopes
  - gas analyses - the composition of the past atmosphere

Ice core drilling

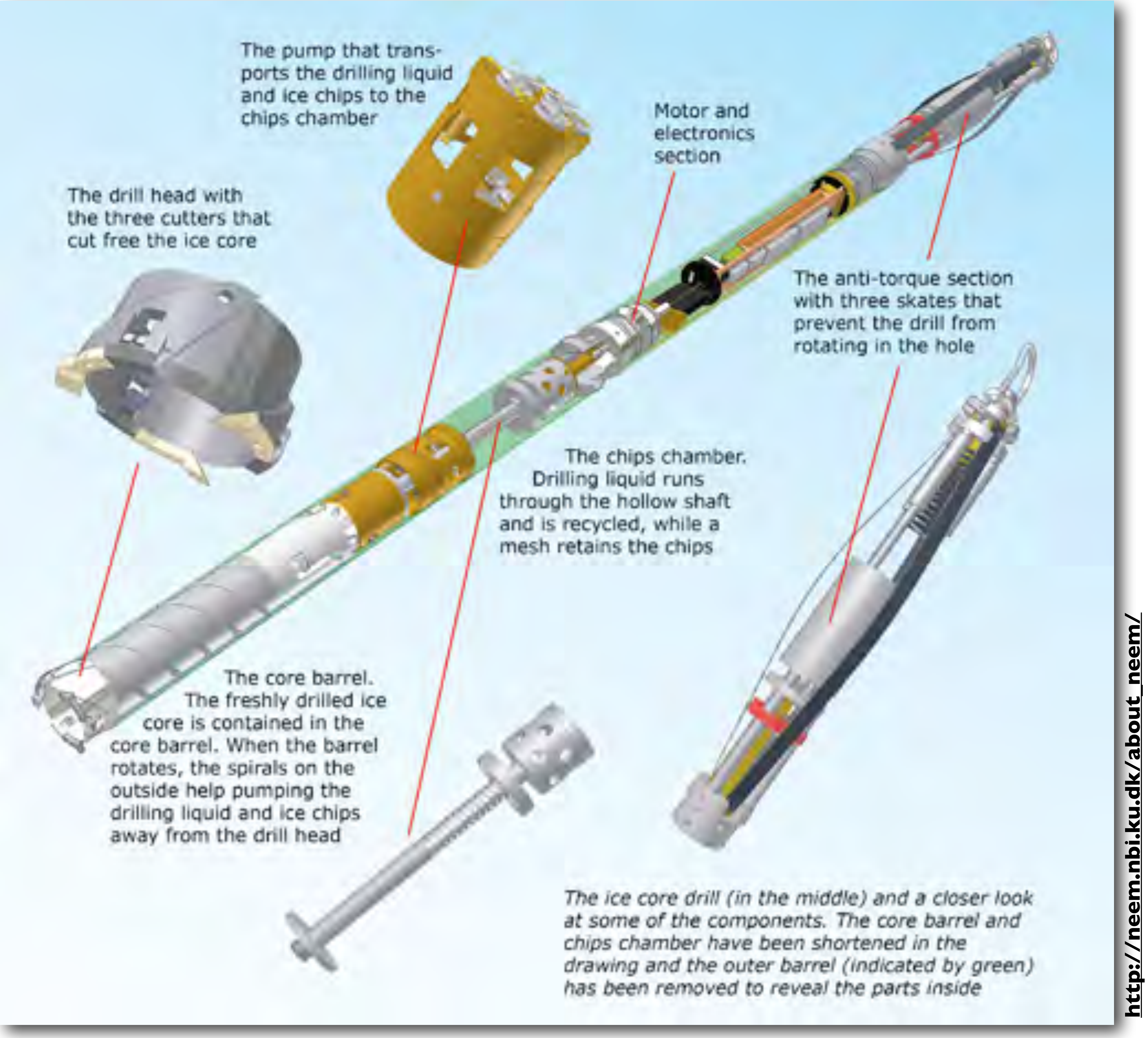
European Project for Ice Coring in Antarctica (EPICA)

1996-2004:
drilling campaign at
Dome C, East Antarctica

ice core:
length 3270m,
age ~800,000 years

Ice core drilling

Ice core drilling



The pump that transports the drilling liquid and ice chips to the chips chamber

Motor and electronics section

The drill head with the three cutters that cut free the ice core

The anti-torque section with three skates that prevent the drill from rotating in the hole

The chips chamber. Drilling liquid runs through the hollow shaft and is recycled, while a mesh retains the chips

The core barrel. The freshly drilled ice core is contained in the core barrel. When the barrel rotates, the spirals on the outside help pumping the drilling liquid and ice chips away from the drill head

The ice core drill (in the middle) and a closer look at some of the components. The core barrel and chips chamber have been shortened in the drawing and the outer barrel (indicated by green) has been removed to reveal the parts inside

http://neem.nbi.ku.dk/about_neem/drillingicecores/

Ice core drilling

Ice core drilling

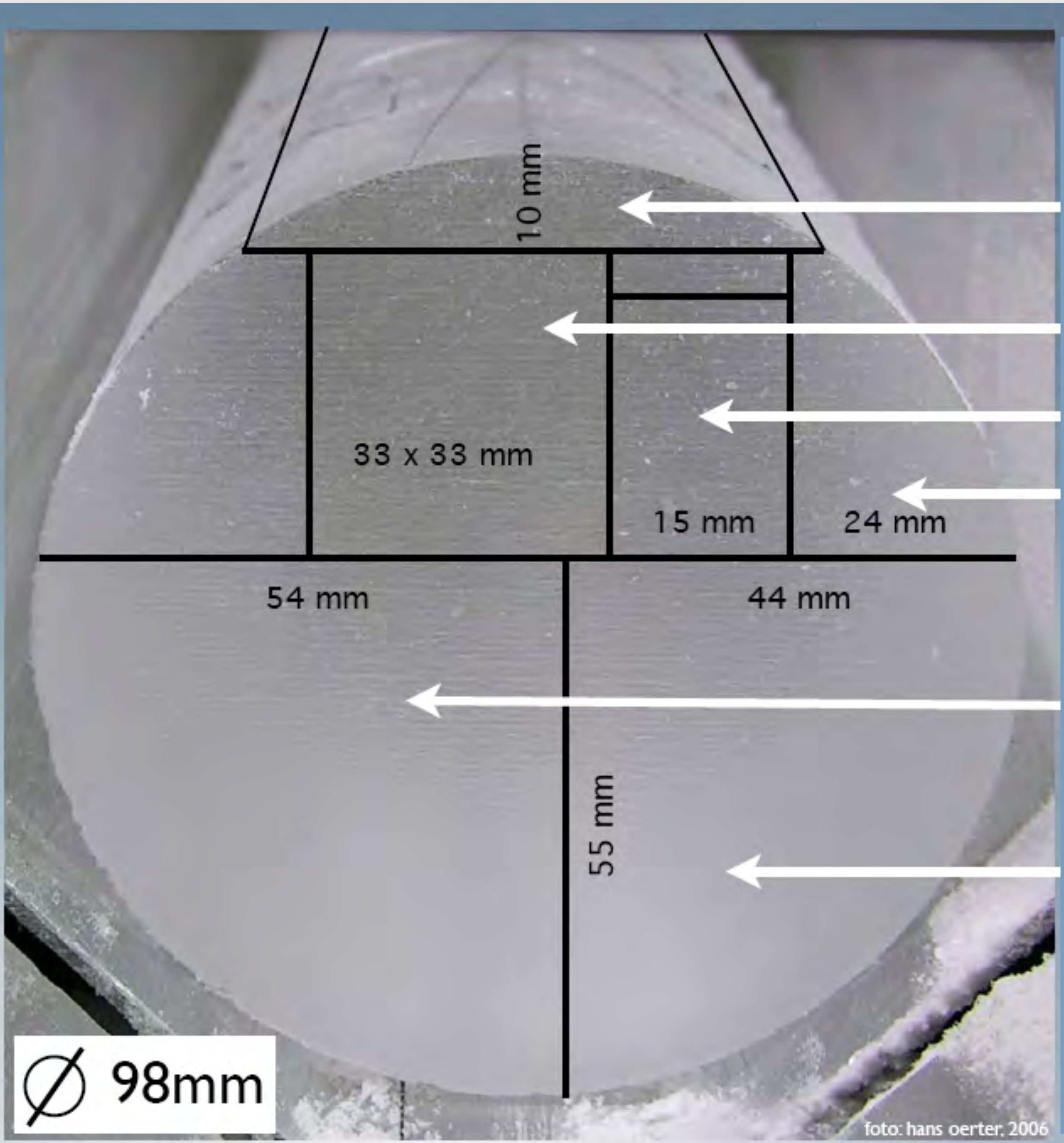
Ice core drilling

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

Ice cores - a key climate archive

- ice cores
    - where are they drilled?
    - how are they drilled?
    - *how are they dated?*

- key analyses
    - temperature reconstruction by stable water isotopes
    - gas analyses - the composition of the past atmosphere

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

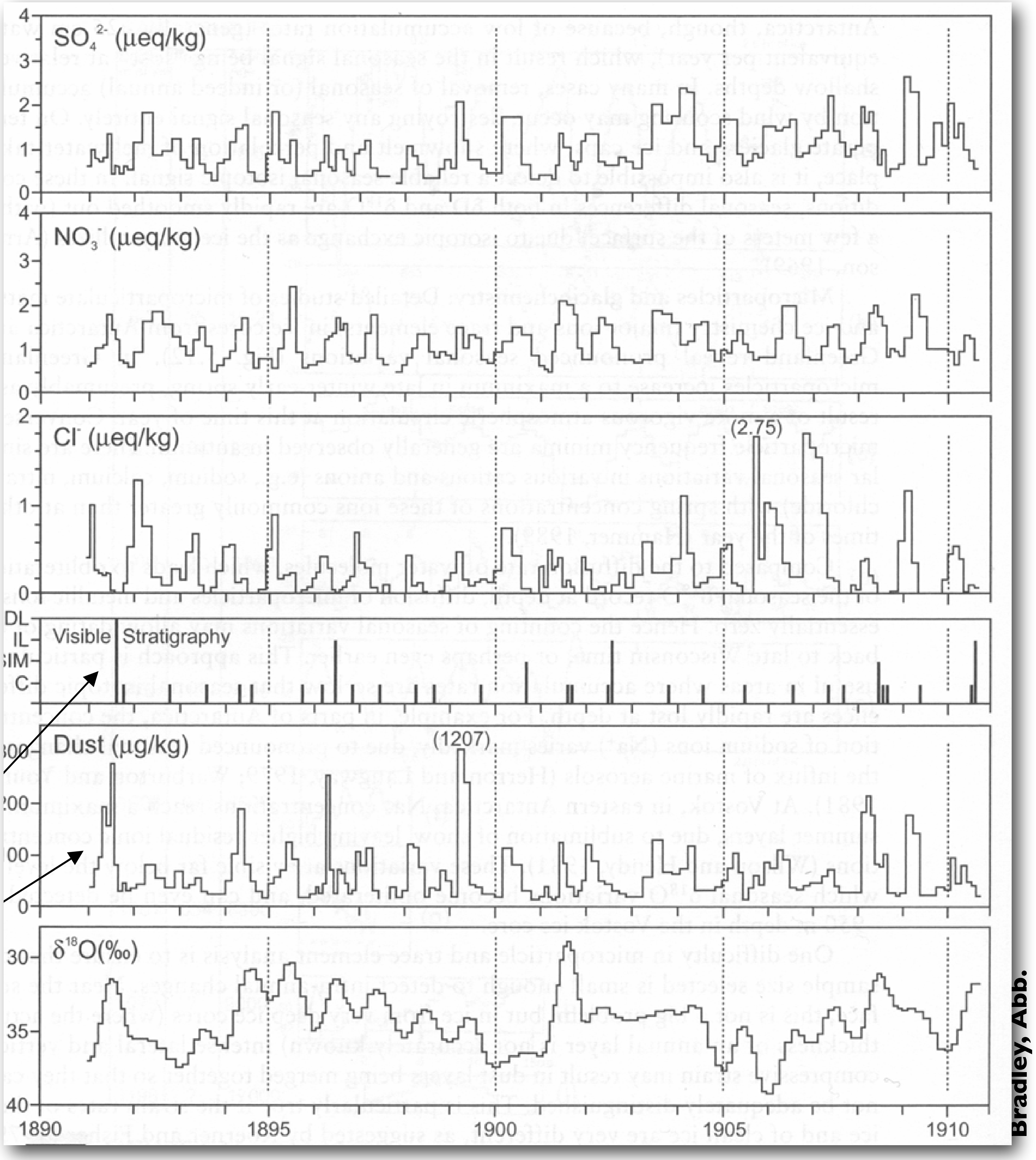
- difference in dating methods
  - absolute dating:
    climate events can be attributed to a specific calendar year
    (or duration of years)
  - relative dating:
    the temporal order of several climate events can be determined,
    but not the absolute timing of these events

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

Example: ice core synchronising

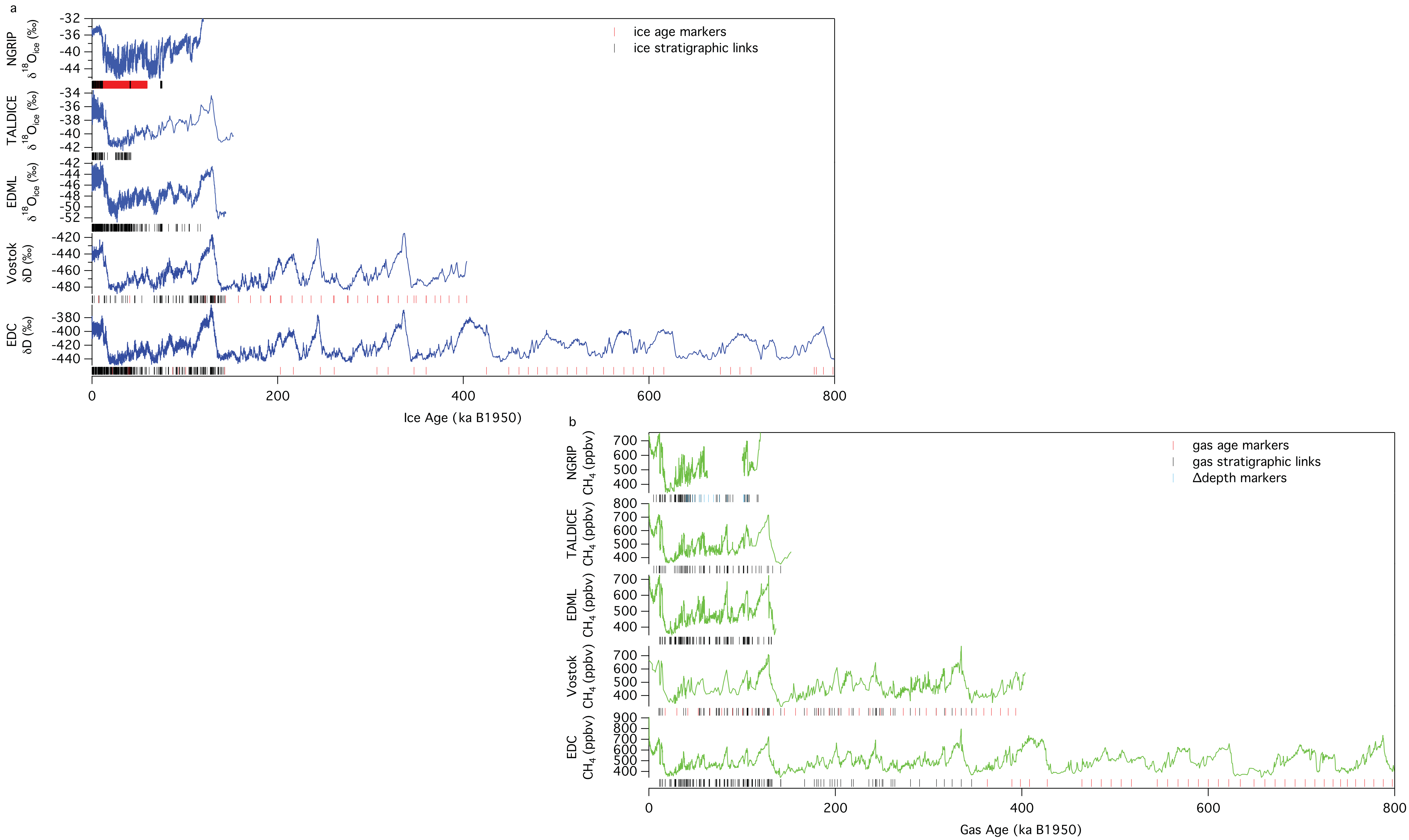


Fig. 5. (a) Water stable isotope records of NGRIP (NorthGRIP Community Members, 2004), TALDICE (Stenni et al., 2011), EDML (EPICA Community Members, 2006, 2010), Vostok (Petit et al., 1999) and EDC (Jouzel et al., 2007) on the AICC2012 age scale. **(b)** Methane records of NGRIP (Greenland composite: Capron et al., 2010; EPICA Community Members, 2006; Flückiger et al., 2004; Huber et al., 2006; Schilt et al., 2010), TALDICE (Buiron et al., 2011; Schüpbach et al., 2011), EDML (EPICA Community Members, 2006), Vostok (Caillon et al., 2003; Delmotte et al., 2004; Petit et al., 1999) and EDC (Loulergue et al., 2008) on the AICC2012 age scale. Stratigraphic links and age marker positions are displayed under each core.

Bazin et al., ClimPast, 2013

Ice cores - a key climate archive

- ice cores
  - where are they drilled?
  - how are they drilled?
  - how are they dated?

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

Ice cores - a key climate archive

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

Ice cores - a key climate archive

- ice cores
  - where are they drilled?
  - how are they drilled?
  - how are they dated?

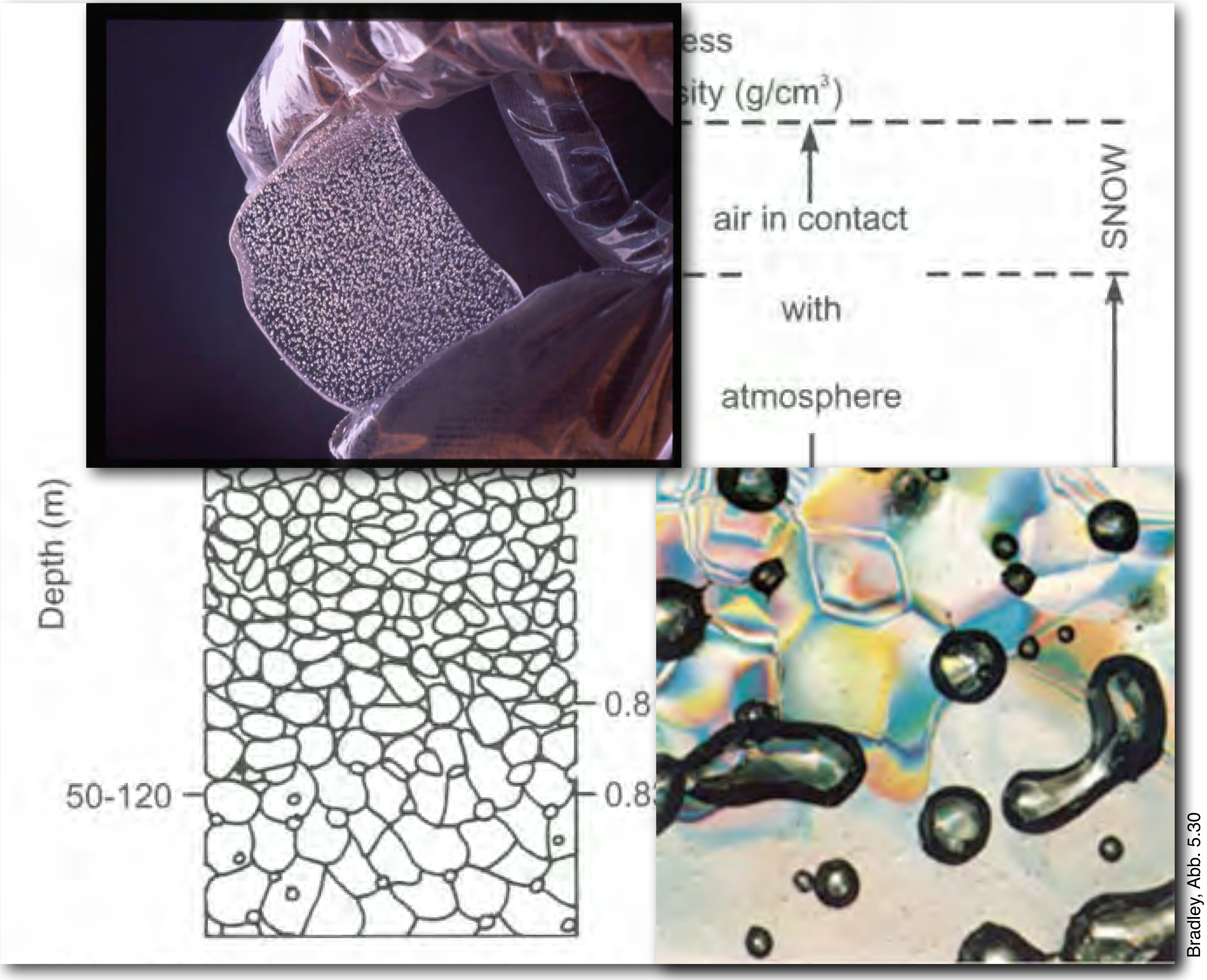
- key analyses
  - temperature reconstruction by stable water isotopes
  - *gas analyses - the composition of the past atmosphere*

Ice cores are currently the only archive

which allow to directly measure

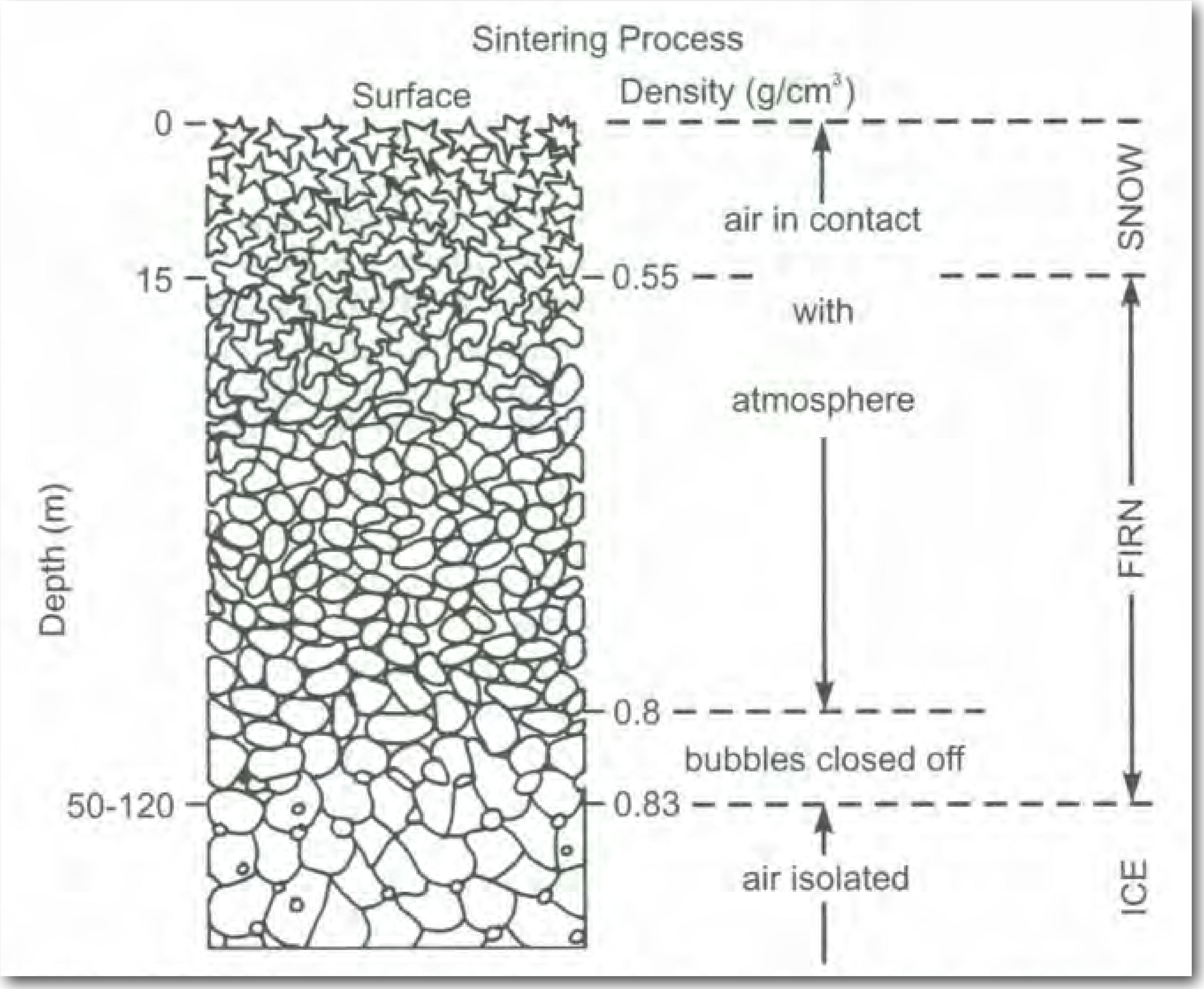
the past atmospheric composition!

Transformation of snow to ice



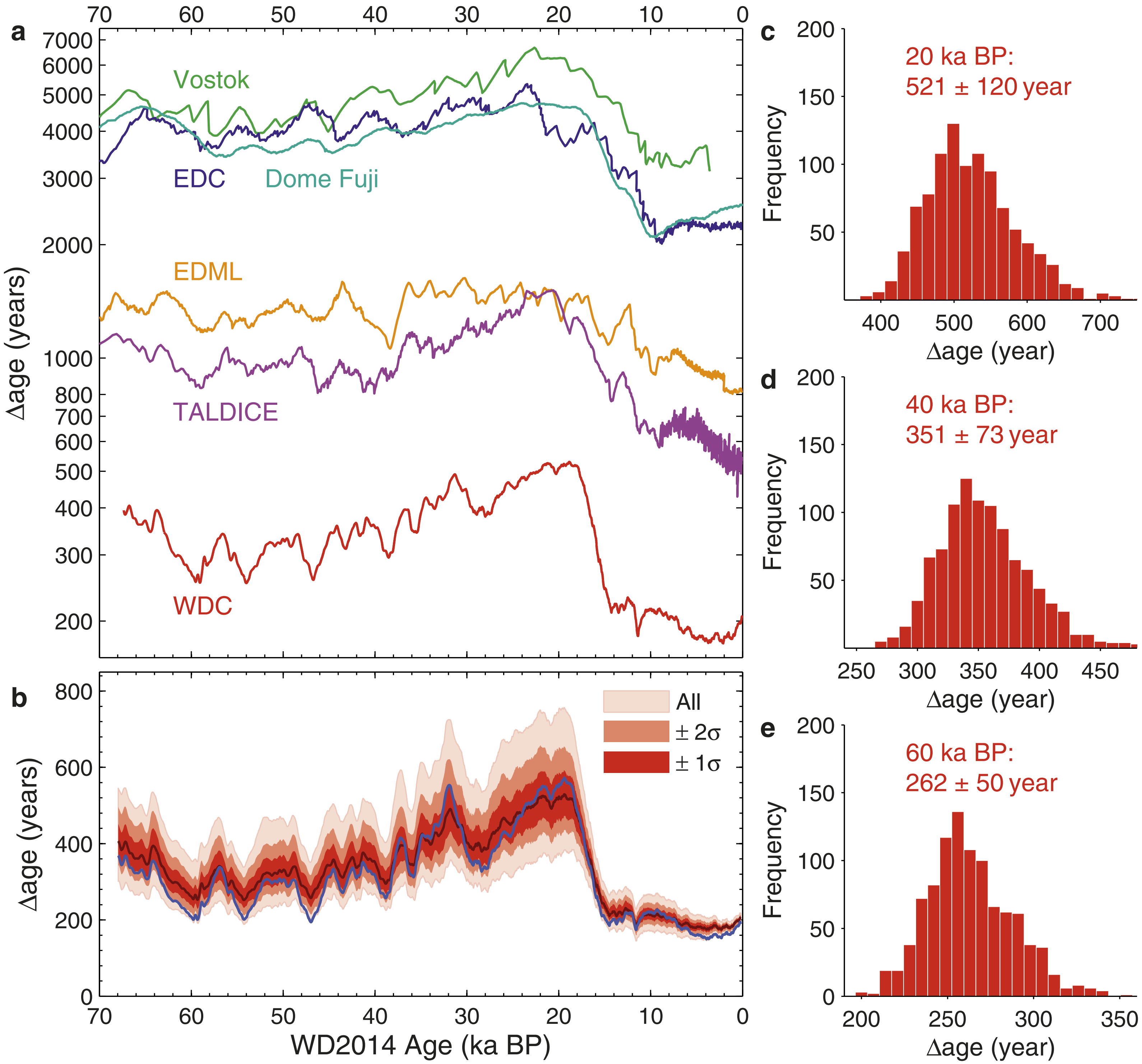
Bradley, Abb. 5.30

Transformation of snow to ice



Bradley, Abb. 5.30

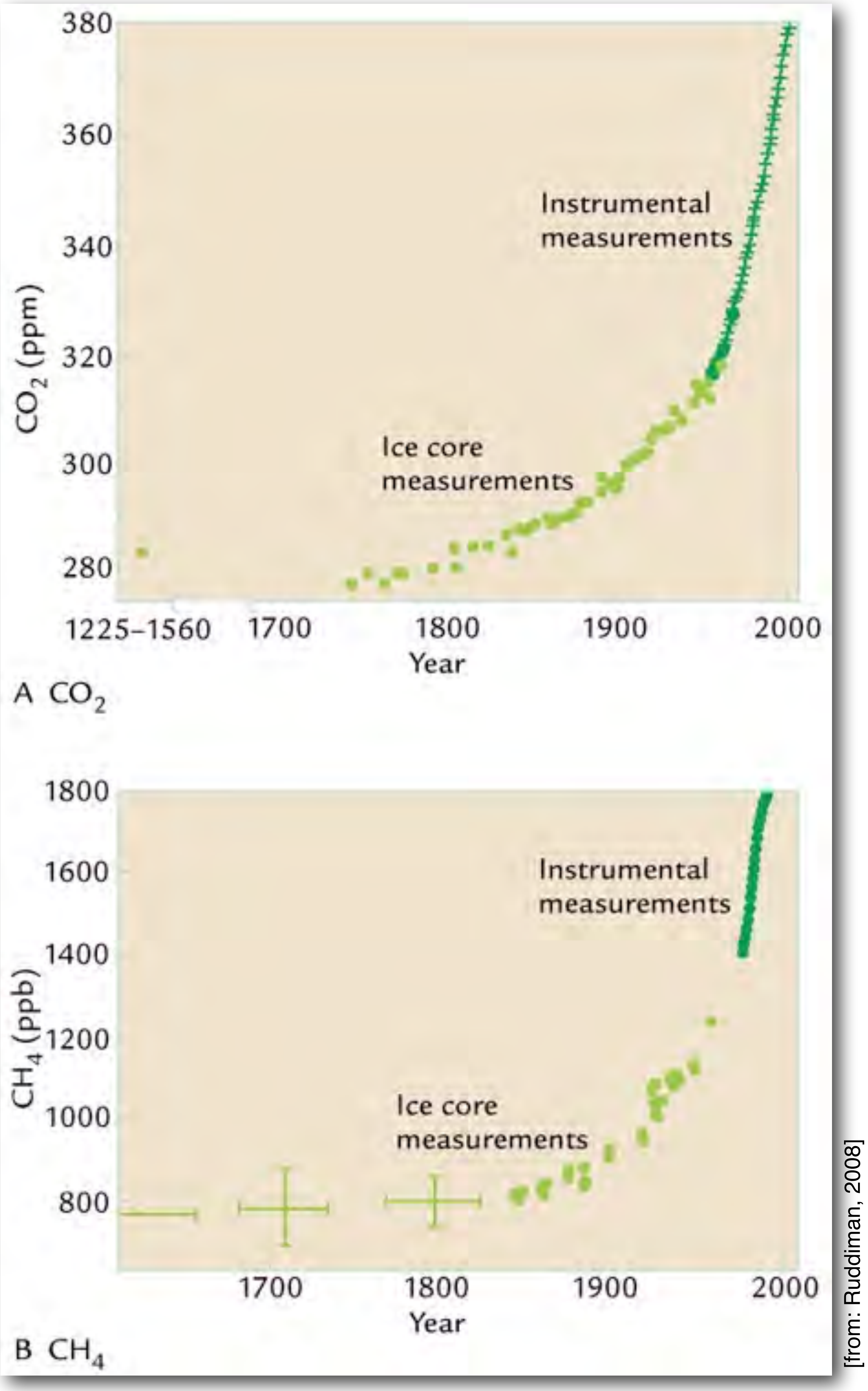
Example: difference between ice age and gas age



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.

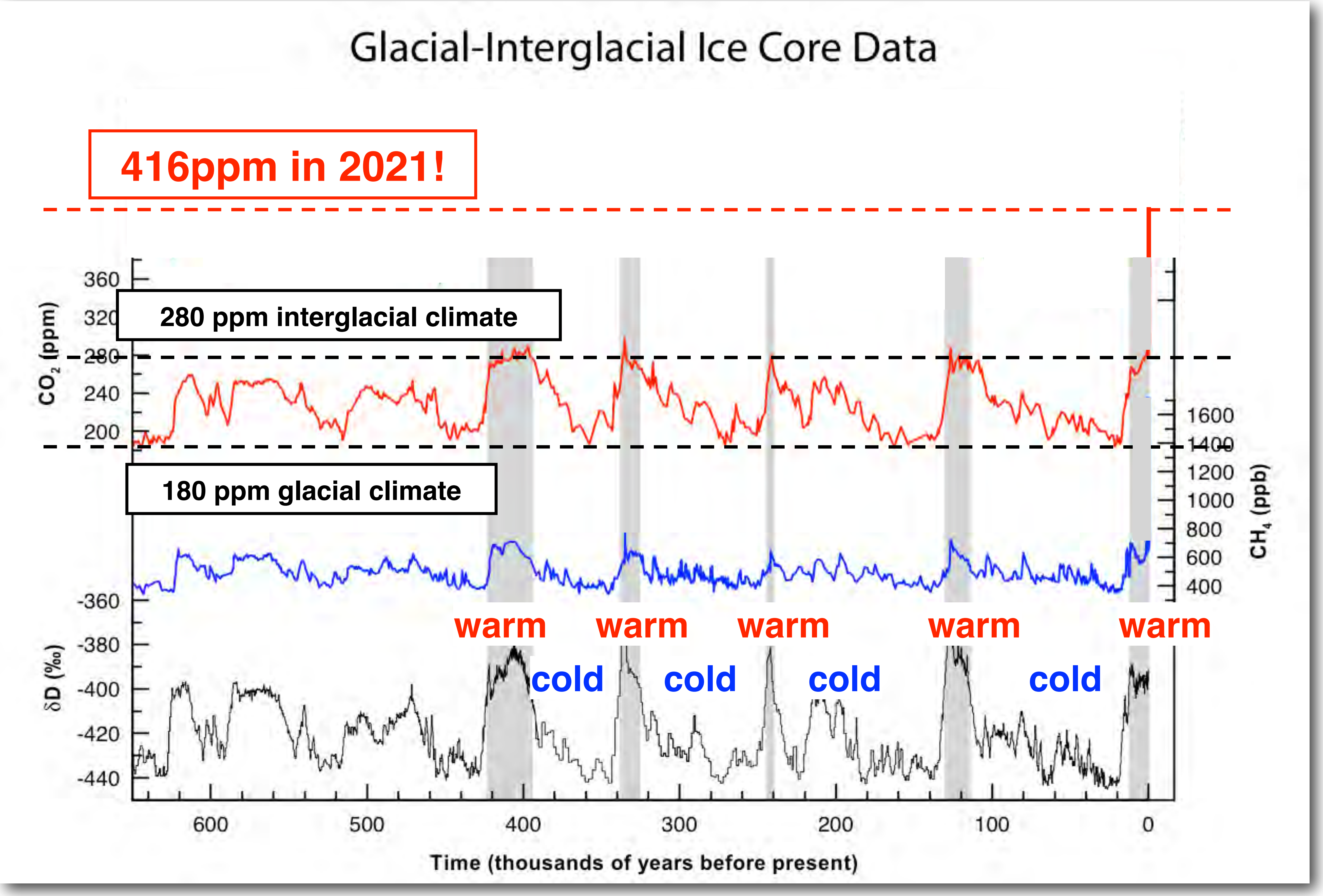
WAIS Divide Project Members, Nature, 2015

Ice core and instrumental CO_2 and CH_4 measurements



[from: Ruddiman, 2008]

Orbital-scale changes of greenhouse gases



Orbital-scale changes of greenhouse gases

- action or reaction?
  - CO_2 and CH_4 go in parallel with temperature changes during the last 800,000 years
    - no large time lags between temperature and GHG changes exist
    - it still remains open if temperature changes are leading or lagging the changes in greenhouse gas concentrations

- where did the CO_2 go?
  - during glacial times, over 1000 billion tons of CO_2 must have been shifted from the atmosphere, land surface and upper ocean towards deeper ocean layers
    - several factors may have contributed (biological pump, ocean circulation changes, increased CO_2 solubility in cold waters)

Orbital-scale changes of greenhouse gases

- example of recent research

nature geoscience

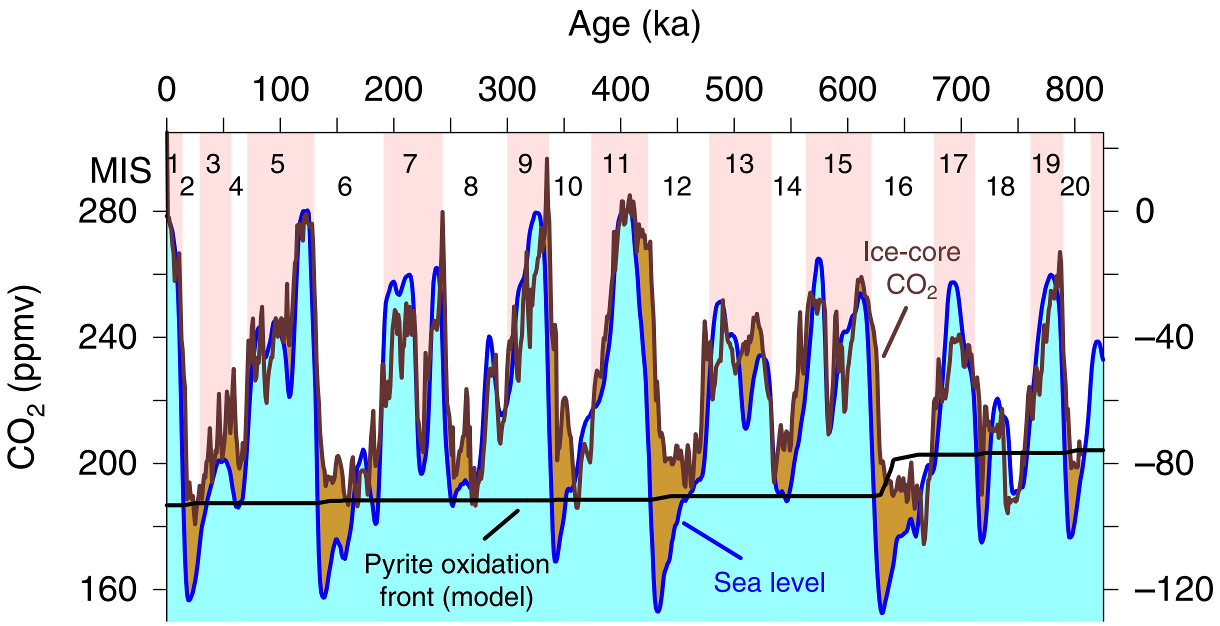
ARTICLES

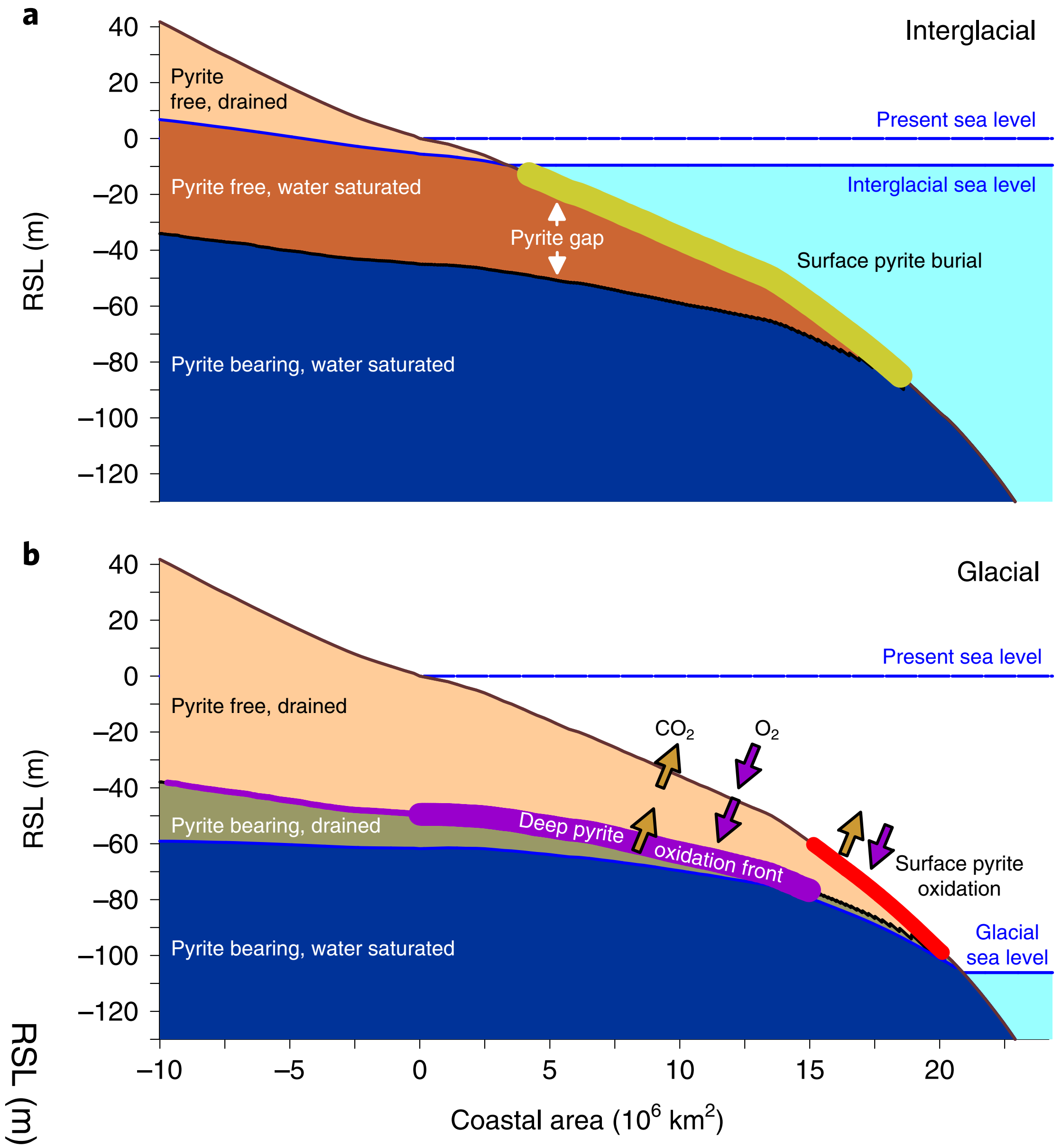
https://doi.org/10.1038/s41561-019-0465-9

Consistent CO_2 release by pyrite oxidation on continental shelves prior to glacial terminations

Martin Kölling[1]*, Ilham Bouimetarhan[1,2], Marshall W. Bowles[1,3], Thomas Felis[1], Tobias Goldhammer[1,4], Kai-Uwe Hinrichs[1], Michael Schulz[1] and Matthias Zabel[1]

Previous evidence suggests enhanced pyrite oxidation on exposed continental shelves during glacial phases of low sea level. While pyrite oxidation directly consumes atmospheric oxygen, acid generated by this reaction should increase the release of CO_2 through carbonate dissolution. This scenario represents a climate control loop that could temper or even prevent glacials because increasing CO_2 triggers warming and rising sea level. However, the amplitudes of sea-level changes increased over the Quaternary, and CO_2 concentrations co-varied with sea level throughout most of the past 800,000 years. Only during peak glacial conditions did CO_2 levels reach an apparent lower threshold independent of falling sea level. Here we suggest that during the last nine glacial–interglacial cycles, pyrite-oxidation-driven release of CO_2 and consumption of O_2 occurred during 10 kyr to 40 kyr periods preceding glacial terminations. We demonstrate that repeated sea-level lowstands force pyrite oxidation to ever-greater depths in exposed shelf sediments and cause CO_2 release that could explain the glacial CO_2 threshold. When the duration of interglacials with high sea level is insufficient to restock the shelf pyrite inventory, this CO_2-releasing process represents a discharging 'acid capacitor'.

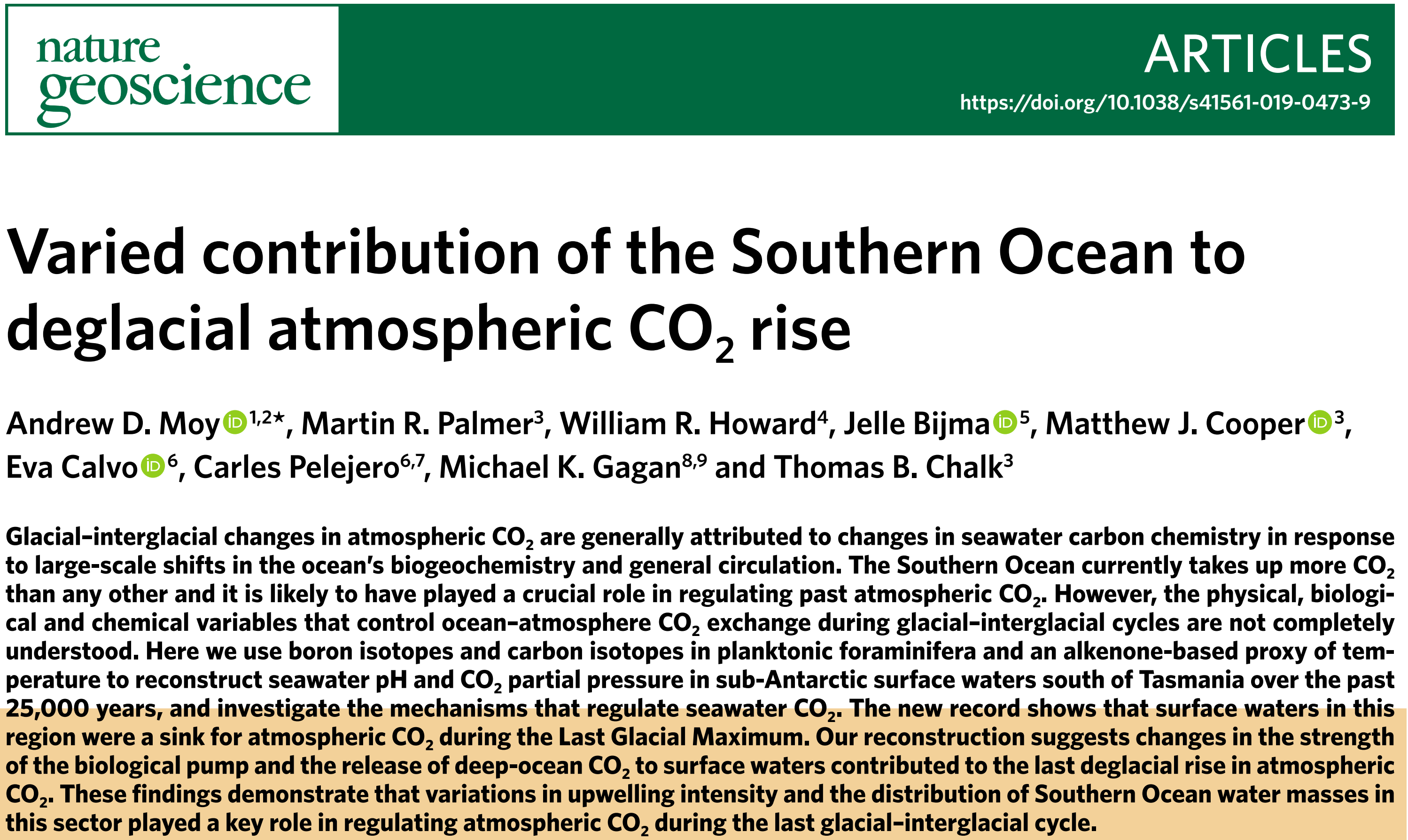




Kölling et al., Nature Geoscience, 2019

Orbital-scale changes of greenhouse gases

- <u>example of recent research</u>



nature geoscience

ARTICLES

https://doi.org/10.1038/s41561-019-0473-9

Varied contribution of the Southern Ocean to deglacial atmospheric CO_2 rise

Andrew D. Moy[1,2*], Martin R. Palmer[3], William R. Howard[4], Jelle Bijma[5], Matthew J. Cooper[3], Eva Calvo[6], Carles Pelejero[6,7], Michael K. Gagan[8,9] and Thomas B. Chalk[3]

Glacial–interglacial changes in atmospheric CO_2 are generally attributed to changes in seawater carbon chemistry in response to large-scale shifts in the ocean's biogeochemistry and general circulation. The Southern Ocean currently takes up more CO_2 than any other and it is likely to have played a crucial role in regulating past atmospheric CO_2. However, the physical, biological and chemical variables that control ocean–atmosphere CO_2 exchange during glacial–interglacial cycles are not completely understood. Here we use boron isotopes and carbon isotopes in planktonic foraminifera and an alkenone-based proxy of temperature to reconstruct seawater pH and CO_2 partial pressure in sub-Antarctic surface waters south of Tasmania over the past 25,000 years, and investigate the mechanisms that regulate seawater CO_2. The new record shows that surface waters in this region were a sink for atmospheric CO_2 during the Last Glacial Maximum. Our reconstruction suggests changes in the strength of the biological pump and the release of deep-ocean CO_2 to surface waters contributed to the last deglacial rise in atmospheric CO_2. These findings demonstrate that variations in upwelling intensity and the distribution of Southern Ocean water masses in this sector played a key role in regulating atmospheric CO_2 during the last glacial–interglacial cycle.

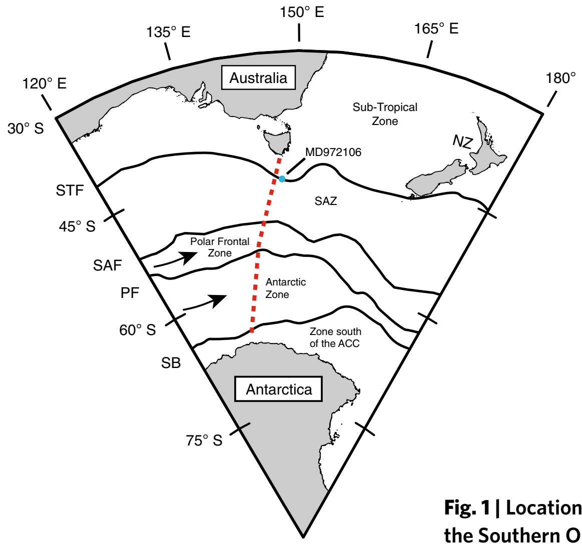


Fig. 1 | Location of sediment core MD972106 and modern positions of the Southern Ocean water masses and frc

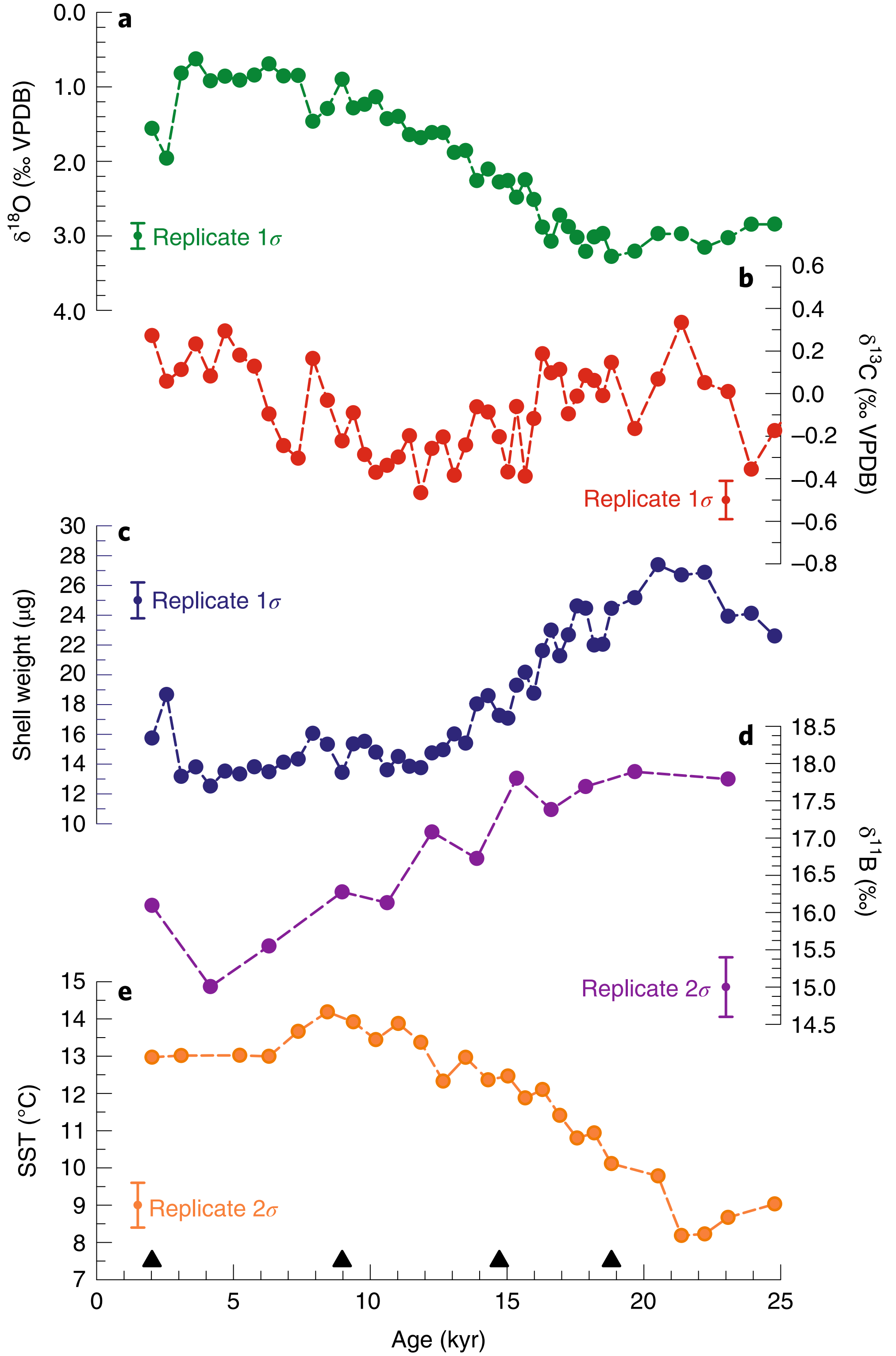
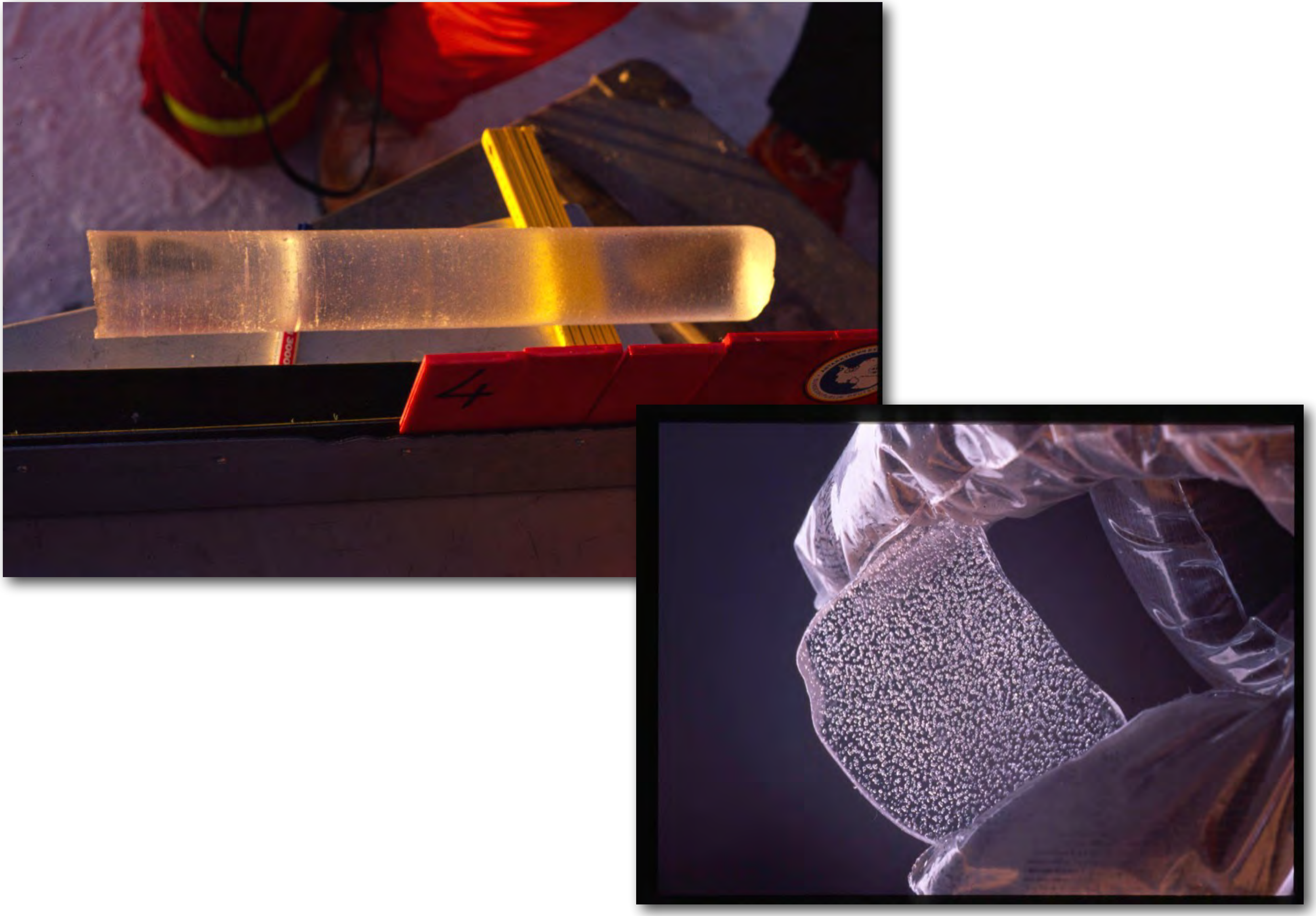


Fig. 2 | $\delta^{18}O$, $\delta^{13}C$, shell weight and $\delta^{11}B$ for the planktonic foraminifer, *G. bulloides* and SST estimates from alkenones in sediment core MD972106.

Moy et al., Nature Geoscience, 2019

Ice cores - a key climate archive



Climate System II

(Winter 2022/2023)

5th 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/climate2022_23.html