# Climate System II

(Winter 2023/2024)

**2nd lecture:**

## The global water cycle

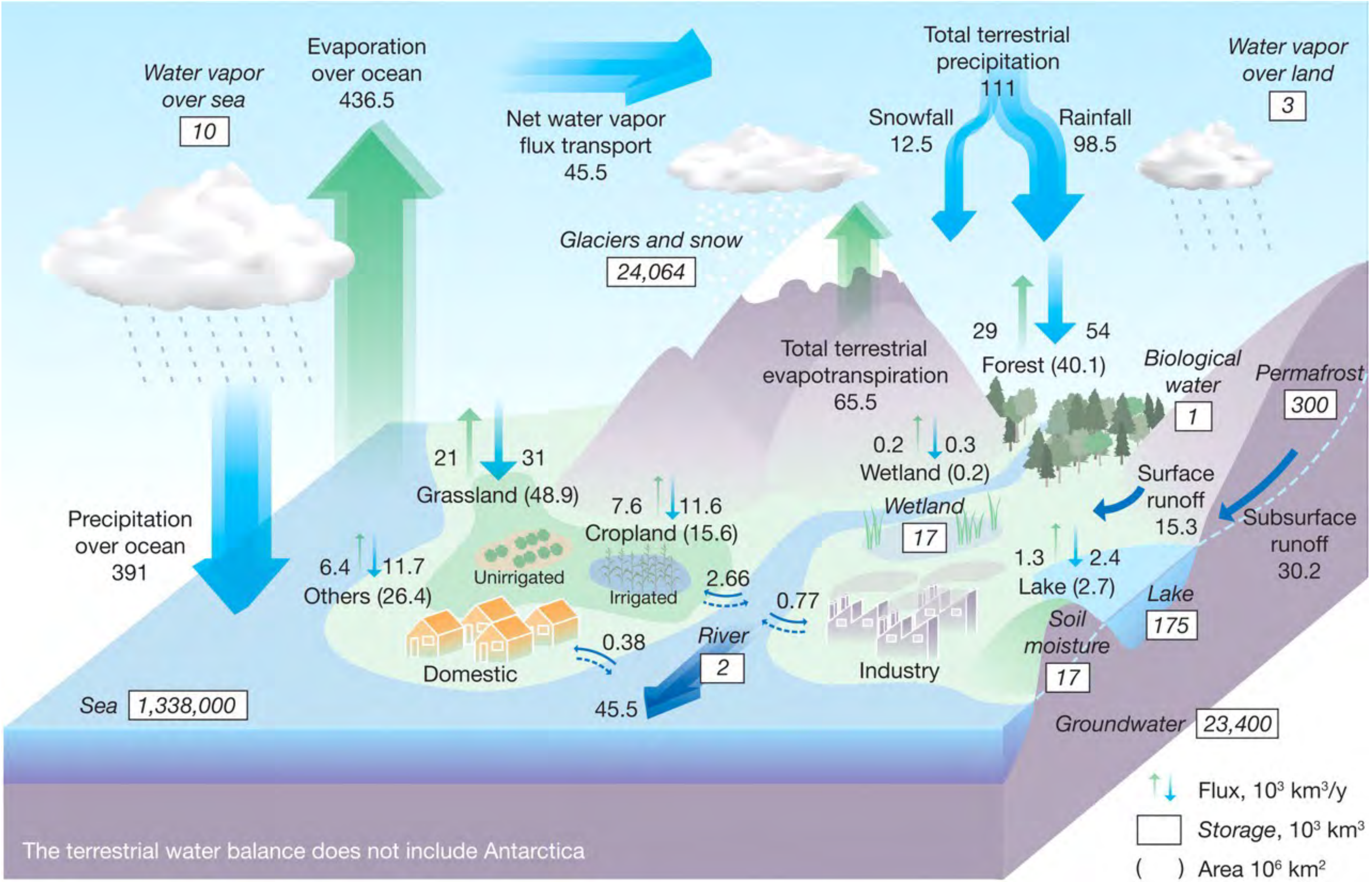
(water cycle, stable water isotopes, ice core records)

**Gerrit Lohmann, Martin Werner**

**Tuesday, 10:15-11:45**

**https://paleodyn.uni-bremen.de/study/climate2023_24.html**

# The global water cycle

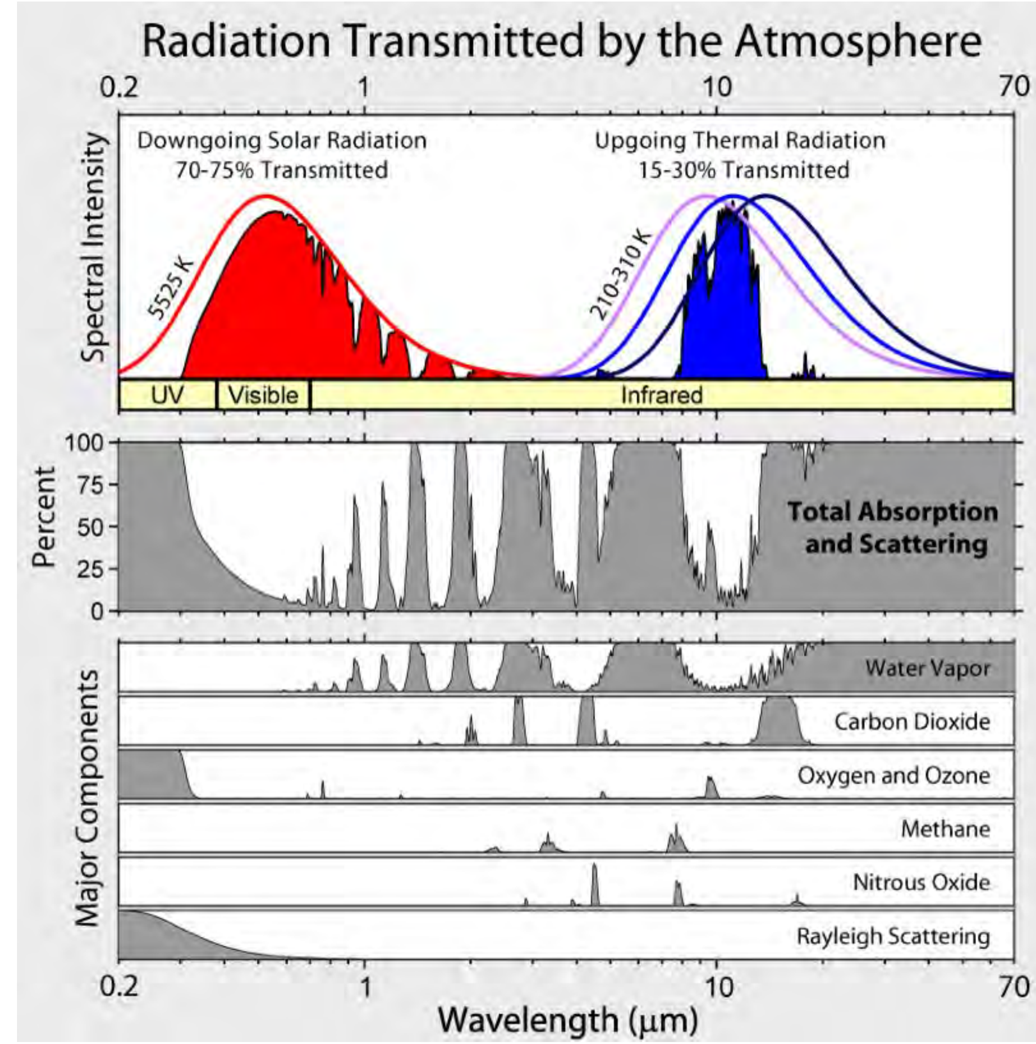



Taikan Oki, and Shinjiro Kanae Science 2006;313:1068-1072

**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: $1{,}338 \cdot 10^6 km^3$
- 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

**<u>Quizz - Questions</u>:**

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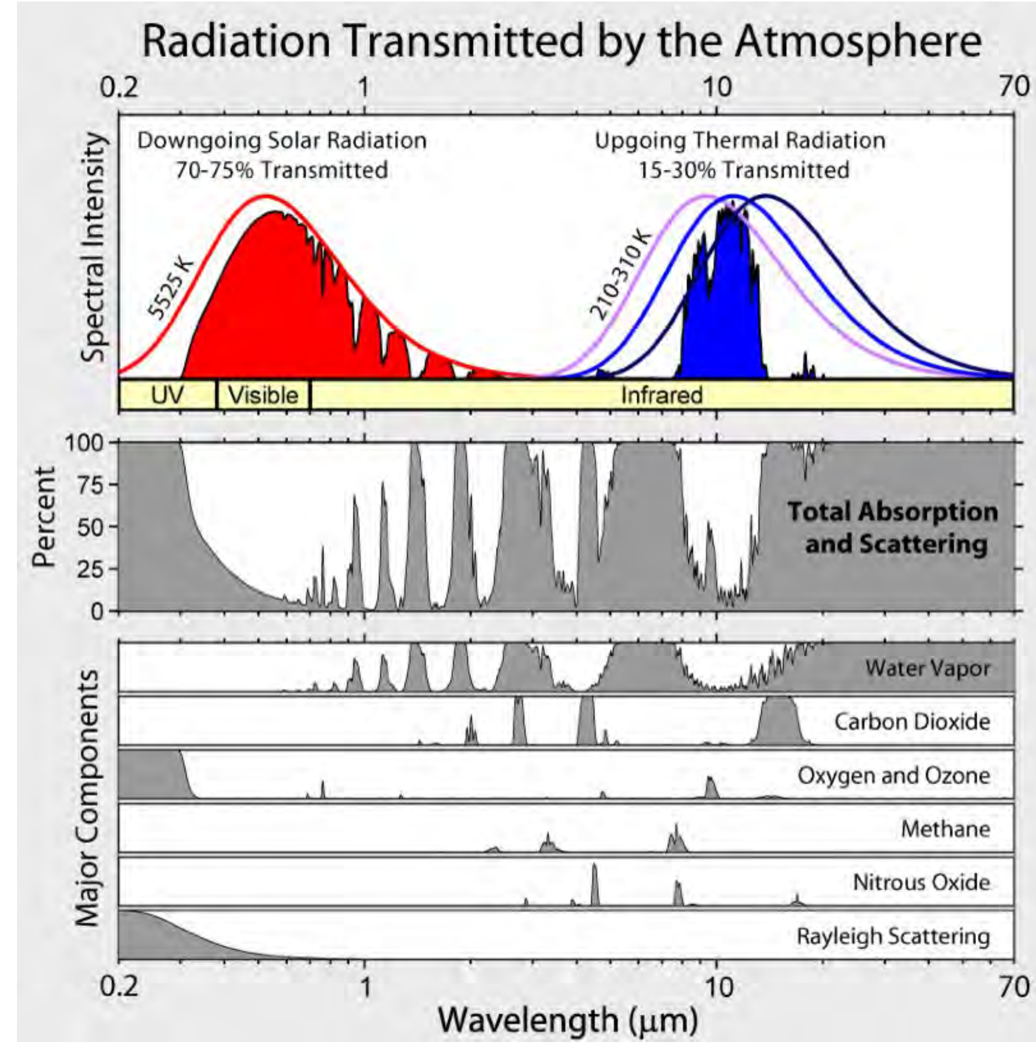
- 97.3% of all available water (liquid equivalent) is stored in the oceans

- 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)

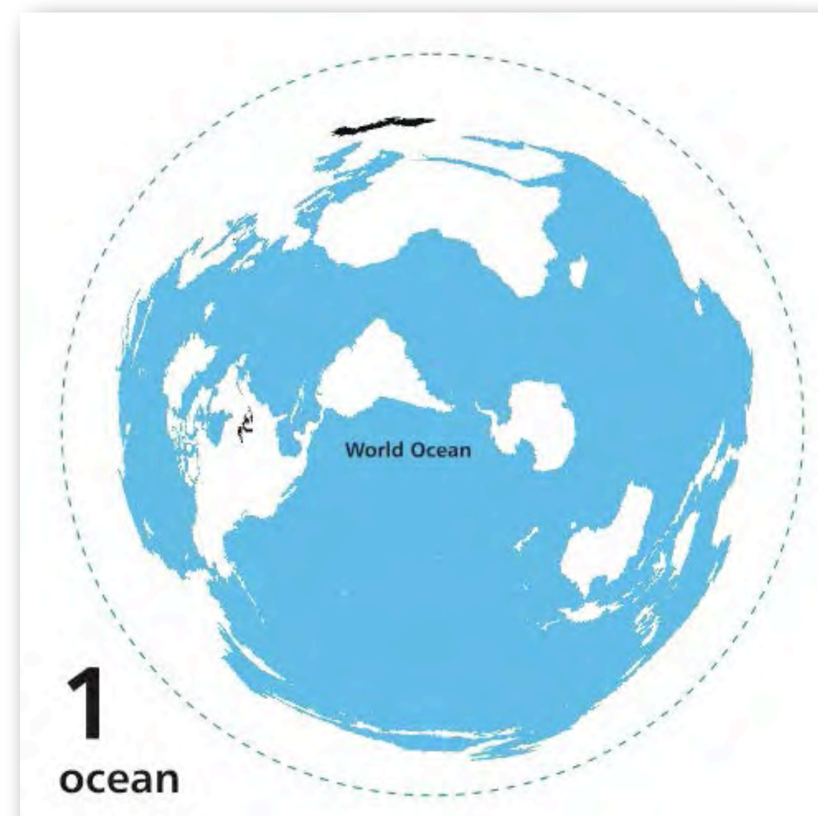
- water is the most important greenhouse gas

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

- all vapour condensed as a liquid layer
  *=> layer would be approx. 2.5cm high*

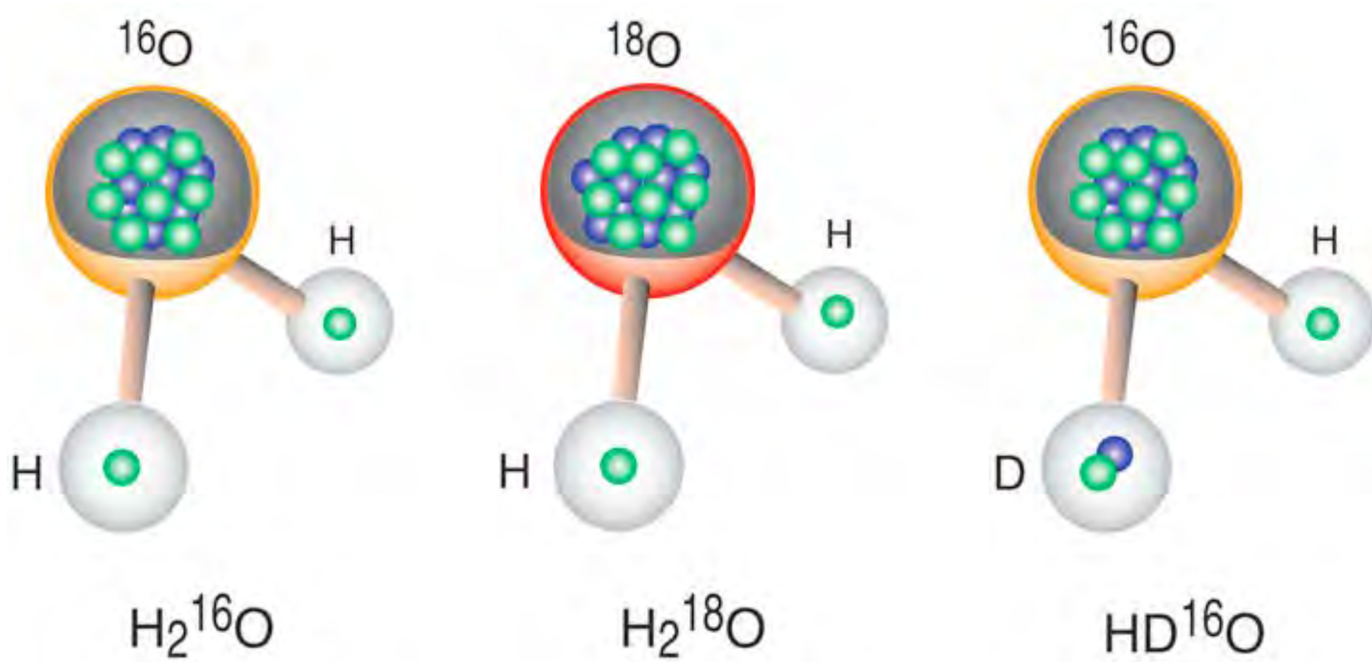



https://en.wikipedia.org/wiki/Greenhouse_gas



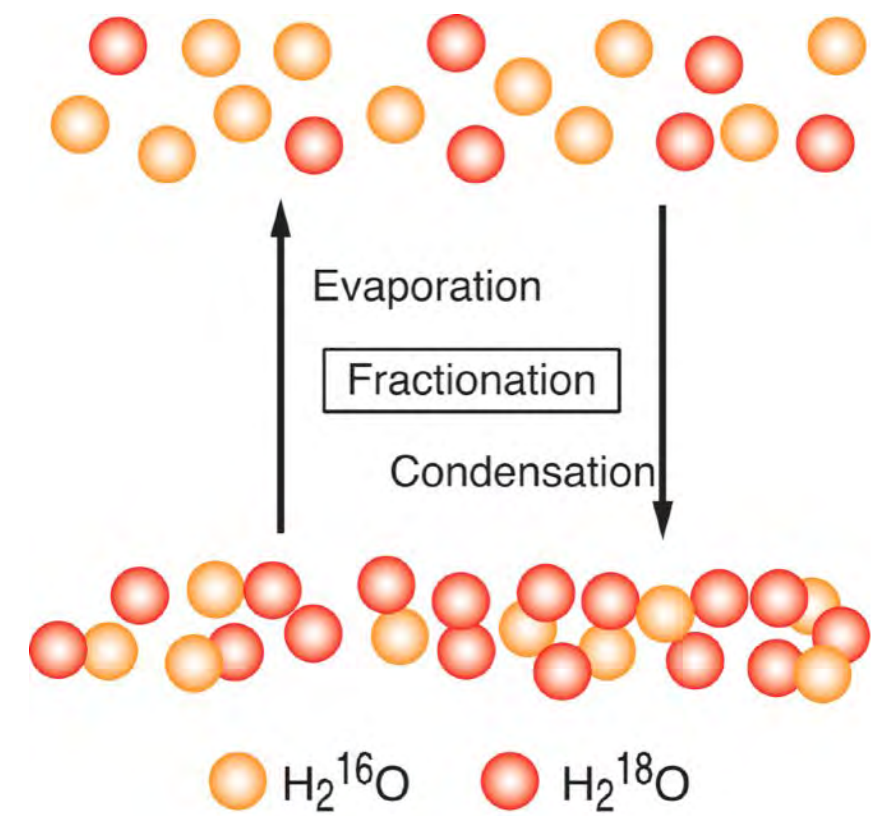

http://en.wikipedia.org/wiki/File:World_ocean_map.gif

# Natural abundance of stable water isotopes




1,000,000 2005.2 311.52

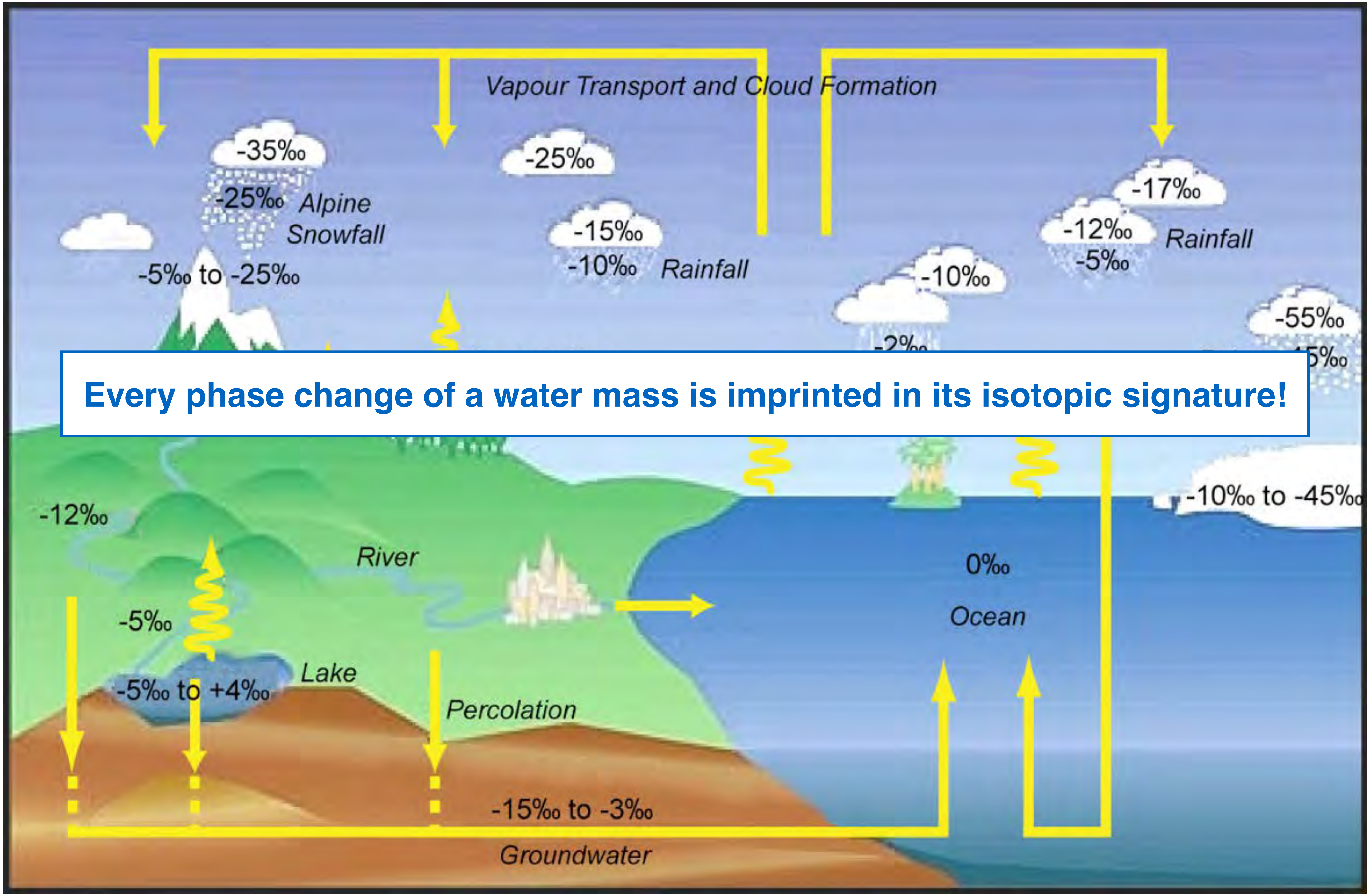
*approx. number of molecules in ocean water*




- **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 ‰)**

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

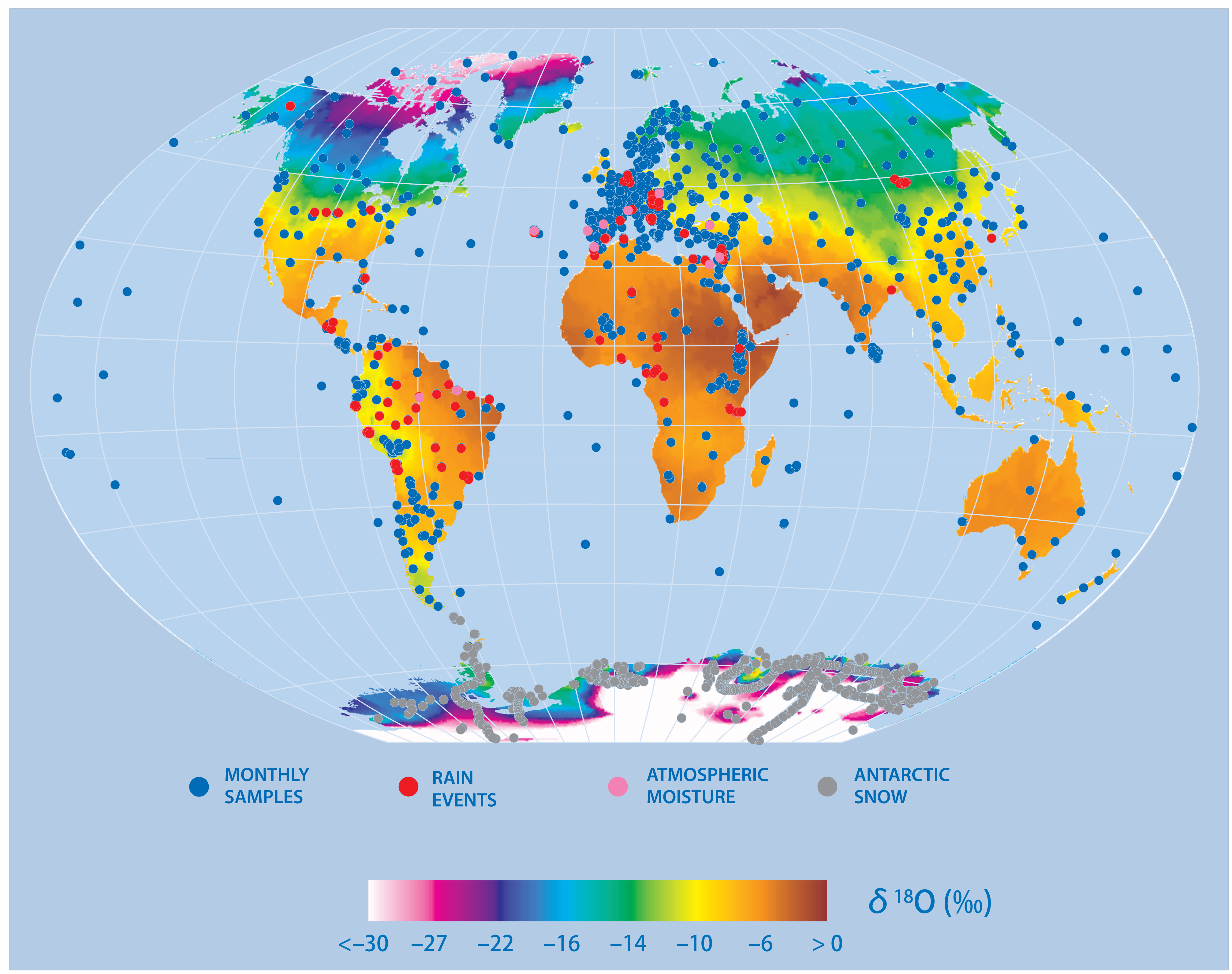
# Global distribution of $\delta^{18}O$ in the hydrological cycle




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

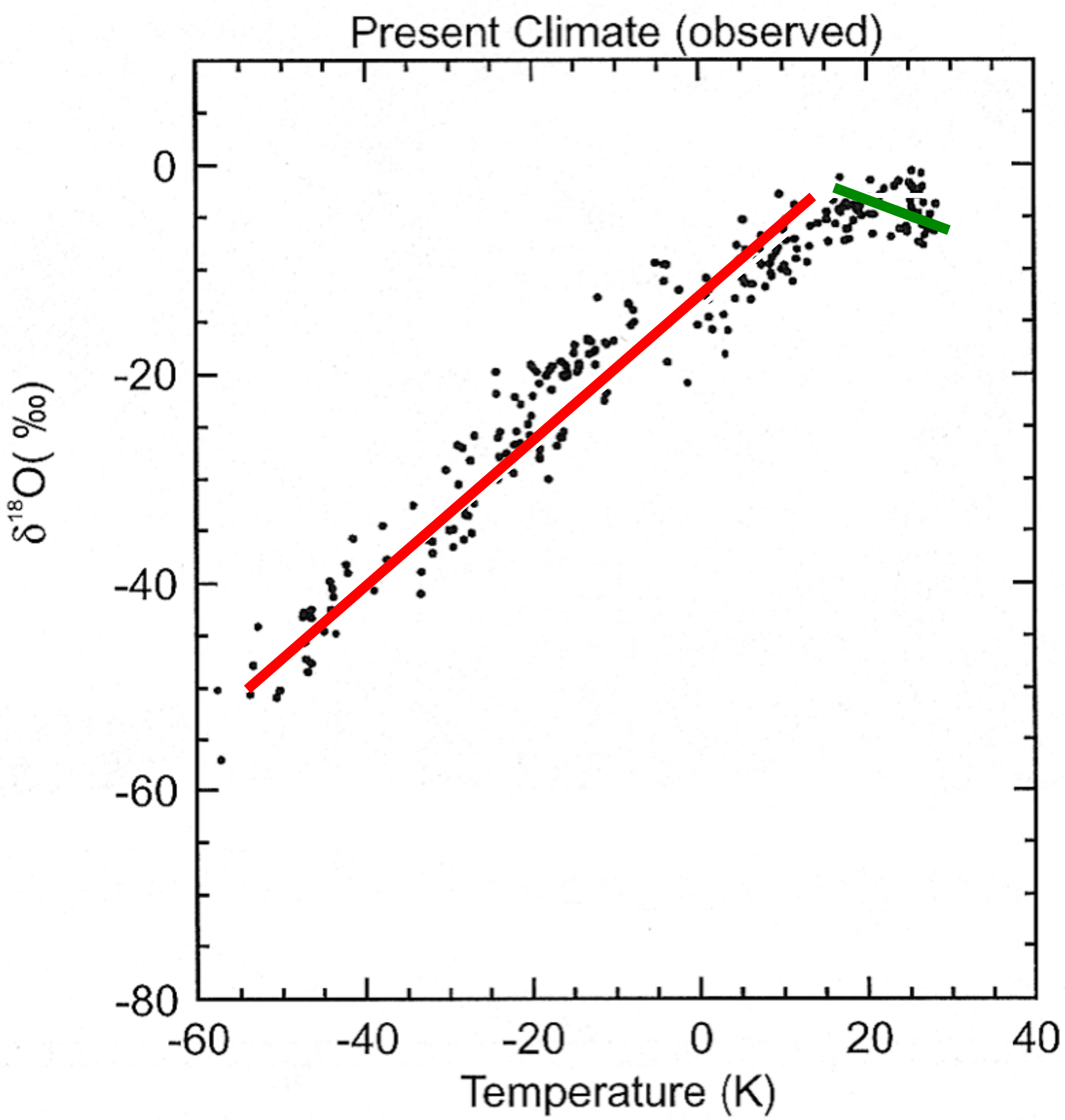
[plot adapted from the GNIP brochure, IAEA, 1996]

# 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

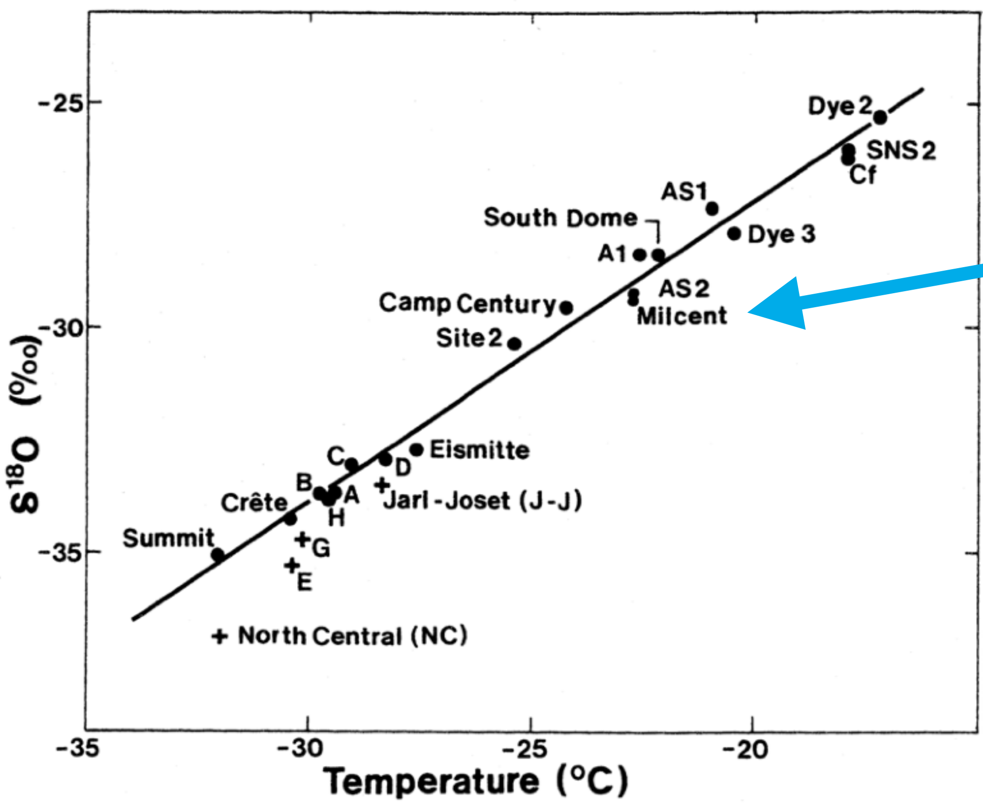



Annual $\delta^{18}O$ in precipitation in relation to mean annual temperature at the same site, based on data from the International Atomic Energy Agency.

(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 $\delta D$ 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 δ18O in precipitation as a temperature proxy

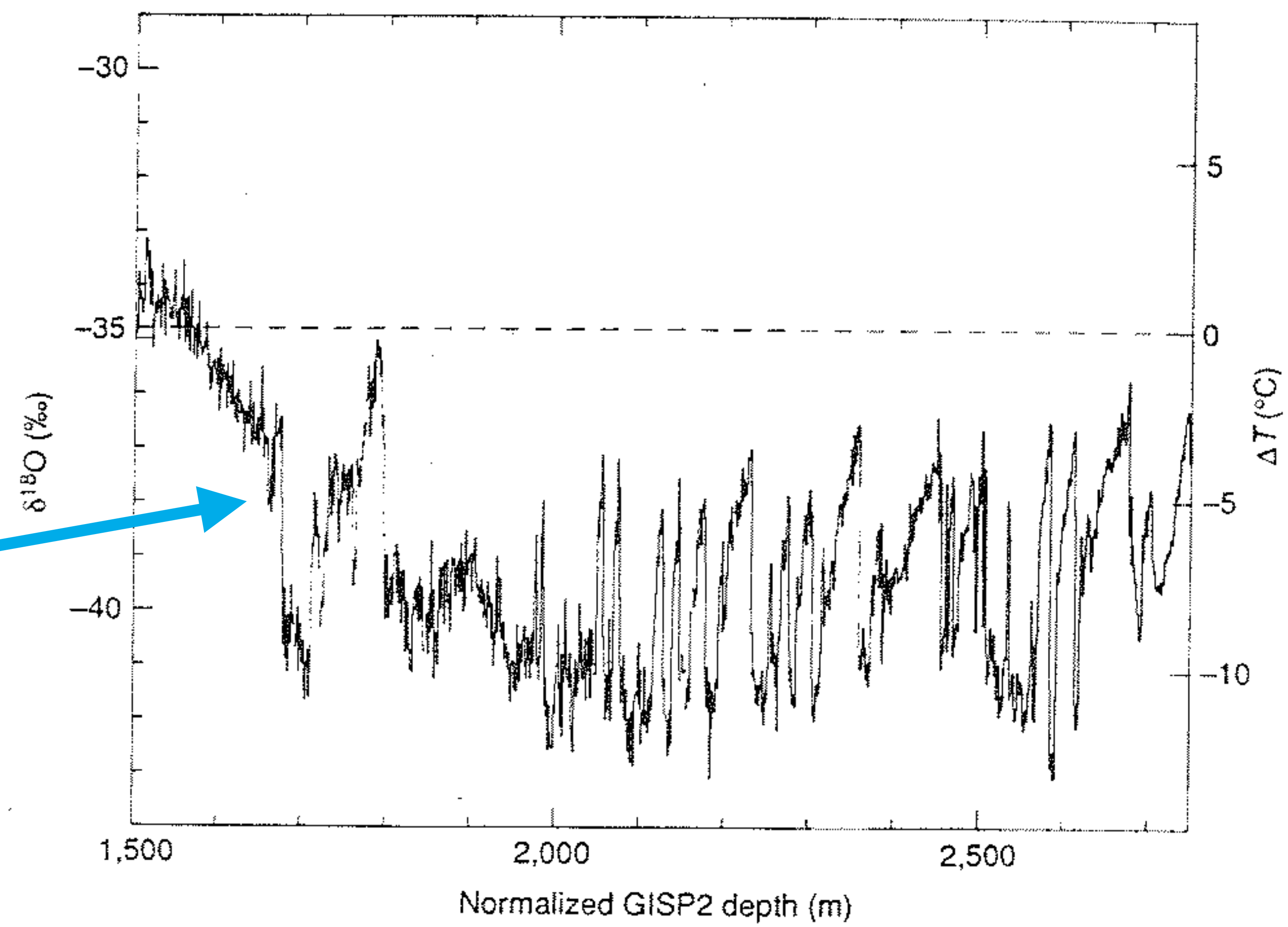



[Johnsen et al., Tellus, 1989]

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

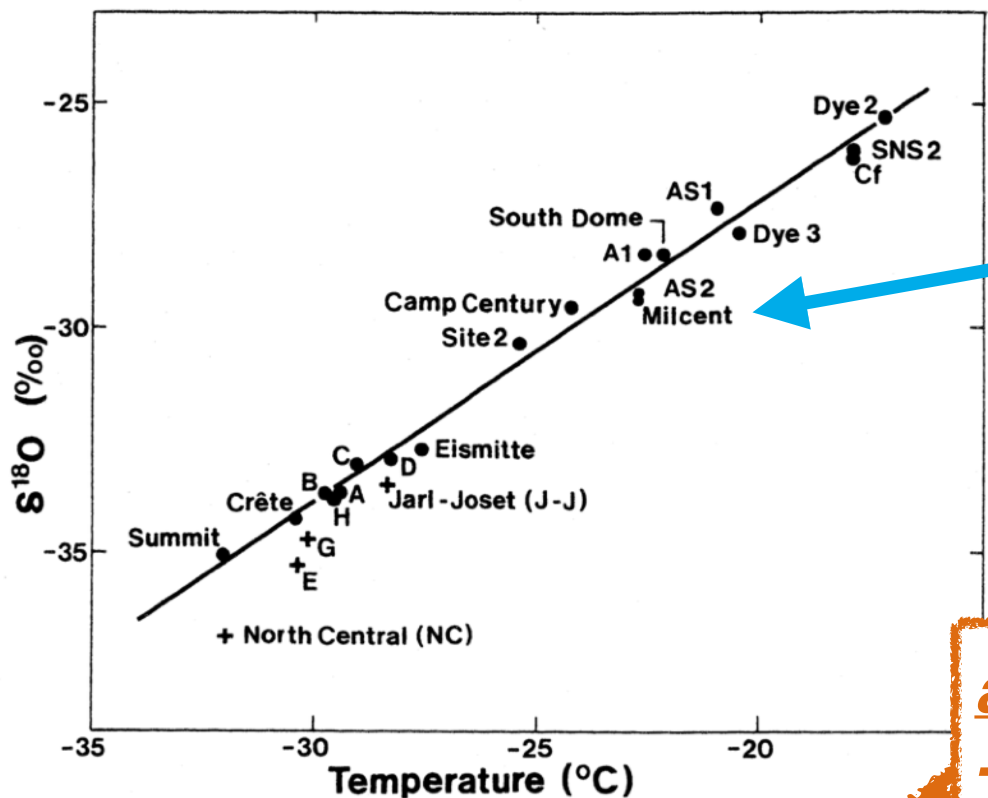
$$\delta^{18}O = 0.67 \cdot T_{surf}$$

**Converting temporal changes of δ18O into past temperature changes**




[Grootes et al., Nature, 1993]

# The use of of δ18O in precipitation as a temperature proxy




[Johnsen et al., Tellus, 1989]

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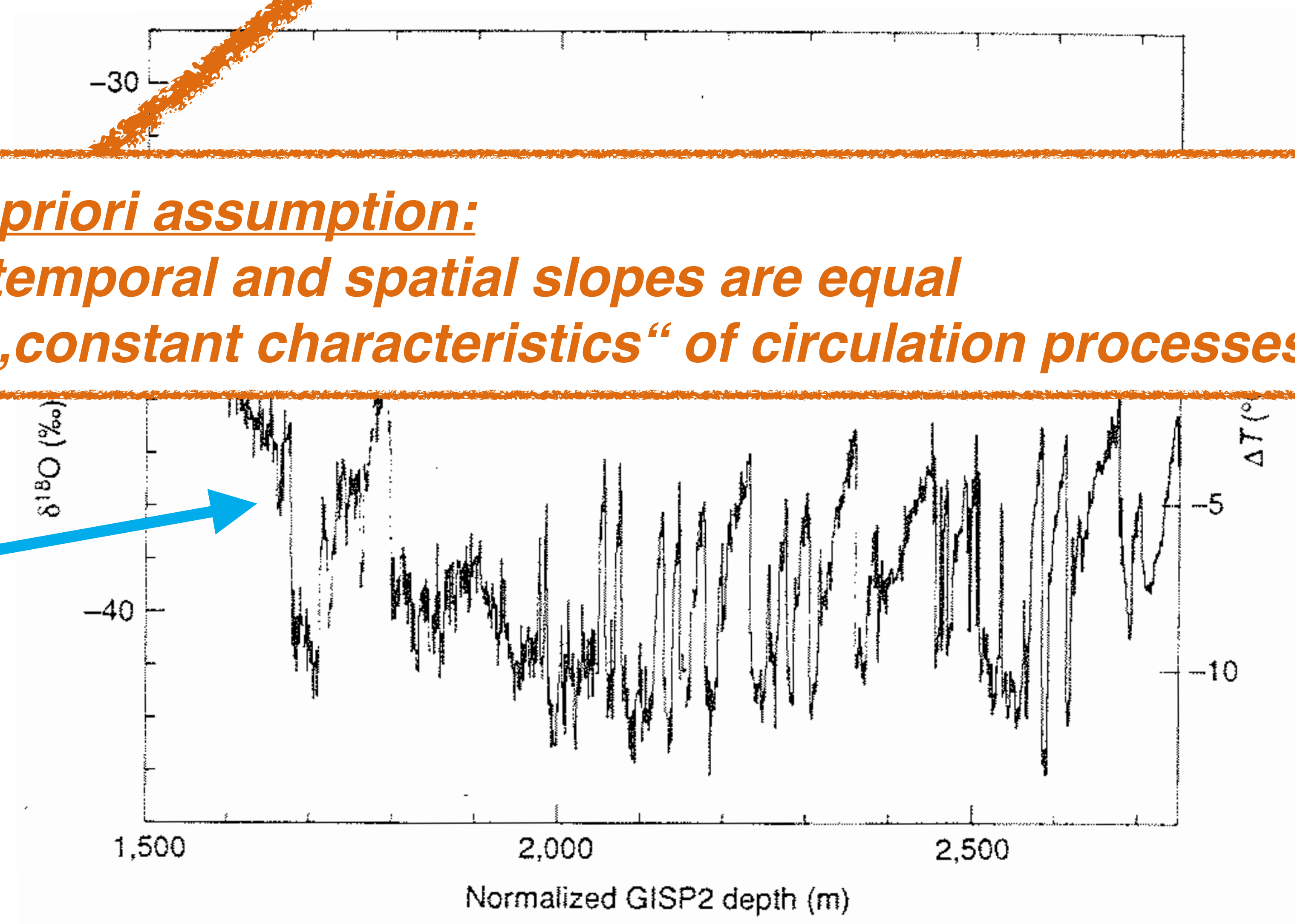



***a priori assumption:***

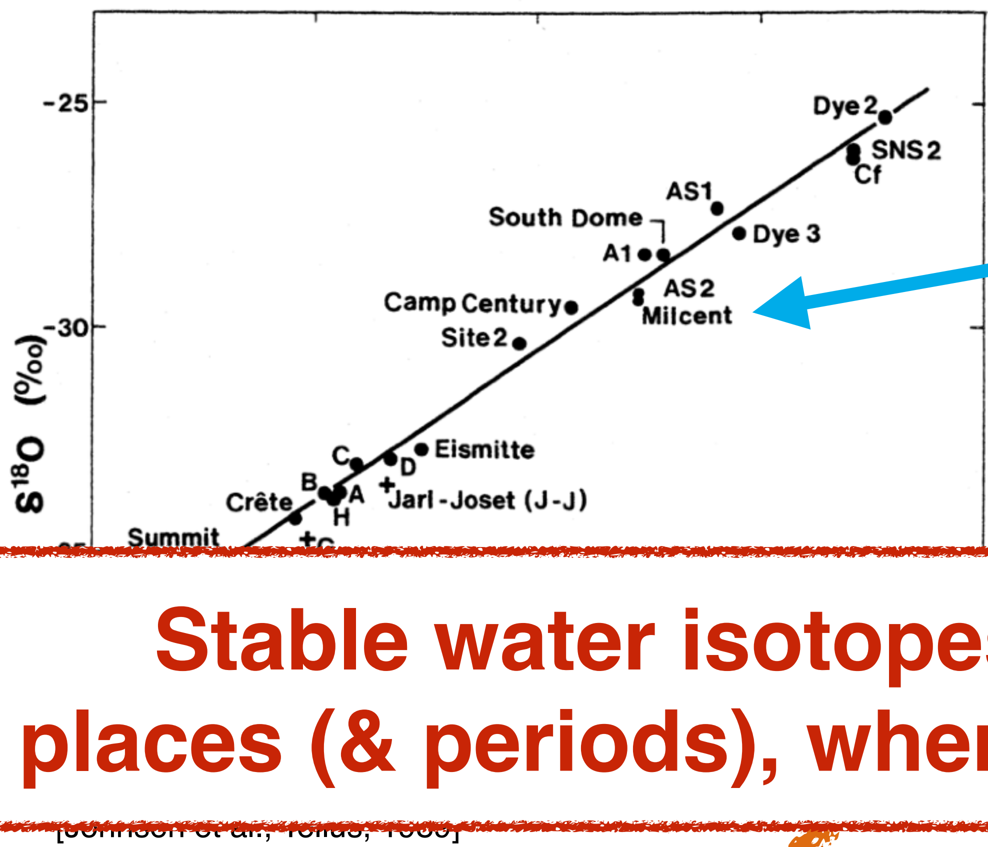
***- temporal and spatial slopes are equal***

***- „constant characteristics“ of circulation processes***

**Converting temporal changes of δ18O into past temperature changes**

[Grootes et al., Nature, 1993]

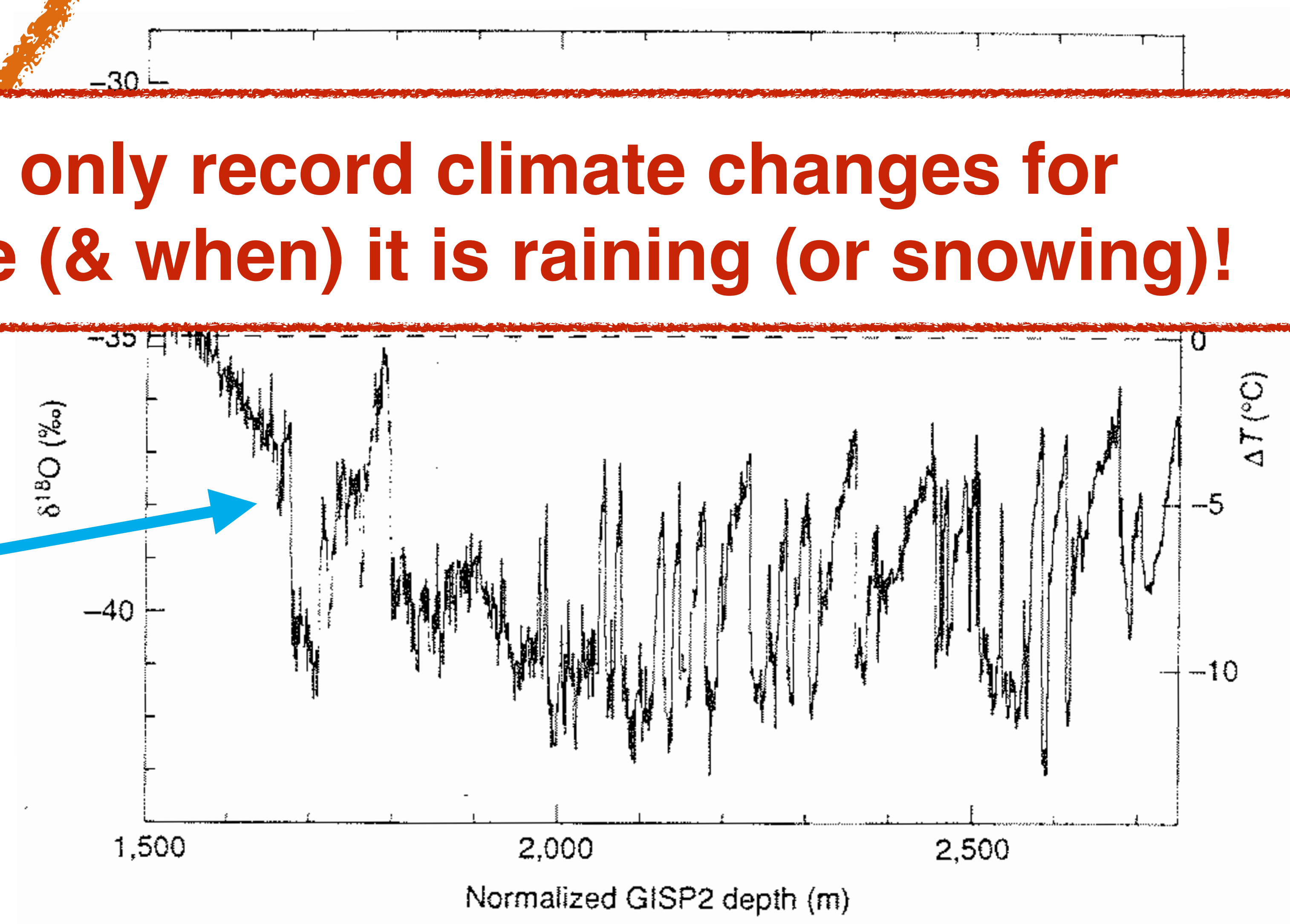
# The use of of δ¹⁸O in precipitation as a temperature proxy




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

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

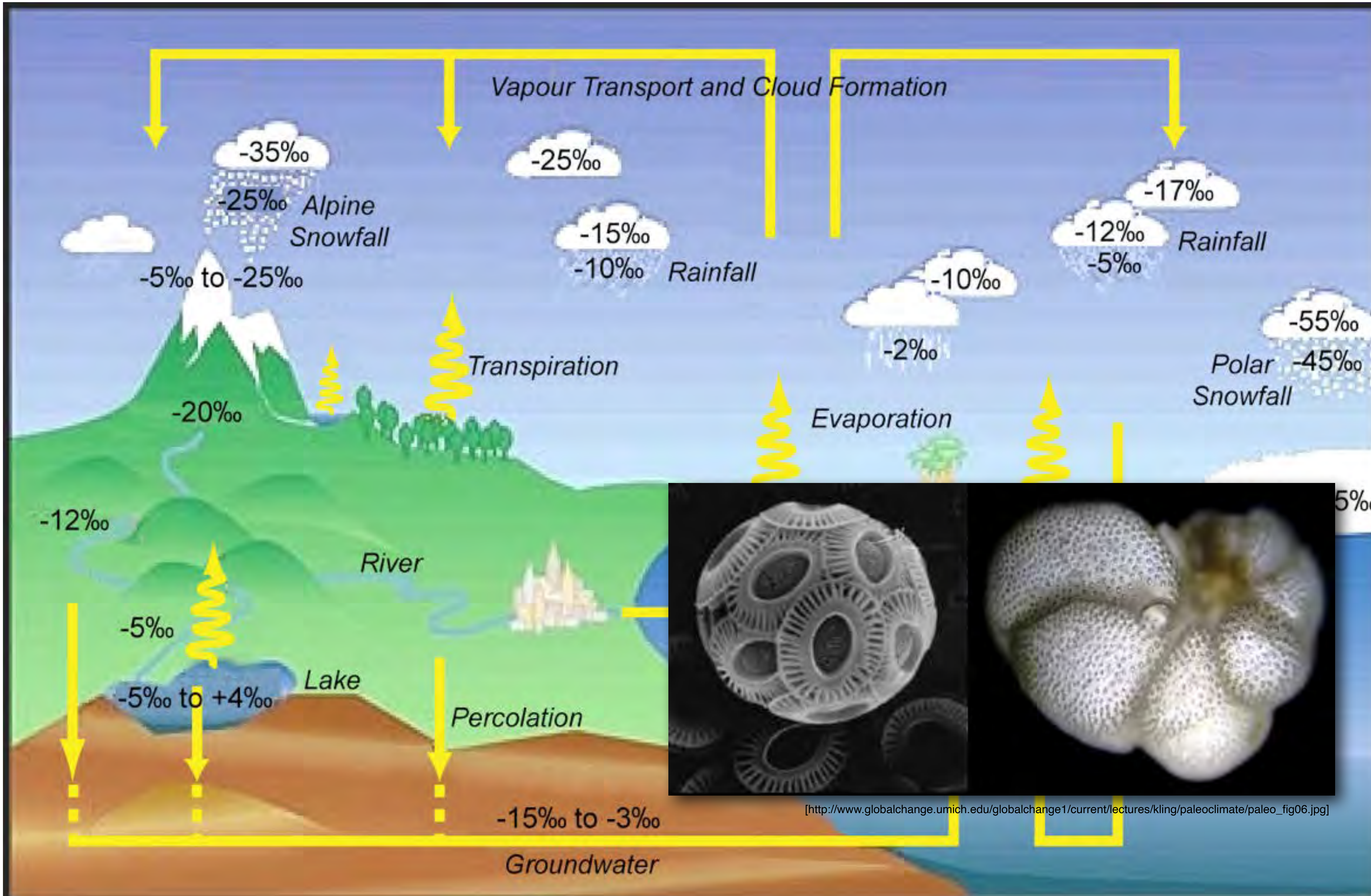
**Stable water isotopes only record climate changes for places (& periods), where (& when) it is raining (or snowing)!**




Converting temporal changes of δ¹⁸O into past temperature changes

[Grootes et al., Nature, 1993]

# The 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**

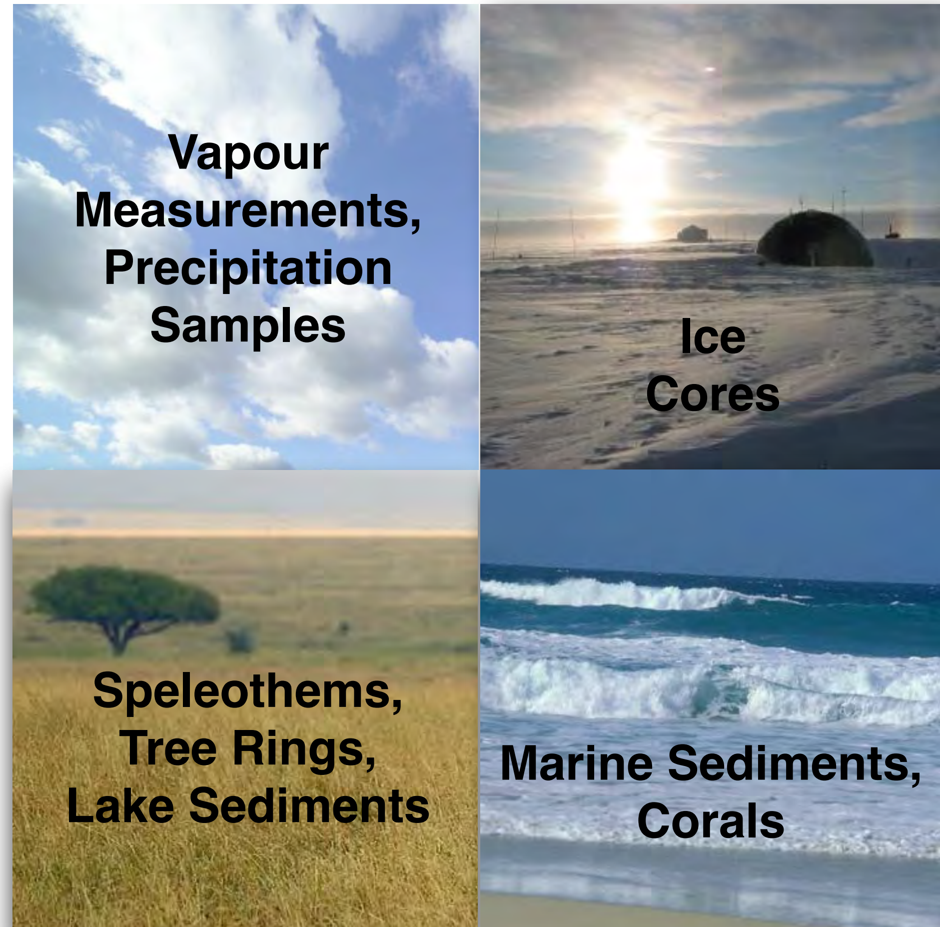
$$T = 16.9 - 4.2 (\delta_c - \delta_w) + 0.13 (\delta_c - \delta_w)^2$$

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

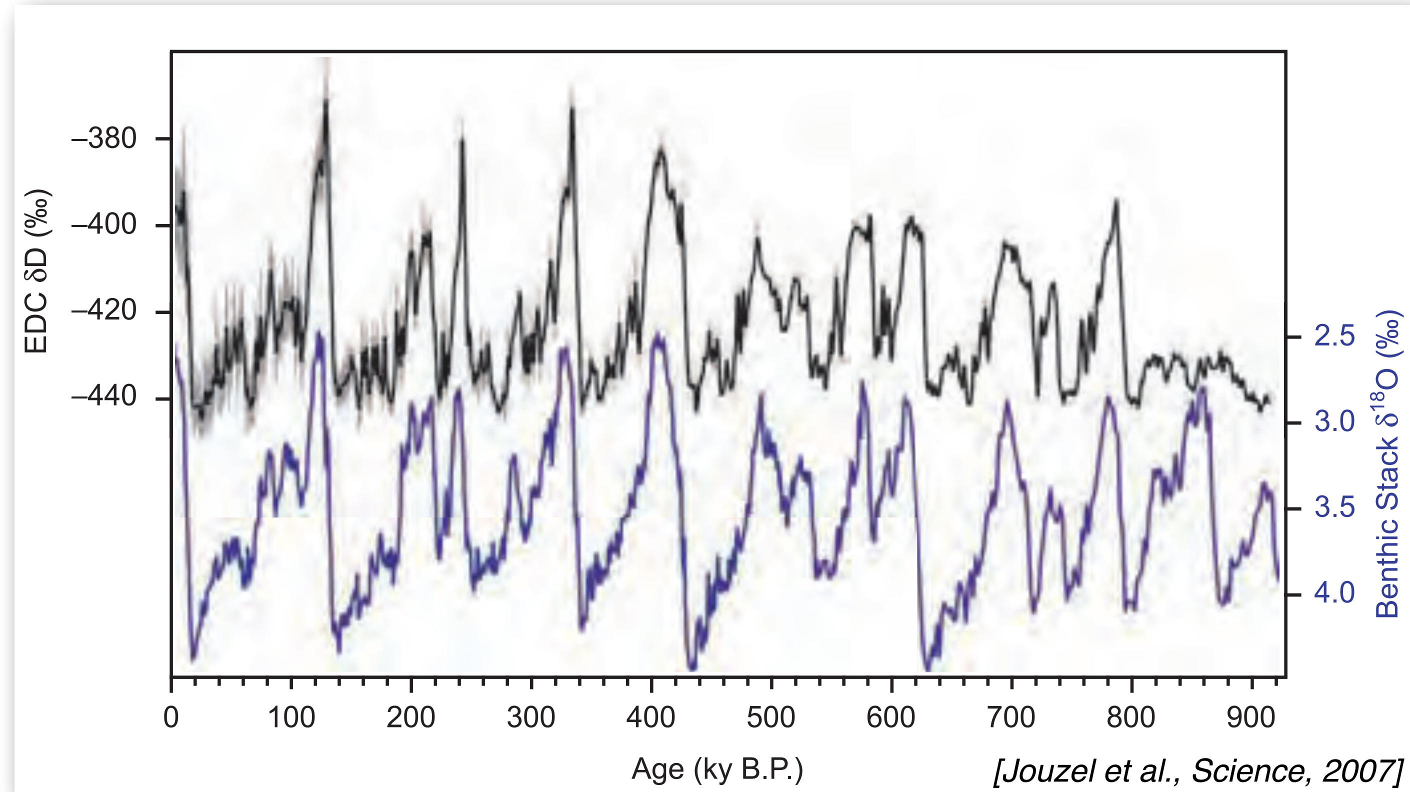
- ***$\delta^{18}O_w$ might be determined by analyses of porewater contained in the core***

- ***$\delta^{18}O_c$ 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

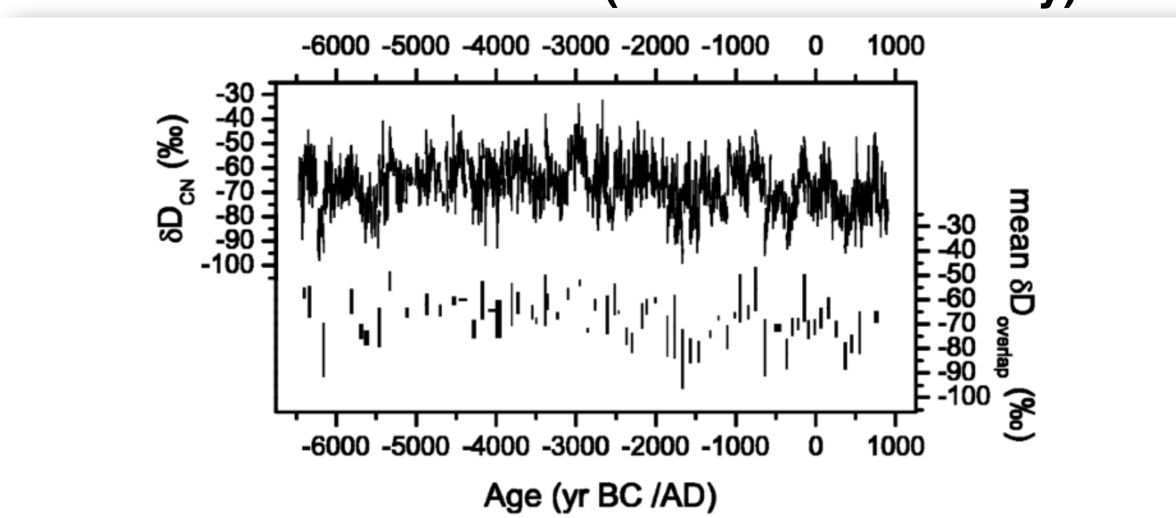



## EPICA Dome C and Benthic Oxygen-18 Records



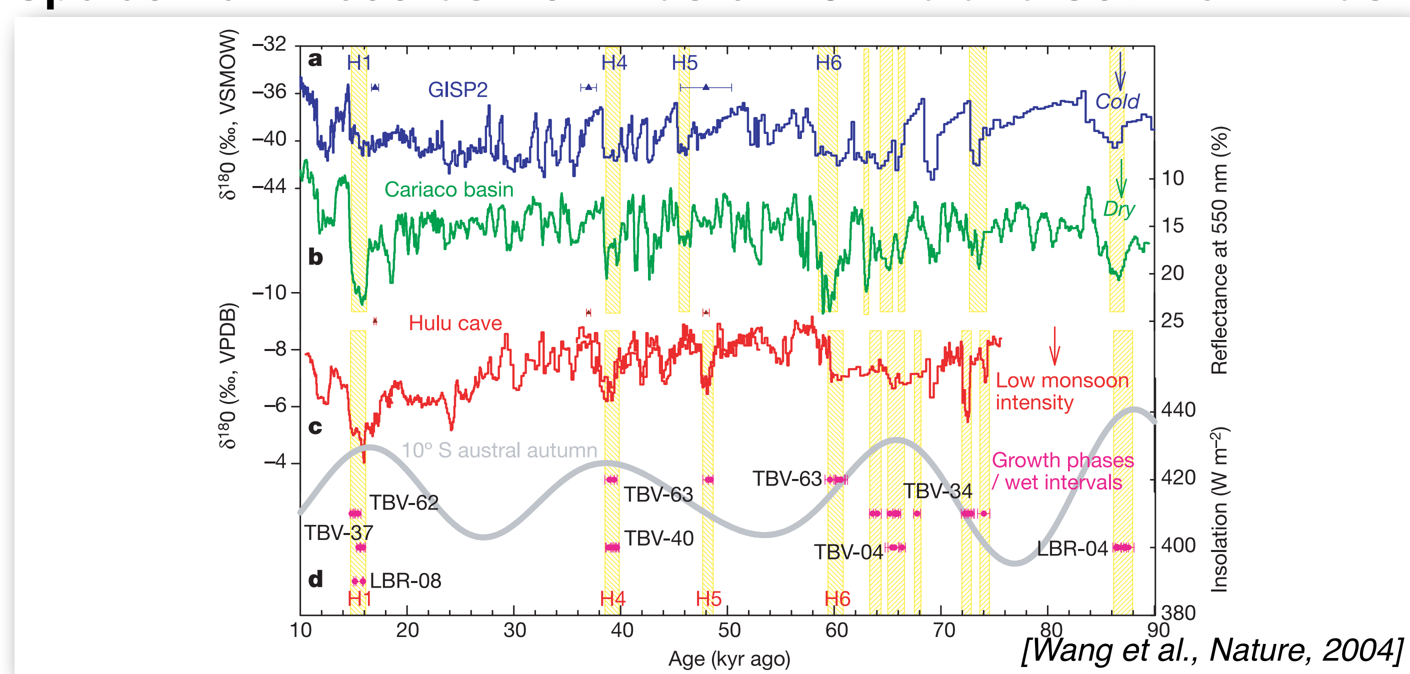

*[Jouzel et al., Science, 2007]*

## Subfossil Holocene Oaks ( Southern Germany)



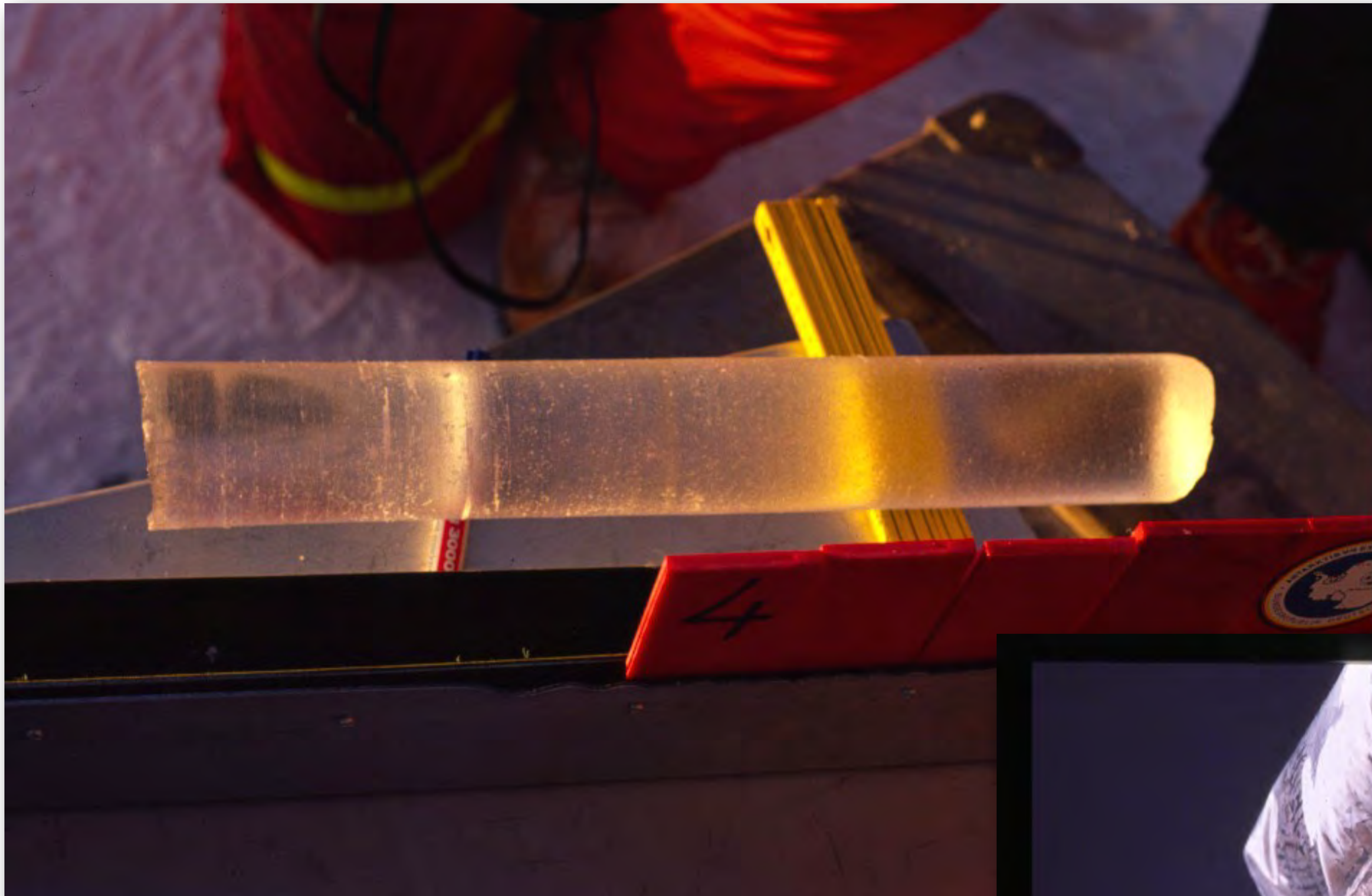

*[Mayr et al., The Holocene, 2003]*

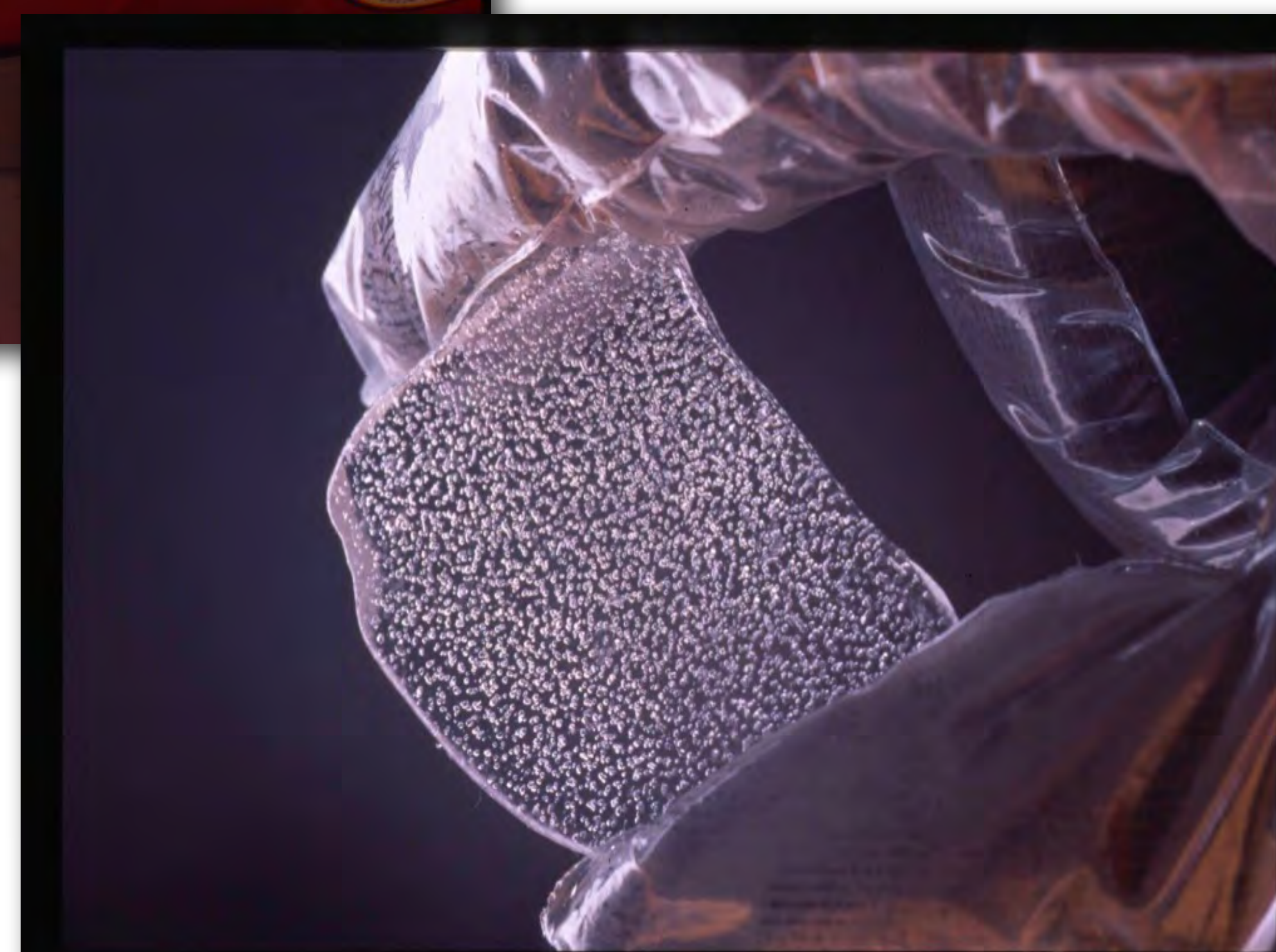
## Speleothem Records from Eastern China and Southern Brasil




*[Wang et al., Nature, 2004]*

# Ice cores - a key climate archive





# 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**

# Cross section of an ice sheet

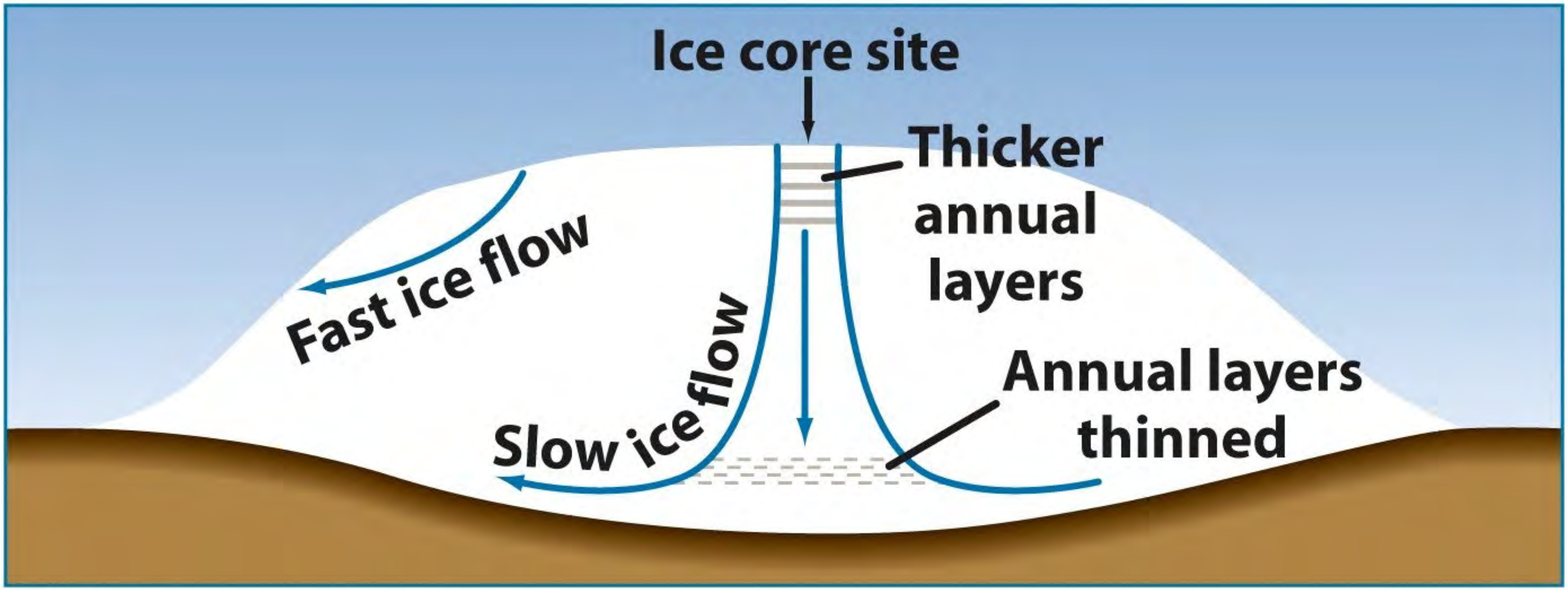
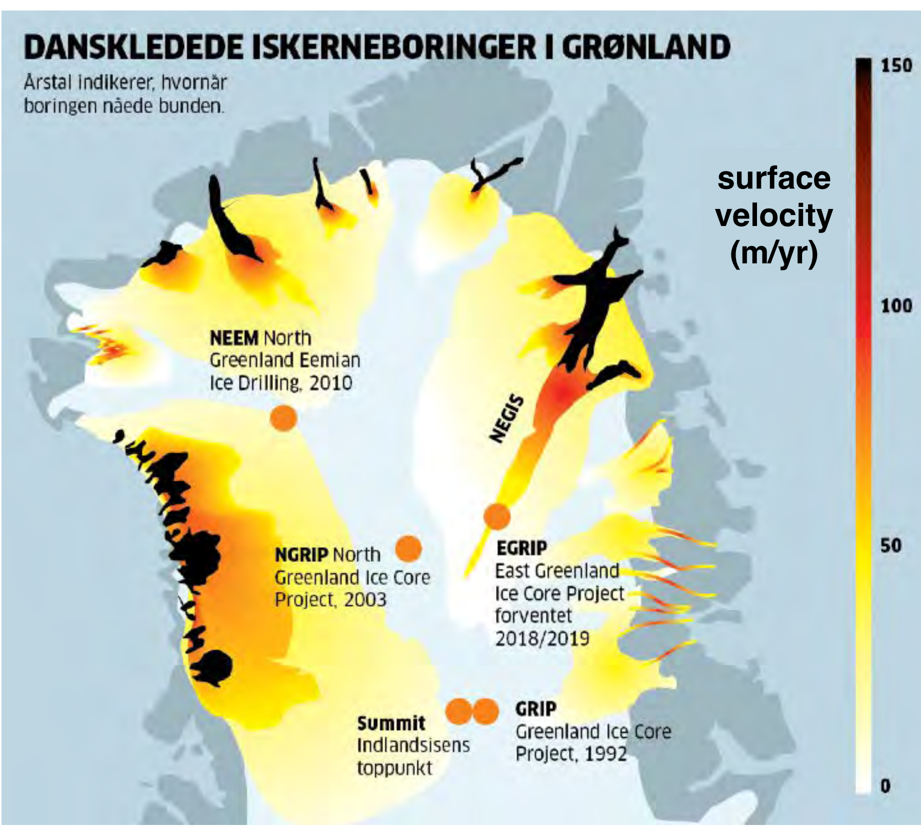
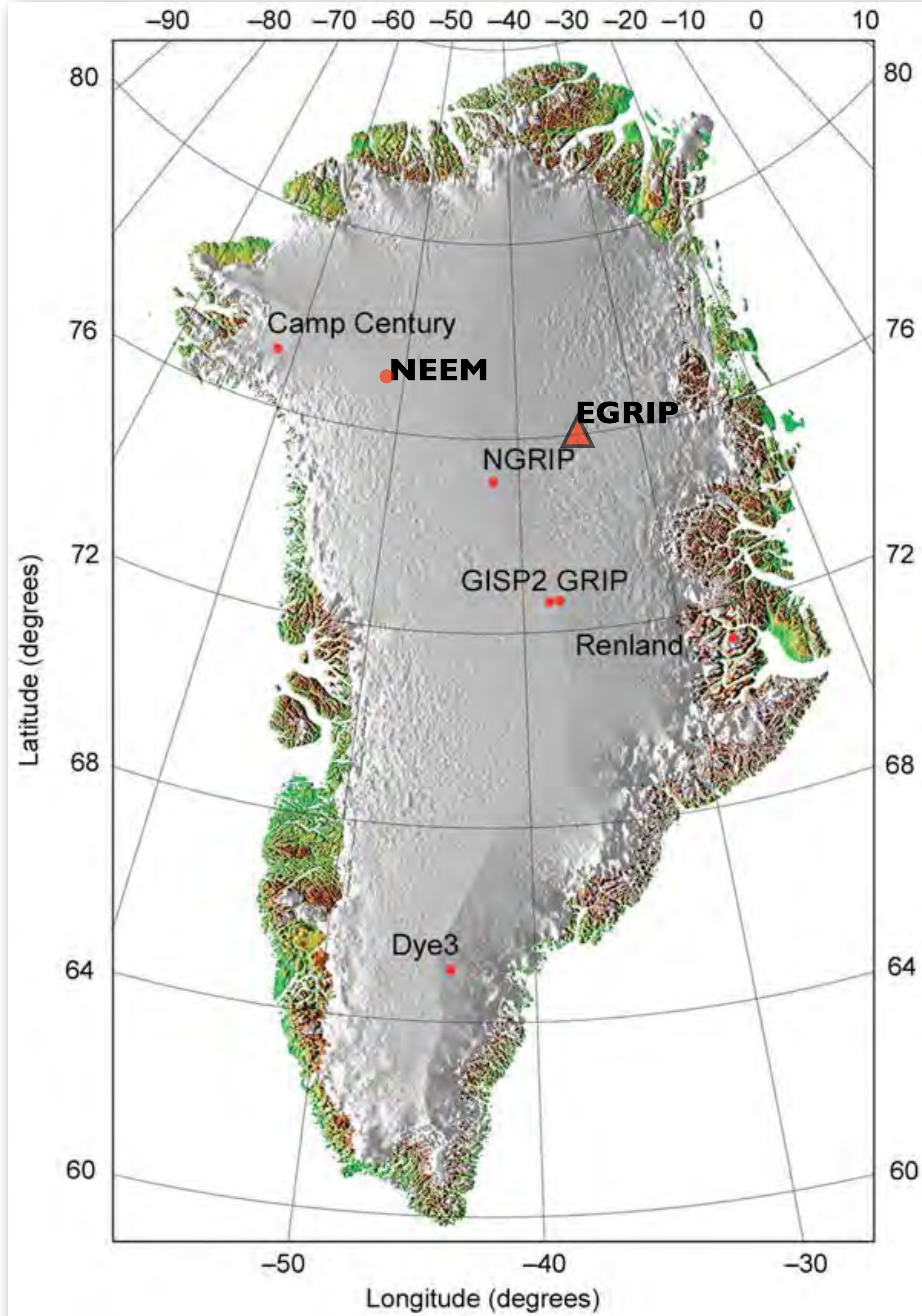



**Figure 10-1**
***Earth's Climate: Past and Future, Second Edition***

# Greenland ice cores

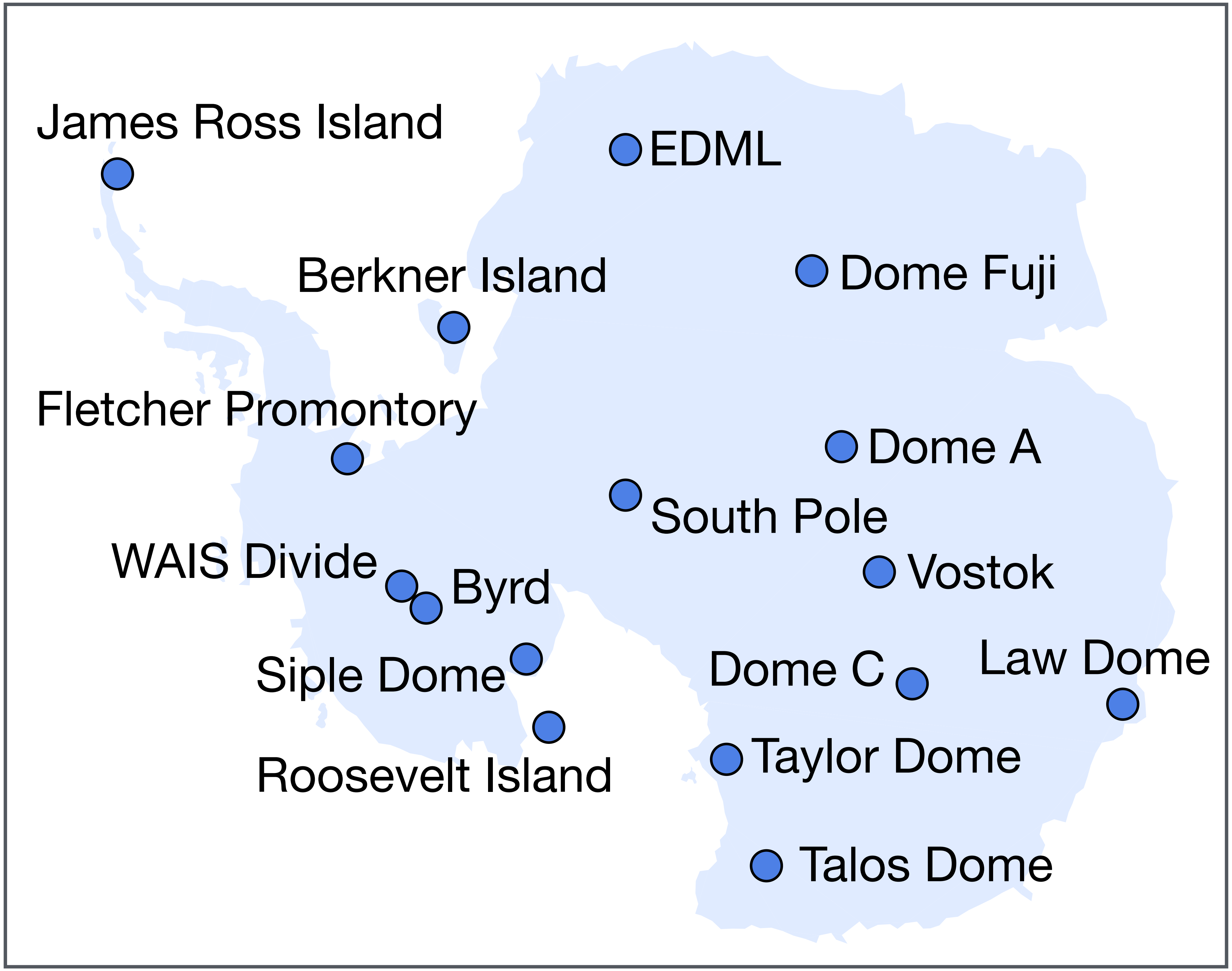



https://ing.dk/artikel/dynamikken-gronlands-isstromme-joker-klimaet-197376




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

# Antarctic ice cores




[Brook and Buizert, Nature, 2018]

# Ice 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

# Ice core drilling

# Ice core drilling


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

# Ice core drilling

# Ice core drilling

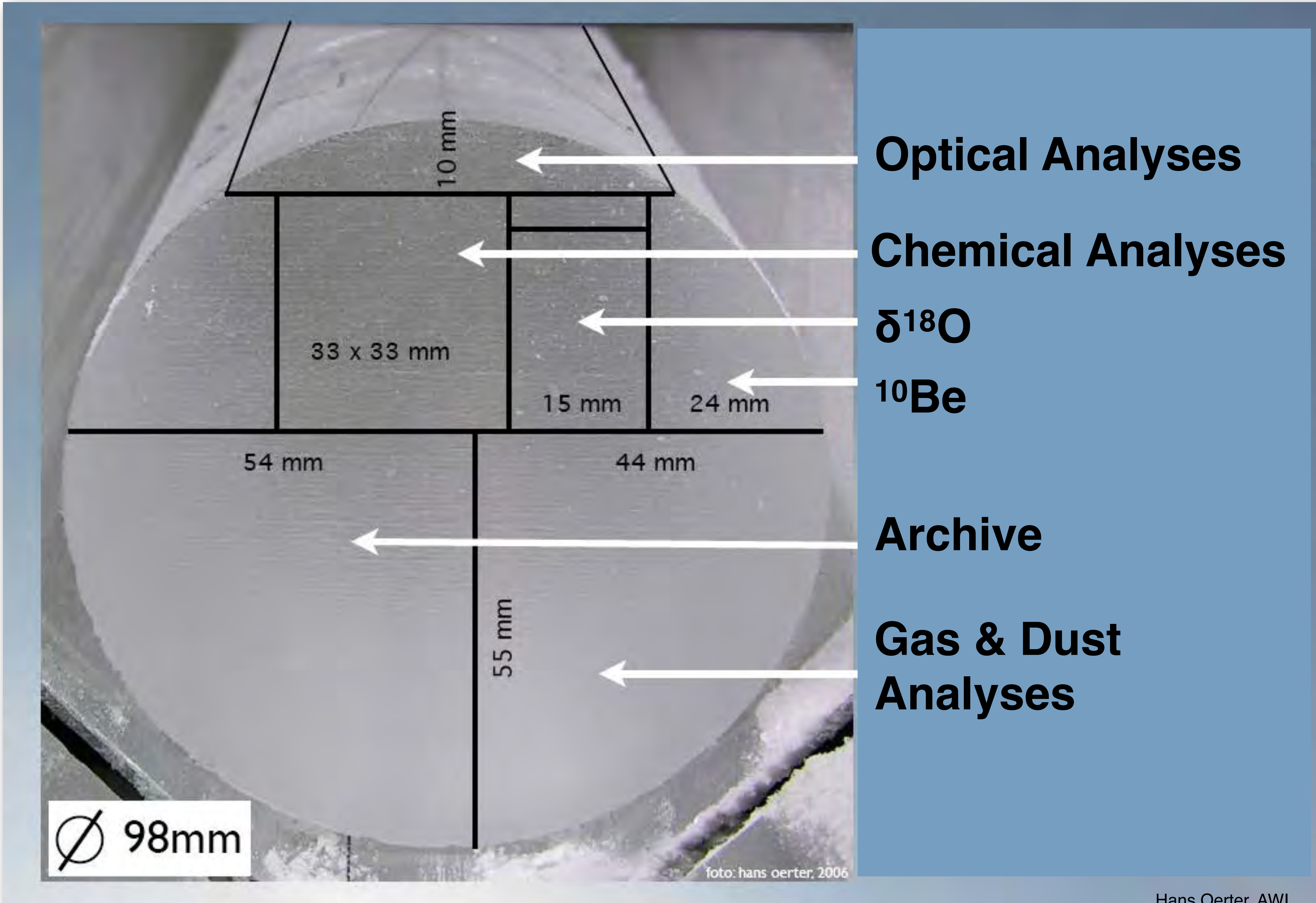
# Ice core drilling

# Ice core drilling

# Ice core drilling

Ice Core Laboratory, AWI Bremerhaven

# Ice core drilling



# Ice cores - a key climate archive

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

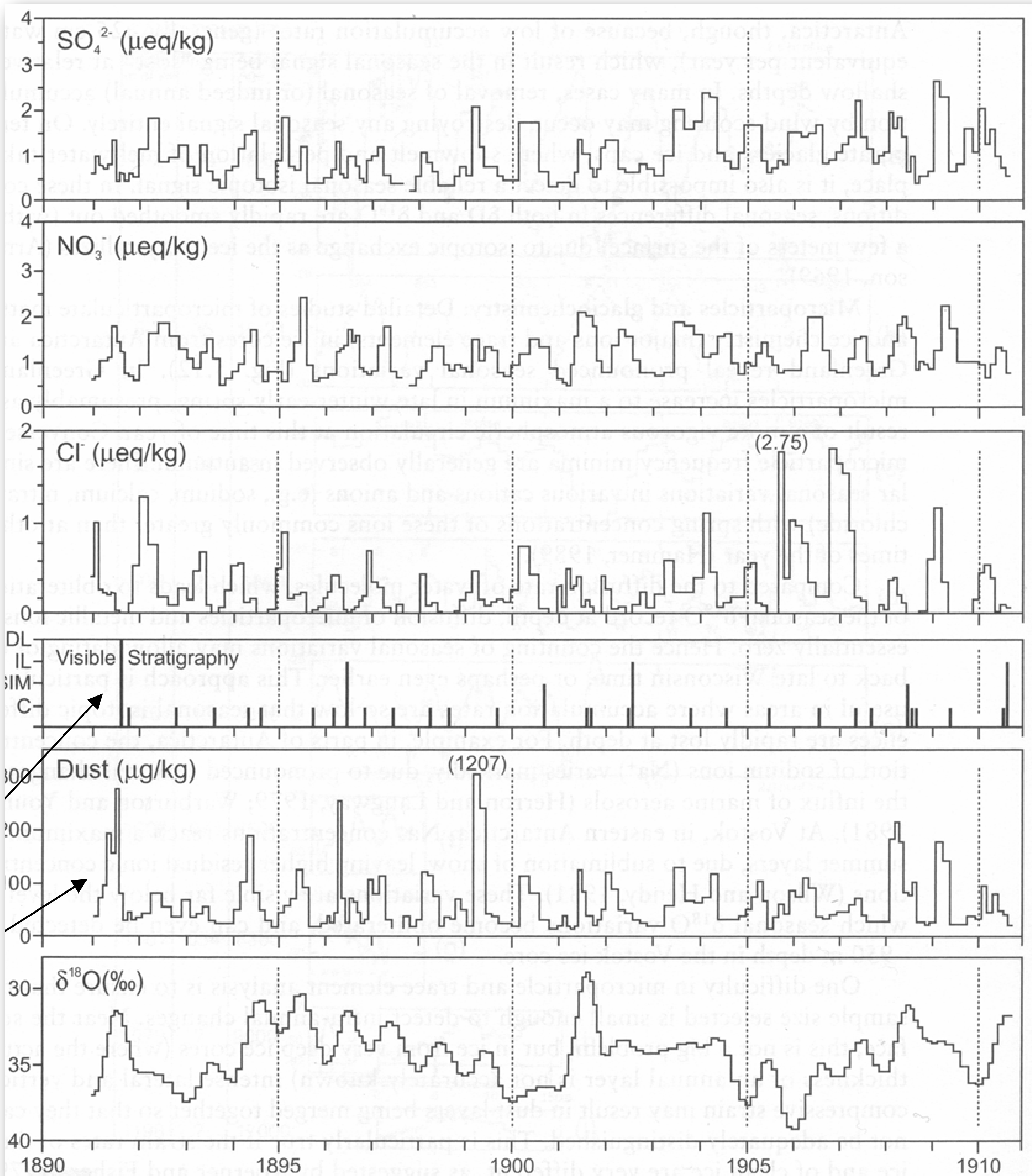
- <u>key analyses</u>
  - temperature reconstruction by stable water isotopes
  - gas analyses - the composition of the past atmosphere

# Dating methods

## Quizz - Questions:

- **Which dating methods can 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 synchronizing

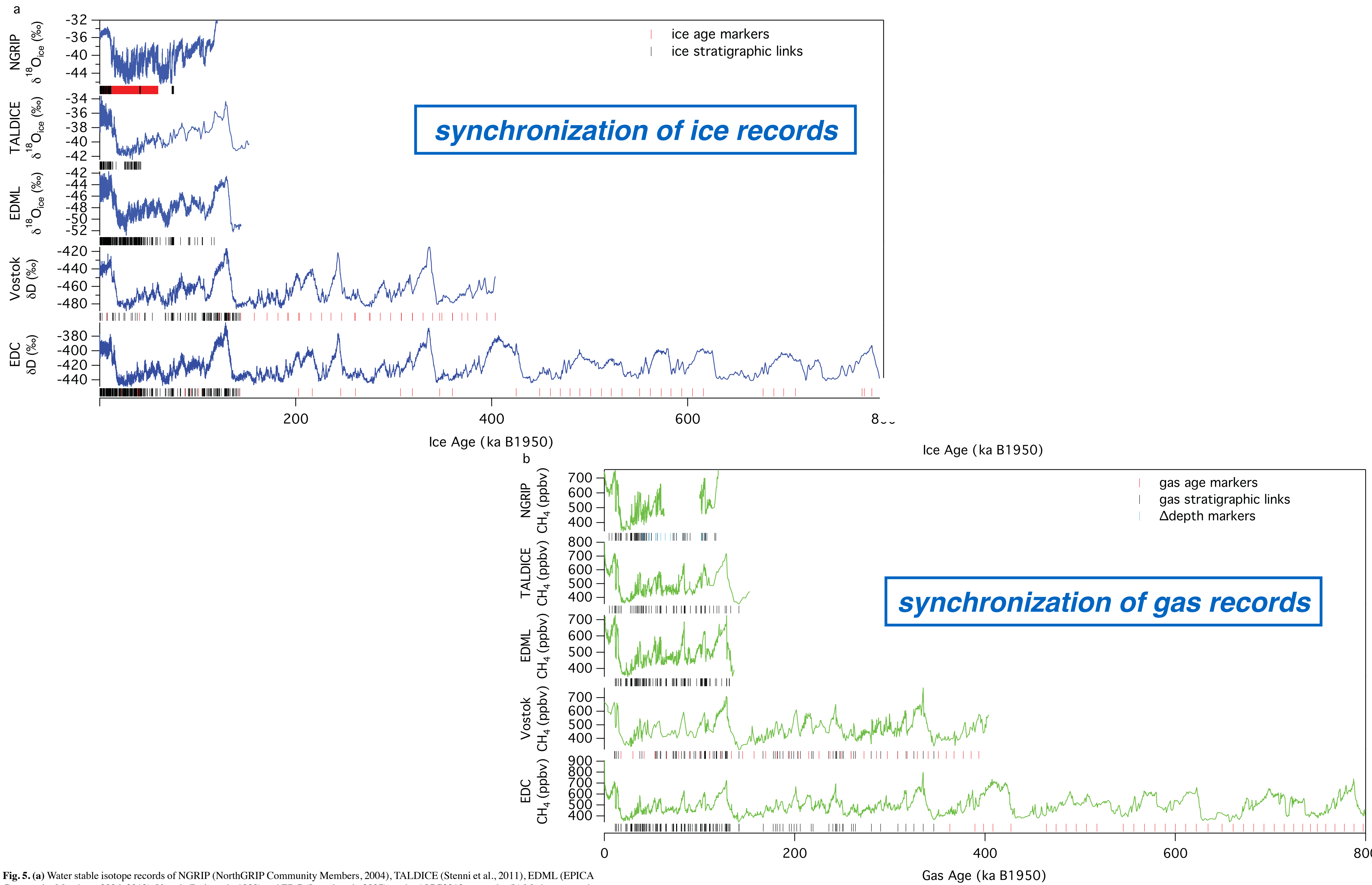



**Fig. 5. (a)** Water stable isotope records of NGRIP (NorthGRIP Community Members, 2004), TALDICE (Stenni et al., 2011), EDML (EPICA Community Members, 2006, 2010), Vostok (Petit et al., 1999) and EDC (Jouzel et al., 2007) on the AICC2012 age scale. **(b)** Methane records of NGRIP (Greenland composite: 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

- <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 - a key climate archive

- ice cores
  - where are they drilled?
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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

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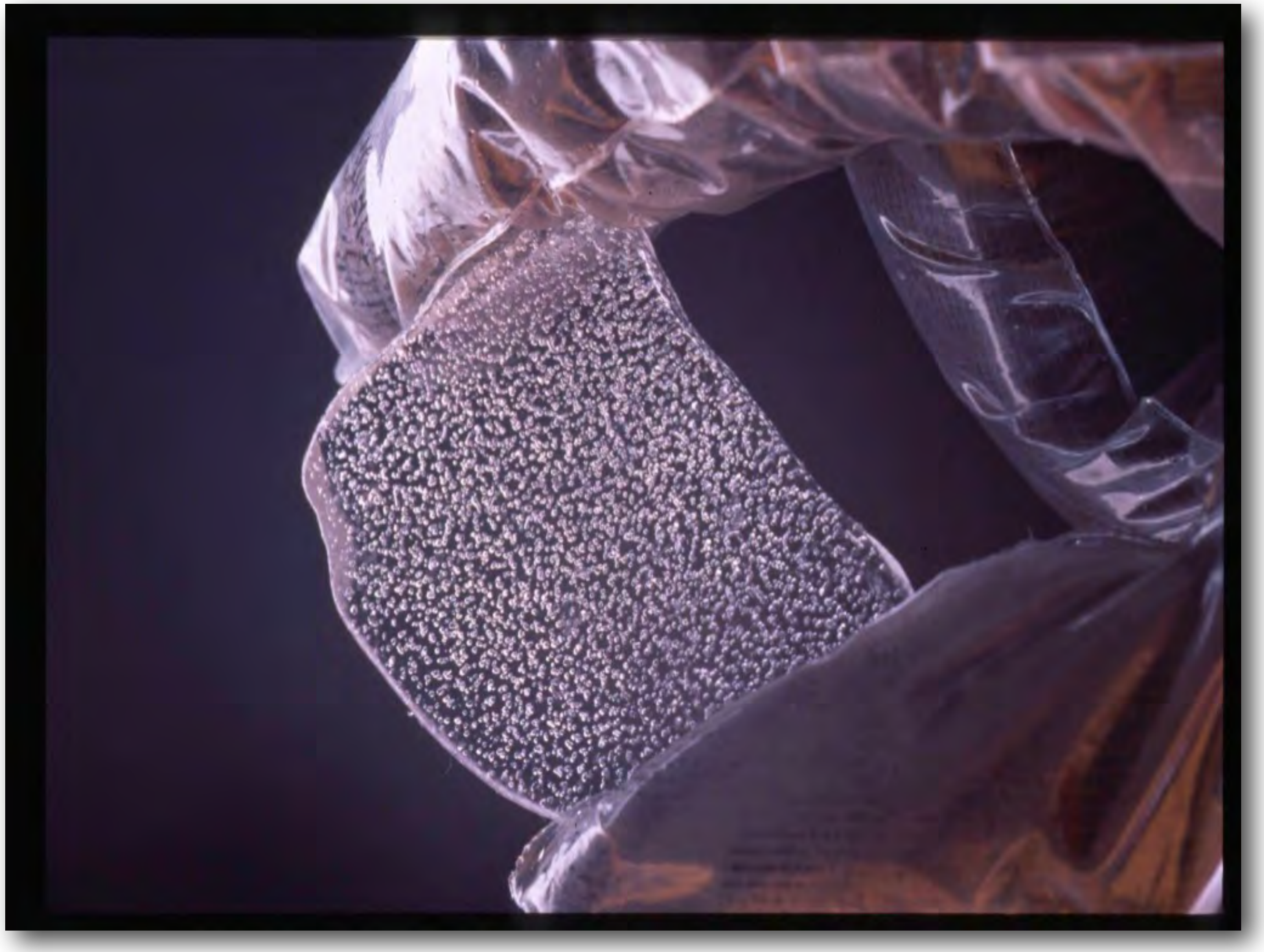
    - how are they drilled?
    - how are they dated?

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

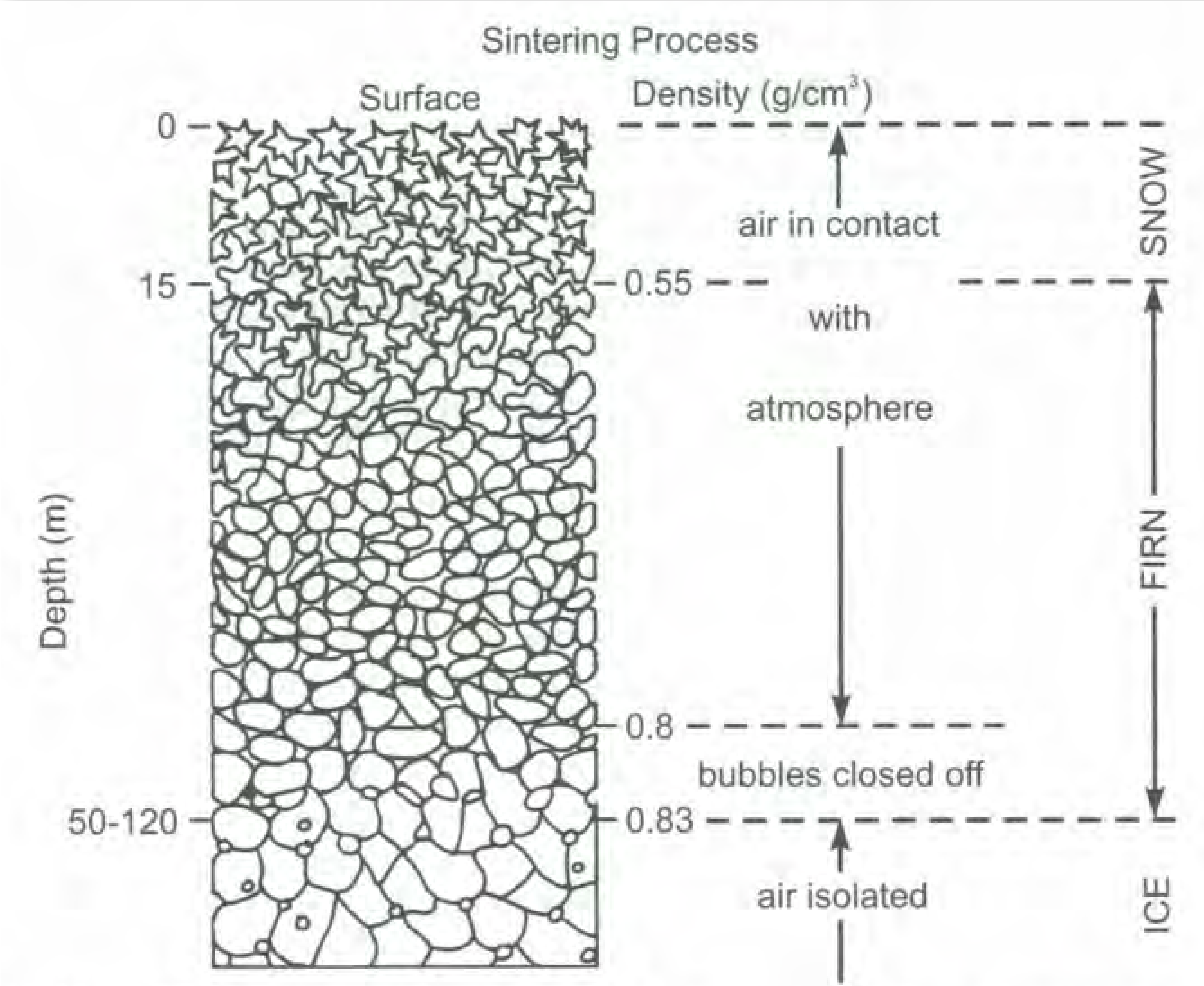
**Ice cores are currently the only archive**

**which allow to directly measure**

**the past atmospheric composition!**

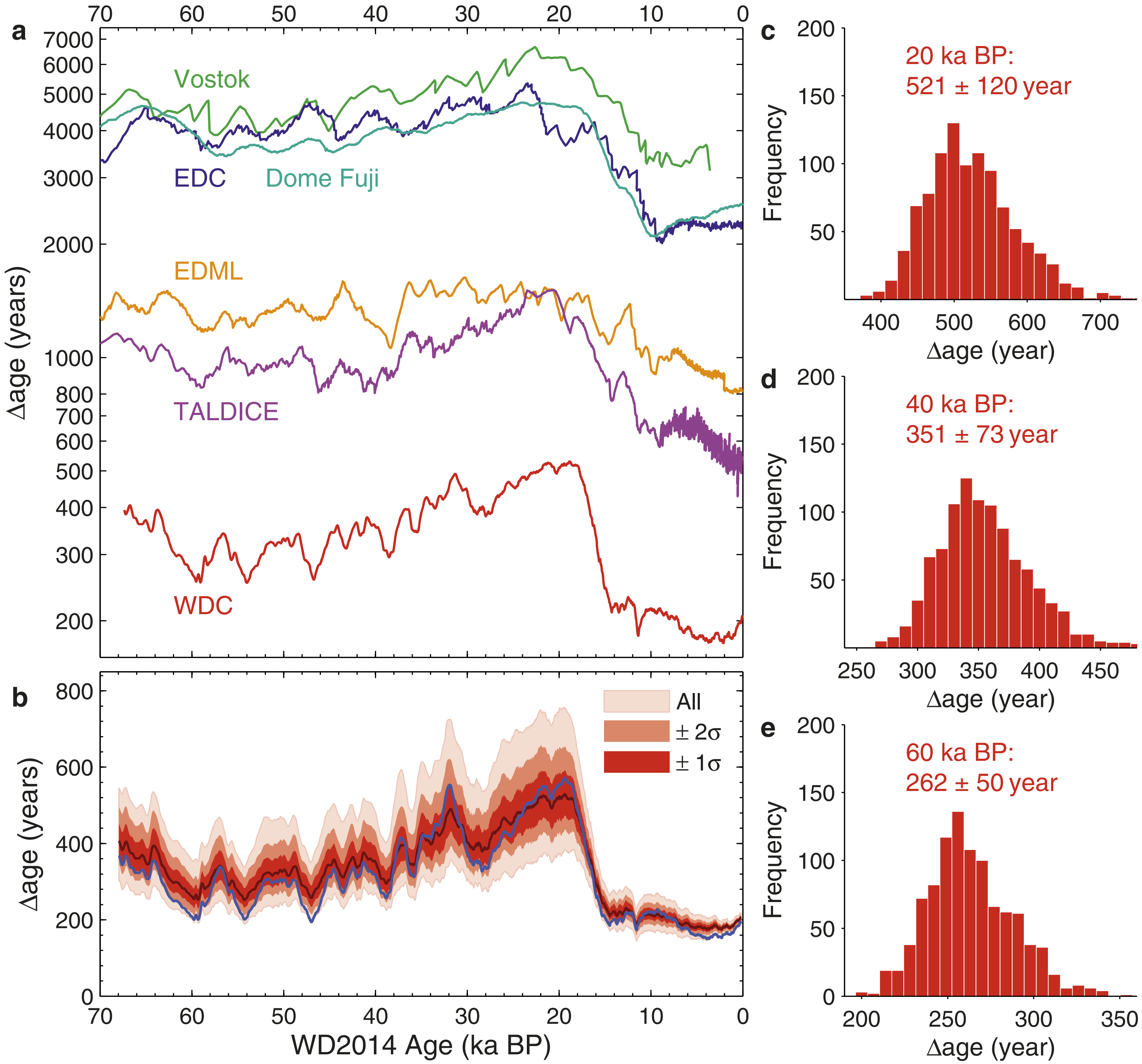


# Transformation of snow to ice




Bradley, Abb. 5.30

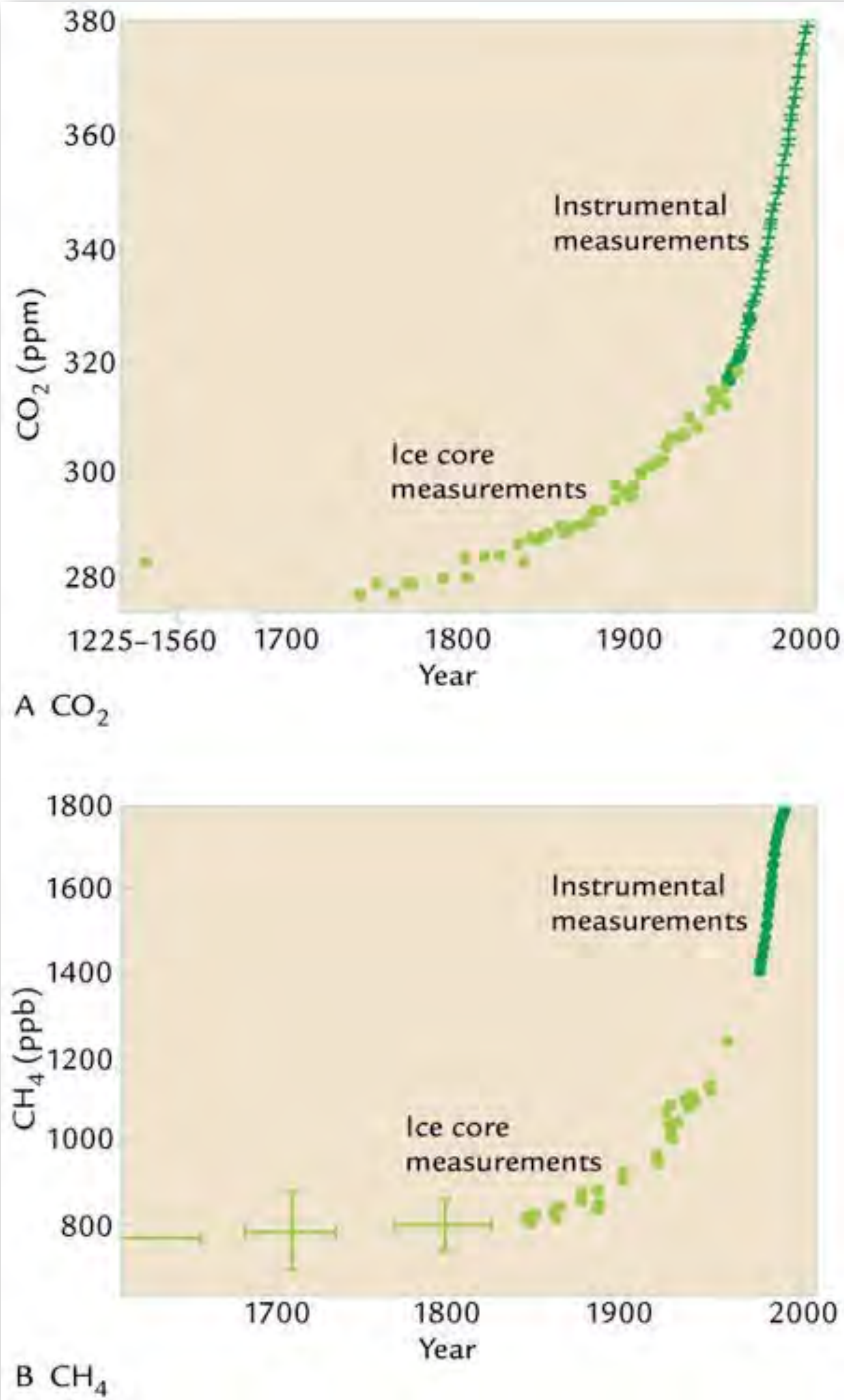
# Example: difference between ice age and gas age




**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 2$\sigma$ standard deviation.

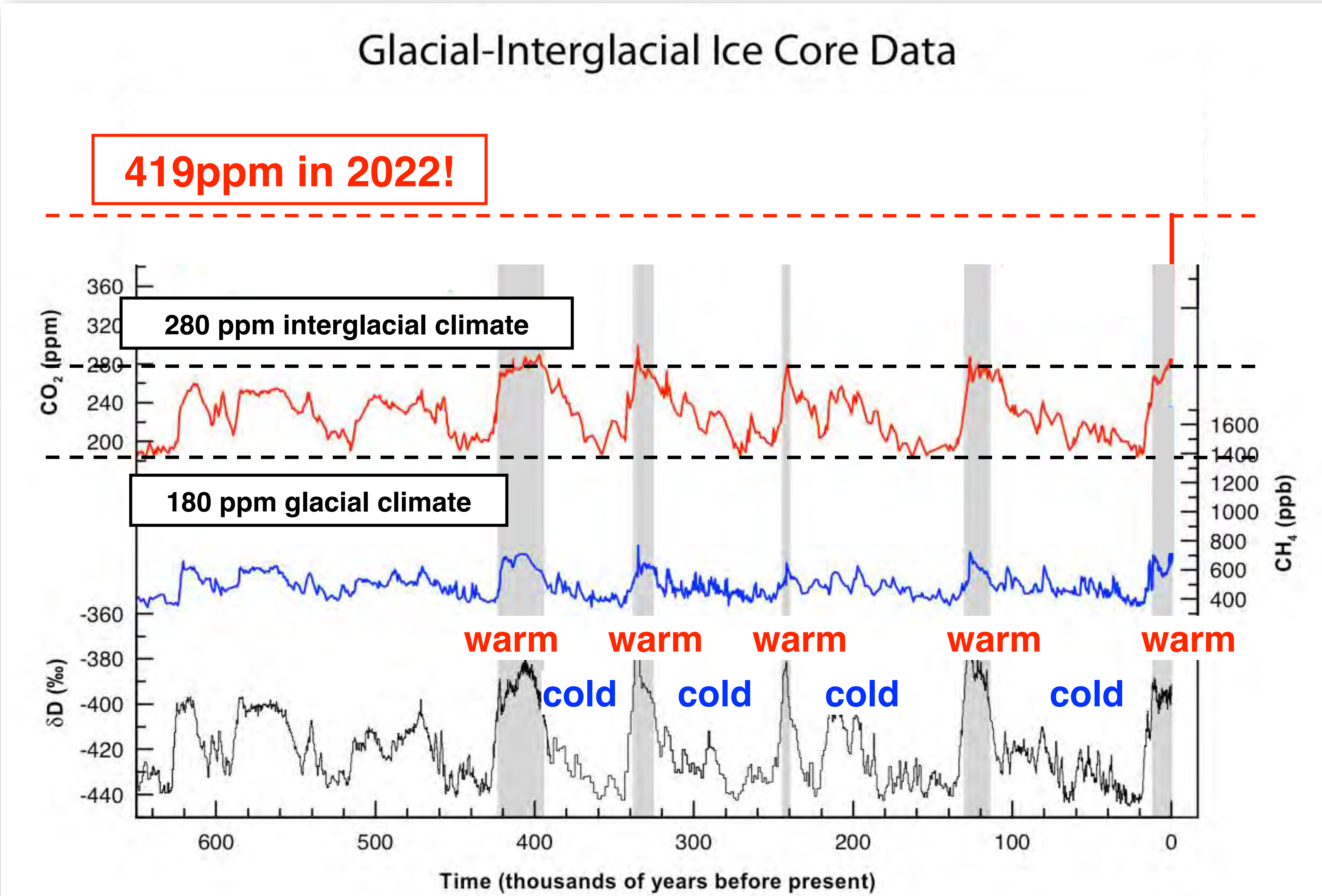
WAIS Divide Project Members, Nature, 2015

# Ice core and instrumental $CO_2$ and $CH_4$ measurements

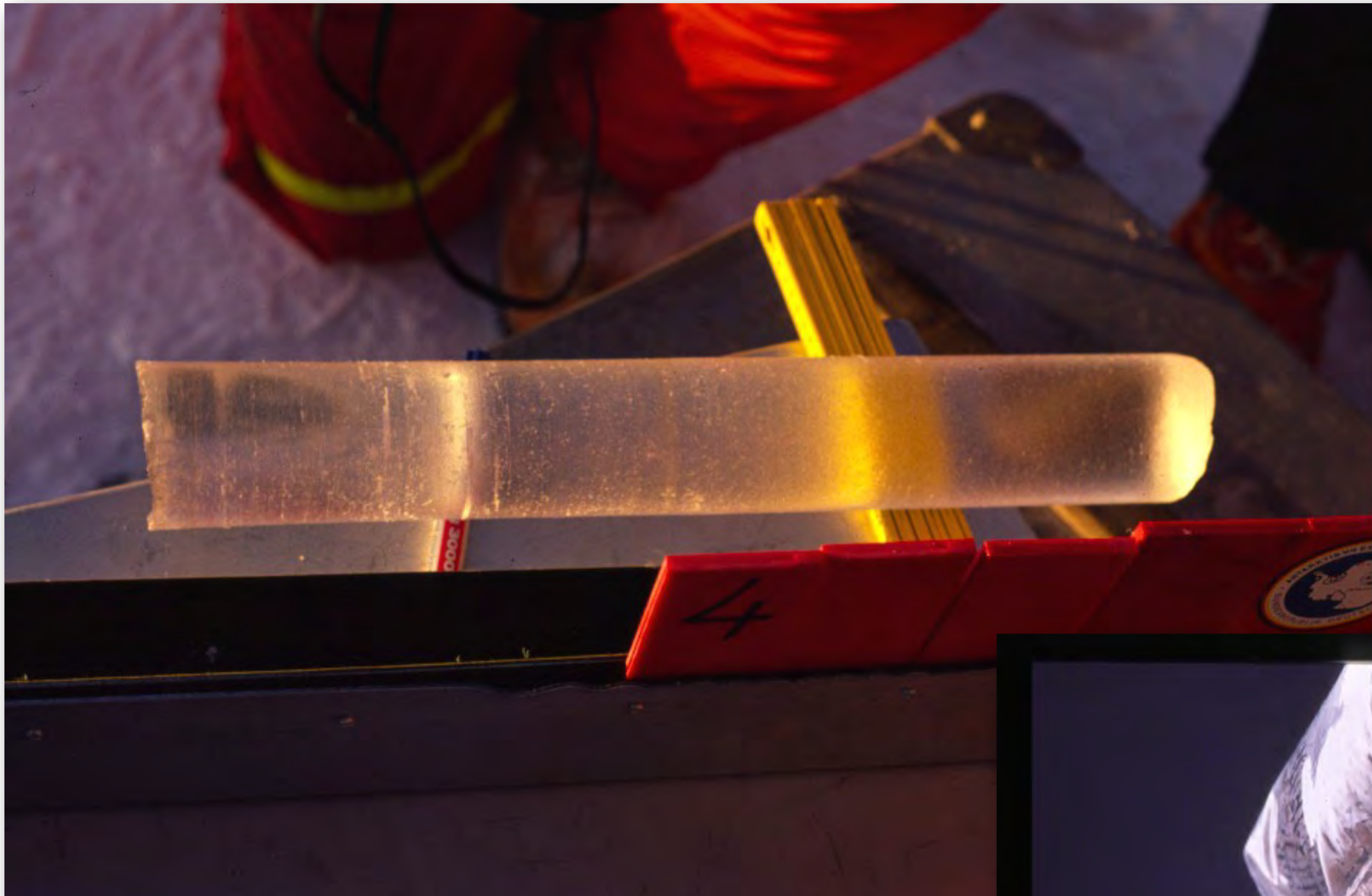


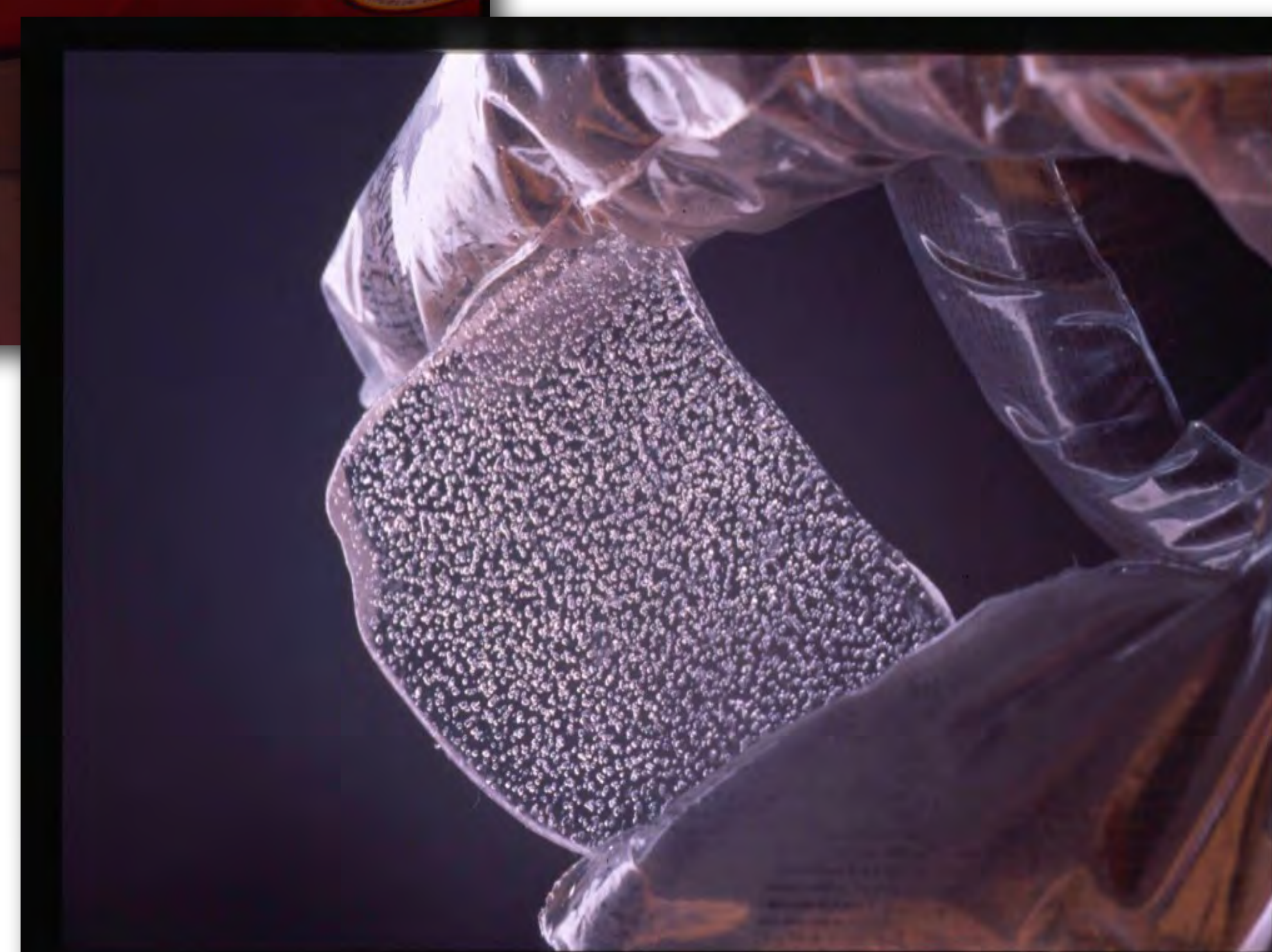

[from: Ruddiman, 2008]

# Orbital-scale changes of greenhouse gases



# Ice cores - a key climate archive



# Climate System II

(Winter 2023/2024)

**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/climate2023_24.html**