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PSI

Giovanni Baccolo :: Ice Core Research Group :: Paul Scherrer Institute

Country you go, glacier you find

the thermodynamic classification of glaciers

Università Milano-Bicocca, 9 giugno 2023

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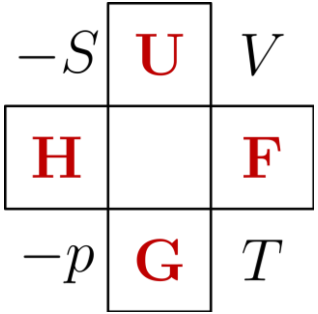
Glaciers and thermodynamic, why?

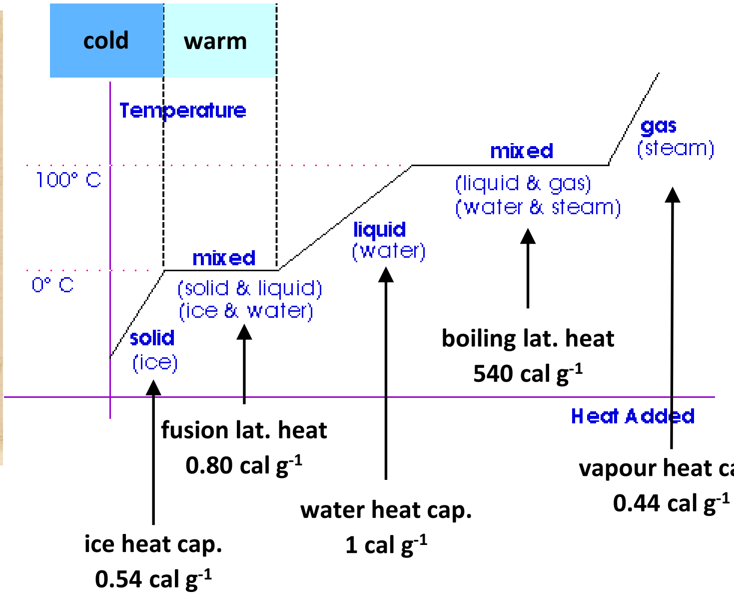
Thermodynamics is that branch of physics (and chemistry) that studies changes of energy and entropy. In short, it is the discipline that deals with the study of energy transfer and its transformations.



Born's square, used to recall the basic elements to describe the thermodynamic state of a system

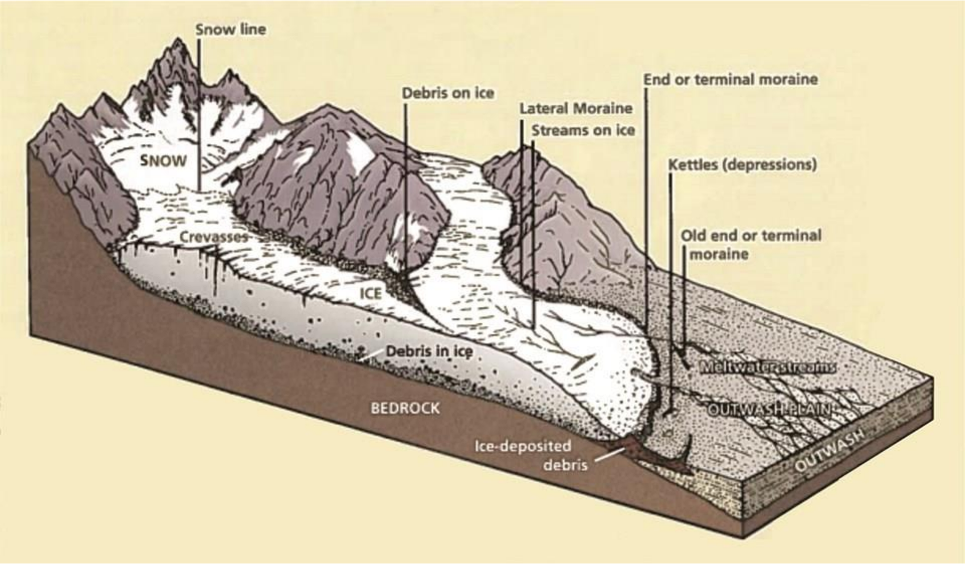
G= Gibbs free energy
p= pressure
H= enthalpy
S= entropy
U= internal energy
V= volume
F= Helmoltz free energy
T= temperature

Thermodynamics is everywhere, assigning natural transformations a specific time direction. [Study of Water, Leonardo Da Vinci 1510].



Un passo indietro, cos’è un ghiacciaio?

A glacier is nature's attempt to establish a balance, it is a wonderful, gigantic mechanism that dispels an excess.



A glacier

A non-glacier, *a climatic fossil*

How many kinds of glaciers exist?

Ardito Desio's classification of glaciations. By this term Desio means 'the totality of glaciers in a region, with their common characteristics', making it possible to delineate the geographical and climatic characteristics of each glaciation on Earth.

Antarctic glaciation: the glaciers cover an entire continent and their extension is limited only by the presence of the ocean towards which they protrude. The glaciers end in the sea, forming an impressive vertical step tens of metres high.

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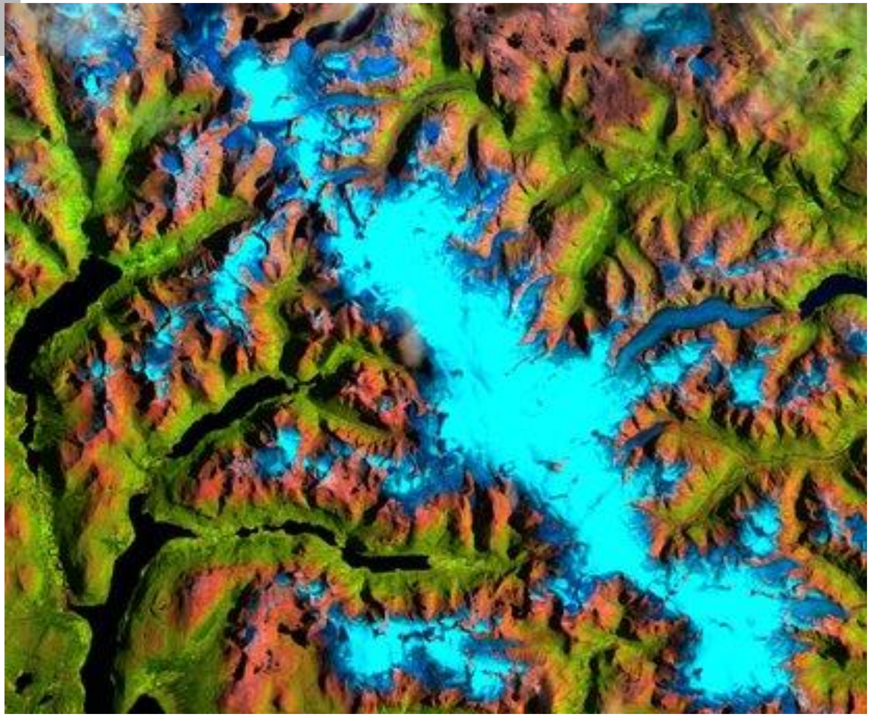
Greenlandic glaciation: characterised by an almost continuous ice cover that covers much of the continental landmass, reaching the sea through distinct tongues that run along the bottom of fjords.

Alaskan glaciation: a vast glacial plateau partially engulfs a mountain system, generating a series of flows that come together in the piedmont region and form an enormous lobe that expands towards the plains.

Himalayan glaciation: ice occupies entire valley systems, creating densely branched glaciers that give rise to valley tongues developed over tens of kilometres.



Scandinavian Glaciation: large ice flows radiate from extensive glacial plains and extend over the bottom of fjords reaching the sea. It is a minor version of the Greenlandic Glaciation.

Alpine glaciation: glaciers fill the highest valley beds, smaller hollows at the head of valleys or mountain sides if orographically favourable for ice preservation. There are some large compound glaciers, fed by the convergence of several flows. It is reminiscent of the Himalayan glaciation, although less developed.

Pyrenean Glaciation: characterised by small, fragmented glaciers mostly located at the bottom of cirques and other minor relief cavities.

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African glaciation: glaciers are present as small ice caps enveloping the tops of the highest peaks, without giving rise to significant flows.

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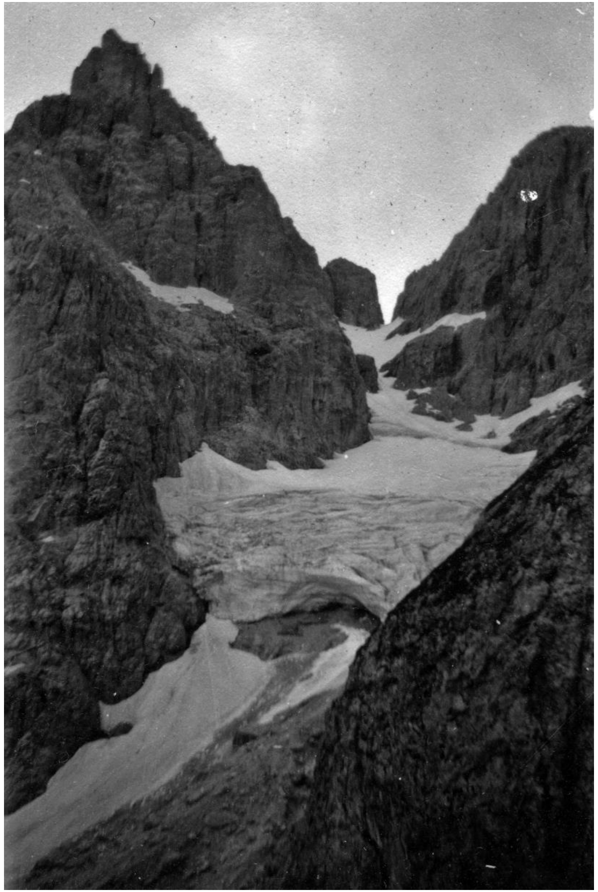


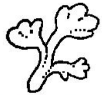
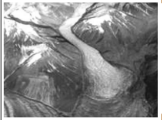
Turkestan Glaciation: defined by tiny glaciers enclosed within deep mountain gorges and gullies. They have almost no snow basin, being largely fed by avalanches.

The GLIMS classification

(Global Land Ice Measurement from Space)

Nine different layers to classify glaciers depending on several parameters. The possible combination are virtually infinite. Thanks to its complexity this classification can really take into account all glaciers of Earth, from a small mountain glacier to a continental ice sheet.

1. **Primary classification**
2. **Form**
3. **Frontal characteristics**
4. **Longitudinal characteristics**
5. **Major source of nourishment**
6. **Tongue activity**
7. **Moraines in contact with present-day glacier**
8. **Downstream moraines**
9. **Debris coverage**

Name	GLIMS glacier parameter identification checklist for remote sensing observations	Definition WGMS	Comment	Satellite Image / Photo / Graphics (numbers in () refer to figure references in 2.10; if present: Primary classification - Form - Frontal Characteristics - Longitudinal Profile - Major source of nourishment)	GLIMS Code
Uncertain or miscellaneous	• Any type not listed below	Any type not listed below			**0**
Compound basins	• Dendritic system of Outlet- or valley glaciers of more than one "compound basin" that merge together	Two or more individual valley glaciers issuing from tributary valleys and coalescing		 Fig. 19 – **Compound basins** (3)  Fig. 20 – Outlet glacier - **Compound basins** – normal – Cascading – Snow (5)	**1**
Expanded	• Frontal expansion on a level surface (not necessary lowland) • Less restricted by topography • Widening of the tongue (lateral expansion is less than for piedmont) • "Terrestrial glaciers" • If it terminates into sea, use class "calving and expanded"!	Lobe or fan formed where the lower portion of the glacier leaves the confining wall of a valley and extends on to a less restricted and more level surface (**WGMS 1970, 1998**) Lobe or fan formed where the lower portion of the glacier leaves the confining wall of a valley and extends on to a less restricted and more level surface. Lateral extension markedly less than for piedmont. (**WGMS 1977**)		 Fig. 41 – **Expanded** (3)  Fig. 42 – **Expanded**(2)	**2**
Lobed	• Initial stage of tongue formation (occurs on both micro and macro scales) • In many cases part of an ice sheet, cap, field • Large or small scale radial ice margin • Is not an outlet or a valley glacier • "Terrestrial glaciers" • If it terminates into	Part of an ice sheet or ice cap, disqualified as an outlet glacier (**WGMS 1970, 1998**) Tongue like form of an ice-field or ice cap. (**WGMS 1977**)		 Fig. 43 – **Lobed** (3)	**3**

What about ice temperature?

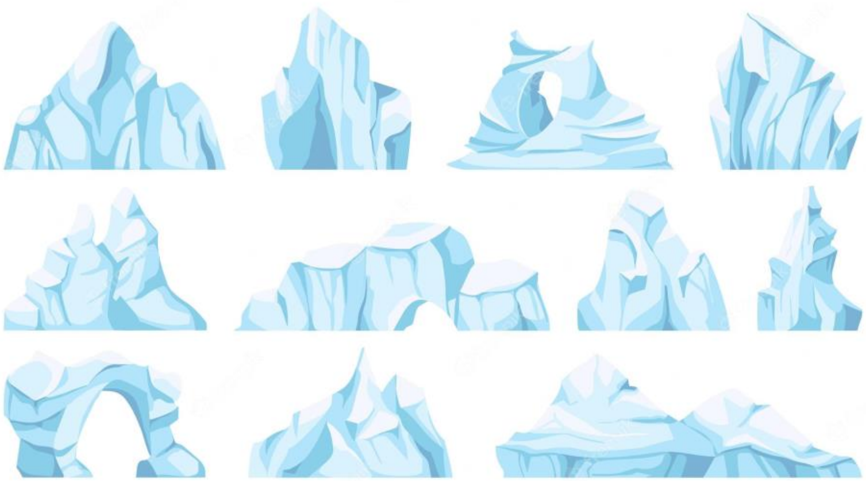
Most glacier classification deal with macroscopic features that it is possible to infer from a visual inspection of glaciers. However, not all important things are visible to the naked eye. Temperature is one of them.

We need to talk about homologous temperature.

$$T_H = \frac{T(K)}{T_{MP}(K)}$$

- It ranges from 0 (absolute zero) to 1 (melting temperature)
- Diffusion and deformation strongly depend on it
- Solid material with similar T_H have similar mechanical properties
- Glacier ice on Earth has a T_H very near to 1, even in the coldest places of the planet

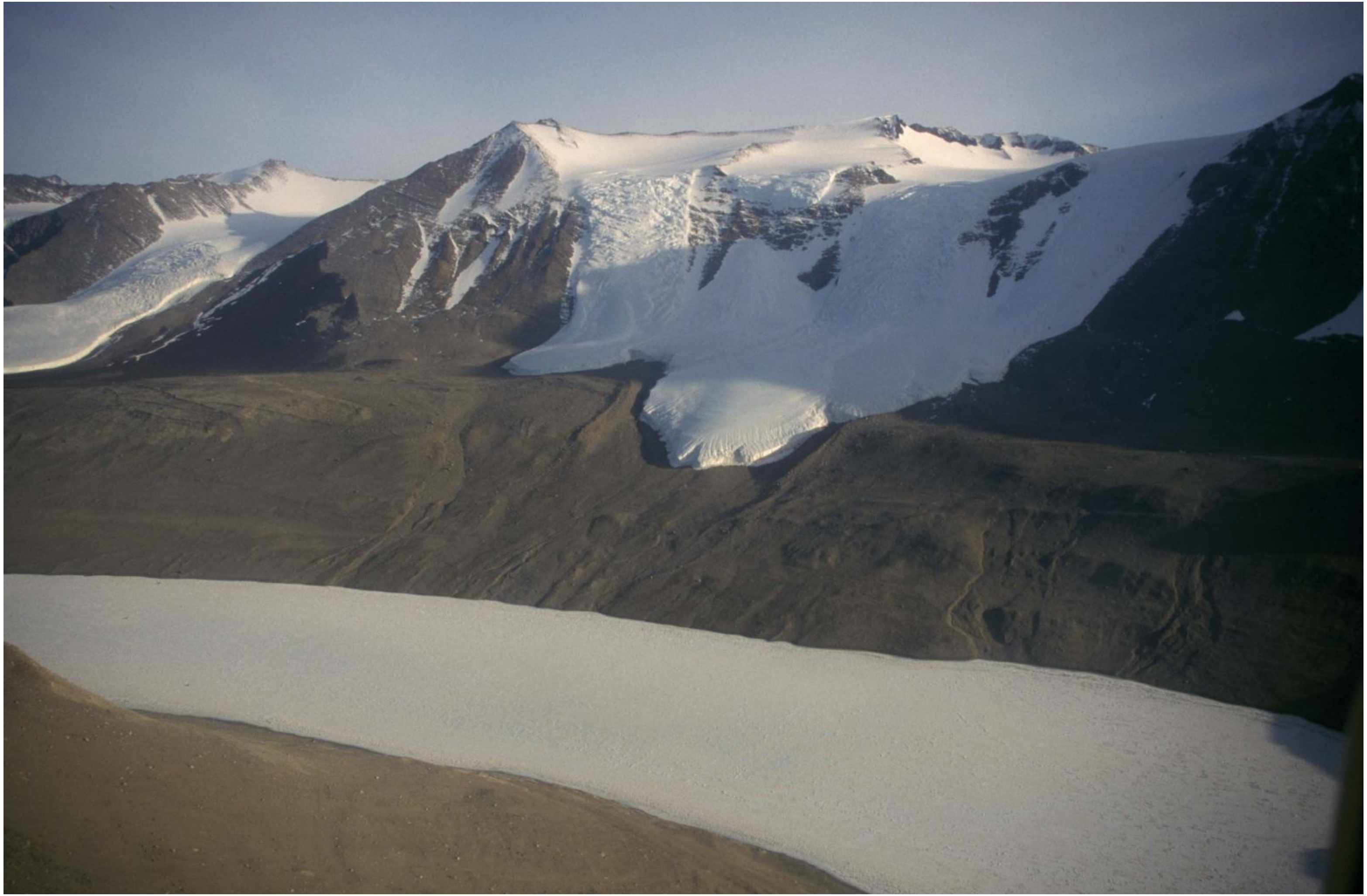
Antarctic ice at -50°C (223 K, very cold ice within the Earth context) has T_H of 0.82, ice at -10°C has a T_H of 0.96. For comparison, a piece of granite with a similar T_H is at 1200°C, thus **ice on Earth is hot!**



Let'introduce the thermodynamic classification of glaciers: The Lagally/Ahlmann classification (1930s)

- 1932, the **Lagally** classification:
  - **Cold glaciers**, they don't reach melting temperature anywhere
  - **Warm glaciers**, they are at melting point everywhere, apart from a surficial layer whose temperature fluctuate with seasons
  - **Transitional glaciers**, they have a cold top layer and a bottom layer at the pressure melting point. Geothermal heat and the heat generated during glacier flow serve to make the bottom of the glacier a source of heat
- 1935, the **Ahlmann** classification:
  - **Temperate glaciers,** they consist of crystalline ice formed by rapid re-crystallization of the annual surplus of solid precipitation. Throughout these glaciers, the temperature corresponds to melting-point of the ice, except in the winter time, when the top layer is frozen to a depth of no more than a few meters.
  - **Polar glaciers,** they consist, at least in their higher and upper parts, of hard crystalline firn formed by slow recrystallization of the annual surplus of accumulated solid precipitation. The temperature of the glacier, at least in the accumulation area, is negative either in summer down to a depth of 100 m or more. They can be divided into:
    - **High-polar glaciers**, which consist, at least in their accumulation area, of crystalline firn to a depth of a couple of hundreds of m or more. Even in summer the temperature in the accumulation area is so low that as a rule there is no melting accompanied by formation of water.
    - **Sub-polar glaciers**, which in their accumulation area consist of crystalline firn down to a depth of some 10-20 m. In the summer the temperature allows melting accompanied by the formation of some water.



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The Avsyuk classification (1955)

- **dry polar glaciers,** when temperature is below the ice melting point throughout the whole glacier thickness

- **humid polar glaciers**, where summer temperature rises above 0 °C and a little melting takes place, but the ice temperature inside the glacier thickness remains below average annual air temperature

- **humid-cold glaciers**, when the ice average temperature is higher than the air average temperature, however, both of them are negative, and the melting takes place in only the upper part of the whole thickness

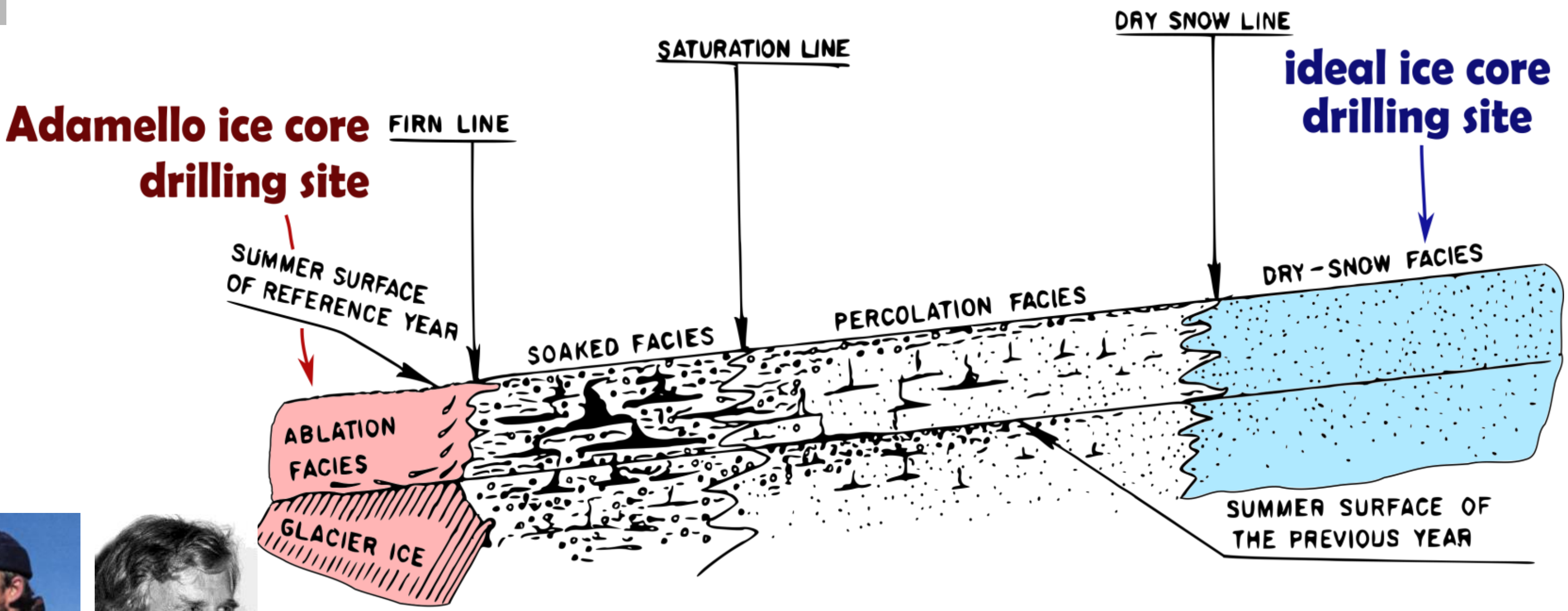
- **marine glaciers,** when zero temperature dominates throughout the whole thickness below the active layer

- **continental glaciers**, when the ice average annual temperature is negative at all depths, although some warming-through takes place in the upper layers followed by melting

The point of view of Benson & Müller (1960s)

Introducing the poly-thermal concept

redrawn from C.S. Benson (1960)



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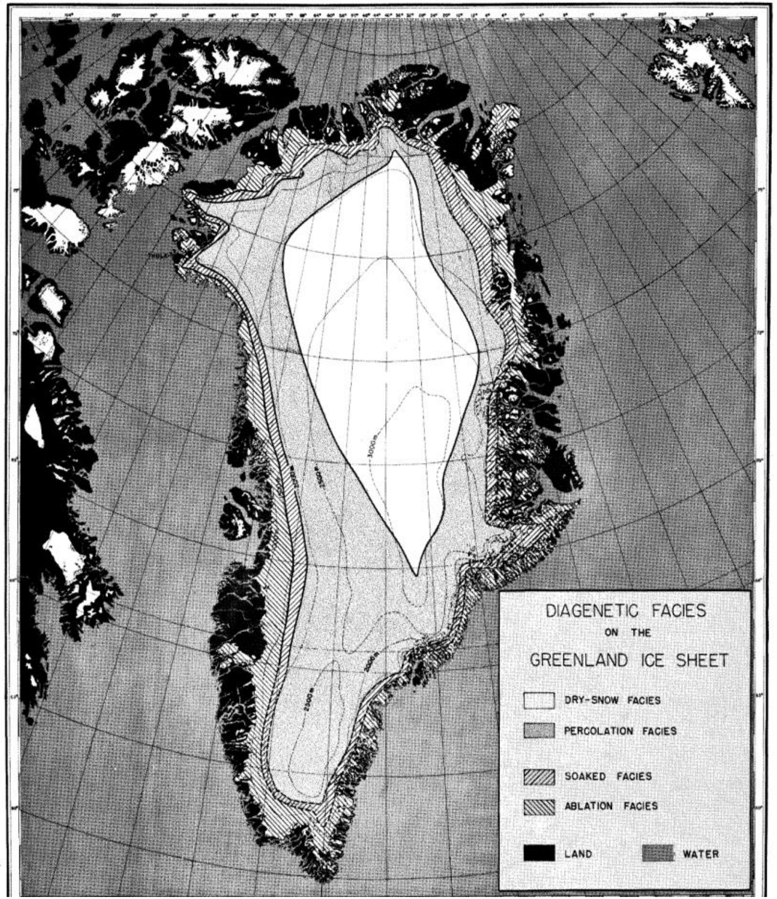

Greenland surface facies of snow and firn

The definitive classification by Shumskii

- **Recrystallization zone; $X = M_r$; $X_l + m = 0$.** Melting is absent, ice formation takes place completely by means of subsidence and re-crystallization. The firn thickness is 50-150 m. The lower boundary, sometimes named as dry snow line, corresponds to the air average summer temperature of about -9 °C and average annual temperature of -25 °C
- **Recrystallization-regelation zone; $X = M_r + M_{rj}$; $X_l + m << p$; $X_l + m << T_c$.** Melting takes less than 0.1 of snow accumulated during a year. Melting water freezes completely inside the annual layer, and ice formation takes place mainly by means of subsidence and re-crystallization. The firn thickness is 20-100 m. The lower boundary is named as saturation line since saturation of the whole annual snow layer takes place at this level.
- **Cold infiltration-recrystallization zone; $X = M_i + M_r$; $X_l + m < p$; $X_l + m < T_c$.** The volume of melting water is sufficient for water yield from the annual layer. It comes into the lower layers where it freezes. At large inclinations it partially goes into a runoff (sub-cold zone). Melting takes from 0.1 to 0.5 of the annual accumulation. The firn thickness with thick ice inter-layers is only 10-20 m, the glacier temperature is negative. About 2/3 of ice formation takes place due to infiltration, and only about 1/3 due to subsidence and re-crystallization.
- **Warm infiltration-recrystallization zone; $X > M_i + M_r$; $X_l + m = Tc$.** The cold storage is not sufficient to freeze the melting water; its volume is equal to 0.4-0.7 of the annual accumulation. Intensive runoff takes place in this zone, and the ice formation takes place equally due to both the infiltration freezing and subsidence with recrystallization. The firn thickness with thin inter-layers is 20-40 m, the glacier temperature is close to zero.
- **Infiltration zone; $X >> M_i$** .Here, the melting water constitutes more than 0.5 of the annual accumulation, it thus exceeds the volume of pores in the annual remainder but the firn partly retains due to accumulations of preceding years in the glacier upper zone, or during the past colder and snowy years. The firn thickness does not exceed 10 m, often, it is less than 5 m, and ice formation is mainly infiltrational. This zone always infringes from below the other firn zones or exists independently due to the climate changes during formation or disappearance of these zones.

- **X** = total annual precipitation
- **X_l** = liquid precipitation
- **X_s** = solid precipitation
- **m** = melting
- **T_c** = layer of water which may be retained due to refreezing in cold firn
- **M_r** = recrystallization ice
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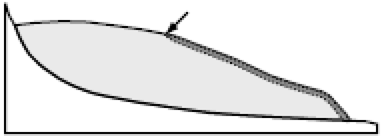
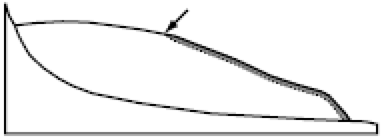
So, we should always talk about polythermal glaciers *(Blatter & Hutter 1991)*

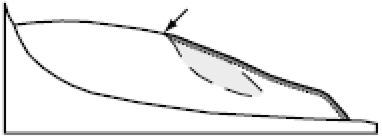


a) Temperate ice exists perennially throughout the glacier body with exception of the seasonally varied near-surface layer in the ablation area
e.g. Haut Glacier d'Arolla (Sharp et al., 1993)

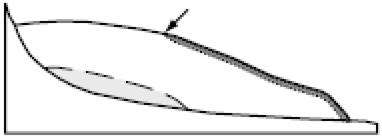


b) Cold ice is sustained throughout the glacier body
e.g. Scott Turnerbreen (Hodgkins et al., 1999); Larsbreen (Etzelmüller et al., 2000)

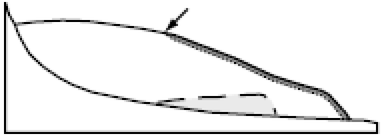
c) Refreezing in the accumulation area leading to latent heat release in the snowpack, and causing a temperate zone close to the surface
e.g. Baby Glacier (Müller & Iken, 1973), Longyearbreen (Etzelmüller et al., 2000)



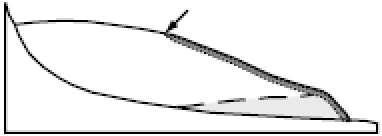
d) Water and refreezing in crevasses leading to latent heat release and causing a temperate zone close to the surface, subsequently advected downglacier
e.g. Steele Glacier (Jarvis & Clarke, 1974)



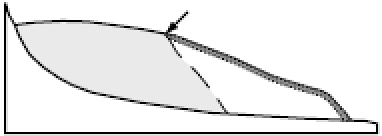
e) Temperate ice exists only as a function of ice thickness and/or geothermal heat flux
e.g. Hannabreen (Sollid et al., 1994); Werenskioldbreen (Pälli et al., 2003); Austre Brøggerbreen pre 1995 (Hagen & Sætrang, 1991; Björnsson et al., 1996)



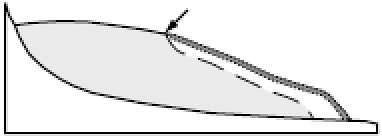
f) In response to ice strain and frictional heating of deformation, temperate ice exists near the bed in the ablation area, or reflecting inheritance from past climate
e.g. John Evans Glacier (Copland & Sharp, 2000); Laika Glacier (Blatter & Kappenberger 1988); White Glacier (Blatter & Hutter, 1991)



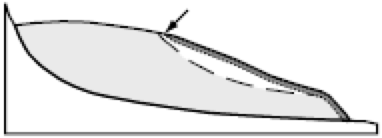
g) Temperate ice exists as a function of ice strain and frictional heating, however strong advection leads to downglacier enlargement of temperate ice zone



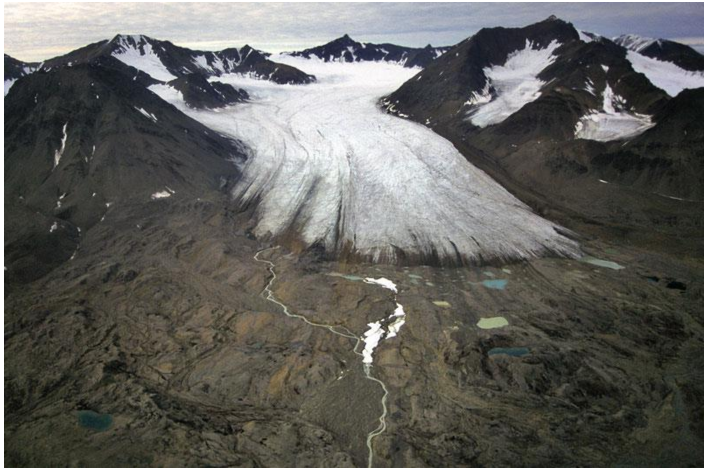
h) Refreezing and latent heat release perpetuate a temperate core beneath the accumulation area which may be further supported by ice thickness and/or geothermal heat
e.g. Midtre Lovénbreen (Björnsson et al., 1996; Rippin, 2001)



i) Accumulation and latent heat release perpetuate a temperate core beneath the accumulation area, and strong advection leads to the elongation of the temperate zone at depth in the ablation area
e.g. Marmaglaciären, Storglaciären (Holmlund et al 1996); Trapridge Glacier (Clarke et al 1984); McCall Glacier (Rabus & Echelmeyer, 1997)



j) Strong advection of temperate ice formed through latent heat release in the accumulation area enables the perpetuation of temperate ice throughout the glacier with exception of a perennial cold surface
e.g. Uvérsbreen (Hamran et al., 1996); Hansbreen (Jania et al., 1996); Kongsvegen (Hagen & Sætrang 1991); Erikbreen (Ødegård et al., 1992); Finsterwalderbreen (Ødegård et al., 1997)



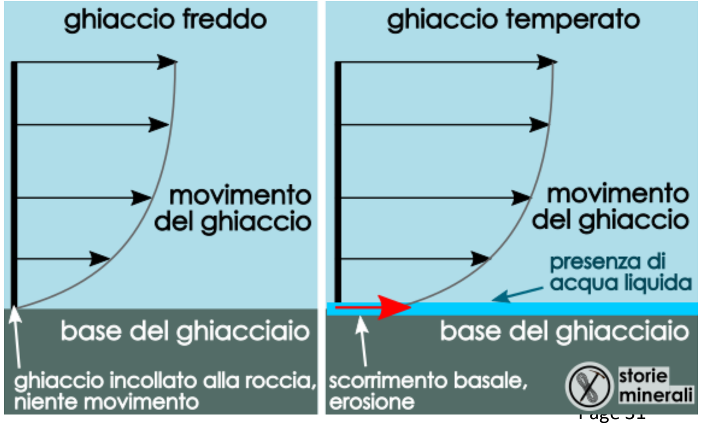
In the end, what's the difference between temperate and cold ice?

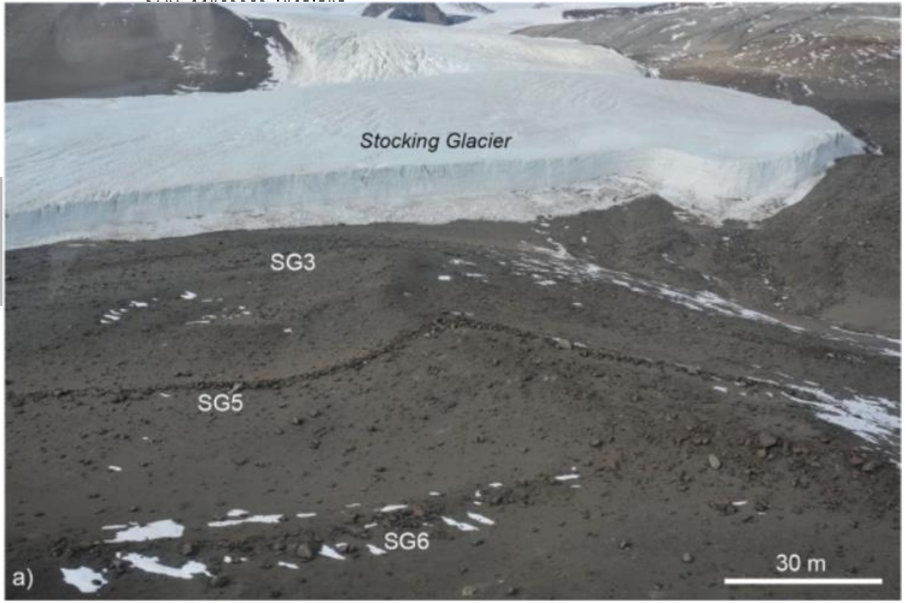
Cold ice

- Temperature below pressure melting point
- Formed by dry recrystallization of firn (slow process)
- Attached to bedrock, it moves primarily because of plastic deformation
- It well preserve chemical and physical signals
- Cold glaciers are slowly moving
- The erosive action is limited
- Small or absent moraines

Temperate ice

- At melting point, liquid and solidus co-exist
- Ice is formed mostly because of meltwater refreezing (fast process)
- Ice flows on the bedrock thanks to the presence of liquid water (fast moving)
- Signals are partially (or completely) destroyed
- High erosive action and big production of sediments
- Deposition of moraines




Stocking Glacier
SG3
SG5
SG6
a)
30 m

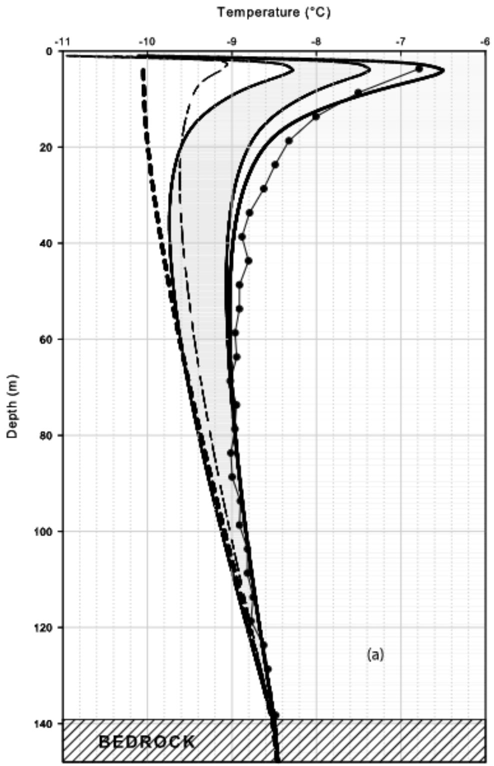
Ice temperature profiles in the mountains
Effects of climate change

Earth temperature is increasing, glaciers are retreating, then ice is also warming?

Yes, but… Let’start with the easy case: a cold glacier in a warming worldC

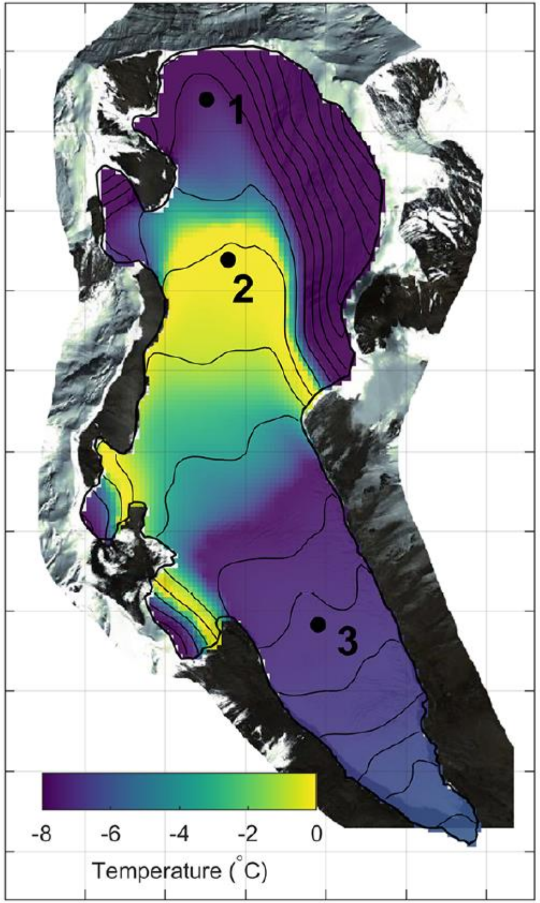
Englacial temperature of Illimani summit ice cap.

- The site is definitely cold
- There is evidence of warming (from the surface to 70 m deep T increases with depth
- The increase of T in the deepest part is related to the geothermal flux



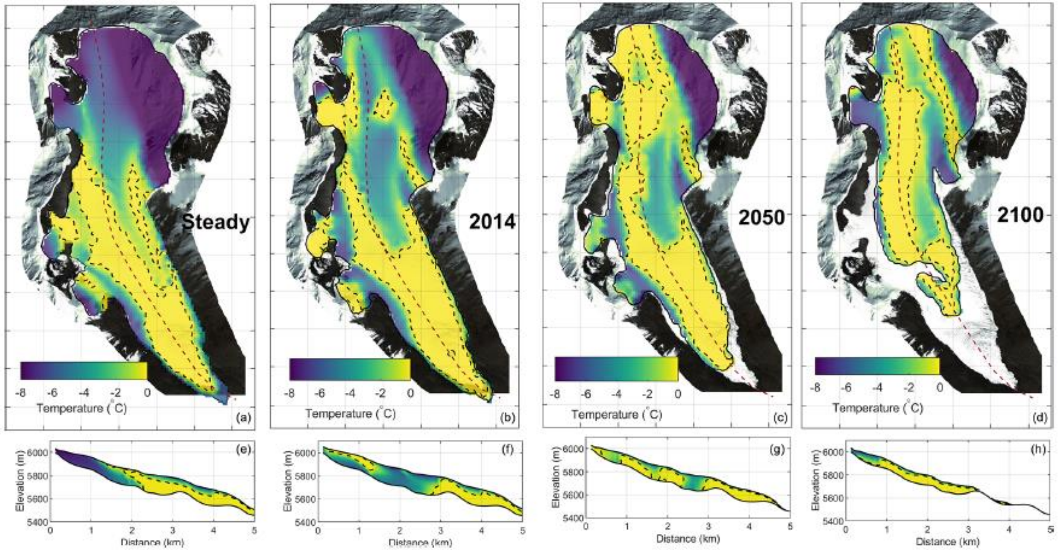
From Gilbert et al., 2010 JGR

High-elevation glaciers, what to expect

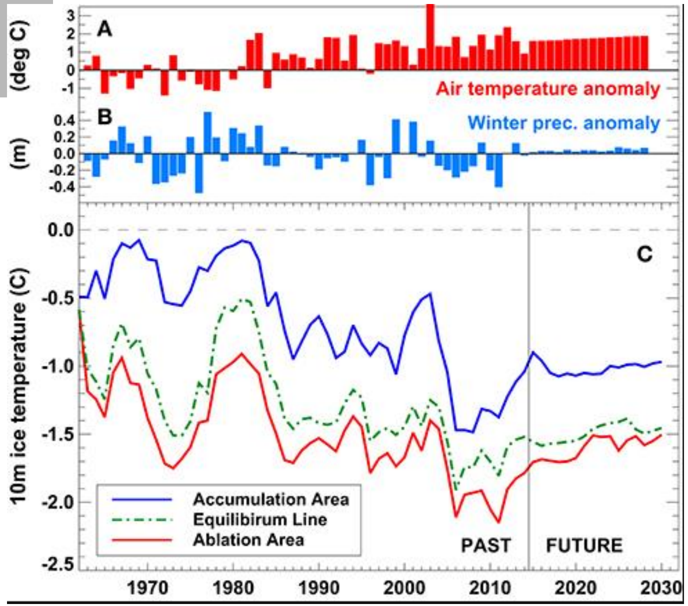


Himalayan glaciers are typically polythermal. Basically they consist in cold ice, but usually a temperate fraction is present because of surficial melting and high ice deformation (internal heat source).

These glaciers are predicted to shift to a fully temperate regime by the end of the century, because of increased melting more than air temperature increase. (*from Gilbert et al., 2020 Cryosphere*)



What for small Alpine glaciers?



From Huss & Fischer 2016

Here ice temperature in small glaciers is actually decreasing, in anti-correlation with the changes that are affecting air-temperature. How is this possible?

Many small glaciers have completely lost the snow-cover, allowing the winter cold wave to penetrate deeper into the glacier. This is producing significant, but still neglected effects, on the dynamic of small glaciers.

An example: the Marmolada event could have been triggered by the closure of draining channels due to the penetration of cold into the glacier during a year without snow.

This is a current topic of research!

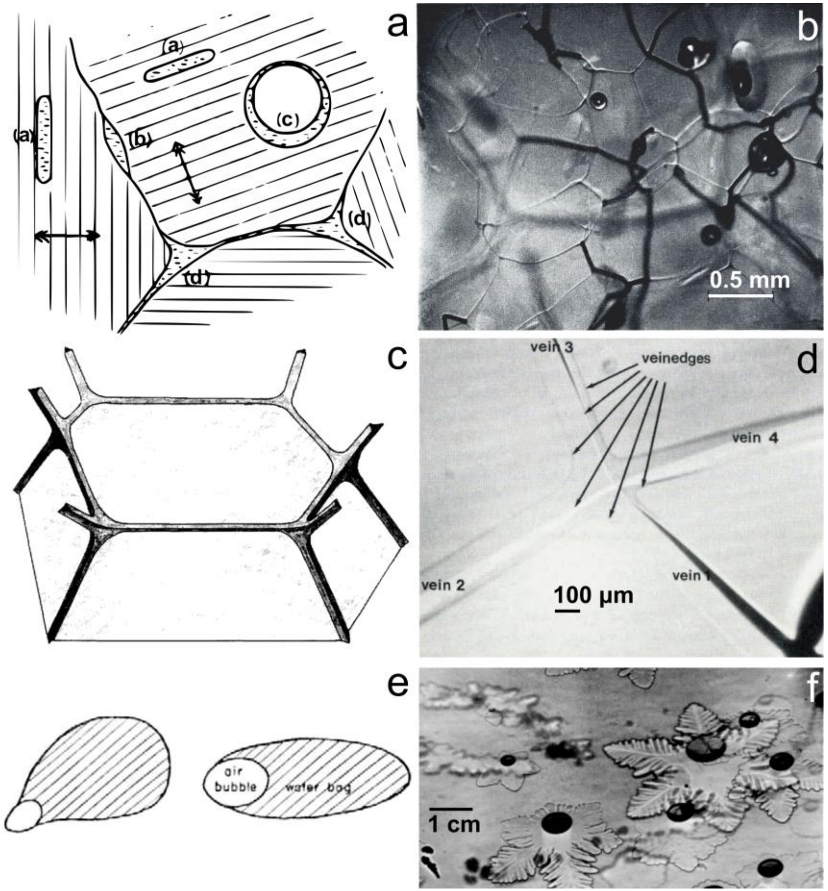
Temperate ice and liquid water

A main feature of temperate ice is that it contains a small fraction of liquid water in thermodynamic equilibrium with the solid phase.

Typically temperate ice can contain up to 5% of liquid water (mass fraction). If the value exceeds the threshold because of intense melt, excess meltwater is removed from the ice via runoff.

Where is the liquid water in temperate ice?

Mostly at ice grain junctions and inside small intra-grain inclusions.



Temperate ice is a self-purifying material

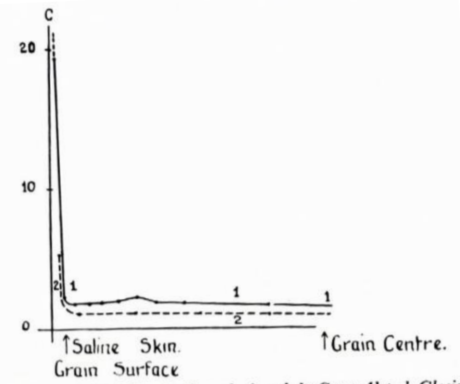
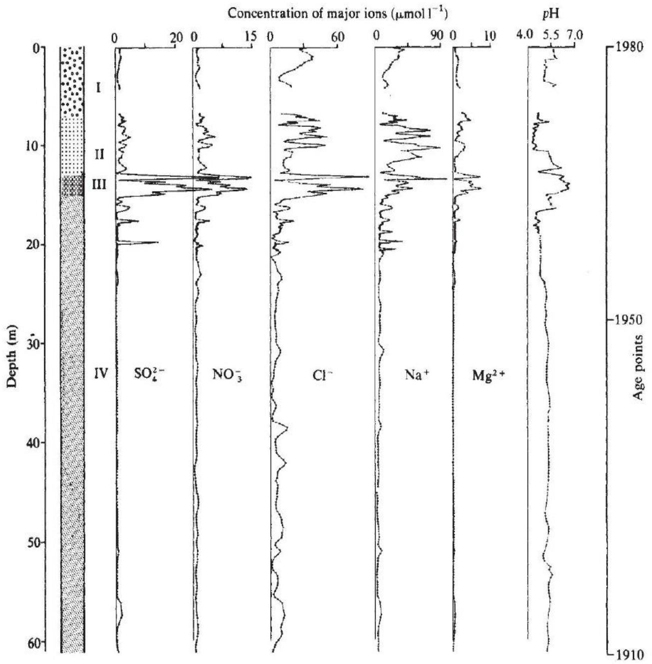
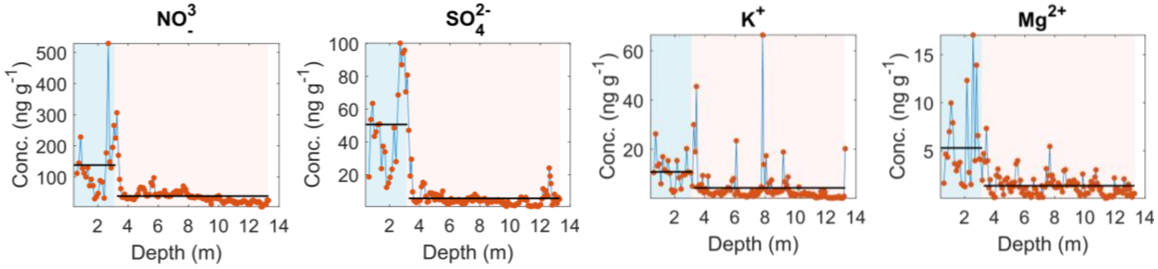


Fig. 1. Conductivity of melt water from the ice of the Great Aletsch Glacier
1. Sample No. 40, from the firn at the Jungfraujoch, 11.4.47
2. Sample No. 18, from the tongue of the glacier, 23.8.41
C. = Conductivity in 10^{-6} Mho/cm.

From Renaud 1948



From Davies 1982



Unpublished data from the Adamello ice core

The ionic pulse and its ecological consequences

The ionic pulse is referred as the strong release of ionic species in first meltwater from snow during spring. This helps the flora and soil communities, providing mineral nutrients that are essential to start the vegetative period after the winter quiescence.

But in the 1980s, when precipitation were acid because of sulphuric acid emitted in the atmosphere, this led to the production of extremely acid (pH<4) and toxic meltwater, with negative impacts on the communities downstream to snow deposits.

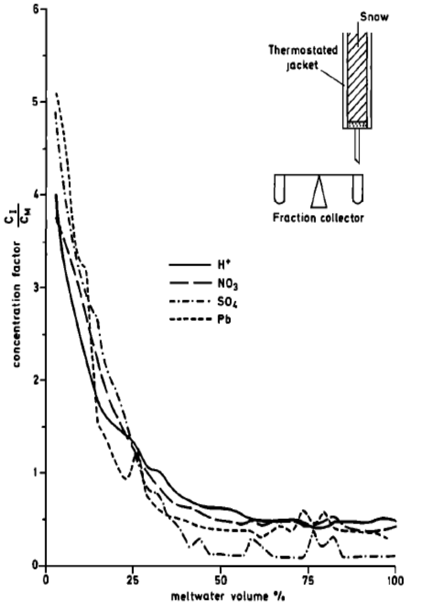
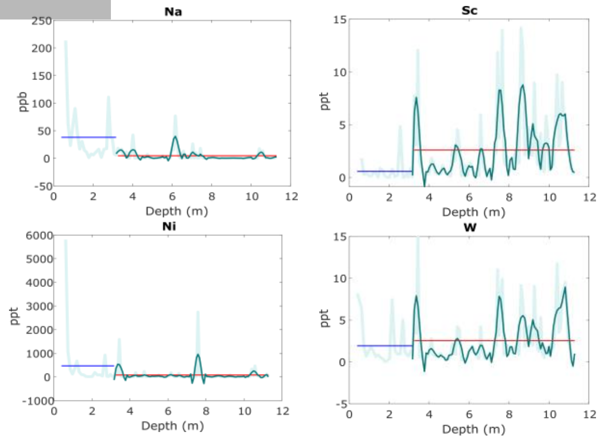


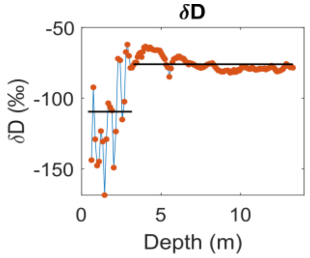
Fig. 2. Concentration factors for H^+ (calculated from pH), SO_4, NO_3, and Pb in fractions of meltwater from snow sample 1. C_I is the concentration in the Ith fraction, and C_M the concentration in the bulk snow. Inset is a schematic diagram of the laboratory lysimeter.

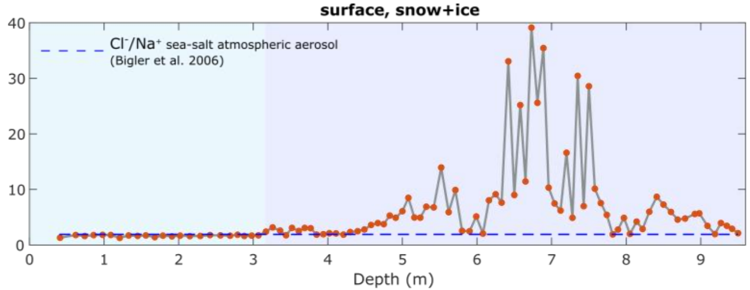
From Johannessen 1978

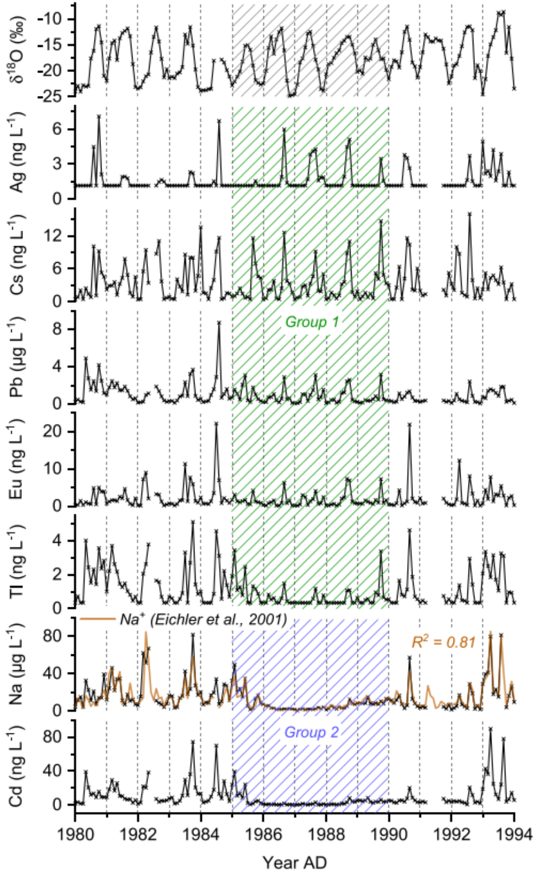
Effects on ice cores

Temperate ice is not ideal for ice core drilling. The presence of meltwater disturb many signals, mixing or even obliterating them. But learning to read temperate ice is the only possibility to guarantee a future to the science of mountain ice cores.





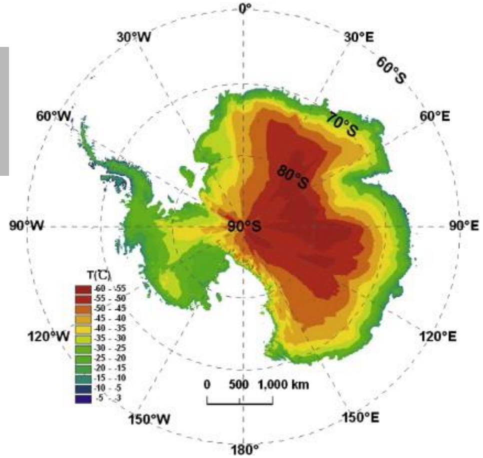




From Avak et al., 2018

PAUL SCHERRER INSTITUT PSI

Case study 1: Antarctica vs. Greenland



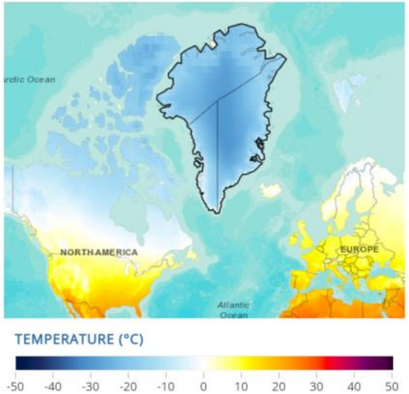
Antarctica and Greenland hosts 60 and 8 % of the total freshwater present on Earth.

Their melting explain 8 and 15 % of the total observed rise of sea-level, corresponding to 0.3 and 0.6 mm yr^{-1}.

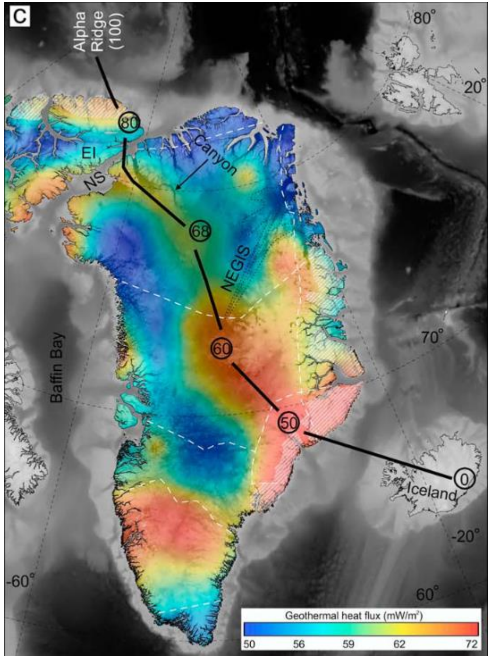
But Greenland is 6 times smaller than Antarctica. This means that Greenland is discharging ice into the ocean 3.2 times faster than Antarctica.

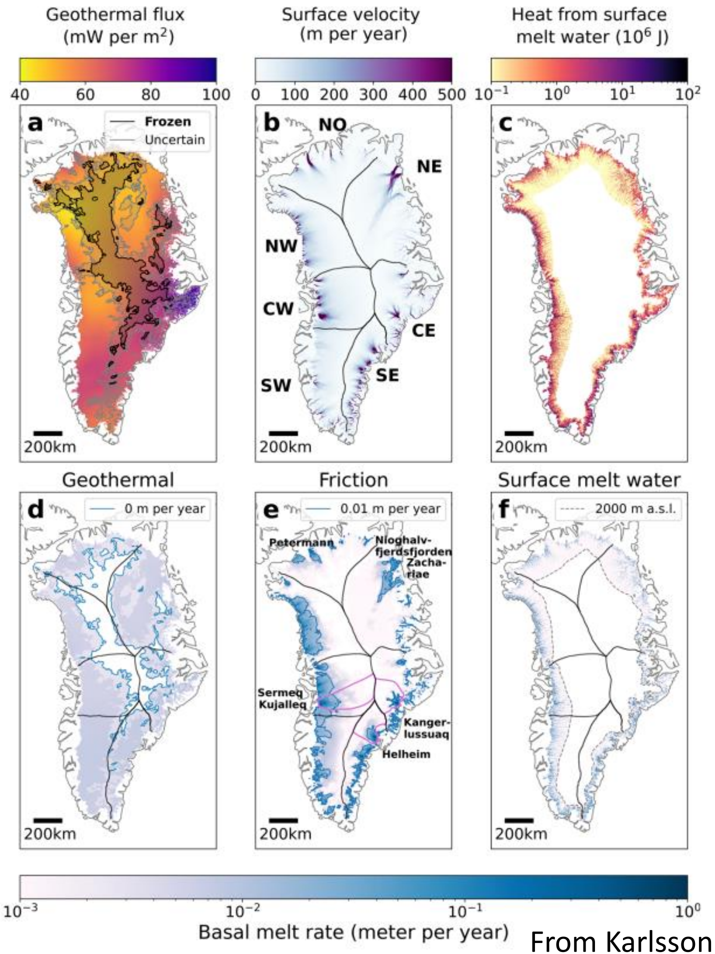
Why?

Temperate vs. cold ice? Also, but only climate and geophysics.

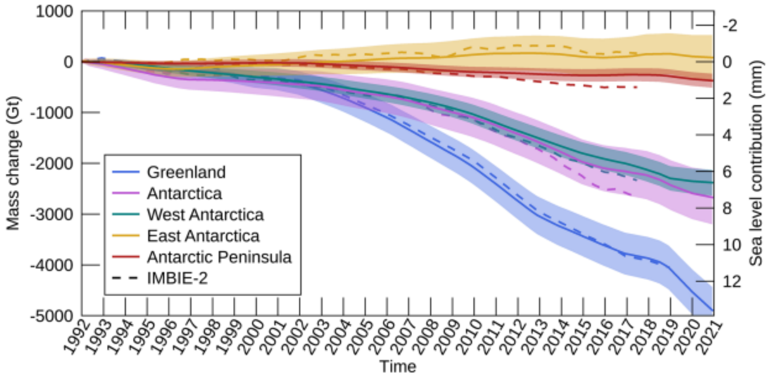


From Martos et al., 2018

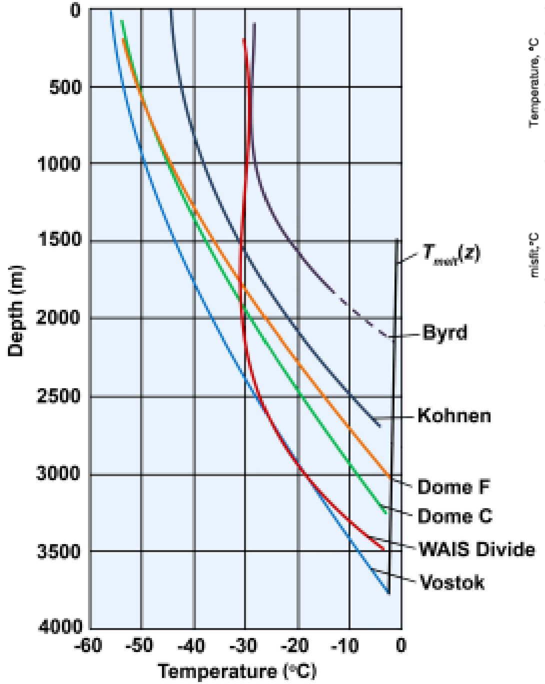




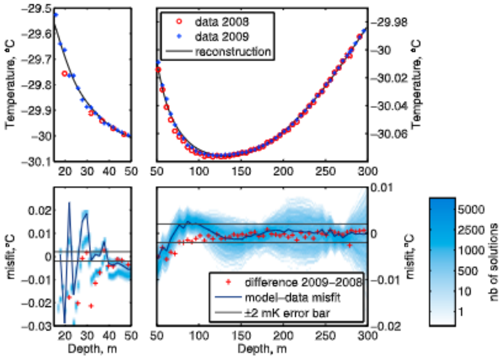
From Karlsson et al., 2021

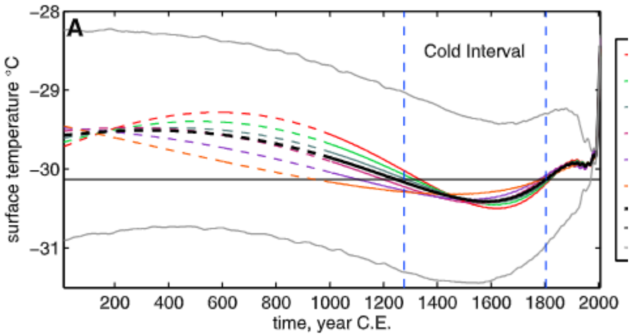


From Otosaka et al., 2023

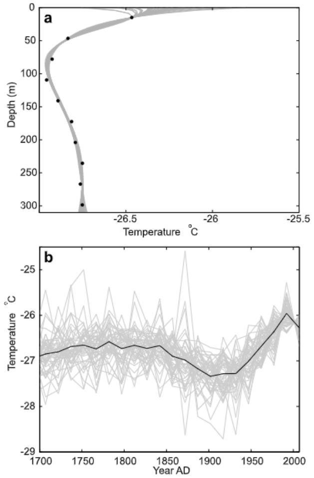


From Talalay et al., 2020





Effect of Little Ice Age on Antarctic ice temperature. From Orsi et al., 2012; WAIS



The recent atmospheric warming is already recorded in surface ice temperature, at least in West Antarctica. From Barrett et al., 2009

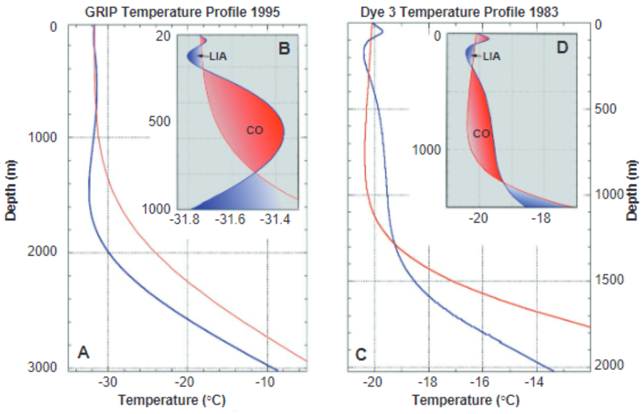


Fig. 1. The GRIP and Dye 3 temperature profiles [blue trace in (A) and (C)] are compared to temperature profiles [red trace in (A) and (C)] calculated under the condition that the present surface temperatures and accumulation rates have been unchanged back in time. **(A)** The GRIP temperature profile measured in 1995. The cold temperatures from the Glacial Period (115 to 11 ka) are seen as cold temperatures between 1200- to 2000-m depth. **(B)** The top 1000 m of the GRIP temperature profiles are enlarged so the Climatic Optimum (CO, 8 to 5 ka), the Little Ice Age (LIA, 1550 to 1850 A.D.), and the warmth around 1930 A.D. are indicated at the depths around 600, 140, and 60 m, respectively. **(C)** The Dye 3 temperature profile measured in 1983. Note the different shape of the temperature profiles when compared to GRIP and the different depth locations of the climate events. **(D)** The top 1500 m of the Dye 3 temperature profiles are enlarged so the CO, the LIA, and the warmth around 1930 A.D. are indicated at the depths around 800, 200, and 70 m, respectively.

From Dahl-Jensen et al., 1998

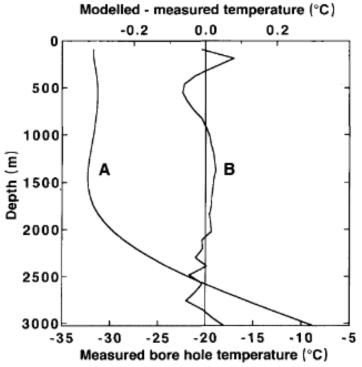


Fig. 1. Curve A: Measured temperature profile along the GRIP Summit bore hole (scale at bottom). The calculated profile is undistinguishable from A. The deviations are shown in curve B (extended scale on top).

From Johnsen et al., 1995

Conclusion: cold ice is a paleo-thermometer!

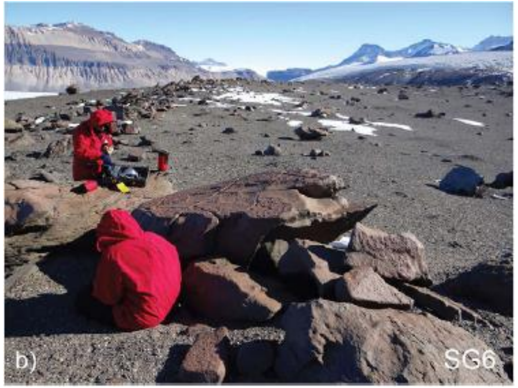
Case study 2: glaciers that work in reverse and advance when the climate is warmer

From Svanger et al., 2017

The Antarctic Dry Valleys are a unique place on Earth. They are concurrently among the coldest and driest places. Ice does not melt there, it sublimates.

The absence of ice allowed to study in detail the glacial history of this place, giving unexpected results.

One of the apparently weirdest evidence is that in the Dry Valleys local glaciers advance during warm periods and retreat during the cold ones.



Wir schaffen Wissen – heute für morgen

Thanks for your attention!