IMPT 2021, 23-26 November 2021
Impacts morphologiques du changement climatique

Ice, glacier and ice-sheet flow

Olivier
Gagliardini

Ice, glacier and ice-sheet flow

- Introduction: Cryosphere and climate change
- Part 1: Ice(s), a material with a complex rheology
- Part 2: Glaciers, basal sliding and risks
- Part 3: Ice-sheets, grounding line and sea-level

Who I am?

- 1993: ENS Cachan – *Agrégation* in Civil Engineering
- 1995-99: PhD on ice anisotropy at LGGE
- 1999: *Maître de conferences* UJF & LGGE
- 2010-2015 : *Institut Universitaire de France*
- 2012: *Professeur* University Grenoble Alpes

Modelling of complex ice flows

Interested in the **processes** that control glacier and ice-sheet dynamics

Who I am not?

- I am not a mathematician
- I am not even a numerical specialist

Institut des Géosciences de l'Environnement (IGE)

IGE

Born in 2017 from the merging of the former **LGGE** (glaciology) and **LTHE** (hydrology) labs.

A joint research unit of CNRS, IRD, **UGA**, Grenoble INP

270 colleagues
150 permanent staff - 60 PhD – 120 trainees

Oceano graphy

Atmos & environm ental sciences

Climate change and anthropogenic influence: the particular case of polar, intertropical and mountain regions

Glaciology

Hydrology

Inter and transdisci plinary sciences

Who has contributed?

- **Colleagues** at IGE: Fabien Gillet-Chaulet, Gael Durand, Christian Vincent, Florent Gimbert,…

- **PhD students**

Fabien Gillet-Chaulet (CR, CNRS) 2003-2006
Basile de Fleurian (postdoc Norway) 2007-2010
Cyrille Mosbeux (postdoc IGE) 2013-2016
Julien Brondex (postdoc CEN) 2014-2017
Olivier Passalacqua (IGN) 2014-2017
Juan Pedro Roldan Blasco (ANR SAUSSURE) 2019-
Benoit Urruty (H2020 TiPACCs) 2019-

- **Post-docs**

Adrien Gilbert 2020-
Lionel Favier 2009-2012 ; 2018
Ma Ying 2009-2010
Gael Durand (DR CNRS) 2007-2009

Essentially with one tool

Contributor of the developments of the open source finite element code **Elmer/Ice**

A code dedicated to solve ice, glaciers and ice-sheet flow

Elmer/Ice is an add-on package to Elmer, a multi-physics FEM suite mainly developed by CSC-IT Center for Science Ltd. (Finland)

“Father” of the **Elmer/Ice** code

Animation of the community: more than 17 courses since 2018

164 publications using Elmer/Ice since 2004

http://elmerice.elmerfem.org

History of IPCC statements

AR1 (1990): “The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability.”

AR2 (1995): “The balance of evidence suggests a discernible human influence on global climate.”

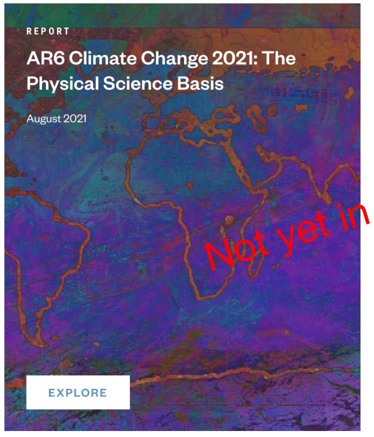
AR3 (2001): “There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.”

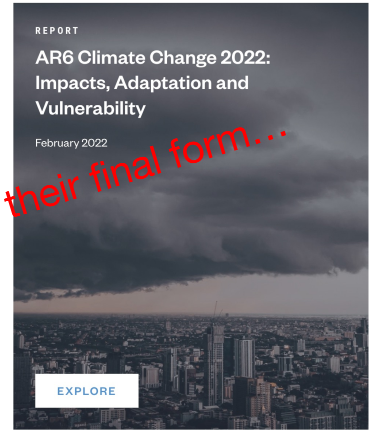
AR4 (2007): “Anthropogenic warming of the climate system is widespread and can be detected in temperature observations taken at the surface, in the free atmosphere and in the oceans. Evidence of the effect of external influences, both anthropogenic and natural, on the climate system has continued to accumulate since the TAR.”

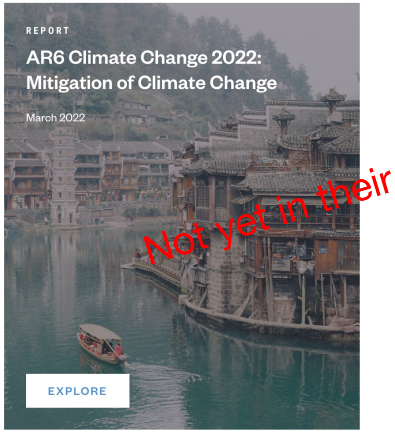
AR5 (2013): “It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.”

AR6 (2020): “It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.”

IPCC Sixth Assessment report: it's not yet over

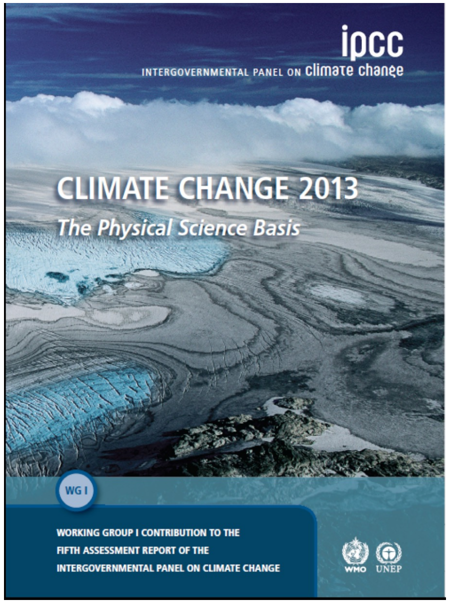






Not yet in their final form…

Not yet in their final form…



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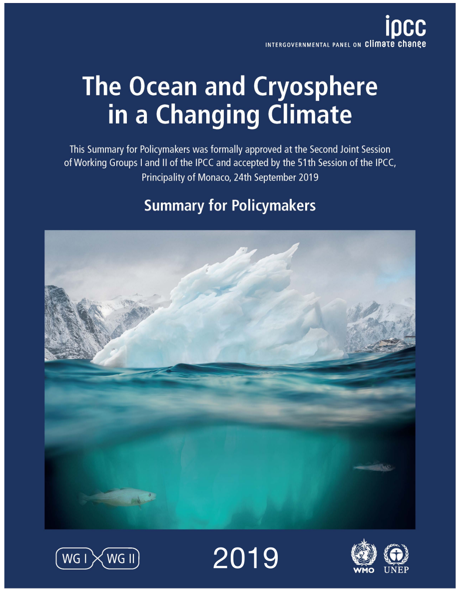


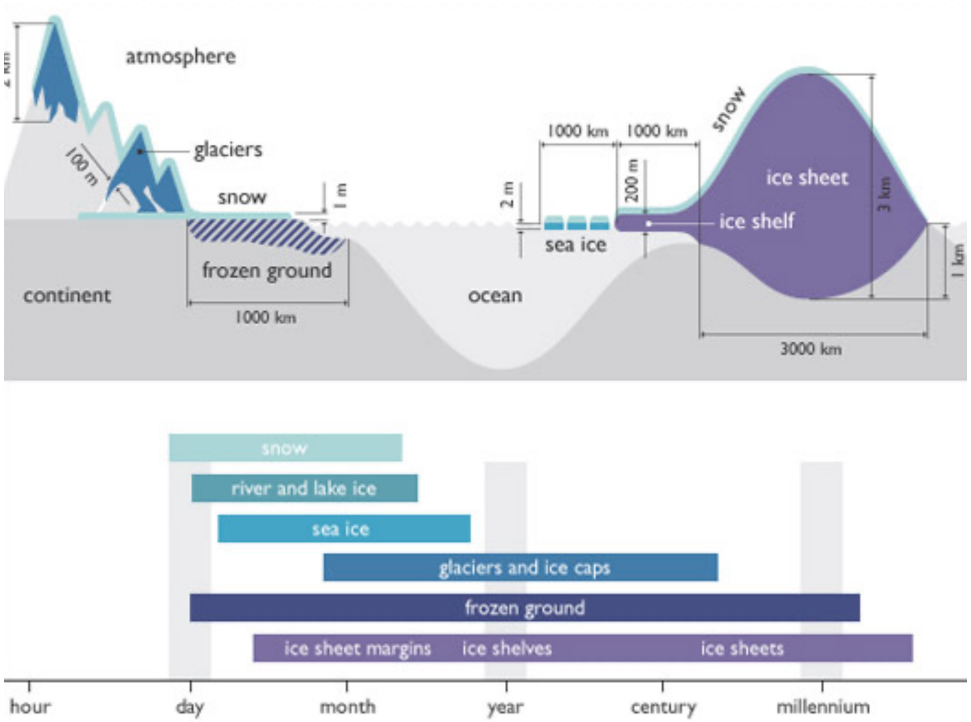
Cryosphere on Earth

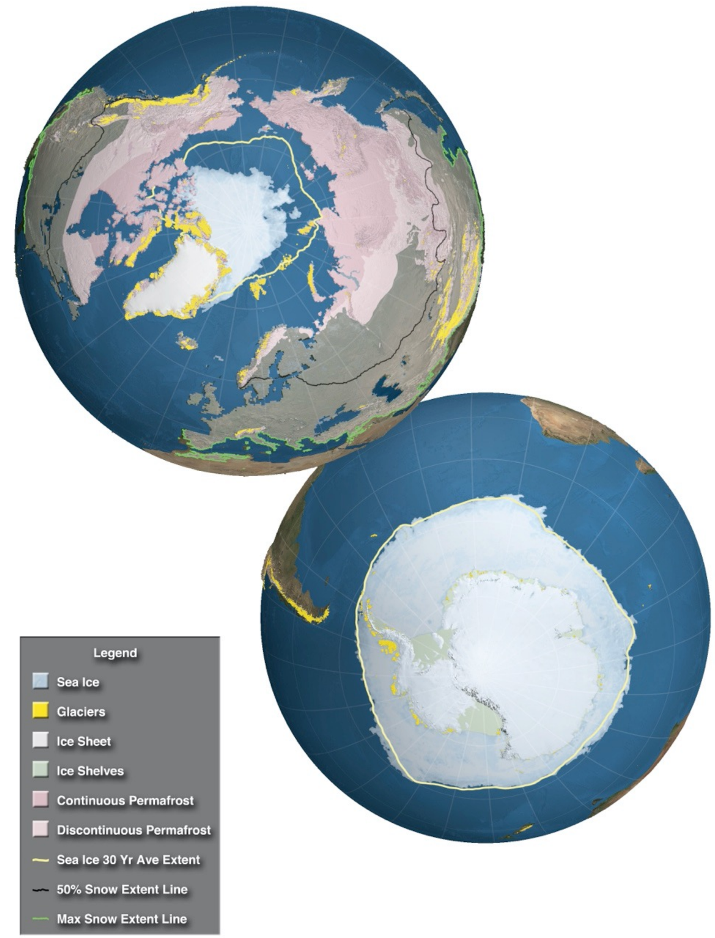
Portions of Earth's surface where water is in solid form

Includes: sea ice, lake ice, river ice, snow cover, **glaciers**, **ice caps**, **ice sheets**, and frozen ground (incl. permafrost)

Plays a significant role in the global climate

Response times vary from days to milleniums



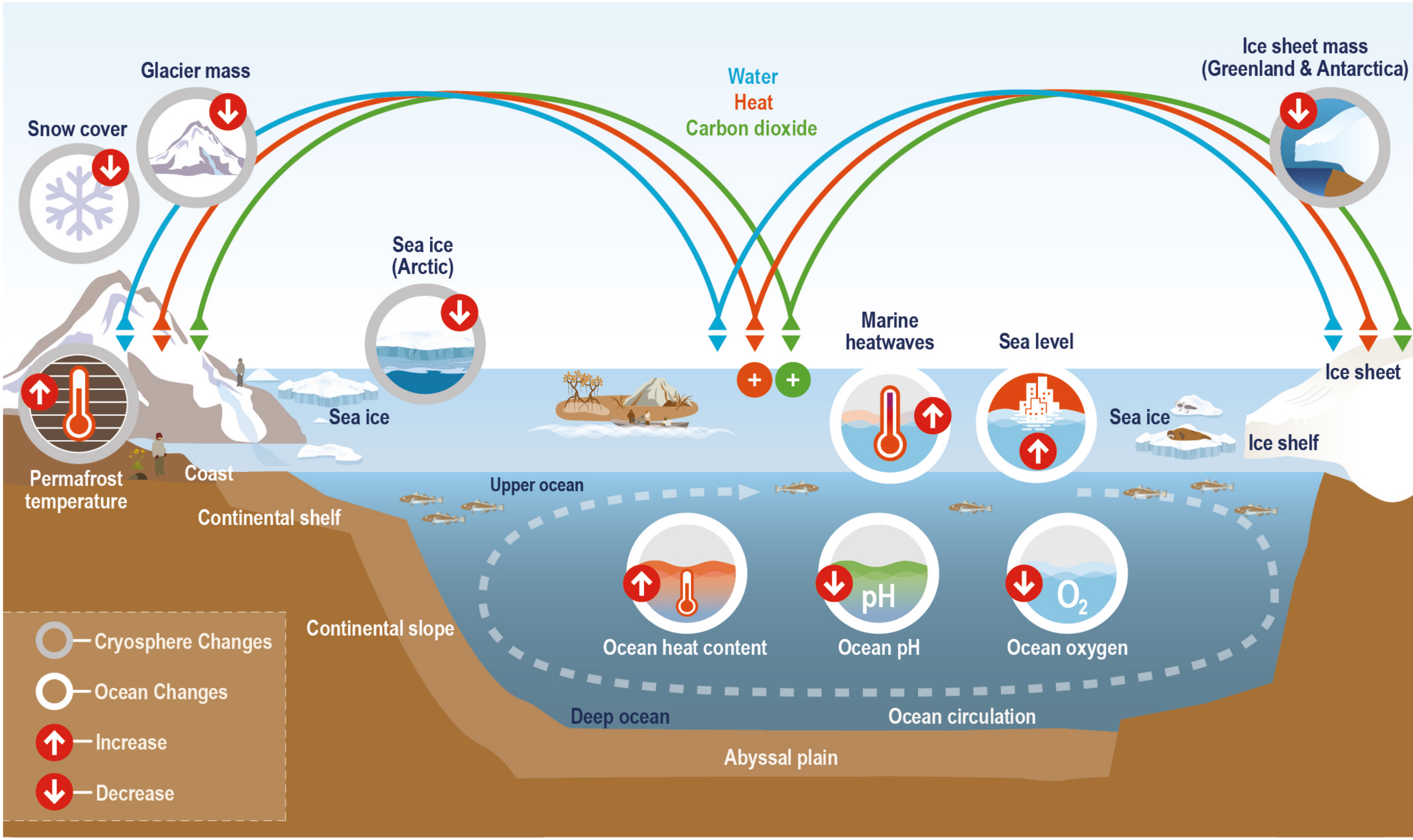


Areas and Volumes

Ice on Land	Percent of Global Land Surface[a]	Sea Level Equivalent[b] (metres)
Antarctic ice sheet[c]	8.3	58.3
Greenland ice sheet[d]	1.2	7.36
Glaciers[e]	0.5	0.41
Terrestrial permafrost[f]	9–12	0.02–0.10[g]
Seasonally frozen ground[h]	33	Not applicable
Seasonal snow cover (seasonally variable)[i]	1.3–30.6	0.001–0.01
Northern Hemisphere freshwater (lake and river) ice[j]	1.1	Not applicable
Total[k]	**52.0–55.0%**	**~66.1**
Ice in the Ocean	**Percent of Global Ocean Area[a]**	**Volume[l] (10^3 km^3)**
Antarctic ice shelves	0.45[m]	~380
Antarctic sea ice, austral summer (spring)[n]	0.8 (5.2)	3.4 (11.1)
Arctic sea ice, boreal autumn (winter/spring)[n]	1.7 (3.9)	13.0 (16.5)
Sub-sea permafrost[o]	~0.8	Not available
Total[p]	**5.3–7.3**	

1 mm SLE ~ 360 Gt of ice

Ocean and Cryosphere key components



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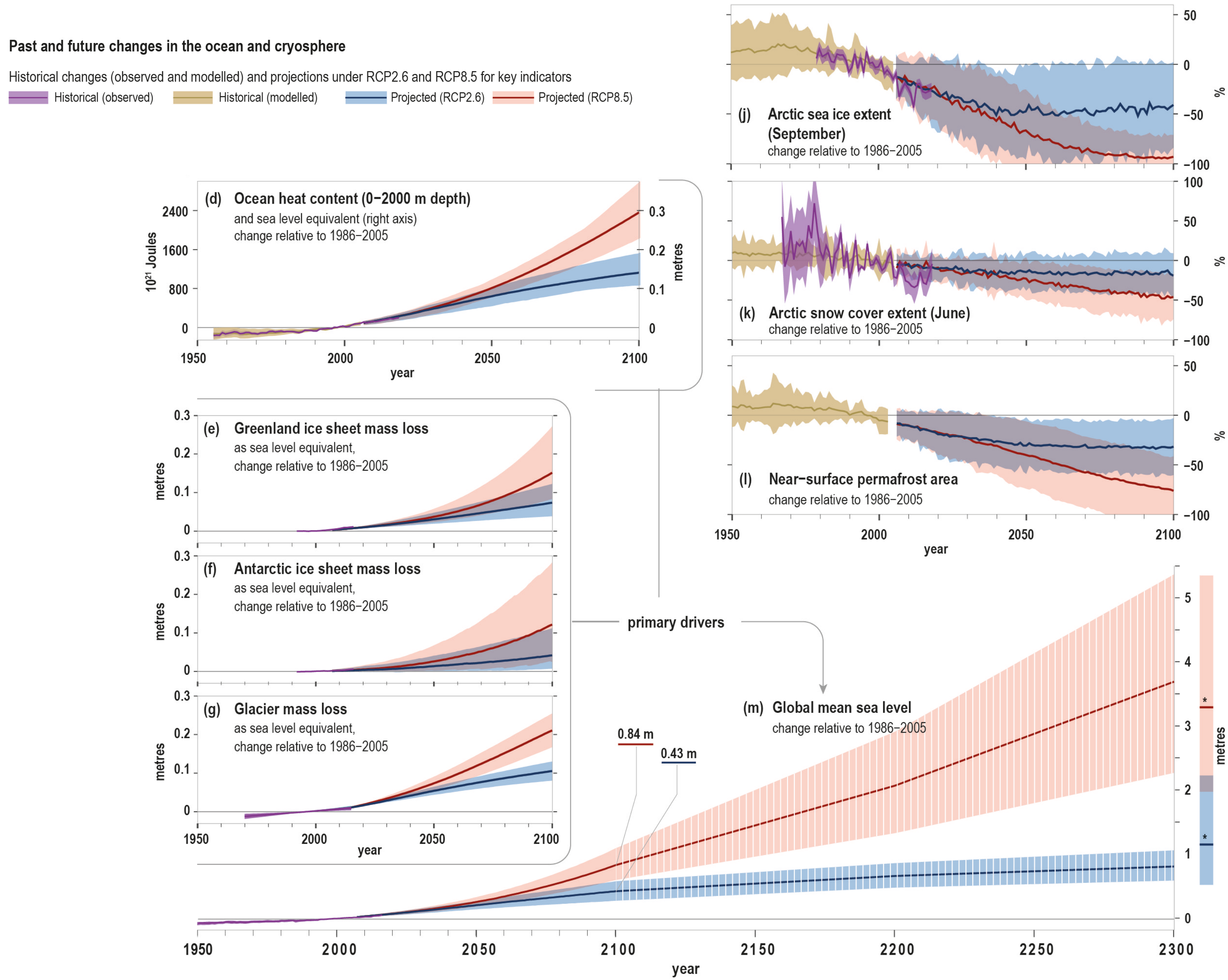
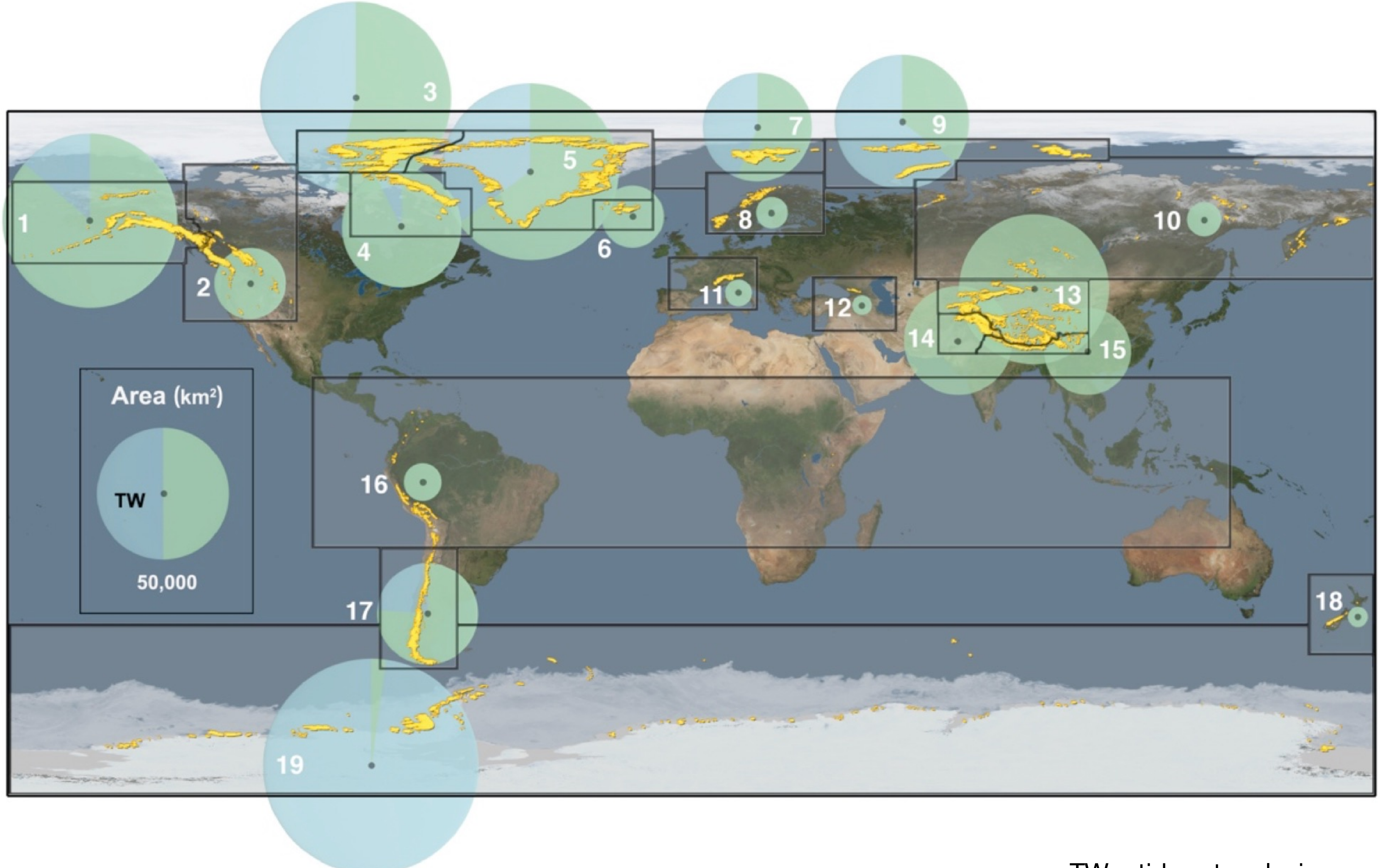
Ocean and cryosphere past and future changes



Glaciers and Ice caps: repartition of Earth



TW = tidewater glaciers

Glaciers and Ice caps: definitions

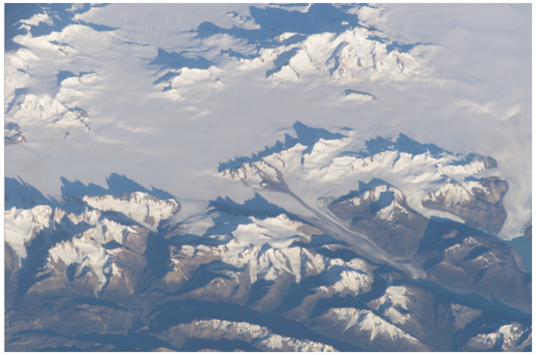
Glaciers:

- Small land-based ice masses in mountainous regions
- Constrained by topographical features
- Are found on every continent
- Many different types: Valley glaciers, cirque glaciers, hanging glaciers, tidewater glaciers
- Important fresh water resource for millions of people

Ice caps and Icefields:

- Ice masses that cover less than 50,000 km^2 of land area
- Icefields are constrained by topographical features
- Ice caps override the underlying topography

Vatnajökull, Iceland

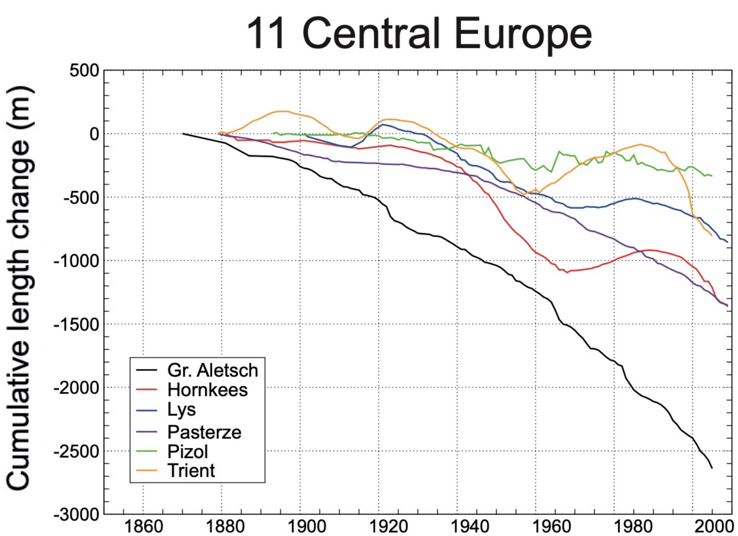


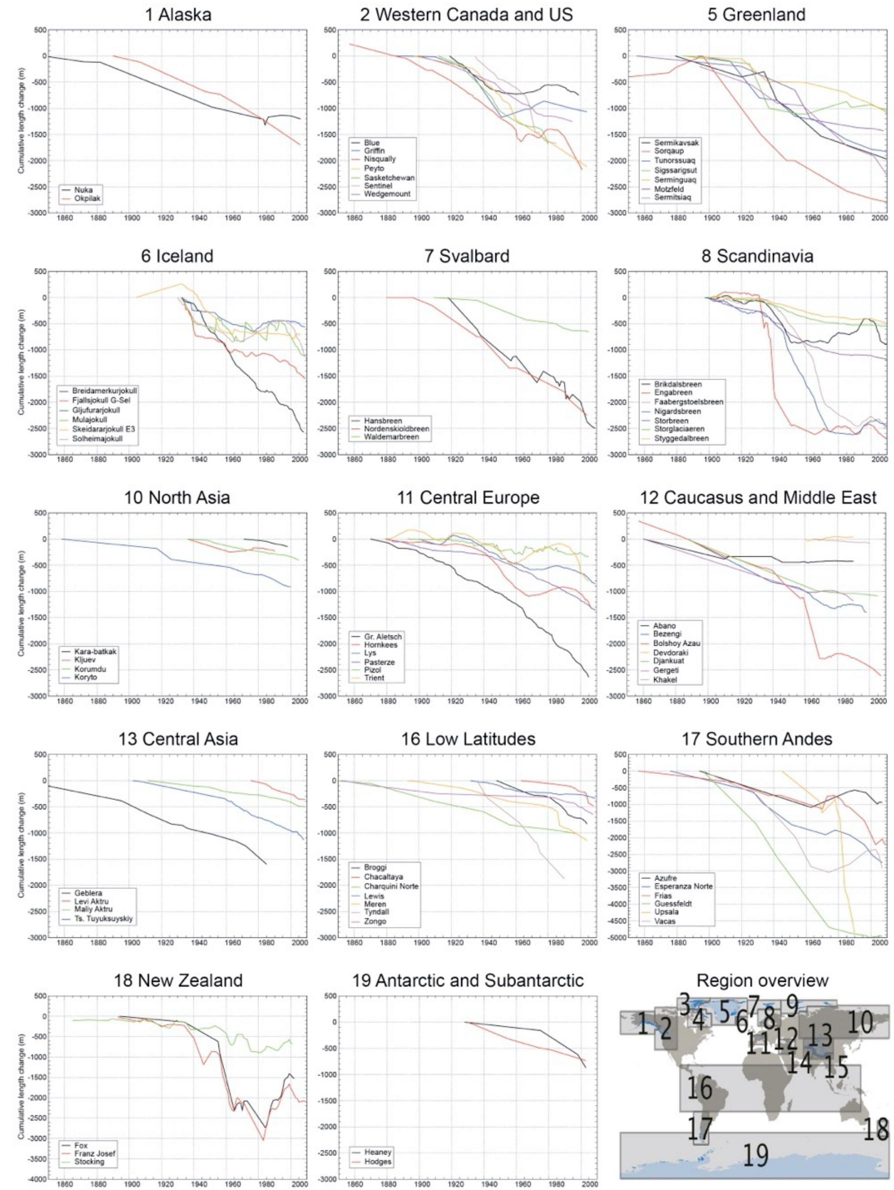
Southern Patagonian Ice Field

Glaciers length

Worldwide retreat since the mid 19th century

Increased mass loss during the last decades

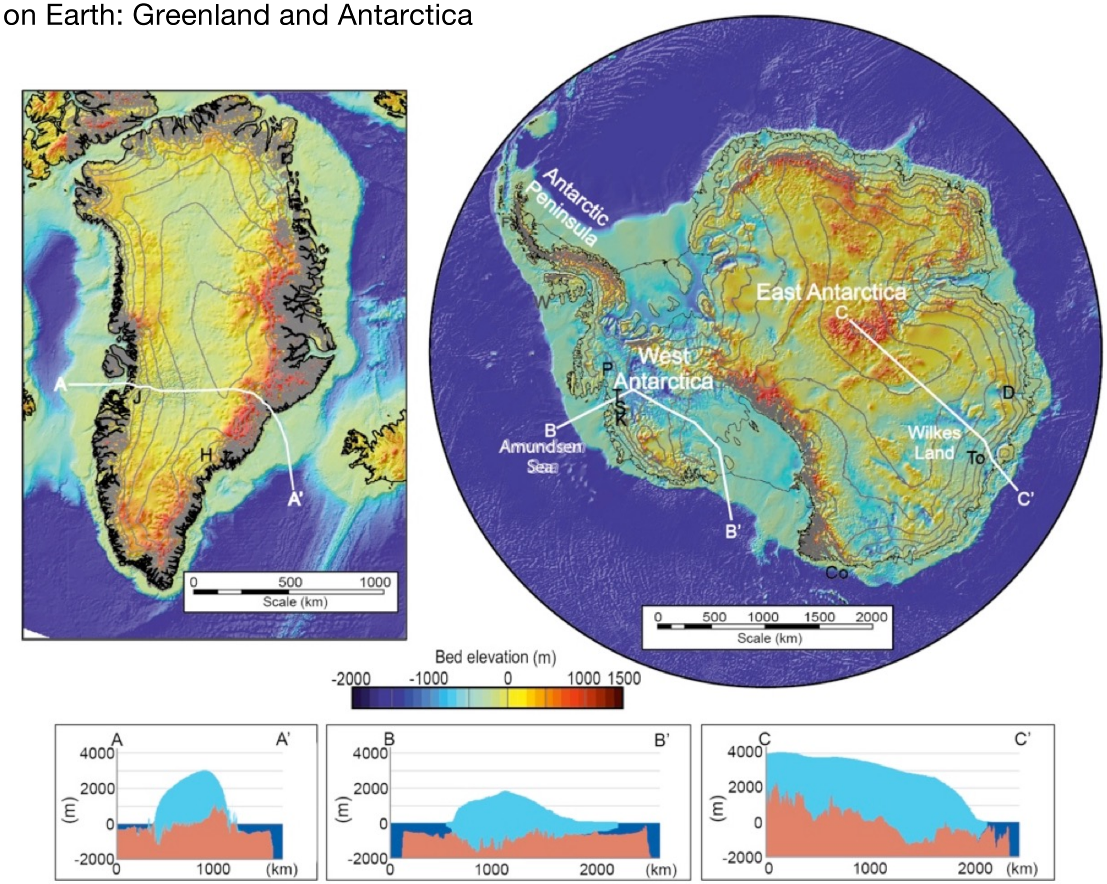




Ice sheets

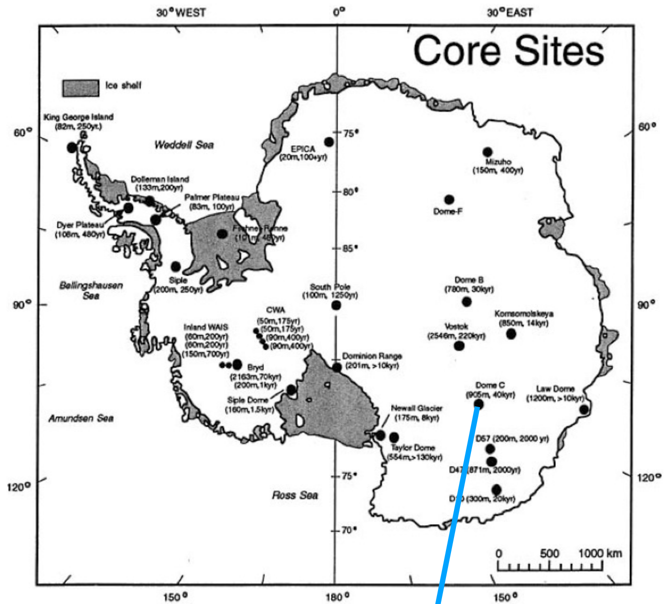
Ice masses that cover more than 50,000 km² of land area

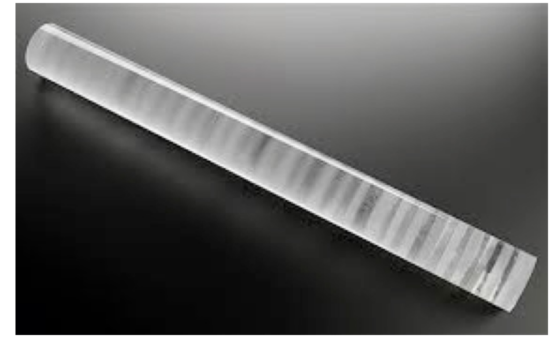
Currently 2 ice sheets on Earth: Greenland and Antarctica

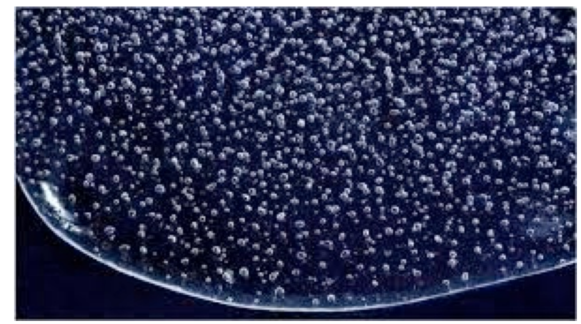


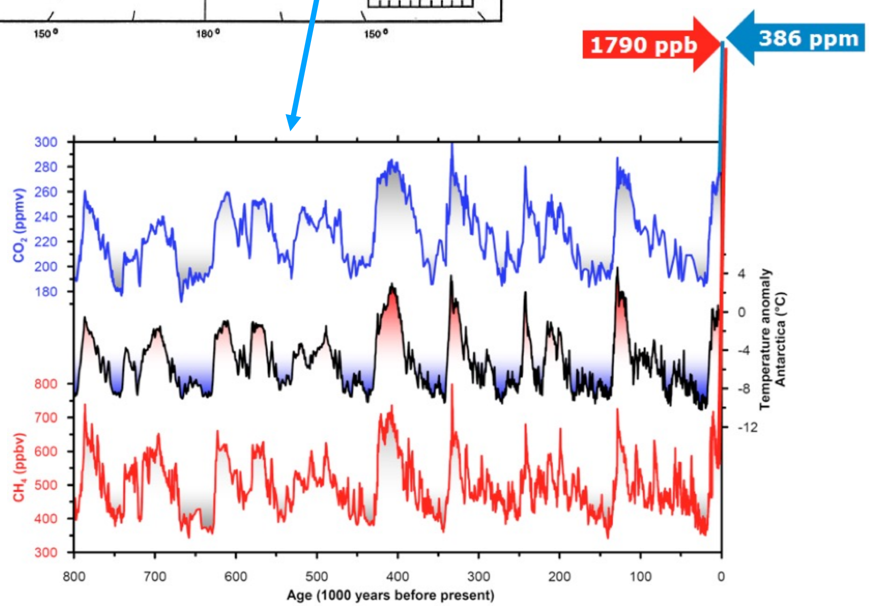
Glossary:
Ice shelf: A floating slab of ice of considerable thickness extending from the coast often filling embayments in the coastline of an ice sheet
Marine-based ice sheet: An ice sheet containing a substantial region that rests on a bed lying below sea level and whose perimeter is in contact with the ocean.

Ice core and climate archives



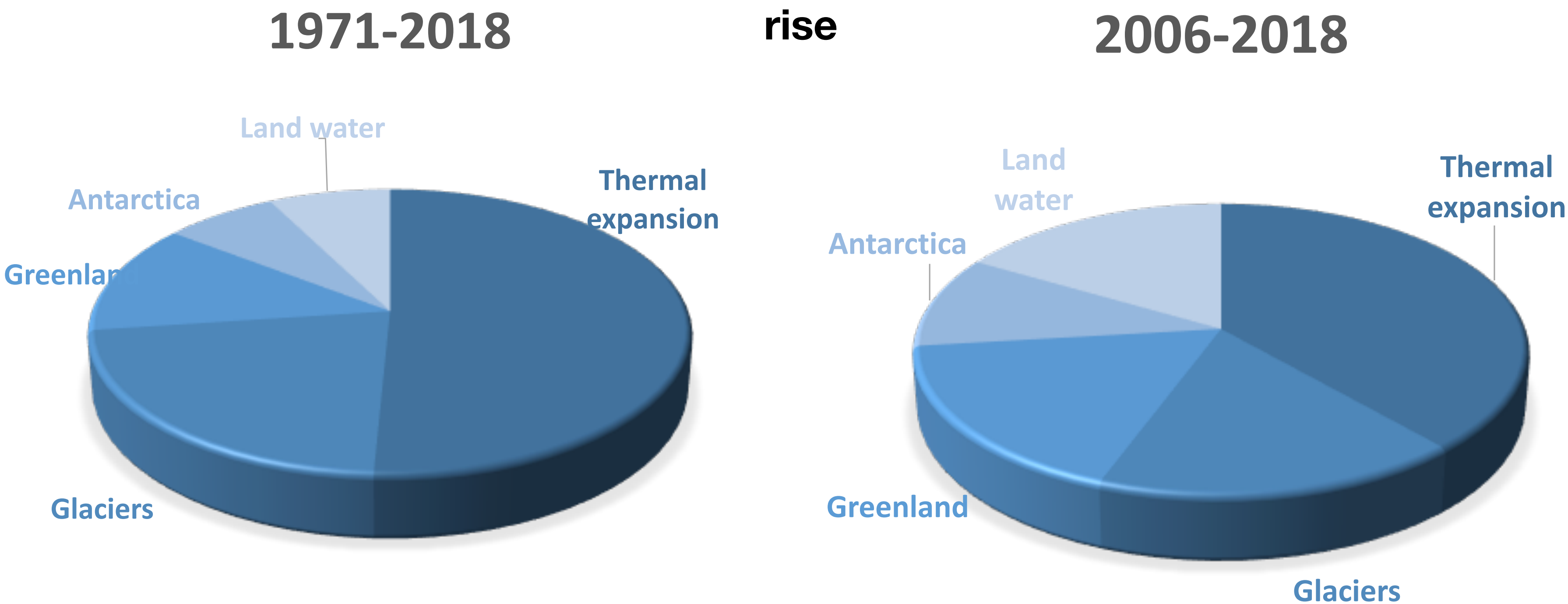






Increasing mass loss contributing to sea level rise

Components of sea level rise

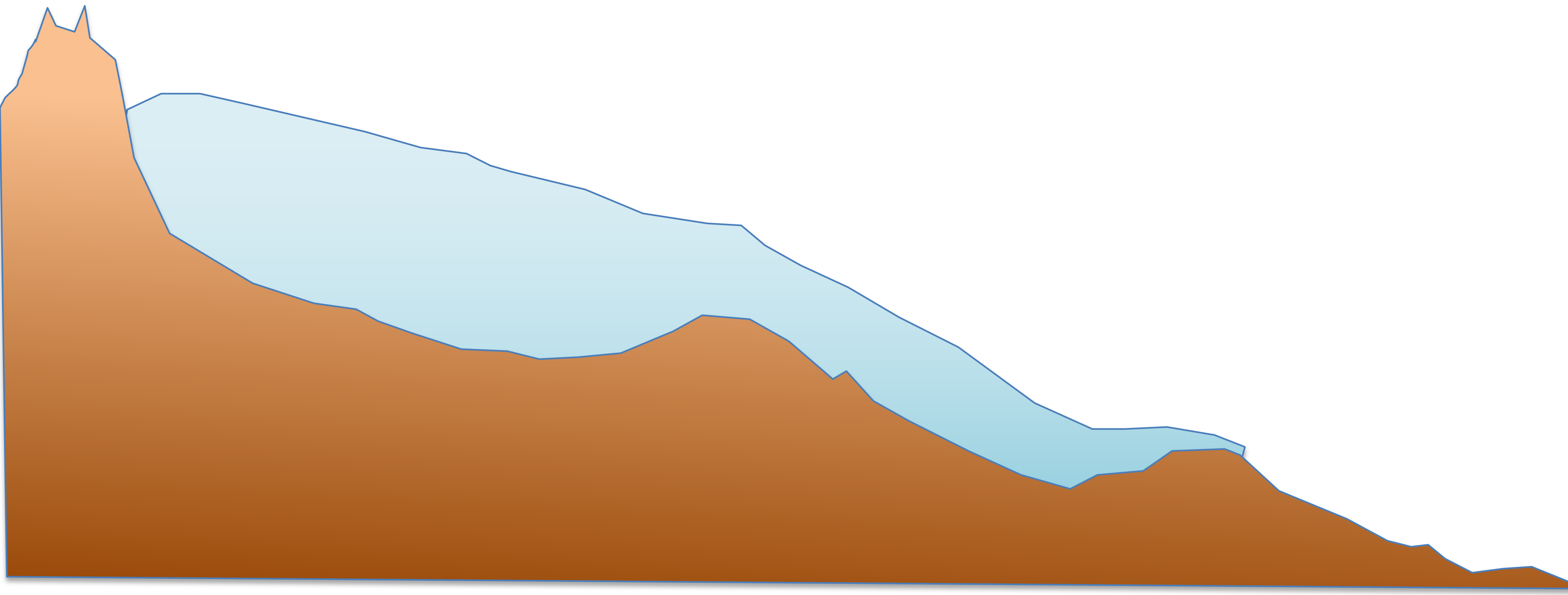


2.3 mm/year

3.7 mm/year

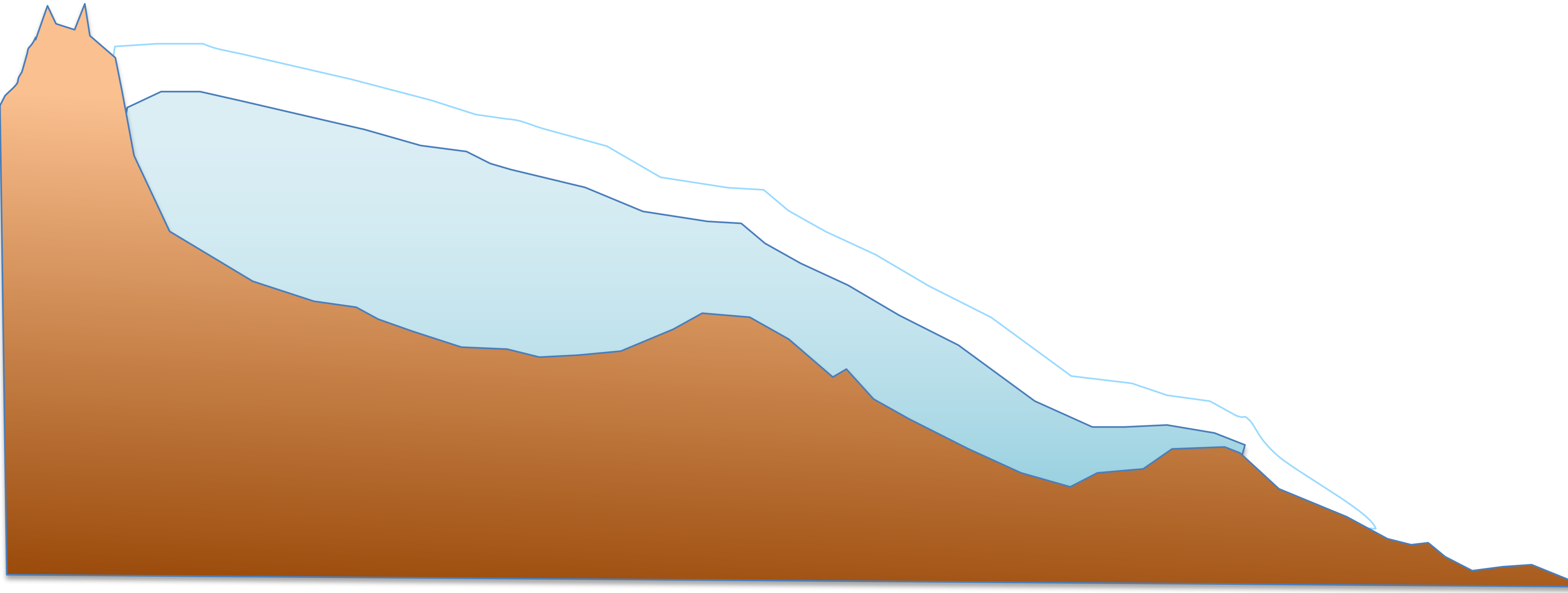
IPCC AR6 (2021)

How does it work?



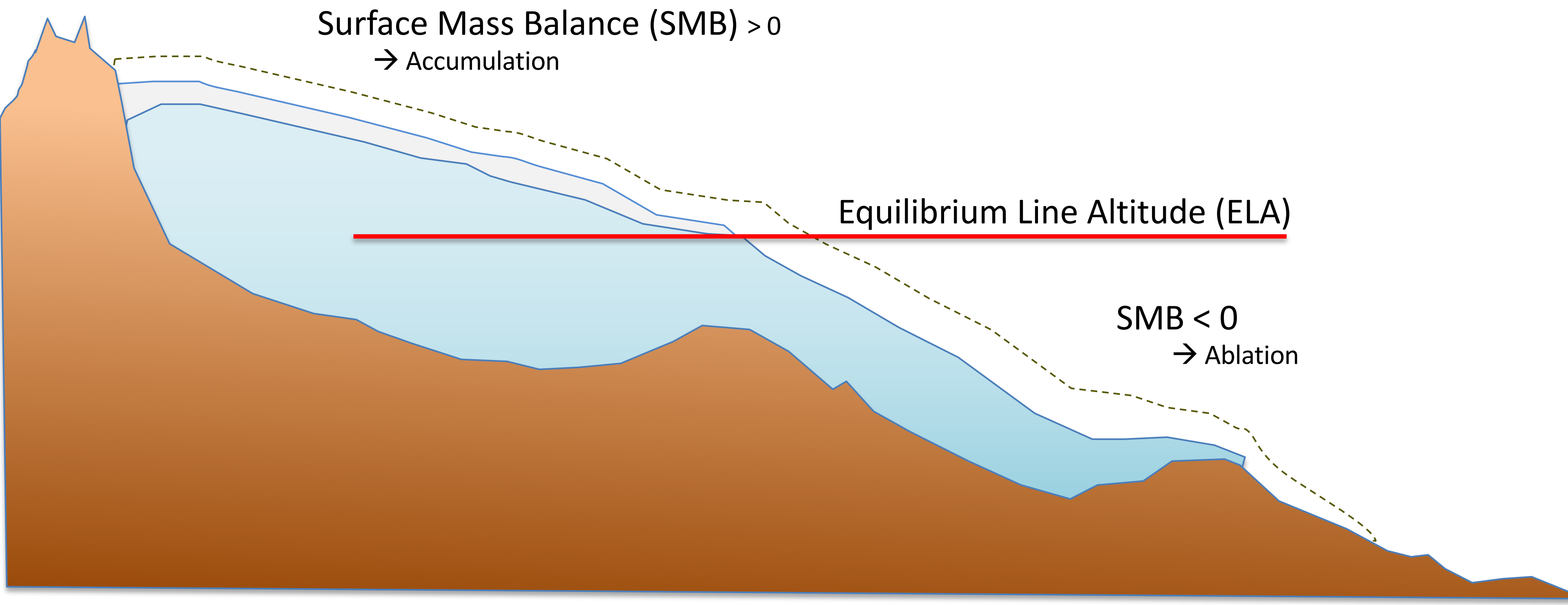
How does it work?

Snow accumulates during winter…

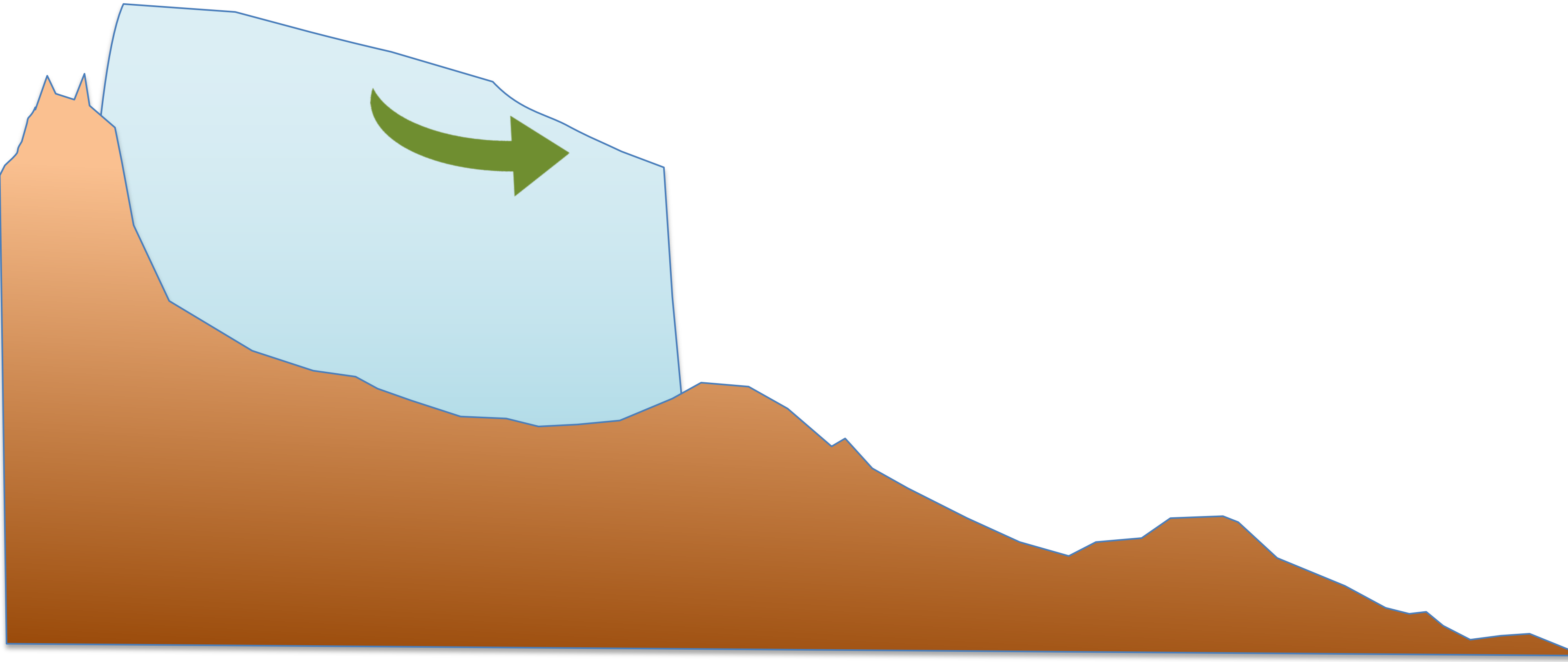


How does it work?

and melt partially during summer…

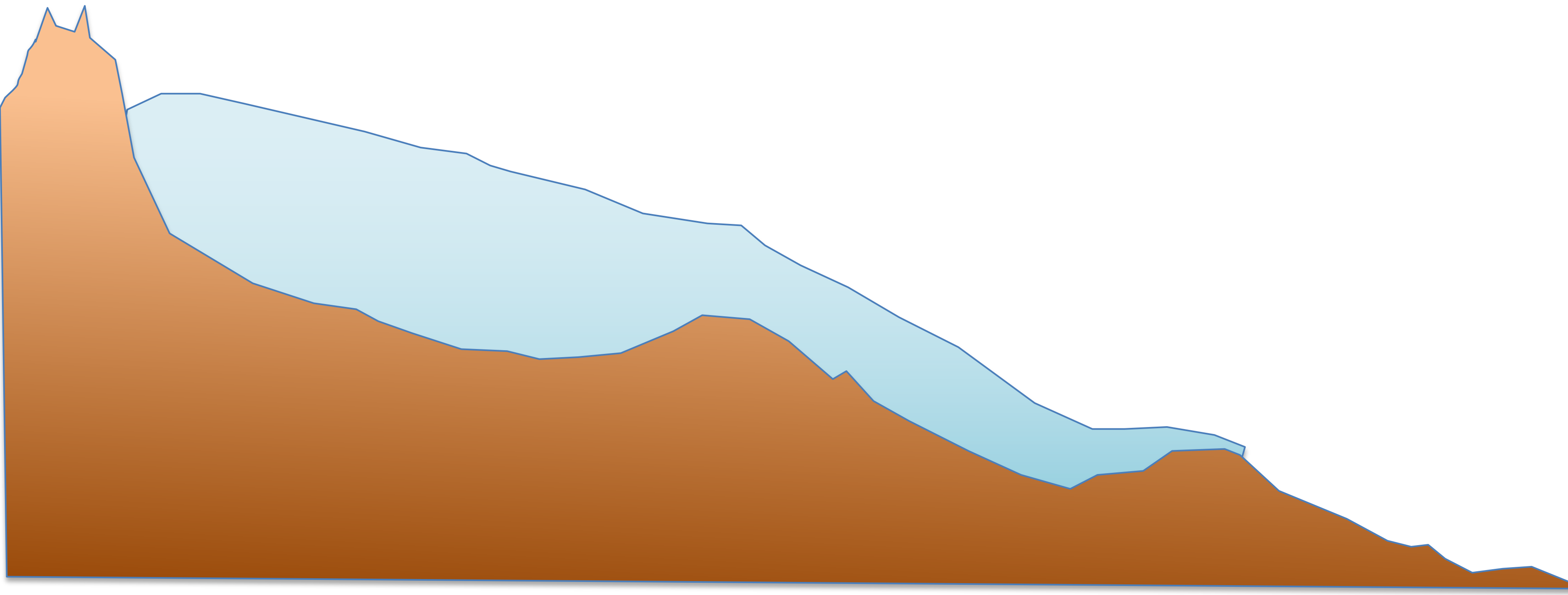


How does it work?



How does it work?

Glacier movements redistribute ice from top to bottom

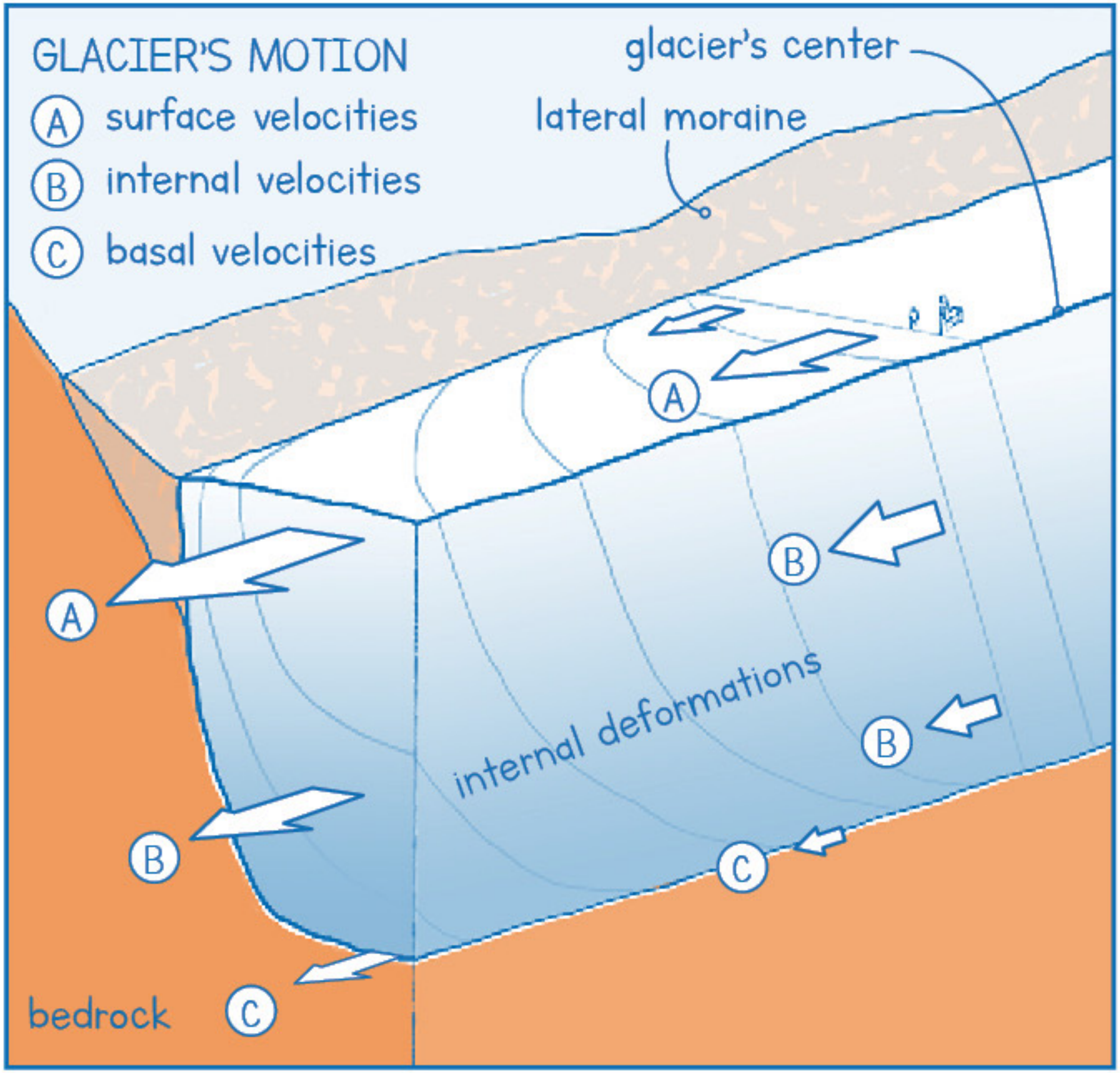


Glacier motion = internal deformation + basal sliding

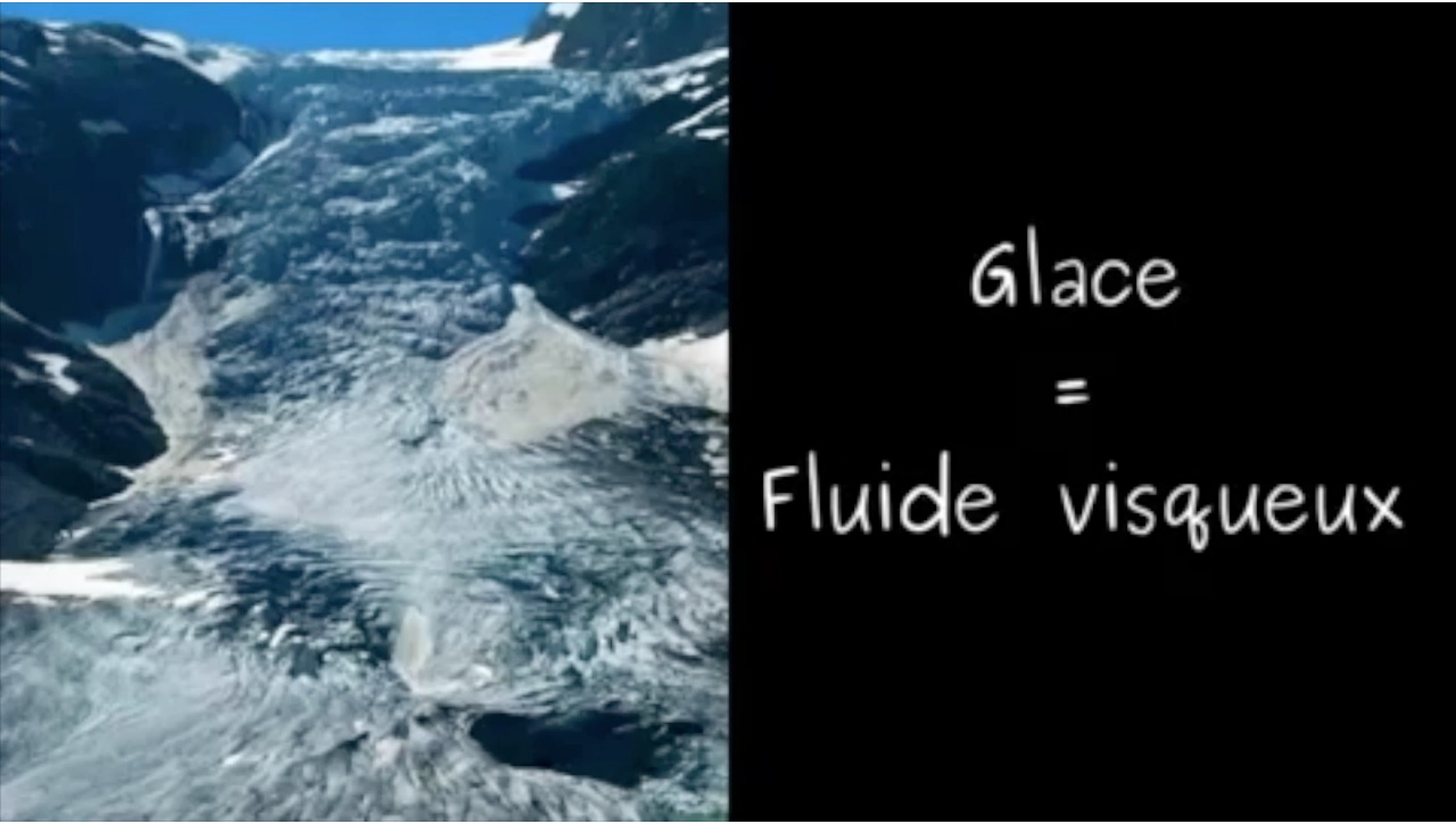
Part 1

Part 2

Glacier motion = internal deformation + sliding

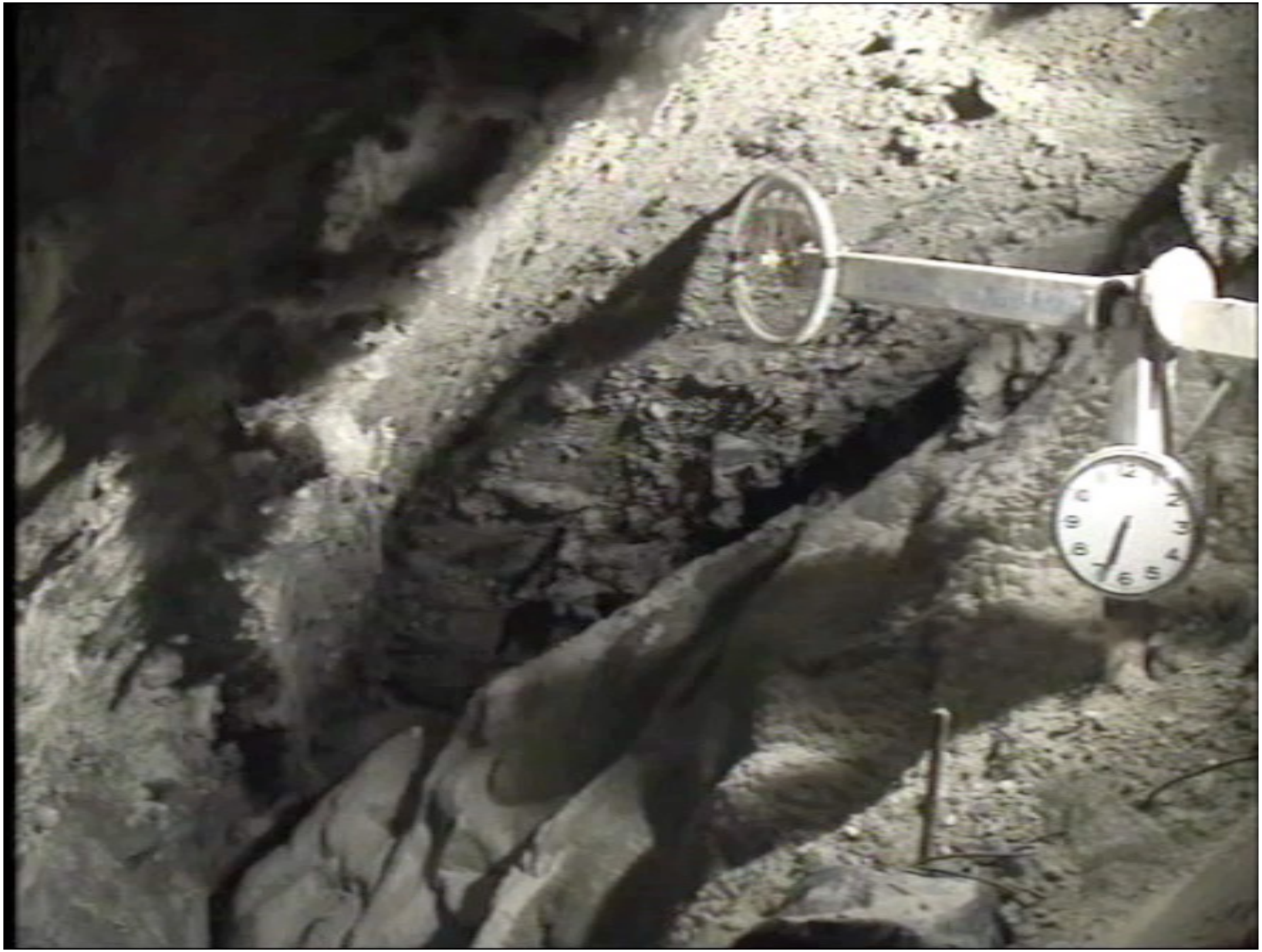


Non-linear viscous flow



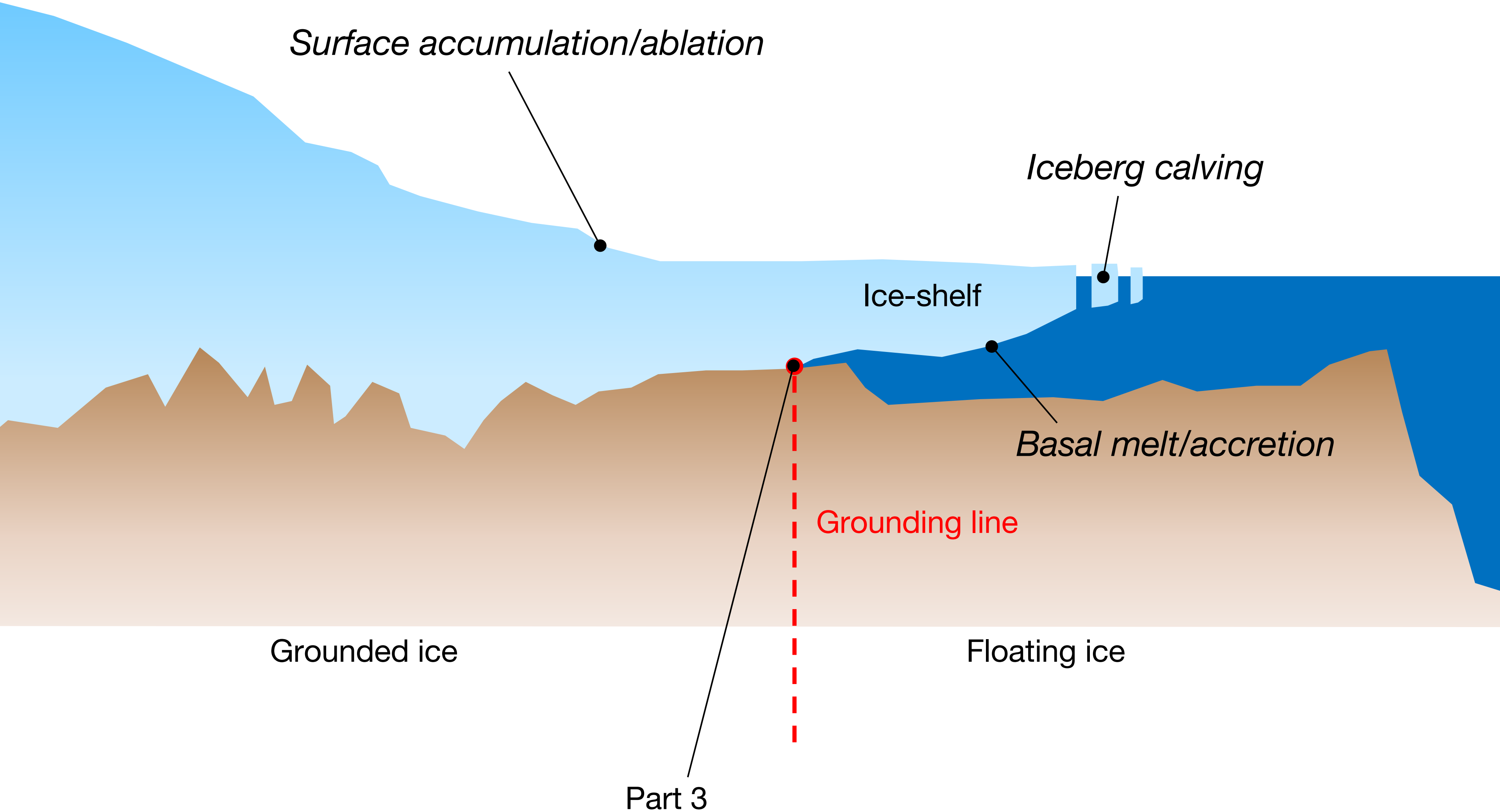
https://www.geo.uzh.ch/~gjouvet/

Basal sliding of ice over the bedrock

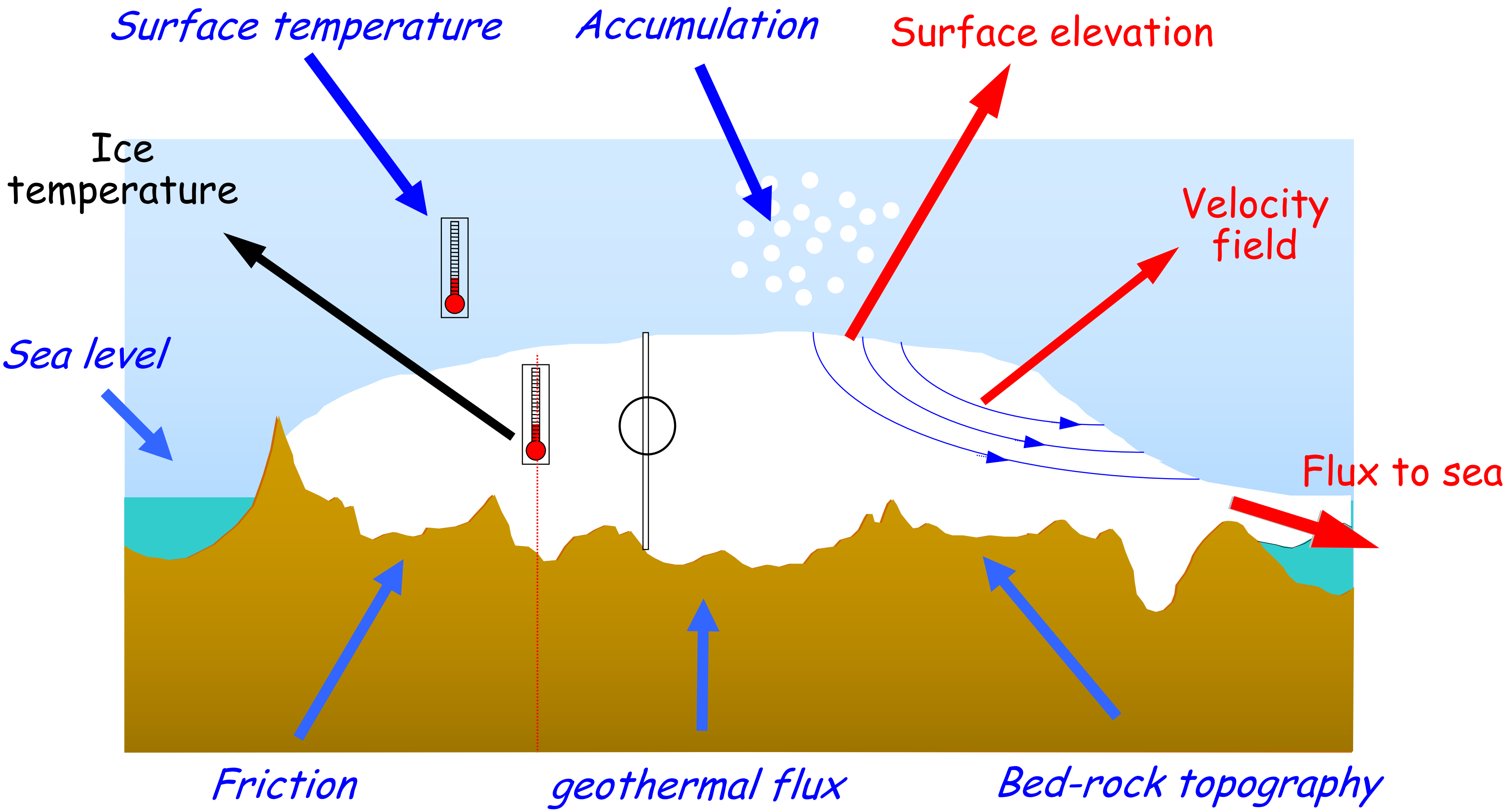


http://www.moreauluc.com

When ice meets water… other processes to loose/gain mass



Problematic of glacier and ice sheet flow modelling

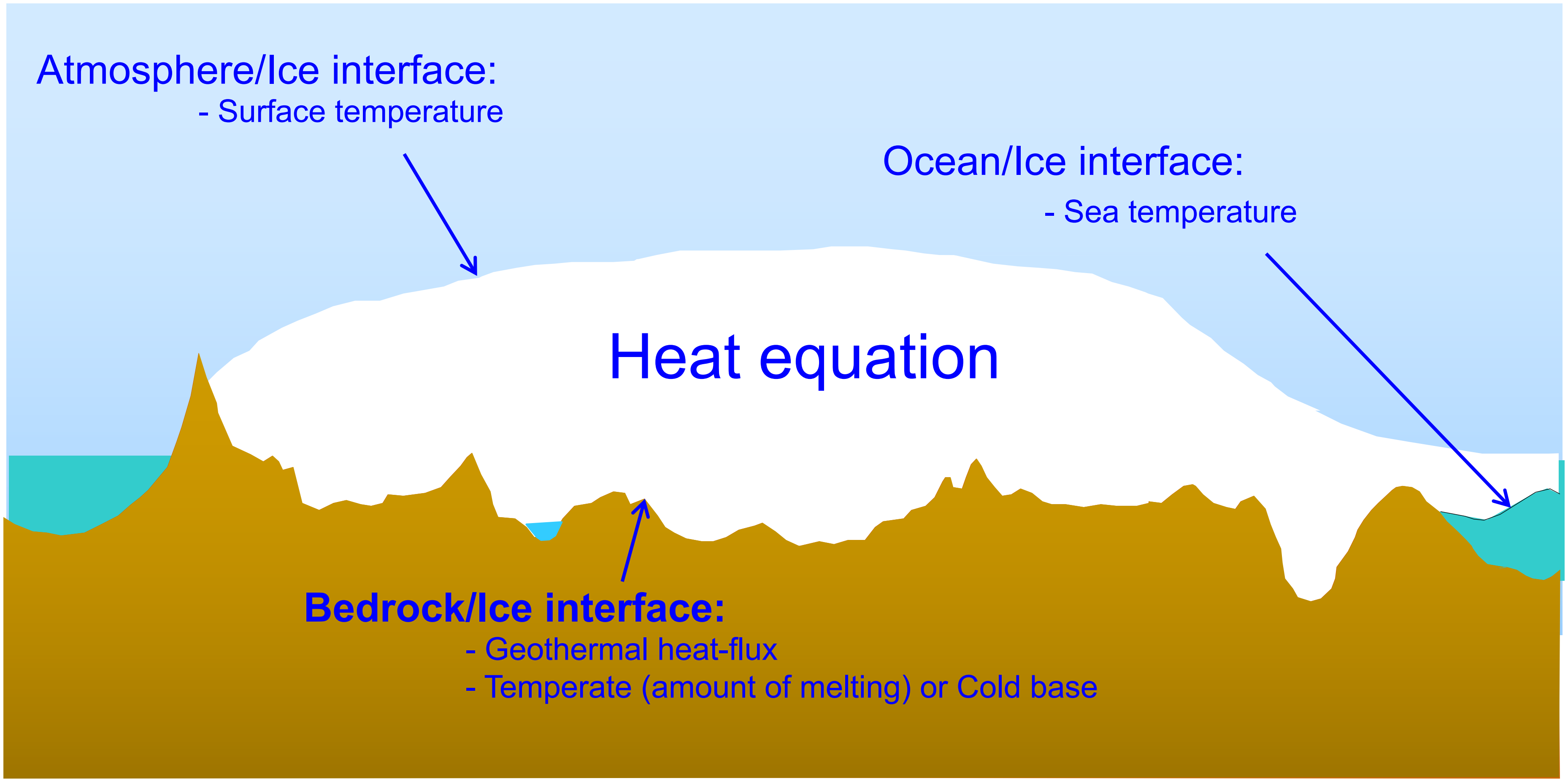


+ other eventual internal variables (density, fabric, damage,…)

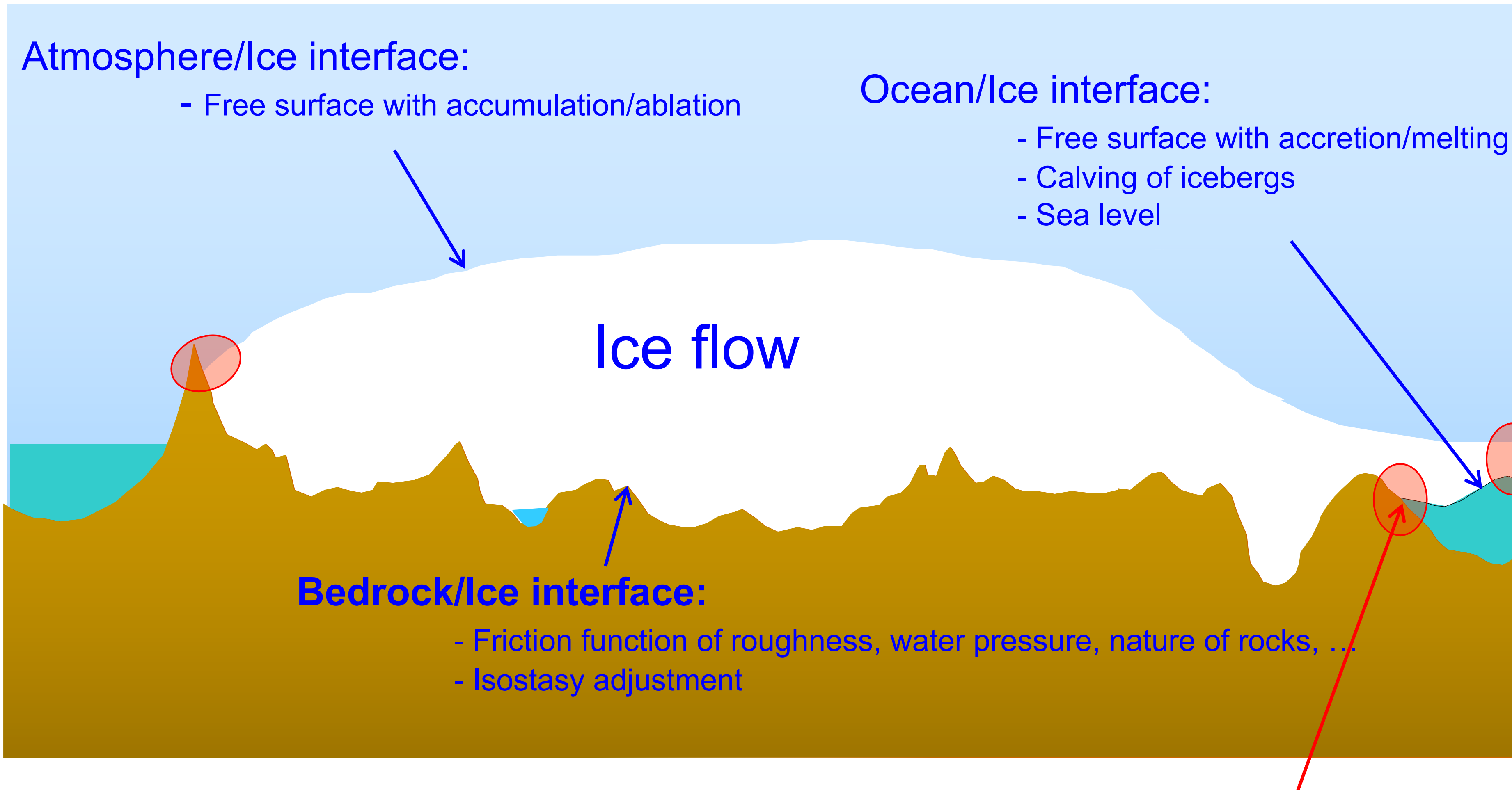
Input

Output

Temperature: complexity of boundary conditions



Ice flow: complexity of boundary conditions



And most boundaries are evolving surfaces (GL, front)

Which equations? Which boundary conditions?