

地球雪氷学基礎論 Introduction to Cryosphere Sciences

氷床物理 Ice Sheet Physics

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Ice sheet physics

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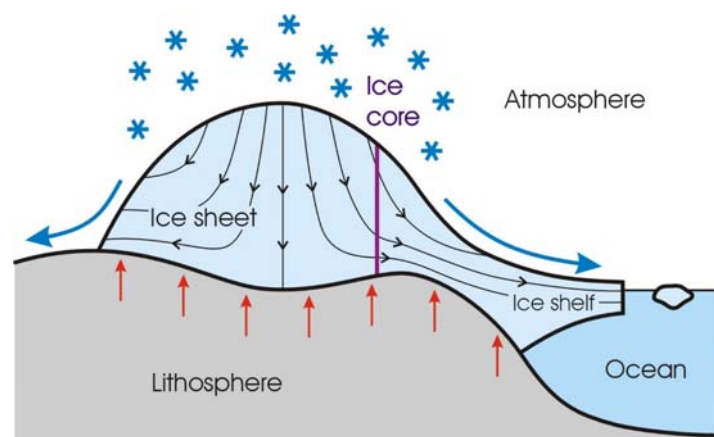
General definitions

Ice sheets

→ grounded ice masses of continental size, area $> 50,000 \text{ km}^2$ (Antarctica, Greenland).

Ice shelves

→ floating ice masses, connected to an ice sheet (Antarctica).



Vertical exaggeration factor ~200...500

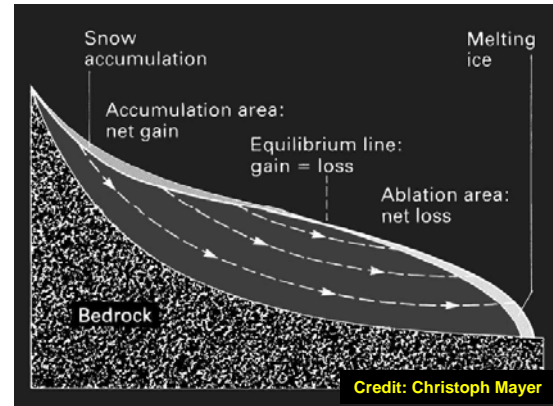
General definitions

Ice caps

→ extended grounded ice masses, area $< 50,000 \text{ km}^2$
(Austfonna, Vatnajökull, North/South Patagonian Icefields...).

Glaciers

→ small grounded ice masses in mountainous regions, constrained by topographical features.

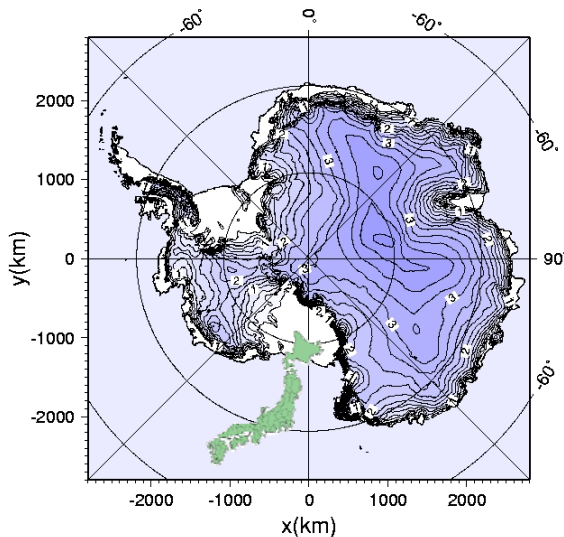


“Glacier” is sometimes also used as an umbrella term for all grounded ice bodies (ice sheets, ice caps and glaciers as defined above). Alternative term: “land ice”.

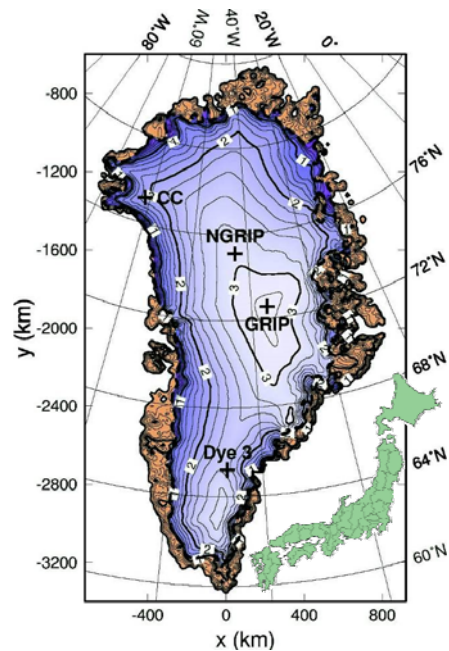
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Ice sheets

Antarctic ice sheet (with ice shelves)



Greenland ice sheet



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Ice inventory

	Glaciers and ice caps	Greenland ice sheet	Antarctic ice sheet
Area (10^6 km ²)	0.73*	1.80	12.3
Volume (metres of sea level equivalent)	0.41*	7.36	58.3
Turnover time (vol/accum, years)	~ 50 – 1000**	~ 5000	~ 12000

Main source: Vaughan et al. (2013) [IPCC AR5 Ch. 4].

(*) Sum for all glaciers and ice caps. (**) Range of values for individual glaciers and ice caps.

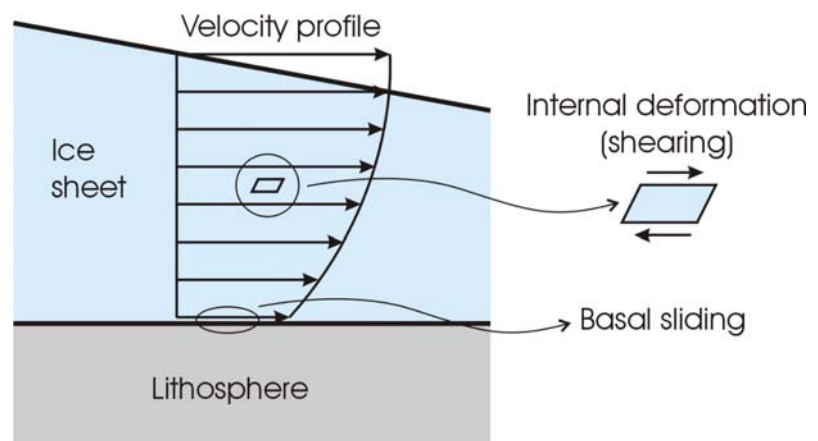
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Why does ice flow?

Two mechanisms

Internal deformation
(ice = viscous fluid).

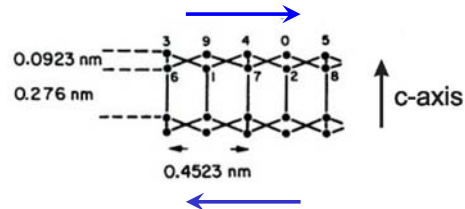
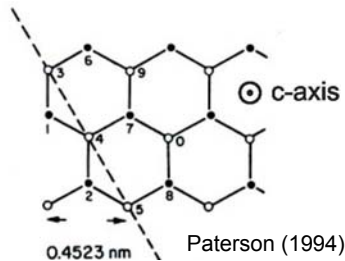
Basal sliding.



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Internal deformation

Structure of the hexagonal ice crystal (“ice Ih”) allows relatively easy gliding of the basal planes.



→ “Deck-of-cards” model

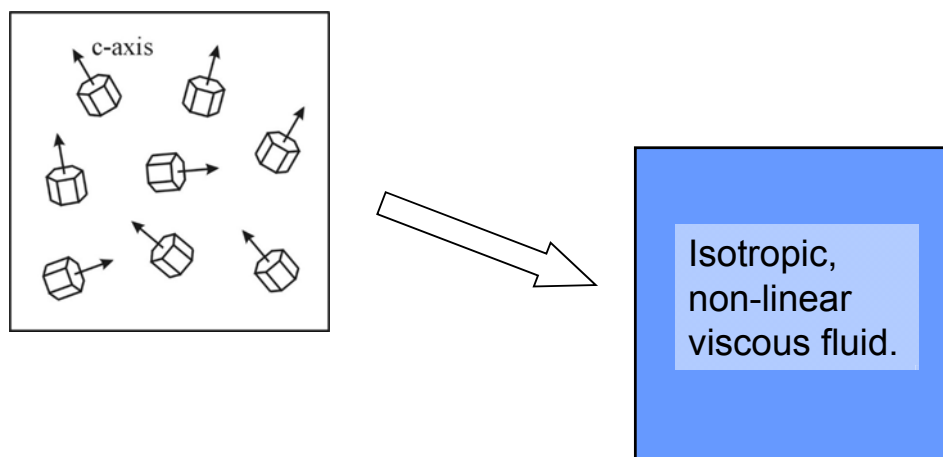


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Internal deformation

Macroscopic description:

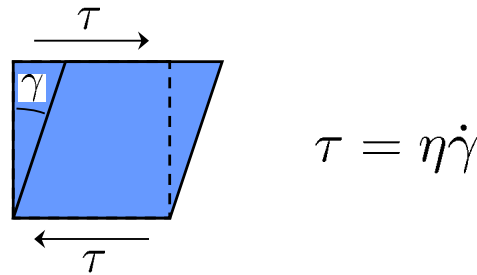
Polycrystalline ice → control volume contains an ensemble of randomly oriented ice crystallites (grains).



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Internal deformation

Simple shear experiment:



Ice fluidity (inverse viscosity):

$$\frac{1}{\eta} = 2EA(T')f(\sigma_e) \quad (\sigma_e = |\tau|, T' = T - T_m)$$

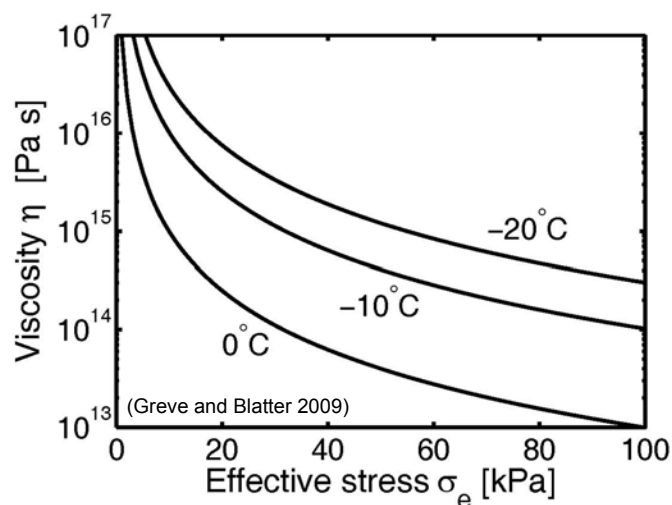
effective stress
temperature relativ to pmp

- Creep function: Power law $f(\sigma_e) = \sigma_e^{n-1}$, exponent $n = 3$ (Glen).
- Rate factor: Arrhenius law $A(T') = A_0 e^{-Q/RT'}$.
- Enhancement factor E (equal to 1 for pure isotropic ice).

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Internal deformation

Viscosity of polycrystalline ice:



For comparison: Oil $\sim 0.1 - 1$ Pa s, Water $\sim 10^{-3}$ Pa s.

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Basal sliding

Two different processes:

sliding on hard rock vs. sliding on deformable sediment.

Difficult to measure, not well understood!

Often “Weertman-type” parameterization is used:

$$v_b \propto \frac{\tau_b^p}{P_b^q}$$

v_b — basal sliding velocity

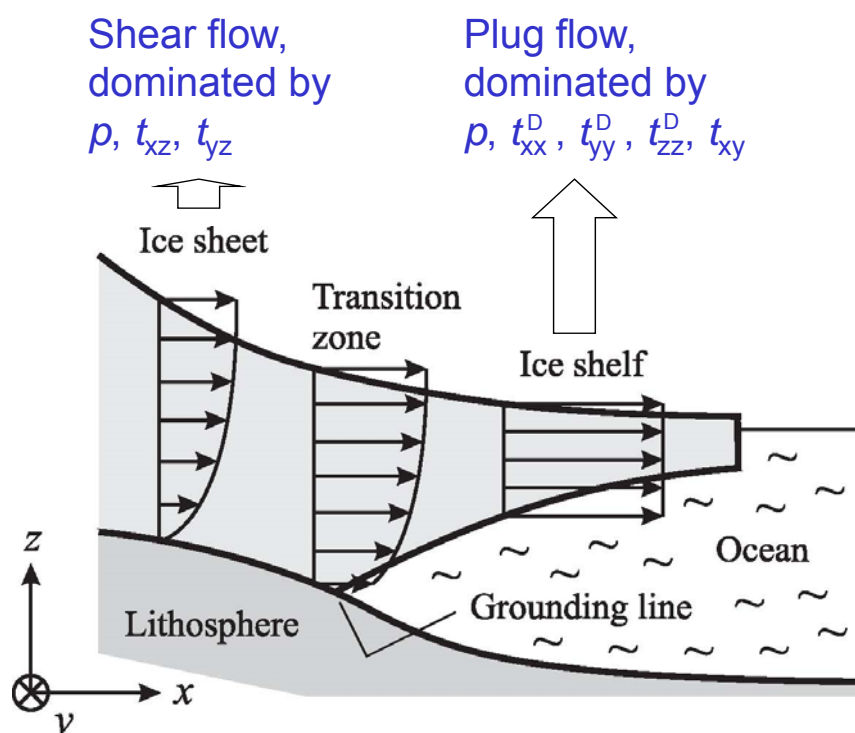
τ_b — basal shear stress

P_b — basal pressure

$$(p, q) = \begin{cases} (3, 0), (3, 1) \text{ or } (3, 2) & \text{for hard rock sliding} \\ (1, 0) & \text{for sediment sliding} \end{cases}$$

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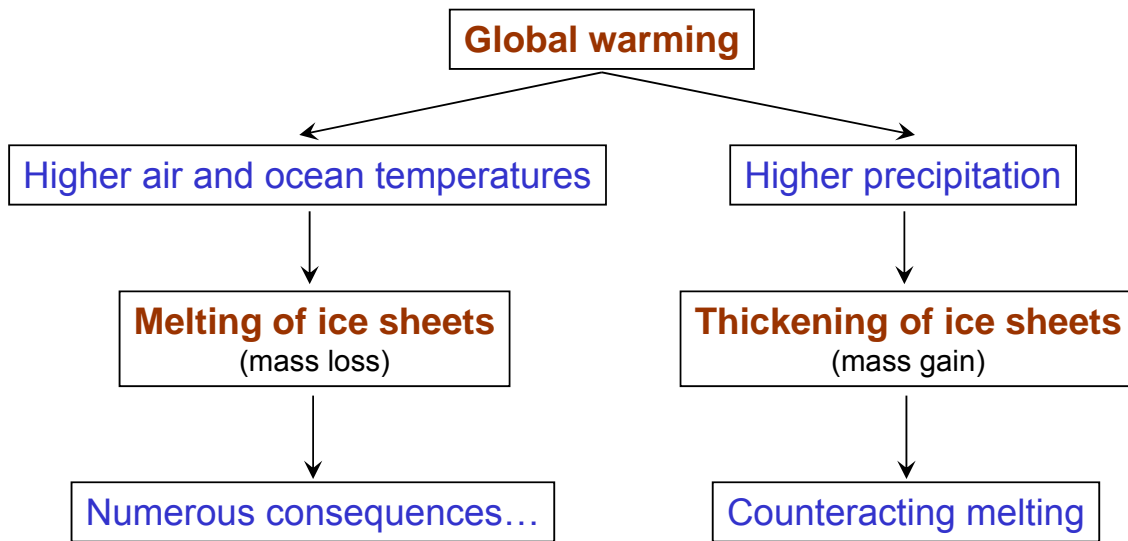
Grounded vs. floating ice



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Response mechanisms to global warming

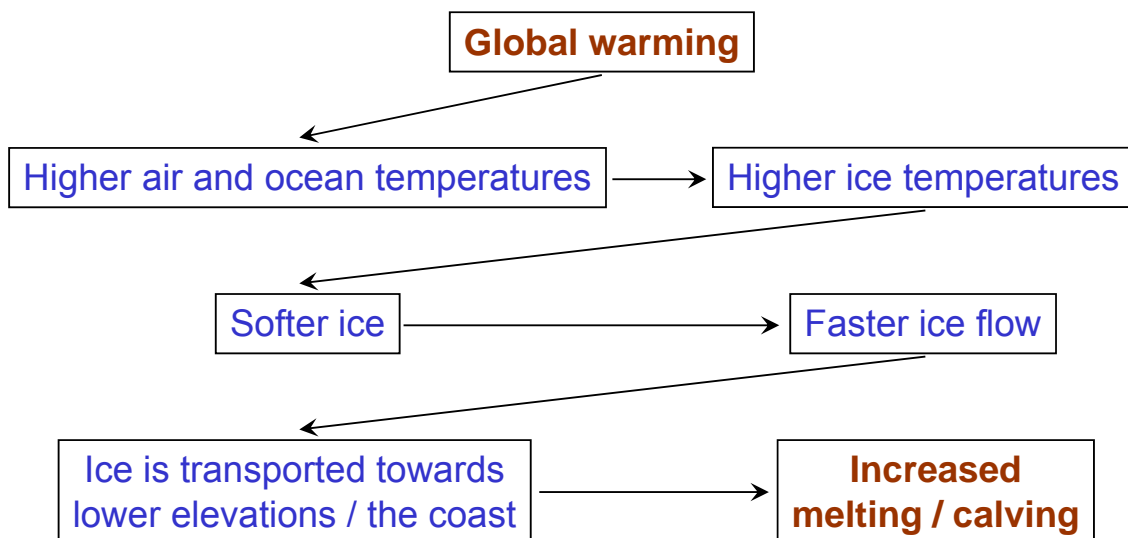
Static response by mass balance



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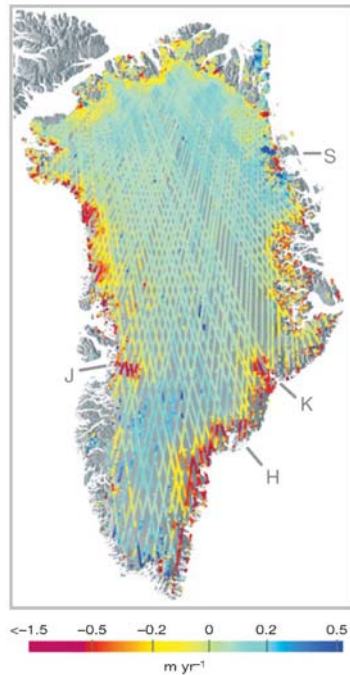
Response mechanisms to global warming

Dynamic response by ice flow



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Recent changes of the Greenland ice sheet



Interior ice sheet:
on average in balance, some regions of
local thickening or thinning.

Marginal areas: thinning predominant.

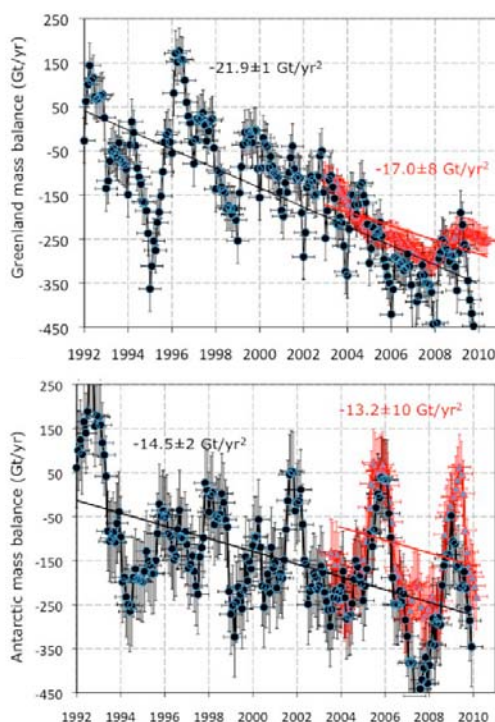
Static (due to melting) and dynamic (due
to flow acceleration) contributions.

Source: Pritchard et al. (2009)

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Recent ice sheet changes (Greenland, Antarctica)

(by Rignot and others 2011)



Greenland ice sheet: ~ 60%.

Antarctic ice sheet: ~ 40%.

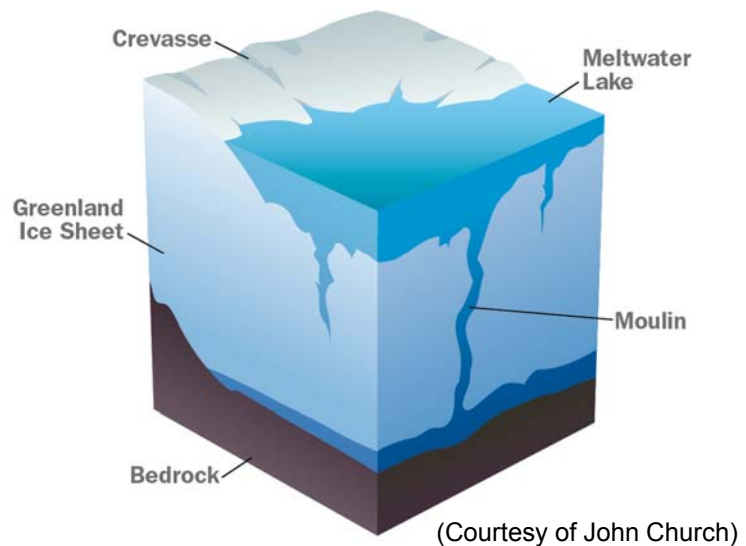
Rate of mass loss is increasing.

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Future ice sheet changes

Ice-dynamic processes may lead to accelerated decay of both Greenland and Antarctica

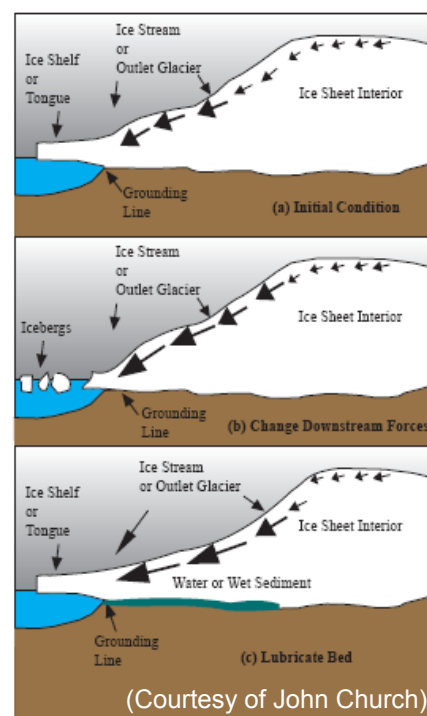
Basal sliding accelerated by surface meltwater
(Greenland ice sheet)



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Future ice sheet changes

Loss of ice shelves
Penetration of ocean water under the ice
(Antarctic ice sheet, ice streams and outlet glaciers in Greenland)



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SeaRISE

= **Sea-level Response to Ice Sheet Evolution**

International multi-ice-sheet model community effort.

Objective:

To predict the likely range of contributions of the Greenland and Antarctic ice sheets to sea level rise over the next 100's of years under global warming conditions.

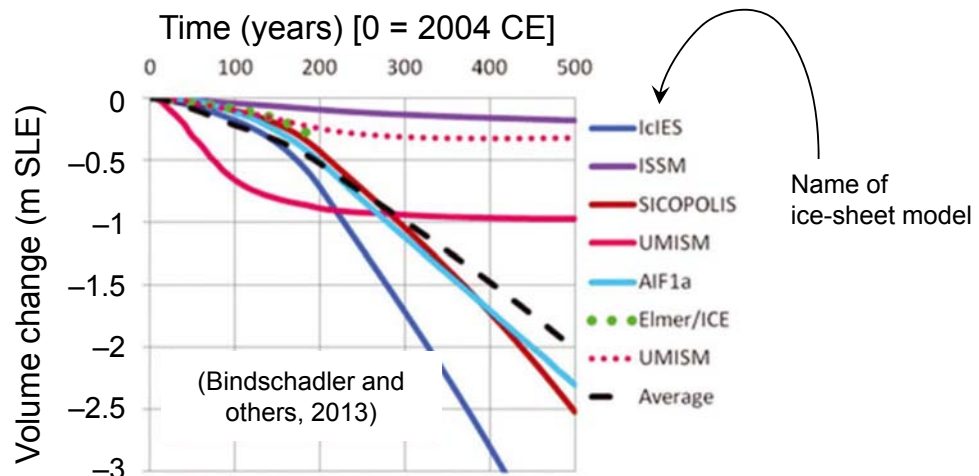


Input for the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013)



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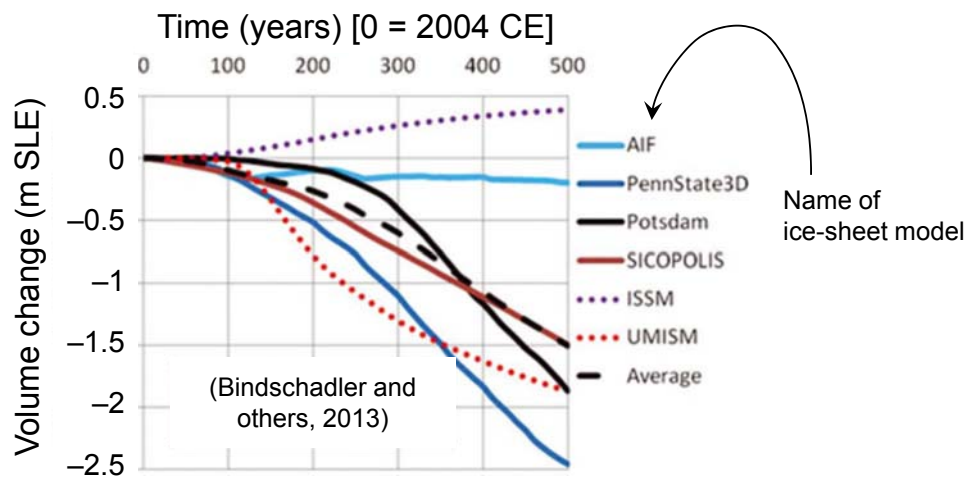
SeaRISE exp. R8 (~ IPCC's RCP8.5 scenario) for Greenland



Average loss after 100 a: 0.22 m SLE
 200 a: 0.53 m SLE
 500 a: 2.02 m SLE

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SeaRISE exp. R8 (~ IPCC's RCP8.5 scenario) for Antarctica



Average loss after 100 a: 0.08 m SLE
 200 a: 0.27 m SLE
 500 a: 1.51 m SLE

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