# 地球雪氷学基礎論
# Introduction to Cryosphere Sciences

## 氷床物理
## Ice Sheet Physics

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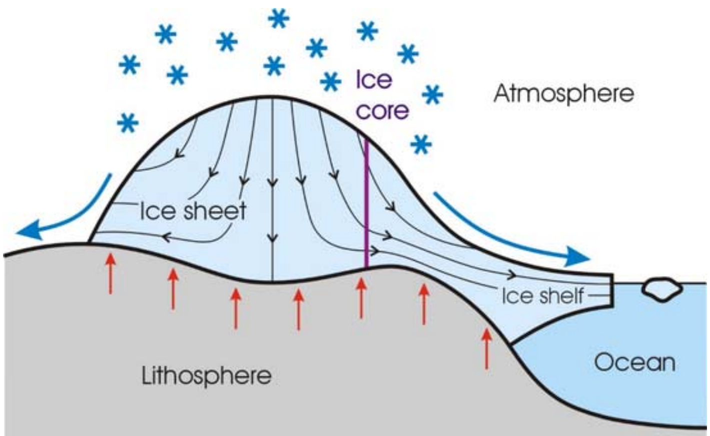
## General definitions

*Ice sheets*

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

*Ice shelves*

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




Vertical exaggeration factor ~200…500

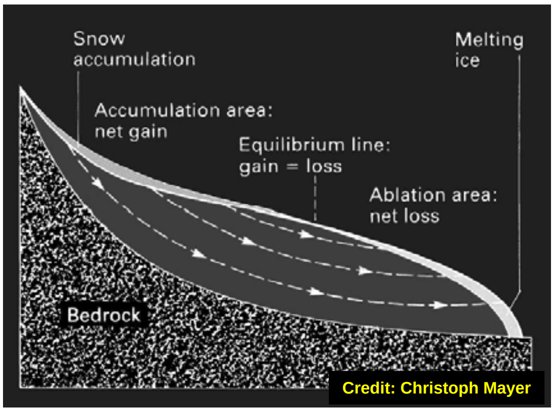
# General definitions

*Ice caps*

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

*Glaciers*

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



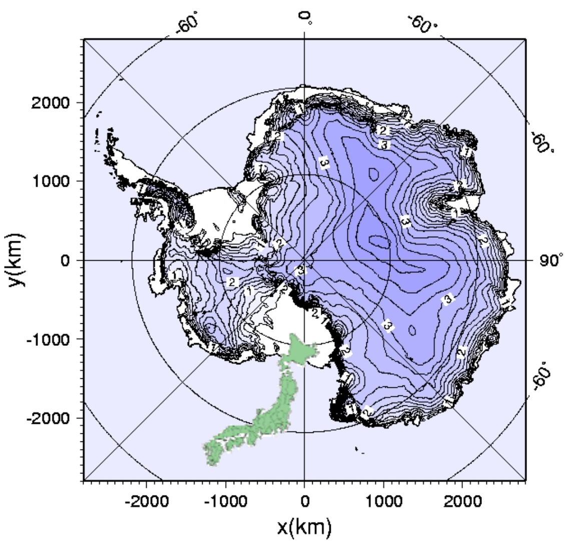

"Glacier" is sometimes also used as an umbrella term for all grounded ice bodies (ice sheets, ice caps and glaciers as defined above). Alternative term: "land ice".



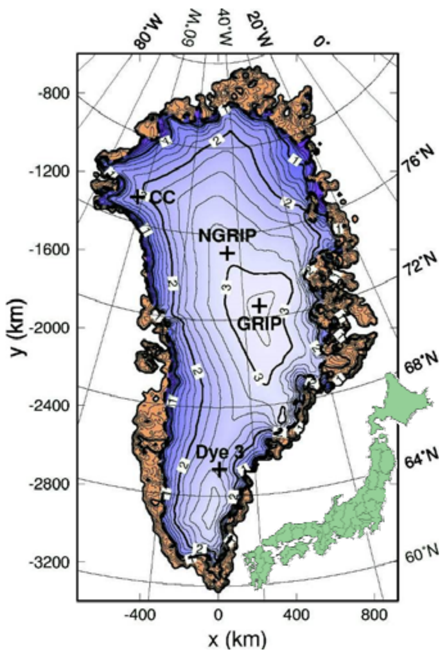


# Ice sheets

Antarctic ice sheet (with ice shelves)




Greenland ice sheet



# 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.



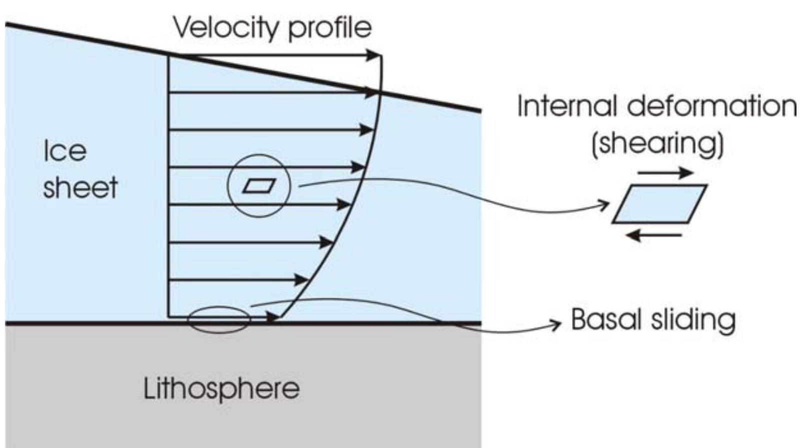


# Why does ice flow?

## Two mechanisms

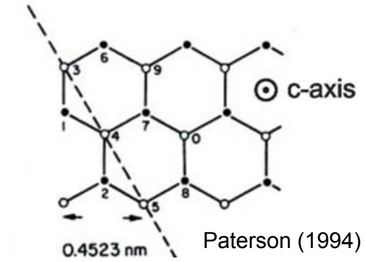
Internal deformation (ice = viscous fluid).

Basal sliding.

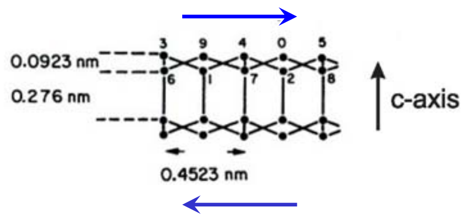


# Internal deformation

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



Paterson (1994)




→ "Deck-of-cards" model

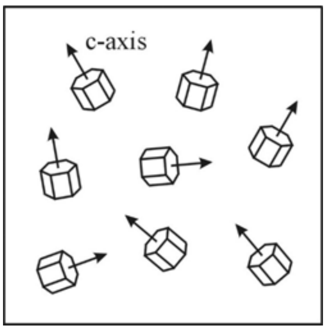




# Internal deformation

Macroscopic description:

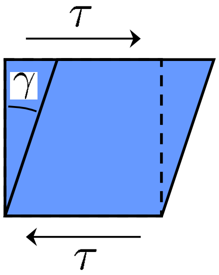
Polycrystalline ice → control volume contains an ensemble of randomly oriented ice crystallites (grains).




Isotropic, non-linear viscous fluid.

# Internal deformation

## Simple shear experiment:




$$\tau = \eta \dot{\gamma}$$

Ice fluidity (inverse viscosity):

effective stress
temperature relativ to pmp

$$\frac{1}{\eta} = 2EA(T')f(\sigma_\mathrm{e}) \qquad (\,\sigma_\mathrm{e} = |\tau|,\;\; T' = T - T_\mathrm{m}\,)$$

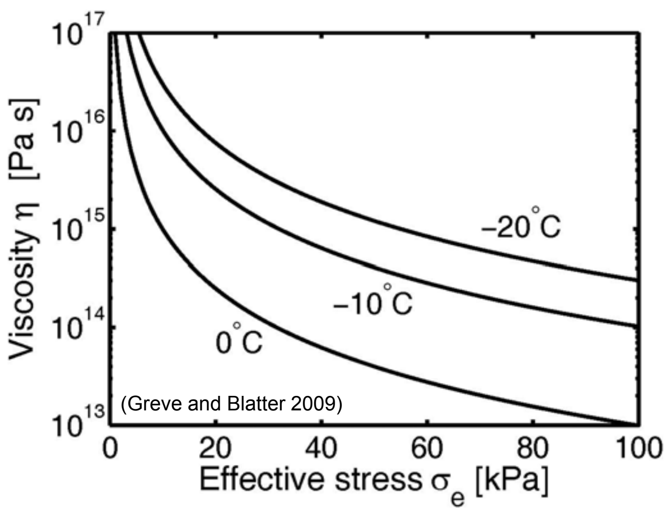
- Creep function: Power law $f(\sigma_e) = \sigma_e^{n-1}$, exponent $n$ = 3 (Glen).
- Rate factor: Arrhenius law $A(T') = A_0\,e^{-Q/RT'}$.
- Enhancement factor *E* (equal to 1 for pure isotropic ice).





# Internal deformation

## Viscosity of polycrystalline ice:




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

## 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:

$$v_\mathrm{b} \propto \frac{\tau_\mathrm{b}^p}{P_\mathrm{b}^q}$$

$v_\mathrm{b}$ – basal sliding velocity
$\tau_\mathrm{b}$ – basal shear stress
$P_\mathrm{b}$ – basal pressure

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

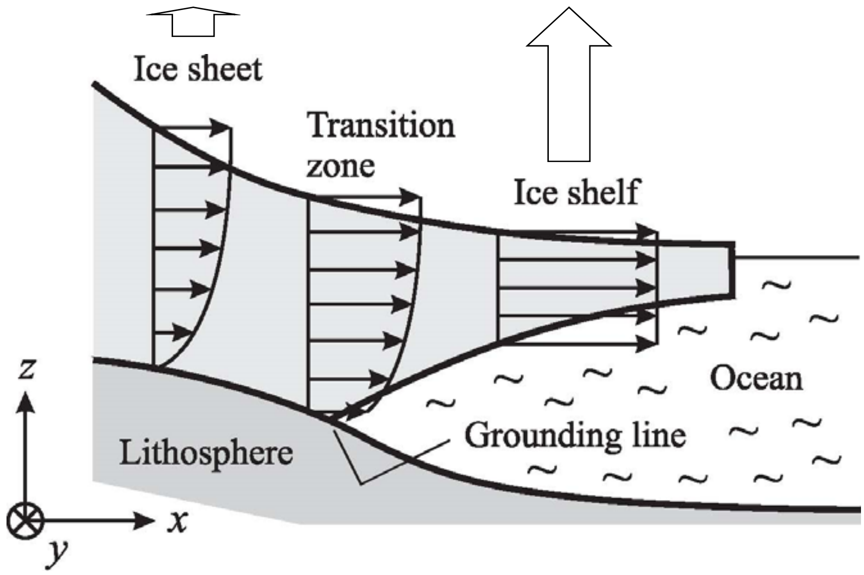




## Grounded vs. floating ice

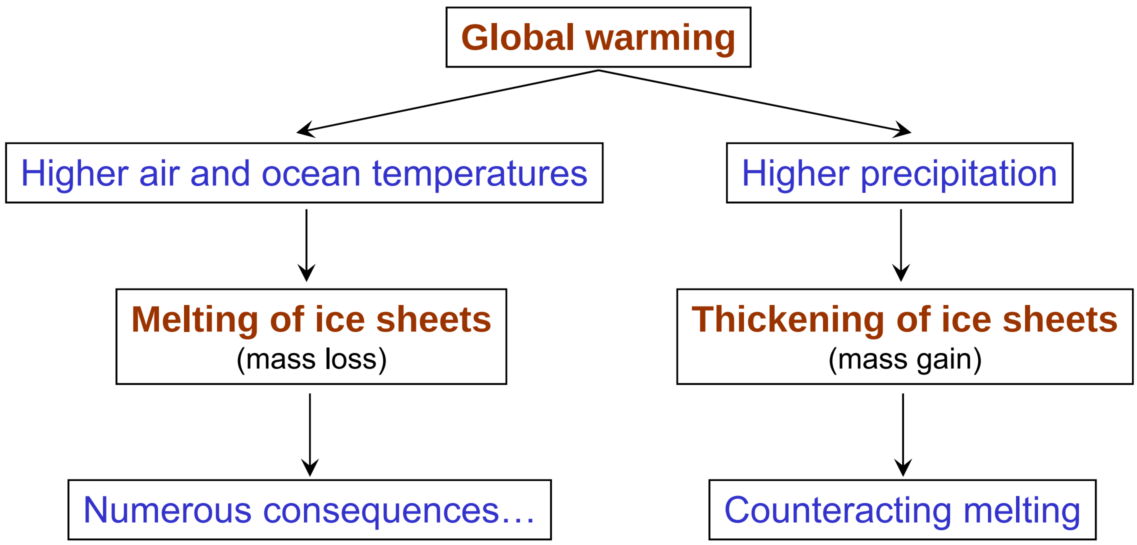
Shear flow,
dominated by
$p$, $t_{xz}$, $t_{yz}$

Plug flow,
dominated by
$p$, $t^\mathrm{D}_{xx}$ , $t^\mathrm{D}_{yy}$ , $t^\mathrm{D}_{zz}$, $t_{xy}$



# Response mechanisms to global warming

## Static response by mass balance

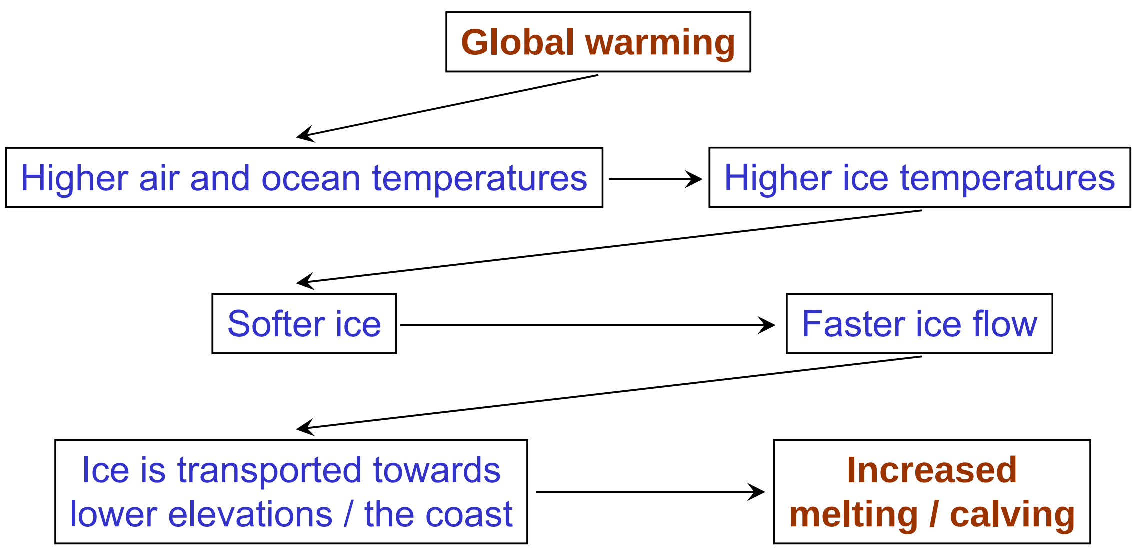




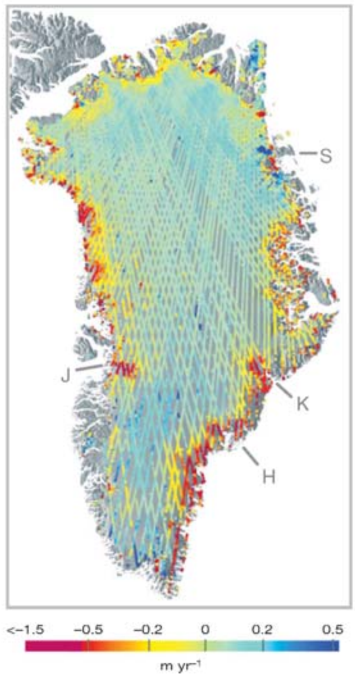



# Response mechanisms to global warming

## Dynamic response by ice flow



# 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.

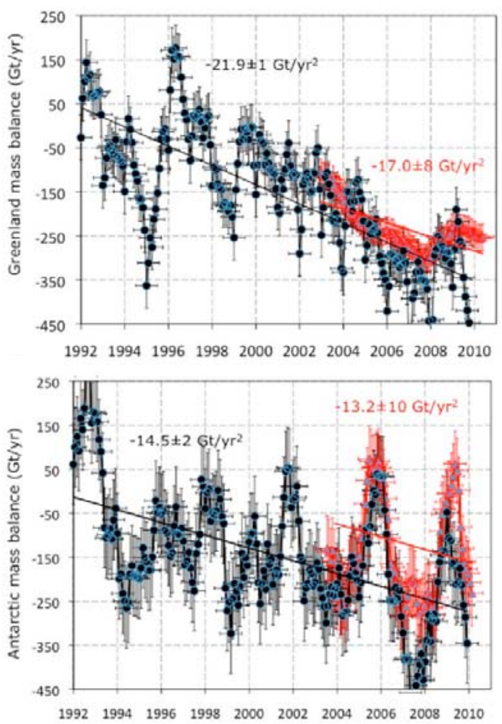
Source: Pritchard et al. (2009)





# Recent ice sheet changes (Greenland, Antarctica)

(by Rignot and others 2011)




Greenland ice sheet: ~ 60%.

Antarctic ice sheet: ~ 40%.

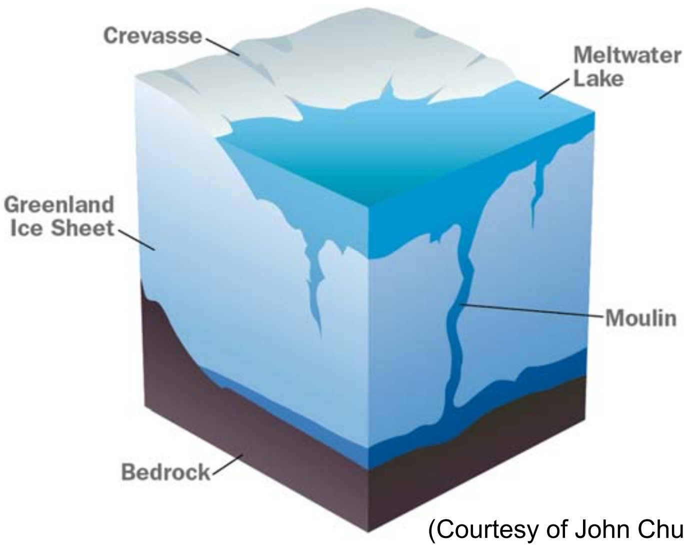
Rate of mass loss is increasing.

# 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)




(Courtesy of John Church)



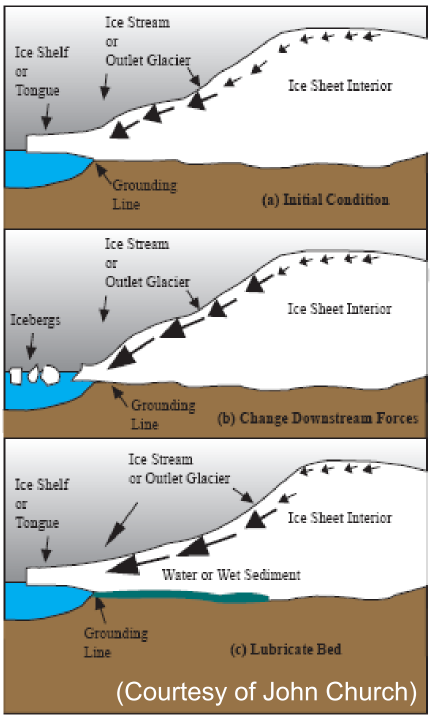


# Future ice sheet changes

Loss of ice shelves

Penetration of ocean water under the ice

(Antarctic ice sheet,
ice streams and outlet glaciers in Greenland)



# SeaRISE

= **Sea**-level **R**esponse to **I**ce **S**heet **E**volution

International multi-ice-sheet model community effort.

**Objective:**

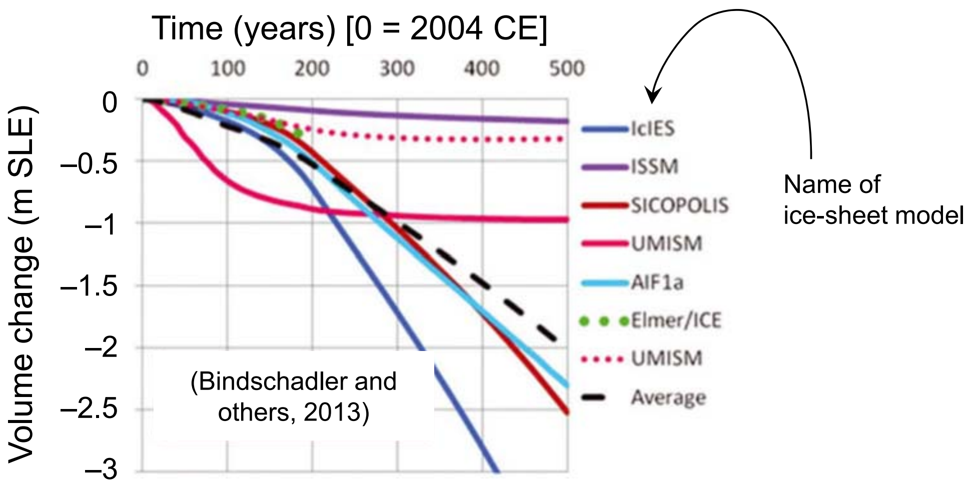
To predict the likely range of contributions of the Greenland and Antarctic ice sheets to sea level rise over the next 100's of years under global warming conditions.

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



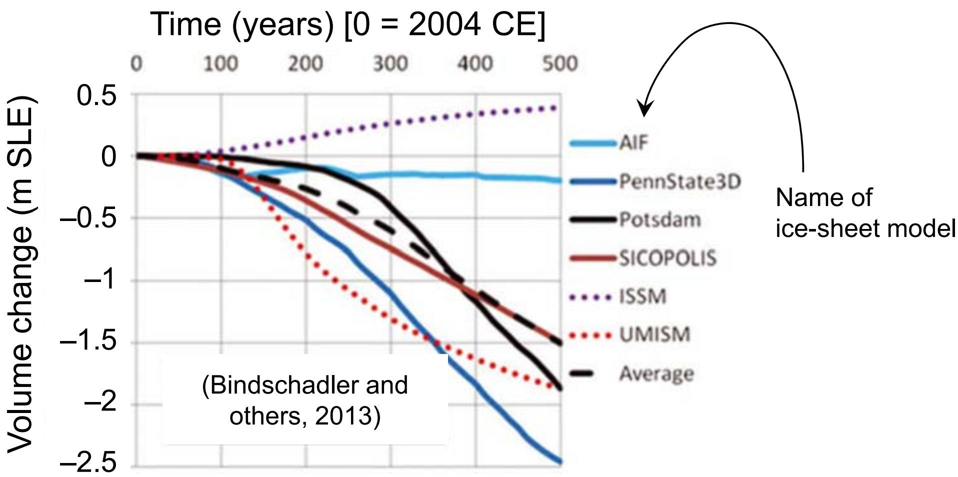



# SeaRISE exp. R8 (~ IPCC's RCP8.5 scenario) for Greenland




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

# 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





# References


- Bamber, J. L., and A. J. Payne (Eds.) 2004. *Mass Balance of the Cryosphere: Observations and Modelling of Contemporary and Future Changes.* Cambridge University Press, Cambridge, UK, and New York, NY, USA.
- Bindschadler, R. A. and 27 others. Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project). *J. Glaciol.* **59** (214), 195-224.
- Cuffey, K. M. and W. S. B. Paterson. 2010. *The Physics of Glaciers.* Elsevier, Amsterdam, The Netherlands etc., 4th edition.
- Greve, R. and H. Blatter. 2009. *Dynamics of Ice Sheets and Glaciers.* Springer, Berlin, Germany etc.
- Hooke, R. LeB. 2005. *Principles of Glacier Mechanics.* Cambridge University Press, Cambridge, UK and New York, NY, USA, 2nd edition.
- Paterson, W. S. B. 1994. *The Physics of Glaciers.* Pergamon Press, Oxford etc., 3rd edition.
- Pritchard, H. D., R. J. Arthern, D. G. Vaughan and L. A. Edwards. 2009. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. *Nature* **461** (7266), 971-975.
- Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan and J. Lenaerts. 2011. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.* **38**, L05503.
- Van der Veen, C. J. 2013. *Fundamentals of Glacier Dynamics.* CRC Press, Boca Raton, FL, USA etc., 2nd edition.
- Vaughan, D. G. and 13 others. Observations: Cryosphere. In: T. F. Stocker and 9 others (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 317-382. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

- Japanese vocabulary glaciology, <http://en.wikibooks.org/wiki/Japanese/Vocabulary/Glaciology>.