



# HOKKAIDO UNIVERSITY

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# Cooperation between the Nordic countries and Japan in advanced ice sheet and glacier modelling



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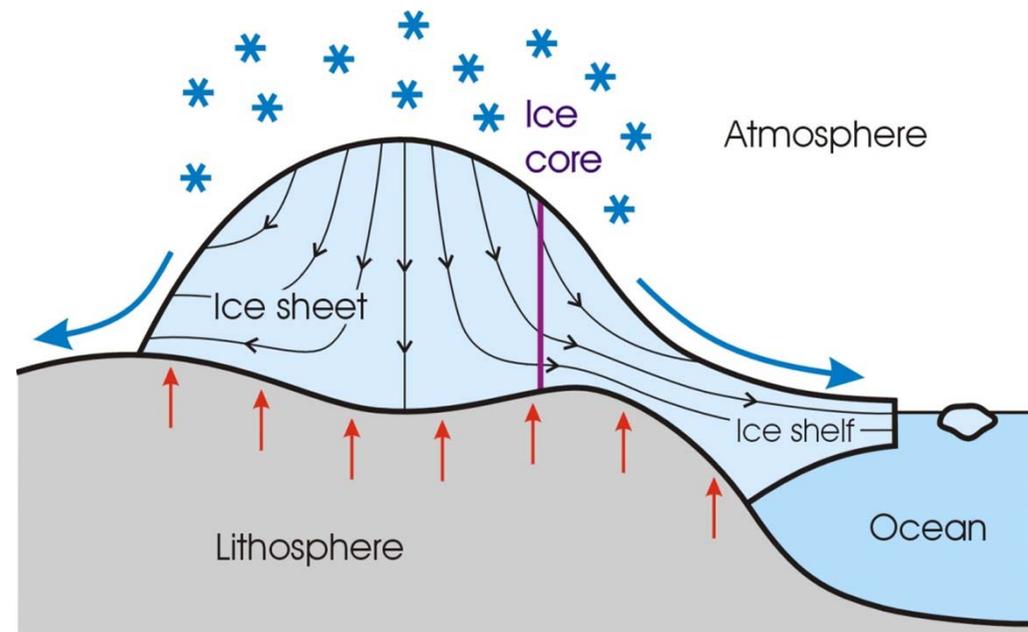
1 ILTS, Hokkaido University, Sapporo, Japan  
2 CSC – IT Center for Science, Espoo, Finland



# Land ice on Earth

## General definitions

- *(Inland-) 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).



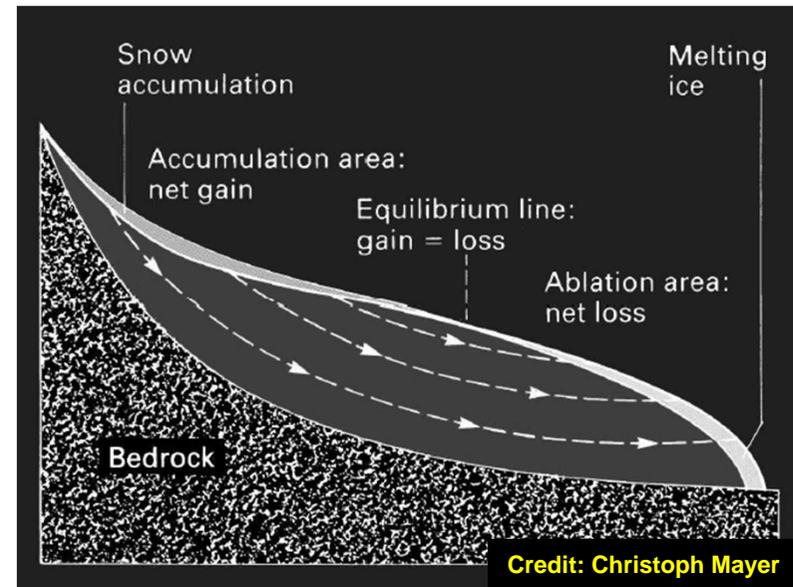
## Land ice on Earth

- *Ice caps*

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

- *Glaciers*

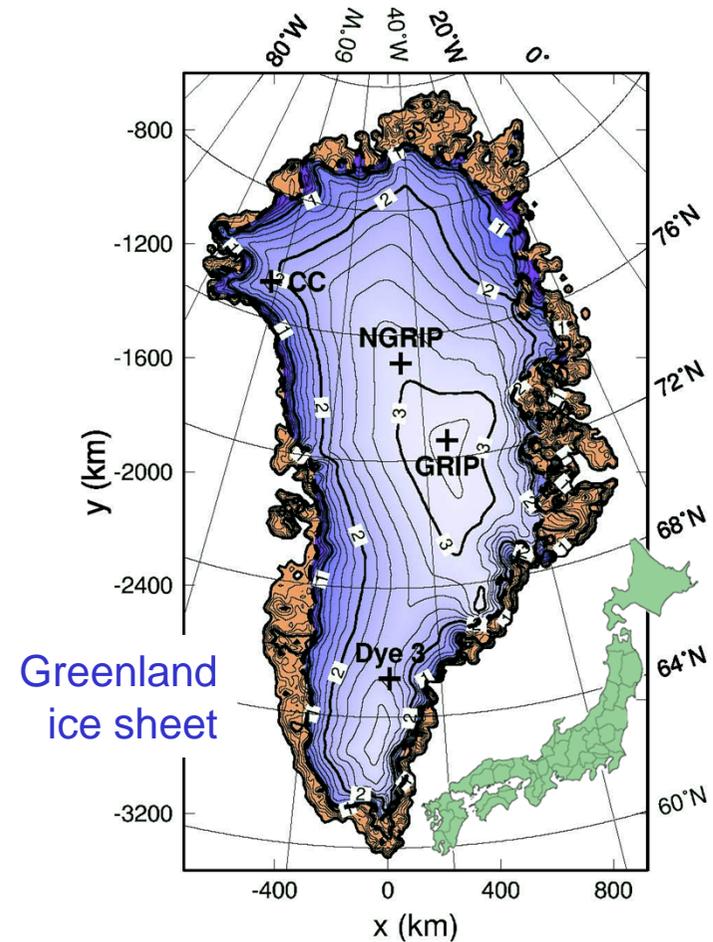
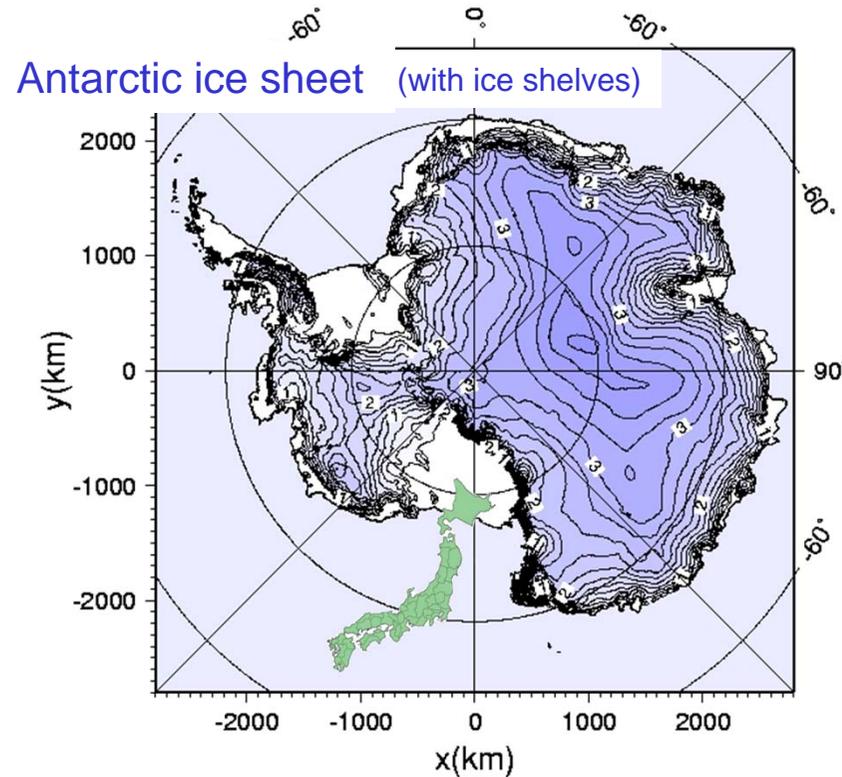
→ small grounded ice masses in mountainous regions, constrained by topographical features.



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

# Land ice on Earth

## Ice sheets



# Land ice on Earth

## Glaciers and ice caps



- Can be found on every continent (polar/subpolar areas, mountains).
- Number: > 160,000 (~ 70 ice caps).
- Many different types:  
Valley glaciers, cirque glaciers, hanging glaciers, tidewater glaciers, rock glaciers...



Photo credit: [www.glaciers-online.net](http://www.glaciers-online.net)

# Land ice on Earth

## Inventory

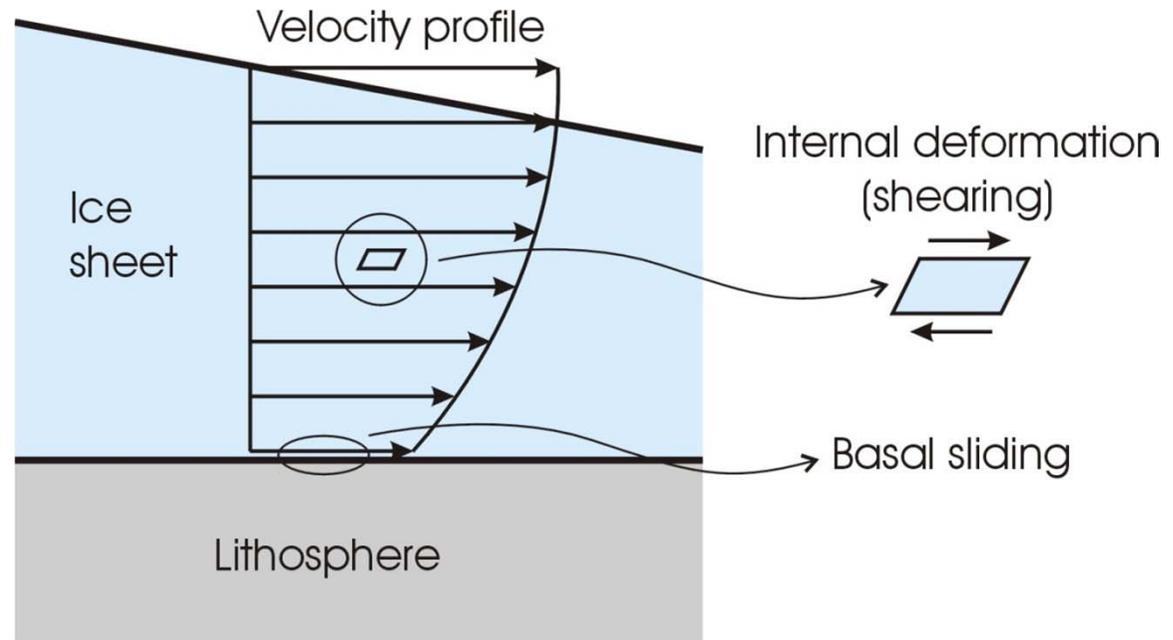
	Glaciers and ice caps	Greenland ice sheet	Antarctic ice sheet (+ shelves)
Area ( $10^6$ km <sup>2</sup> )	0.51 - 0.54	1.7	12.3 (+ 1.5)
Volume ( $10^6$ km <sup>3</sup> )	0.05 - 0.13	2.9	24.7 (+ 0.7)
Sea level equivalent (m)	0.15 - 0.37	7.3	56.6 (+ 0)
Sea level rise 1993 - 2003 (mm/a)	$0.77 \pm 0.22$	$0.21 \pm 0.07$	$0.21 \pm 0.35$

Sources: Lemke et al. (2007) [IPCC AR4 Ch. 4], Bindoff et al. (2007) [IPCC AR4 Ch. 5].

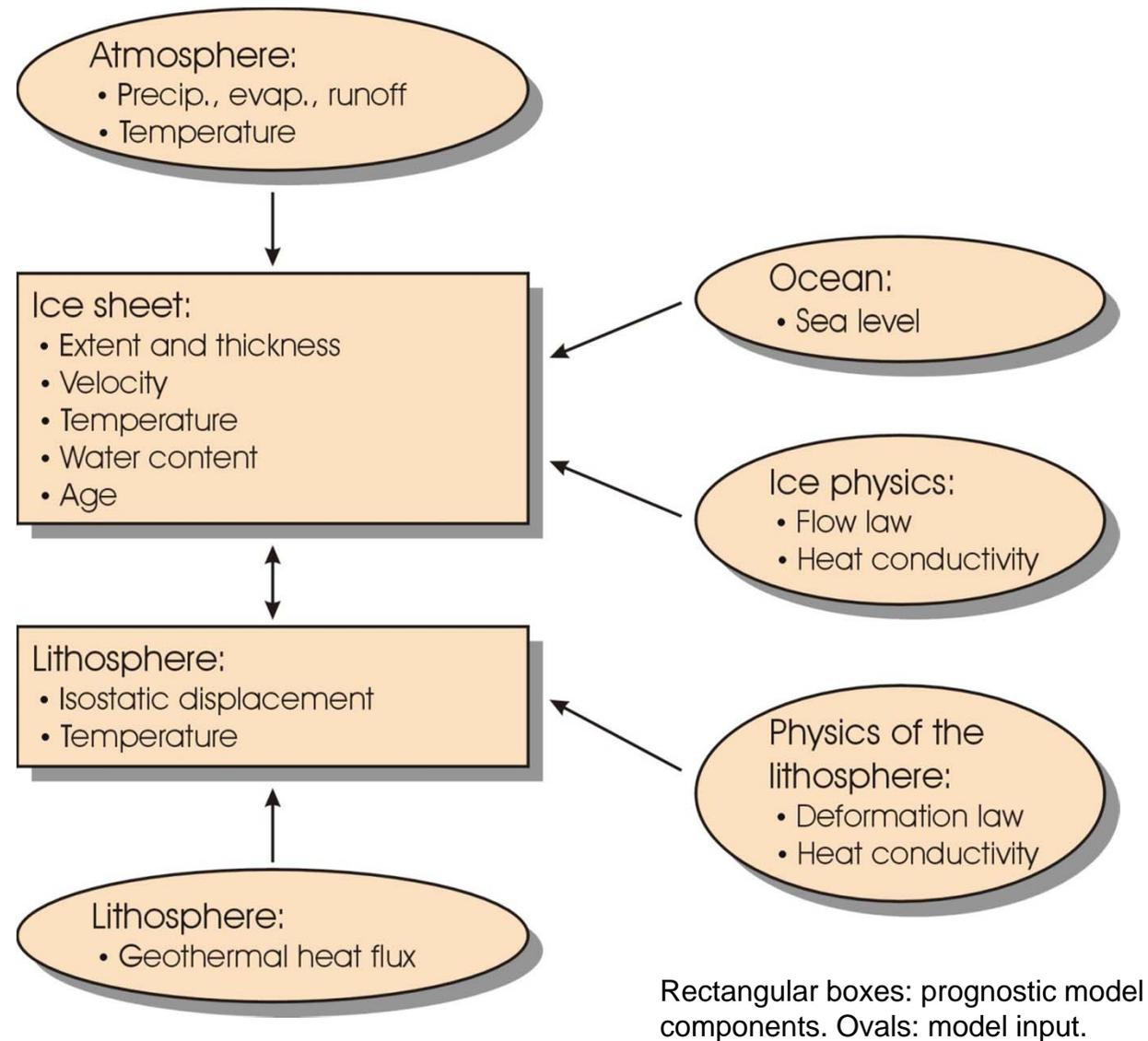
## Why does ice flow?

### Two mechanisms

- Internal deformation (ice = viscous fluid).
- Basal sliding.



# Ice sheet modelling



## Ice sheet and glacier model Elmer/Ice

- FEM model, based on CSC's open-source multi-physical simulation software **Elmer**.



[www.csc.fi/elmer](http://www.csc.fi/elmer)

[www.elmerfem.org/wiki/index.php/Elmer\\_Ice\\_Sheet\\_modeling](http://www.elmerfem.org/wiki/index.php/Elmer_Ice_Sheet_modeling)

- Solves the full Stokes flow problem (no stresses neglected).
- Applied to the Greenland ice sheet, the Dome Fuji region in Antarctica, the Gorshkov crater glacier etc.

# Ice sheet model SICOPOLIS

```

...
kc=KRWAX
kc=0
lgs_e0(kc) = -(ccb1+ccb2)
lgs_e1(kc) = ccb1
lgs_e2(kc) = ccb3+ccb4
lgs_b(kc) = ccb3+ccb4

do kc=1, KRWAX-1
  lgs_e0(KRWAX+kc) = -0.5d0*(ct1(kc)-ct2(kc)-ct3(kc)-ct4(kc)) &
    -ct5(kc)+ct6(kc)
  lgs_e1(KRWAX+kc) = 1.0d0*(ct1(kc)+ct6(kc-1))
  lgs_e2(KRWAX+kc) = 0.5d0*(ct1(kc)-ct2(kc)-ct3(kc)-ct4(kc)) &
    -ct5(kc)+ct6(kc)

  #if ADV_HOB==1
    lgs_b(KRWAX+kc) = temp_c(kc,j,i) + ct7(kc) &
      -dt_t2dxt1 * &
      ( vx_c(kc,j,i)-abs(vx_c(kc,j,i)) ) &
      *(temp_c(kc,j,i+1)-temp_c(kc,j,i)) &
      +insq_g11_sgx(j,i) &
      +vx_c(kc,j,i-1)+abs(vx_c(kc,j,i-1)) &
      *(temp_c(kc,j,i)-temp_c(kc,j,i-1)) &
      +insq_g11_sgx(j,i-1) &
      -dt_t2deta * &
      ( vy_c(kc,j,i)-abs(vy_c(kc,j,i)) ) &
      *(temp_c(kc,j+1,i)-temp_c(kc,j,i)) &
      +insq_g22_sgy(j,i) &
      +vy_c(kc,j-1,i)+abs(vy_c(kc,j-1,i)) &
      *(temp_c(kc,j,i)-temp_c(kc,j-1,i)) &
      +insq_g22_sgy(j-1,i) &
      -dt_t2deta * &
      ( fty_c_r(kc)-fty_c_l(kc) ) &
      -dt_t2deta * ( fty_c_r(kc)-fty_c_l(kc) )

  #endif
  #endif ADV_HOB==2
  lgs_b(KRWAX+kc) = temp_c(kc,j,i) + ct7(kc) &
    -dt_t2dxt1 * ( fty_c_r(kc)-fty_c_l(kc) ) &
    -dt_t2deta * ( fty_c_r(kc)-fty_c_l(kc) )

  #endif
end do
kc=KRWAX
lgs_e0(KRWAX+kc) = 0.0d0
lgs_e1(KRWAX+kc) = 1.0d0
lgs_b(KRWAX+kc) = temp_s(j,i)
...

```

“Simulation  
Code  
for  
POLythermal  
Ice  
Sheets”

- Open-source model, mainly developed at ILTS ([sicopolis.greveweb.net](http://sicopolis.greveweb.net)).
- Shallow ice + shallow shelf approximations.
- Finite difference method.

## Application of Elmer/Ice and SICOPOLIS to the Greenland ice sheet

### Collaborators:

Hakime Seddik (ILTS),

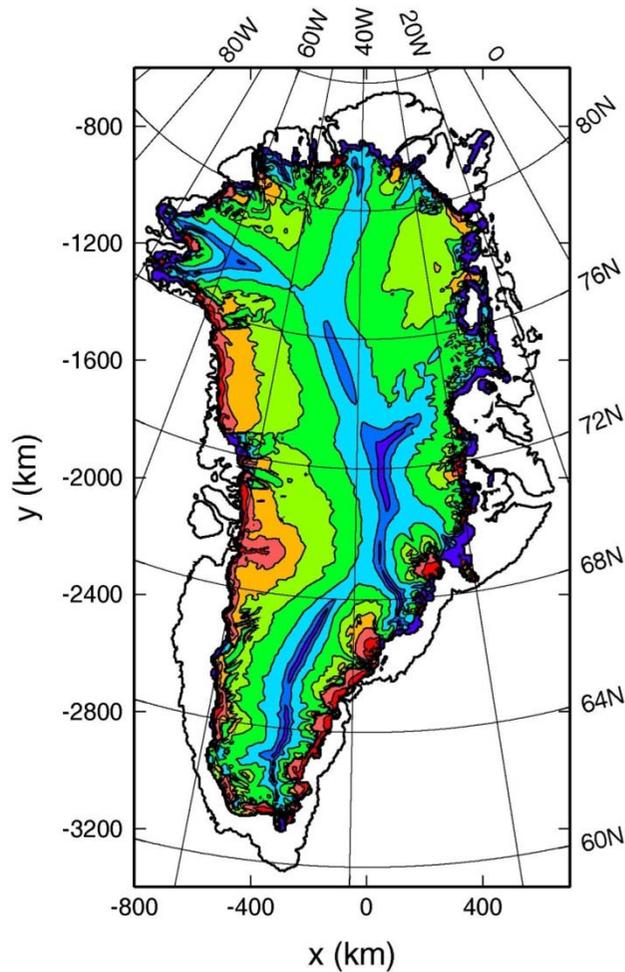
Fabien Gillet-Chaulet, Olivier Gagliardini (LGGE Grenoble).

### Objective:

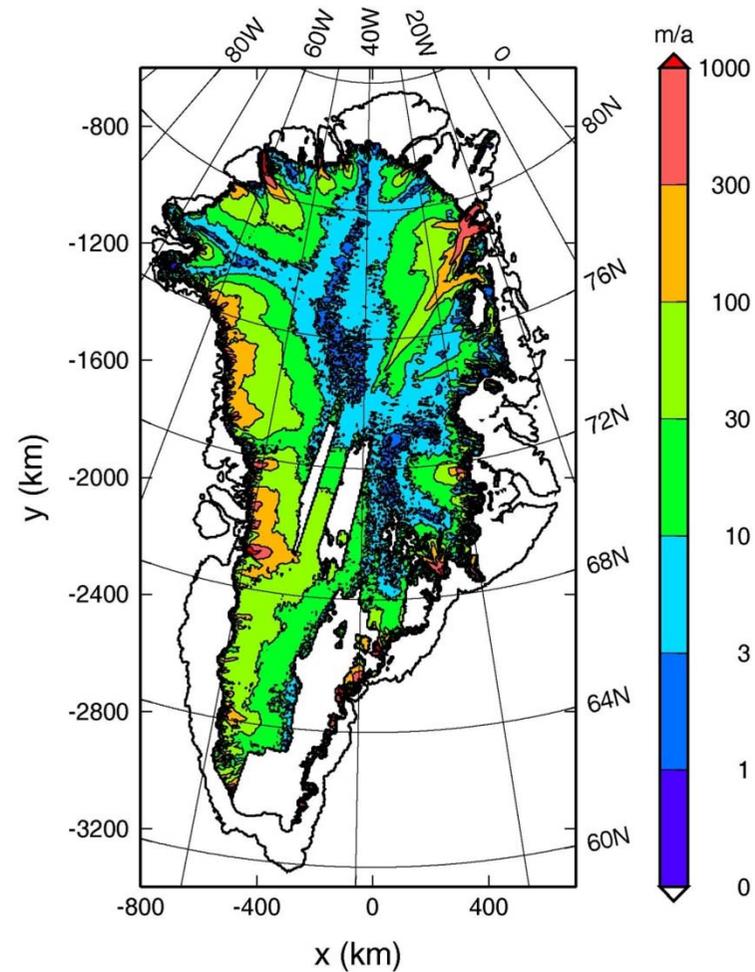
To predict the likely range of the contribution of the Greenland ice sheet to sea level rise over the next 100's of years under global warming conditions (within the SeaRISE community effort).

# Spin-up with SICOPOLIS → present-day conditions

Surface velocity

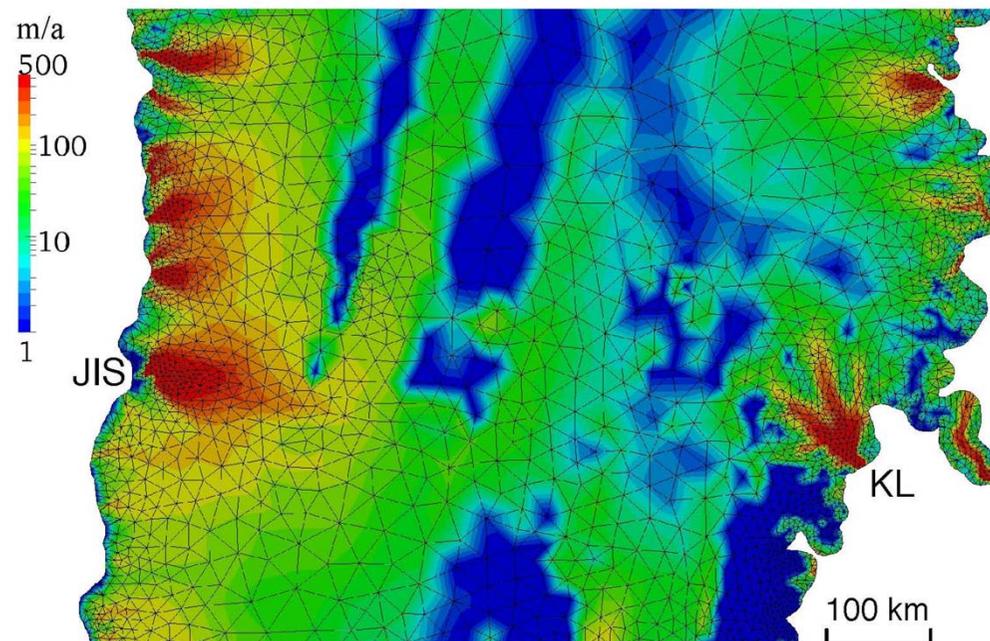


Obs. (Joughin et al.,  
SeaRISE website)



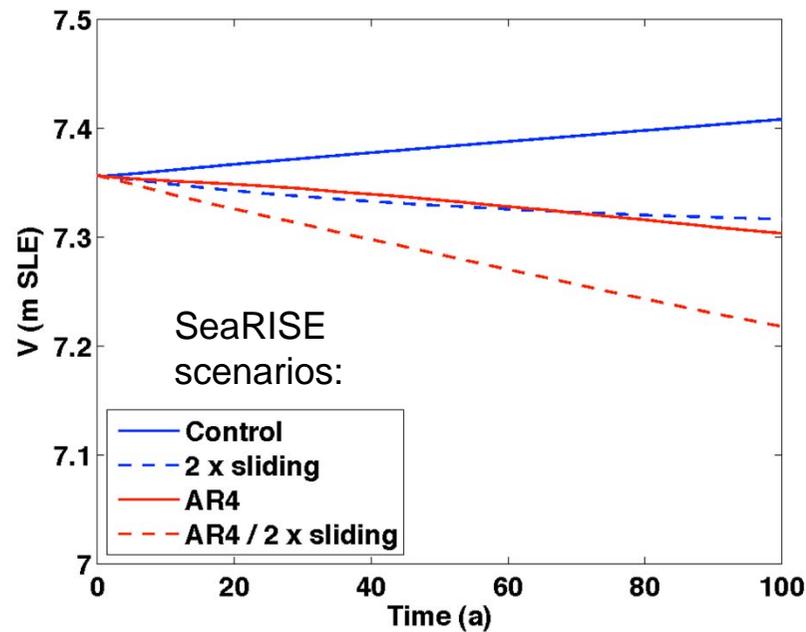
## Future climate change simulations with Elmer/Ice and SICOPOLIS

Variable mesh size of Elmer/Ice captures fast-flowing ice streams and outlet glaciers very well:

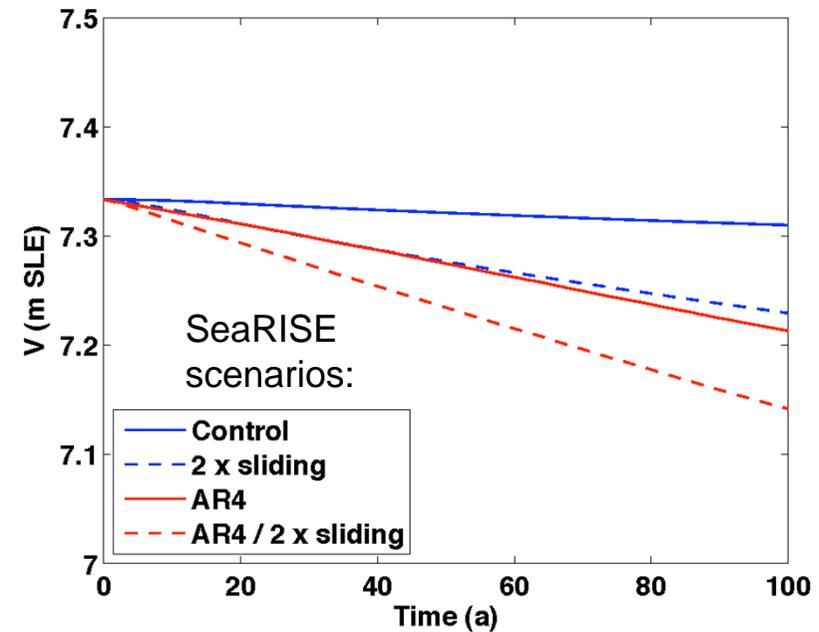


## Future climate change simulations with Elmer/Ice and SICOPOLIS

### Ice volume – Elmer/Ice



### Ice volume – SICOPOLIS



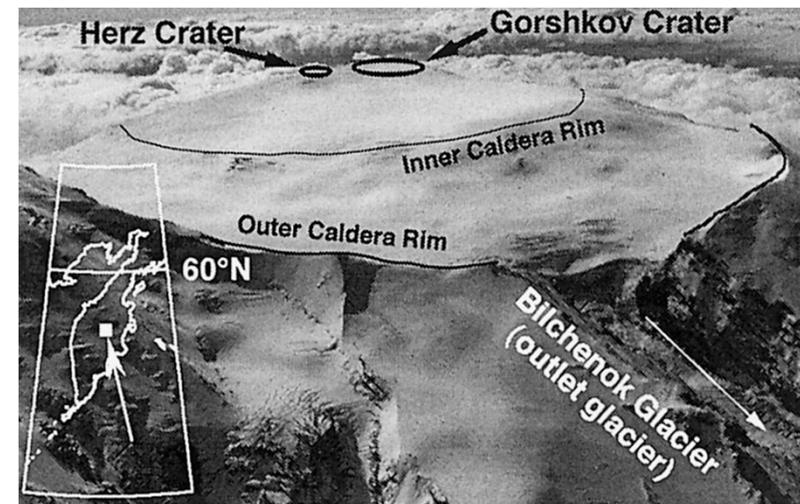
## Application of Elmer/Ice to the Gorshkov crater glacier on Ushkovsky volcano, Kamchatka

### Collaborators:

Takayuki Shiraiwa, Hakime Seddik (ILTS),  
Mikko Lyly, Erik Edelman (CSC),  
Olivier Gagliardini  
(LGGE Grenoble).

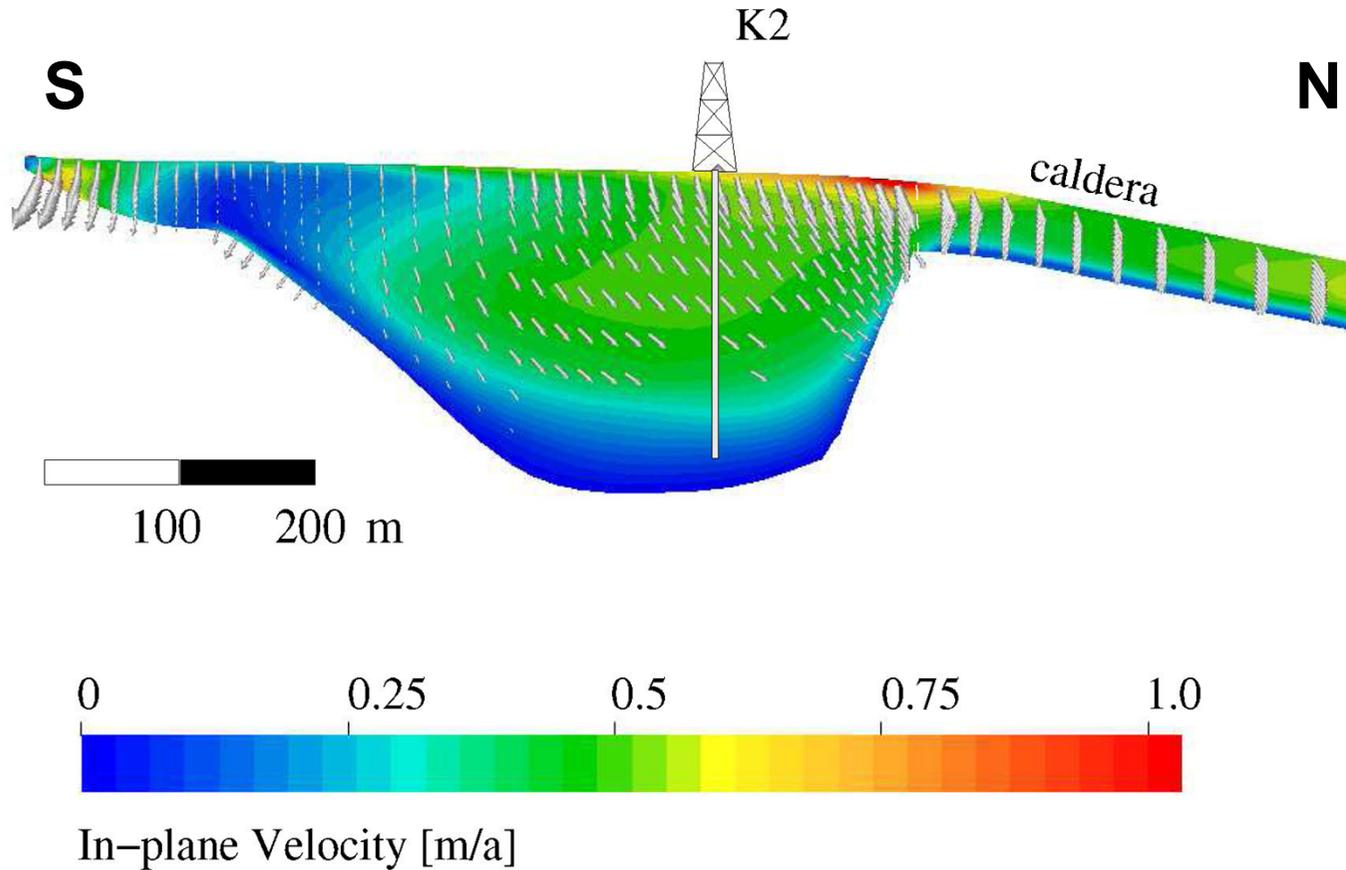
### Objective:

To understand the flow pattern  
of a very unusual glacier  
(large aspect ratio, “fire and ice”,  
high basal melting, firn).



56.1° N, 160.5° E (Shiraiwa et al. 2001)

## Reference simulation: velocity in S-N transect



# Application of SICOPOLIS to the Austfonna ice cap, Svalbard

## Collaborators:

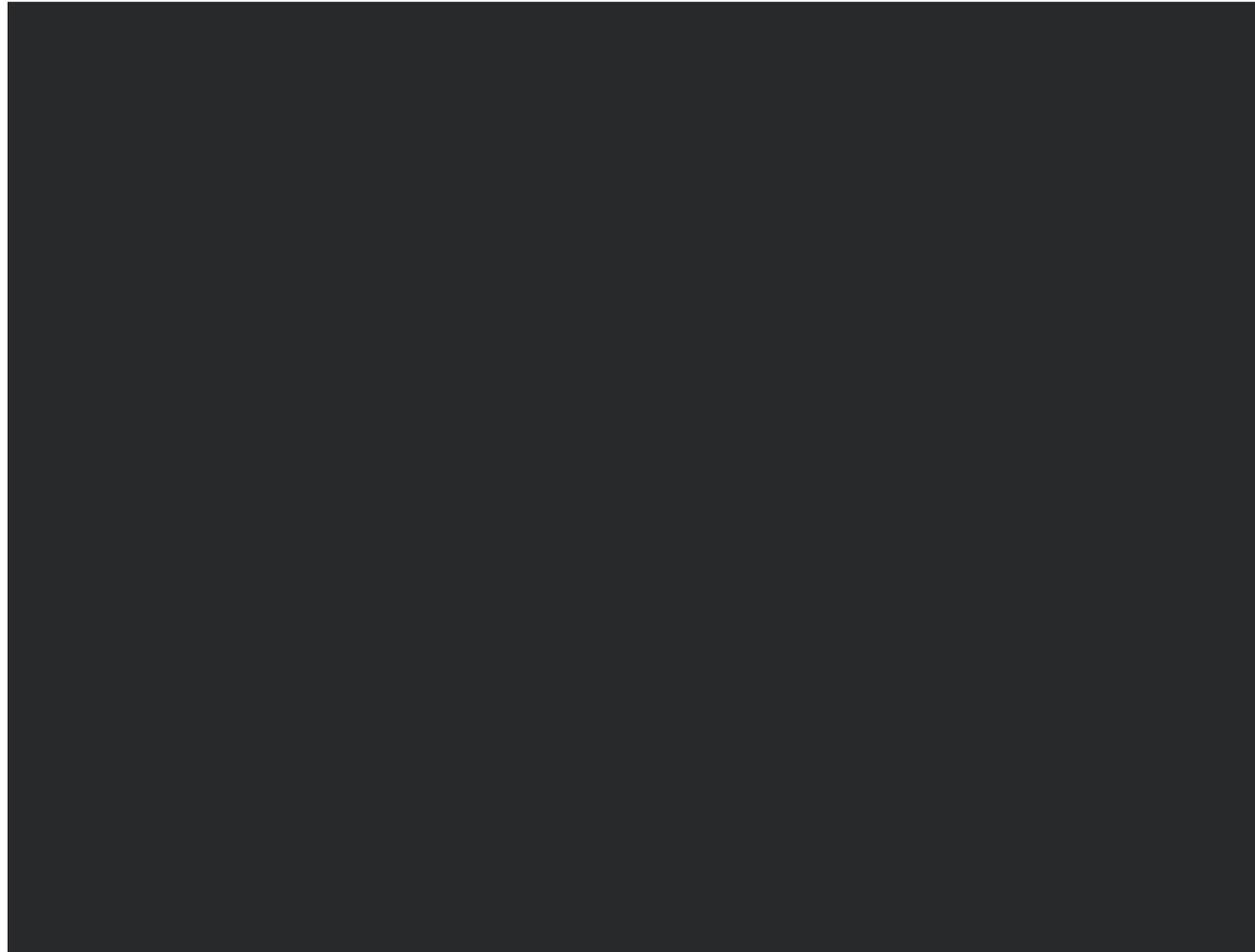
Thorben Dunse, Thomas Vikhamar Schuler, Jon Ove Hagen (Univ. Oslo).

## Objective:

To reproduce the observed surge-recovery cycles of several drainage basins of Austfonna.



## **Simulated surface velocity field over 1000 years of present-day climate conditions**



## Further collaborative projects

- Simulation of the vicinity of Dome Fuji, Antarctica, with induced anisotropy and fabric evolution  
(Hakime Seddik, ILTS; Luca Placidi, Univ. Rome).
- Assessing the timing, extent and volume of Tibetan Plateau ice during the last 130,000 years  
(Nina Kirchner, Arjen Stroeven, Jakob Heyman, Univ. Stockholm).
- Ice flow modelling of the Greenland ice sheet in support of the NEEM deep drilling project  
(Center of Excellence for Ice and Climate, Univ. Copenhagen).
- Transport and effects of aerosols on the Greenland ice sheet  
(Thomas Gölles, Carl Egede Bøggild, UNIS Longyearbyen).

**... to be continued ...**



*Thank you !*

*R. Greve (ILTS), T. Zwinger (CSC)*

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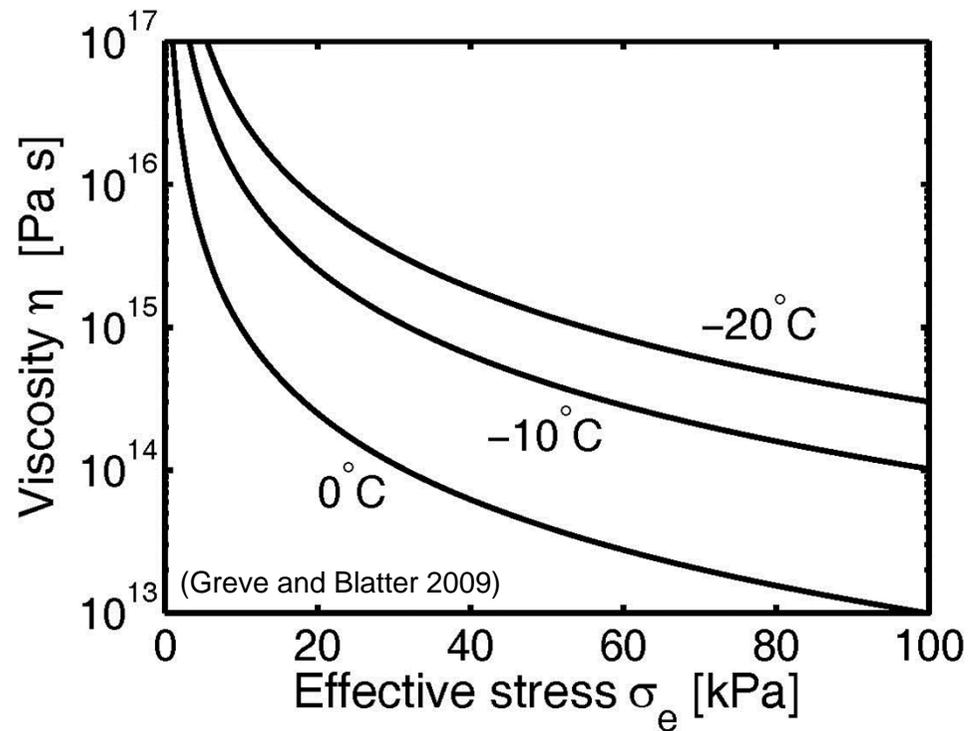
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# Appendix

## Internal deformation

Viscosity of polycrystalline ice:



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

## Basal sliding for grounded ice

- 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

$\tau_b$  — basal shear stress

$P_b$  — basal pressure

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

## Grounded vs. floating ice

