ChEESE

ChEESE: Pilots with workflow issues Glacier hazards

ChEESE: Workflows for Glaciological and Cryospheric hazards

Thomas Zwinger (CSC)

with direct contributions from
Tómas Jóhannesson (IMO)
Samuel Cook (UNIL)

CSC

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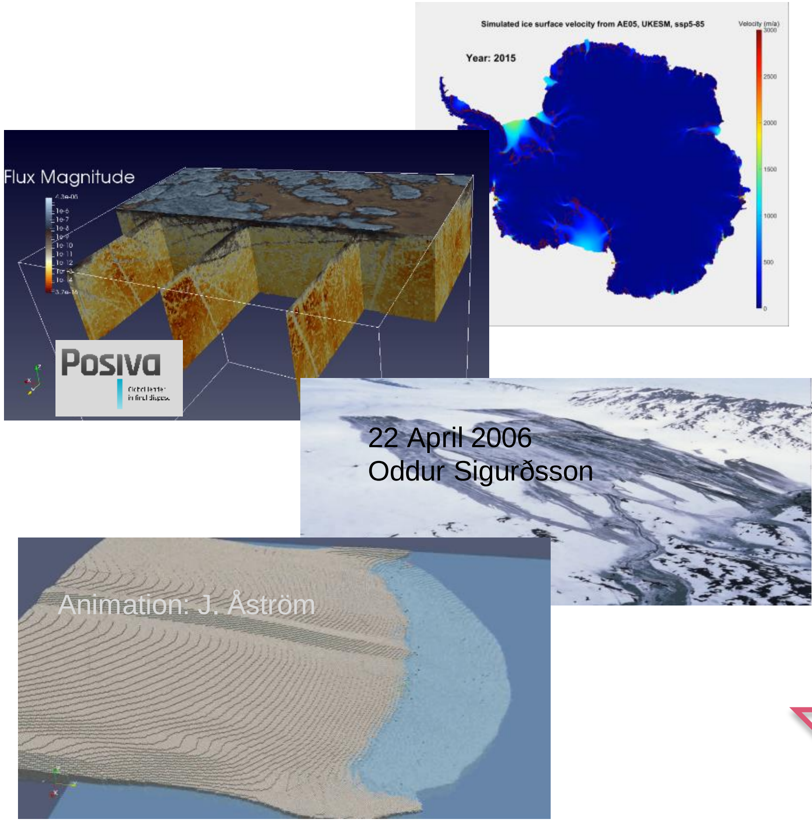
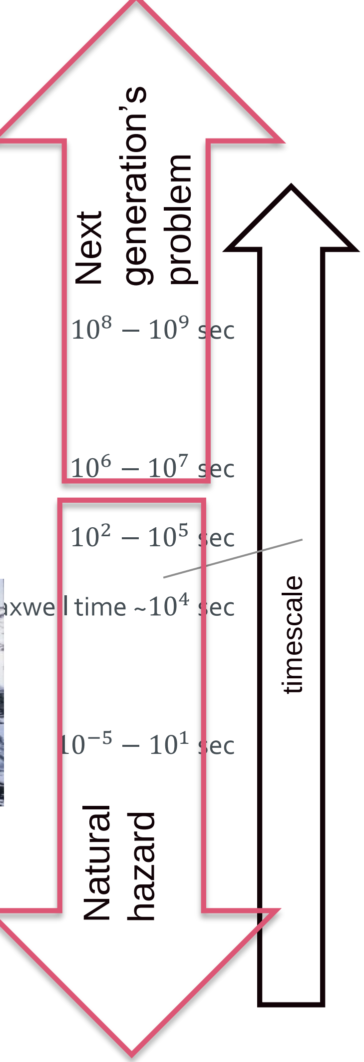
EuroHPC
Joint Undertaking

~~Glacier~~ Cryospheric Hazards



22 April 2006
Oddur Sigurðsson

Animation: J. Åström



Next generation's problem

$10^8 - 10^9$ sec

$10^6 - 10^7$ sec

$10^2 - 10^5$ sec

axwell time ~10^4 sec

$10^{-5} - 10^1$ sec

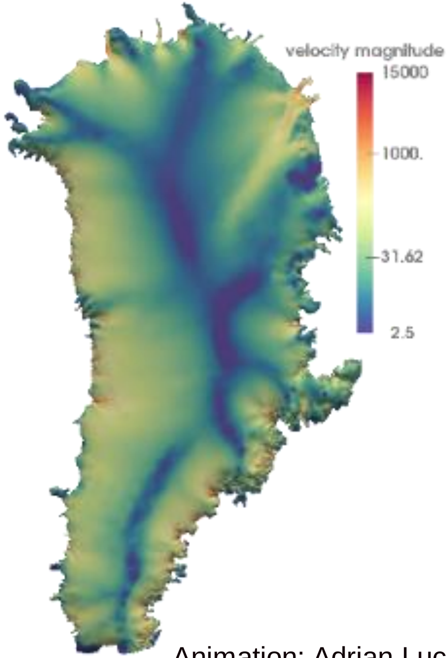
Natural hazard

timescale

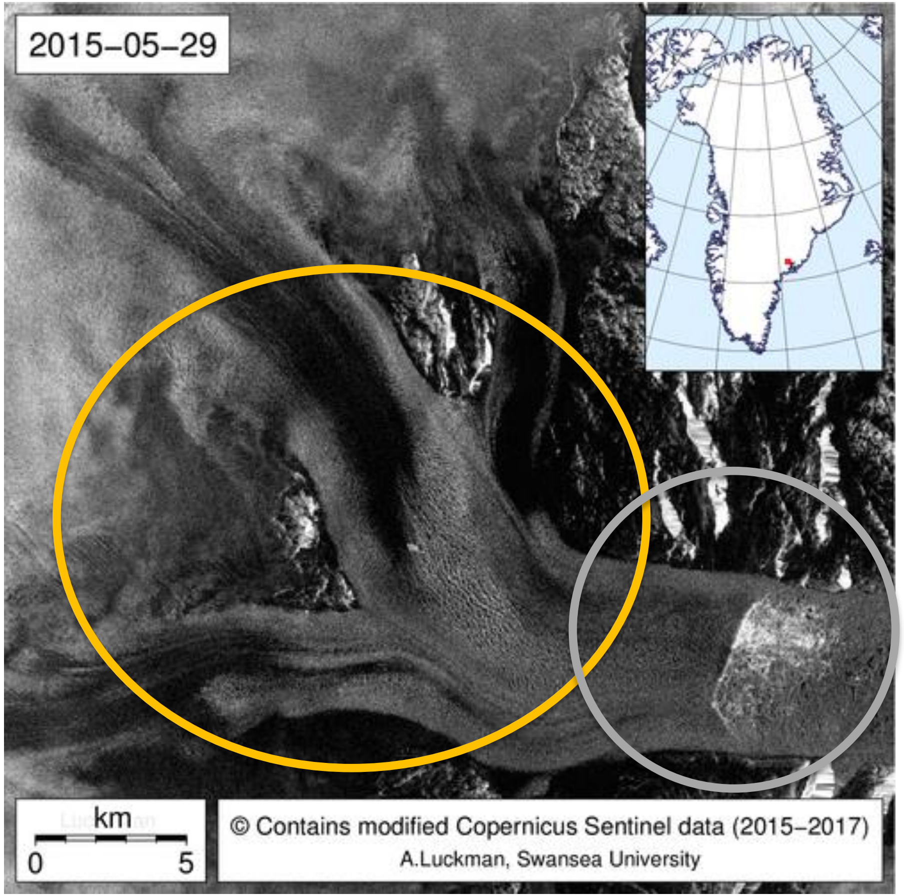
- Sea Level Rise (SLR), Glacial Isostatic Adjustment (GIA)
- Permafrost (nuclear waste repo)
- Glacier Outburst Floods (GLOFS)
- Calving events
  - Including ice front calving and thereby triggered tsunamis
  - Calving from overhanging glaciers
  - Complete disintegration of glaciers
  - Ice and snow avalanches

Ice is a fluid

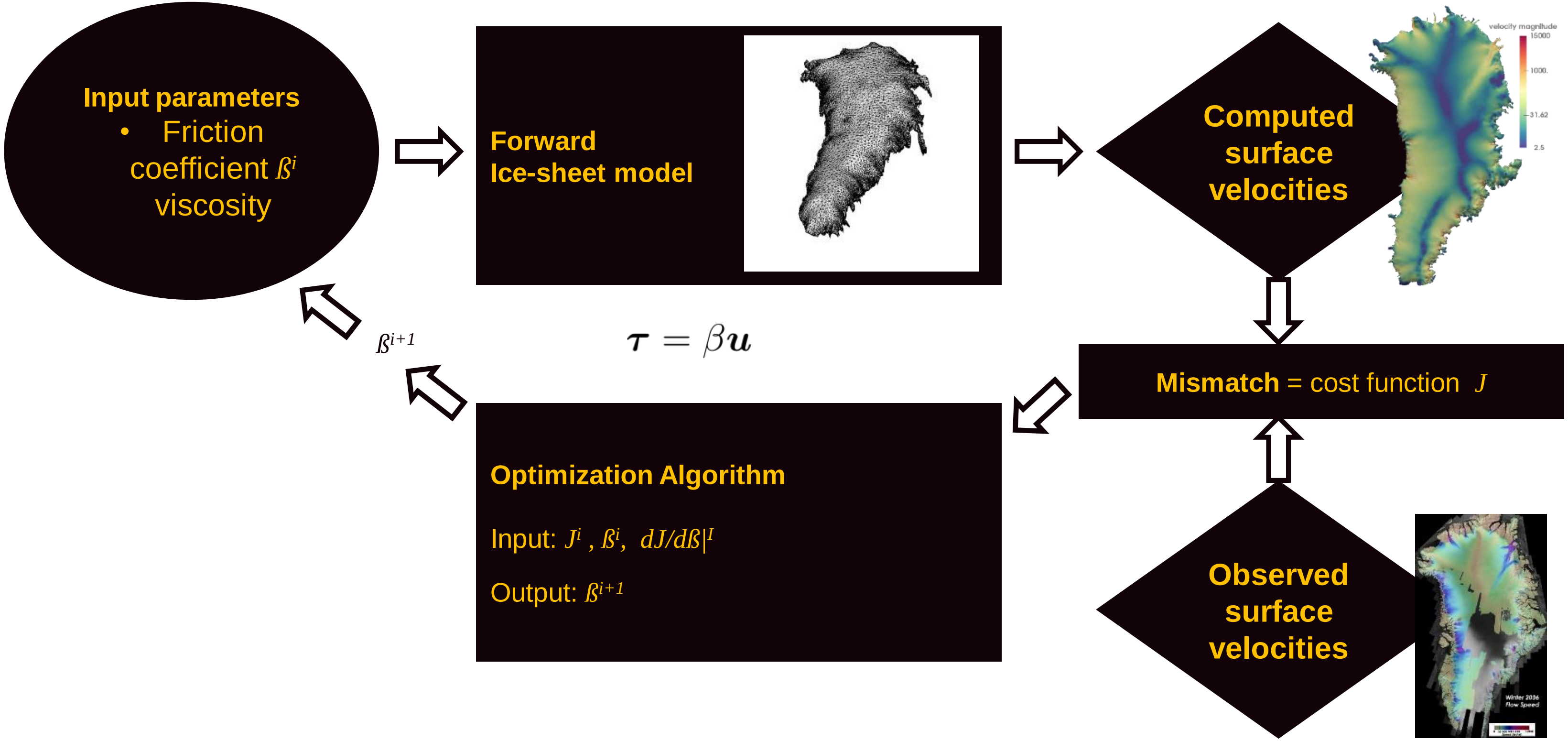
but also a solid



Animation: Adrian Luckman,
Swansea Univ., UK



Sea Level Rise: Data Assimilation – Inverse Methods



Input parameters

- Friction coefficient ß^{i} viscosity

Forward Ice-sheet model

Computed surface velocities

Mismatch = cost function J

Observed surface velocities

$$\boldsymbol{\tau} = \beta \boldsymbol{u}$$

ß$^{i+1}$

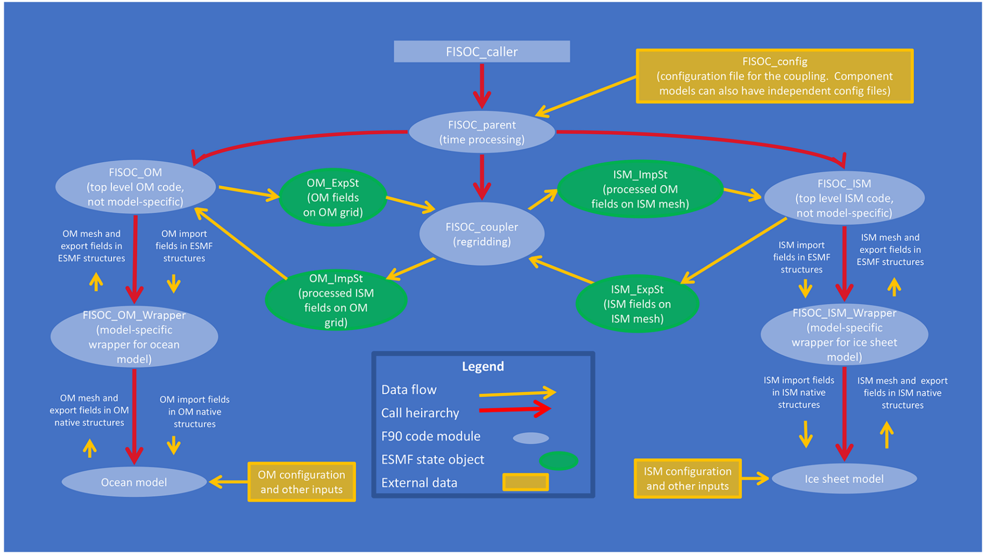
Optimization Algorithm

Input: J^{i}, ß^{i}, dJ/dß$|^{I}$

Output: ß$^{i+1}$

Sea Level Rise: Ice-ocean Coupling

- Framework for Ice Sheet Ocean Coupling (FISOC)
- Based on ESMF (interpolation, meshing routines)



FISOC_caller

FISOC_config
(configuration file for the coupling. Component models can also have independent config files)

FISOC_parent
(time processing)

FISOC_OM
(top level OM code, not model-specific)

OM_ExpSt
(OM fields on OM grid)

FISOC_coupler
(regridding)

ISM_ImpSt
(processed OM fields on ISM mesh)

FISOC_ISM
(top level ISM code, not model-specific)

OM mesh and export fields in ESMF structures

OM import fields in ESMF structures

OM_ImpSt
(processed ISM fields on OM grid)

ISM_ExpSt
(ISM fields on ISM mesh)

ISM import fields in ESMF structures

ISM mesh and export fields in ESMF structures

FISOC_OM_Wrapper
(model-specific wrapper for ocean model)

FISOC_ISM_Wrapper
(model-specific wrapper for ice sheet model)

OM mesh and export fields in OM native structures

OM import fields in OM native structures

ISM import fields in ISM native structures

ISM mesh and export fields in ISM native structures

Ocean model

OM configuration and other inputs

ISM configuration and other inputs

Ice sheet model

Legend

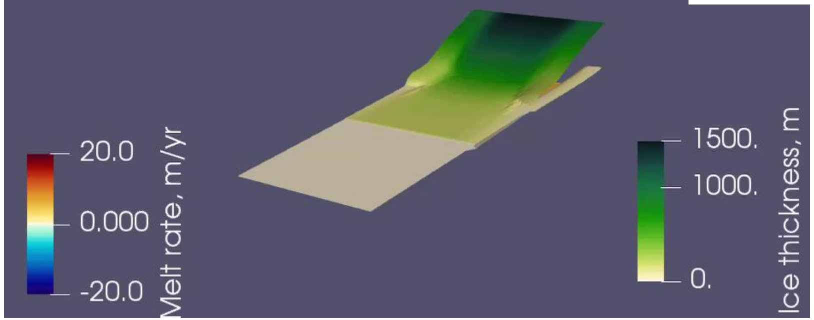
Data flow →

Call heirarchy →

F90 code module ⬭

ESMF state object ●

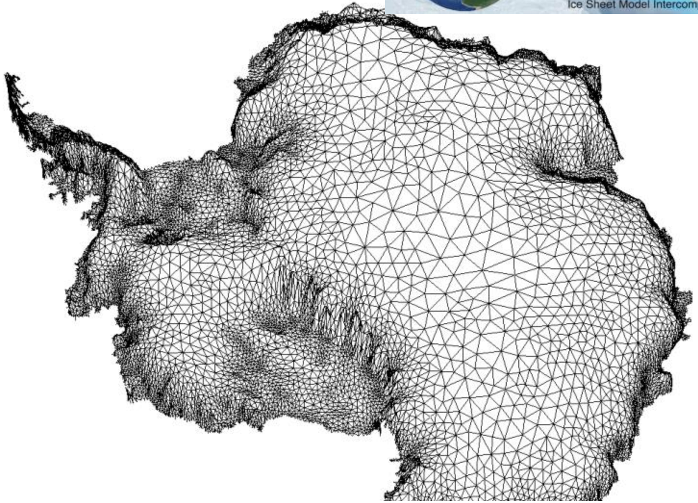
External data ▭



Gladstone, R., Galton-Fenzi, B., Gwyther, D., Zhou, Q., Hattermann, T., Zhao, C., Jong, L., Xia, Y., Guo, X., Petrakopoulos, K., Zwinger, T., Shapero, D., and Moore, J., 2021. The Framework For Ice Sheet–Ocean Coupling (FISOC) V1.1. Geosci. Model Dev.,14,889–905. https://doi.org/10.5194/gmd-14-889-2021.

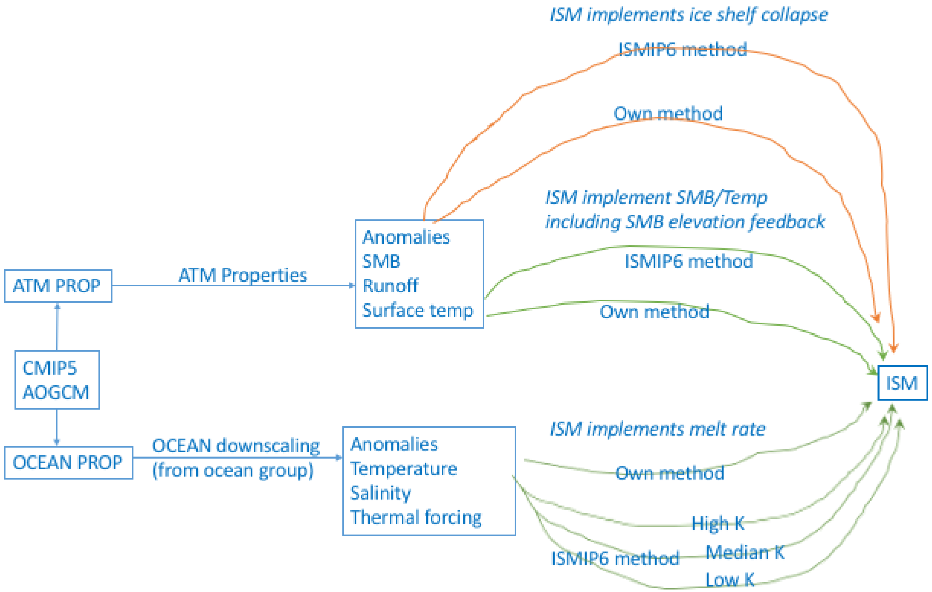
Sea Level Rise

ISMIP6
Ice Sheet Model Intercomparison Project for CMIP6



Scenario	Conservative	Risk-averse *)
SSP1-19	13 [0, 28]	30 [12, 56]
SSP1-26	16 [3, 30]	33 [15, 58]
SSP2-45	20 [7, 35]	38 [20, 63]
NDCs (Paris)	**25 [11, 40]**	**42 [25, 67]**
SSP3-70	27 [13, 41]	44 [27, 70]
SSP5-85	30 [16, 46]	48 [30, 75]

SLR in cm until the end of this century



https://www.climate-cryosphere.org/wiki/images/5/5b/Antarctic_exp_design.png

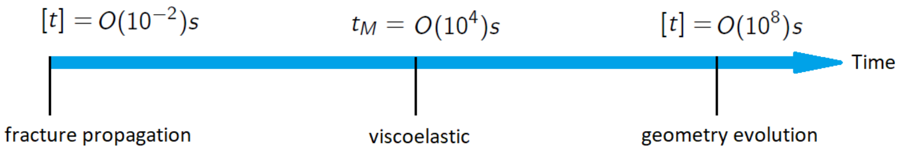
Edwards et al., 2021

Glacier Hazards: Calving (SC in ChEESE2)

ChEESE

Calving processes

Time scale separation:



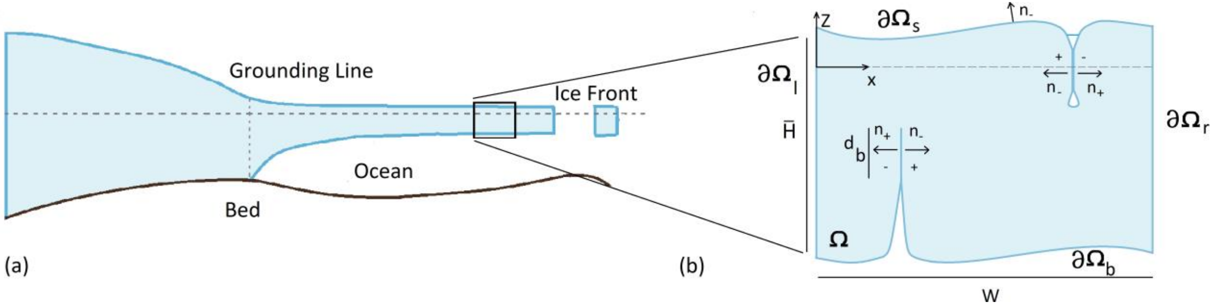
$[t] = O(10^{-2})s$ $t_M = O(10^4)s$ $[t] = O(10^8)s$

Time

fracture propagation

viscoelastic

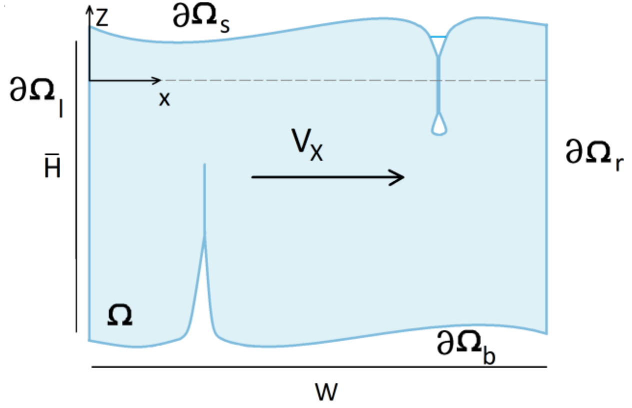
geometry evolution



Zarrinderakht, M., Schoof, C., and Zwinger, T.: A leading-order viscoelastic model for crevasse propagation and calving in ice shelves, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-807, 2023.

Calving processes

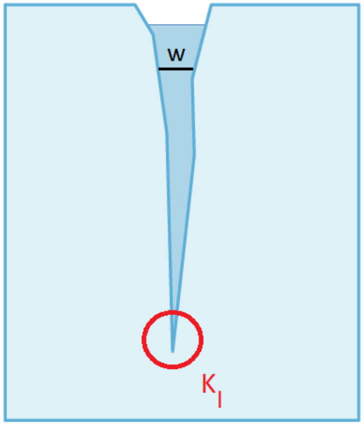
- **Elastic model** (GNU-Octave) computing crack propagation based on intensity factor (below Maxwell time)
- **Viscous model** (Elmer/Ice) computes the geometry change and provides updated stress-field



$K_I = K_{Ic} \Rightarrow$ crack propagates

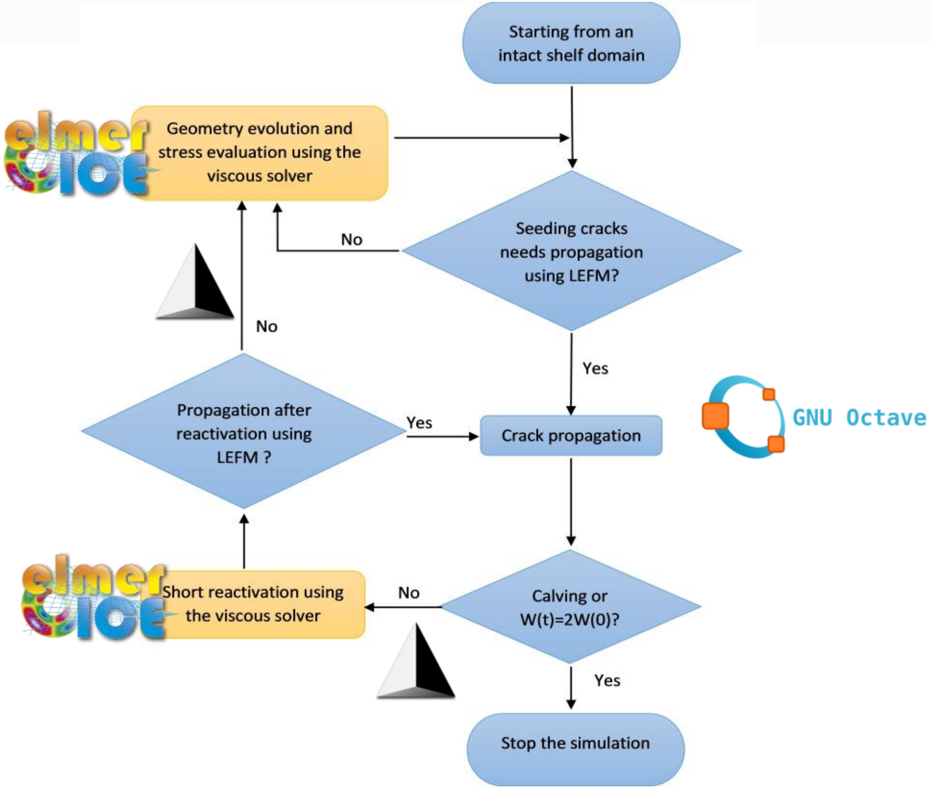
$$\dot{d} = \max\left(-\frac{K_{I,stat}-K_{Ic}}{K_{Ic}K'(0)},0\right)$$

Freund (1990)



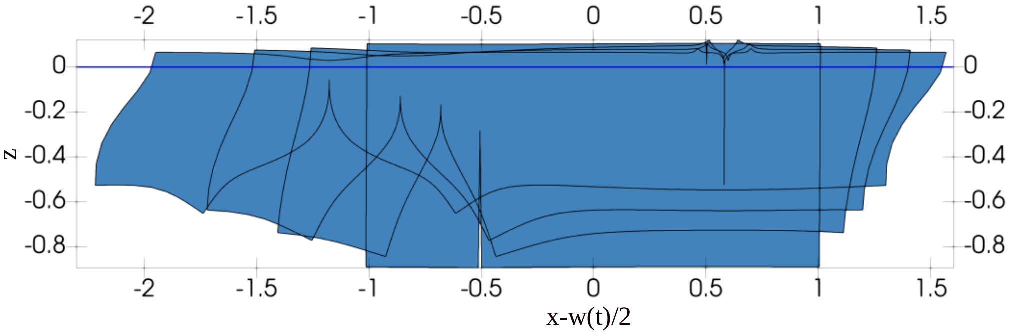
Zarrinderakht, M., Schoof, C., and Zwinger, T.: A leading-order viscoelastic model for crevasse propagation and calving in ice shelves, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-807, 2023.

Calving processes

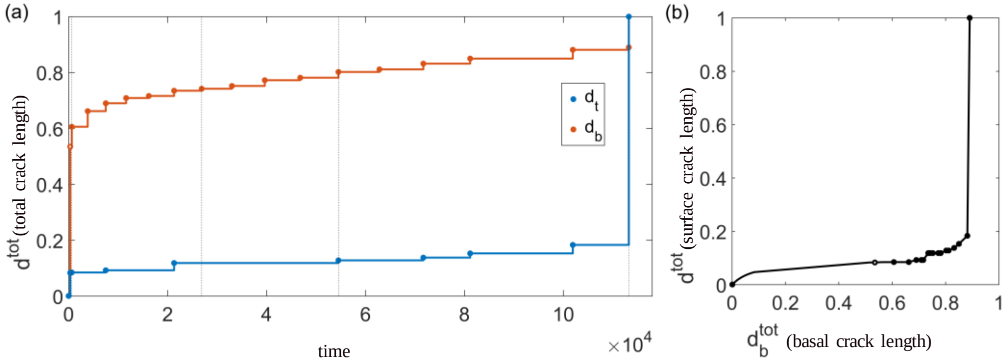


Zarrinderakht, M., Schoof, C., and Zwinger, T.: A leading-order viscoelastic model for crevasse propagation and calving in ice shelves, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-807, 2023.

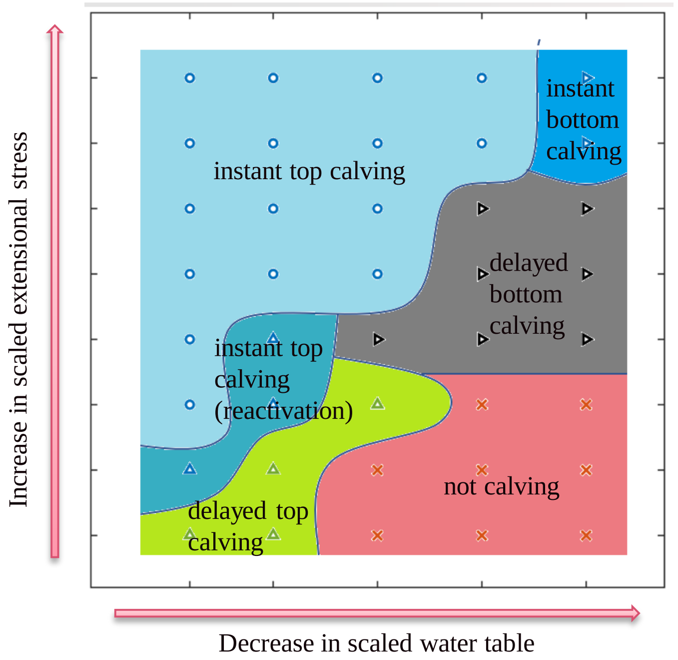
Results



z
x-w(t)/2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
0
-0.2
-0.4
-0.6
-0.8



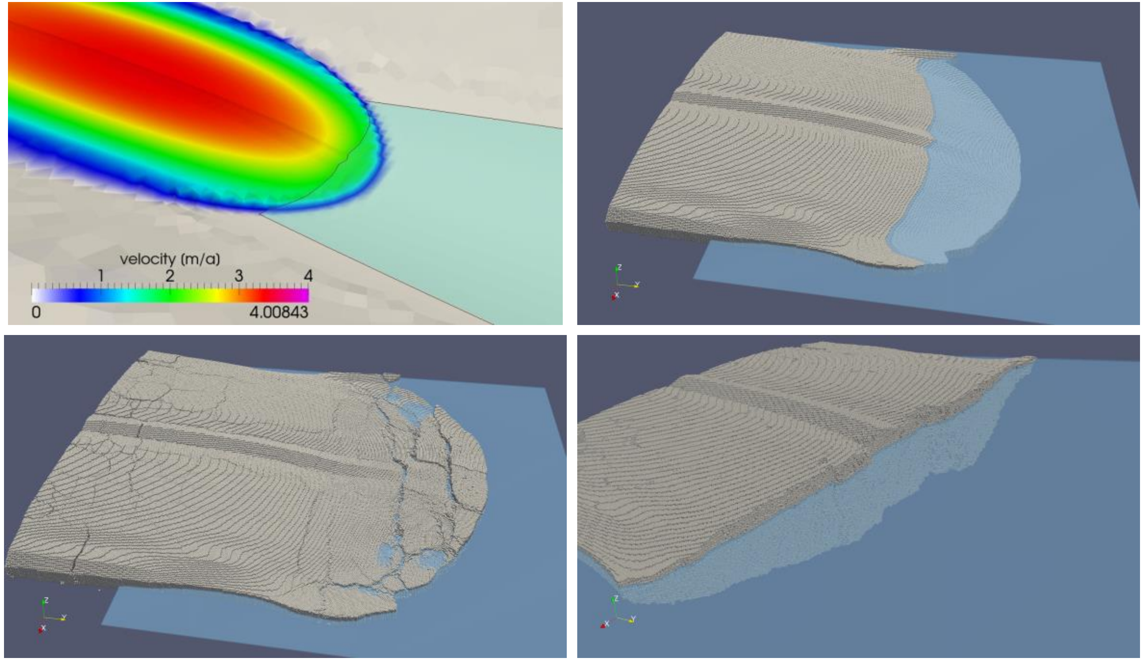
(a)
d^{tot}(total crack length)
time
$\times 10^4$
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1
d_t
d_b
(b)
d^{tot}(surface crack length)
d_b^{tot} (basal crack length)
0
0.2
0.4
0.6
0.8
1



Zarrinderakht, M., Schoof, C., and Zwinger, T.: A leading-order viscoelastic model for crevasse propagation and calving in ice shelves, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-807, 2023.

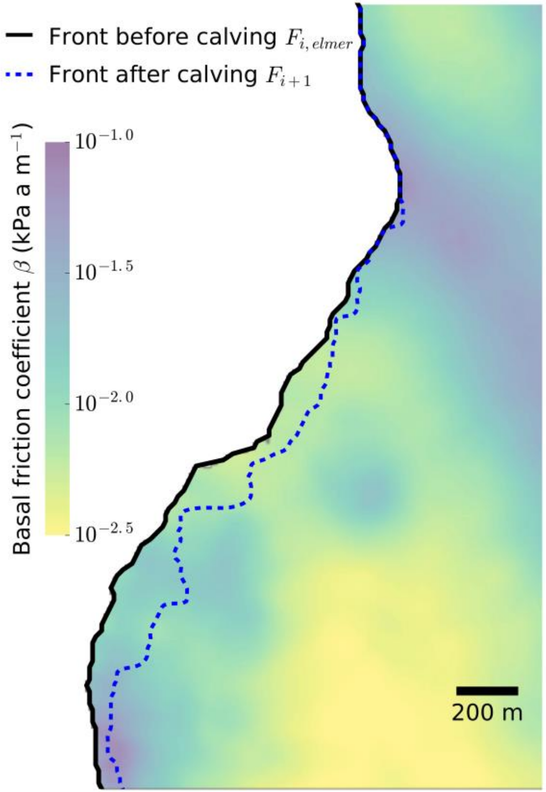
Calving processes

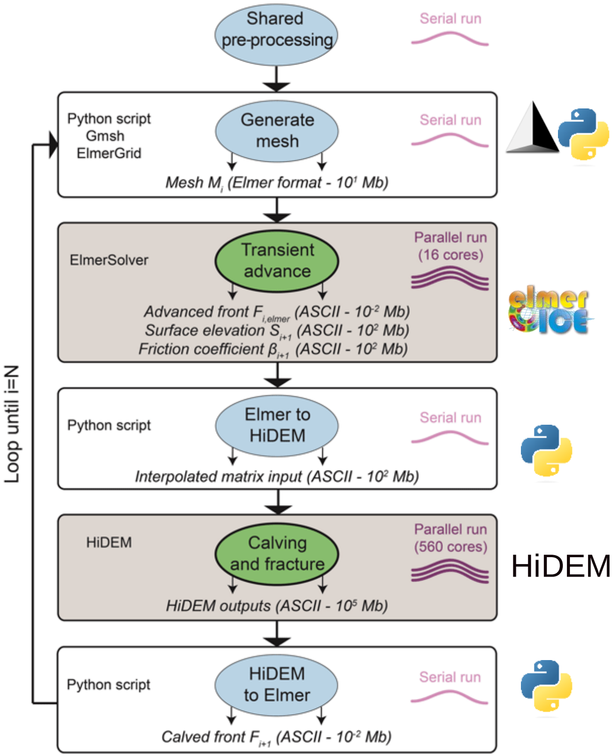
- Coupling between Elmer/Ice and HiDEM (discrete particle model)



Åström, J.A., D. Vallot, M. Schäfer, E.Z. Welty, S. O’Neel, T.C. Bartholomaus,Yan Liu, T.I. Riikilä, T. Zwinger, J. Timonen, and J.C. Moore, 2014. ***Termini of calving glaciers as self-organized critical systems***, Nature Geoscience, **7**, 874-878

Calving processes





Shared pre-processing

Serial run

Python script
Gmsh
ElmerGrid

Generate mesh

Serial run

Mesh M_i (Elmer format - 10^1 Mb)

ElmerSolver

Transient advance

Parallel run (16 cores)

Advanced front $F_{i,elmer}$ (ASCII - 10^{-2} Mb)
Surface elevation S_{i+1} (ASCII - 10^2 Mb)
Friction coefficient β_{i+1} (ASCII - 10^2 Mb)

Python script

Elmer to HiDEM

Serial run

Interpolated matrix input (ASCII - 10^2 Mb)

HiDEM

Calving and fracture

Parallel run (560 cores)

HiDEM

HiDEM outputs (ASCII - 10^5 Mb)

Python script

HiDEM to Elmer

Serial run

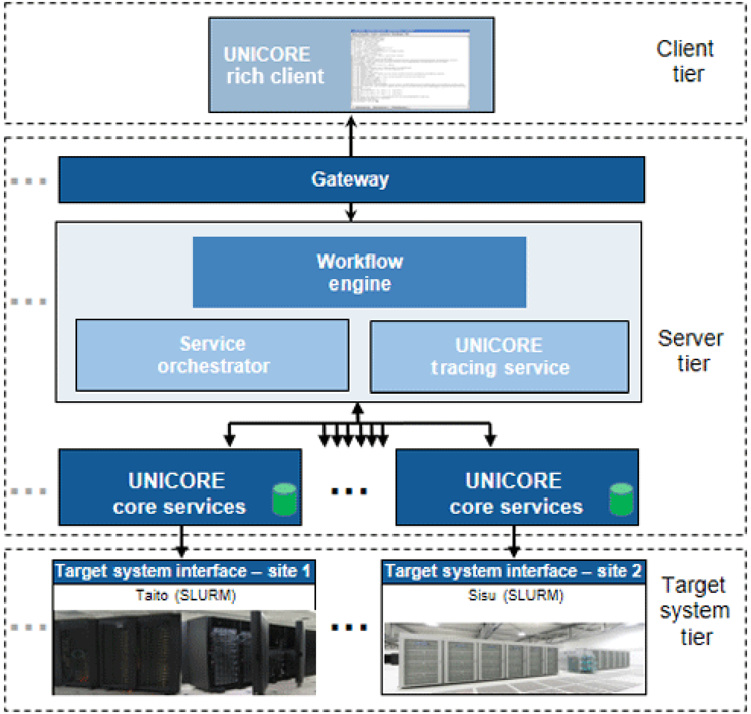
Calved front F_{i+1} (ASCII - 10^{-2} Mb)

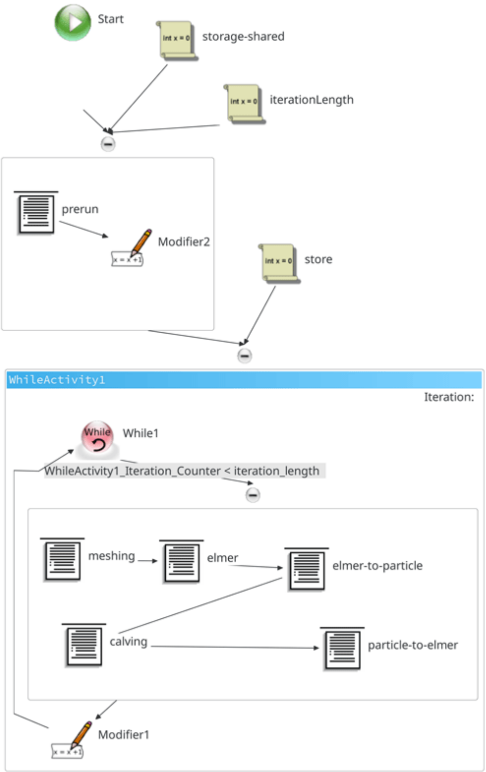
Loop until i=N

eSTICC norden NordForsk

Memon S., D. Vallot, T. Zwinger, J. Åström, H. Neukirchen, M. Riedel and M. Book, 2019. ***Scientific workflows applied to the coupling of a continuum (Elmer v8.3) and a discrete element (HiDEM v1.0) ice dynamic model***, Geosci. Model Dev., **12**, 3001-3015, doi:10.5194/gmd-12-3001-2019

Calving processes





Memon S., D. Vallot, T. Zwinger, J. Åström, H. Neukirchen, M. Riedel and M. Book, 2019. ***Scientific workflows applied to the coupling of a continuum (Elmer v8.3) and a discrete element (HiDEM v1.0) ice dynamic model***, Geosci. Model Dev., **12**, 3001-3015, doi:10.5194/gmd-12-3001-2019

Glacier Hazards: Glacial Ouburst Floods (GLOFs) real-time simulation (input from Tómas Jòhannesson, IMO)

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GLOFS: Jökulhlaups Conceptional model

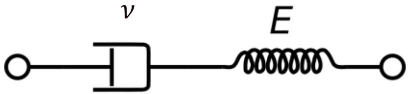

Photo: Tómas Jóhannesson

- Increased volcanic activity melts ice and creates **highly elevated subglacial lake**
- The initial subglacial flood path is created by the **passage a localized wave of over-pressure** followed by lower pressure that leads to rapid lifting and subsequent partial lowering.
- The glacier **is initially lifted** and accelerated downslope over a several-km wide area.
- The flood path **subsequently develops conduits** through the traditional melt–discharge feedback analyzed by Nye (1976).
- Rapid inflow into the floodpath, for example during subglacial eruptions may lead to very rapid propagation of the flood wave down the glacier bed.

See Einarsson et al. (2016). A spectrum of jökulhlaup dynamics revealed by GPS measurements of glacier surface motion. *Ann. Glaciol.*, **57**(16).

GLOFS: Conceptional model

- Visco-elastic Maxwell model



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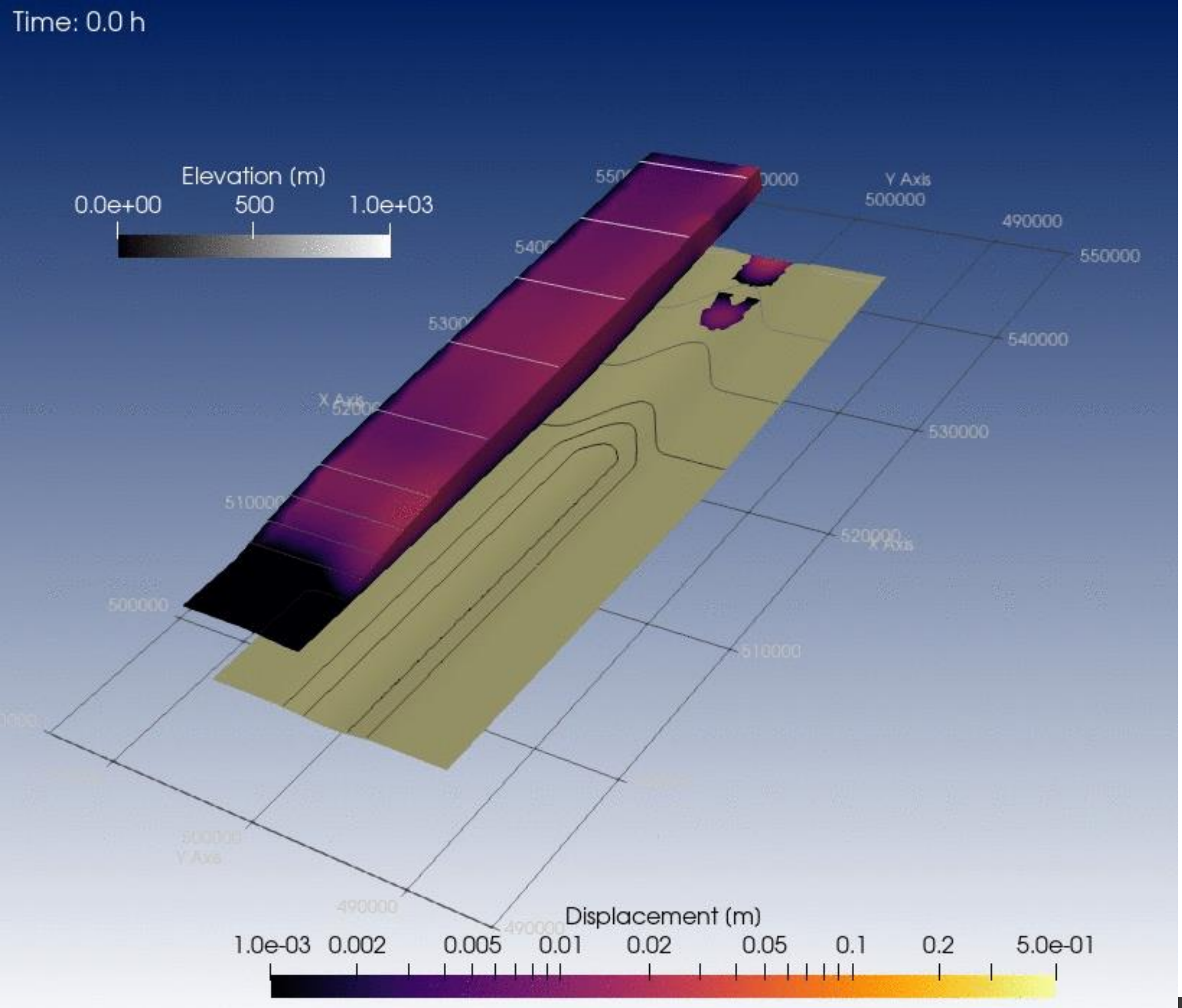
$$\frac{\partial \boldsymbol{\tau}}{\partial t} = \frac{\partial \boldsymbol{\tau}_0}{\partial t} - \frac{\mu}{\nu}(\boldsymbol{\tau} - \Pi\mathbf{1})$$

- Introduction of visco–elastic stress (Wu, 2004)

$$\boldsymbol{\tau}_0 = \Pi\mathbf{1} + 2\mu\epsilon$$

  - At the same time, we introduce pressure Π to enable incompressibility
  - Viscosity, ν, expressed as shear thinning (Glen) using time derivatives of deformation (strain)
  - “Contact problem” solving variational inequality by Elmer-library

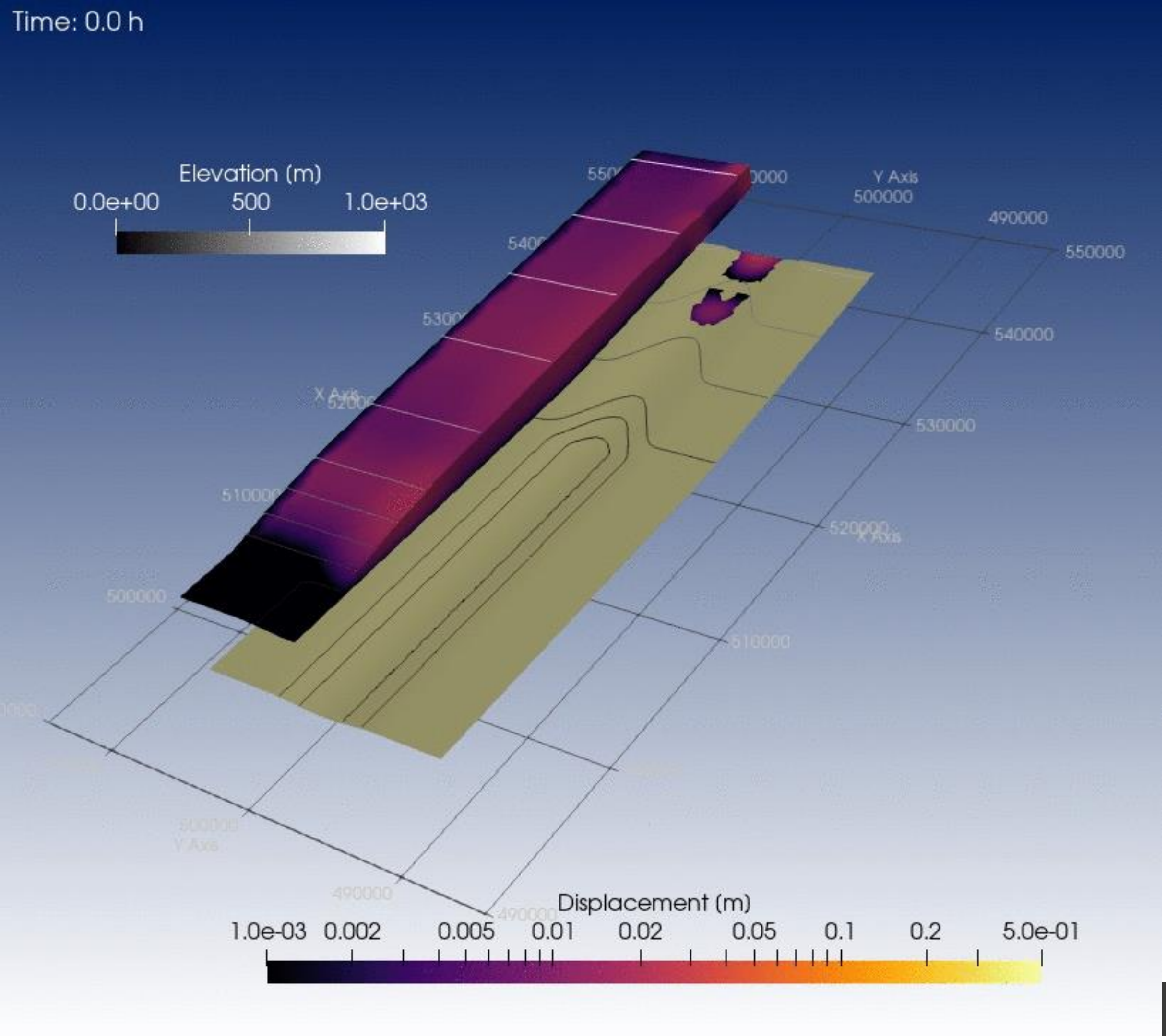


Numerical model

- The overall dimensions of the model are based on the geometry of Skaftárjökull outlet glacier and the flood path of jökulhlaups in river Skaftá.
- A 50-m deep, smooth depression in the bottom topography represents a subglacial valley along which the flood travels.
- The pressure disturbance is ~3000 m long and ~2000 m wide, with a +200 kPa (over)pressure near the tip that decreases linearly to a −50 kPa (under)pressure with respect to overburden at the back, extending upstream as far as the pressure bulge has travelled.

Zwinger et al. (2020)

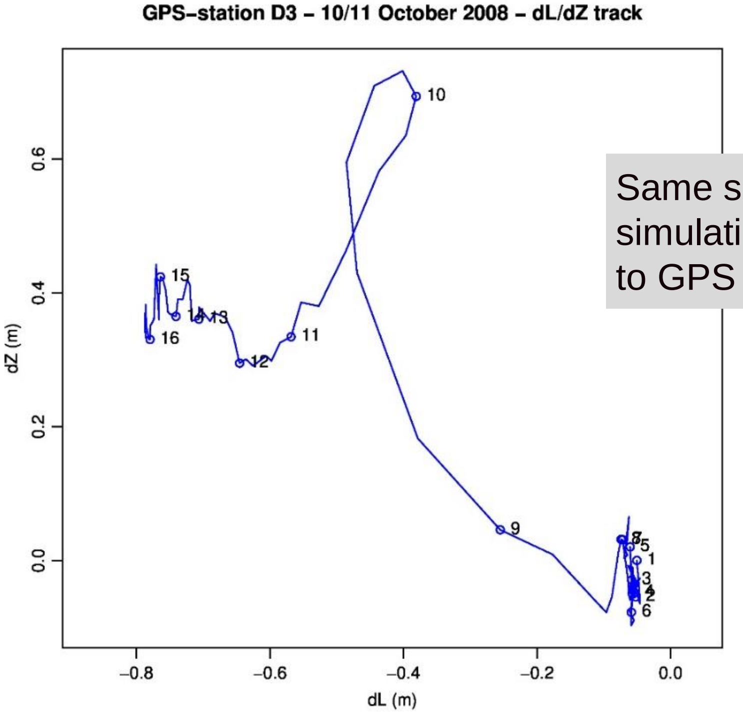
Numerical model



- Elmer FE-modelling environment
- Visco–elastic glacier model with Glen’s flow-law viscosity combined with linear elasticity.
- Contact problem implementation to represent the time-dependent development of the subglacial cavity filled by flood water.
- The current model under development computes the response of the glacier to a prescribed pressure disturbance that travels downglacier.
- A planned further development will couple a thin-sheet model component based on the Reynolds equation for fluid flow in a shallow or thin enclosure with Manning friction with the glacier model.

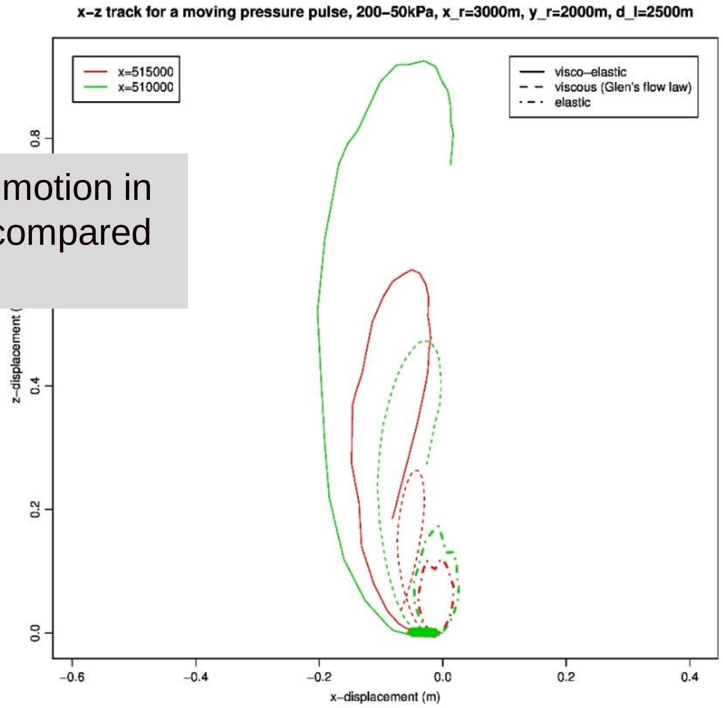
Zwinger et al. (2020)

Passage of the simulated subglacial flood front; comparison with the October 2008 flood



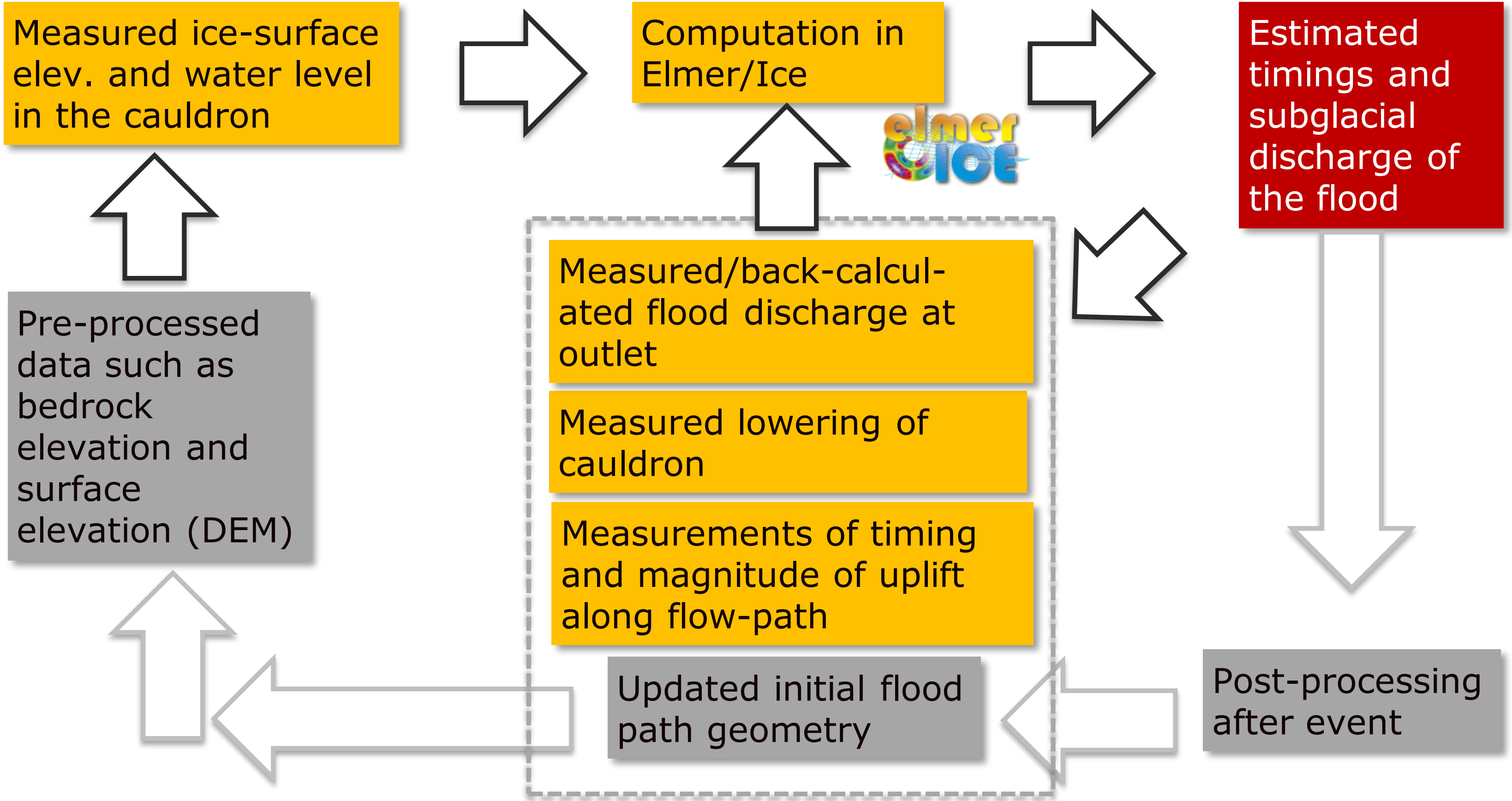
GPS–station D3 – 10/11 October 2008 – dL/dZ track

Same somersault motion in simulation (right) compared to GPS signal left)



x–z track for a moving pressure pulse, 200–50kPa, x_r=3000m, y_r=2000m, d_l=2500m

GLOFS: Suggested workflow for outburst simulation



Measured ice-surface elev. and water level in the cauldron

Computation in Elmer/Ice

Estimated timings and subglacial discharge of the flood

Pre-processed data such as bedrock elevation and surface elevation (DEM)

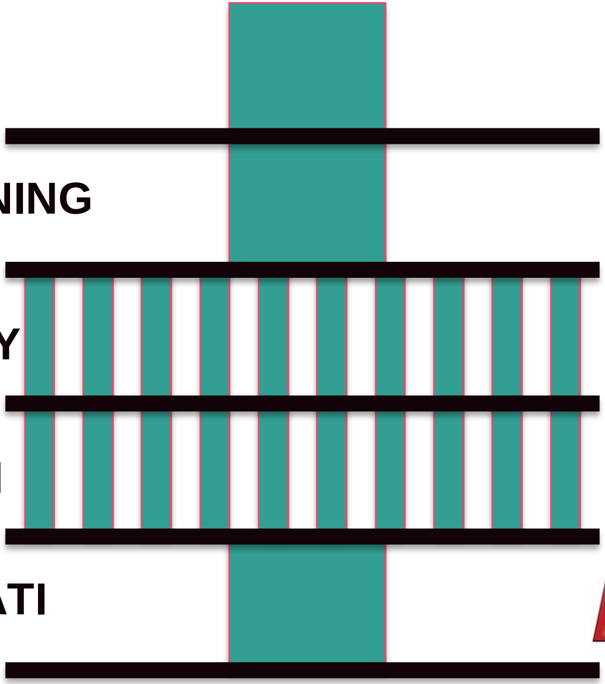
Measured/back-calculated flood discharge at outlet

Measured lowering of cauldron

Measurements of timing and magnitude of uplift along flow-path

Updated initial flood path geometry

Post-processing after event



MESHING

Gmsh

NETGEN

PARTITIONING

ElmerGrid

METIS

ASSEMBLY

SOLUTION

Elmer

hypre high performance preconditioners

MUMPS

VISUALIZATION

ParaView

Glacier Hazards: Glacial Ouburst Floods (GLOFs) hazard mapping (input from Samuel Cook,UNIL)

potentially ChEESE

GLOFs: Hazard Mapping

- Rate of glacier thinning doubled globally in last 20 years (Hugonnet et al. 2021)
- Glacier retreat uncovers **overdeepenings** that can fill and become lakes dammed by unstable features (moraines, relict ice…)
- These **lakes can drain catastrophically** in glacier lake outburst floods (GLOFS)
- Frequency is predicted to increase into next century due to lagged response to warming (Harrison et al., 2018)
- Therefore**, need better modelling of timing and location of glacier-lake formation, and the extent of damage should they cause a GLOF**

Picture: D. Binder, ZAMG

Recorded GLOFS in Europe

●

Iceland

270 events: 41 volcanic; 167 ice; 62 unknown

●

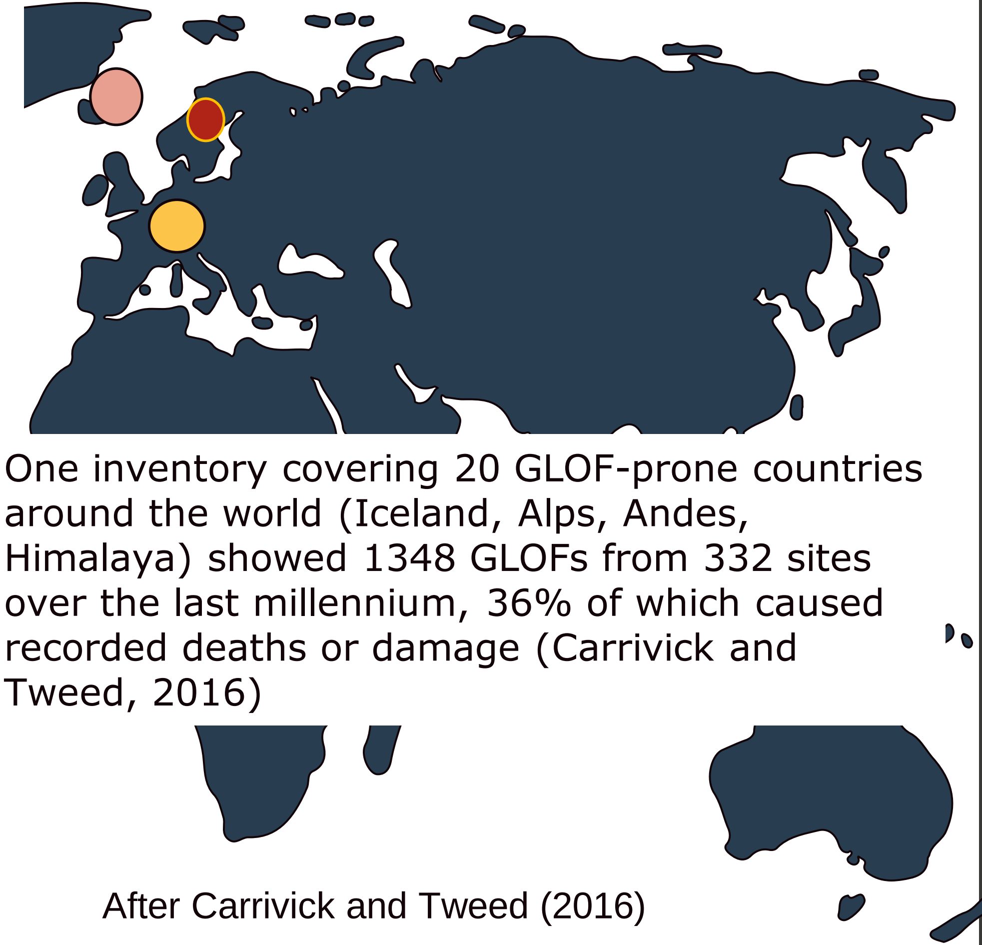
European Alps

301 events: 29 moraine; 197 ice; 1 bedrock; 71 unknown

●

Scandinavia

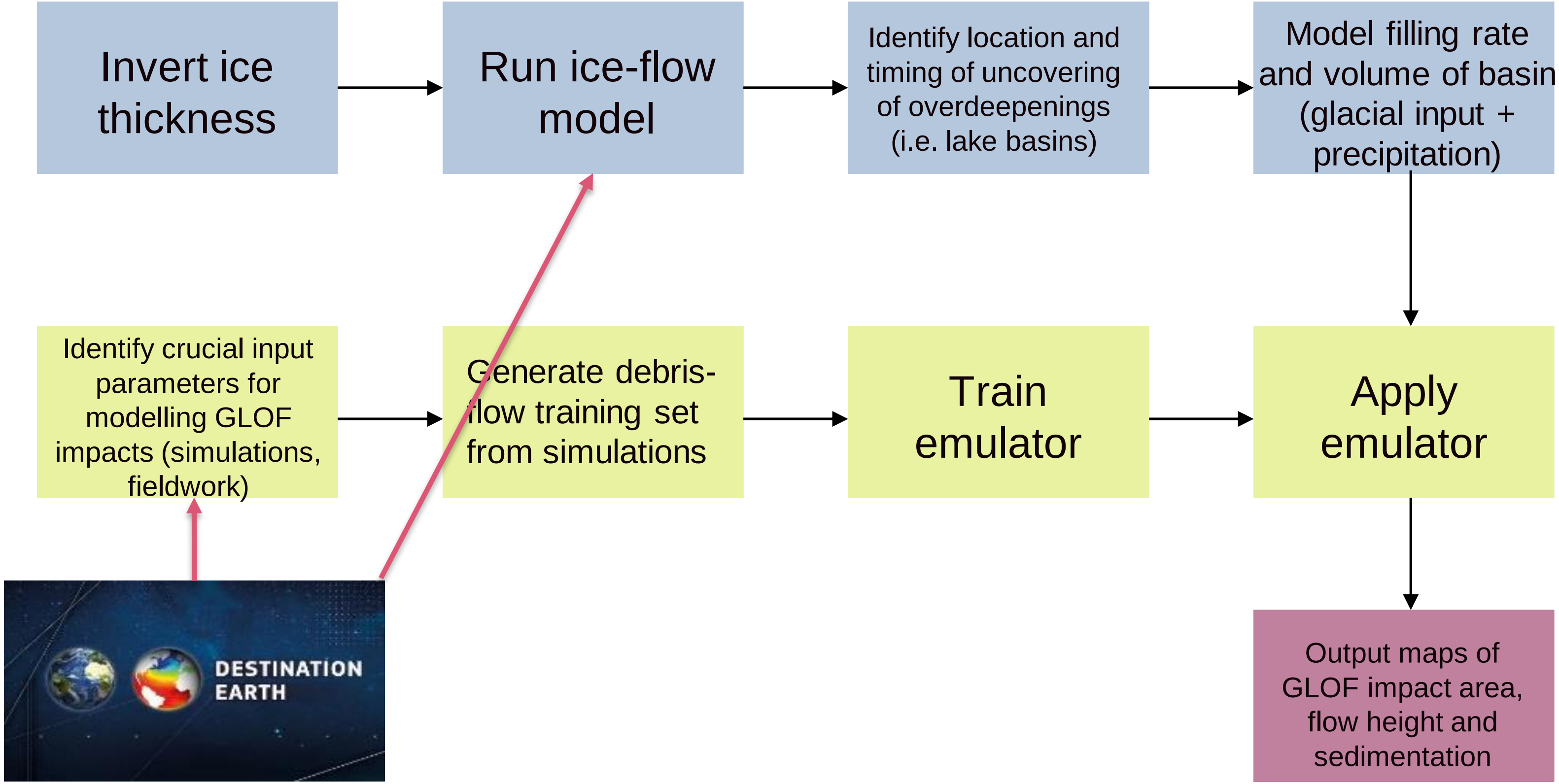
212 events: 4 moraine; 94 ice; 23 unknown



One inventory covering 20 GLOF-prone countries around the world (Iceland, Alps, Andes, Himalaya) showed 1348 GLOFs from 332 sites over the last millennium, 36% of which caused recorded deaths or damage (Carrivick and Tweed, 2016)

After Carrivick and Tweed (2016)

Workflow



Invert ice thickness

Run ice-flow model

Identify location and timing of uncovering of overdeepenings (i.e. lake basins)

Model filling rate and volume of basin (glacial input + precipitation)

Identify crucial input parameters for modelling GLOF impacts (simulations, fieldwork)

Generate debris-flow training set from simulations

Train emulator

Apply emulator

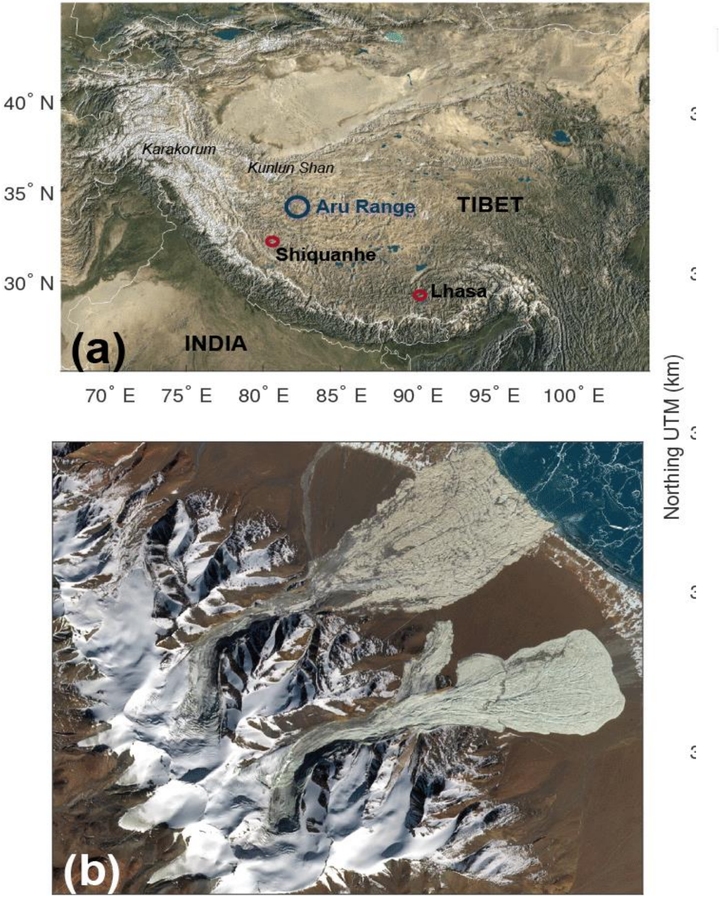
Output maps of GLOF impact area, flow height and sedimentation

What else?

potentially **ChEESE**

What else?

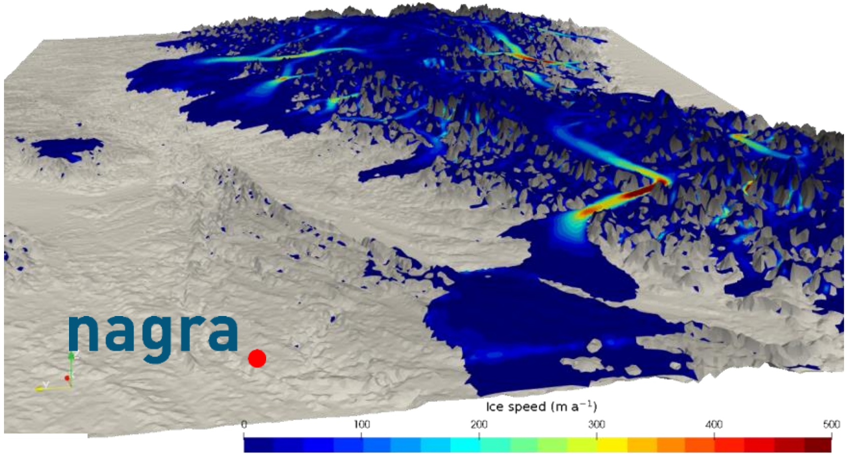
- Glacier-permafrost interaction (including basal hydrology) for **glacier stability** (e.g. Marmolada tragedy in 2022 or Aru glaciers – to the right)



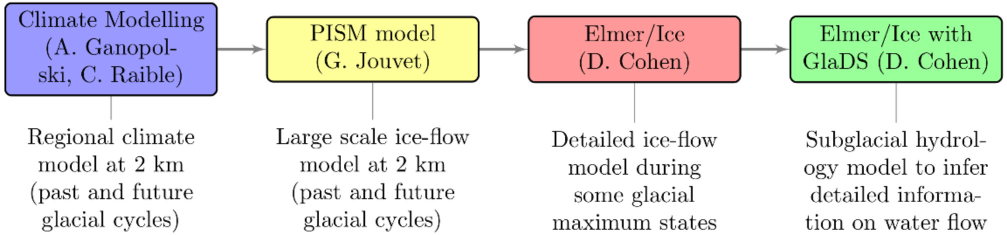
Gilbert et al., 2016

What else?

- Glacier-permafrost interaction (including basal hydrology) for **glacier stability**
- Long term studies of glacier hydrology as well as permafrost for nuclear **waste repository safety assessment**



Animation courtesy Denis Cohen, CoSci



Climate Modelling (A. Ganopolski, C. Raible) → PISM model (G. Jouvet) → Elmer/Ice (D. Cohen) → Elmer/Ice with GlaDS (D. Cohen)

Regional climate model at 2 km (past and future glacial cycles)

Large scale ice-flow model at 2 km (past and future glacial cycles)

Detailed ice-flow model during some glacial maximum states

Subglacial hydrology model to infer detailed information on water flow

Figure 1: Overview of the intended use of models from climate to detailed ice-flow modelling.

What else?

- **Snow avalanches**
  - **Hazard zone mapping**
  - Evaluation of **protective measures** (see r.h.s.)

avalanche deflecting dams in western Norway (photos: NGI)

Thank you!

@cheese-coe

http://cheese2.eu

@cheese-coe

@cheese_coe@techhub.social

References

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