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Modeling glacier thermal regime with Elmer/Ice

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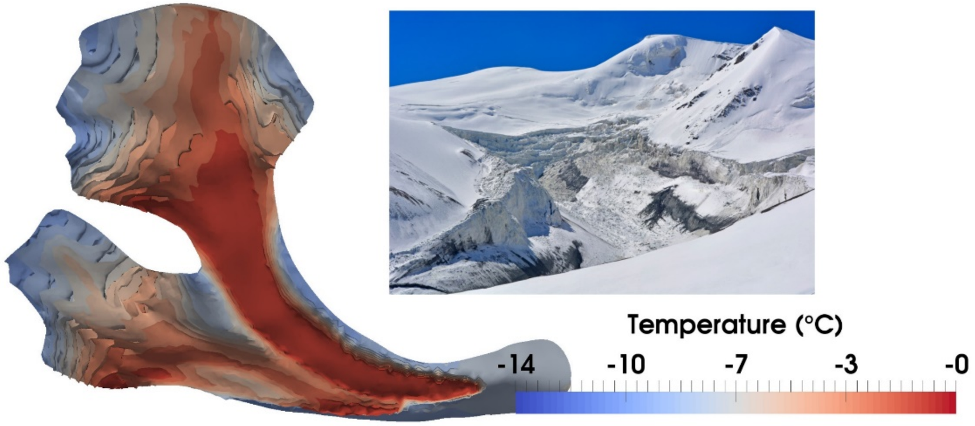
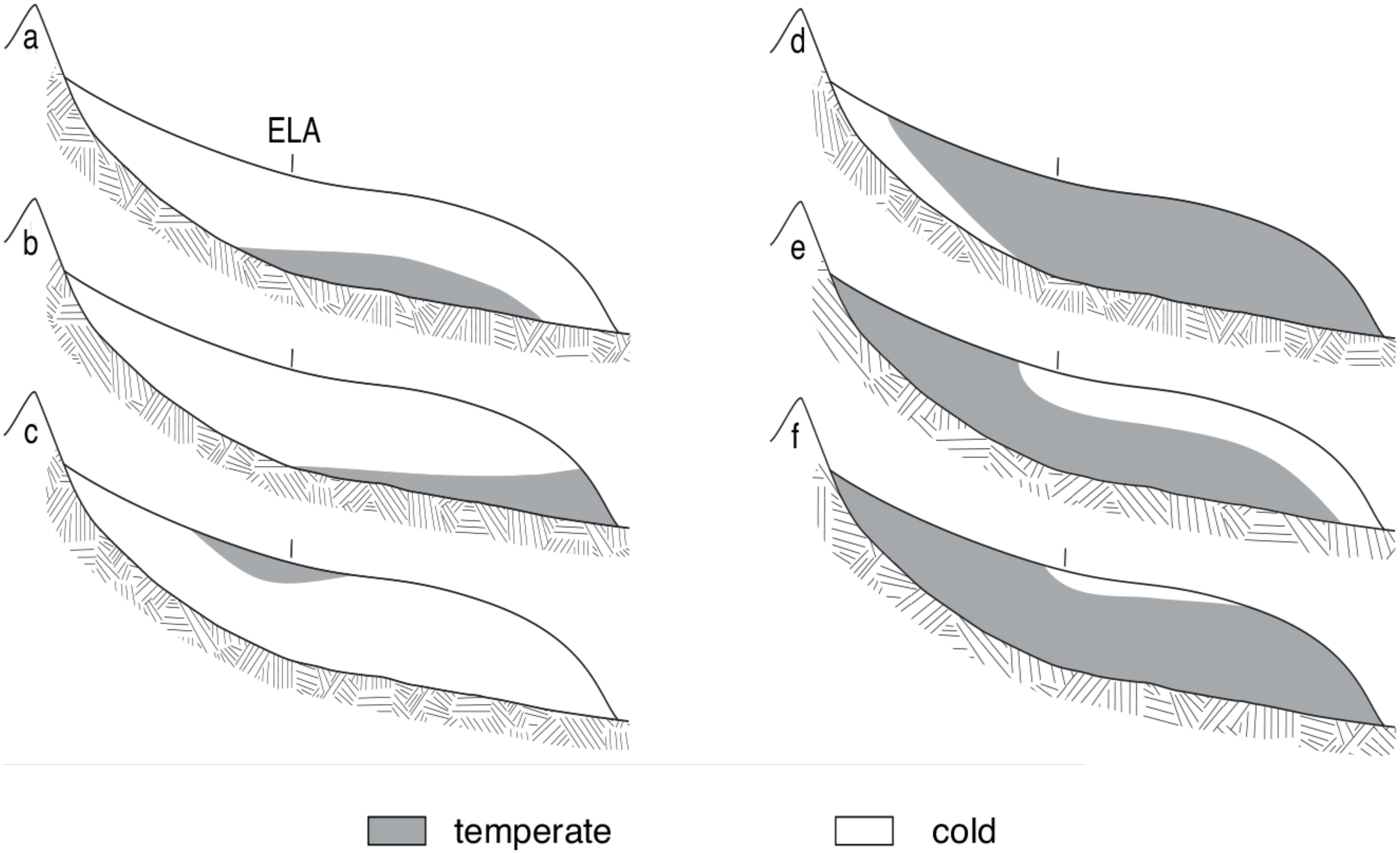
Elmer/Ice Workshop 2017 – IGE Grenoble

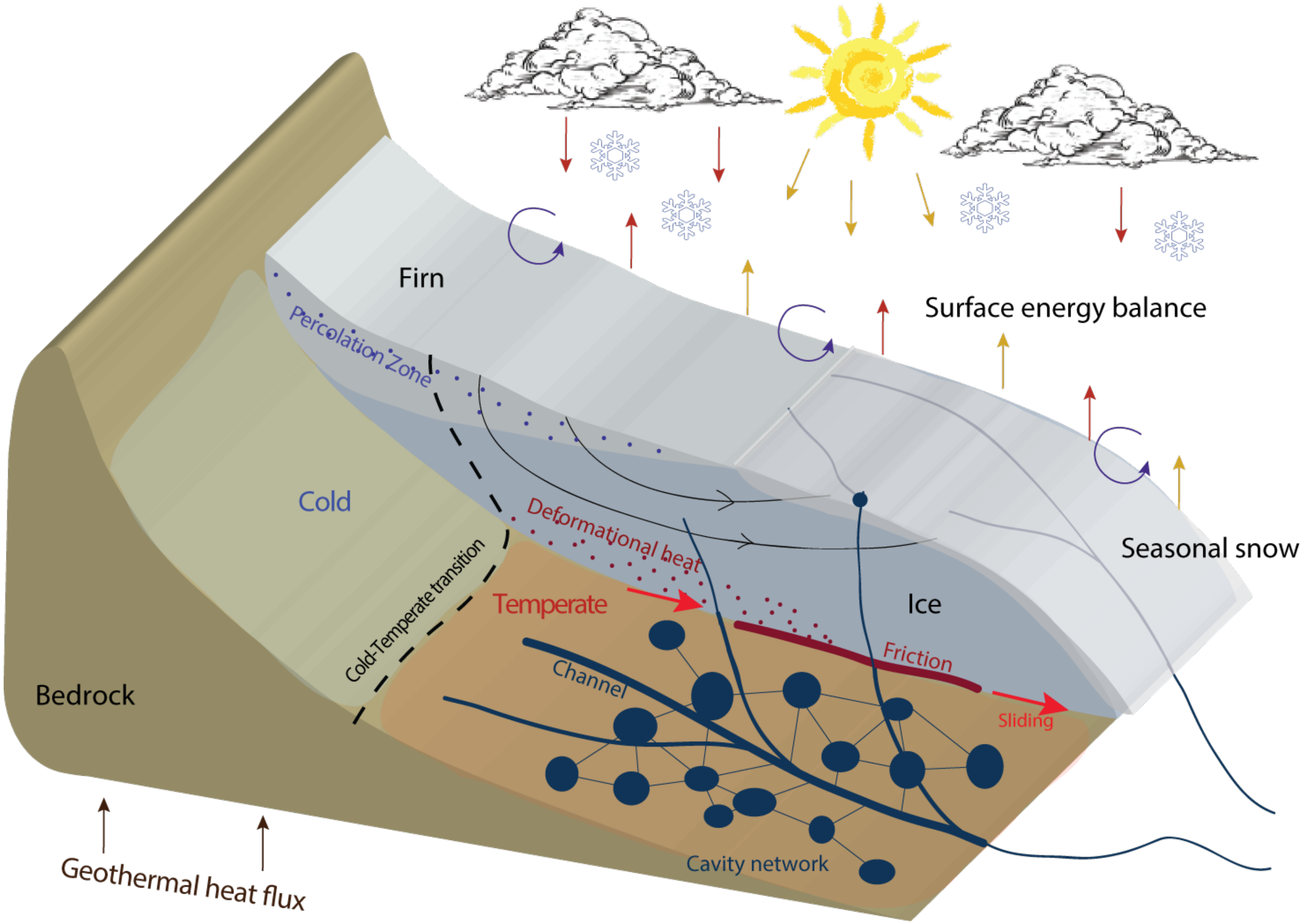


CSC

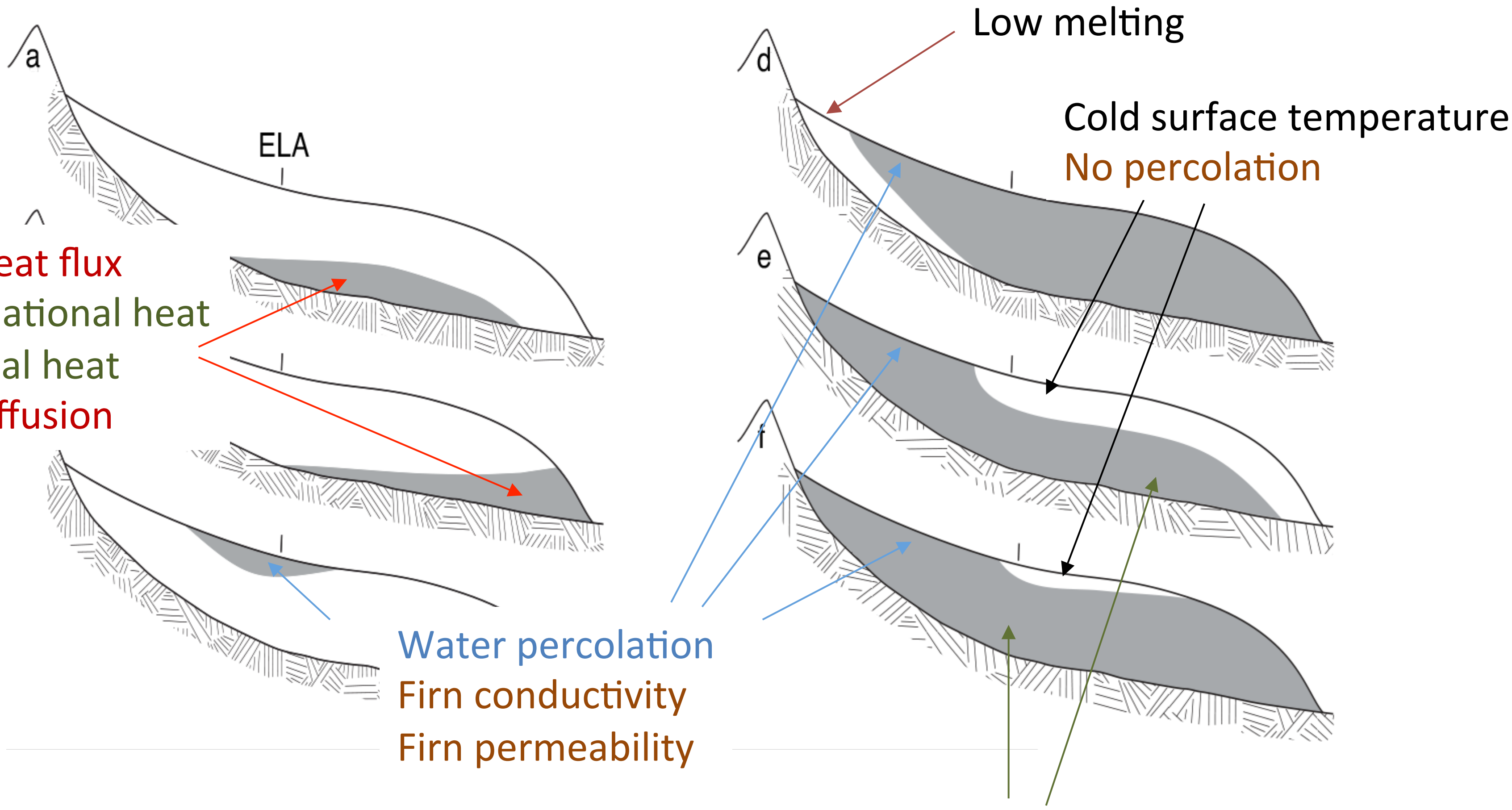
Glacier thermal regime



Glacier thermal regime



Key aspects



Low melting

Cold surface temperature

No percolation

Basal heat flux

Deformational heat

Frictional heat

Heat diffusion

Water percolation

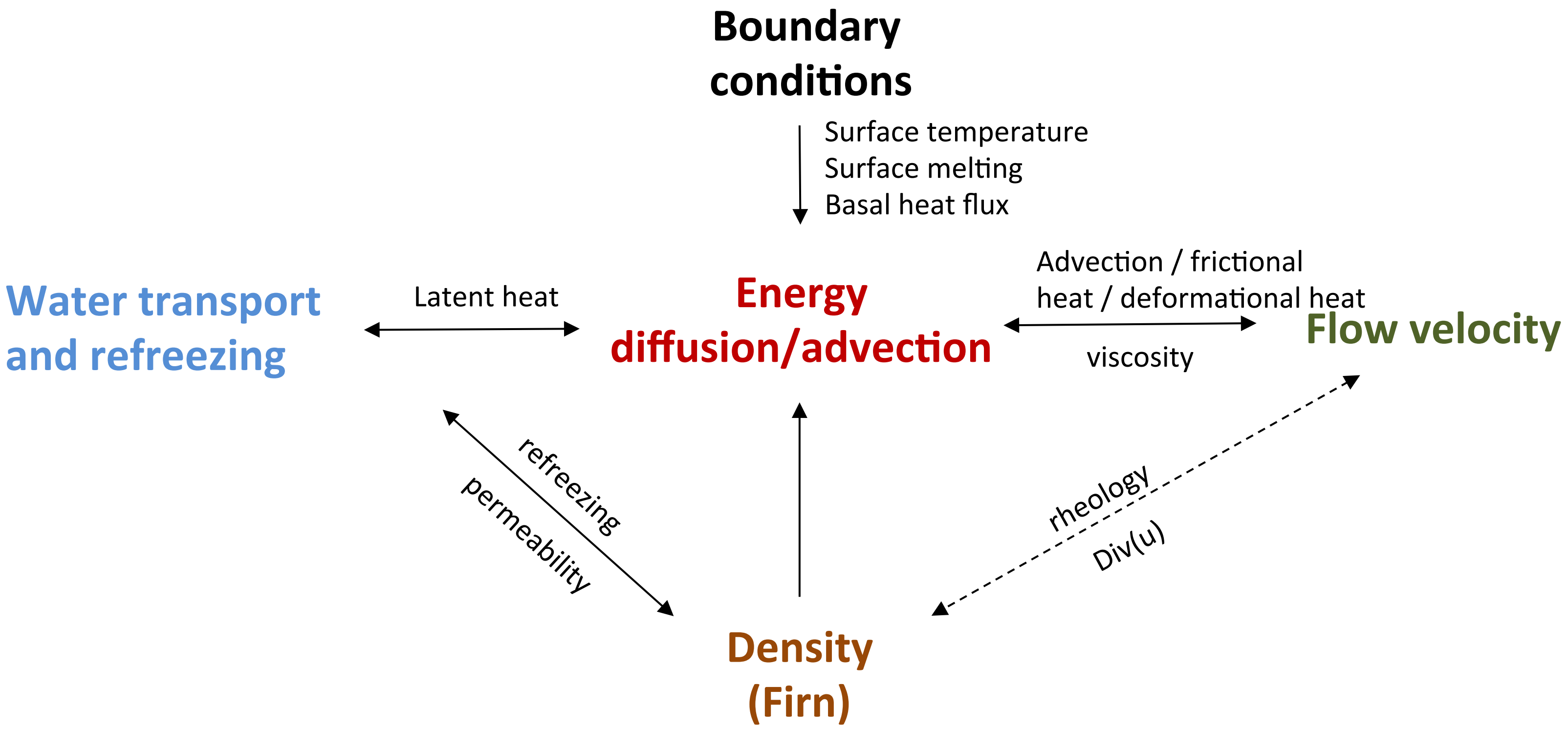
Firn conductivity

Firn permeability

Ice advection

Ice moisture

Key aspects



Thermal regime does not result of one process but from the **interaction** between several

Energy diffusion/advection

Enthalpy method :

$$\rho(\partial H/\partial t+v\cdot\nabla H)=\nabla(\kappa\nabla H)+tr(\sigma\epsilon)+Q\downarrow lat$$

Water Content

Heat capacity

$$H(T,\omega)=\{\blacksquare\int T\downarrow 0\ \uparrow T\ C\downarrow p\ (T)dT, \qquad H<Hf(p)\ \int T\downarrow 0\ \uparrow T\downarrow m\ (p)\ c\downarrow p\ (T)d$$

Enthalpy of fusion

Temperature

Latent heat of fusion

Thermal conductivity : strongly dependent on density

$$\kappa=\{\blacksquare k(\rho,T)/C\downarrow p\ (T)\ , \qquad H<Hf(p)\kappa\downarrow 0\ , \qquad H\geq H\downarrow f\ (p)$$

Moisture diffusivity

Take into account water in temperate ice
No boundary condition for CTS

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Energy diffusion/advection

```
Solver XX

  Equation = String "Enthalpy Equation"
  Procedure = File “ElmerIceSolvers" "EnthalpySolver"
  Variable = String "Enthalpy_h"
  Linear System Solver = "Iterative"
  Linear System Iterative Method = "BiCGStab"
  Linear System Max Iterations = 500
  Linear System Convergence Tolerance = 1.0E-07
  Linear System Abort Not Converged = True
  Linear System Preconditioning = "ILU0"
  Linear System Residual Output = 1
  Steady State Convergence Tolerance = 1.0E-04
  Nonlinear System Convergence Tolerance = 1.0E-07
  Nonlinear System Max Iterations = 3
  Nonlinear System Relaxation Factor = Real 1.0
  Apply Limiter = Logical true
  Apply Dirichlet = Logical True
  Stabilize = True

  Exported Variable 1 = String "Phase Change Enthalpy"
  Exported Variable 1 DOFs = 1
  Exported Variable 2 = String "water content"
  Exported Variable 2 DOFs = 1
  Exported Variable 3 = String "temperature"
  Exported Variable 3 DOFs = 1
End
```

```
Constants
 T_ref_enthalpy = real 200.0
 L_heat = real 334000.0
! Cp(T) = A*T + B
 Enthalpy Heat Capacity A = real 7.253
 Enthalpy Heat Capacity B = real 146.3
 P_triple = real 0.061173
 P_surf = real 0.1013
 beta_clapeyron = real 0.0974
End
```

```
Material 1

  Enthalpy Density = XX
  Enthalpy Heat Diffusivity = XX
  Water Diffusivity = XX

End
```

k/C_p

```
Body Force 1

  Heat Source = XX
  Enthalpy_h Upper Limit = Variable Phase
Change Enthalpy
        real MATC "tx+0.03*334000.0"
  Enthalpy_h Lower Limit = real 0.0

End
```

Strain Heating

Water Content limited to 3%

Energy diffusion/advection

```
! Upper Surface
Boundary Condition 3
  Target Boundaries = 3

Enthalpy_h = XX


End

! Bedrock
Boundary Condition 1
  Target Boundaries = 1
    Name = "bed"

  Enthalpy Heat Flux BC = logical True
  Enthalpy Heat Flux = real $0.040*3600*24*365.25
End
```

Dirichlet

Basal heat flux (J yr^{-1} m^{-2})

Percolation and Refreezing

Three different approaches with decreasing complexity:

1 – Water percolation based on Colbeck 1973
- 30min time step and few centimeter vertical resolution

Advection/Reaction solver

See [*Gilbert et al., Cryosphere*, 2014]

Total saturation

Residual saturation

Effective Saturation

$$S_e = (S - S_r)/(1 - S_r)$$

$$\Phi(1 - S_r)\,\partial S_e/\partial t + n\rho g K \mu^{-1} S_e^{n-1}\,\partial S_e/\partial z = -\mathrm{R}$$

Refreezing

n=3, non linear

Percolation and Refreezing

Three different approaches with decreasing complexity:

1 – Water percolation based on Colbeck 1973
  - 30min time step and few centimeter vertical resolution

2 – Water percolation at constant speed
  - Daily time step, 10 to 50 cm vertical resolution

Advection/Reaction solver

See [*Gilbert et al., Cryosphere*, 2014]

$$S_e = \frac{S - S_r}{1 - S_r}$$

$$\frac{\partial S_e}{\partial t} + v_p \frac{\partial S_e}{\partial z} = -\mathrm{R}$$

Constant

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Percolation and Refreezing

Three different approaches with decreasing complexity:

1 – Water percolation based on Colbeck 1973
  - 30min time step and few centimeter vertical resolution

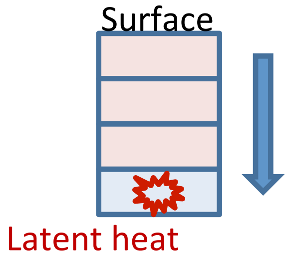
2 – Water percolation at constant speed
  - Daily time step, 10 to 50 cm vertical resolution

Advection/Reaction solver

See [*Gilbert et al., Cryosphere*, 2014]

3 – Simple box model
  - No kinetic aspect, 50cm to 1m vertical resolution

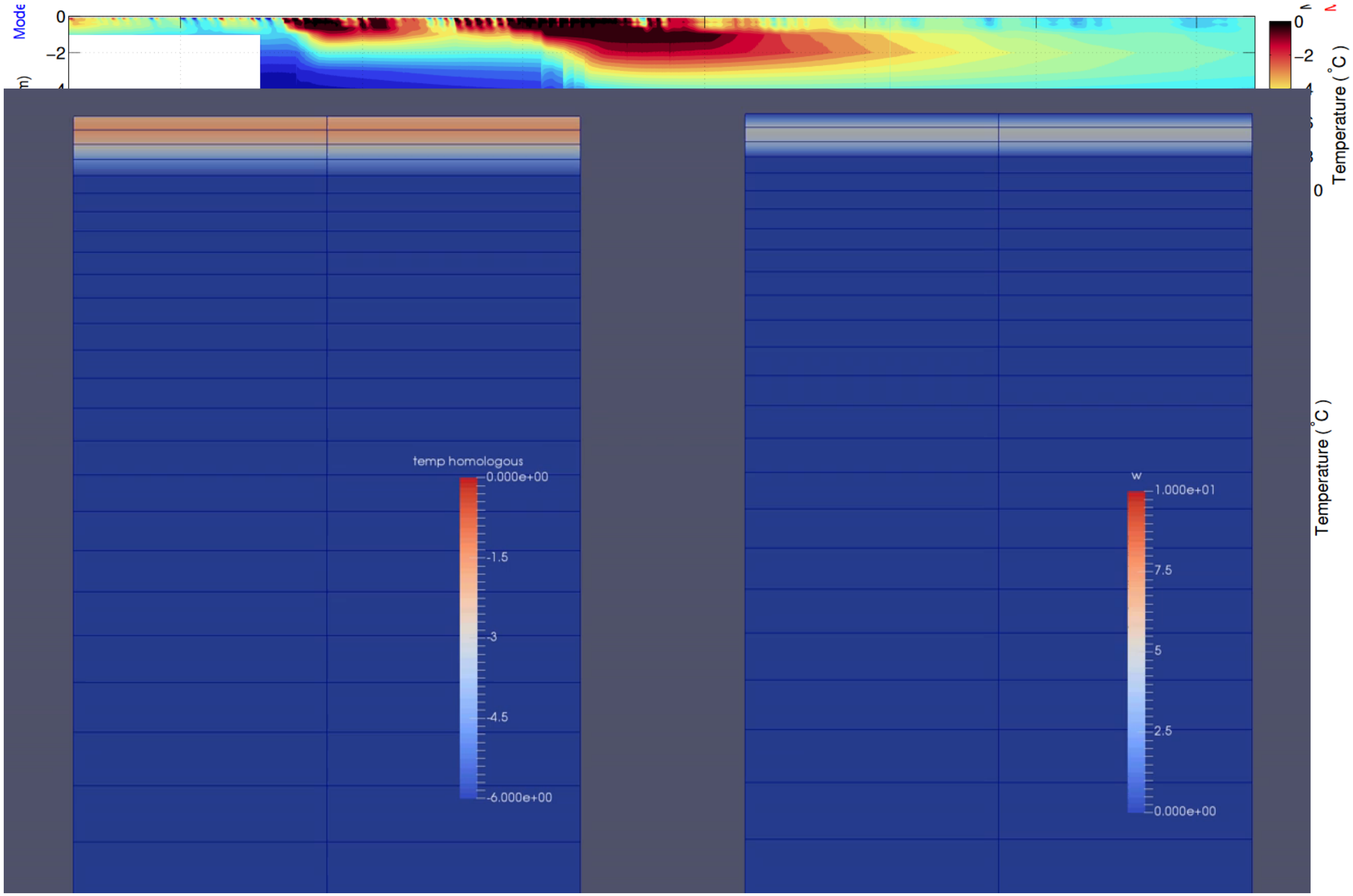
Simple solver for vertical transfer



Latent heat released in the first cold layer from the top

$$S_{e} = S - S_{r} / 1 - S_{r}$$

Percolation and Refreezing



DATA

METHOD 1

METHOD 2

Percolation and Refreezing

For large scale application: box model

```
Solver XX

Equation = String "percol_1D"
Procedure = File "bin/Percol_1D_solver" "percol_1D_solver"

End
```

```
Constants
 L_heat = real 334000.0
 rho_ice = real 917.0
 rho_w = real 1000.0
 Sr = real 0.01
End
```

Water content in wet firn

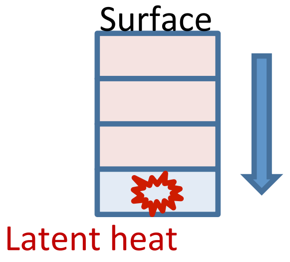
```
Material 1
  Enthalpy Density = XX
EnD
```

```
! Upper Surface
Boundary Condition 2
Target Boundaries = 2
Surf_melt = XX
END
```

Need **enthalpy_h** and **depth** variable

Works only for vertically extruded 3D mesh

Directly modifies the enthalpy variable



Latent heat released in the first cold layer from the top

Firn/snow density model

```
Material 1
  Enthalpy Density = ??
EnD
```

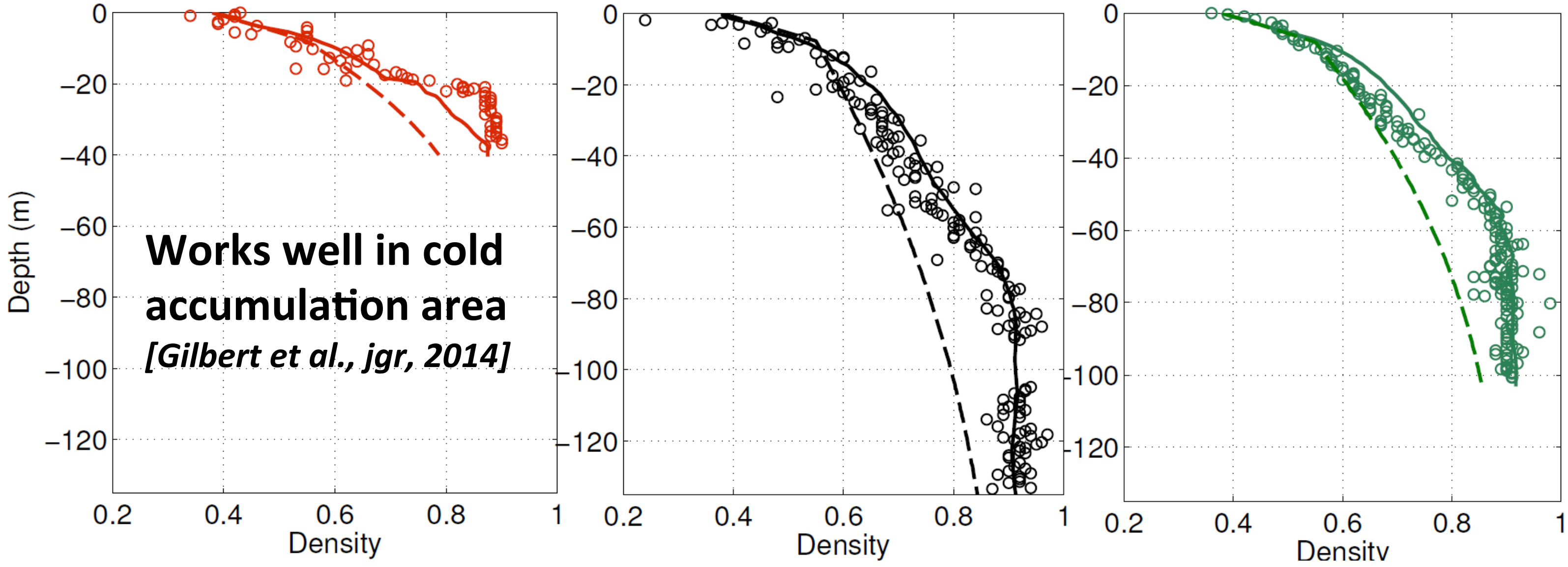
1 – Coupling density equation, porous solver and percolation/refreezing

Solved with advection/reaction →

$$\partial\rho/\partial t + div(\rho u) = R$$

Refreezing rate (kg m^{-3} yr^{-1}) from percolation / refreezing

Velocity from porous solver (div(u)≠0)



Works well in cold accumulation area

[Gilbert et al., jgr, 2014]

Firn/snow density model

```
Material 1
  Enthalpy Density = ??
EnD
```

2 - For **wet accumulation area** and around equilibrium line better to use a **proper snow model** providing input for Elmer/Ice

3 - **Alternative simple option:** compute firn thickness as a surface variable calculated from mass balance:

$$H_{firn}(t+dt)=H_{firn}(t)+(m_b-H_{firn}\times a)dt$$

If $H_{firn}(t+dt)<0$ then $H_{firn}(t+dt)=0$

At steady state: $H_{firn}=(m_b/a)$

Densification parameter

Compute the variable density from H_{firn} **(m w.eq.)** assuming **linear profile:**

$$\rho(z)=\rho_0+(\rho_{ice}^2-\rho_0^2)/2\rho$$

Surface density

Depth

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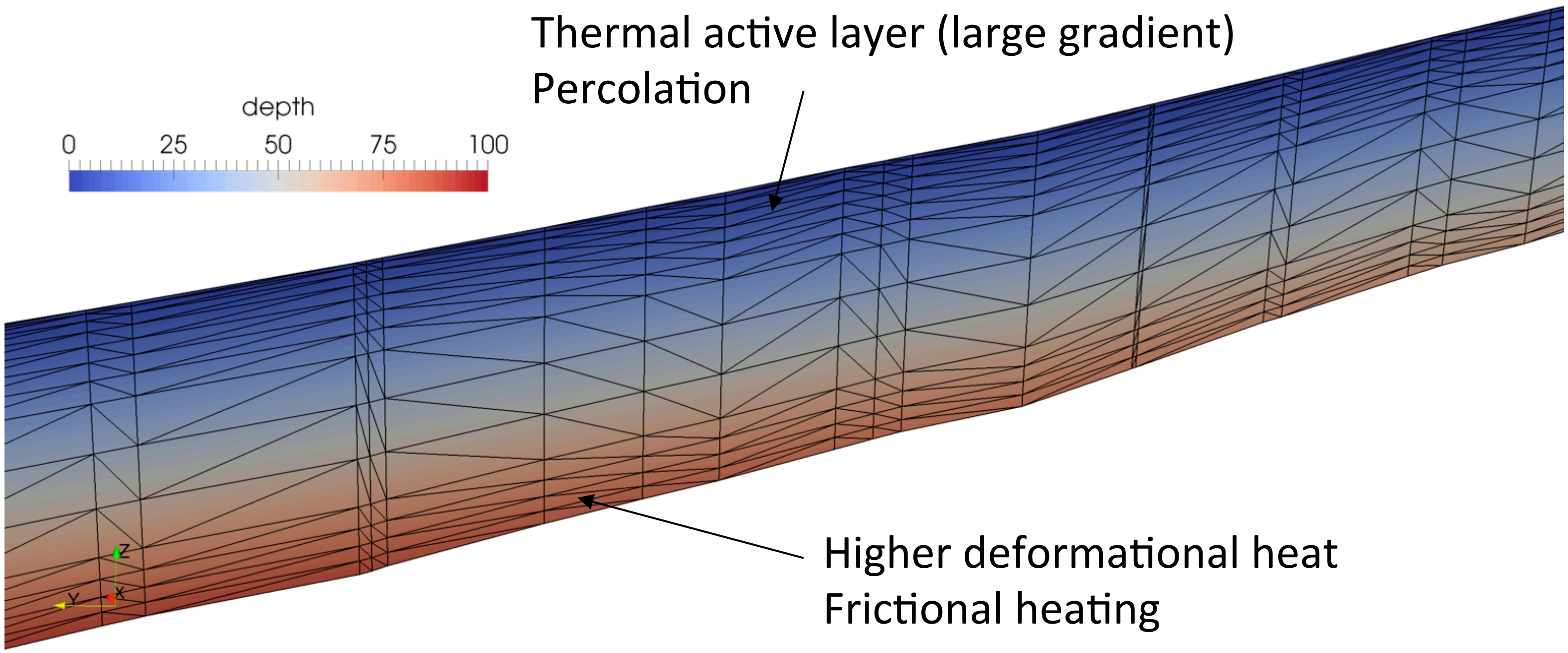
Mesh vertical resolution

- **Refine at the surface according to time-step**
- **Refine at the bottom**

~~LINEAR REPARTITION FROM EXTRUSION~~



Thermal active layer (large gradient)
Percolation

Higher deformational heat
Frictional heating

Boundary conditions

Surface :

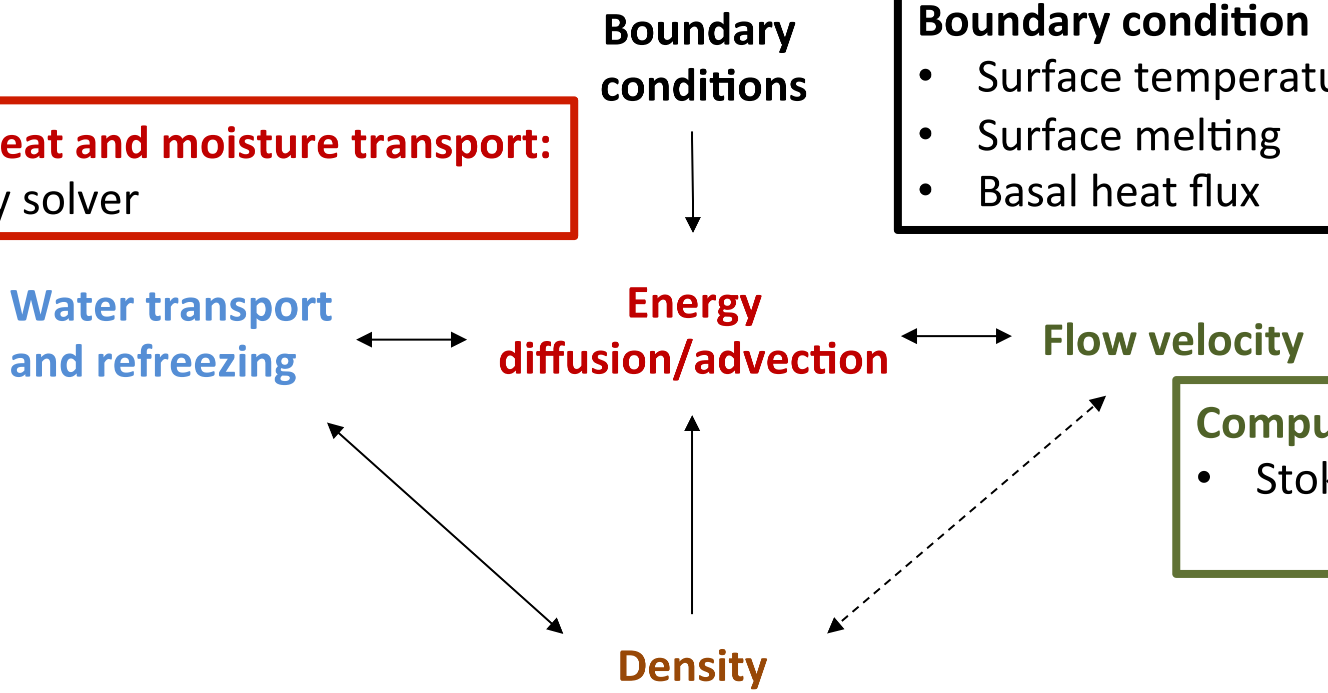
- **Surface temperature** imposed by the surface energy balance or air temperature

- **Surface melting** imposed by the surface energy balance or degree day model

Bottom :

- Heat flux
- Frictional heating

Key aspects



Boundary condition
- Surface temperature
- Surface melting
- Basal heat flux

Compute heat and moisture transport:
- Enthalpy solver

Compute ice flow
- Stokes or Porous

Compute percolation and refreezing:
- Enthalpy solver and **adv/reac solver**
    - Constant velocity
    - Non linear approach Colbeck 1973
- Enthalpy solver and **Box model**

Compute density:
- **Porous** and **adv/reac** solver
- Simple custom function from mass balance
- External snow model

Aru twin glacier collapse

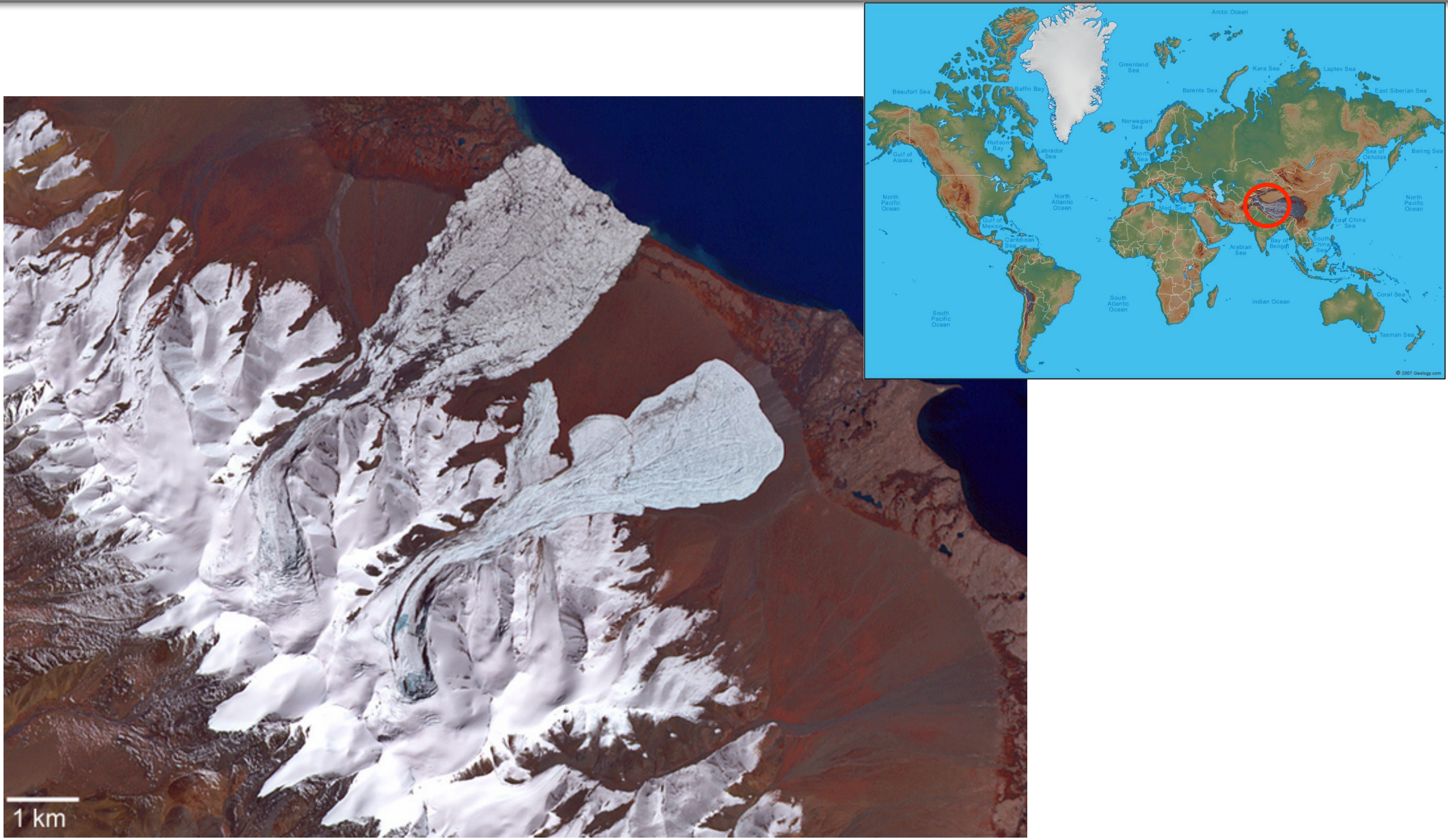
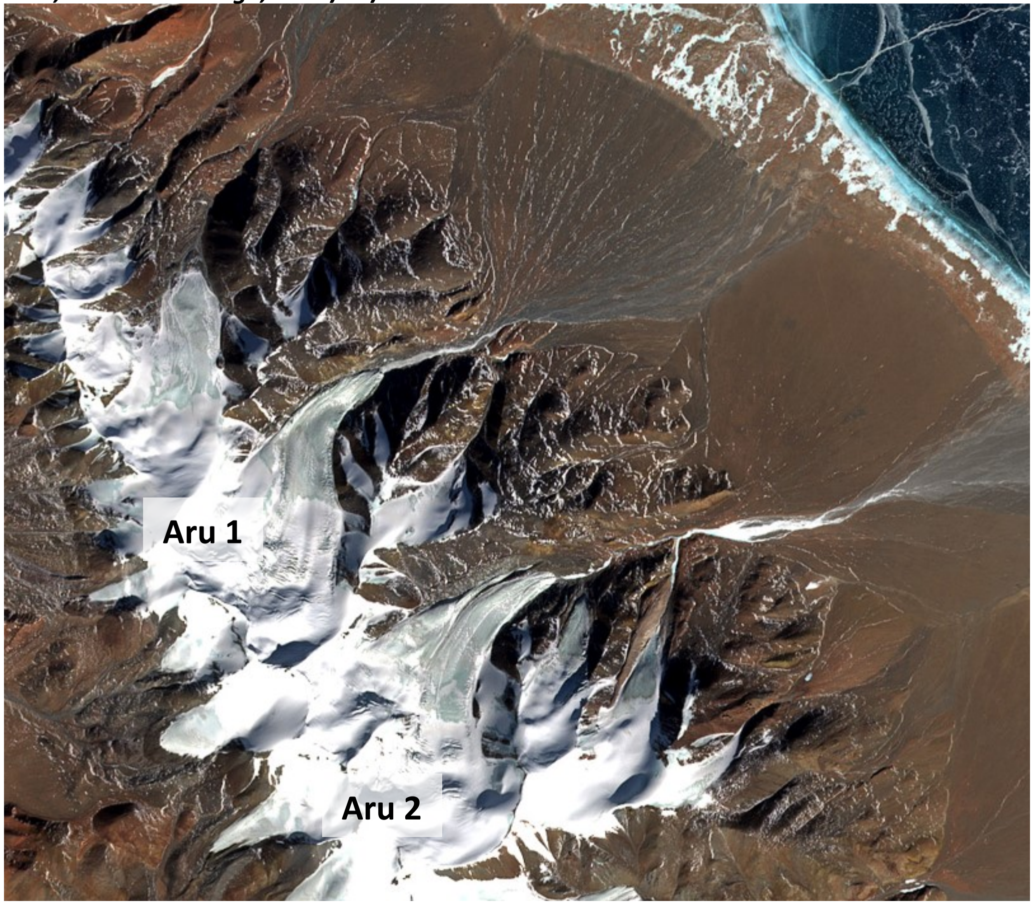


Image acquired by NASA's satellite ASTER on 4th October 2016.

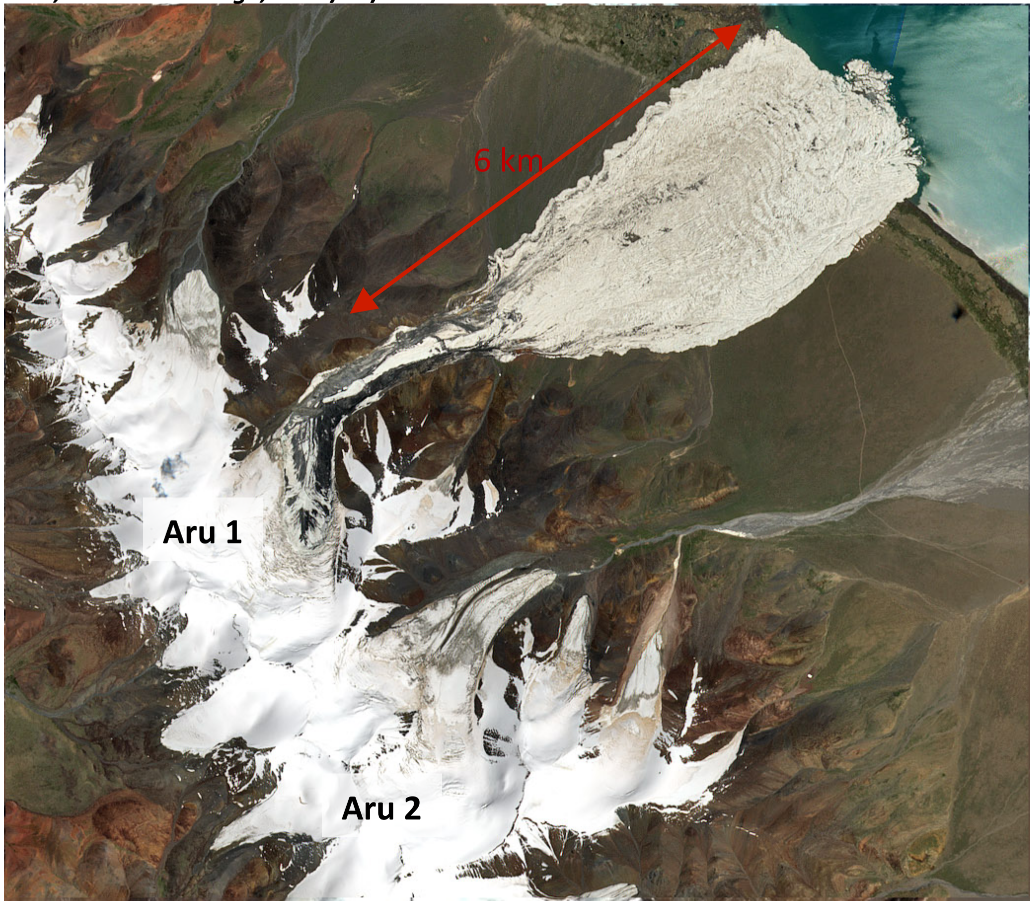
Aru twin glacier collapse

ESA, Sentinel 2 image, 2016/01/10



Aru twin glacier collapse

ESA, Sentinel 2 image, 2016/07/21



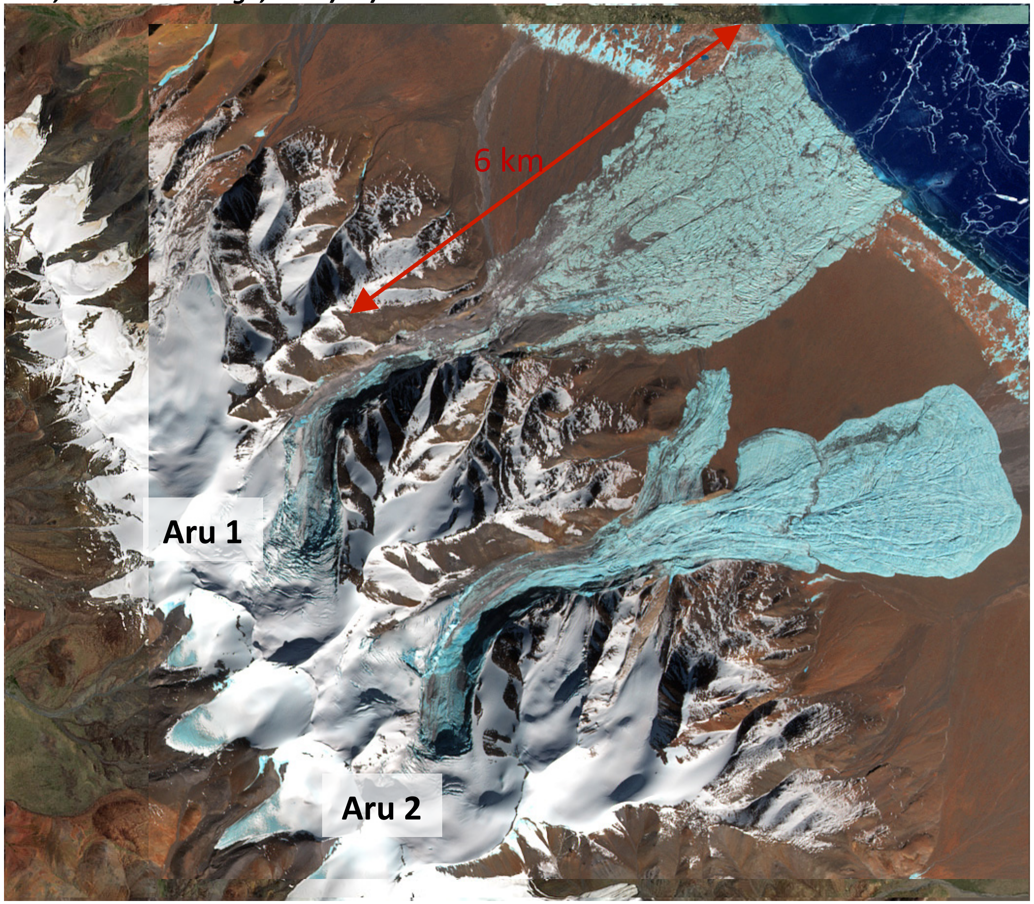
17 July 2016: first avalanche *Tian et al.*, JOG, 2016

- Detachment elevation: 5750-5200 m a.s.l.
- Glacier slope ≈ 13°
- Cone slope ≈ 3°
- Volume ≈ **68 M m^3**
- Deposit area ≈ **8-9 km^2**

Nine people killed

Aru twin glacier collapse

ESA, Sentinel 2 image, 2016/12/08



17 July 2016: first avalanche *Tian et al.*, JOG, 2016

- Detachment elevation: 5750-5200 m a.s.l.
- Glacier slope ≈ 13°
- Cone slope ≈ 3°
- Volume ≈ **68 M m^3**
- Deposit area ≈ **8-9 km^2**

Nine people killed

21 September 2016: second avalanche

- Detachment elevation: 5800-5250 m a.s.l.
- Glacier slope ≈ 11°
- Cone slope ≈ 3°
- Volume ≈ **83 M m^3**
- Deposit area ≈ **6-7 km^2**
- **Two distinct events** at about 8 hours interval

No casualties

Aru twin glacier collapse


Glacier level !

2016/10/23

Aru 1 (northern glacier)


2016/10/04

Aru 2 (southern glacier)

Pictures: Tandong Yao

Aru twin glacier collapse

DATA:

- 6 DEM before collapses (2000, 2011, 2013, 2014, 2015a,2015b)
- 1 DEM after collapses
- ERA-interim reanalysis

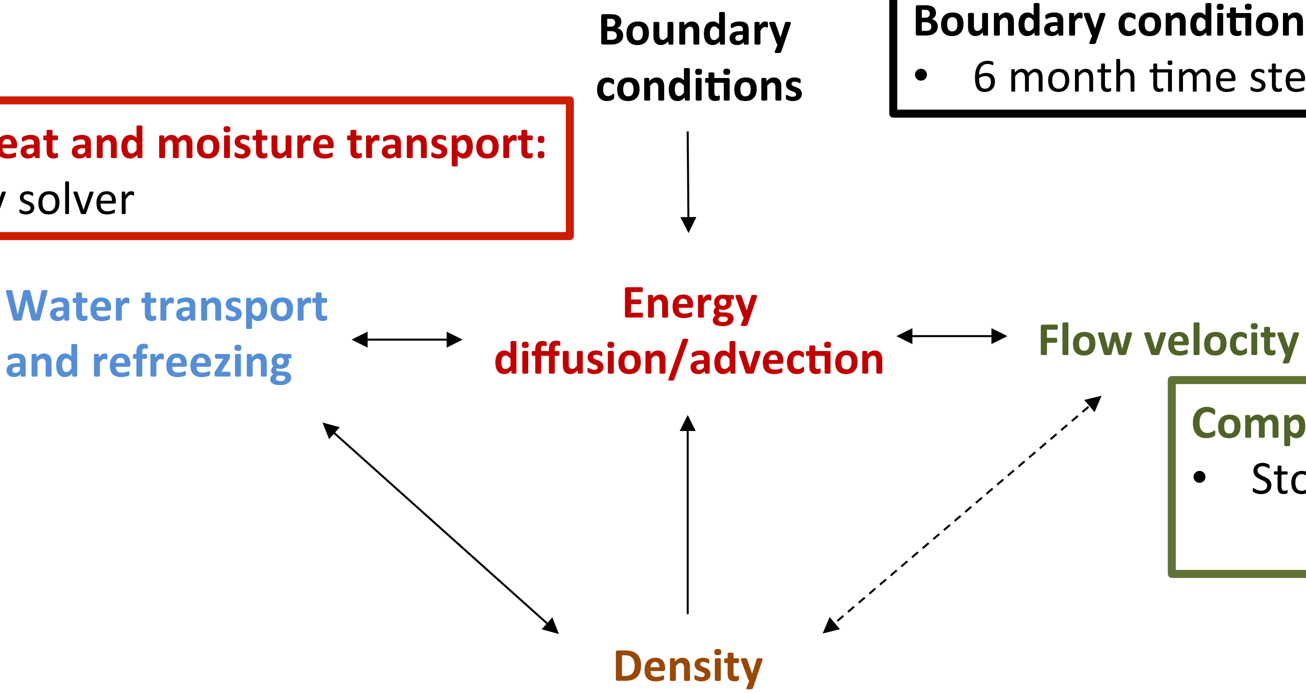
OBJECTIVES:

- Model thermal regime
- Model mass balance
- Model basal condition and force balance evolution of the detachment prior to collapse

Aru twin glacier collapse

Boundary condition
- 6 month time step

Compute heat and moisture transport:
- Enthalpy solver



Boundary conditions

Water transport and refreezing

Energy diffusion/advection

Flow velocity

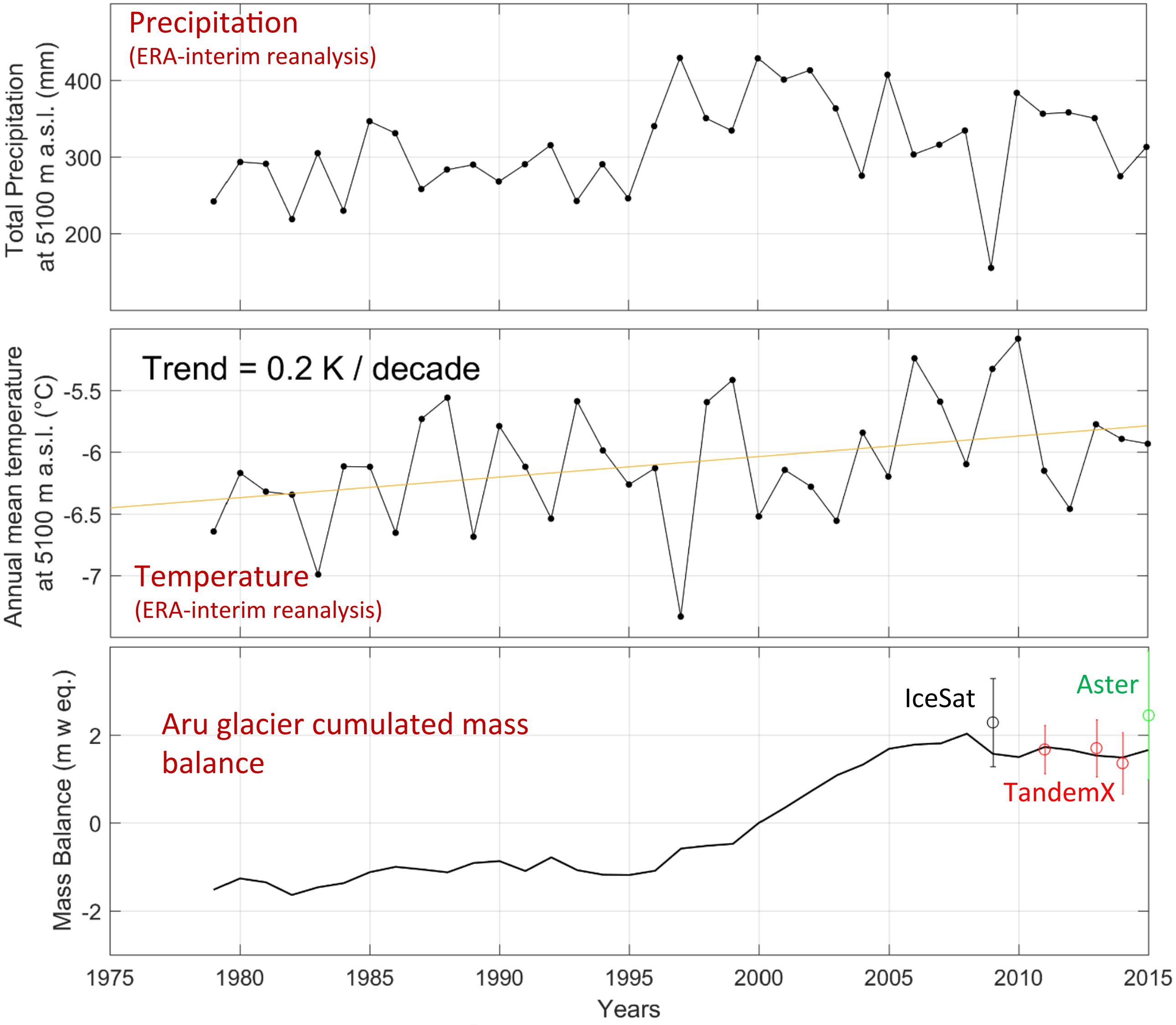
Density

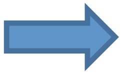
Compute ice flow
- Stokes

Compute percolation and refreezing:
- Enthalpy solver and **Box model**

Compute density:
- Simple custom function from mass balance

Aru twin glacier collapse

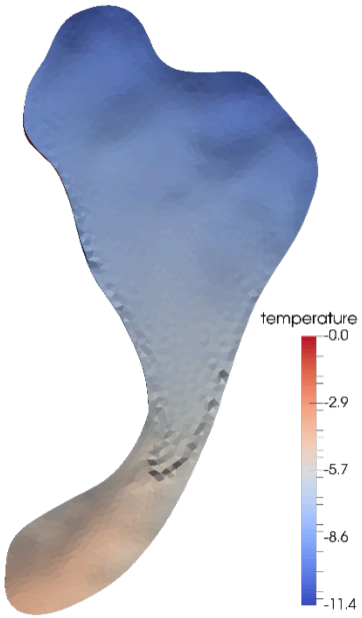




Surface melting
Surface temperature
Firn thickness

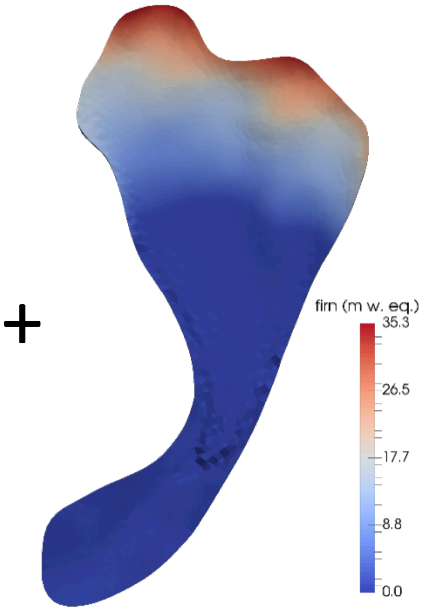
Aru twin glacier collapse

Steady State mass balance condition



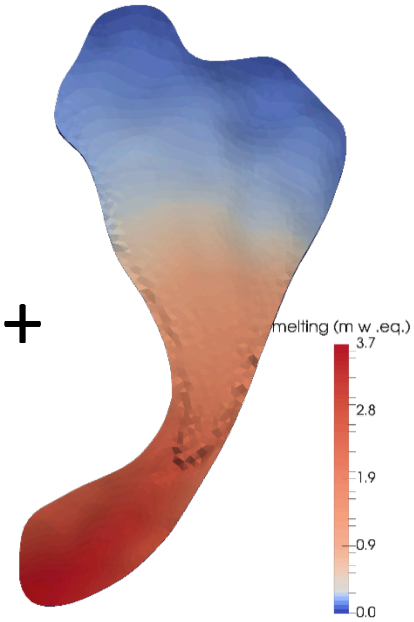
Surface Temperature

+



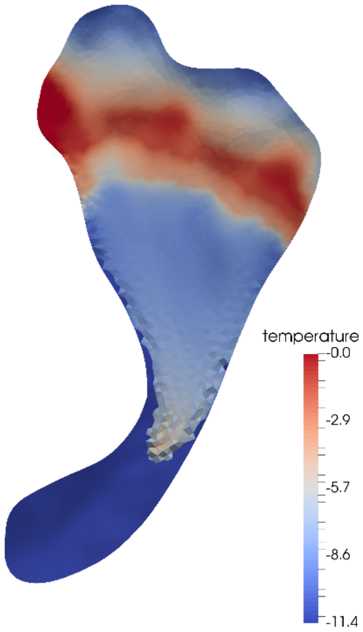
Firn thickness

+



Surface melting

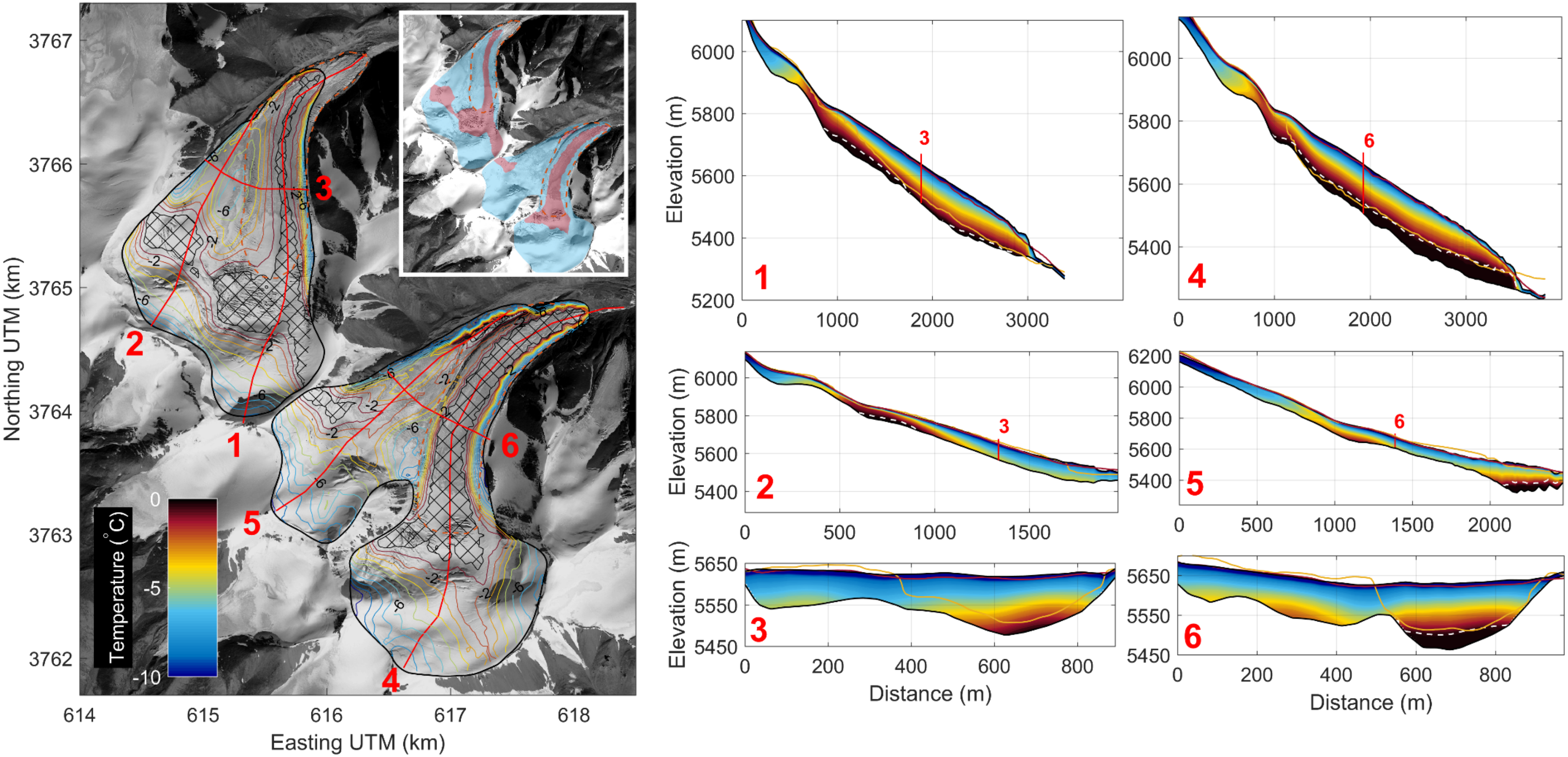
=



10 m depth temperature

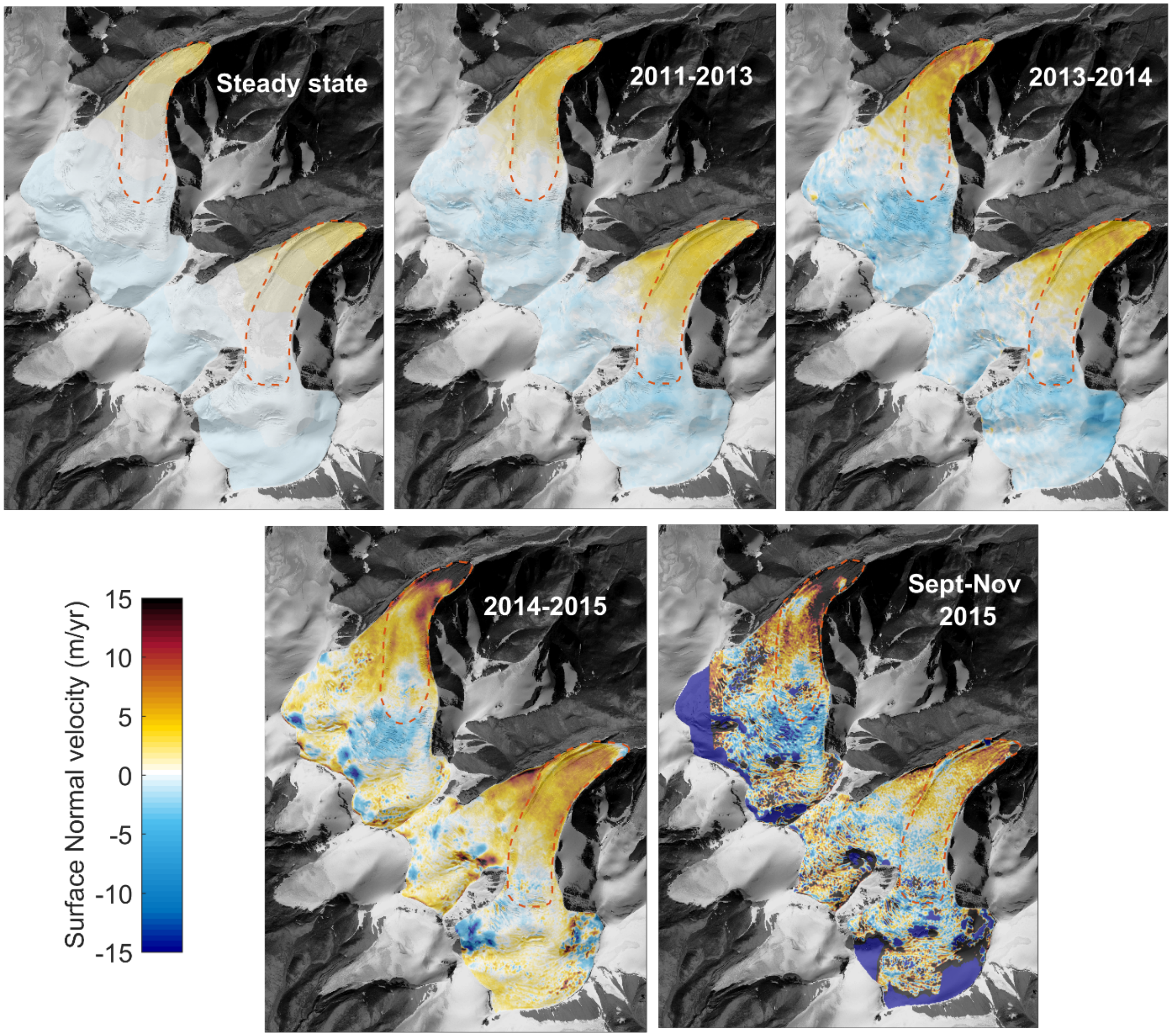
Simple approach = box model + simple firn parametrization + enthalpy solver + stokes solver

Aru twin glacier collapse



3D steady state temperature

Aru twin glacier collapse

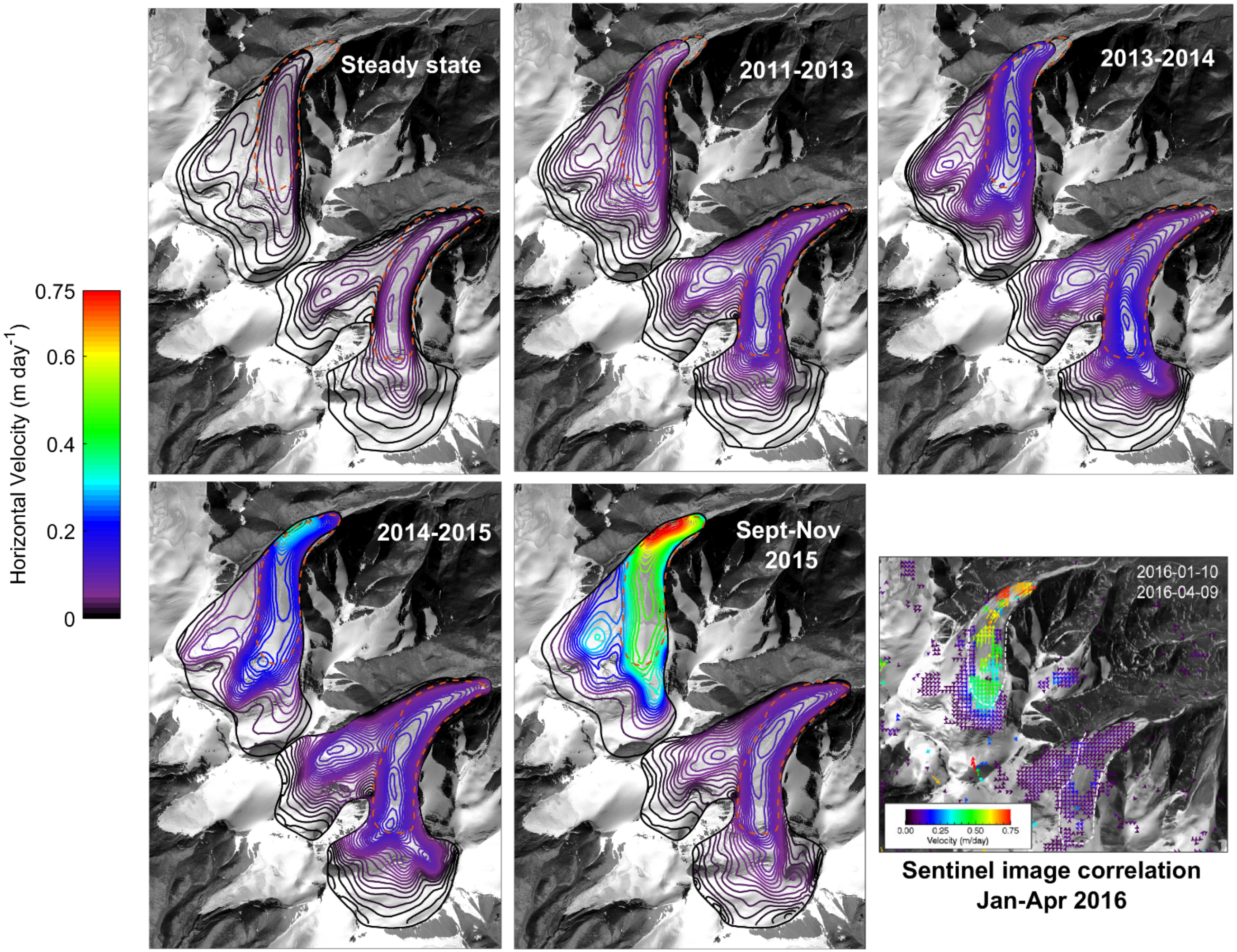


Infer glacier dynamics from elevation change

=

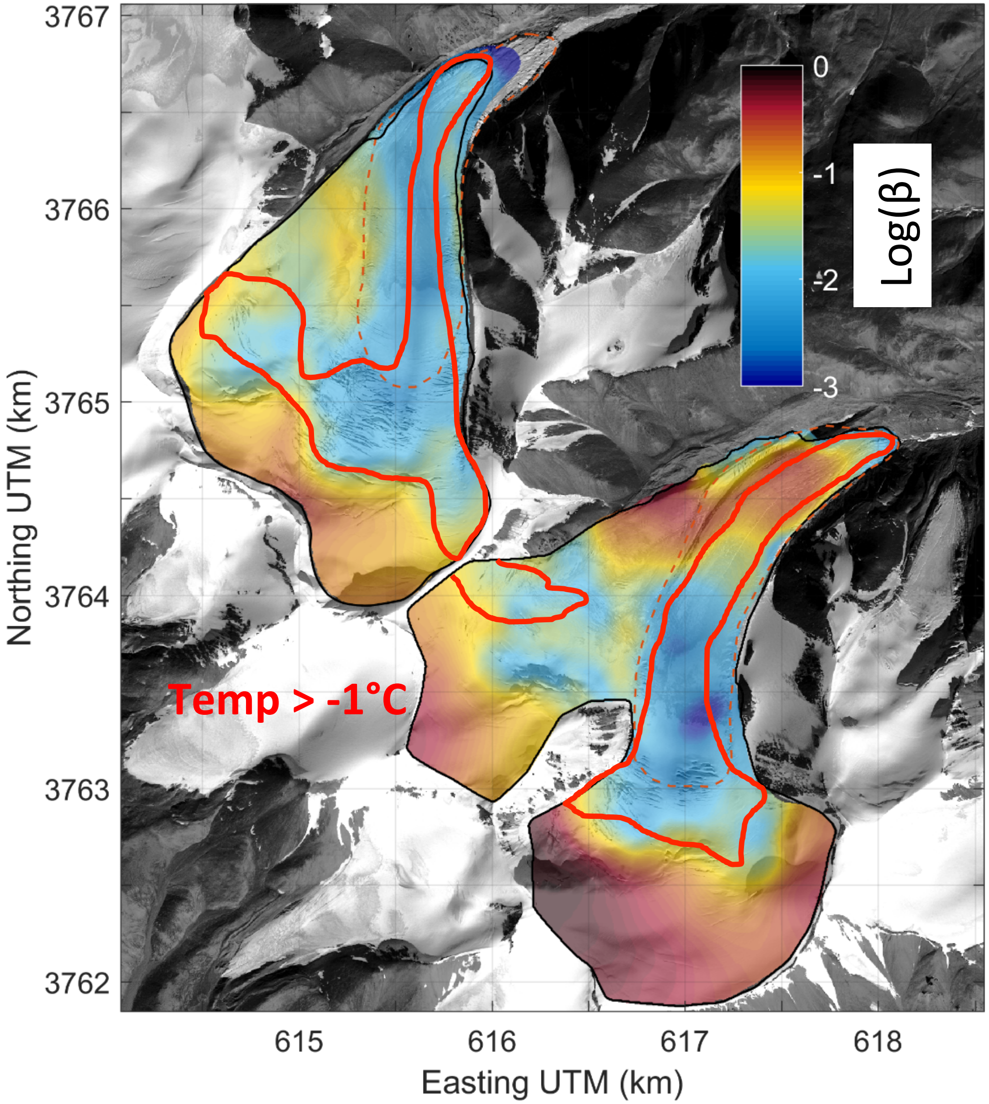
Invert for friction using surface-normal velocity

Aru twin glacier collapse



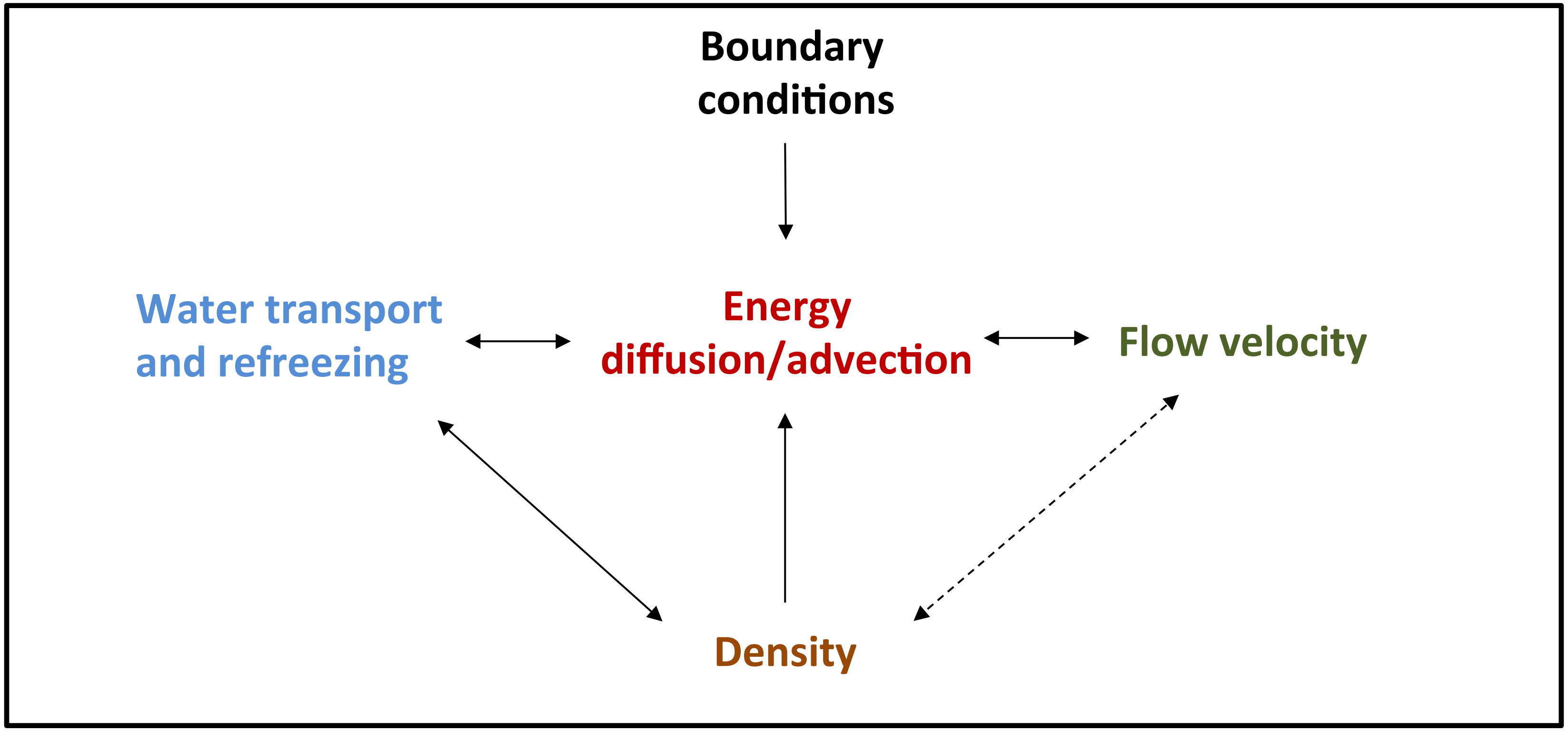
Sentinel image correlation Jan-Apr 2016

Aru twin glacier collapse



Fairly good agreement with modeled temperature

Thermal Regime with Elmer/Ice



Coupled system to solve with different approaches possible depending on data, computation time and expected precision of the results

Thermal Regime with Elmer/Ice

Recommended approaches:

Cold accumulation zone on restricted area, firn thickness >≈ 40% total thickness

Porous solver coupled with density / Advect-React Solver / sub-daily to daily timestep /Enthalpy solver

Use different time-steps for porous/density or stokes
Solve advec/react only on a firn body

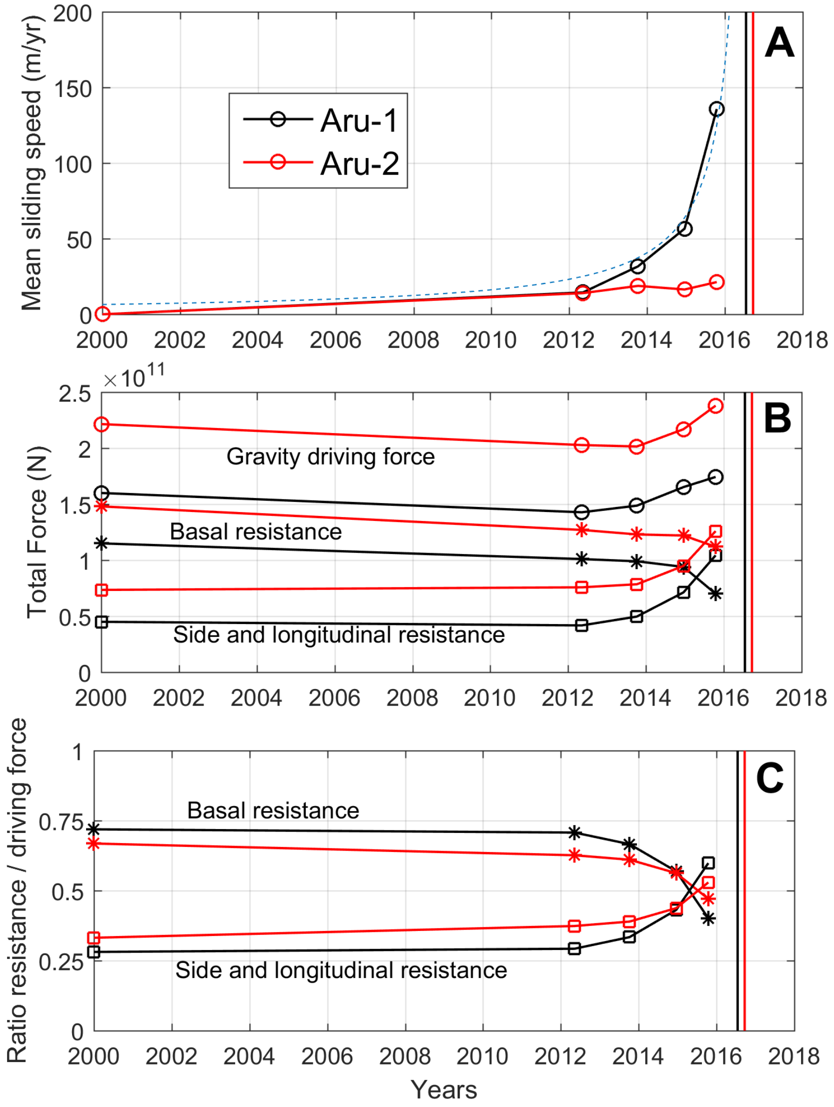
Entire glacier

Higher reliability	**Lower reliability**
External snow model	Firn parametrization from mass balance
Advect-Reat Solver (const velocity)	Box model
Daily timestep	Daily to 6 month time step
Stokes solver	Stokes solver
Enthalpy solver	Enthalpy solver

Further developments to be done …

- Include gravitational moisture transport in temperate ice [*Hewitt and Schoof*, 2017]
- Model water transport through fracture in pure ice
- Coupling Enthalpy solver and subglacial hydrology (GLaDs)

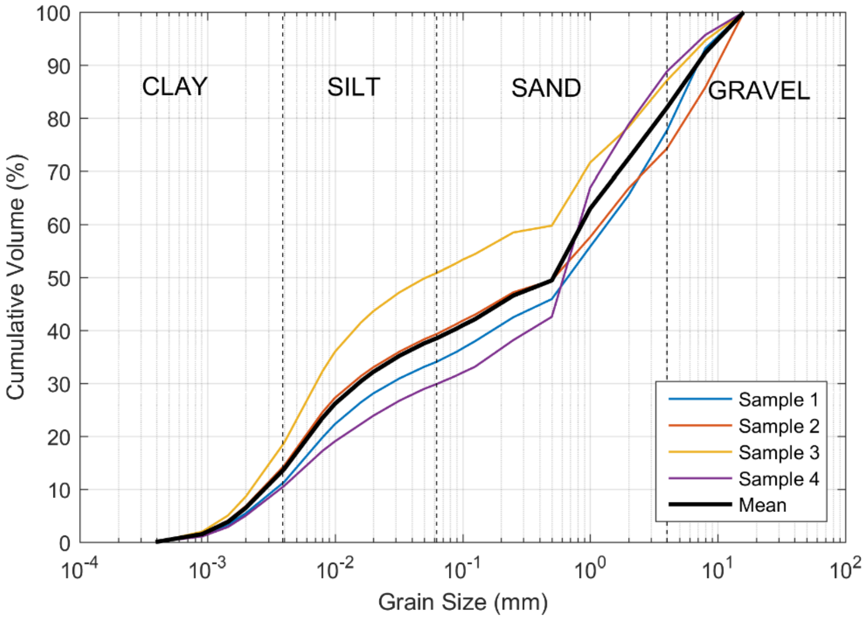
Aru twin glacier collapse

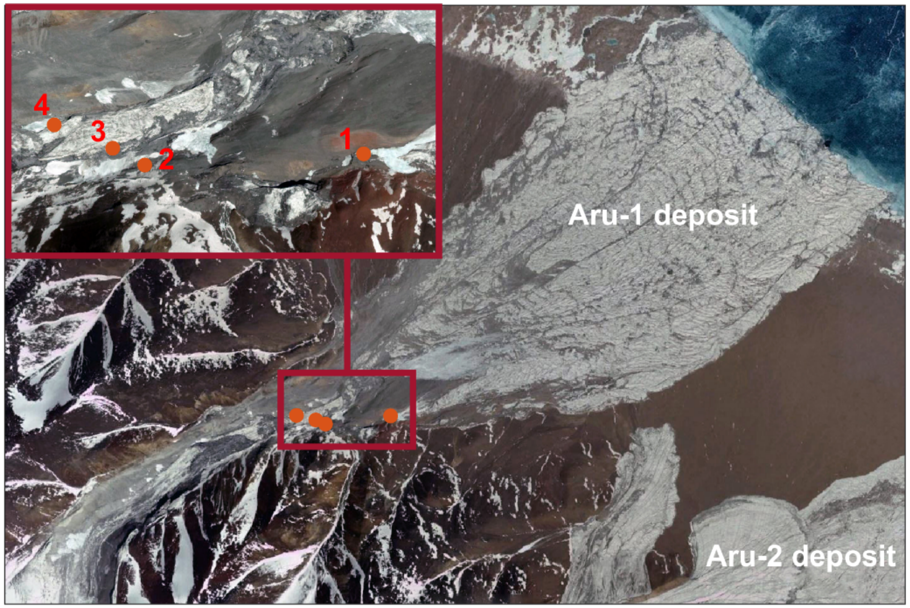


Different behavior in velocity but similar evolution of the force balance

Aru-2 less sensitive to basal resistance ?

Aru twin glacier collapse





Role of soft-bed property

- Low bed roughness
- Plastic behaviour in the till
- Low friction angle
- Hydrology?