

Numerical investigation of evapotranspiration processes in a forested watershed of Central Siberia

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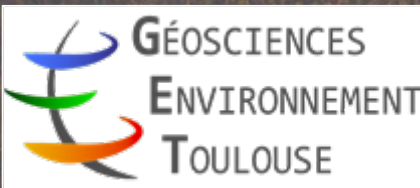
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Vegetation and active layer in boreal forests - evapotranspiration



Problematic: quantitative assessment of seasonal and spatial variabilities of evapotranspirative water fluxes from the active layer of forested, permafrost-dominated areas

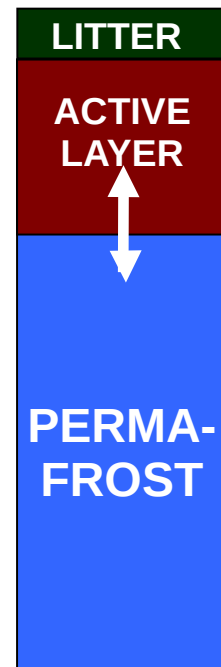
Studied area:

- Central Siberia, sub-watershed of the Nizhnyaya Tunguska
- Vegetation cover: larch forest ; lithology: basalts and tuffs
- Main spatial variability: south aspected / north aspected slopes



Goals:

- Model accurately the thermo-hydrological transfers in soils of forested, permafrost-dominated areas
- Study the impact of evapotranspiration conditions on active layer dynamics



Methodological approach :

Mechanistic modeling of thermal and hydrological transfers at the experimental watershed scale

- Time scales : years
- Space scales : 10's of km²

Case of application: permafrost annual dynamics in Kulingdakan watershed

Mechanistic modeling of thermal and hydrological transfers

Numerical modelling of coupled transfers of water and energy with phase change within soils: **complex problem, broad associated literature** (e.g.: Guymon and Luthin, 1974, Sjöberg et al., 2016).

Large computation times may be encountered: need of HPC methods. Use of **massively parallel computation** is necessary (e.g.: Painter *et al.*, 2013, Walvoord and Kurylyk, 2016).

=> a devoted solver with the **open source, generalist CFD tool**
OpenFOAM®: permaFoam

permaFoam: considered conservation equations

3D coupled heat and water transfers in variably saturated porous media, taking into account evapotranspiration and freeze/thaw of the poral water (Orgogozo et al., 2016, under review)

couplings, non linearities

Richards equation with evapotranspiration:

$$C_H(h) \frac{\partial h}{\partial t} = \nabla \cdot (K_H(h, T) \nabla (h + z)) + Q_{AET}(h, T)$$

Thermal transfer equation with freeze/thaw:

$$\frac{\partial (C_{T_{eq}}(h, T) T)}{\partial t} + \nabla \cdot (\mathbf{v}(h, T) C_{T_{liquid}} T) = \nabla \cdot (K_{T_{eq}}(h, T) \nabla T) + L \frac{\partial \theta_{ice}(h, T)}{\partial t}$$

Stiff problems, non linearities, couplings, few references solutions:
InterFrost Benchmark (Grenier et al., 2018)

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Term of evapotranspiration water uptake within soil

- **Geometry of the root layers (rooting depth $\rightarrow V_{root\ zone}$, $\chi_{root\ zone}(\mathbf{x})$) in Kulingdakan watershed slopes: Field survey (Viers *et al.*, 2013)**
- **Potential Evapotranspiration estimator: Hamon formula (e.g.: Lu *et al.*, 2005) Already used in forested boreal areas (Frolking *et al.*, 1996 ; Frolking 1997)**

$$PET_d = \begin{cases} 218,527 \frac{L_d}{(T_{air}+273.3)} \exp\left(17.26939 \frac{T_{air}}{T_{air}+237.3}\right) & \text{if } T_{air} > 0 \\ 0 & \text{if } T_{air} \leq 0 \end{cases}$$

- **Field of actual evapotranspiration within soil with freeze/thaw (Modified from Orgogozo, 2015)**

$$Q_{AET}(h, \mathbf{x}) = \begin{cases} Q_{PET}(\mathbf{x}) & \text{if } \left(\frac{(\theta_l(h, \mathbf{x}) - \theta_{WP}(\mathbf{x}))}{\Delta t} - Q_{PET}(\mathbf{x})\right) \geq 0 \\ \frac{(\theta_l(h, \mathbf{x}) - \theta_{WP}(\mathbf{x}))}{\Delta t} & \text{if } -Q_{PET}(\mathbf{x}) < \left(\frac{(\theta_l(h, \mathbf{x}) - \theta_{WP}(\mathbf{x}))}{\Delta t} - Q_{PET}(\mathbf{x})\right) < 0 \\ 0 & \text{if } \left(\frac{(\theta_l(h, \mathbf{x}) - \theta_{WP}(\mathbf{x}))}{\Delta t} - Q_{PET}(\mathbf{x})\right) \leq -Q_{PET}(\mathbf{x}) \end{cases}$$

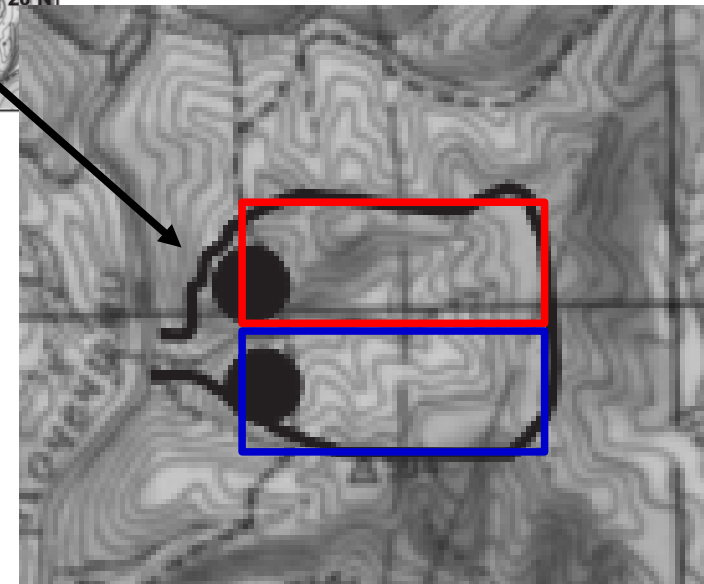
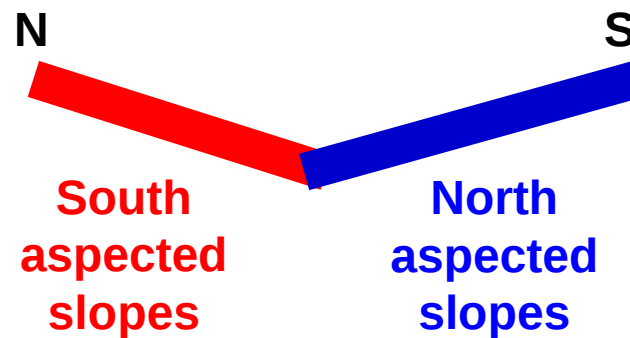
with:

$$Q_{PET}(\mathbf{x}) = PET * (S_{soil}/V_{root\ zone}) * \chi_{root\ zone}(\mathbf{x})$$

Kulingdakan: a catchment in a continuous permafrost area



(according to Prokushkin et al., 2005)



Orientation and shape of the **Kulingdakan watershed** (e.g.: Prokushkin et al., 2005, Viers et al., 2015) well suited for a **dual (N/S) 2D simplified representation**

Kulingdakan: a catchment in a boreal larch forest



South aspected slopes (SAS) North aspected slopes (NAS)



Tree stands



Soil profiles



Strong vegetation cover variability between SAS and NAS:

- aerial biomass SAS: 3.02 kgC/m²
NAS: 1.53 kgC/m²
- Leaf Area Index SAS: 0.69 m²/m²
NAS: 0.2 m²/m²
- **Rooting depth SAS: 60 cm**
NAS: 10 cm

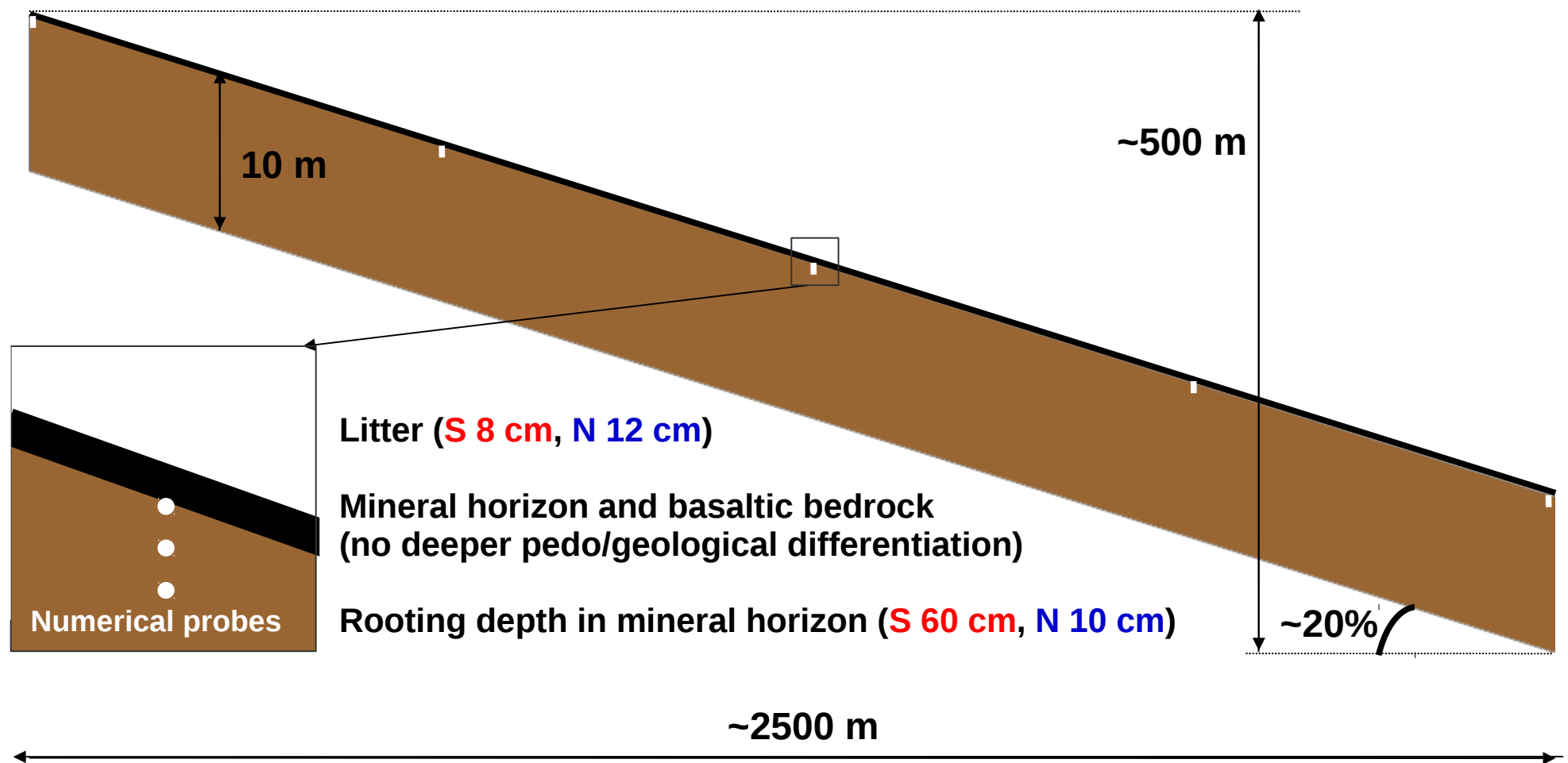
Better insolation in SAS
→ fewer but higher, larger and healthier larch trees than in NAS

More details on Kulingdakan vegetation cover: Viers et al., 2013, 2015, Prokushkin et al., 2018.

Strong SAS/NAS variability in ALT (Gentsch, 2011):

- **Maximum ALT SAS: 1.22 m**
NAS: 0.58 m

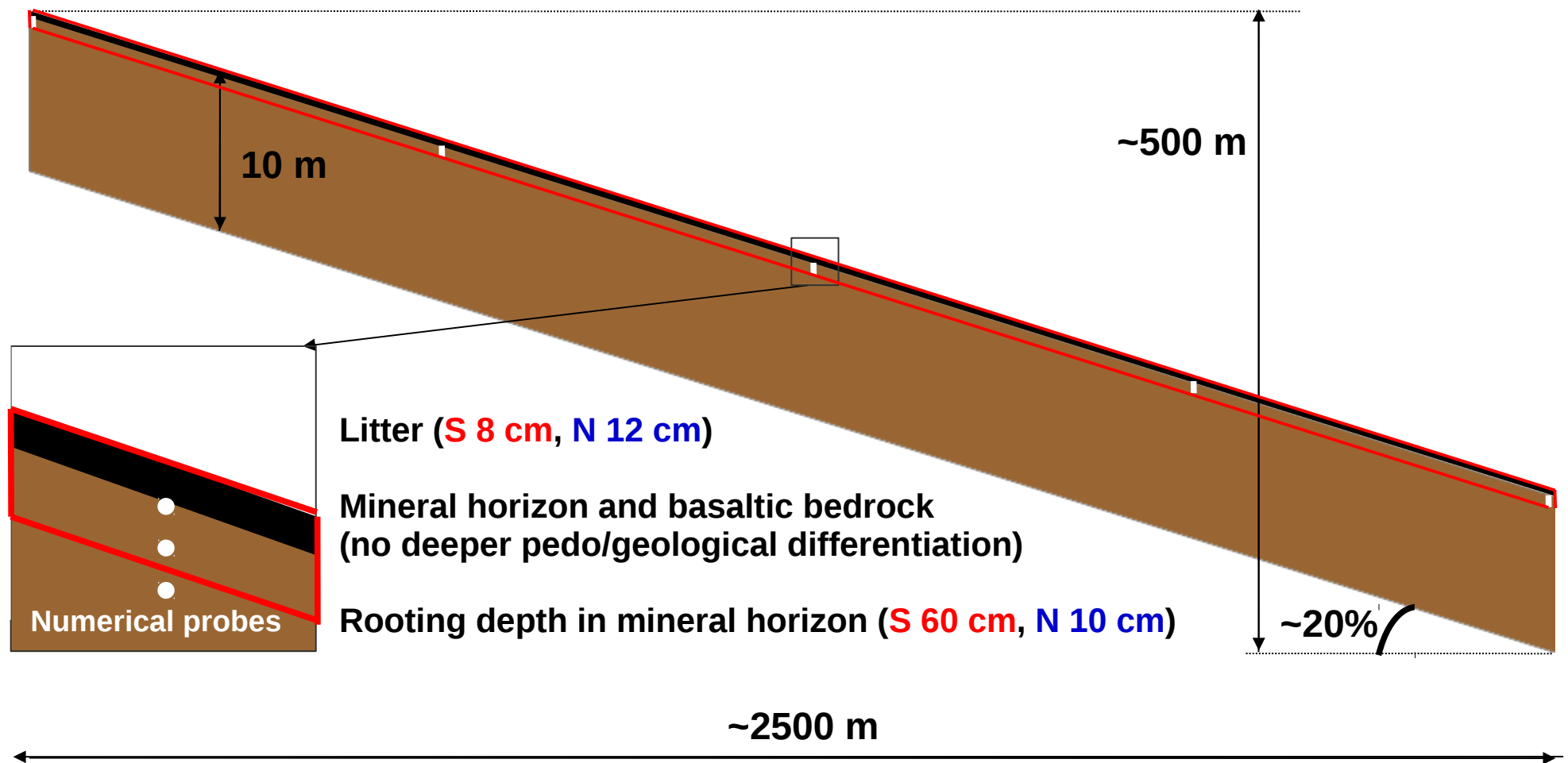
2D representation of the slopes of the catchment



Mesh:

2.5 millions of cells, thicknesses from $5 \cdot 10^{-3}$ m (top) to 0.2 m (bottom), 0.2 m width

2D representation of the slopes of the catchment

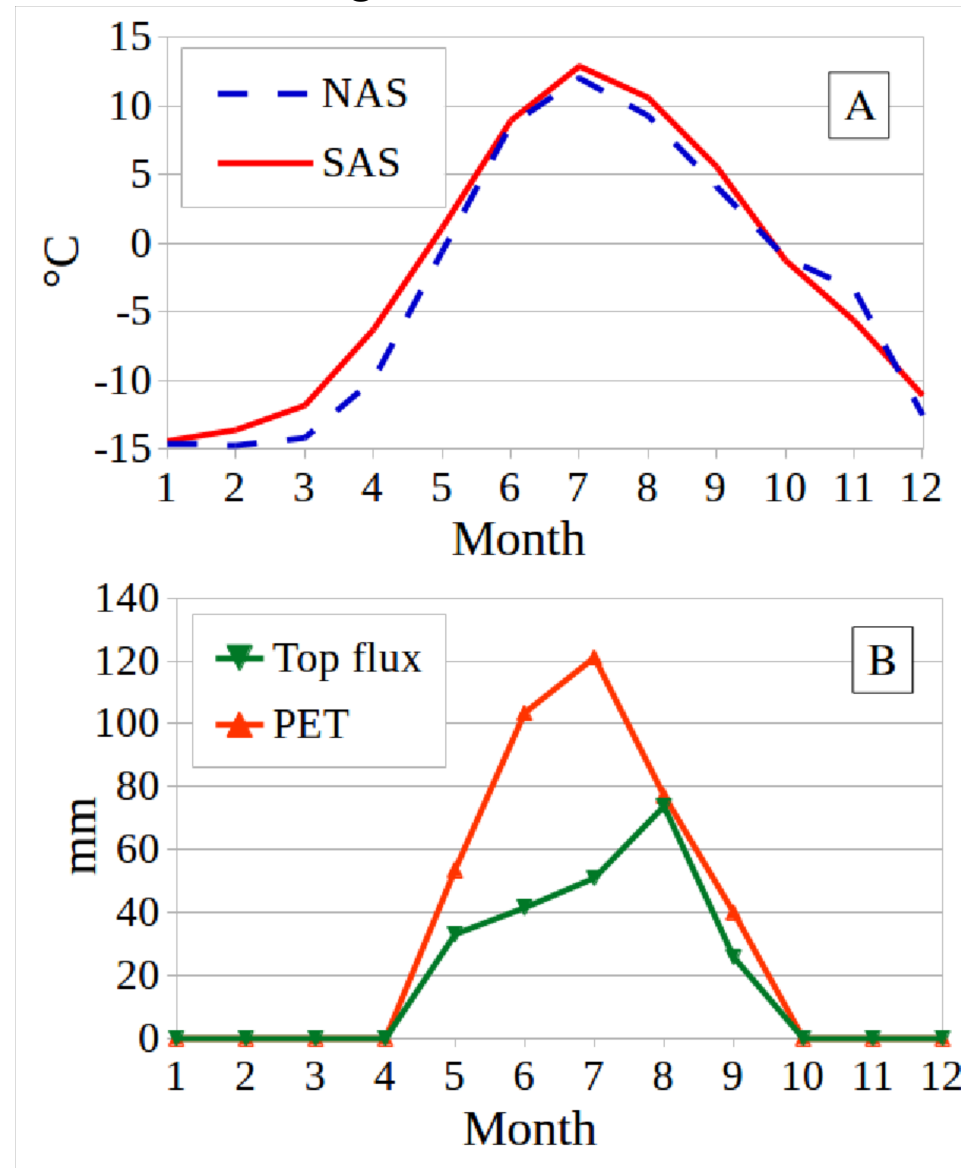


Mesh:

2.5 millions of cells, thicknesses from $5 \cdot 10^{-3}$ m (top) to 0.2 m (bottom), 0.2 m width

Climatic conditions

Multi-annual averages of the **observed monthly forcings**



Input data for a transient modeling in the N/S aspected slopes along an hydrological cycle.
(initial conditions: multi-annual cycling)

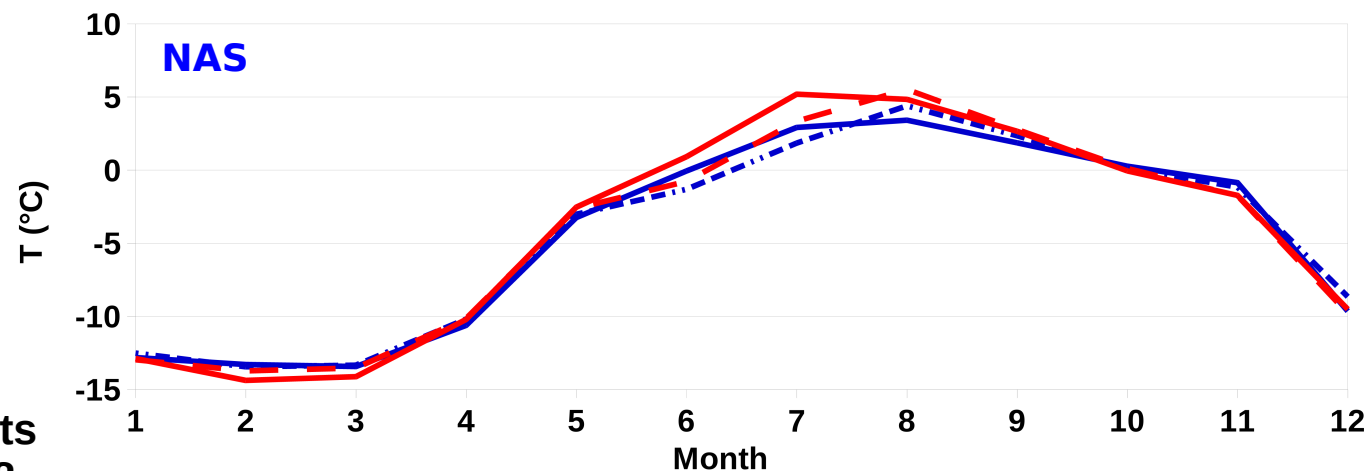
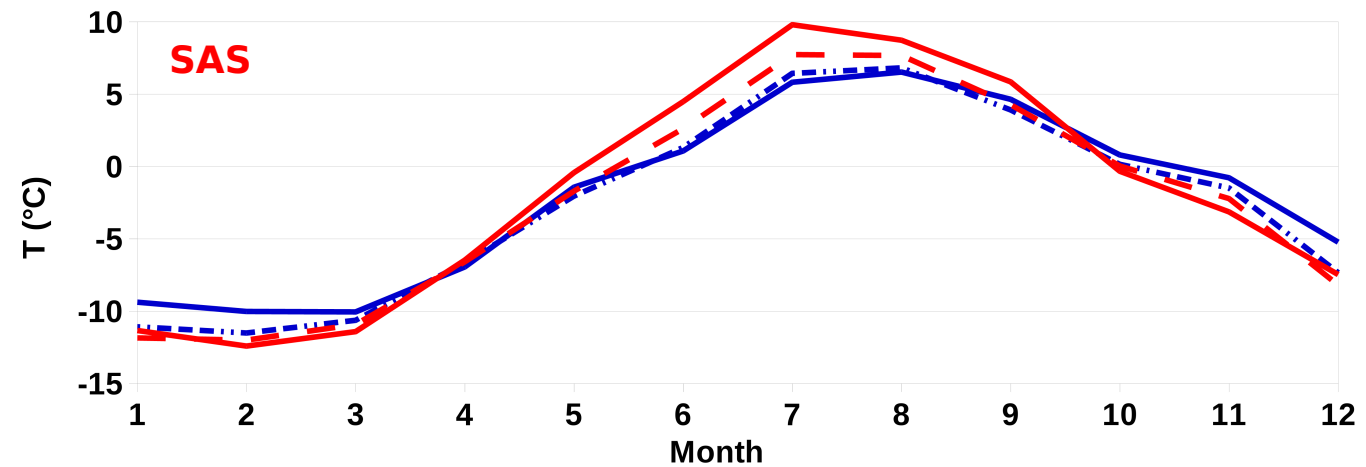
Temperatures in the mineral horizon

Reasonable agreement
observations / modelling results

RMSE between measured and
computed values SAS: 1.07 °C
NAS: 0.74 °C

Computational facts:

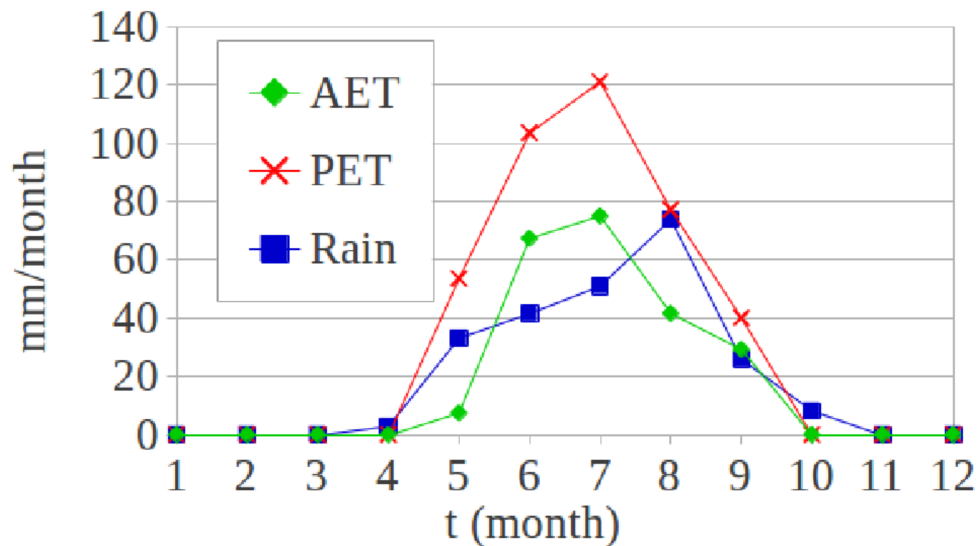
- Mesh: ~ 2 400 000 cells
- Max time step: 5s to 1h
- Computational resources:
From 20 cores to 500 cores requests
(processors: Intel(r) IVYBRIDGE 2,8
Ghz 10-cores) on CALMIP cluster
EOS (www.calmip.univ-toulouse.fr)



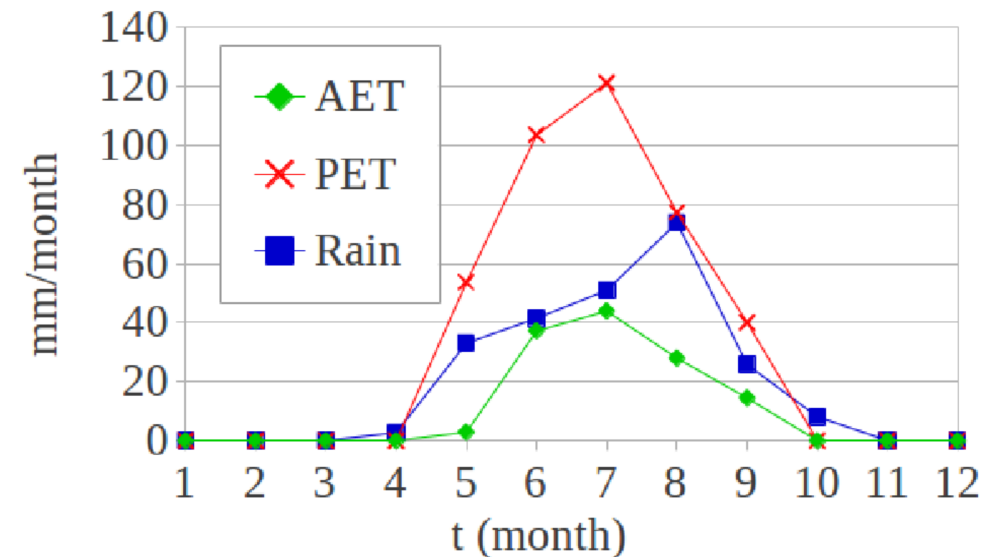
— Mineral horizon – 10cm (measured) - - Mineral horizon – 10cm (computed)
— Mineral horizon – 20cm (measured) - - Mineral horizon – 20cm (computed)

Actual evapotranspiration

SAS – actual rooting depth
0.6m in the mineral layer



NAS – actual rooting depth
0.1m in the mineral layer



Rain, PET: forcings - **AET:** numerical results

Two limitations to AET: frost and dryness

South aspected slopes experienced 2 months of «drying conditions» (AET > rain)

Sensitivity to root layer thickness ?

Two test cases :

- the Actual Condition case (**AC case**): true rooting depths, case presented until now
- the Arbitrary Deeper Roots Case (**ADR case**): an arbitrary rooting depth equal to the global average rooting depth (1 m – according to Schenk and Jackson, 2002) is considered in both slopes

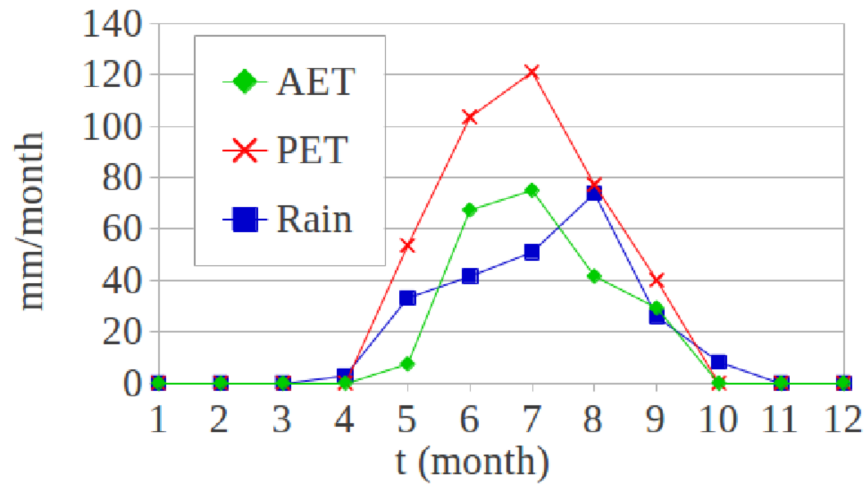
How compare AET, water fluxes and ALT in both cases ?

Is rooting depth an important parameter from a thermo-hydrological prospect ?

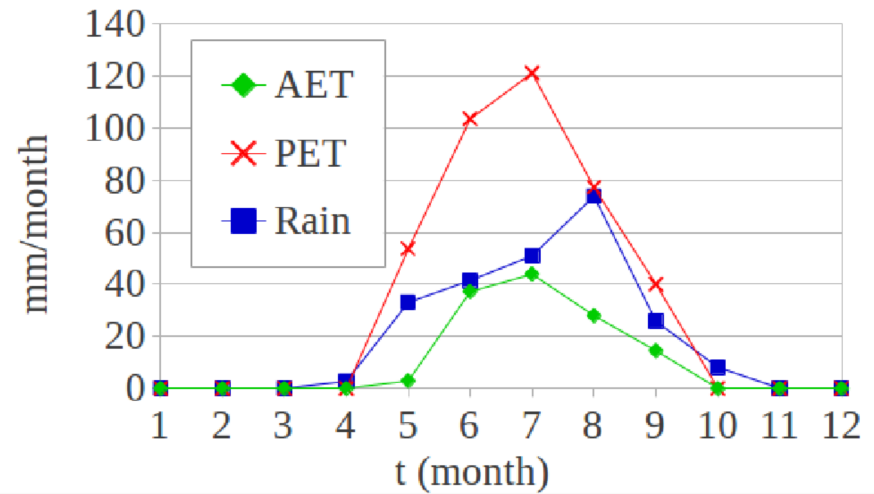
Sensitivity to root layer thickness ? AET

AC case

SAS – actual rooting depth
0.6m in the mineral layer

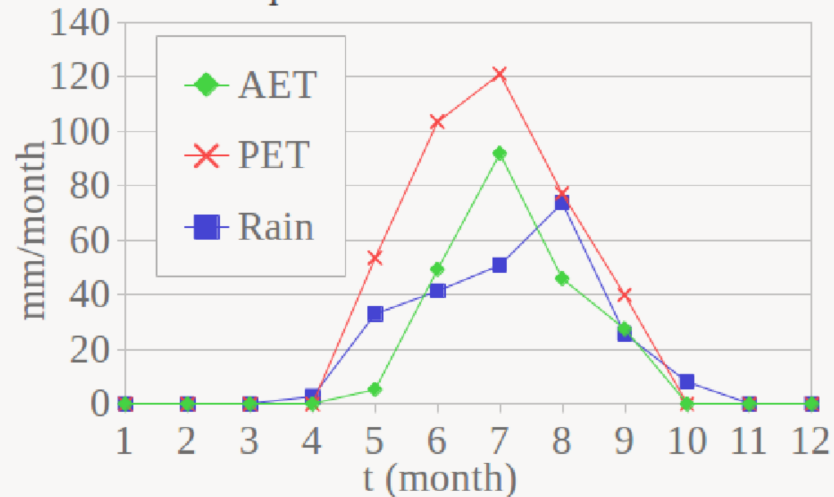


NAS – actual rooting depth
0.1m in the mineral layer

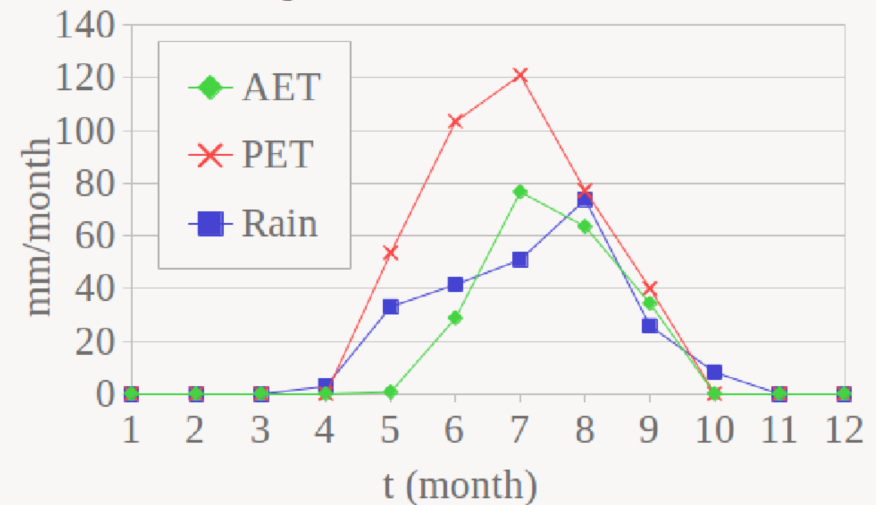


ADR case

SAS – arbitrary rooting depth
equal to 1m

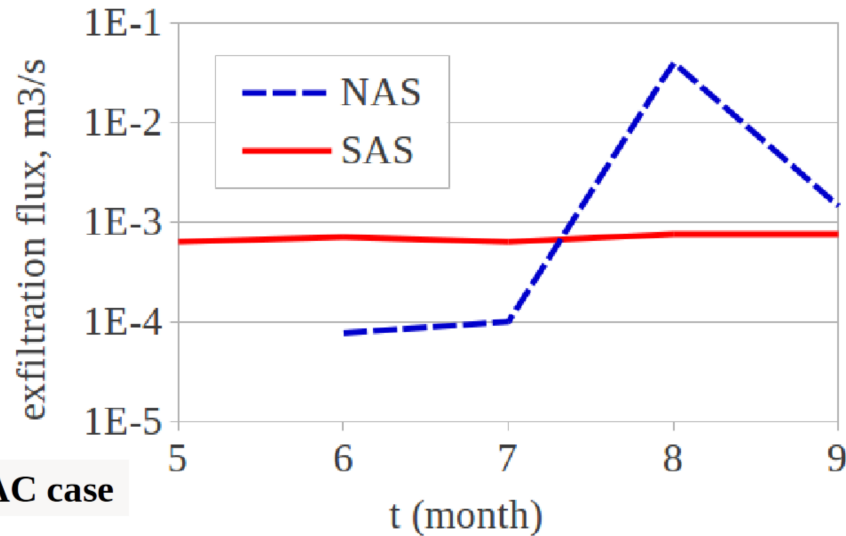


NAS – arbitrary rooting depth
equal to 1m



Sensitivity to root layer thickness ? Water fluxes, ALT

Considering the **actual rooting depths**
(SAS: 0.6m / NAS: 0.1m in the mineral layer)

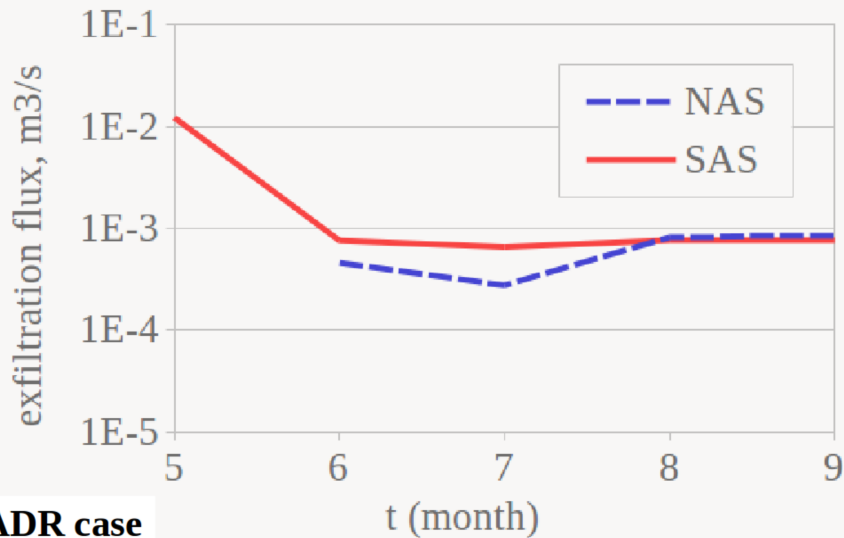


Observed maximum ALT SAS: 1.22 m
NAS: 0.58 m

Maximum ALT in AC case SAS: 1.41 m
NAS: 0.62 m

Maximum ALT in ADR case SAS: 1.1 m
NAS: 0.9 m

Considering an **arbitrary rooting depths**
(1m in both SAS and NAS)



AC / ADR cases: strong differences!

AC case is in good agreement with available observations (water fluxes: Prokushkin *et al.*, 2007, Bagard *et al.*, 2013 ; Active Layer Thickness: Gentsch 2011).

Concluding remarks

PermaFoam allows to **model mechanistically coupled thermo-hydrological dynamics of permafrost** at the slope scale (parallel performances), enables to catch the first order spatial variability observed in the field (**N/S slopes**).

Is **rooting depth** an important parameter for modeling thermo-hydrological transfers in permafrost-dominated, forested areas? Yes! **Huge impact on spatial variability and temporal dynamics of water fluxes, strong impact also on ALT distribution.**

Next steps

Modeling of the transfers within the **moss layer**

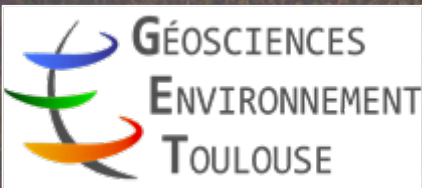
Back to the field with the understanding and issues raised from the simulation

Modeling of the permafrost dynamics in Kulingdakan under various scenarii of **climate change**



Thank you for your attention.

Contact: laurent.orgogozo@get.omp.eu



OpenFoam®: an open source CFD tool box for HPC

Developed in C++
(Weller et al., 1998; openfoam.com)

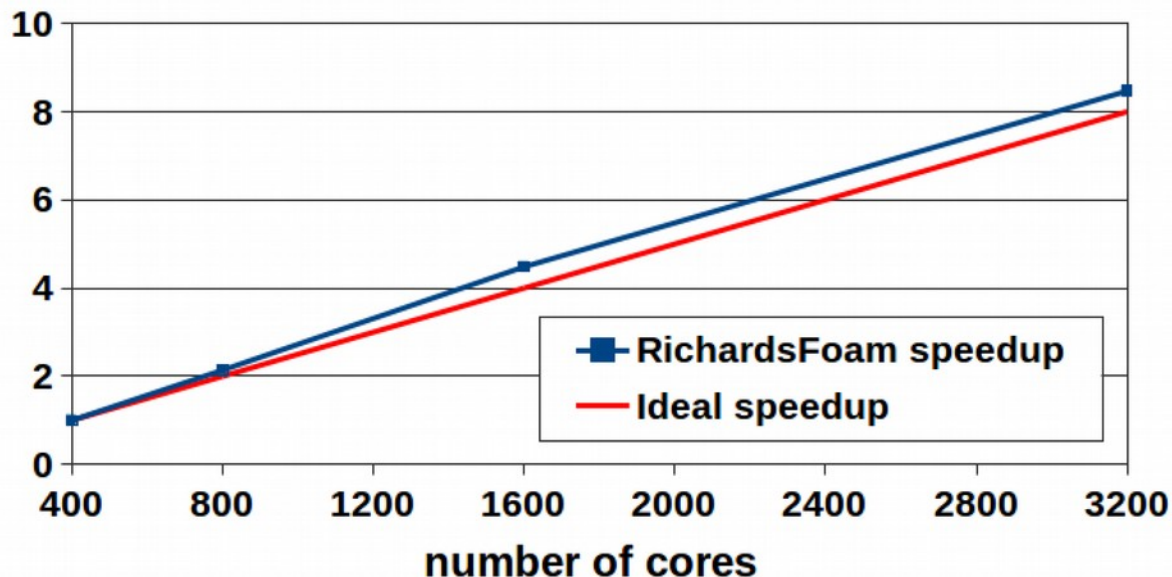
Finite volumes

Allow **multiphysics modelling**

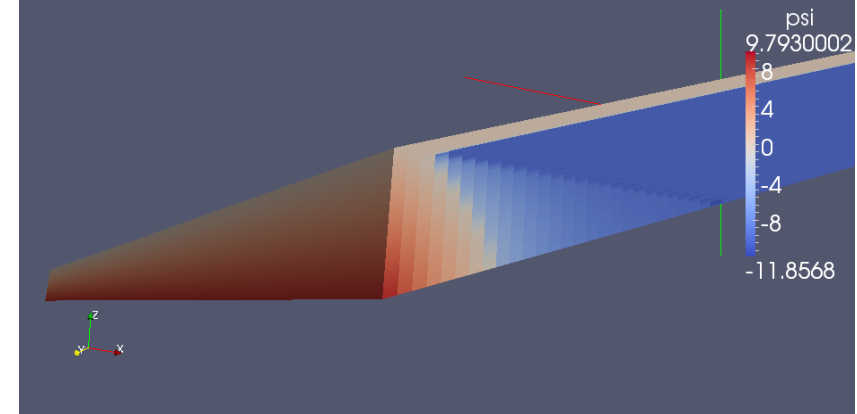
Enable to implement home-made solvers

Designed for **High Performance Computing**
(especially massively parallel computing)

OF for hydrological transfers in soil: RichardsFoam
(Orgogozo et al., CPC 2014, Orgogozo, CPC 2015)



A RichardsFoam Test case :infiltration of rain in a parallelepipedic 3D slope



RichardsFoam parallel performances:

- **1.2 billion cells mesh**
- **From 400 to 3200 cores**
- **Scaling curve obtained on EOS**
(www.calmip.univ-toulouse.fr)

permaFoam: numerical strategy

Couplings: - sequential operator splitting approach

- impedance factor approach for permeability in frozen state

Non linearities: - a Picard loop for each equation

- temporal shift of the latent heat term

- adaptive time steps based on Picard loops convergence

Richards equation with evapotranspiration:

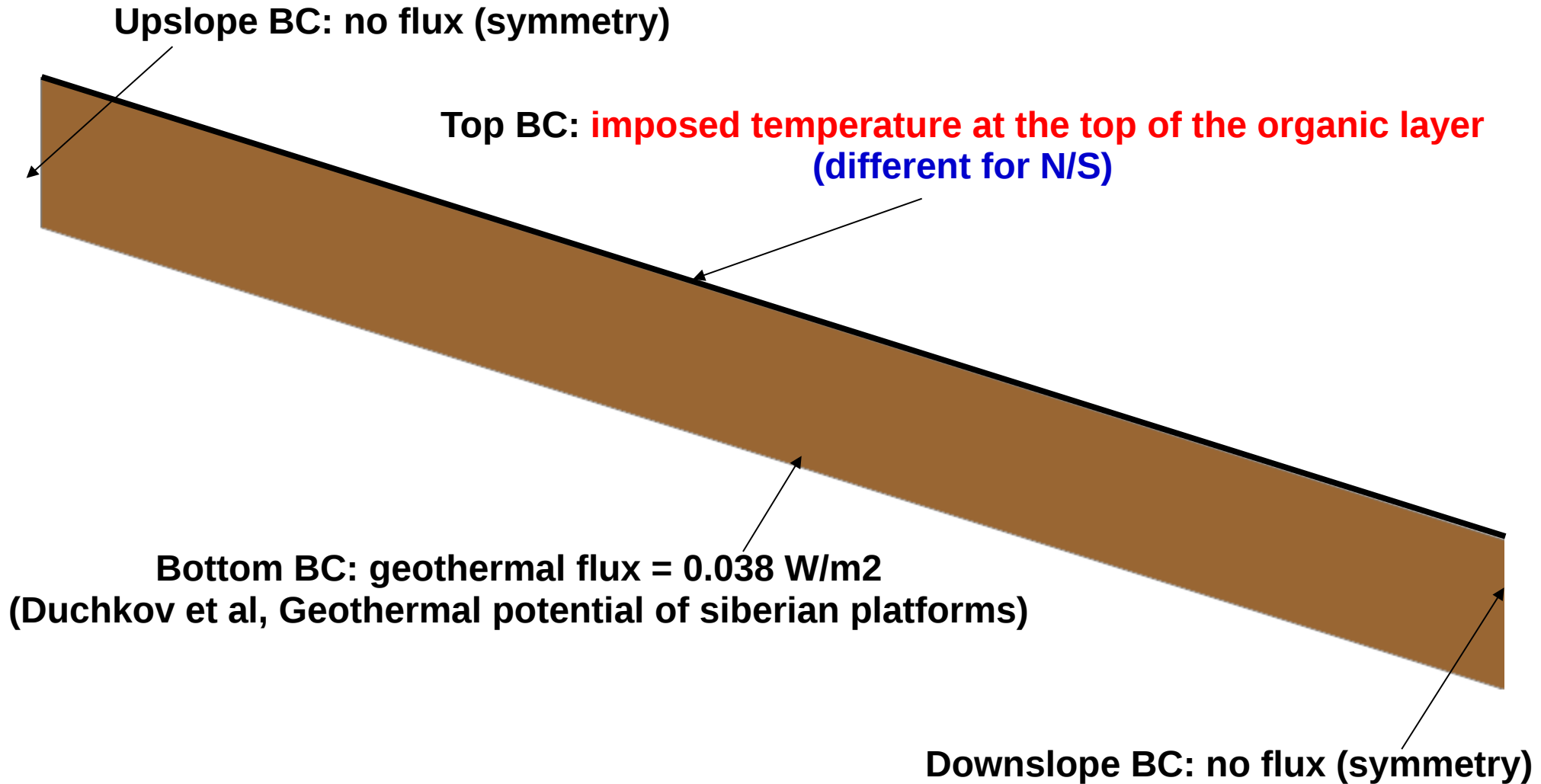
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Thermal transfer equation with freeze/thaw:

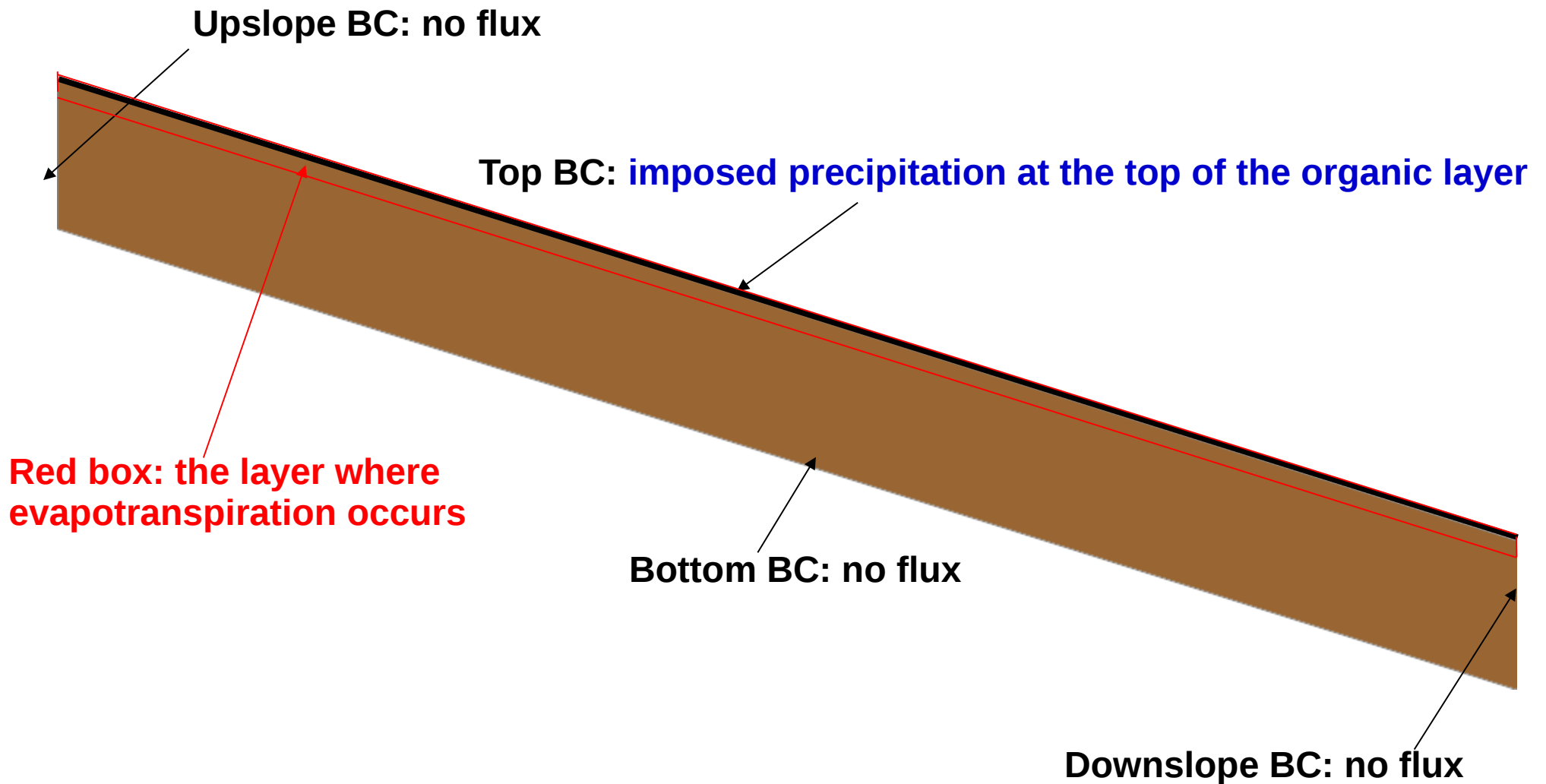
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Boundary conditions for the thermal equation



Boundary conditions for the hydrological equation

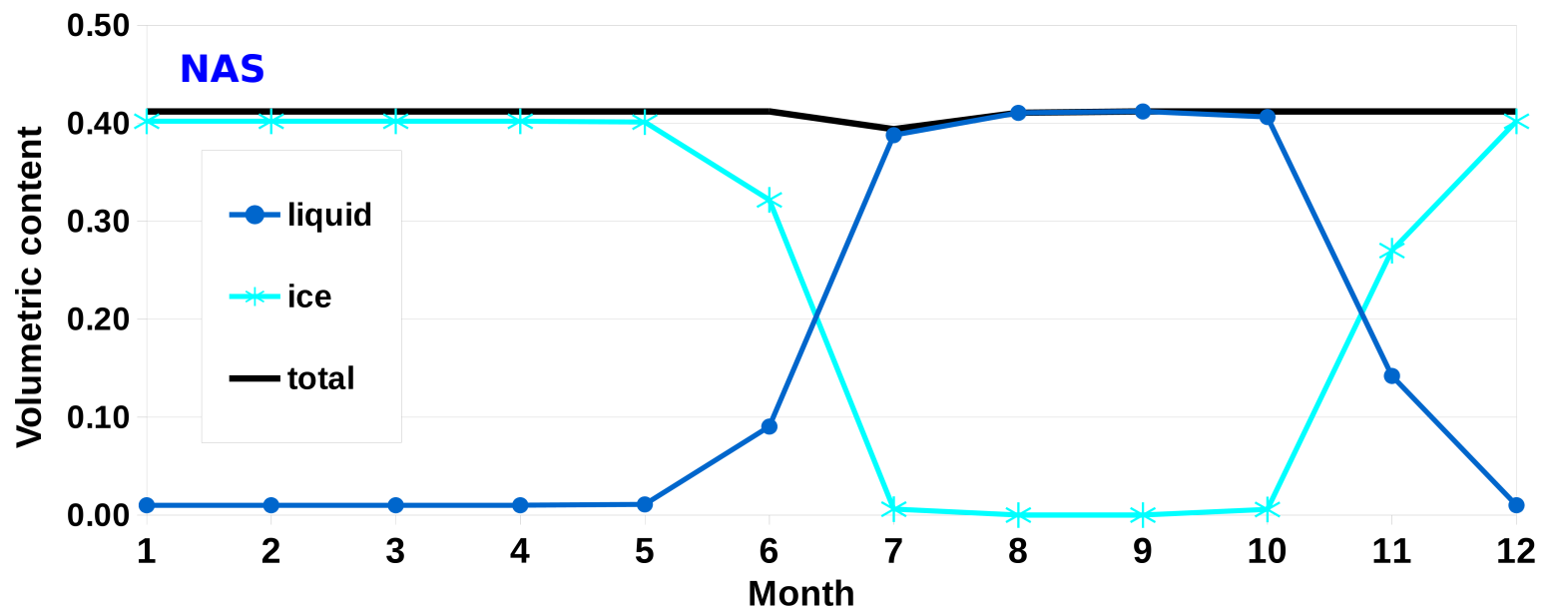
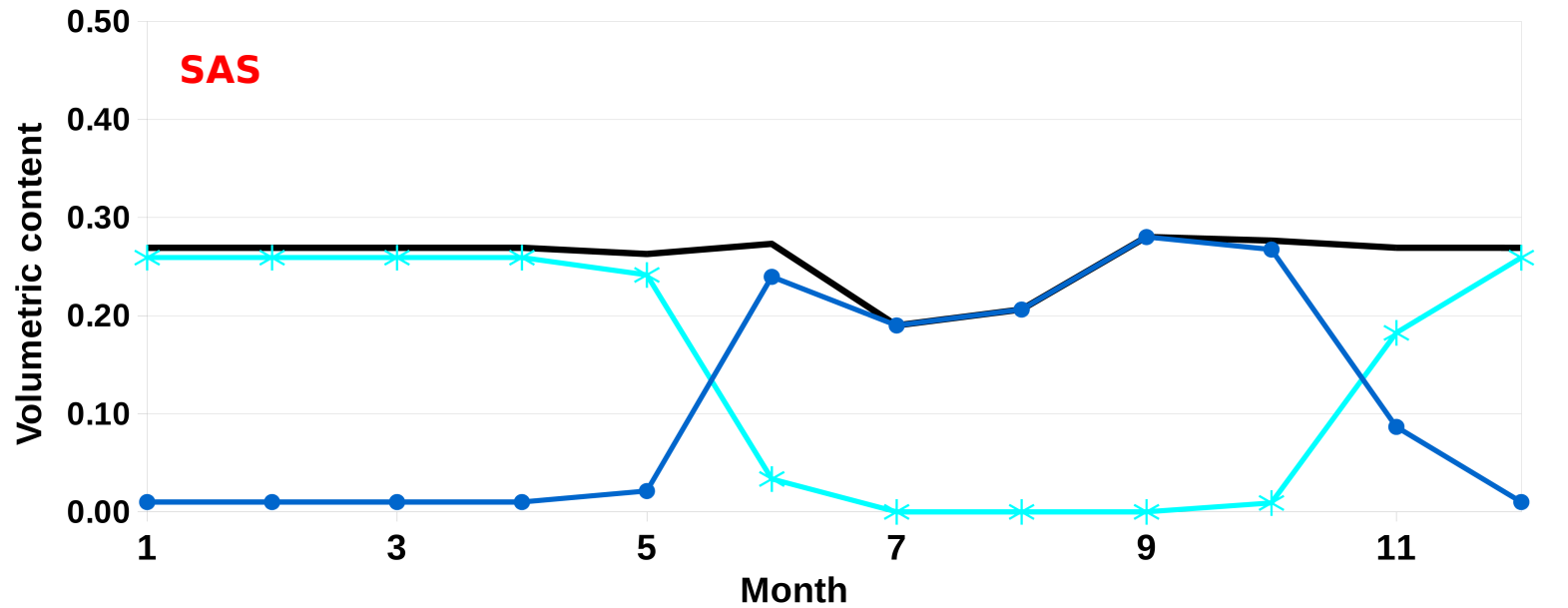


Water content in mineral horizon

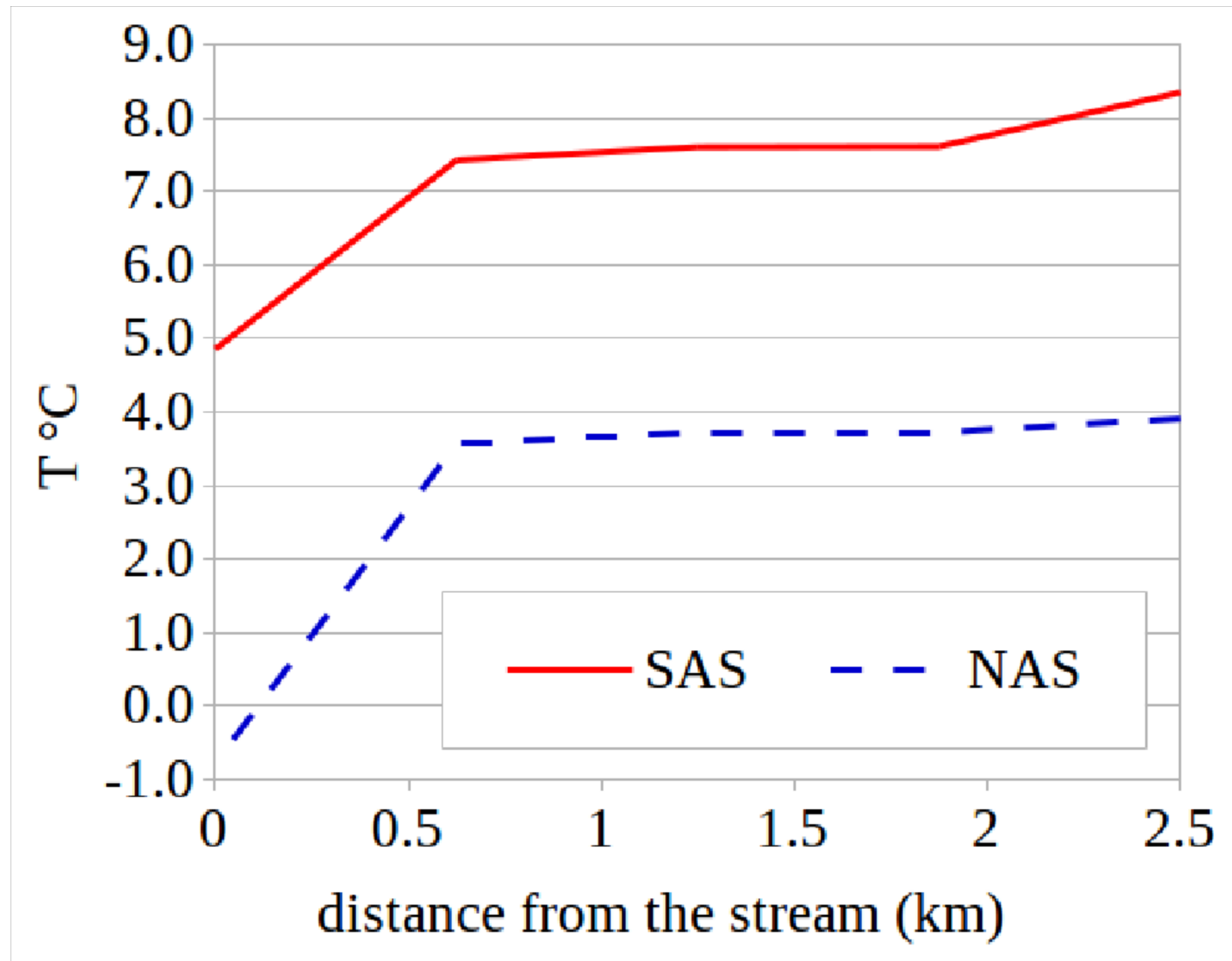
Numerical results

20cm depth within the mineral horizon

As expected, south aspected slopes are dryer and thaw faster than north aspected slopes



Variability along slopes



Variability along slopes is **detectable**:
hotter conditions upslope than downslope