

# Transfers along slopes in a permafrost-dominated watershed of Central Siberia: a mechanistic 2D coupled thermo-hydrological modeling study.

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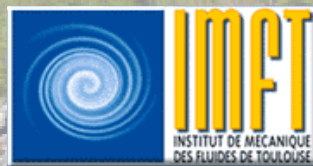
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# Transfers on boreal continental surfaces: role of the permafrost ?



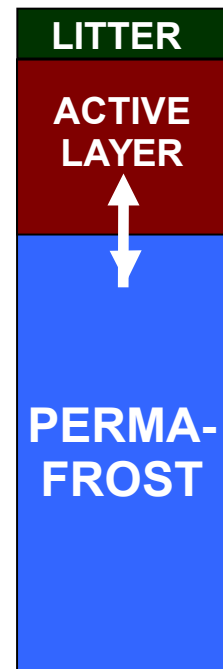
**Problematic:** climate change and weathering in boreal areas with a continuous permafrost

**Studied area:**

- Central Siberia, sub-watersheds of the Nizhnyaya Tunguska
- homogeneous vegetation cover and lithology
- main spatial variability: south aspected / north aspected slopes

**Goals:**

- Influence of seasonal freeze/thaw of the active layer on the geochemical fluxes related to weathering
- Impact of the interannual variations of these cycles due to anthropogenic climate change



**Methodological approach :**

**Mechanistic modeling of thermal and hydrological transfers** from the pedon scale to the **experimental watershed scale**

→ Time scales : annual to multidecennial  
Space scales : 1 m<sup>2</sup> to 10's of km<sup>2</sup>

**First 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.: Kennedy and Lielmezs, 1973, Harlan 1973, Guymon and Luthin 1974, Jame and Norum 1980, Seregina 1989, Boike *et al.*, 2003, Hansson *et al.*, 2004, McKenzie *et al.*, 2007, Weismüller *et al.*, 2011, Painter 2011, Frampton *et al.*, 2011, Grenier *et al.*, 2012, Rivière 2012, Endrizzi *et al.*, 2013, Kurylyk *et al.*, 2014, Karra *et al.*, 2014, Frederick and Buffet, 2014 ...)

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

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

# OpenFoam®: an open source CFD tool box for HPC

Developed in C++

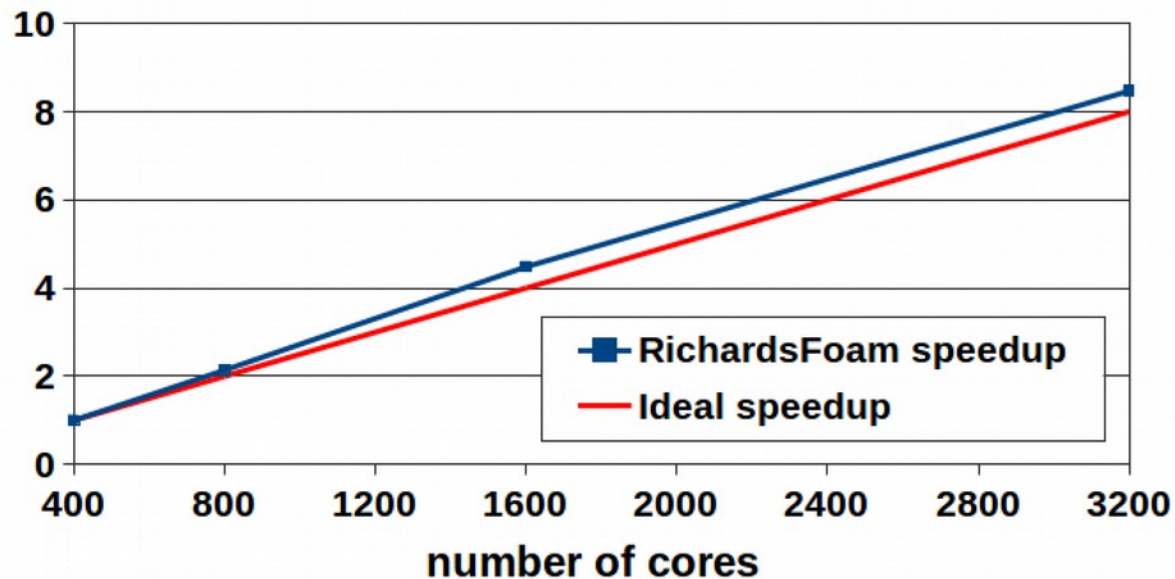
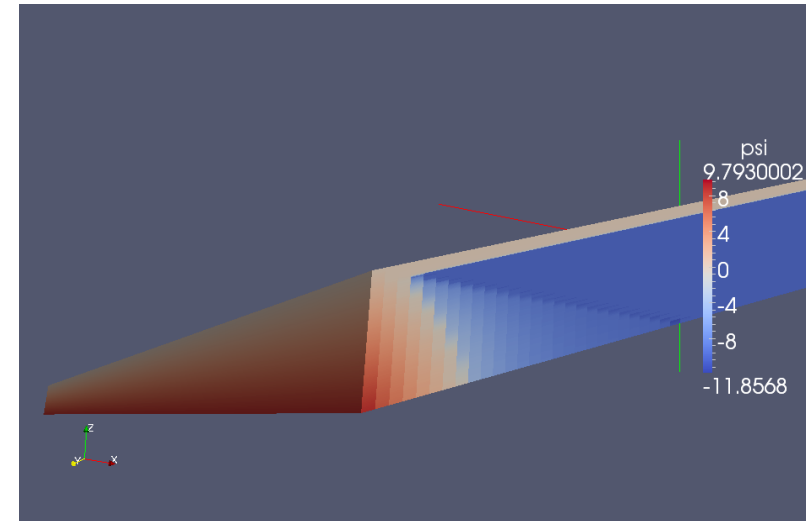
Finite volumes

Allow **multiphysics modelling**

Enable to implement home-made solvers

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

**OF for geosciences**, e.g.: Orgogozo *et al.*, CPC 2014,  
Horgue *et al.*, CPC 2014, Orgogozo, CPC 2015



Parallel performances of RichardsFoam:

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



## permaFoam: considered conservation equations

3D transient thermal and water transfers

in variably saturated and heterogeneous porous media

with taking into account of evapotranspiration and freeze/thaw of the poral water:

**couplings, non linearities**

**Richards equation with evapotranspiration:**

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

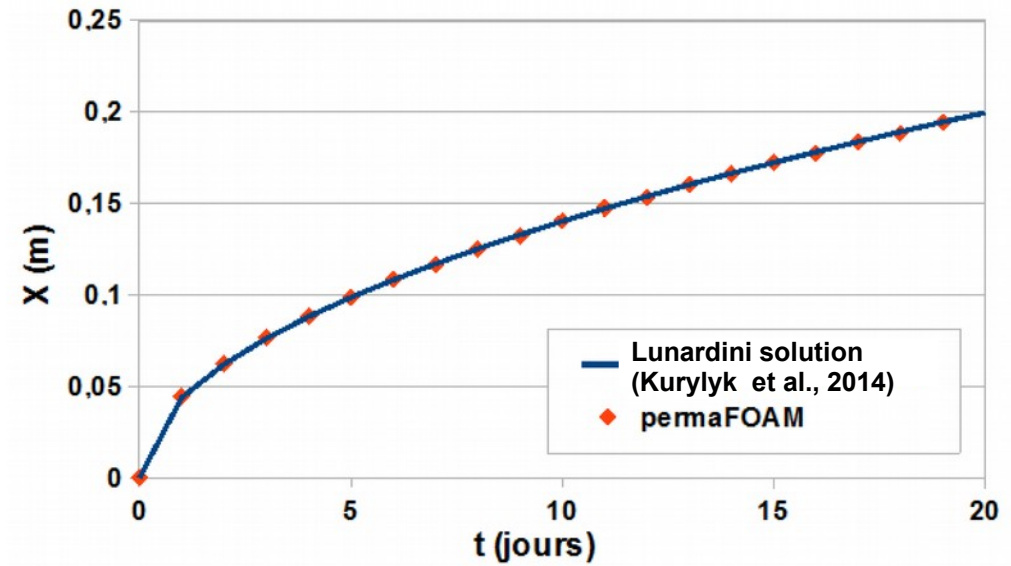
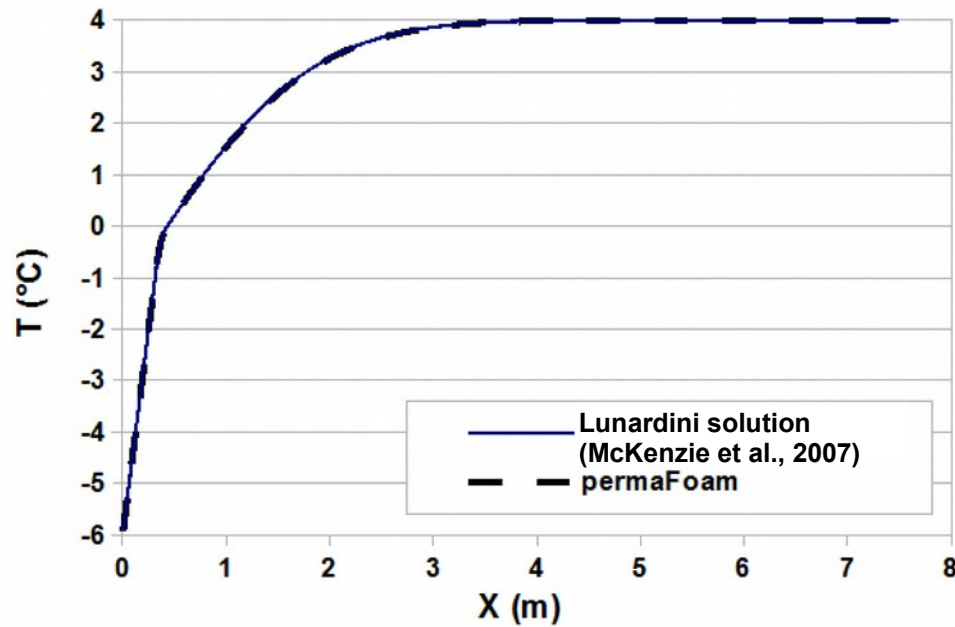
**Thermal transfer equation with freeze/thaw:**

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

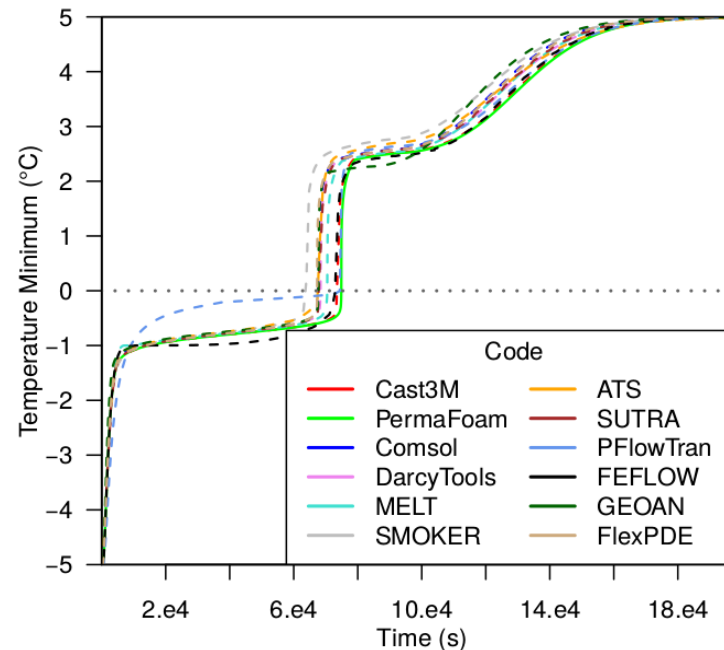
**Stiff problems, nonlinearities, couplings, few references solutions:**

**INTERFROST Benchmark** (C. Grenier, [wiki.lsce.ipsl.fr/interfrost](http://wiki.lsce.ipsl.fr/interfrost))

## Validation and benchmarking



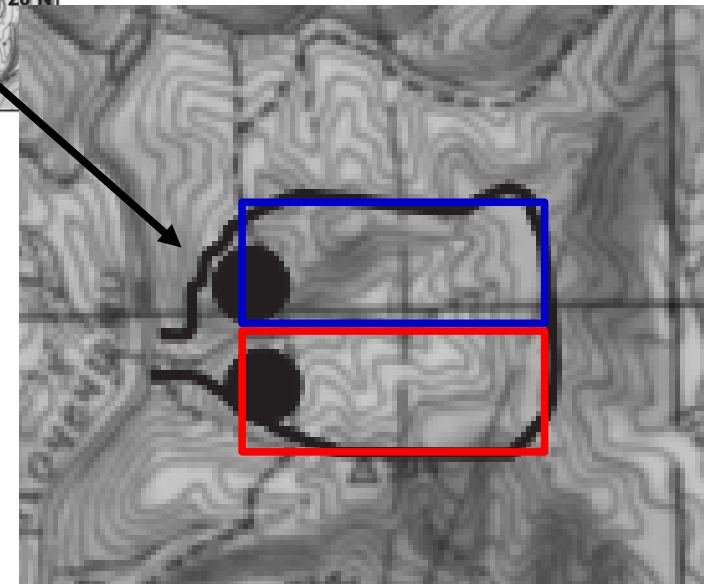
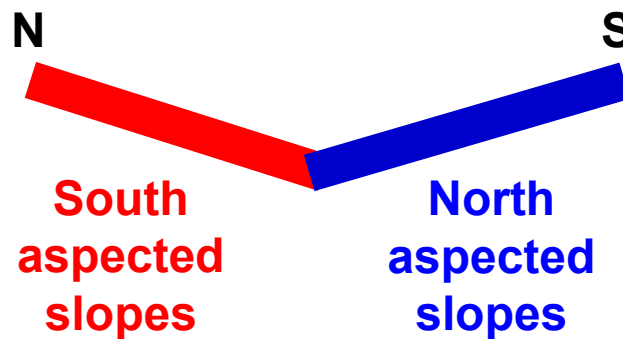
**Interfrost benchmark:** [wiki.lscce.ipsl.fr/interfrost](http://wiki.lscce.ipsl.fr/interfrost) (Grenier *et al.*, AGU 2013, EGU 2015, ICOP 2016 - next talk)



## Kulingdakan: a stream in a continuous permafrost area

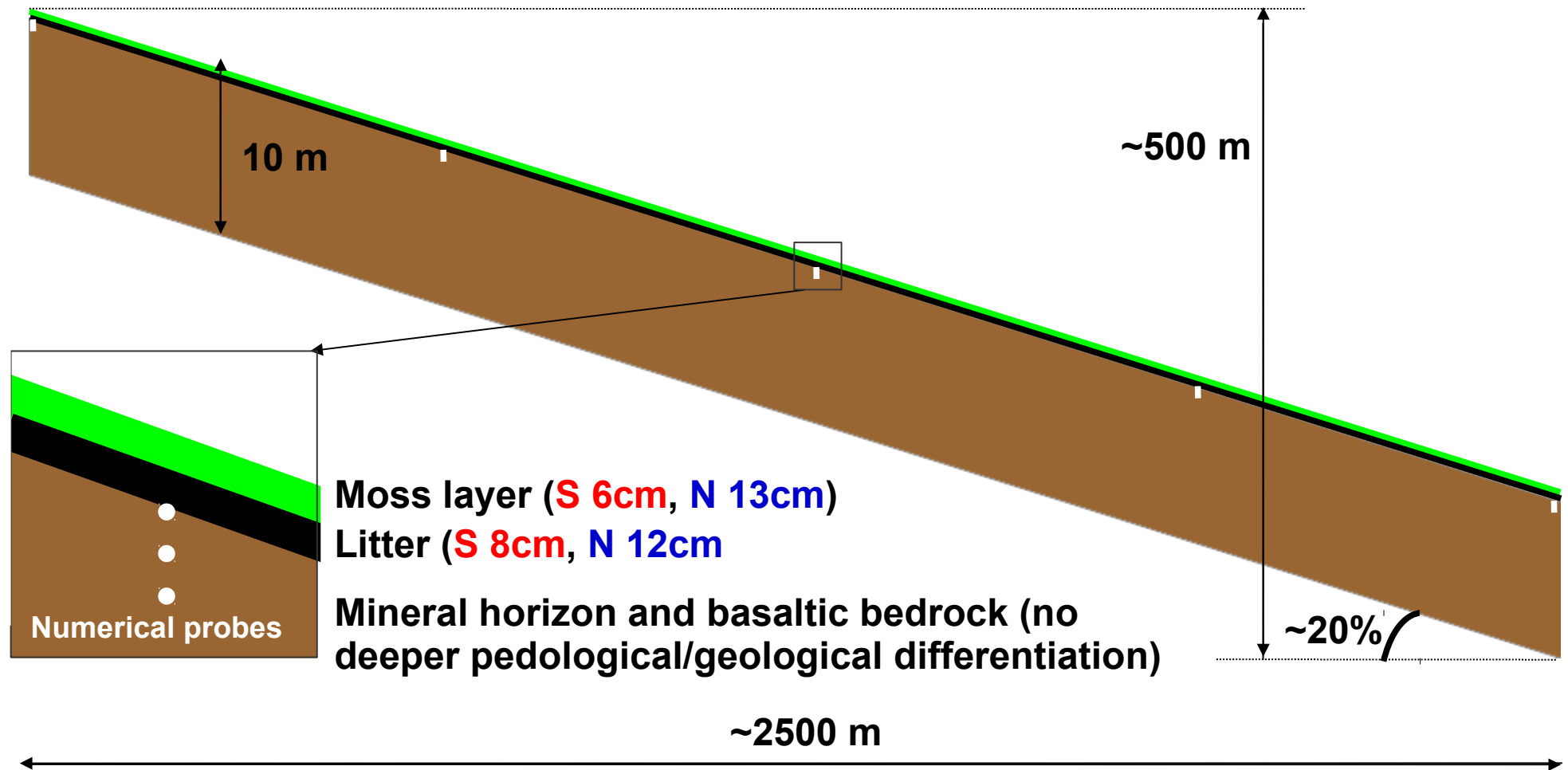


(according to Prokushkin et al., 2005)



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**

## 2D representation of the slopes of the catchment

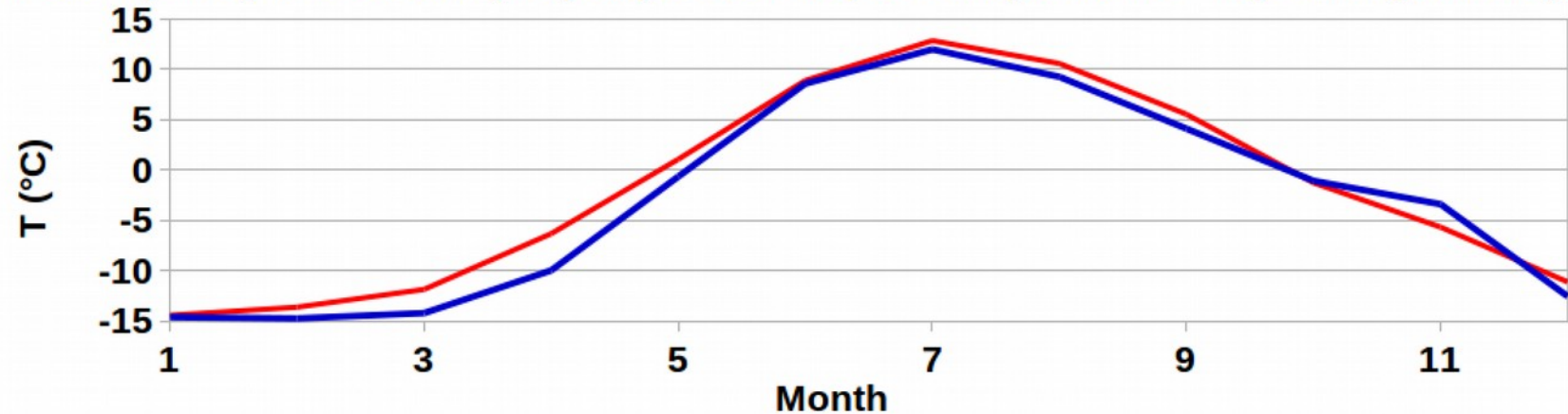




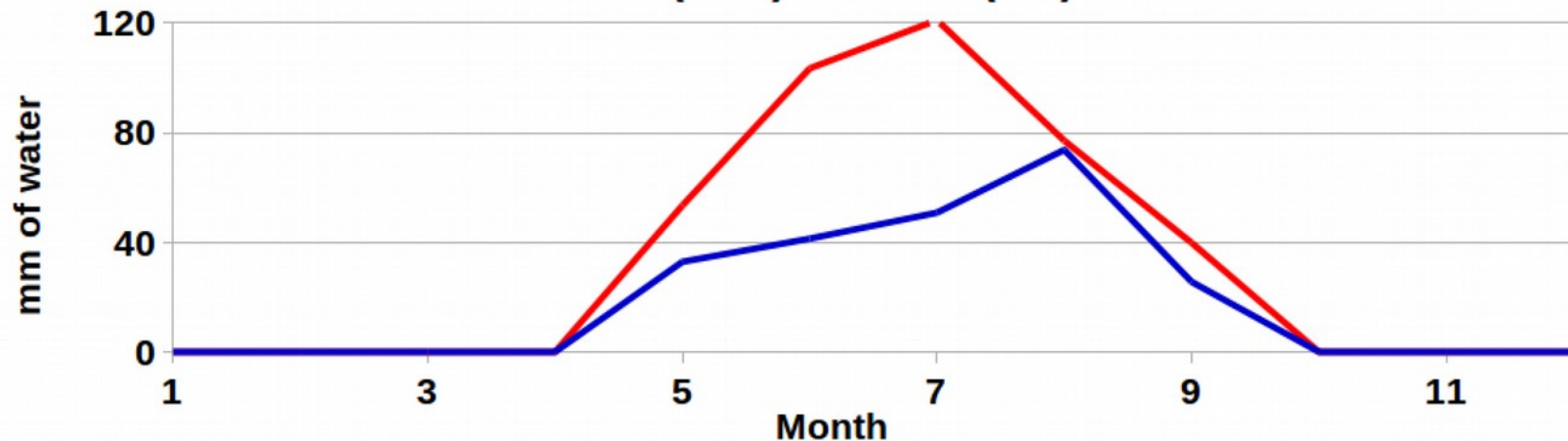
## Climatic conditions

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

North (blue) and south (red) aspected slopes temperature - top of organic layer

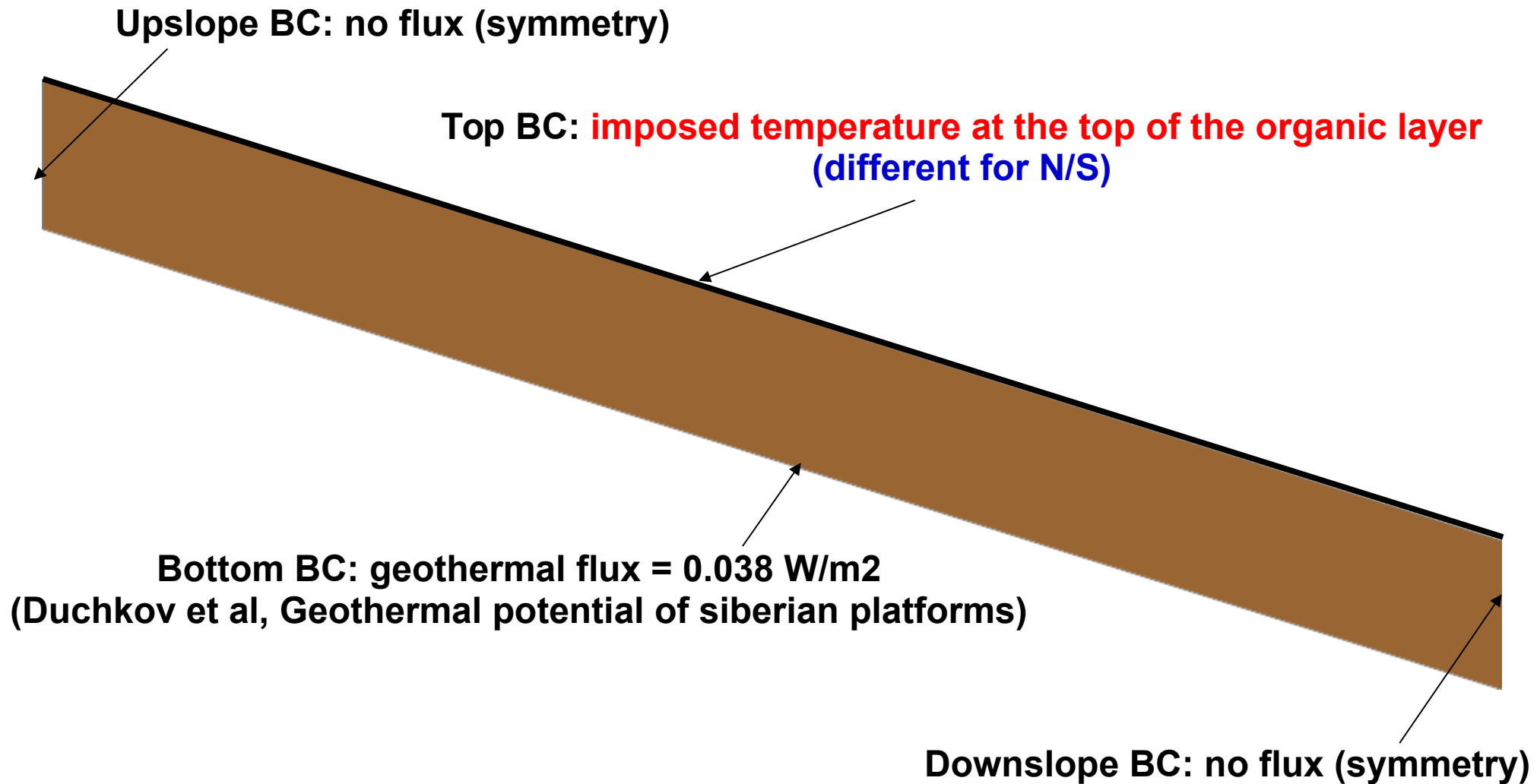


Rain (blue) and PET (red)



**Input data for a transient modeling** in the N/S aspected slopes along an hydrological cycle.

## Boundary conditions for the thermal equation



## Boundary conditions for the hydrological equation

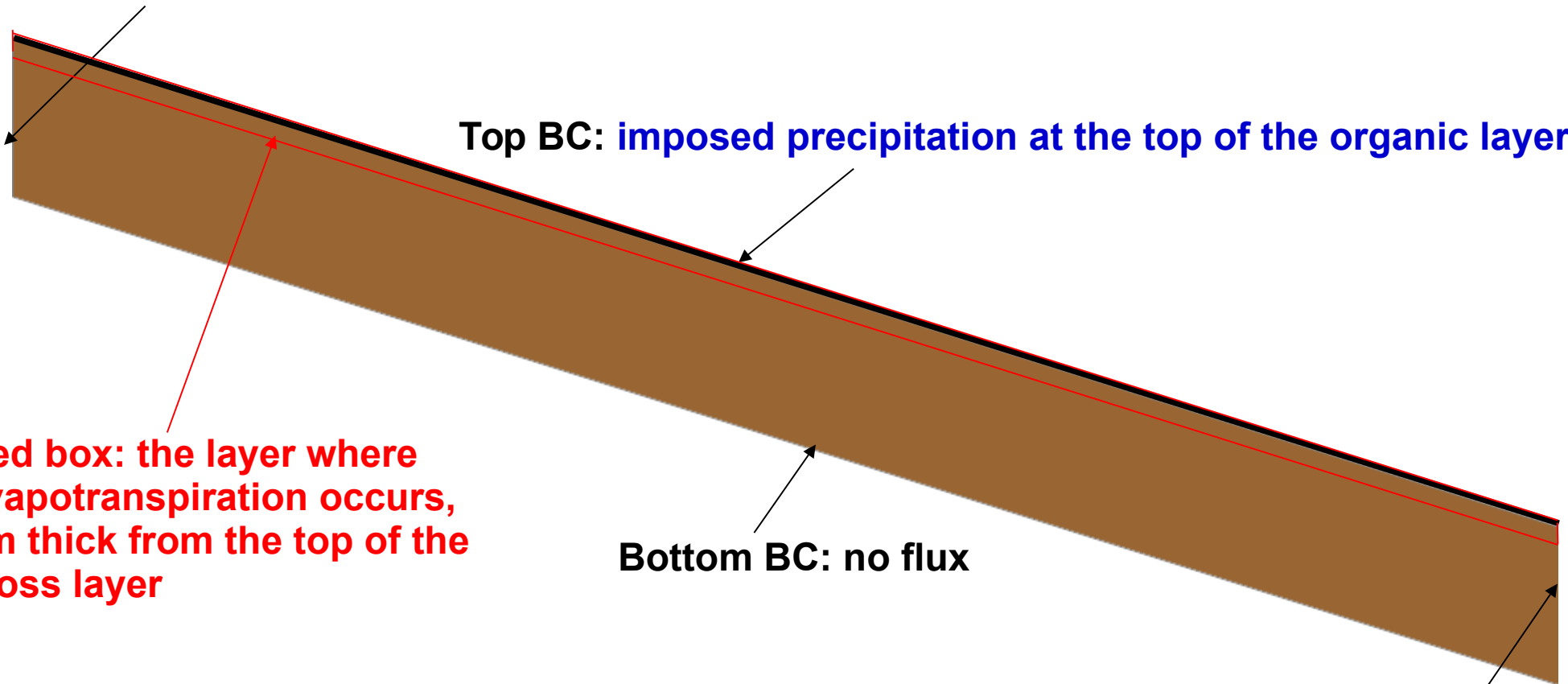
Upslope BC: no flux

Top BC: imposed precipitation at the top of the organic layer

Bottom BC: no flux

Downslope BC: no flux

Red box: the layer where evapotranspiration occurs, 1m thick from the top of the moss layer



## Temperatures in the mineral horizon

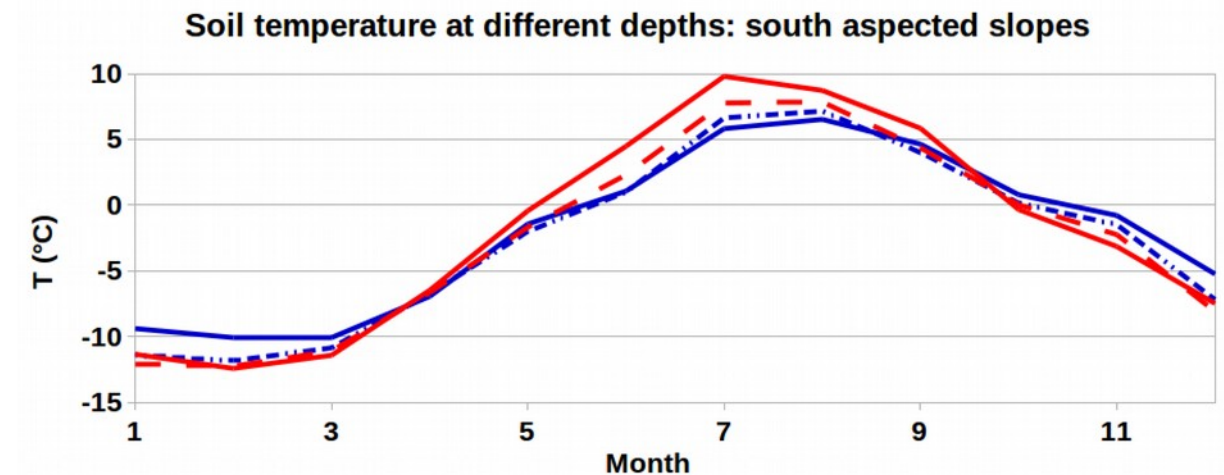
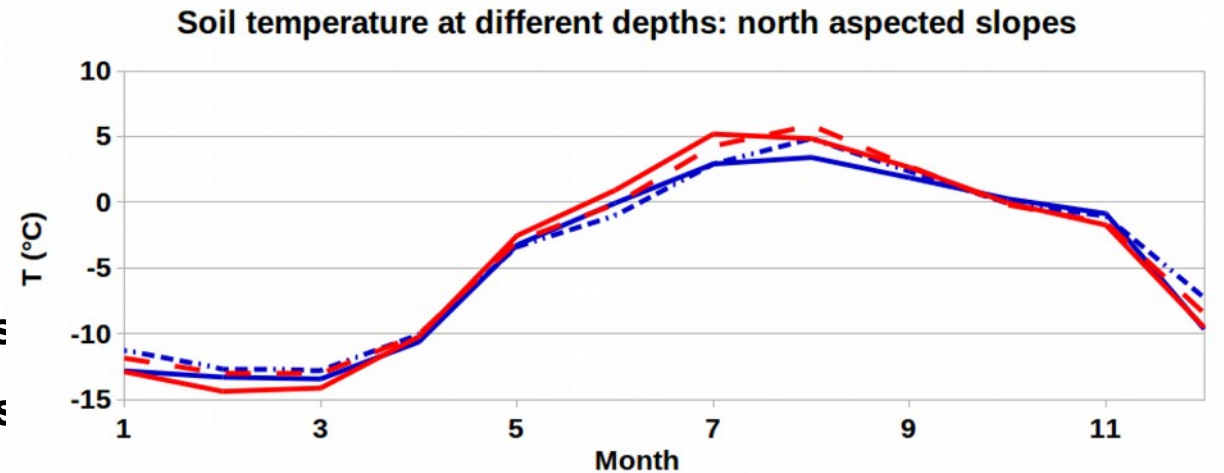
**Reasonable agreement** between observations and modelling results

Generally, observations warm up and cool down faster than modeling results

→ macroporosities, thermal properties estimations, ... ?

Computational facts:

- ~ 10 000 CPU hours
- Mesh: ~ 2 400 000 cells
- Max. time step: 4mn
- Computational resources:  
From 20 cores to 100 cores requests  
(processors: Intel(r) IVYBRIDGE 2,8 Gh  
10-cores) on **CALMIP** cluster EOS  
([www.calmip.univ-toulouse.fr](http://www.calmip.univ-toulouse.fr))



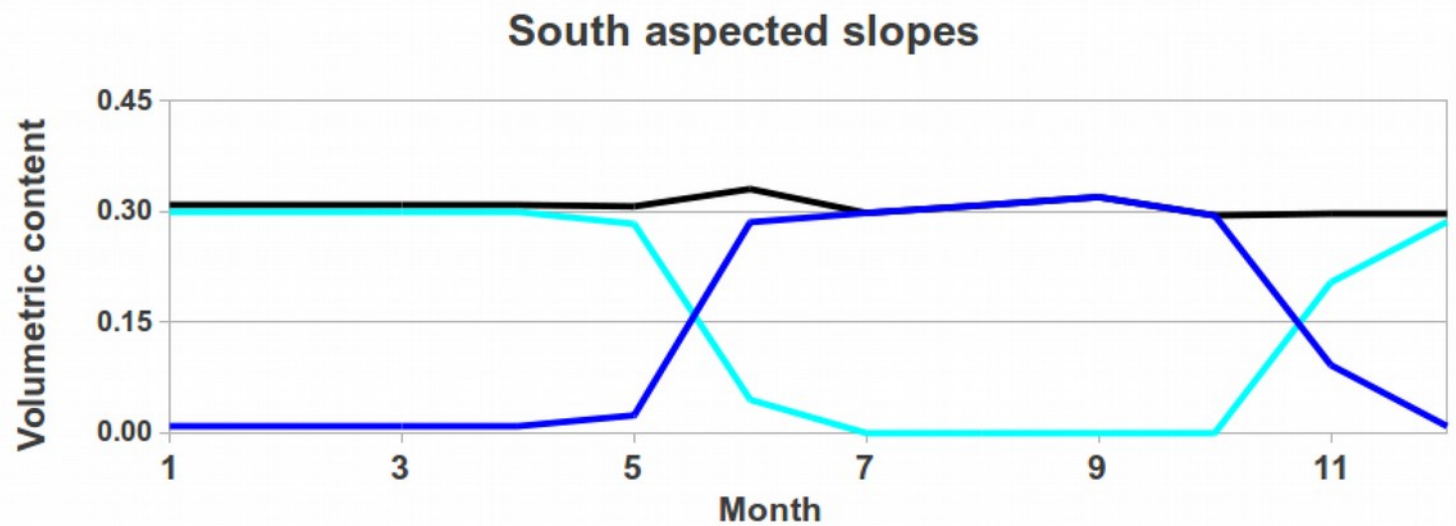
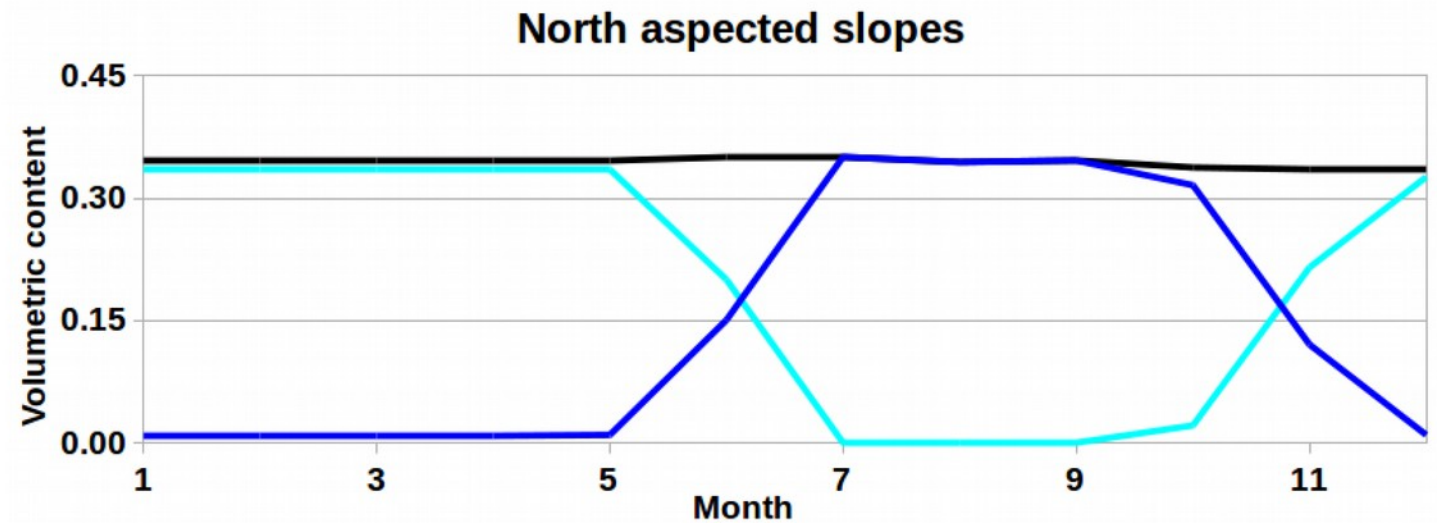
— Mineral horizon – 10cm (measured)    - - Mineral horizon – 10cm (computed)  
— Mineral horizon – 20cm (measured)    - - Mineral horizon – 20cm (computed)

## 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



— liquid

— ice

— total



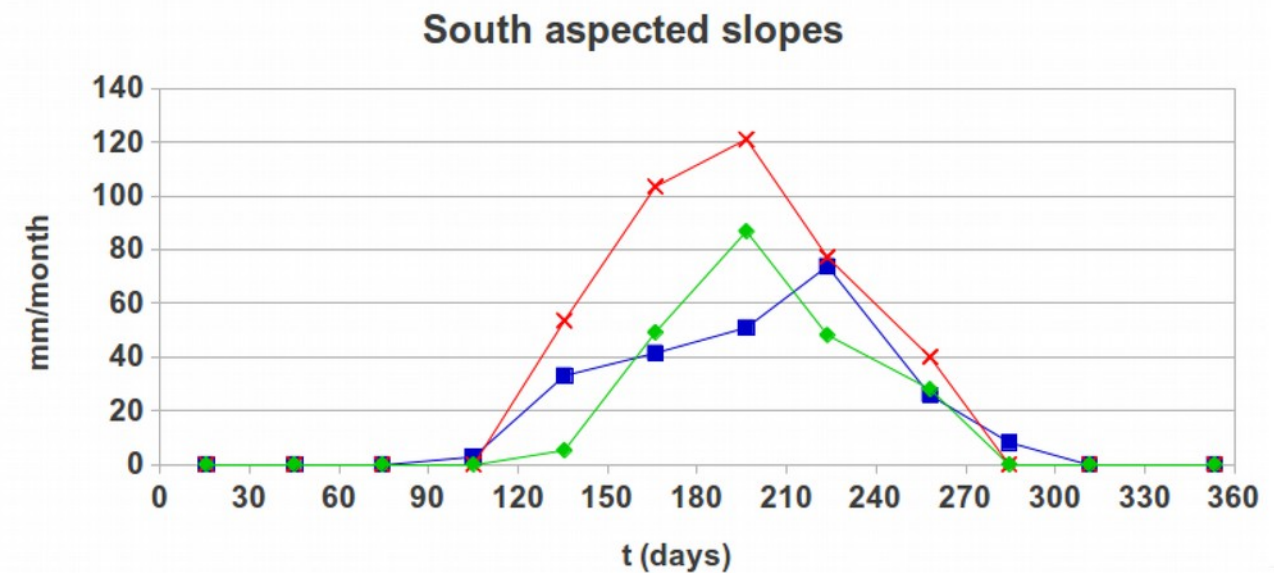
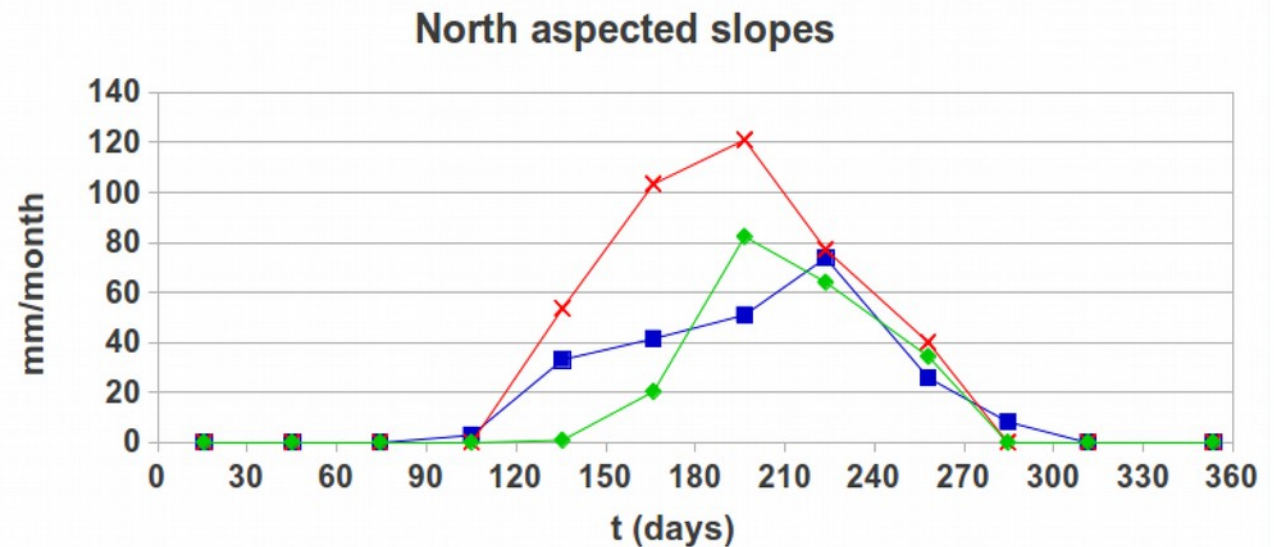
## Actual evapotranspiration

Rain, PET: forcings

AET: numerical results

Two limitations to AET:  
frost and dryness.

South aspected slopes  
experienced 1 more month  
of «drying conditions»  
(AET > rain) than north  
aspected slopes.

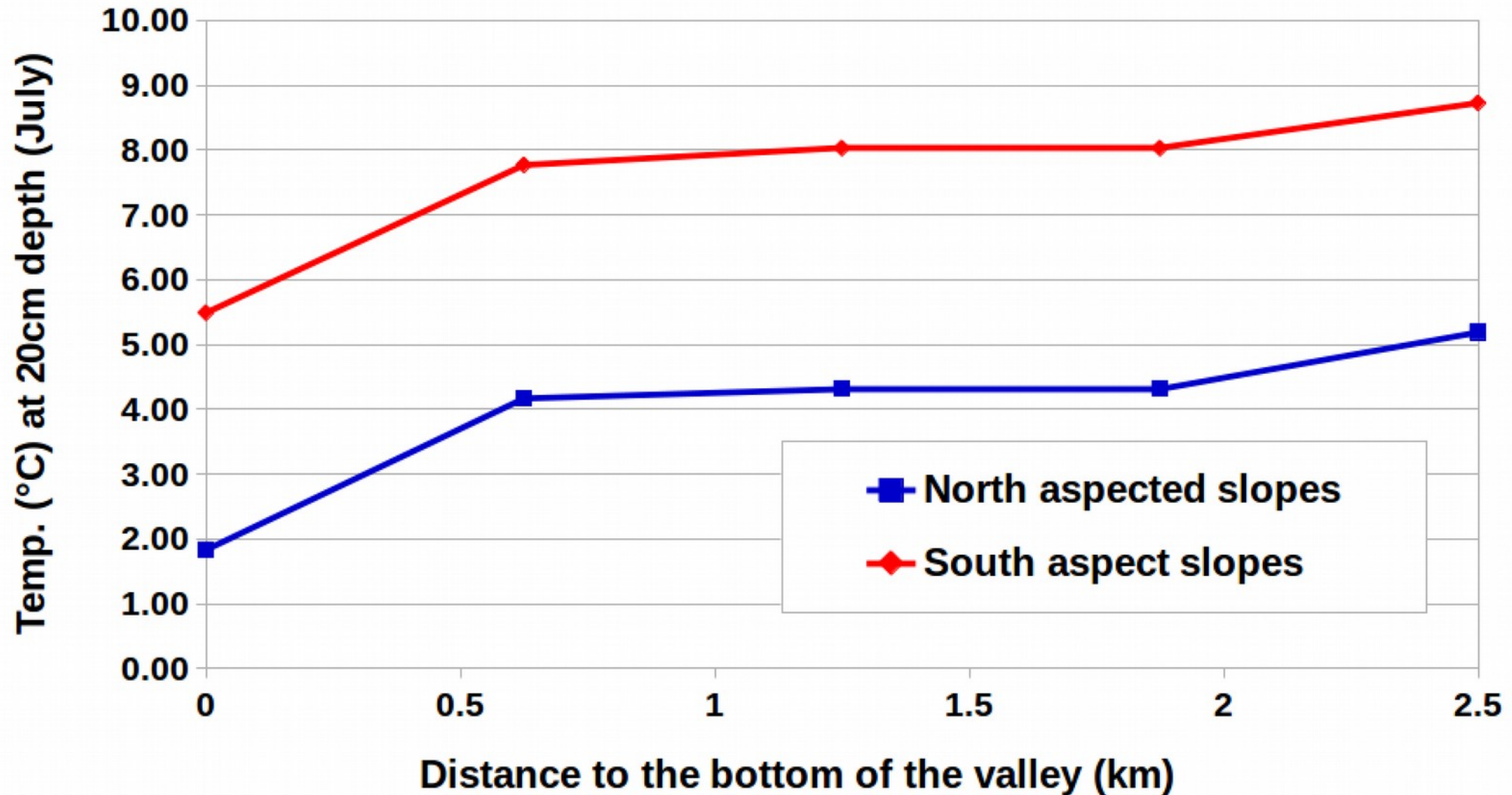


◆ AET

× PET

■ Rain

## Variability along slopes



Variability along slopes is **detectable**:

**hotter conditions upslope** than downslope

## Concluding remarks

### permaFoam:

- allows to model permafrost dynamics at the slope scale.
- enables to catch the first order spatial variability observed in the field (**N/S slopes**).
- gives some insights on **lateral variability** along slopes.

## Next steps

Quantification of **fluxes at the watershed scale**

Sensitivity studies

Modeling of the transfers within the moss layer

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

## Perspectives

Produce thermo-hydrological input data for **weathering** modeling in permafrost affected catchments in boreal areas in current conditions and under climate change

Add solute transport phenomena

Towards more realistic modelings at the **watershed scale**: meshing DEM, pedological/geological models, taking into account soil cover heterogeneities, etc



XI. International Conference on Permafrost  
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**Thank you for your attention.**

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