

Numerical modeling of coupled heat and water transport for the study of permafrost dynamics: High Performance Computing simulations for watershed scale analysis

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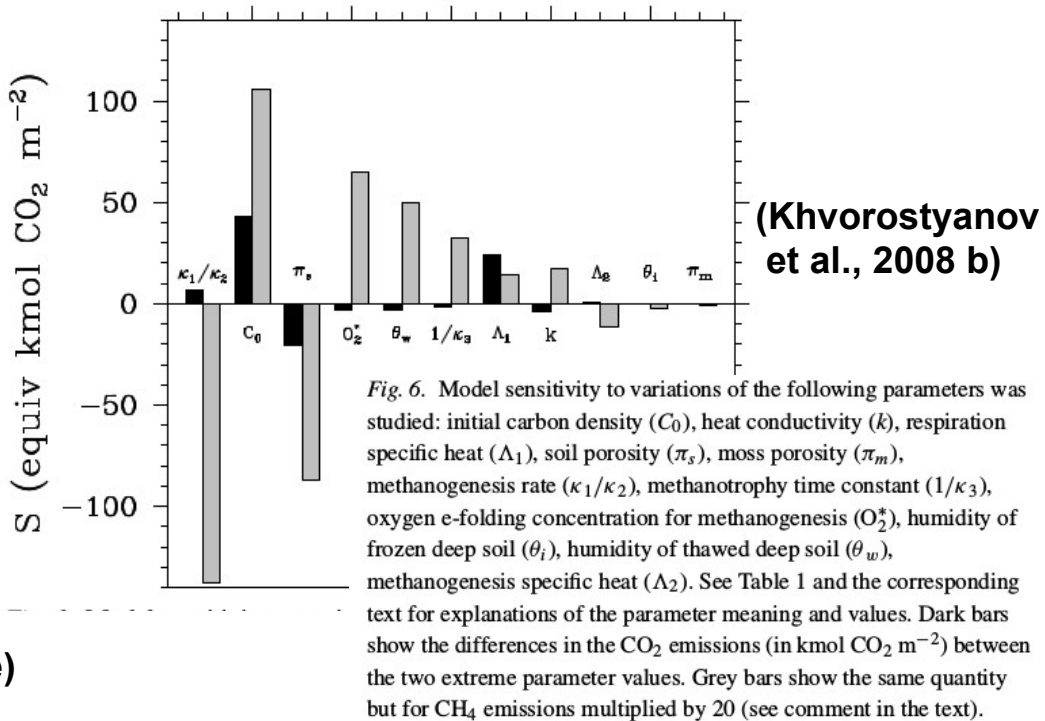
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Лаборатория
биогеохимических
и дистанционных методов мониторинга
окружающей среды

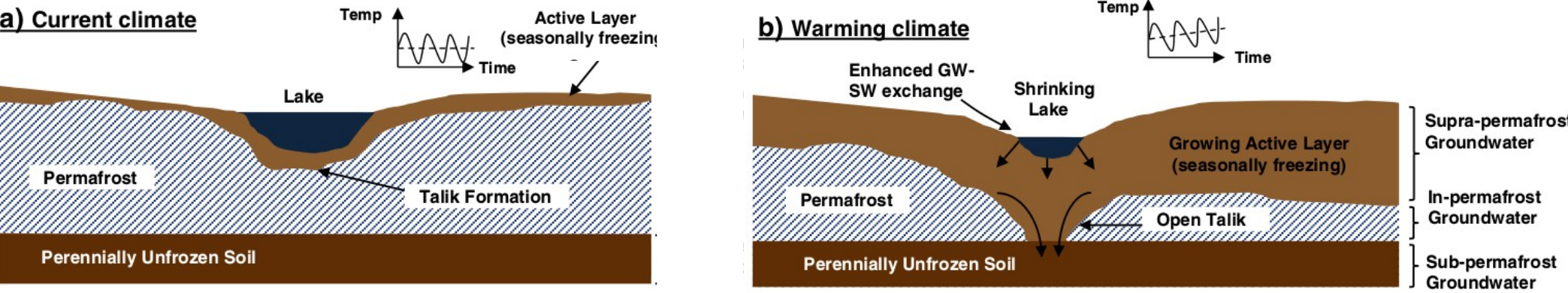


Permafrost modeling: impacts of global warming on boreal areas ?



Thawing Permafrost in Siberia (Imaggeo, Guido Grosse)

Permafrost modeling: impacts of global warming on boreal areas ?



(adapted from Kurylyk et al., 2014)

Substantial potential impacts on groundwater availability

Severe impacts on buildings stability

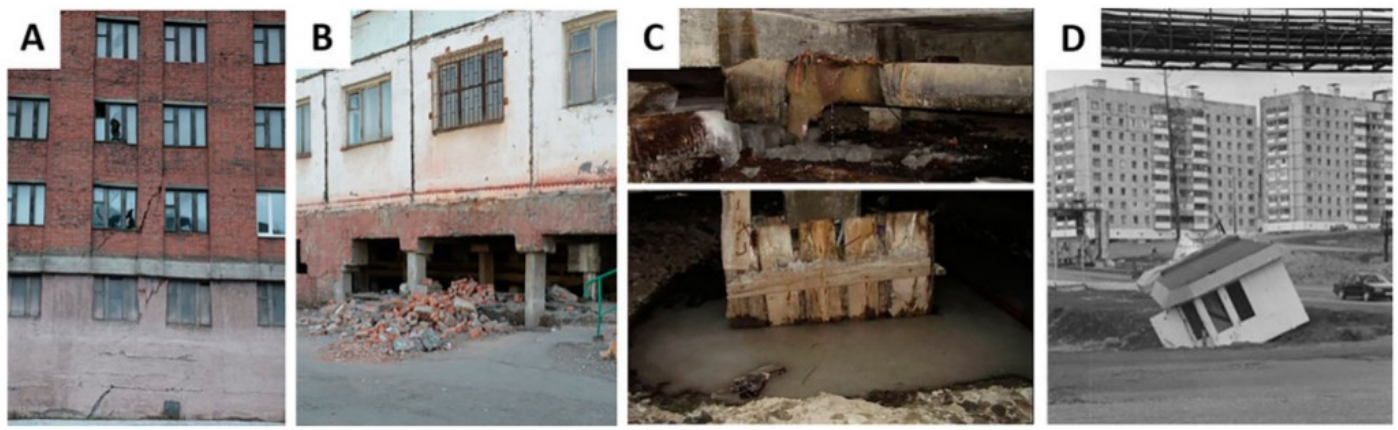


Figure 2. (a) Example of structural deformation of building caused by inadequate structural design exacerbated by permafrost warming. (b) Example of cryogenic weathering of the foundation. (c) Water leakage and accumulation around foundation piles. (d) Ground settlement developed under small heated kiosk due to permafrost degradation (Photographs by V.I. Grebenets and N.I. Shiklomanov). (Shiklomanov et al., 2017)

Potential engineering applications: ice wall around Fukushima Daichi

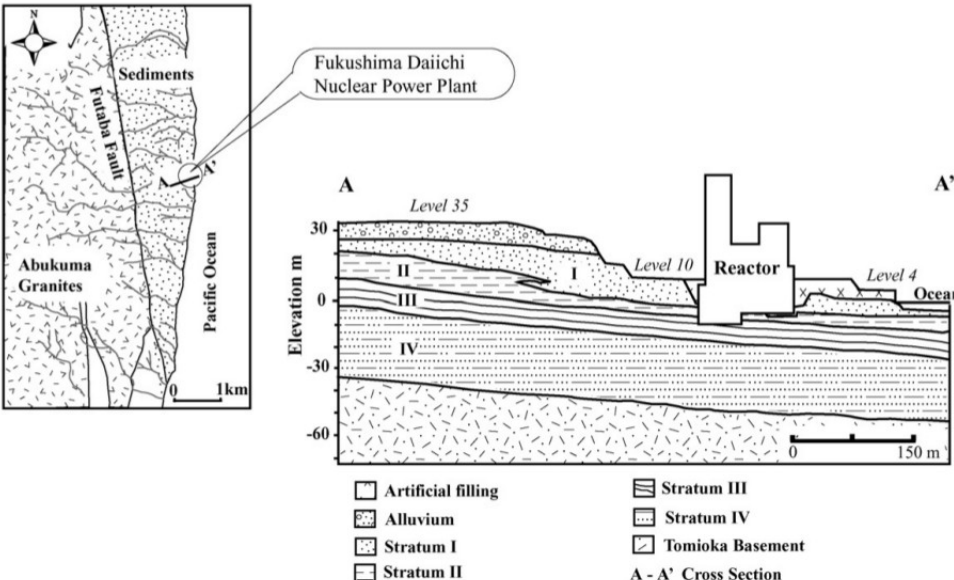


Fig. 1. Location and geological setting in vicinities of the Fukushima Daiichi nuclear power plant.



Fig. 2. Plan view of storage facilities and engineering works to contain radioactively contaminated groundwater.

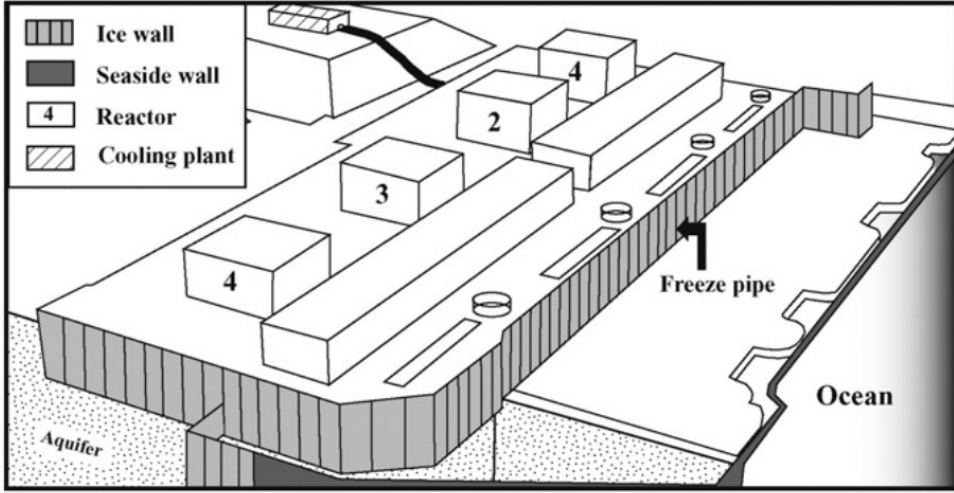


Fig. 6. Overview of the wall barriers around the nuclear reactors.

(from Gallardo and Marui, 2016)

Potential engineering applications: artificial ground freezing method

There are numerous ways and technique of soil stabilization for deep excavation or tunneling. Some of them are grouting, heat treatment method and many more. One of the common and popular method used in the recent times is ground freezing technique.



Ground freezing is a process of converting pore water or pores into ice by continuously

(from <https://theconstructor.org/geotechnical/ground-freezing-technique/16944/>)

Potential engineering applications: cold regions infrastructures



DOMAINES

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Les fondations de l'usine Yamal LNG font appel à une ingénierie particulière et dédiée aux sols de type permafrost.



(example taken from <https://www.ep.total.com/fr/domaines/gaz-naturel-liquefie/yamal-lng-decouvrir-notre-projet-en-russie/fondations-sur-permafrost>)

Thermo-hydrological modeling of permafrost

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, Lamontagne-Hallé et al., 2020).

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 (Orgogozo et al., 2019)

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.*, 2019):

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, wiki.lsce.ipsl.fr/interfrost)**

permaFoam: considered conservation equations

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:

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

Thermal transfer equation with freeze/thaw:

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

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openfoam.com:

OpenFOAM

The open source CFD toolbox



openfoam.org:

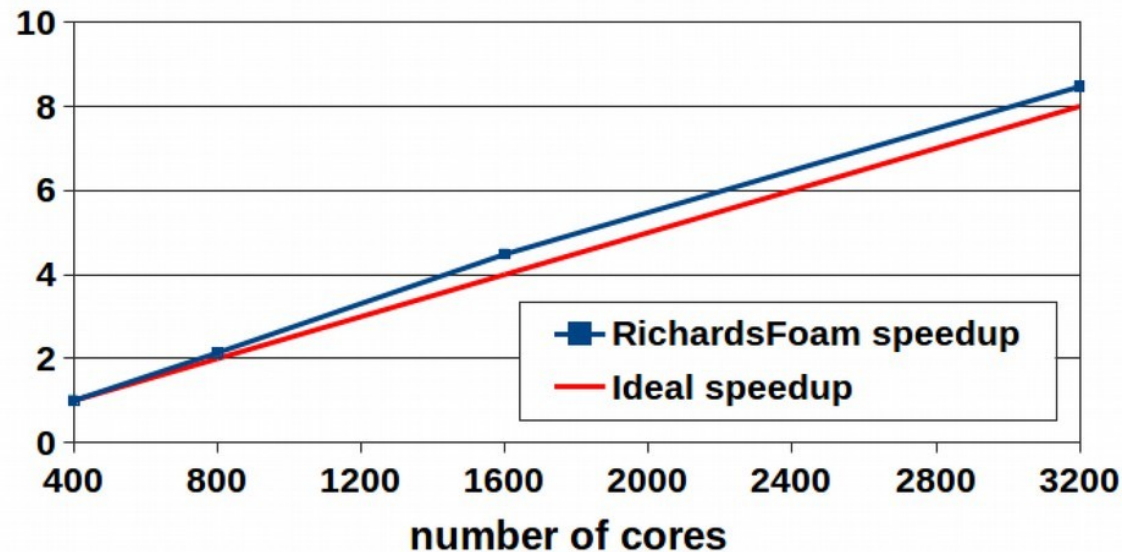


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OpenFOAM®: a well-known **open source, generalist** Computational Fluid Dynamics tool box (C++, Finite Volumes, Multi-physics, Massively Parallel Computing)

Collaborative developments of a large and diverse **community**, including both **academics** (e.g.: CINECA, IHPC, HLRS) and **industry** (e.g.: Volkswagen, Huawei, FM Global)

Continuously maintained capability to use efficiently modern computing architectures (Orgogozo et al., 2014, Bricteux et al., 2017)



Scaling curve from Orgogozo et al., 2015

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

Le Système de Calcul OLYMPE

(CALMIP regional supercomputing center)

- Cluster de calcul SEQUANA (ATOS-BULL) 1,365 Pflop/s
- 374 nœuds de calcul (36 cœurs/nœud) soit un total de **13 464 cœurs + 48 cartes GPU nvidia**
- Processeurs Intel® Skylake 6140 à 2.3 Ghz 18-cores
- Cartes GPU Nvidia V100 « Volta » 7.8 TF DP
- RAM : 192, 384 et 1536 Go/nœud soit un total de 76 To de RAM
- Réseau d'interconnexion rapide (Infiniband EDR 100 Gb/s)
- Espace de stockage permanent de 60 To (NFS)
- Espace de stockage temporaire de **1 500 To** (Lustre) - 40 Go/s

OCCIGEN : Bullx DLC - 3.5 Pflops

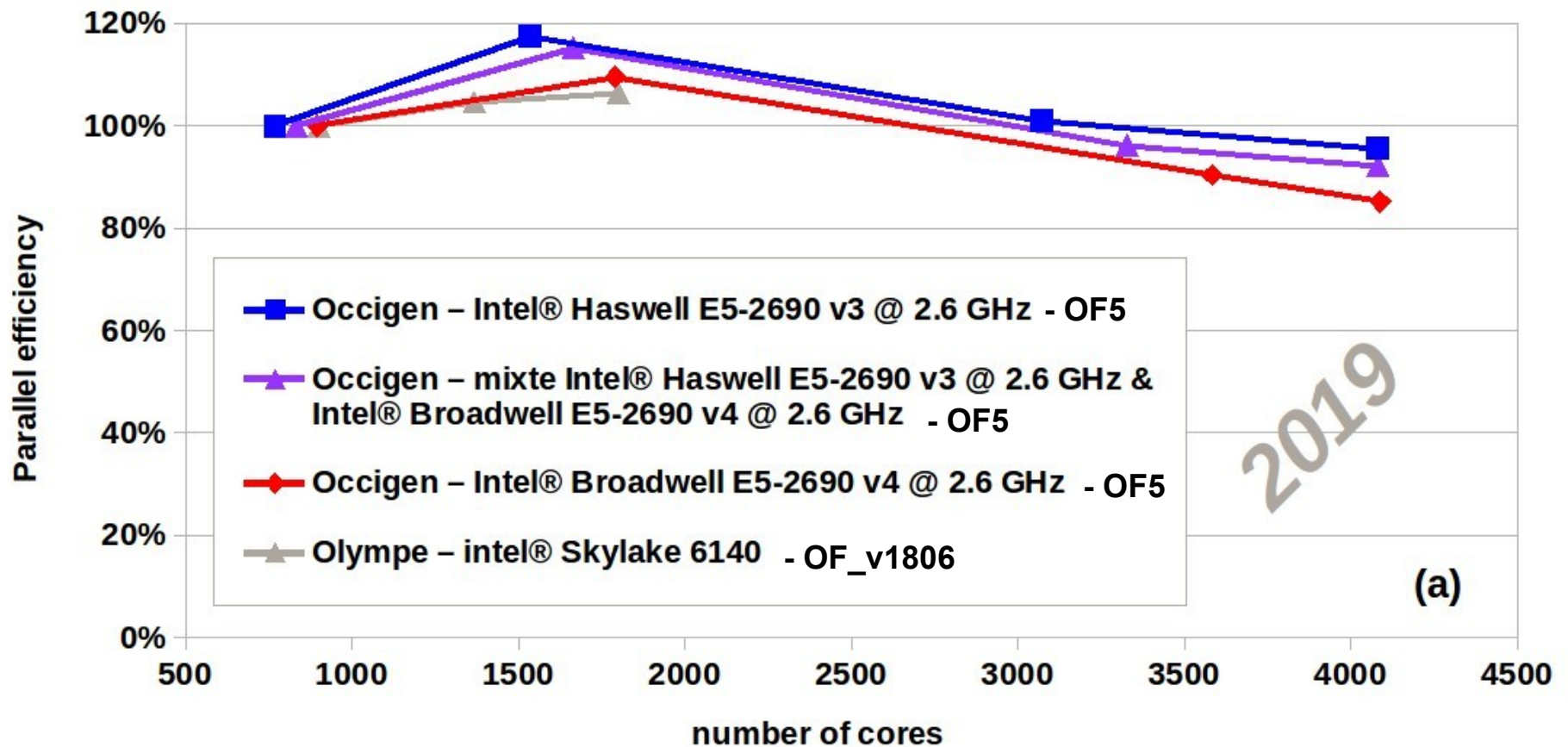
3366 x B720 nodes

- 50544 cores: Intel Haswell E5-2690 v3 @ 2.6 GHz
- 35280 cores: Intel Broadwell E5-2690 v4 @ 2.6 GHz
- 75% of compute nodes with 2,6 GB/core, 25% with 5,3 GB/core
- Infiniband FDR
- /scratch : Lustre, 5,2 PB @ 100 GB/s
- /home : Panasas, 400 TB @ 5 GB/s

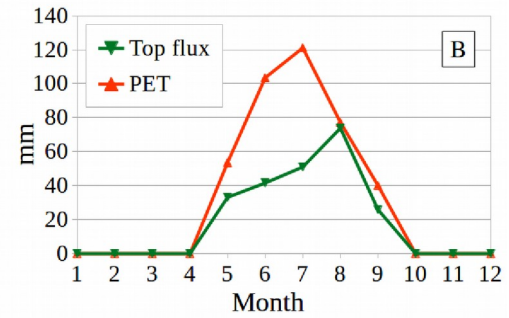
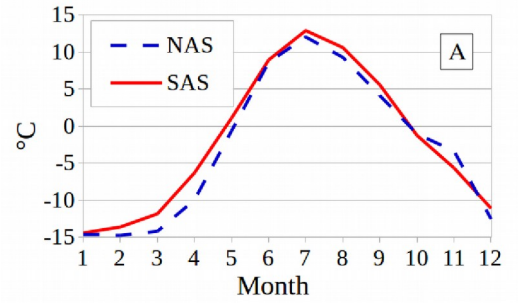
(CINES national supercomputing center)

Pré-Post & Visualisation

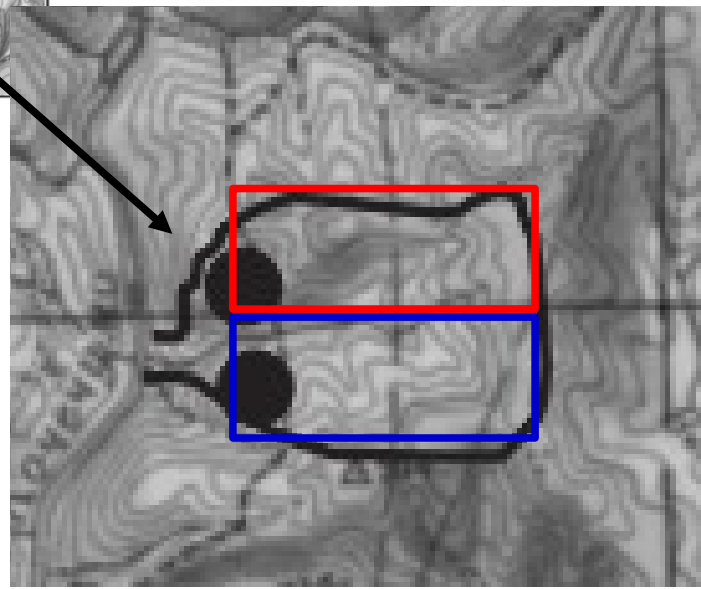
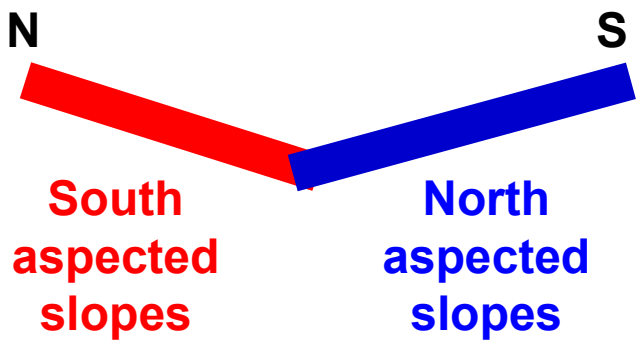
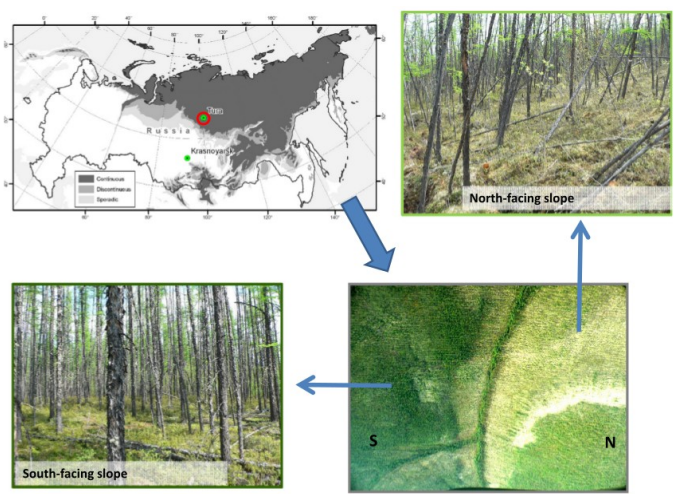
- Nœud large « Mesca »: 8 processeurs Skylake 8176 / 3 TB mémoire / 2 GPU P100
- 4 nœuds de visualisation distante :
 - 2 Broadwell E5-2690 v4 @ 2,6 GHz
 - 1 carte NVIDIA P100



2D application: comparison between numerical results and observations in a pristine Siberian watershed

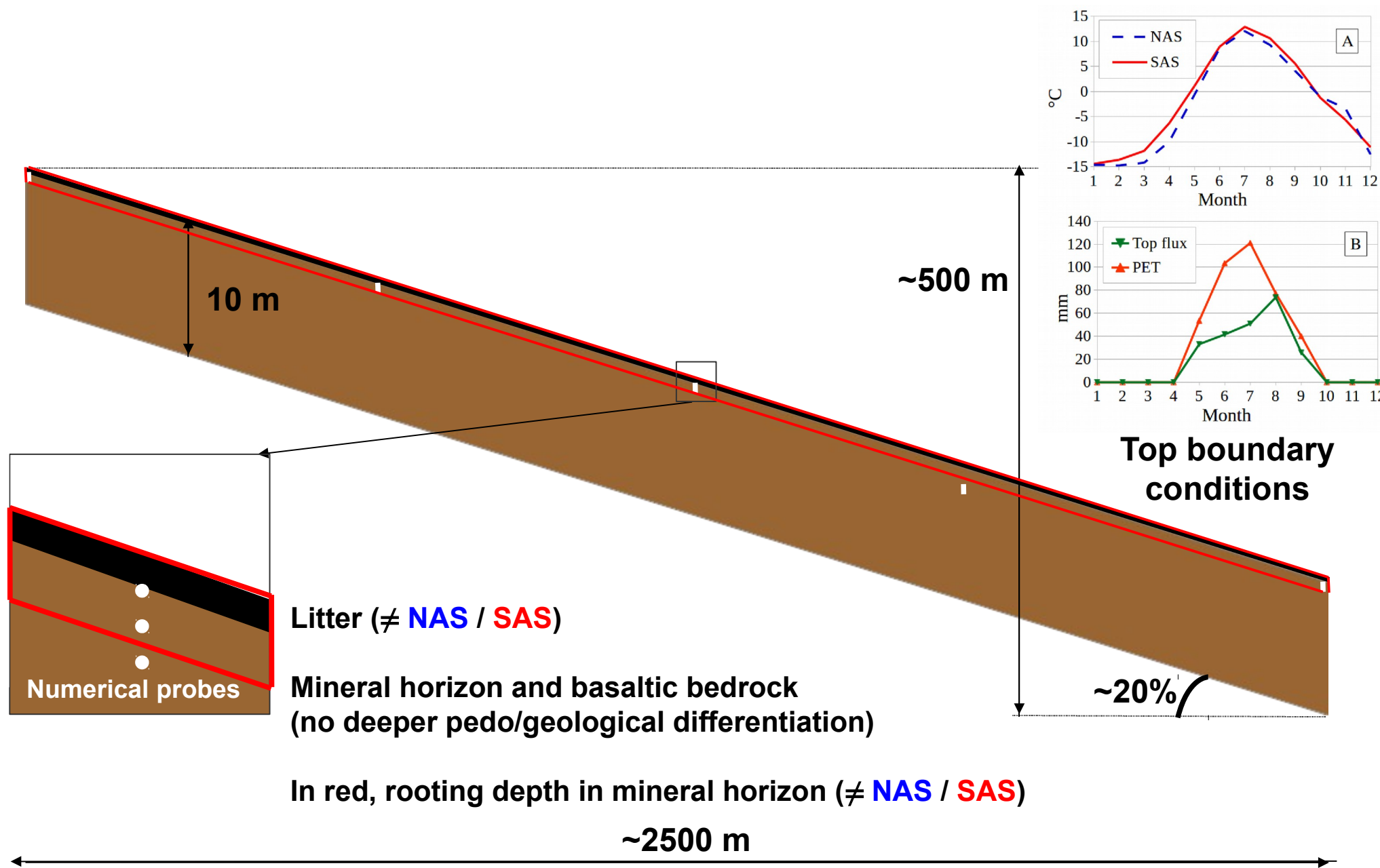


(according to Prokushkin et al., 2005, Viers et al., 2015)



Orientation and shape of the **Kulingdakan watershed** well suited for a **dual (N/S) 2D simplified representation**

2D application: comparison between numerical results and observations in a pristine Siberian watershed



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

2D application: comparison between numerical results and observations in a pristine Siberian watershed

Reasonable agreement
observations / modelling results

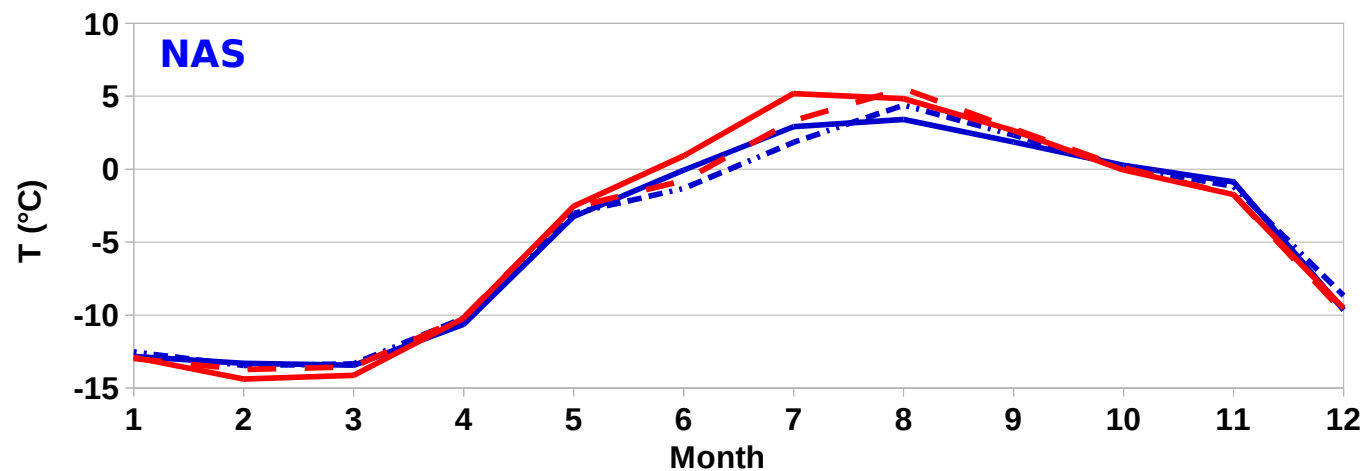
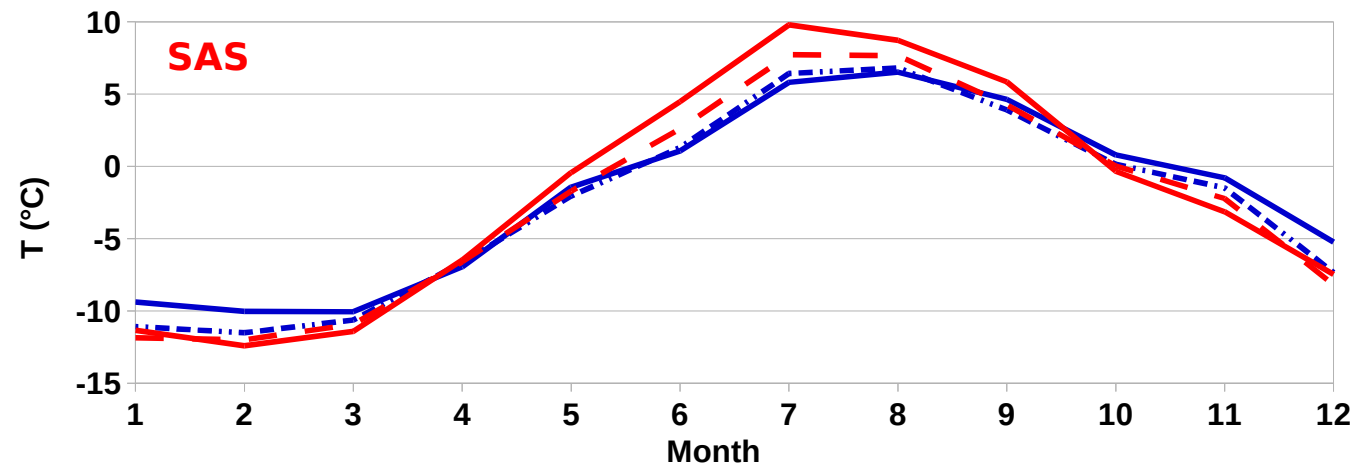
RMSE between measured and computed values

South Aspected Slopes: 1.07 °C

North Aspected Slopes: 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)

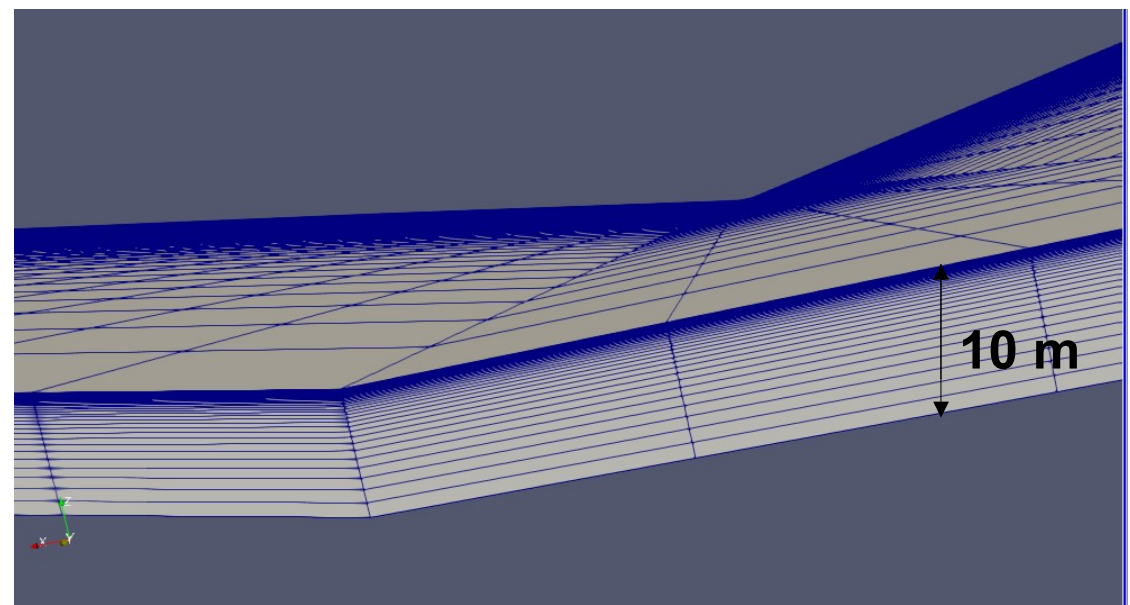
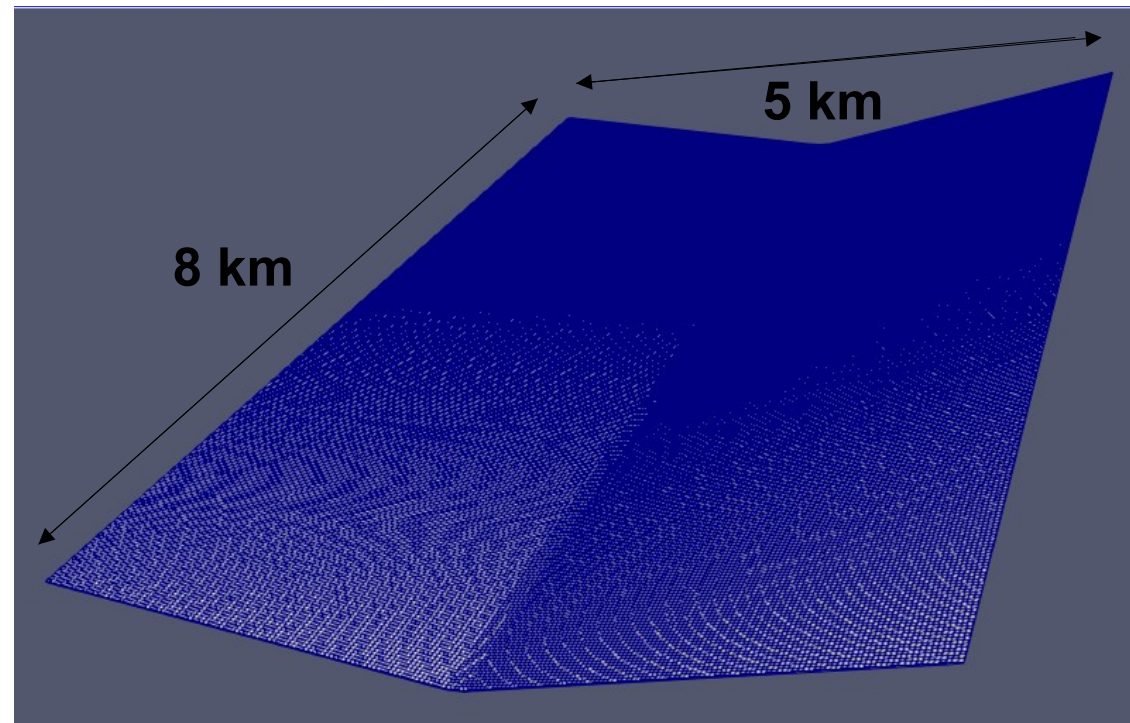
3D application: a V-tilted catchment representation of Kulingdakan watershed (work in progress)

First action of the HiPerBorea project (ANR-19-CE46-0003-01, hiperborea.omp.eu)

Simplified 3D representation: vertically graded mesh, 60M cells

BC: use of synthetic climate forcings constructed with sums of sinusoidal functions of time

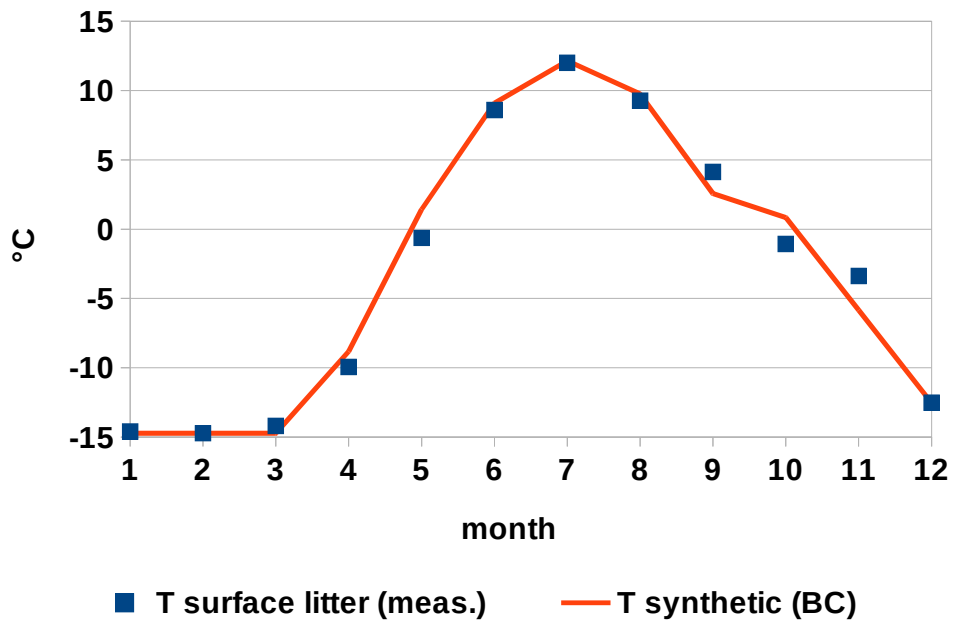
Spin-up not completed, no numerical convergence study yet => preliminary results



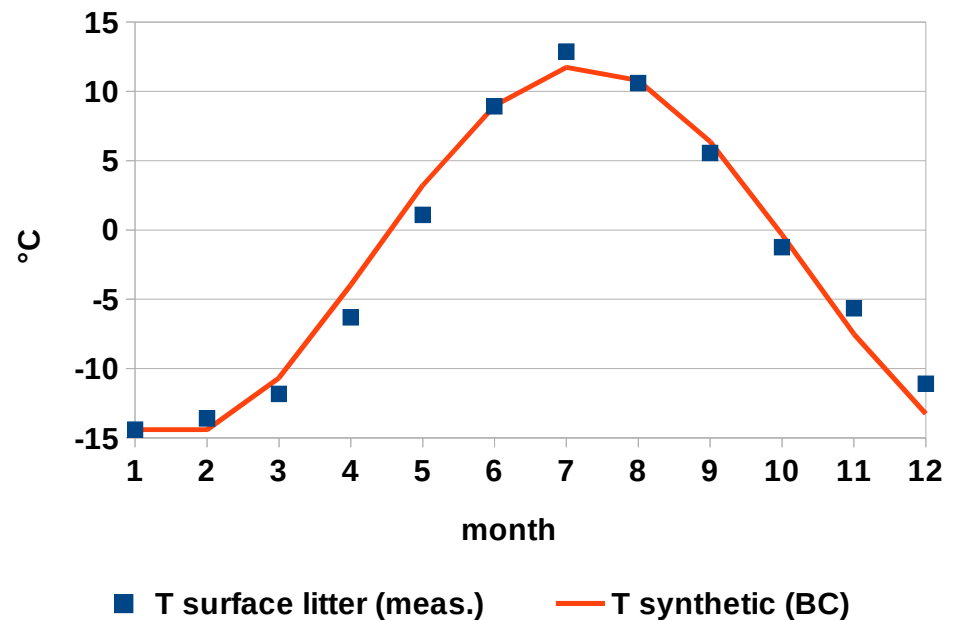
3D application: a V-tilted catchment representation of Kulingdakan watershed (work in progress)

Top boundary conditions : use of synthetic climate forcings constructed with sums of sinusoidal functions of time

Measured and synthetic temperature signals - NAS



Measured and synthetic temperature signals - SAS

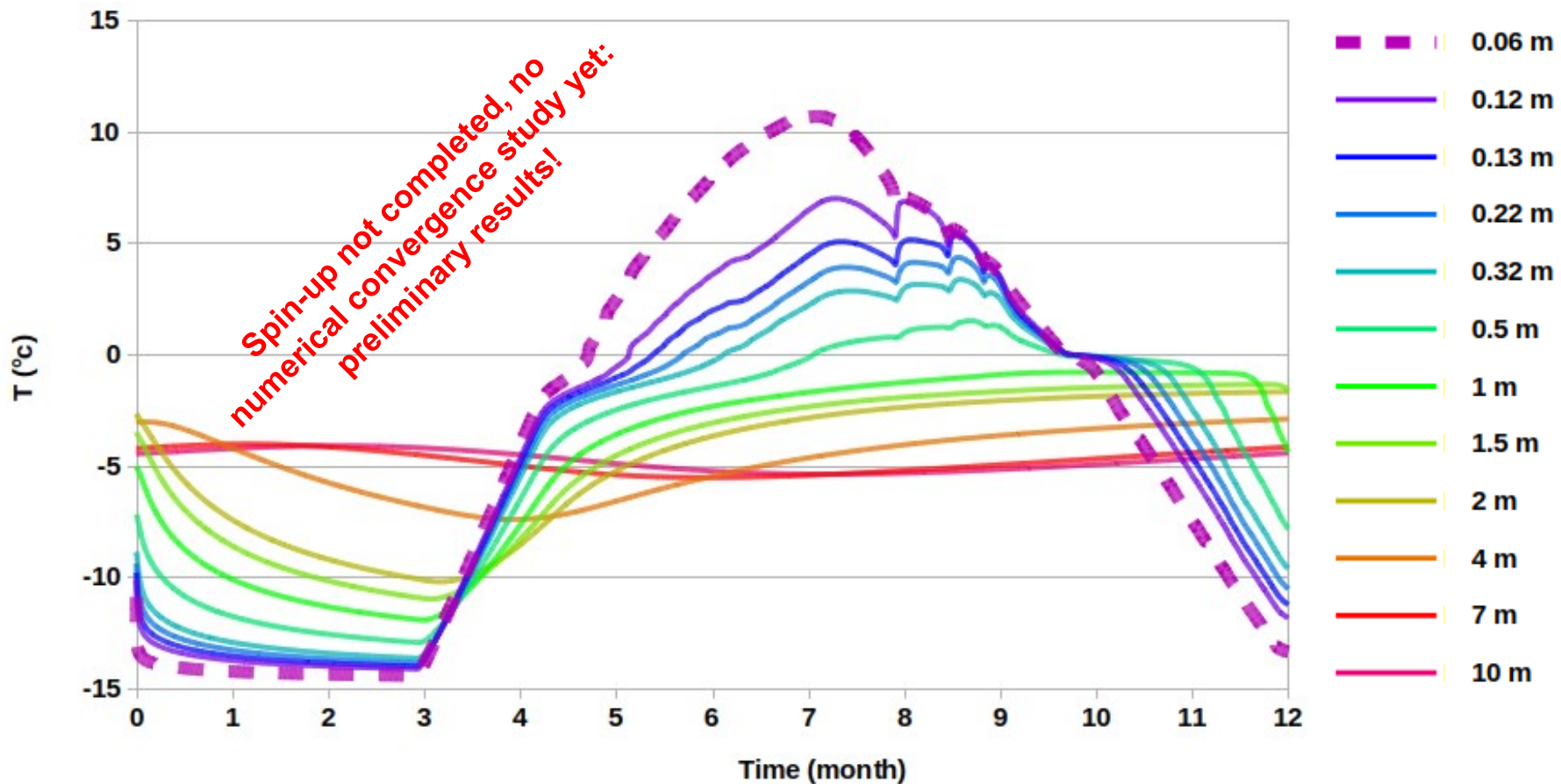


For temperature, water flux (and potential evapotranspiration sink term)

Goal: avoid temporal discontinuities that are computationally costly (see Orgogozo et al., InterPore 2017)

3D application: a V-tilted catchment representation of Kulingdakan watershed (work in progress)

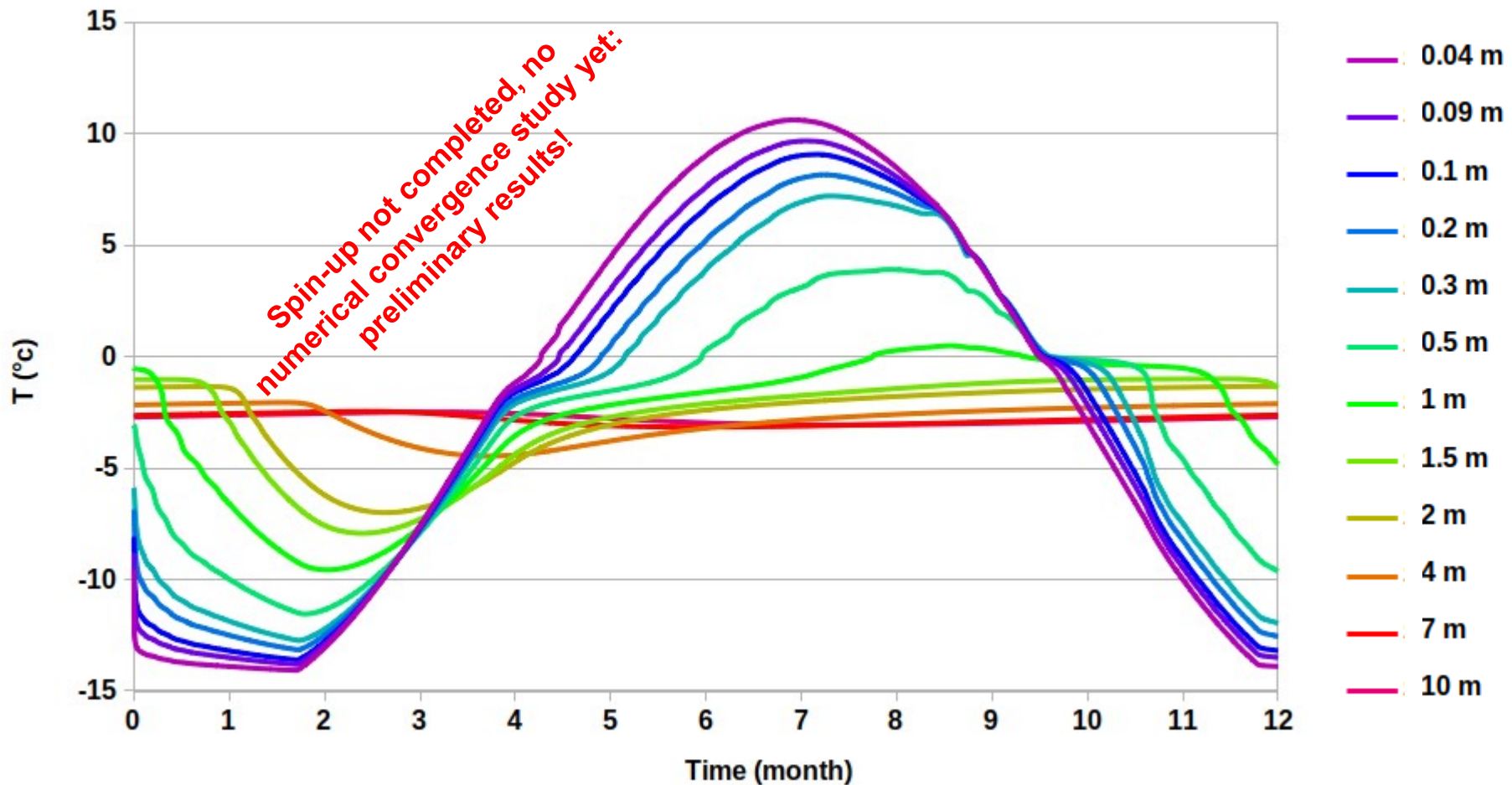
Preliminary results: North Aspected Slope temperature at different depths



Active (seasonally thawed) layer thickness between 0.5 m and 1 m: good agreement with the observations (0.6 m in NAS)

3D application: a V-tilted catchment representation of Kulingdakan watershed (work in progress)

Preliminary results: South Aspected Slope temperature at different depths



**Active (seasonally thawed) layer thickness between 1 m and 1.5 m:
good agreement with the observations (1.2 m in SAS)**

Conclusions and perspectives

3D modeling of the permafrost of Kulingdakan catchment
in current climatic conditions: new insights on water pathways and residence times for biogeochemical studies

Next: 3D modeling of the permafrost of Kulingdakan catchment **under climate change** at the century time scale

Difference between impacts of various scenarios of CC?
role of vegetation cover (PET) and topography (NAS/SAS)?

Thank you for your attention

Contact: laurent.orgogozo@get.omp.eu

HiPerBorea project, ANR-19-CE46-0003-01,
hiperborea.omp.eu