

High Performance Computing for permafrost modeling: towards mechanistic assessments of climate change impacts at the scale of the experimental watershed

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Лаборатория
биогеохимических
и дистанционных методов мониторинга
окружающей среды

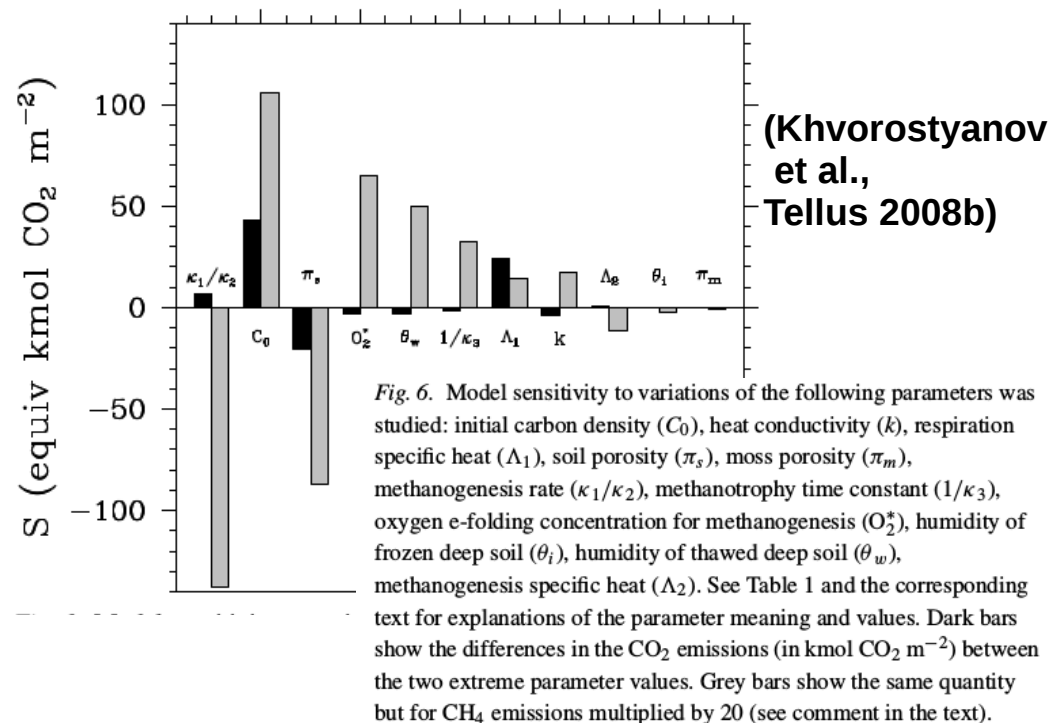


Permafrost dynamics and climate change



Feedbacks between climate change and continental surfaces especially strong in boreal areas, mostly covered by permafrost (e.g.: 500 GtC stored in the Yedoma, Khvorostyanov et al., GRL 2008).

Continental/global modelings of climate-permafrost feedbacks **highly sensitive to hydrological parameterizations** (e.g.: Khvorostyanov et al., Tellus 2008a, 2008b, Dantec-Nédélec et al., 2016, Peng et al., 2016).



Climate change

→

Important changes in spatial distribution of permafrost (Grosse et al., 2016)

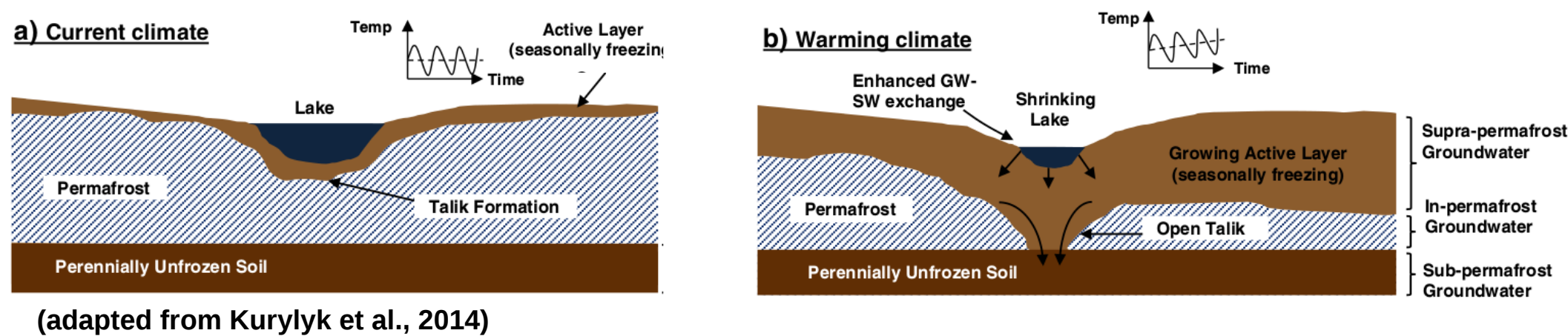
→

Strong impacts on hydrological regimes (Wrona et al., 2016).

Water fluxes → biogeochemical transfers in continental surfaces (e.g.: carbon cycle)

→ **Need to improve our understanding of driving thermo-hydrological processes at stake**

Impacts of permafrost thaw induced by climate change



Substantial potential impacts on groundwater availability

Severe impacts on buildings stability

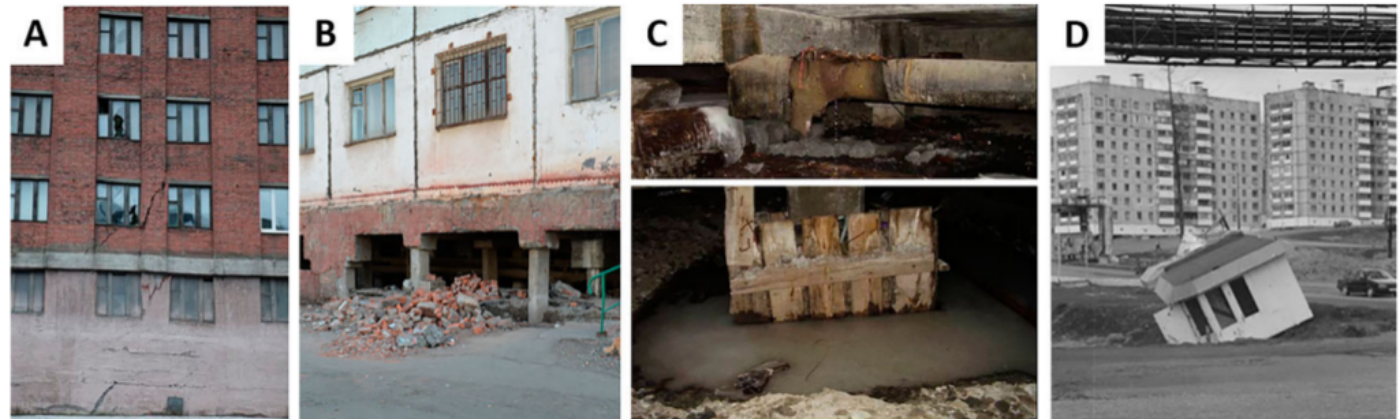


Figure 2. (a) Example of structural deformation of building caused by inadequate structural design exacerbated by permafrost warming. (b) Example of cryogenic weathering of the foundation. (c) Water leakage and accumulation around foundation piles. (d) Ground settlement developed under small heated kiosk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

Cryohydrogeological modelling

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, Yu et al., 2018).

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

the permaFoam solver

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:

$$\frac{\partial [C_{T,eq}(h, T) T]}{\partial t} + \nabla \cdot [v(h, T) C_{T,eq}(h, T) T] - \nabla \cdot [K_{T,eq}(h, T) \nabla T] + L \frac{\partial \theta_{ice}(h, T)}{\partial t}$$

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

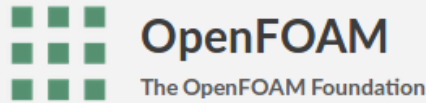
openfoam.com:

OpenFOAM

The open source CFD toolbox



openfoam.org:

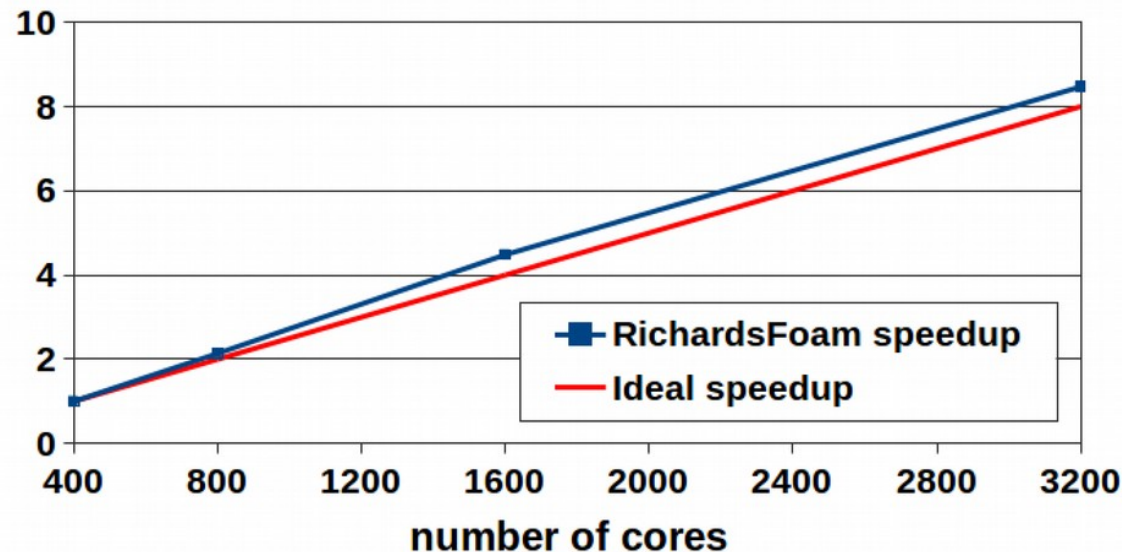


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OpenFOAM: a well-known **open source, generalist** Computational Fluid Dynamics tool box (C++, Finite Volumes, Multi-physics, Massively Parallel Computing)

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

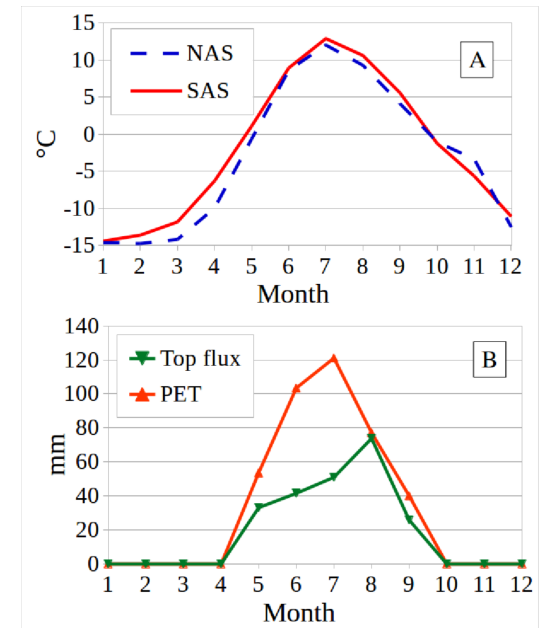
Continuously maintained capability to use efficiently modern computing architectures (Orgogozo et al., 2014, Bricteux et al., 2017)



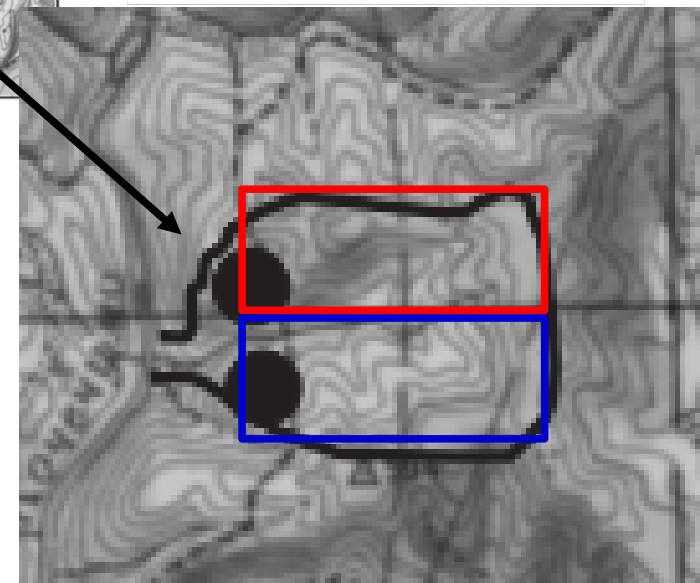
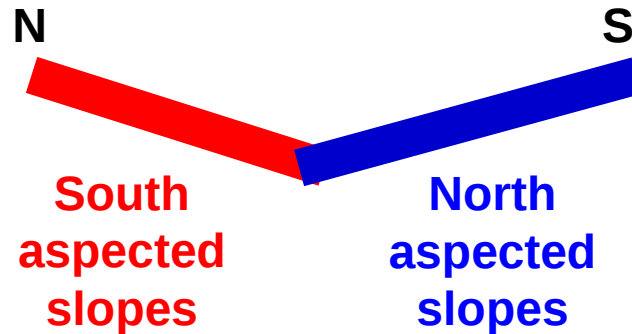
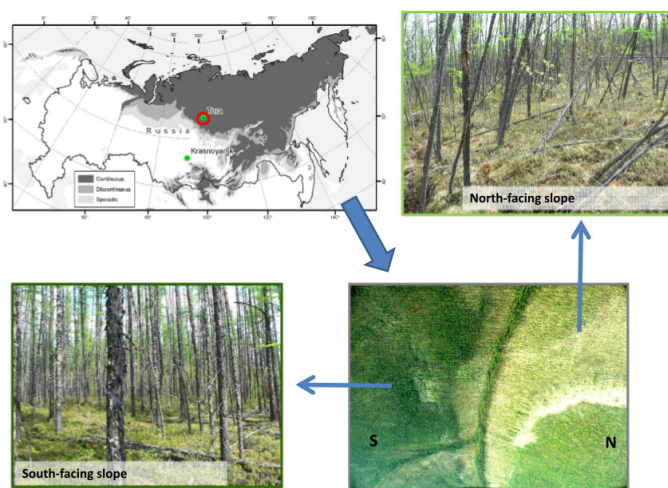
Scaling curve from Orgogozo et al., 2015

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

Active layer dynamics in a Taiga environment in current climate



(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**

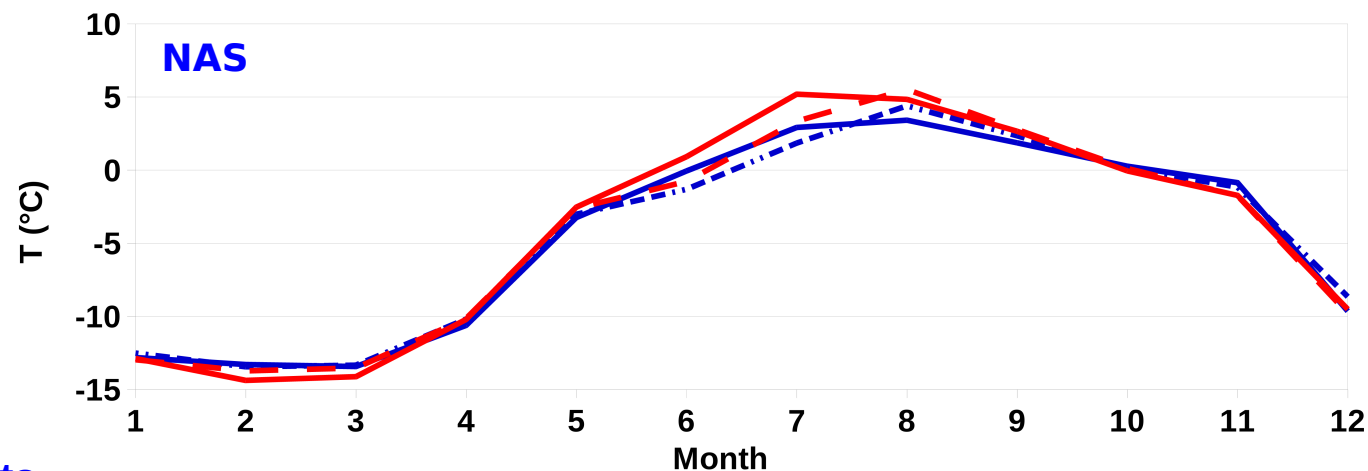
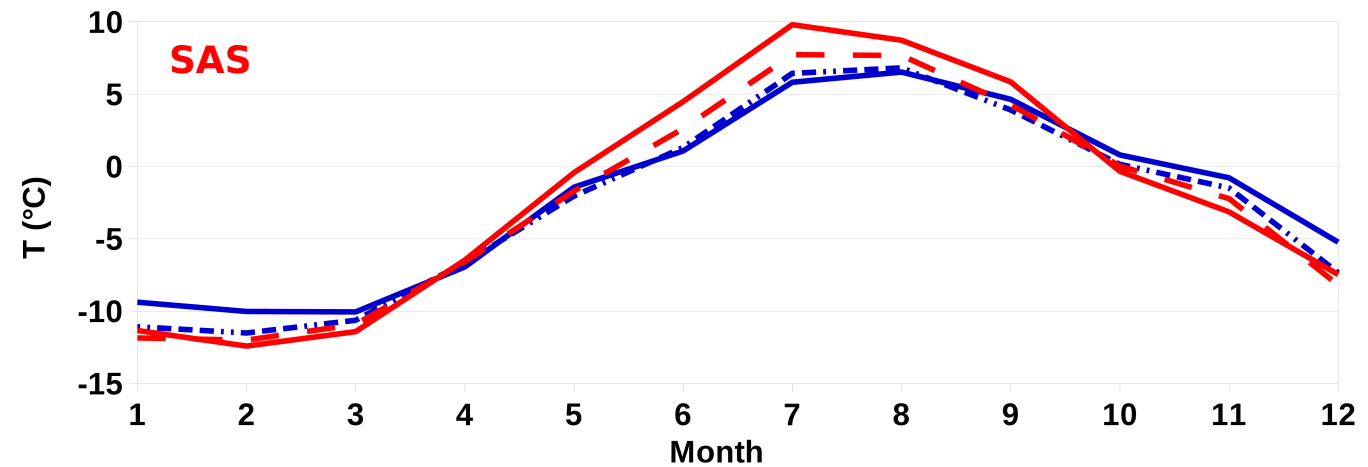
Active layer dynamics in a Taïga environment in current climate

Reasonable agreement
observations / modelling results
without any calibration

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)

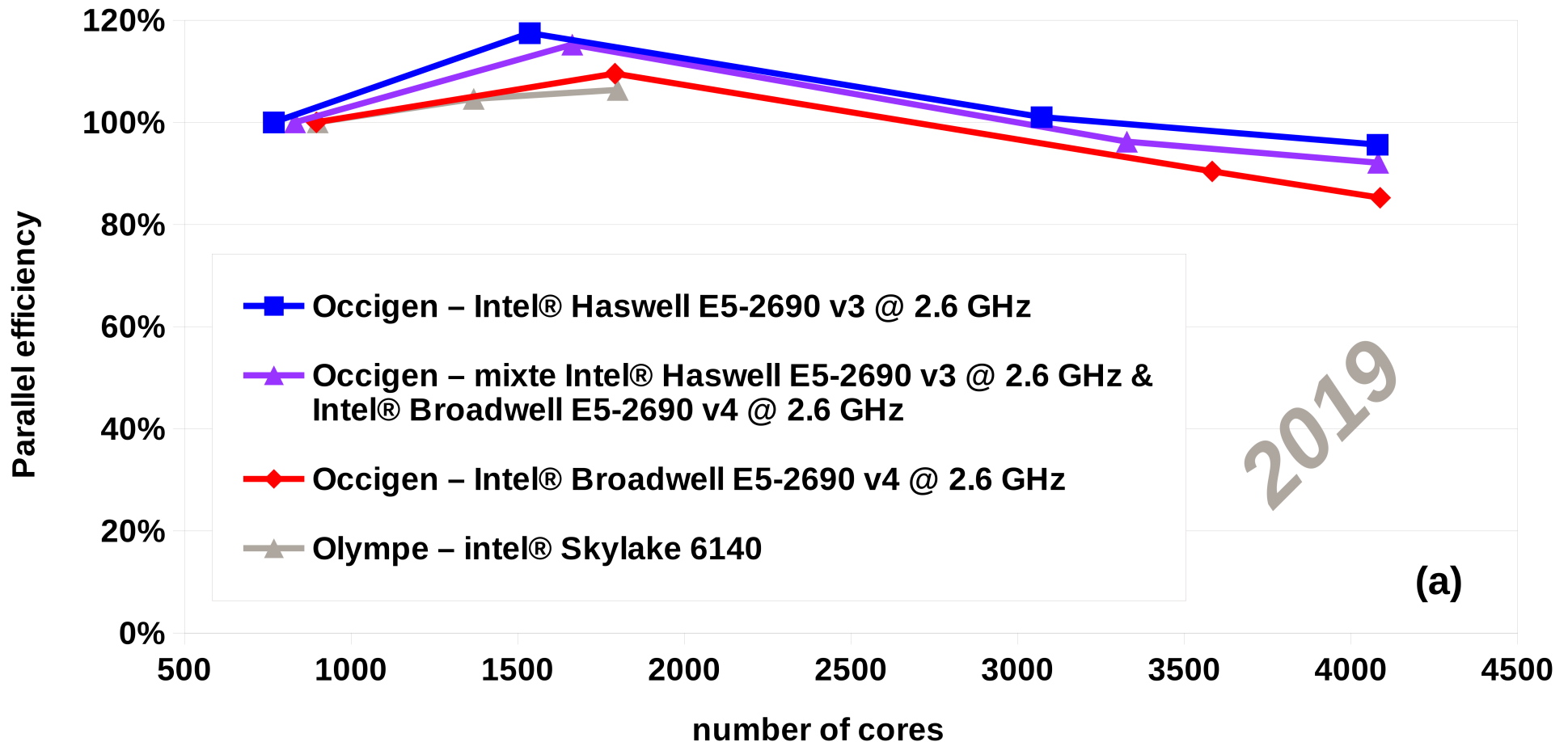
OCCIGEN : Bullx DLC - 3.5 Pflops

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

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



ANR Project HIPERBOREA: High Performance computing for quantifying climate change impacts on Boreal Areas

Principal Investigator: Orgogozo L., Geosciences Environment Toulouse

4 Partner laboratories: 3 in Toulouse, 1 in Paris (+ intl partners from Russia and Sweden):

- **Geosciences Environment Toulouse (Pokrovsky O., Shirokova L., Audry S., Auda Y., Gondet E.)**
- **Institut de Mécanique des Fluides de Toulouse (Marcoux M, Quintard M., Davit Y.)**
- **Laboratoire des Sciences du Climat et de l'Environnement (Grenier C., Mouche M., Mügler C.)**
- **Centre d'Etude Spatiale de la Biosphère (Gascoin S.)**

Goal: use OpenFOAM® to enable unprecedented simulations of cold environments dynamics

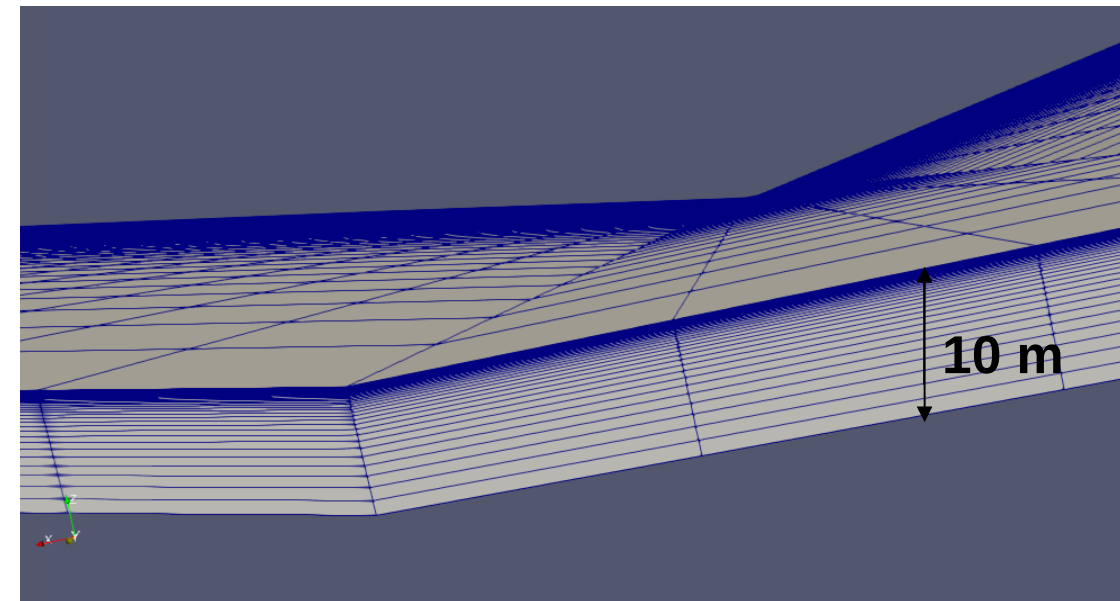
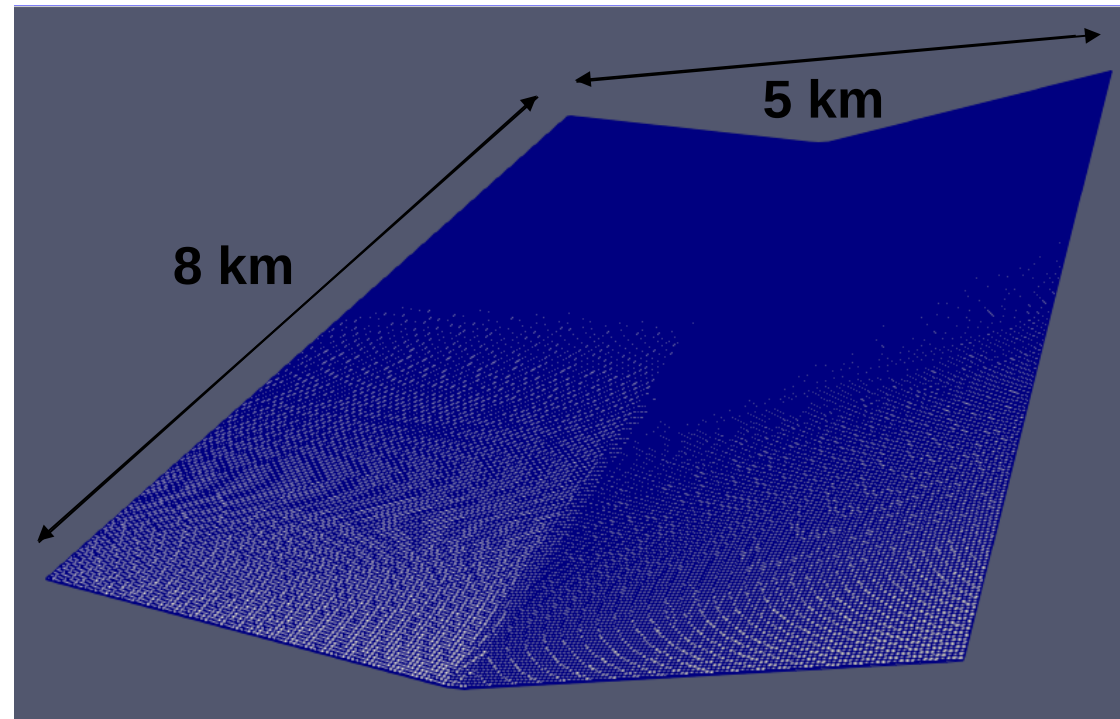
Attributed budget: 630 kEuros (1 post-doc, 1 PhD, students - consolidated budget 1,7 mEuros)

Duration: 4 years, 2020 - 2023

Scientific goals and technical challenges

Modeling century time scale evolutions of experimental watersheds of several 10's of km² for various scenarios of climate change (e.g.: RCP 2.6 and RCP 8.5):

- 10's of billions of cells meshes
- 10's of thousands of cores
- Runs of several 100's of thousands to millions CPU hours
- Computational resources:
 - Tier-2 (CALMIP)
 - Tier-1 (CINES)
 - Tier-0 (PRACE)



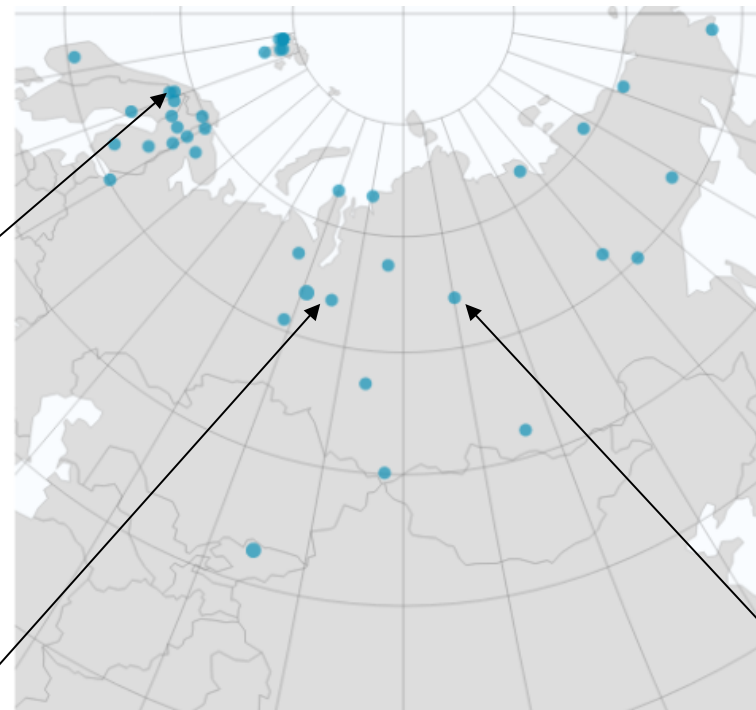
Field data: INTERACT network and IRN TTS

Four long term monitoring sites of environmental changes in arctic and sub-arctic regions: Abisko Station in Sweden, Khanymey Station in Western Siberia, Evenkian Station in Central Siberia and Syrdakh Station in Eastern Siberia

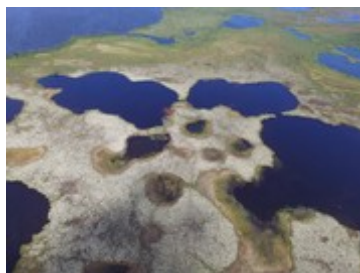
Chosen to sample the variety of geographical contexts in arctic/sub-arctic areas: permafrost type and distribution, air temperature, precipitation, lithology, vegetation cover, landform and latitude.



Abisko INTERACT Station, Sweden



+ Syrdakh watershed, Eastern Siberia (IRN TTS)



Khanimey INTERACT Station, Western Siberia



Evenkian INTERACT Station, Central Siberia

Thank you for your attention.

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