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Toward HPC simulations of climate warming impacts on Eurasian permafrost: the HiPerBorea project

Orgogozo L.¹, Xavier T.¹

¹ GET (Geosciences Environment Toulouse), UMR 5563 CNRS/UR 234 IRD/UPS,
Observatory Midi Pyrénées, University of Toulouse

Permafrost covers 25% of northern hemisphere lands

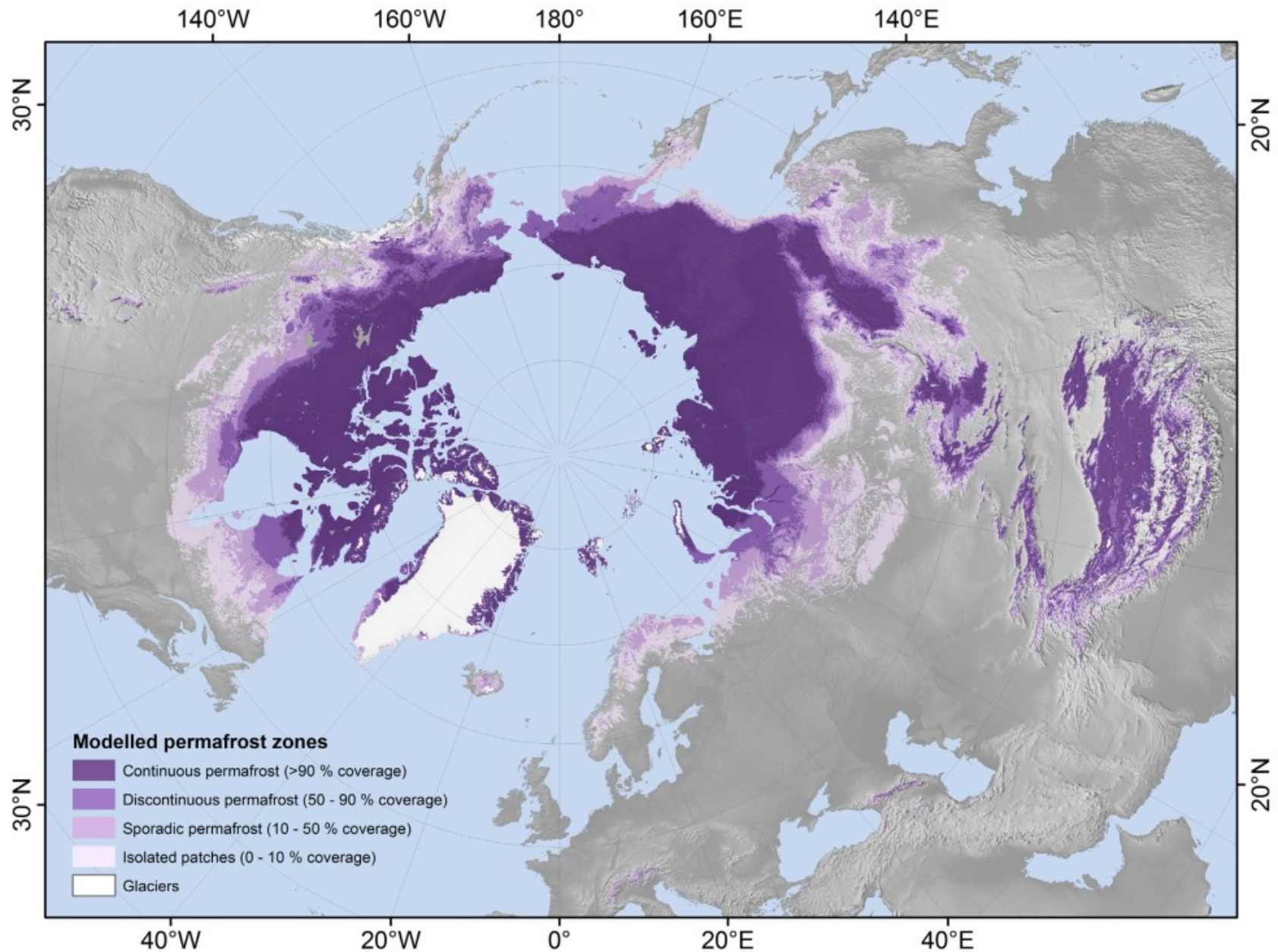
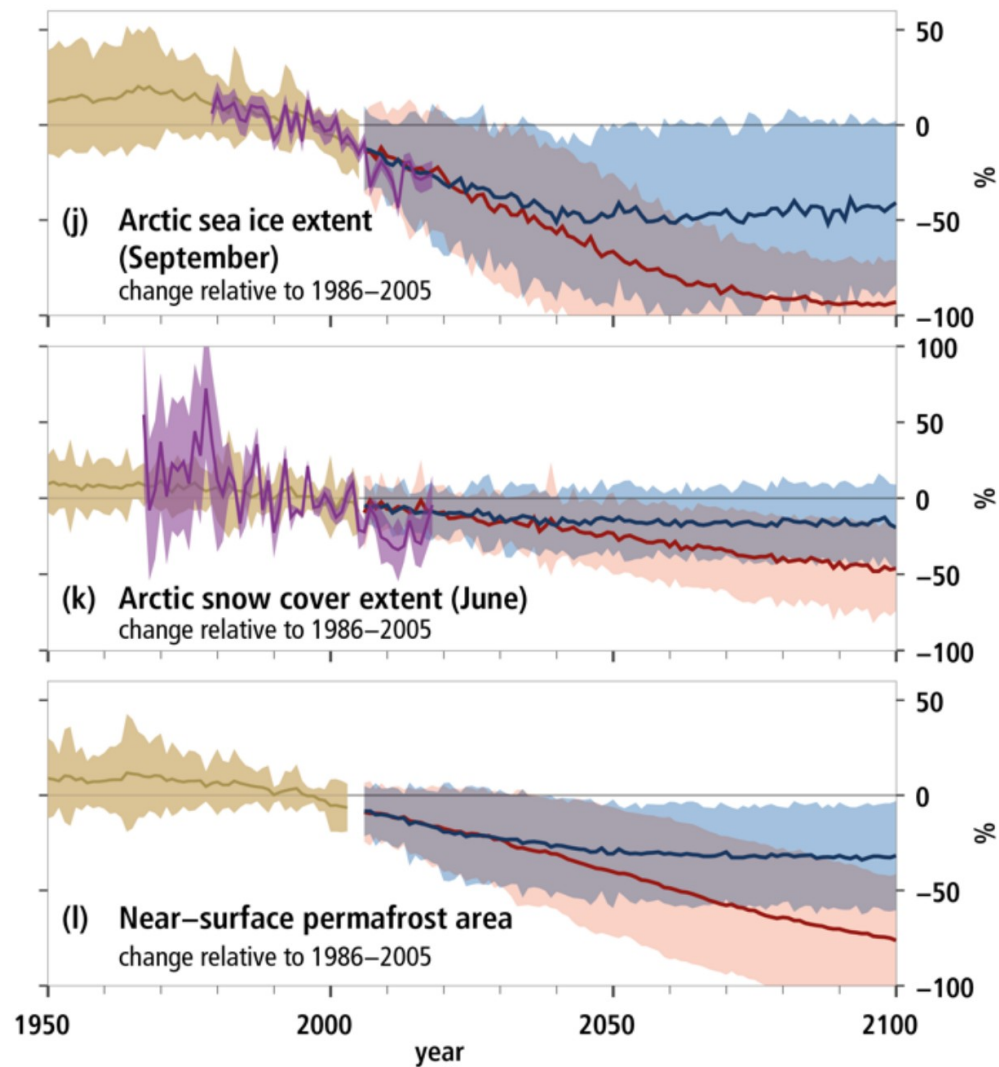
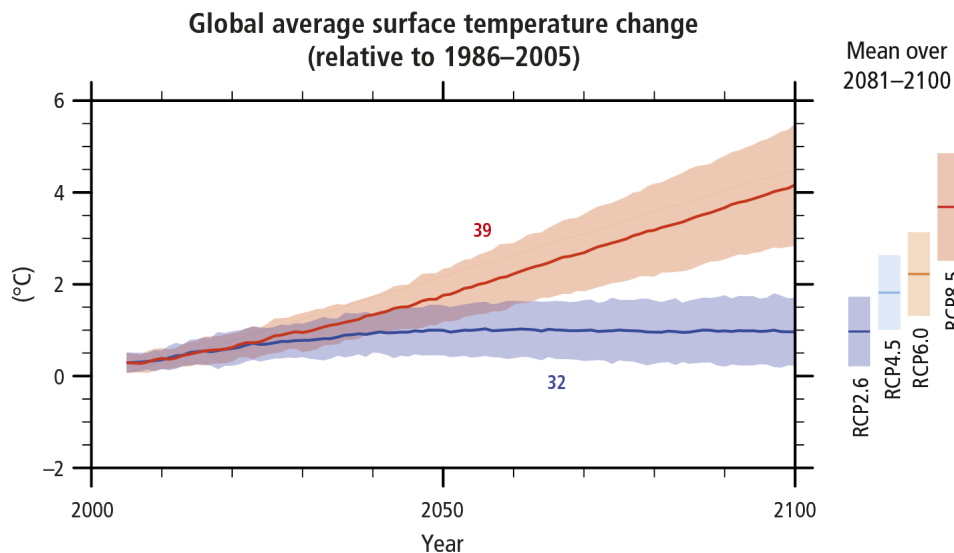
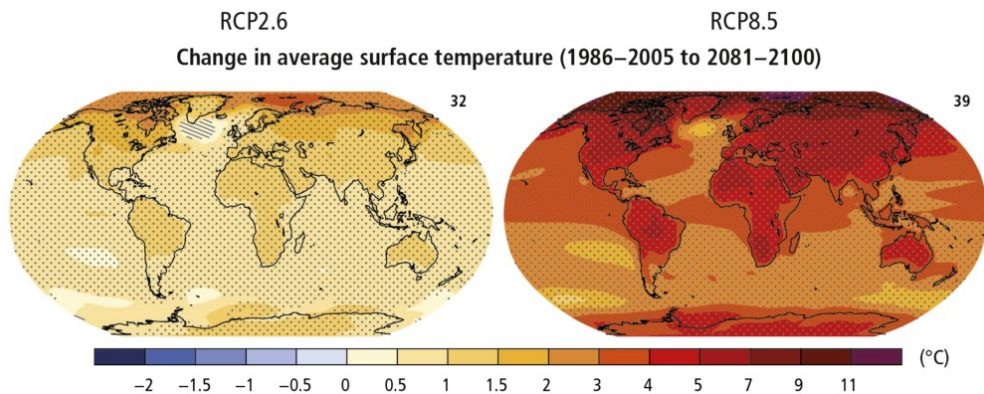


Fig. 5. Permafrost zonation based on classified modelled permafrost probabilities (Fig. 4) which correspond with the fraction of each 1 km² pixel underlain by permafrost.

(Obu et al., 2019)

Arctic change

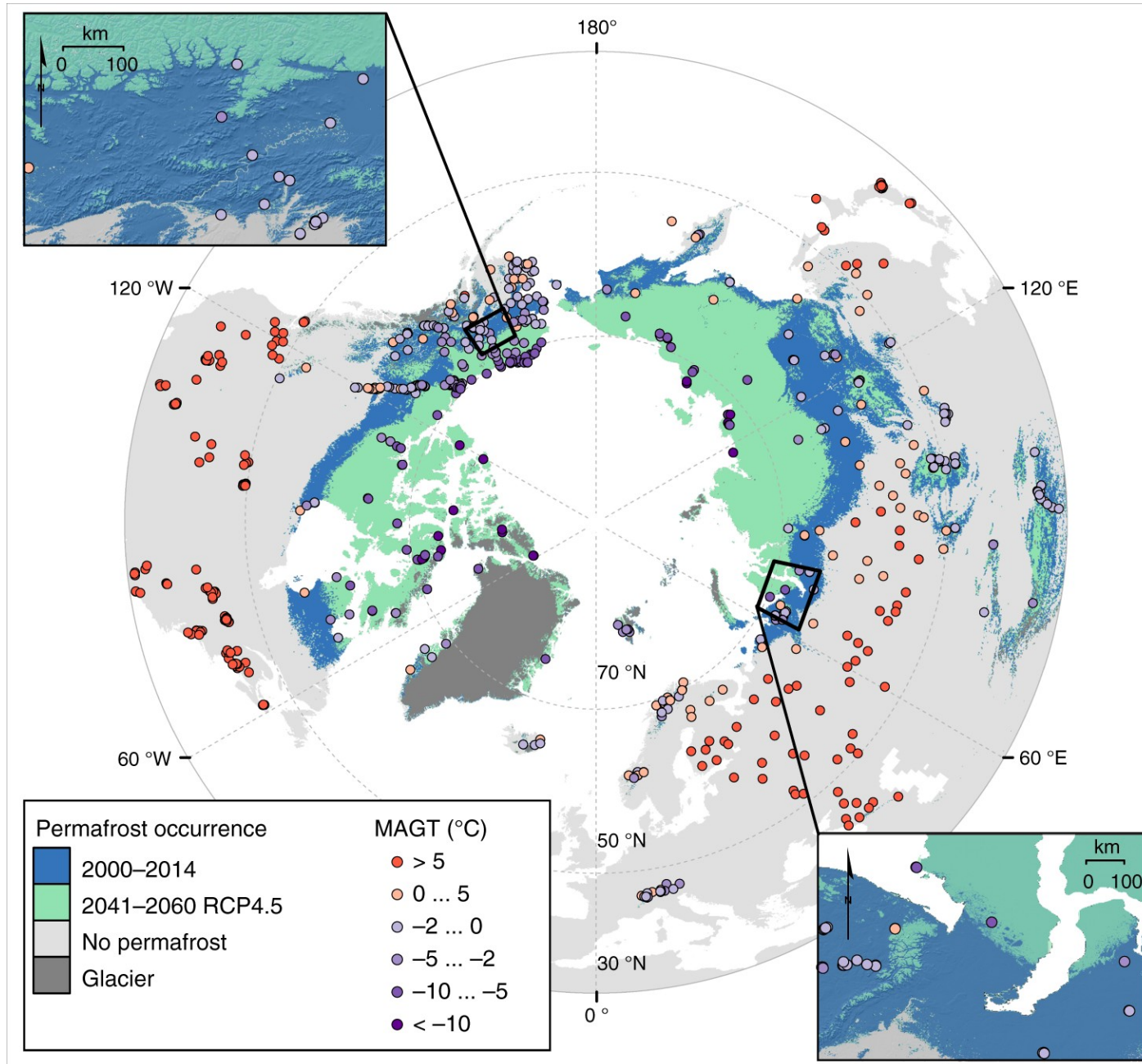
Climate warming is especially strong at high latitudes



Adapted from the Climate Change Synthesis report 2014 of the IPCC

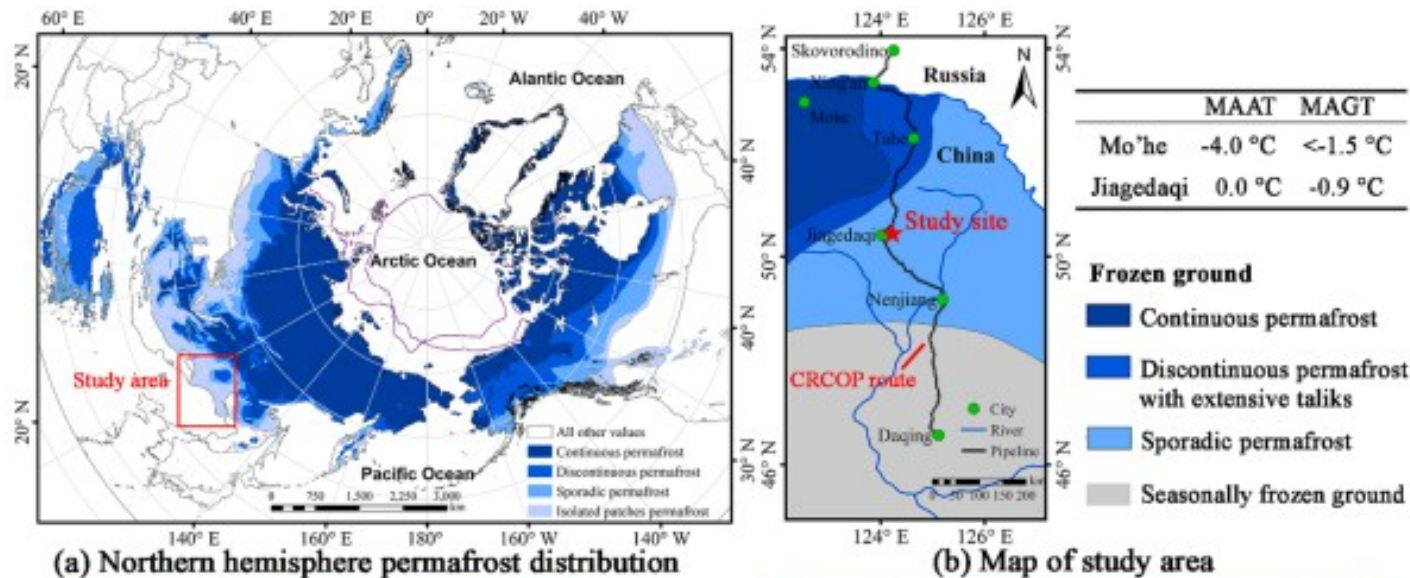
Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) – IPCC 2019

Climate warming: permafrost thaws



Hjort et al., 2018

Technogenic warming: permafrost thaws



“For a buried oil pipeline built on permafrost, the main hazard is represented by the talik [...] formation around the pipes [...]. The talik initiated and enlarged quickly after the several-year operation.”

Chen et al., 2021

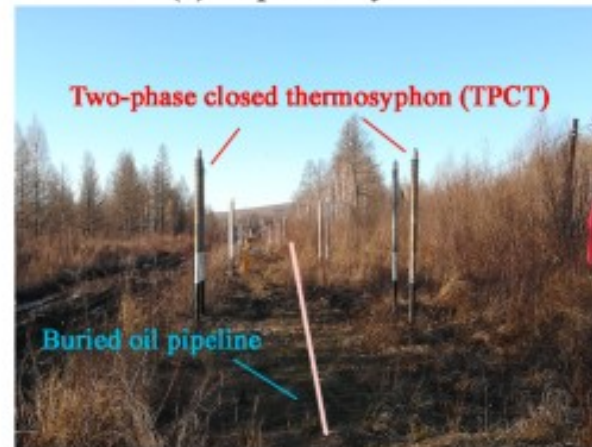


Fig. 1. (a) Circum-Arctic permafrost map (source: Brown et al., 2002 [26]); (b) Map of study area (source: Zhou et al., 2000 [27]); (c) China-Russia crude oil pipeline, Northeastern China; and (d) Photo of the buried oil pipeline mitigated with two-phase closed thermosyphons. Photos were taken by Yan Lu and Wenbing Yu on October 8th, 2019. Note: mean annual air temperature (MAAT), mean annual ground temperature at the depth of zero annual amplitude.

Hjort, J., Streletskiy, D., Doré, G. et al. (2022). Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment

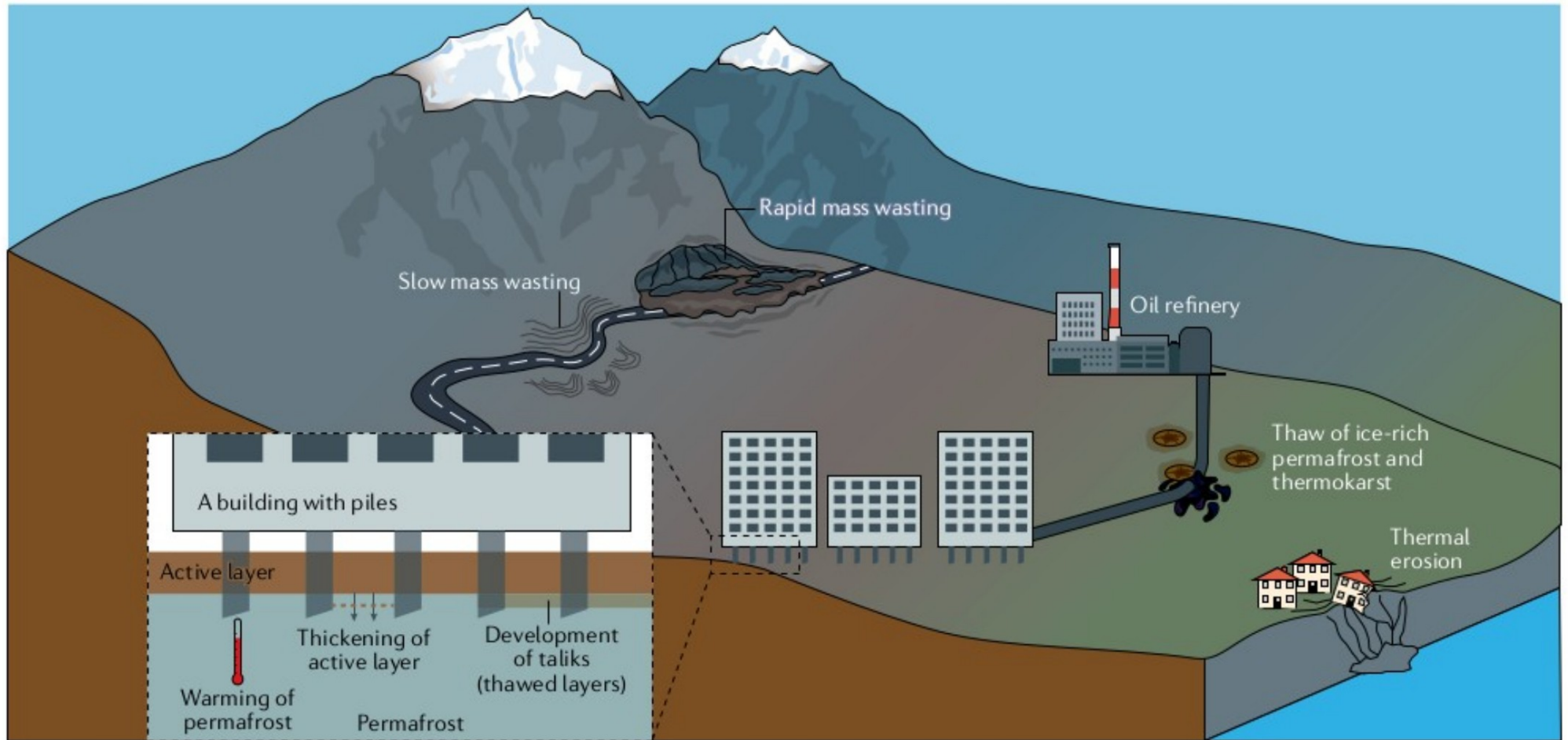


Fig. 2 | **Permafrost hazards damaging infrastructure.** Schematic presentation of permafrost degradation-related natural hazards that threaten the integrity of critical infrastructure (roads, pipelines, buildings and industrial facilities) in permafrost areas.

« [...] infrastructure damage is projected to continue, with 30–50% of critical circumpolar infrastructure thought to be at high risk by 2050. Accordingly, **permafrost degradation-related infrastructure costs could rise to tens of billions of US dollars by the second half of the century.** »

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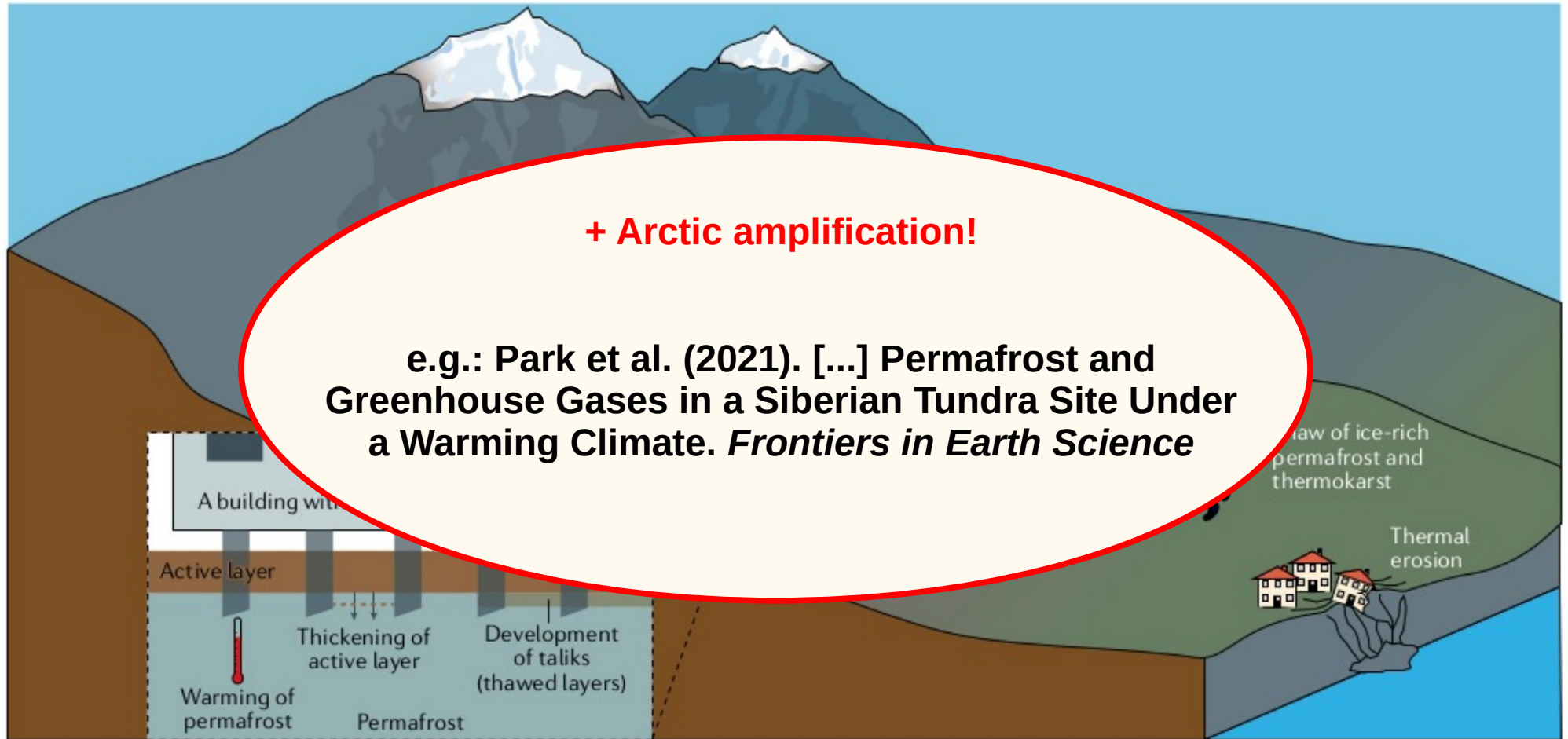


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HIPERBOREA - ANR funded project - High Performance computing for quantifying climate change impacts on Boreal Areas hiperborea.omp.eu

Scientific coordinator: Orgogozo L., Géosciences Environnement Toulouse

4 partner laboratories: 3 in Toulouse, 1 in Paris (+ Intl collaborations: Russia, 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® for making simulations of permafrost dynamics at unprecedented scales and resolutions

Granted budget: 630 k€ (1 post-doc, 1 PhD, master stud. - consolidated budget: 1,7 m€)

Duration: 4 years, 2020 - 2023

PermaFoam : solving the equations of thermo-hydrological permafrost dynamics

3D transient heat and water transfers in variably saturated porous media with freeze/thaw of pore water and evapotranspiration (Orgogozo et al., 2019, 2022)

couplings, non-linearities

Richards equation with evapotranspiration:

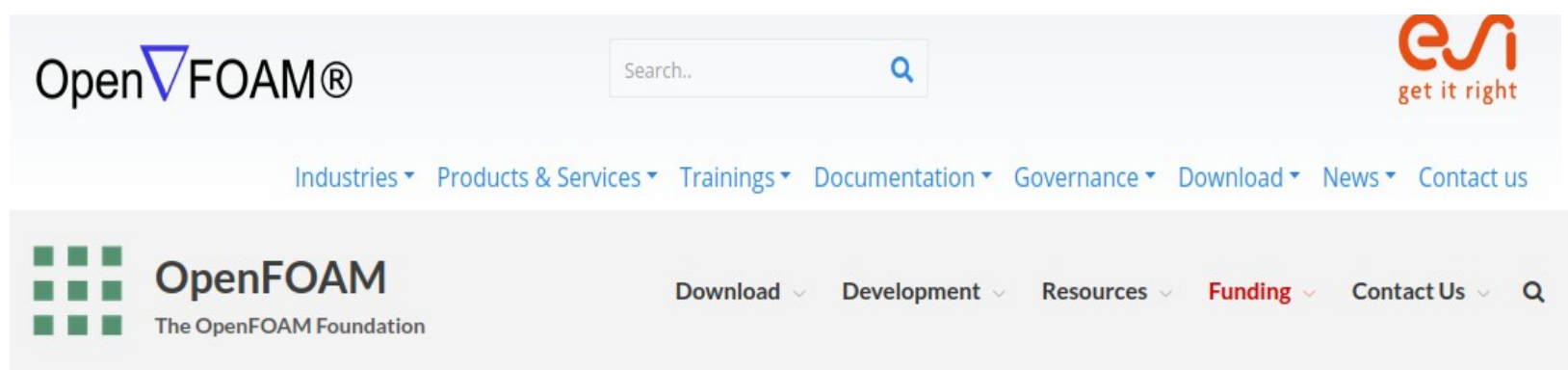
$$C_H(h) \frac{\partial h}{\partial t} = \nabla \cdot (K_H(h, T) \nabla (h + z)) + Q_{AET}(h, T)$$

Heat transfer with freeze/thaw:

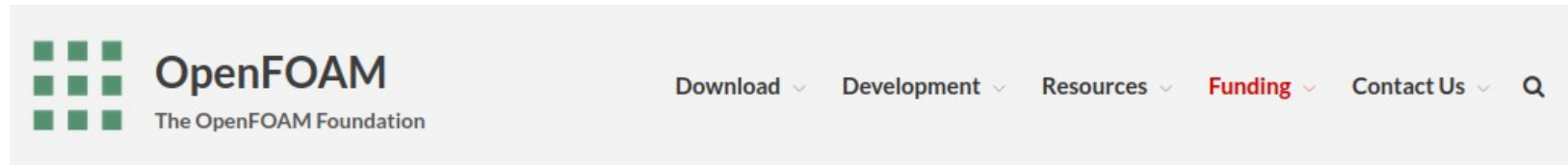
$$\frac{\partial (C_{T_{eq}}(h, T) T)}{\partial t} + \nabla \cdot (\mathbf{v}(h, T) C_{T_{liquid}} T) = \nabla \cdot (K_{T_{eq}}(h, T) \nabla T) + L \frac{\partial \theta_{ice}(h, T)}{\partial t}$$

Stiff problems, non-linearities, couplings, only few reference solutions: validation through the InterFrost benchmark (Grenier et al., 2018)

openfoam.com:



openfoam.org:

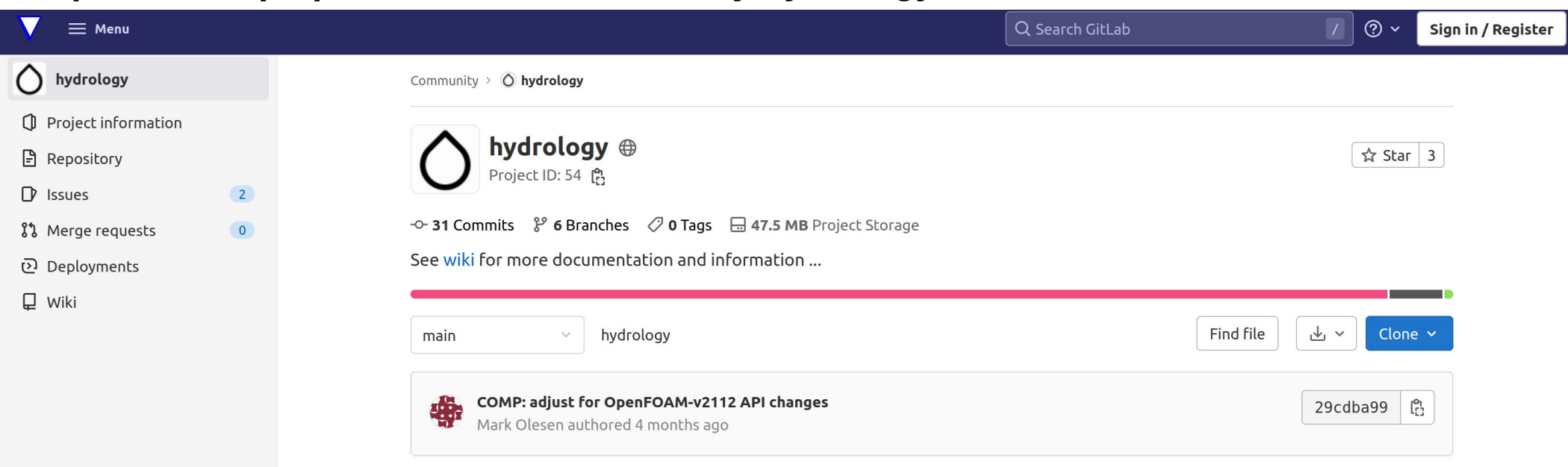


OpenFOAM®: the well-known **open source, generalist Computational Fluid Dynamics tool box (C++, Finite Volumes, Multi-physics, Massively Parallel Computing)**

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 (e.g.: Orgogozo *et al.*, 2014, Bricteux *et al.*, 2017, Rettenmaier *et al.*, 2019, Garcia-Casulla *et al.*, 2020)

The hydrology package (Orgogozo, 2022, Orgogozo et al., 2022):
<https://develop.openfoam.com/Community/hydrology/>



Performance assessments done on

Irene-ROME

the ~300 000 AMD cores partition

of the most powerful French supercomputer for french and european research: Joliot-Curie

Irene-ROME: ~12 Pflop/s over the total 22 Pflop/s of the whole Joliot-Curie supercomputer.

TGCC Joliot Curie



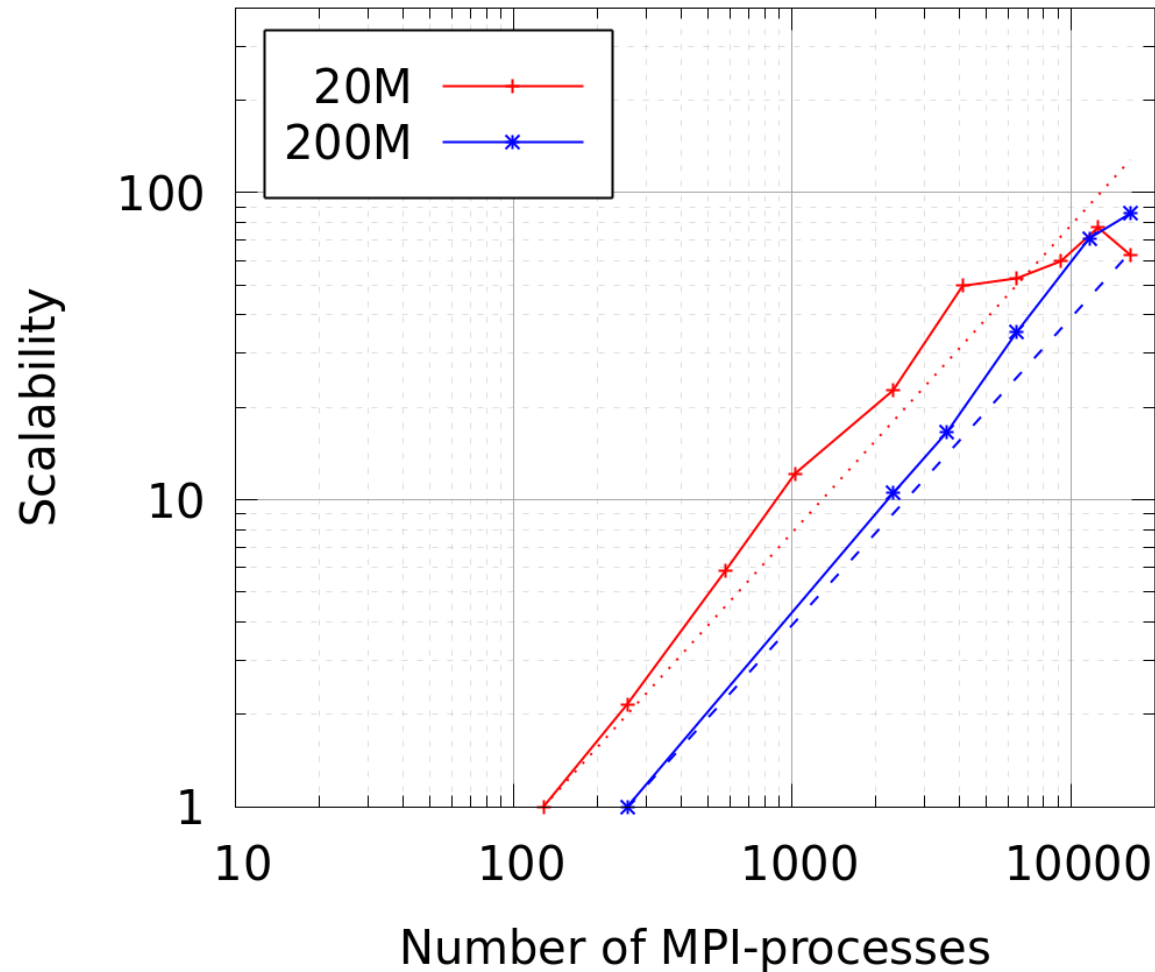
Since the end of 2019, a second phase composed of Bull Sequana XH2000 cells adds the following partition :

- AMD Irene ROME
 - 2292 dual-processor AMD Rome (Epyc) compute nodes at 2.6 GHz with 64 cores per processor, for a total 293,376 computing cores and a power of 11.75 Pflop/s,
 - 256 GB DDR4 memory/node,
 - Infiniband HDR100 interconnect network.

www-hpc.cea.fr/en/complexe/tgcc-JoliotCurie.htm

Super-linear scalability up to **16 384 cores** on IRENE-ROME
with a 200 millions cells mesh
(Orgogozo et al., 2022 ; scaling study by T. Xavier)

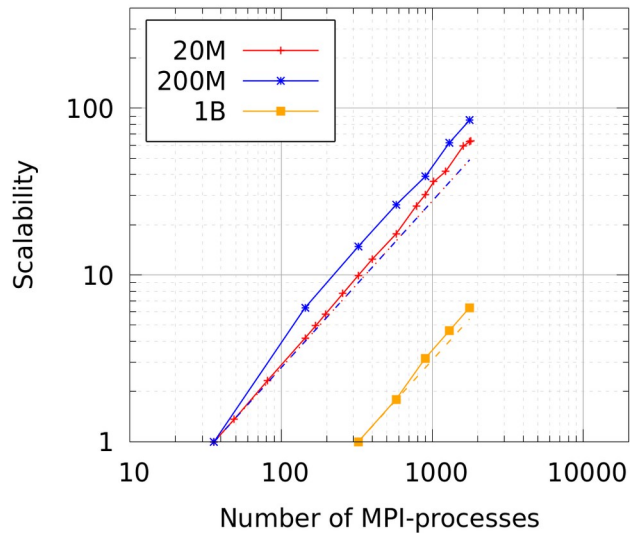
(c) Supercomputer IRENE
AMD® Rome Epyc
(2.6 Ghz, 64 cores)



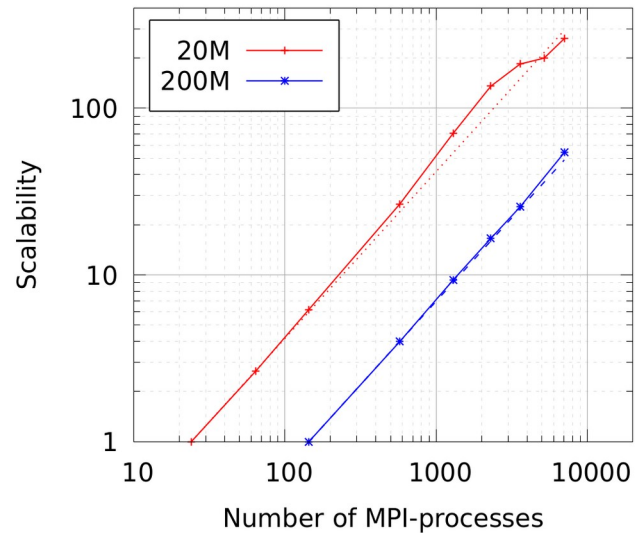
=> **7 millions CPU hours** granted to HiPerBorea
by GENCI (www.genci.fr/en) on DARI A12 session (may 2022 - april 2023)

Super-linear scalability up to **16 384 cores** on IRENE-ROME with a 200 millions cells mesh (Orgogozo et al., 2022 ; scaling study by T. Xavier)

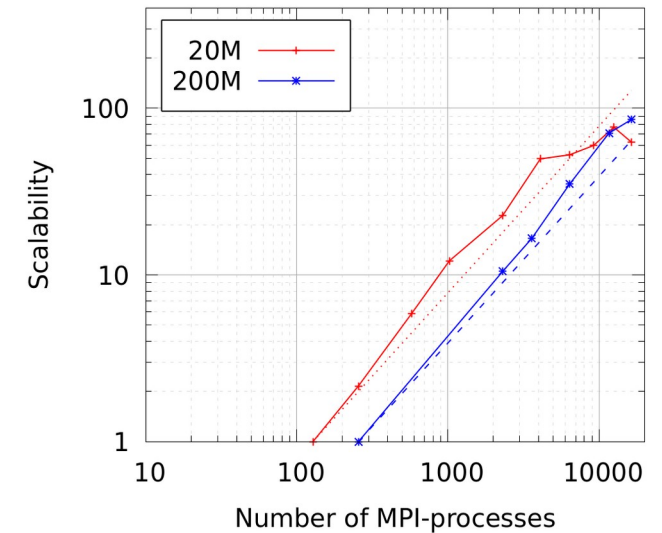
(a) Supercomputer OLYMPE
Intel® Skylake 6140
(2.3 Ghz, 18 cores)



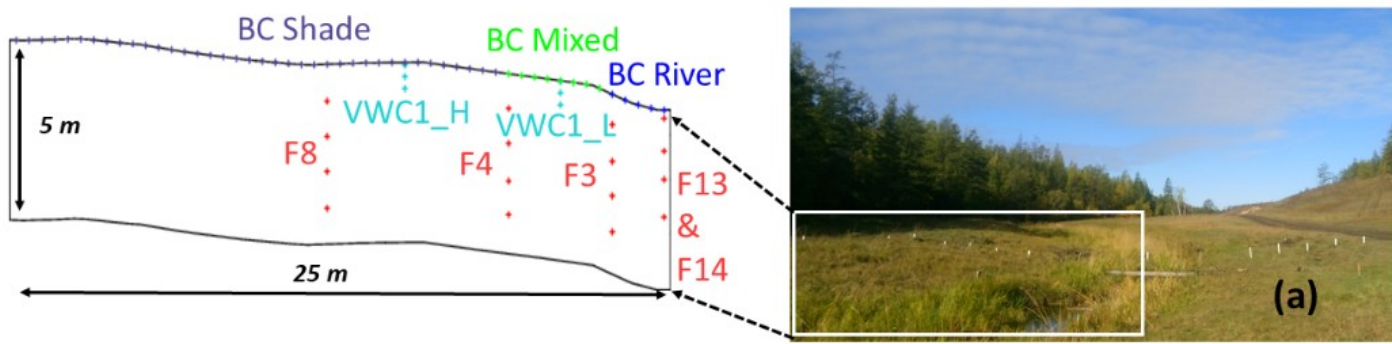
(b) Supercomputer OCCIGEN
Intel® Xeon Haswell E5-2690V3
(2.6 Ghz, 12 cores)



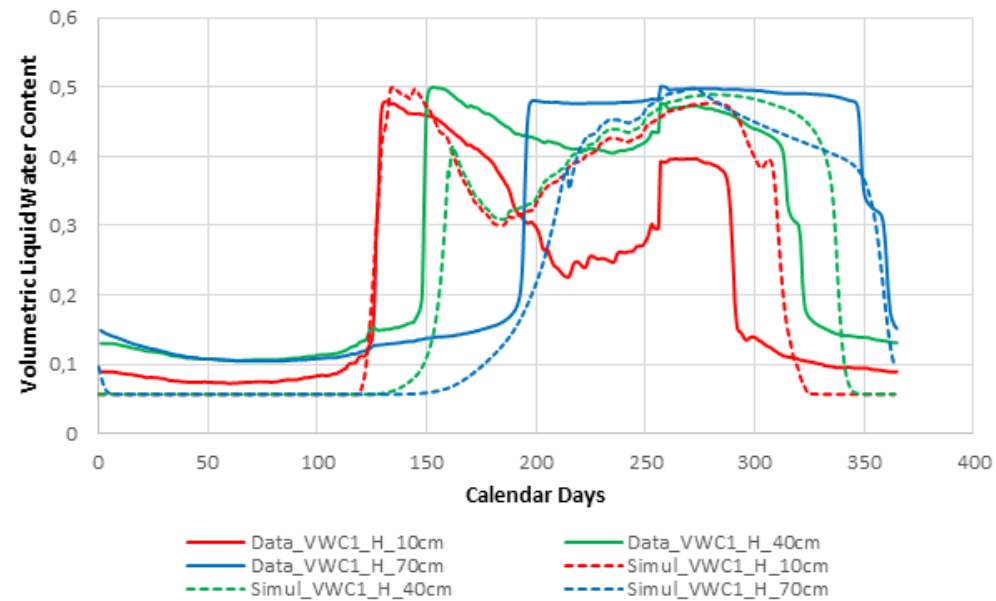
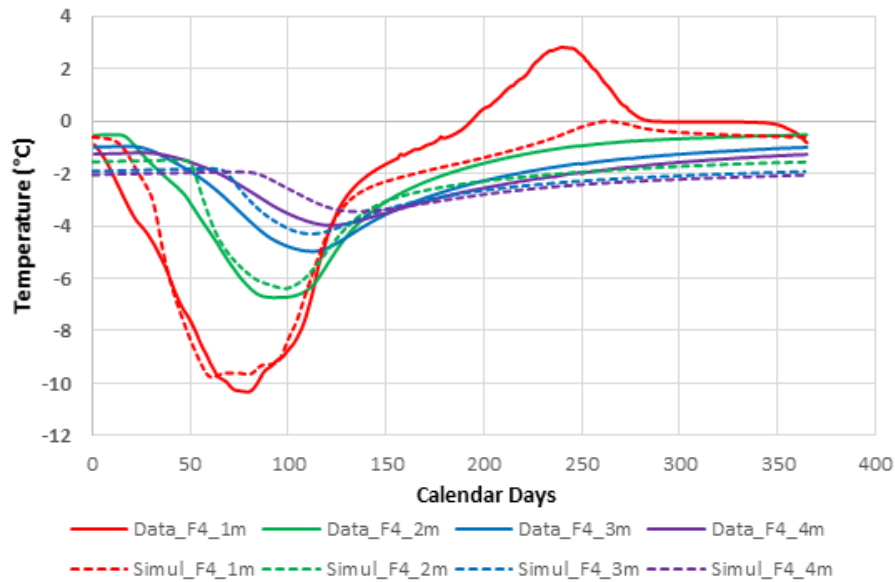
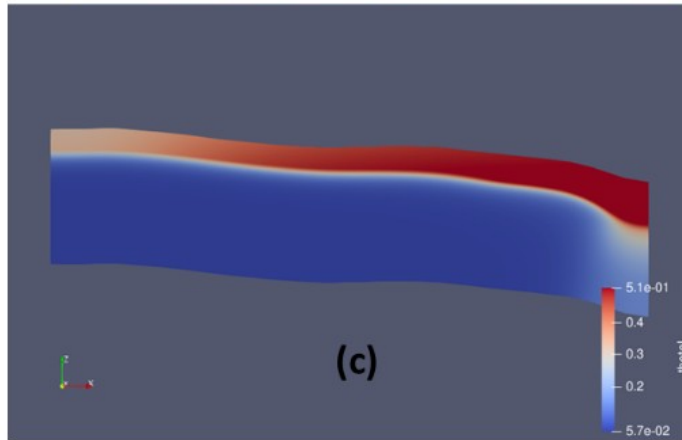
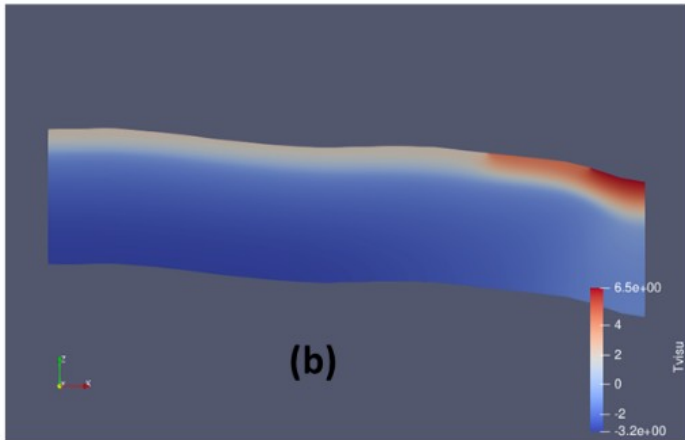
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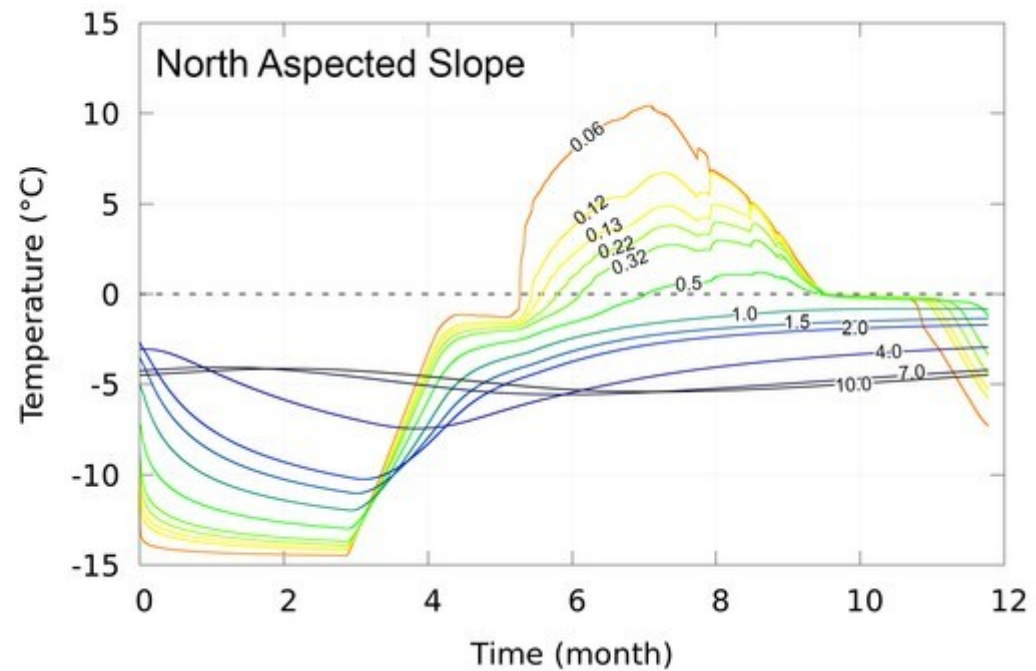
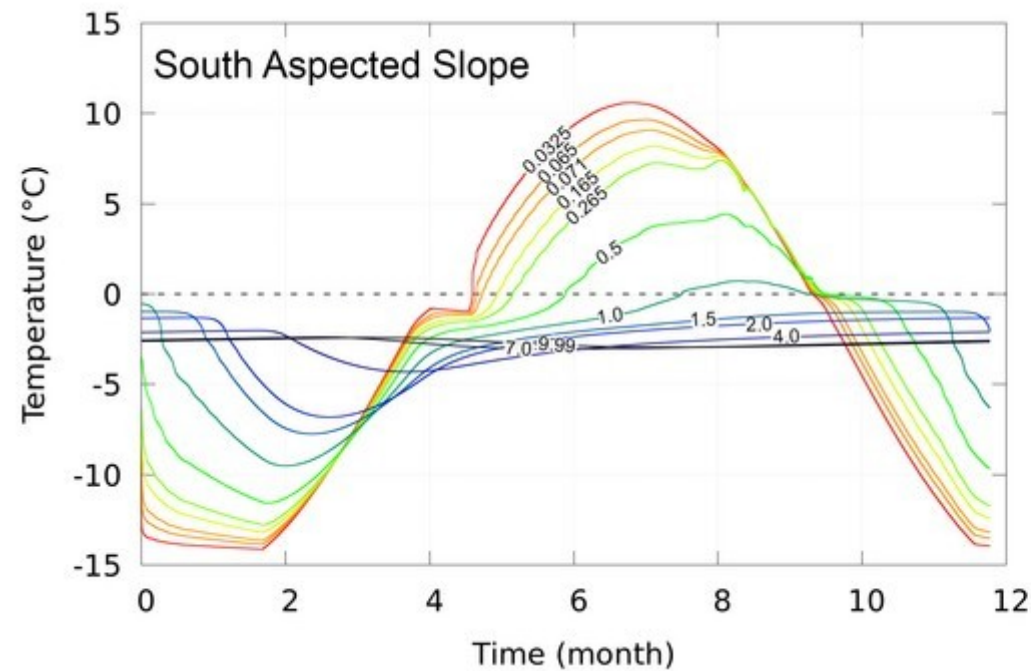
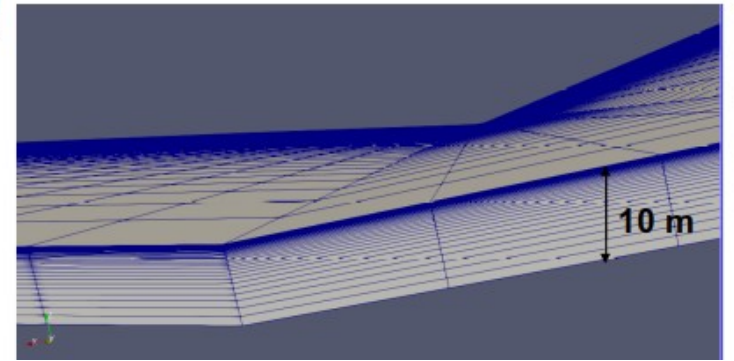
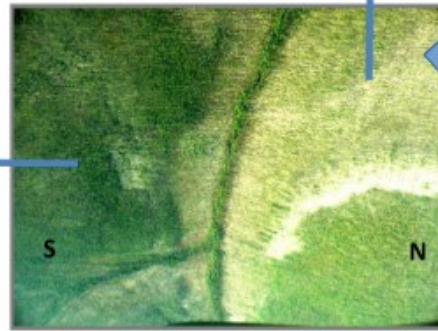
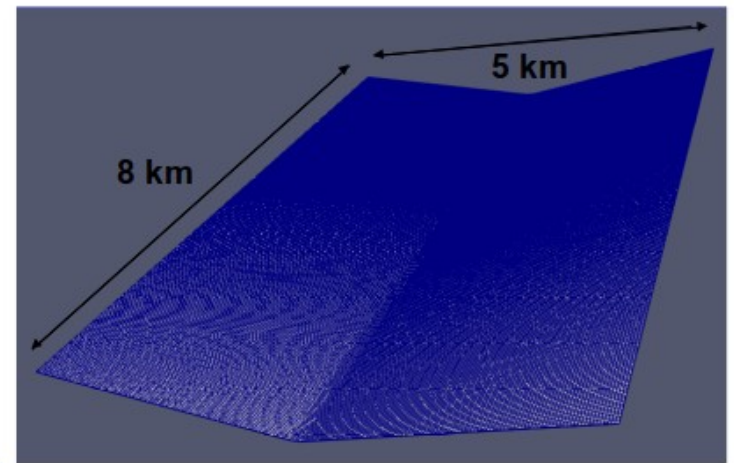
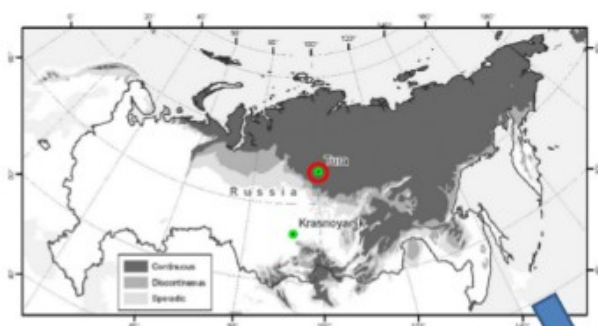
Application:
Syrdakh, Eastern Siberia
Hatté et al., 2018,
Orgogozo et al., 2022



(a)

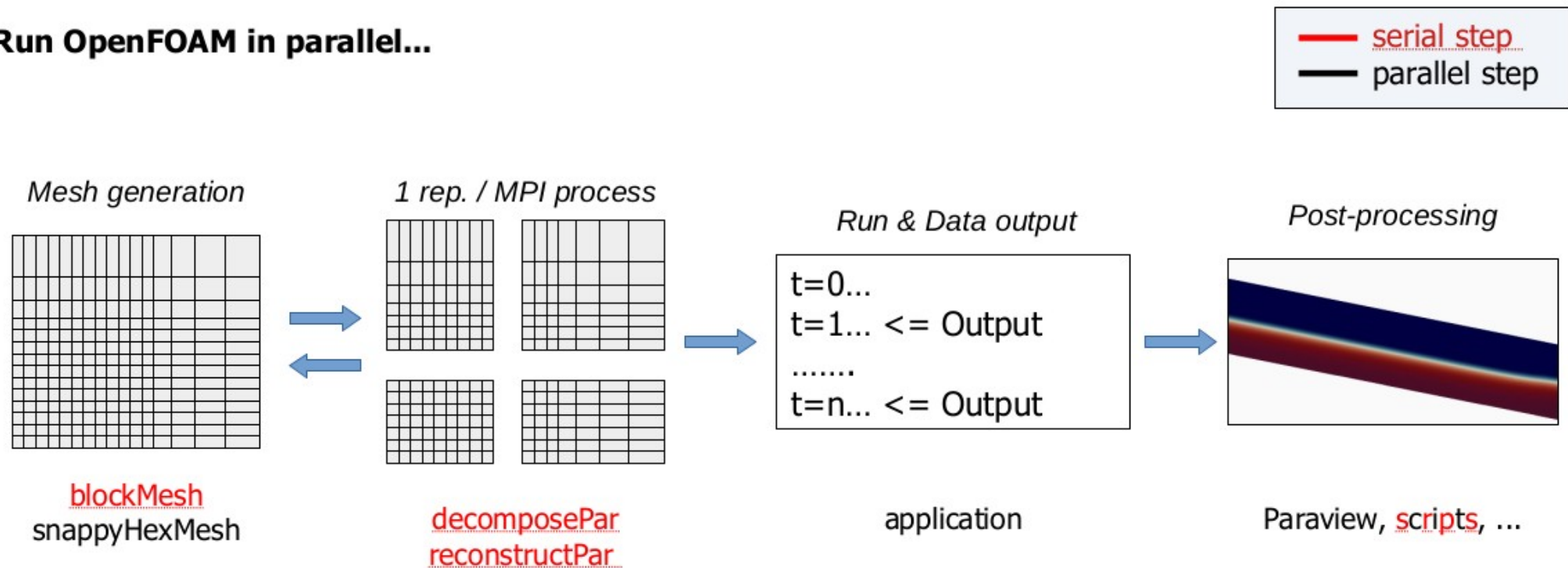
(b)

Application: Kulingdakan, Central Siberia: 40 km² watershed, 3D case, 60 millions of cells (Orgogozo et al., 2019, 2022)



OpenFOAM as development framework for permaFoam

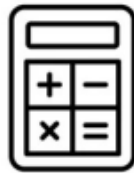
Run OpenFOAM in parallel...



Managing a “large” 2D parametric study

Need for 2D parametric study to explore water transfer influence on permafrost dynamics.

4 variables identified : litter and mineral soil conductivity, water transfer around freezing point
3 values for each parameters 5 years-long calculation 4 iterations saved by year
Calculation on 512 cores. 36 files / proc / iteration



$3^4 = 81$ calculations
 $81 \times 5 \times 4 = 1620$ iterations saved
 $1620 \times 512 \times 36 = \mathbf{30M}$ inodes
~**6 To** of data expected

==> **How to efficiently manage (follow+post-treat) these calculations ?**

Managing a “large” 2D parametric study

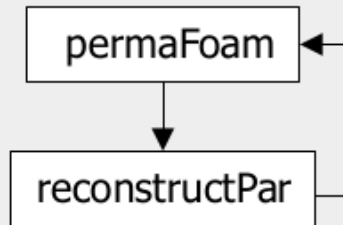
Strategy applied : formatting is a key

Calculation Management

Formatting !

Bash script to check code logs

Automate calculation relaunch



Paraview operation

On calculation nodes
No data repatriation

Python script + pvbatch
(using trace)

See basic presentation :
<https://youtu.be/pem4QSVUGmA>
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Other post-treatment

Exploiting OpenFOAM probes
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FORTRAN90 or C++ code
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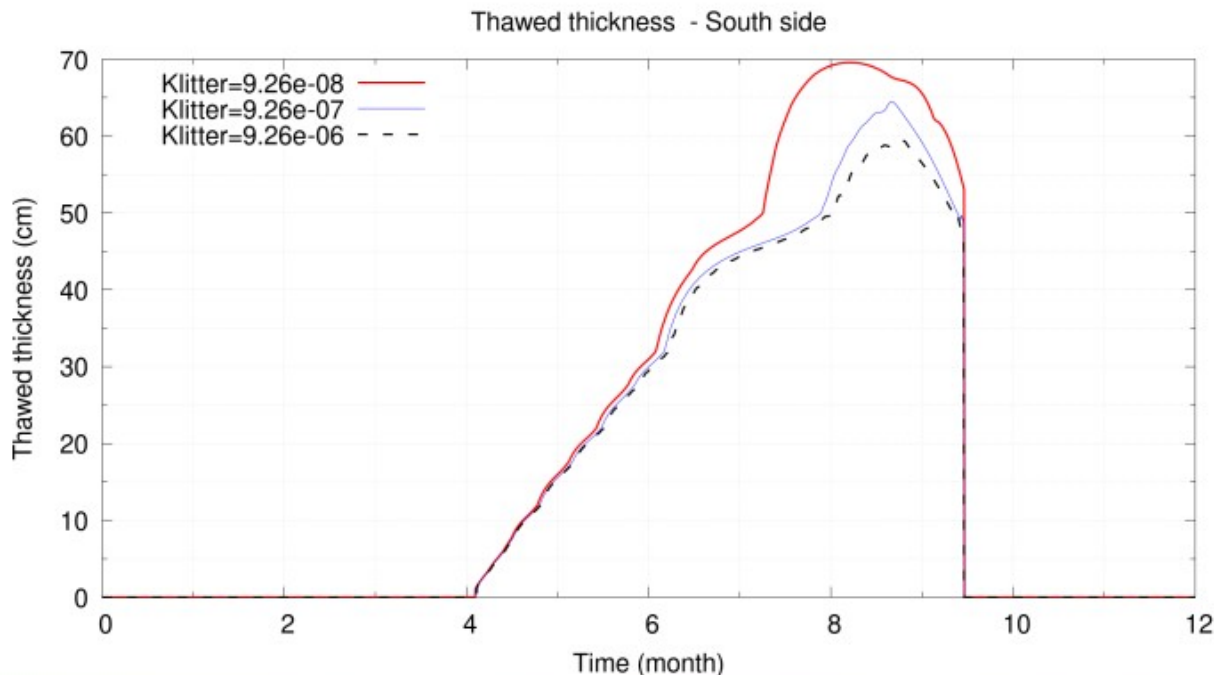
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One job for each calculation repertory
(SLURM scripts generation automated from models)

Managing a “large” 2D parametric study

Results : 2To of data, ~1,5M h.cpu in a few days...

→ Under (human) analysis



Are lateral water fluxes and related convective heat fluxes important for permafrost dynamics ?

Still a debated question !

Sjöberg, et al (2016) : yes

Kurylyk et al. said yes in (2016) : yes

Lamontagne-Hallé et al. (2018) : yes

Gao and Coon (2022)* : no

Xavier et al.... (in prep) : [to be continued]

ON-GOING WORKS

- Sensitivity tests for assessing the importance of lateral water flux in permafrost dynamics of Kulingdakan watershed (Xavier and Orgogozo, in prep)**
- Permafrost dynamics in Kulingdakan watershed until 2100 (Xavier et al., in prep)**
- Conditionning simulations in Abisko with satellite data (Auda et al., in prep)**
- Permafrost dynamics in Abisko, Khanymey and Syrdakh watersheds until 2100**

PERSPECTIVES

What's next after HiPerBorea?

A focus on cold regions infrastructures with the **PERMACHANGE project, to be submitted to the **Horizon Europe** program.**

We are looking for international collaborations! Field of interests:

- High Performance Computing**
- Innovative numerical analysis and schemes**
- CFD empowered AI**

Interested? Please contact us! => laurent.orgogozo@get.omp.eu



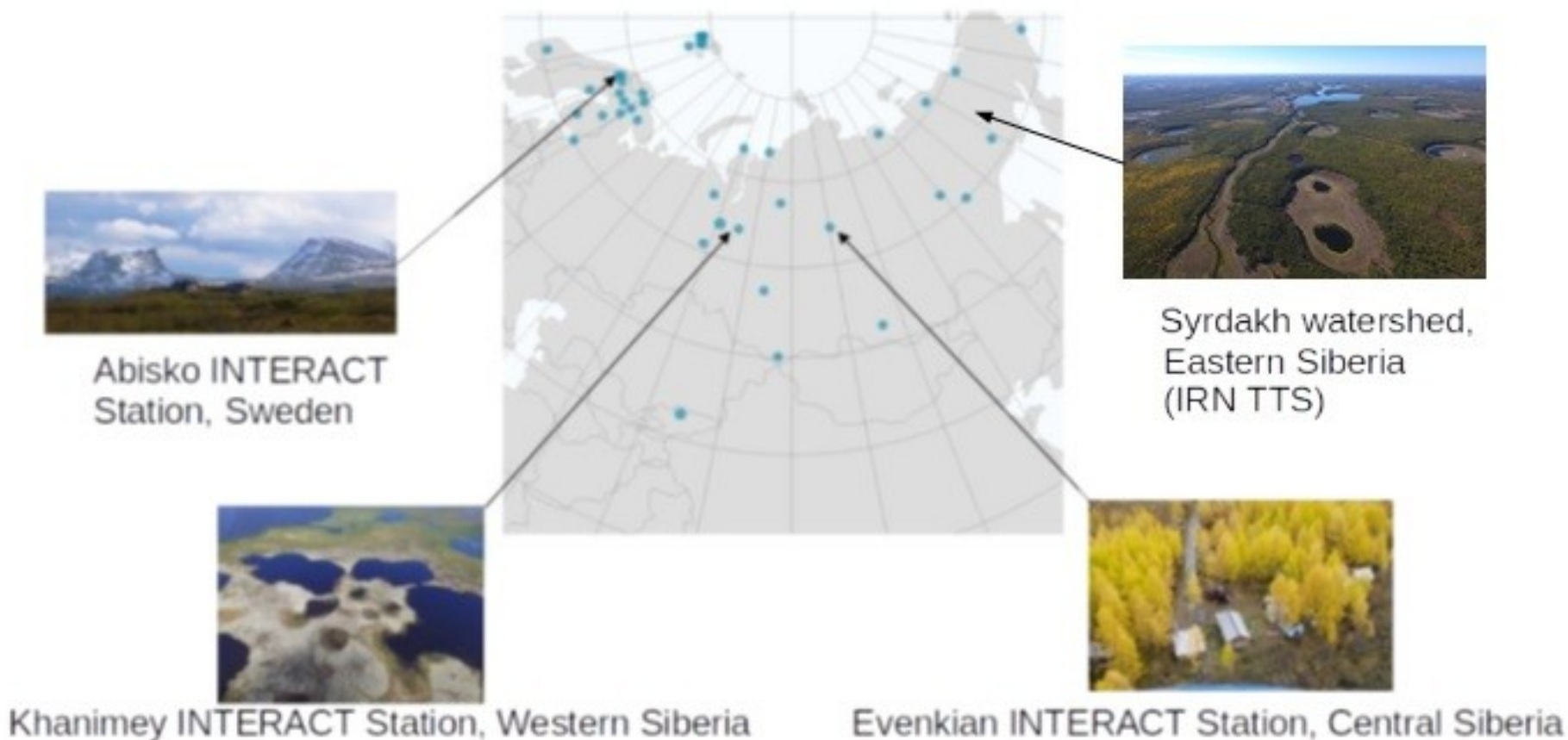
Thank you for your attention.

Contact: laurent.orgogozo@get.omp.eu

HiPerBorea (hiperborea.omp.eu): anticipation of climate change impacts on permafrost.

Our methodology is based on mechanistic numerical modelling of permafrost evolution in key sites of boreal environments monitoring.

Every modeling of natural phenomena lays on (and must honoured!) the available observations, thus HiPerBorea is in close interaction with the operators of the selected boreal observation stations: the INTERACT network (eu-interact.org) and the International Research Network Tundra – Taïga – Steps.



PermaFoam : solving the equations of thermo-hydrological permafrost dynamics

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:

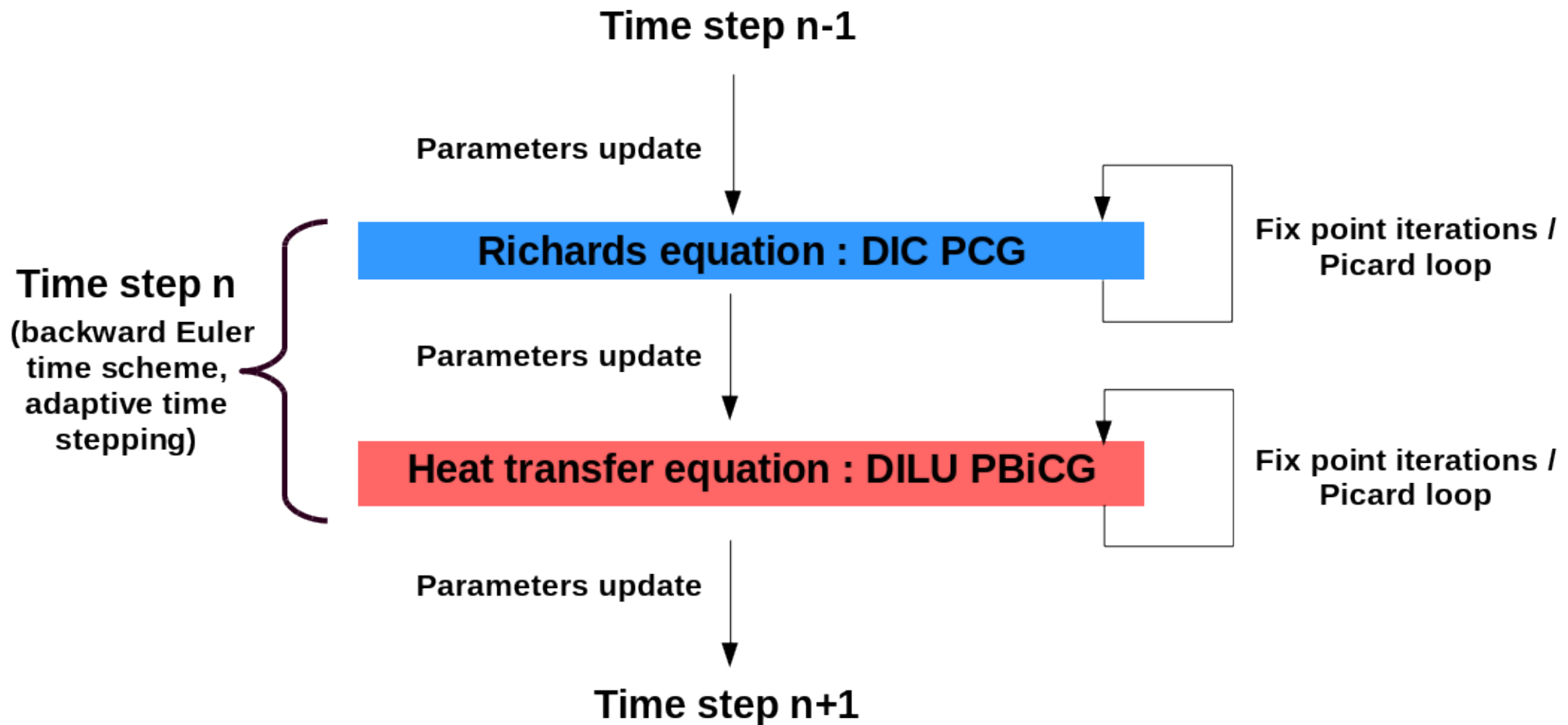
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Stiff problems, non-linearities, couplings, only few reference solutions: validation through the InterFrost benchmark (Grenier et al., 2018)

PermaFoam numerical scheme



Implemented within the 3D finite volumes HPC framework OpenFOAM

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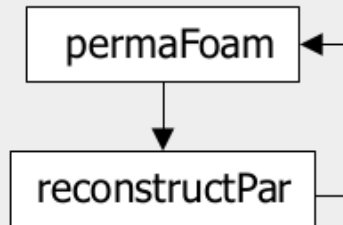
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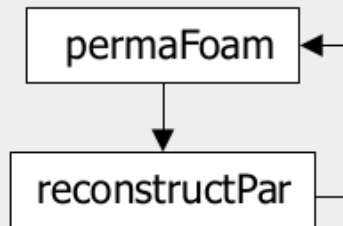
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More info: <https://forgeanalytics.io/blog/creating-a-python-trace-in-paraview/>

<https://forgeanalytics.io/blog/executing-paraview-in-batch/>

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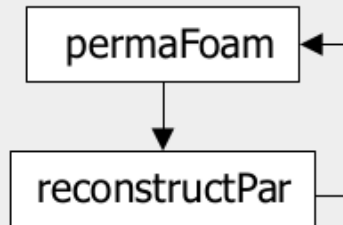
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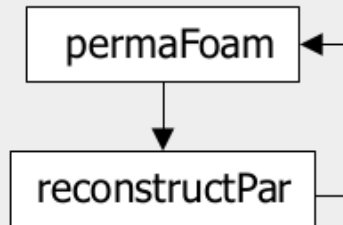
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