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Thermo-hydrologic modelling of permafrost with OpenFOAM®: perspectives of applications to the study of weathering in boreal areas



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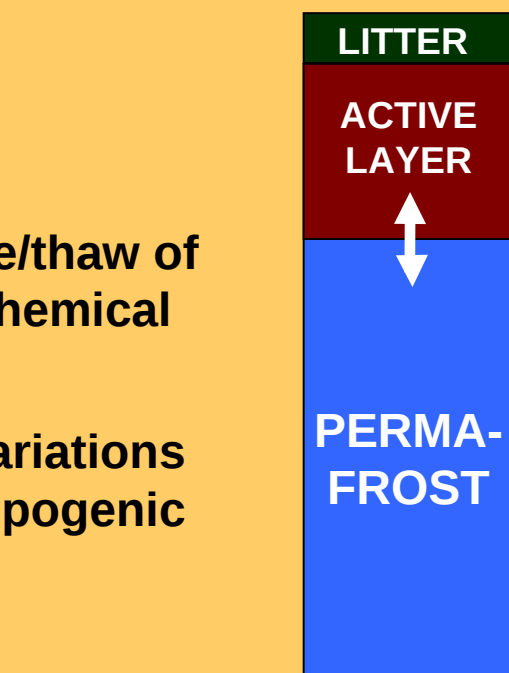
Context : study of the element fluxes in permafrost catchments of central Siberia in the frame work of the GDRi CAR WET SIB.

Problematic:

Climate change and weathering in boreal areas with a continuous permafrost

Studied area:

Central Siberia, watersheds of the Nizhnaya Tunguska, homogeneous vegetation cover and lithology ; main spatial variability : south aspect / north aspect slopes



Methodological approach :

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

→ Time scales : annual to multidecadal
 Space scales : 1 m² to 10's of km²

(i) Coupled transfers within soils of water and energy with phase change : 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, Painter 2011, Frampton et al. 2011, Grenier et al. 2012, Rivière 2012, Kurylyk et al. 2014, ...

(ii) Large computation times may be encountered : use of parallel computation is expected to be necessary (Painter et al. 2013).
 => Our approach : developing a devoted solver with OpenFOAM® :

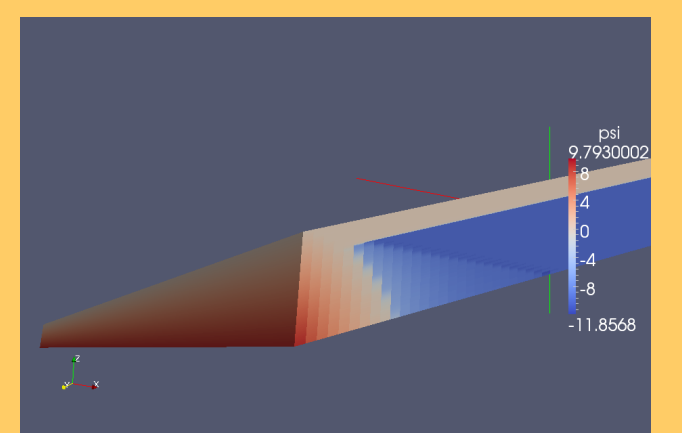
permaFOAM

See Orgogozo et al., 2014, in « Permafrost distribution, composition and impacts on infrastructure and ecosystems », ed. O.S. Pokrovsky.

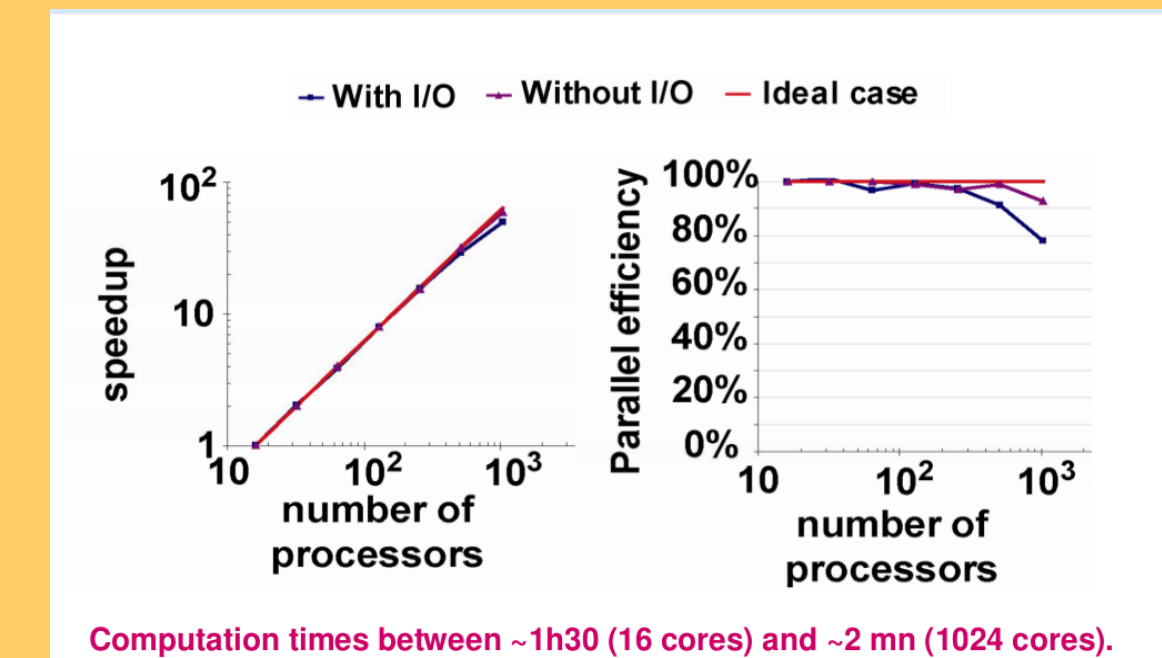
(ii) Steep problems, non-linearities, couplings, few references solutions :
 INTERFROST Benchmark, C. Grenier (LSCE, Continental Hydrology) 1D analytical validation cases, 2D intercomparison cases
<https://wiki.lscce.ipsl.fr/interfrost/doku.php?id=home>
 See talk of C. Grenier, Session CR1.1/SSS0.20, 15/04 14H room B13

OpenFOAM® : an open source CFD tool box

- Developed in C++
- Finite volumes
- Allow multiphysics modelling
- Enable to implement home-made solvers
- Designed for massively parallel computing
- OF for geosciences, e.g.: Orgogozo et al., CPC 2014



RichardsFOAM



Parallel performances of RichardsFOAM:
 3 km², 10 m thick loam slope
 36 millions mesh cells
 10 days of infiltration

Goals :

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

Other potential context of application: thermokarstic areas in Western Siberia

Accuracy of the numerical modeling : example of the mesh refinement and of the constitutive laws

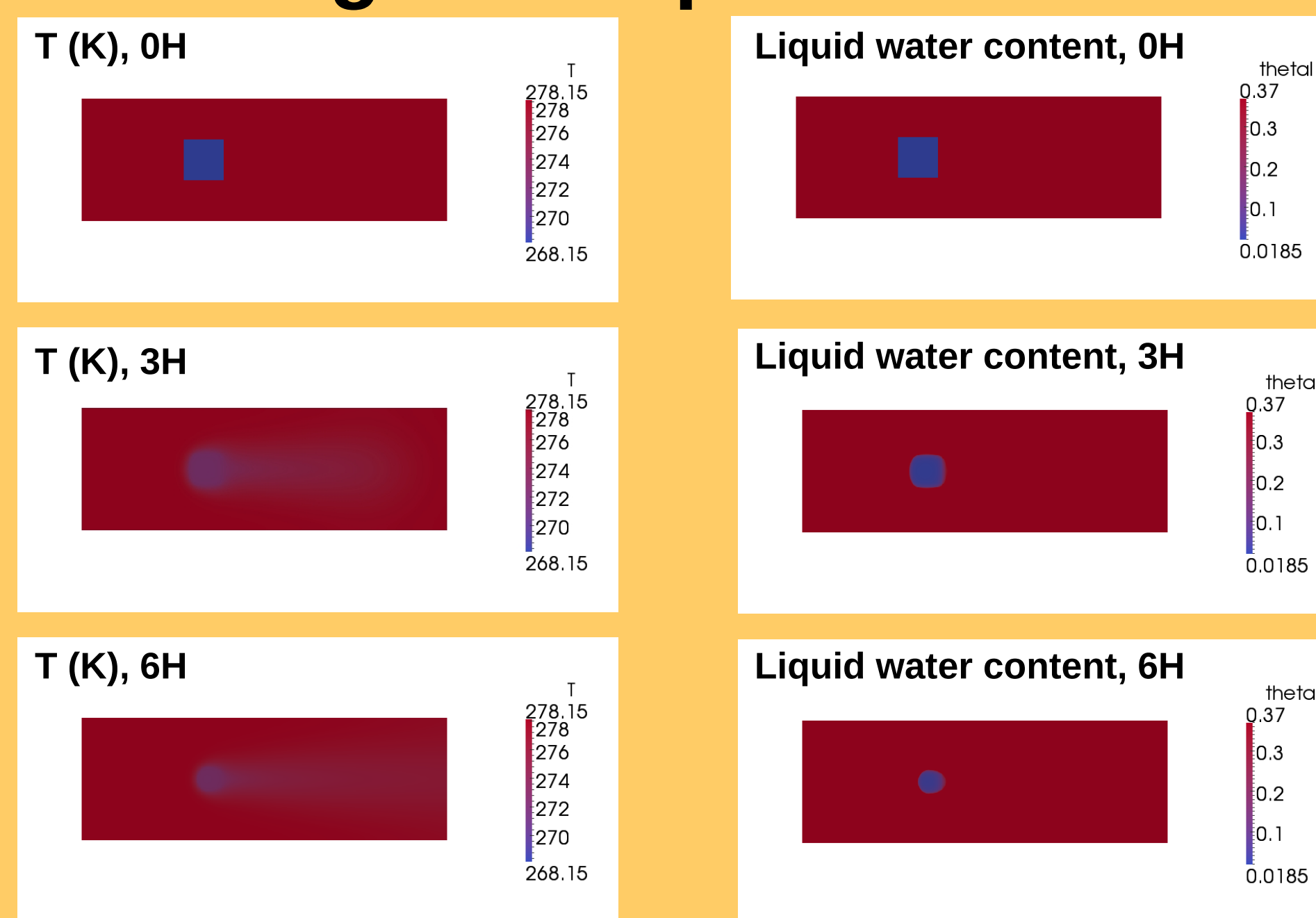
2D test case: the frozen inclusion Interfrost benchmark* TH2

A sand box of 3m*1m, initially at 5°C, with a frozen inclusion (-5°C).

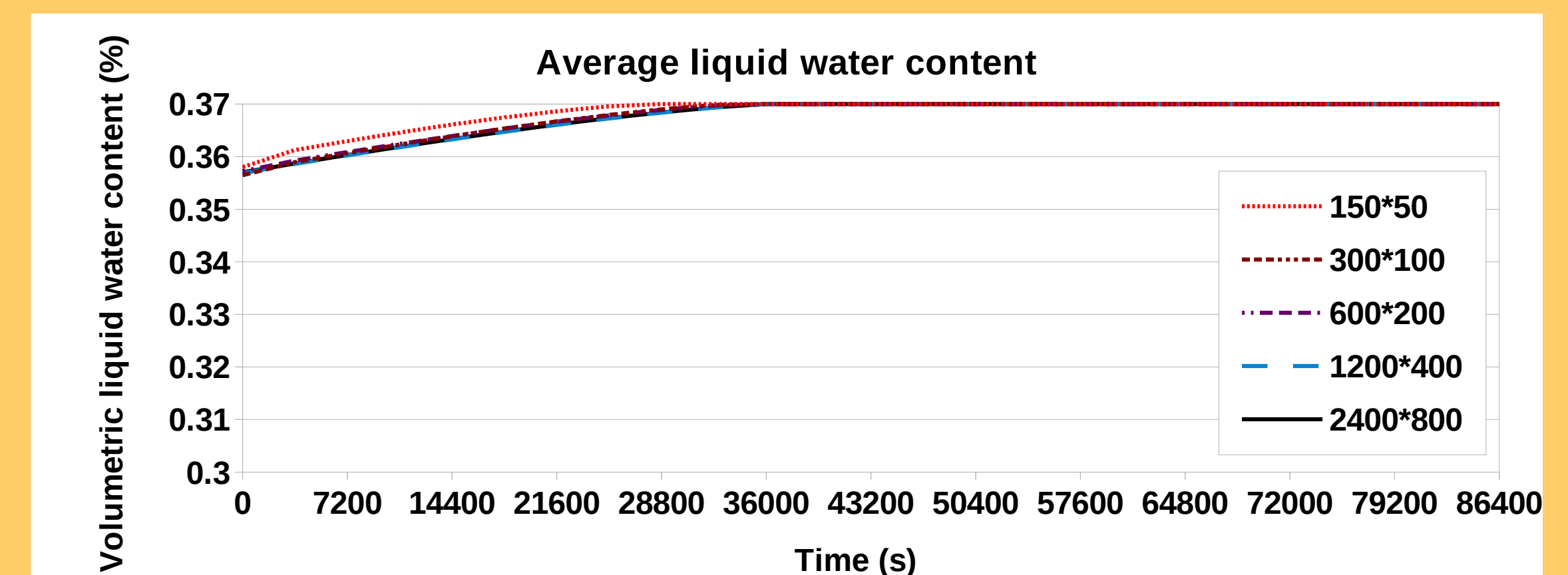
The medium is submitted to a hydraulic gradient of 0.15

Exponential constitutive laws for the frozen soil (freezing curve and frozen permeability).

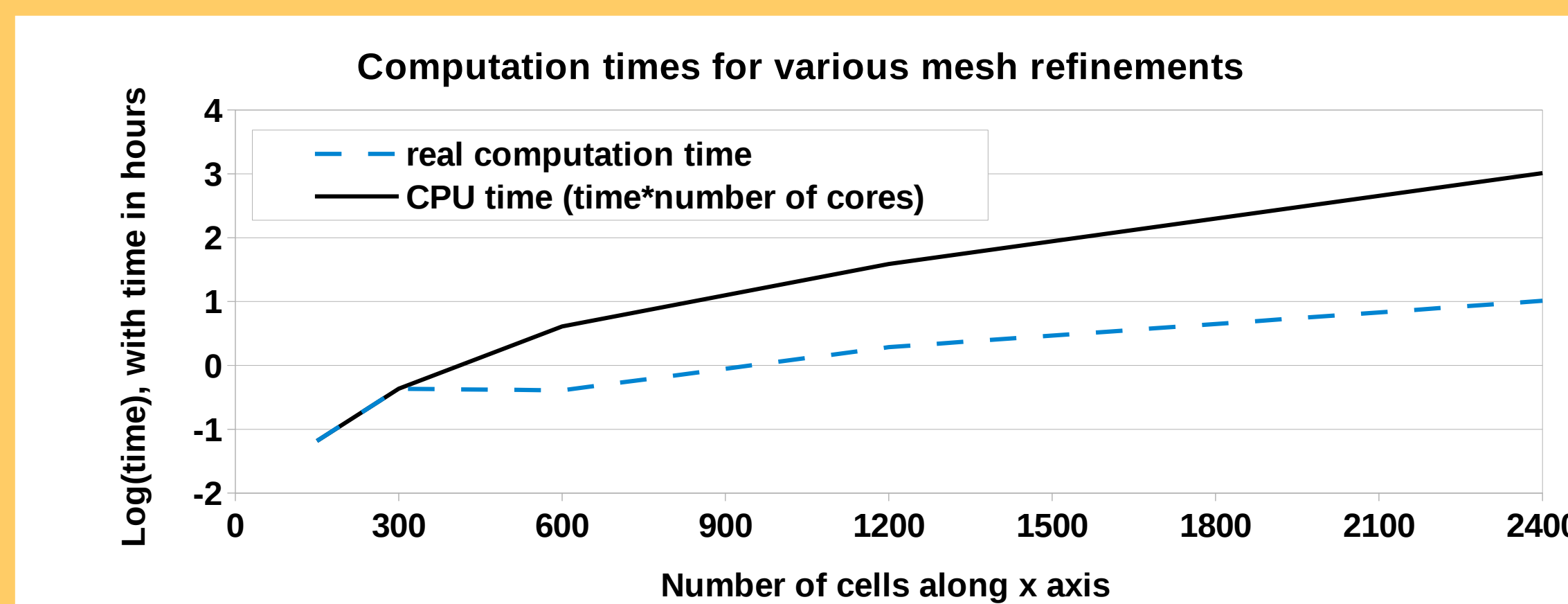
*<https://wiki.lscce.ipsl.fr/interfrost/doku.php>



Results with exponential constitutive laws

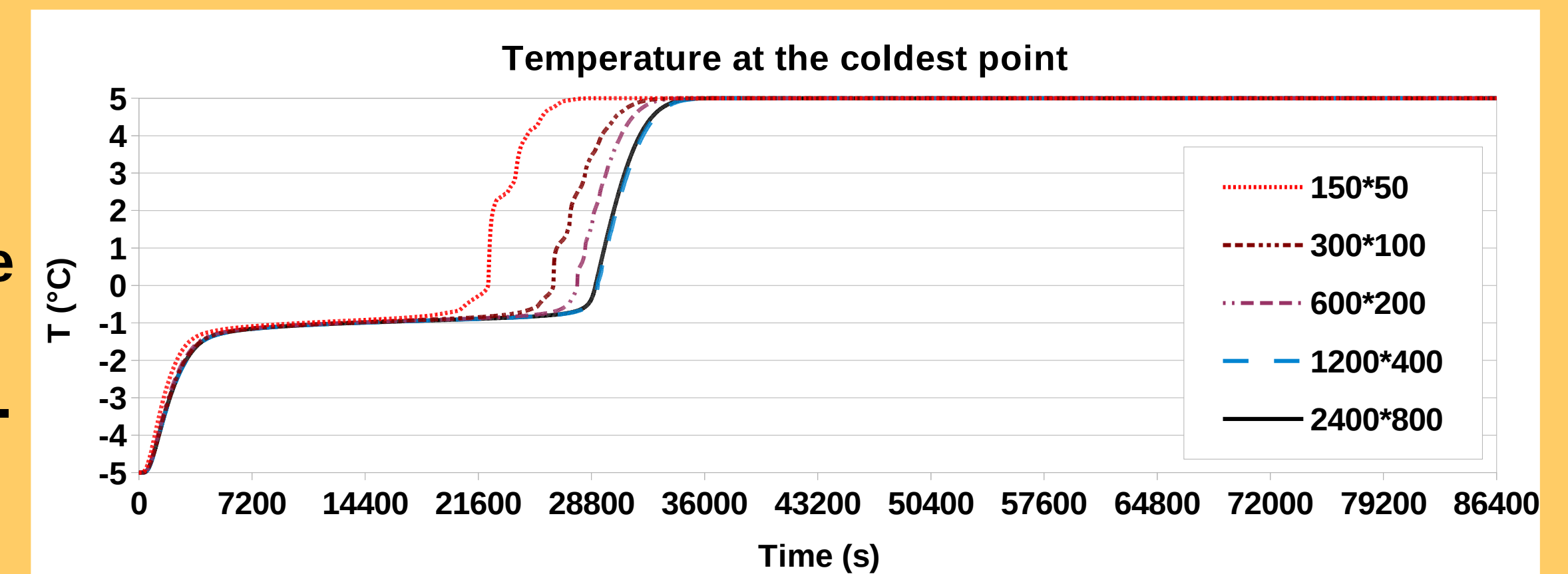


Convergence study regarding the refinement of the mesh: for an average quantity (mean liquid water content) above and for a punctual quantity (T at the center of the frozen inclusion) below. The convergence is obtained for a coarser mesh for the mean value (1cm length cells, 300*100) than for punctual value (0.25cm, 1200*400). The relevant mesh refinement depends on the kind of results that are needed.

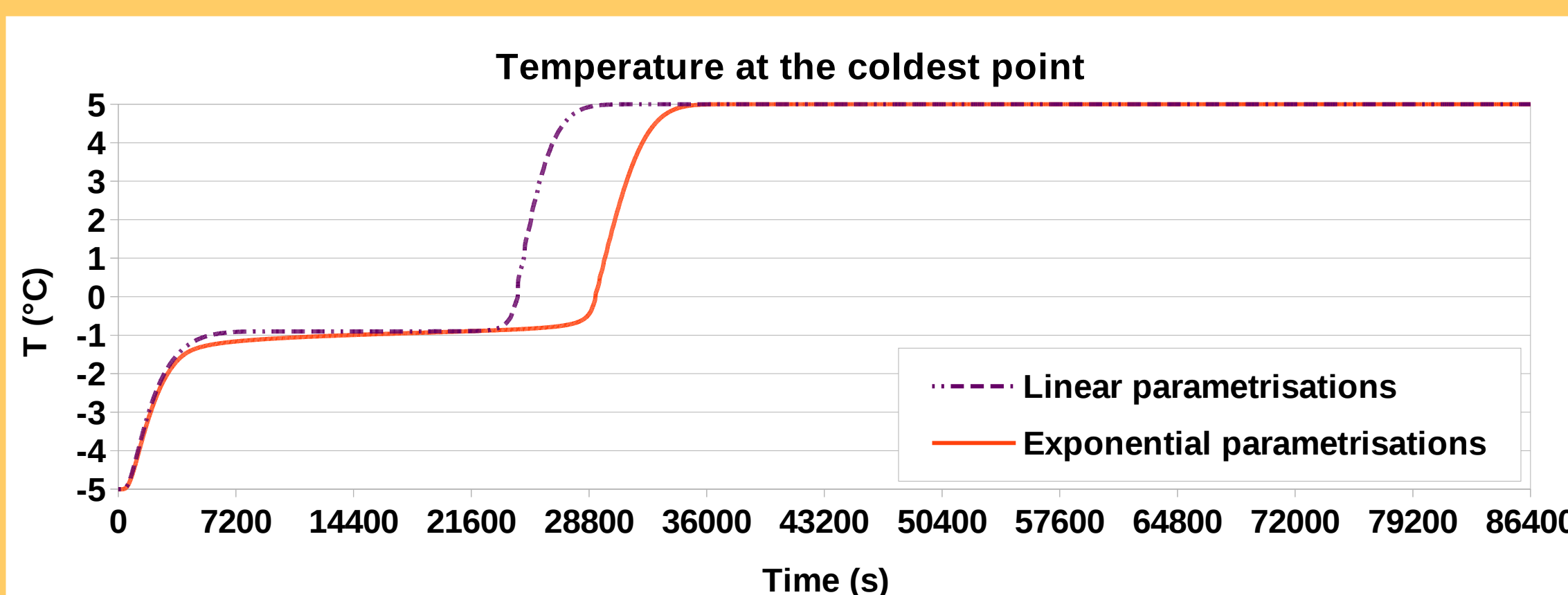


The mesh refinement has a strong impact on the computation times, and thus on the scales of applicability of the modelling tool.

All computations done with permaFOAM on the CALMIP cluster (<http://www.calmip.univ-toulouse.fr>)



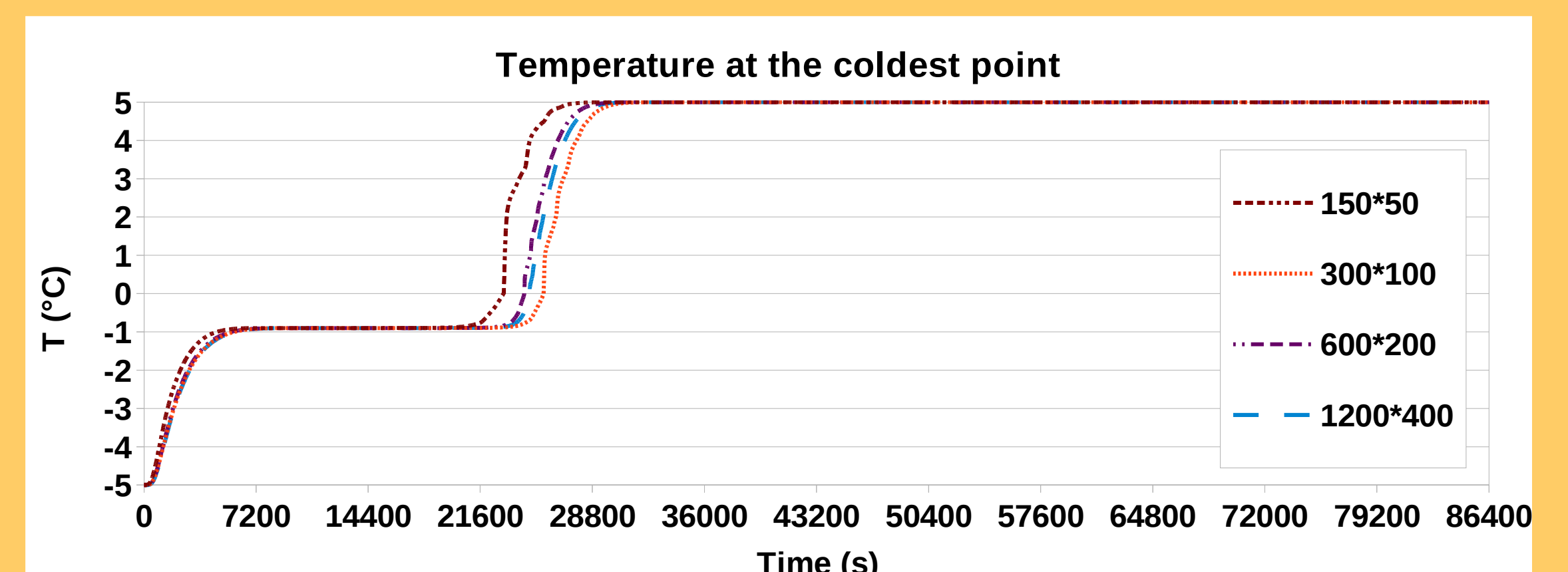
Linear constitutive laws of the freezing curve and of the frozen permeability ?



Results may be sensitive to the chosen parametrisation of the constitutive laws of the medium. A careful attention must then be paid to the choice of these laws (see Kurylyk and Watanabe AWR 2014 for a discussion on this topic)

On the right : convergence study regarding mesh refinement in the case of a linear parametrisation.

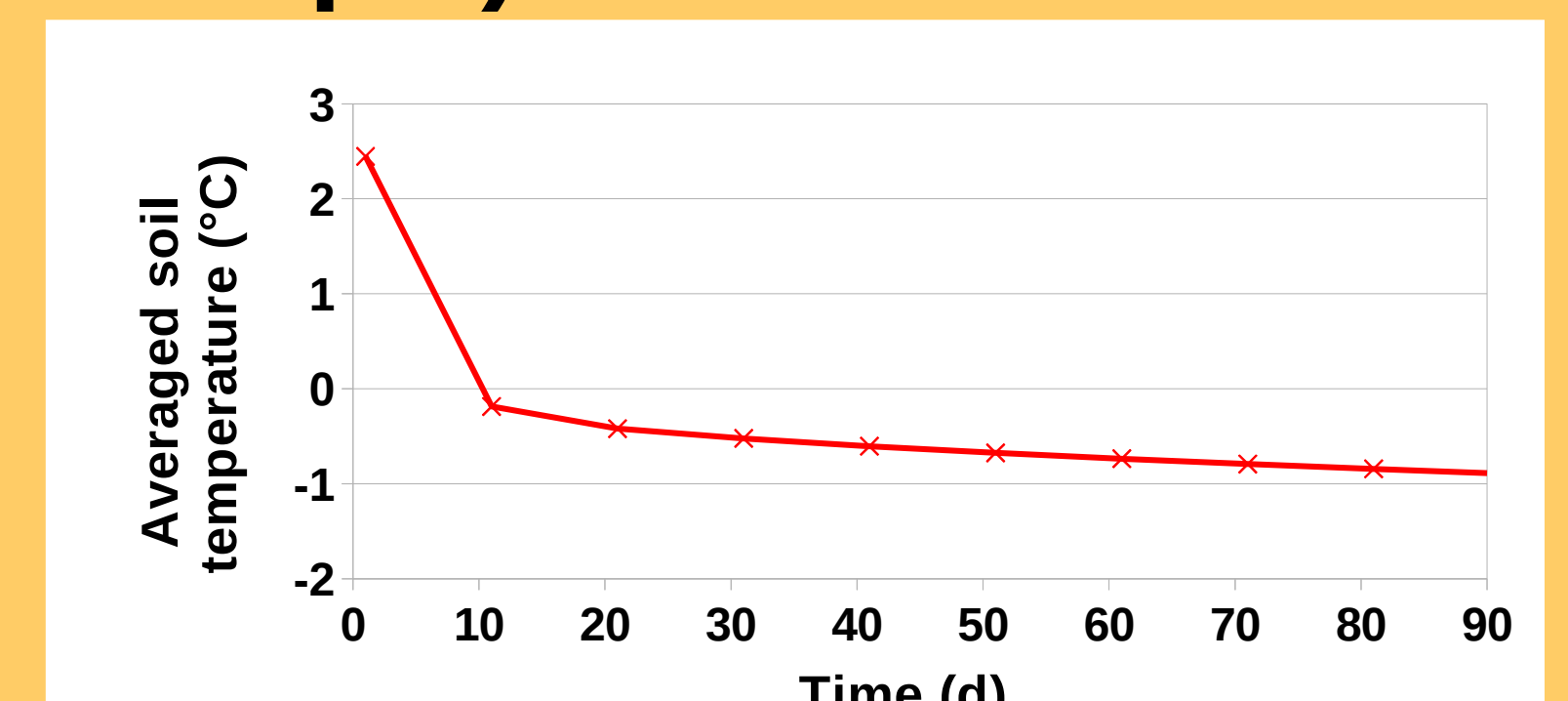
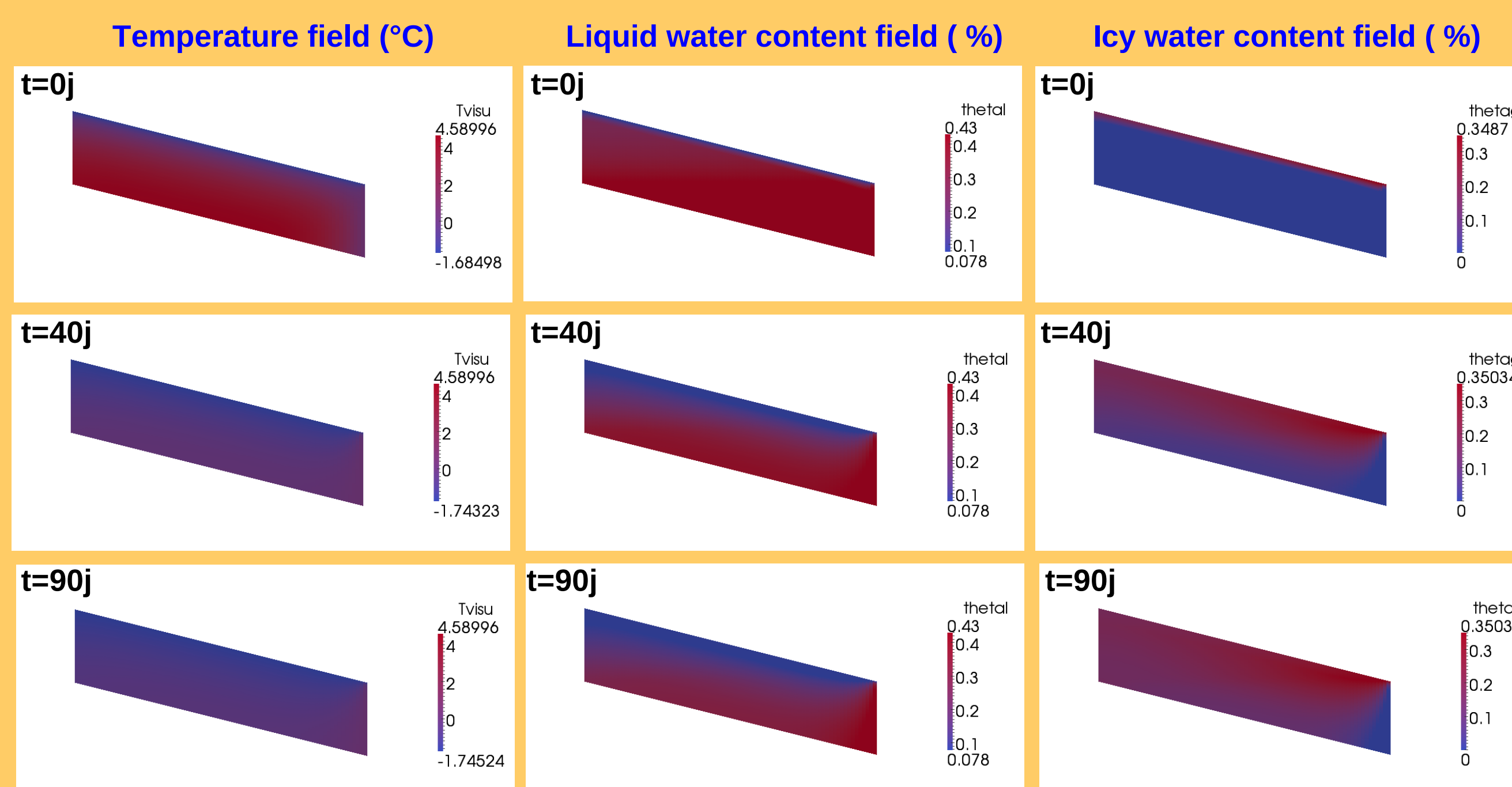
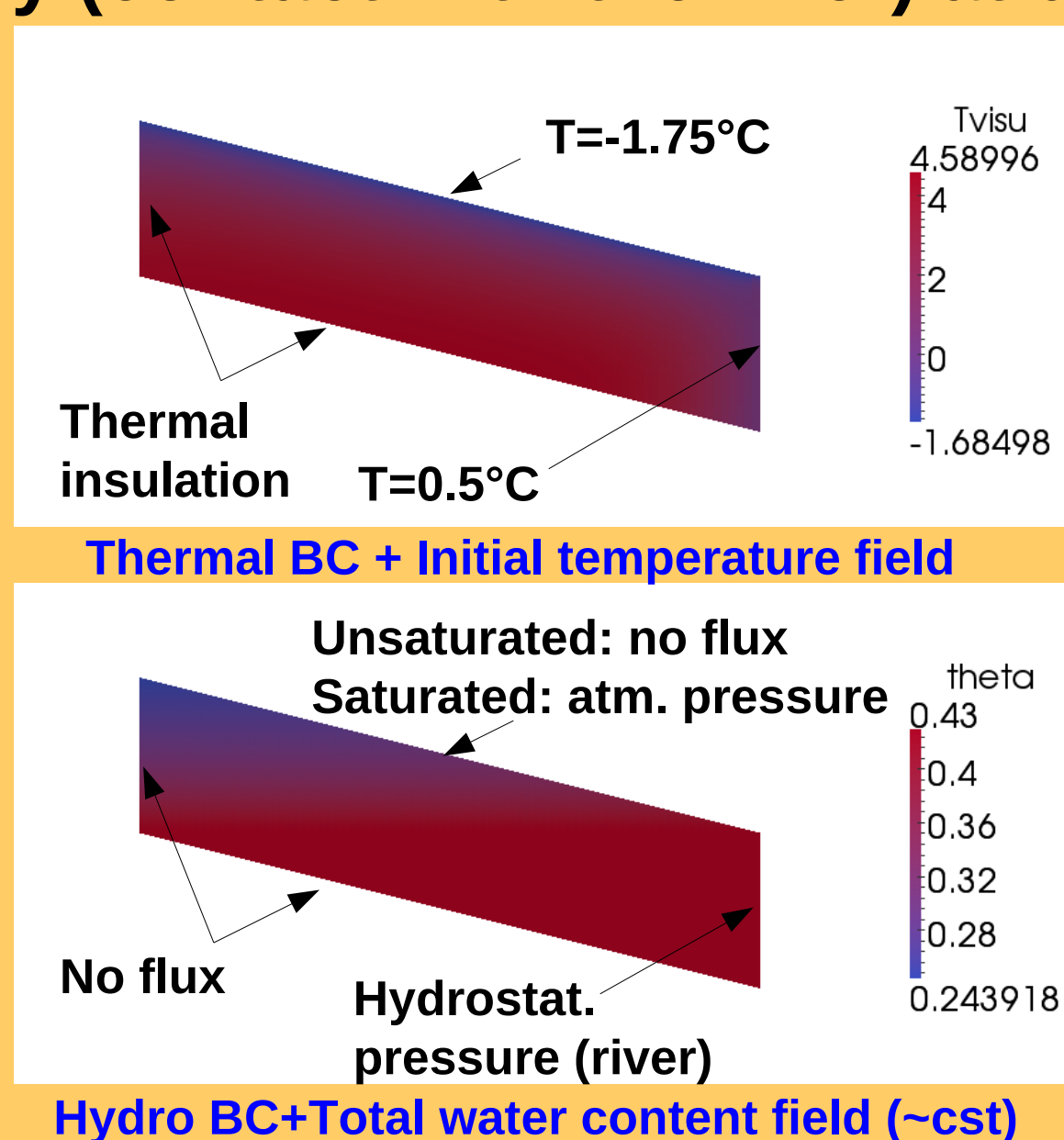
It shows that relevant results are obtained with a mesh with 0.5cm cell length (600*200 cells). It is less than in the exponential case (see above). Thus the parametrisation may also impact strongly the needed computation times.



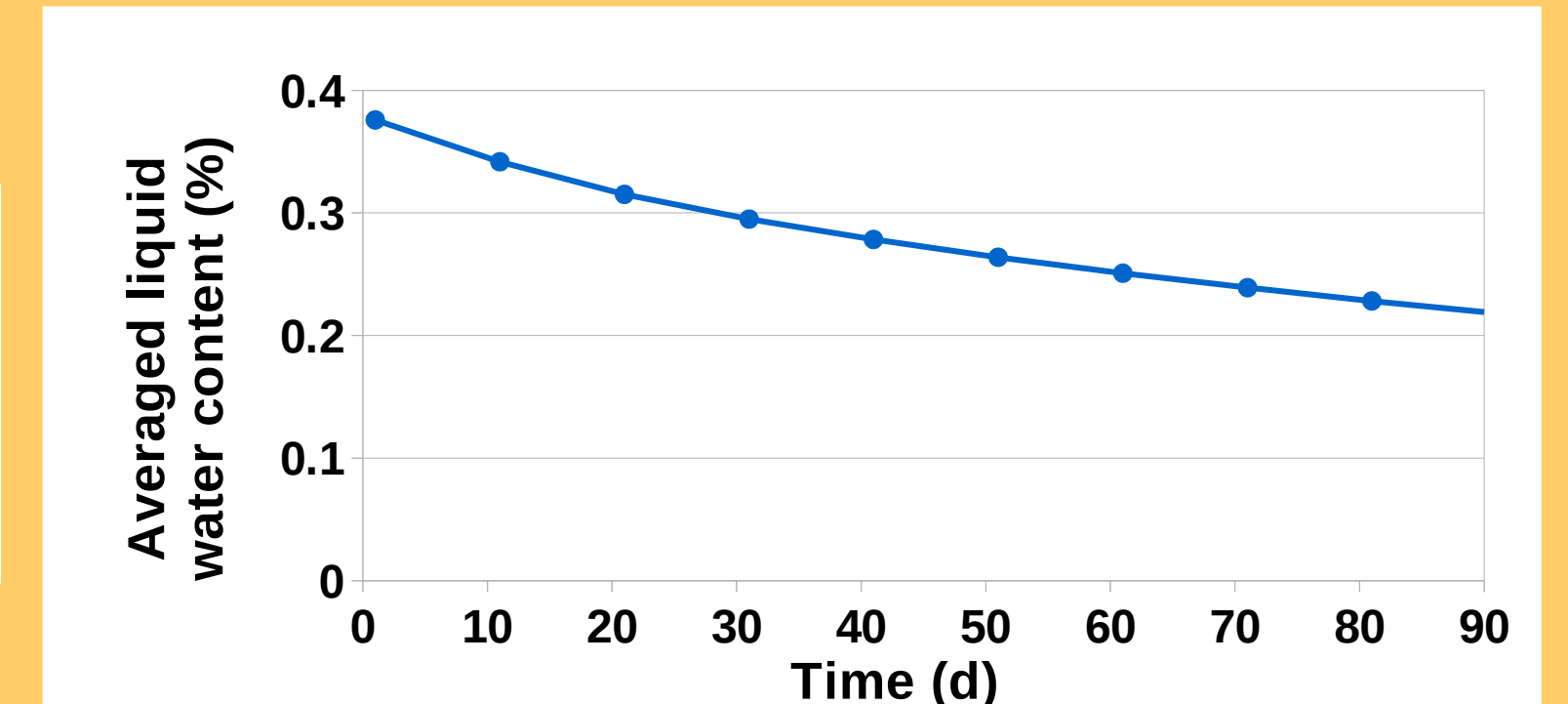
Hydro-thermal conditioning of weathering modelisations : computing water and thermal fluxes in a river bank of a permafrost affected watershed (illustrative example)

2D illustrative case: freezing of a river bank initially at 5°C submitted to a freezing event: top boundary at -1.75°C and downslope boundary (contact with the river) at 0.5°C

Loamy bank
 Length: 4m
 Thickness: 1m
 Slope = 25 %
 Duration of the freezing event : 90d



Time evolution of averaged temperature and water content fields in the soil : typical thermo-hydrologic input data for weathering modelisations (e.g.: Goddérés et al. 2006, 2012)



Conclusion : permaFOAM allows to give relevant thermo-hydrologic input data for weathering modelling in permafrost dominated areas.

Next step : application to a field data set of the Kulingdakan watershed (e.g.: Prokushkin et al., 2007). Slope space scale, annual time scale, layered medium, use of massively parallel computing. (Orgogozo et al., in prep.)