The InterFrost benchmark of Thermo-Hydraulic codes for cold regions hydrology – first inter-comparison phase results

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Abstract ICOP2016 for topics 18. Permafrost Hydrology & 19. Groundwater systems under a changing permafrost

Climate change impacts in permafrost regions have received considerable attention recently due to the pronounced warming trends experienced in recent decades and which have been projected into the future. Large portions of these permafrost regions are characterized by surface water bodies (lakes, rivers) that interact with the surrounding permafrost. For example, the thermal state of the surrounding soil influences the energy and water budget of the surface water bodies. Also, these water bodies often generate taliks

(unfrozen zones) within the permafrost that allow for hydrologic interactions between the surface water bodies and underlying aquifers and thus influence the hydrologic response of a landscape to climate change.

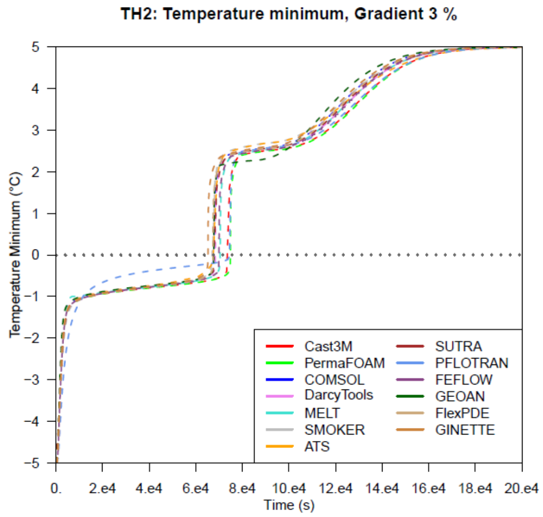
Recent field studies and modeling exercises indicate that a fully coupled 2D or 3D Thermo-Hydraulic (TH) approach is required to understand and model past and future evolution of landscapes, rivers, lakes and associated groundwater systems in a changing climate (Kurylyk et al. 2014). However, there is presently a paucity of 3D numerical studies of permafrost thaw and associated hydrological changes, which can be partly attributed to the difficulty in verifying multi-dimensional results produced by numerical models.

Numerical approaches can only be validated against analytical solutions for a purely thermic 1D equation with phase change (e.g. Neumann, Lunardini). When it comes to the coupled TH system (coupling two highly non-linear equations with phase change introduces steep fronts), the only possible approaches are to compare the results from different codes to provide test cases and/or to have controlled experiments for validation. Such inter-code comparisons can provide the impetus to improve code performance.

A benchmark exercise was initialized at the end of 2014. Participants convened from USA, Canada, Germany, Sweden, Great Britain, The Netherlands and France, representing 13 simulation codes. The benchmark exercises consist of several test cases inspired by existing literature (e.g. McKenzie et al., 2007) as well as new ones (Kurylyk et al. 2014; Grenier et al. in prep.; Rühaak et al. 2015). They range from simpler, purely thermal 1D cases to more complex, coupled 2D TH cases (benchmarks TH1, TH2, and TH3). Some experimental cases conducted in a cold room complement the validation approach. A web site hosted by LSCE (Laboratoire des Sciences du Climat et de l'Environnement) is an interaction platform for the participants and hosts the test case databases at the following address: https://wiki.lsce.ipsl.fr/interfrost.

The results of the first stage of the benchmark exercise will be presented. We will mainly focus on the inter-comparison of participant results for the coupled cases TH2 & TH3. Both cases are essentially theoretical but include the full complexity of the coupled non-linear set of equations (heat transfer with conduction, advection, phase change and Darcian flow). TH2 considers an initially frozen square inclusion within a warmer domain. The initial inclusion progressively warms up due to conduction and heat exchange by water advection. TH3 considers a domain with two conflicting effects associated with imposed negative temperatures on the top and bottom while the input of warm water from the left side provides heat to the system. This system exhibits a threshold response to the flow velocity: the central talik closes for lower velocities and opens for higher velocities.

A series of Performance Measures (PMs) was introduced to provide easy and tractable comparisons. These include thermal and hydrological variables or their associated fluxes in the form of point values or values averaged over a surface area or volume. In the first approach, the time evolution of all PMs are plotted for each contributing code. A PM example is provided in the figure below for TH2. These data represent the evolution of the temperature field minimum for a hydraulic gradient of 3% (low velocity).



The complete set of inter-comparison results shows that the participating codes all produce simulations which are quantitatively similar and correspond to physical intuition. From a quantitative perspective, they agree well over the whole set of performance measures. However, discrepancies exist resulting from 1) differences in the set of simulated equations or characteristic curves (some participants were not able to run the test cases with identical conditions) and 2) precision issues resulting from spatial and temporal discretization and convergence (e.g. imprecise initial conditions due to non-dedicated meshing especially for TH3, temporal discretization strategies and convergence criteria for non-linear loops or other algorithms).

The differences among the simulation results will be discussed in more depth throughout the test cases and PMs, especially for the identification of the threshold times for each system as these exhibited the least agreement. However, the results suggest that in spite of the difficulties associated with the resolution of the set of TH equations (coupled and non-linear structure with phase change providing steep slopes), the developed codes provide robust results with a qualitatively reasonable representation of the processes and offer a quantitatively realistic basis.

These test case results, as well as the associated overview of the numerical approaches used, will hopefully propel future code development, improvements, and application.

Further perspectives of the exercise will also be presented. Extensions to more complex physical conditions (e.g. unsaturated conditions and geometrical deformations) are contemplated. In addition, 1D vertical cases of interest to the climate modeling community, as well as comparisons to observed laboratory and field site data will be proposed during the year to come.

The InterFrost project is very thankful to the International Permafrost Association for the 2016-2017 IPA Action Group funding.

Keywords: Permafrost; Numerical modeling; River-soil interaction; Arctic systems; soil freeze-thaw

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