AMANZI ATS

Permafrost Thermal Hydrology

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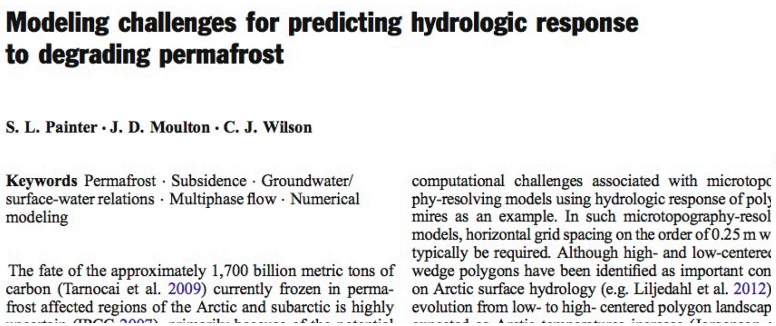
Outline

- Basic intro to permafrost processes
  - Flow + energy + surface energy balance/snow
  - Optional polygonal ground, subsidence
- What makes freezing soils weird
  - Thermal expansion
  - cryosuction
- Demo: lab experiment on cryosuction
- Modeling permafrost: spinup and initialization
- Demo: transient column run
- Fancier runs overview: transect/discontinuous permafrost, Seward Pen 3D run, Intermediate scale model

Permafrost in ATS

Hydrogeology Journal, 2014



Modeling challenges for predicting hydrologic response to degrading permafrost

S. L. Painter · J. D. Moulton · C. J. Wilson

Keywords Permafrost · Subsidence · Groundwater/surface-water relations · Multiphase flow · Numerical modeling

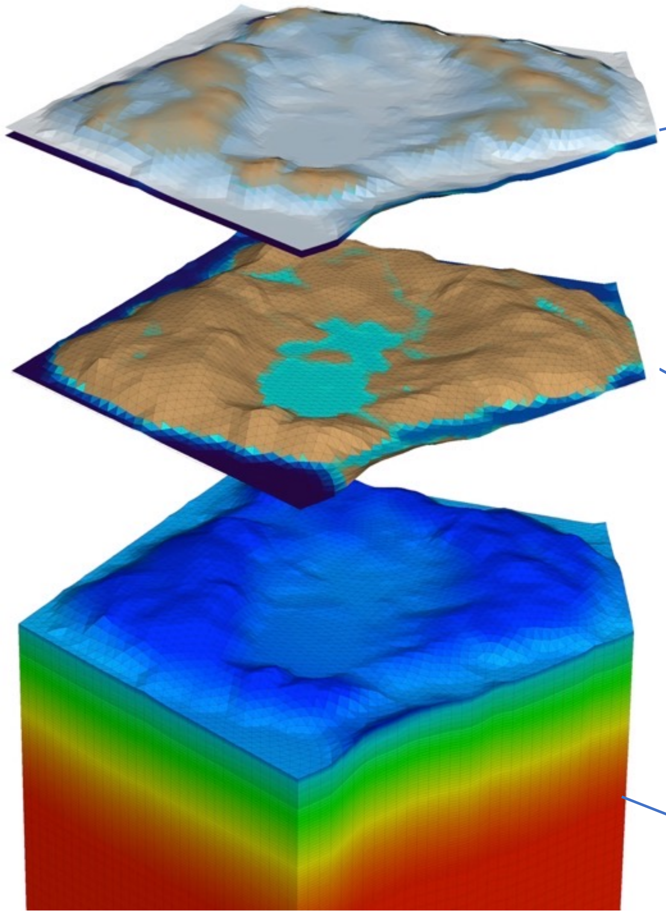
The fate of the approximately 1,700 billion metric tons of carbon (Tarnocai et al. 2009) currently frozen in permafrost affected regions of the Arctic and subarctic is highly

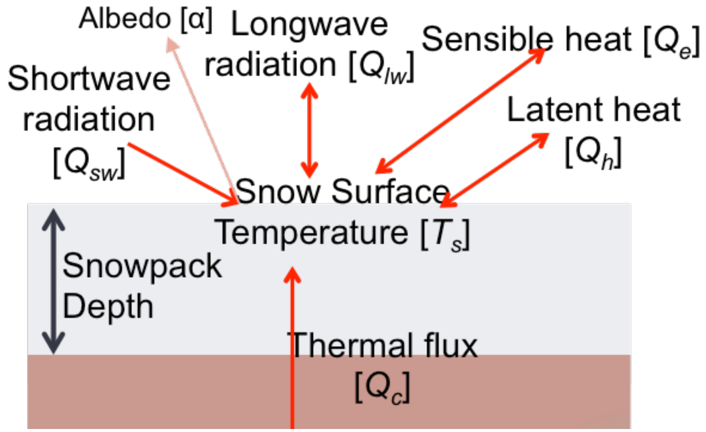
computational challenges associated with microtopo phy-resolving models using hydrologic response of poly mires as an example. In such microtopography-resol models, horizontal grid spacing on the order of 0.25 m w typically be required. Although high- and low-centere wedge polygons have been identified as important con on Arctic surface hydrology (e.g. Liljedahl et al. 2012) evolution from low- to high- centered polygon landscap

Water Resources Research, 2016

Integrated surface/subsurface permafrost thermal hydrology: Model formulation and proof-of-concept simulations

Scott L. Painter[1], Ethan T. Coon[2], Adam L. Atchley[2], Markus Berndt[3], Rao Garimella[4], J. David Moulton[4], Daniil Svyatskiy[4], and Cathy J. Wilson[5]





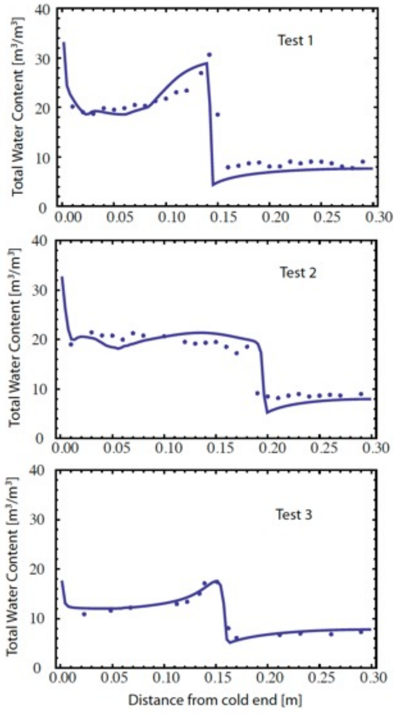
- Overland flow (diffusion wave approximation)
- Energy equation allowing freezing of ponded water
- Coupled to subsurface with flux and pressure continuity

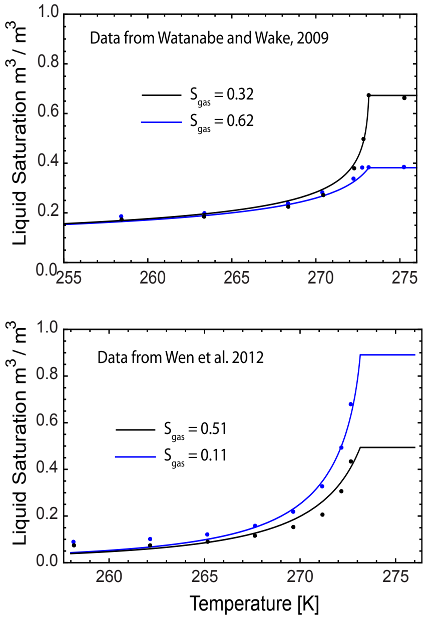
Subsurface:
New 3-phase thermal hydrology model

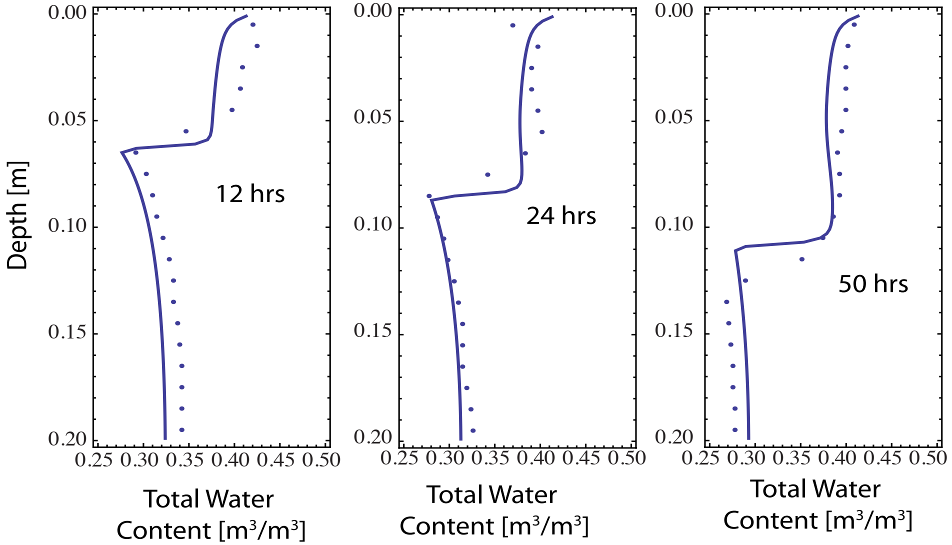
Thermal hydrology model for freezing soil

S. L. Painter, Computational Geosciences 2011
S. L. Painter and S. Karra, Vadose Zone Journal, 2014
S. Karra, S. L. Painter and P.C. Lichtner, The Cryosphere, 2014

- Conservation equation for water and energy with phase change
  - Passive gas – Richards-type
- New constitutive models relating liquid pressure, liquid content and temperature
- Careful comparisons to multiple lab experiments
- Weird processes
  - Multiple feedbacks between thermal and flow processes
  - Cryosuction
  - Expansion upon freezing







Note on specifying bottom boundary conditions

- Geothermal flux is a problematic as a BC because of past climate
- Better to specify a bottom temperature below Z* based on deep boreholes in the region
- Thickness of permafrost can be controlled by imposed temperature BC, but requires some trial and error

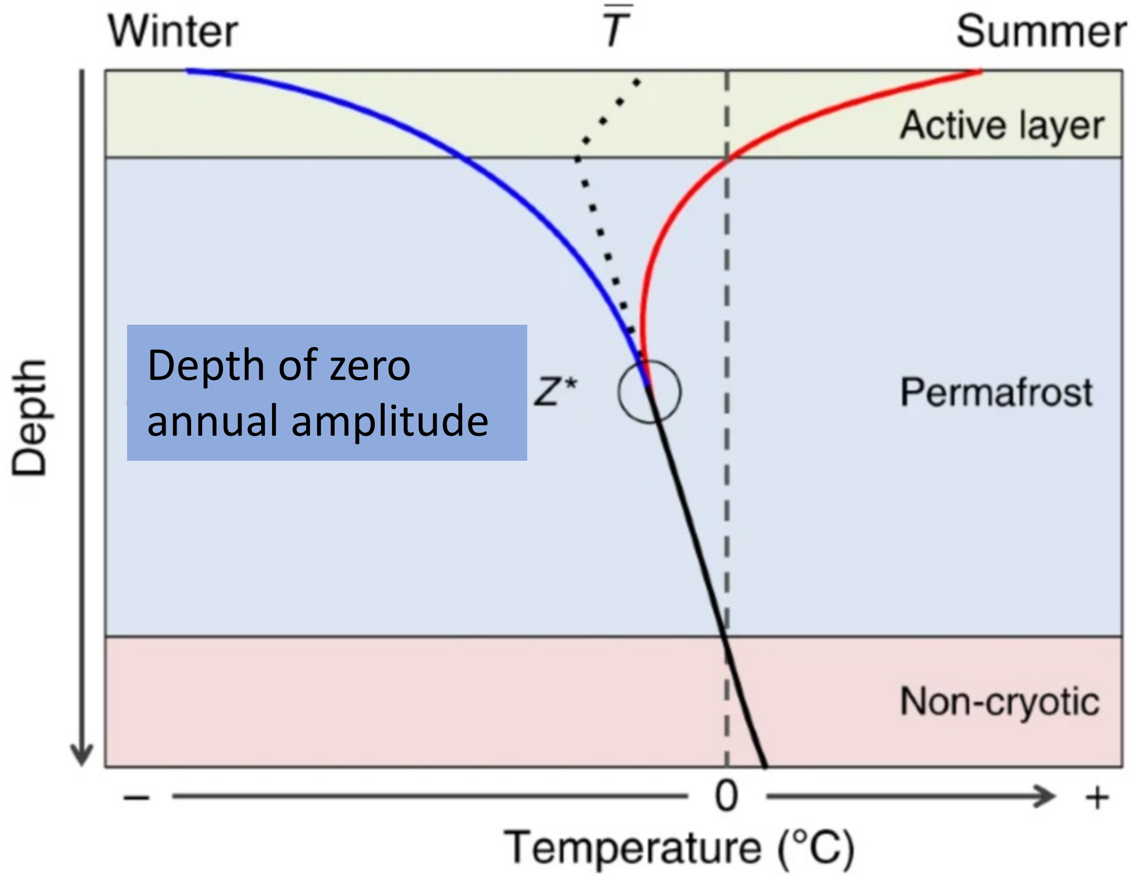


Image modified from Biskaborn, B.K., Smith, S.L., Noetzli, J. *et al.* Permafrost is warming at a global scale. *Nat Commun* **10,** 264 (2019). https://doi.org/10.1038/s41467-018-08240-4

A note on model spinup

- Freeze from below on a single column
  - Start with hydrostatic initial conditions with constant T>0 C
  - At t=0, lower bottom temperature BC to desired value
  - Use T=0.5 C and "seepage face" condition at surface
  - Run to steady state
  - Ice table position can be controlled by initial water table location
- Transient spinup
  - Use "initialize from 1D column" option to map the column to 2D or 3D
  - Loop several times with "typical year" BCs at surface
- Discard first 1-2 years in transient runs with real forcing

Demo1 Lab Experiment vs. Modeling for Cryosuction

- Cryosuction
  - The increase of ice content in frozen zone can increase matric suction, attracting soil water from unfrozen zone to the freezing front.
  - Unfrozen water content ~ **f** (temperature, suction)
  - **f** ⇒ soil-freezing characteristic curve (SFCC)
  - SFCC

    1) empirical expression :

       sat_liq ~ **f** (temperature) ⇒ no cryosuction included (McKenzie et al., 2007)

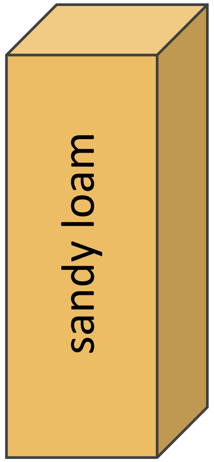
    2) physically based expression (Clapeyron equation):

       sat_liq ~ **f** (temperature, suction) ⇒ describe cryosuction (Painter et al., 2016)

       analogous to soil-water retention curve (SWCC)

Demo1 Lab Experimental Setup

T_{top} = -6 ℃



20 cm

BC_{bottom} = No flux

Total water content was measured.

Parameter	
Permeability (m^2)	3.19e-13
Porosity	0.535
Van Genuchten α (Pa^{-1})	1.11e-4
Van Genuchten m	0.32
Residual water saturation	0.093
Saturated thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.67
Dry thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.07
Initial temperature (℃)	6.7
Initial water content	0.34
Measurement times (hours)	12, 24, 50

Mizoguchi, 1990; Stuurop et al., 2021 (demo1 folder)

Demo1 Model Setup

cd 04_arctic_hydrology/demo1_cryosuction/cryos_labexpVSmodel

There are two .xml input files, one including cryosuction and the other not.

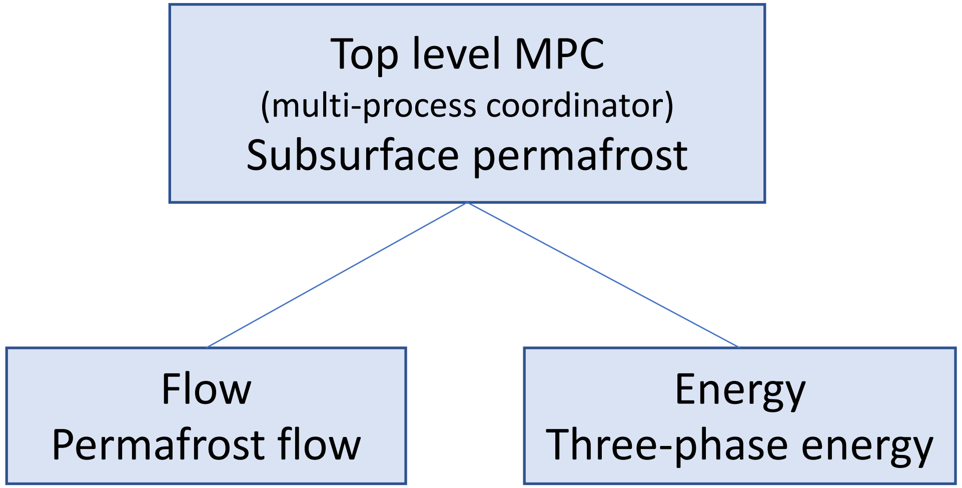
vim model_cryosuction.xml

/cycle driver

- The basic model configuration
- Only freezing process inside soil is simulated.
- Simulation time: 100 hours

/PKs

Detailed setup for each part.



Demo1 Model Setup

- Required for cryosuction setup.

/pc_ice

```
<Parameter name="use pc_ice to determine sfc" type="bool" value="true" />
```

"true" – include cryosuction
"false" – no cryosuction

/water retention evaluator

```
<Parameter name="liquid-ice capillary pressure key" type="string" value="capillary_pressure_liq_ice" />
```

```
<ParameterList name="permafrost model parameters" type="ParameterList">
  <Parameter name="permafrost WRM type" type="string" value="fpd permafrost model" />
  <Parameter name="minimum dsi_dpressure magnitude" type="double" value="1e-12" />
</ParameterList>
```

- Change in matric suction due to freezing is taken account.
- How: by fpd model.

(freezing point depression)
(Painter et al., 2016)

```
<Parameter name="liquid-ice capillary pressure key" type="string" value="temperature" />
```

```
<ParameterList name="permafrost model parameters" type="ParameterList">
  <Parameter name="permafrost WRM type" type="string" value="mck permafrost model" />
  <Parameter name="freezing point [K]" type="double" value="273.15" />
  <Parameter name="residual saturation [-]" type="double" value="0.093" />
  <Parameter name="sfc fitting coefficient" type="double" value="3" />
</ParameterList>
```

- capillary_pressure_liq_ice evaluator will not be called.
- unfrozen content is temperature dependent.
- How: by mck model

(McKenzie et al., 2007)

Demo1 Model Setup

- Boundary and initial conditions

/flow

```xml
<ParameterList name="boundary conditions" type="ParameterList">
</ParameterList>
```

Neumann BC: J = 0

```xml
<ParameterList name="initial condition" type="ParameterList">
  <Parameter name="hydrostatic head [m]" type="double" value="-2.4" />
  <Parameter name="hydrostatic water density [kg m^-3]" type="double" value="1000.0" />
</ParameterList>
```

Set water table at -2.4m (try)

/energy

```xml
<ParameterList name="boundary conditions" type="ParameterList">
  <ParameterList name="temperature" type="ParameterList">
    <ParameterList name="top" type="ParameterList">
      <Parameter name="regions" type="Array(string)" value="{surface}" />
      <ParameterList name="boundary temperature" type="ParameterList">
        <ParameterList name="function-constant" type="ParameterList">
          <Parameter name="value" type="double" value="267.15" />
        </ParameterList>
      </ParameterList>
    </ParameterList>
  </ParameterList>
</ParameterList>
```

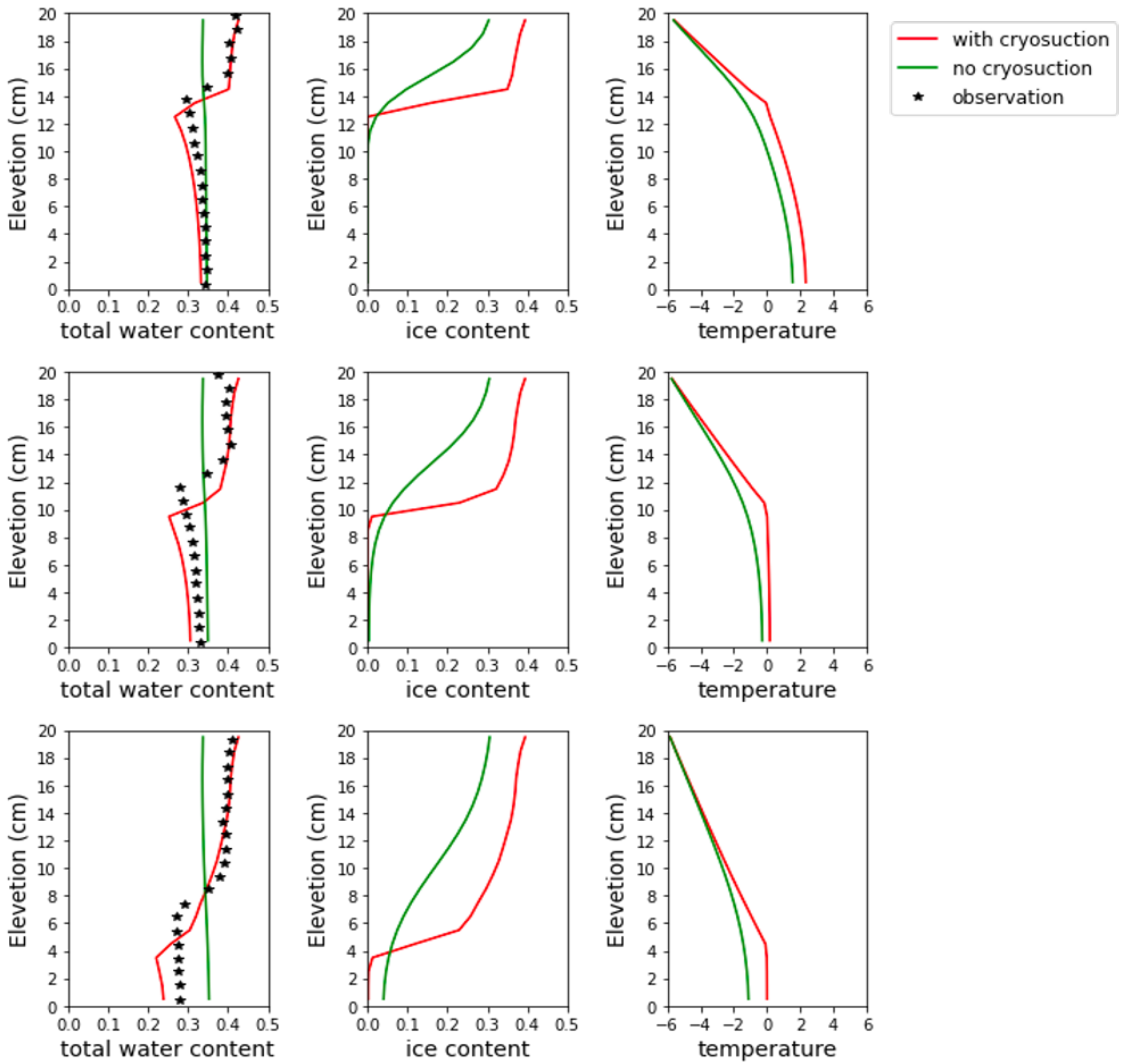
T_{top} = -6 ℃

```xml
<ParameterList name="initial condition" type="ParameterList">
  <ParameterList name="function" type="ParameterList">
    <ParameterList name="initial temperature cells" type="ParameterList">
      <Parameter name="region" type="string" value="domain" />
      <Parameter name="components" type="Array(string)" value="{face,cell}" />
      <ParameterList name="function" type="ParameterList">
        <ParameterList name="function-constant" type="ParameterList">
          <Parameter name="value" type="double" value="279.85" />
        </ParameterList>
      </ParameterList>
    </ParameterList>
  </ParameterList>
</ParameterList>
```

T_{ini} = 6.7 ℃

Demo1 Experiment vs. Modeling

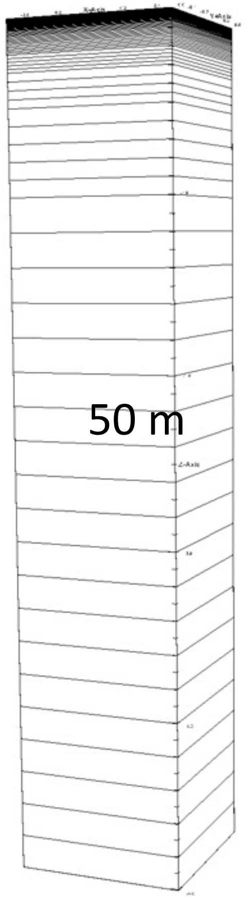
Underestimation of ice content and temperature if no cryosuction is considered.



Demo1 Model Change for practice

- initial condition for flow:
  - hydrostatic head
- boundary condition for energy:
  - no flux bottom → constant temperature at bottom (e.g., 2 °C)
- soil properties:
  - base porosity
  - permeability
  - Van Genuchten parameters

Demo2 Transient Arctic Modeling

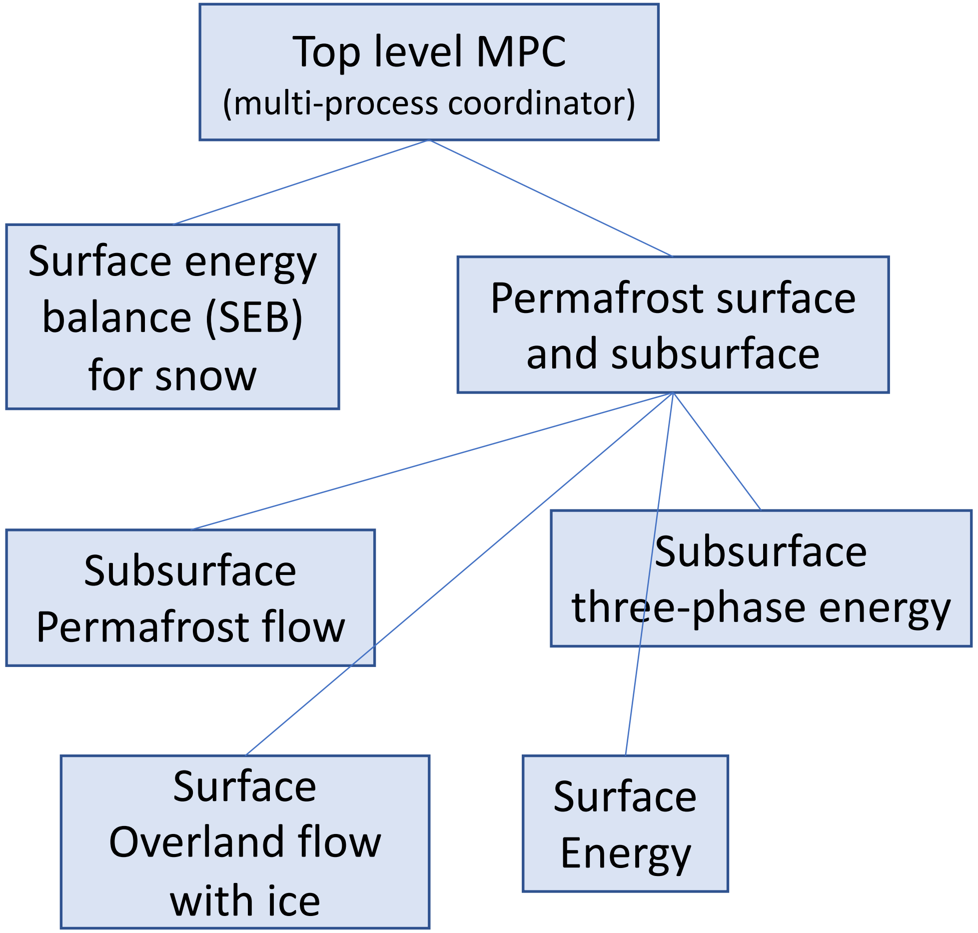


T_{bottom} = -10 °C

Soil layer	Moss	Peat	Mineral
Thickness	2 cm	8 cm	49.9 m
Porosity	0.9	0.876	0.596
Permeability (m^2)	1.7e-11	9.38e-12	6e-13
VG α (Pa^{-1})	2.3e-3	9.5e-4	3.3e-4
VG *n*	1.38	1.44	1.33
Residual saturation	0.056	0.388	0.334
Thermal conductivity unfrozen ($Wm^{-1}K^{-1}$)	0.446	0.427	0.788
Thermal conductivity dry ($Wm^{-1}K^{-1}$)	0.024	0.025	0.104

(Atchley el at., 2015)

Forcing data from Daymet (https://daymet.ornl.gov/single-pixel/api)
Get these data by ATS tool daymet_to_ats.py



Demo2 Model Setup – Initialization

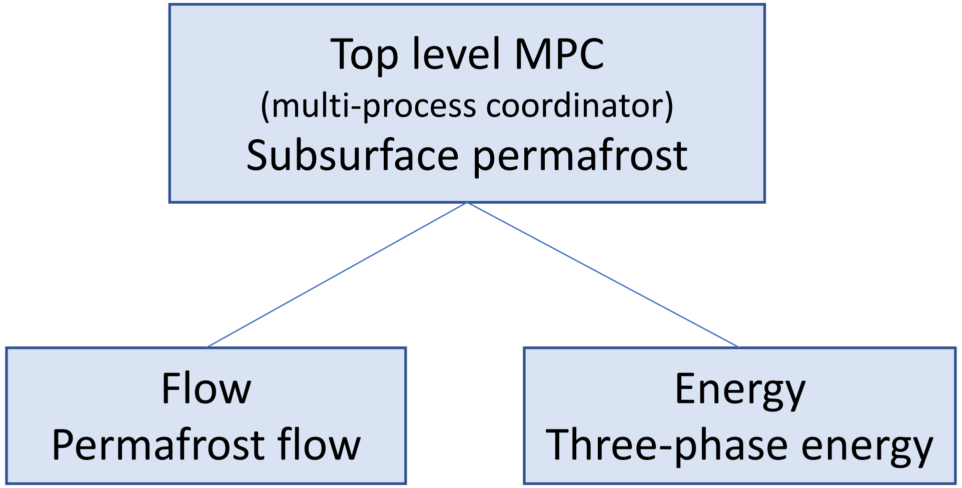
cd 04_arctic_hydrology/demo2_transient_column

- Purpose

  Freezing a soil column from bottom to top to obtain an initial freezing soil domain.

- Model setup

  - Same configuration with demo 1.
  - Initial water table depth: -5.78 m.
  - Run for a long time for a steady state (1000 years)
  - Obtain the final pressure and temperature profile using ATS tool column_data.py



Demo2 Model Setup – Transient

vim transient.xml

/cycle driver

- Basic configuration
- Run for 1 year

/subsurface flow

- Initial condition: from freezeup
- Boundary condition: J = 0

/surface flow

- Initial condition: from subsurface
- Boundary condition: outlet at surface

/subsurface energy

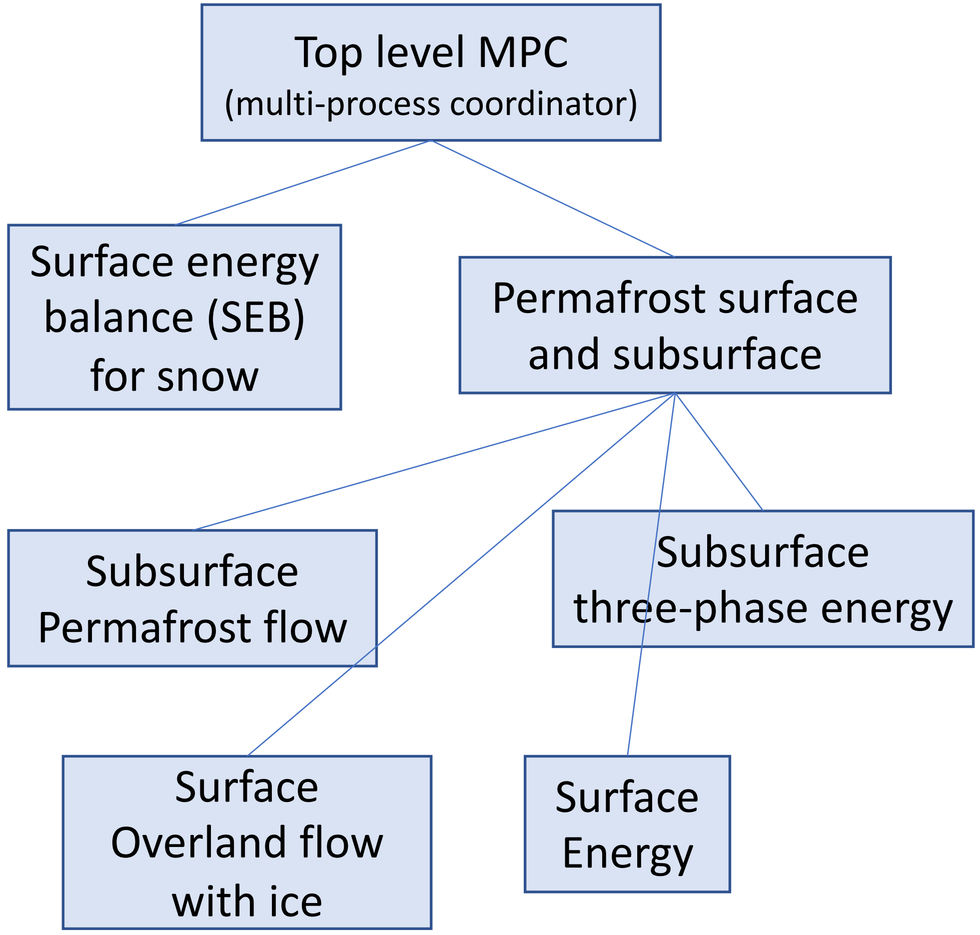
- Initial condition: from freezeup
- Boundary condition: T_{bottom} = -10℃

/surface energy

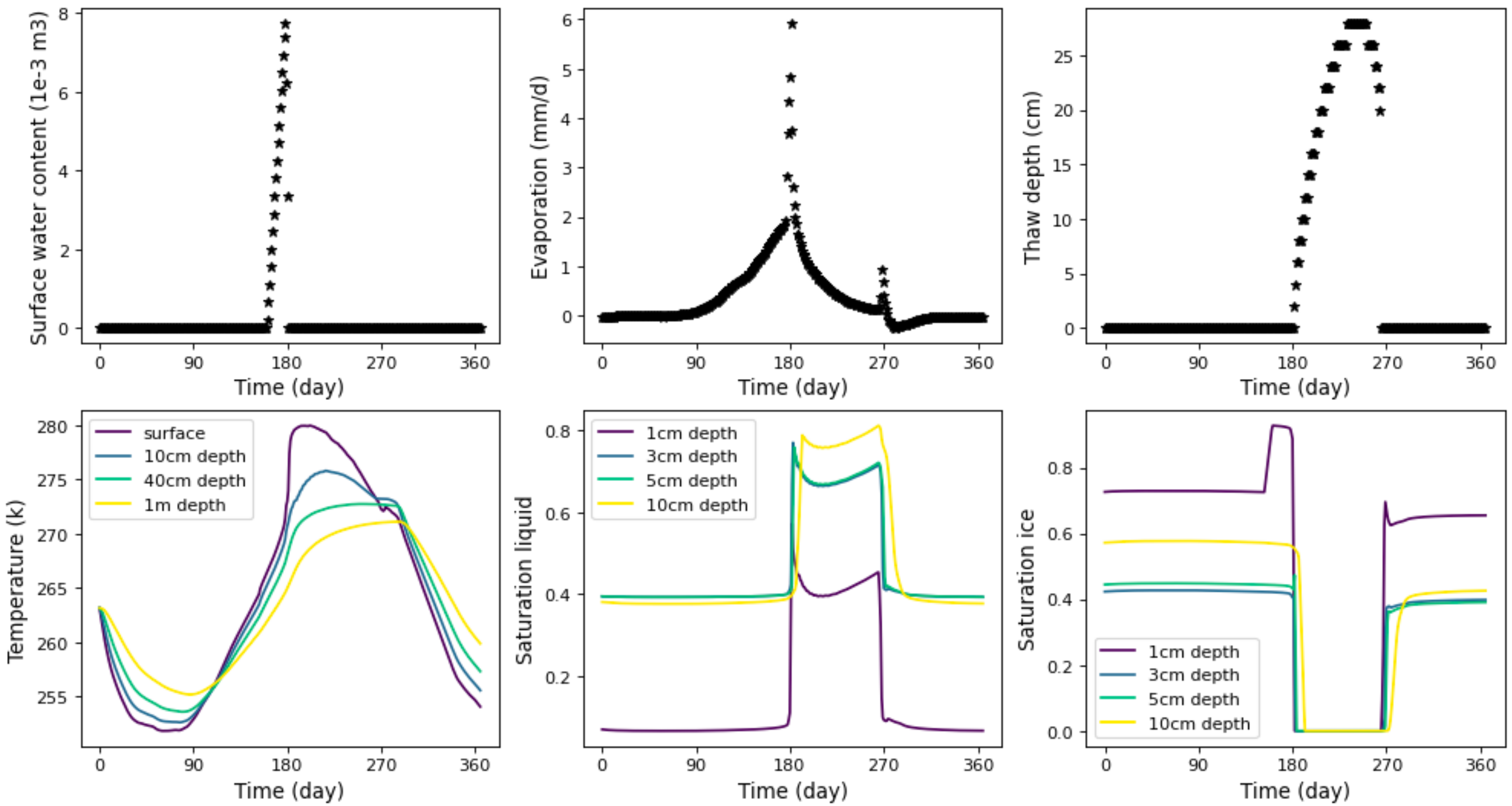
- Initial condition: from subsurface
- Boundary condition: J = 0

/SEB

- Initial condition:
  snow depth from spinup

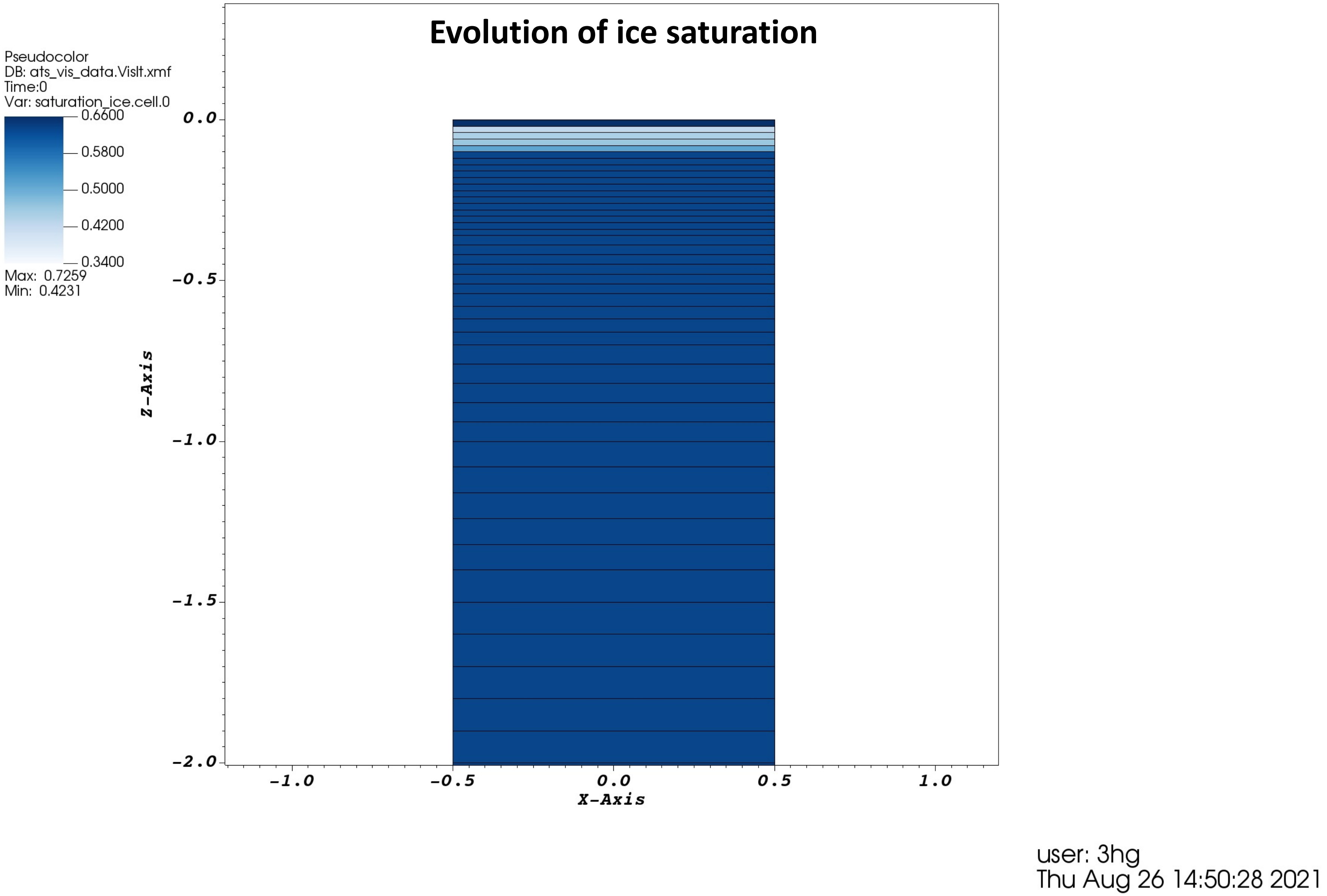


Demo2 Model Observation



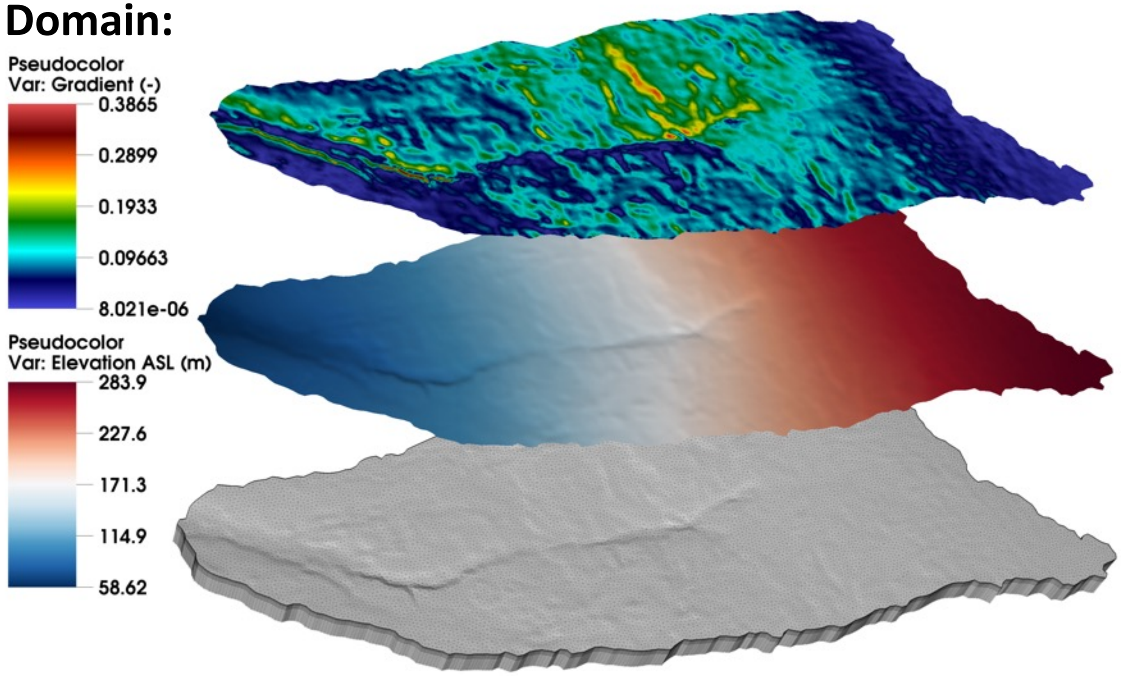
(1) surface water content
(2) evaporation
(3) thaw depth
(4) temperature
(5) saturation liquid
(6) saturation ice

Demo2 Model Observation

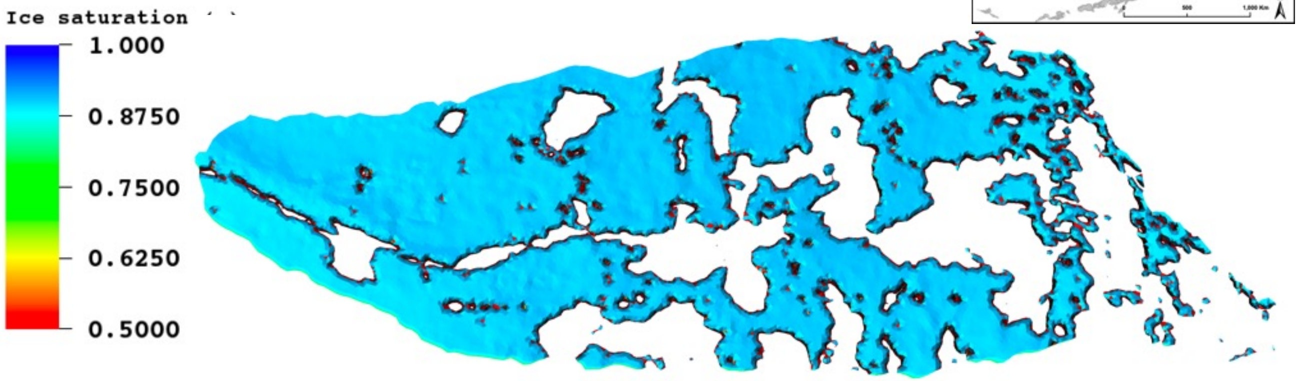


Teller Watershed 3D Modeling

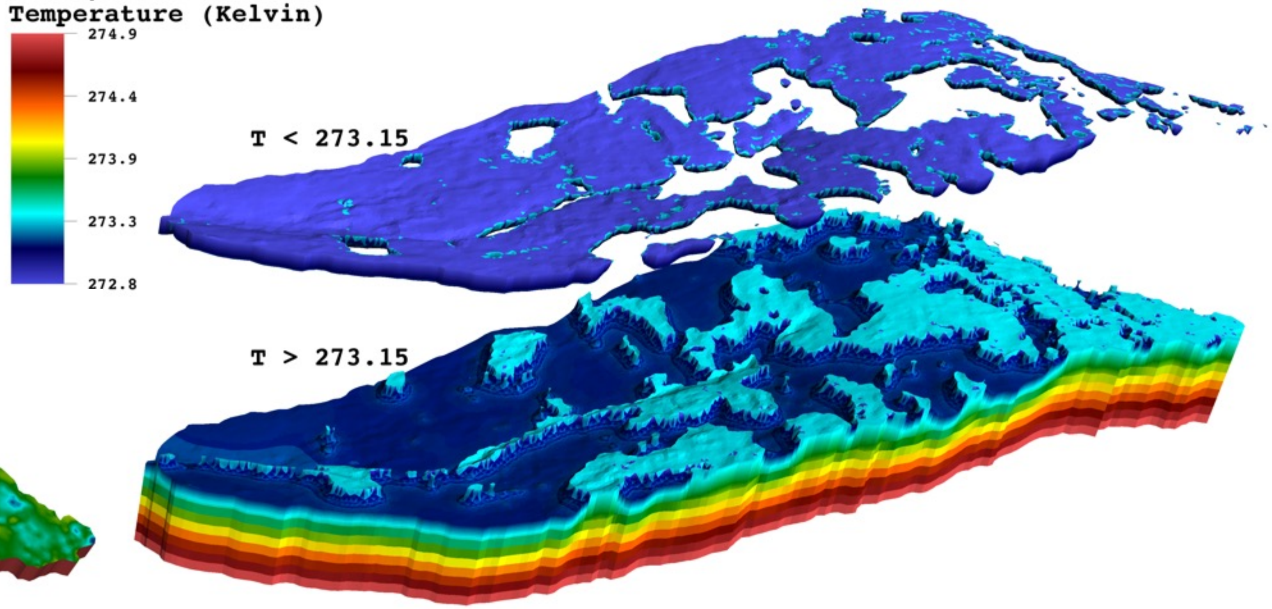
Domain:



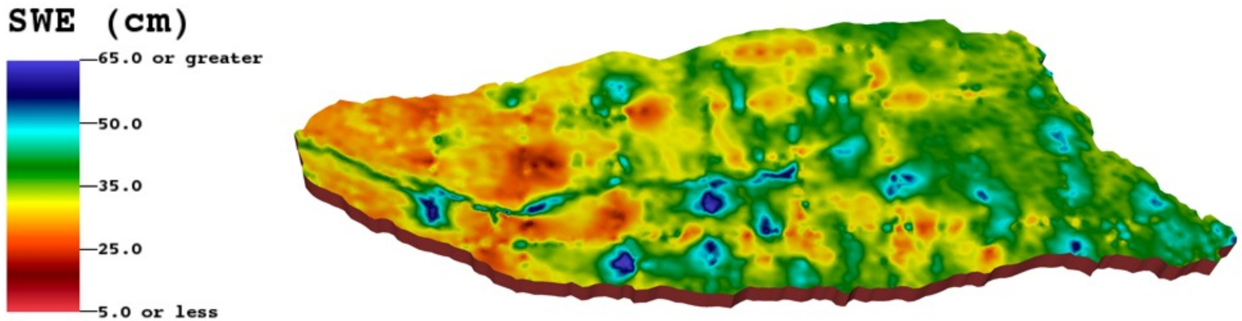
Plan view of permafrost distribution:



Temperature distribution:



Interpolated SWE model:



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