Transient modelling of permafrost dynamics in changing climate scenarios

Andrew Frampton[1], Scott Painter[2], Steve W. Lyon[1], Ylva Sjöberg[1], Georgia Destouni[1]

[1] Department of Physical Geography and Quaternary Geology
Stockholm University, Sweden

[2] Computational Earth Sciences Group
Earth and Environmental Sciences Division
Los Alamos National Laboratory, USA

Stockholm University

Motivation

- Thawing increases in a warming climate
- Storage release of water and more importantly nutrients
- May alter subsurface flow pathways
- May impact nutrient cycles
- Potential feedback effects further inducing climate change

- Need to better understand changes in hydrogeological flow pathways in response to permafrost formation and degradation
- Using a numerical model of water migration in partially frozen geological media

Mathematical / Numerical model

- Mass conservation eqns for three-phase, two-component system
  p → ice, liquid, gas
  β → air, water

$$\frac{\partial}{\partial t}\left[\sum_{p=l,g,i}\phi\omega_p^\beta n_p s_p\right] = -\sum_{p=l,g}\nabla\cdot\left[\omega_p^\beta n_p \mathbf{V}_p\right] + \sum_{p=l,g}\nabla\cdot\left[\phi\tau_p n_p D_p \nabla\omega_p^\beta\right] + S^\beta$$

- Combined with the extended Darcy law for unsaturated flow

$$\mathbf{V}_p = -\frac{k_{rp}k}{\mu_p}\left(\nabla P_p + \rho_p g \nabla z\right)$$

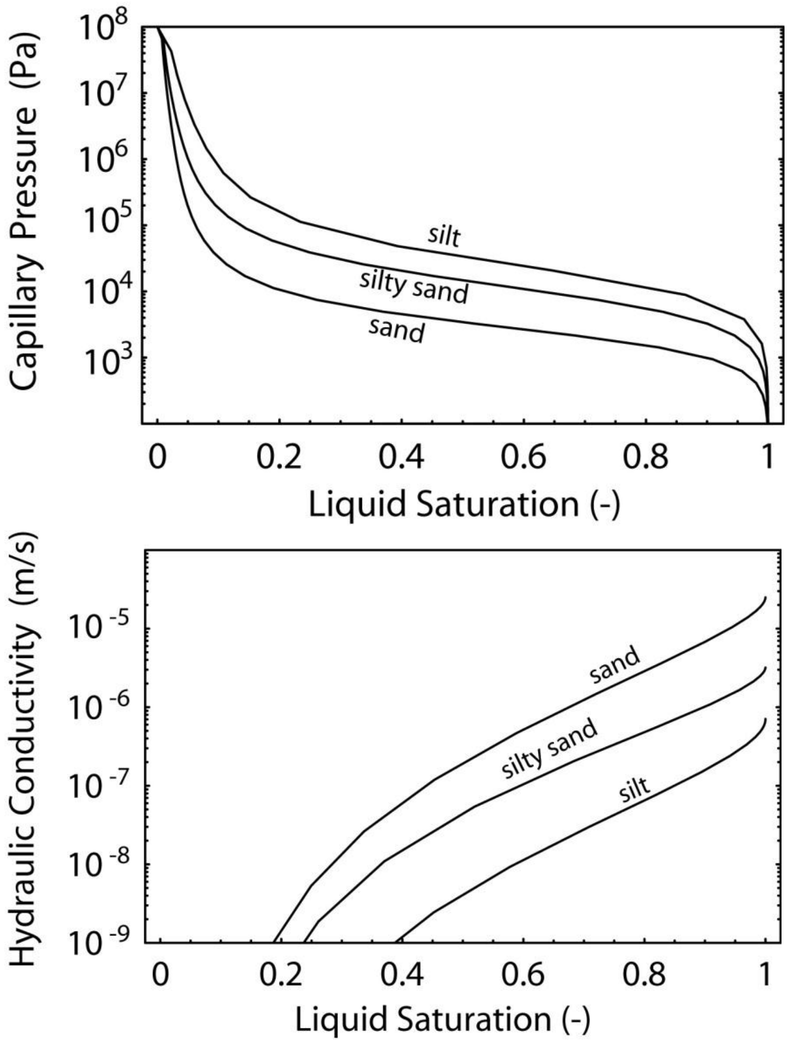
- Energy conservation eqn assumes local thermal equilibrium among the ice, liquid, gas phases and the supporting (porous) media

$$\frac{\partial}{\partial t}\left[\sum_{p=l,g,i}\left(\phi\rho_p s_p u_p\right) + (1-\phi)\rho_m u_m\right] = -\sum_{p=l,g}\nabla\cdot\left(\rho_p h_p \mathbf{V}_p\right) + \nabla\cdot\left[\kappa_e \nabla T\right] + S_E$$

Scott Painter (2011) *Three-phase numerical model of water migration in partially frozen geological media: Model formulation, validation, and applications*, Comput Geosciences, 15:69–85

Mathematical / Numerical model

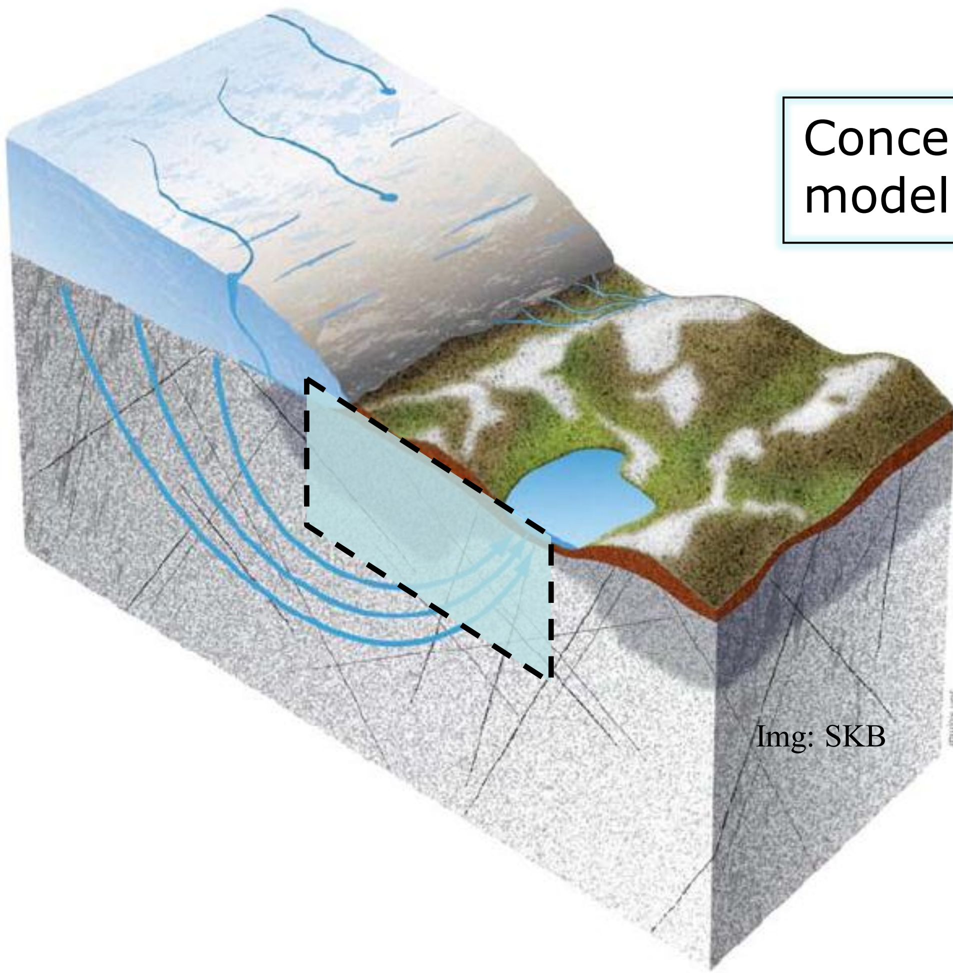
- Numerically solving the multiphase groundwater PDE coupled to heat transport
- Unfrozen water fraction and relative permeabilities obtained from unfrozen moisture retention curves
- Avoids use of empirical impedence factors
- Eg the van Genuchten and Mualem models to relate capillary pressure with phase saturation, and hydraulic conductivity to phase saturation
- Other constituative relationships also needed to relate primary variables to secondary variables



Scott Painter (2011) *Three-phase numerical model of water migration in partially frozen geological media: Model formulation, validation, and applications*, Comput Geosciences, 15:69–85

Simulation configuration

- Seasonal variability – Sinusoidally varying surface T
- Warming trends – Annually increasing mean T
  Three cases – 0.5, 0.01, 0.05°C/yr over 10 years
- Heterogeneous domain – two vertically stratified textures

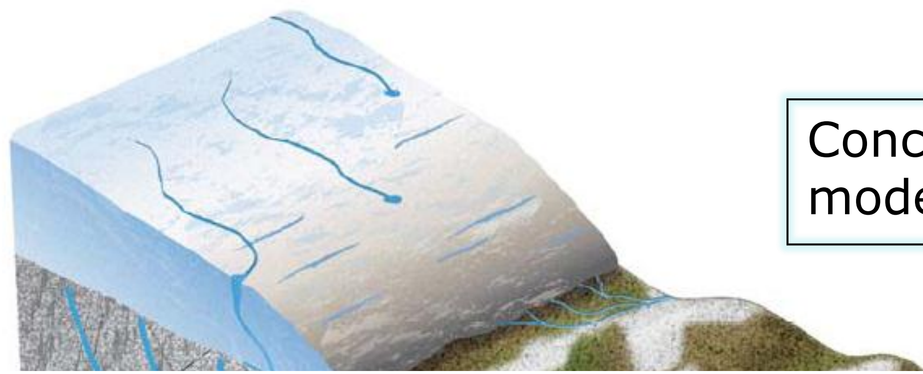


Conceptualisation of modelling approach

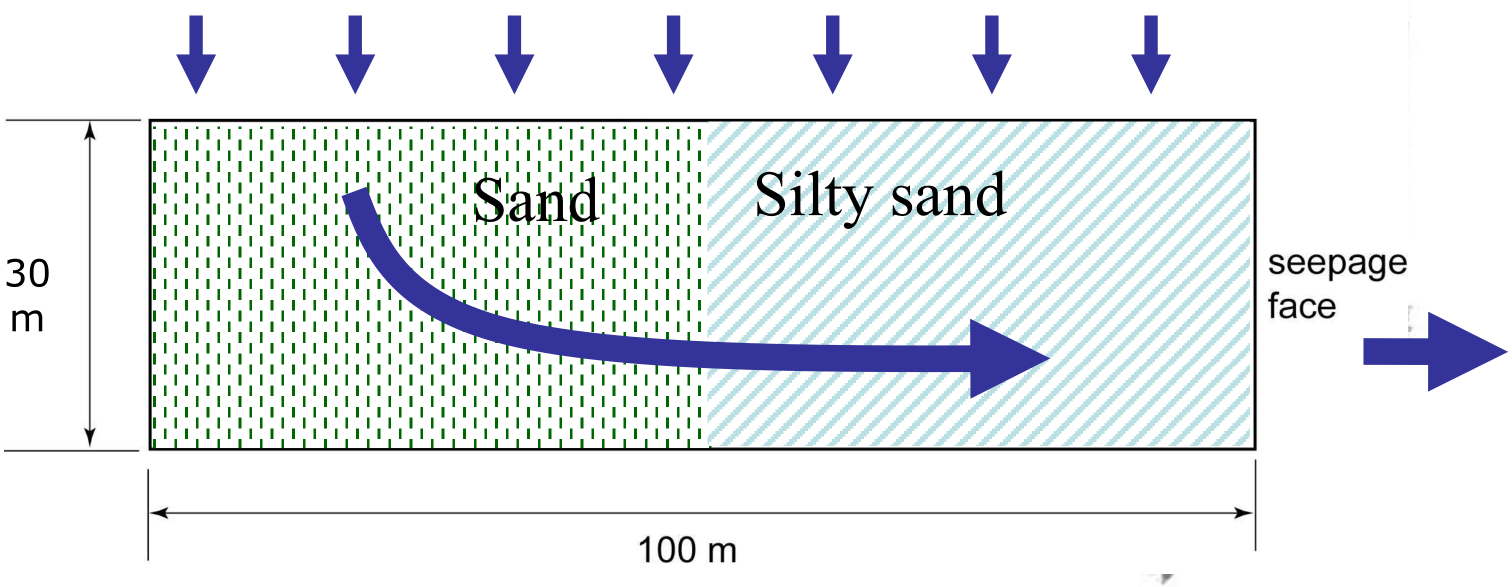
Simulation configuration

- Seasonal variability – Sinusoidally varying surface T
- Warming trends – Annually increasing mean T

  Three cases – 0.5, 0.01, 0.05°C/yr over 10 years
- Heterogeneous domain – two vertically stratified textures

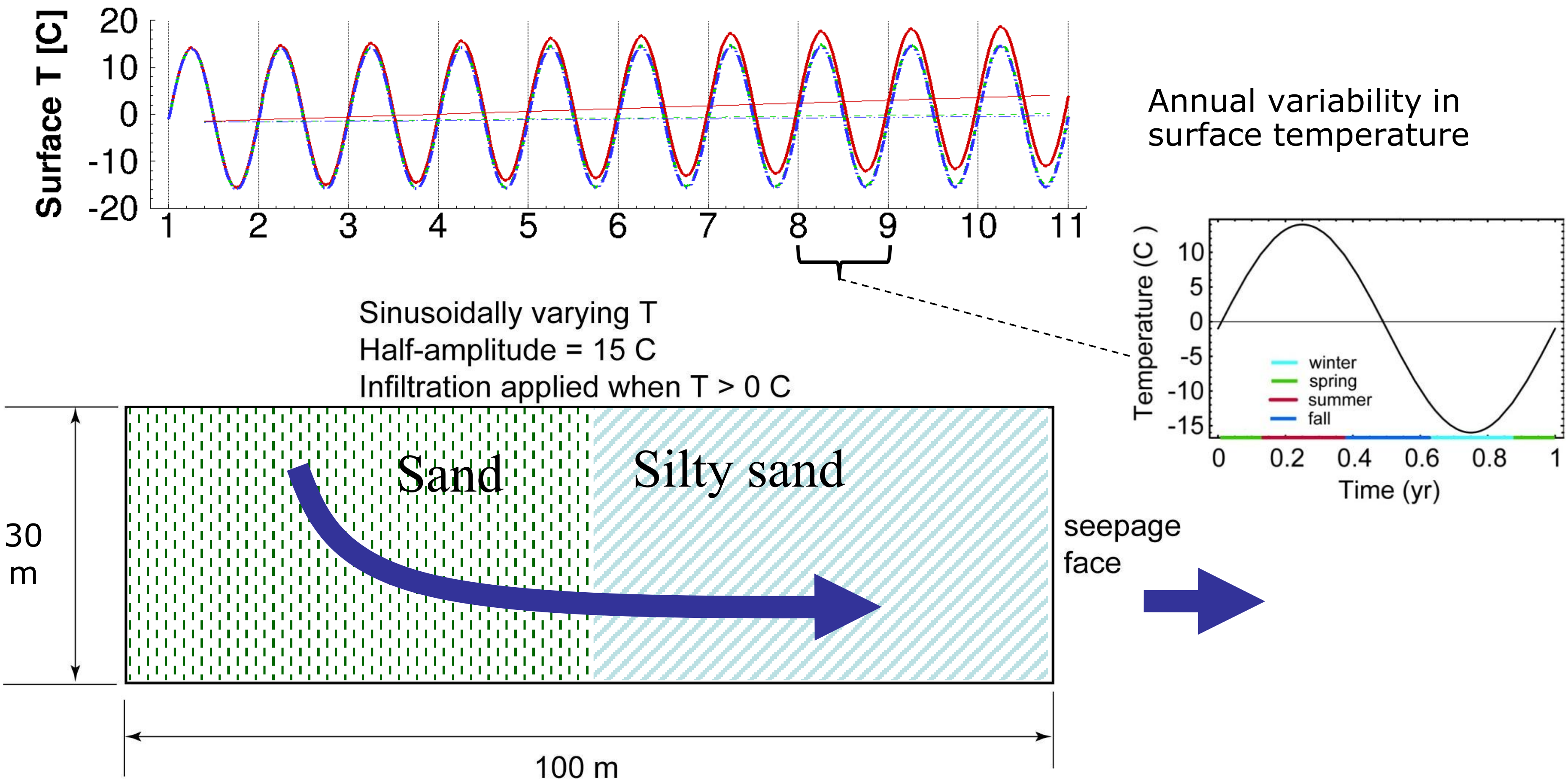


Conceptualisation of modelling approach



Simulation configuration

- Seasonal variability – Sinusoidally varying surface T
- Warming trends – Annually increasing mean T
  Three cases – 0.5, 0.01, 0.05°C/yr over 10 years
- Heterogeneous domain – two vertically stratified textures



Resulting phase saturation fractions for the case of a steep warming trend

Temperature

Geothermal flux at base

Seasonal T pulse

Liquid saturation

Perched layer seasonally dependent

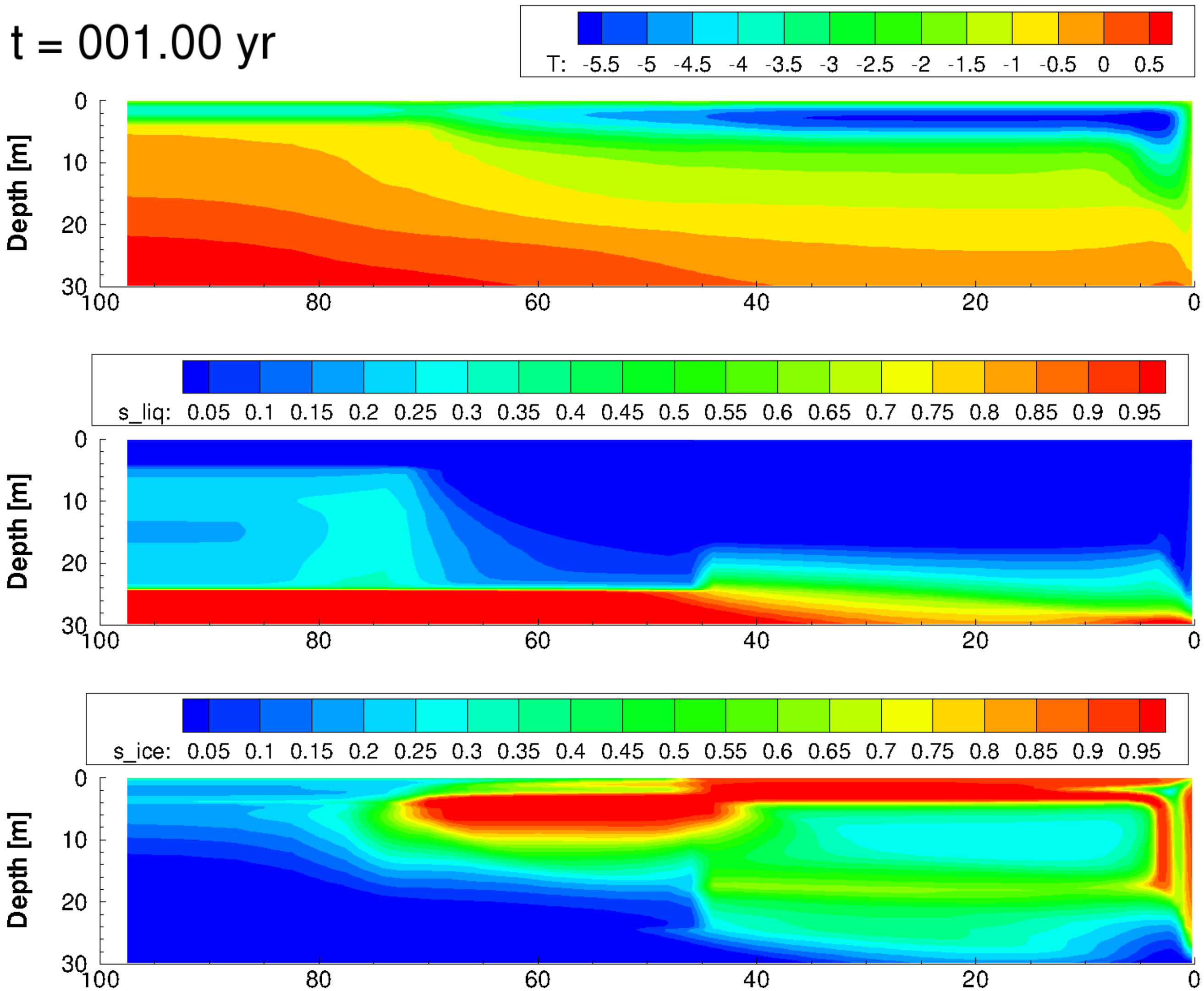
~Steady GW table

Bimodal flow around ice saturated regions

Ice saturation

Seasonally variable

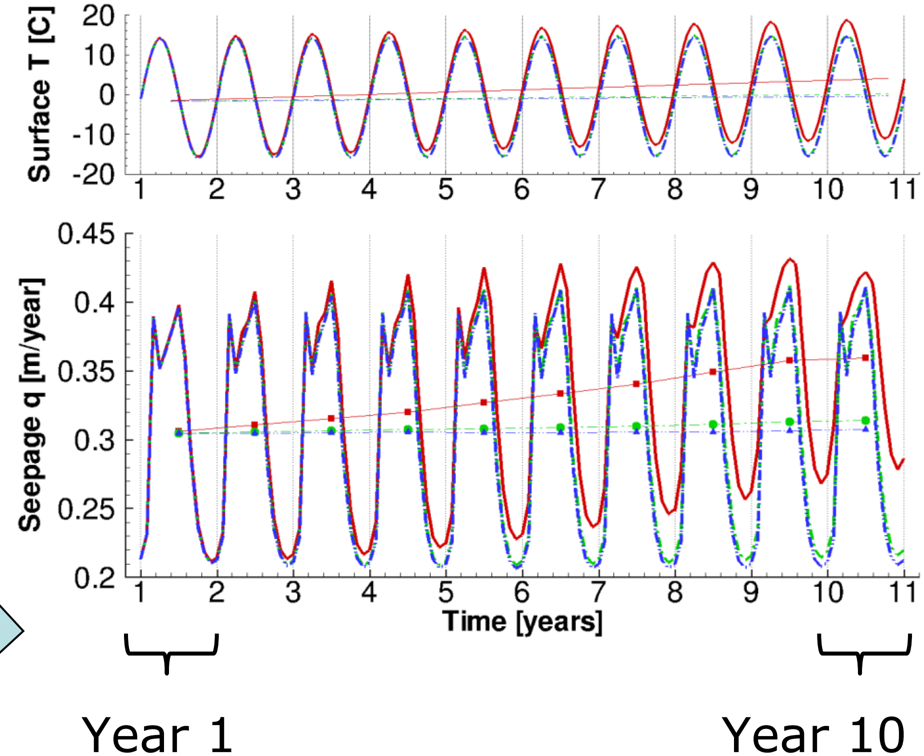
Decreases with time

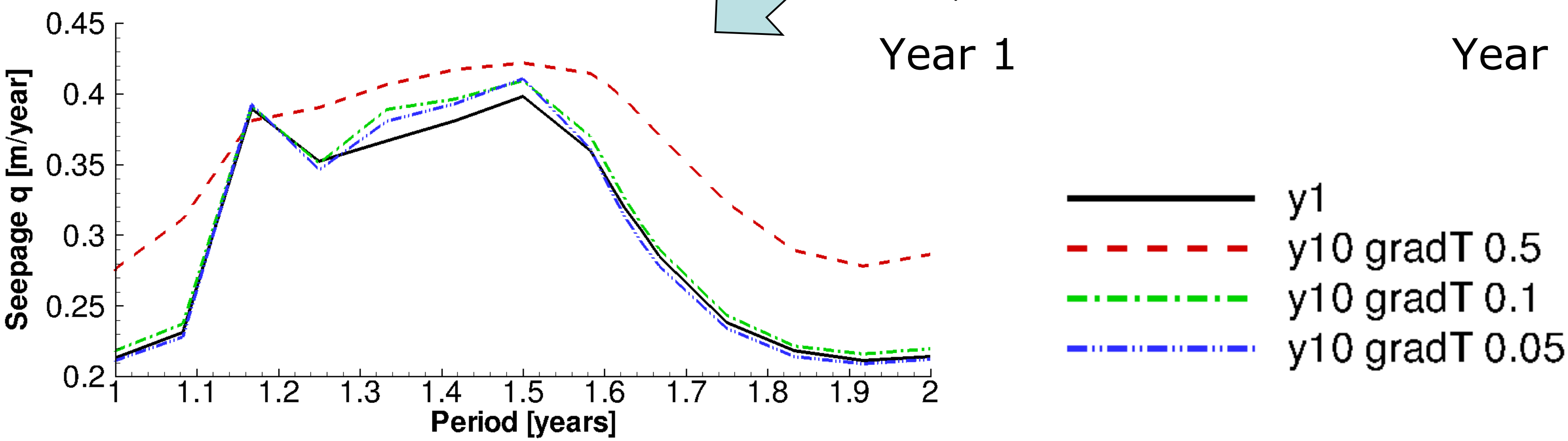


Implications on discharge variability along seepage face

- Decrease in seasonal variability
- Shift in peak discharge
- Reduction in episodic flows

➢ *Permafrost change may be detectable through hydrological flow signals*





Effect of a step increase in infiltration rate without a warming trend

Temperature

Geothermal flux at base

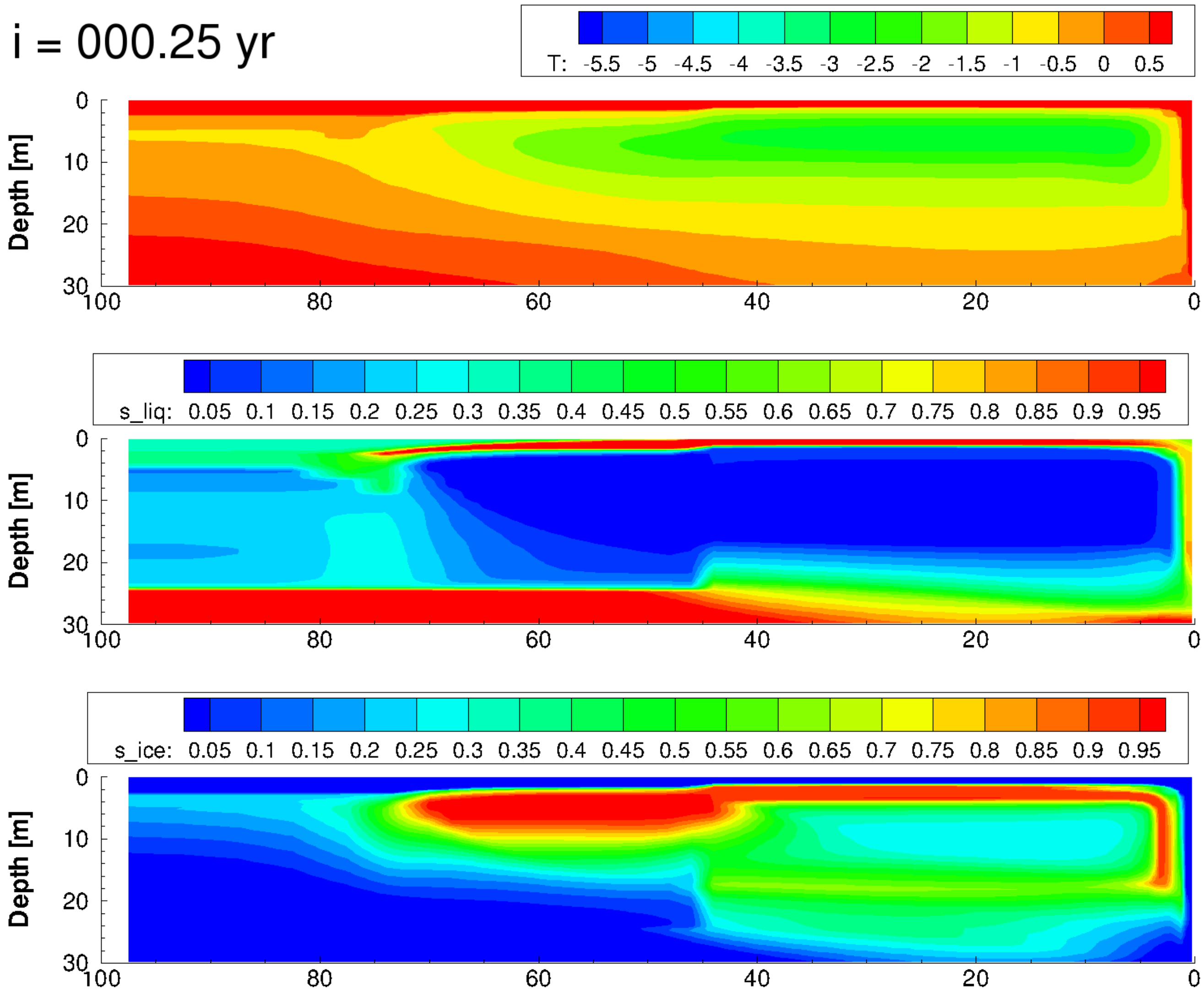
(Seasonal T pulse not shown)

Liquid saturation

Base GW table generally increases with time

Ice saturation

Here thawing on left side due to heat from increase in infiltrating water



Summary

- Using a numerical model for multiphase, non-isothermal flow
- Can handle transient permafrost dynamics & subsurface flow
- Results show permafrost change is detectable through hydrological flow signals
- Both for warming trends and changes in infiltration
- In particular
  - Thawing in warming climate may be identified by decrease in seasonal variability of flow
  - Tendency toward episodic flows also reduced

References

- Painter, S. (2011), *Three-phase numerical model of water migration in partially frozen geological media: Model formulation, validation, and applications*, Comput Geosciences, 15:69–85, DOI:10.1007/s10596-010-9197-z
- Frampton, A., Painter, S.L., Lyon, S.W., Destouni, G. (2011), *Non-isothermal, three-phase simulations of near-surface flows in a model permafrost system under seasonal variability and climate change,* J Hydrology, 403:352–359, DOI:10.1016/j.jhydrol.2011.04.010
- Frampton, A., Painter, S.L., Sjöberg, Y., and Destouni, G. (2011). *Transient modelling of permafrost dynamics in changing climate scenarios*, 7th IEEE proceedings, Dec 5 – 8, 2011, Stockholm, Sweden (in press)