Solute transport modelling in a coupled water and heat flow system applied to cold regions hydrogeology

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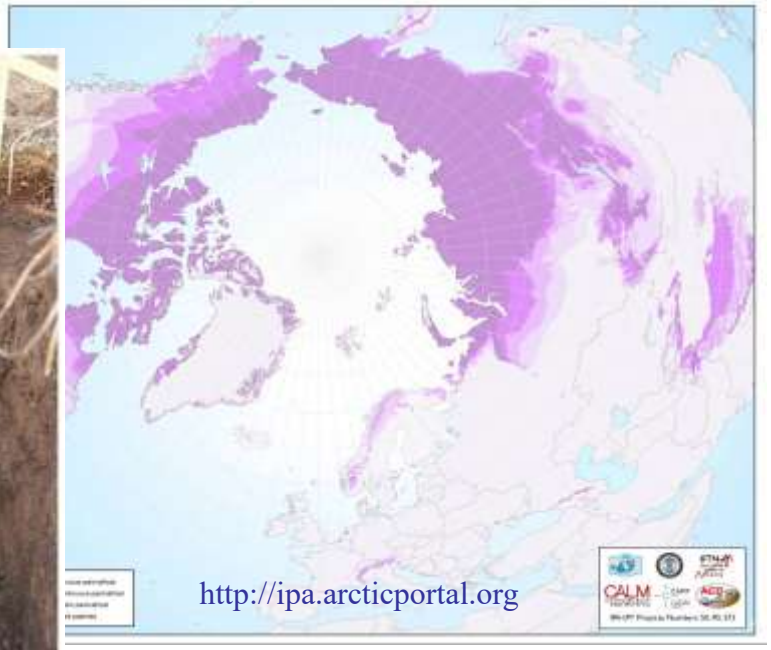
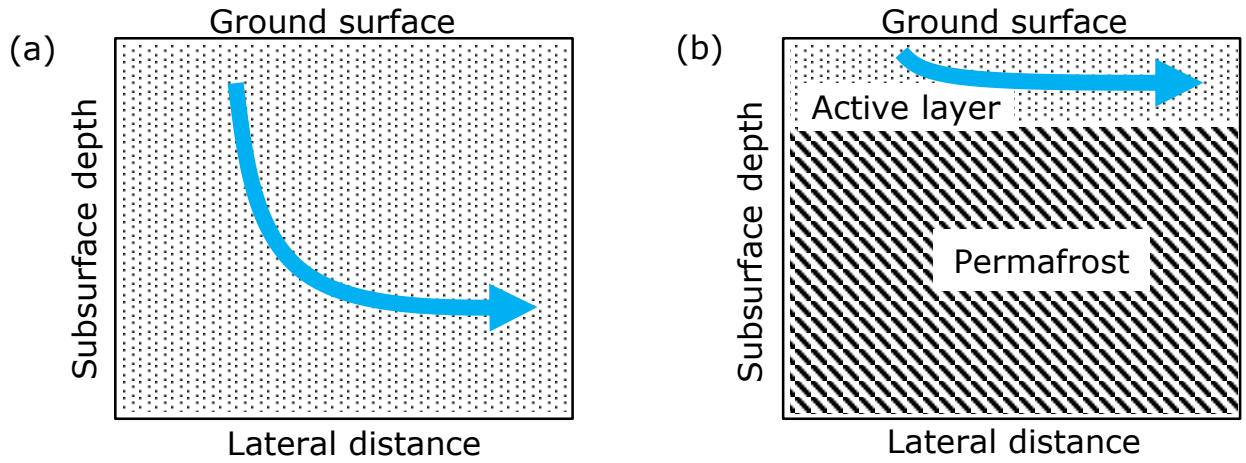
Motivation



- Permafrost covers ~24% of N. hemisphere, stores ~1700 Gt carbon, more than twice current atmospheric content
- Permafrost carbon feedbacks – links between changing climate, permafrost, hydrogeology, solute transport, and carbon release
- How quantify changes in groundwater flow, discharge and transport?
- How do changes in GW flow impact solute transport in subsurface?

Cryotic hydrogeology – Groundwater in cold regions



- Permafrost constrains soil moisture and groundwater flow to the near-surface regime, the 'active layer'
- Active layer is seasonally transient with fluctuations in moisture and ice content
- Heat flux and water flow strongly coupled
- Highly dynamic systems, seasonal & climatic dependence

Numerical model for coupled heat & water flow

- Physically-based numerical model
- Couples mass and energy conservation equations for water transport in partially frozen ground
- Accounts for
  - Partitioning of water between the liquid, vapour, and ice phases
  - Cryosuction
  - Advective transport (liquid, vapour) and diffusive transport (vapour)
  - Conductive and convective transport of heat and latent heat transfer

- Mass conservation equations

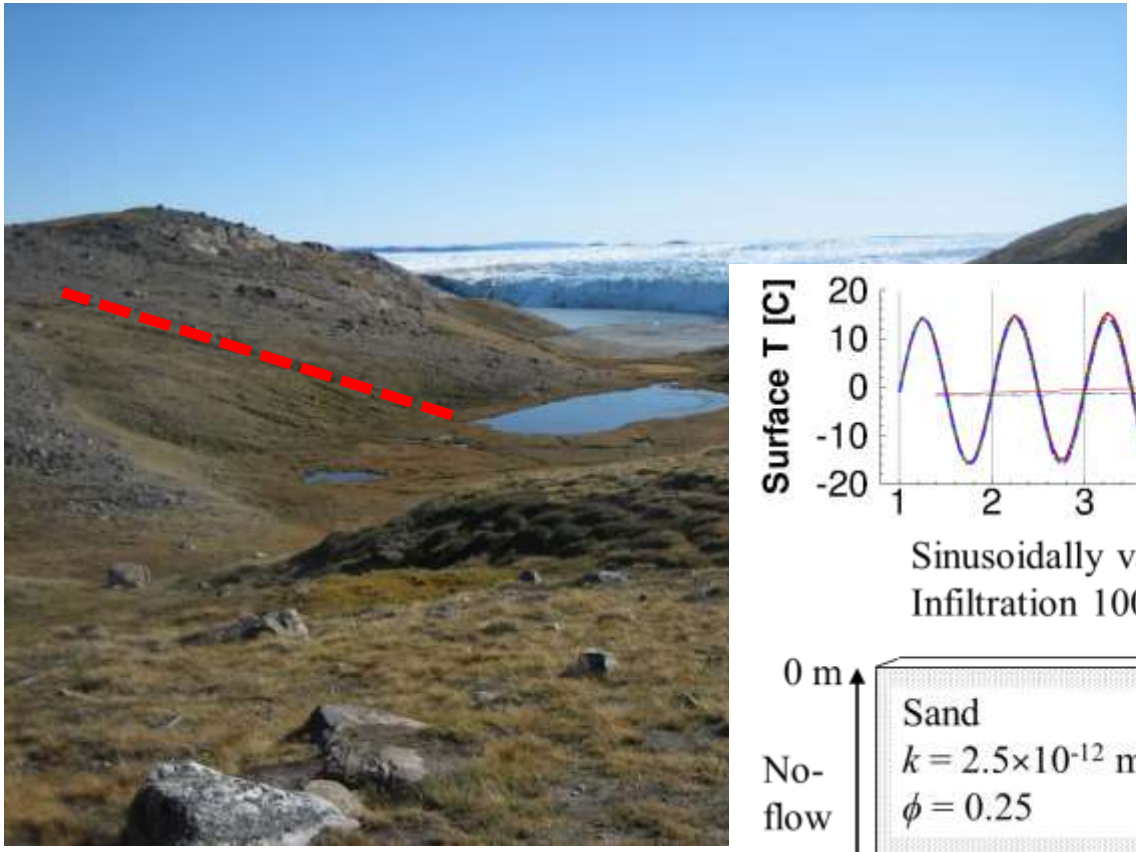
$$\frac{\partial}{\partial t}\left[\sum_{p=l,g,i}\phi\omega_p^\beta n_p s_p\right] = -\sum_{p=l,g}\nabla\cdot\left[\omega_p^\beta n_p \mathbf{v}_p\right] + \sum_{p=l,g}\nabla\cdot\left[\phi\tau_p n_p D_p \nabla\omega_p^\beta\right] + S^\beta$$

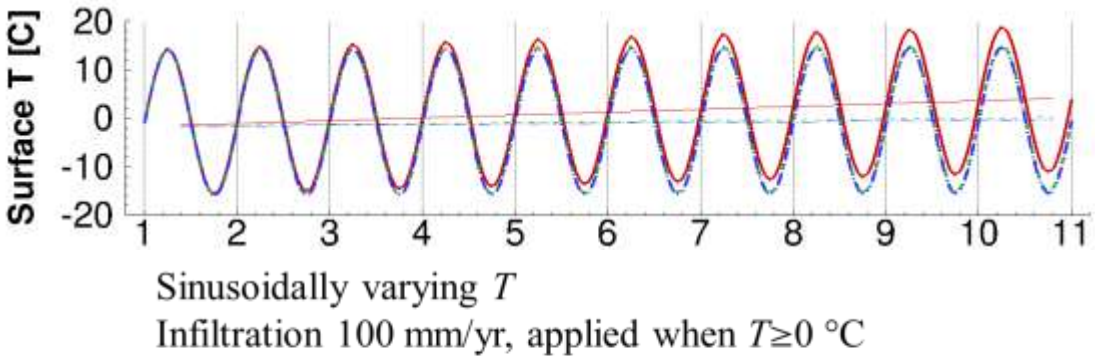
- Energy conservation equations

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

Painter (2011) Comp Geosciences; Frampton et al (2011), JoH; Frampton et al (2013), HJ

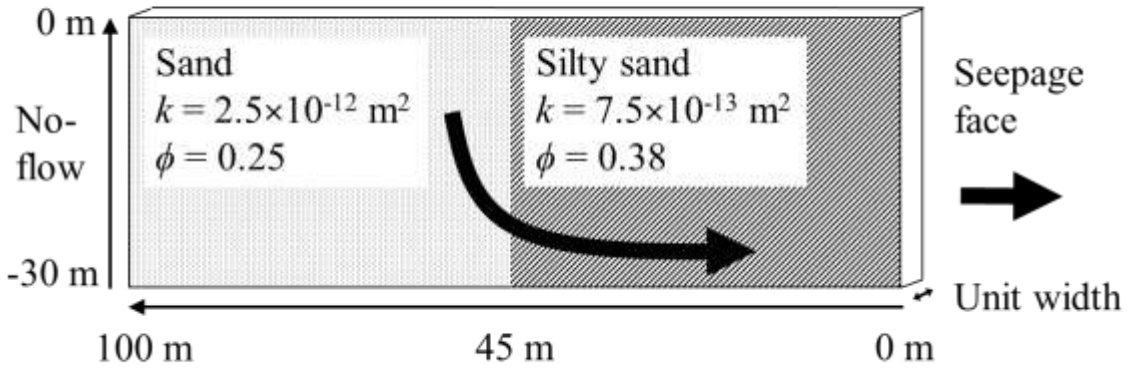
How do water flows and associated inert solute transport change in degrading permafrost?





Sinusoidally varying T

Infiltration 100 mm/yr, applied when $T \geq 0$ °C

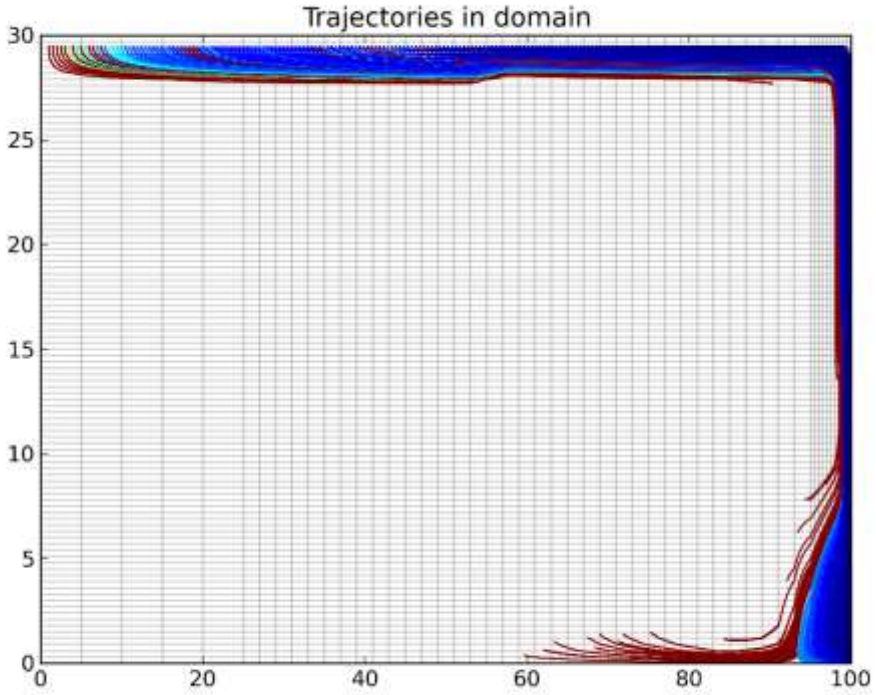


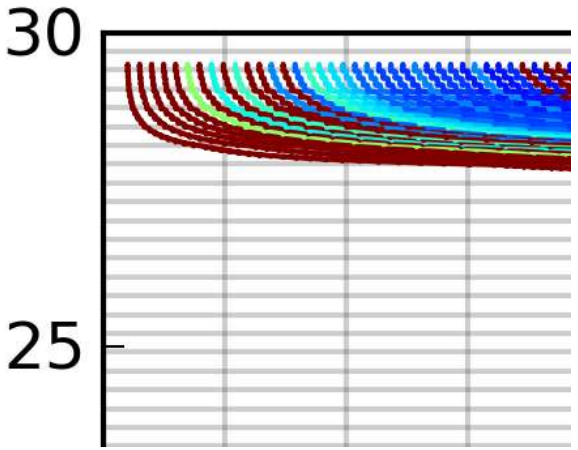
No-flow, geothermal flux 0.1 W/m^2

Painter (2011) Comp Geosciences; Frampton et al (2011), JoH; Frampton et al (2013), HJ

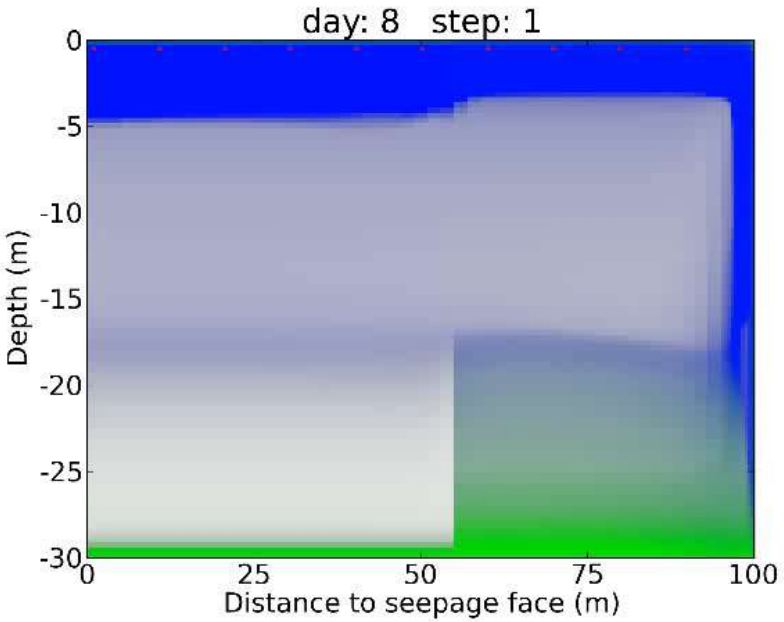
Model for solute transport

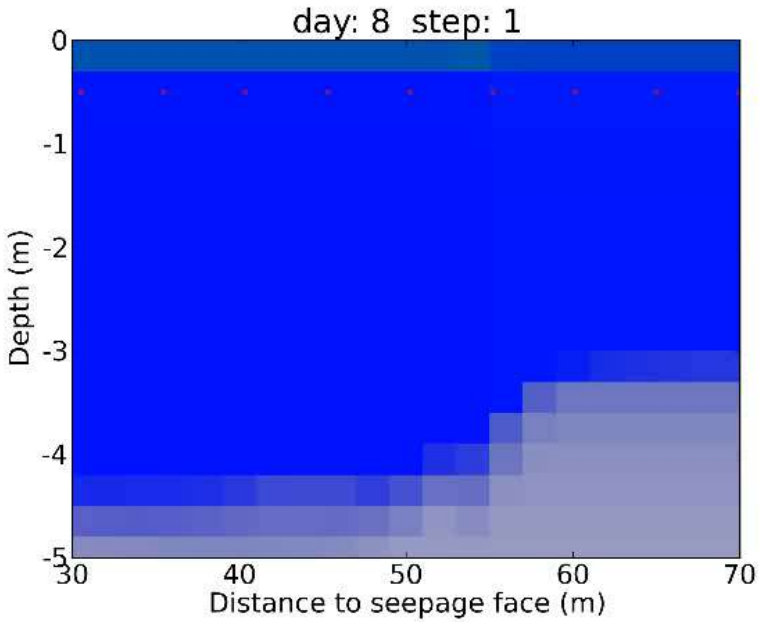
- Pollock's (1980) method for particle tracking over finite volume elements
- Based on a linear interpolation over interfacial fluxes
- Tracking performed over water fluxes
- Transient tracking, based on a given time step resolution
- Requires regular volume elements, extensions exist for irregular mesh elements



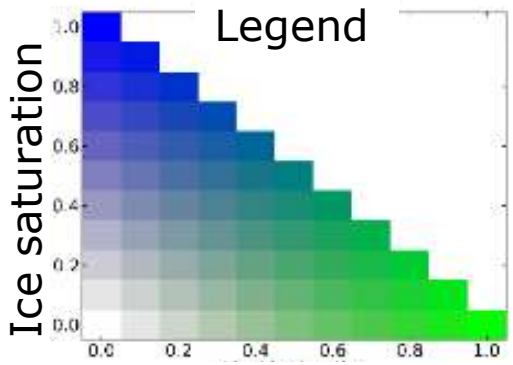


Permafrost degradation and flow pathways during 100 years simulated warming (0.05 °C/yr)



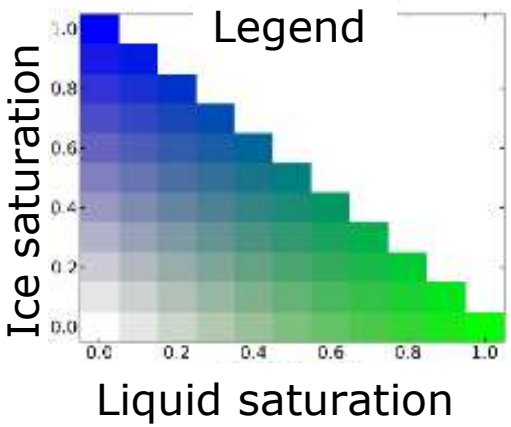


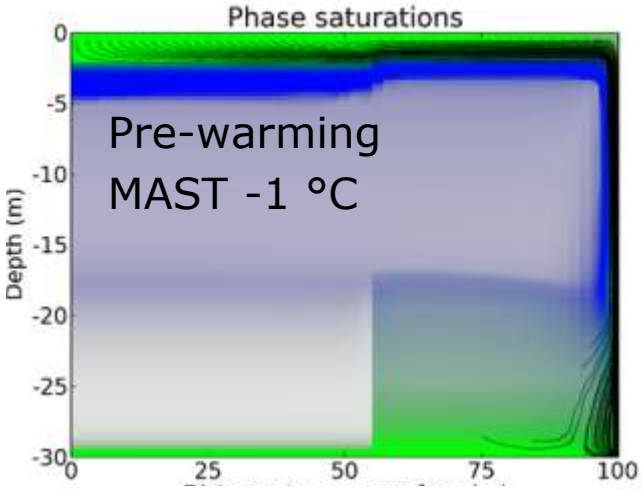
Pre warming
MAST -1 °C

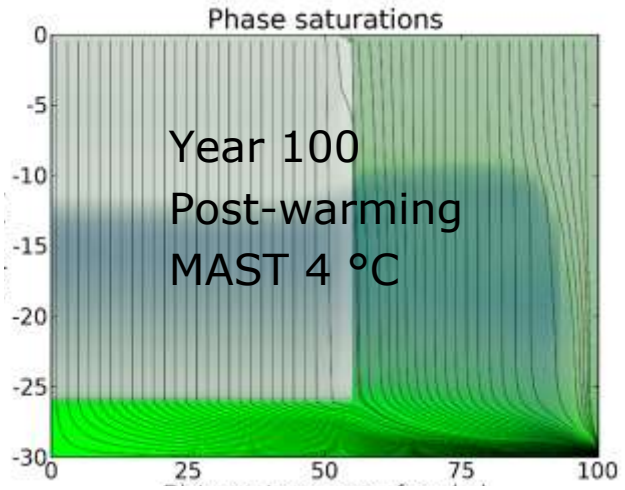


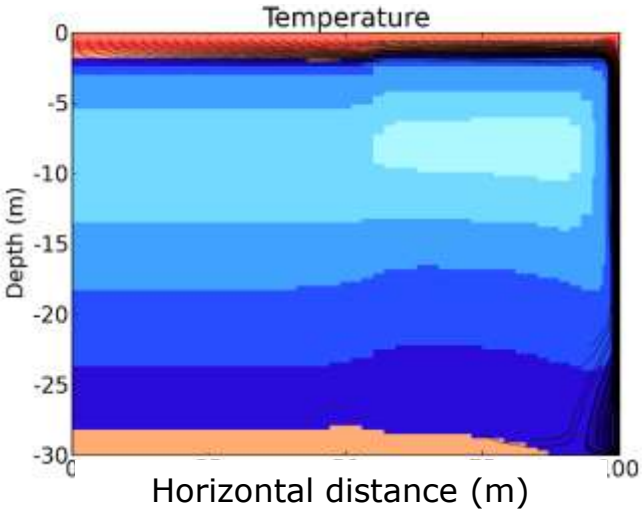
Detail of animation

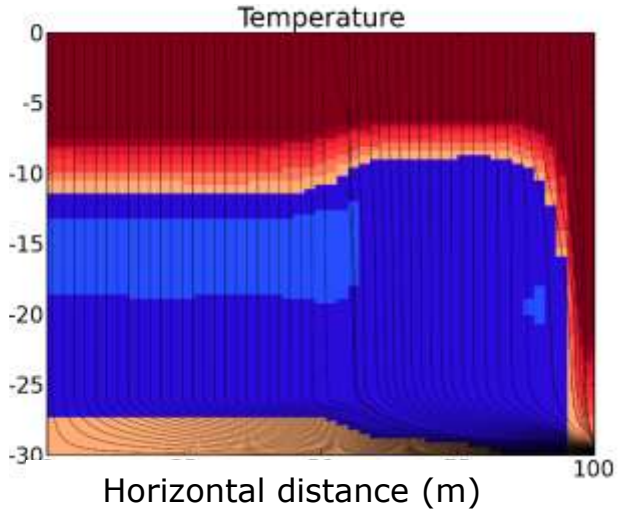
Permafrost degradation and flow pathways during 100 years simulated warming (0.05 °C/yr)





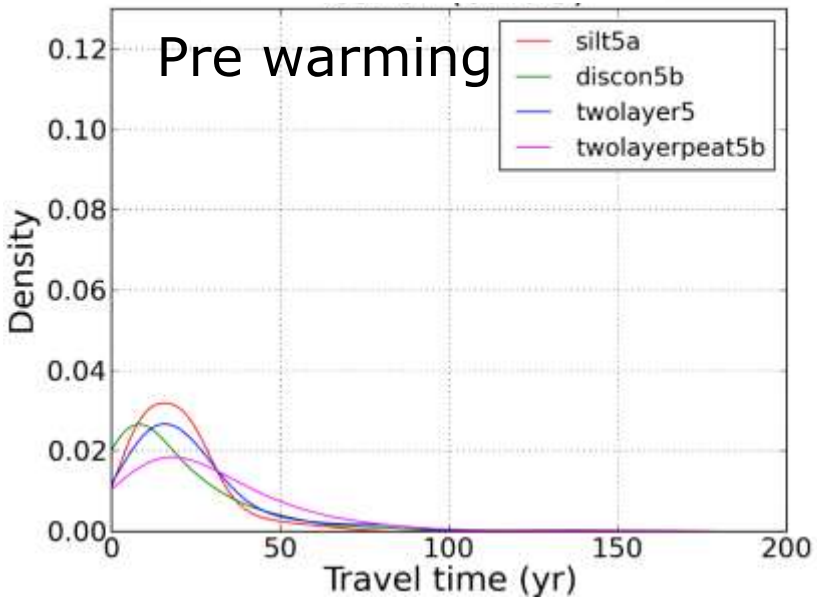


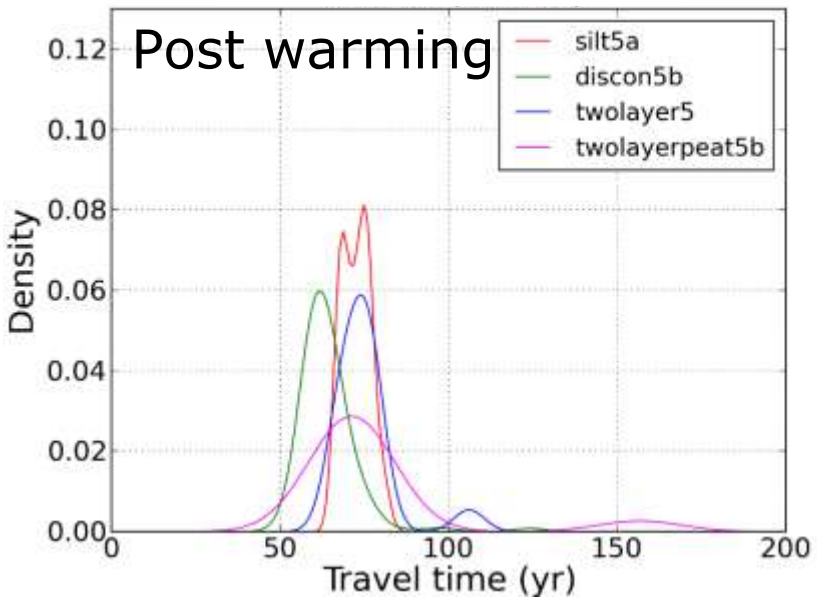




Frampton and Destouni (2015), WRR

Changes in travel times

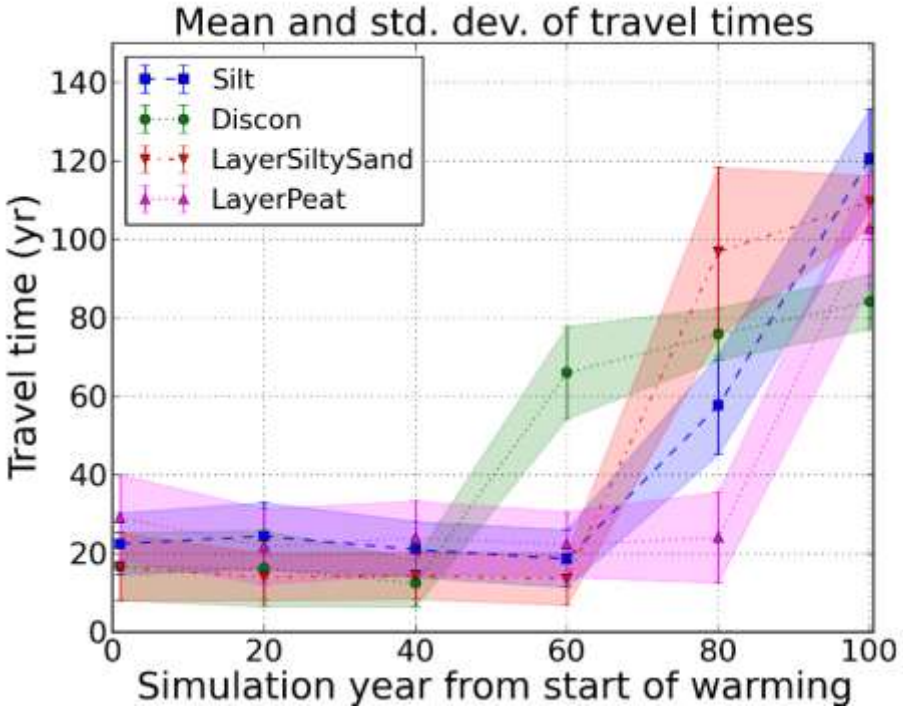




- Travel times increase with warming (peaks delayed)
- Variability also increases (greater spread in distribution)
- Slightly different behaviour between heterogeneity cases mainly due to differences in thermal properties

Frampton and Destouni (2015), WRR

Changes in travel times



- Non-linear increase in travel times as warming progresses
- Typically a 'turning point' around 40-60 years after start of warming in these simulations
- Then travel time increases more rapidly

Frampton and Destouni (2015), WRR

Discussion

- Several processes contribute to increase in travel times (Frampton and Destouni, 2015)
  - Pathway lengths increase with degrading permafrost
  - Warming induces slow vertical flow percolation rather than fast horizontal saturated groundwater flow
  - Seasonal freezing re-routes the carrier flow by cryosuction which increases travel times
  - Seasonal freezing-induced immobilization increases total travel times
- Physically-based modelling can help improve understanding of coupled nonlinear processes and bridge gaps between scales
- Further modelling includes considerations of heterogeneity (eg. Fiori, A. et al., 2010) and reactive material transport in a Lagrangian setting (Cvetkovic and Frampton, 2012; Frampton and Cvetkovic, 2011), as well as carbon transport, linking to climate feedback mechanisms

Summary & Outlook

- Northern permafrost environments contain significant amounts of frozen carbon in near-surface, much susceptible to climate change
- Subsurface solute transport travel times increase with warming
- Transport pathways also change – may significantly impact reactive transport
- Increased pathway lengths and travel times may influence carbon release to biosphere
- Carbon feedbacks to climate change involve often neglected but important hydrogeological flow and transport processes

References

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