Modelling hydro-mechanical coupling under ice sheet conditions in Greenland : preliminary results

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In2Earth

Outline

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3. Geomodelling & parameters
4. Boundary conditions
5. Hydro-mechanical modelling
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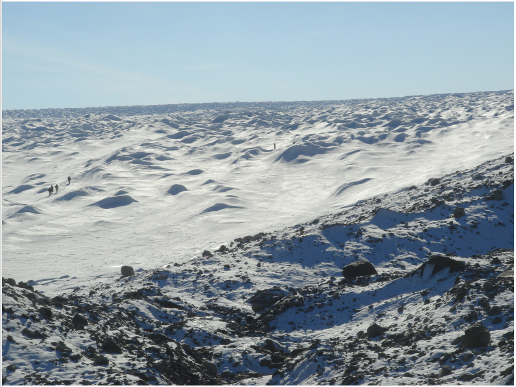
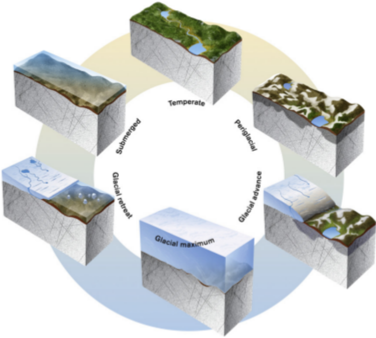
Framework & objectives

- Greenland ice sheet considered as modern analogue for conditions of future glacial periods with ice sheets in Fennoscandinavia
- Evaluation of potential impact of long-term climate change with respect to performance & safety for deep geologic repository
- Based on GAP (Greenland Analogue Project) groundwater flow modelling concept on reduced domain size
- Evaluation of impact of hydro-mechanical processes during glacial cycle



Conceptualisation

- **Geological medium**
  - 3D stochastic continuum (K-PHI) with conductive deformation zones and subglacial layer
  - 3D poroelastic medium with deterministic mechanical properties (linear, reversible & isotropic)
- **Processes**
  - Regional groundwater flow (density-driven induced by variable salinity)
  - Hydro-mechanics : coupling between rock deformation & flow (Biot model)
  - Transport for tracing of glacial meltwater
- **Ice sheet**
  - Boundary conditions taken from ice sheet model



Glaciation period with glacial advance, glacial maximum and glacial retreat (Courtesy of Selroos et al., 2012)

Phenomenology

- Groundwater flow

$$-\frac{\partial}{\partial x}\left(\frac{\rho K_x}{\mu}\frac{\partial P}{\partial x}\right)-\frac{\partial}{\partial y}\left(\frac{\rho K_y}{\mu}\frac{\partial P}{\partial y}\right)-\frac{\partial}{\partial z}\left(\frac{\rho K_z}{\mu}\left(\frac{\partial P}{\partial z}+g\left(\rho-\rho_0\right)\right)\right)=Q$$

- Deformation of rock skeleton

$$\frac{\partial}{\partial x}\left(G\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(G\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(G\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial x}\left(\left(K_d+G/3\right)\varepsilon_v\right)=F_x+b\frac{\partial P}{\partial x}$$

$$\frac{\partial}{\partial x}\left(G\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(G\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(G\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial y}\left(\left(K_d+G/3\right)\varepsilon_v\right)=F_y+b\frac{\partial P}{\partial y}$$

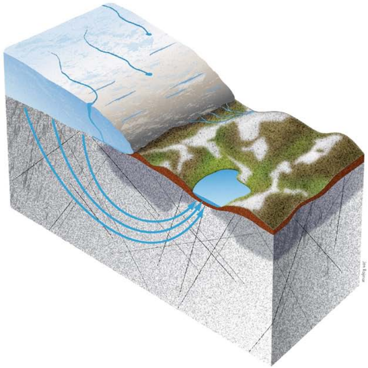
$$\frac{\partial}{\partial x}\left(G\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(G\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(G\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial z}\left(\left(K_d+G/3\right)\varepsilon_v\right)=F_z+b\frac{\partial P}{\partial z}$$

- Hydraulic conductivity - stress

$$e=e_r+e_{max}\exp(-\alpha\,\sigma_n)$$
$$K/K_0=\left(e/e_0\right)^3$$

Data from GAP & Forsmark

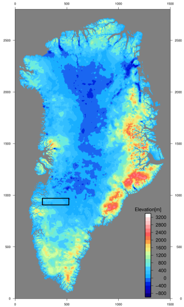
- **GAP**
  - Bed elevation (DEM)
  - Taliks (satellite data)
  - Vertical deformation zones
  - Horizontal deformation zones
- **Forsmark**
  - Hydraulic properties

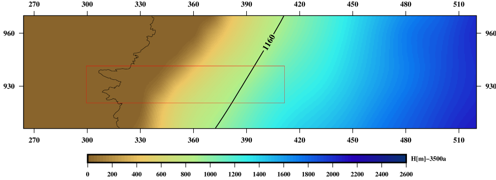


Ice sheet, groundwater flow, crystalline rocks & taliks

Model domain, location & size

- Near Kangerlussuaq, domain $\approx$ 112km x 21km x 5km
- Discretisation 500m x 500m x (25 - 50 - 100m)
- Size $\approx$ 612’000 cells





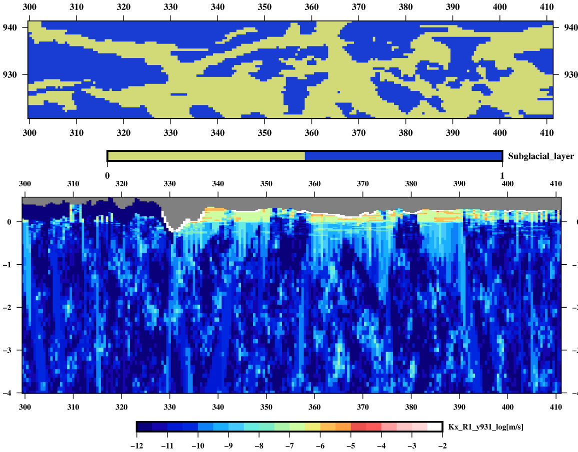
Forsmark hydraulic properties: analogue data set

Lithology	**Depth [m]**	**K [m/s]**	**St. dev. [log 10]**	**Corr. scale [m]**
Crystalline	0 - 225	$2.3 \cdot 10^{-9}$	1.44	(775, 775, 275)
Crystalline	225 - 425	$2.3 \cdot 10^{-11}$	1.07	(775, 775, 275)
Crystalline	425 - 5000	$1.1 \cdot 10^{-11}$	1.12	(775, 775, 275)

- From Forsmark rock mass domain (Follin et al., 2011)
- Exponential anisotropic variogram
- Log-normal distributions for K
- Permafrost=10^{-12} m/s with thickness=350m
- PHI=f(K)

Stochastics: K & subglacial layer

- Subglacial layer (stochastic geometry) : hydraulic conductivity (10^{-2}; 10^{-3}m/s)
- Stochastic simulation of hydraulic conductivity with subglacial layer & permafrost (thickness=350m)

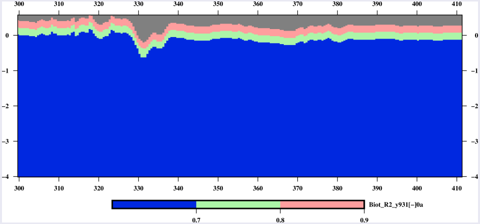


Hydro-mechanical parameters

Site	Shear modulus [GPa]	Drained bulk modulus [GPa]	Fluid bulk modulus [Pa]
Forsmark	28.2	44.9	$2 \cdot 10^9$

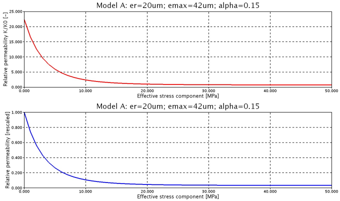
with Young's modulus=70 GPa; Poisson's ratio=0.24

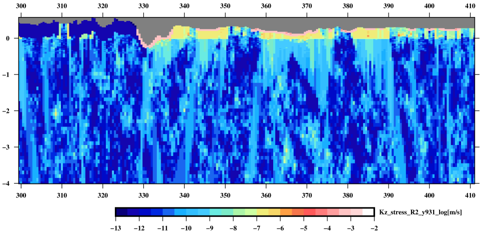
Depth [m]	Biot coefficient [-]
0 - 200	0.9
200 - 400	0.8
below 400	0.7

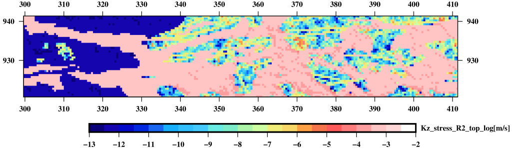


Hydraulic conductivity - stress relation

- **Anisotropic hydraulic conductivity**
  - Effective normal stress in three principal effective stress directions
  - $K(stress) = f_{model\,A}(stress) \Rightarrow$ Forsmark exponential model A (Hökmark et al. 2010)
  - $K(faceX) = f_{model\,A}[mean(\sigma_{xx}(cellX_i), \sigma_{xx}(cellX_{i+1}))]$; $idem\ for\ K(faceY)\ \&\ K(faceZ)$

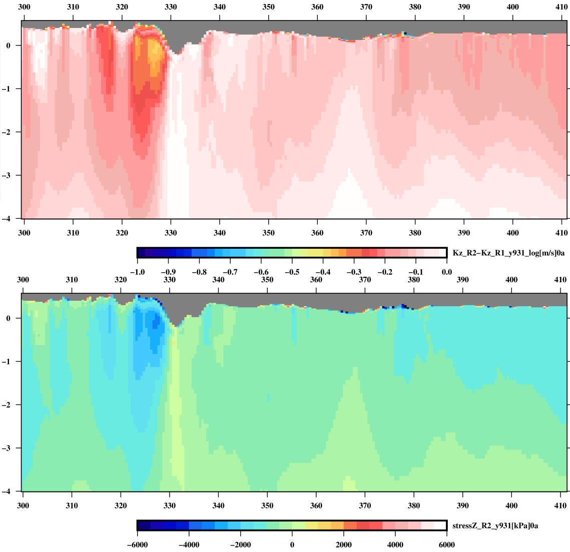






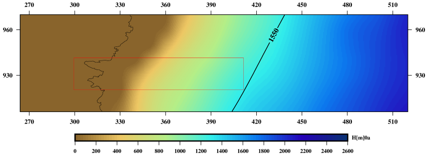
Hydraulic conductivity - stress relation (2)

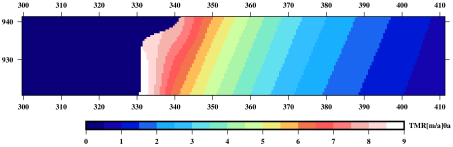
- $K_z(case\,2) - K_z(case\,1)$
- σ_{zz}: effective normal stress influence on hydraulic conductivity



Ice sheet model: boundary conditions

- **Ice sheet model for glacial cycle -115 to 0ka**
  - SICOPOLIS (Simulation COde for POLythermal Ice Sheets) used by Stockholm University
  - Boundary conditions for hydro-mechanical model
  - Ice thickness & total meltwater rate at 0ka before 2000 AD (SICOPOLIS data – lhs92)





Boundary conditions: case 2

- **Flow**

  $Surface\, under\, ice\, (mixed\, BC):$ *below ELA, total meltwater rate constrained by ice thickness*

  $Surface\, free\, of\, ice\, (Dirichlet): \; P = \rho g\, z;\; or\; P = \rho g\, z_{talik}$

  $West\, (Dirichlet): \; P = \rho g\, z_{mean}$

  $Elsewhere\, (Neumann):$ *no flow conditions*

- **Geomechanics**

  $Surface\, under\, ice\, (Neumann): \; \sigma_{zz} = -\rho g\, z - \rho_{ice} g\, h_{ice}$

  $Surface\, free\, of\, ice\, (Neumann): \sigma_{zz} = -\rho g\, z;\; or\; \sigma_{zz} = -\rho g\, z_{talik}$

  $Surface\, (Neumann): \sigma_{zx} = \sigma_{zy} = 0$

  $West\, (Neumann): \; \sigma_{zz} = -\rho g\, z_{mean}$

  $West - East\, (geometry): \; \frac{du}{dx} = 0;\; \frac{dv}{dy} = 0;\; \frac{dw}{dz} = 0;\; u = v = w = 0$

  $North - South\, (Neumann): \; \frac{du}{dx} = 0;\; \frac{dv}{dy} = 0;\; \frac{dw}{dz} = 0$

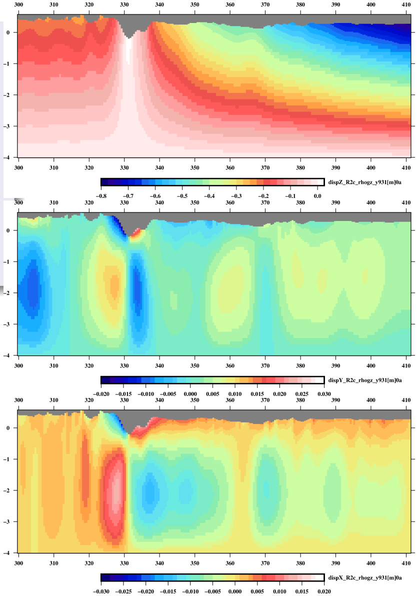
  $Bottom\, (Dirichlet): \; u = v = w = 0$

Case 2c

- **Process**
  - Geomechanics
  - Steady state conditions
- **Ice sheet**
  - Present day conditions (0ka before 2000 AD)

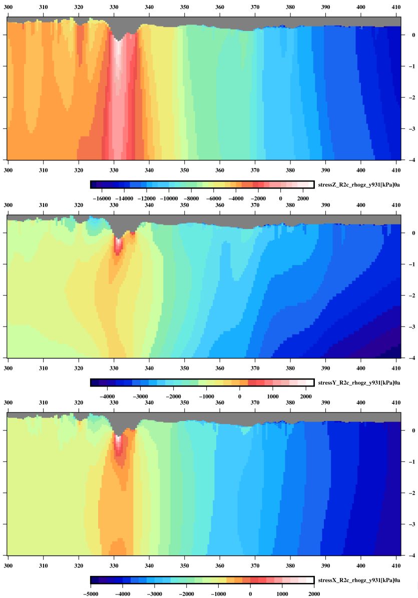
Case 2c: displacement components

- w=displacement in Z direction (mostly negative due to compression from ice sheet)
- v=displacement in Y direction
- u=displacement in X direction
- Values comparable to Case M7 (Ferry, 2017) in 3D steady state



Case 2c: normal stress components

- σ_{zz}(mostly negative due to compression from ice sheet)
- σ_{yy}
- σ_{xx}
- Highest (negative) stress values encountered underneath the ice sheet towards the east in relation to increasing ice thickness ; highest (positive) stress values in relation to trough topography (near X=330km)

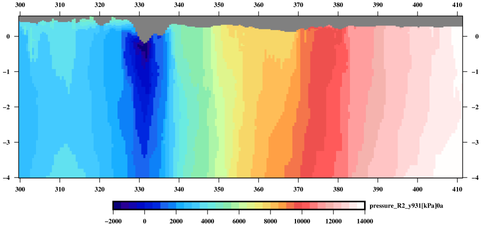


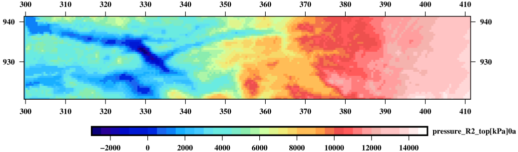
Case 2

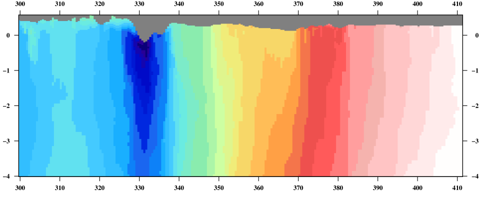
- **Processes**
    - Hydro-mechanical coupling (with improved convergence)
    - Steady state conditions
- **Ice sheet**
    - Present day conditions (0ka before 2000 AD)

Case 2: dynamic fluid pressure

- Case 2 with hydro-mechanics (⇒ hydraulic conductivity reduction induced by stress)
- Case 1 with flow

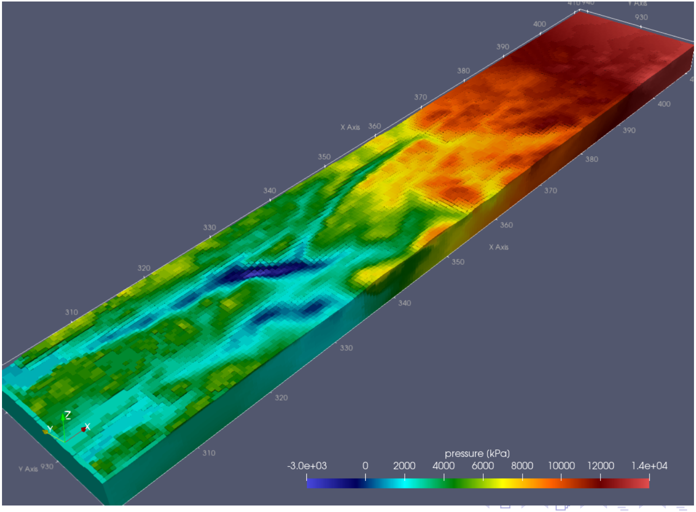






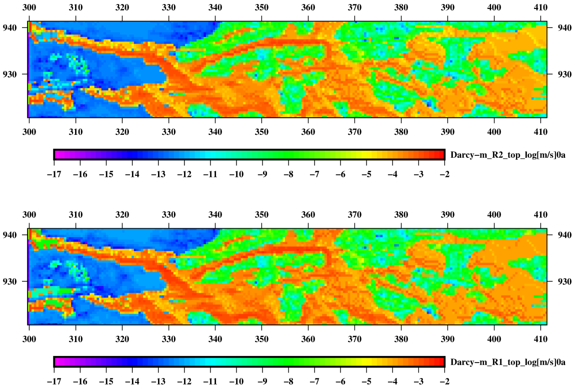
Case 2: dynamic fluid pressure (2)

- Case 2 with hydro-mechanics ⇒ effects of ice sheet & topography



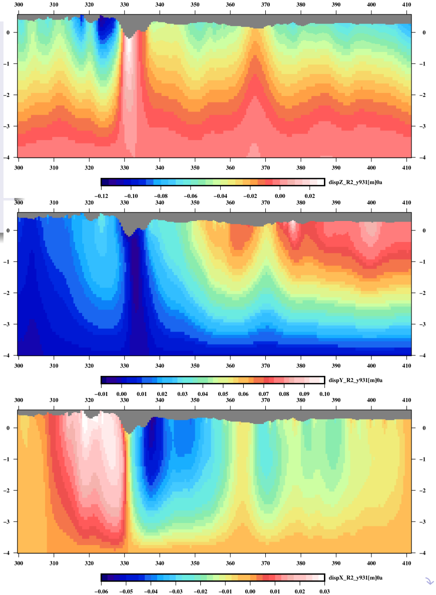
Case 2 : Darcy velocity module

- Case 2 with hydro-mechanics : Darcy velocity module decreases in front of the ice sheet (stronger towards West) + effect of hydraulic conductivity reduction induced by stress
- Case 1 with flow : sligthy higher Darcy velocity module



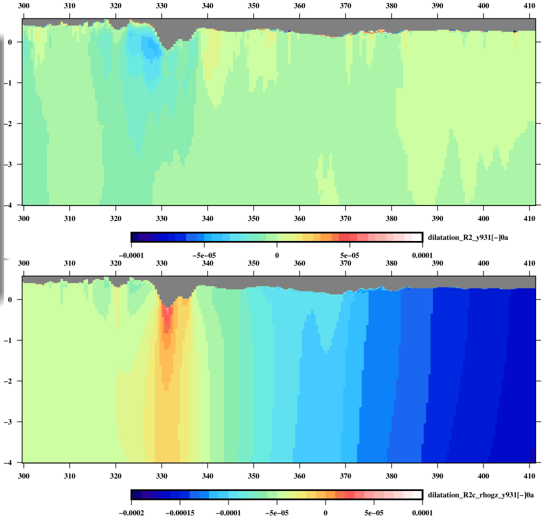
Case 2 : displacement components

- w=displacement in Z direction (mostly negative due to compression from ice sheet ; except at depth & in trough)
- v=displacement in Y direction
- u=displacement in X direction



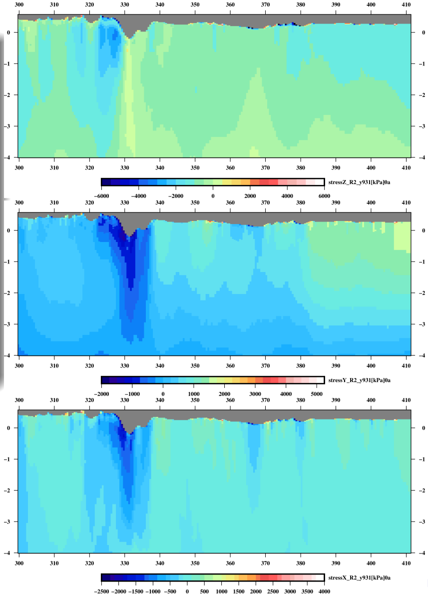
Case 2: volumetric strain (dilatation)

- Case 2 (reduction due to water pressure)
- Case 2c (solely geomechanic: highest volumetric strain values observed underneath the ice sheet)



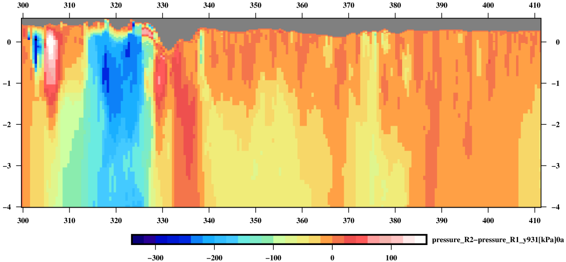
Case 2: effective normal stress components

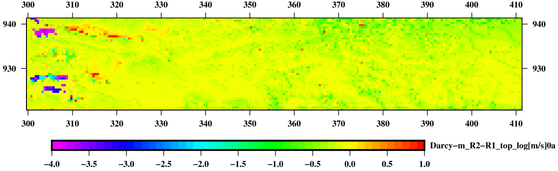
- σ_{zz}: effect of increasing ice sheet thickness toward east (effect of stress dampened by water pressure governed by ice thickness; cf. Case 2c)
- σ_{yy}: largest topographic effect of glacial trough
- σ_{xx}



Effects of Geomechanics (1)

- $Pressure\,(case\,2) - Pressure\,(case\,1)$
  - Maximum differences located in front of ice sheet (towards the west)
- $Velocity\,(case\,2) - Velocity\,(case\,1)$
  - Darcy velocity module differences in relation to hydraulic conductivity reduction induced by stress

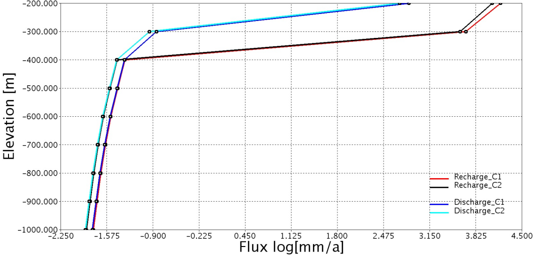




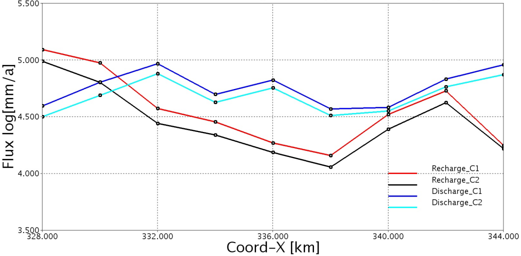
Effects of Geomechanics (2)

- *Horizontal planes*
  - Solely minor flux differences at high elevation due to hydro-mechanical coupling
- *Vertical planes – near ice margin*
  - Flux reduction due to permeability change in relation to hydro-mechanical coupling (about 20 %)

CASES 2 & 1: horizontal planes



CASES 2 & 1: vertical planes (near ice margin)



Results

- **Parameters & boundary conditions**
  - Stochastic hydraulic conductivity with deformation zones, subglacial layer and permafrost with constant thickness
  - Variation of hydraulic conductivity due to stress field up to one order of magnitude decrease
  - Testing & selection of adapted boundary conditions for geomechanics
- **Simulation under steady state conditions**
  - Simulation of hydro-mechanical coupling: improvement of results convergence
  - Centimetric order of magnitude for displacement (maximum to about 0.1 m); largest range of values for displacement W
  - Effective stress governed by ice sheet thickness and topography ; likely dominance of stress component σ_{zz}
  - Pressure field impacted by hydro-mechanical coupling (range variation of about 500 kPa)
  - Reduction in fluxes due to hydro-mechanical coupling to about 20 %

Recommendations & next

- Steady cases (with infinite time scale) likely provide smoothing effects of the results leading to a potential underestimation of their associated impact variability
- Impact of density driven flow in relation to hydro-mechanical coupling likely to increase variability of performance measures
- Investigation of alternative models for hydraulic conductivity - stress (e.g. with K-increase)
- Sensitivity of Biot coefficient (in terms of values & zonality)
- **Case 3** : transient reference case, groundwater flow with variable density (glaciation scenario : SICOPOLIS data – lhs92)
- **Case 4** : transient case, hydromechanics with variable density (glaciation scenario : SICOPOLIS data – lhs92)
- **Case 5** : transient case, hydromechanics with variable density (glaciation scenario : SICOPOLIS data – extreme case)

To be followed...