Effect of en-glacial water on ice sheet temperatures in a warming climate - a model approach

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Each summer, significant amount of melt is generated in the ablation zones of large glaciers and ice sheets. This melt does not run off on the surface of the glacier or ice sheet. In fact a significant fraction enters the glacier and flows through en-glacial and sub-glacial hydrologic systems. Correspondingly, the en-glacial and sub-glacial hydrologic systems are brought to a temperature close to the pressure melting point of ice. The thermal influence of these hydrologic processes is seldom incorporated in heat transfer models for glaciers and ice sheets. In a warming climate, as melt water generation is amplified, en-glacial and sub-glacial hydrologic processes can influence the thermal dynamics of an ice sheet significantly, a feedback which is not included in current models. Although the role of refreezing melt water in the firn is often accounted for to explain warmer near-surface temperatures, the role of melt water flow within a glacier is not considered in ice sheet models. We propose a simple parameterization of the influence of en-glacial and sub-glacial hydrology on the thermal dynamics of ice sheets, in the form of a dual-column model. Our model modifies the classical column model for temperature variations in ice sheets by introducing an interaction with an en-glacial column, where the temperature is increased to the melting point during the melt season, and winter-time refreezing is dependent on latent heat. A cryo-hydraulic heat exchange coefficient ς is definedwhich quantifies the interaction. The parameter ς is related to kappa/R^2 , where R is the characteristic spacing between en-glacial passages and kappa is the heat diffusivity.

FIELD SITE IN WESTERN GREENLAND:

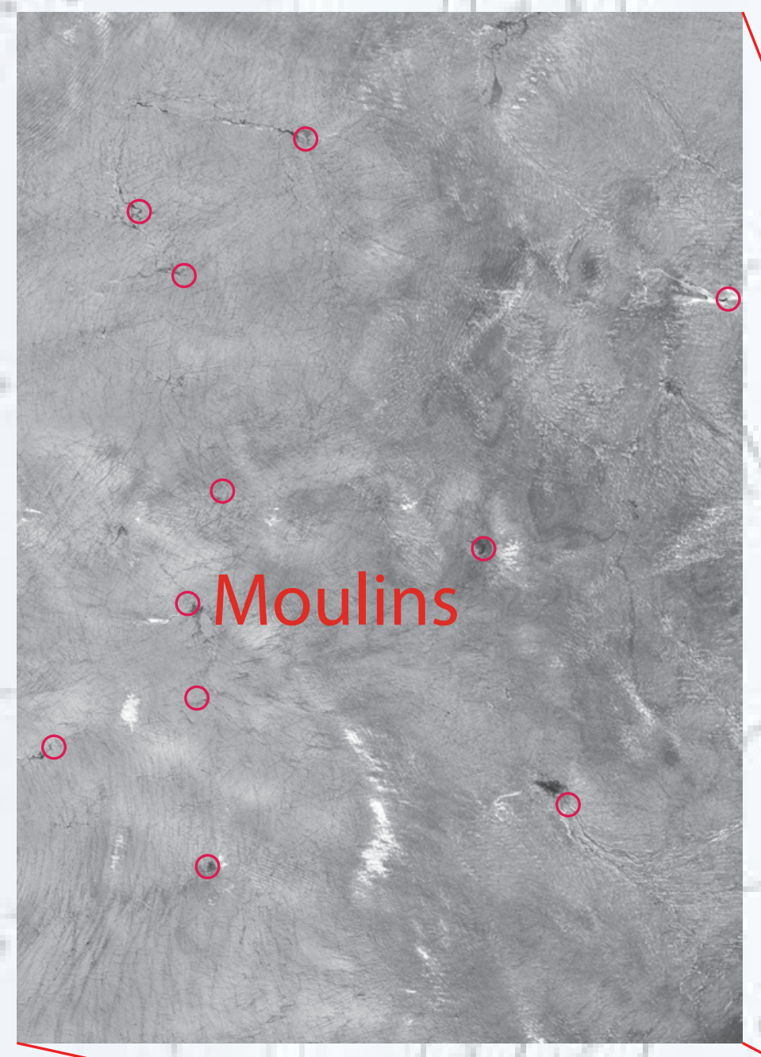


Figure 2: A worldview image of Sermeq Avannarleq in Western Greenland showing the lakes, channels and moulins for July 15th, 2009.

The University of Colorado and CIRES have an Arctic research station (Swiss Camp) in Western Greenland at 59.5732 N 49.3952 W and at an altitude of1149m. In the Jakobshavn area we have a number of weather stations which have been recording temperature, wind, radiation and snow temperature for more than 10 years. Thomsen et al. (1992) had a field campaign during which the deep ice temperature profile was measured.

An area with a large density of active moulins is located to the North of our main study area. We have visited and studied these moulins for the past two years.We are able to study the geometry of the moulins. We intend to use this data as initial condition for our model.

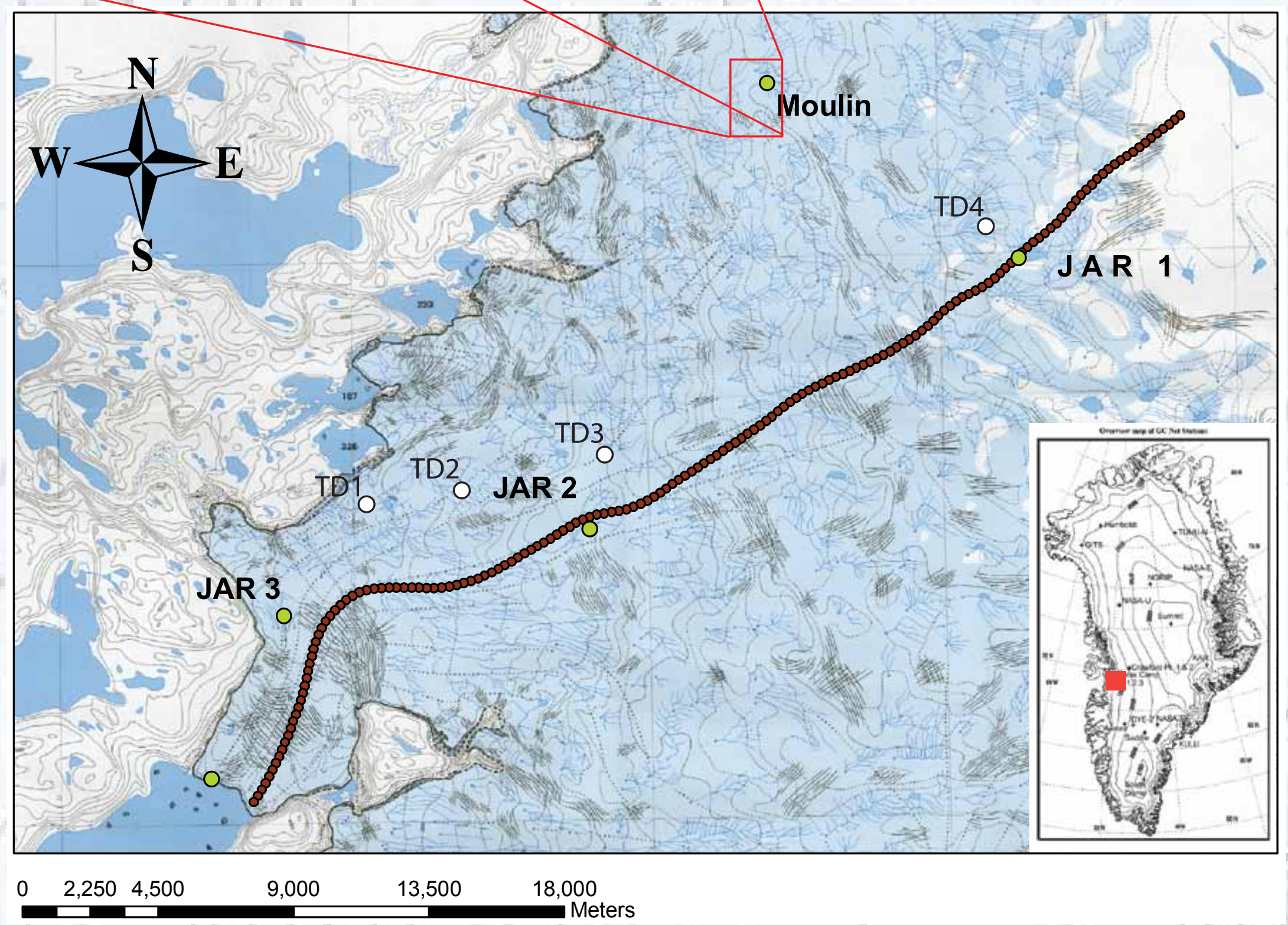
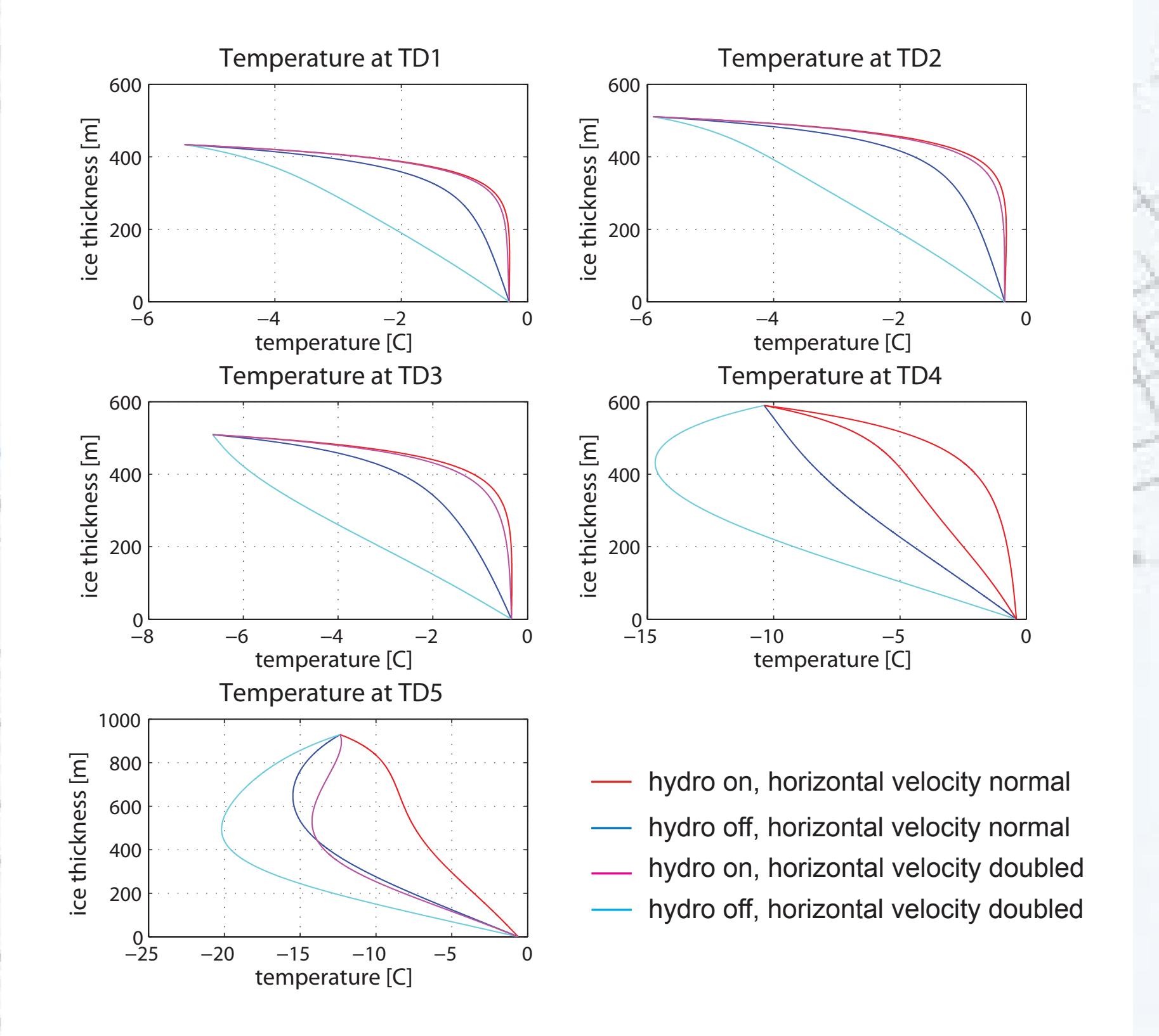


Figure 1: A section of the Thomsen et al. 1988 map for Sermeq Avannarleq Glacier, north of Jakobshavn Isbrae. The Automatic Weather Stations JAR1-3, the Moulin, the borehole locactions TD1-4 and the extracted central flow line for the Glacier are shown. The central flow line was used to simulate the influence of the en-glacial water on the ice temperature.

PRELIMINARY RESULTS:

Our model simulations show that a small residual amount of water (about 0.5%) can influence the background ice temperature significantly. The background ice temperature increases and approaches a steady state after 7 years in spin-up simulations. After this spin-up phase, the cryo-hydraulic column contains some amount of water and remains temperate throughout the year. As a result, the background ice column is significantly warmed by heat exchange with the cryo-hydraulic column.

The steady-state temperatures in the background ice column are very sensitive to the cryo-hydraulic exchange coefficient. However, they are less sensitive to the amount of remaining water in the cryo-hydraulic column during the winter. In both columns, the effects of cold wintertime air temperatures are mostly reflected in the near-surface background ice temperatures. Refreezing and cooling occurs in the near-surface portions of the cryo-hydraulic column.



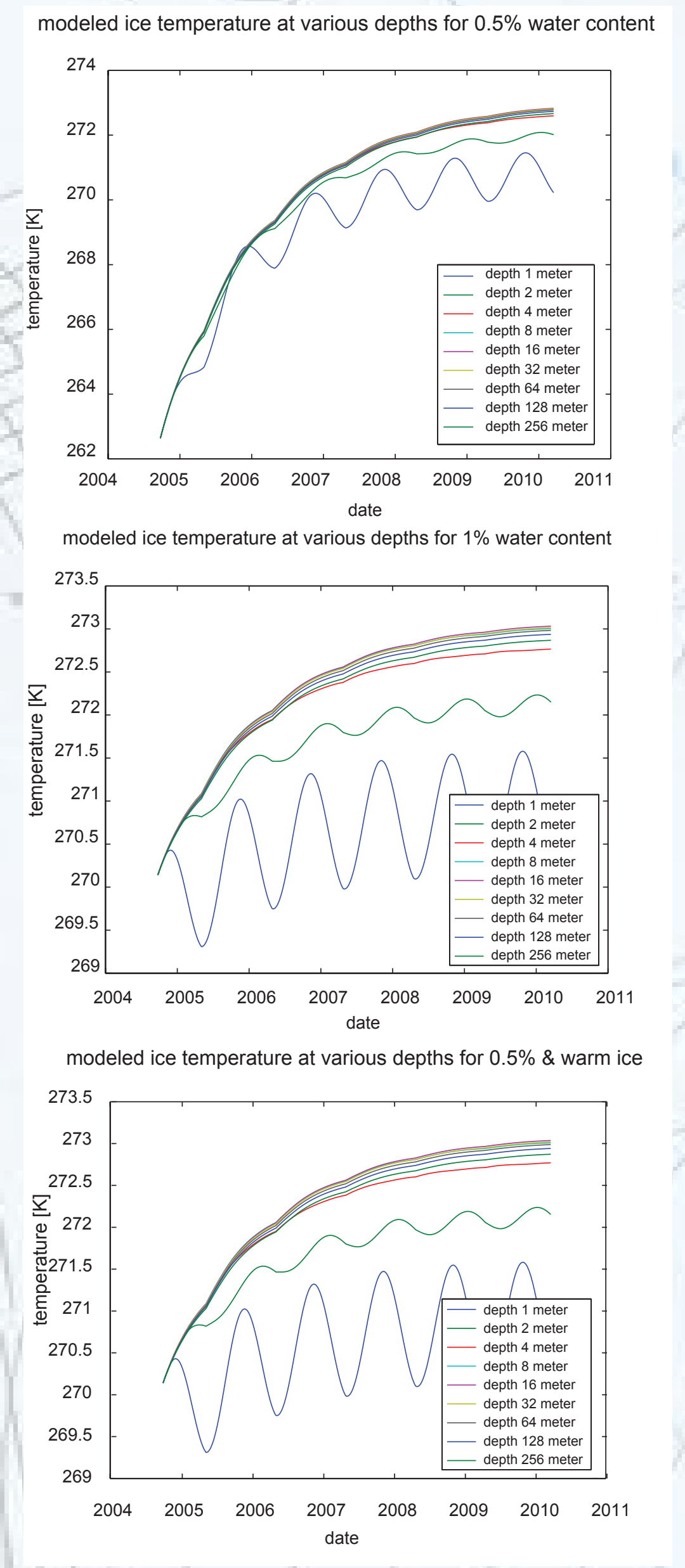
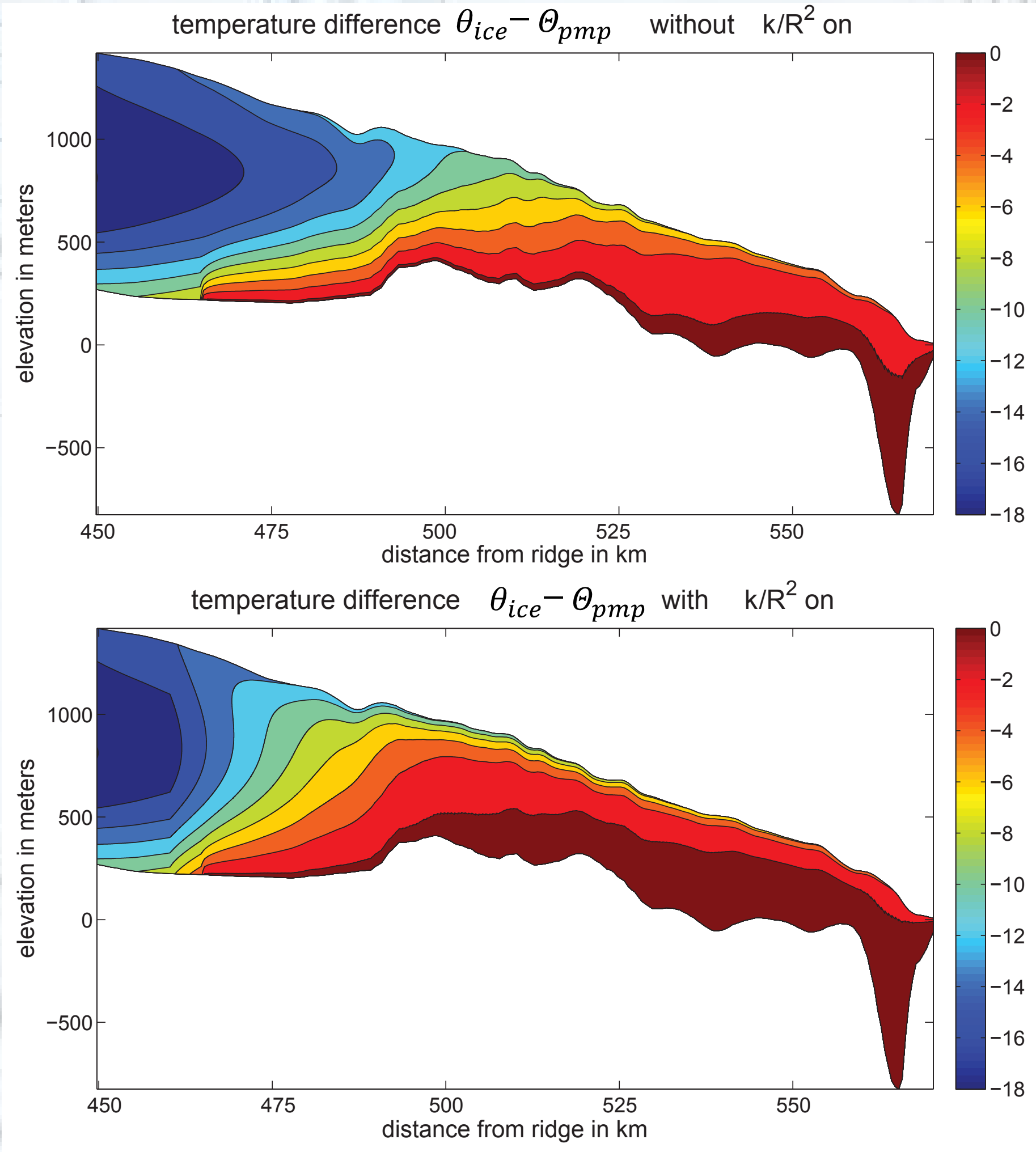


Figure 3: (top) The influence of different velocities and of the en-glacial hydraulic system on the ice temperature in the ablation are shown. The curves in red and blue are at observed horizontal velocity, the curves in magenta and cyan have a doubled velocity componant.
(right): The one dimensional model was used to simulate the influence of the hydraulic system over time. The initial water content and initial ice temperature have no influence on the outcome: The ice sheet reaches a steady temperature profile after approx. 7 years in a stable climate.

ALONG FLOW MODEL:

The Funk et al. (1995) approach is used in order to simulate the en-glacial temperature along the central flow line of Sermeq Avannarleq. We modified their approach by including the cryo-hydraulic heat exchange term and producing a parallel temperature-enthalpy model. The cryo-hydraulic heat exchange term depends on the density of the en-glacial hydraulic network, reflected in the spacing R. A channel spacing of 500m is assumed at the equilibrium line and decreases linearly with decreasing elevation to 25m spacing at the margin.

It is important to note that after a spin-up phase, the ice column temperatures do not show a significant seasonality despite the seasonality inherent in the cryo-hydraulic column. This result is consistent with the fact that englacial temperatures seldom exhibit a seasonal signal at greater depths from the surface. Yet, the warming influence of the cryo-hydraulic exchange term may potentially explain warmer than expected englacial temperatures in the upper portions of the ablation zone.



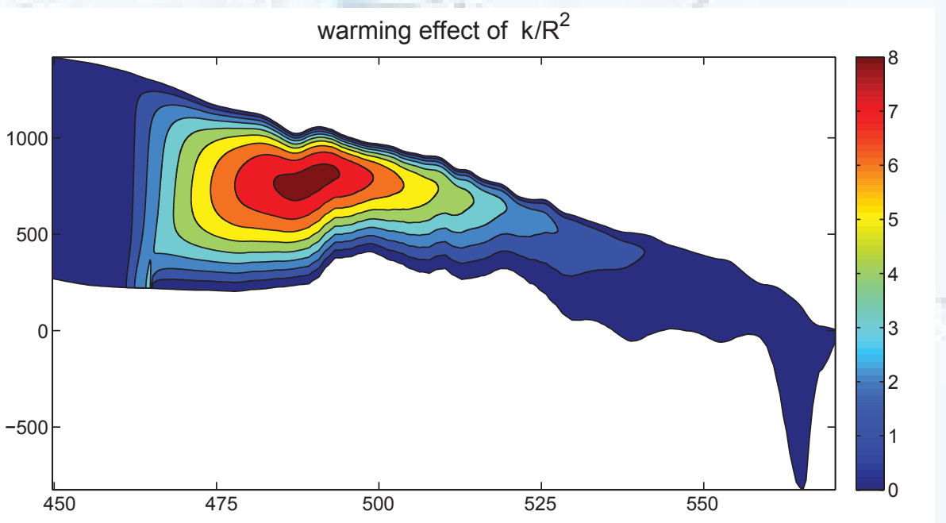


Figure 4: (left, top) The temperature difference between the calculated ice temperature and the pressure melting point temperature for the ablation zone. The dark red area is the temperate ice. The ice is temperate at larger depths due to the geothermal heat and the shear stress. Closer to the surface the cold horizontal advection and the heat conduction from the atmosphere are dominant. (left) The cryo-hydraulic term warms the ice in the central depths. The climate at the surface keeps the ice cold in the near surface area.
(top) The temperature difference between the two runs indicates that the cryo-hydraulic term is especially influental in the area close to the ELA.

DUAL COLUMN MODEL - IDEA:

Figure 2: Moulin in Western Greenland (Picture: Konrad Steffen 2007)

1) A dual column concept is introduced, involving two interacting columns representing “background ice” (that is already considered in the conventional column model) and a second (cryo-hydraulic) column that is within the “influence region” of a moulin or en-glacial hydraulic system
2) In the cryo-hydraulic column, the temperature is assumed to be raised to the pressure melting point during the melt season. At the end of the melt season it is assumed to contain a small fraction of liquid water.
3) An interaction or coupling term is included in the heat transport equation for both columns to allow for heat exchange between them. During the summer the cryo-hydraulic column warms the background ice, and during the winter the water content remaining in it the releases latent heat as it cools below the freezing point, moderating winter-time cooling in both columns.
4) We include a snow cover that insulates the ice from the atmosphere.

DUAL COLUMN MODEL - Equations:

The modified heat transfer eqaution is:

$$\frac{\partial(\rho_{ice} * c_{p_{ice}} * \Theta_{ice})}{\partial t} - \frac{\partial^2(k_{ice} * \Theta_{ice})}{\partial^2 z} + \frac{\partial(\rho_{ice} * c_{p_{ice}} * u * \Theta_{ice})}{\partial x} + \frac{\partial(\rho_{ice} * c_{p_{ice}} * w * \Theta_{ice})}{\partial z} = Q + \frac{k_{ice}}{R^2}(\theta_m - \theta_{ice})$$

The equation used to calculate the temperature and energy change in the column influence by the moulin are:

$\Theta_m = \Theta_{pmp}$ for summer and

$$\frac{\partial(\overline{\rho_m H})}{\partial t} - \frac{\partial}{\partial z}\left(\frac{\partial(\overline{k_m} * \Theta_m)}{\partial z}\right) = \frac{k_{ice}}{R^2}(\theta_{ice} - \theta_m)$$

for the winter.

Θ	temperature	u	horizontal advection
ρ	density	Q	internal energy
c_p	heat capacity	H	enthalpy
k	heat conduction	R	conduit spacing
w	vertical advection	x,z	horiz. & vert. distance

Table 1: The definitions of all variables used in this presentation are listed in this table.

Subscript “ice” refers to the background ice column and the subscript “m” refers to the variables of “moulin influence” column.
“pmp” refers to the pressure melting point.

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