Effect of fast dynamics on the centennial mass loss of the Greenland Ice Sheet

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Abstract

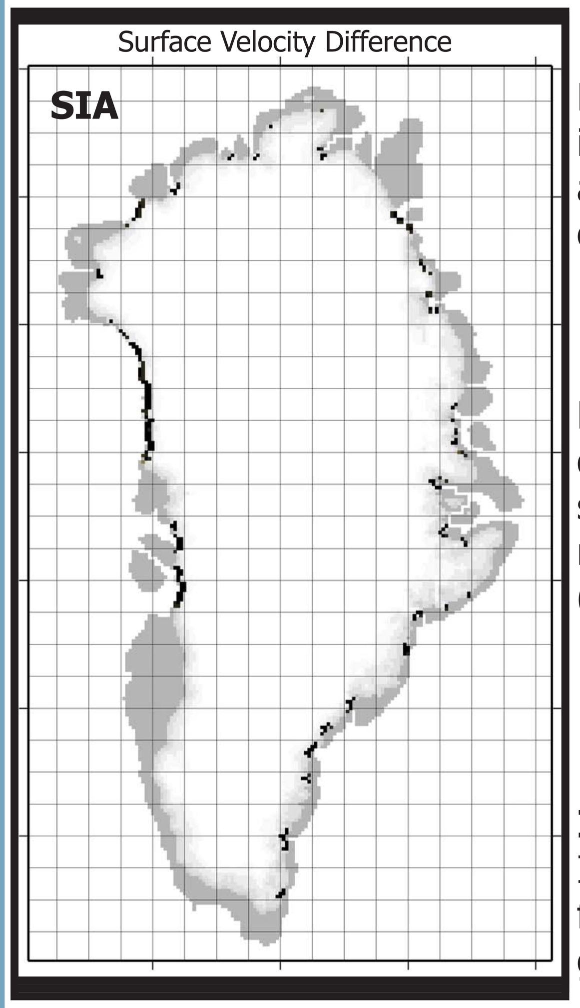
Observations have revealed high-frequency fluctuations in outlet glacier discharge around the margin of the Greenland Ice Sheet (GIS). It has been estimated that the net effect of these fluctuations may have contributed up to half of the increased mass loss of the GIS during the last decade. If such marginal accelerations are to have an appreciable effect on total mass loss on a century time scale, a fast mechanism to transmit such perturbations inland is required. Almost instantaneous transmission of marginal perturbations is effectuated by gradients in longitudinal stresses and facilitated by high basal sliding. The effectiveness of these mechanisms on the transient response of the GIS however remains controversial because of potentially strong feedbacks from basal sliding (driving stress) and surface mass balance (hypsometry). Here we use a three-dimensional thermo-mechanically coupled model of the Greenland ice sheet to assess the effects of marginal perturbations on volume changes on centennial time scales. The model is designed to allow for three different ice-dynamic cores using different approximations to the force balance. The reference model is based on the shallow ice approximation (SIA) for both ice deformation and basal sliding. A second version confines longitudinal stress gradients to the basal sliding layer using the shallow shelf approximation (SSA). The third model version relies on a higher-order Blatter/Pattyn type of core that includes longitudinal stress gradients and lateral drag throughout the entire ice column. In terms of complexity, the three models allow for gradually more dynamic feedbacks and together form a feasible tool to study the potential effect of fast stress transmission.

Idealised experiments were conducted to compare the time-dependent response of all three model versions forced by imposed accelerations at the marine calving front. In model versions allowing for longitudinal stress transmission, there is an instantaneous speedup of upstream ice some distance inland. However the total ice volume loss after 100 years differs only slightly from the SIA model as most of the response is due to common changes in driving stress that are moreover strongly dampened. If at all, the inclusion of fast dynamics in the full higher-order model even serves as a negative feedback mechanism, as it allows for a faster attenuation of the initial perturbation. These experimental results are robust starting from different initial conditions, using horizontal grid sizes between 5 and 20 km, and using different step changes in the ice discharge flux.

Experimental Setup

Shallow Ice Approximation
- local solution to force balance
- immediate stress transmission is not accounted for

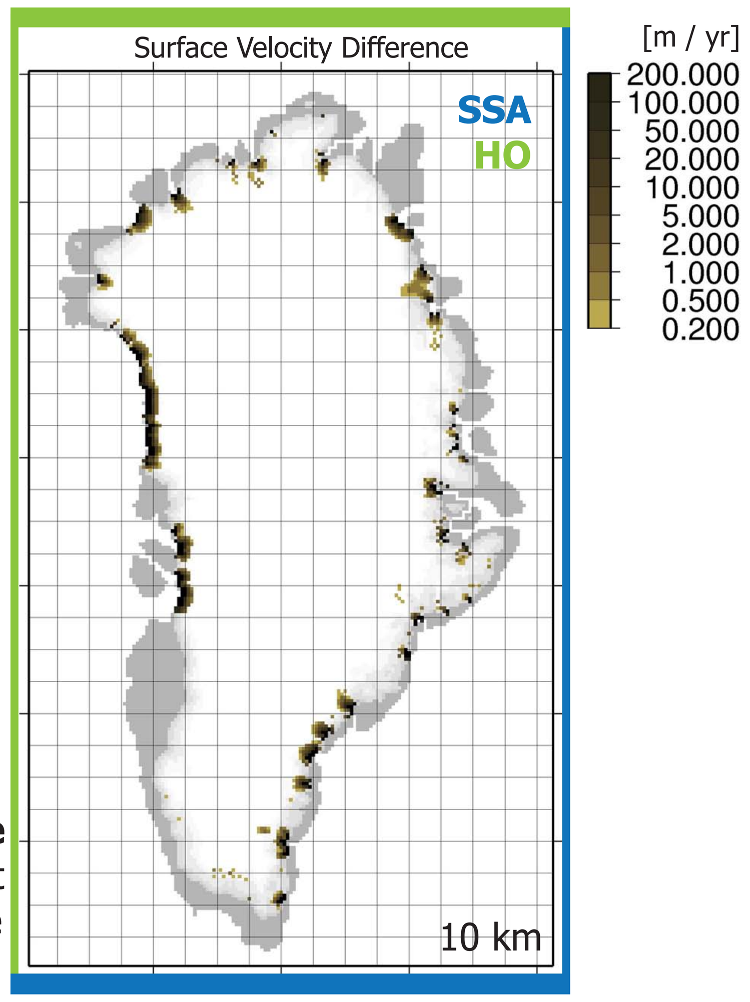
Shallow Shelf & Higher-order Approximation
- velocity field affected by surrounding area
- lateral shear and longitudinal stress gradients allow fast signal transmission



Idea
Marine forcing induces marginal acceleration of outlet glaciers

Setup
Mimic forcing by doubling of basal sliding at marine margin (forcing imposed by SIA dynamics)

Initial Response
Immediate effect for an identical ice geometry

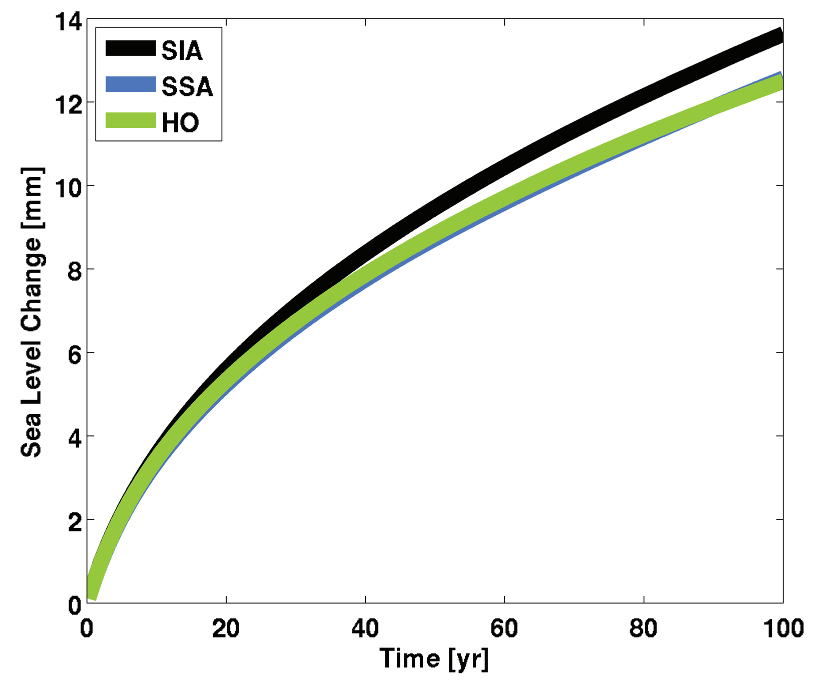


➔ initial acceleration confined to periphery

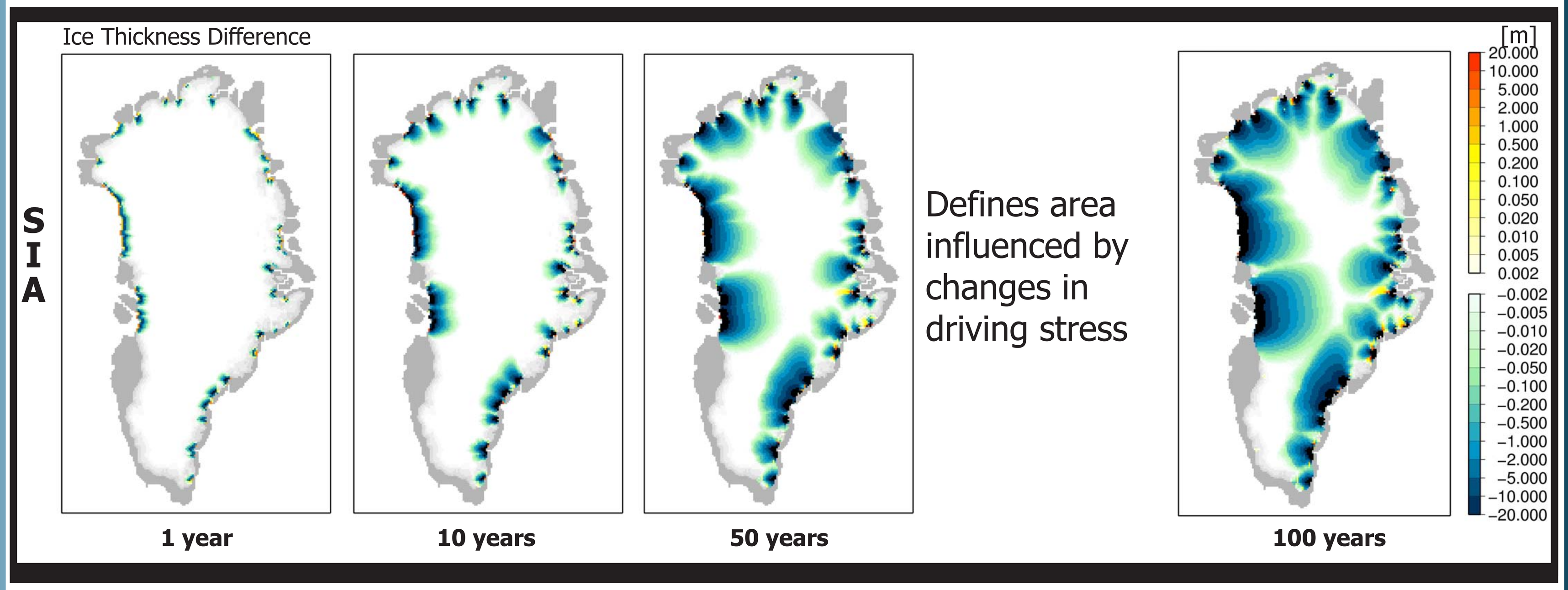
marginal acceleration affects surroundings ➔ allowing for extended drainage of interior

Can fast stress transmission alter the centennial response of large ice sheets ?

In General
- marginal flow acceleration increases GIS mass loss
- dynamic discharge for speed-up of all outlet glaciers limited by inland drainage
- centimeter scale sea level contribution by extensive outlet speed-up



Dynamic Influence
- fast stress transmission reduces dynamic discharge by ~10%
- both models with enhanced dynamics give comparable centennial mass loss
- cross-over indicates different response in SSA and HO model

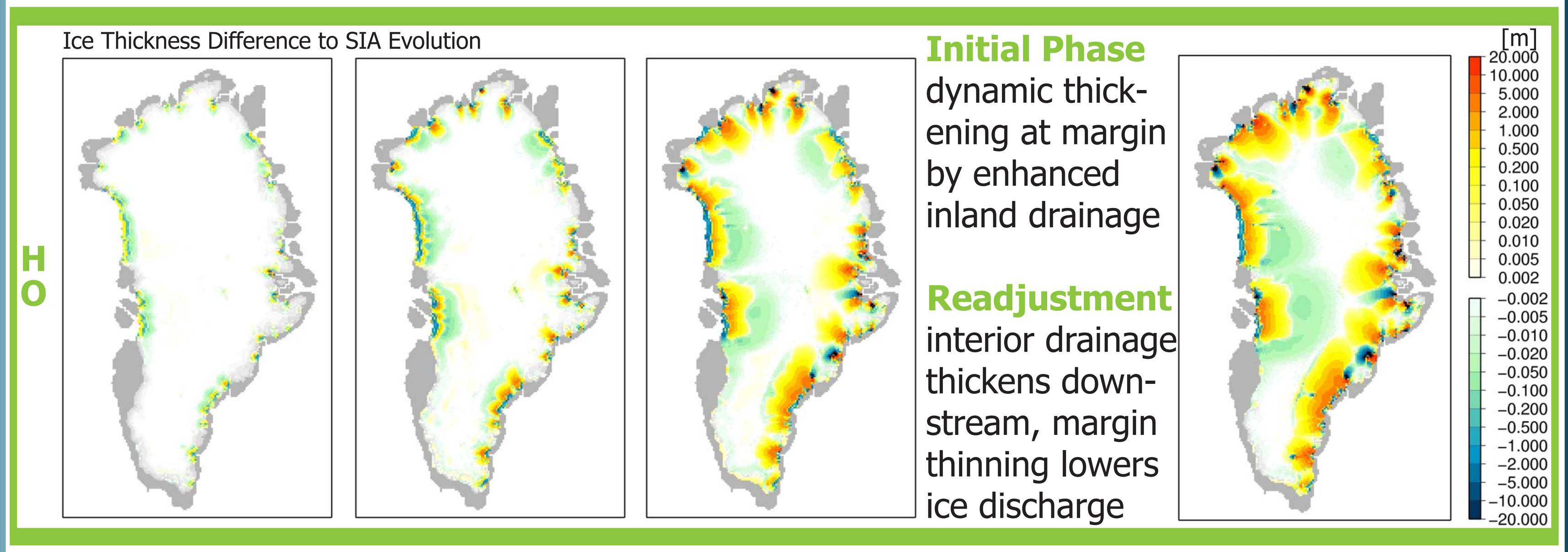


Defines area influenced by changes in driving stress

Spatial Pattern in Inland Transmission of Peripheric Forcing

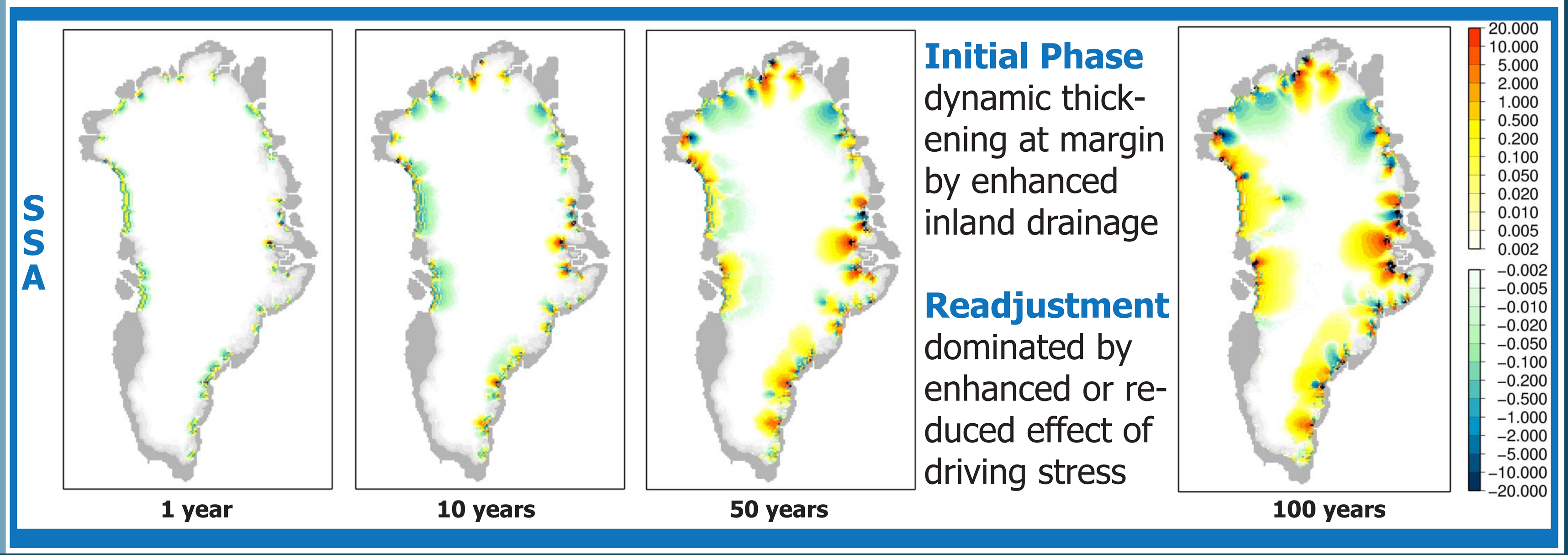
- radial inland propagation of dynamic thinning mainly coincides in all models
- along flow inland transmission via changes in driving stress dominates

- propagation perpendicular to flow direction amplified by lateral shearing
- gradients in longitudinal stresses enhance drainage of upsheet areas



Initial Phase
dynamic thickening at margin by enhanced inland drainage

Readjustment
interior drainage thickens downstream, margin thinning lowers ice discharge



Initial Phase
dynamic thickening at margin by enhanced inland drainage

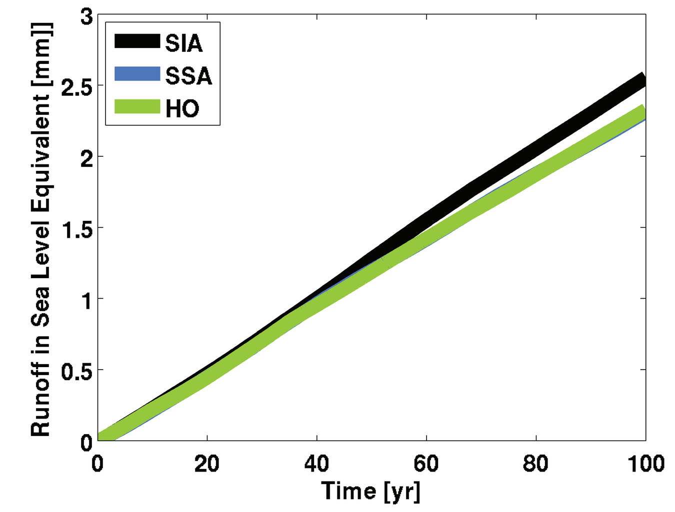
Readjustment
dominated by enhanced or reduced effect of driving stress

Mass Loss Contributions

Meltwater Runoff

- dynamic response to marginal forcing causes
- almost linear increase in meltwater runoff
- higher-order dynamics reduce runoff by ~10%
- because of a redistribution of ice mass

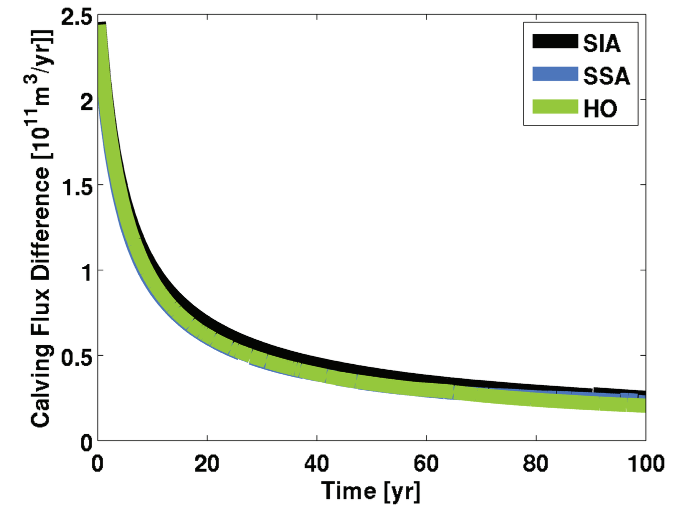
➔ negative feedback from enhanced dynamics
➔ on meltwater runoff
➔ negative feedback accounts for 25% of total
➔ discharge difference between SIA and HO



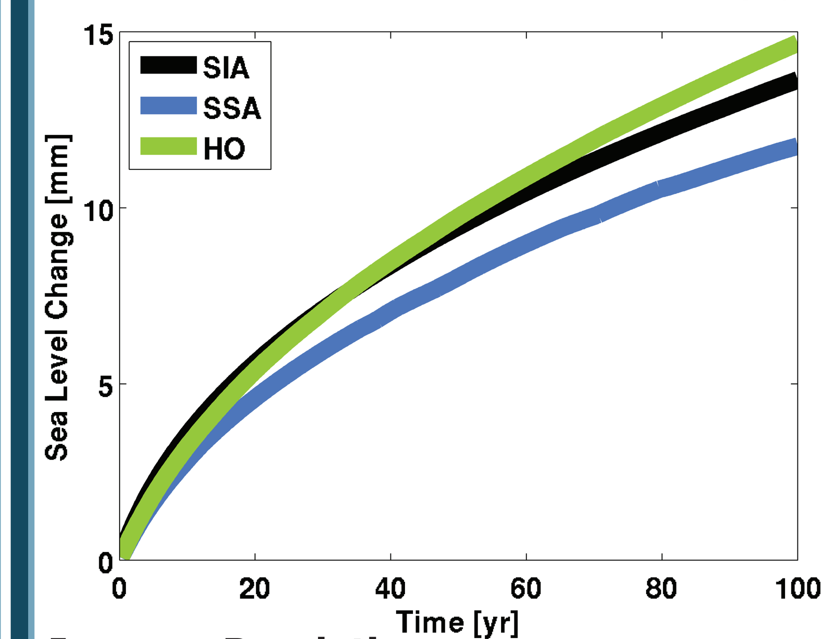
Calving Discharge

- initial calving flux signal identical
- exponential attenuation of marginal
- perturbation
- higher-order dynamics allow faster adjustment
- to perturbed situation

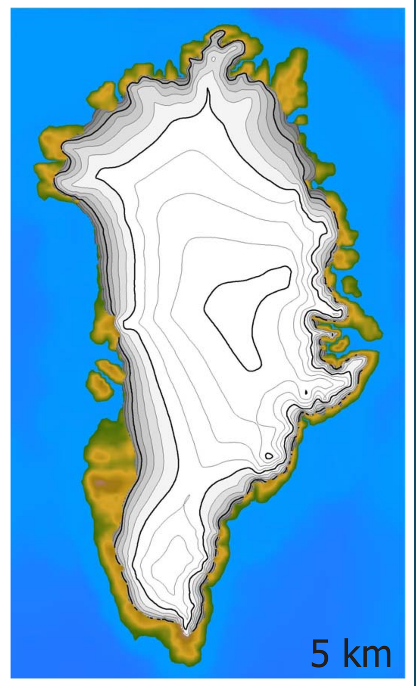
➔ enhanced attenuation of perturbation signal
➔ by fast dynamic processes
➔ main process for total discharge difference



Outlook



Outlet Glacier Forcing
- forcing induced by increased basal sliding differs dependent on model dynamics
  ➔ centennial response highly sensitive to precise forcing at the margin
- specify relation between small scale calving processes and large scale forcing
- consider feedbacks of local hypsometry and bathymetry on calving process



Improve Resolution
- reduced grid spacing allows to resolve narrow troughs in bed topography
- longitudinal stresses act on horizontal scales beneath several ice thickness

Take Away

Fast signal transmission by gradients in longitudinal stress or lateral shear does not significantly alter centennial response of ice sheet interior.

Integrated ice discharge from a HO and a SSA model ressemble one another but spatial pattern of signal transmission differs.

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