Inverse modelling of the englacial stratigraphy of the Greenland ice sheet

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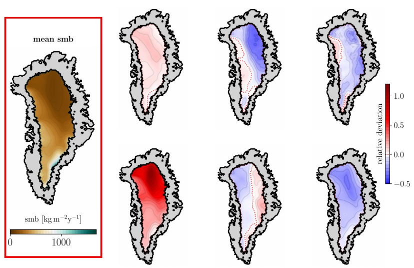
Frames are clickable!

Intro

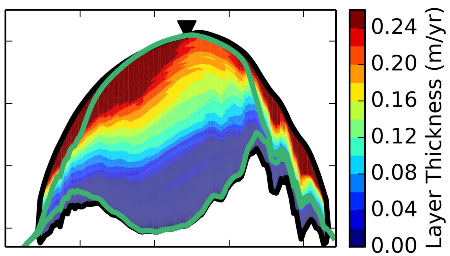
Why?

Challenges

Initialization & parameters



Simulation of isochrones



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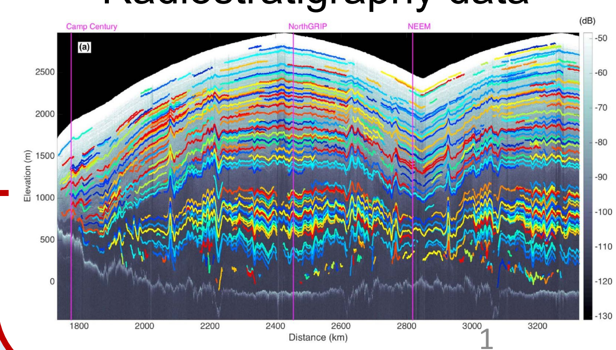
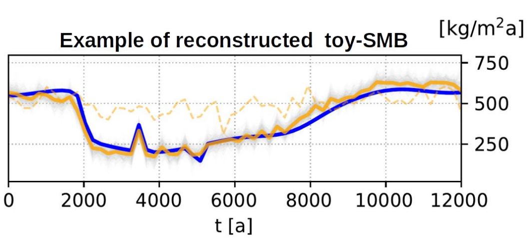
Radiostratigraphy data



Data assimilation

Reconstructions

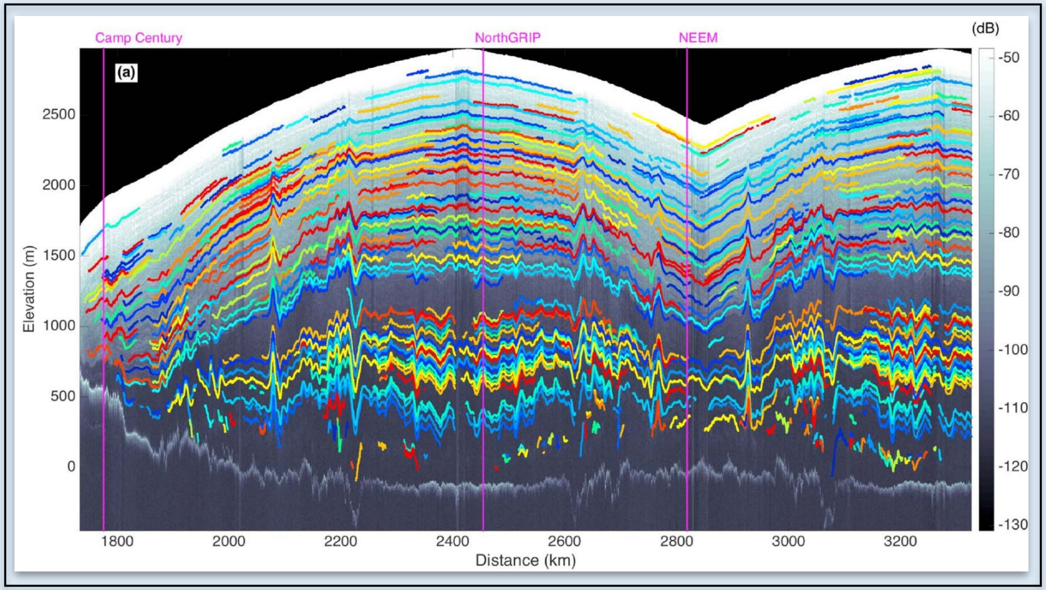


Introduction

- Stratigraphy depends on accumulation and dynamics
- Dynamics depend on accumulation rates
- Direct simulations of stratigraphy by Englacial Layer Simulation Architechture (ELSA)

For the last glacial cycle...

- **Surface mass balance?**
- **Sea level contribution?**
- **Ice flow parameters?**



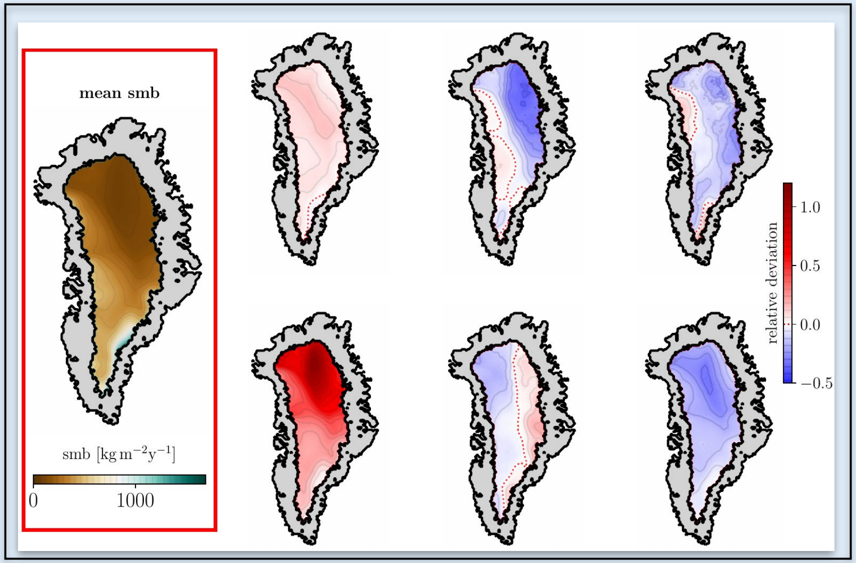
(MacGregor et al. [2015])

Why?

- Stability of the Greenland ice sheet (GrIS) poorly constrained even for the last glacial cycle
- Large radiostratigraphy data set available, containing the signal of past accumulation patterns and ice dynamics
- Since both the ice stratigraphy and dynamics depend on accumulation rates, transient numerical simulations will be deployed to account for changes in accumulation
- When the simulated stratigraphy matches the observed, the net accumulation and other parameters are considered reconstructed
- This also yields an optimal simulation of the ice sheet – hence the sea level contribution by the GrIS can be constrained
- Sensitivity analysis can give further insights into uncertainties of the reconstructions

Initialization (simulation)

- The parameters to be reconstructed are perturbed around their initial guess, giving rise to different parameter sets
- Of particular interest are the spatiotemporal changes in surface mass balance (SMB) fields, and ice flow parameters
- The ice stratigraphy is simulated for each of the parameter sets, hence we obtain an ensemble of simulations



Example of characteristic SMB fields. The Bergen Snow SImulator (Born et al. [2019]) was used with BedMachine data set (surface and bed topography, Morlighem et al. [2022].) and ERA5 forcing, and analyzed by first performing a principle component analysis and then deploying k-means clustering (k = 6).

Simulation of isochrones

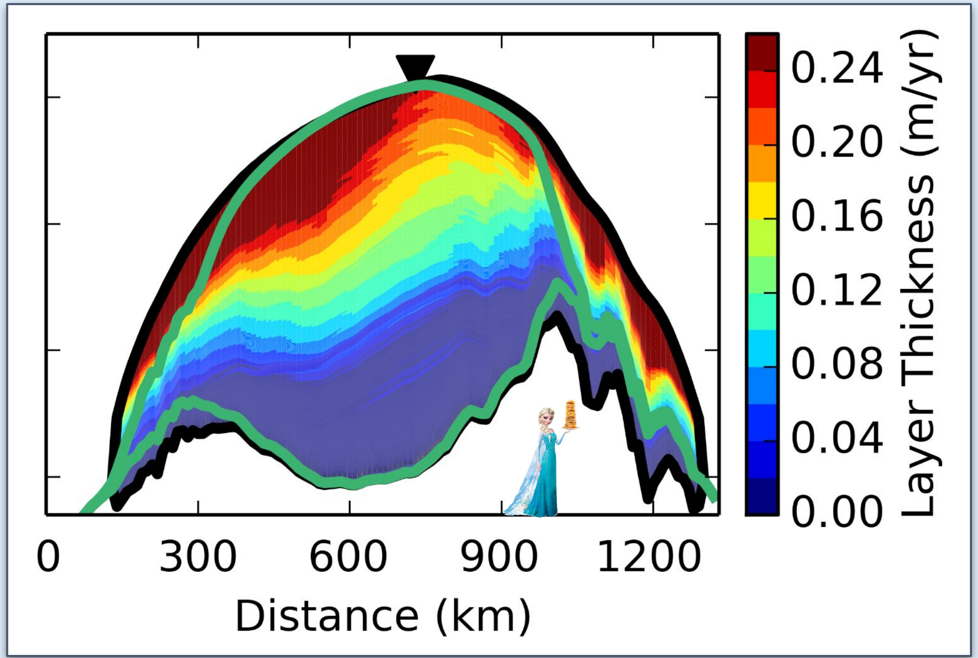
Stratigraphy model: ELSA (Englacial Layer Simulation Architecture)

- Vertical dimension defined in time and not space; gives rise to layers of equal age and eliminates numerical diffusion of age tracers
- This results in a direct simulation of ice stratigraphy
- Needs host model for computing ice dynamics!

⟶ **Both models coupled: Transient simulation of ice stratigraphy and dynamics (Born and Robinson [2021])**

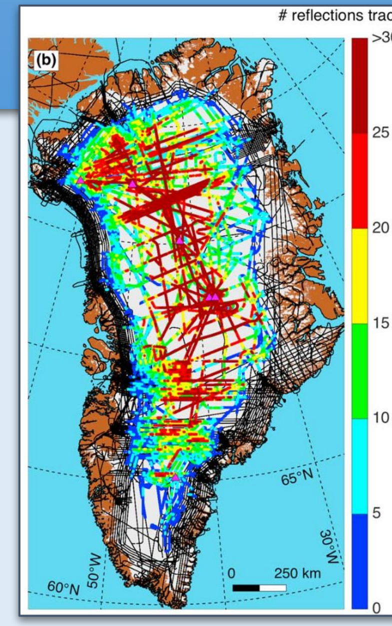
Host model: Yelmo

- Thermomechanical ice sheet model
- Handles the ice dynamics, forcing adjusted for reconstruction

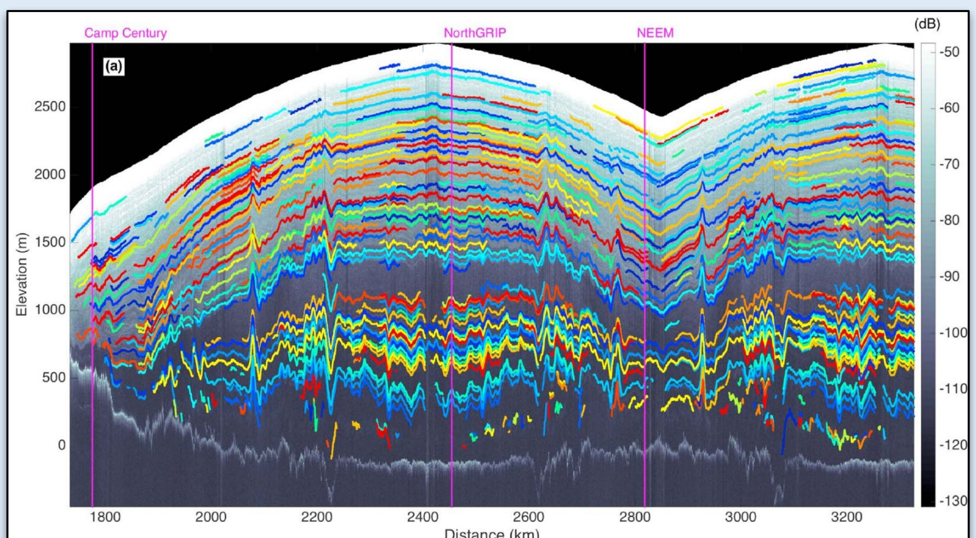


(Born [2017])

Radiostratigraphy data



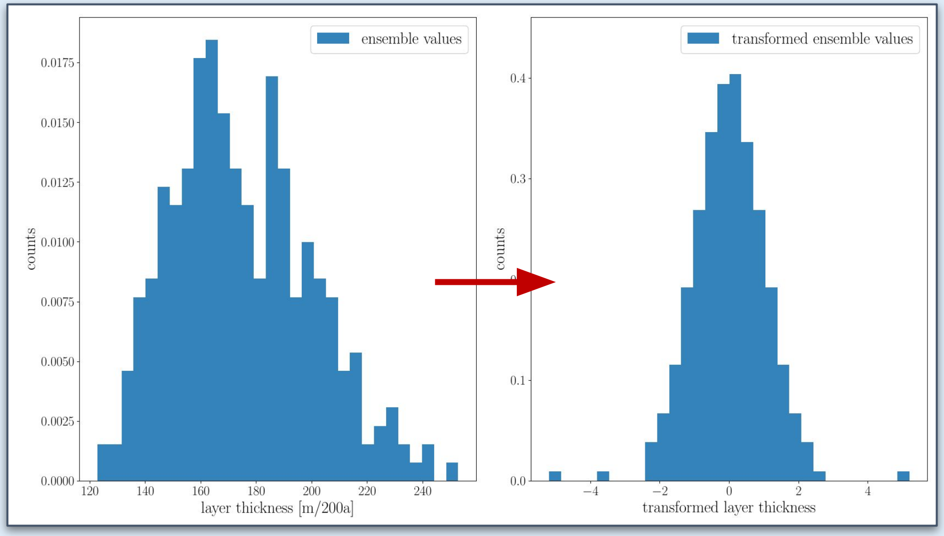
- Comprehensive data set of internal ice layers as well as the glacier bed
- Sampled by the University of Kansas in the period 1993-2013, by the use of airborne ice-penetrating radar (150 and 195 MHz)
- The radar data set was analyzed and dated by MacGregor et al. [2015], and comprises 512 transects of Greenland with a total length of 479 595 km



(Both fig.: MacGregor et al. [2015])

Data assimilation

- **Goal: match simulation and data as informed by uncertainties and prior knowledge, by adjusting parameters and accumulation**
- So far: use ensemble runs and the ensemble Kalman smoother to iteratively adjust the variables of interest until convergence
  - The ensembles are created by perturbing the variables. Non-gaussian distributions (e.g. layer thickness) are transformed to normal distributions by Gaussian anamorphosis (see figure)
- Other approaches (3D-Var etc.) may be considered at a later stage



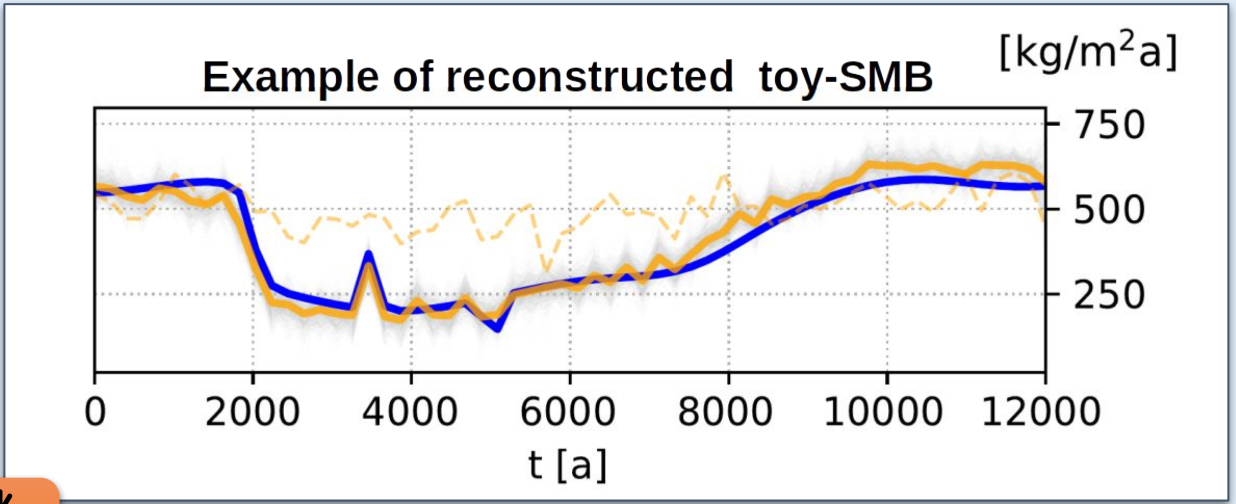
Gaussian anamorphosis

Reconstructions

- When the simulation match the observations and the parameters have converged, the final result is obtained.
- This yields an optimized simulation of GrIS using the reconstructed accumulation and flow parameters, enabling to also constrain sea level contribution.

So far:

- Initial test with synthesized data promising (figure)
- Using radiostratigraphy data still in starting phase



Blue line: toy-SMB (accumulation)
Orange lines: reconstruction (solid line) and first iteration (dashed)

Challenges at this stage

- Initialization and priors have large influence on final solution
- Overcome local minima (e.g. alternating high/low accumulation) can be difficult
- Ensemble Kalman smoother seemingly too “unstable” and the solution is confined to ensemble subspace
- 3D-Var? Needs gradient, which is to expensive to calculate directly (automatic differentiation possible work around?)

Ideas, discussions and input are very welcome!

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BedMachine data set:

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