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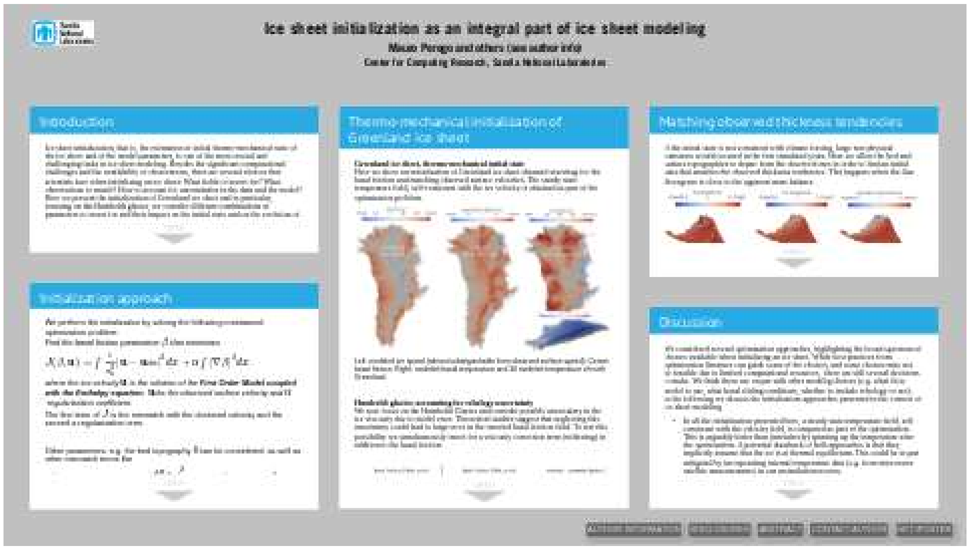
Ice sheet initialization as an integral part of ice sheet modeling



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PRESENTED AT:

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INTRODUCTION

Ice sheet initialization, that is, the estimation of initial thermo-mechanical state of the ice sheet and of the model parameters, is one of the most crucial and challenging tasks in ice sheet modeling. Besides the significant computational challenges and the availability of observations, there are several choices that scientists face when initializing an ice sheet: What fields to invert for? What observations to match? How to account for uncertainties in the data and the model? Here we present the initialization of Greenland ice sheet and in particular, focusing on the Humboldt glacier, we consider different combinations of parameters to invert for and their impact on the initial state and on the evolution of the glacier.
The initializations are preformed using the thermo-mechanically coupled higher-order MALI model and adopting a partial-differential-equation constrained optimization approach.

INITIALIZATION APPROACH

We perform the initialization by solving the following constrained optimization problem:
Find the basal friction parametner β that minimizes

$$J(\beta, \mathbf{u}) = \int \frac{1}{\sigma_u^2} |\mathbf{u} - \mathbf{u}_{\text{obs}}|^2 \, dx + \alpha \int |\nabla \beta|^2 dx$$

*where the ice velocity $\mathbf{u}$ is the solution of the **First Order Model coupled with the Enthalpy equation**, $\mathbf{u}_{\text{obs}}$ the observed surface velocity and α regularization coefficient.*

The first term of J is the mismatch with the observed velocity and the second a regularization term.

Other parameters, e.g. the bed topography b can be considered, as well as other mismatch terms like

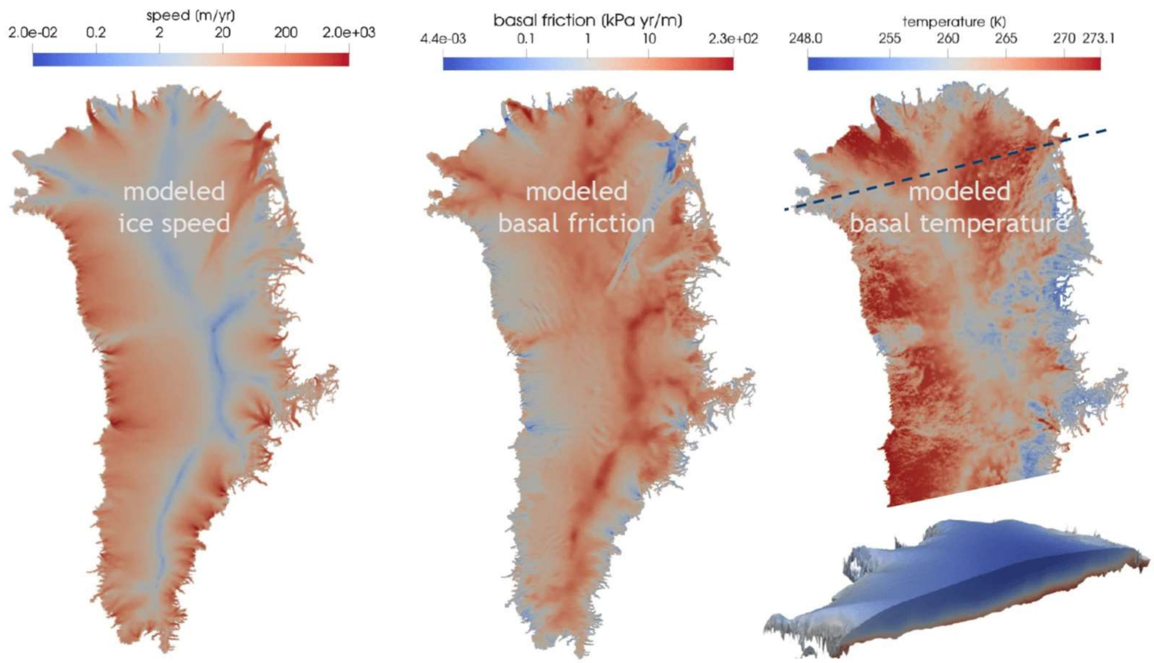
$$\int \left| \text{div}(\bar{\mathbf{u}} H) - SMB + \frac{dH_{\text{obs}}}{dt} \right|^2 dx + \int \frac{1}{\sigma_b^2} |b - b_{\text{obs}}|^2 dx$$

where the first term represents the mismatch between the flux divergence and the observed apparent mass balance. Minimization of this term ensures that the inital state is consistent with the observed thickness tendencies. Note that our approach is different from the mass conservative approach used by BedMachine because in our case the velocity is computed with the ice flow model (FO) we use for ice sheet simulations. In fact we use the topography from BedMachine as the "observed" topography field.

The problem is solved using a reduced-space Trust Region approach.

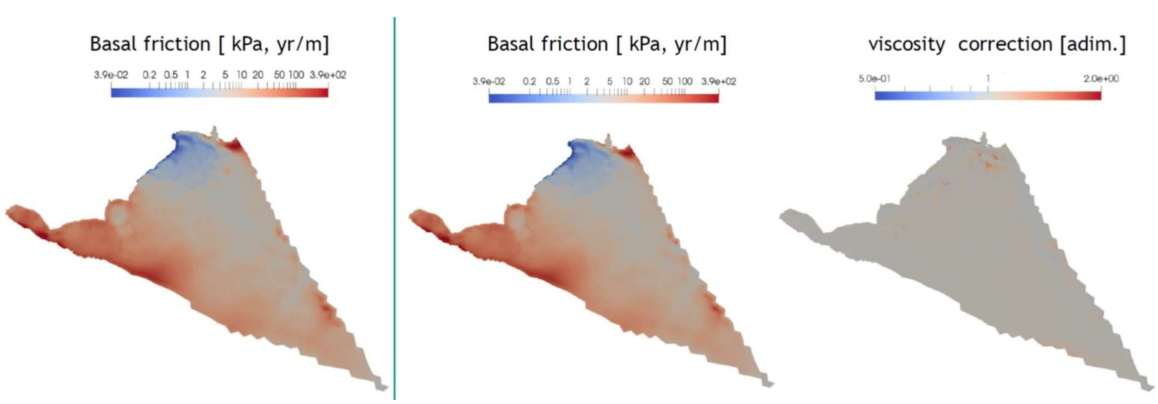
THERMO-MECHANICAL INITIALIZATION OF GREENLAND ICE SHEET

Greenland ice sheet, thermo-mechanical initial state
Here we show an initialization of Greenland ice sheet obtained inverting for the basal friction and matching observed surface velocities. The steady state temperature field, self-consistent with the ice velocity is obtained as part of the optimization problem.



Left: modeled ice speed (almost indistiguishable from observed surface speed). Center: basal friction. Right: modeled basal temperature and 3d modeled temperature of north Greenland.

Humboldt glacier, accounting for rehology uncertainty
We now focus on the Humboldt Glacier and consider possible uncertainty in the ice viscosity due to model error. Theoretical studies suggest that neglecting this uncertainty could lead to large error in the inverted basal friction field (see T. Harland AGU talk (https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/985074)). To test this possibility we simultaneously invert for a viscosity correction term (stiffening) in addition to the basal friction.

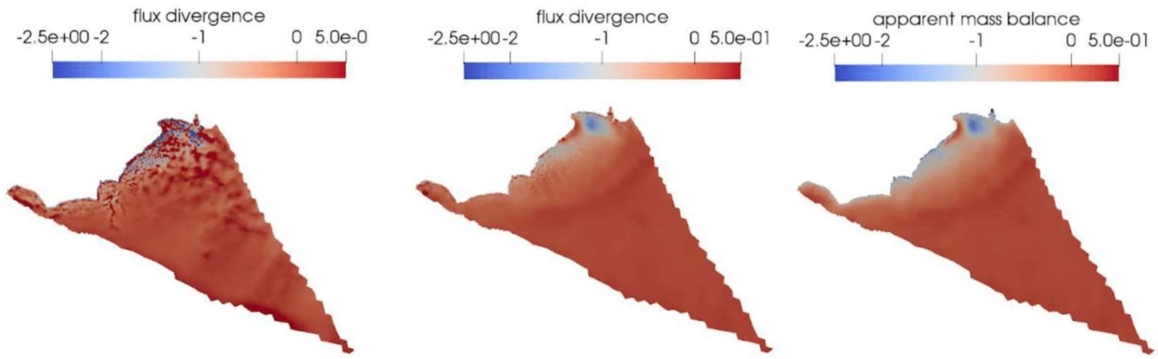


Left: basal friction when neglecting model errors in the viscosity term. Center and Right: results for simultaneous inversion of basal friction and viscosty correction.

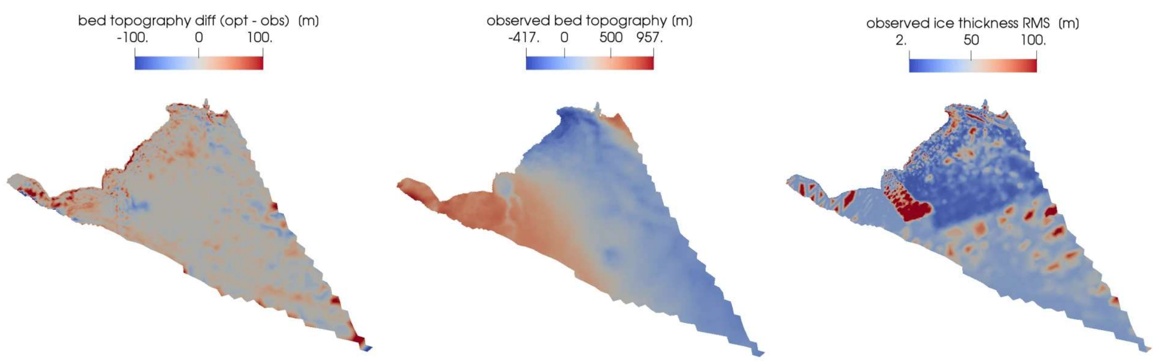
The fact that the viscosity correction factor is close to 1 (that is, no correction) suggests that the rheology term, based on temperature, is rather accurate.

MATCHING OBSERVED THICKNESS TENDENCIES

If the initial state is not consistent with climate forcing, large non physical transients would occured in the first simulated years. Here we allow the bed and surface topographies to depart from the observed ones in order to find an initial state that matches the observed thickenss tendencies. This happens when the flux divergence is close to the apparent mass balance.



Left: flux divergence when inverting only for β. Center: flux divergence when inverting also for the bed topography. Right: observed apparent mass balance.



Left: difference between the inverted bed topography and the observations. Center: observed bed topography. Right: ice thickness uncertainty.

In order to closely match the observed thickness tendencies the bed topography is significantly altered.

DISCUSSION

We considered several optimization approaches, highlighting the broad spectrum of choices available when initializing an ice sheet. While best practices from optimization literature can guide some of the choices, and some choices may not be feasible due to limited computational resources, there are still several decisions to make. We think these are on par with other modelig choices (e.g. what flow model to use, what basal sliding conditions, whether to include rehology or not). In the following we discuss the initialization approaches presented in the context of ice sheet modeling

- In all the initialization presented here, a steady state temperature field, self consistent with the velocity field, is computed as part of the optimization. This is arguably better than (interatively) spinning up the temperature after the optimization. A potential drawback of both approaches is that they implicitly assume that the ice is at thermal equilibrium. This could be in part mitigated by incorporating internal temperature data (e.g. from microwave satellite measurements) in our assimilation process.

- All result presented here are deterministic, and uncertainties in the data are accounted for by weighing the misfit terms on the basis of the data uncertainty (data with high uncertainty will be trusted and weighed less than data with smaller uncertainty). A more rigorous approach to account for uncertainty would be to perform Bayesian inversion. However, that is extremely challenging from a computational point of view due to the curse of dimensionality.

- The approach proposed here is not limited to a linear sliding law. In fact it can be used for estimating parameters of other sliding laws, like Weertman or Budd-type sliding laws (see T. Hillebrand AGU talk (https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/982391)). Moreover, if a hydrology model is available it could be used as an additional constraint allowing the inversion of the parameters of the hydrology model (see L. Bertagna AGU talk (https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/840213))

- Accounting for uncertainty in the model (model error) is dfficult. Here we accounted for uncertainties in the viscosity by inverting for a viscosity correction term in addition to the basal friction term. In the case of Humboldt glacier, it seems that neglecting the uncertainty in the rehology does not have a big impact on the inversion of the basal friction. However, we observed that for the Thwaites glacier (results not reported here) neglecting the rehology uncertainty has a larger impact.

- In order to compute an initial state that is consistent with observed thickness tendencies, we pertubed the bed and surface topographies. This is important to reduce non physical transients that would appear during the first simulated years, if the intial state is not consistent with climate frocings. There is a balance to strike between staying as much as possible close to the surface and bed topography data, and accurately matching the observed thickness tendencies. This is utimately a modeling choice, especially because the uncertainties on observed thickness transients and surface mass balance are not well known.

- Here we adopted a snapshot optimization that requires all the data to be available at one time instant. This is not the case in practice and the observations used here have been collected over a few years. This introduces an error in addition to the observation uncertainties that it is hard to quantify. Transient optimization approaches, while more expensive, can mitigate this issue by aquiring data only when available.

DISCLOSURES

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ABSTRACT

Ice sheet initialization, i.e. the estimation of initial thermo-mechanical state of the ice sheet and of the model parameters, is one of the most crucial and challenging tasks in ice sheet modeling.

Until recently, a common workflow for making the initialization problem tractable has been to neglect uncertainties in many poorly known model parameters, estimate the basal friction field and "spin up" the ice sheet model for several thousand years to bring it closer to equilibrium with present-day climate forcing. While this process removes the majority of large and undesirable transients associated with a nonequilibrium initial state, there are drawbacks associated with this approach: the basal friction coefficient is estimated at the beginning and never updated, the ice sheet model state (velocity, temperature, and geometry) at the end of the spin-up may be very different from that of the present-day, and errors in other uncertain parameters are ignored. These shortcomings will bias the model and its projections.

In general, besides the significant computational challenges and the availability of observations, there are several choices that scientists face when initializing an ice sheet: What fields to invert for? What observations to match? How to account for uncertainties in the data and the model? How to avoid overfitting the data? How to minimize numerical transients resulting from inconsistencies between the model state and the applied climate forcing?

Here, we share our experience in ice sheet initialization and in trying to address these questions. Using a partial-differential-equations constrained optimization approach, we present initializations of Humboldt and Thwaites glaciers and of the entire Greenland ice sheet using the thermo-mechanically coupled higher-order MALI model.

We consider different combinations of parameters to invert for and their impact on the initial state and on the evolution of the ice sheet. In particular we will consider different sliding laws and invert for their parameters by matching velocity observations. We tune the bedrock topography field so that the initial state is consistent with present-day climate forcing. Further, we explore the use of the Bayesian approximation error approach to simultaneously account for the uncertainty in measurements and in the forward model.

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