Recession of Thwaites Glacier: inferring relevant processes using the ice sheet model Elmer/Ice

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1-Introduction

The Thwaites Glacier in Amundsen Bay has experienced a notable speed up during the last two decades [1]. The stability of its grounding line remains an open question with a potential large contribution to sea-level rise if marine ice sheet instability (MISI) is initiated. Some properties such as the ice viscosity or the basal friction are poorly known and inverse methods are required to better represent current ice flow in ice-sheet models. Here we present a method to allow the inference of both parameters at the same time from the observed velocities. The background solution for the ice viscosity depends on the observed crevassed areas. We study 80 years of evolution of Thwaites Glacier.

2-Model equations and Geometry

The Full Stokes equations are solved using the finite element **Elmer/Ice** code [2]. It is based on the mass and momentum conservation laws as follow:

$$\begin{cases} \mathrm{div}\ \mathbf{v} = 0 \\ \mathrm{div}\ \sigma + \rho \mathbf{g} = 0 \end{cases} \quad (1) \qquad \sigma = \tau - pI \quad (2)$$

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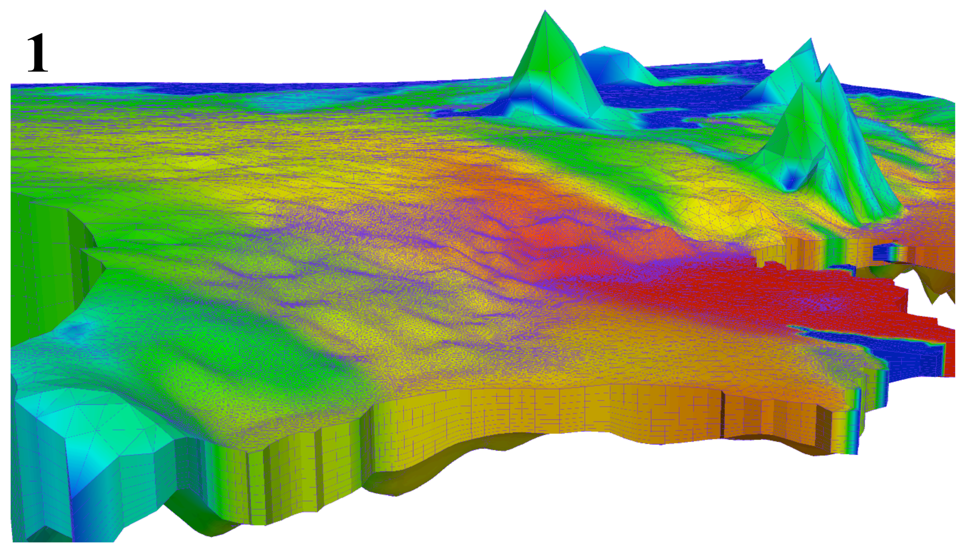

where **v** is the velocity vector, **g** is gravity, σ the stress tensor with p the isotropic pressure, and τ the deviatoric stress tensor. The ice flow law is given by a non-linear Glen-Nye constitutive relation between deviatoric stresses and strain-rates.

Geometry

Surface velocities, bedrock topography and ice thickness from BEDMAP2 are interpolated in a 2D non structured optimal grid. It is formed by about **75,000 elements and 37,000 nodes**. The 2D grid is vertically extruded using 10 levels (**Figure 1**).

3-Methods

3.1-Inverse Model

Two main parameters are poorly known when initializing our flow model.

Viscosity: The Glen's law introduces a viscosity factor μ_0 depending on temperature. We aim to optimize an enhancement factor E as:

$$\mu = E^2 \mu_0$$

The slip coefficient β^2 from a linear friction law applied at the bottom surface of grounded ice. It is optimized through parameter B as:

$$\beta^2 = B^2 \beta_0^2$$

The purpose of the inverse method is to **reproduce the observed surface velocity** by solving a minimisation problem. We deal with a cost function accounting for the misfit between modeled and observed velocities, together with the misfit from background solutions. The background enhancement E is 0.5 in observed crevassed areas and 1.0 elsewhere. The two terms of the cost function are:

$$J_{vel} = \frac{1}{2}\int_{\Gamma_s}\left(\left(u-u^{obs}\right)^2 + \left(v-v^{obs}\right)^2\right) dS \quad (3) \qquad J_{priori} = \frac{1}{2}\left(\int_{\Gamma_{OptB}} \lambda_{\beta Priori}\left(\beta-\beta^p\right)^2 dS + \int_{\Gamma_{OptE}} \lambda_{\mu Priori}\left(\mu-\mu^p\right)^2 dS\right) \quad (4)$$

$\lambda_{\beta Priori}$ and $\lambda_{\mu Priori}$ are the weights of the cost functions corresponding to the basal friction coefficient and viscosity factor respectively. Optimisation is made using the gradients computed with the **adjoint method** and **Quasi Newton steepest descent algorithm**.

3.2-Relaxation and prognostic run

After the inverse method, a free surface relaxation is needed in order to reduce the non physical flux divergence anomalies due to the remaining model errors. Some small time step iterations (from 0.01yr to 0.03yr) are crucial when starting the prognostic run, letting the ice shelf find its hydrostatic equilibrium and to sufficiently reduce the vertical velocities. Therefore, a free surface equation is solved in the upper boundary and under the ice shelf:

$$\frac{\partial z_s}{\partial t} + u\frac{\partial z_s}{\partial x} + v\frac{\partial z_s}{\partial y} = w + a_s \quad (5)$$

Where z_s is the surface elevation, a_s the accumulation rate mass balance and u, v and w the velocity components in the x, y and z directions. Under the ice shelf we apply a **depth dependent basal melting rate** fitting the overall 15,22 Gt/yr budget proposed by Depoorter el. al 2013 [3] for the Thwaites Glacier.

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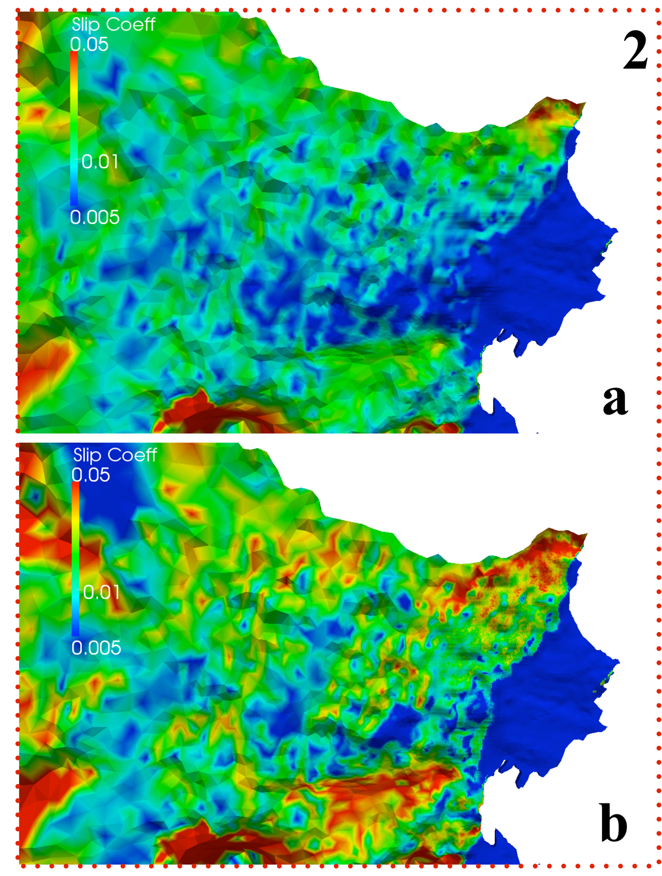
4-Thwaites coupled basal and viscosity inversion



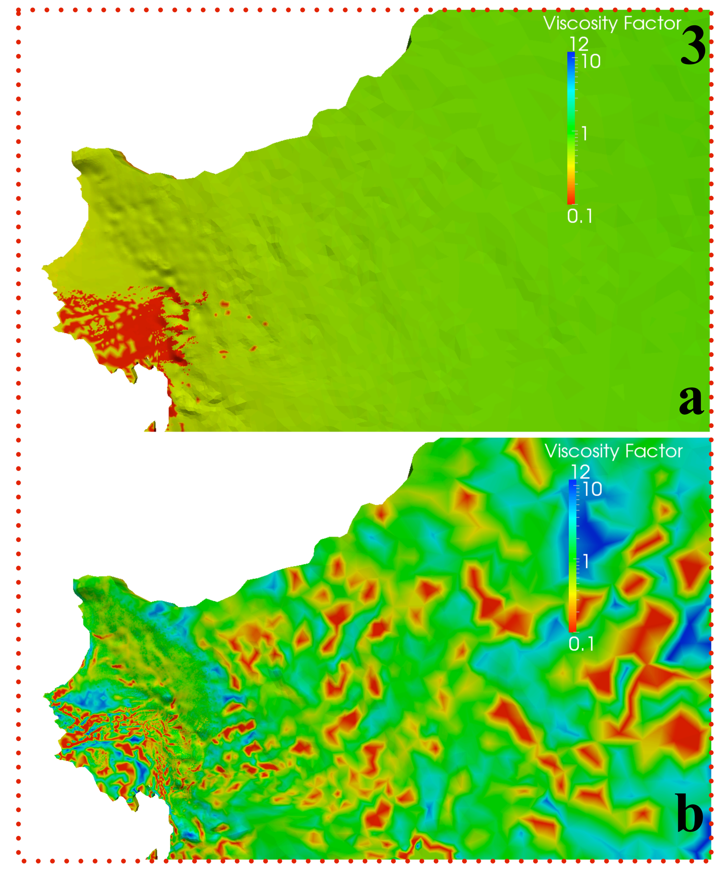
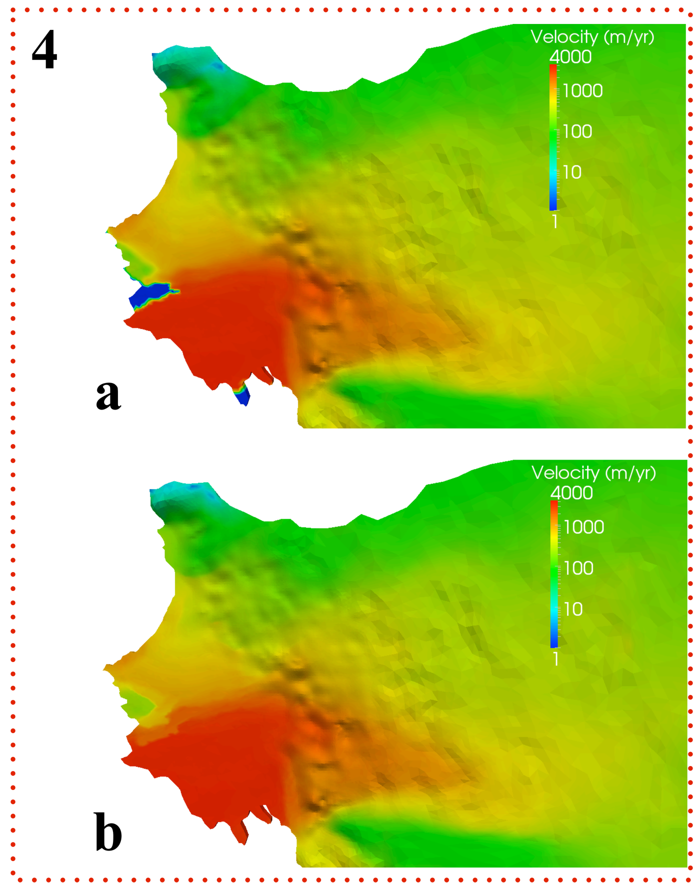


Figure 2 shows the background basal friction field (figure 2a) and the optimal solution (figure 2b).

In **Figure 3** is shown the background viscosity on the upper surface depending on temperature and observed crevassed areas (figure 3a), and the optimized viscosity (figure 3b).

Several sets of viscosity and basal friction fields may lead to equally good solutions in terms of modeled surface velocities. The regularisation parameters $\lambda_{\beta Priori}$ and $\lambda_{\mu Priori}$ can be tuned to give preference to changes in viscosity or basal friction. This solution is a good compromise between having a crevassed ice shelf and a weak friction in the main stream.



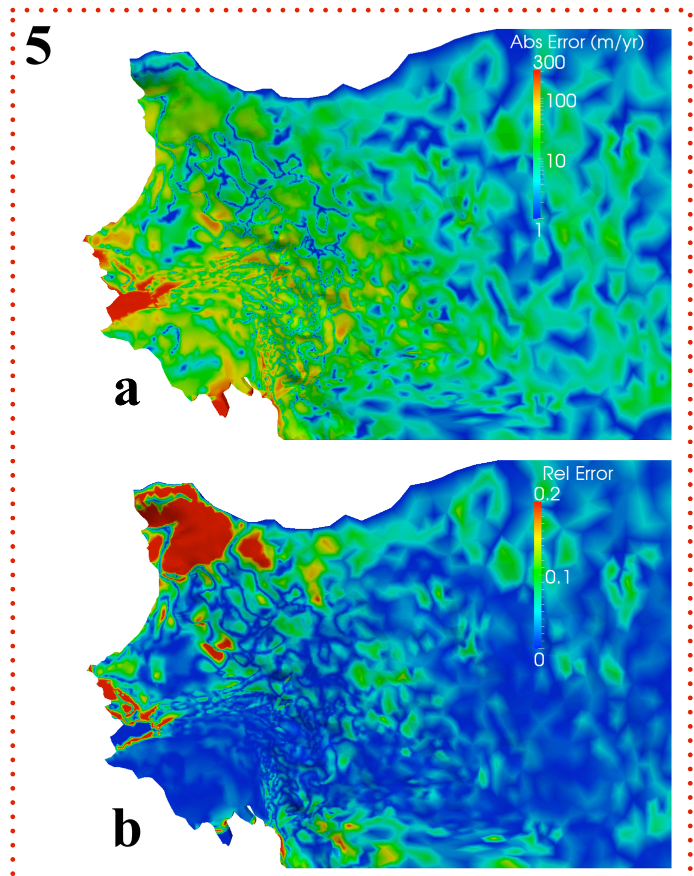
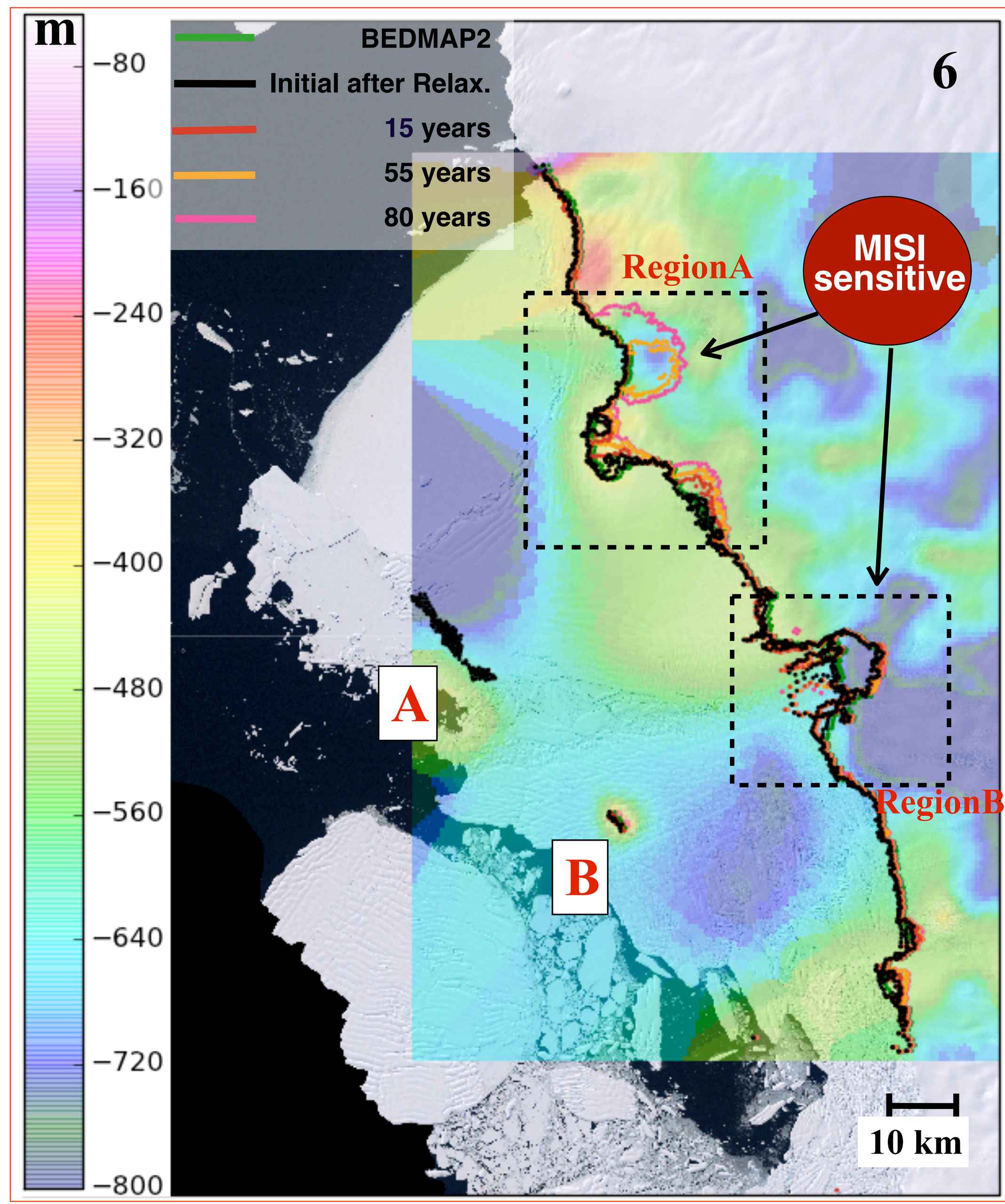


Figure 4 is a comparison between observed (figure 4a, no data in blue) and modeled (figure 4b) surface velocities.

Figure 5 shows the absolute (figure 5a) and relative (figure 5b) surface velocity errors in the ice shelf. A good fit with observations is reached particularly in the fastest parts of the ice shelf, the main region of interest.

5-Grounding line retreat of Thwaites glacier



We use the inferred properties from section 4 in order to initialize Thwaites Glacier flow.

Two ice rises in the ice shelf (A and B in **Figure 6**) are slowing down and giving stability to the main ice stream. **The contact with A is erased** and the grounding line stability is studied during 80 years of prognostic run. Figure 5 shows some snapshots of this grounding line evolution and the original grounding line as proposed in BEDMAP2 (in green). In color, the bedrock depth in meters is superimposed.

After 4 years of relaxation process, the relaxed position of grounding line belonging to **RegionB**, is placed deeper than the initial measured grounding line proposed in BEDMAP2. Despite being within a possible MISI sensitive region (retrograde bed slope), once the run has started the grounding line remains stable.

Otherwise, a moderate retreat is observed in **RegionA** after removing ice Rise A. The speed up related to the loss of contact increases the flux in a retrograde bedslope region. MISI in that region may be the driver of the modeled moderate retreat. Whether the grounding line may overpass or not the small sill just upstream the grounding line at year 80 in Region A needs further work and sensitivity study of possible enhanced sub ice shelf melting

Conclusion

Inversion of both viscosity and basal friction improves the way we initialize outlet glacier models. The inversion method described here fits better the observed surface velocities than most of single parameter inversion methods, adding a good representation of crevassed areas of the ice shelf. Therefore, the initial state given by our inverse method may better reproduce evolution of marine outlet glaciers. Section 5 conclusions remains open. The results suggest an influence of the ice rise A in the instability, but further work testing different melting perturbations seems to be important before extracting more firm conclusions.

References

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