Surface curvature as a signature of dynamical thinning

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Introduction

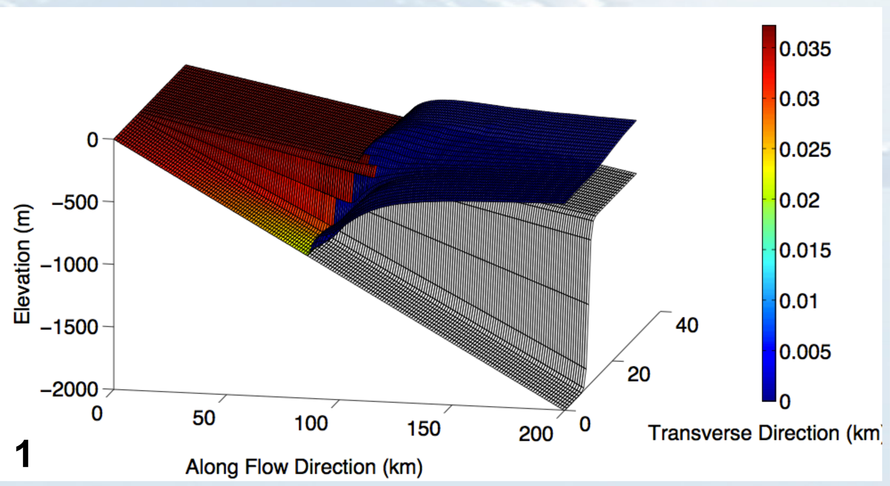
The contribution of polar ice sheets is one of the largest uncertainties in the estimate of the 21st century sea level rise. In particular, the dynamics of polar outlet glaciers is still not precisely constrained. Curvature of the surface in the across-slope direction could be an important parameter to better describe the local behaviour of an ice sheet. Here, we propose to use the **surface curvature as a surface signature** for outlet glacier dynamics **through modelling and satellite radar altimetry comparisons**.

Modelling Setup

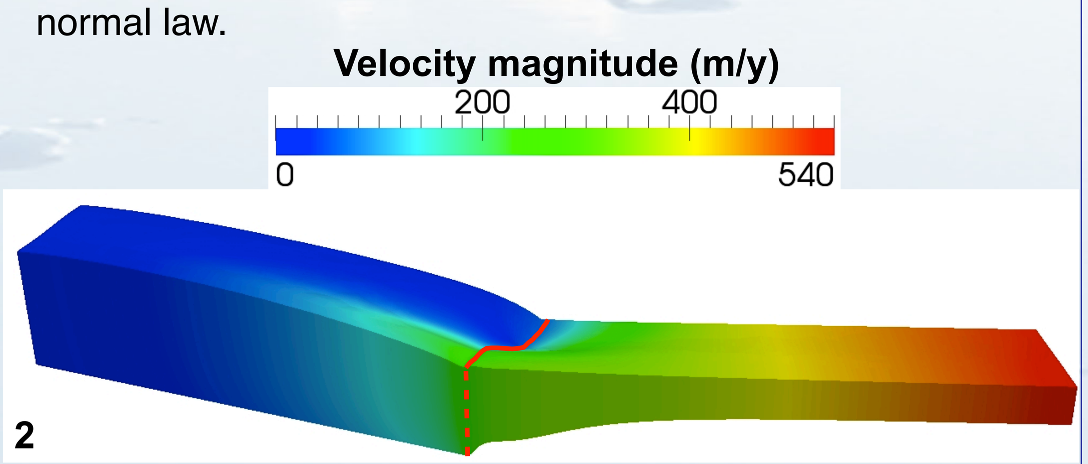
We run a three-dimensional **full-Stokes ice-flow model** (Elmer/Ice) on a fjord-like geometry. The geometry exhibits a convergence of grounded ice toward an ice stream that further extent to floating ice shelf (fig. 1 and 2.). The submarine melting is concentrated under the stream, in the vicinity of the grounding line, using a log-normal law.

The bedrock topography and the basal friction coefficient are shown on fig.1. Friction at the bedrock is defined by :

$$\tau_b = C.u_b^3$$

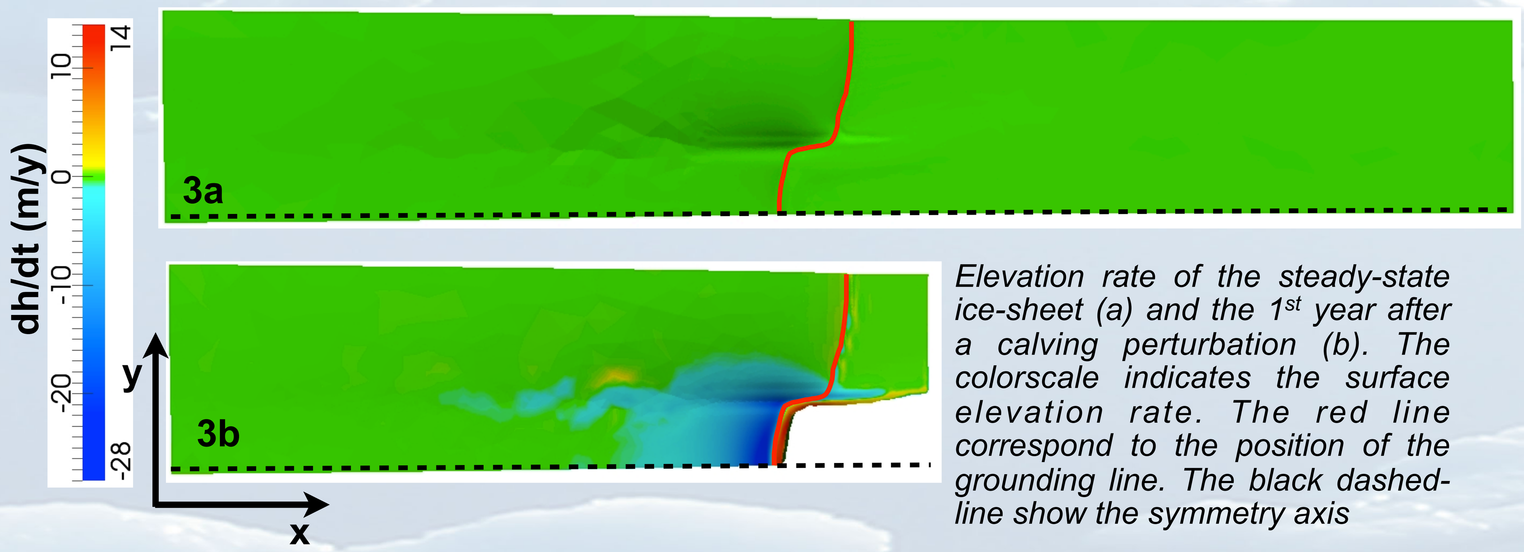


Topography of the bedrock (grey mesh) and the bottom surface of the ice-sheet (coloured mesh). The colorscale represent the spatial distributions of the basal friction coefficient (MPa.m$^{-1/3}$.a$^{1/3}$)



Velocity magnitude over the ice-sheet. The red line show the difference between grounded and floating ice

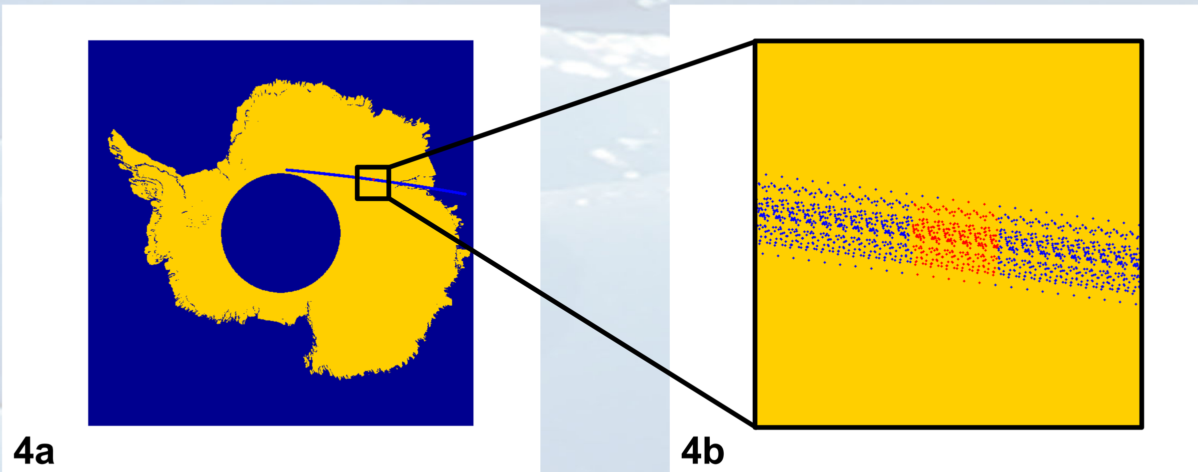
From the steady state (fig.3a), **several perturbations are imposed through the calving of the shelf**, at several distances from the grounding line. The figure 3b represent the collapse of almost the whole ice shelf. The variations of surface elevation are recorded over the 10 years following the collapse.



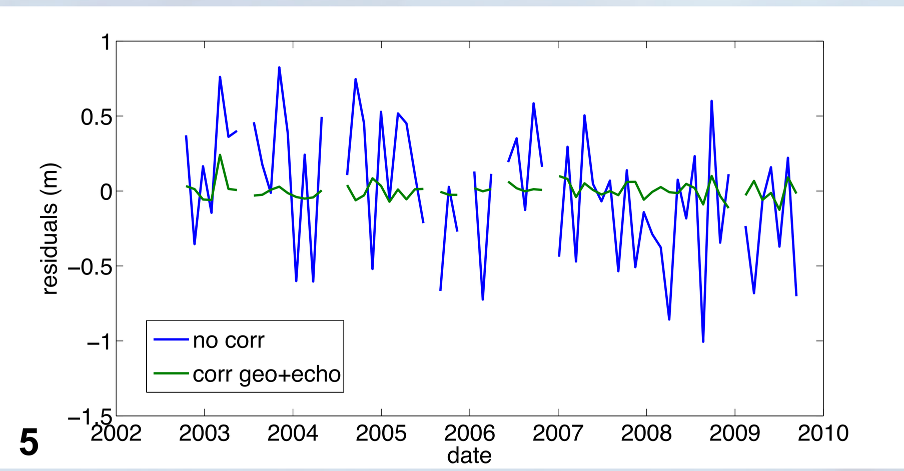
Elevation rate of the steady-state ice-sheet (a) and the 1st year after a calving perturbation (b). The colorscale indicates the surface elevation rate. The red line correspond to the position of the grounding line. The black dashed-line show the symmetry axis

Processing of Radar Elevation Measurement

The dataset is from **ENVISAT RA-2 Radar Altimeter** record from Autumn 2002 to Autumn 2010 (cycle 9 to 94). The **along-track processing** of the 20Hz record yields one measurement of elevation trend every kilometre along-track (fig. 4), which increases the number of data points by 20 in comparison with classical cross-over analyses.



(a) Satellite track (blue line) over Antarctica and (b) detail of a 500m-radius area in which the least square method is applied (red point)

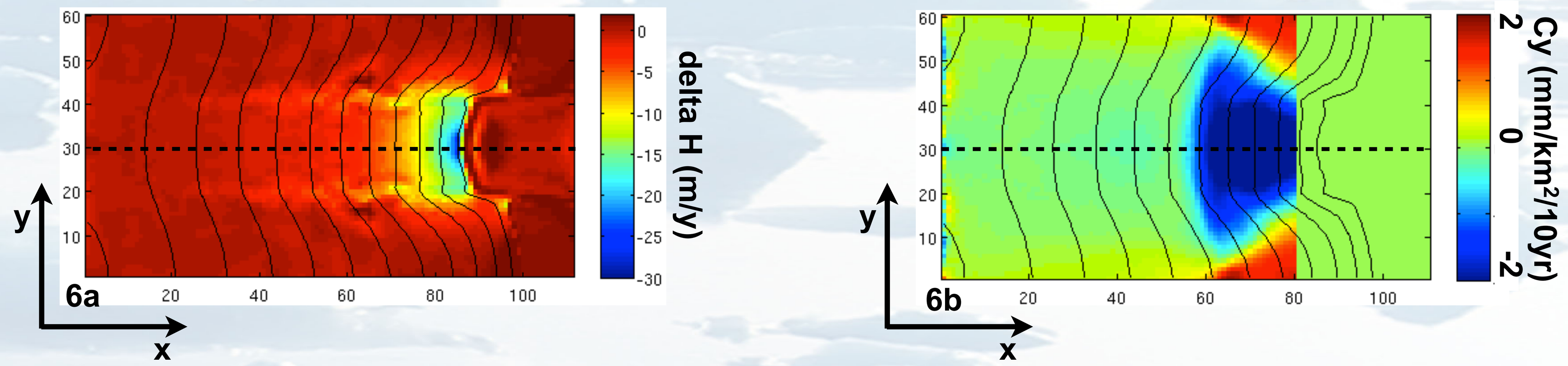


The measured elevation undergoes a least square fit which details are given in *Rémy and Parouty, 2009.*

The least square model uses parameters from the radar echo (the backscatter, the leading edge width and the trailing edge slope) to correct the measured elevation. The residuals remaining from the process are illustrated on the figure 5.

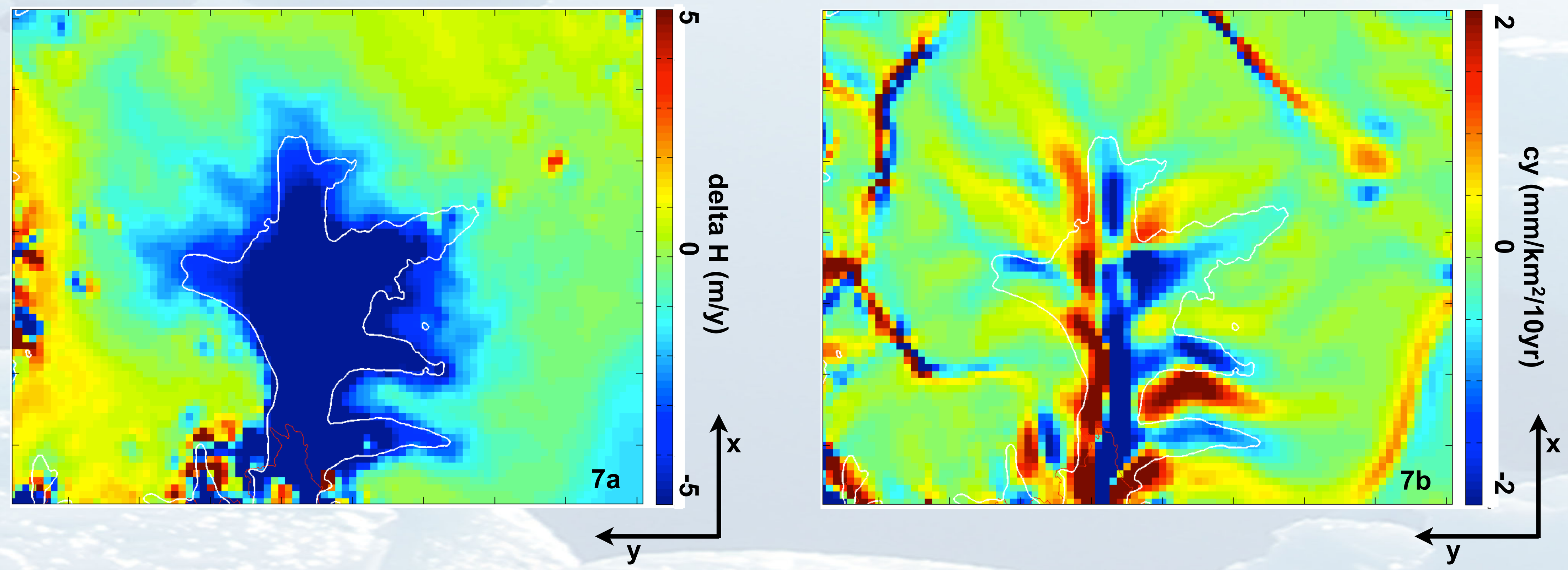
Curvature Criterion

The plan curvature is known to be linked to the convergence or divergence of the flow, and it clearly highlights fast flowing regions (convergence) and ice ridges (divergence). **The transverse curvature is calculated at each point** by fitting a biquadratic form on the surrounding points, within a 30km-radius circle. This process is applied both on the model outputs and the satellite data, and the results are compared below.



Variation of elevation (a) and transverse curvature (b) of the upper surface over 10 years following a calving event. The colorscale indicates the change in surface elevation (a) and the change in transverse curvature (b). The black dashed-line shows the symetry axis introduced in fig. 3a. The black solid lines are the contour lines of surface elevation.

A perturbation similar to the calving event illustrated on figure 3b is applied, and the variation of elevation is plotted on fig. 6a above. The record spreads over 10 years, and the whole glacier is recomposed using the symmetry axis. The thinning is concentrated from the central deeper channel to the valley walls, and upstream the grounding line. The corresponding variation of transverse curvature is plotted on the figure 6b. **The thinning of the ice sheet is spatially linked with the decrease in curvature, and the latter seems to spread faster than the change of surface elevation.**



Variation of elevation (a) and transverse curvature (b) of the upper surface over 10 years of observation on Pine Island Glacier. The colorscale indicates the change in surface elevation (a) and the change in transverse curvature (b). The red line shows the position of the grounding line, and the white line correspond to 100m/y velocity contour line.

The same parameters are calculated on Pine Island Glacier (PIG), in the Amundsen Sea sector, based the data obtained with Envisat and processed with the method described previously. The blue regions on figure 7a undergo a thinning, which corresponds to the fast-flowing regions, highlighting several ice streams. These streams for the most part are observed on figure 7b through a decrease of transverse curvature.

For both numerical data and experimental measurements, a **dynamical thinning is linked with a decrease in transverse curvature**, and the orders of magnitude of **magnitude of cy are in the same range**, spreading between -2 mm/km² and +2 mm/km² over the 10 years of analysis.

Conclusion

The across-slope curvature has been used as a **criterion for surface signature** to described the dynamical response of an ice sheet to a perturbation. Two sets of results from both modelling and radar altimetry show **similar response in terms of spatial distribution and amplitude** : a decrease of transverse curvature is linked to a local thinning of the ice sheet. However, further 3D simulations on more realistic geometries have to be undertaken to improve our confidence in this criterion.

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Estimating the future contribution of continental ice to sea-level rise.
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