What can we learn from **inverse methods** regarding the processes behind the acceleration and retreat of **Helheim glacier** (Greenland)?

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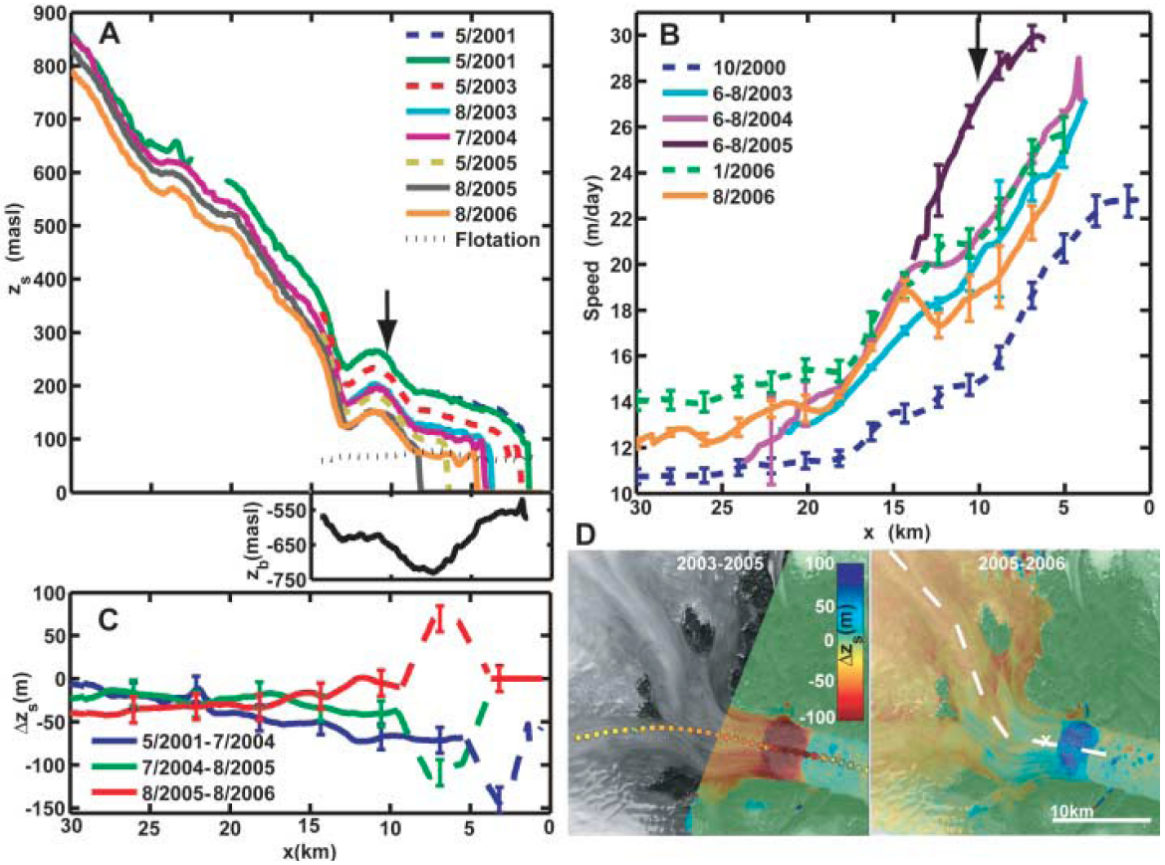
Helheim observations

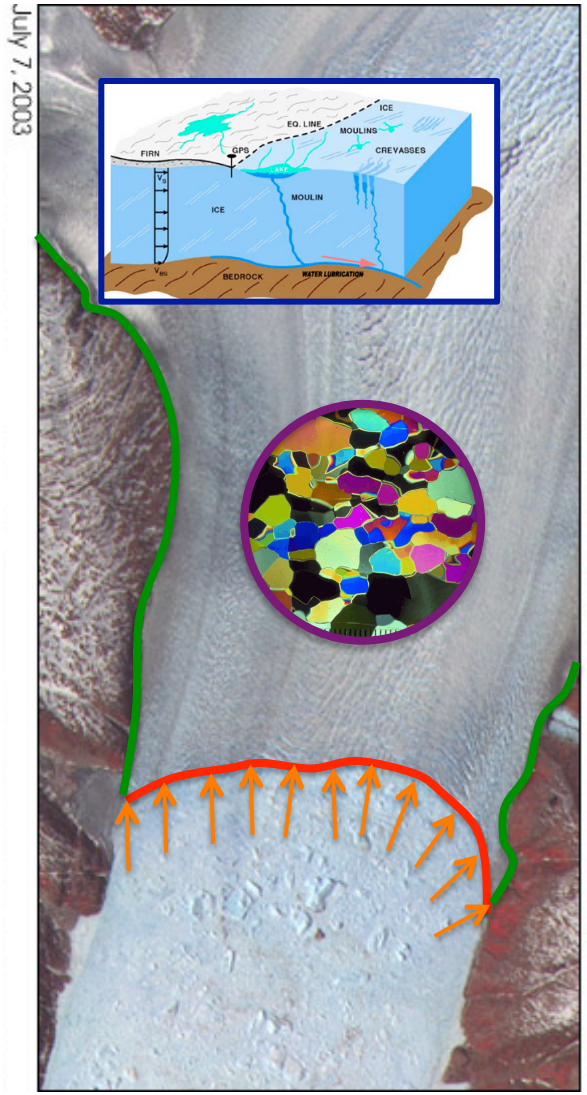


Observed changes (surface elevation and velocities) at Helheim glacier.

[Howat et al., 2007]

What are the processes at the root of these observed changes ?

Potential Processes



Changes at the ice/ocean front

- increased calving rate
- decreased of melange stiffness

Changes at the base

- decreased basal friction (zwally effect)

Changes at the lateral margin

- decreased lateral friction (water in crevasses)

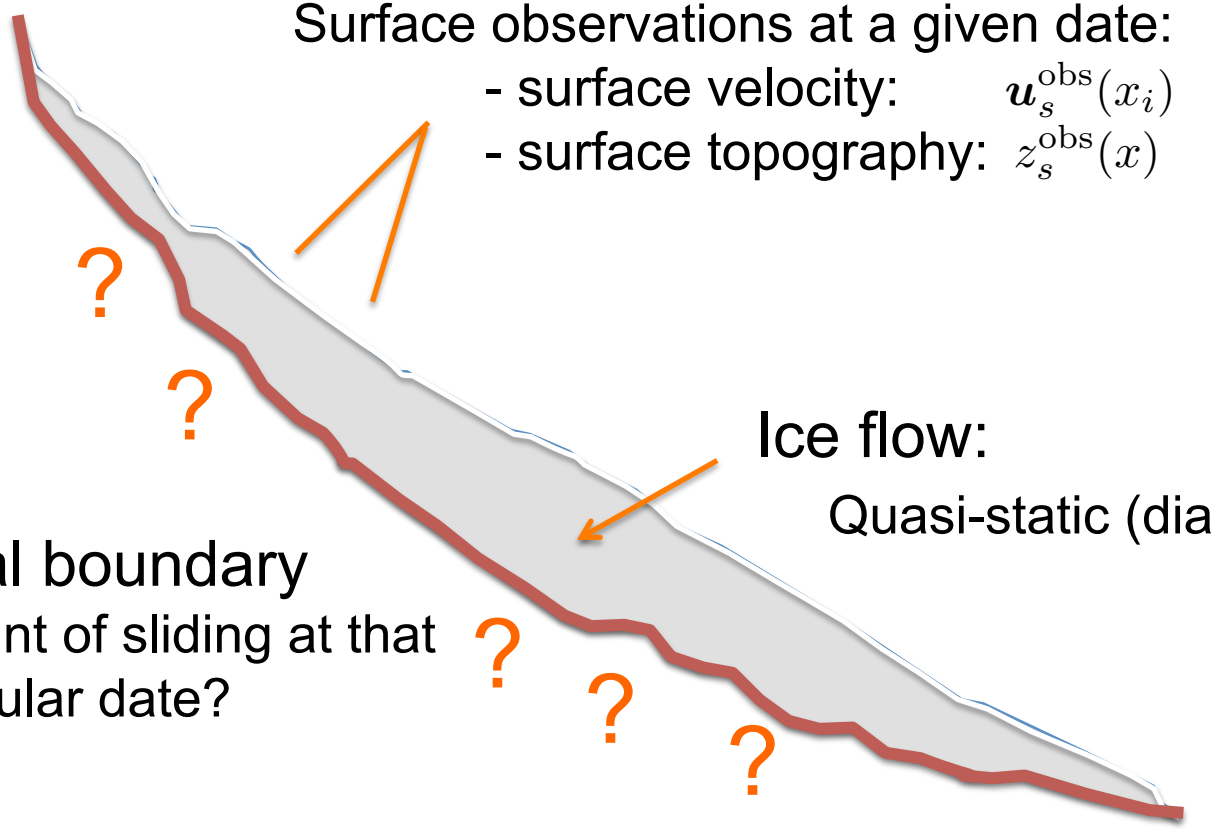
Changes in the ice rheology

- decreased viscosity, ...

Data assimilation techniques can tell us which processes are contributing.

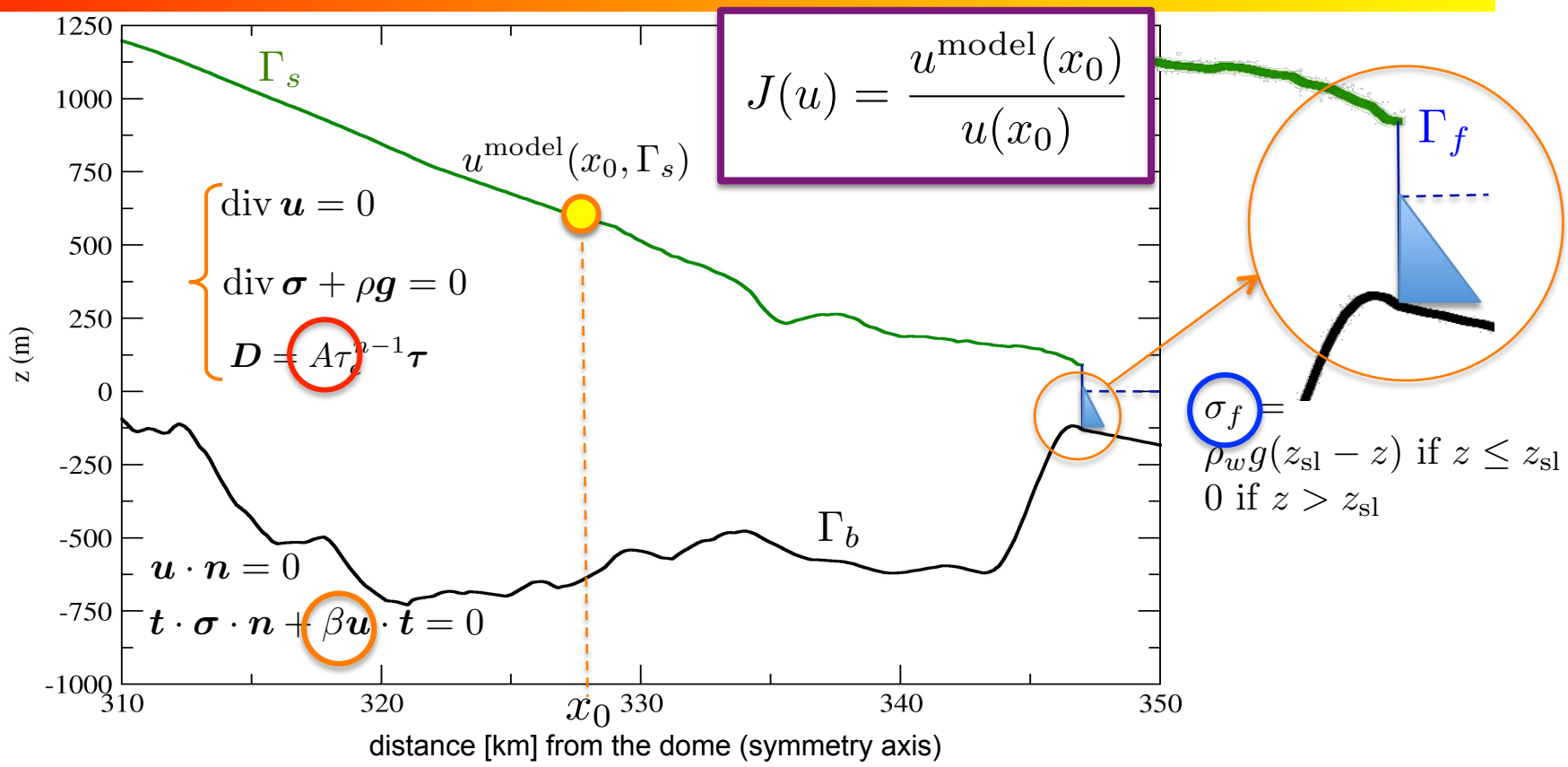
Specificity of ice flow

Very low Reynolds -> no history in the velocity



Observed surface velocities reflect the current state

Sensitivity experiments



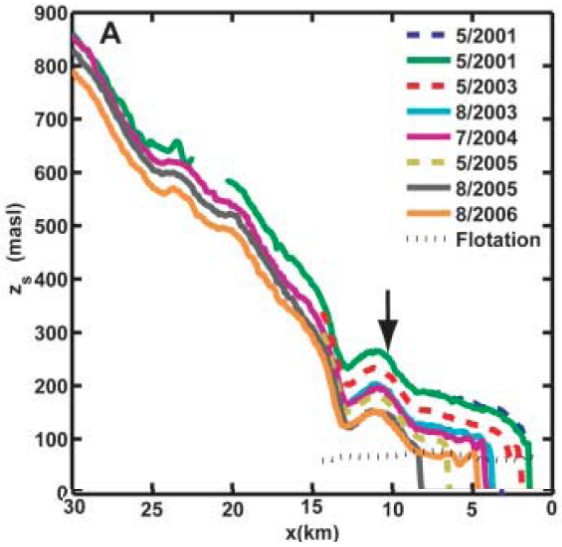
$\dfrac{\partial J}{\partial \beta}, \dfrac{\partial J}{\partial A}, \dfrac{\partial J}{\partial \sigma_f}$ give the sensitivity of the surface velocity $u^{\text{model}}(x_0, \Gamma_s)$ to

- basal drag $\beta = \beta(x, \Gamma_b)$
- fluidity parameter $A = A(x, y)$
- front stress $\sigma_f = \sigma_f(\Gamma_f, y)$

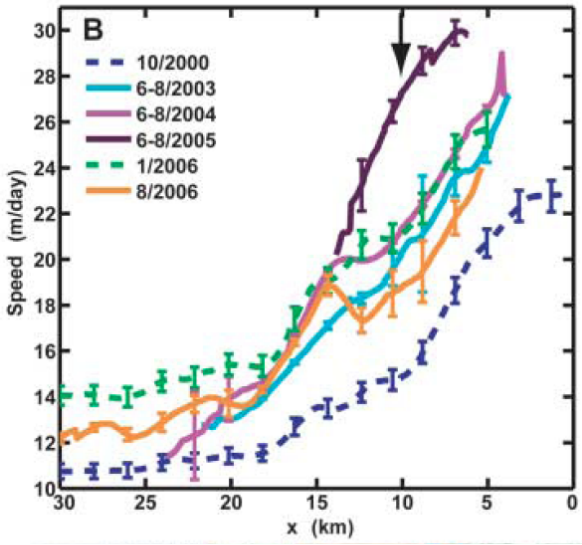
Application to Helheim flowline

Observations from 2001 to 2006 [Howat et al., 2007]

surface elevation



surface velocity



Surface + velocity in 2001, 2003, 2004, 2005, 2006

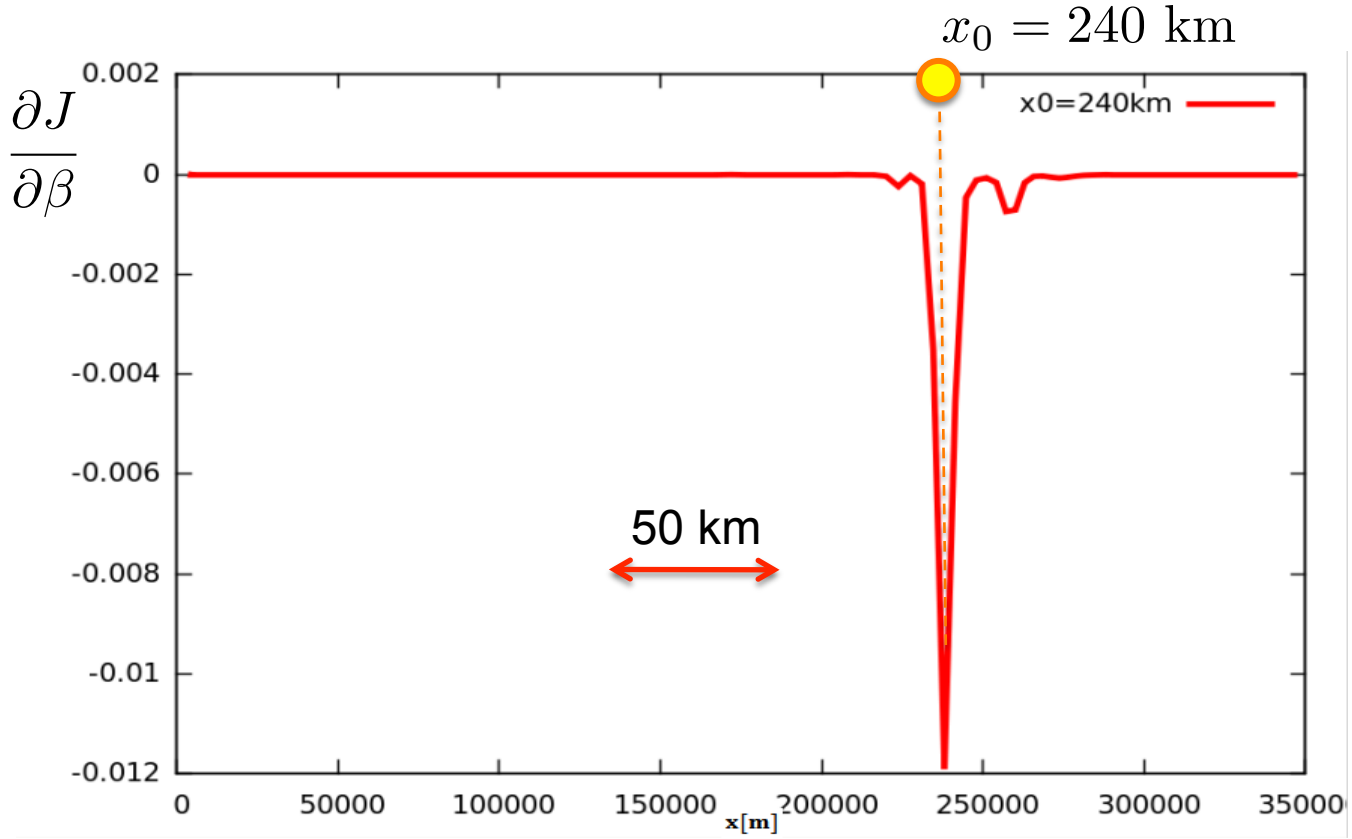
(velocity used to infer basal drag to construct the reference state)

Questions :

Sensitivities to $\beta = \beta(x, \Gamma_b)$, $A = A(x, y)$, and $\sigma_f = \sigma_f(\Gamma_f, y)$ and evolution over years

Sensitivity to basal drag

$$J(u) = \frac{u^{\text{model}}(x_0)}{u(x_0)}$$



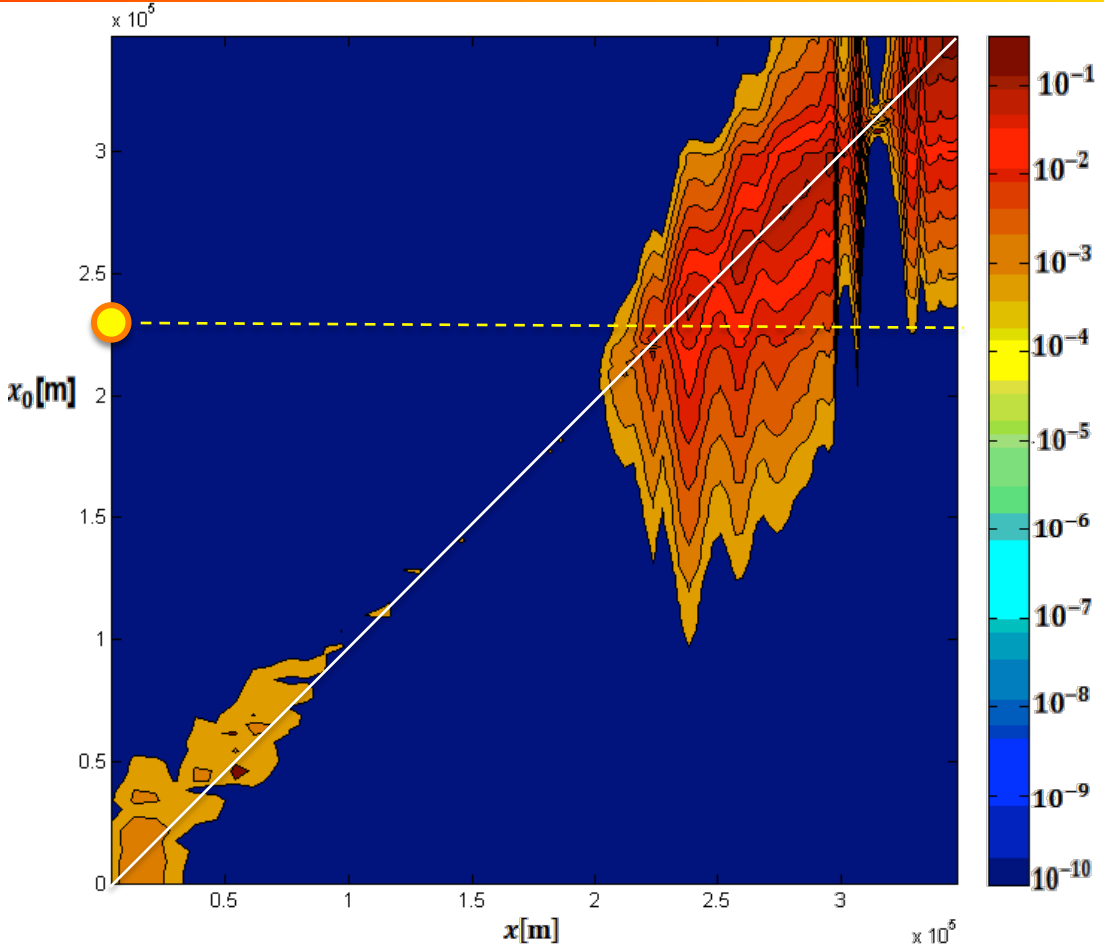
How to read this graph?

A 1% change of $\beta(x_i)$ will modify $u(x_0)$ by $\frac{\partial J}{\partial \beta}|_{x_i} \beta(x_i)\%$

Changes of basal drag influences $x_0 \pm 20\text{km}$

Sensitivity to basal drag

$$J(u) = \frac{u^{\text{model}}(x_0)}{u(x_0)}$$



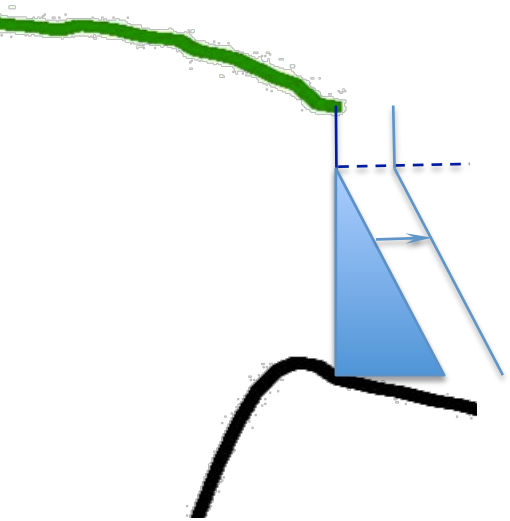
$$\frac{\partial J}{\partial \beta}|_{x_i} \beta(x_i)$$

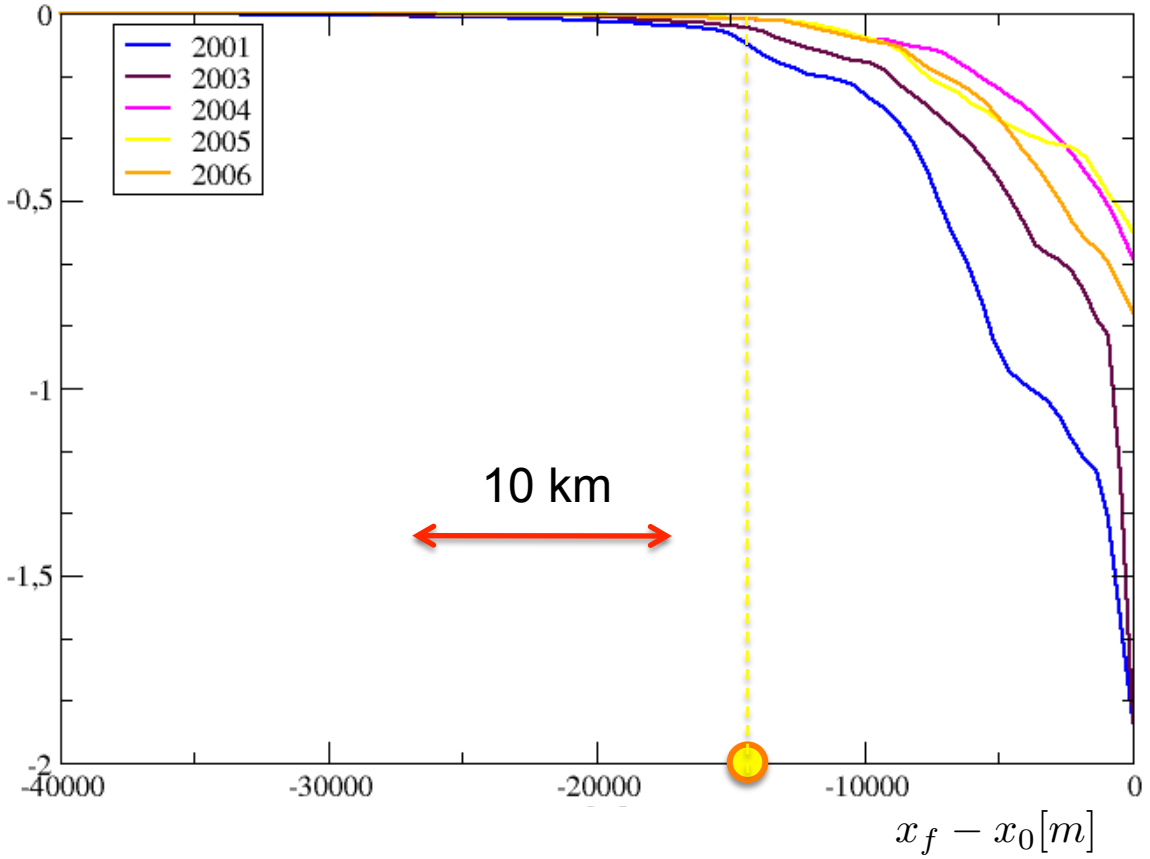
- ✓ Sensitivity in an area of $x_0 \pm 20\text{km}$
- ✓ Higher sensitivity to $\beta = \beta(x, \Gamma_b)$ near the front
- ✓ Some area along the flowline with very low sensitivity

Sensitivity to front stress

$$J(u) = \frac{u^{\text{model}}(x_0)}{u(x_0)}$$

$$\sum_z \frac{\partial J}{\partial \sigma_f} \times \text{Mean}(\sigma_f)$$

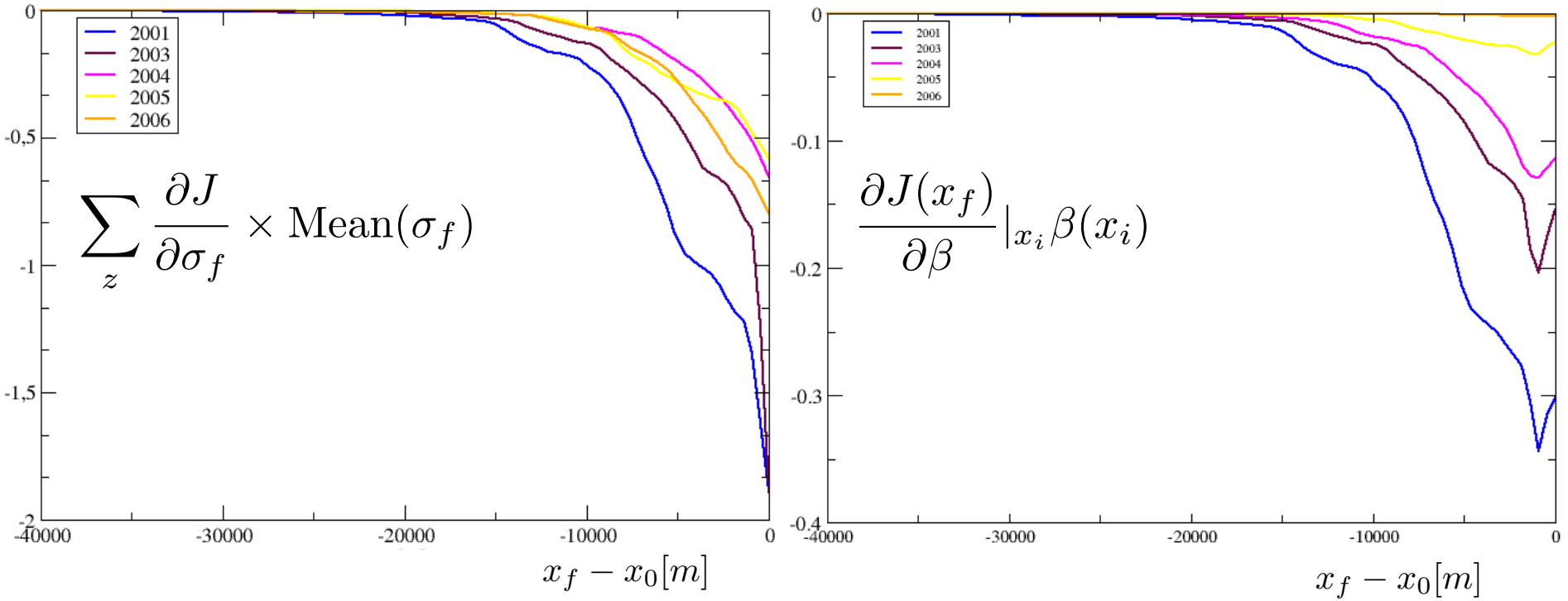




- ✓ Change of stress front has an influence up to 15 to 20 km upstream
- ✓ Sensitivity seems to decrease from 2001 to 2006

Front stress / basal drag at the front

$$J(u) = \frac{u^{\text{model}}(x_0)}{u(x_0)}$$

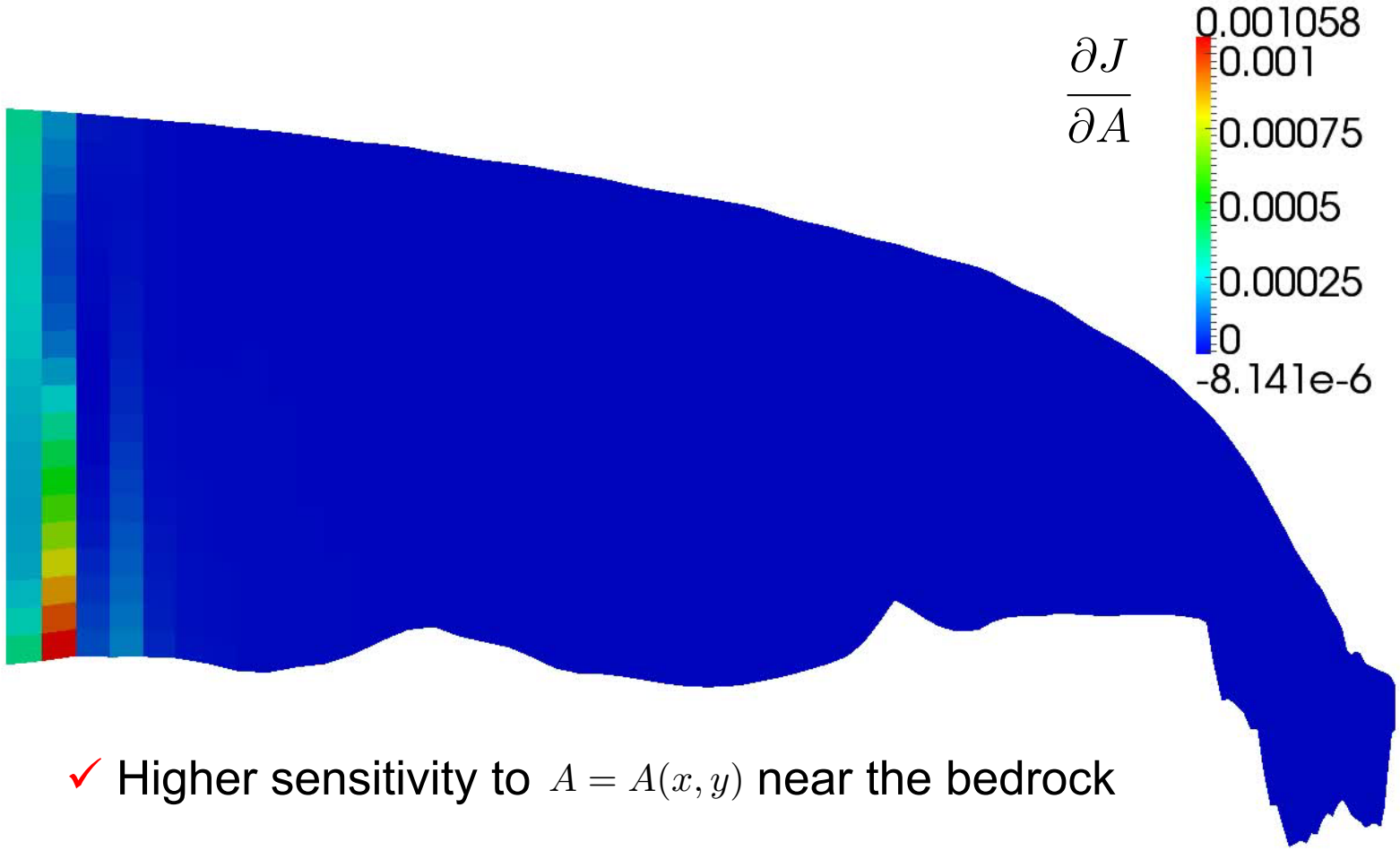


✓ Difficult to distinguish the signature of a change in basal drag at the front and a change in stress front

✓ Both sensitivities seem to decrease from 2001 to 2006

Sensitivity to fluidity parameter

$$J(u) = \frac{u^{\text{model}}(x_0)}{u(x_0)}$$

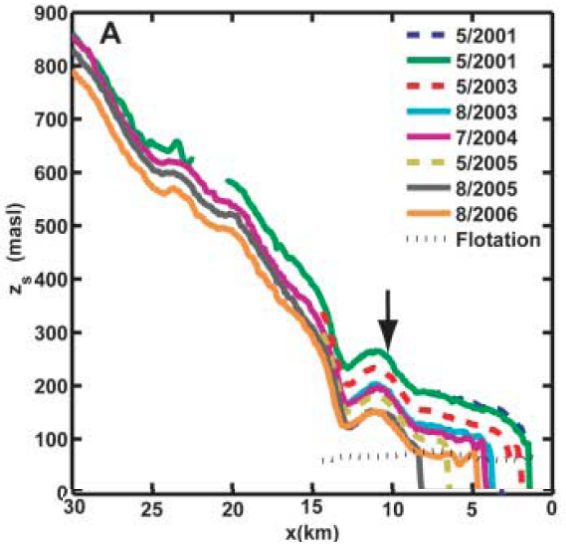


- ✓ Higher sensitivity to $A = A(x, y)$ near the bedrock
- ✓ Higher sensitivity to $A = A(x, y)$ where sliding is low

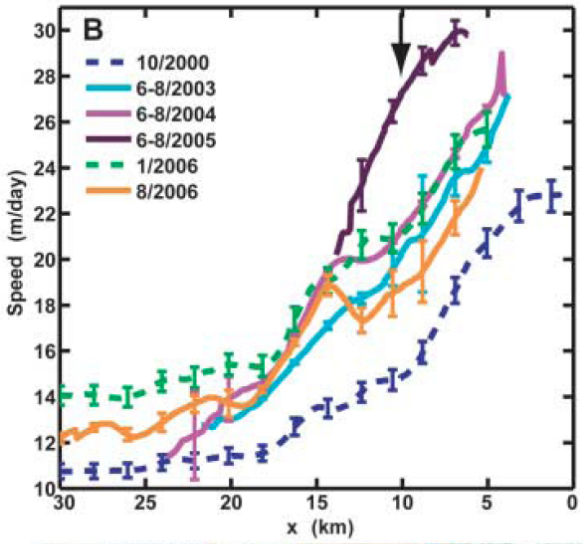
Application to Helheim flowline

Observations from 2001 to 2006 [Howat et al., 2007]

surface elevation



surface velocity



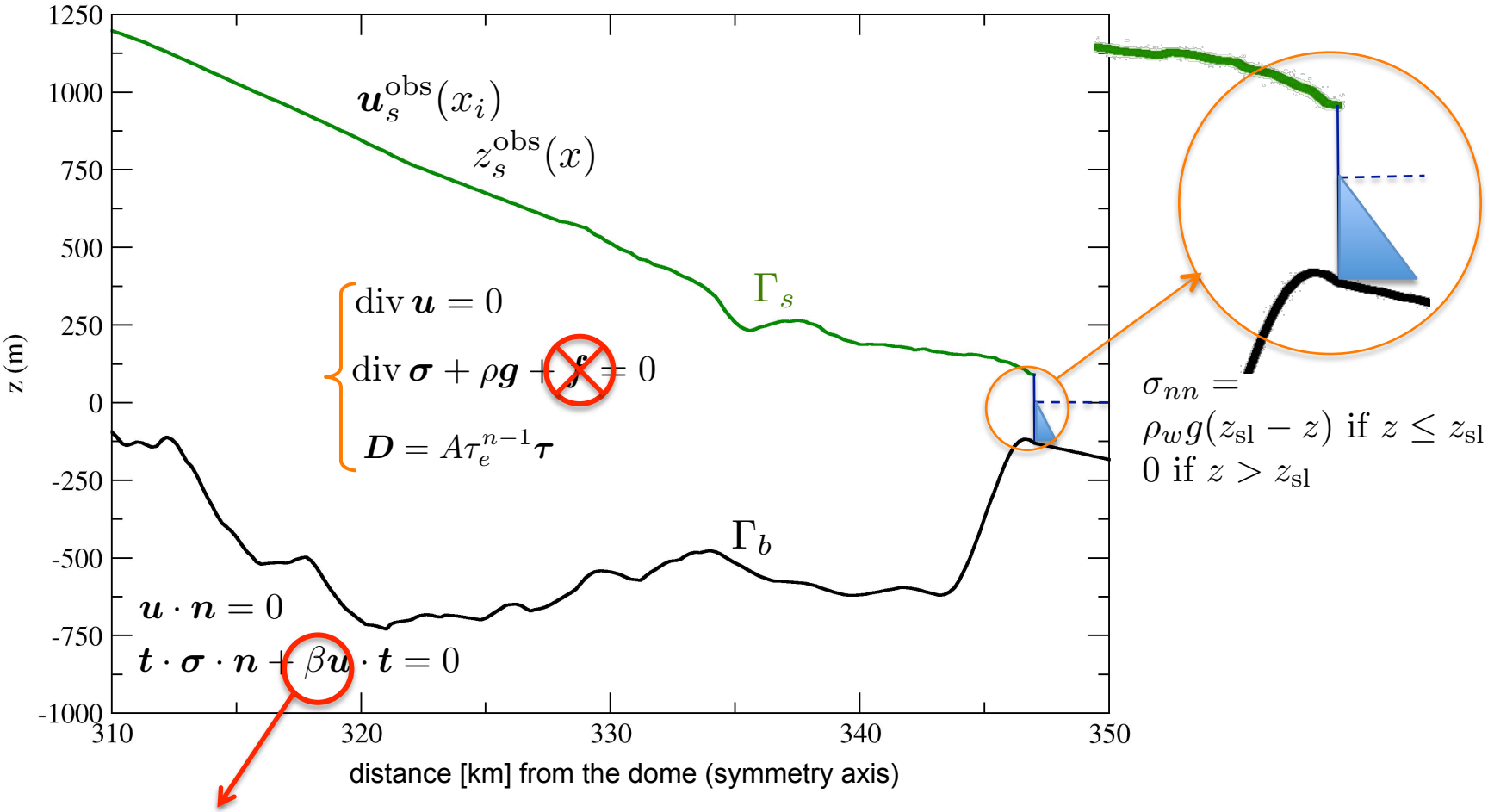
Surface + velocity in 2001, 2003, 2004, 2005, 2006

(not exactly synchronized, but will survive with this)

Question :

how basal conditions have involved between 2001 to 2006 all other things being equal ?

Geometry and BC



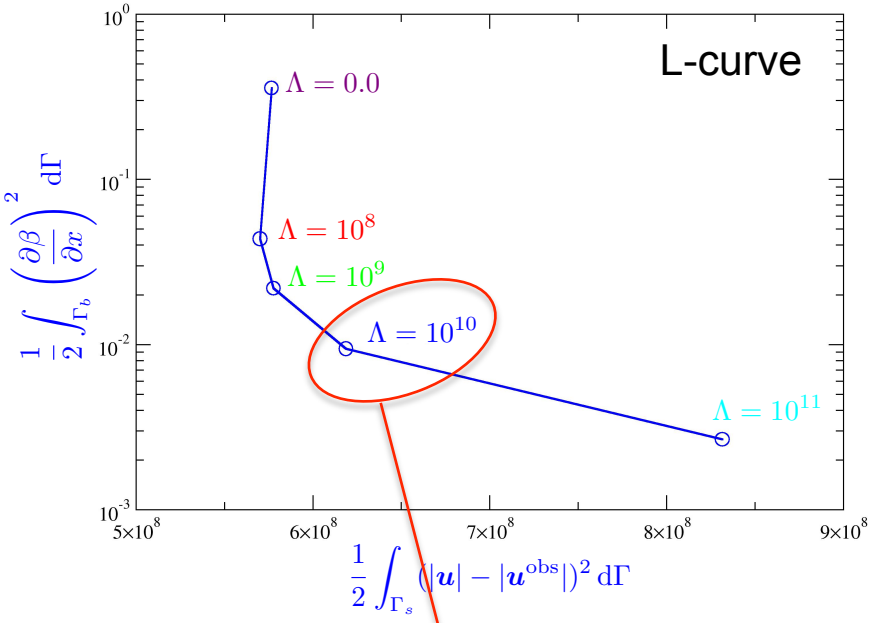
$$j(\boldsymbol{\beta}) = \frac{1}{2}\int_{\Gamma_s}(|\boldsymbol{u}| - |\boldsymbol{u}^{\rm obs}|)^2\,\mathrm{d}\Gamma + \underbrace{\frac{1}{2}\Lambda\int_{\Gamma_b}\left(\frac{\partial\beta}{\partial x}\right)^2\mathrm{d}\Gamma}_{\text{Tikhonov regularization}}$$

β , control parameters, account for both basal and lateral frictions

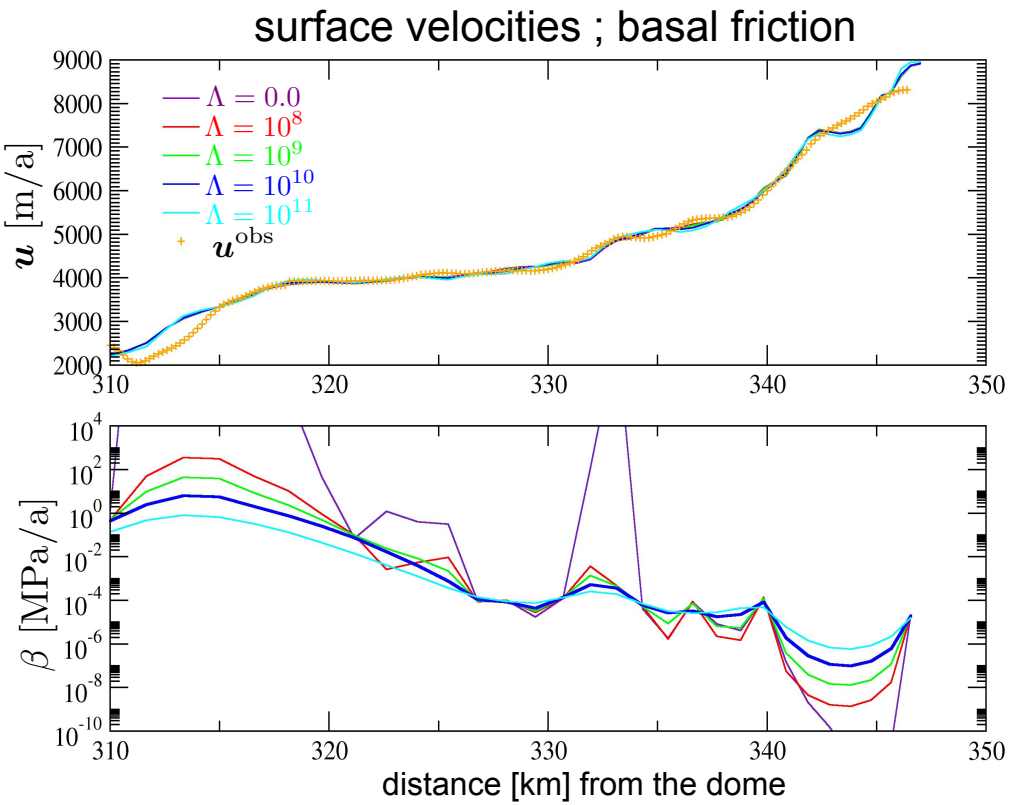
Effect of the penalization : L-curve

Find the best compromise between
reproducing the observations and having a relatively smooth $\beta(x)$

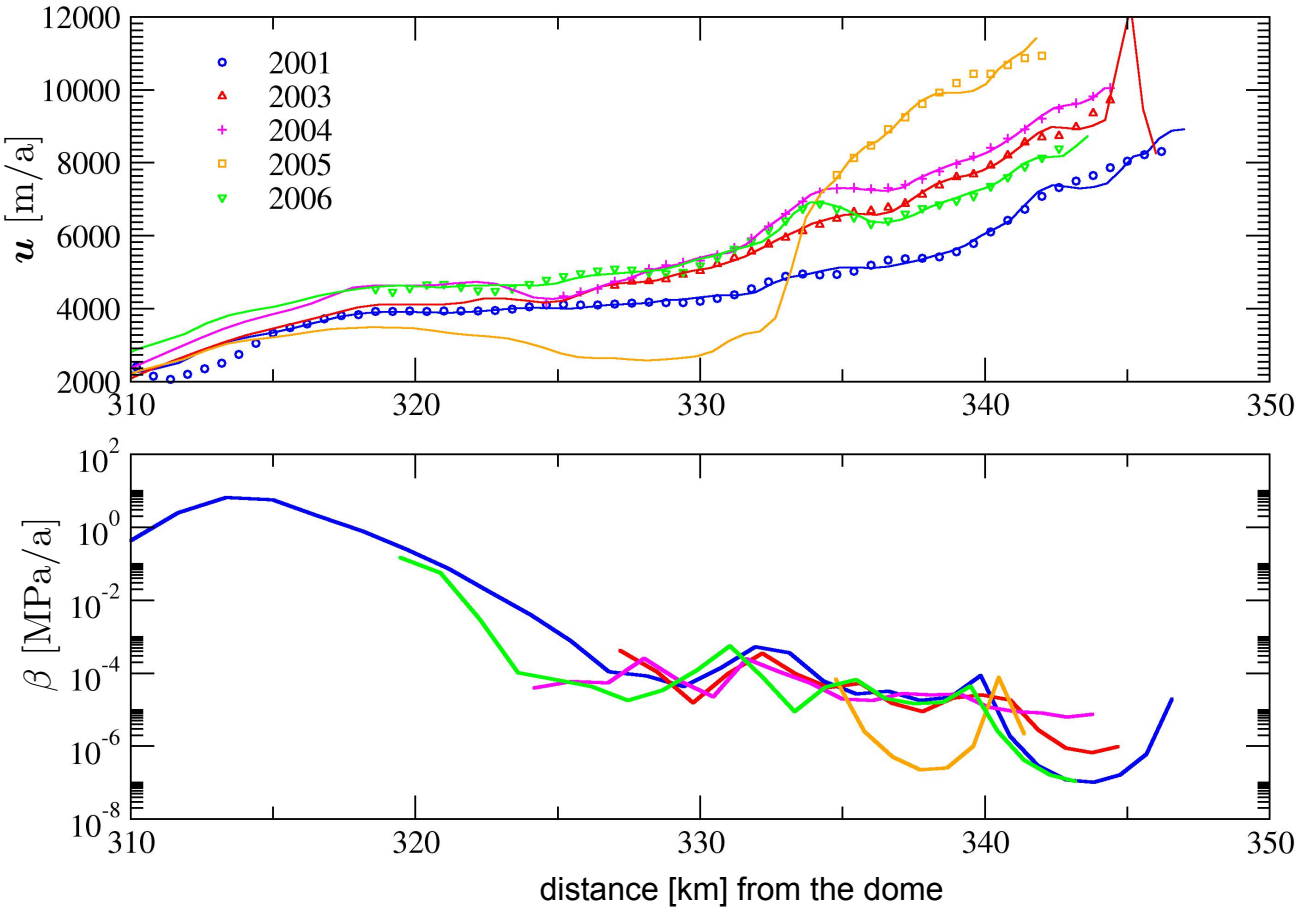
On the 2001 dataset



Adopt the same penalization $\Lambda = 10^{10}$ for all the datasets



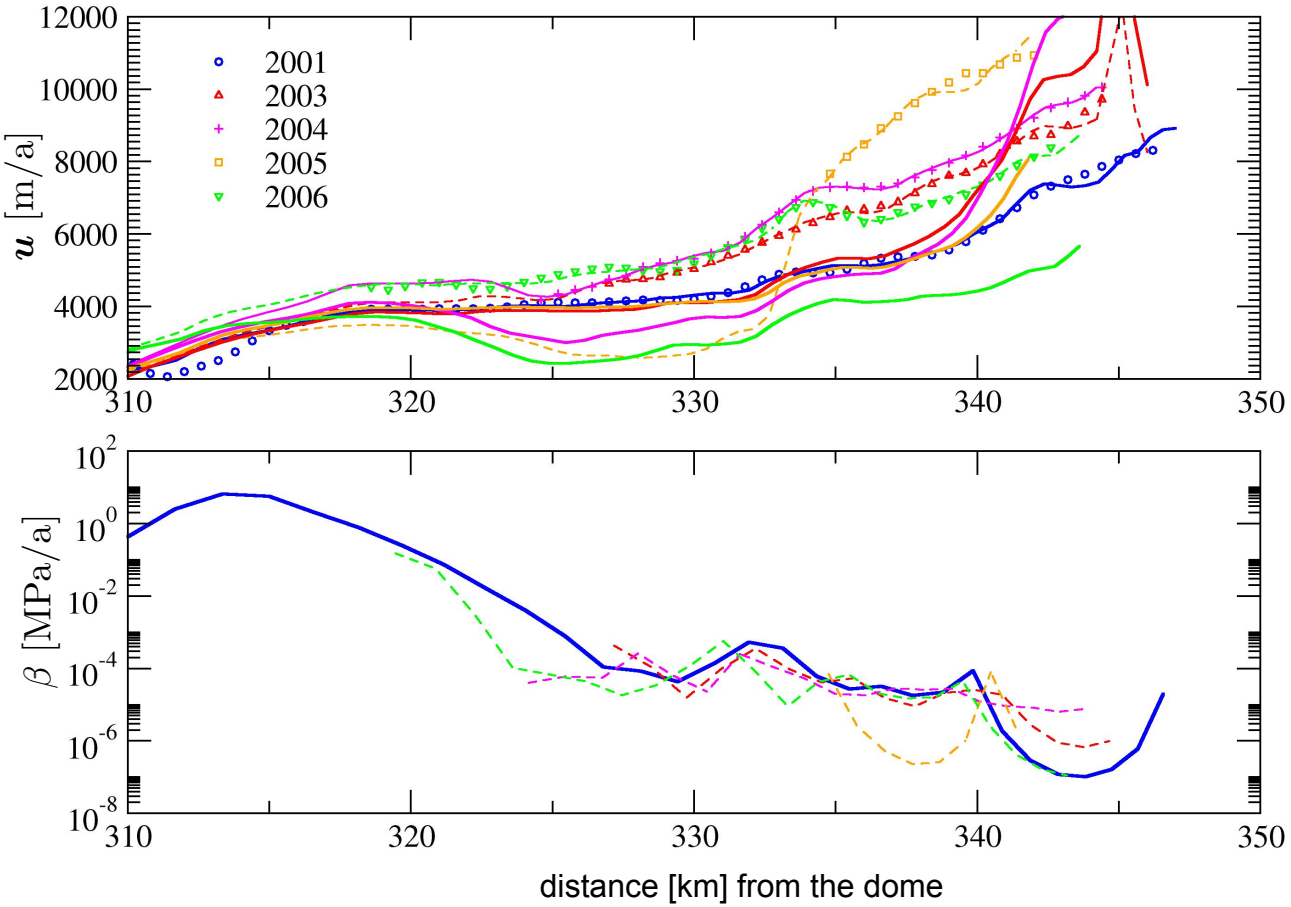
Evolution of β from 2001 to 2006



What can we conclude ? Are the modelled changes of β significant ?

What would be the surface velocities with a constant β (that one of 2001) ?

Velocities with a constant β (2001)



"Small" changes of β seem to have large impact on surface velocities !

Conclusions

✓ Adjoint model useful for data assimilation but also sensitivity experiments

✓ Sensitivity experiments allows to locate places / dates of strongest influence and estimate which control parameters have the most influence

✓ Difficult to discriminate the signature of changes in front stress to changes in basal sliding near the front