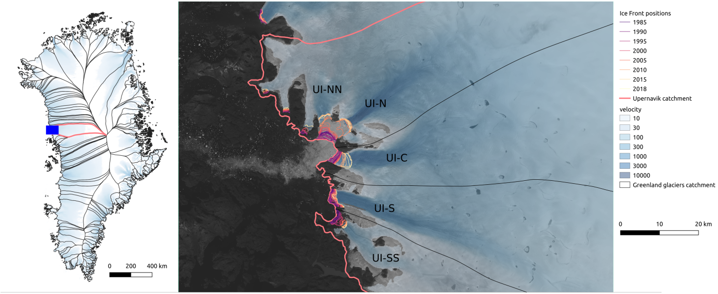
Ensemble simulation for ice sheet model initialisation

Method and application to Upernavik Isstrøm



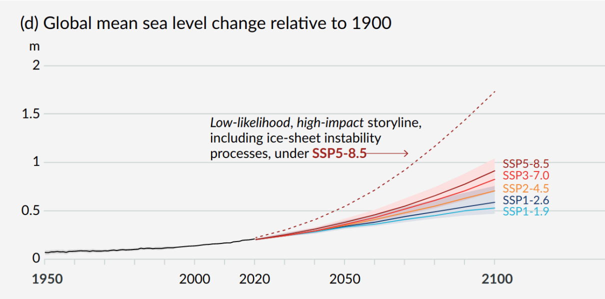
Eliot Jager (PhD sudent / 3rd year)

IGE, CNRS, Université Grenoble-Alpes

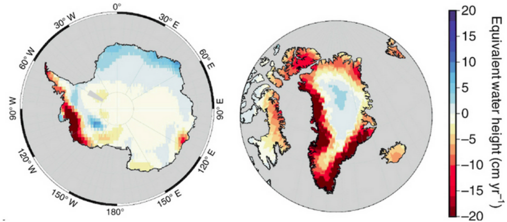
Supervisors : Gillet-Chaulet Fabien, Champollion Nicolas, Mouginot Jérémie

Tuesday April 4th 2023

Sea level rise



source : IPCC AR6 Summary for policymakers



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- High uncertainties of the future of AIS and **GrIS**

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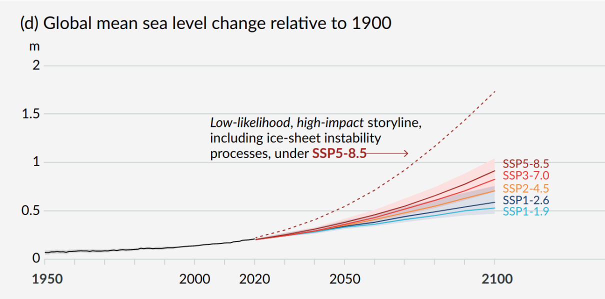

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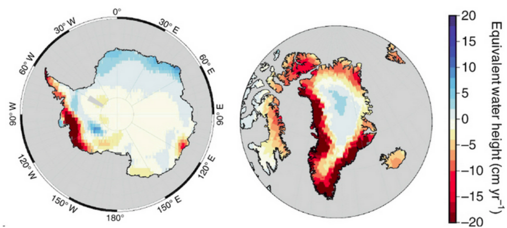

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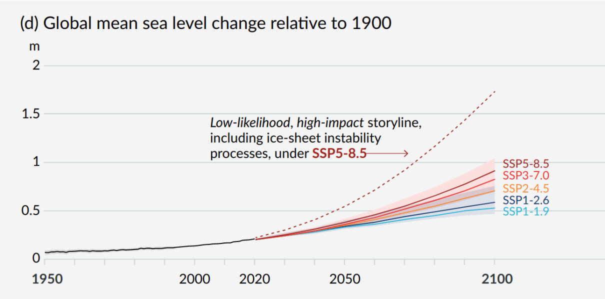

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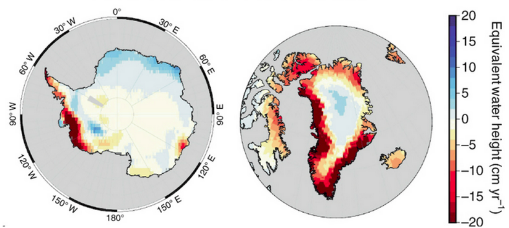

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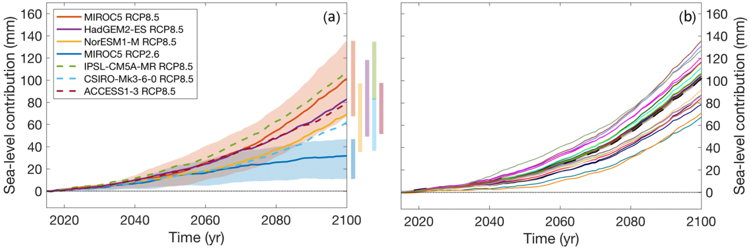
ISMIP6 Greenland



Ensemble sea-level projections. a) Different GCM for all ISM. b) Different ISM results for one forcing (Heiko Goelzer et al.)

State of the art for sea-level projection :

- Great representation of uncertainty related to GCM and different ISM
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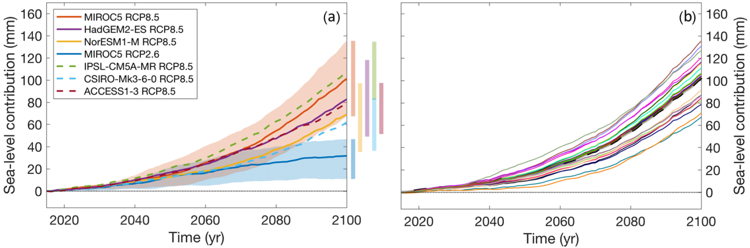

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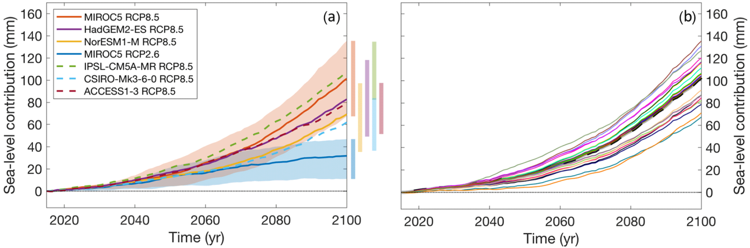

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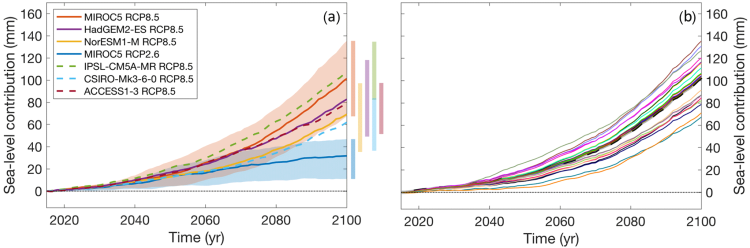

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1. Uncertainty quantification for our local ISM : Elmer/Ice
2. Ability of Elmer/Ice to represent past changes : velocity, elevation, ice discharge and ice mass loss

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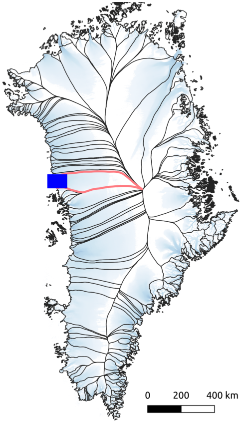
Why Upernavik Isstrøm ?



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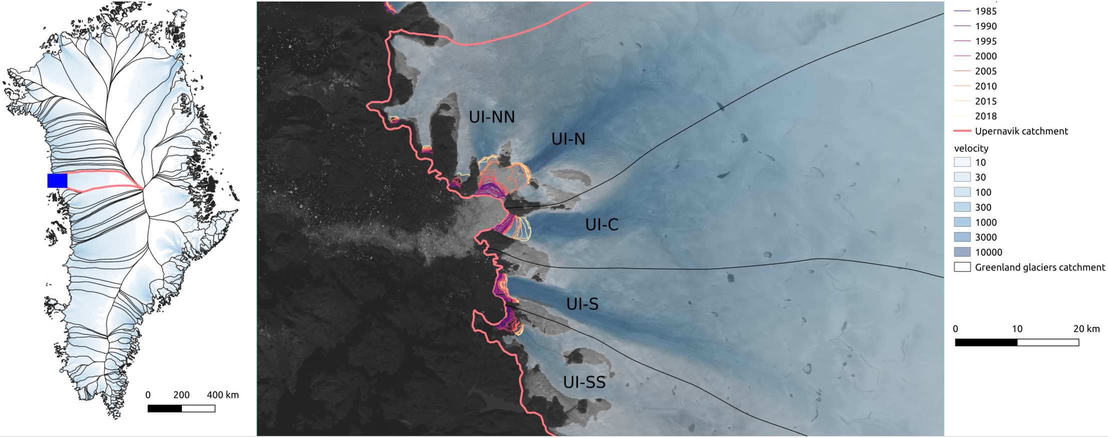
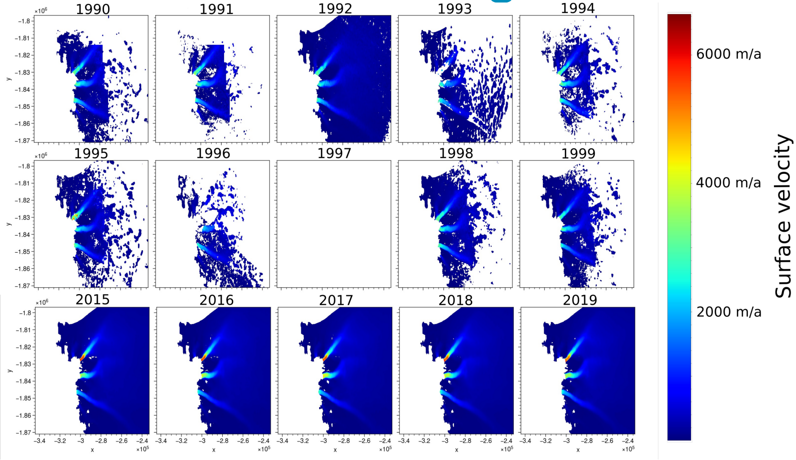


Upernavik Isstrøm catchment situation and front evolution since 1985

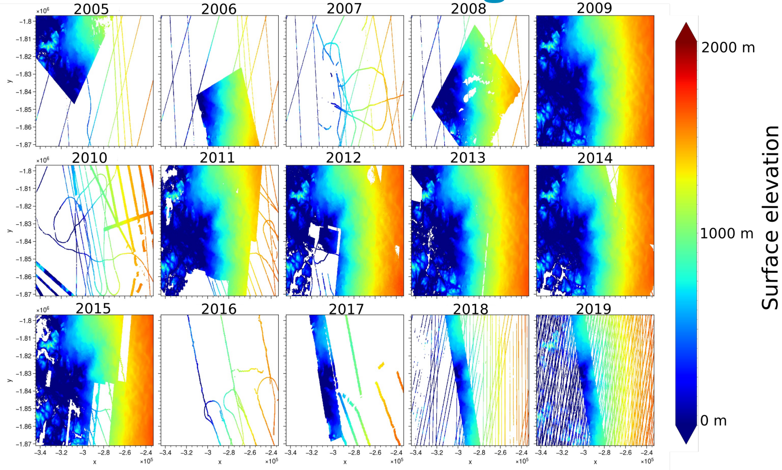
Big data era



Velocity maps of Upernavik Isstrøm (90's and 2010's)

- Increase of velocity and elevation observations ⇒ How can we use this increasing amount of data to better constrain the uncertain initial parameters?

Big data era



Elevation maps of Upernavik Isstrøm (2005-2019)

- Increase of velocity and elevation observations ⇒ How can we use this increasing amount of data to better constrain the uncertain initial parameters?

Uncertainty quantification

1. Which variables are uncertain?
2. Putting it in the form of a probability law
3. Drawing parameter sets by Latin Hypercube sampling

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Inverse method uncertainties

$$J = J_0 + \lambda_{reg} J_{reg} + \lambda_{div} J_{div}$$

$$J_0 = \sum_{i=1}^{N_{obs}} \frac{1}{2} (||\mathbf{u}_i^{\mathbf{mod}} - \mathbf{u}_i^{\mathbf{obs}}||)^2$$

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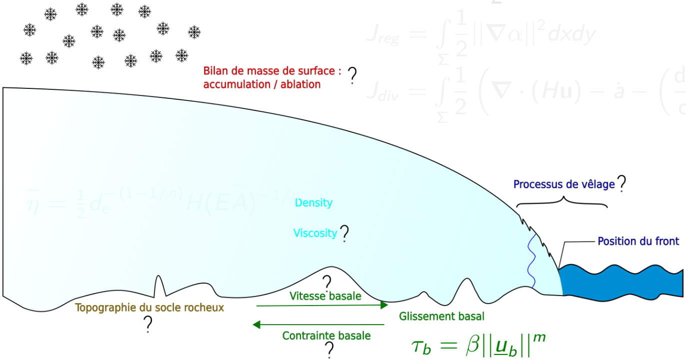

Uncertain parameters :

- **friction law (m)**
- viscosity (E)
- year of observation velocity (u_{obs})
- weight of cost functions (λ_{reg} et λ_{div})

Processes influencing glacial dynamics and their uncertainties

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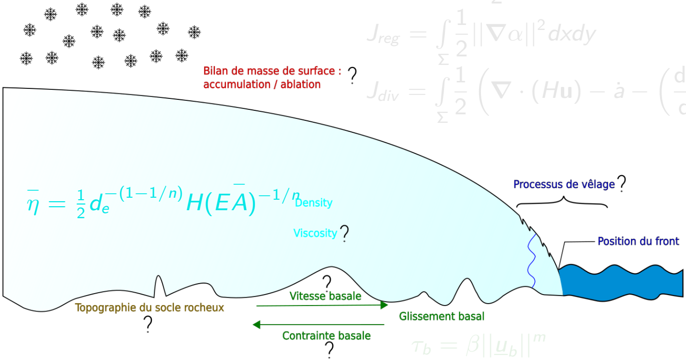

$$\bar{\eta} = \frac{1}{2} d_e^{-(1-1/n)} H(E\bar{A})^{-1/n}$$

$$\tau_b = \beta ||\underline{u}_b||^m$$

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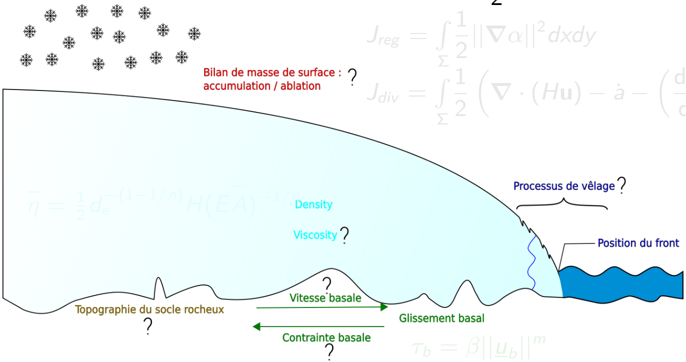

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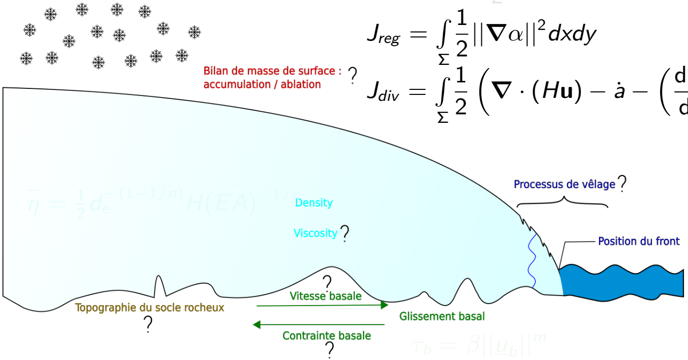

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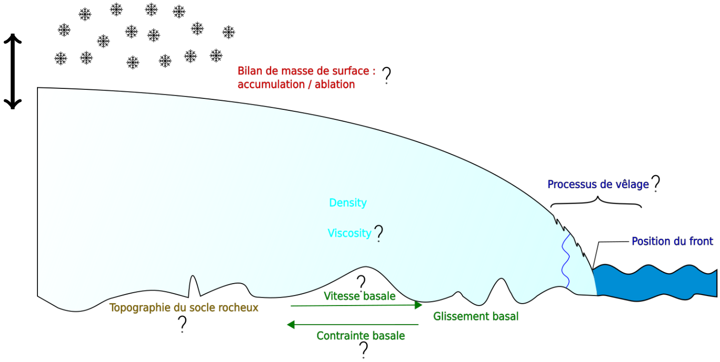
Processes influencing glacial dynamics and their uncertainties

Initial surface uncertainty

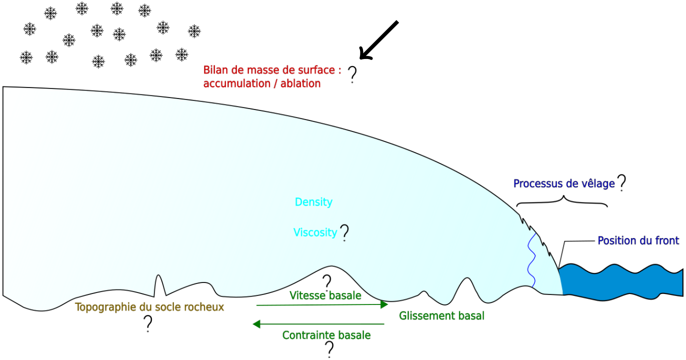


Processes influencing glacial dynamics and their uncertainties

Variable parameters :

- Relaxation time t_{relax}
- Constant surface mass balance SMB_{date}

Forcing uncertainty



Uncertain parameters :

- Two different SMB models (SMB_{model})
- No uncertainty of front position

Processes influencing glacial dynamics and their uncertainties

Experimental design

Results for the ensemble using the regularised Coulomb law:

1. Drawing of uncertain parameter sets
2. Inversions to calibrate β_{RC} with data from the 2010-2020 period
3. Ensemble of surfaces obtained with relaxations (constant forcing)
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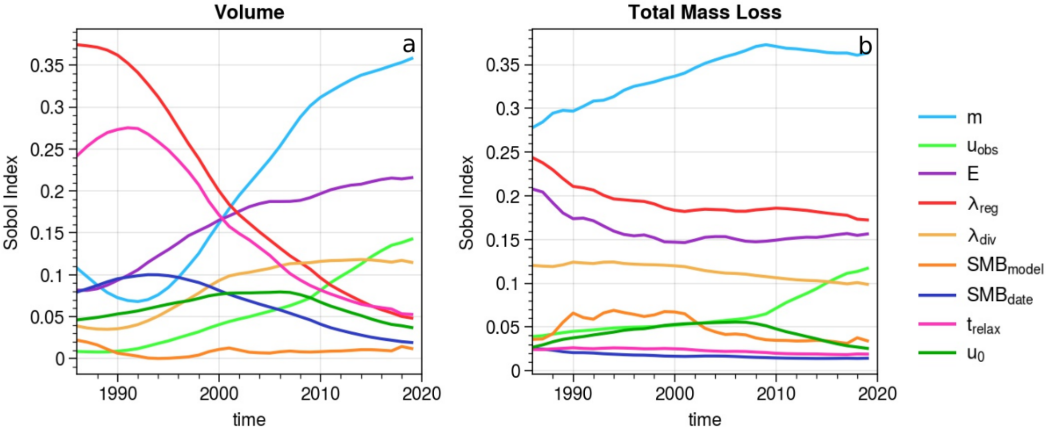
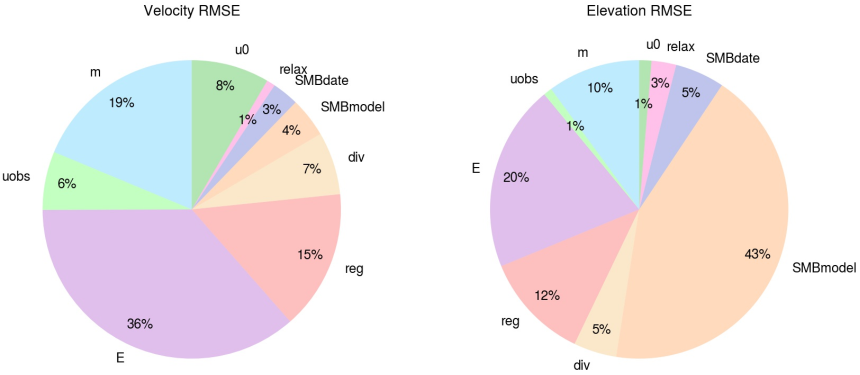
Global variables



Sobol index for volume and mass change for RCE over time

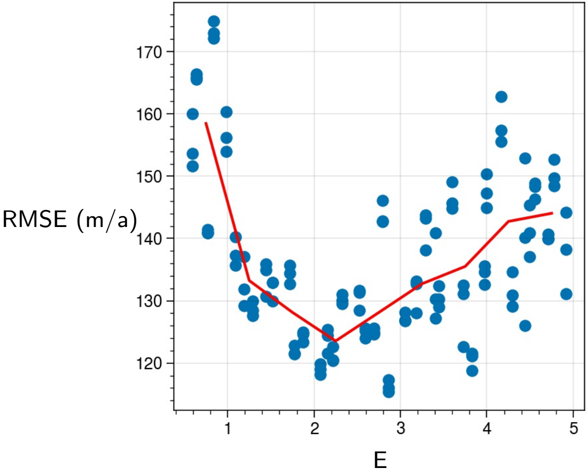
Influence on scores

Sobol Index



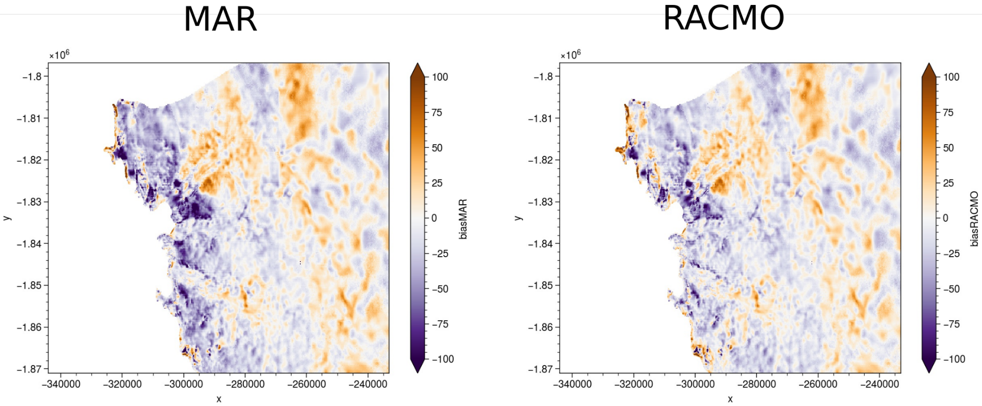
Sobol index for RMSE on velocities (left) and elevations (right)

Influence of E



RMSE in function of E

Influence of SMB



Bias for the mean member depending on the SMB model used

Take home messages

1. Initial surface has little influence on total mass loss
2. The calibration parameters have a strong influence on the different quantities
3. Possibility to refine uncertain parameters (E, SMB_{model})

Jager et al., 2023, JOG, (submitted)

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Conclusion on the method

Our new initialisation method:

1. reproduces the past trend without bias and we arrive at a dynamic state ensemble close to reality ⇒ Allows confidence in projections.
2. allows the representation of internal uncertainty of our ISM Elmer/Ice

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Perspectives

1. Upernavik projections : the importance of uncertainties related to dynamics (friction, rheology) compared to those related to forcing (surface mass balance, interaction with the ocean); Jager et al., 2023, (in prep.)
2. Assessment projections : What is the right way to score members to evaluate projections ? Jager et al., 2023, (in prep.)
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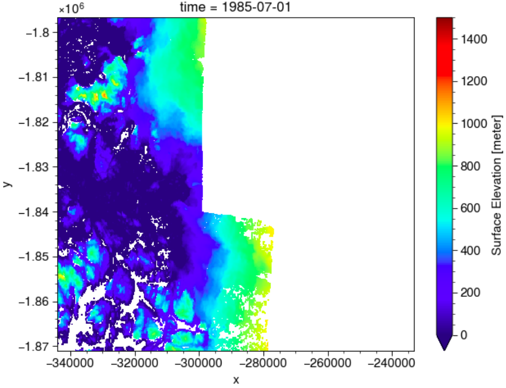
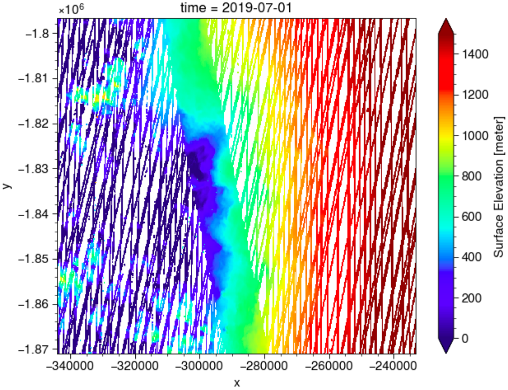
References

- Front positions : Wood et al. 2021
- Velocity : Joughin et al. 2018, Mouginot et al. 2017, Derkacheva et al. 2020
- Elevation : Howat et al. 2017, Howat et al. 2014, Korsgaard 2016, Brunt 2016, Moller 2019
- Bedmachine : Morlighem et al. 2017
- Assimilation : Gillet-Chaulet 2020
- Elmer/Ice : Gagliardini et al. 2013
- Numerical environnement : Most of the computations presented in this study were performed using the GRICAD infrastructure (https://gricad.univ-grenoble-alpes.fr), which is supported by Grenoble research communities.

Observations





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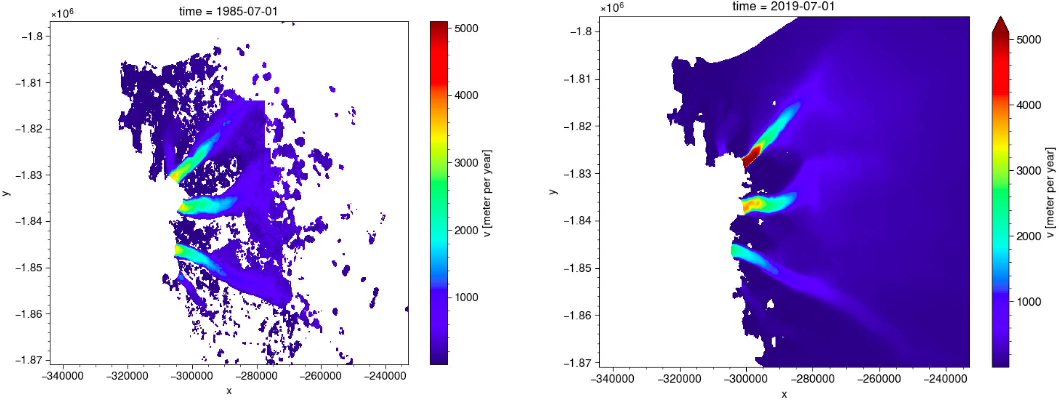
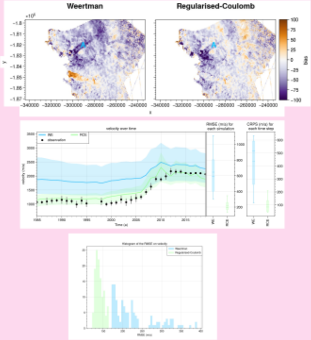


Analyse

Scores :

bias, RMSE, CRPS



What we do

1. Part of the data used for calibration and initialisation.
2. A large part of it is kept for validation! The scores allow the performance of the model to be quantified.
3. For greater robustness of the results, a set of simulations is carried out: this makes it possible to take into account the uncertainties of the calibration, the initialization, the forcing and the physical assumptions

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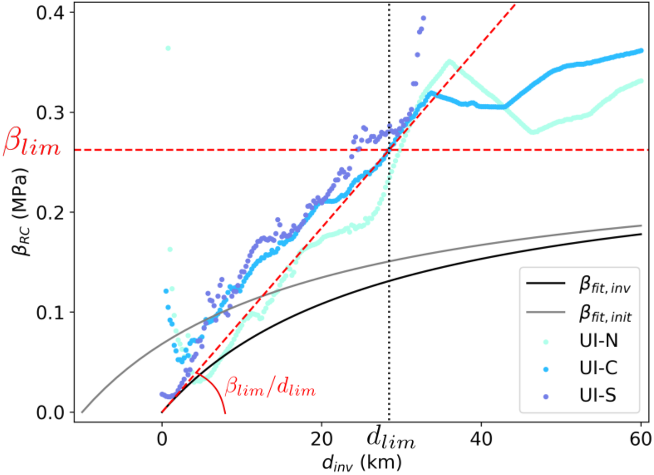

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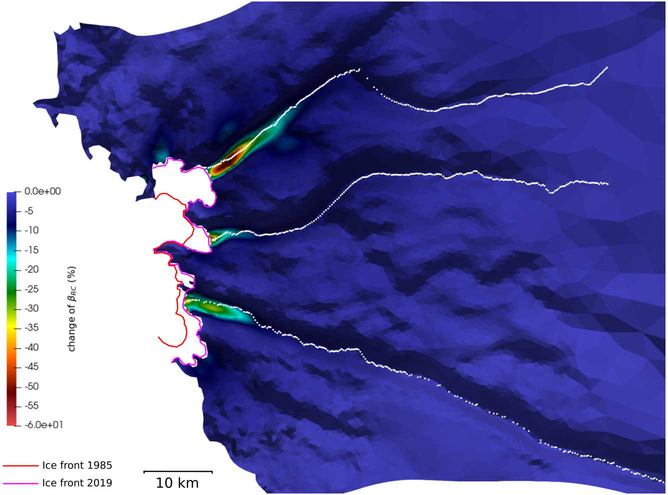
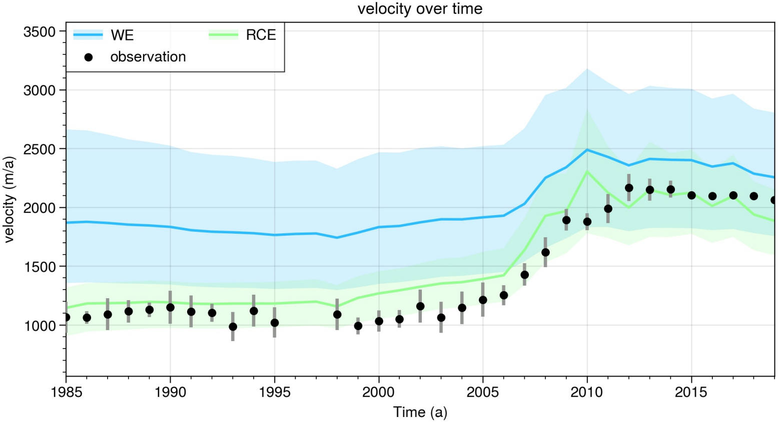
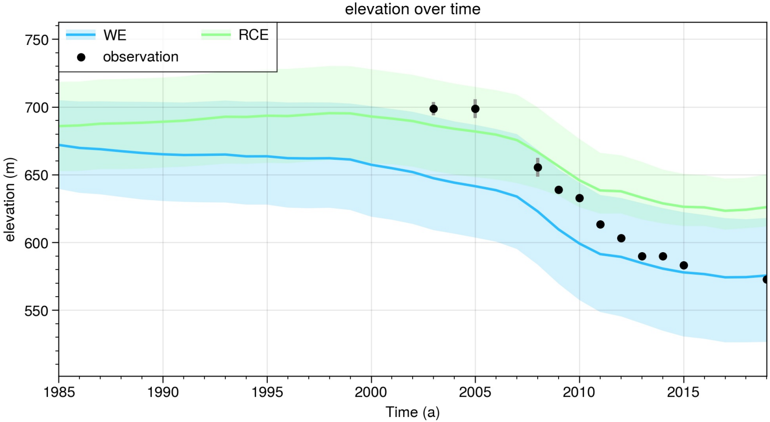


Transient: velocity



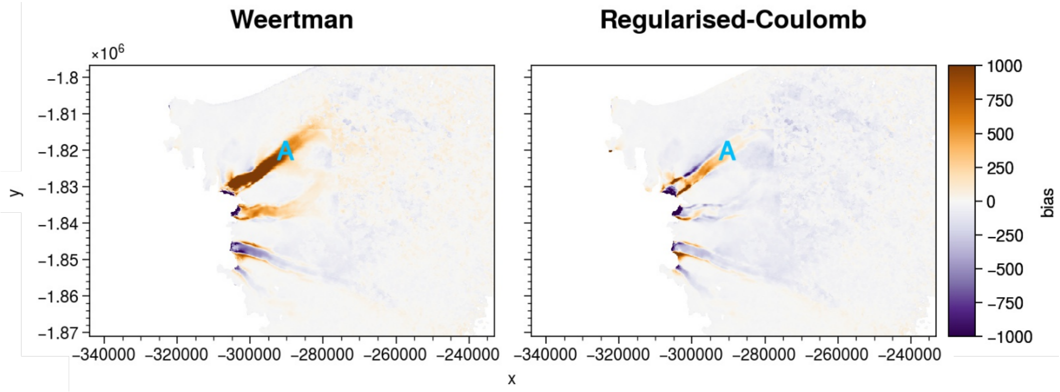
Changes in WE and RCE velocities over time at point A (UI-N)

Transient: elevation



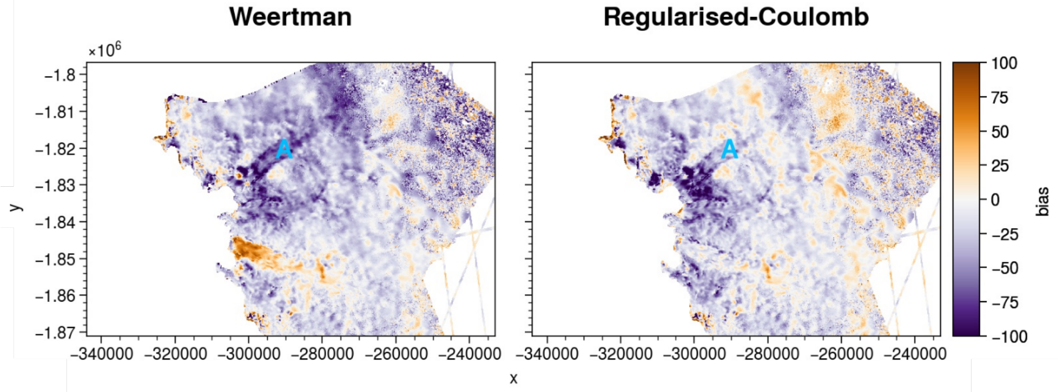
Changes in WE and RCE elevations over time at point A (UI-N)

Initial period : velocities



Surface velocity bias of the **ensemble mean** during the period 1985-2005

Initial period : elevations



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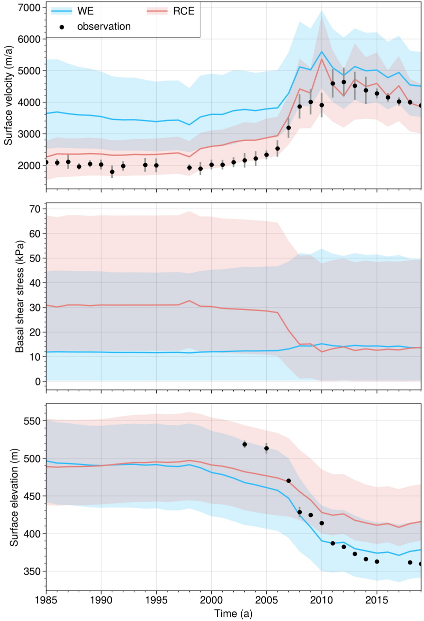
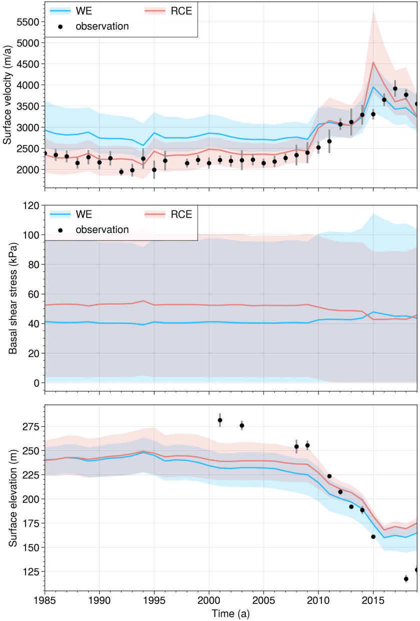
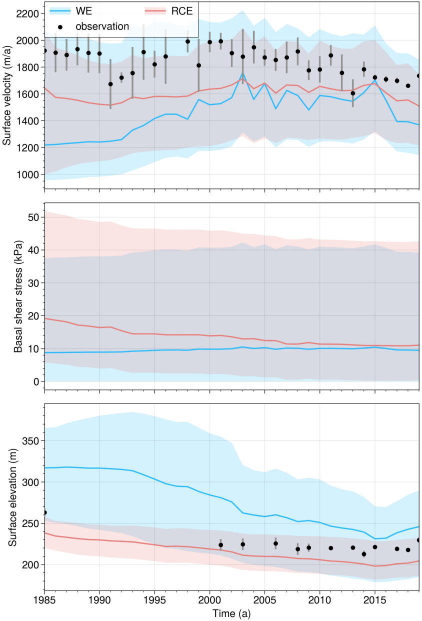
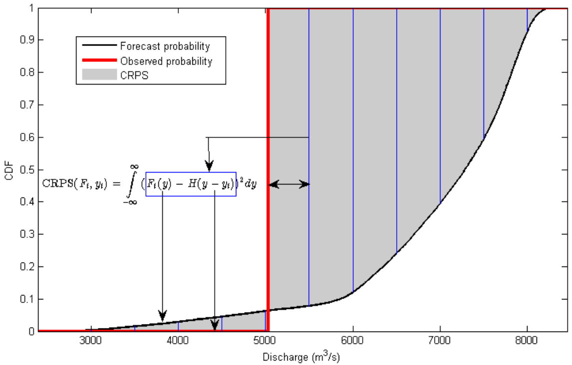

WE
RCE
observation
Surface velocity (m/a)
7000
6000
5000
4000
3000
2000
Basal shear stress (kPa)
70
60
50
40
30
20
10
0
Surface elevation (m)
550
500
450
400
350
1985
1990
1995
2000
2005
2010
2015
Time (a)


WE
RCE
observation
Surface velocity (m/a)
5500
5000
4500
4000
3500
3000
2500
2000
WE
RCE
observation
Basal shear stress (kPa)
120
100
80
60
40
20
0
Surface elevation (m)
275
250
225
200
175
150
125
1985
1990
1995
2000
2005
2010
2015
Time (a)


WE
RCE
observation
Surface velocity (m/a)
2200
2000
1800
1600
1400
1200
1000
Basal shear stress (kPa)
50
40
30
20
10
0
Surface elevation (m)
350
300
250
200
1985
1990
1995
2000
2005
2010
2015
Time (a)

Scores

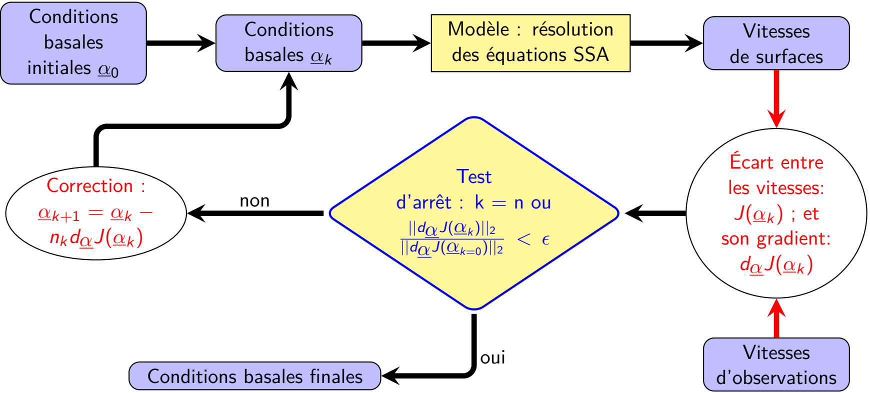


Calculation of the CRPS (source : Matlab site, by Durga Lal Shrestha)

Two different scores for simulation :

- The Root Mean Square Error allow us to compare simulations one by one
- The Continuous Rank Probability Score allow us to compare different ensemble of simulation : if we are overconfident, we will have a bad score if the observation is outside of the spread. However, if we catch the observation, a thinner spread will have a better score.

Inverse method



Conditions basales initiales $\underline{\alpha}_0$

Conditions basales $\underline{\alpha}_k$

Modèle : résolution des équations SSA

Vitesses de surfaces

Écart entre les vitesses: $J(\underline{\alpha}_k)$; et son gradient: $d_{\underline{\alpha}} J(\underline{\alpha}_k)$

Vitesses d'observations

Test d'arrêt : k = n ou $\frac{||d_{\underline{\alpha}} J(\underline{\alpha}_k)||_2}{||d_{\underline{\alpha}} J(\underline{\alpha}_{k=0})||_2} < \epsilon$

non

Correction : $\underline{\alpha}_{k+1} = \underline{\alpha}_k - n_k d_{\underline{\alpha}} J(\underline{\alpha}_k)$

oui

Conditions basales finales

Add a regularisation function to smooth the obtained solution and a flow divergence function to minimise the difference between the observed and modelled one. Weighting by 2 coefficients: λ_{reg} and λ_{div}.

Diagram of how the inverse method works in glaciology, inspired by `https://interstices.info/`

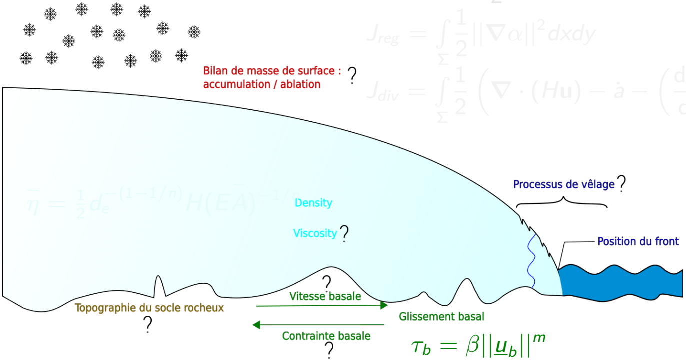
Inverse method uncertainties

$$J = J_0 + \lambda_{reg} J_{reg} + \lambda_{div} J_{div}$$

$$J_0 = \sum_{i=1}^{N_{obs}} \frac{1}{2} (||\mathbf{u_i^{mod}} - \mathbf{u_i^{obs}}||)^2$$

$$J_{reg} = \int_\Sigma \frac{1}{2} ||\nabla \alpha||^2 dxdy$$

$$J_{div} = \int_\Sigma \frac{1}{2} \left(\nabla \cdot (H\mathbf{u}) - \dot{a} - \left(\frac{\mathrm{d}H}{\mathrm{d}t} \right)_{obs} \right)^2 dxdy$$



Uncertain parameters :

- **friction law (m)**
- viscosity (E)
- year of observation velocity (u_{obs})
- weight of cost functions (λ_{reg} et λ_{div})

Processes influencing glacial dynamics and their uncertainties

Inverse method uncertainties

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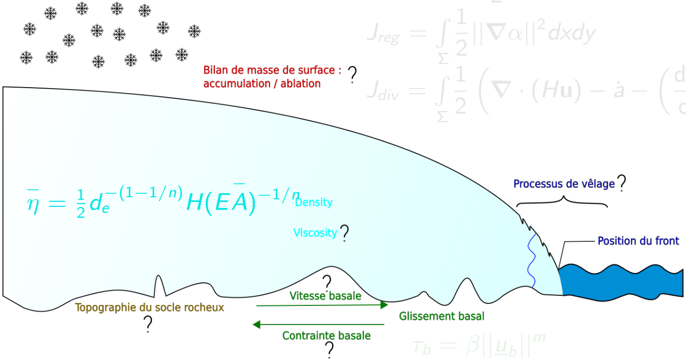

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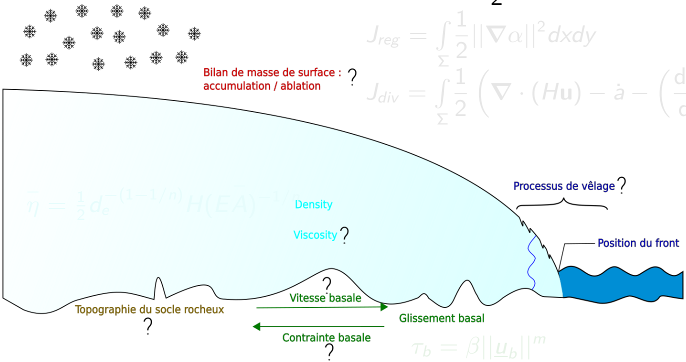

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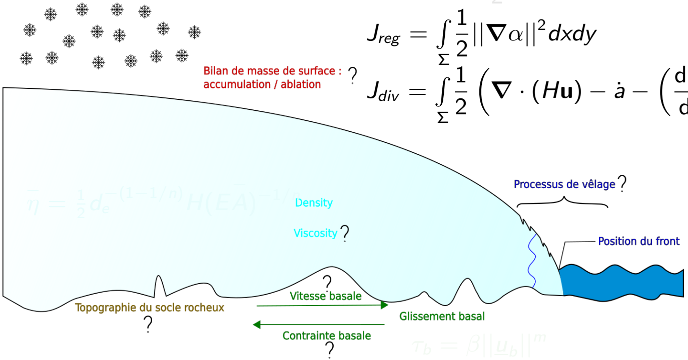

$$\overline{\eta} = \frac{1}{2} d_e^{-(1-1/n)} H (E\overline{A})^{-1/n}$$

$$\tau_b = \beta ||\underline{u}_b||^m$$

Processes influencing glacial dynamics and their uncertainties

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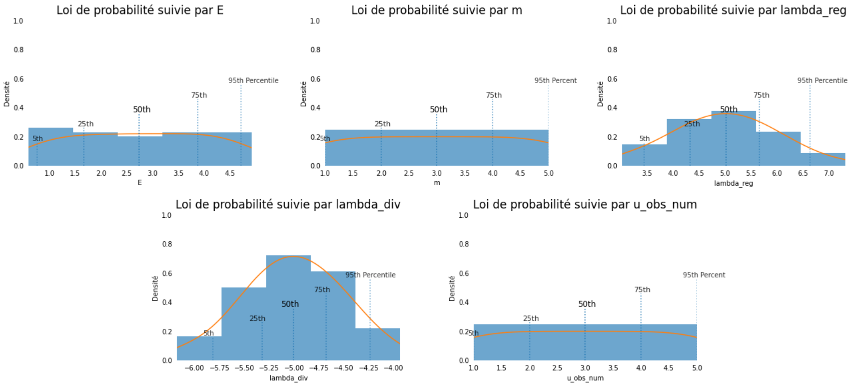
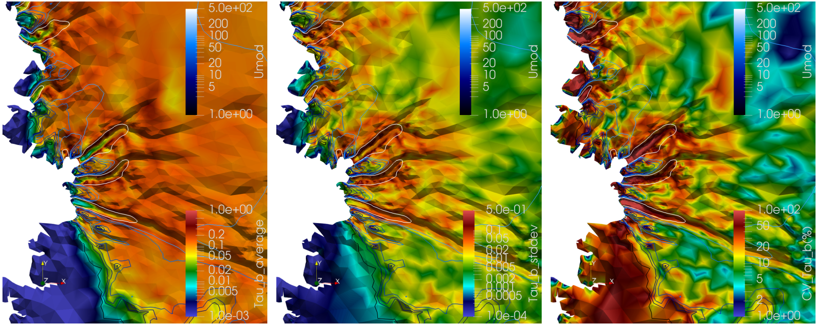
Probability laws



Les lois de probabilités de chaque paramètre

2. Putting uncertainties into the form of a probability law
3. Random draw (Latin Hypercube actually) for each of the 40 parameter sets (40 simulations)
4. For each set of parameters, an inversion is performed to obtain a friction field

Final results

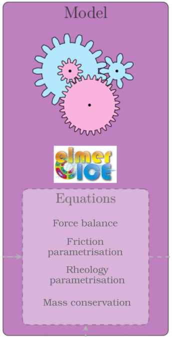


Mean, standard deviation (MPa) and coefficient of variation (in %) of basal stresses for the set of inversions in the Upernavik area.

5. We obtain a set of friction fields and basal stresses that represent our uncertainty about these parameters.

Take home messages

1. Creation of an ensemble of friction fields representative of the uncertainty on this parameter (low confidence due to not taking into account topography changes and modelling uncertainties).
2. Reusable ensemble for simulations/projections with Elmer/Ice (or others ISM ;)).



Model

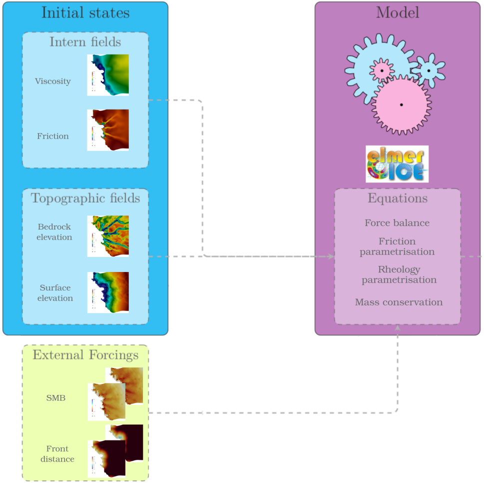
Equations

Force balance

Friction parametrisation

Rheology parametrisation

Mass conservation


Initial states
Intern fields
Viscosity
Friction
Topographic fields
Bedrock elevation
Surface elevation
External Forcings
SMB
Front distance
Model
elmer ICE
Equations
Force balance
Friction parametrisation
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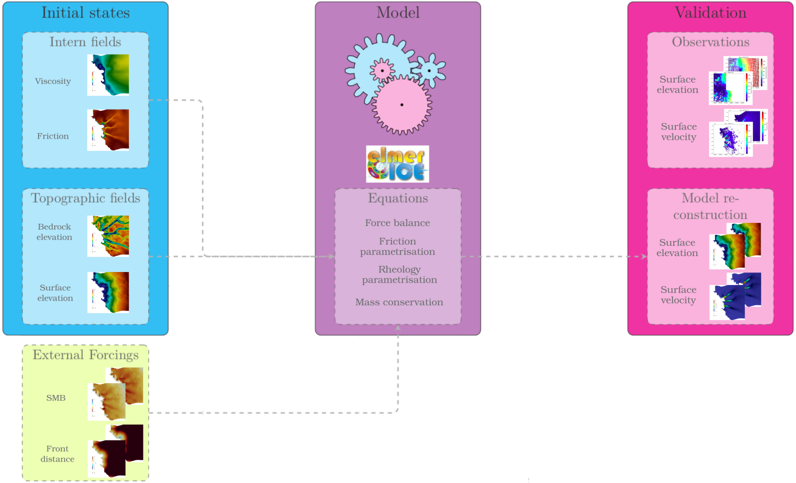

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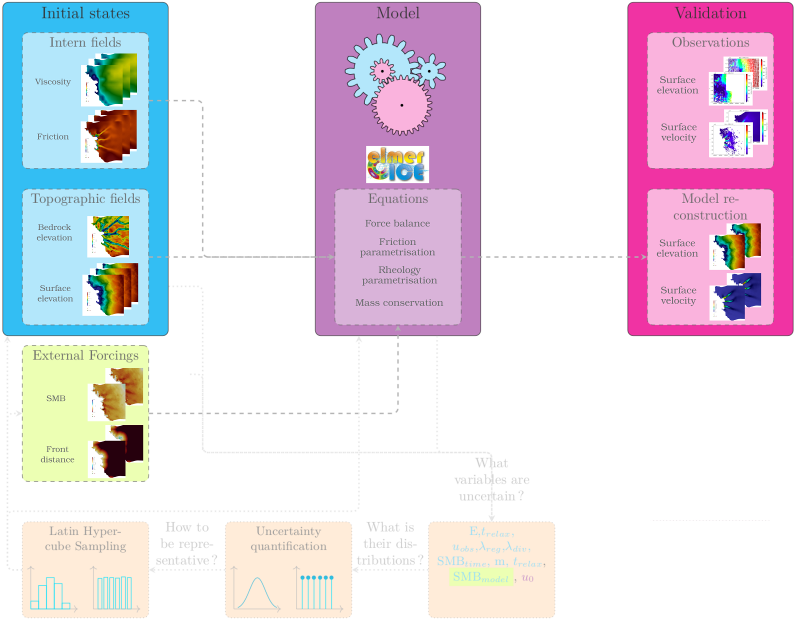
Validation

Observations
- Surface elevation
- Surface velocity

Model re-construction
- Surface elevation
- Surface velocity



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Model reconstruction

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Surface velocity

What variables are uncertain ?

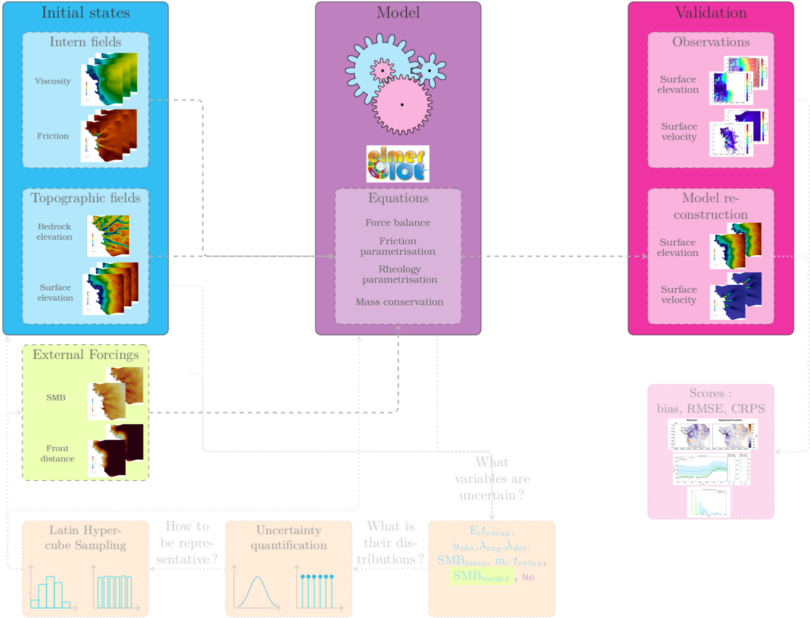
$E, t_{relax}, u_{obs}, \lambda_{reg}, \lambda_{div}, SMB_{time}, m, t_{relax}, SMB_{model}, u_0$

What is their distributions ?

Uncertainty quantification

How to be representative ?

Latin Hypercube Sampling



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Scores : bias, RMSE, CRPS

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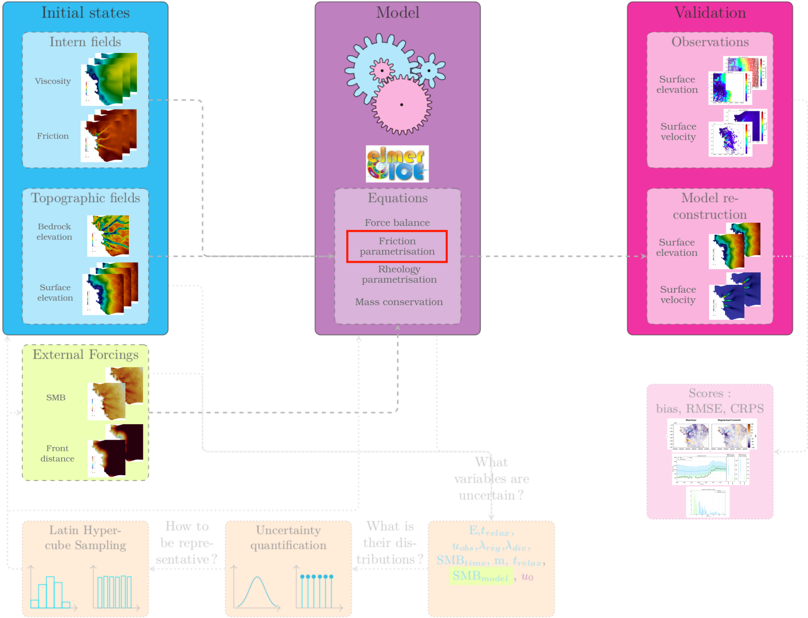

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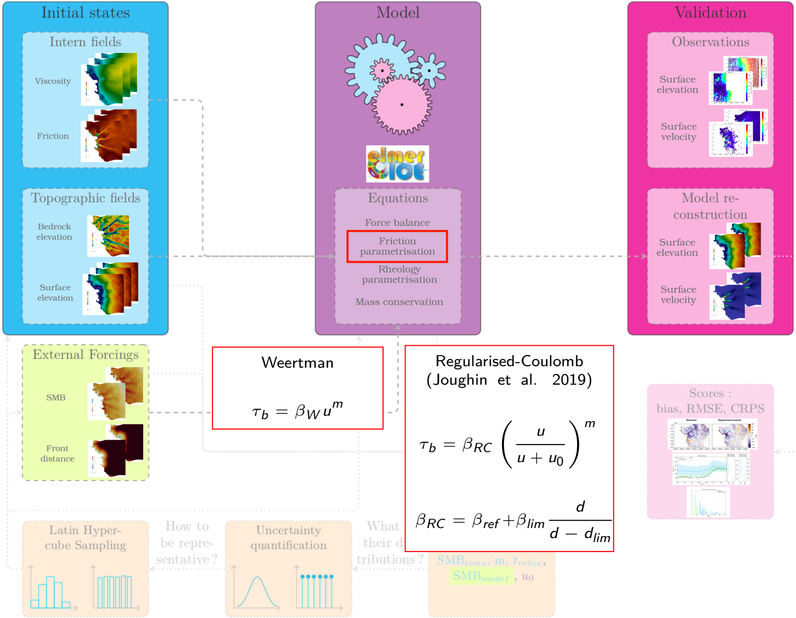

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Latin Hyper-cube Sampling

How to be repre-sentative ?

Uncertainty quantification

What their d
tributions ?

SMB_{time}, m, t_{relax}, SMB_{model}, u_0

Weertman

$$\tau_b = \beta_W u^m$$

Regularised-Coulomb (Joughin et al. 2019)

$$\tau_b = \beta_{RC} \left(\frac{u}{u + u_0} \right)^m$$

$$\beta_{RC} = \beta_{ref} + \beta_{lim} \frac{d}{d - d_{lim}}$$

Experimental design

1/ for a given friction law, the parameters that vary in the ensemble :

- Initial friction field obtain by **inverse method**, calibrated with data of the **2010-2020 period**
- Initial surface elevation obtain after a **relaxation**
- Forcing (SMB)
- Dynamic laws (friction, rheology)

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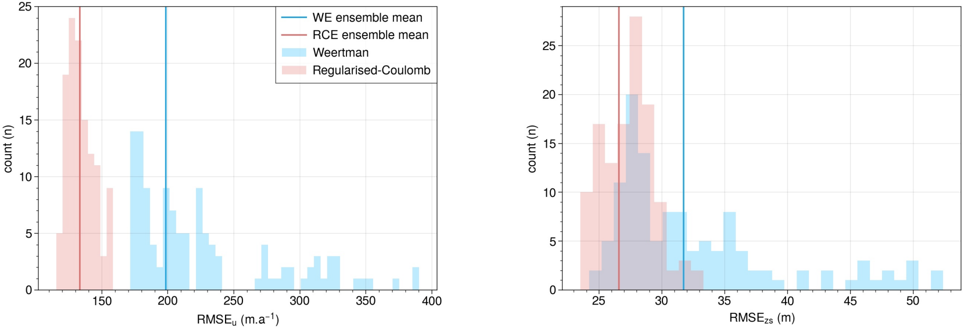
2/ **2 ensemble** simulations with **different friction parameterisations** where the position of the front and the surface mass balance are forced **between 1985 and 2019**. Each ensemble has **120 members**.

3/ Validation with data :

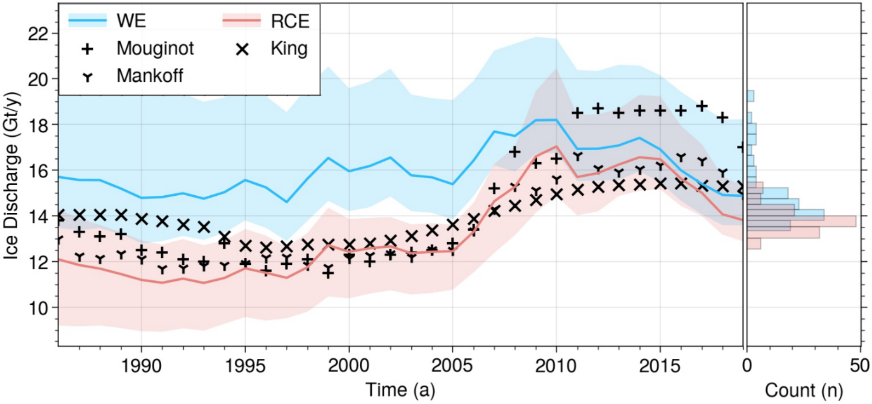
- Surface elevation
- Surface velocity
- Ice discharge
- Volume changes

In a nutshell



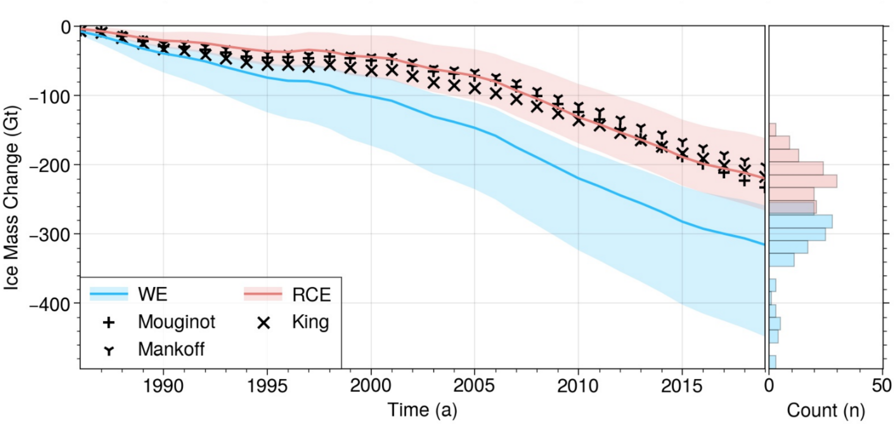
Distribution of WE and RCE RMSE for the surface velocity (left) and the surface elevation (right) in the validation area over the full period (1985-2019)

Global variables: Ice discharge



Ice discharge evolution for **Weertman Ensemble (WE)** and **Regularised-Coulomb Ensemble (RCE)** between 1985 and 2019

Global variables: Ice mass loss



Ice mass change for Weertman Ensemble (WE) and Regularised-Coulomb Ensemble (RCE) between 1985 and 2019

Take-home messages

1. Weertman : unable to reproduce observations under geometric conditions different from those of the calibration + unable to reproduce the acceleration.
2. Regularised-Coulomb with a parameterisation that reduces the friction near the front addresses these 2 issues.
3. Choices of extrapolation can have huge impact for historical reconstruction.
4. A good reproduction of velocities and partly of elevations allows to reproduce the observations of ice discharges and ice volume changes.

Jager et al., 2023, JOG, (submitted)

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