Inferring mantle viscosity through data assimilation of relative sea-level observations in a glacial isostatic adjustment model

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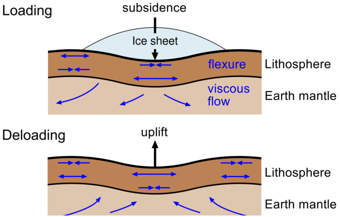
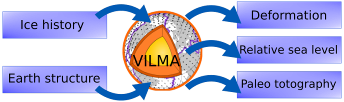
Overview

- Assimilation of relative sea level observations in GIA model VILMA
- Estimation of **mantle viscosities** with the help of a particle filter
- Sandbox experiment with observations taken from reference run (identical twin setup)
- Assimilation of **sea level rates of change**
- Two viscosity distribution parameterizations:
  1. 3-layer model with two viscous mantle layers and (fixed) elastic lithosphere
  2. 1D profile with 152 viscous mantle layers and (fixed) elastic lithosphere

VILMA





- Model for Earth's visco-elastic deformation due to glaciation / deglaciation
- Forward modelling of visco-elastic response of spherical Earth to surface mass load
- Uses spectral finite-element approach (Martinec, 2000)
- Models deformation & solves sea-level equation to obtain relative sea levels

Data assimilation

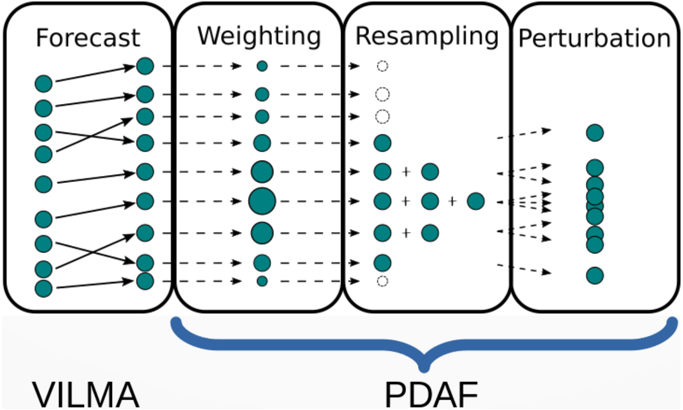
- Combines a dynamic model with observations
- Updates the model based on observations
- Uncertainties of model state and observations are considered in update step
- Our choice: particle filter

The particle filter

- Ensemble based method
- Members develop individually
- During assimilation step particle performance is estimated based on observations
- Resampling of low-weight particles to model states of higher-weight particles, and perturbation
- Result is a weighted sum of the particle states

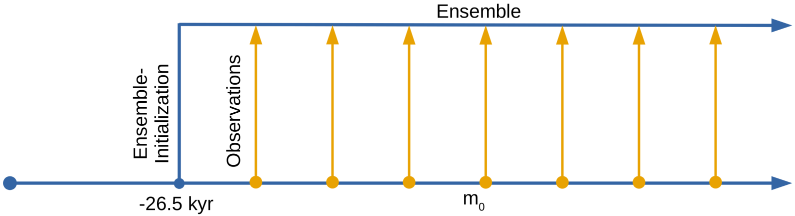
The particle filter

- Particle filter with resampling and perturbation
- Make use of Parallel Data Assimilation Framework PDAF (Nerger et al., 2005)



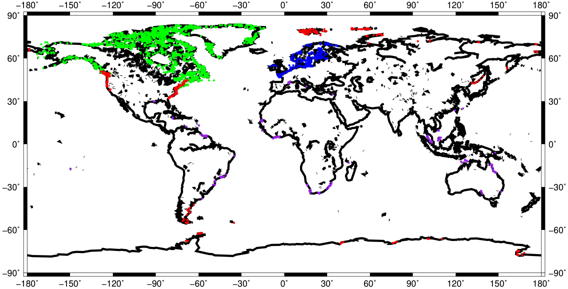
Identical twins

- Reference run m_0 with target viscosity values
- Ensemble initialization from reference model at 26.5 kyrs BP
- Observations at regular time intervals (1 kyr)
- Synthetic observations at locations where real observations exist



Observations

Locations of real observations, projected onto VILMA grid points:



Region	Num. of observations
Global	1807
NA & Greenland	1309
Fennoscandia	209

Results Part I: The 3-layer model

Investigate dependence on:

- Observation uncertainty
- Observation distribution
- Observation period

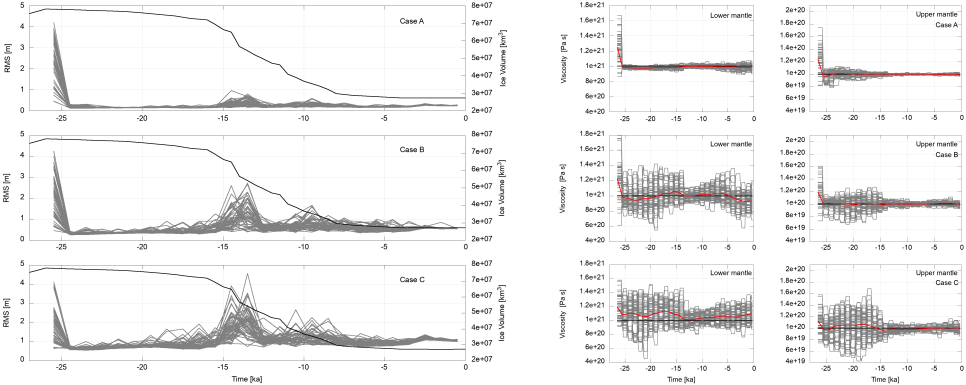
Observation uncertainty

Obs. uncert.

0.1 m

0.25 m

0.5 m



RMS development for RSL (grey)

Ice volume (black)

Viscosity development (grey)

Ensemble mean (red)

Target values (black)

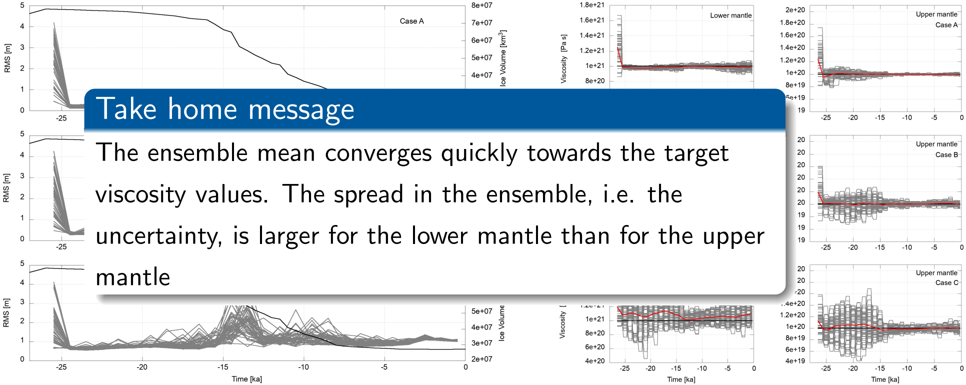
Observation uncertainty

Obs. uncert.

0.1 m

0.25 m

0.5 m



RMS development for RSL (grey)

Ice volume (black)

Viscosity development (grey)

Ensemble mean (red)

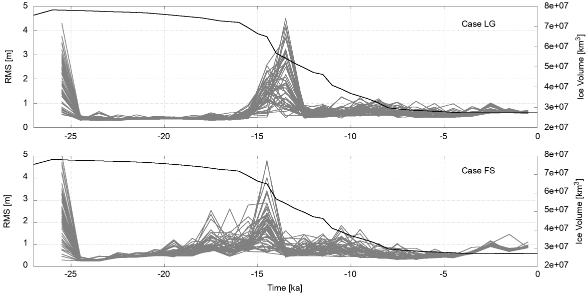
Target values (black)

Take home message

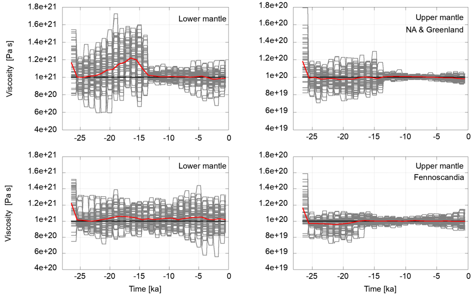
The ensemble mean converges quickly towards the target viscosity values. The spread in the ensemble, i.e. the uncertainty, is larger for the lower mantle than for the upper mantle

Observation distribution

Obs. uncertainty: 0.25 m (same as case B)



RMS development for RSL (grey)
Ice volume (black)



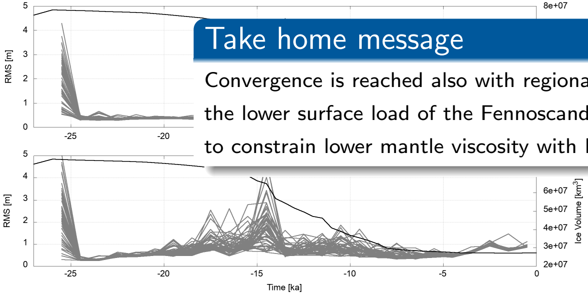
Viscosity development (grey)
Ensemble mean (red)
Target values (black)

Observation distribution

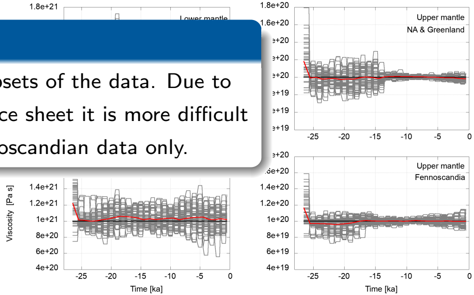
Obs. uncertainty: 0.25 m (same as case B)

Take home message

Convergence is reached also with regional subsets of the data. Due to the lower surface load of the Fennoscandian ice sheet it is more difficult to constrain lower mantle viscosity with Fennoscandian data only.



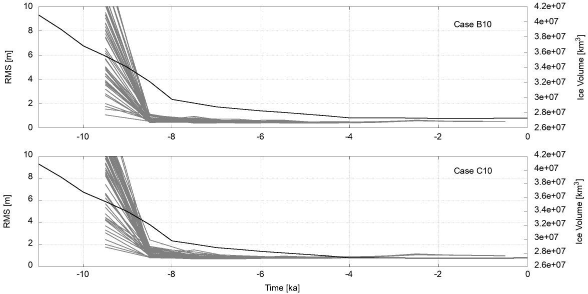
RMS development for RSL (grey)
Ice volume (black)

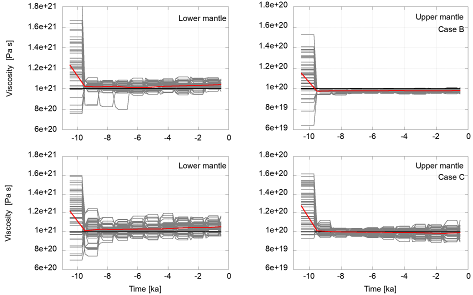


Viscosity development (grey)
Ensemble mean (red)
Target values (black)

10 kyrs of observations

Global data set, observations from 10 ka BP till present day





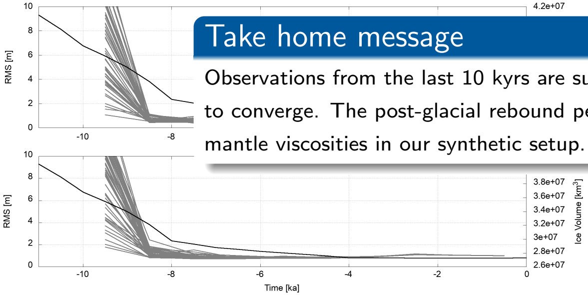
RMS development for RSL (grey)
Ice volume (black)

Obs. uncertainty B10: 0.25 m
C10: 0.5 m

Viscosity development (grey)
Ensemble mean (red)
Target values (black)

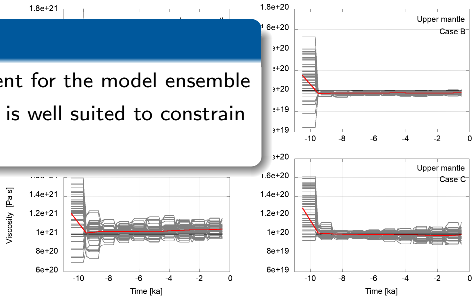
10 kyrs of observations

Global data set, observations from 10 ka BP till present day



Take home message

Observations from the last 10 kyrs are sufficient for the model ensemble to converge. The post-glacial rebound period is well suited to constrain mantle viscosities in our synthetic setup.



RMS development for RSL (grey)
Ice volume (black)

Obs. uncertainty B10: 0.25 m
C10: 0.5 m

Viscosity development (grey)
Ensemble mean (red)
Target values (black)

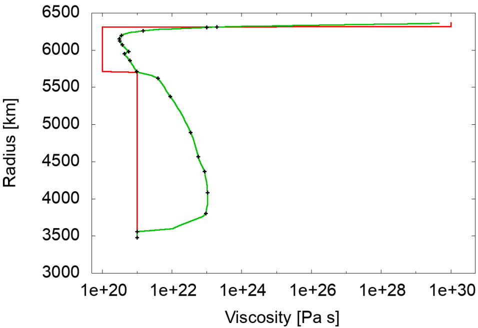
Results Part II: The 1D-profile model

Perturbation strategies:

1. Scaling entire profile with common factor
2. Profile parameterization with cubic splines
3. Combination of 1 & 2

3-layer model vs. 1D profile

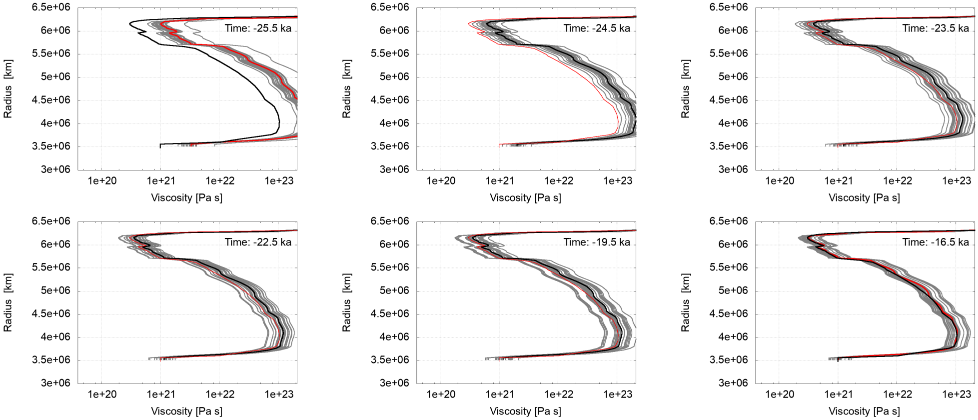
Comparison 3-layer model (red) vs. 1D profile (green)



1D profile:

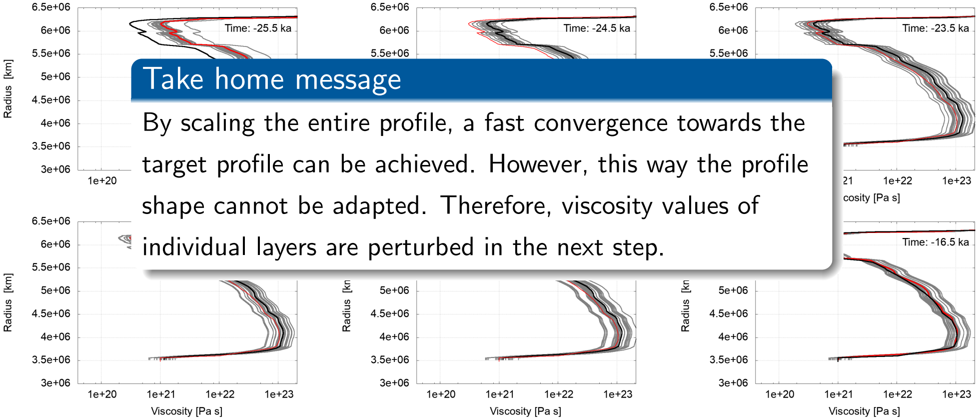
- 12 fixed lithospheric layers
- 152 viscous mantle layers
- Viscosity in mantle layers parameterized with cubic hermite splines to ensure smoothness (20 knots)
- Perturbation of viscosity values of spline knots (black crosses) during assimilation
- Values for layers obtained by spline interpolation

1D profile: scaling



Red: target profile, grey: ensemble models, black: ensemble mean

1D profile: scaling

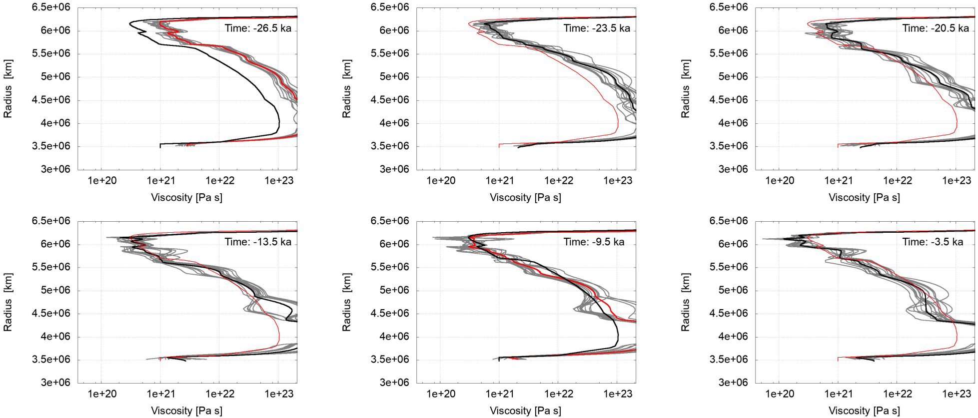


Take home message

By scaling the entire profile, a fast convergence towards the target profile can be achieved. However, this way the profile shape cannot be adapted. Therefore, viscosity values of individual layers are perturbed in the next step.

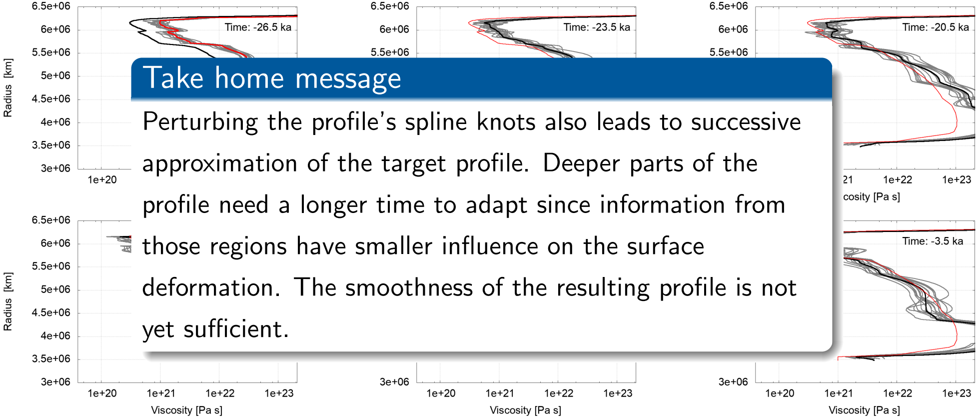
Red: target profile, grey: ensemble models, black: ensemble mean

1D profile: spline parameterization



Red: target profile, grey: ensemble models, black: ensemble mean

1D profile: spline parameterization



Take home message

Perturbing the profile's spline knots also leads to successive approximation of the target profile. Deeper parts of the profile need a longer time to adapt since information from those regions have smaller influence on the surface deformation. The smoothness of the resulting profile is not yet sufficient.

Red: target profile, grey: ensemble models, black: ensemble mean

Next steps

- Combine profile scaling and fine tuning by spline-based perturbation
- Improve profile smoothness by handling segments between known discontinuities separately
- Steps towards a more realistic temporal observation distribution

Acknowledgements

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Selected references

R. Schachtschneider, J. Saynisch-Wagner, V. Klemann, M. Bagge, M. Thomas: An approach for constraining mantle viscosities through assimilation of paleo sea level data into a glacial isostatic adjustment model. *submitted.*

Z. Martinec: Spectral-finite element approach for three-dimensional viscoelastic relaxation in a spherical earth. *Geophys. J. Int.*, 142:117–141, 2000. doi: 10.1046/j.1365-246x.2000.00138.x.

V. Klemann, Z. Martinec, and E. R. Ivins: Glacial isostasy and plate motion. *J. Geodyn.*, 46(3-5):95–103, 2008. ISSN 02643707. doi: 10.1016/j.jog.2008.04.005.

P. J. Van Leeuwen: Particle Filtering in Geophysical Systems. *Mon. Weather Rev.*, pages 4089–4114, 2009. doi: 10.1175/2009MWR2835.1.

L. Nerger, W. Hiller, and J. Schröter: PDAF - The parallel data assimilation framework: experiences with kalman filtering. In *Use of High Performance Computing in Meteorology*, pages 63–83. World Scientific, 2005. doi: 10.1142/9789812701831_0006.