A GRAVIMETRIC METHOD TO DETERMINE STRESS RELATED TO GLACIAL ISOSTATIC ADJUSTMENT IN FENNOSCANDIA: Sub-Crustal Stress Determination

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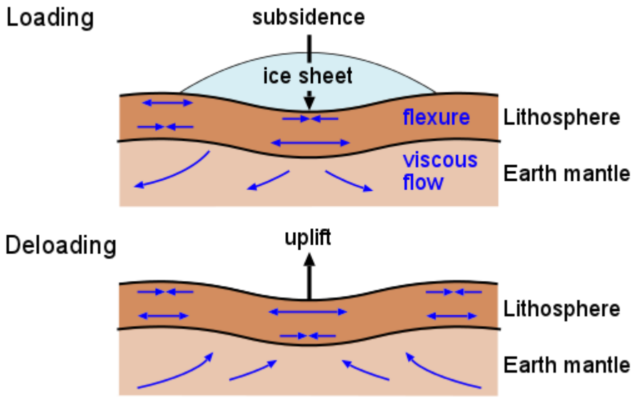
Objectives

- To determine crustal stress and its secular rate change due to ongoing GIA process and mantle convection in Fennoscandia using gravimeric approach (sub-crustal stress determination)

- Is the GIA is the origin of earthquakes in Fennoscandia or not?

Glacial isostatic adjustment (GIA)



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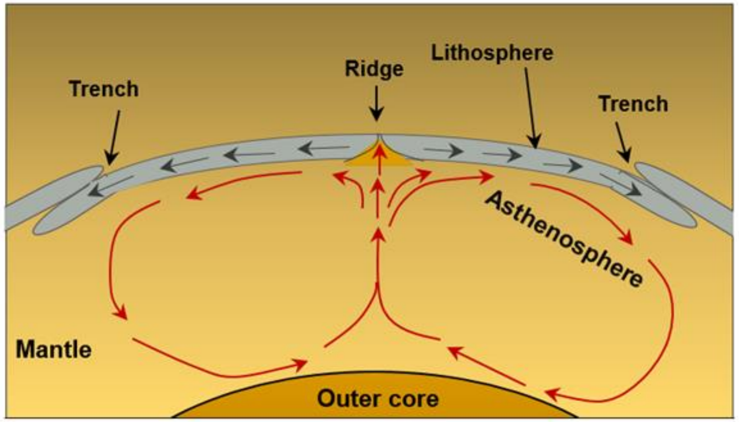
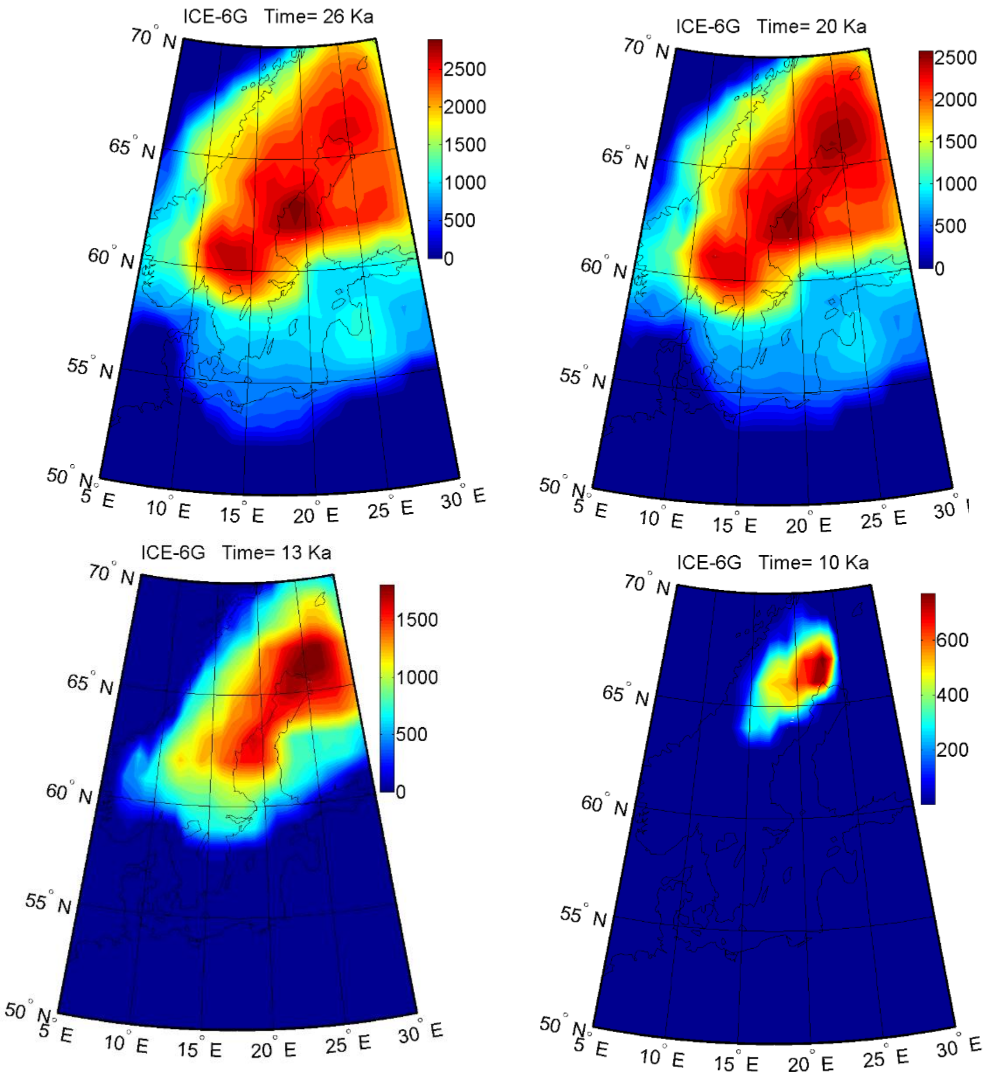
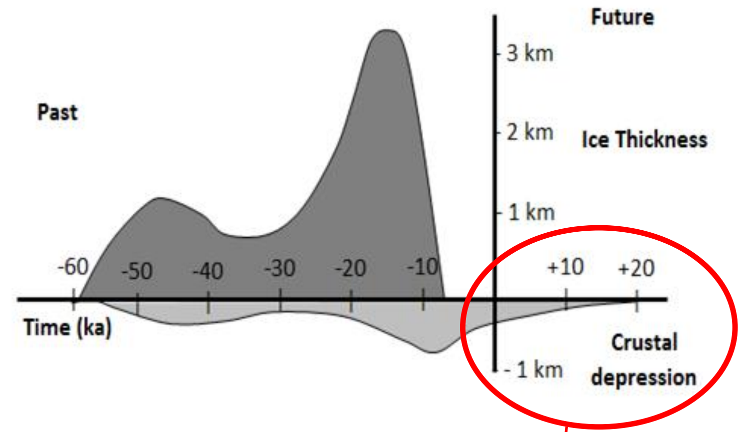


The Earth's structure: mantle convection and land uplift

Ice model ICE-6G: Historic status



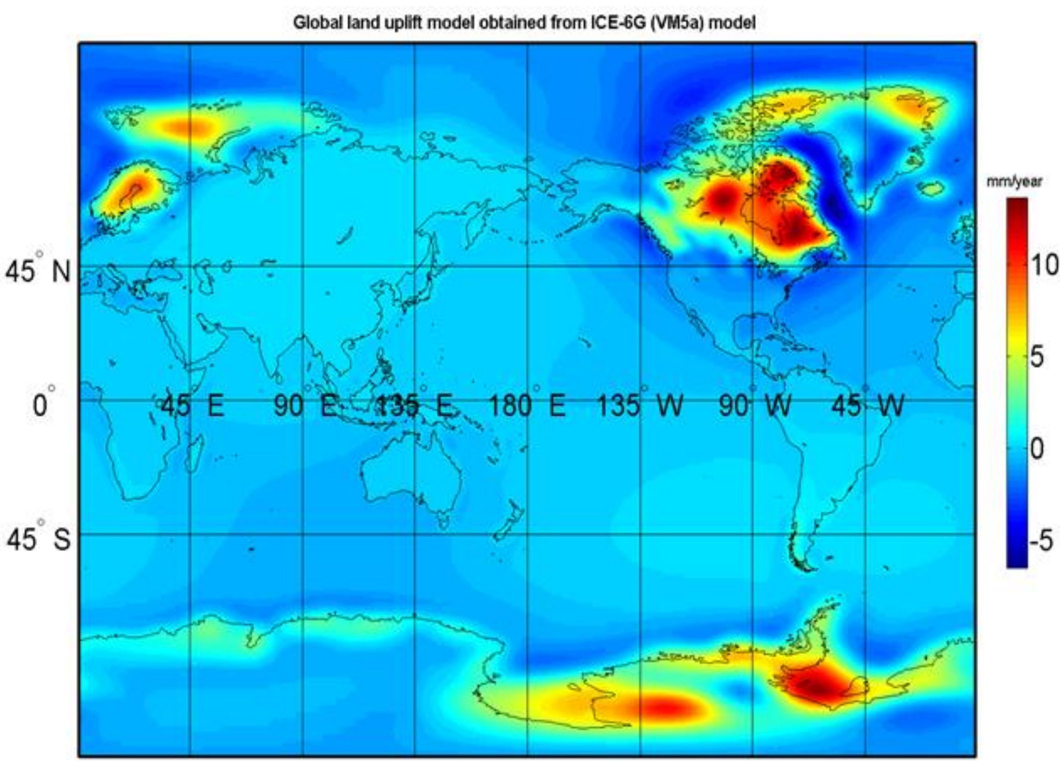
A simplified loading history for Fennoscandia (Talbot, 1999).



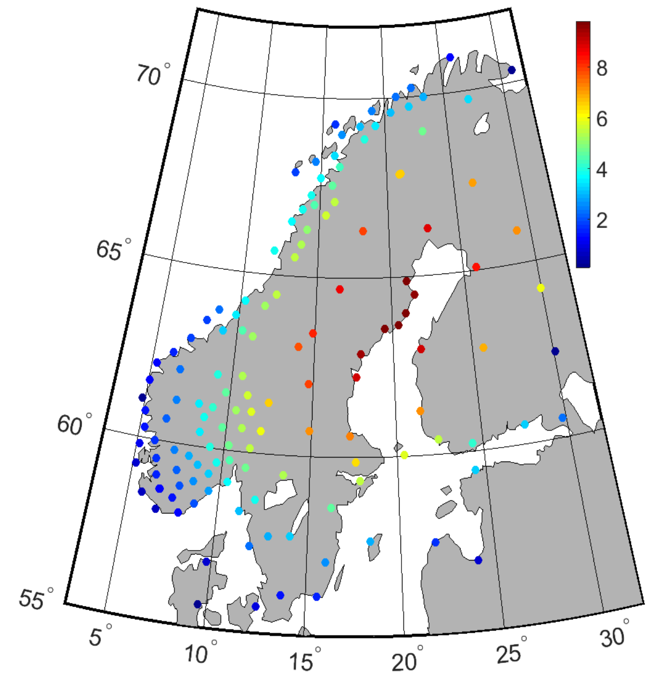
Relaxation time (decay time)

© Peltier et al. 2015, Unit: meter

How we model the land uplift?



Global land uplift model (vertical motion) obtained from synthetic model and ice model ICE-6G (VM5a) using SELEN software. Unit: mm/year



Vertical velocities from GPS results, (Kierulf et al. 2014).
Unit: mm/year

GIA conceqences

- Vertical & Horizontal crustal motion
- Sea level change
- Gravity field change
- **Crustal stress**
- Earthquakes

How to model sub crustal stress due to mantle convection and GIA

- Runcorn (1967) presented the stress between two different Earth layers using the **Navier-Stokes** equation.
- Large mass distributions and irregularities in the Earth's layers (mantle convection /GIA) can be studied by **long-to-medium wavelengths** of the Earth's gravity field.

Crustal horizontal stress determination

Absolute part

$$\sigma_x = \frac{Mg}{4\pi R^2}\sum_{n=2}^{n_{\max}}\left(\frac{R}{R-D_0}\right)^{n+3}\frac{2n+1}{n+1}\sum_{m=-n}^{n} C_{nm}Q_m(\lambda)\frac{\partial \bar{P}_{n|m|}(\theta)}{\partial\theta}$$

$$\sigma_y = \frac{Mg}{4\pi R^2}\sum_{n=2}^{n_{\max}}\left(\frac{R}{R-D_0}\right)^{n+3}\frac{2n+1}{n+1}\sum_{m=-n}^{n} m\,C_{nm}Q_{-m}(\lambda)\frac{\bar{P}_{n|m|}(\theta)}{\sin\theta}$$

$$\mathrm{S} = \sqrt{\sigma_x^2+\sigma_y^2}$$

$$\alpha = \arctan\left(\sigma_y/\sigma_x\right)$$

From EGM08
or using an isostatic model

Temporal change

$$\dot{\sigma}_x = \frac{Mg}{4\pi R^2}\sum_{n=2}^{\infty}\left(\frac{R}{R-D_0}\right)^{n+3}\frac{2n+1}{n+1}\sum_{m=-n}^{n}\dot{C}_{nm}Q_m(\lambda)\frac{\partial \bar{P}_{n|m|}(\theta)}{\partial\theta}$$

$$\dot{\sigma}_y = \frac{Mg}{4\pi R^2}\sum_{n=2}^{\infty}\left(\frac{R}{R-D_0}\right)^{n+3}\frac{2n+1}{n+1}\sum_{m=-n}^{n} m\,\dot{C}_{nm}Q_{-m}(\lambda)\frac{\bar{P}_{n|m|}(\theta)}{\sin\theta}$$

Using GRACE data

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$$\dot{S} = \sqrt{\dot{\sigma}_x^2+\dot{\sigma}_y^2}$$

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Estimation of crustal horizontal stress using gravimetric-isostatic crustal model: Isostatic disturbing potential

Vening Meinesz isostatic model

$$\delta g^I = \delta g^B + A_C = \delta g - A^t + A_C$$

Isostatic gravity disturbance $\delta g^I = 0$

Isostatic disturbining potential:

$$T = \sum_{n=0}^{n_{max}} \sum_{m=-n}^{n} \frac{R}{n+1} \left(A^t - \frac{4\pi G \Delta\rho R}{3} \left[\left(1 - \frac{D_0}{R}\right)^3 - 1 \right] - 2\pi G \Delta\rho D \right) Y_{nm}(P)$$

Crust-mantle density contrast

Mean crustal thickness

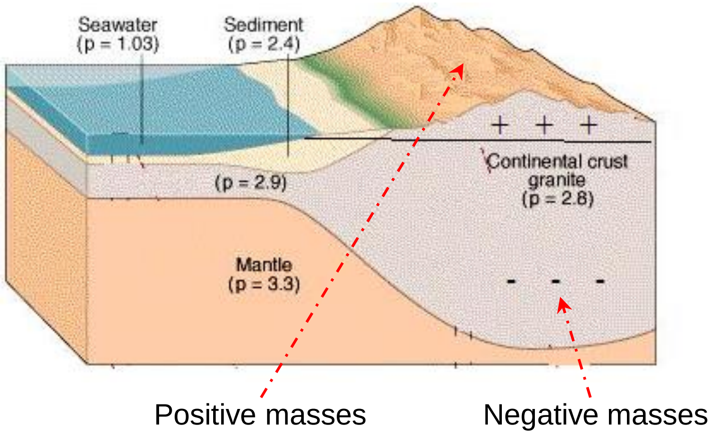
Crustal thickness (using seismic models)
CRUST1.0 (Laske et al. 2013)

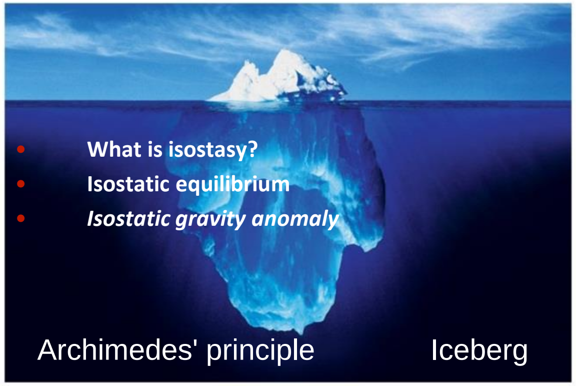
$$C_{nm} = \frac{1}{4\pi} \iint_{\sigma} T Y_{nm}(P)\, d\sigma$$

$$\sigma_x = \frac{Mg}{4\pi R^2} \sum_{n=2}^{n_{\max}} \left(\frac{R}{R - D_0} \right)^{n+3} \frac{2n+1}{n+1} \sum_{m=-n}^{n} C_{nm} Q_m(\lambda) \frac{\partial \bar{P}_{n|m|}(\theta)}{\partial \theta}$$

$$\sigma_y = \frac{Mg}{4\pi R^2} \sum_{n=2}^{n_{\max}} \left(\frac{R}{R - D_0} \right)^{n+3} \frac{2n+1}{n+1} \sum_{m=-n}^{n} m\, C_{nm} Q_{-m}(\lambda) \frac{\bar{P}_{n|m|}(\theta)}{\sin\theta}$$

$$S = \sqrt{\sigma_x^2 + \sigma_y^2} \qquad \alpha = \arctan\left(\sigma_y / \sigma_x\right)$$





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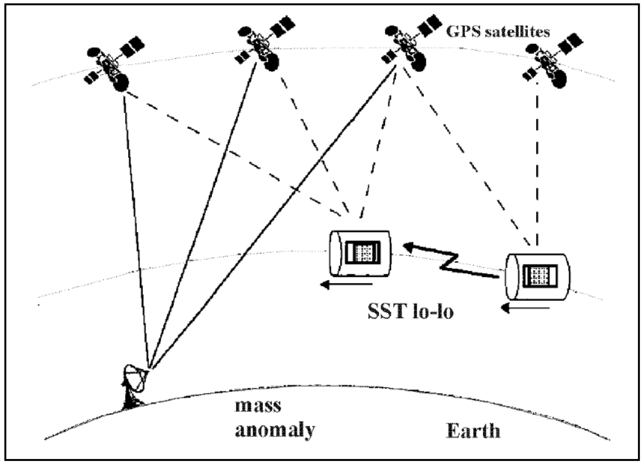
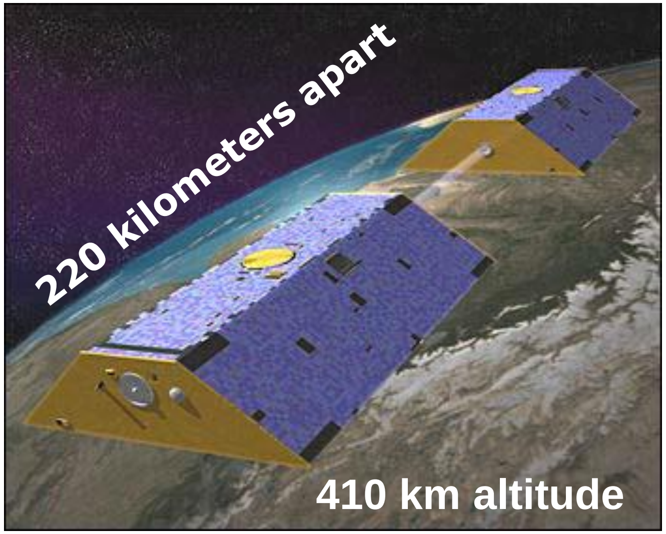
GRACE mission

- GRACE (the Gravity Recovery and Climate Experiment) is a joint US-German mission to map both the **static** and a **time-variable** parts of the Earth’s external gravity field.
- It includes two satellites following each other on the same orbital track.
- GRACE will obtain a gravity field map by looking at how the Earth's mass varies from place to place on the surface as the twin satellites pass over.



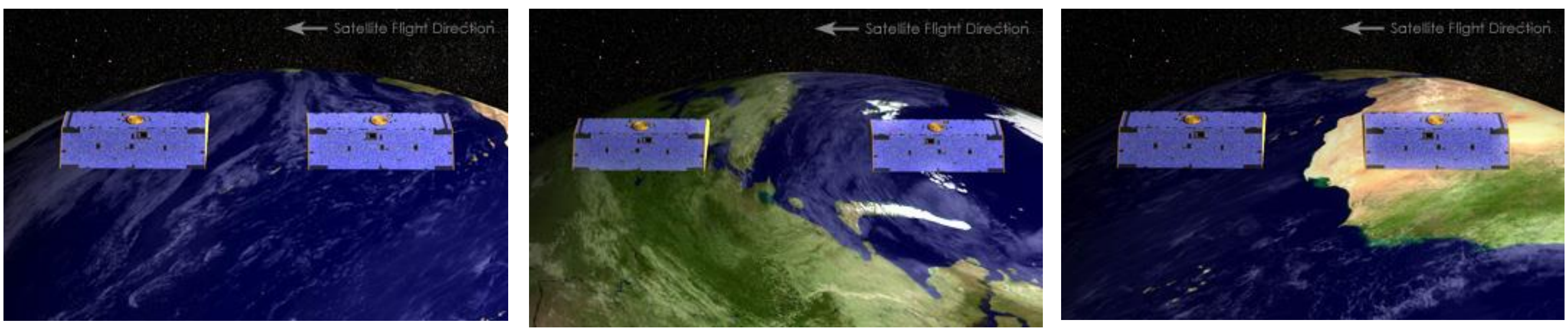
Satellite to satellite tracking in the low-low mode (SST-lo): the GRACE concept



- The positions of the two GRACE satellites change in response to variations in Earth's gravity field.

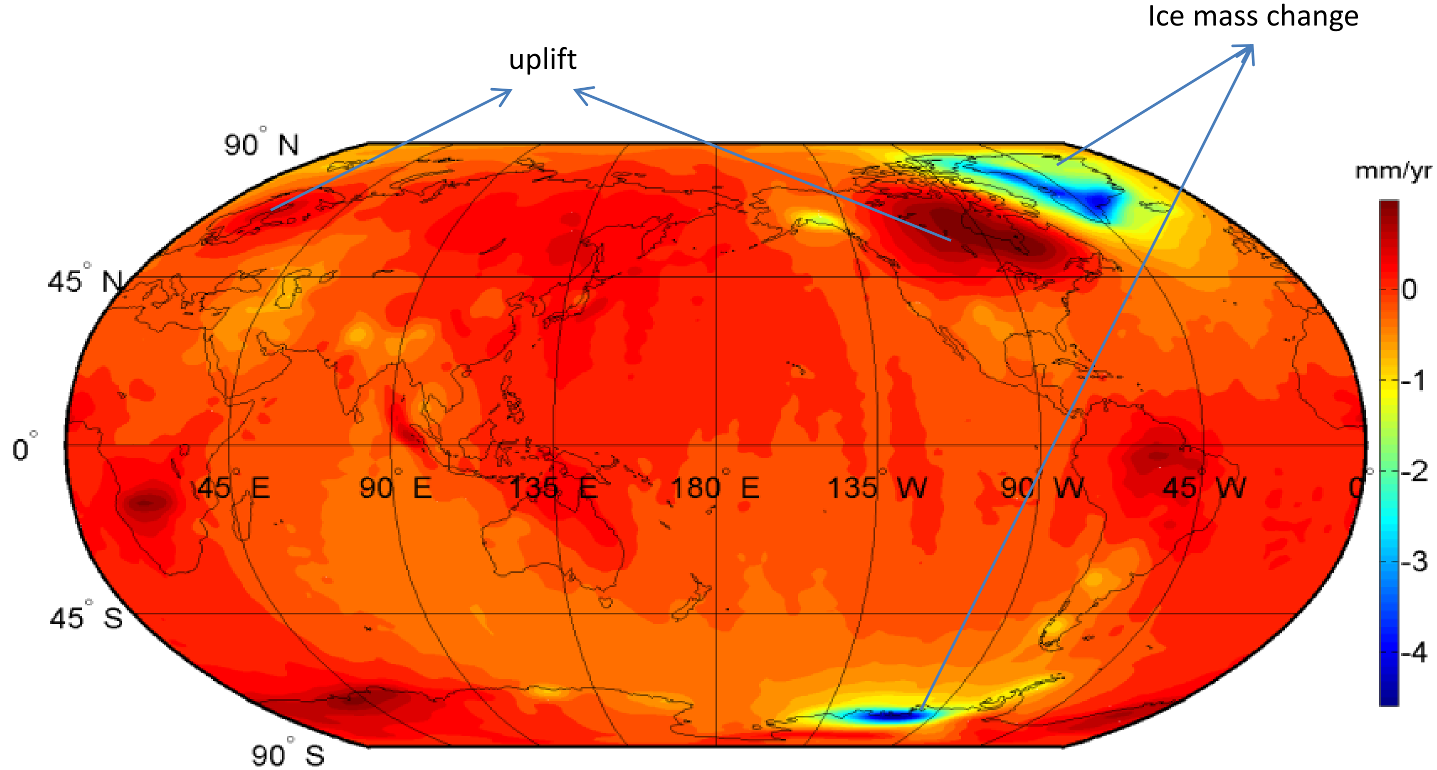
How GRACE works

- The positions of the two GRACE satellites change in response to variations in Earth's gravity field.
- When the two spacecraft pass over the ocean, the distance between them is unchanged (first panel).
- But when the lead spacecraft encounters a change in gravity over a denser land mass (second panel), it pulls away from the trailing spacecraft, which is still over water.
- The lead spacecraft moves back over water (third panel), but now the trailing spacecraft changes position in response to the greater pull of gravity over the land mass.



Source: http://www.csr.utexas.edu/grace/publications/fact_sheet/4.html

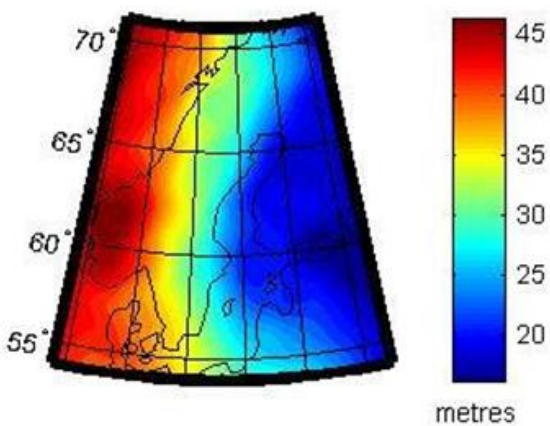
Secular rate of the geoid



The secular rate of the geoid change for the time period of the data between April 2002 and October 2016 obtained from linear regression for each point, (Sjöberg and Bagherbandi, 2017).

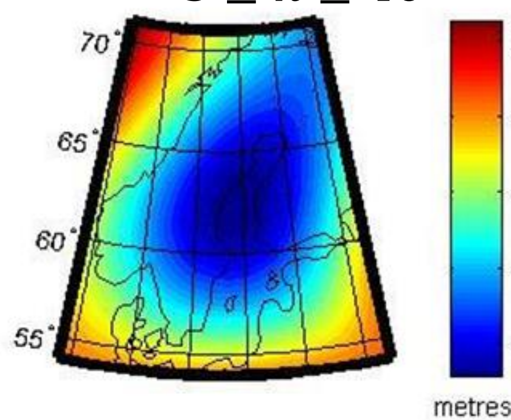
Correlation analysis

- The problem is to find the relation between the gravity potential signal and mantle convection/GIA in Fennoscandia
- Which part of the gravity field can sense the present glacio-isostatic relaxation of the Earth?

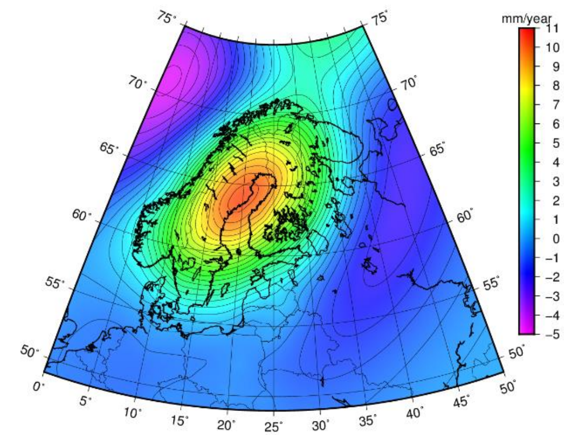


Gravity potential for all harmonics ($2 \leq n \leq 180$) scaled by the reference gravity $\gamma = 9.78\ m/s^2$

$$5 \leq n \leq 40$$

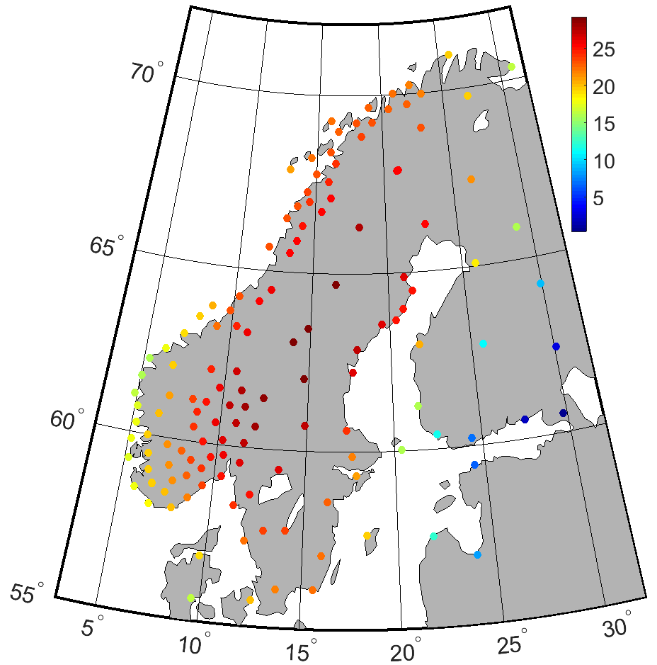


The gravity potential signals scaled with $\gamma = 9.78\ \mathrm{m/s^2}$



Land uplift

Absolute horizontal stress due to GIA/mantle convection in GPS stations



Absolute horizontal stress due to GIA/mantle convection. Unit: MPa

$$\sigma_x = \frac{Mg}{4\pi R^2} \sum_{n=2}^{n_{\max}} \left(\frac{R}{R - D_0} \right)^{n+3} \frac{2n+1}{n+1} \sum_{m=-n}^{n} C_{nm} Q_m(\lambda) \frac{\partial \bar{P}_{n|m|}(\theta)}{\partial \theta}$$

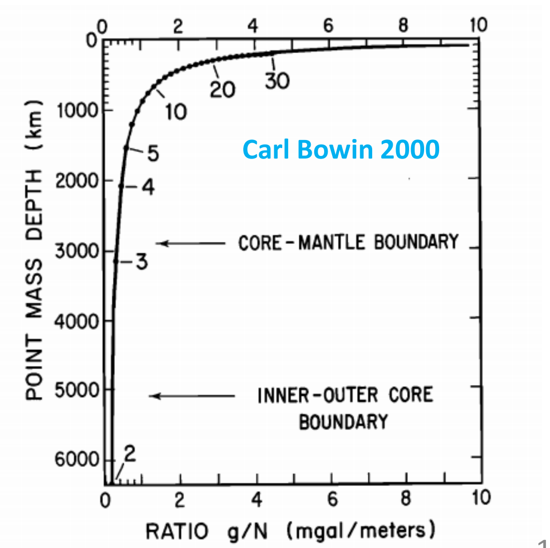
$$\sigma_y = \frac{Mg}{4\pi R^2} \sum_{n=2}^{n_{\max}} \left(\frac{R}{R - D_0} \right)^{n+3} \frac{2n+1}{n+1} \sum_{m=-n}^{n} m\, C_{nm} Q_{-m}(\lambda) \frac{\bar{P}_{n|m|}(\theta)}{\sin \theta}$$

$$S = \sqrt{\sigma_x^2 + \sigma_y^2}$$

$$\alpha = \arctan\left(\sigma_y / \sigma_x\right)$$

$5 \leq n \leq 40$

	Min	Max	Mean	STD
σ_x	-16	8	-6	6
σ_y	-27	1.6	-15	7
$S = \sqrt{\sigma_x^2 + \sigma_y^2}$	0.2	29	17	7



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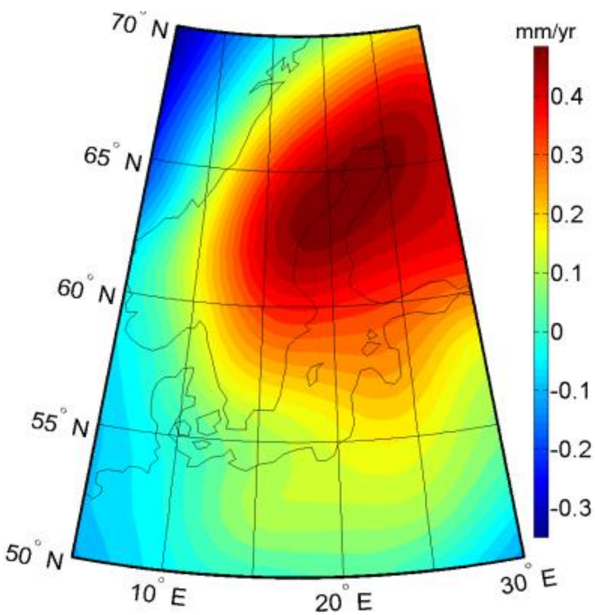
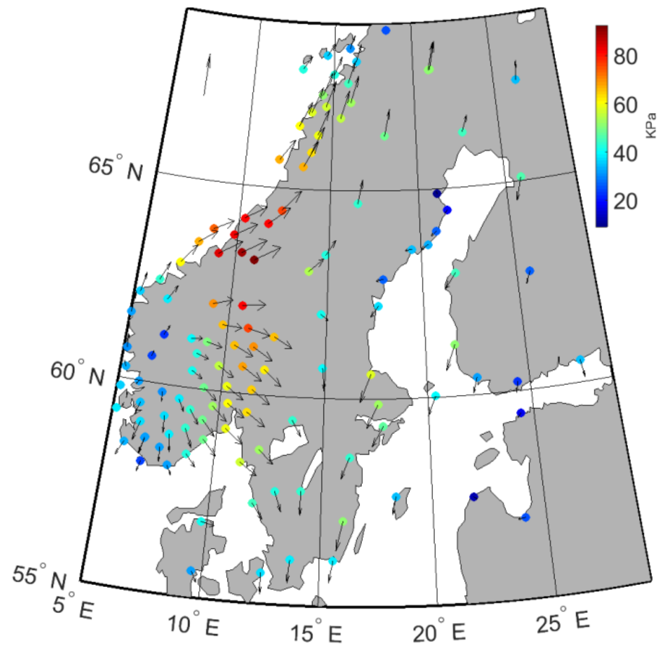
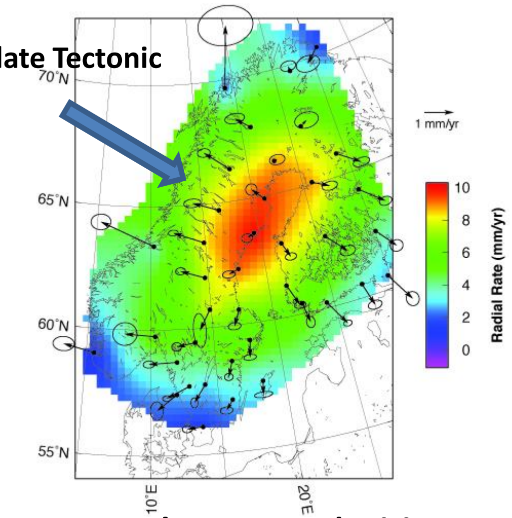
Secular rate of the Geoid change & horizontal stress due to GIA/mantle convection using GRACE data



Secular rate of the Geoid height change obtained from GRACE. Unit: mm/year



Secular rate of the horizontal stress due to GIA and mantle convection obtained from GRACE 2003-2016. Unit: kPa/year



Arrows shows Hz velocities Due to land uplift

	Min	Max	Mean	STD
$\dot{\sigma}_x$	-65	59	-2	29
$\dot{\sigma}_y$	-68	92	8	32
$\dot{S} = \sqrt{\dot{\sigma}_x{}^2 + \dot{\sigma}_y{}^2}$	4	95	38	20

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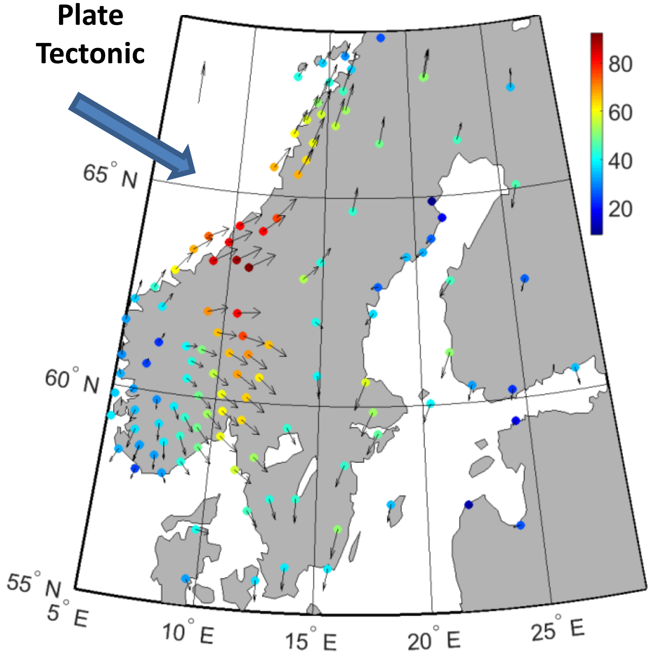
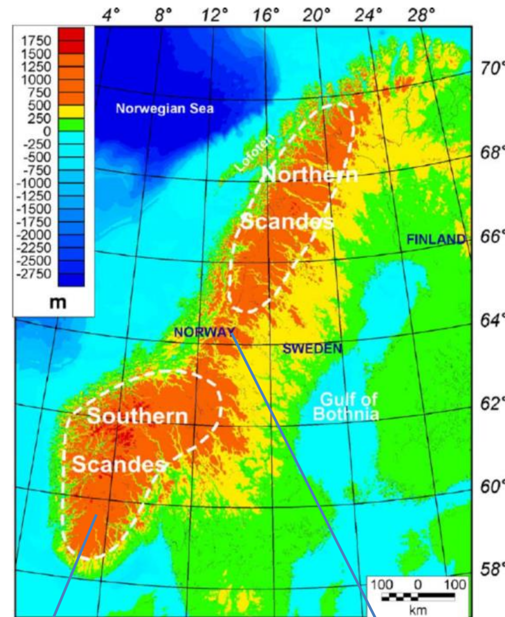
Temporal changes in horizontal stress and earthquakes

Plate Tectonic



Secular rate of the horizontal stress due to GIA and plate tectonic obtained from GRACE 2003-2016.

Unit: KPa/year



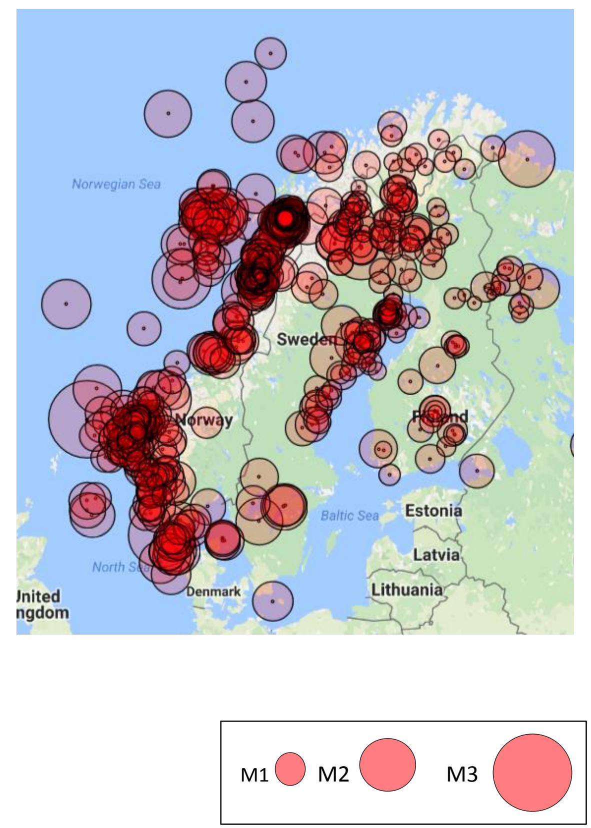
Topography/bathymetry of Fennoscandia.
The data set was compiled by Dehls et al. (2000).

Huge Topographic mass

Less Topographic mass

Earthquakes from FENTEC

2007-2008



End

Thank you