Height and gravity changes due to glacial isostatic adjustment

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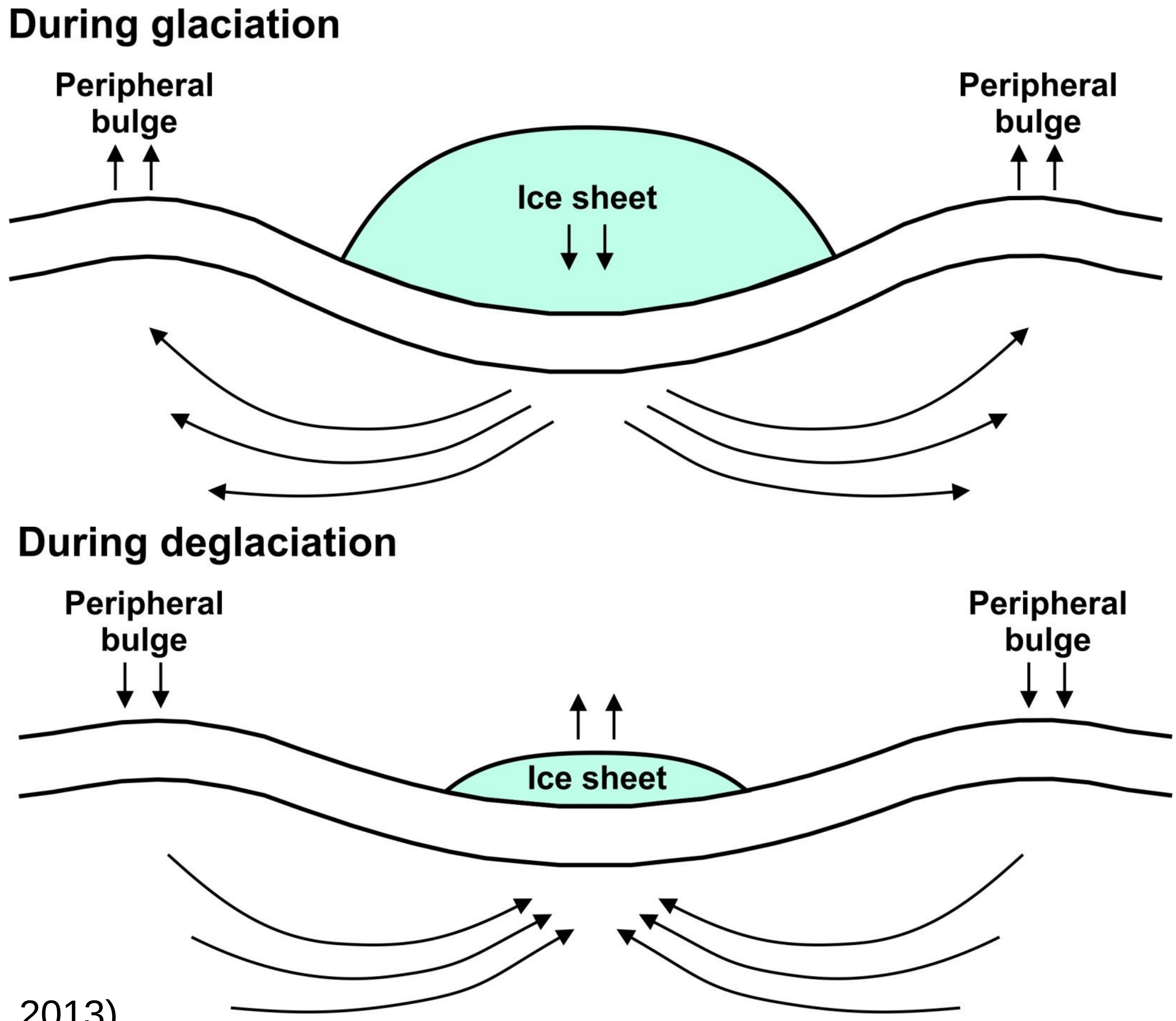
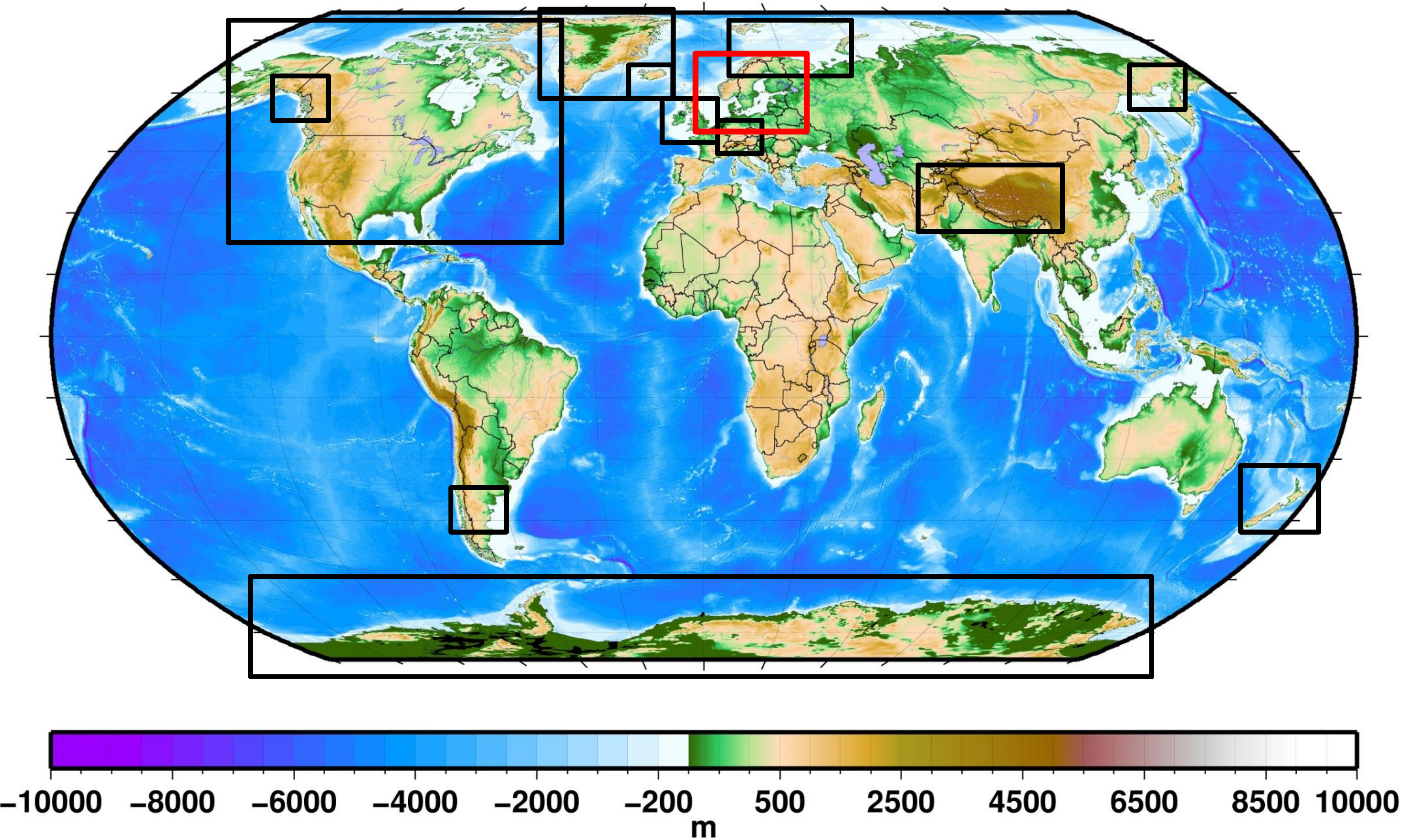
Glacial Isostatic Adjustment



(R. Steffen, 2013)

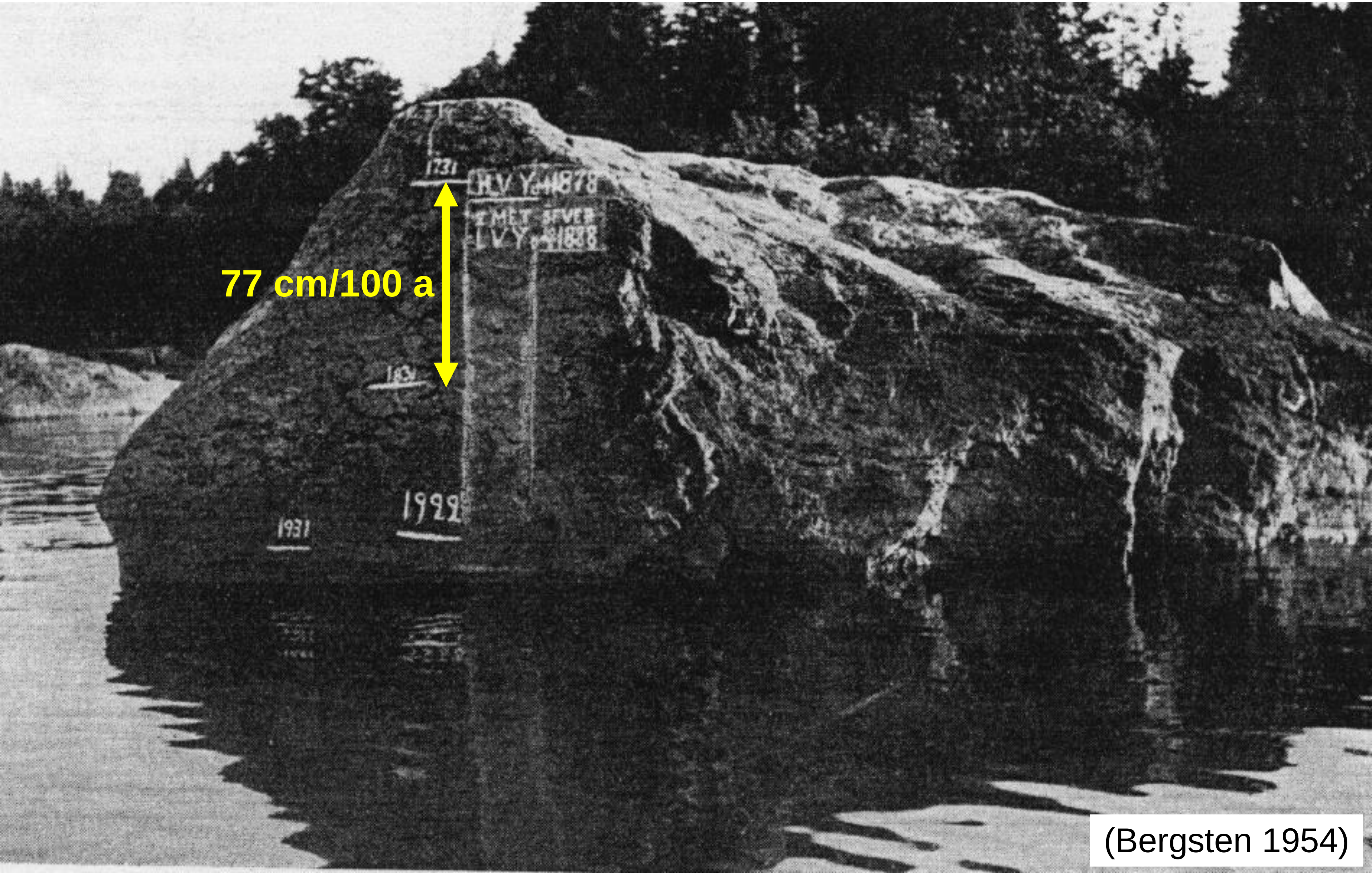
GIA around the world



GIA observations – used in modelling

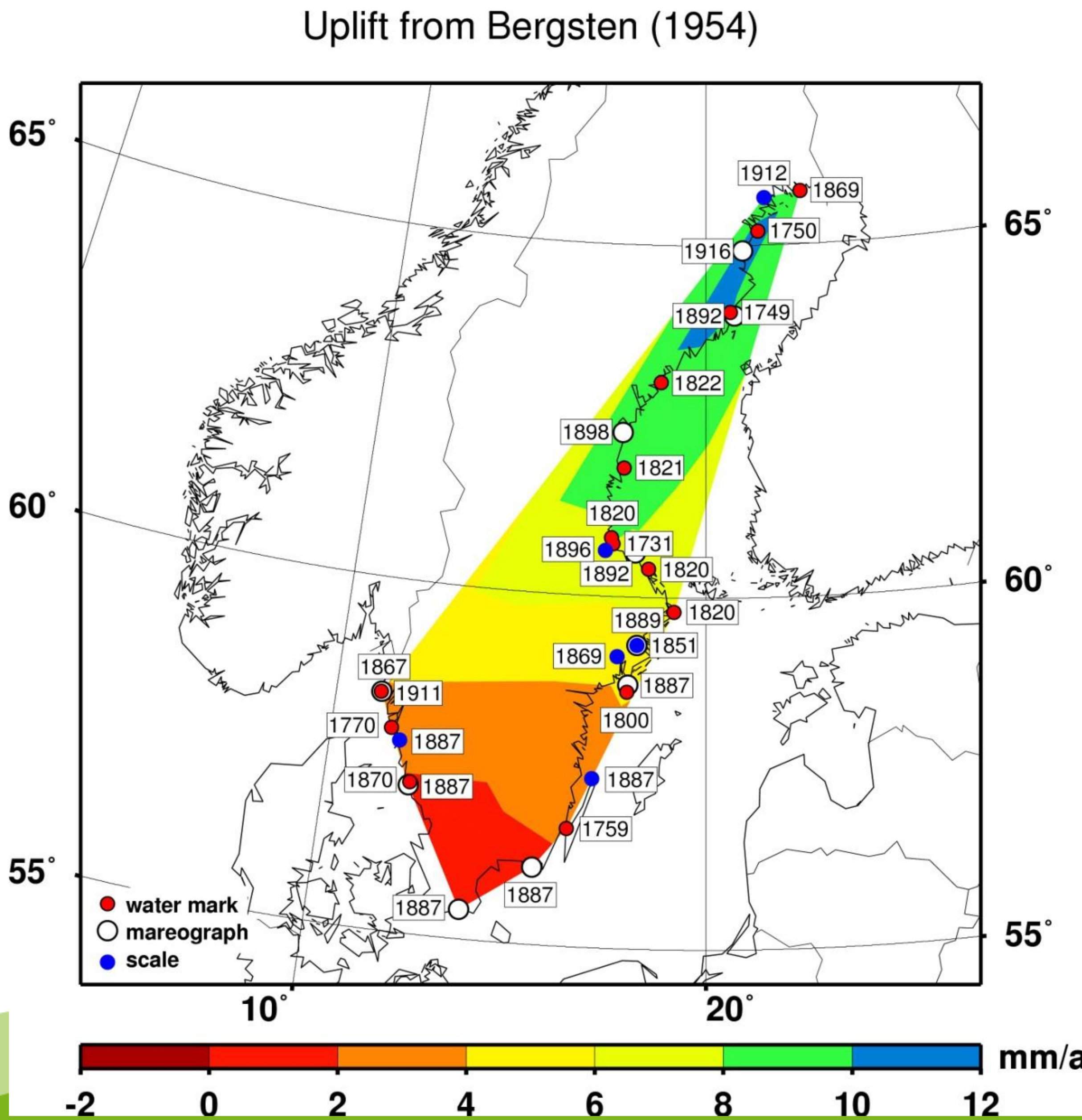
- Vertical motion
  - Relative sea levels
  - Present-day rate of uplift - GPS, tide gauges, altimetry
- Horizontal motion - GPS, VLBI, DORIS(?)
- Gravity change due to redistribution of mass – terrestrial and space-geodetic techniques (CHAMP, GRACE)
- Change in Moments of Inertia
  - Polar wander
  - Non-tidal acceleration (Length Of Day)
- Changes in the state of stress - earthquakes

Water marks: example Celsius rock



(Bergsten 1954)

Uplift rate from water marks in Fennoscandia



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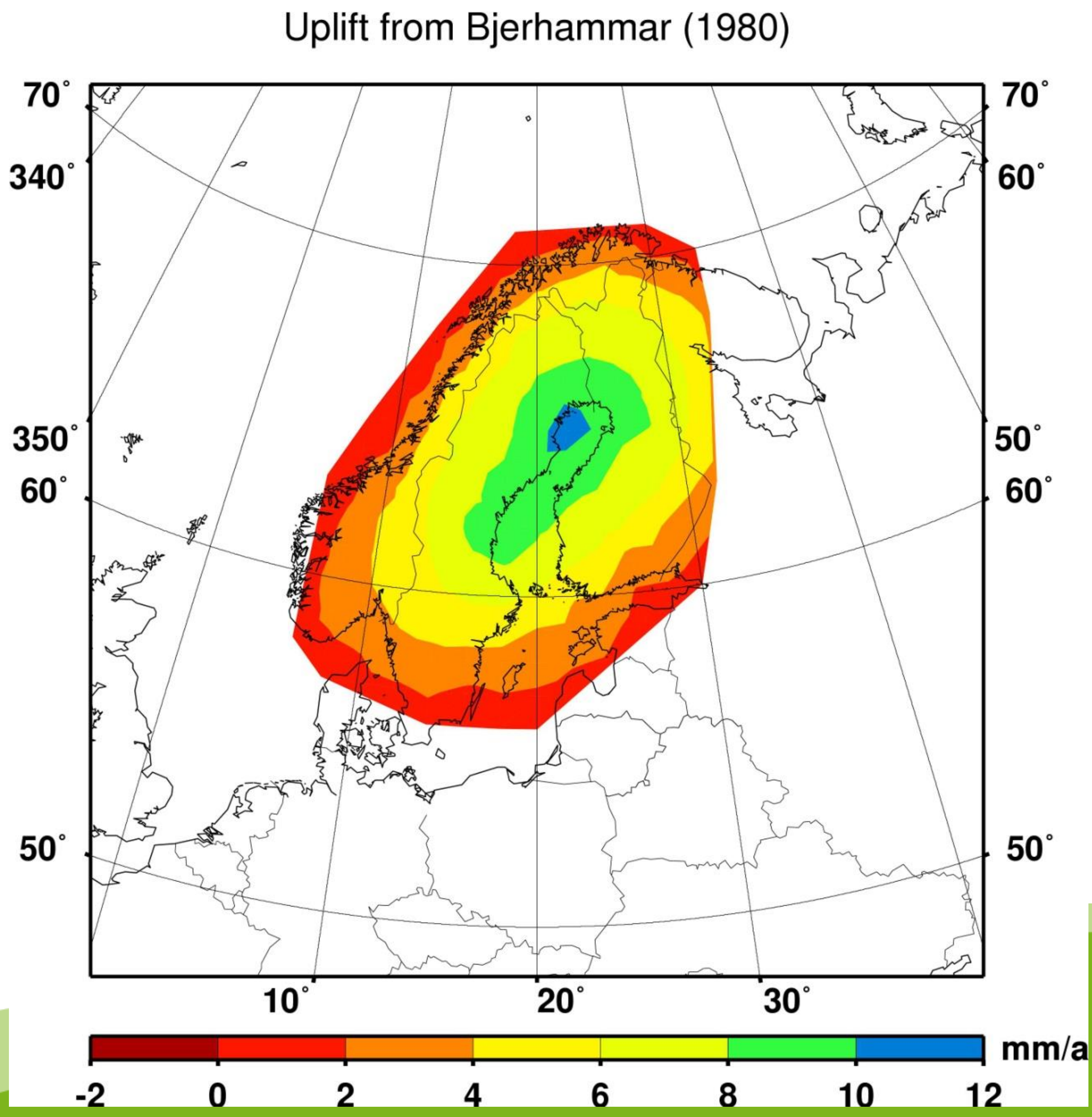
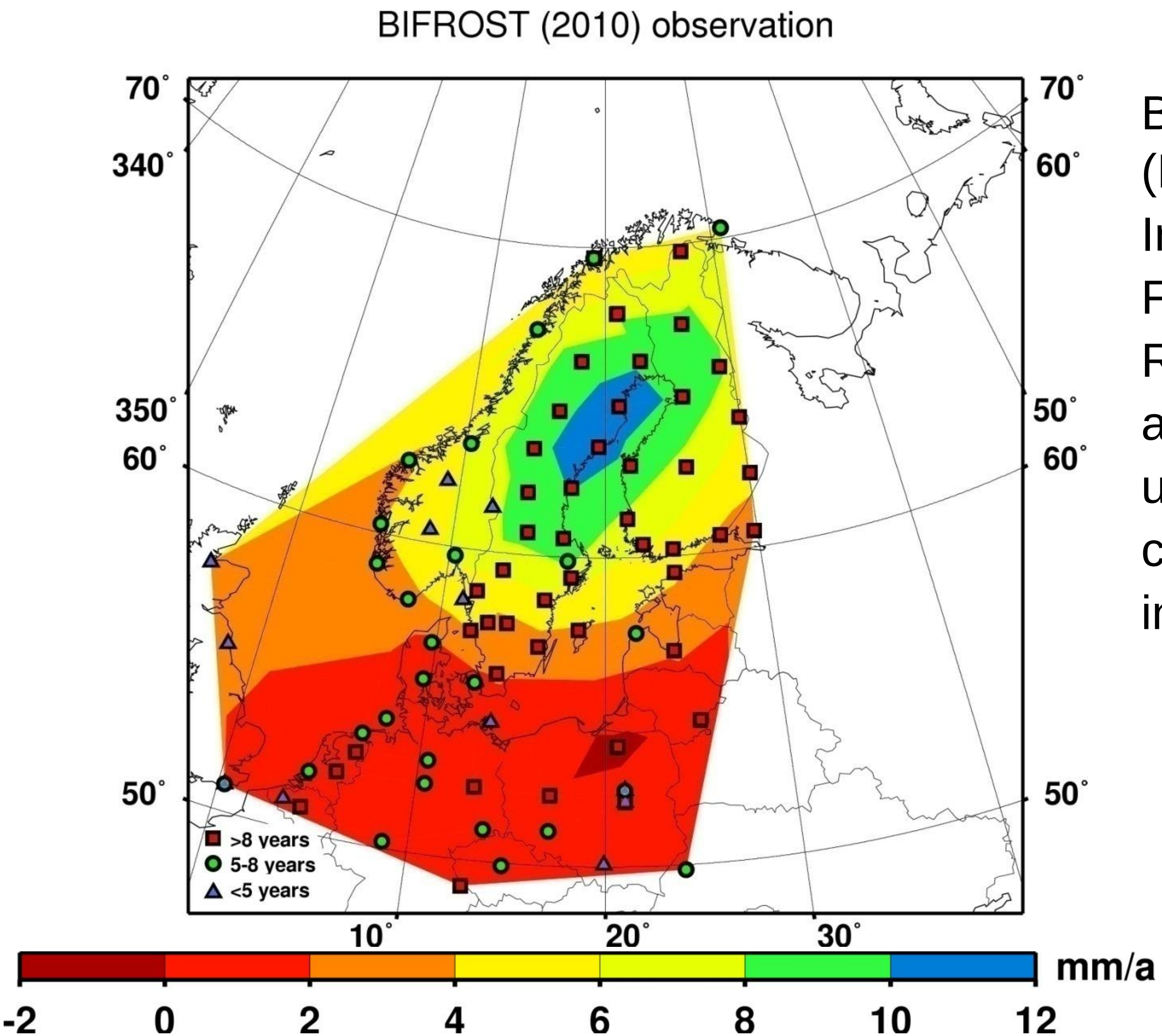
(Steffen and Wu 2011)

Uplift rate mainly from levelling



(Steffen and Wu 2011)

GPS determined uplift rate in Fennoscandia



BIFROST Project (Baseline Inferences for Fennoscandian Rebound, Sea-level, and Tectonics) uses GPS to measure crustal deformation in Fennoscandia

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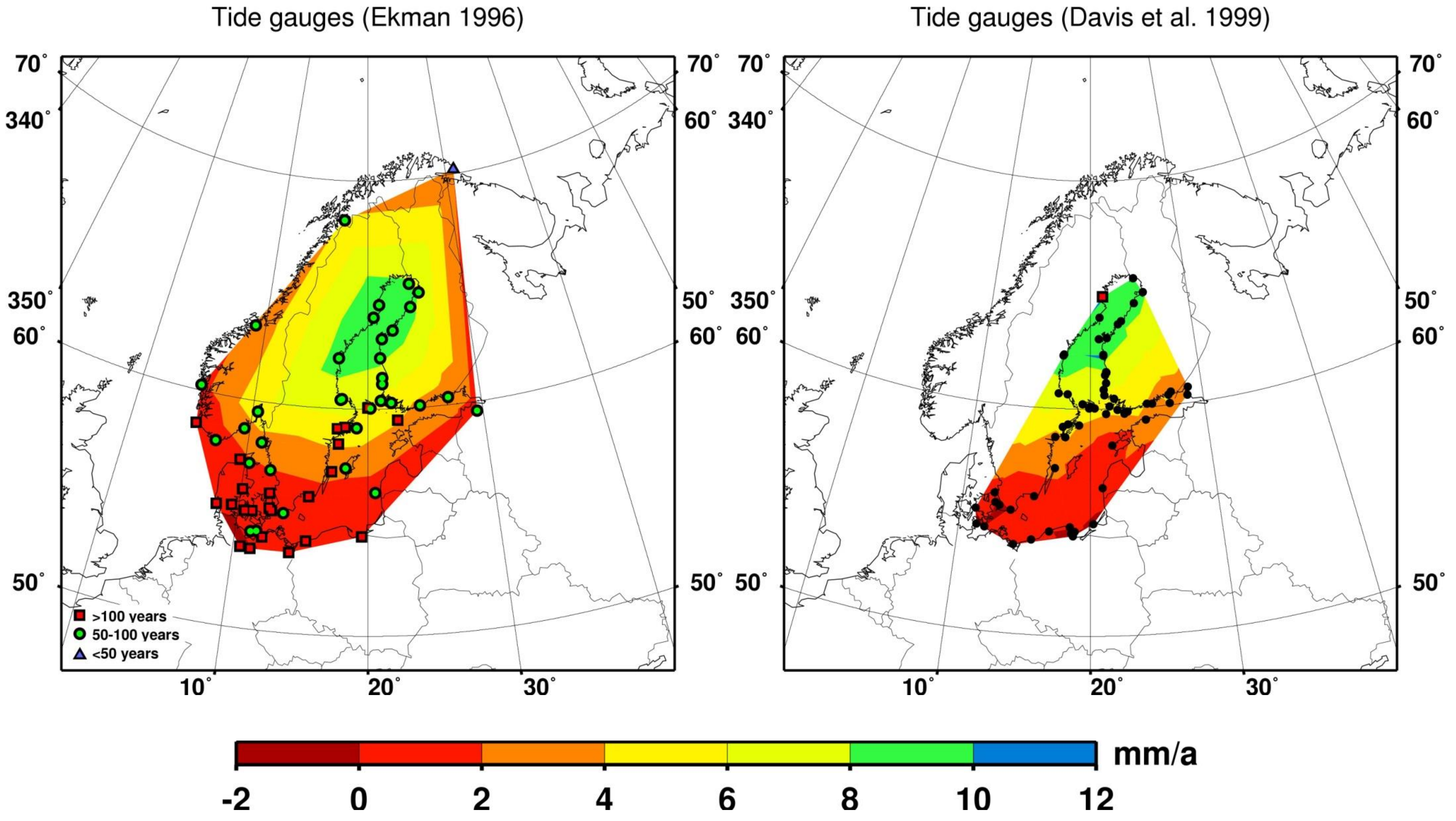
Data from Lidberg et al. (2010)

(Steffen and Wu 2011)

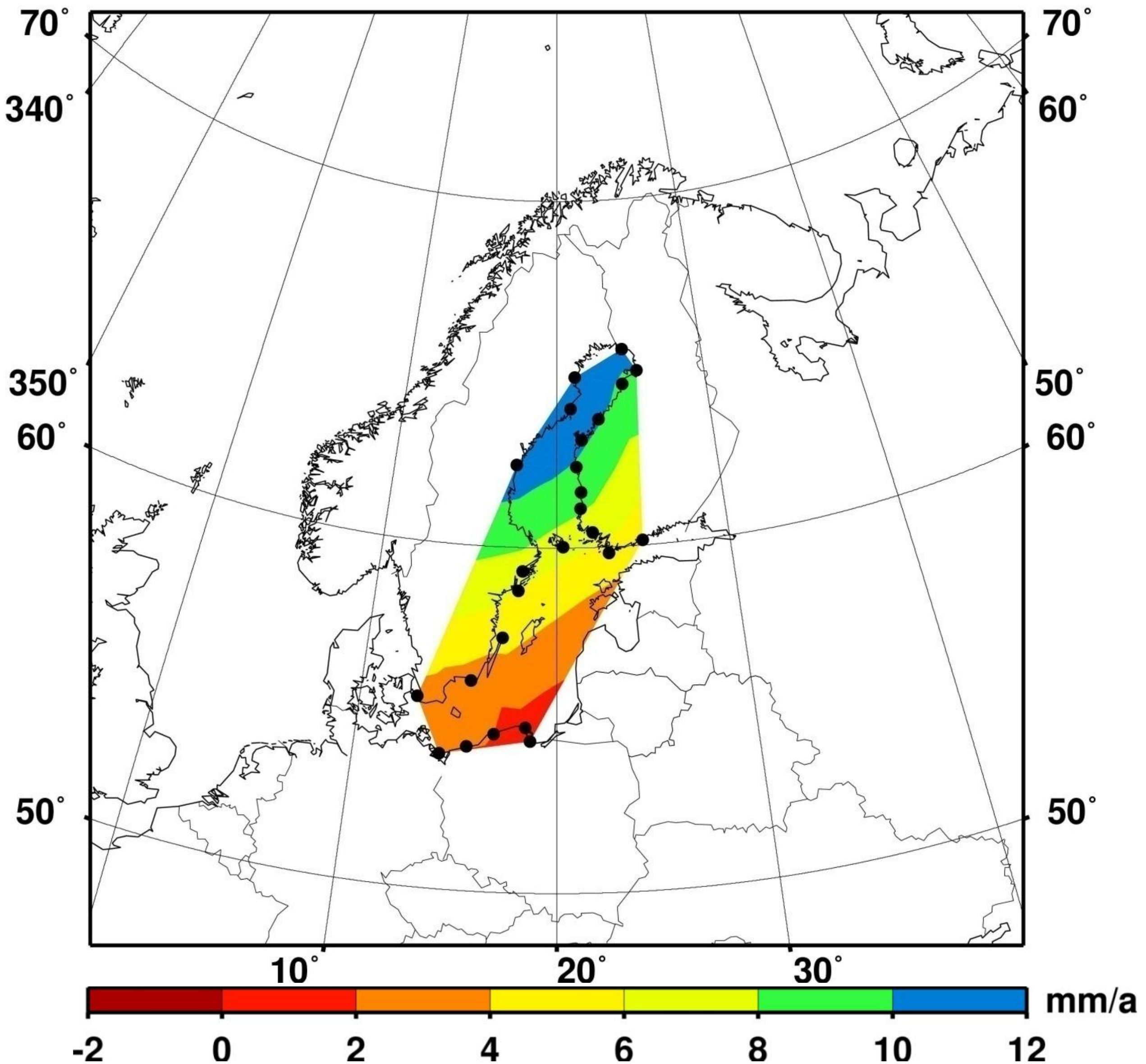
Tide gauge & uplift rate



(Steffen and Wu 2011)

Satellite altimetry & uplift rate

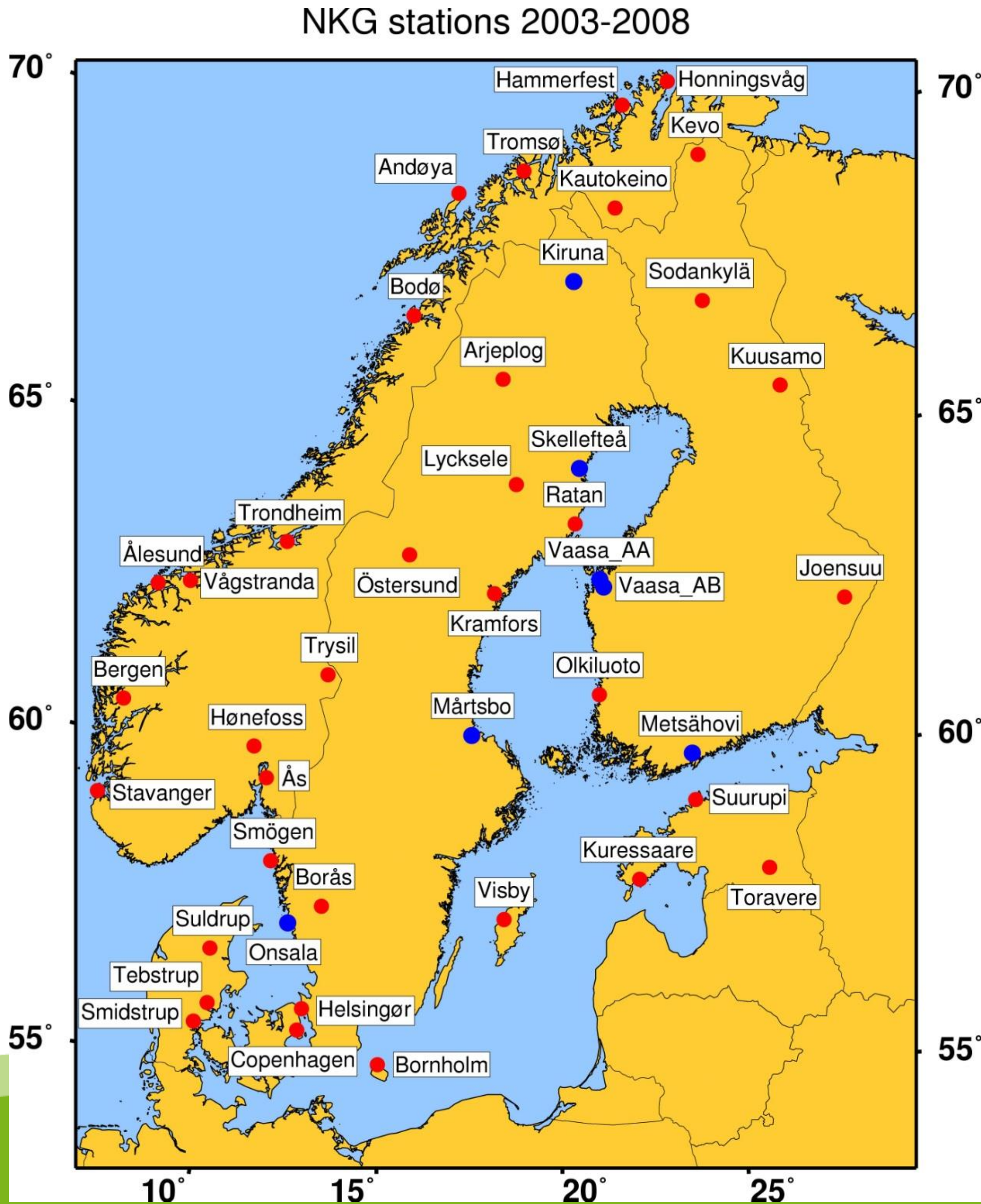
TOPEX/POSEIDON + tide gauges (Kuo et al. 2008)



(Steffen and Wu 2011)

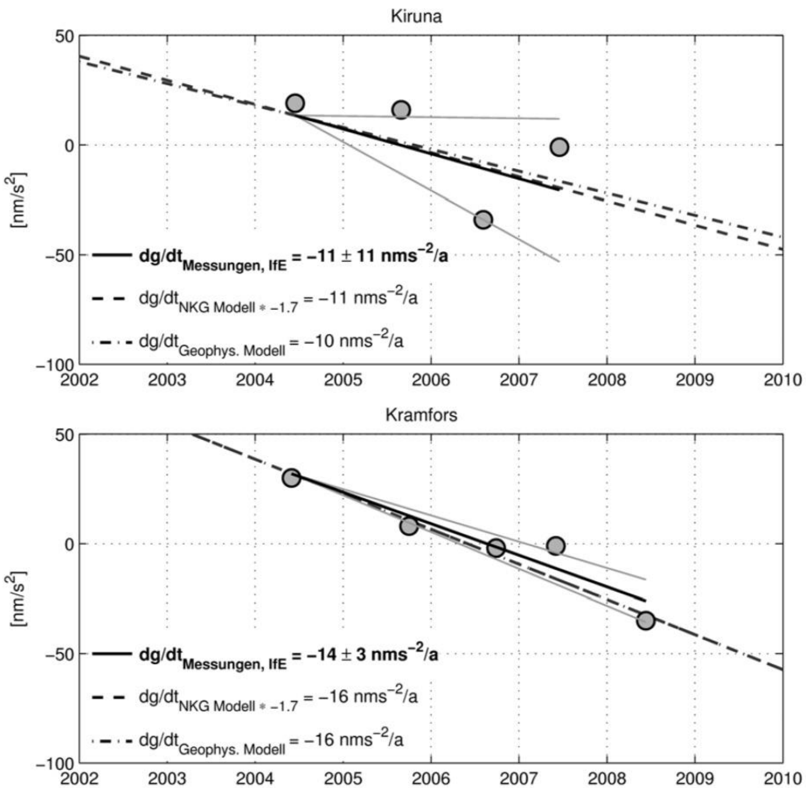
Absolute gravity stations in Fennoscandia

FG5-220 from IfE (Photo: Gitlein)

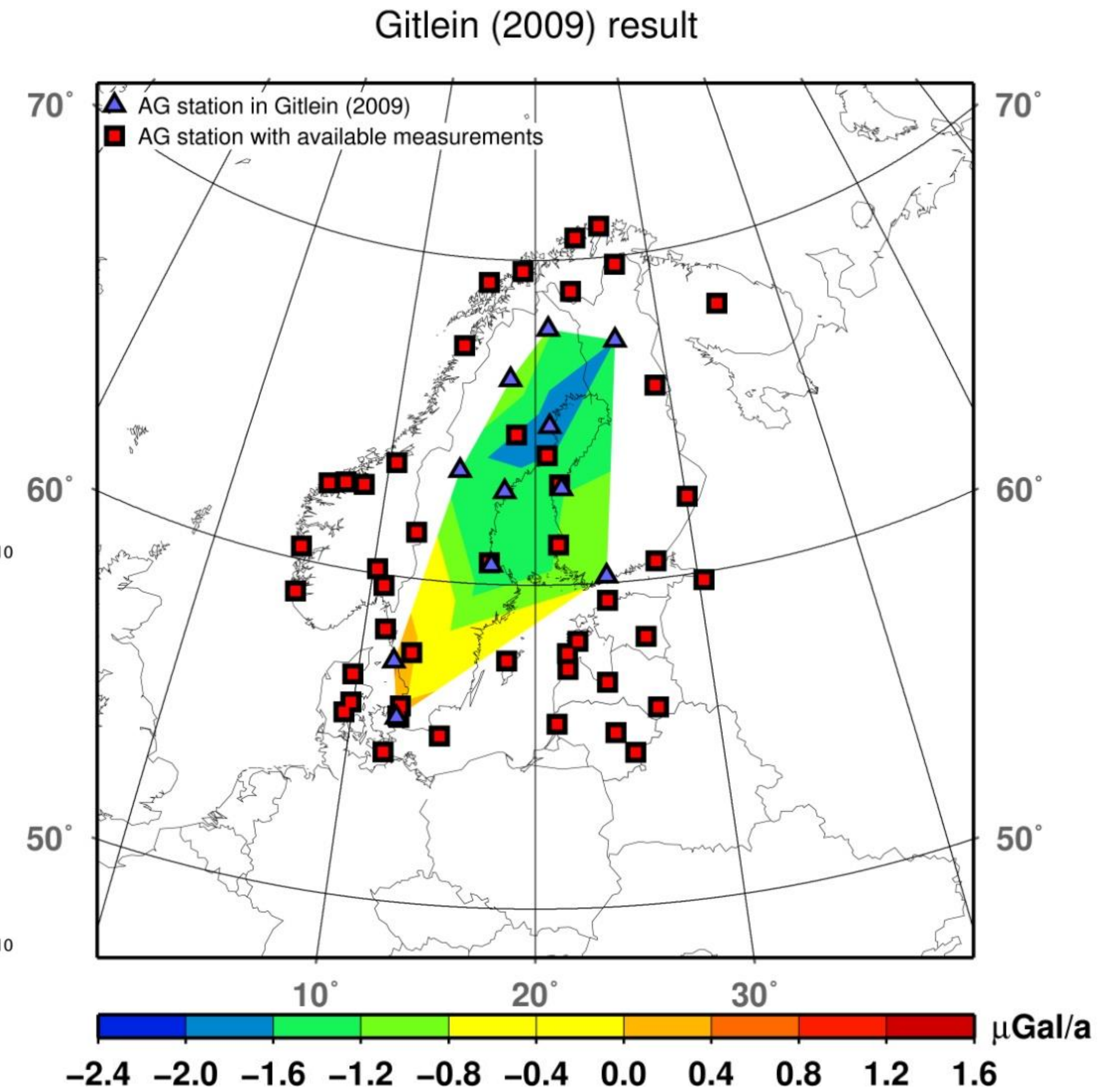


(Steffen and Wu 2011)

Vertical gravity rate from absolute gravity measurements in Fennoscandia

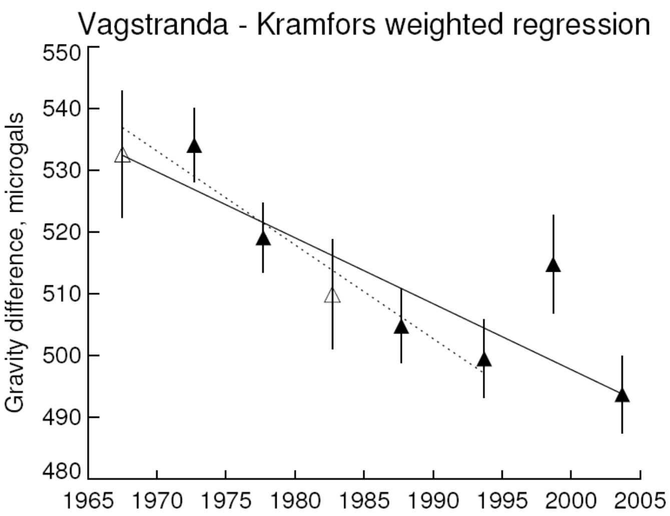


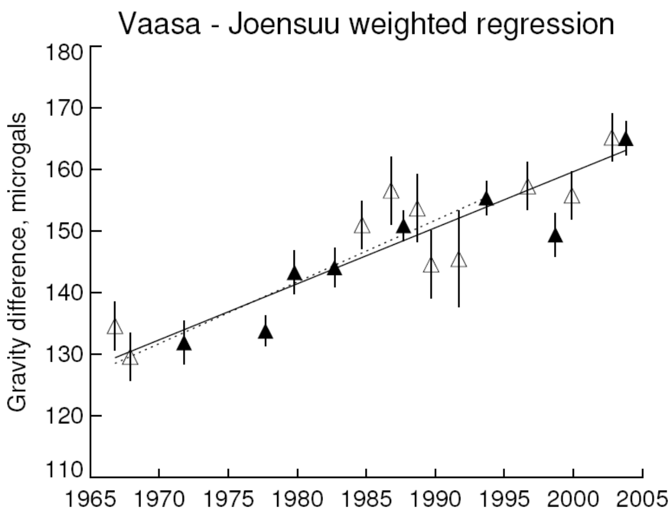
(Gitlein 2009)



(Steffen et al. 2012, GJI)

Relative gravity measurements in Fennoscandia

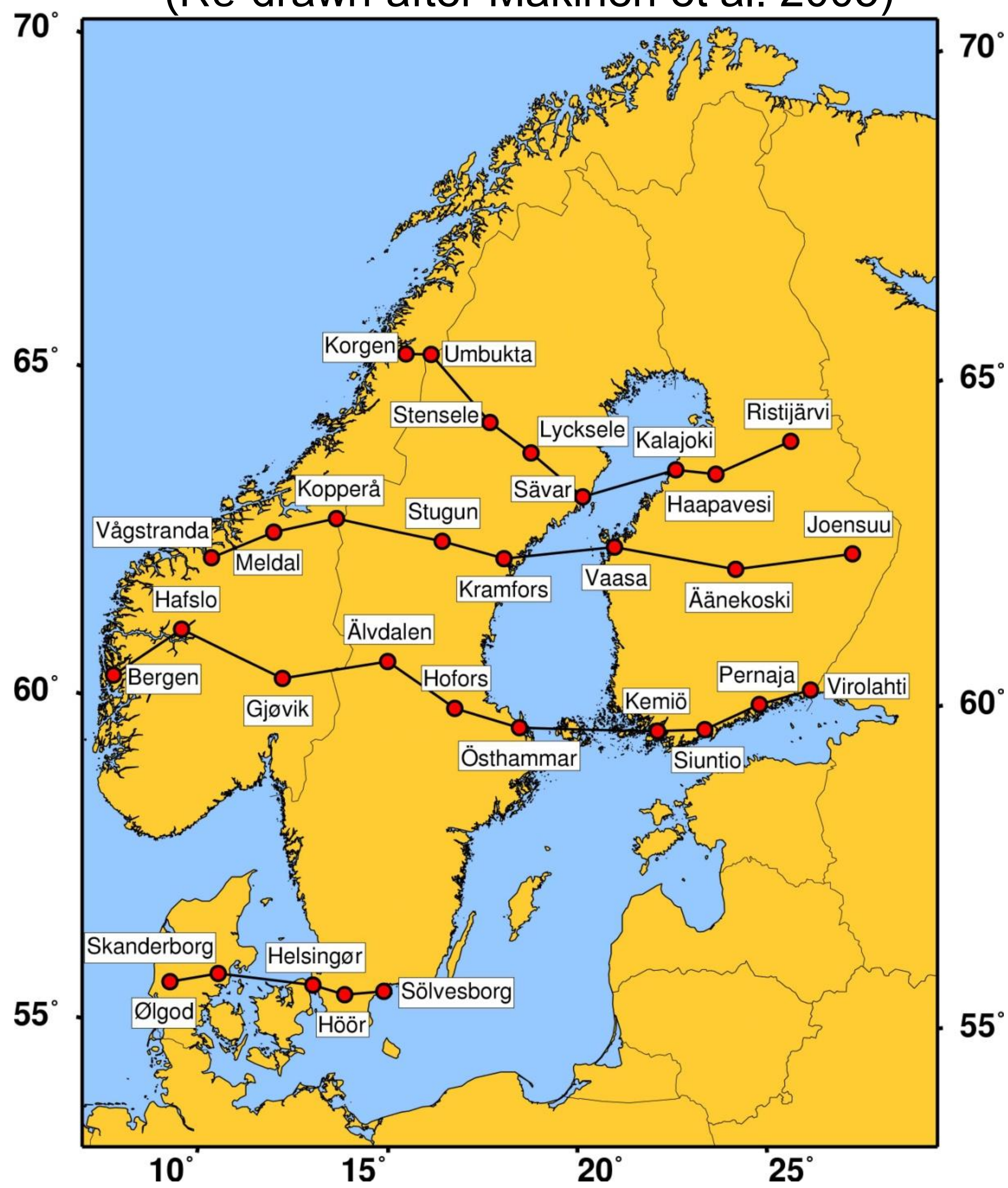




Solid symbols = five or more gravimeters
Dotted line = last published

(Mäkinen et al. 2005)

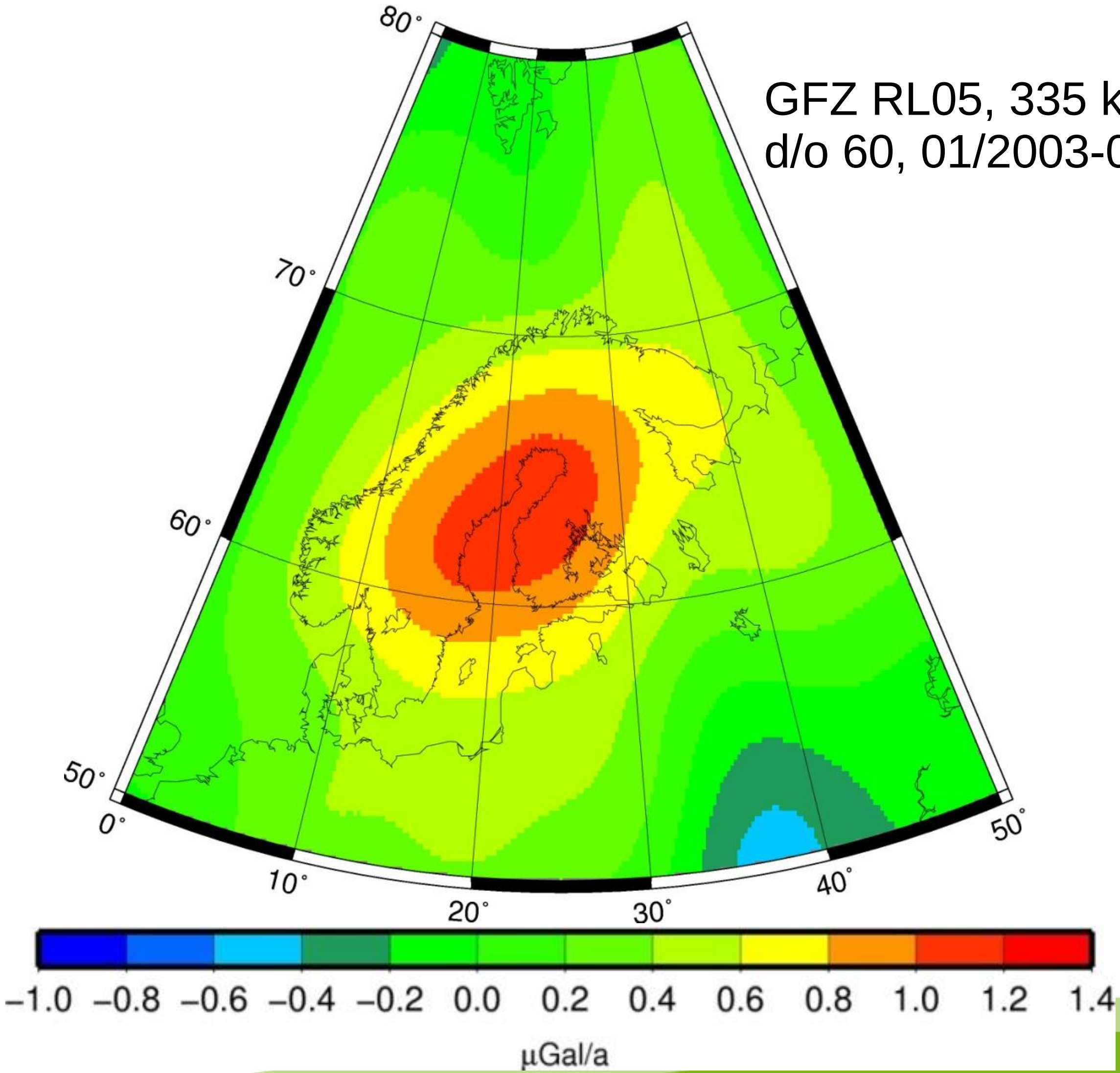
(Re-drawn after Mäkinen et al. 2005)



(Steffen and Wu 2011)

Vertical gravity rate from GRACE

GFZ RL05, 335 km Gaussian,
d/o 60, 01/2003-02/2013



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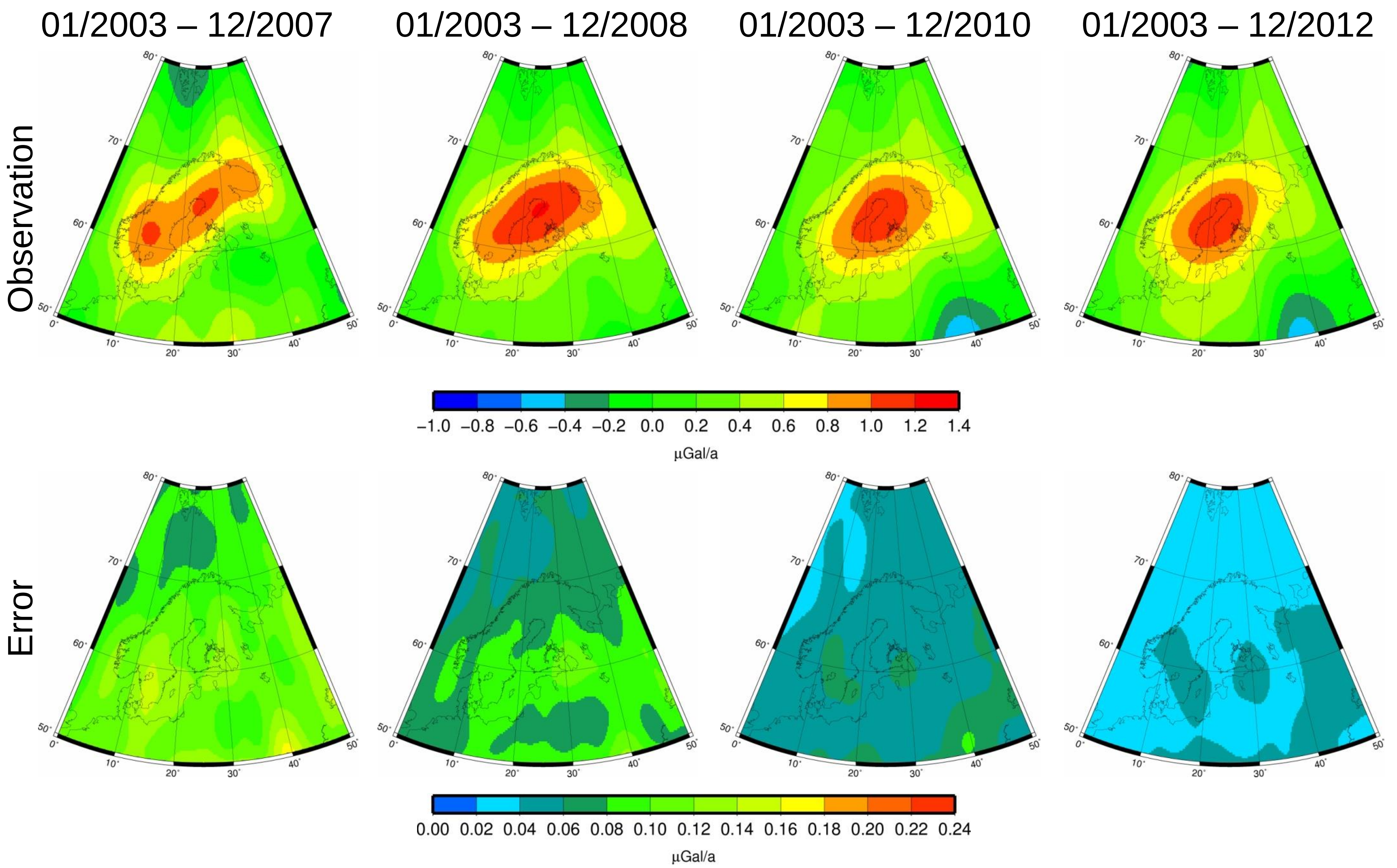
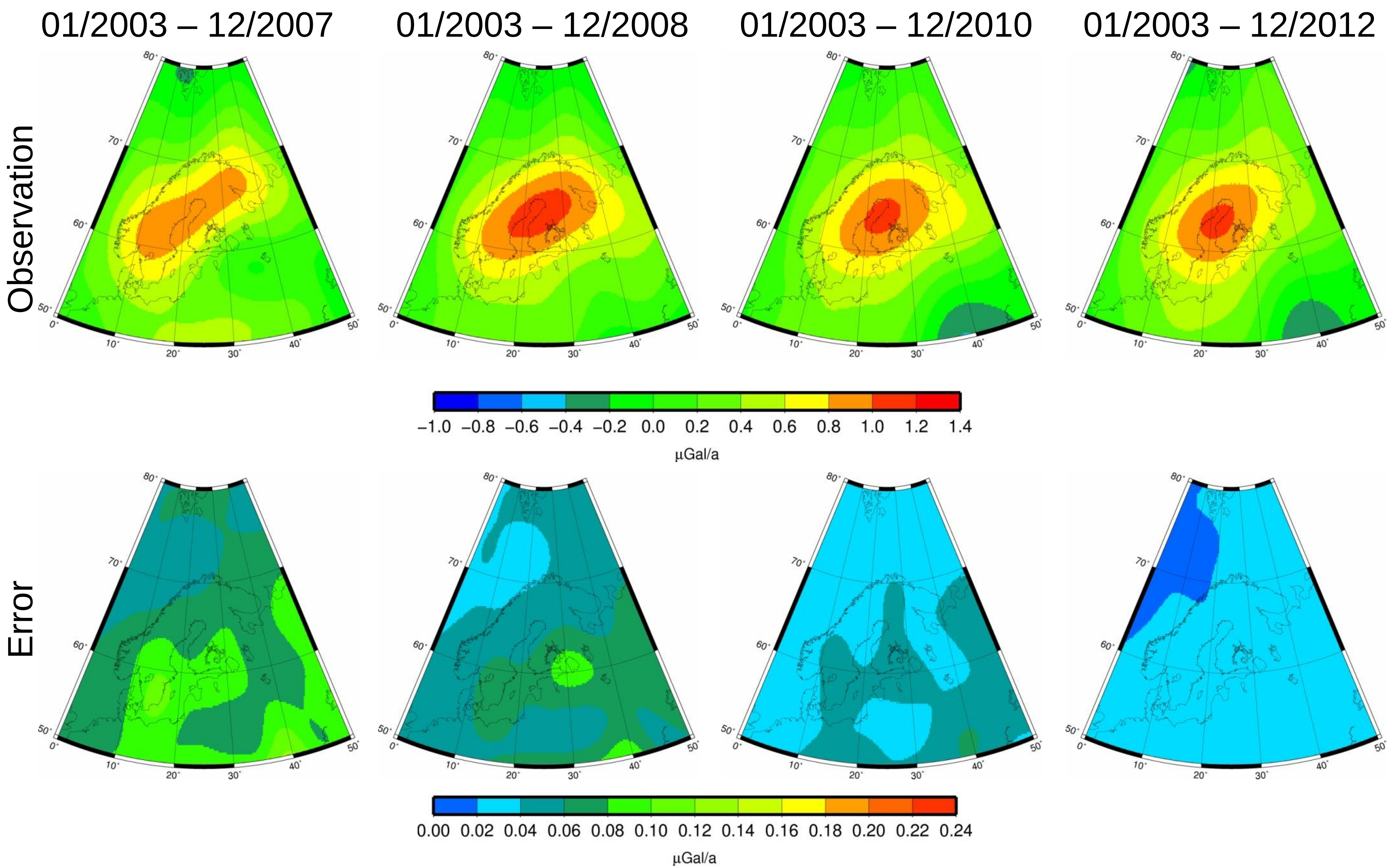
Accuracy of GRACE for different time spans



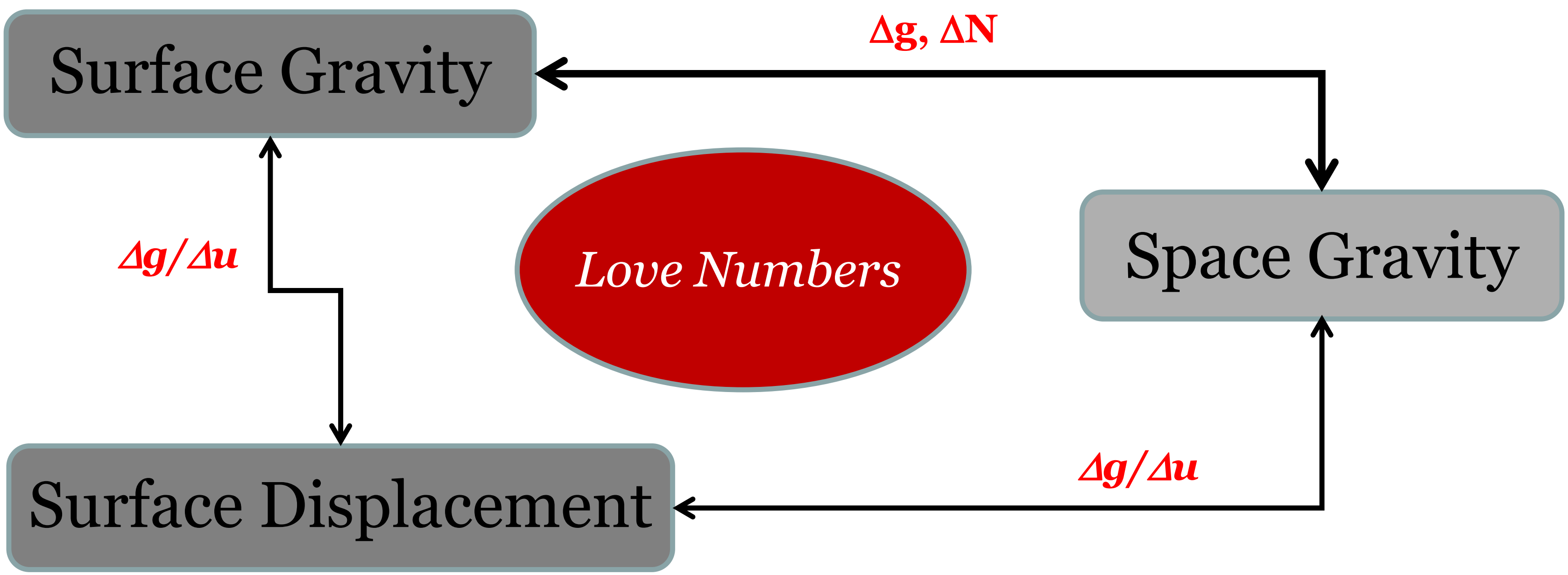
GFZ RL05 335 km Gaussian, d/o 60

Accuracy of GRACE for different time spans



GFZ RL05 400 km Gaussian, d/o 50

Space-, ground-gravity and height changes intercomparison



Space/ground measurements

	GPS "vertical"	Absolute Gravimeter	GRACE
	Radial displacement (h_n')	Newtonian attraction (global + local *(e.g. soil moisture)*) + vertical displacement in gravity field (h_n') + mass redistribution (k_n')	Newtonian attraction (global) - + mass redistribution (k_n')
Resolution Spatial resolution λ/2 SH coefficients Temporal resolution Long-term stability	mm Point N/A 1 s No drift	1-3 μGal Point N/A variable no drift	10 μGal 0.5 μGal 400 km 2,000 km n_{max} = 50 n_{max} = 10 10 days - 1 month No drift

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Transfer function ratios Δg/Δu

$$\Delta g = \Delta g^{elastic} + \Delta g^{Newtonian} + \Delta g^{viscous}$$

(gravity variations)

$$\Delta u = \Delta u^{elastic} + \Delta u^{viscous}$$

(vertical displacement)

→ Separation of present-day ice mass changes (elastic) and (viscoelastic) glacial isostatic adjustment (post-Pleistocene deglaciation)

Viscous Transfer function $\Delta g^v/\Delta u^v$

Glacial Isostatic Adjustment (mantle density) ($n \geq 2$)

$$\frac{\Delta g^v}{\Delta u^v} = 2\pi G\rho_m \frac{n+1}{n+1/2}$$

ρ_m density of lithosphere (3.0 - 3.5 g/cm^3)

(Wahr et al. 1995 GRL;
Fang & Hager 2001, GRL)
Viscoelastic Earth response

≈ -0.15 µGal/mm

$$\frac{\Delta g^v}{\Delta u^v} = \frac{g_0}{a}\frac{n+1}{1.1677n-0.5233}$$

g_0 surface gravity
a Earth's radius

(Purcell et al. 2011, GRL)
Empirical model ($n < 60$)

Observations: -0.15 <$\Delta g^v/\Delta u^v$<-0.18 µGal/mm (roughly constant)

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Absolute gravity network

FG5-220 from IfE (Photo: Gitlein)

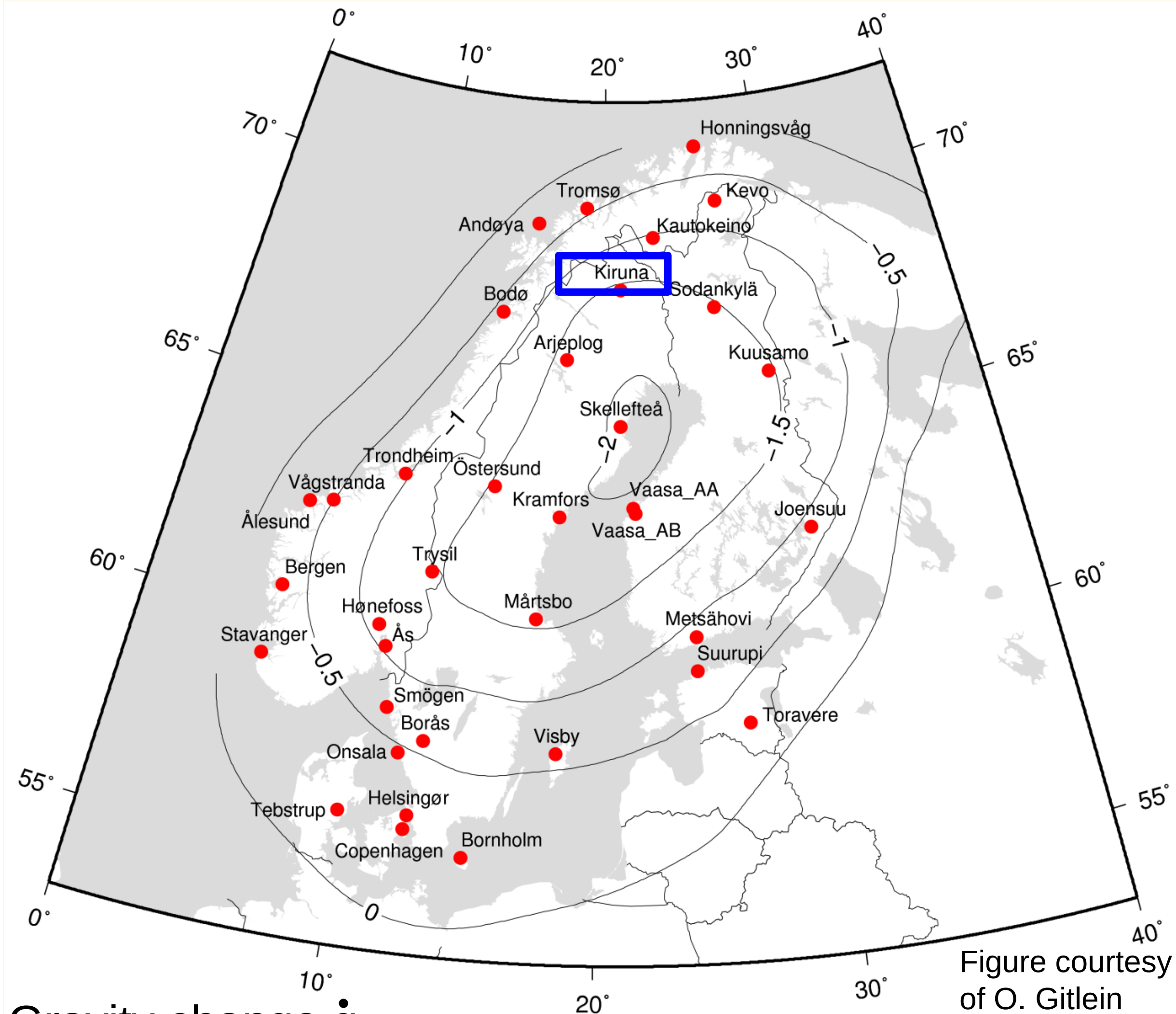
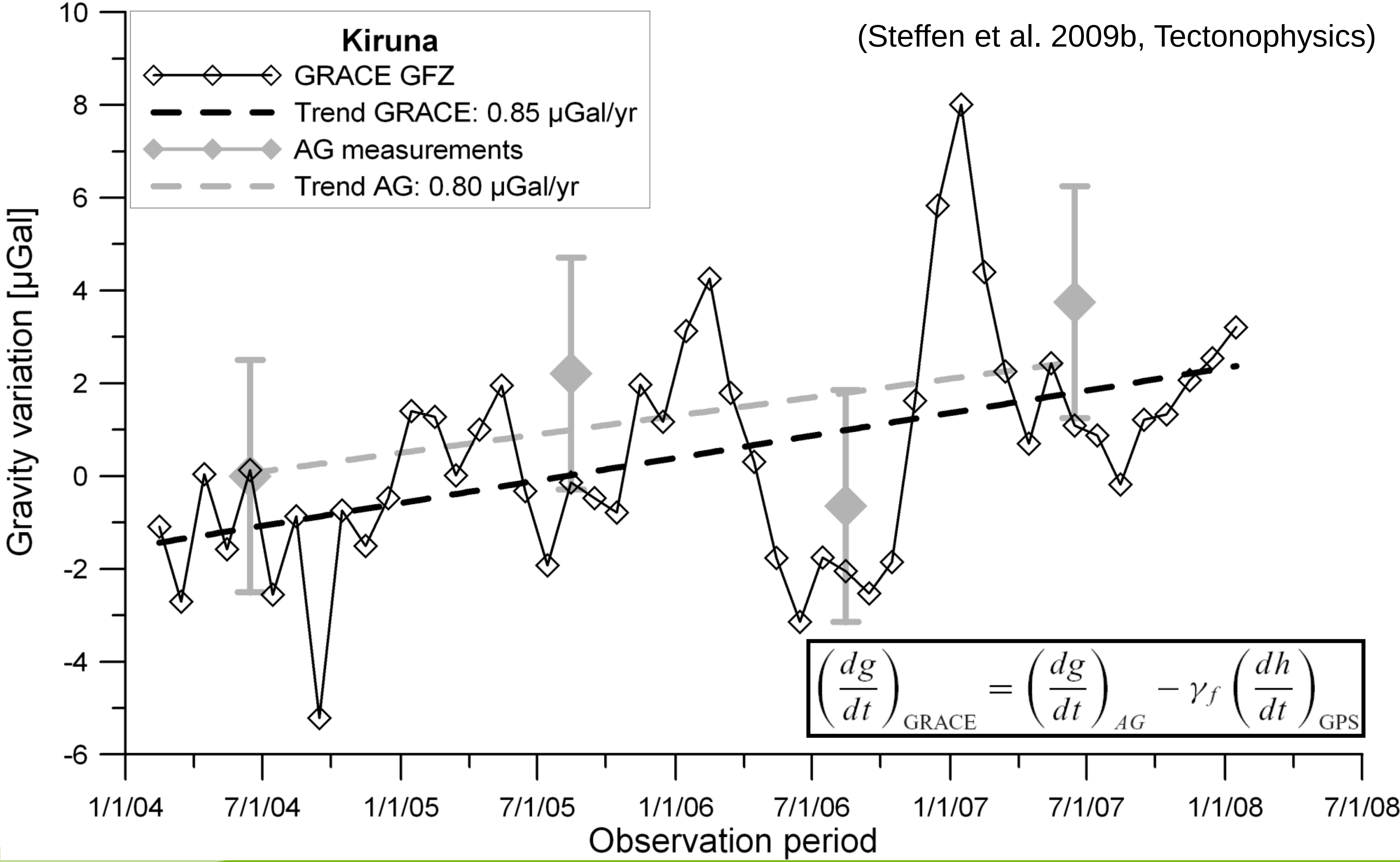


Figure courtesy of O. Gitlein

Gravity change ġ
after Ekman and Mäkinen (1996)

Comparison to absolute gravity

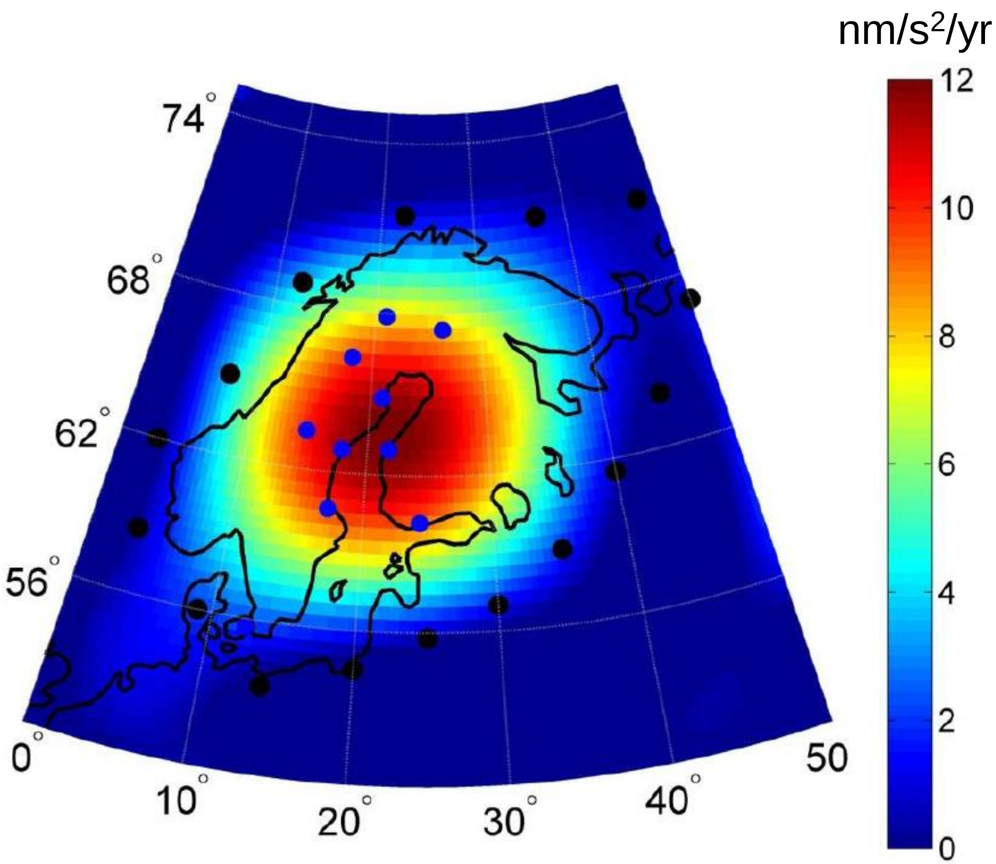
(Steffen et al. 2009b, Tectonophysics)



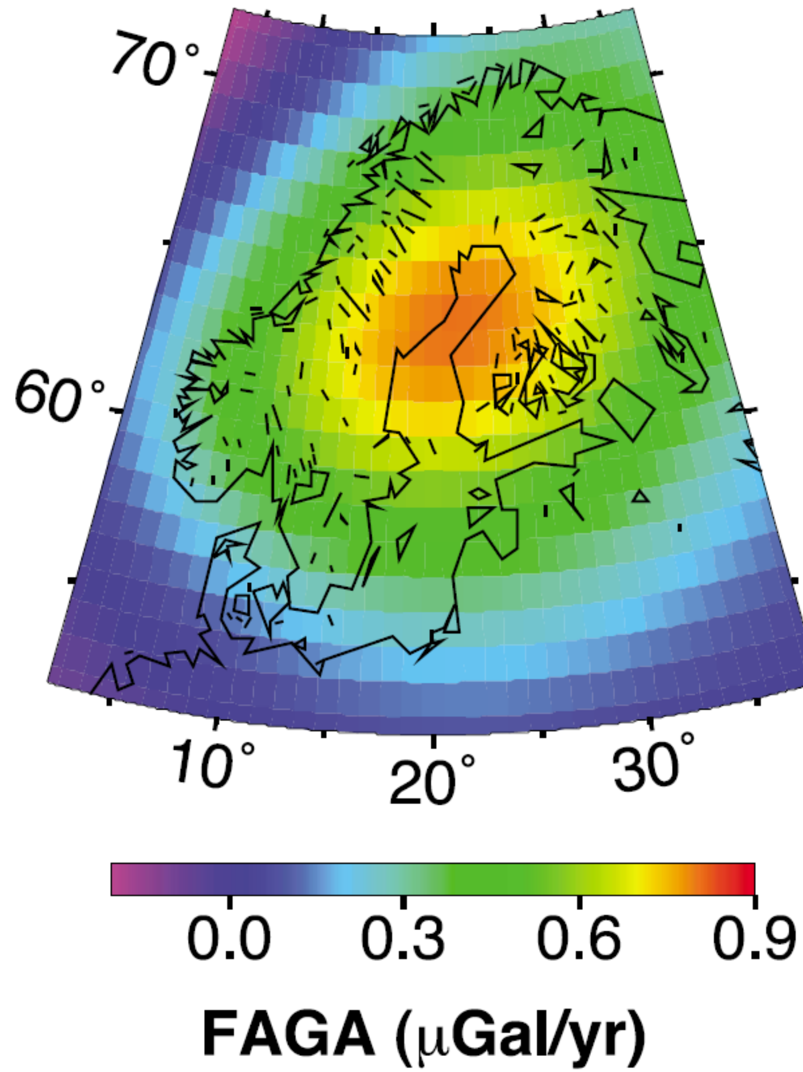
$$\left(\frac{dg}{dt}\right)_{\mathrm{GRACE}} = \left(\frac{dg}{dt}\right)_{AG} - \gamma_f \left(\frac{dh}{dt}\right)_{\mathrm{GPS}}$$

Data combination

GRACE + AG (+ GPS) + geophysical model



GRACE + GPS + tide gauges



(Müller et al. 2012, PCE)

(Hill et al. 2011, JGR)

Conclusions

- GIA in many parts of the world
- In Fennoscandia, excellent velocity and gravity observations of high accuracy (partially long records)
  - GPS, tide gauge, levelling, absolute and relative gravimetry, GRACE
- Data needed for GIA models, which can provide inside into Earth's structure
- $\Delta g^v / \Delta h^v$ in Fennoscandia about -0.16 – -0.17 μGal/mm
- Data combination of vertical (uplift) rates and gravity change possible – will be used to develop new GIA model for Fennoscandia

Acknowledgements

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Thank you for your attention!

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