On the accuracy of Glacial Isostatic Adjustment models with special attention to ice models

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What is a GIA model?

- Actually developed to determine mantle viscosity for convection models and to describe sea-level variations
- Two major parts: (I) Earth model and (II) ice model
- Other information: Topography model (for ocean basin structure)
- Mathematical-physical theory relating the physics of the ice-earth-ocean changes to observational quantities
  - Earth and ice models are coupled via the sea-level equation
- Needs (III) observations to tune it
- Can take different processes/effects into account:
- Deformation
- Mass redistribution (ice, water, earth, sedimentation)
- Earth rotation
- Geoid & sea-level changes
- Stress changes

What do we expect from a GIA model?

A reference of/for

- Vertical motion (Present-day rate of uplift)
  - GPS, tide gauges, altimetry, levelling
  - Sea-level change
- Horizontal motion
  - GPS, VLBI, DORIS(?)
- Gravity change
  - AG, RG, GRACE/GRACE-FO, GOCE
- Geoid change
- Rotation changes (e.g. help in archaeology)

Help explain

- postglacial and recent seismic activity
- volcanic activity

Provide

- Excellent fit to observations in all parts of the world
- Uncertainty estimates or upper & lower bounds

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Overview of ice models (not complete)

- Global: ICE (Peltier & Andrews 1976), ICE-2 (Wu & Peltier 1983), ICE-3G (Tushingham & Peltier 1991), ICE-4G (Peltier 1994), ICE-5G (Peltier 2004), ICE-6G (Peltier, in prep.), Amantev & Fjeldskaar, ANU-ICE (Lambeck et al., in prep.)

- Northern Hemisphere: NAWI (Zweck and Huybrechts 2005)

- Europe: FBKS8 (Lambeck et al. 1998, 2010), UMISM (Näslund 2008), “Stocchi model” (Stocchi et al., in prep.), GLAC (Tarasov et al. 2012)
- Greenland: KL05 (Fleming & Lambeck 2004), Milne et al. (in prep.)
- Antarctica: Huybrechts (1990), Hughes (1981), Ivins & James (2005), Whitehouse et al. (2012), Ivins et al. (2013)

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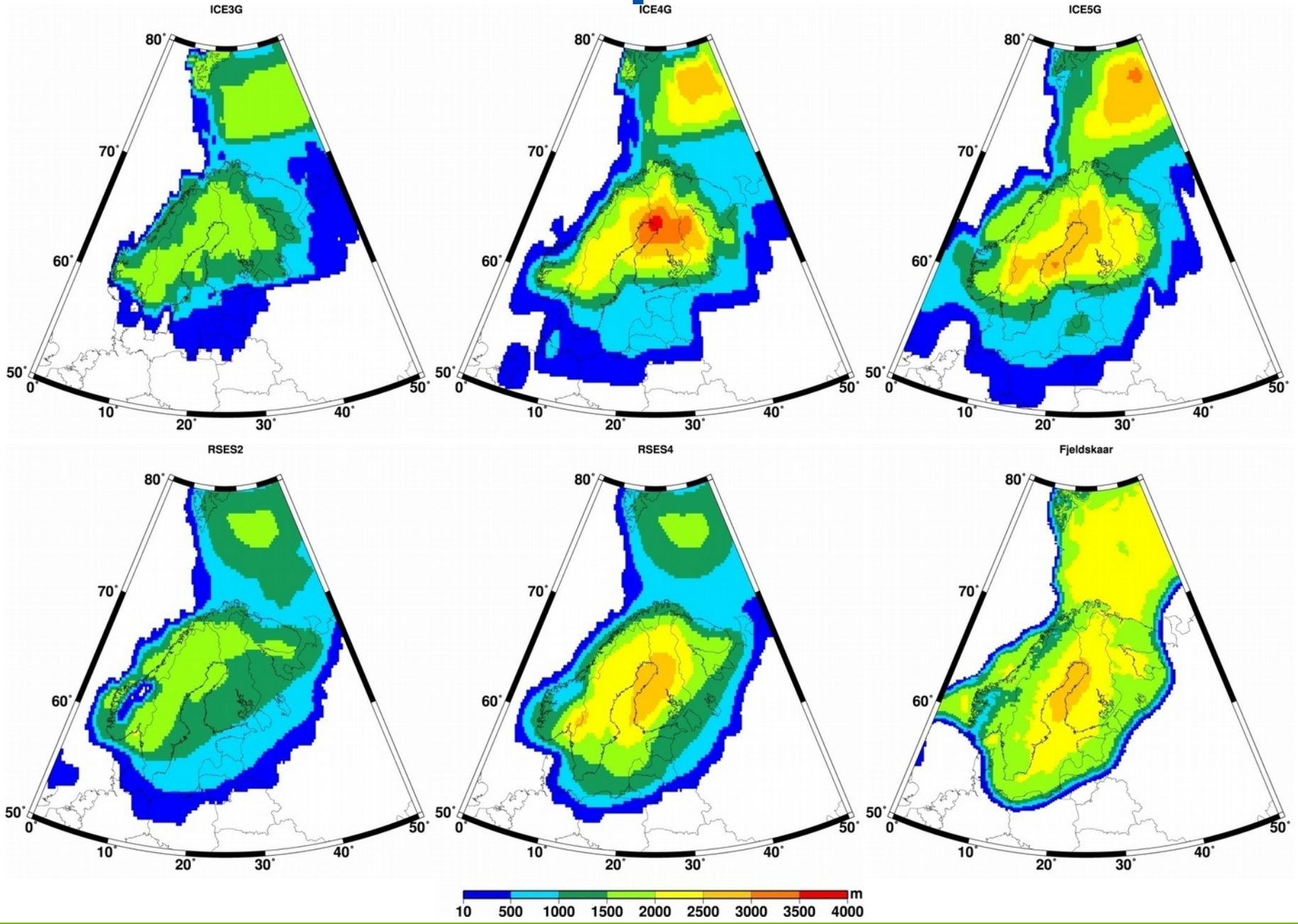
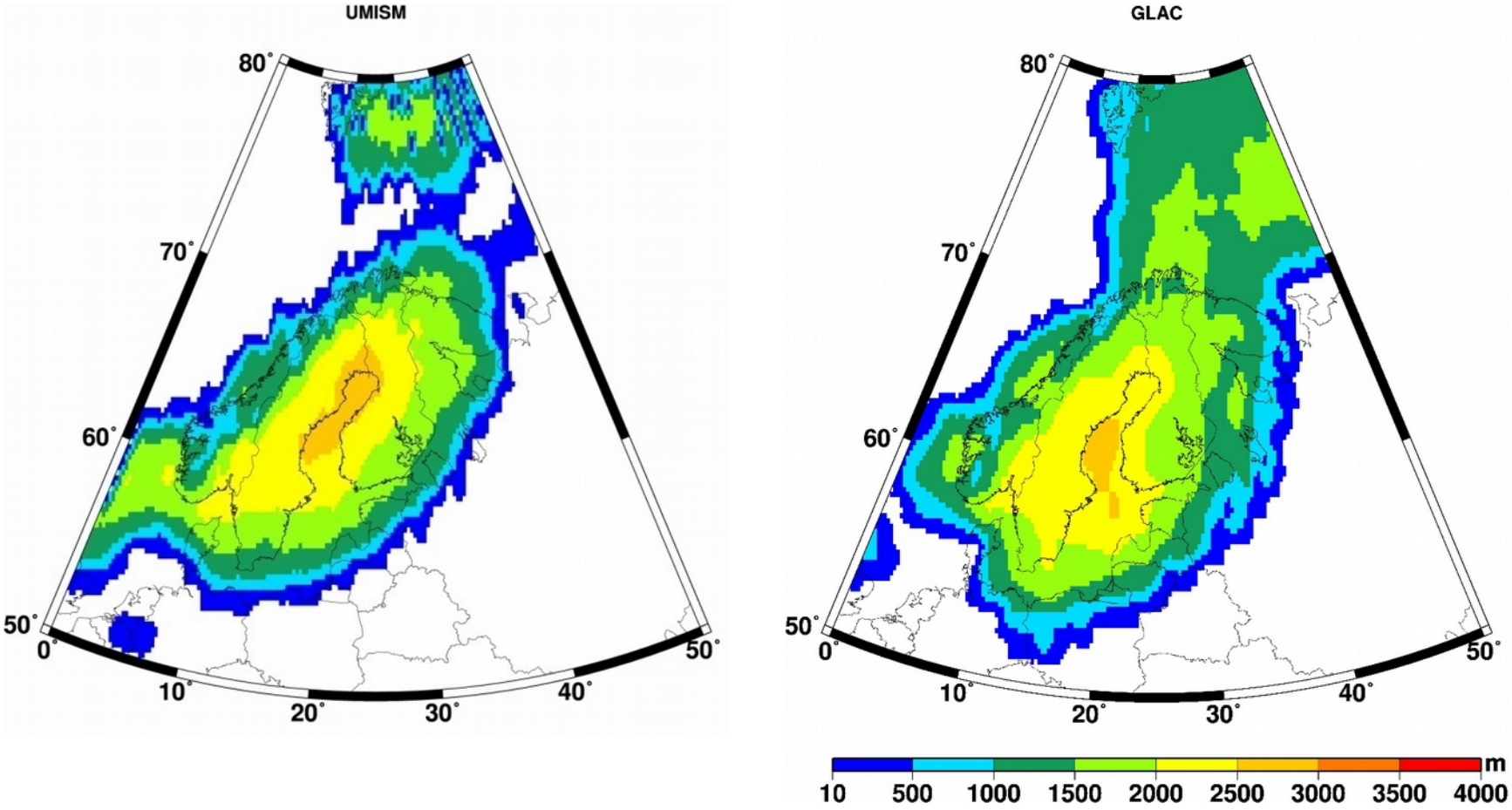
The two types of ice models in GIA models

- "Classical approach":
  - Extent at different times from geological markers
  - Ice thickness adjusted with sea-level equation; solution fits available data, mainly RSL and tide-gauge data
  - Contains (strong) earth model information
- Thermo-mechanical:
  - Palaeo-climate data to govern the evolution of the ice sheet
  - Includes basal sliding, ice streams, ice-thickness distribution, growth and decay properties
  - Geological markers and RSL data **may** be used to constrain the reconstruction
  - **May** contain (weak) earth model information, mainly due to topography information

SLE ice model examples at LGM



Thermal ice model examples at LGM



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What about their accuracy/uncertainty/errors?

- They (ice models) are not provided with uncertainty estimates…
- Many developers of SLE-driven ice models **insist** that their ice model is used with the nominal/corresponding earth model, especially when the GIA model is used in investigations!

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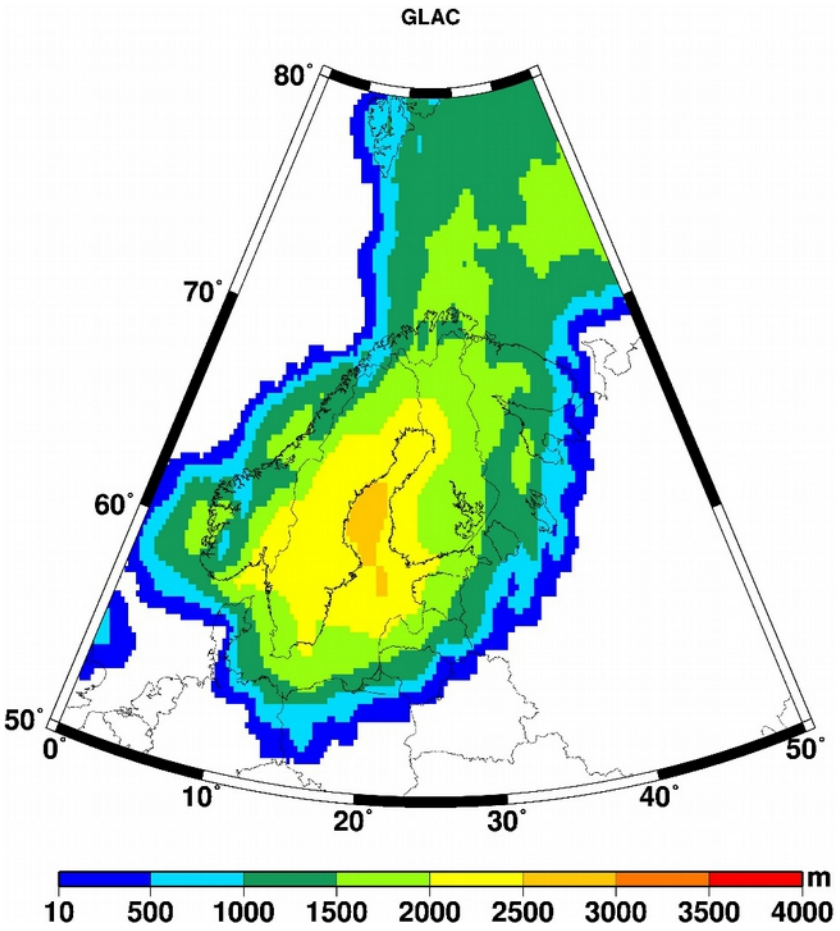
GLAC models by Lev Tarasov

- Glaciological Systems Model (GSM)
- 3D thermo-mechanically climate-forced model
- Tuned to ice margin information, present-day uplift, relative sea-level records
- Contains further input parameters (39 in total)
- Takes uncertainties in the constraints into account → generates posterior probability distributions for past ice sheet evolution (Tarasov et al., 2012)



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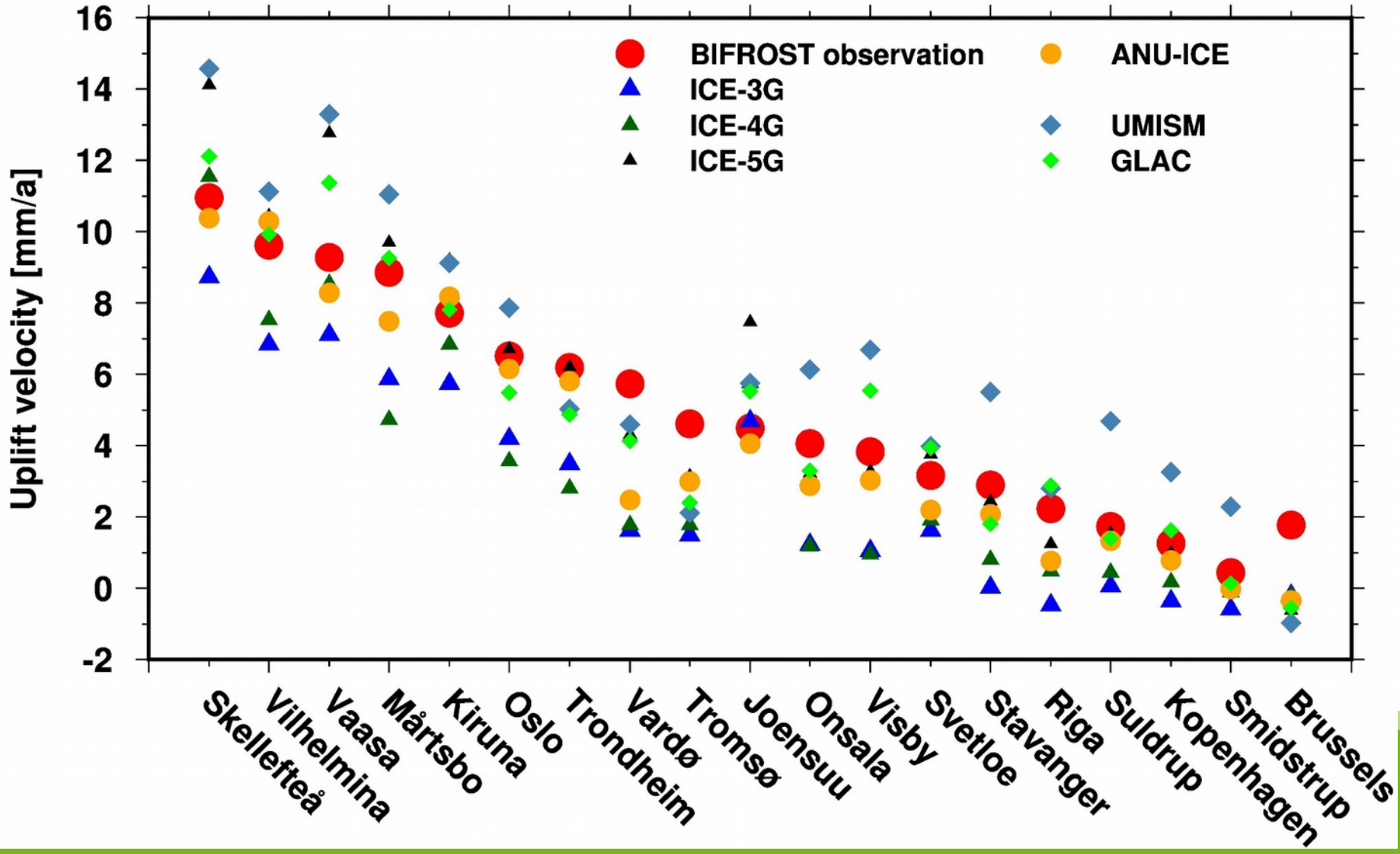
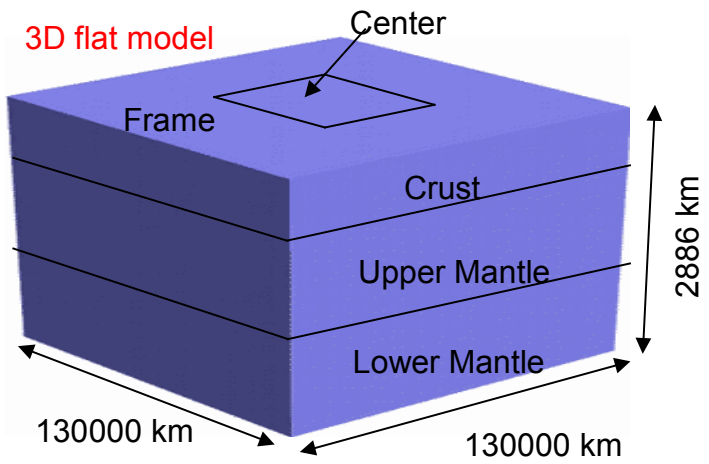
Observations vs. GIA model results

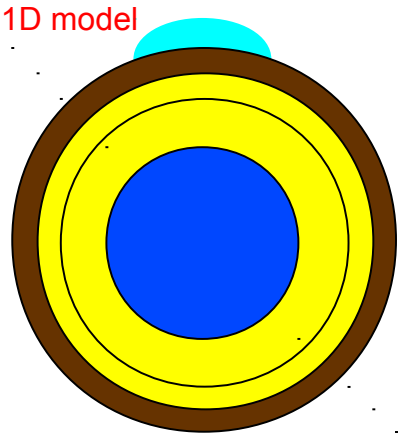
Different ice models with a VM2-like earth model



Earth models

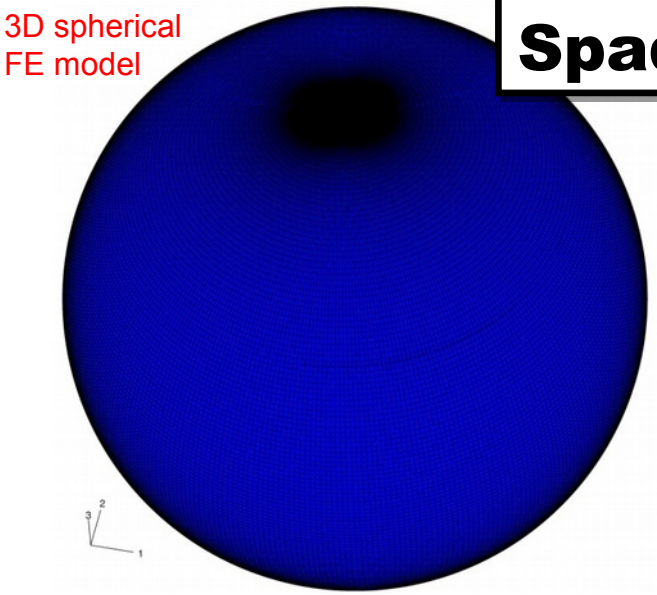


(Wu 2004, GJI)

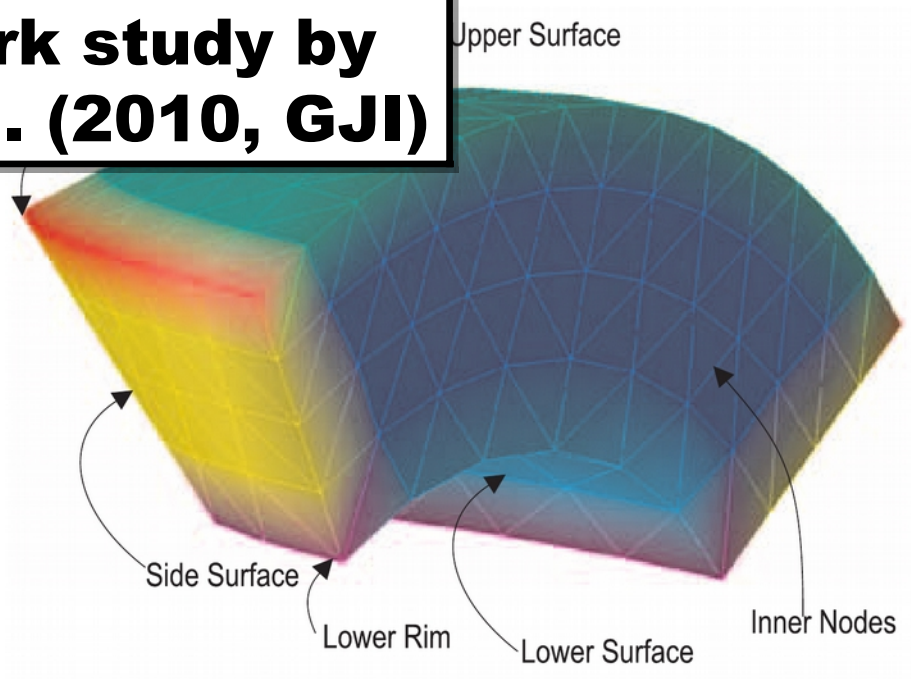


(Munk & MacDonald 1960; Farrell and Clark 1976; Mitrovica et al. 1994, JGR; Mitrovica and Milne 1998; Kaufmann et al. 2002, JGR Spada et al. 2007)

Benchmark study by Spada et al. (2010, GJI)



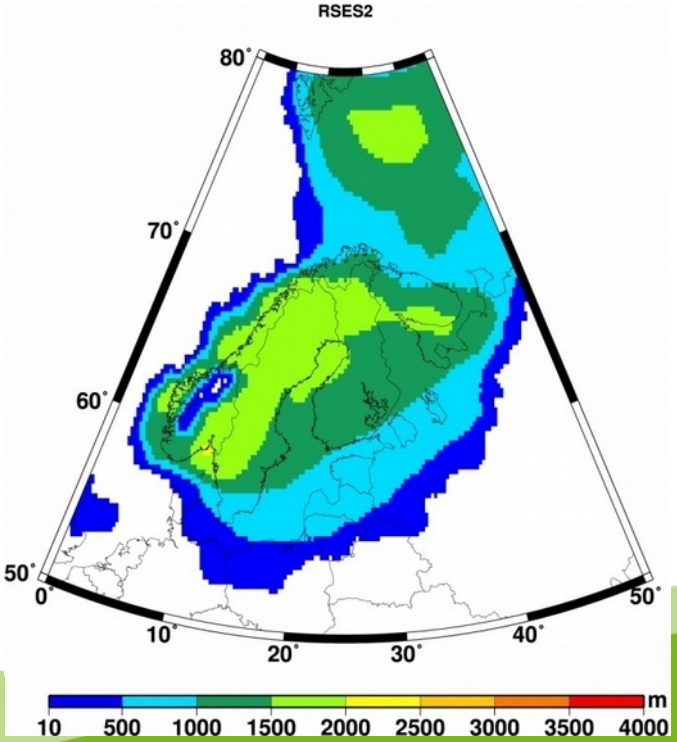
(Wu 2004, GJI)

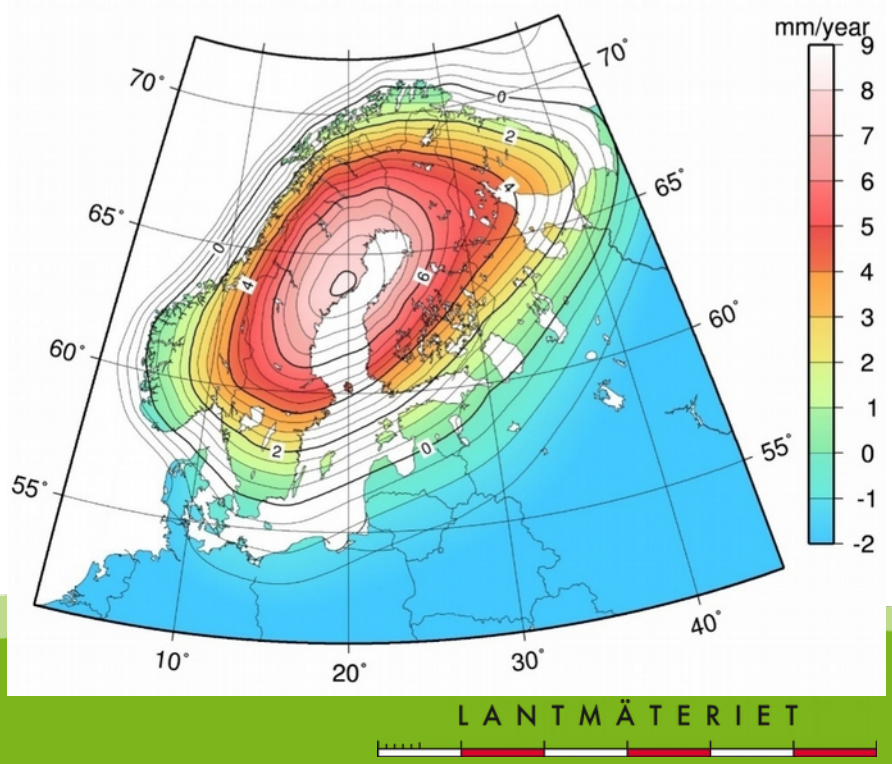


(Latychev et al. 2005, GJI)

How well fits a GIA model?

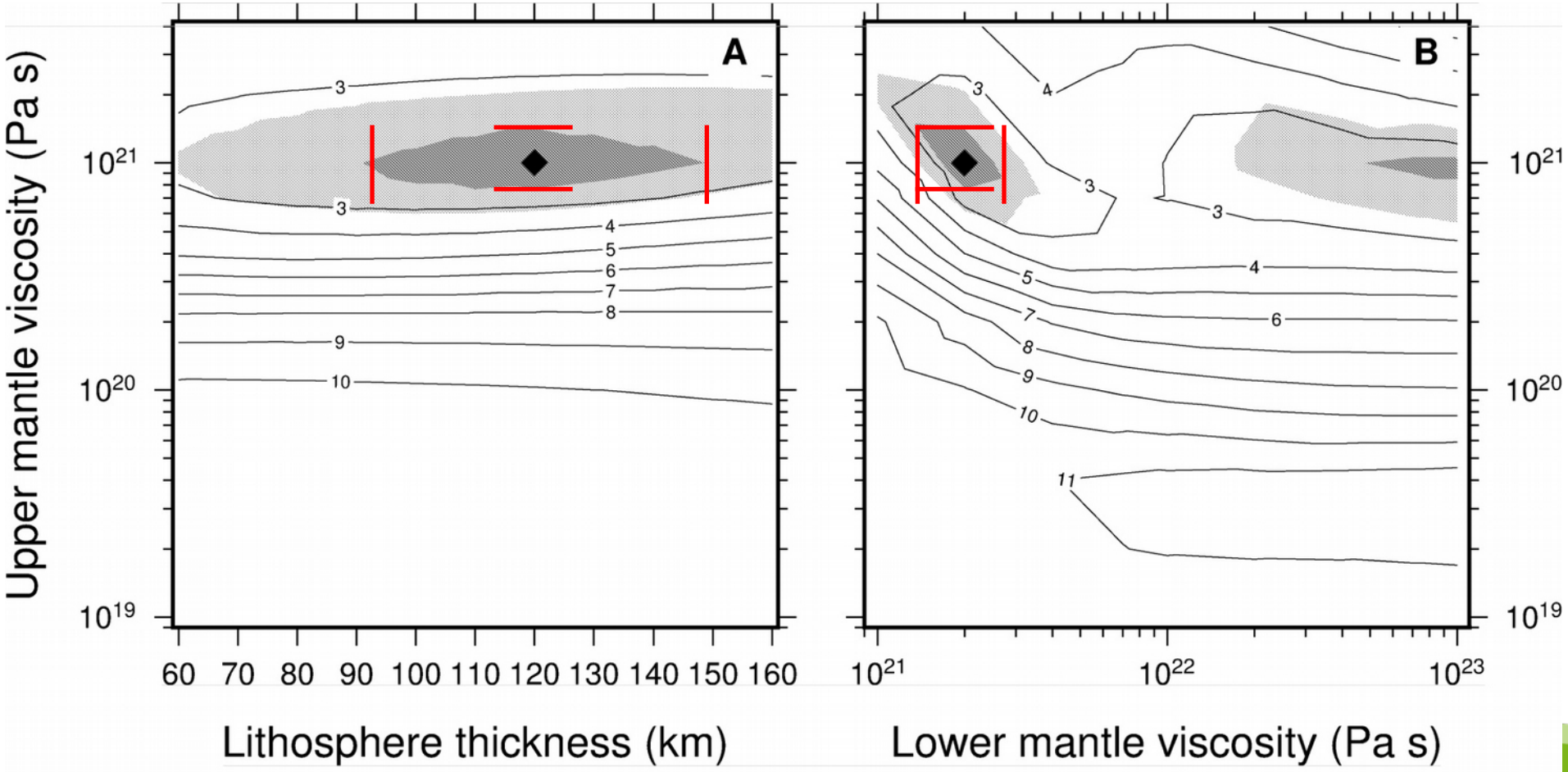
- ~1100 GIA models are compared to the NKG2005LU model
- GIA model: RSES ice model and a 1D (spherically symmetric) earth model with three varied parameters
- Best earth model: lithospheric thickness = 120 km, upper-mantle viscosity = 10^{21} Pa s, lower-mantle viscosity = 2 x 10^{21} Pa s





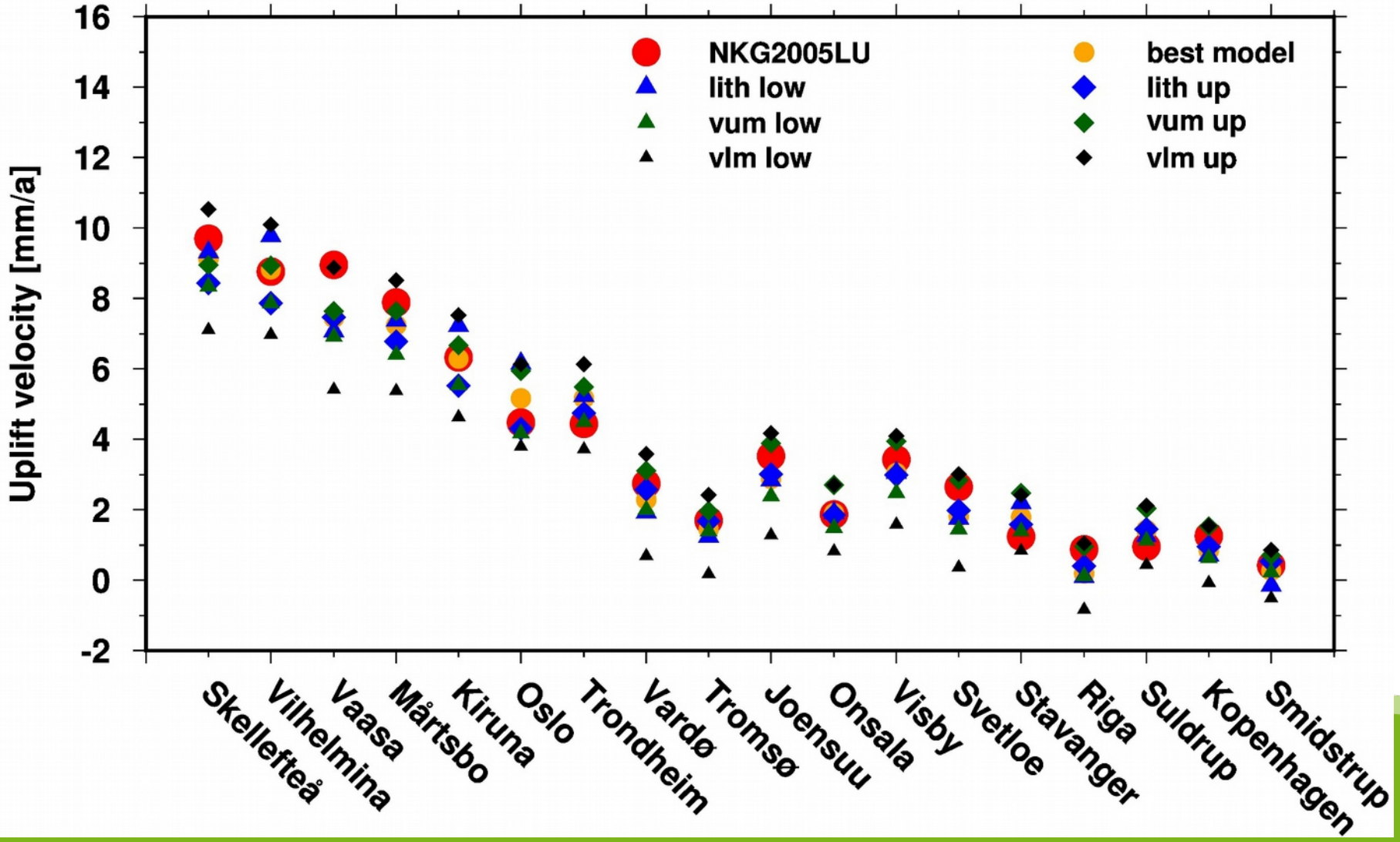
How good fits a GIA model?

Diamond: best model; Dark gray: σ_1; Light gray: σ_2

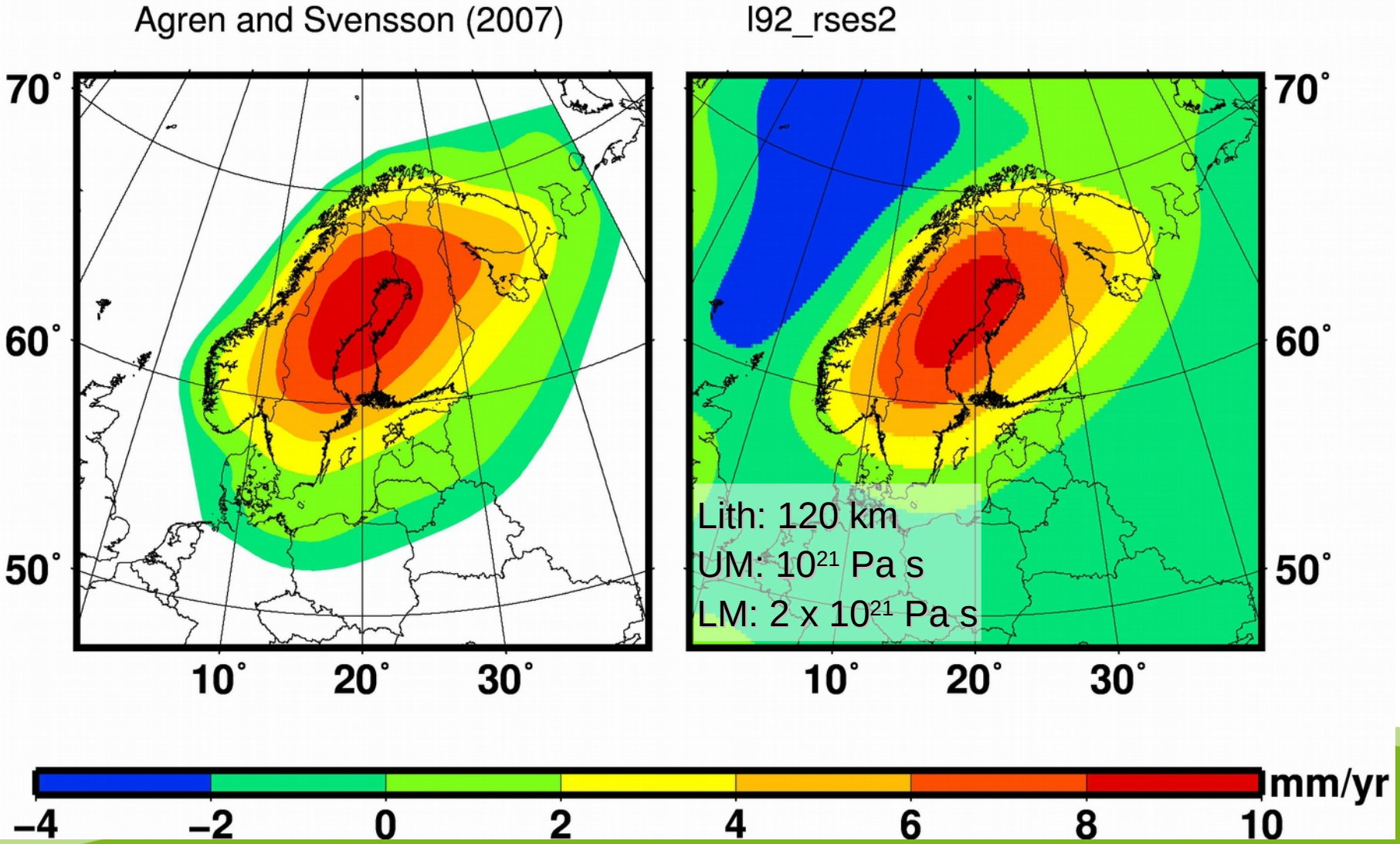


How well fits a GIA model?

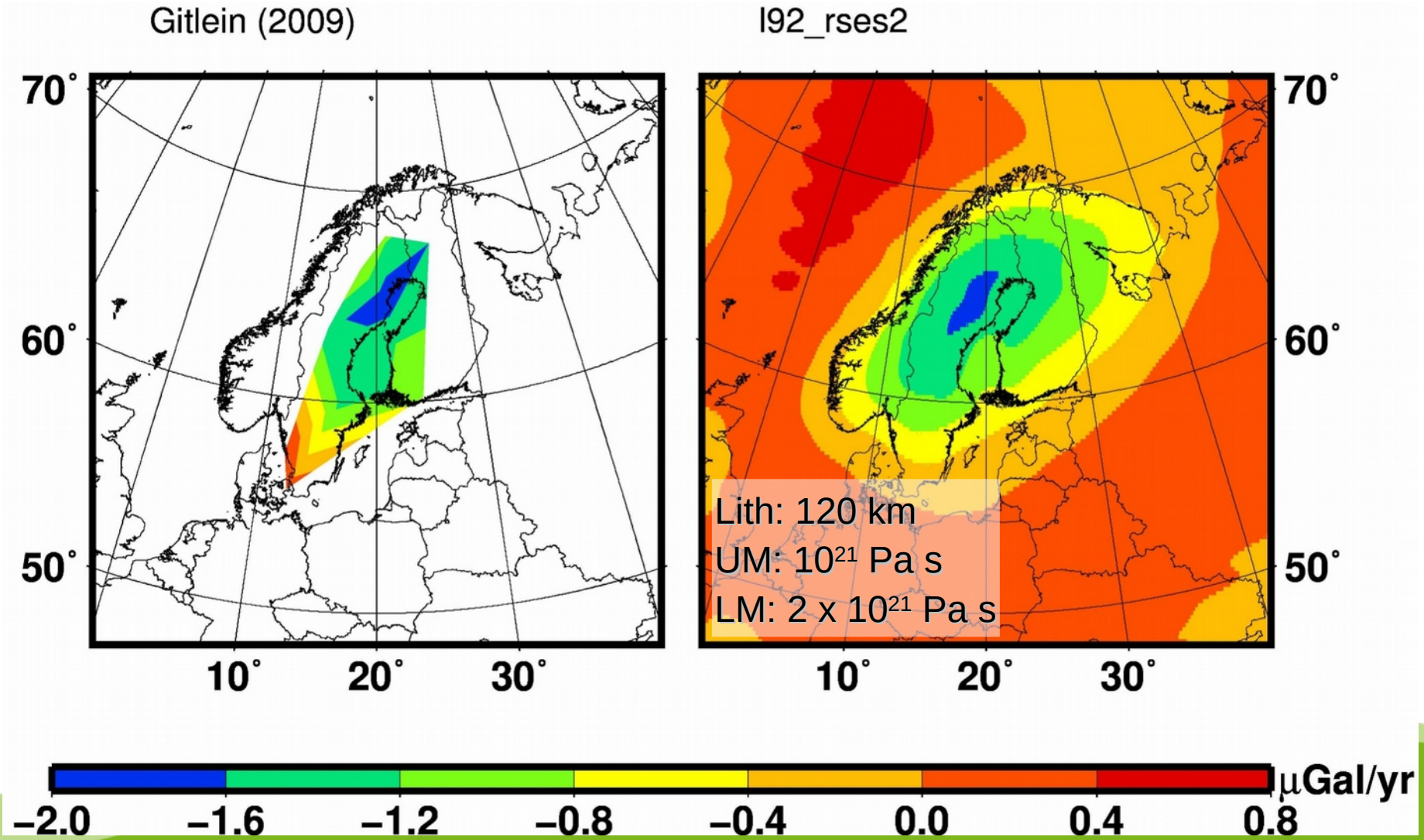
RSES ice model with different earth models



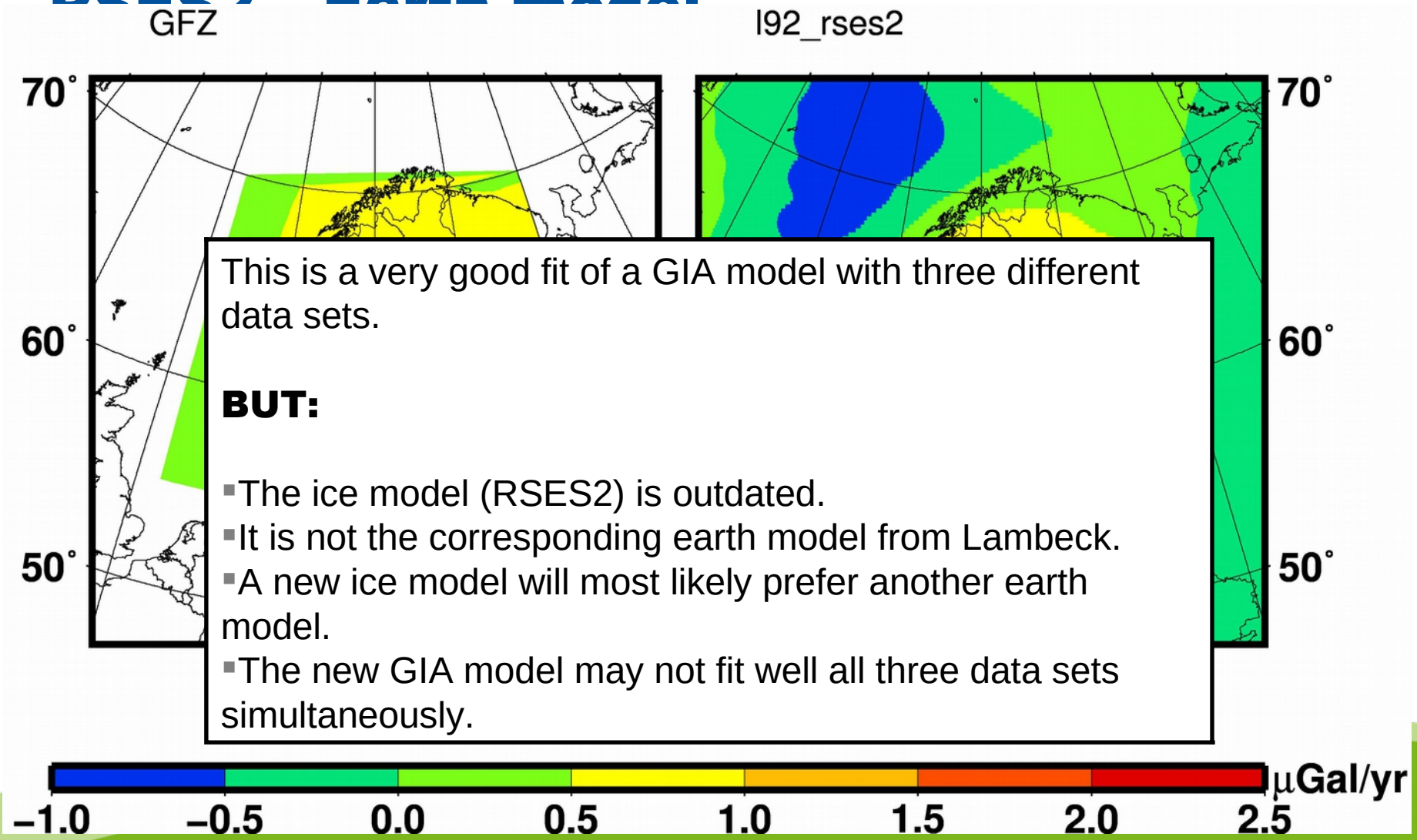
Comparison NKG2005LU to best-fitting RSES2 – Earth model



Comparison Gitlein (2009) AG observations to this RSES2 – Earth model



Comparison GRACE RL04 observation to this
RSES2 – Earth model

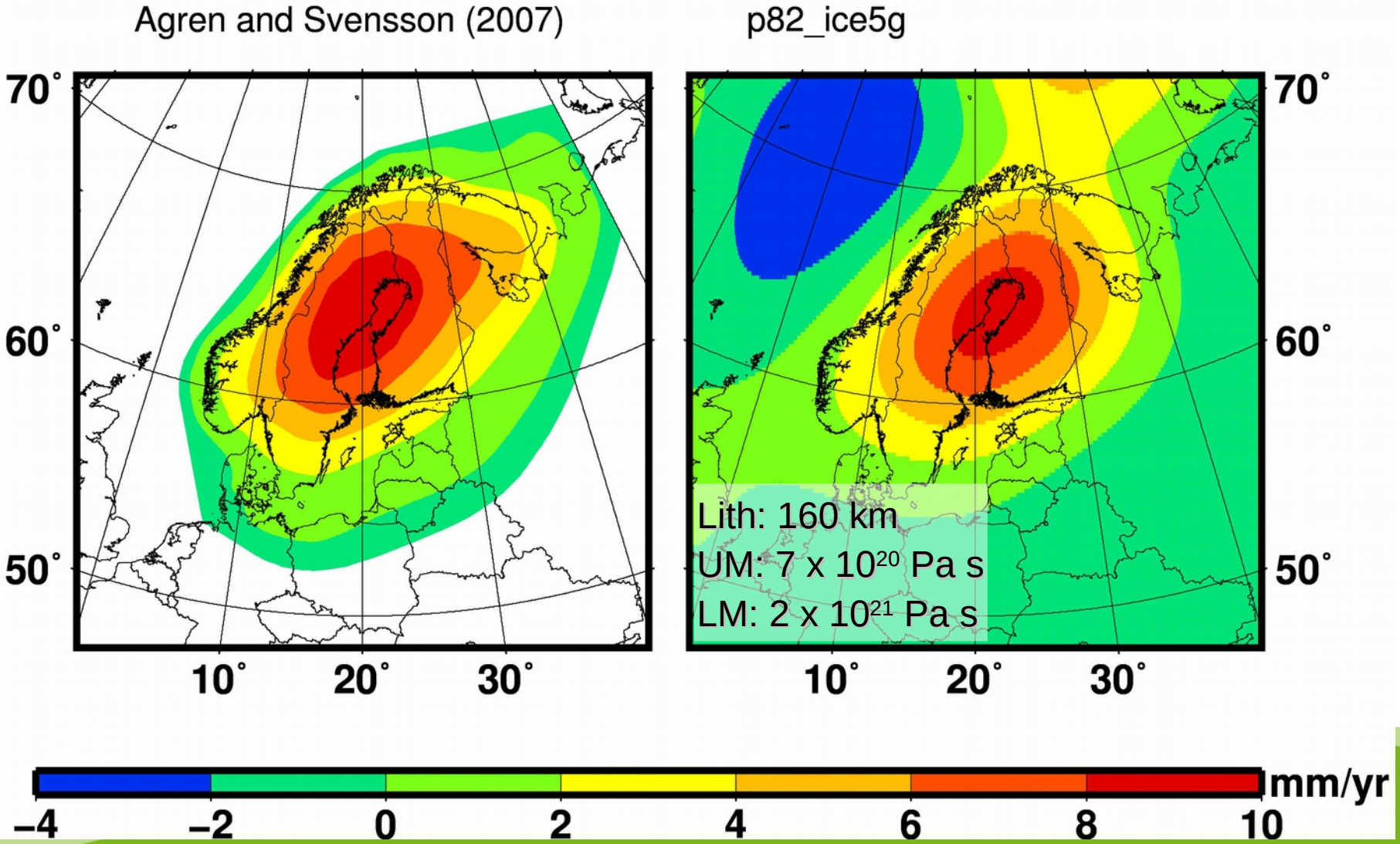


This is a very good fit of a GIA model with three different data sets.

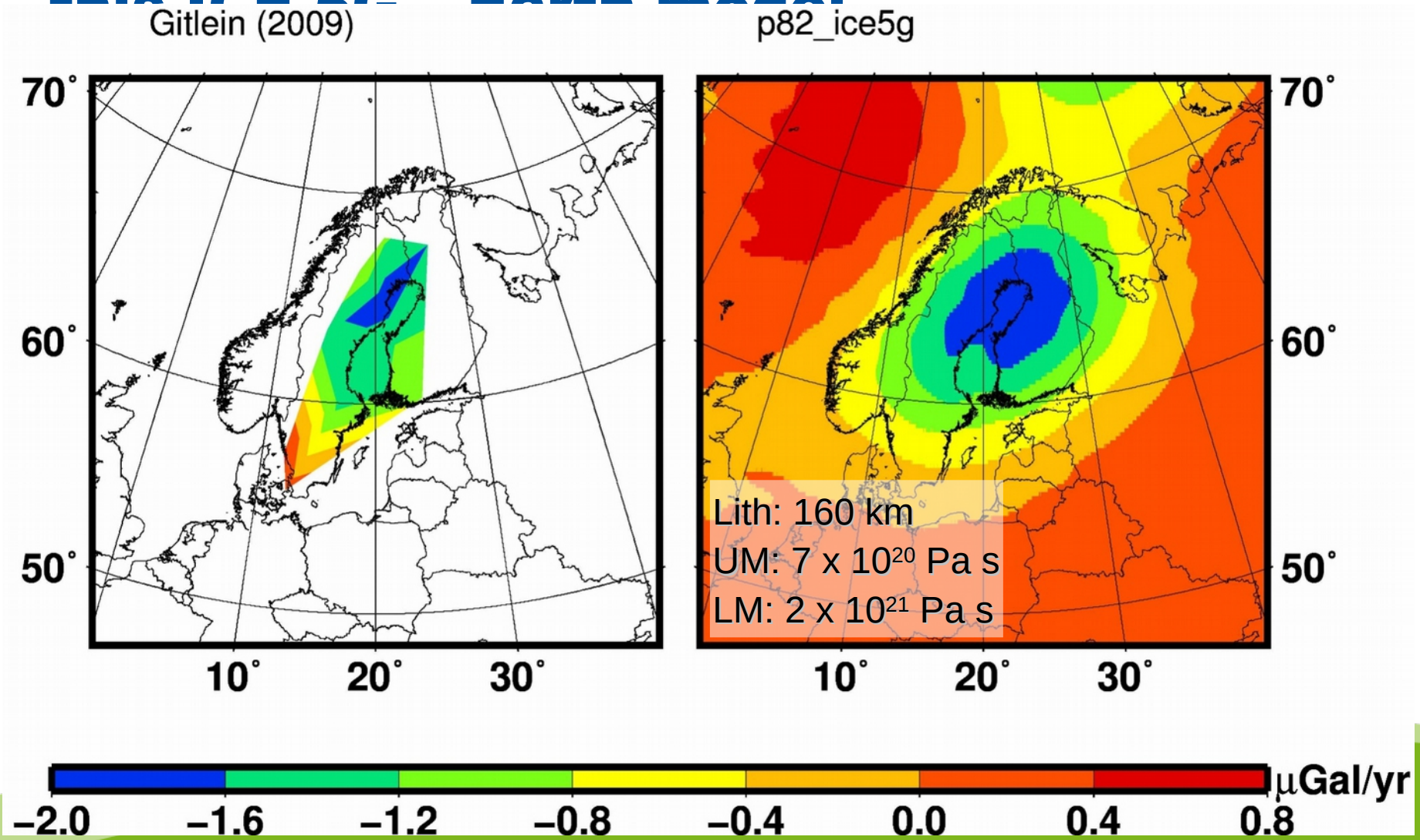
BUT:

- The ice model (RSES2) is outdated.
- It is not the corresponding earth model from Lambeck.
- A new ice model will most likely prefer another earth model.
- The new GIA model may not fit well all three data sets simultaneously.

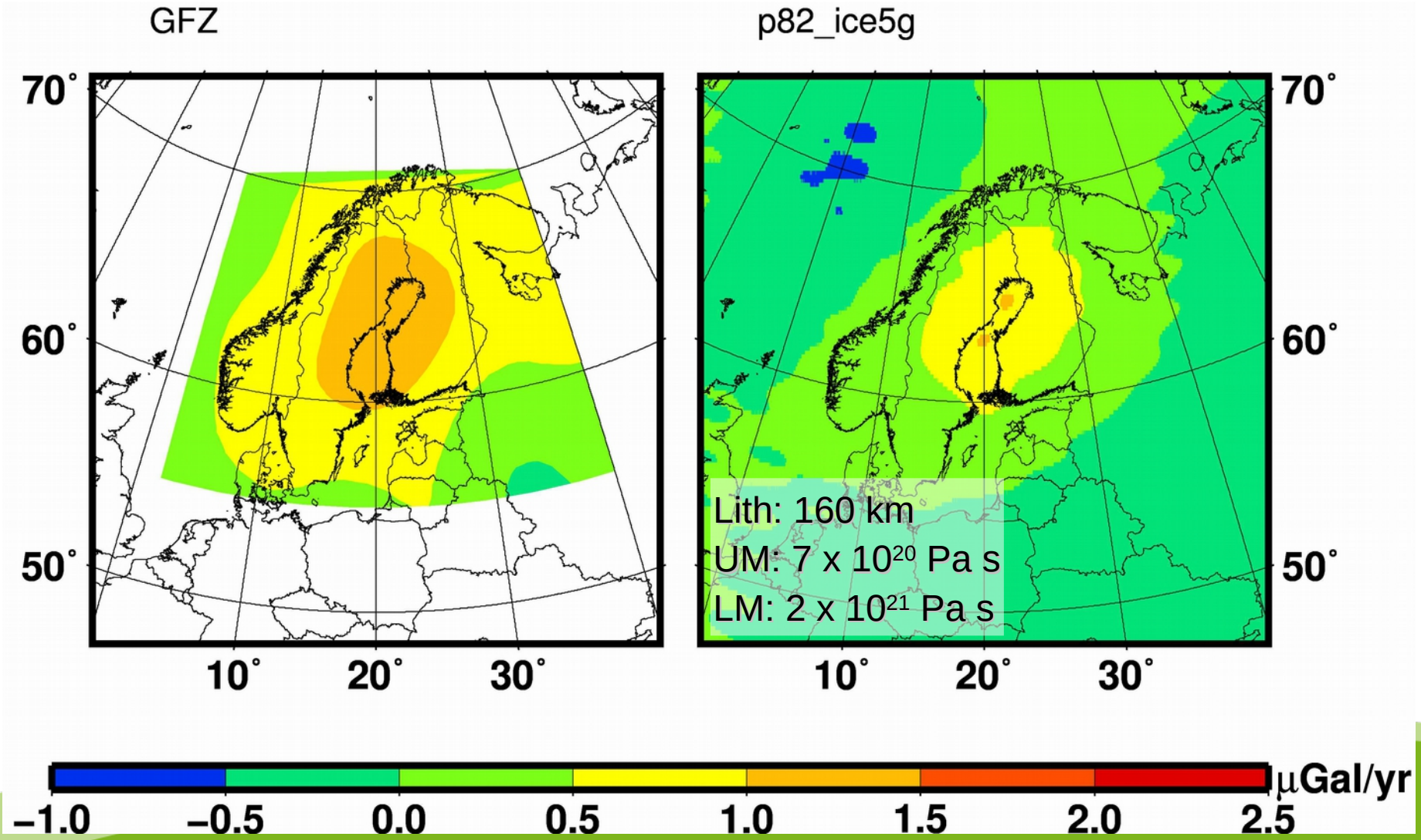
Comparison NKG2005LU to best-fitting ICE-5G – Earth model



Comparison Gitlein (2009) AG observations to this ICE-5G Earth model



Comparison GRACE observation to this ICE-5G – Earth model



Take-homes

- A GIA model is a combination of an earth model and an ice model
- There are different types of ice models
- There are different types of earth models (rheology, heterogeneity,…) and modelling techniques
- (GIA) modelling techniques are benchmarked and agree quite well

- The majority of ice models does NOT provide uncertainty estimates

- GIA model development is an iterative process
- A well-fitting GIA model for one quantity may NOT fit another quantity well!

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Thank you for your attention!

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