GLACIAL ISOSTATIC ADJUSTMENT AND ITS ROLE IN GEODESY

REBEKKA STEFFEN

GGOS DAYS 2023

LANTMÄTERIET

NKG – NORDIC GEODETIC COMMISSION

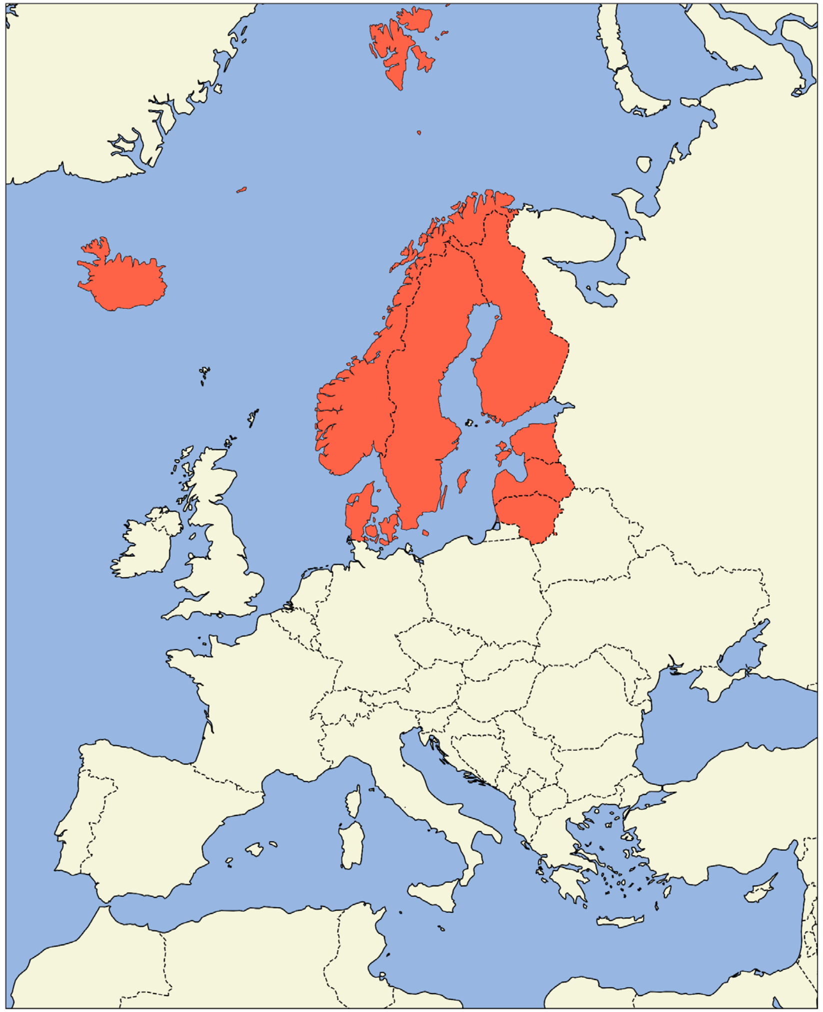
Cooperation by researchers in geodesy within the Nordic countries

⇨ national mapping authorities, universities and research institutes

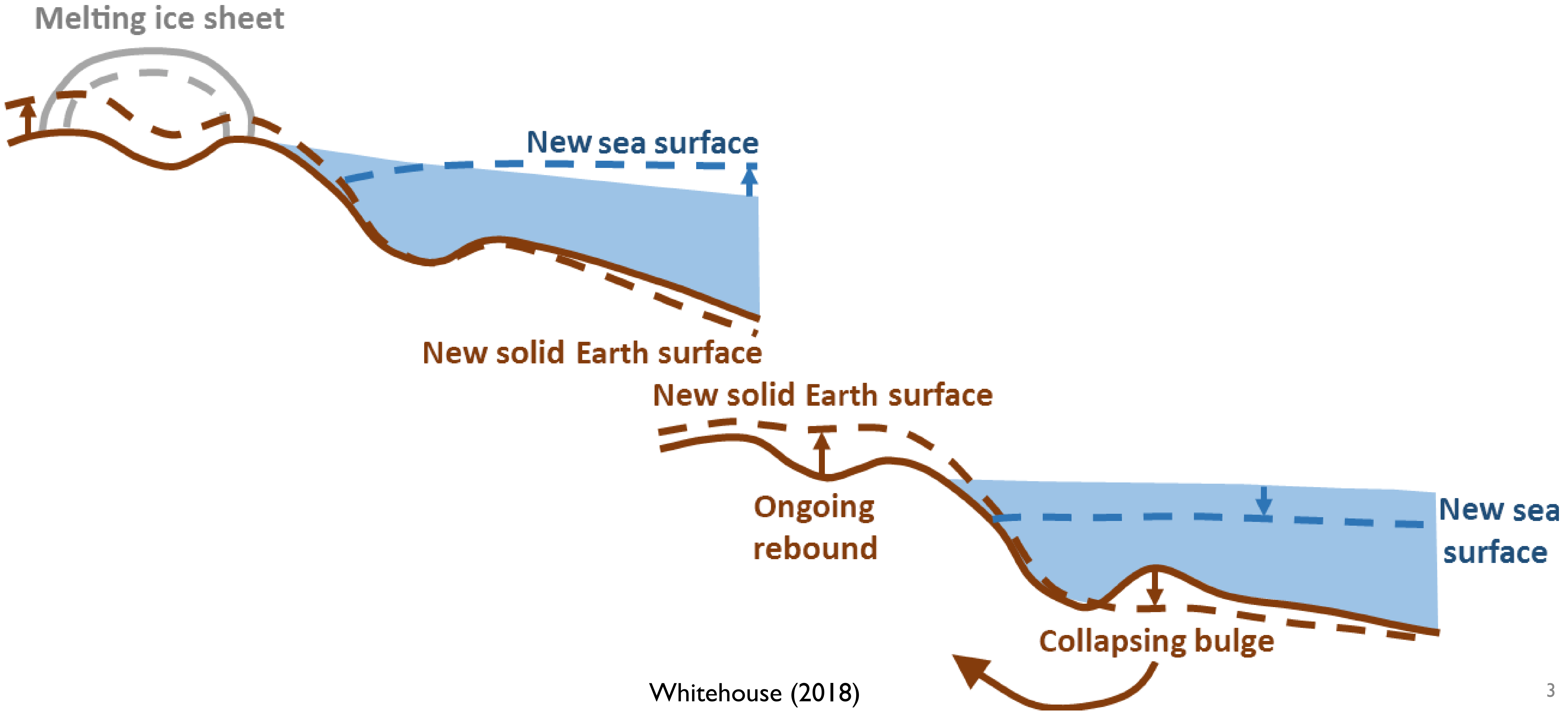
⇨ most work is done within the working groups

- WG of Reference Frames
- WG of Height and Geoid
- WG of Geodynamics and Earth Observation
- WG of GNSS Positioning

⇨ addresses topics that are of common Nordic interest (e.g., glacial isostatic adjustment)



GLACIAL ISOSTATIC ADJUSTMENT (GIA)



Whitehouse (2018)

WHY IS GIA OF INTEREST FOR GEODESY?

TECHNISCHE UNIVERSITÄT DRESDEN

Fakulty of Environmental Sciences, Chair of Geodetic Earth System Research

Martin Horwath

The ice sheets' contribution to sea-level rise

- **Estimates**
- **Uncertainties**
- **Processes**

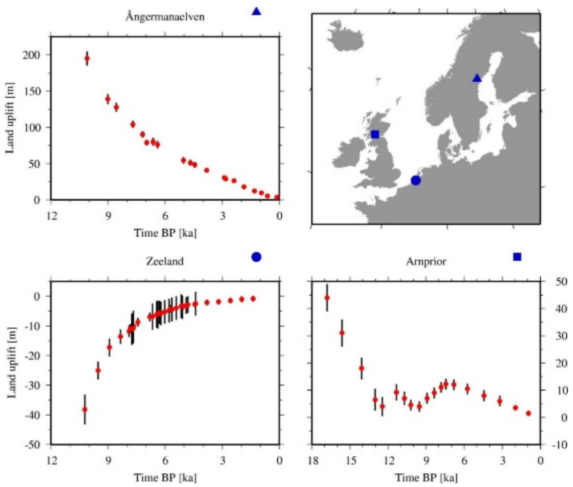
GGOS Days 2022 | 14-15 November 2022 | Munich

Conclusions

- The **Greenland** Ice Sheet and the **Antarctic** Ice Sheet contribute **~24%** and **~ 9%** to global mean sea-level rise over the last two decades.
- For **Antarctica, acceleration of outlet glaciers** (triggered by ice-ocean interaction) is the main mechanism of mass change.
- For **Greenland**, increased **surface melt** and **glacier acceleration** are about equally important.
- **Antarctica** bears the **largest uncertainties** for sea-level projections due to limited understanding of ice flow dynamics and its interactions with oceanic, atmospheric, and solid Earth processes.
- Major **uncertainties** in present-day volume and mass changes of ice and ocean are associated to **core elements of geodetic data acquisition and analysis** (hence to **GGOS**):
  - degree-1 mass redistribution and geocenter motion
  - other low-degree components of the gravity field
  - reference frames
  - (glacial-isostatic adjustment).

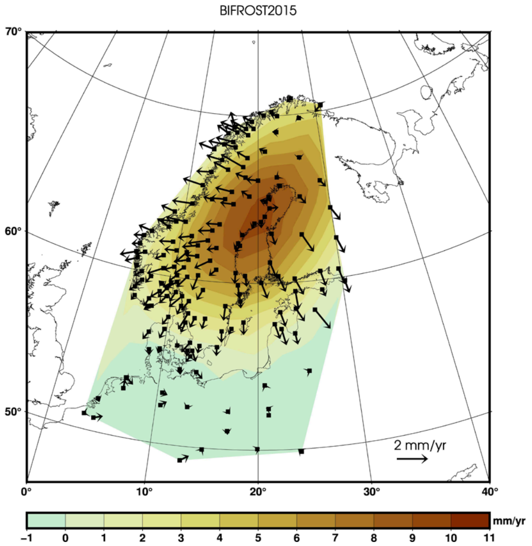
GIA – OBSERVATIONS

The reliable past



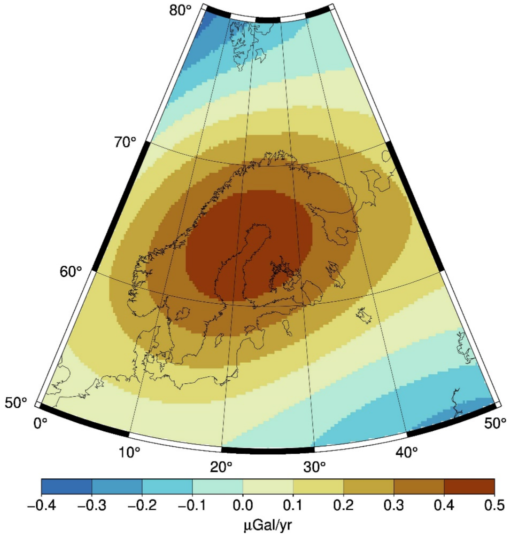
Relative sea level (paleo)

Today's accurate snapshot



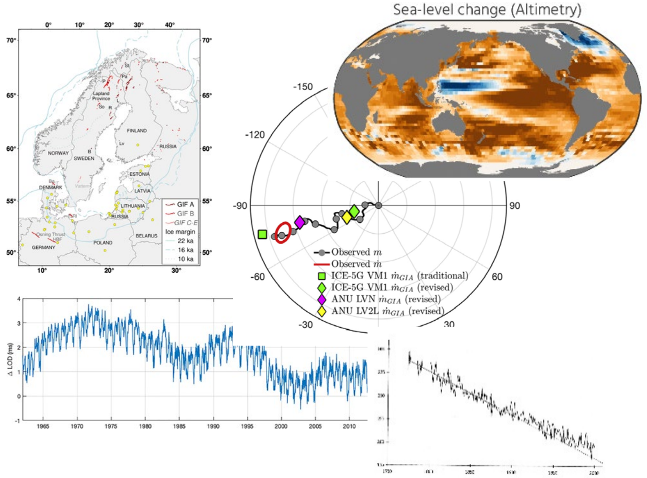
3D land motion

The blurry future



Gravity changes

Helpful constraints

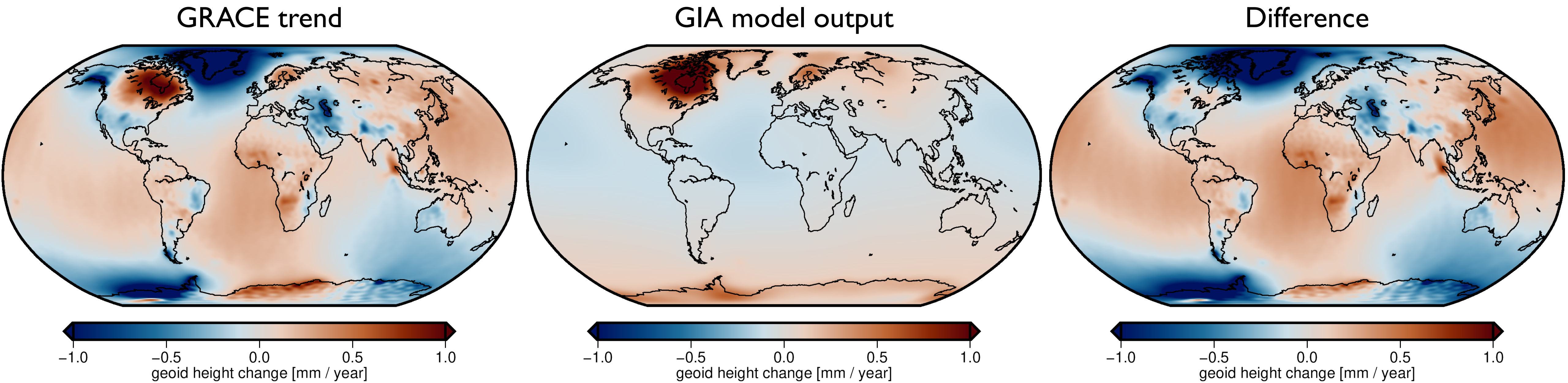


Seismicity, relative sea level (geodetic), Earth rotation parameters

A model that can describe all that (and more) will provide us the view into the future!

WHY DO WE NEED A GIA MODEL IN GEODESY?

GIA ⇨ signal vs. noise



Atmosphere

Ocean

Hydrosphere

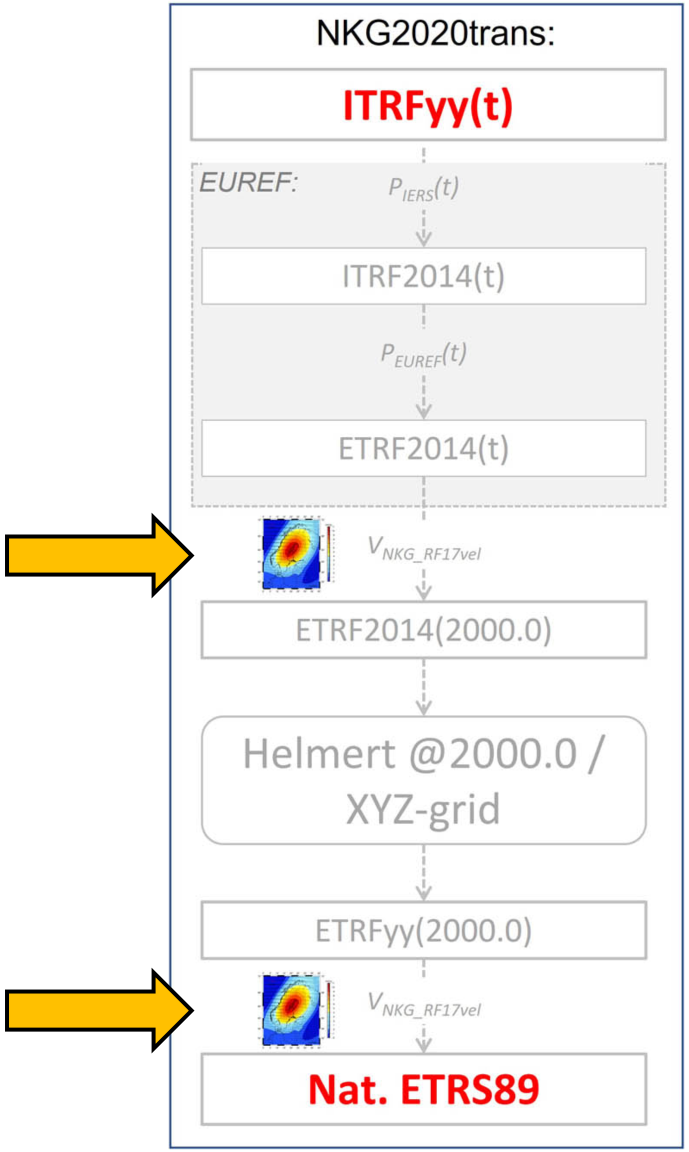
Ice sheets

Solid Earth (without GIA)

Figure courtesy: Andreas Kvas (Uni Graz)

WHY DO WE NEED A GIA MODEL IN GEODESY?

GIA ⇨ additional constraints

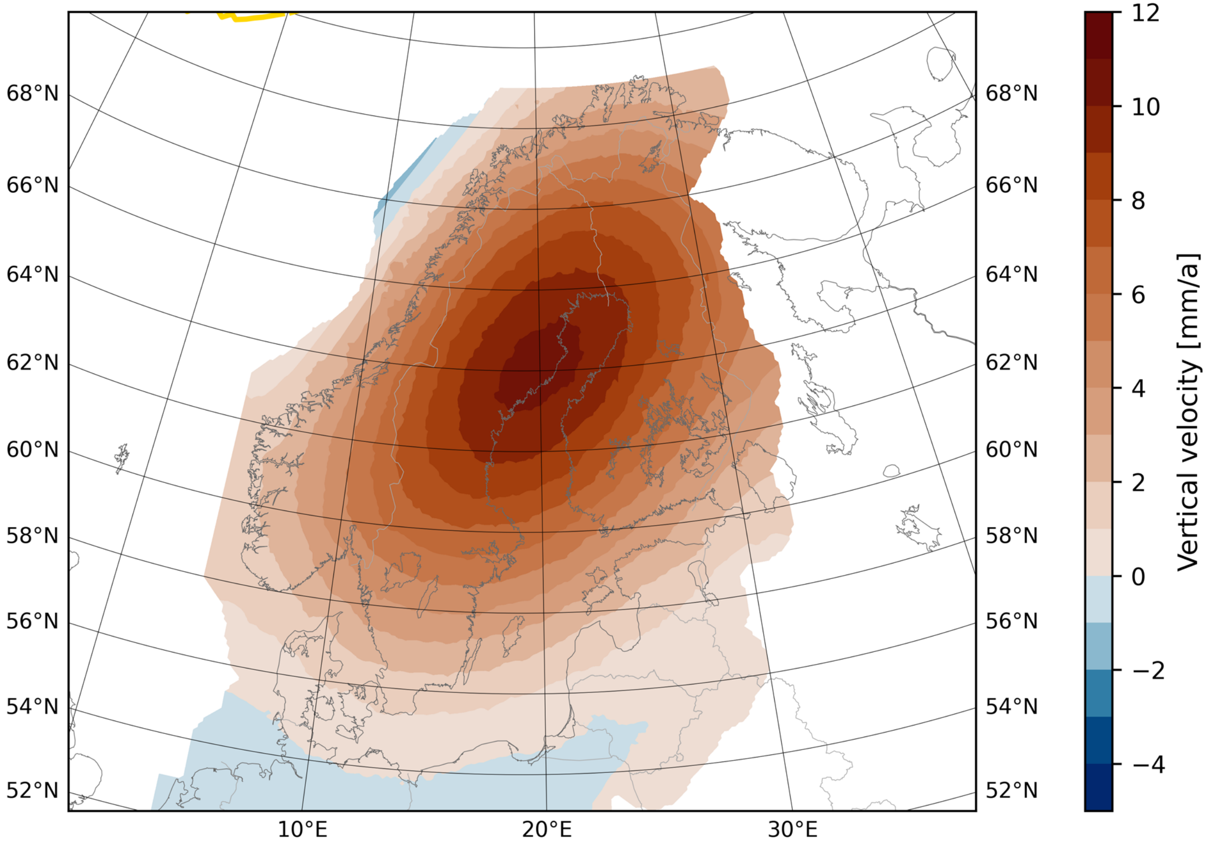


Häkli et al. (2023)

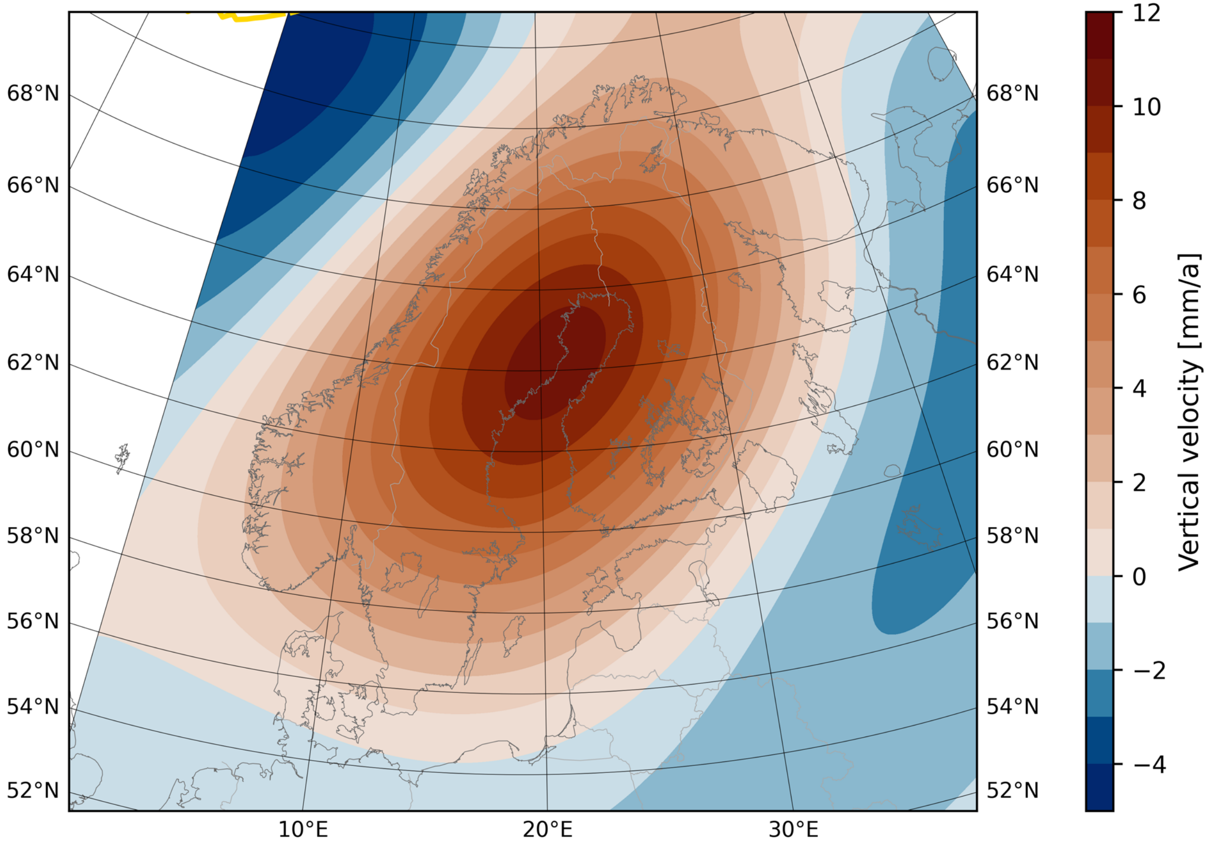
APPLICATION OF GIA MODELS IN GEODESY

Example for northern Europe – NKG2016LU (Vestøl et al., 2019)

Empirical model based on observations



Best-fitting GIA model (based on GNSS and RSL data)



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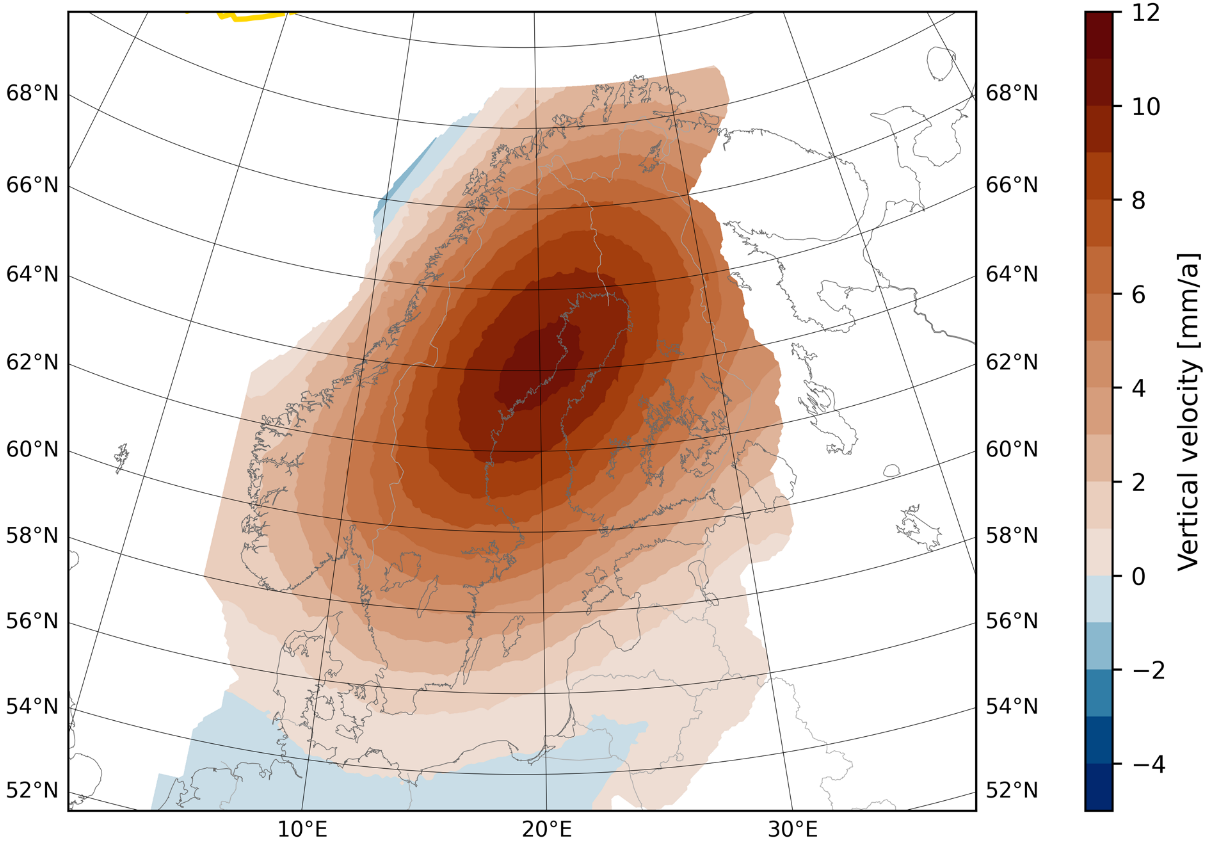
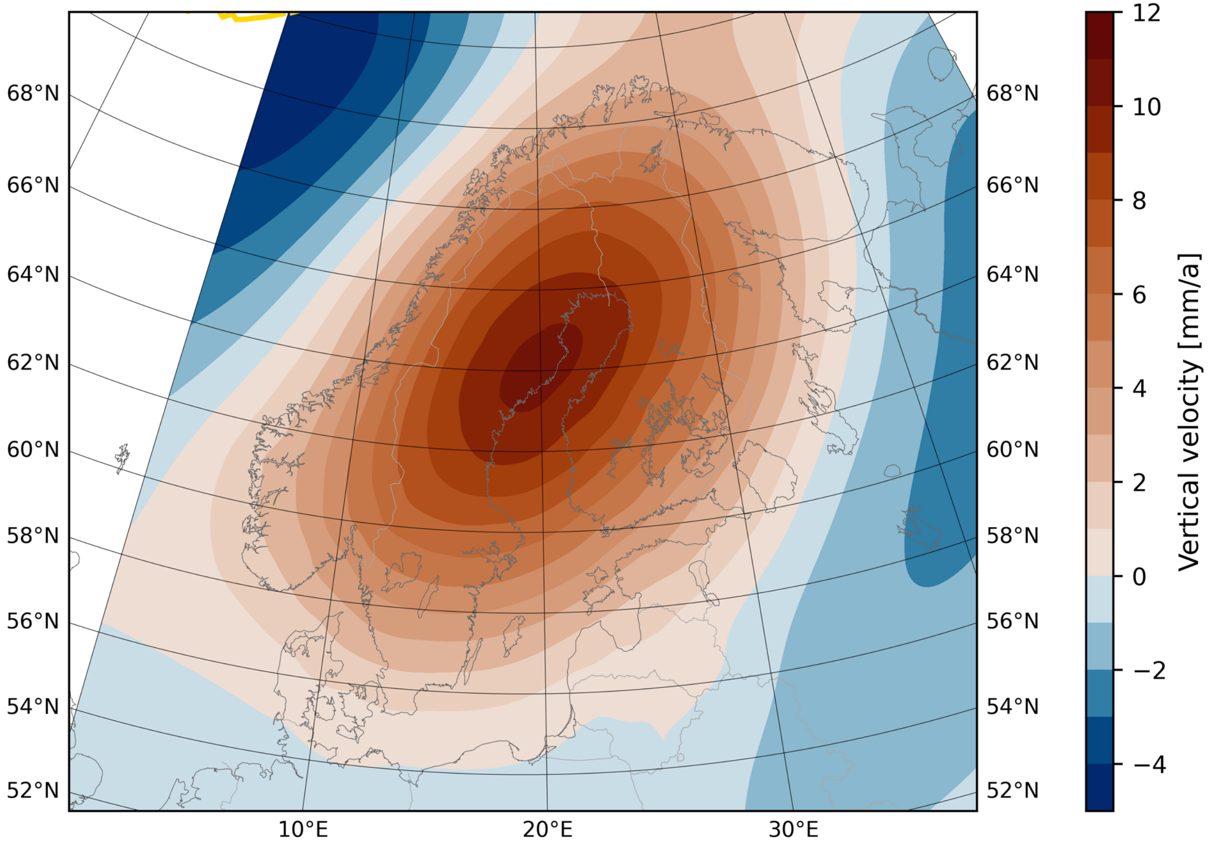
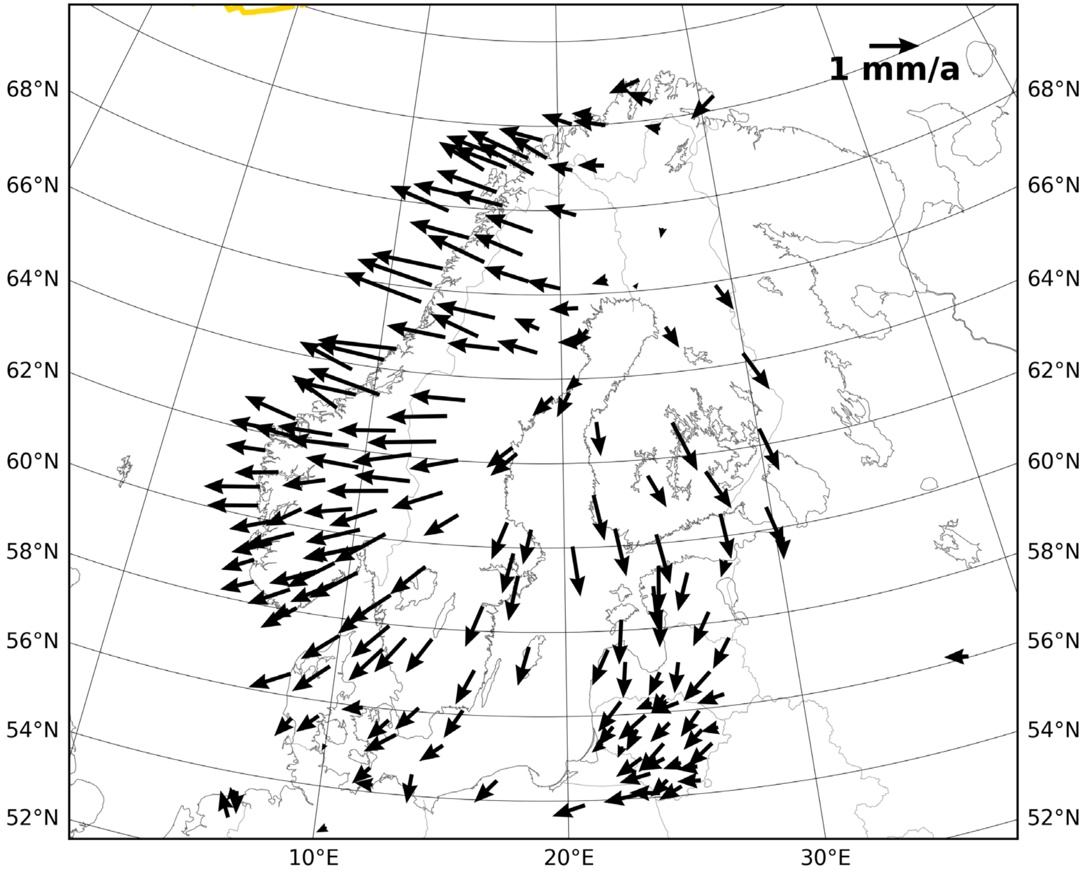


Final land uplift model



APPLICATION OF GIA MODELS IN GEODESY

Example for northern Europe – NKG_RF17_vel (Häkli et al., 2019)



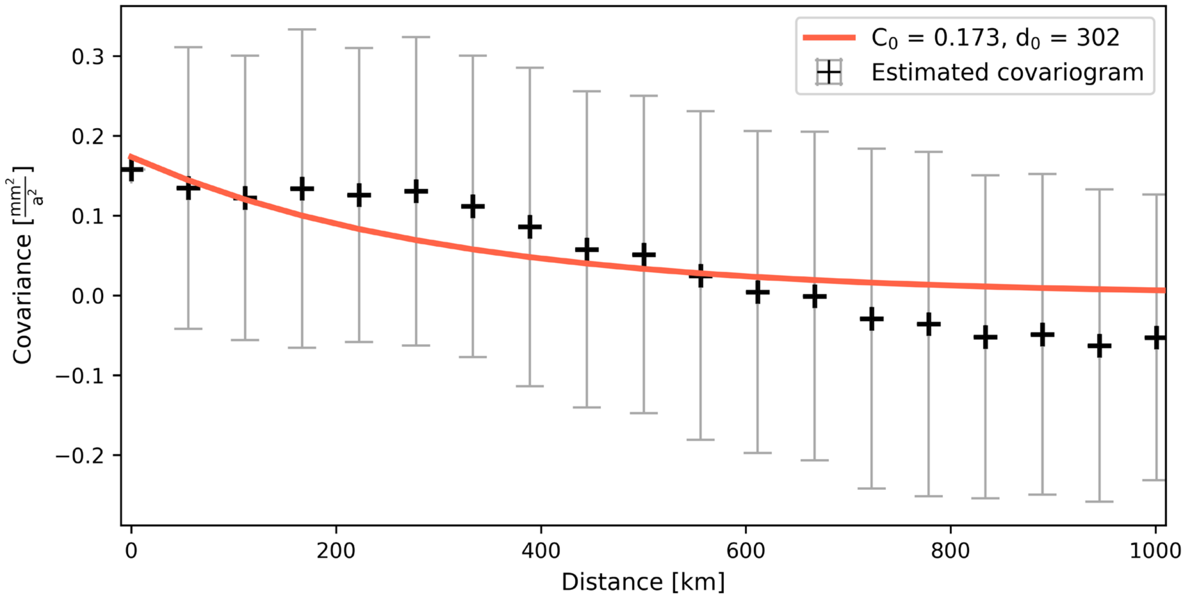
- Interpolation and extrapolation via least-squares collocation
  - ⇨Requires input parameters
    - ⇨Covariance analysis

APPLICATION OF GIA MODELS IN GEODESY

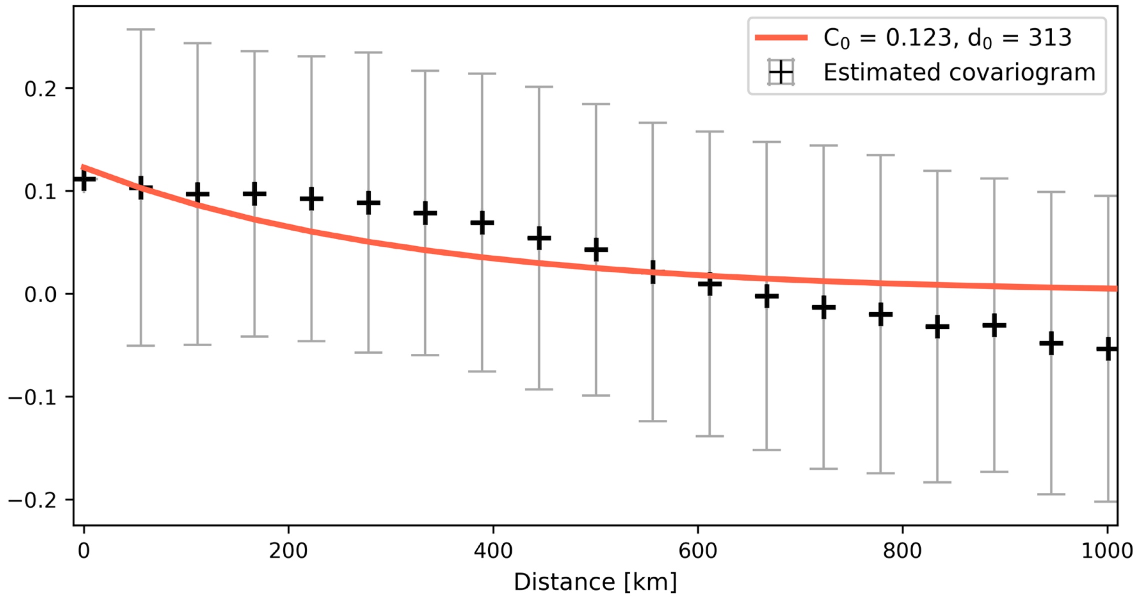
Example for northern Europe – NKG_RF17_vel (Häkli et al., 2019)

- Covariance analysis without reducing a GIA model and doing a separate analysis for each horizontal GNSS component

EW component



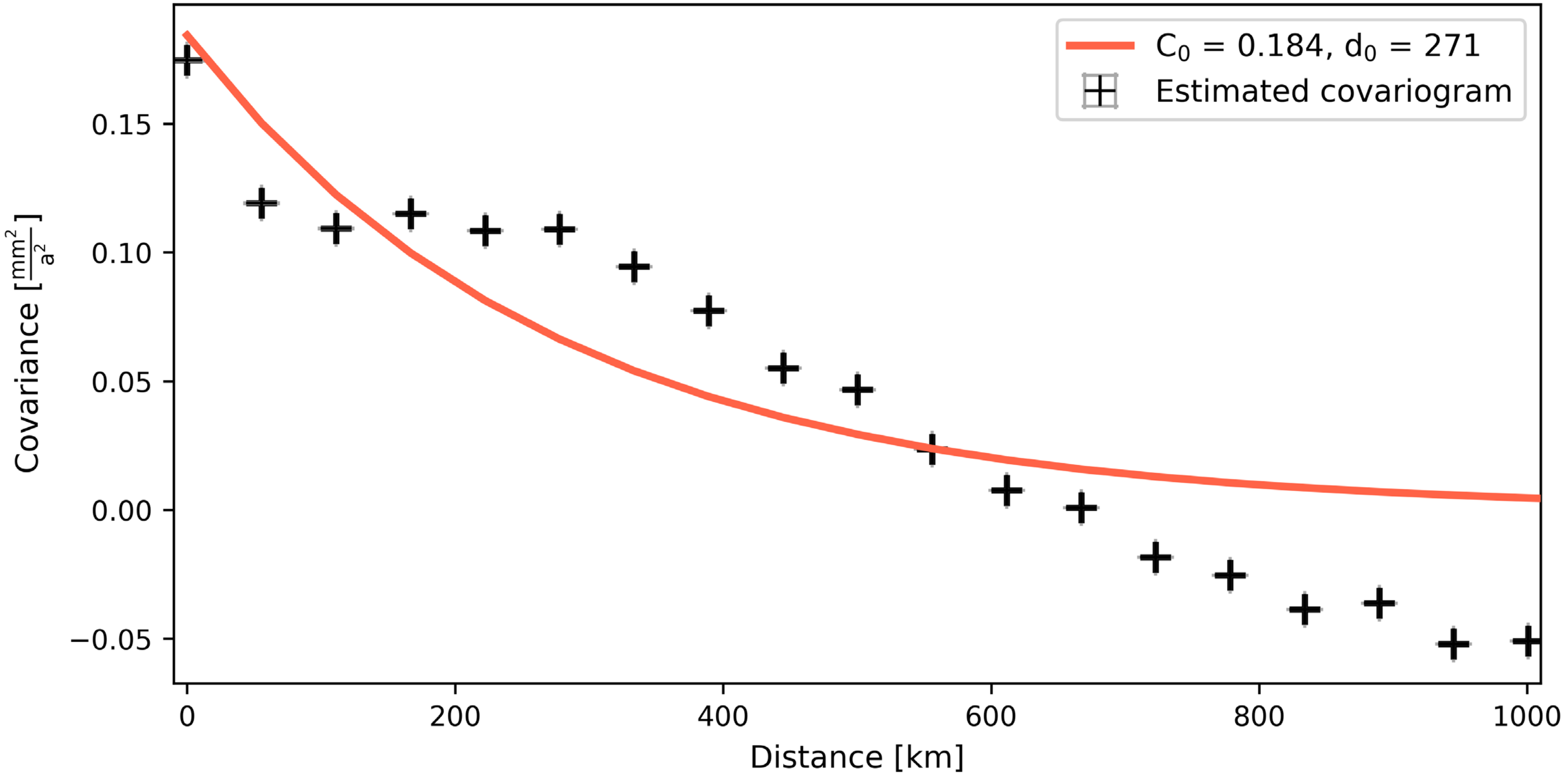
NS component

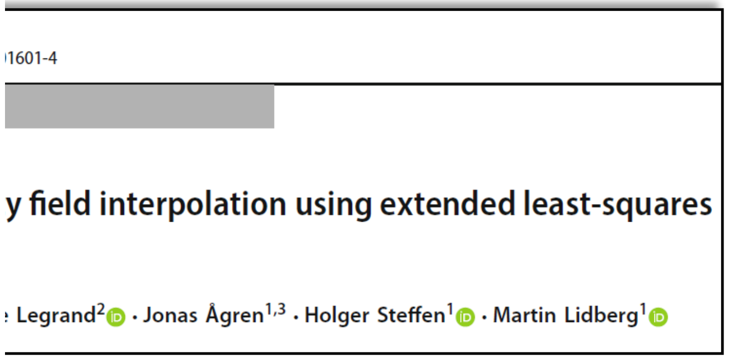


APPLICATION OF GIA MODELS IN GEODESY

Example for northern Europe – NKG_RF17_vel (Häkli et al., 2019)

- Covariance analysis without reducing a GIA model and doing a combined analysis of both horizontal GNSS components

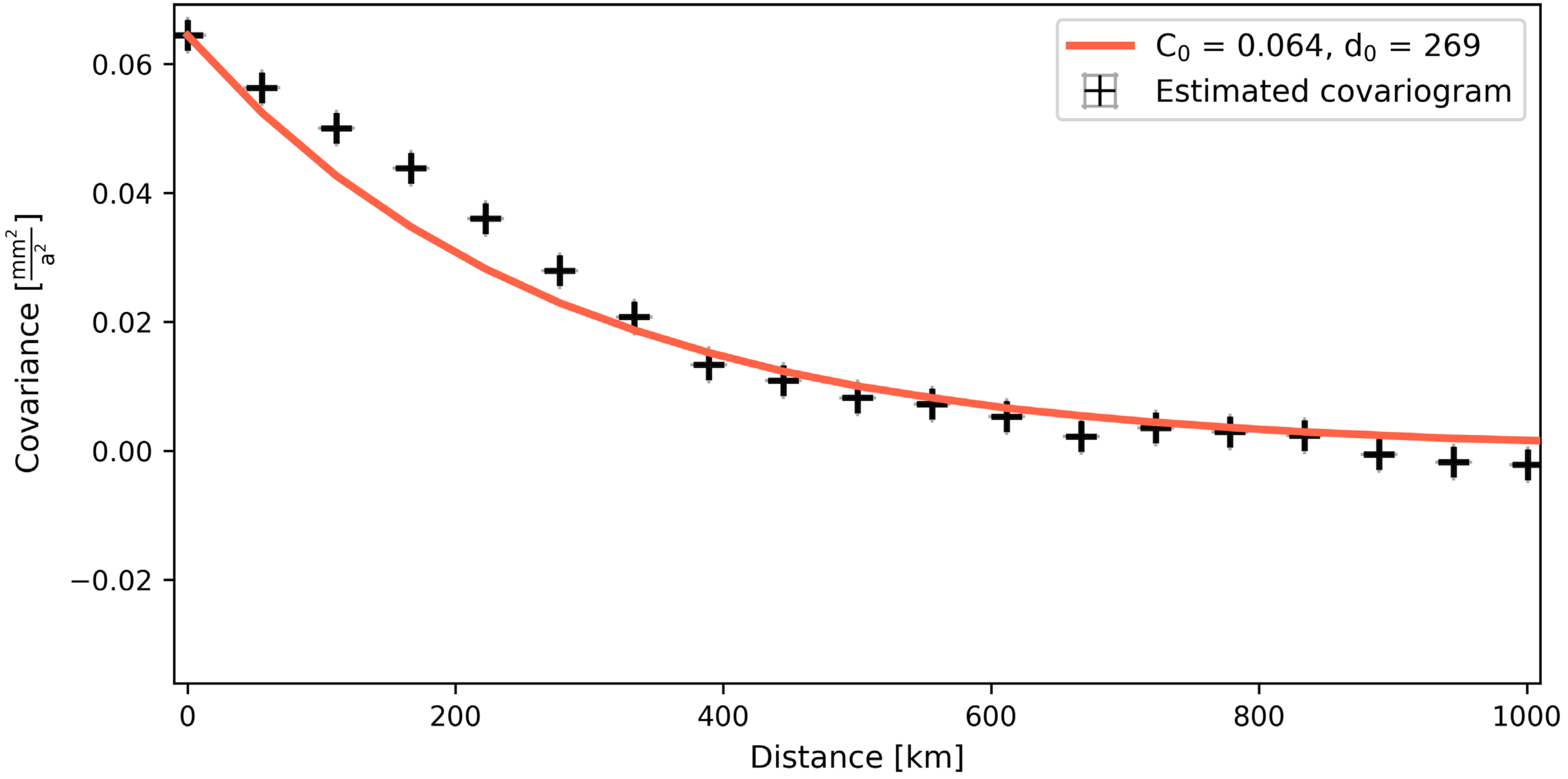




APPLICATION OF GIA MODELS IN GEODESY

Example for northern Europe – NKG_RF17_vel (Häkli et al., 2019)

- Covariance analysis **with** reducing a GIA model and doing a combined analysis of both horizontal GNSS components

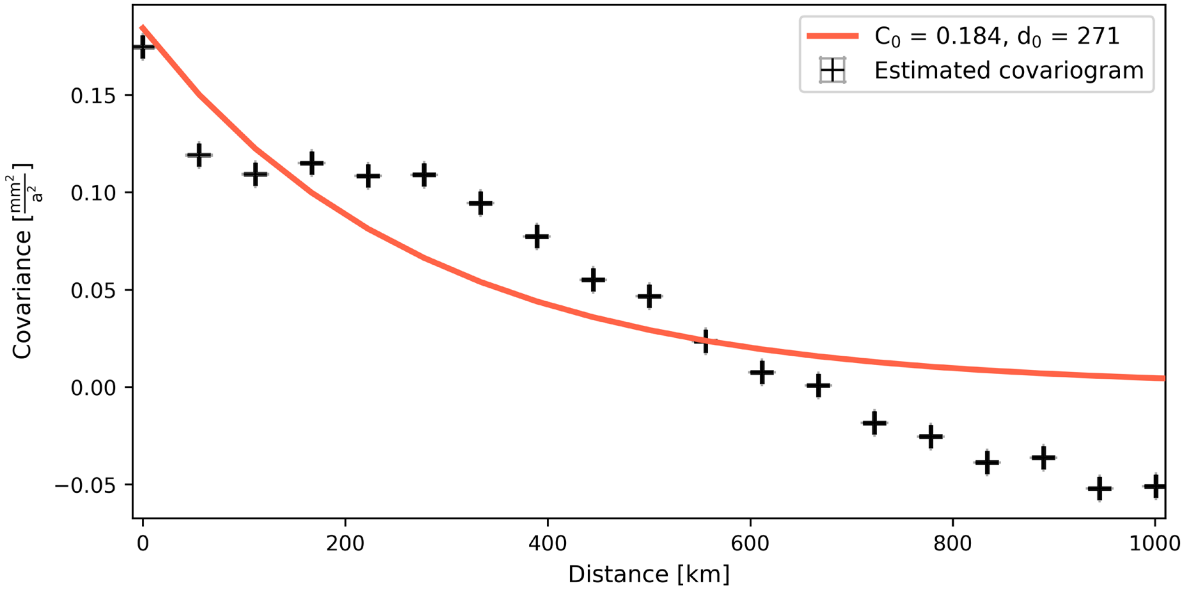


APPLICATION OF GIA MODELS IN GEODESY

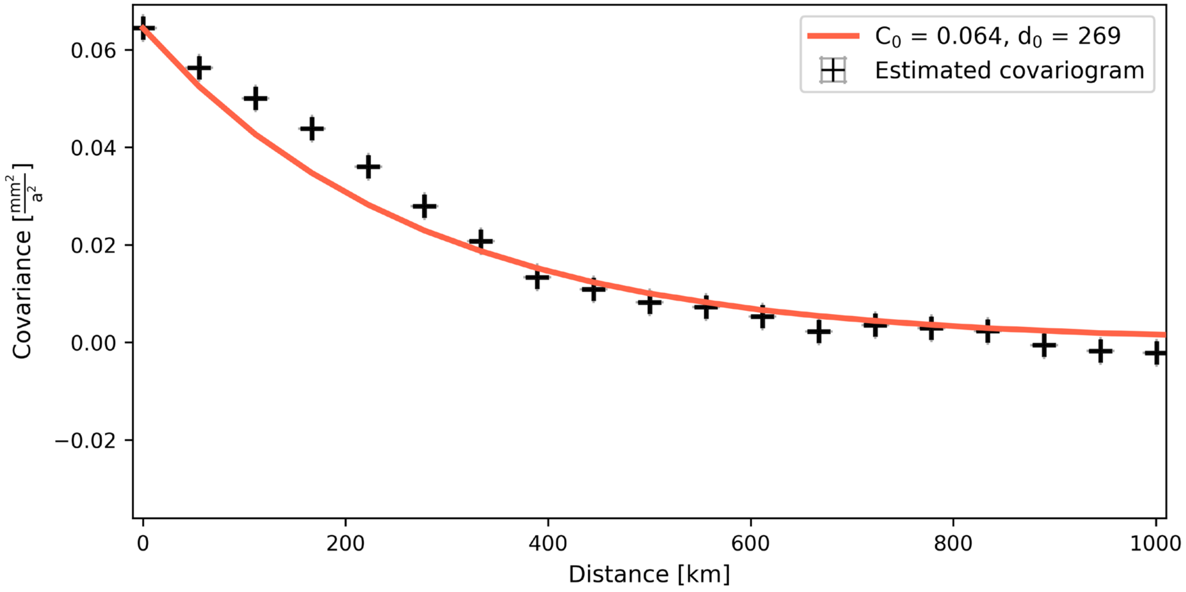
Example for northern Europe – NKG_RF17_vel (Häkli et al., 2019)

- Covariance analysis **with** reducing a GIA model and doing a combined analysis of both horizontal GNSS components

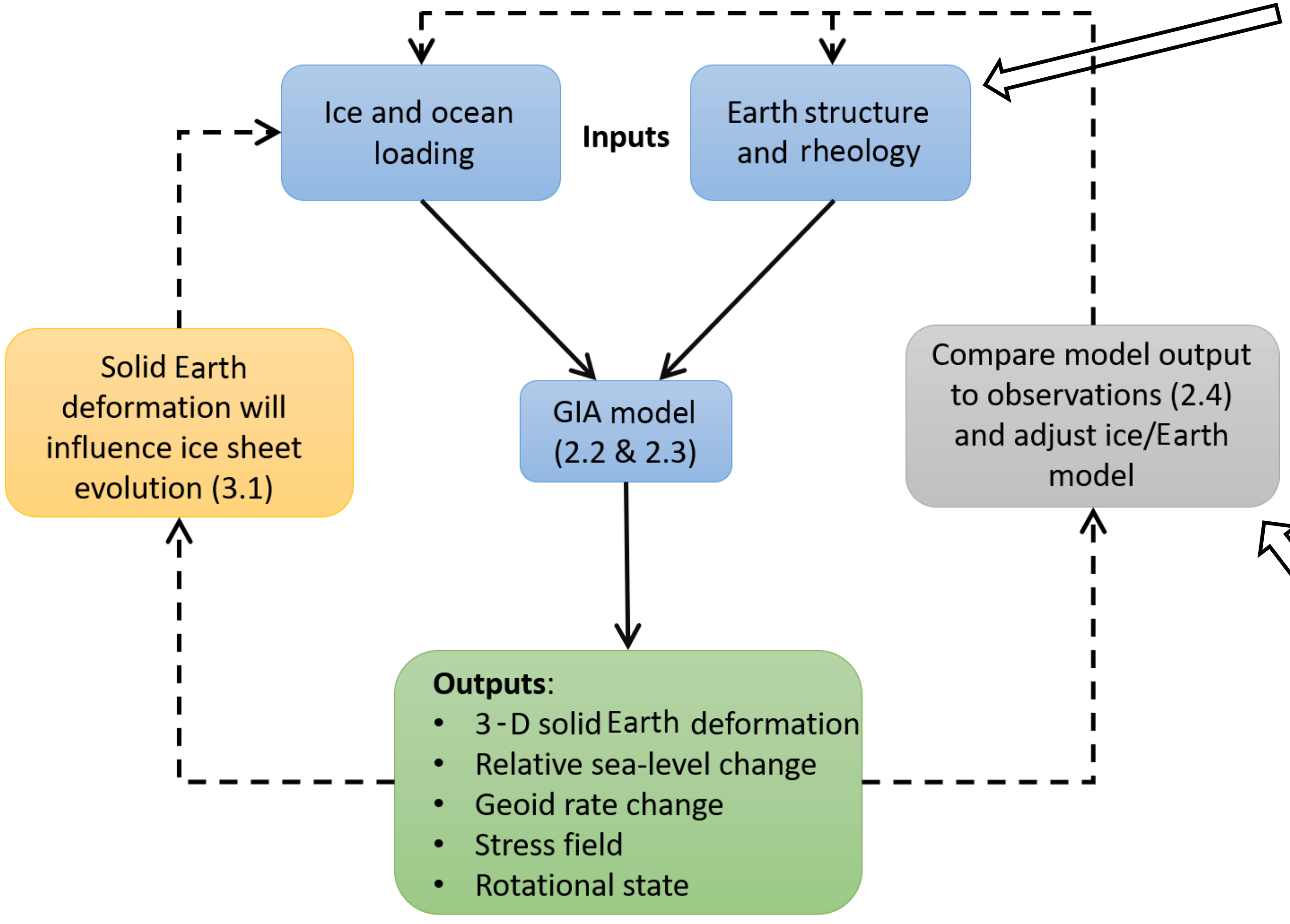
Without reducing the GIA model



Reducing the GIA model



GIA – MODELLING



Whitehouse (2018)

Earth parameters:

Mantle viscosity

Lithospheric thickness

Rheological parameters (Poisson's ratio, Young's modulus, density)

Rheological model

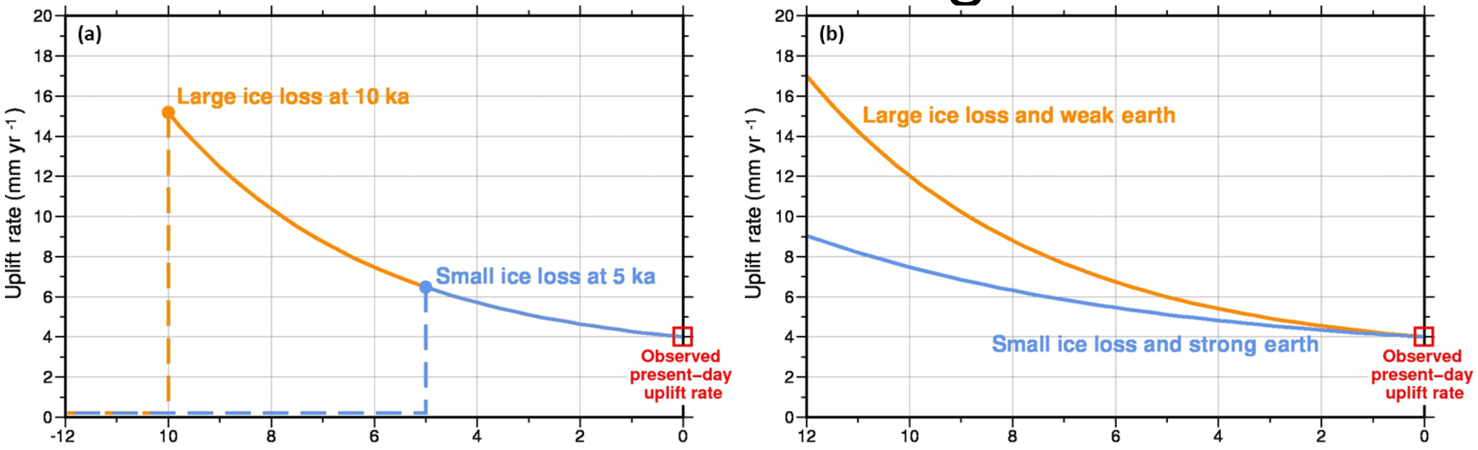
GIA observables:

Geodetic (3D land motion, gravity changes, earth rotation changes, relative sea level and ice extent)

Paleo (relative sea level, lake leves, ice extent, seismicity)

GIA – MODELLING

Uncertainties in GIA modelling



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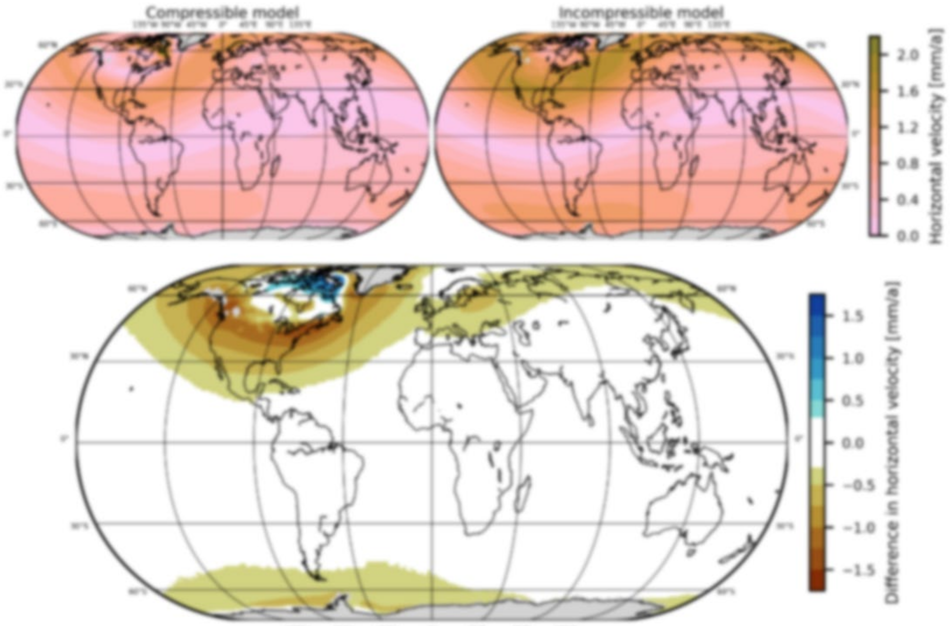
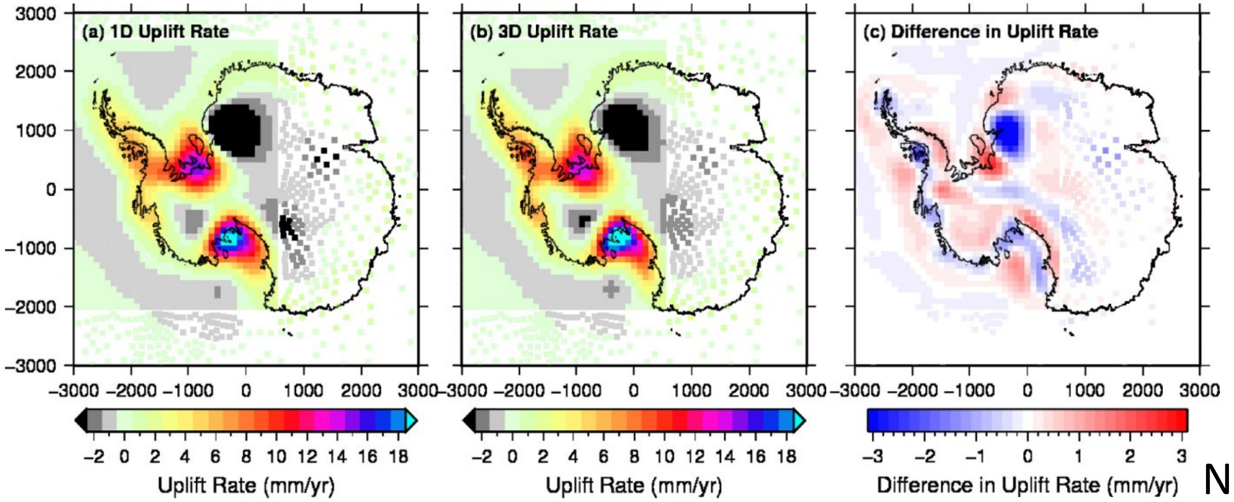


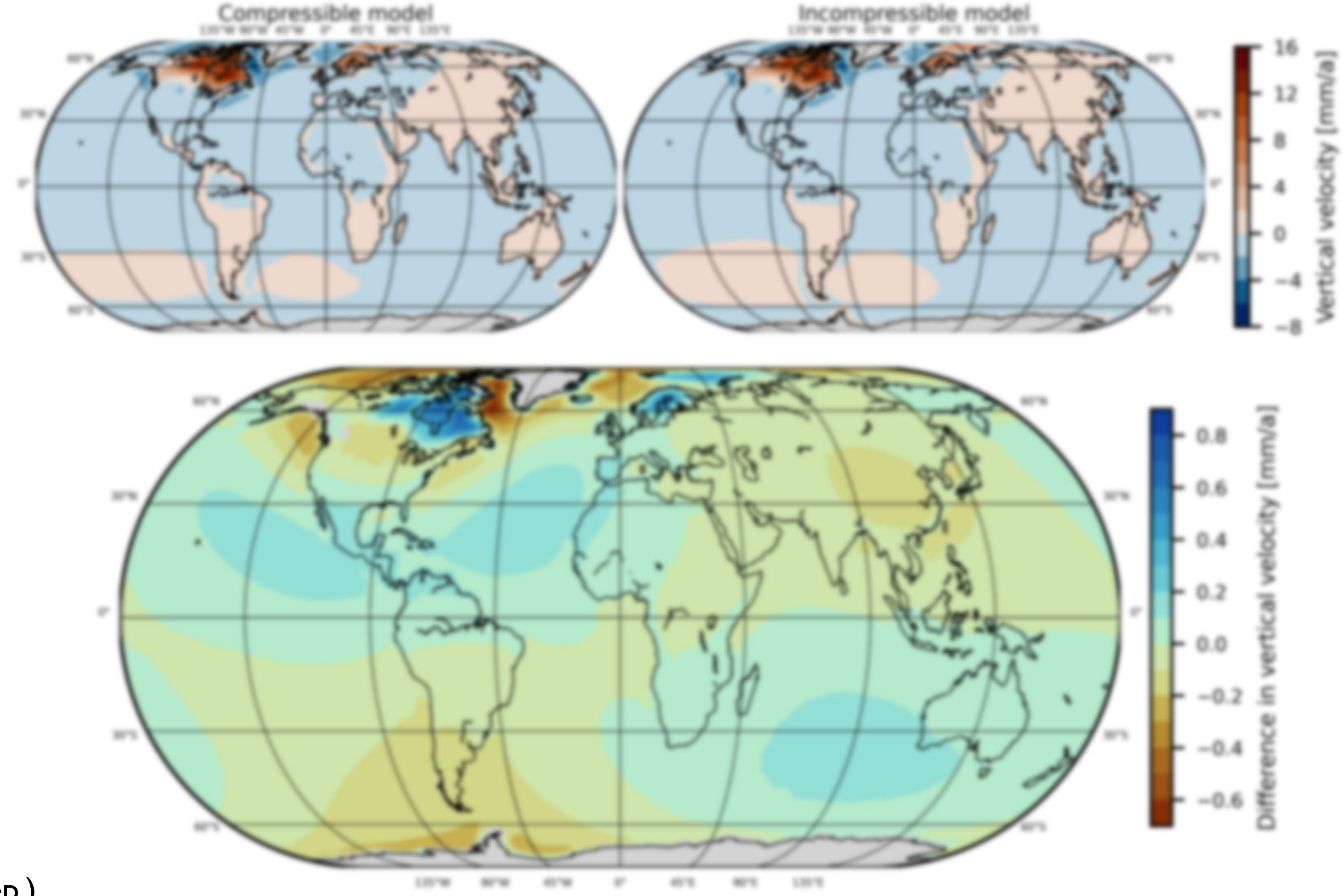
Steffen & Steffen (in prep.)



Nield et al. (2018)

Ice model: ICE-6G
Earth model: VM5a
GIA code: ICEAGE

GIA – VERTICAL VELOCITIES



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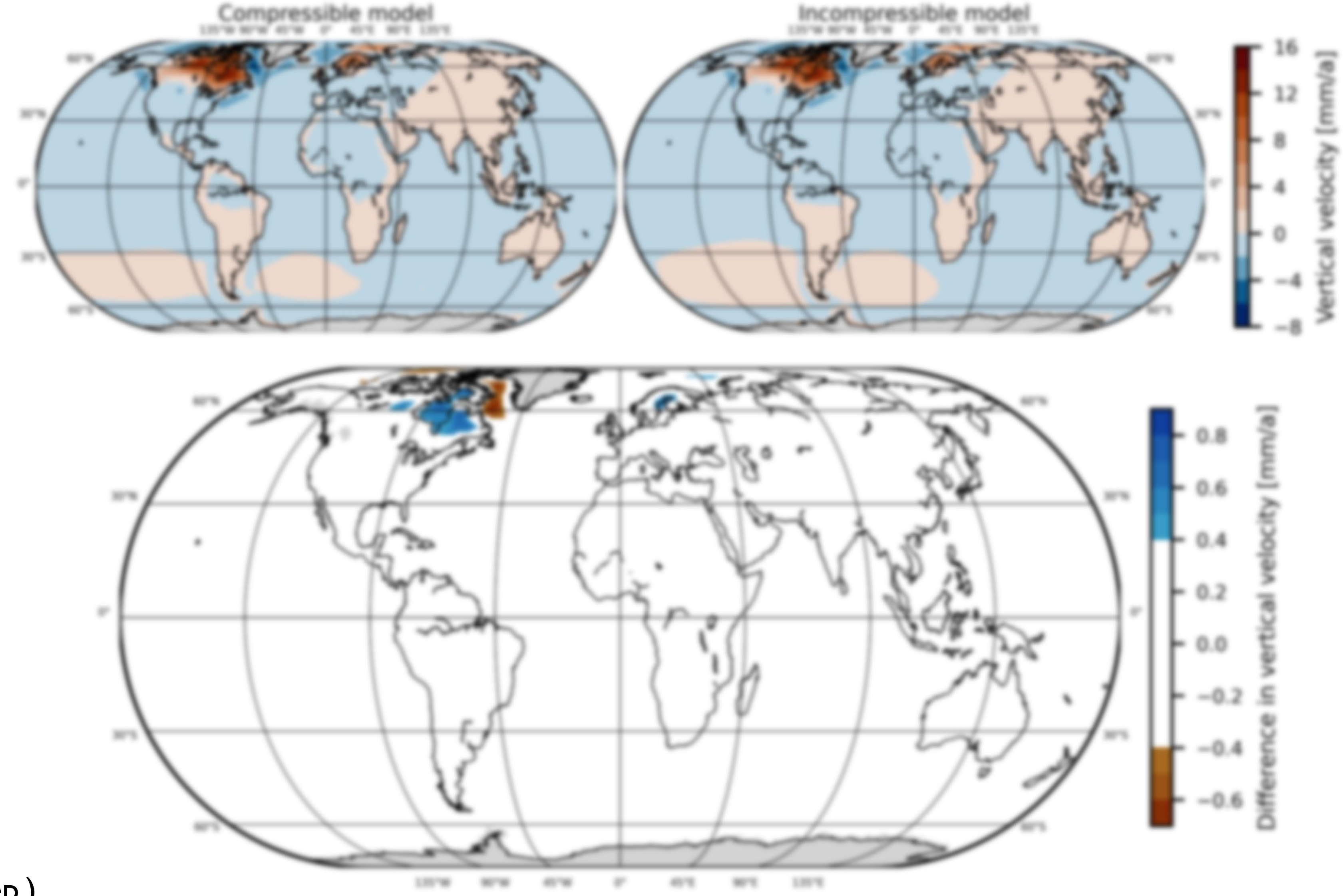

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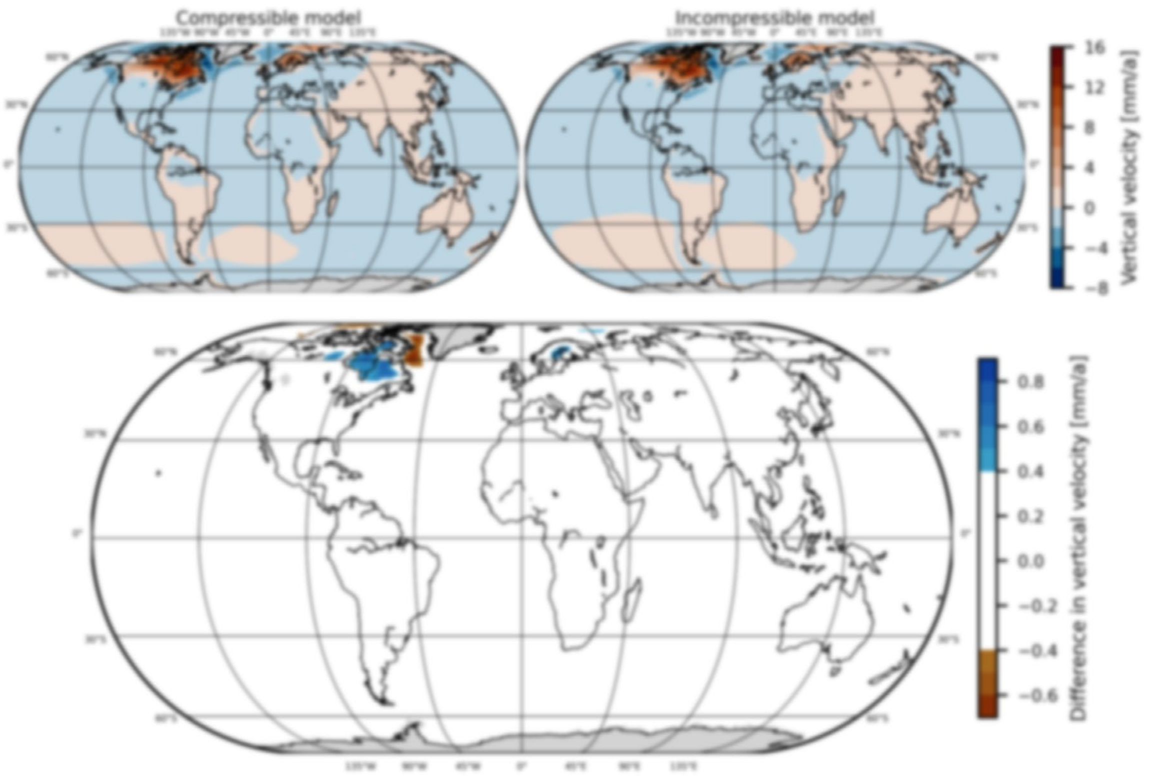
GIA – VERTICAL VELOCITIES

WORK IN PROGRESS



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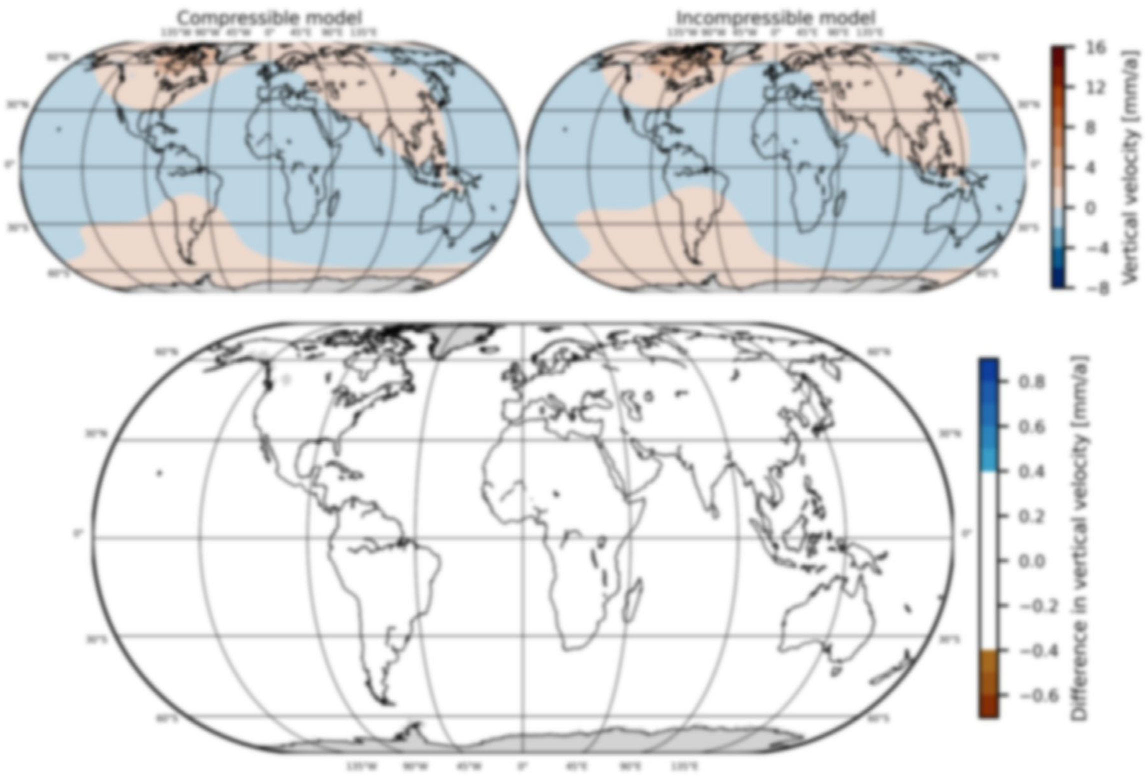
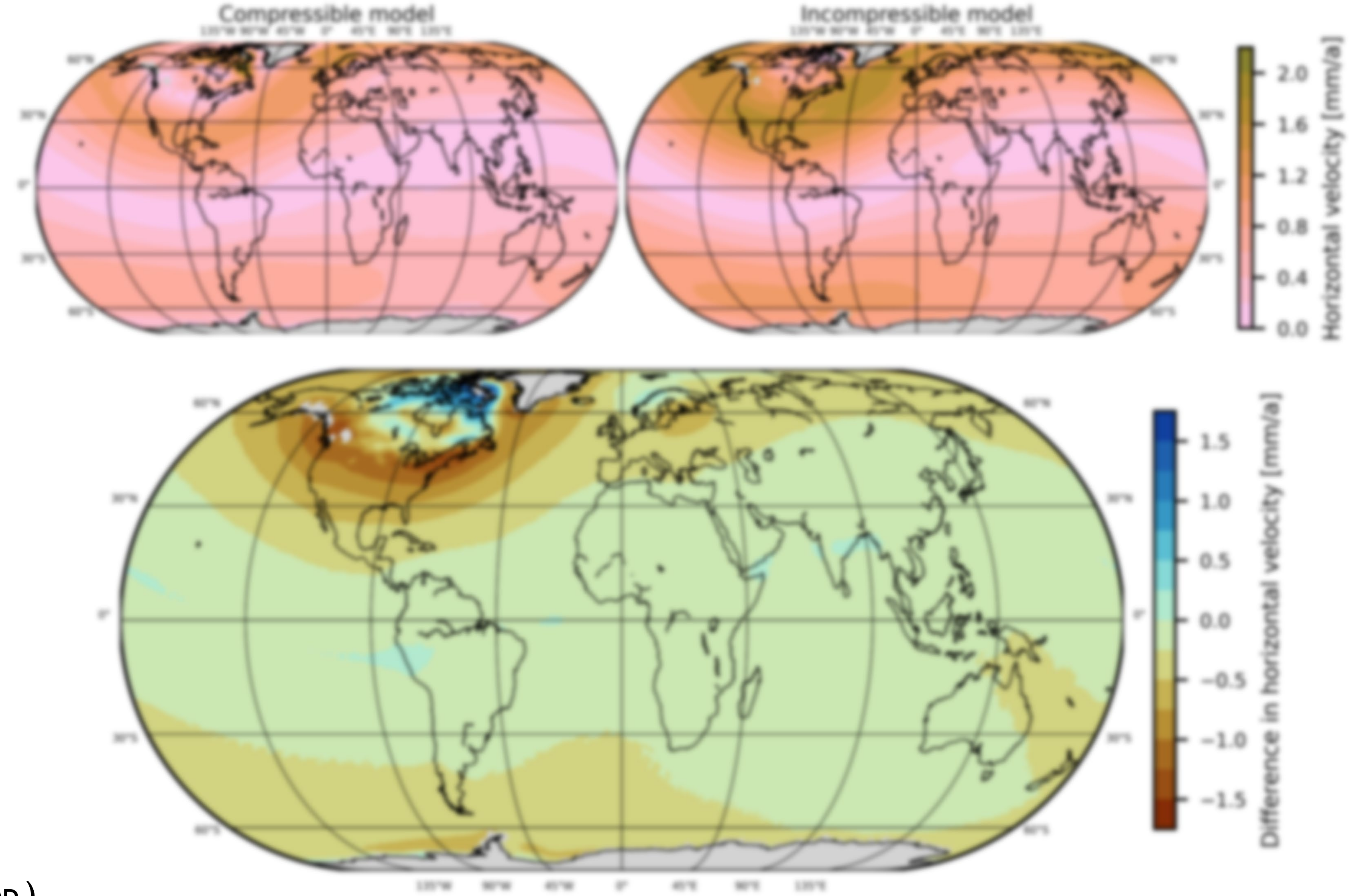


Ice model: ICE-6G
Earth model: 90 km, $4 \cdot 10^{19}\ Pa \cdot s$, $2 \cdot 10^{21}\ Pa \cdot s$
GIA code: ICEAGE

Steffen & Steffen (in prep.)

GIA – HORIZONTAL VELOCITIES

Ice model: ICE-6G
Earth model: VM5a
GIA code: ICEAGE



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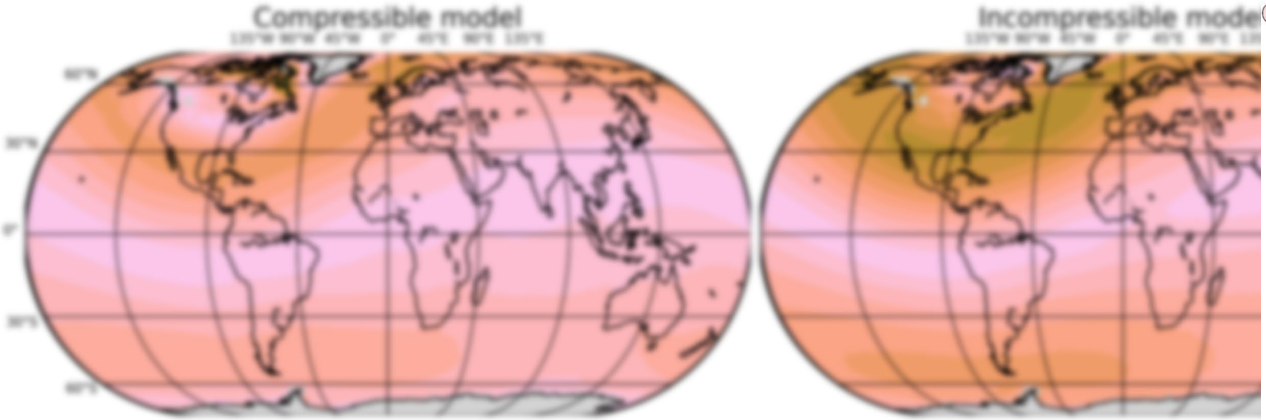

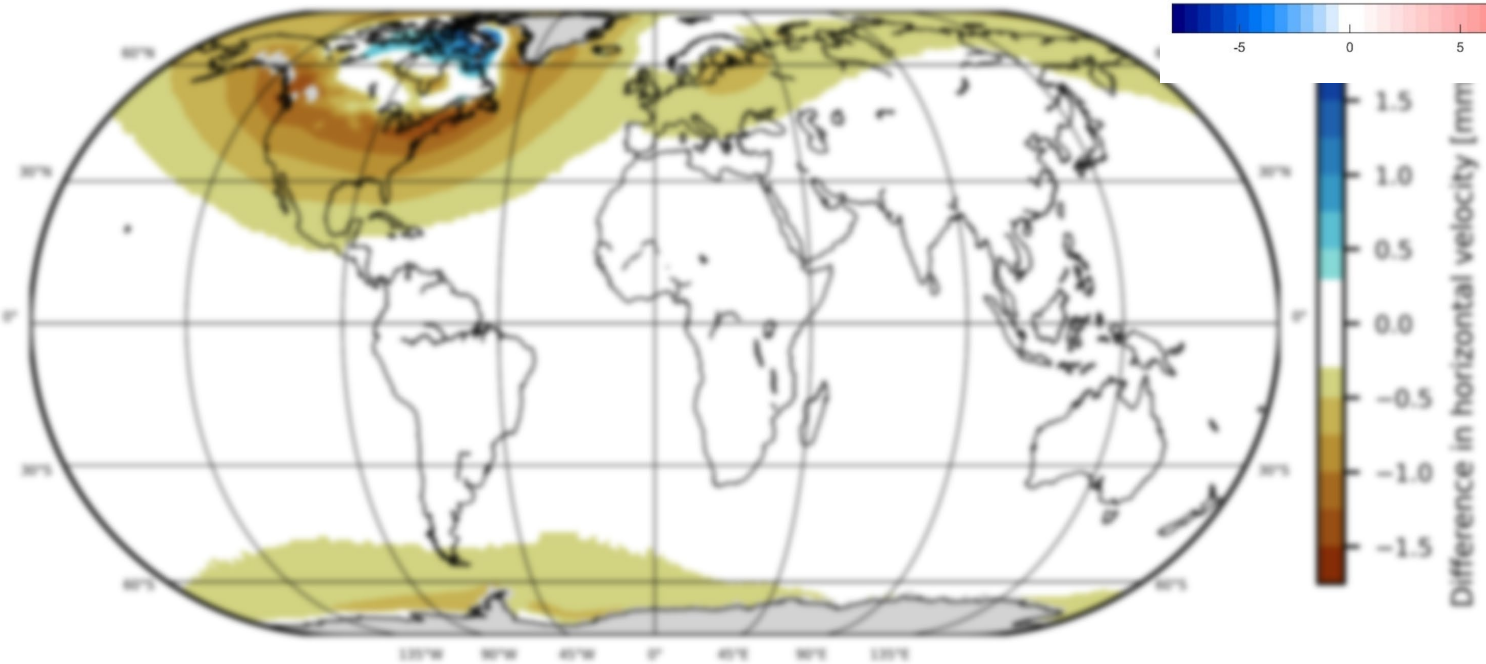

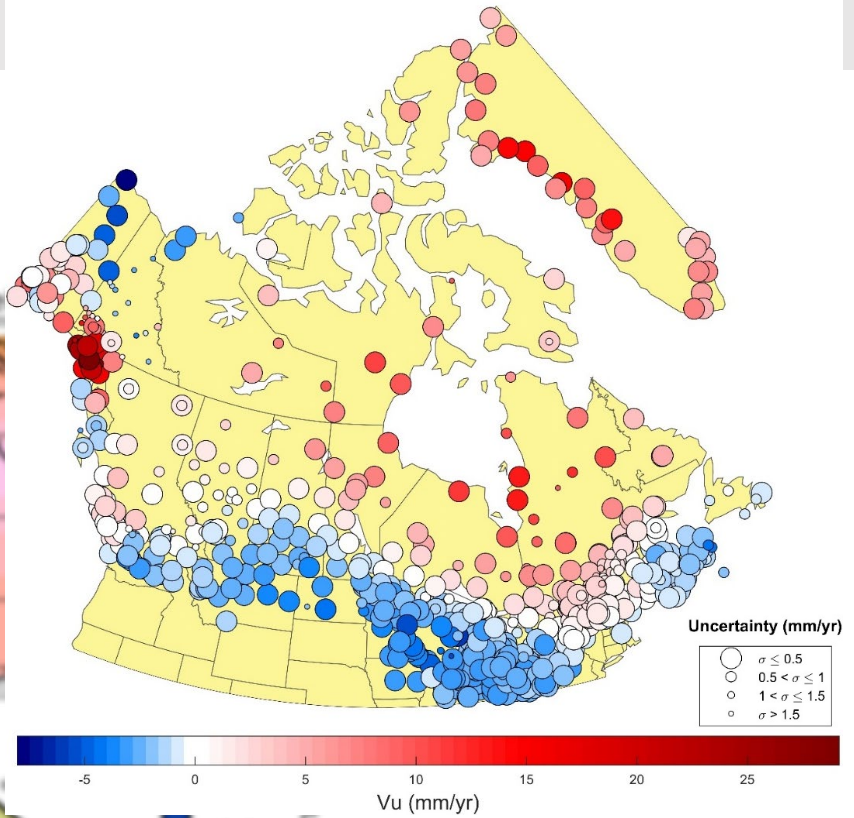

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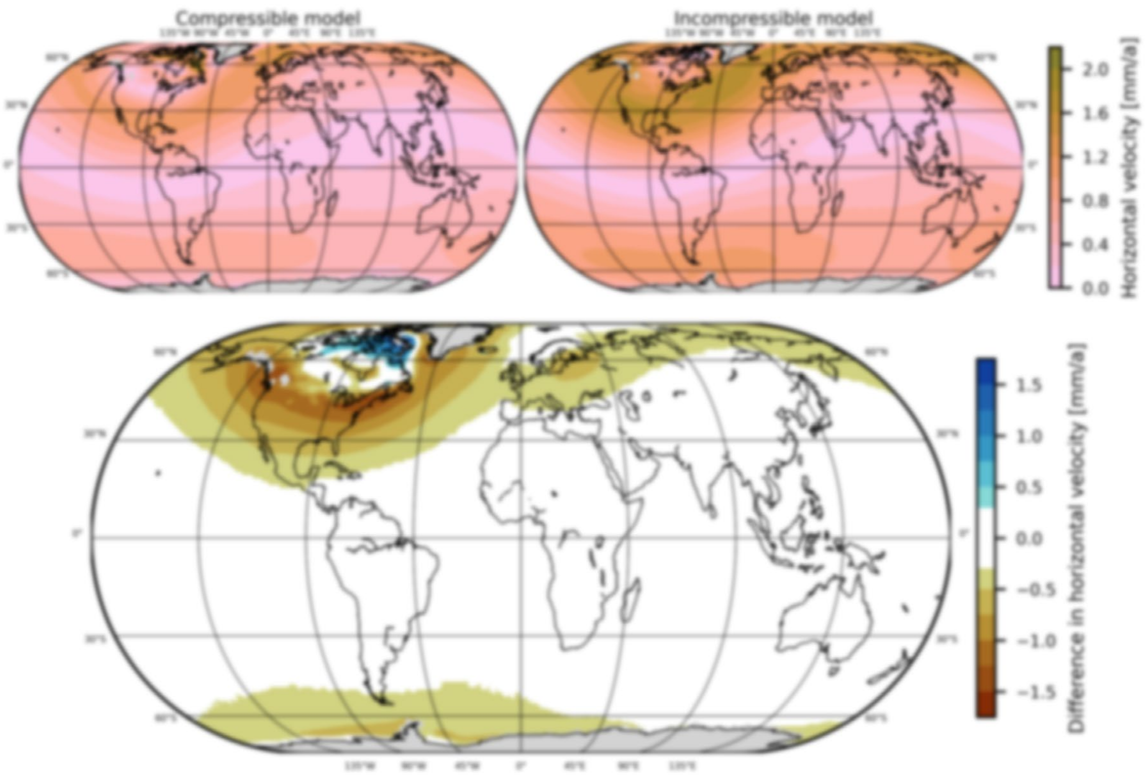

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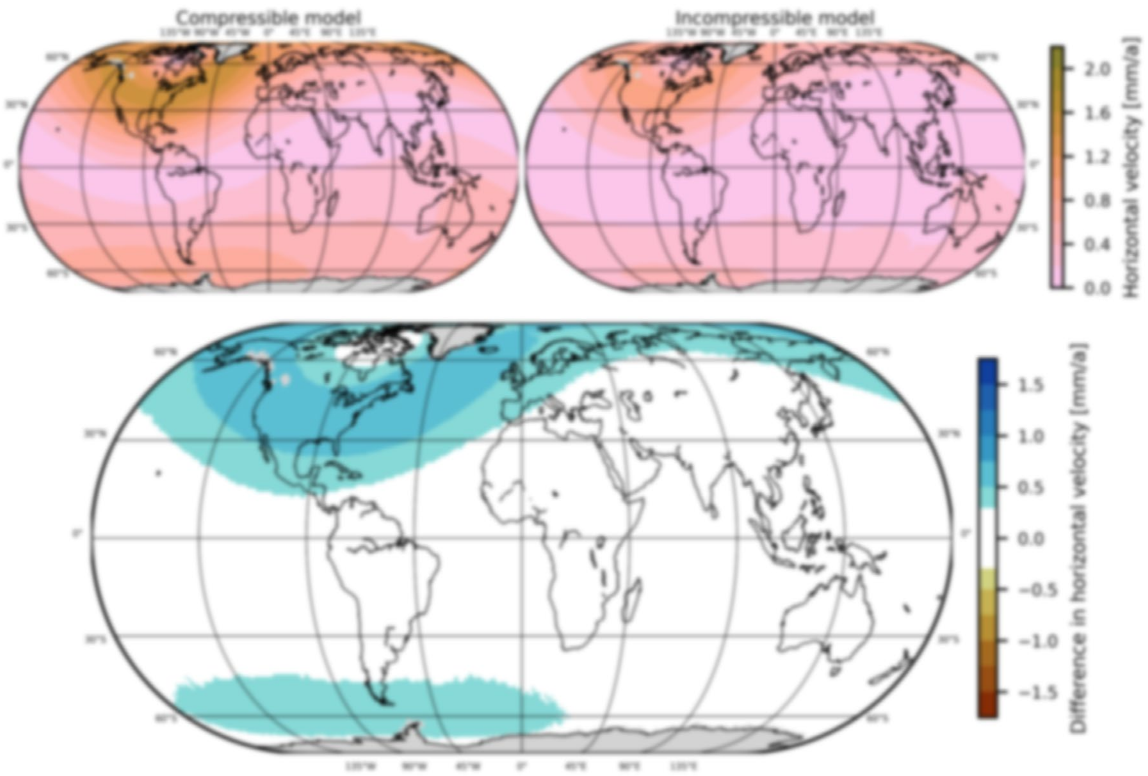

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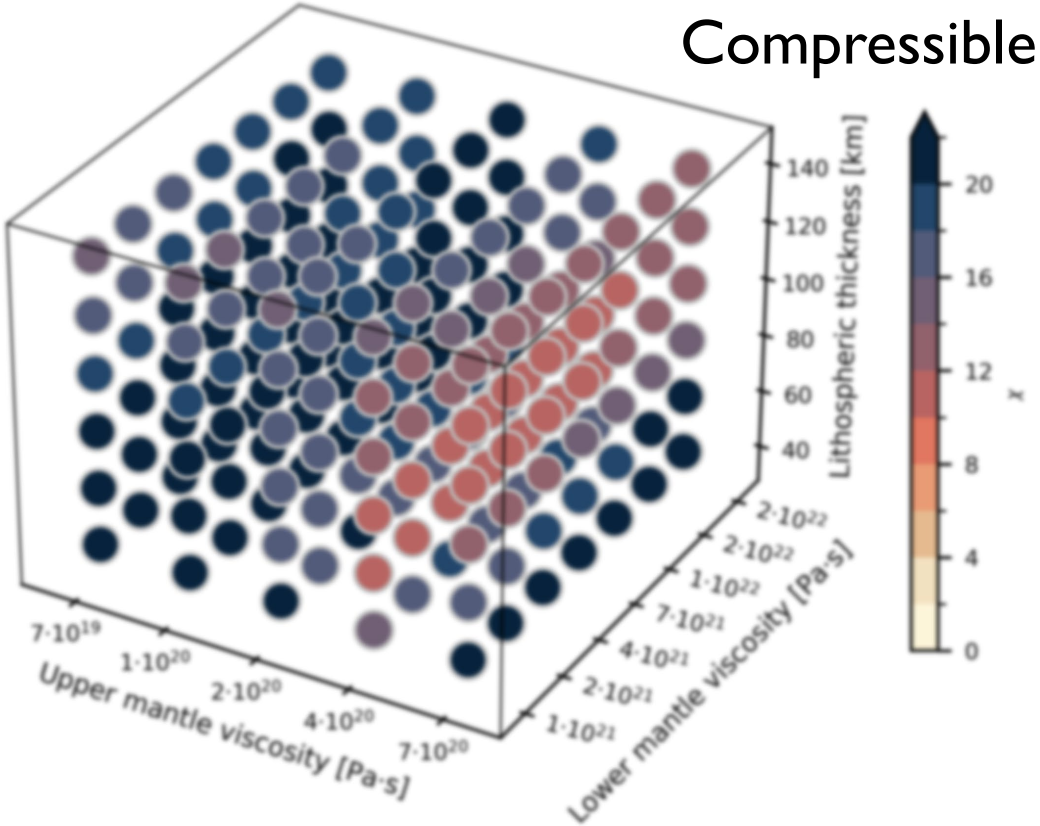
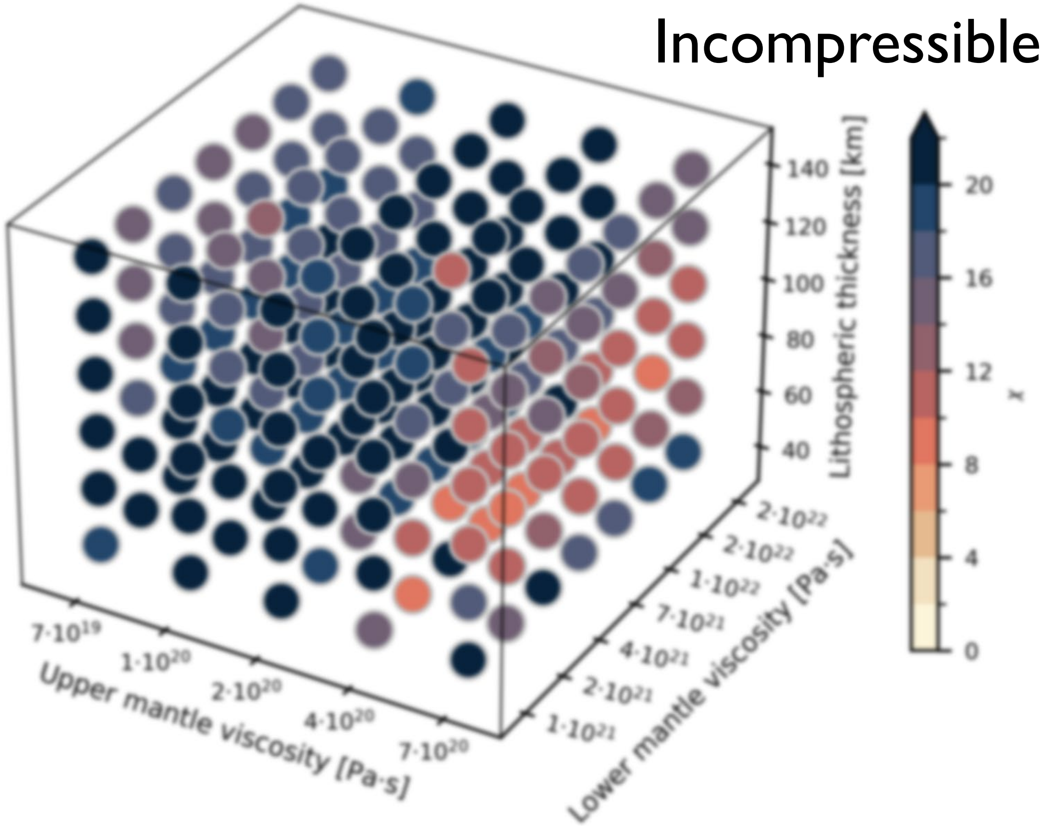
GIA – MODEL CHOICE

Compressible



Incompressible



Lithospheric thickness: 80 km

Upper mantle viscosity: $4 \cdot 10^{20}\ Pa \cdot s$

Lower mantle viscosity: $2 \cdot 10^{21}\ Pa \cdot s$

Best fit χ to vertical GNSS data based on Khan et al., 2016

Lithospheric thickness: 60 km

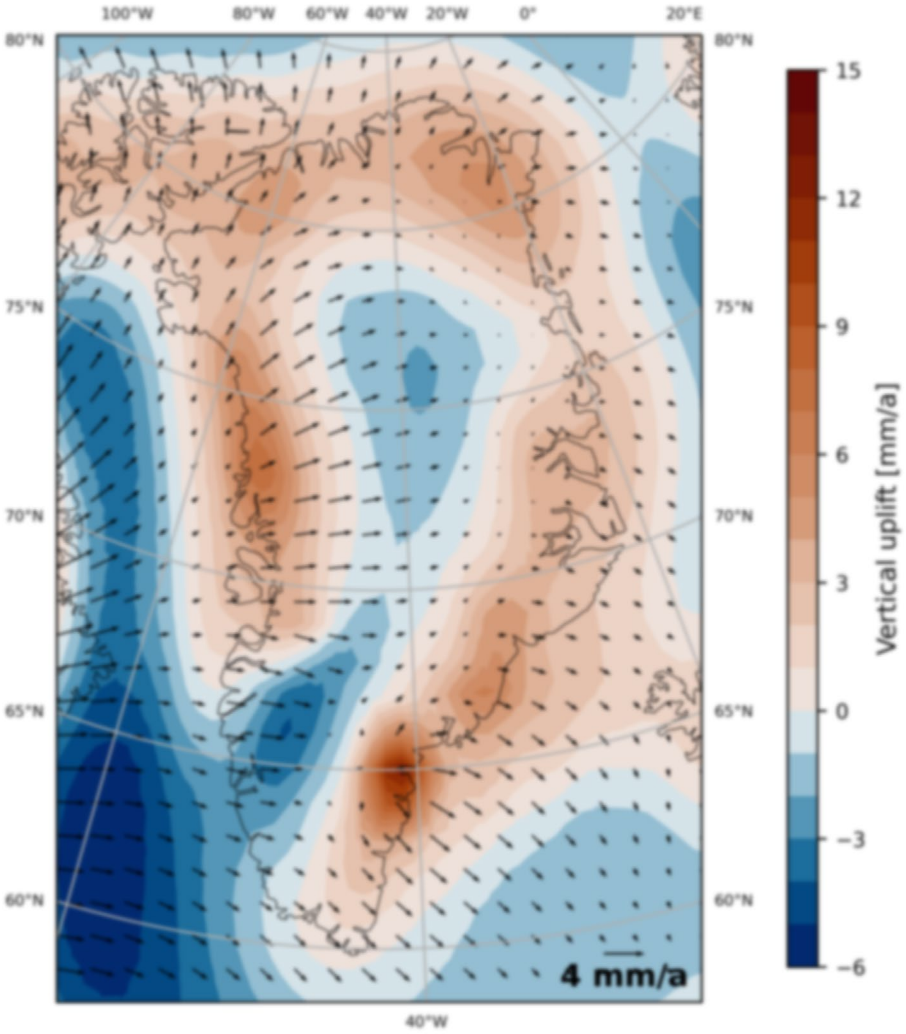
Upper mantle viscosity: $4 \cdot 10^{20}\ Pa \cdot s$

Lower mantle viscosity: $4 \cdot 10^{21}\ Pa \cdot s$

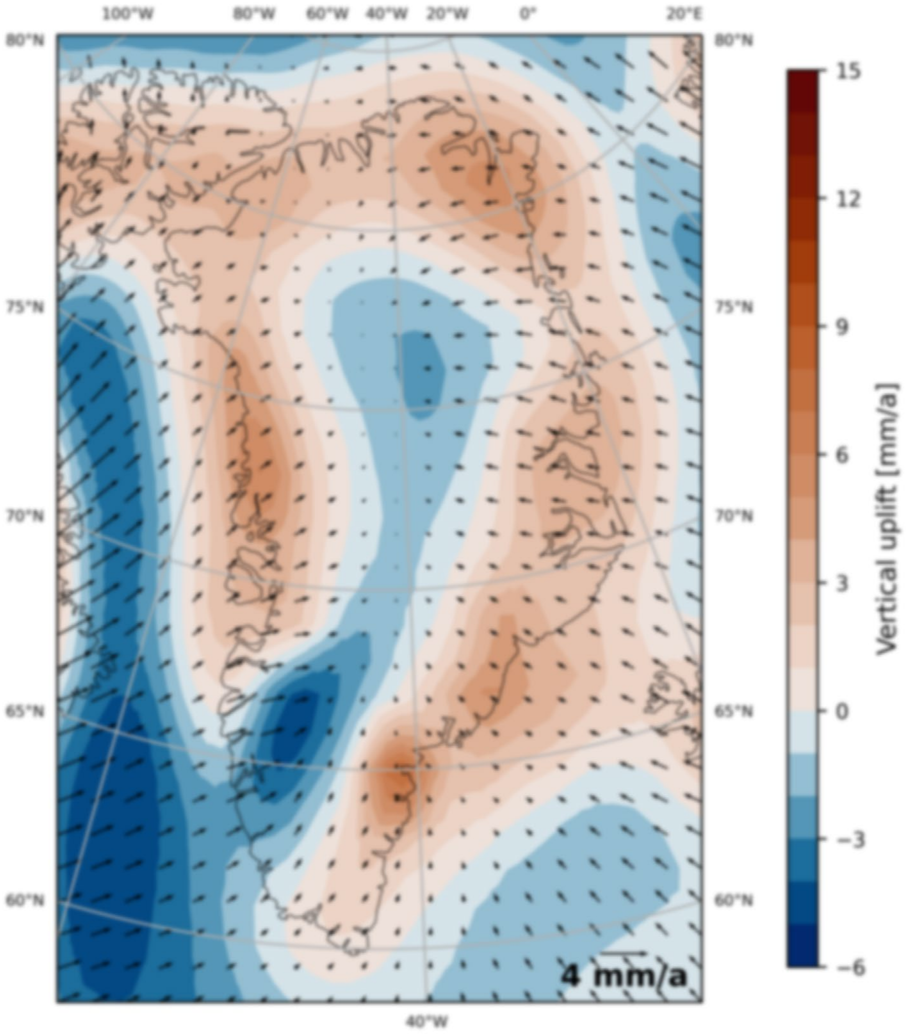
GIA – MODEL CHOICE

WORK IN PROGRESS

Compressible best-fit model

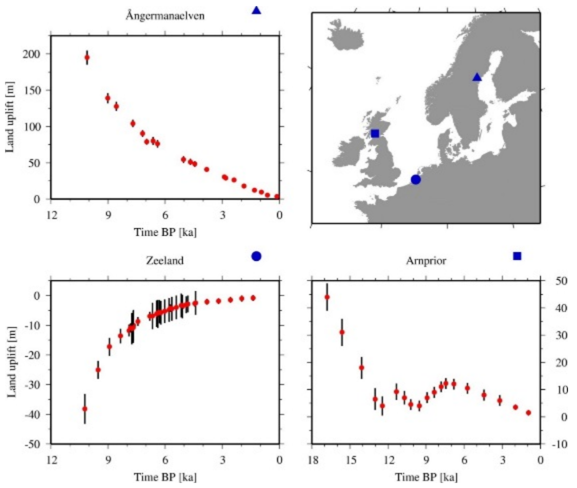


Incompressible best-fit model



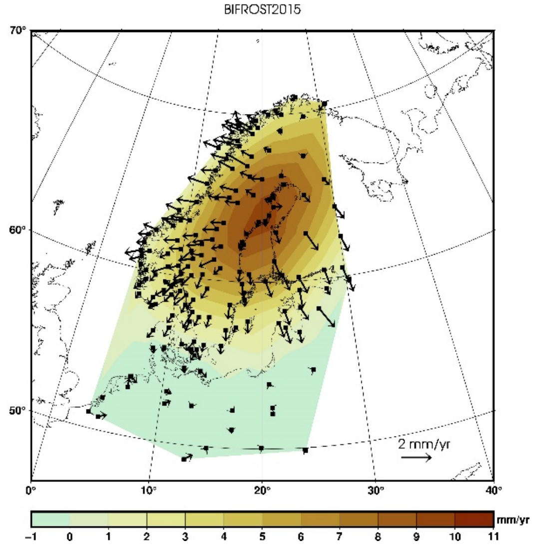
GLACIAL ISOSTATIC ADJUSTMENT (GIA) – OBSERVATIONS

The reliable past



Relative sea level (paleo)

Today's accurate snapshot



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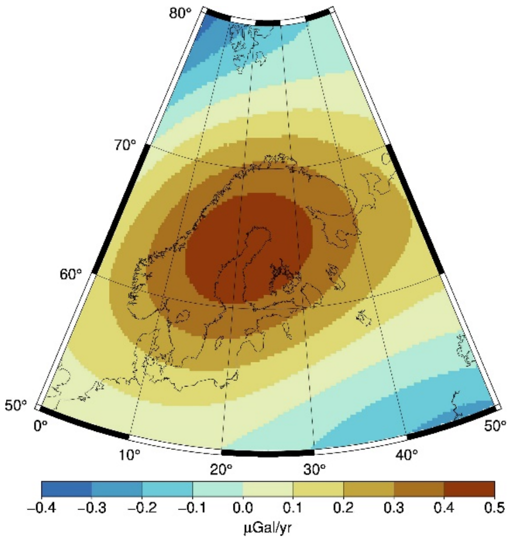
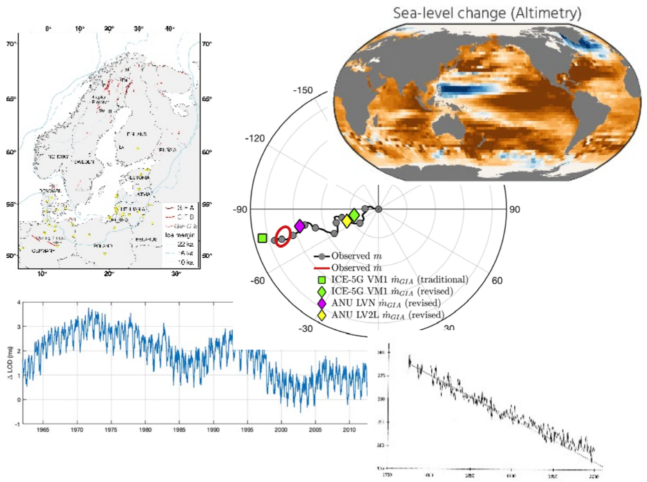
The blurry future



Gravity changes

Helpful constraints



Seismicity, relative sea level (geodetic), Earth rotation parameters

A model that can describe all that (and more) will provide us the view into the future!

⇨GIA models are needed in various geoscientific fields, especially in geodesy

⇨Requires the availability of openly accessible model results, including uncertainty and details about the input parameters