

Validation of GIA models in north-east Greenland using densified GNSS measurements and refined estimates of present-day ice-mass changes

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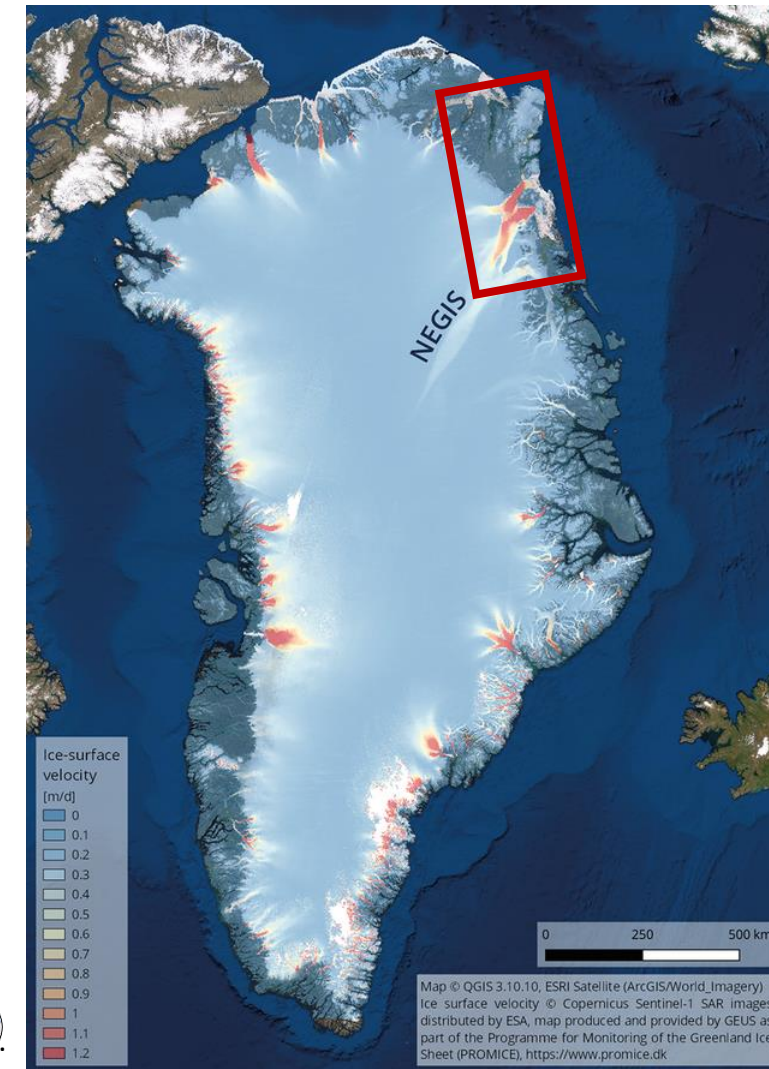
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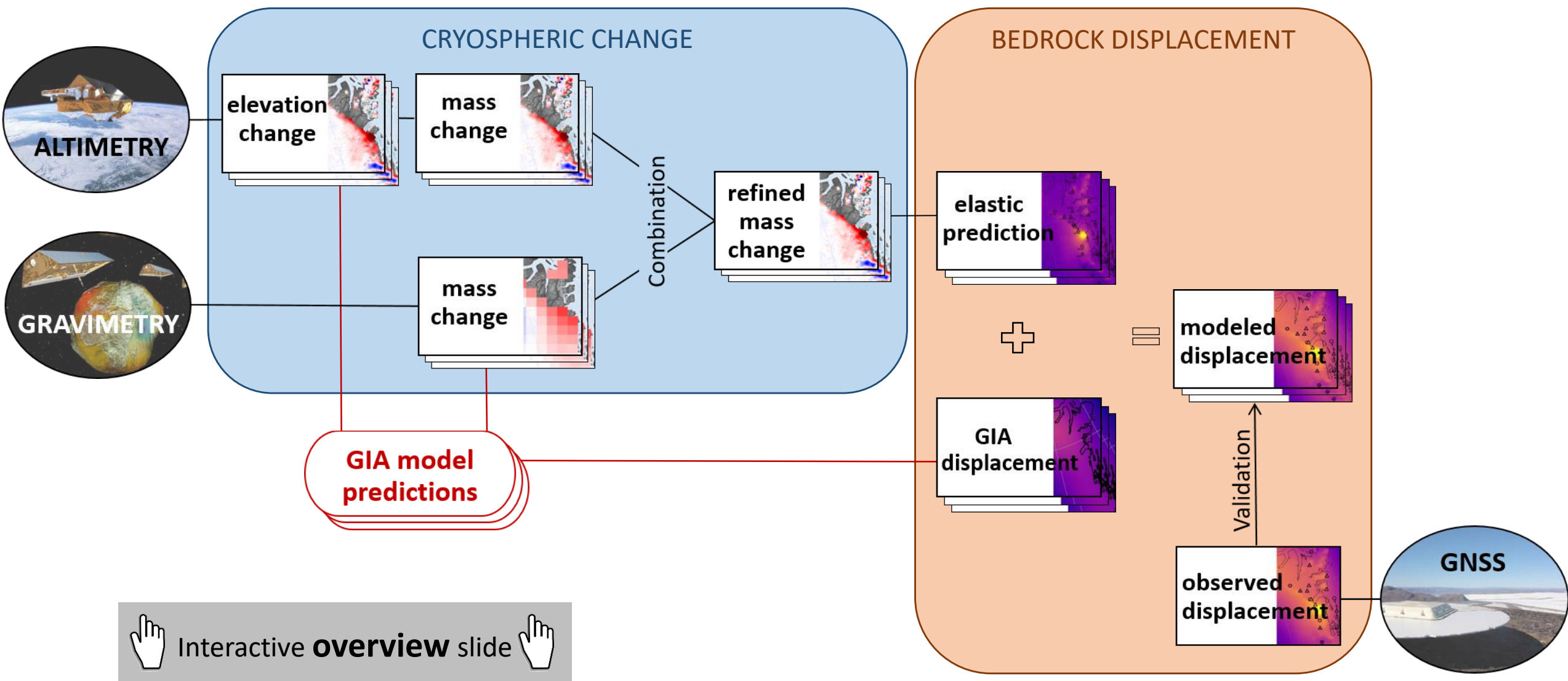
Motivation

Interaction between ice, ocean and solid Earth in north-east Greenland

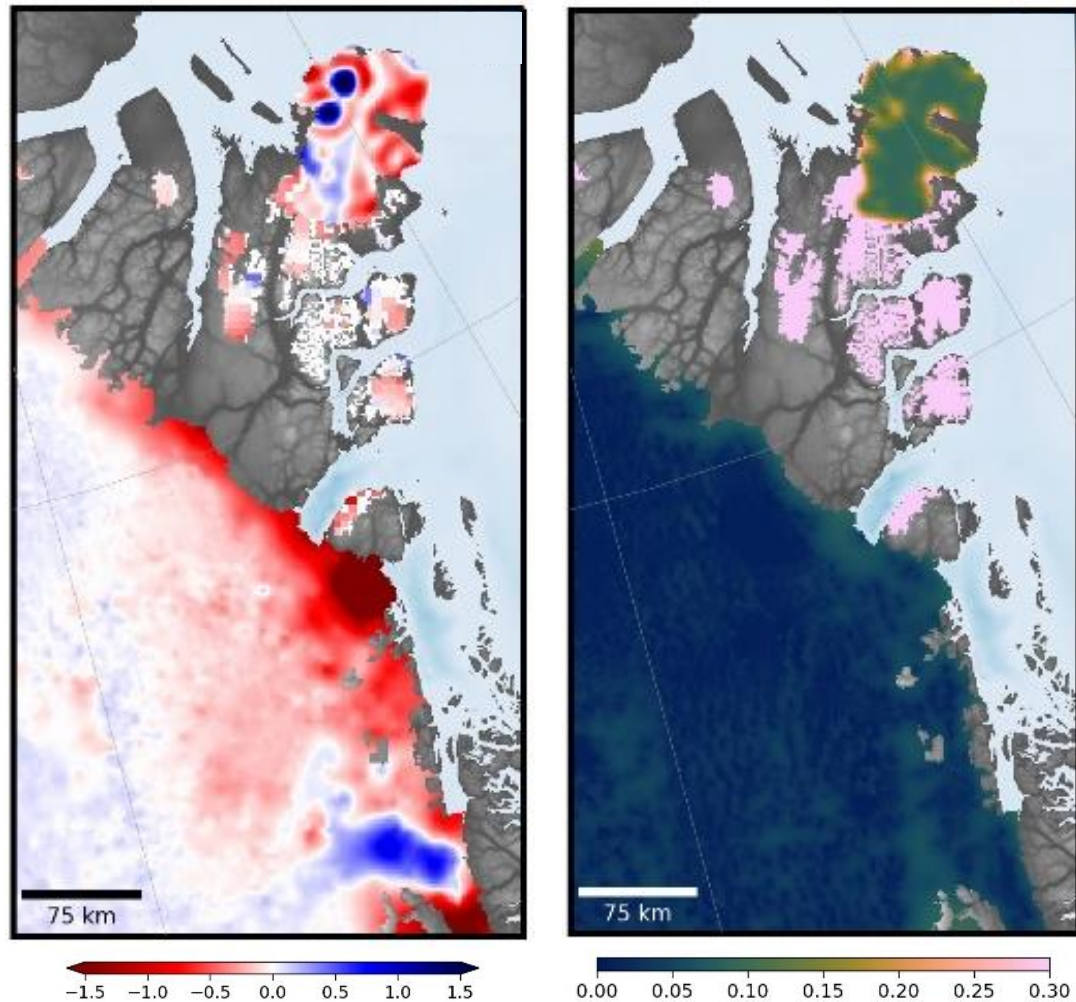
- Models of the glacial-isostatic adjustment (GIA) to past ice-mass changes exhibit large differences in north-east Greenland (click  for a comparison of different models)
 - insufficient knowledge about glacial history and Earth rheology
 - GIA uncertainties feed back to uncertainties in present-day mass-balance estimates from satellite gravimetry:
 - For the Greenland Ice Sheet the GIA-related uncertainty is in the order of 10% of the mass-loss signal (Wake et al., 2016)
 - For individual drainage basins the GIA contribution and its uncertainty can be significantly larger in relation to the ice-mass change
- Glaciers in north-east Greenland have shown an increase in dynamic thinning (Khan et al., 2014) and surface melt water runoff (Noël et al., 2019) since the early 2000s
 - North-East Greenland Ice Stream with its three main outlet glaciers Nioghalvfjærdsbræ, Zachariae Isstrøm and Storstrømmen
 - Peripheral glaciers and ice caps (Flade Isblink)

For a detailed map of the study area click



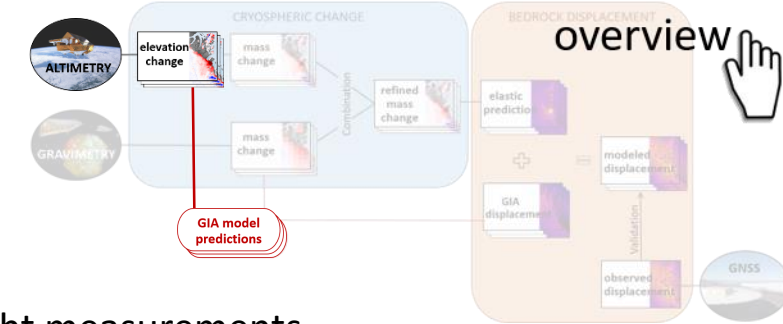


Surface-elevation change from CryoSat-2 data



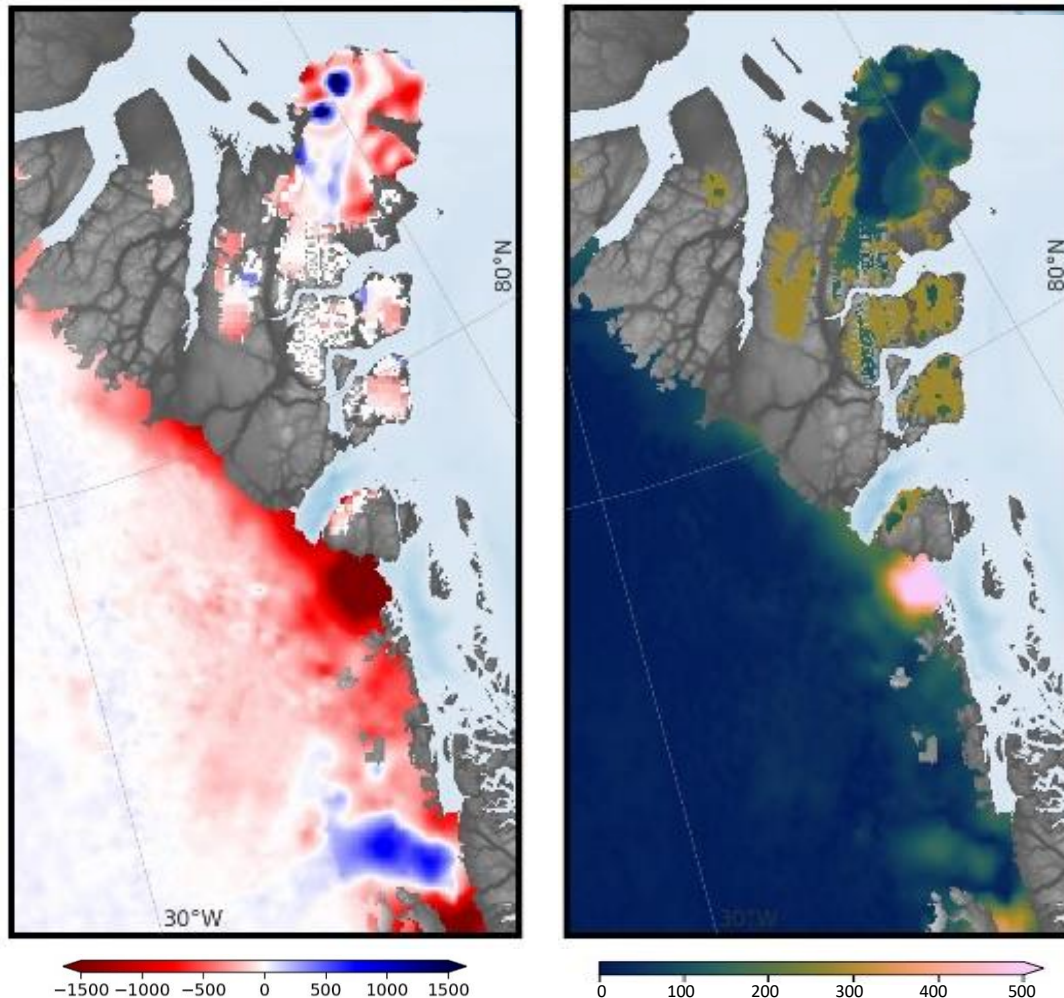
Rates of surface-elevation change and uncertainties (m yr^{-1})

In this figure, the GIA model by Caron et al. (2018) is used for GIA correction.



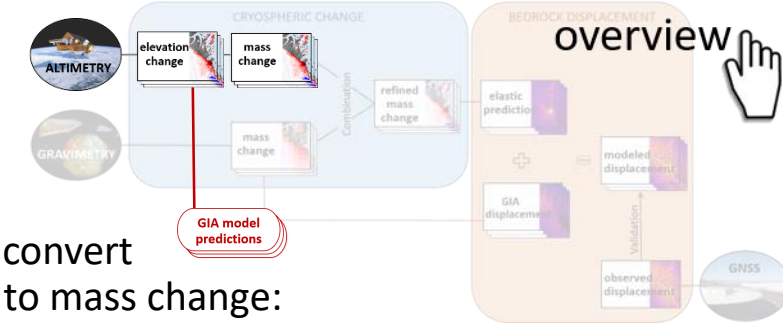
- June 2010 – June 2017
- CryoSat-2 Baseline C height measurements
- Greenland Ice Sheet and Flade Isblink:
 - LRM data: relocated (Roemer et al., 2007) and retracked (OCOG; 10% threshold; Wingham et al., 1986)
 - SARIn data: by V. Helm (Helm et al., 2014)
 - Linear rate derived by repeat altimetry analysis on a polar-stereographic grid of $1.5 \times 1.5 \text{ km}^2$ (topographic corrections by ArcticDEM)
 - Interpolation and filtering by heterogeneous measurement-error filtered kriging (Ströbenreuther et al., 2020)
- Greenland's peripheral glaciers:
 - mean rates from Simonsen & Sørensen (2017)
- **GIA correction for each of the global GIA models under investigation → different versions of rates of surface-elevation change**

Ice-mass change from CryoSat-2 data



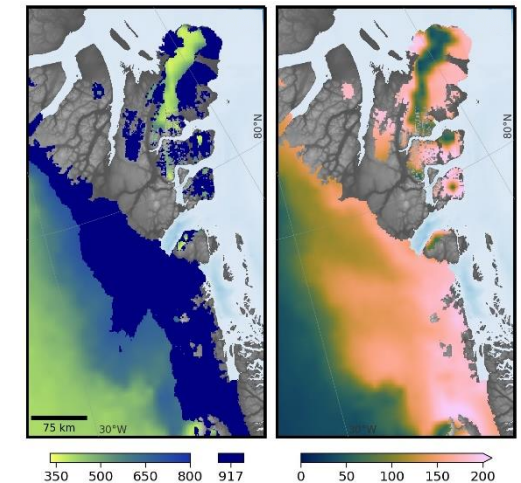
Rates of ice-mass change and uncertainties ($\text{m kg}^{-2} \text{ yr}^{-1}$)

In this figure, the GIA model by Caron et al. (2018) is used for GIA correction.



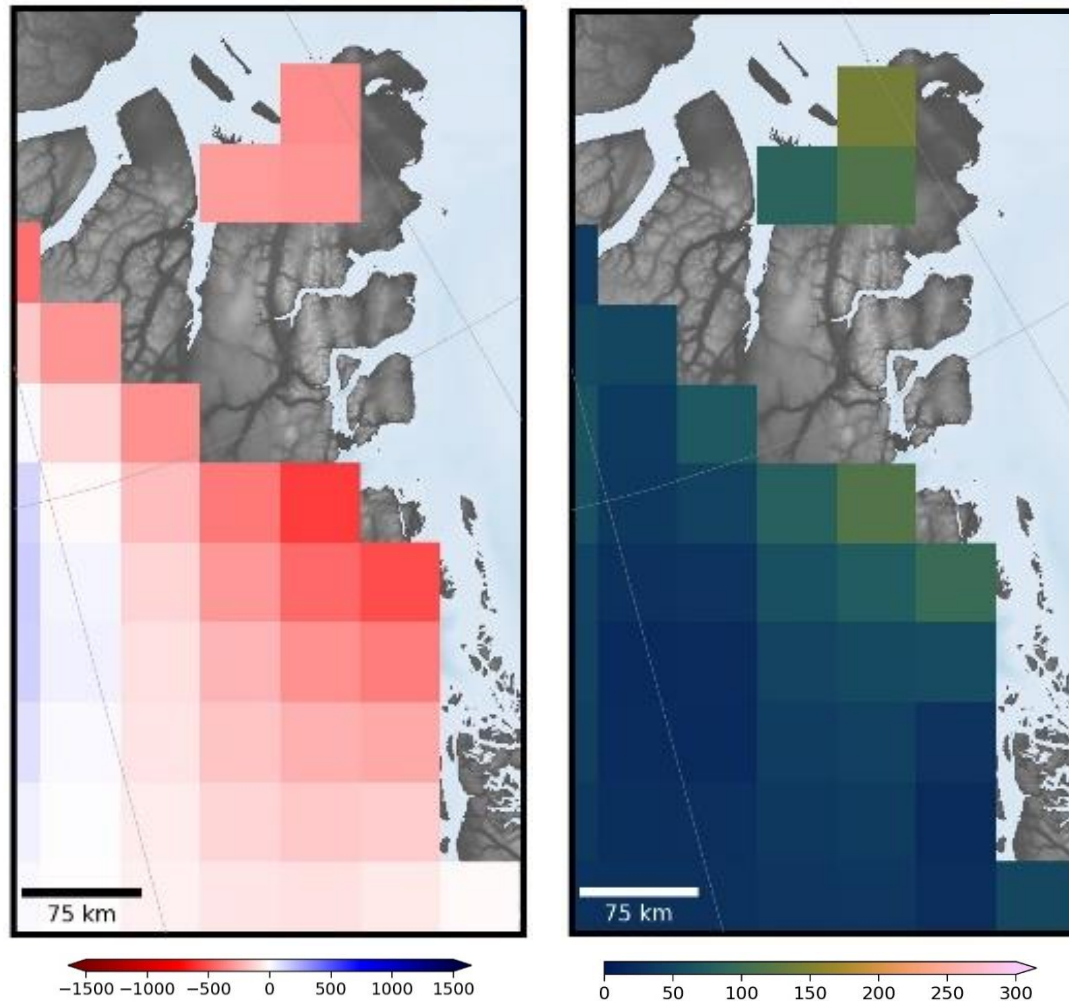
- Density model applied to convert rates of elevation change to mass change:
 - Ice density where surface-mass balance is negative (Noël et al., 2016, 2018)
 - Ice density where dynamically induced changes are expected to dominate (using flow velocities from Nagler et al., 2015)
 - Firn density elsewhere (Kuipers Munneke et al., 2015; Ligtenberg et al., 2018)

Density model and uncertainties (m kg^{-3})



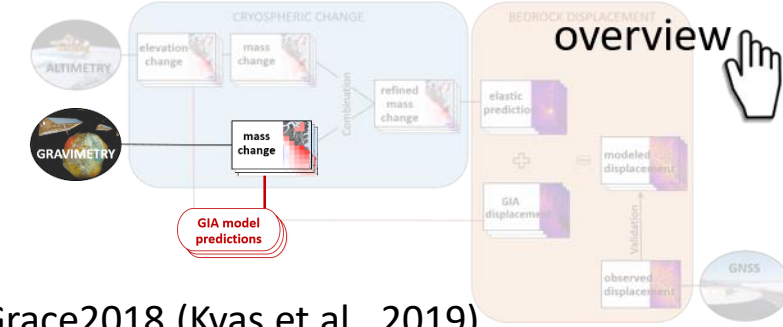
- Error propagation from the uncertainties of the surface-elevation change and the density model

Ice-mass change from GRACE data



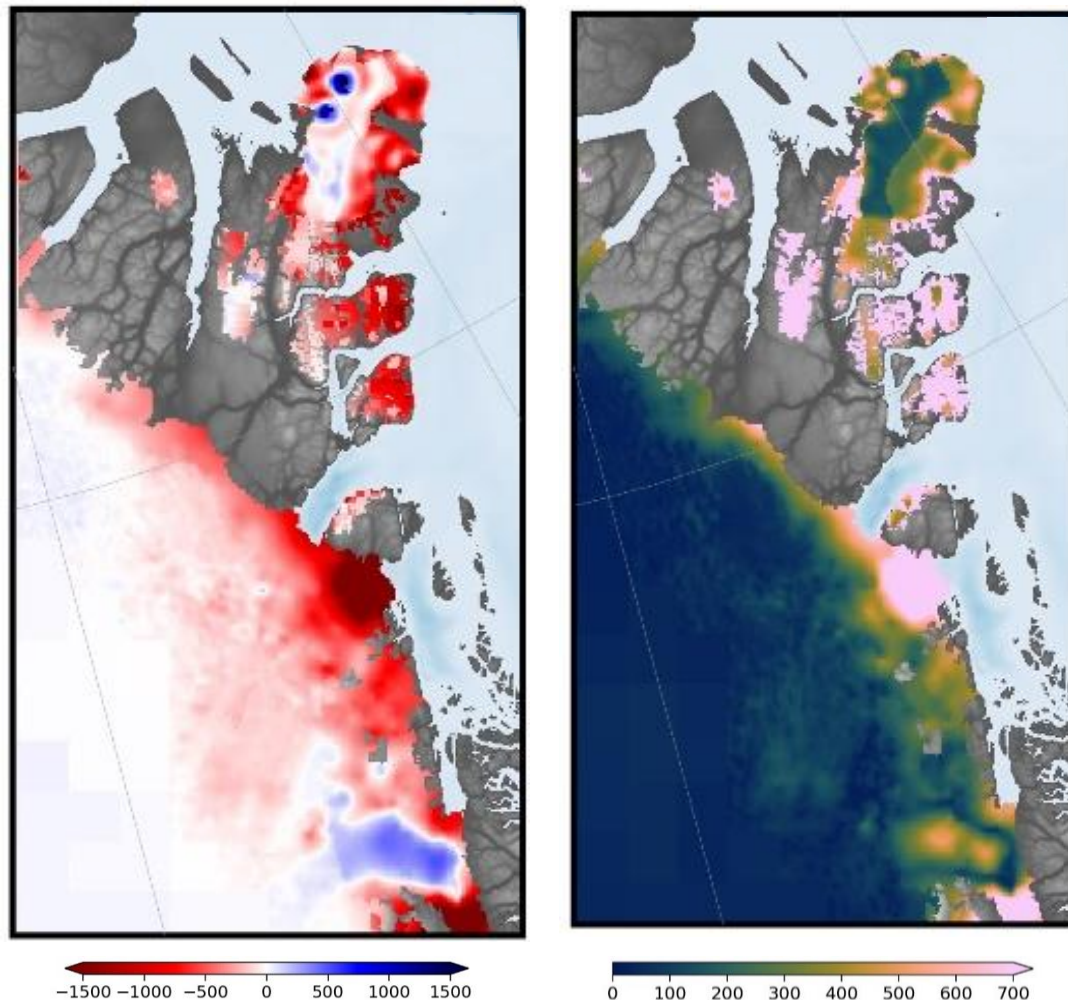
Rates of ice-mass change and uncertainties ($\text{m kg}^{-2} \text{yr}^{-1}$)

In this figure, the GIA model by Caron et al. (2018) is used for GIA correction.



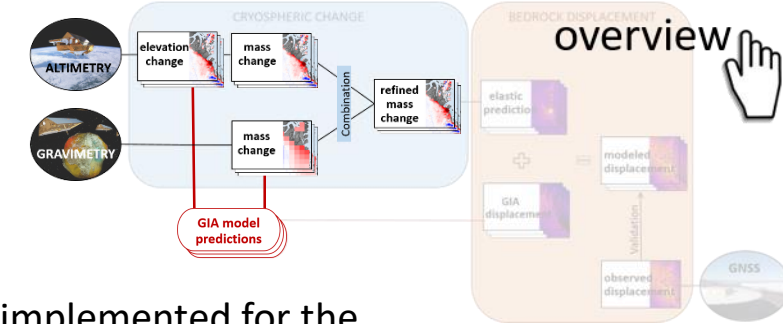
- June 2010 – June 2017
- Monthly solutions ITSG-Grace2018 (Kvas et al., 2019)
- Replacement of C_{20} and C_{30} as of 11/2016 (Loomis et al., 2019)
- **Addition of degree-one components (depending on GIA models)**
- Regional integration approach (Groh & Horwath, 2016) to infer a time series of gridded ($50 \times 50 \text{ km}^2$) ice-mass changes
- Linear rate from fitting linear, period and quadratic terms
- Products available at: https://data1.geo.tu-dresden.de/gis_gmb/
- **GIA correction for each of the global GIA models under investigation → different versions of rates of ice-mass change**
- **Effect of the different GIA corrections on the estimated ice-loss rate:**
 - Entire Greenland: in the range of 0.0 to 4.3%
 - North-east Greenland: in the range of 30.1 to 39.8%
- Uncertainty assessment includes uncertainties of the formal trend, C_{20} time series, degree-one terms and signal leakage

Refined ice-mass change: combining CryoSat-2 and GRACE results



Estimated rates of ice-mass change and a posteriori uncertainties ($\text{m kg}^{-2} \text{yr}^{-1}$)

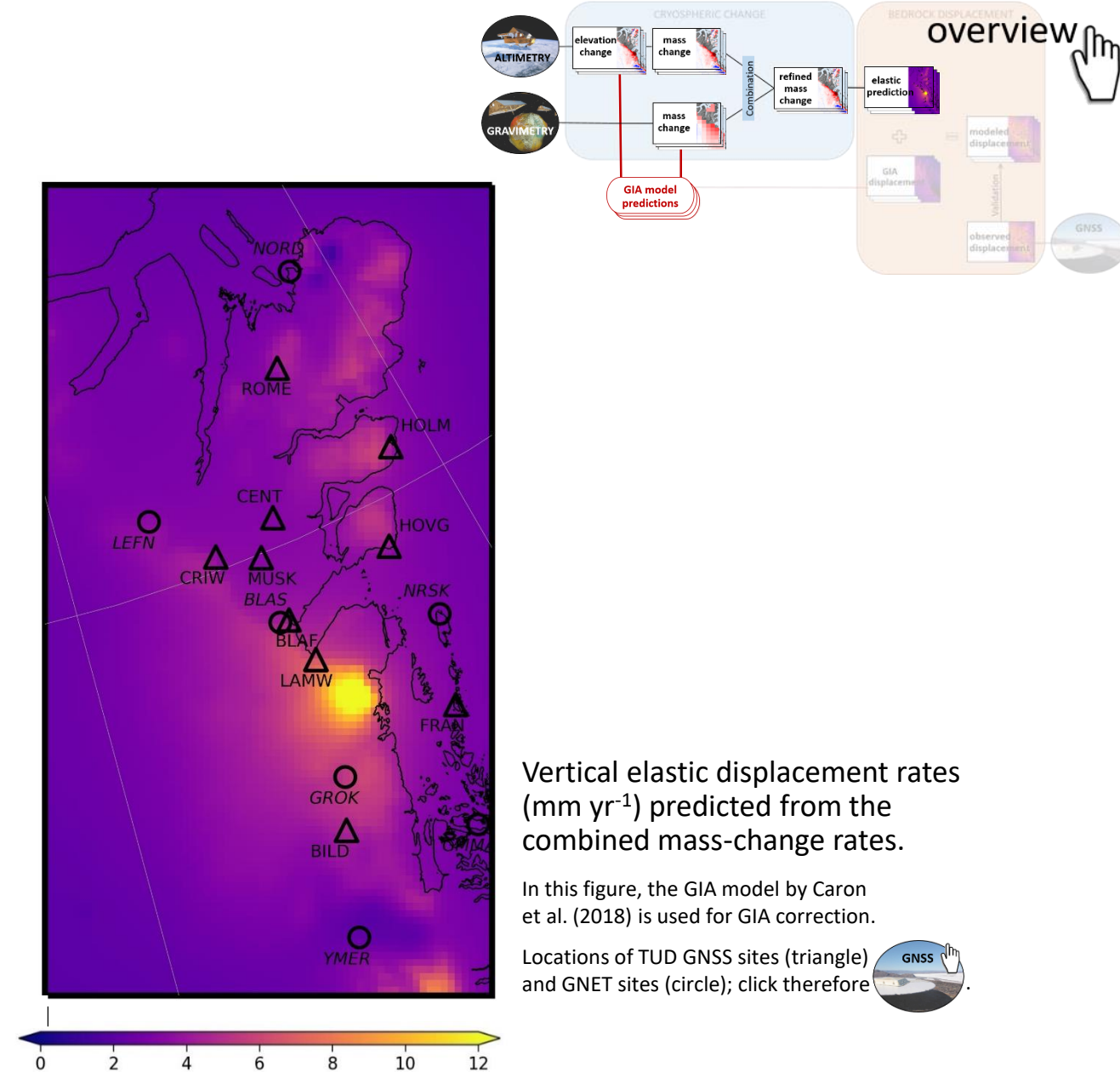
In this figure, the GIA model by Caron et al. (2018) is used for GIA correction.



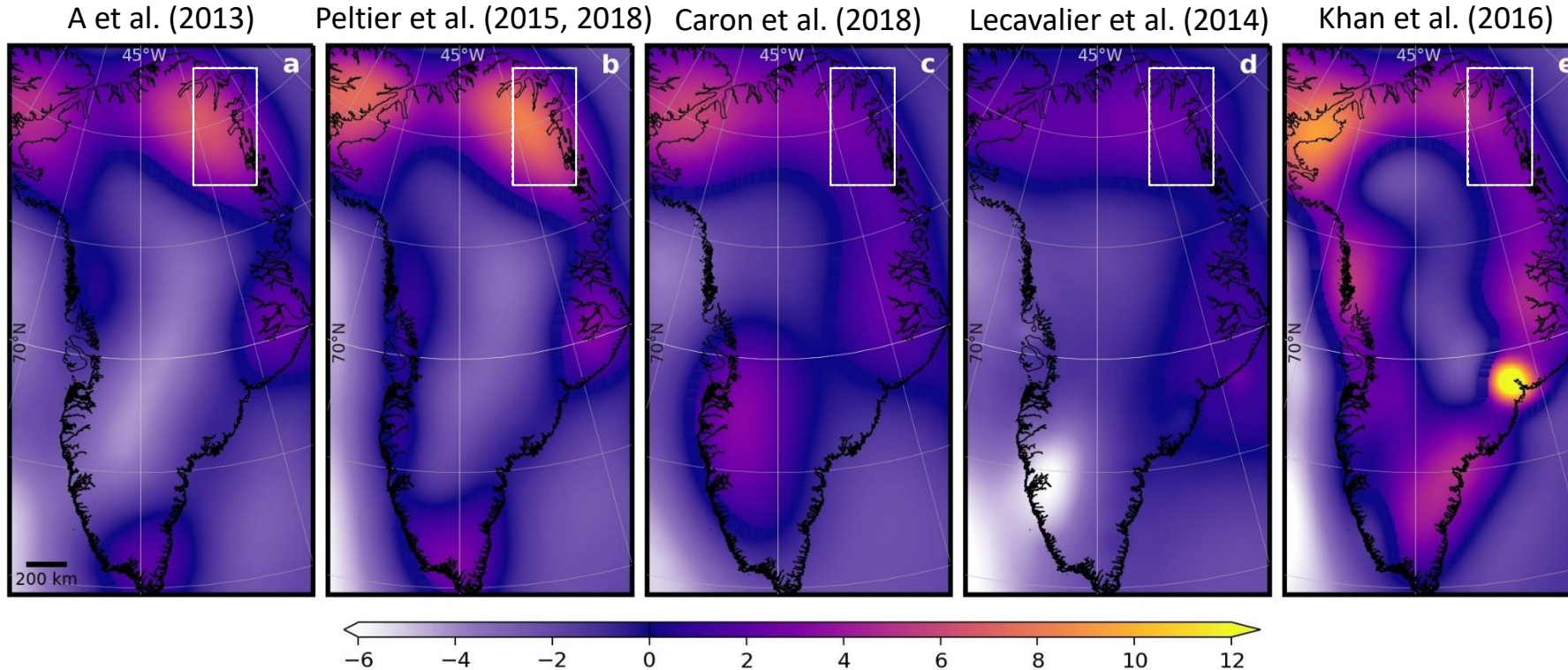
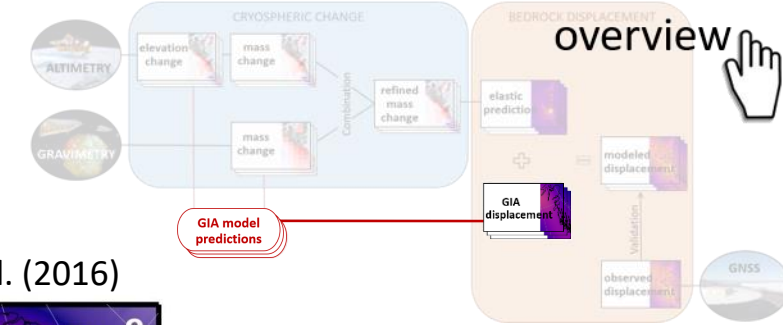
- Combination approach is implemented for the entire Greenland Ice Sheet and includes peripheral glaciers and ice caps
- Least squares adjustment
- Results from GRACE and CryoSat-2 are used as two complementary sets of observations with associated uncertainties
- Variance-component estimation to account for different uncertainty levels
- Refined ice-mass change estimates **exploit the advantages of each satellite technique**:
 - **CryoSat-2: high spatial resolution**
 - **GRACE: direct sensitivity to mass redistributions**
- **Combination is conducted separately for each of the global GIA models under investigation. The GIA model is consistently used to correct CryoSat-2 and GRACE data.**

Prediction of elastic bedrock displacement

- Green's function approach (Farrell, 1972)
- Load input: refined ice-mass change estimates from the GRACE-CryoSat-2-combination (**depending on the GIA model used for GIA correction**)
- Error propagation from the uncertainties of the refined-ice mass change estimates (for the locations of the GNSS sites)
- Elastic prediction at the GNSS sites:
 - **Minimum of $2.4 \pm 1.2 \text{ mm yr}^{-1}$ at YMER**
 - **Maximum of $7.0 \pm 2.6 \text{ mm yr}^{-1}$ at LAMW**
- Elastic prediction for the study area of north-east Greenland:
 - Maximum of 13.8 mm yr^{-1} at the terminus of Zachariae Isstrøm



GIA models under investigation



GIA vertical displacement rates (mm yr^{-1}). The white box indicate the study area in north east-Greenland.

Range of GIA displacement rates at the locations of the GNSS sites (mm yr^{-1}):

3.3 to 6.7
(global model)

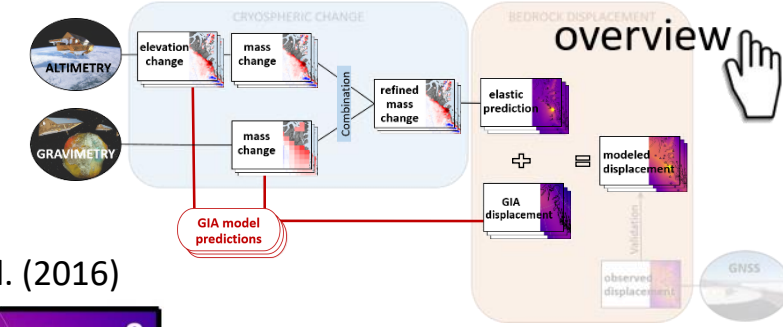
4.0 to 8.3
(global model)

1.3 to 2.9
(global model)

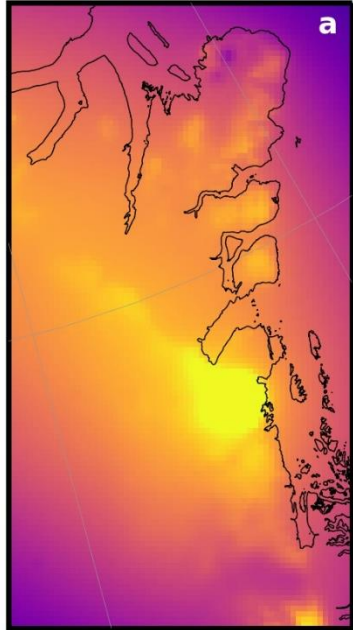
0.7 to 2.5
(Greenland model)

2.1 to 4.4
(Greenland model)

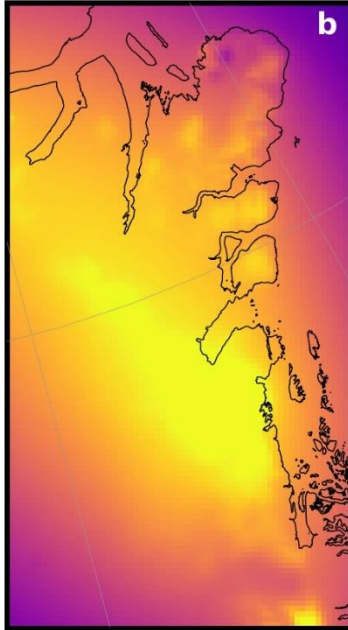
Total bedrock displacement (elastic prediction + GIA model)



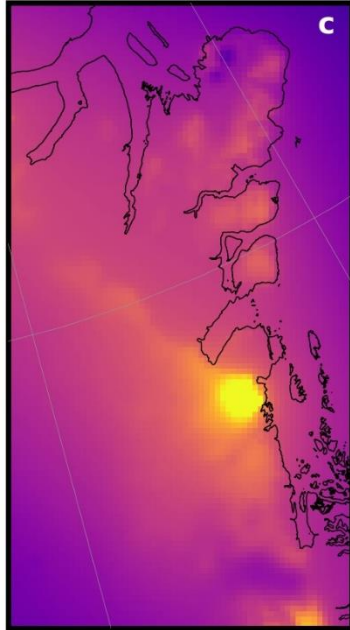
A et al. (2013)



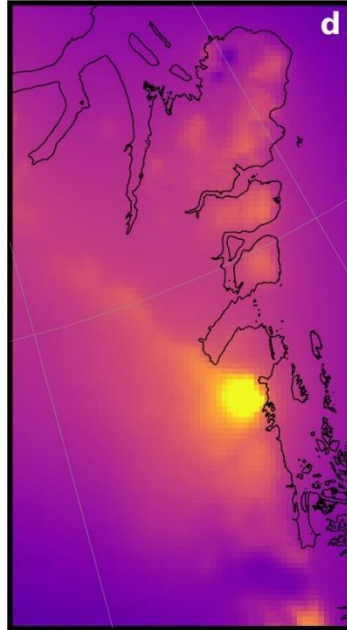
Peltier et al. (2015, 2018)



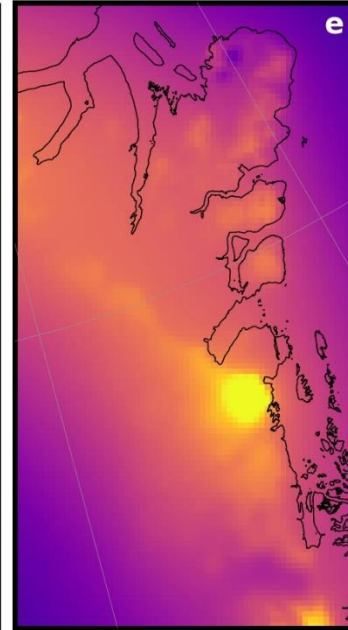
Caron et al. (2018)



Lecavalier et al. (2014)



Khan et al. (2016)

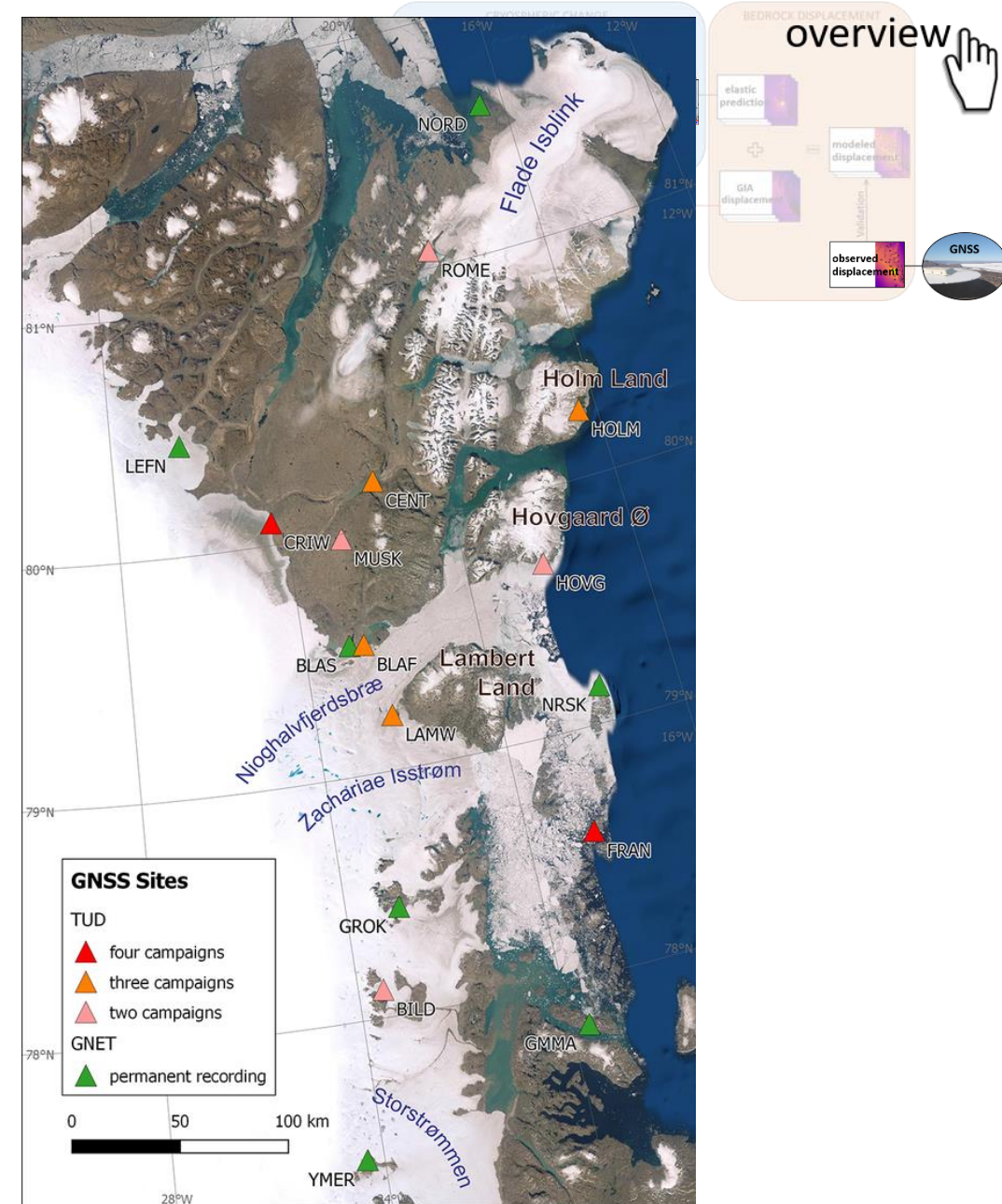


Total modeled vertical displacement rates (mm yr^{-1}) on basis of the different GIA models.

Observed bedrock displacement from GNSS

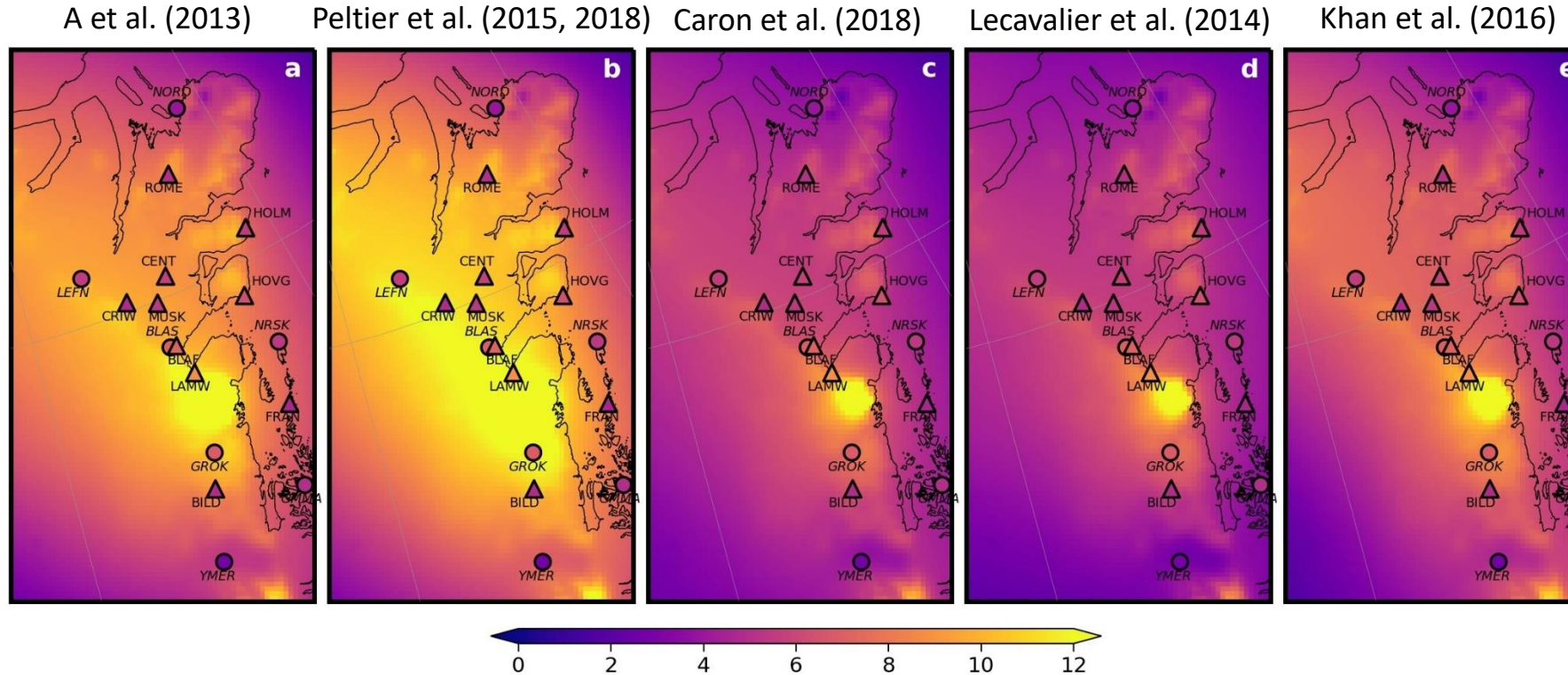
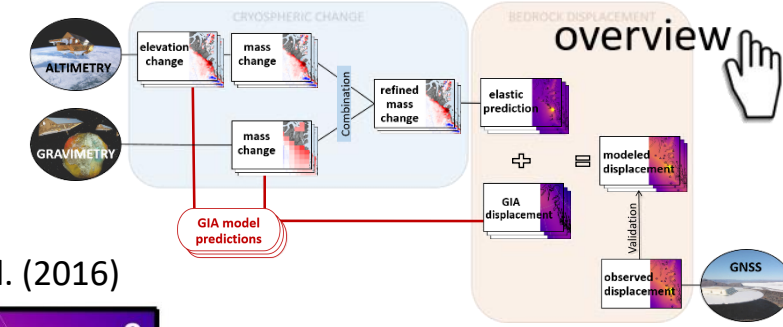
- 2008/2009 – 2016/2017
- Stable bedrock monumentation
- Coverage coordinated between Technische Universität Dresden (TUD) sites and Greenland Global Positioning System network (GNET)
- Campaign-style TUD measurements (10 sites) and continuous GNET measurements (7 sites) treated as campaign sites
- Bernese GNSS Software v5.2 (Dach et al., 2015)
- Observed uplift rates:
 - **Minimum of $2.8 \pm 1.6 \text{ mm yr}^{-1}$ at YMER**
 - **Maximum of $8.9 \pm 1.7 \text{ mm yr}^{-1}$ at LAMW**

Map of the study area:
TUD GNSS (with the measured number of campaigns) and GNET sites; the main outlet glaciers, Nioghalvfjedsbræ, Zachariae Isstrøm and Storstrømmen, the ice caps Flade Isblink and Holm Land, the islands Hovgaard Ø and Lambert Land.



Validation of GIA models

Modeled vs. observed bedrock displacement

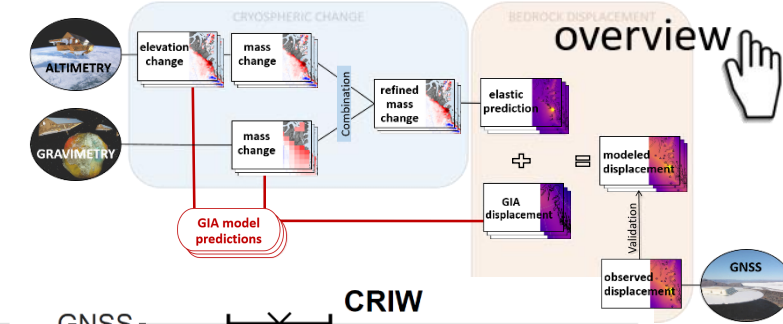


Modeled vertical displacement rates (mm yr^{-1}) on basis of the different GIA models displayed against GNSS-observed uplift rates (TUD sites: filled triangles; GNET sites: filled circles).

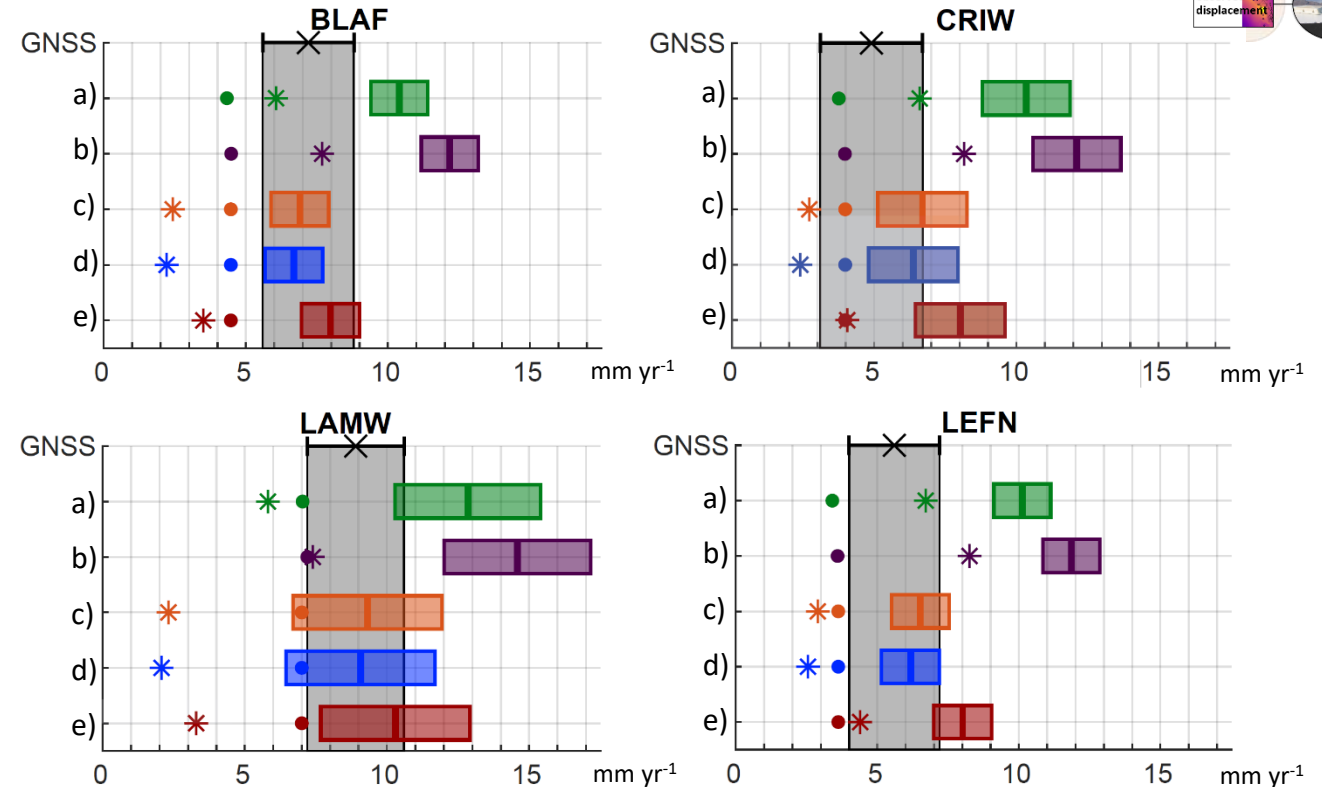
- Bedrock displacements predicted by using GIA models by A et al. (2013) and Peltier et al. (2015, 2018) are larger than observed by GNSS
- Bedrock displacements predicted by using GIA models by Caron et al. (2018), Lecavalier et al. (2014) and Khan et al. (2016) are similar to the GNSS results

Validation of GIA models

Agreement (within uncertainties) between modeled and observed rates



- a) A et al. (2013): 7 out of 17 sites
- b) Peltier et al. (2015, 2018): 2 out of 17 sites
 - GIA in north-east Greenland is overestimated by a), b)
- c) Caron et al. (2018): 17 out of 17 sites
 - ➔ No integration of Greenland GNSS data and only few records of relative sea-level
- d) Lecavalier et al. (2014): 17 out of 17 sites
 - ➔ No integration of Greenland GNSS data but comprehensive records of past ice extent and relative sea-level
- e) Khan et al. (2016): 17 out of 17 sites
 - ➔ Adjustment to the GNET GNSS observations
 - GIA predictions in north-east Greenland from c), d), e) are compatible with the observations from GNSS, GRACE and CryoSat-2



Vertical displacement rates at 4 GNSS sites. Grey: GNSS-observed rates. Colors: modeled rates using GIA models a)-e). Boxes show 1-sigma uncertainty ranges. Points and asterisks show the two components of modeled displacement: the elastic displacement and the GIA uplift rates, respectively.

Summary

- **Geodetic GNSS measurements** at bedrock sites in north-east Greenland reveal uplift rates in the range of 2.8 to 8.9 mm yr⁻¹ (time period: 2008/2009 – 2016/2017).
- Independent GNSS observations provide **validation** of modeled bedrock displacement rates.
- **Combination of satellite gravimetry (GRACE) and satellite altimetry data (CryoSat-2)** with including peripheral glaciers improve estimates of Greenland's ice-mass change and the associated elastic deformation.
- In north-east Greenland, the effect of the GIA correction on the GRACE-derived ice-loss rate is about 31%. This number is based on the Caron et al. (2018) GIA model, which has been validated in this study.
- **Elastic displacement rates** exhibit strong regional variability (2.4 to 7.0 yr⁻¹ mm yr⁻¹ at the GNSS sites).
- Consistent treatment of the GIA effect based on model predictions was accomplished throughout the whole analysis.
- **Models predicting low GIA rates** in north-east Greenland (0.7 to 4.4 yr⁻¹ mm yr⁻¹ at the GNSS sites) were confirmed.
- This work is published at: Kappelsberger, M. T., Strößenreuther, U., Scheinert, M., Horwath, M., Groh, A., Knöfel, C., Lunz, S., Khan, S. A. (2021). Modeled and observed bedrock displacements in north-east Greenland using refined estimates of present-day ice-mass changes and densified GNSS measurements. *Journal of Geophysical Research: Earth Surface*, 126, e2020JF005860. <https://doi.org/10.1029/2020JF005860>

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List of images

- CryoSat-2: https://www.esa.int/Space_in_Member_States/Germany/CryoSat-2_Flugkontrollteams_bereiten_sich_intensiv_vor
- GRACE: <https://www.br.de/wissen/grace-satelliten-mission-erdgravitation-gfz-dlr-nasa-100.html>
- GNSS: <https://tu-dresden.de/bu/umwelt/geo/ipg/gef/die-professur/news/messkampagne-westgroenland-2018>
- Cursor: <https://www.nicepng.com/maxp/u2q8a9o0t4o0e6e6/>