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Importance of Northern Hemisphere Vertical Land Motion for Geodesy and Coastal Sea Levels

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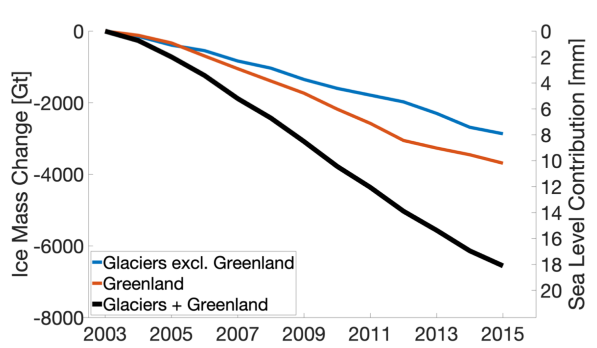
Abstract

Vertical land motion (VLM) of Earth's surface can aggravate or mitigate ongoing relative sea level change. The near-linear process of Glacial Isostatic Adjustment (GIA) is normally assumed to govern regional VLM. However, present-day deglaciation of primarily the Greenland Ice Sheet causes a significant non-linear elastic uplift of >1 mm yr^{-1} in most of the wider Arctic. The elastic VLM exceeds GIA at 14 of 42 Arctic GNSS-sites, including sites in non-glaciated areas in the North Sea region and along the east coast of North America. The combined elastic VLM + GIA model is consistent with measured VLM at three-fourth of the GNSS-sites (R=0.74), which outperforms a GIA-only model (R=0.60). Deviations from GNSS-measured VLM, are interpreted as estimates of local circumstances causing VLM. Future accelerated ice loss on Greenland, will increase the significance of elastic uplift for North America and Northern Europe and become important for coastal sea level projections.

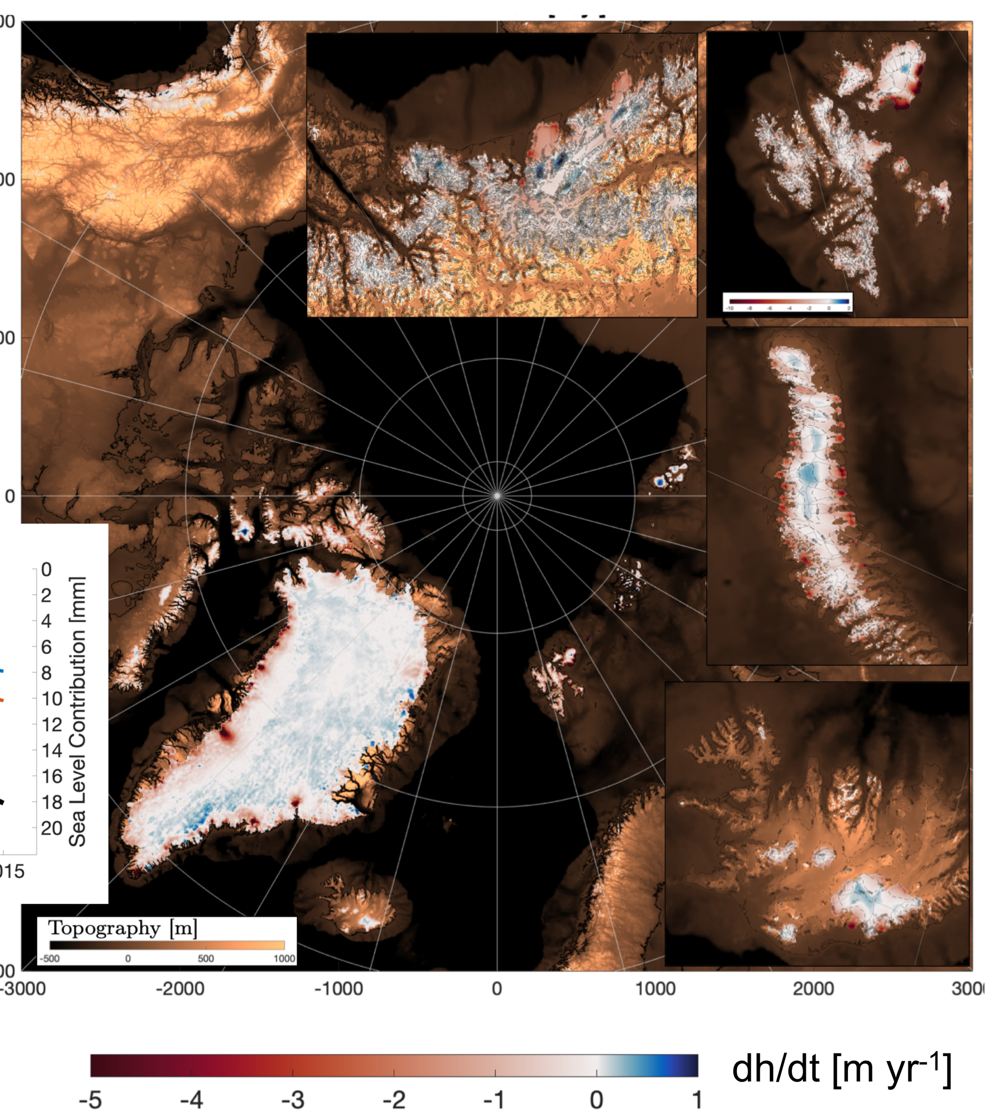
Ice loading model

The main component of the elastic VLM model is the ice loading model. The mean elevation change [m yr^{-1}] rate from 2003-2015 for the ice areas included is shown in the figure below. We include all We are aware that also Southern Hemisphere may impact the region of this study (Riva et al., 2017). However, mass loss of the Southern Hemisphere is considerably smaller and specifically Antarctica is so far away, that it safely can be neglected.

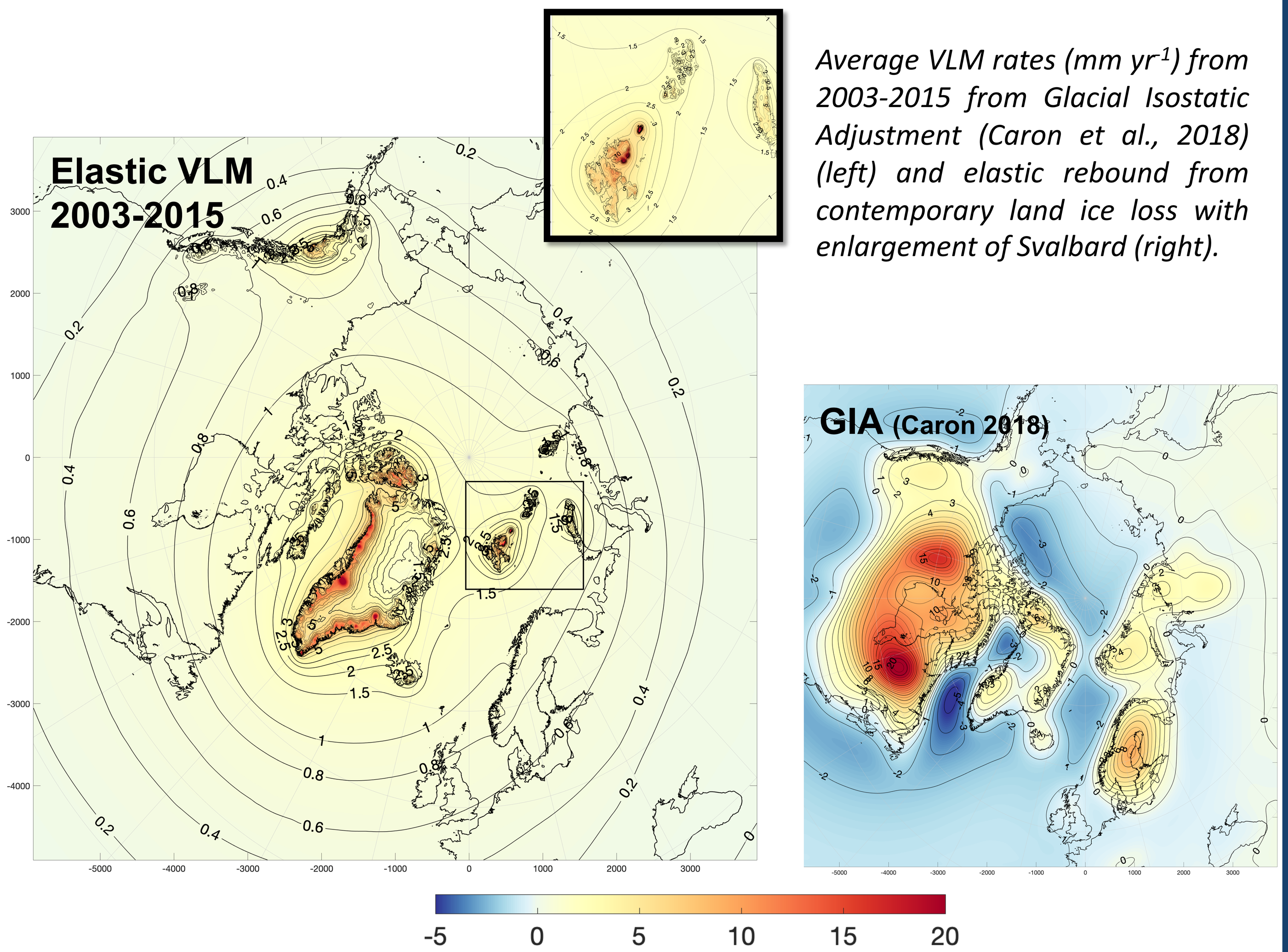
Glacial mass balance change estimates from Marzeion et al. (2012) and shapefiles of the Randolph Glacier Inventory (RGI 6.0) (Pfeffer et al., 2014) are used to create estimates of yearly ice elevation change in a 2x2 km spatial grid assuming uniform ice density of 917 kg m^{-3}. This combined with a Greenland Ice Sheet model build on Khan et al, 2013.



Top: Total ice loss and equvalent sea level contribtuion. The ice loss included accounts for 80% of the global ice loss.



Maps of elastic deformation and GIA



Average VLM rates (mm yr^{-1}) from 2003-2015 from Glacial Isostatic Adjustment (Caron et al., 2018) (left) and elastic rebound from contemporary land ice loss with enlargement of Svalbard (right).

Key points:

1. **Elastic Vertical Land Motion caused by present-day melt of Greenland causes significant uplift of coastlines in North America and Northern Europe and thus is Greenland ice loss in part mitigated by rising coastlines in the Northern Hemisphere.**
2. **A combination of GIA and the elastic deformation from present-day ice loss yields good agreement, and outperforms a GIA-only model at most GNSS-sites located above 50N.**
3. **Differences between GNSS and the combined VLM-model can potentially quantify local circumstances causing VLM, like past earthquakes or extraordinary subsurface properties, like Iceland.**

Calculating elastic VLM

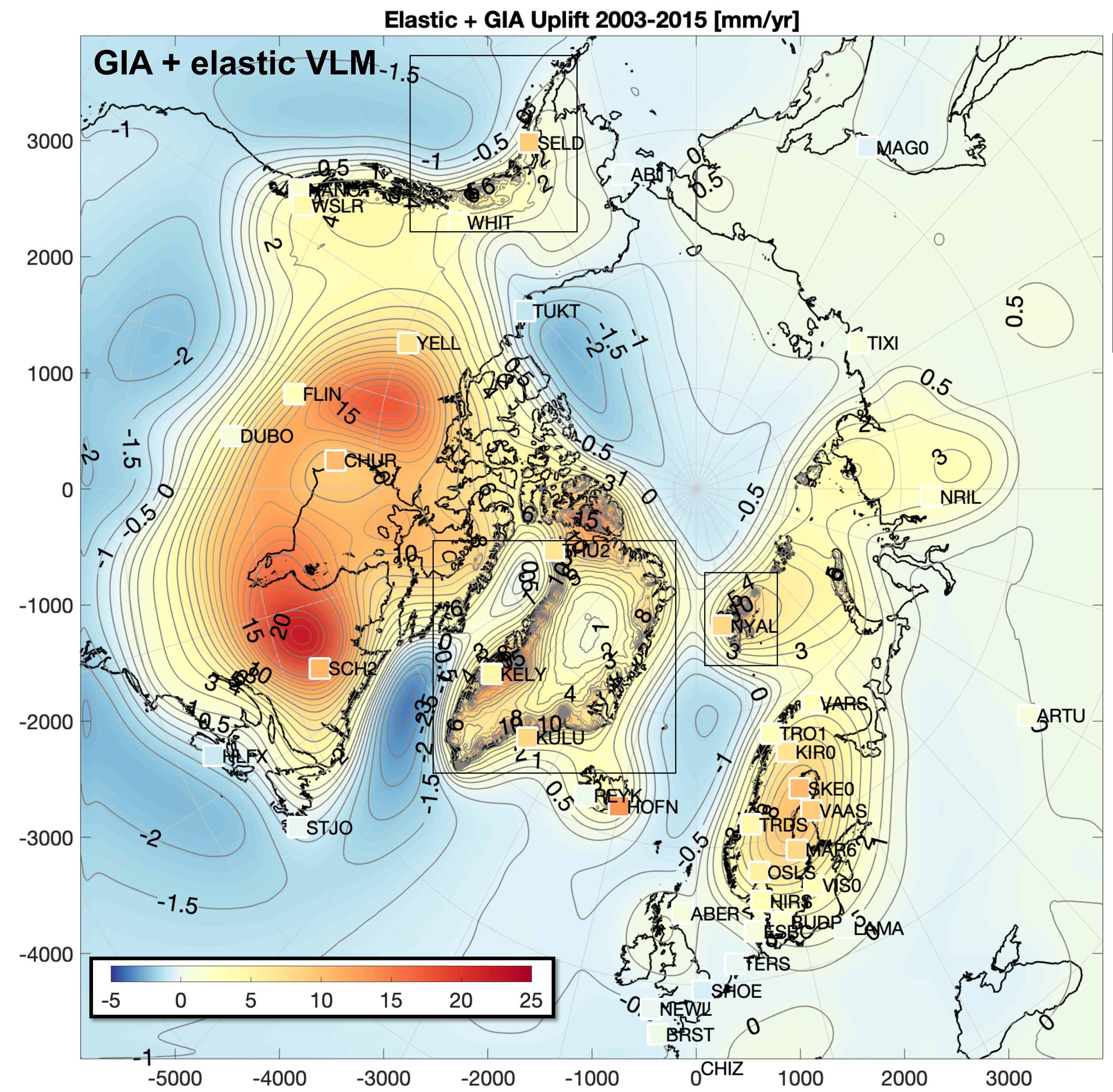
Elastic VLM is the immediate rebound when mass is removed from the surface, i.e. by melting Ice Sheets. The ice-model surface loading described above, used as input for the **REAR-model** (Regional ElAstic Rebound calculator, Melini et al., 2014) to make an elastic VLM-model with the same, high resolution (2x2 km). REAR is build on the sea level equation of Farrell and Clark (1976) and assumes a solid, non-rotating and isotropic earth. By combining GIA with the elastic VLM-model, the combined VLM-model can be evaluated against GNSS measurements. The Love numbers used in REAR are defined with respect to Earth's centre of mass (CM-frame).

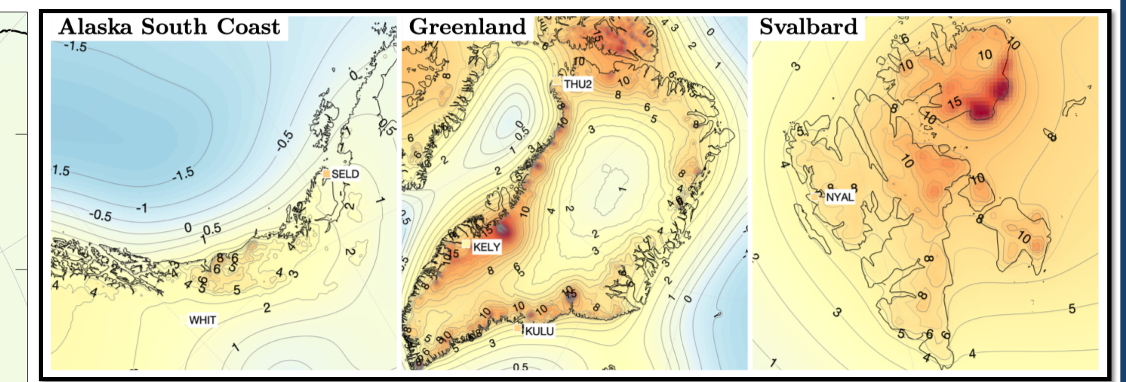
References and Data:

- *Marzeion, B., Jarosch, A. H., & Hofer, M. (2012). Past and future sea-level change from the surface mass balance of glaciers. The Cryosphere*
- *Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S. et al. (2014). The randolph glacier inventory: a globally complete inventory of glaciers. Journal of Glaciology.*
- *Khan, S. A., Kjær, K. H., Korsgaard, N. J., Wahr, J., Joughin, I. R., Timm, L. H., Babonis, G. (2013). Recurring dynamically induced thinning during 1985 to 2010 on upernavik isstrøm, west greenland. Journal of Geophysical Research: Earth Surface*
- *Riva, E., Frederikse, T., King, A., Marzeion, B., & Van Den Broeke, R. (2017). Brief communication: The global signature of post-1900 land ice wastage on vertical land motion. Cryosphere*
- *Melini, D., Spada, G., Gegout, P., & King, M. (2014, 01). Rear - a regional elastic rebound calculator. user manual for version 1.0. http://hpc.rm.ingv.it/rear/REAR-v1.0-User-Guide.pdf*

- *Caron 2018 GIA-model: https://vesl.jpl.nasa.gov/solid-earth/gia/*
- *elastic VLM-model available: ftp.space.dtu.dk/pub/DTU20/VLM*
- *Ludwigsen et al (submitted) – ESSOAr Open Archive: https://www.essoar.org/doi/abs/10.1002/essoar.10502890.1*

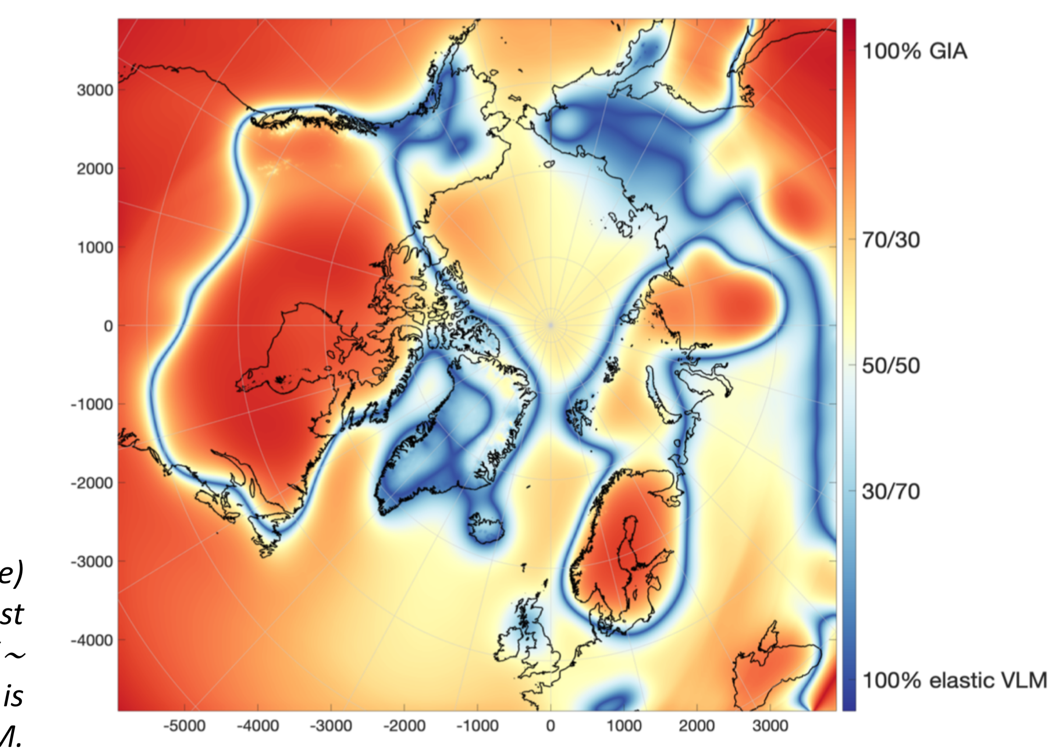
VLM-model compared to GNSS and GIA



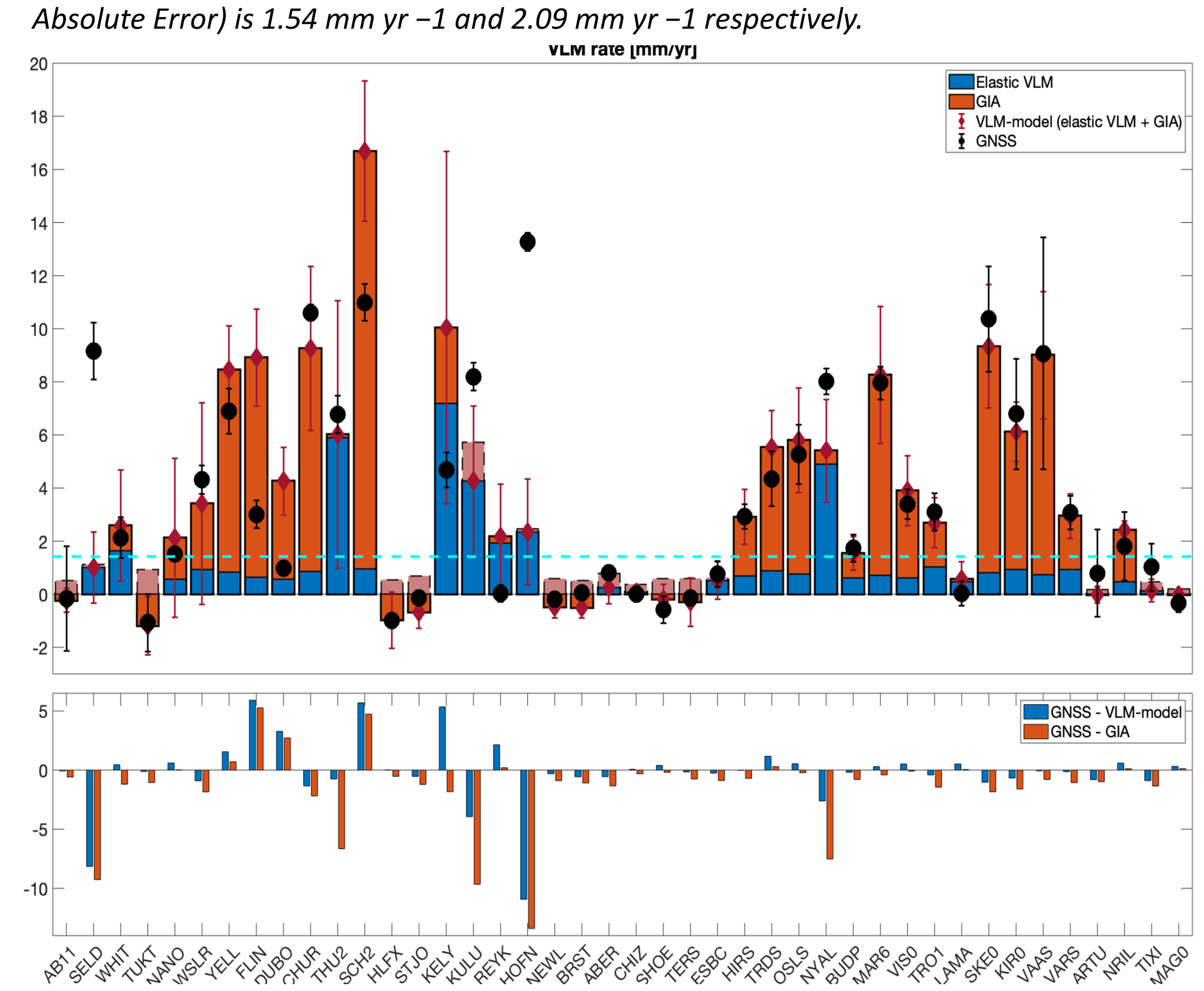


Left and top: *Average VLM-rates (mm yr^{-1}) from 2003-2015 from the VLM-model (Glacial Isostatic Adjustment + elastic VLM). The color of the squares represent the GNSS measured average VLM-rate for the same period. For clarification Alaska South Coast, Greenland and Svalbard are enlarged (top).*

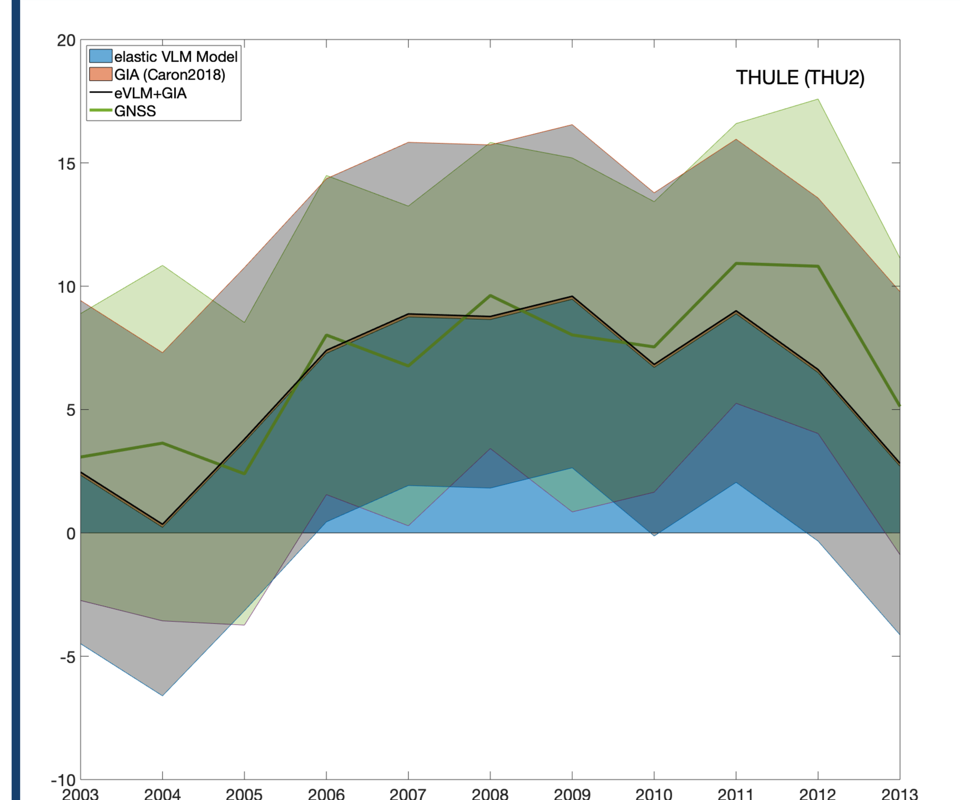
Below: *The share of GIA-rate and elastic VLM-rate from the total absolute VLM-rate (in absolute terms) in percentage. Red colors indicate areas where GIA dominates VLM while blue colors indicate where the elastic VLM is larger.*



Below: *2003-2015 average VLM change [mm yr −1] from the elastic VLM model (blue) and GIA (red) at 42 GNSS-sites shown in the figure above from most west (left) to most east (right). The dotted cyan-colored line indicates the average barysteric sea level rise (~ 1.4 mm yr^{-1}) from the ice loss included in this study. The lighter red indicates where GIA is negative and hence overlaps the positive elastic VLM.* ***Bottom****: The residuals between GNSS-measured VLM and the combined VLM-model (blue) and GIA-only (red). The average of the absolute residuals (equivalent to Mean Absolute Error) is 1.54 mm yr −1 and 2.09 mm yr −1 respectively.*



Temporal varying VLM



Below: *Yearly displacement (mm) for Thule (Northeast Greenland) from 2003 to 2013, measured by GNSS (green line - shaded green area is 1σ)) and from the VLM-model (black line shaded grey area is 1σ). The elastic VLM is represented by the blue area and GIA by the orange area, which in this case is small.*