Vertical Land Motion from Present-Day Deglaciation in the Wider Arctic

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Key Points:

- Elastic VLM from present-day ice loss in the Arctic causes significant uplift of coastlines in North America and Northern Europe.
- A combined VLM-model that includes GIA and elastic VLM, yields good agreement with GNSS-stations in the wider Arctic.
- Residuals between GNSS and modeled VLM provides an approximation of extraordinary VLM caused by local circumstances.

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Abstract

Vertical land motion (VLM) from past and ongoing glacial changes can amplify or mitigate ongoing relative sea level change. We present a high resolution VLM-model for the wider Arctic, that includes both present-day ice loading (PDIL) and glacial isostatic adjustment (GIA). The study shows that the non-linear elastic uplift from PDIL is significant (0.5-1 mm y^{-1}) in most of the wider Arctic and exceeds GIA at 15 of 54 Arctic GNSS-sites, including sites in non-glaciated areas of the North Sea region and the east coast of North America. Thereby the sea level change from PDIL (1.85 mm y^{-1}) is significantly mitigated from VLM caused by PDIL. The combined VLM-model was consistent with measured VLM at 85% of the GNSS-sites (R=0.77) and outperformed a GIA-only model (R=0.64). Deviations from GNSS-measured VLM can be attributed to local circumstances causing VLM.

Plain Language Summary

From 2003 to 2015, the Northern Hemisphere lost more than 6,000 gigatons of land ice, which added nearly 18 mm to the global mean sea level rise. Loss of land-based ice results in the vertical deformation of the Earth's surface. Ongoing rebounding or subsidence caused by the end of the last ice age is often assumed to govern vertical deformation. However, present-day ice loss from Greenland and Arctic glaciers also cause an immediate vertical deformation. By using an vertical deformation model, that includes both components, we can explain GPS-measured deformation occurring in the Arctic. Our results show that the present-day Arctic ice loss contribution to vertical deformation is approximately 0.5 to 1 mm y^{-1} in the wider northern region. This exceeds deformation caused by the disappearance of the last ice ages at many coastal regions, including the North Sea region and the North American Atlantic coast. The Arctic present-day ice loss included in the VLM-model equals a global sea level rise of 1.5 mm y^{-1}, which means that 30-80% of the sea level rise caused by Arctic ice loss is mitigated by surface uplift caused by the same ice loss.

1 Introduction

The Arctic region is warming faster than any other region on Earth (Post et al., 2019). Deglaciation of Arctic land-based ice accounts for 70% of all barystatic sea level change (Abram et al., 2019) and has increased the sea level rise by 0.035 mm y^{-2} over the last three decades (Nerem et al., 2018). From 2003 to 2015 the Greenland Ice Sheet and adjoining glaciers produced 1 cm of sea level rise, while the contribution of other Arctic glaciers was 0.8 cm (Zemp et al., 2019).

Change in ice loading not only contributes to sea level change, but also alters Earth's solid surface, which commonly is called Vertical Land Motion (VLM). Accurate quantification of VLM and its causes is key for understanding relative sea level (RSL) (Watson et al., 2015; Wöppelmann & Marcos, 2016), which is the sea level change measured by tide gauges (TG).

VLM can be modeled for a given ice loading by employing the sea level equation of Farrell and Clark (1976) or in its elastic adaptation by Clark and Lingle (1977). viscoelastic relaxation of Earth's surface caused by past ice loading changes, also known as Glacial Isostatic Adjustment (GIA), has historically been the most important component of VLM (Farrell & Clark, 1976; Tushingham & Peltier, 1991; Milne & Mitrovica, 1998; Peltier et al., 2015) and is often assumed to be the key contributor to VLM in sea level studies from tide gauges (Church & White, 2011; Jevrejeva et al., 2014). This assumption is in particular inadequate in the Arctic region (Henry et al., 2012), where the change in present-day ice loading (PDIL) is extensive and the corresponding VLM equals GIA in order of magnitude.

Here we quantified the VLM resulting from changes in PDIL from 2003-2015 in the wider Arctic (the region above 50 deg latitude). After considering GIA, ocean loading, rotational feedback (RF) and non-secular geocenter motion, the total VLM uplift is predicted and compared to GNSS-measured VLM at 54 locations.

In recent years, data products from the Gravity Recovery And Climate Experiment (GRACE) satellite mission have been used to estimate PDIL and the corresponding VLM (Adhikari et al., 2016; Riva et al., 2017; Frederikse et al., 2019). While this is a reasonable estimate for regional and global VLM-patterns, the native resolution of GRACE is around 300-km half width at the equator (Tapley et al., 2004) which is insufficient for estimating VLM close to glaciers and ice sheets.

Here we combined a high-resolution (2x2 km) ice mass balance data in the Arctic to compute VLM from PDIL (VLM_{PDIL}), with a resolution that is suitable in both the near- and far-field in the Arctic region.

2 Data and Method

The solid-earth response of PDIL is assumed to be purely elastic and the viscoelastic response is considered to be negligible. This includes the ongoing solid-earth response from modern changes in ice loading prior to 2003, which is not considered in the applied GIA-models. In particular, the deglaciation after the Little Ice Age (LIA) that ended in the 19th century can create a GIA-like viscoelastic response that is not captured by GIA-models (Simon et al., 2018).

Contrary to studies using GRACE-measurements for ice loading, we used mass balance data from glaciers (Marzeion et al., 2012; Pfeffer et al., 2014; Zemp et al., 2019) that were transformed into an ice-elevation model (details in Supporting Information S1) with a 2x2 km spatial resolution by applying a mass balance distribution function and assuming a uniform density of 917 kg m^{-3}. Glaciers were combined with elevation changes from Greenland (updated version of the data from S. A. Khan et al. (2013), see section 2.1).

Separately, Antarctic yearly mass equivalent surface elevation changes for 2003-2015 from Schröder et al. (2019) were used to estimate the present-day Antarctic contribution to VLM in the Arctic.

The elastic VLM (VLM_{PDIL}) was computed with REAR (Regional Elastic Rebound calculator) (Melini et al., 2014, 2015). REAR calculates the elastic response to a disc load (Farrell, 1972) and assumes a solid, non-rotating and isotropic earth. Load Deformation Constants (LDC's) used for solving the Green's Functions were obtained from the REF6371 model by Kustowski et al. (2007) which is similar to the PREM-model (Dziewonski & Anderson, 1981), however the REF6371 model includes more realistic seismic properties of the crust (Kustowski et al., 2007). The LDC's from REAR are by default defined with respect to Earth's center of mass (CM-frame), which is consistent with the GIA-model of Caron et al. (2018). The ICE6G_D-model of Peltier et al. (2018) is referenced to the center of solid-earth (CE). The surface loading change included in GIA is however prehistoric and current viscoelastic mass transport induces a negligible CM-CE motion (King et al., 2012; Argus et al., 2014).

Rotational feedback (Milne & Mitrovica, 1998) was added to the elastic VLM-model by using equation 1 and 2 from King and Watson (2014). Position changes of the pole (x_p,y_p) for ITRF2008 are available from IERS (Bizouard & Gambis, 2009). Since REAR is not solving the sea level equation (Farrell & Clark, 1976; Milne et al., 1999), it does not account for the effect of extra water mass added to the oceans because of PDIL, which results in a measurable deformation (van Dam et al., 2012; Santamaría-Gómez & Mémin, 2015). Non-tidal ocean loading (NOL) is predicted by estimating the elastic deformation of ocean bottom pressure (OBP, shown in Figure S2.2 in Supporting Information) grids from the latest version of Estimating the Circulation and Climate of the Ocean (ECCO) project (version 4, release 4) (Fukumori et al., 2019; Forget et al., 2015).

GNSS data are referenced to ITRF2008 (Altamimi et al., 2011), which has secular trends in CM, while non-secular trends of ITRF are in center of figure (CF) (Dong et al., 2003). Therefore, when studying ongoing mass changes, we need to make a ITRF to CM translation by considering non-linear geocenter motion (GCM). GCM is obtained from first-order Stokes coefficients from 2002-2019 provided by Sun et al. (2016) available from `https://grace.jpl.nasa.gov/data/get-data/geocenter/`, which are detrended in order to make the ITRF to CM translation. An VLM-model (eq. 2) is created that is comparable to adjusted GNSS-measured VLM (eq. 3):

$$\mathrm{VLM}^{CM}_{ela} = \mathrm{VLM}^{CM}_{PDIL} + \mathrm{VLM}^{CM}_{NOL} + \mathrm{VLM}_{rot} \quad (1)$$

$$\mathrm{VLM}^{CM}_{model} = \mathrm{VLM}^{CM}_{GIA} + \mathrm{VLM}^{CM}_{ela} \quad (2)$$

$$\mathrm{VLM}^{CM}_{GNSS} = \mathrm{VLM}^{ITRF}_{GNSS} - \mathrm{GCM}^{ITRF-CM} \quad (3)$$

Where VLM^{CM}_{ela} is the elastic VLM-model, VLM^{CM}_{GIA} represents VLM caused by GIA, VLM_{rot} indicates the deformation caused by rotational feedback and VLM_{NOL} is the contribution from NOL. VLM^{CM}_{GNSS} is GNSS-measured VLM after non-secular geocenter motion is removed. Average VLM-rates from 2003-2015 are shown in Figure 1, while $\mathrm{VLM}^{CM}_{model}$ is evaluated against VLM^{CM}_{GNSS} in section 3. The contribution of Antarctic ice loading (including Southern Hemisphere glaciers) is shown together with the contribution of VLM^{CM}_{NOL} and VLM_{rot} in Figure S2.1 in Supporting Information.

Caron2018 (Caron et al., 2018) is the default GIA-model throughout this study. Caron2018 used 128000 forward models of different 1D Earth rheologies and ice elevation histories to create a statistical distribution of the GIA signal representative of long term GNSS observations and relative sea level records from paleo RSL indicators. In some parts of the analysis, we include the ICE-6G_D GIA model of Peltier et al. (2018), since large discrepancies between the $\mathrm{VLM}^{CM}_{model}$ and VLM^{CM}_{GNSS} can be explained by the choice

of GIA-model. Recent study using an ensemble of simulations with 3D-earth rheologies (Li et al., 2020), seems to favor the results GIA-rates of Peltier et al. (2018).

Though we limited this study to the wider Arctic area, both the elastic VLM-components and GIA have a global impact. However, if we neglect the VLM caused by Antarctica, the VLM-signal from PDIL is relatively small ($< \pm 0.2$ mm y^{-1}) outside the region of this study. The estimated uncertainty of the $\mathrm{VLM}^{CM}_{model}$ originates from the standard uncertainty of the ice model combined with a 10% uncertainty that represents the uncertainity from the REF6371 earth model (Wang et al., 2012).

While the ice model of Greenland is well constrained, mass balance errors of individual glaciers from the glacial model can be large (several times the glacial signal). We therefore divide the glacial model into 25x25 km tiles, which reduces the uncertainty significantly, but might also introduce unrealistic low uncertainty in areas with large glacial signals or where glaciers are poorly constrained. Glaciers are, however, still the largest source of regional uncertainty (see Supporting Information Figure S3.1.). The Caron2018 GIA-model has standard uncertainty estimates included in the product, while there is no uncertainty estimate associated with the ICE6G-model. Uncertainties of geocenter motion from Sun et al. (2016) contributes to the GNSS-uncertainty estimate. The spatial distribution of the uncertainty estimates are shown in Supporting Information Figure S3.1.

2.1 Ice Loading

The main component of VLM_{PDIL} is the ice loading model and consist of a combined water equivalent elevation model from Greenland and mass balance estimates from glaciers. Rate of elevation change is shown in Supporting Information Figure S1.1. While only Northern Hemisphere ice history is created with high resolution, changes of Antarctic and Southern Hemisphere ice loading is computed on a 0.5x0.5° grid and included in the computation of VLM^{CM}_{PDIL}. The low resolution does not have any impact on VLM in the Arctic. The total mass loss of the Southern Hemisphere is 140 Gt y^{-1}, equivalent of to 0.38 mm y^{-1} barystatic sea level rise.

2.1.1 Glaciers

A total of 62,000 individual glaciers from the Randolph Glacier Inventory (RGI 6.0) (Pfeffer et al., 2014; RGI Consortium, 2017) located in North America, Russia, Scandinavia (incl. Svalbard) and Iceland have been included in this study. Mass loss from included glaciers accounts for 95 % of the registered glacial mass loss of the Northern Hemisphere and constitutes 80% of the global glacial mass loss (Zemp et al., 2019).

Mass change estimates for each glacier were estimated using an updated version of a model reported in Marzeion et al. (2012). Direct mass balance observations (Zemp et al., 2019) were used to calibrate and validate the glacier model. The glacier model translates information about atmospheric conditions into glacier mass change, while considering various feedback mechanisms that occur between glacier mass balance and glacier geometry. Glacial mass balance was combined with a distribution function to calculate glacier-wide surface elevation change. This ensured that the lower parts of glaciers are thinning, while upper parts experience small elevation gains. This 'slope steepening' of glaciers is characteristic of glaciers of many regions (Nuth et al., 2010; Foresta et al., 2016; Ciracì et al., 2018) and is assumed to apply to all glaciers included in this study (see Supporting Information S1 for an enhanced description of glacial elevation change).

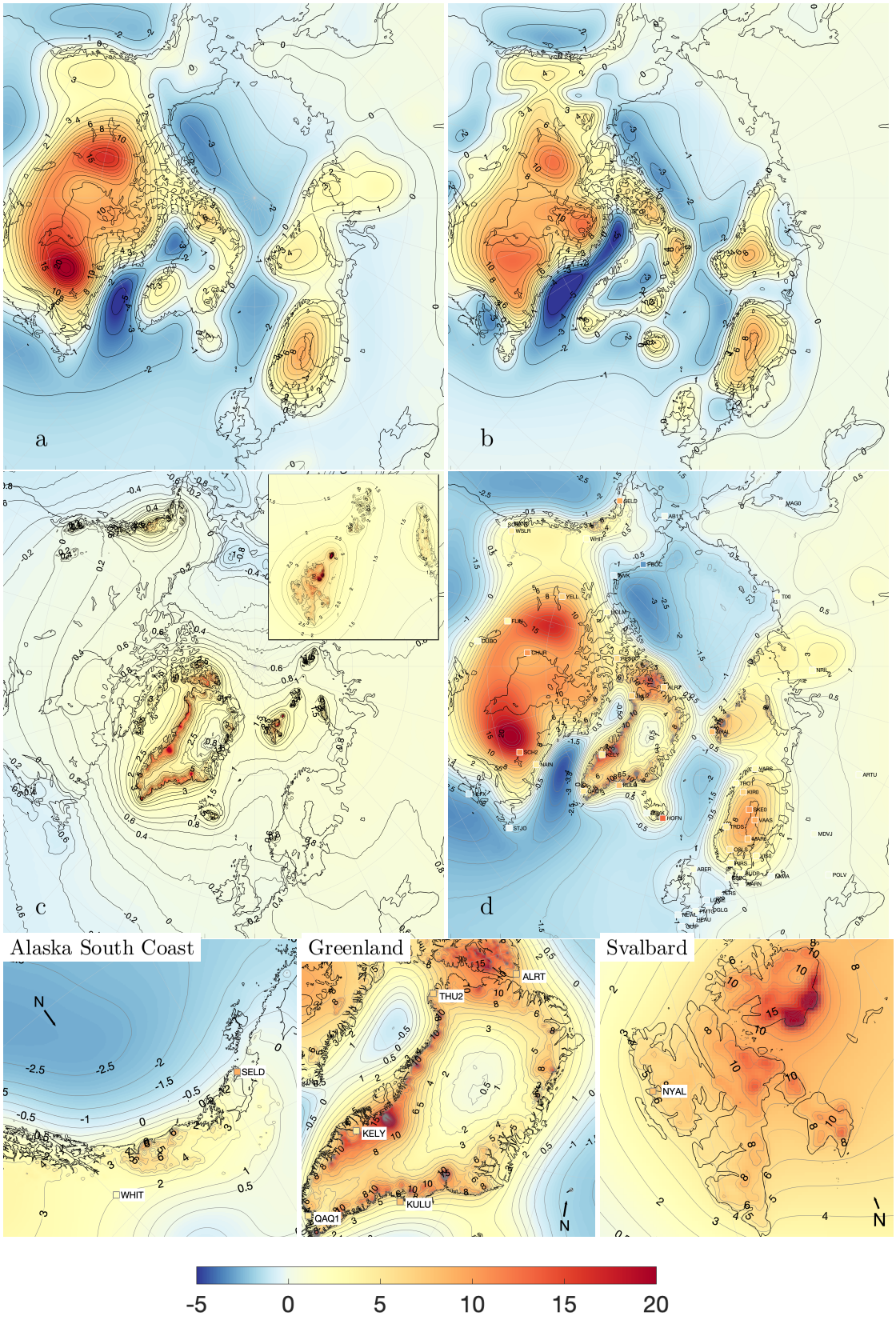

Figure 1. Average VLM-rates (mm y^{-1}) for 2003-2015 using the GIA-model of Caron2018(Caron et al., 2018) (a) and ICE6G_D (Peltier et al., 2018) (b). Modeled elastic rebound from contemporary land ice loss (including ocean loading and corrected for rotational feedback) (VLM_{ela}^{CM}) with enlargement of Svalbard is displayed in (c). The total VLM-model, VLM_{model}^{CM}, (a + c), with the square color representing average GNSS-determined VLM-rates (d). Enlargements of the south coast of Alaska, Greenland and Svalbard of (d) is shown in the bottom three panels. Spatial distribution of uncertainity estimates of (a),(c) and (d) are shown in Supporting Information Figure S3.1.

2.1.2 Greenland

Glacial ice history was combined with elevation change of the Greenland Ice Sheet and adjoining glaciers. We estimated the rate of ice volume change from 2003-2015 by using altimeter surveys from NASA's ATM flights (Krabill, 2011) that took place between 2003 and 2015 supplemented with high-resolution Ice, Cloud and land Elevation Satellite (ICESat) data (Zwally et al., 2011) from 2003-2009 and CryoSat-2 data from 2011-2015 (Helm et al., 2014). Our procedure for deriving ice surface elevation changes has previously been described in detail by S. A. Khan et al. (2013) and is similar to the method used by, e.g. Ewert et al. (2012); Smith et al. (2009) and Kjeldsen et al. (2013). We used the observed ice elevation change rates to interpolate (using collocation) ice elevation changes onto the 2x2 km spatial grid.

2.2 GNSS data

Timeseries of vertical deformation and uncertainty estimates of 54 GNSS-sites from the sixth release of the consortium led by University of La Rochelle (ULR-6) (Santamaría-Gómez et al., 2017) were used. A detailed map and timeseries of all GNSS-sites are shown in Supporting Information Figure S4.1 and Figure S5.1. ULR-6 includes 125 GNSS-sites located within the area of interest, but only GNSS-sites with data for at least 120 of 156 months from 2003 to 2015 known not to be impacted by human activities were selected. One GNSS site was selected based on lowest observed standard deviation of timeseries when multiple GNSS sites were located within 100 km of each other. Nome (AT11), Esbjerg City (ESBC) and Magadan (MAG0) were exempted from the temporal selection criteria, because of their location which has a special interest for interpretation.

Annual averages and combined uncertainties were calculated for each GNSS-site from the vertical component and standard uncertainty included in URL-6a. Hereafter, the linear trend was calculated for the years available between 2003 and 2015.

3 Evaluating the VLM model

From Figure 1 it is seen that the VLM-model is dominated by the pattern of the GIA-model, with rates above 20 mm y^{-1} east of the Hudson Bay and another local maximum of over 15 mm y^{-1} in north-west Canada. The elastic rebound is evident in most of the Arctic, particular in Greenland with large areas exceeding 10 mm y^{-1}, with maximum value at Jakobshavn Isbræ (69.1N, 49.5W) with an average modeled uplift of 40 mm y^{-1}. Large areas around Svalbard and Alaska have modeled elastic VLM-rates of more than 8 mm y^{-1}. The uncertainty is significantly larger in glaciated regions than in the far field (see Figure 3.1 in Supporting Information).

Most depression zones are found over the ocean, with the Beaufort Sea and Labrador Sea subsiding with 2 mm y^{-1} and the Norwegian Sea with 1.5 mm y^{-1}. Subsiding coastal areas are found in North America, where Nova Scotia and most of the US east- and west coast subsides with more than 1 mm y^{-1}, while smaller subsidence (0.0 - 0.5 mm y^{-1}) is found in Northern Europe along the North Sea and Atlantic coastlines. From Figure 1 we see that most subsiding areas are caused by GIA.

Figure 2 shows that $\mathrm{VLM}^{CM}_{model}$ predicts VLM within the range of VLM^{CM}_{GNSS} at 46 of 54 GNSS locations considered. The mean absolute error (MAE) for the 54 GNSS-sites was 1.45 mm y^{-1} (1.33 mm y^{-1} for ICE6G_D), which was 0.53 mm y^{-1} better than MAE from only VLM_{GIA}. For less than half (27) of the 54 GNSS-sites considered was the VLM-model with Caron2018 outperforming the ICE6G_D GIA model.

Barystatic sea level change for VLM_{PDIL} was 1.5 mm y^{-1} (ice loss-mediated global average sea level change (excl. Antarctica)). As shown in Figure 2, elastic VLM values

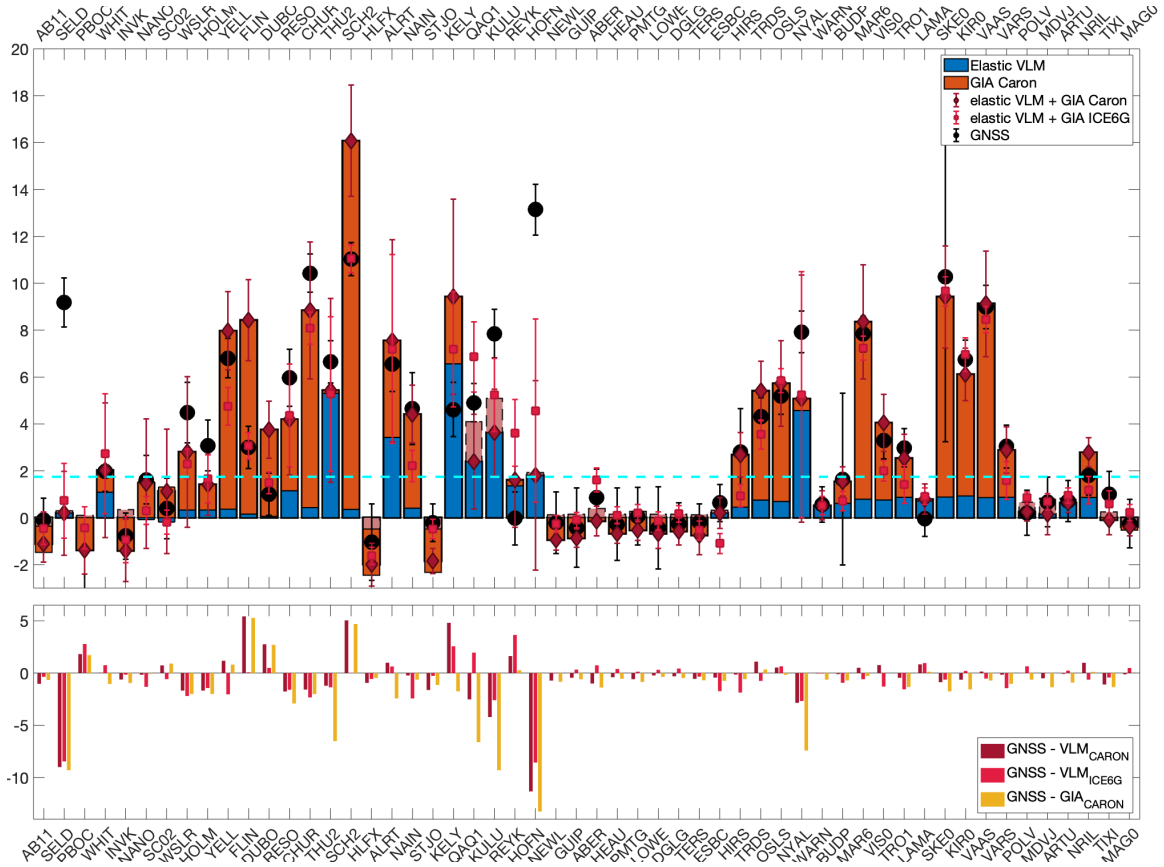

Figure 2. Average VLM change (mm y^{-1}) from 2003-2015 determined using the elastic VLM model (blue) and GIA (red) at the 54 GNSS-sites from Figure 1 and Supporting Information Figure S4.1 are shown (top). Sites are listed from most west (left) to most east (right). The dotted-cyan line indicates the average barystatic sea level rise ($\sim$ 1.85 mm y^{-1}) from the ice loss used in this study. The total modeled VLM uncertainty are indicated with red error bars and the GNSS-measured VLM is shown with black errorbars. Light red indicates locations in which GIA is negative and overlaps the positive elastic VLM. Residuals between GNSS-measured VLM (VLM^{CM}_{GNSS}) and the VLM-model (VLM^{CM}_{model}) (blue) and GIA (red) are shown (bottom). The average of the absolute residuals (equivalent to mean absolute error) are 1.45 mm y^{-1} and 1.98 mm y^{-1} respectively. All values used in this figure are included within Table S4.1 in Supporting Information.

between 0.5-1 mm y^{-1} were observed at many far field GNSS-sites in this study and partly mitigated the barystatic sea level change.

The effect of non-cryospheric mass change is not included in VLM^{CM}_{model}. In particular terrestial water storage (TWS) causes a small uplift over large parts of North America (0.4 - 0.8 mm y^{-1}) and North-Central Siberia (0.2 - 0.4 mm y^{-1}), while TWS is causing a subsidence in most of Scandinavia of 0.2 - 0.4 mm y^{-1} (Frederikse et al., 2019).

Glaciated regions show particularly large residuals between the predicted VLM and VLM measured by GNSS (Figure 3), but also exhibit the largest associated uncertainties of GNSS estimates. Predicted VLM at 26 of 54 GNSS-sites are within a range of 0.75 mm y^{-1} to GNSS (the three center bins in the right panel of Figure 3). The VLM-model has a tendency to underestimate the GNSS-measured VLM, which is evident in North

America and Europe. From figure 2, we see that a different choice of GIA-model would yield enhance the accuracy of the VLM-model in these regions. The most significant discrepancies between measured and predicted VLM is explained in the following for every region.

3.1 North America

Alaska is located in the transition zone between GIA-uplift and GIA-subsidence, which is also reflected in the GNSS-rates. Nome (AB11), Prudhoe Bay (PBOC) and Inuvik (INVK) all experience an GIA-subsidence that is larger than the elastic uplift. While Nome and INVK are well matched with VLM^{CM}_{GNSS}, PBUC has the largest measured subsidence (3.2±1.6 mm y^{-1}), while $\mathrm{VLM}^{CM}_{model}$ only shows a subsidence of 1.4±1.4 mm y^{-1}. An extraordinary subsidence is likely caused by oil extraction in the Prudhoe Bay area.

The Alaska south coast accounts for more than 25% of the total glacial melt and is naturally dominated by elastic uplift while the uplift from GIA is below 1 mm yr^{-1}. Seldovia (SELD) shows an observed average rate of 9.2 ± 1.0 mm yr^{-1}, while VLM^{CM}_{ela} is only 0.3 ± 1.6 mm yr^{-1} and GIA-rate -0.1 ± 0.8 mm yr^{-1}. Seldovia is located on the Kenai Peninsula close to the Kenai Fjords, which experienced an accelerated glacial ice loss in the 20th century (VanLooy et al., 2006). This is, however, not enough to explain the increased measured uplift. GIA-estimates vary in the region (Larsen et al., 2005; Hu & Freymueller, 2019), but is not more than around 1-2 mm yr^{-1}. The residual seems explained by a postseismic signal following the Prince Willam Sound Earthquake in 1964 (Cohen & Freymueller, 2001; Huang et al., 2020) which is still causing a local uplift on this side of the peninsula. The residuals estimates this effect to be 9.0 mm yr^{-1} from 2003-2015, which is slightly less than the value found by Cohen and Freymueller (2001) of 9.3 mm yr^{-1} from 1994-2001. This rebound is expected to decay further over time, but will still be relevant for decades to come (Cohen & Freymueller, 2001; Huang et al., 2020).

Discrepancies between GNSS and modeled VLM in central North America, are likely due to uncertain GIA-estimates. A significantly better alignment between $\mathrm{VLM}^{CM}_{model}$ and GNSS is reached if Caron2018 is replaced by ICE-6G. The GIA-overestimate of Caron2018 in North America has been demonstrated by other studies (Schumacher et al., 2018; Frederikse et al., 2019) and is likely caused by large differences between estimated viscosity properties of paleo-RSL indicators and GNSS in North America (Caron et al., 2018). TWS-change causes a small uplift below 1 mm y^{-1} over large parts of North America (Frederikse et al., 2019), which enhances the difference between $\mathrm{VLM}^{CM}_{model}$ and VLM^{CM}_{GNSS}.

3.2 Greenland

Four GNSS-sites on Greenland and Alert (ALRT) on Baffin Island measure a significant elastic uplift. While Pittuffik/Thule (THU2) and ALRT agree with $\mathrm{VLM}^{CM}_{model}$, Kangerlussuaq (KELY) is overestimated quite a bit and $\mathrm{VLM}^{CM}_{model}$ at Kulusuk (KULU) and Qaqortoq (QAQ1) is below VLM^{CM}_{GNSS}. GIA on Greenland is poorly constrained in Caron2018, which can exaggerate VLM-estimates from GIA. A low-viscosity zone stretching from Iceland beneath Southeast Greenland (S. A. Khan et al., 2016) enables a significant viscoelastic rebound caused by ice loss since LIA (S. Khan et al., 2014).

3.3 Iceland

The two GNSS-sites on Iceland show very different uplift rates of 0.0 ± 1.1 mm yr^{-1} in Reykjavik (REYK) and 13.1 ± 1.1 mm yr^{-1} at Hoefn (HOFN) at the southern edge of the largest ice cap on Iceland, Vatnajökull. $\mathrm{VLM}^{CM}_{model}$ overestimates the rebound in Reykjavik while it largely underestimates it at Hoefn. Similar to south east Greenland a soft viscoelastic mantle layer (Fleming et al., 2007) creates a present-day viscoelas-

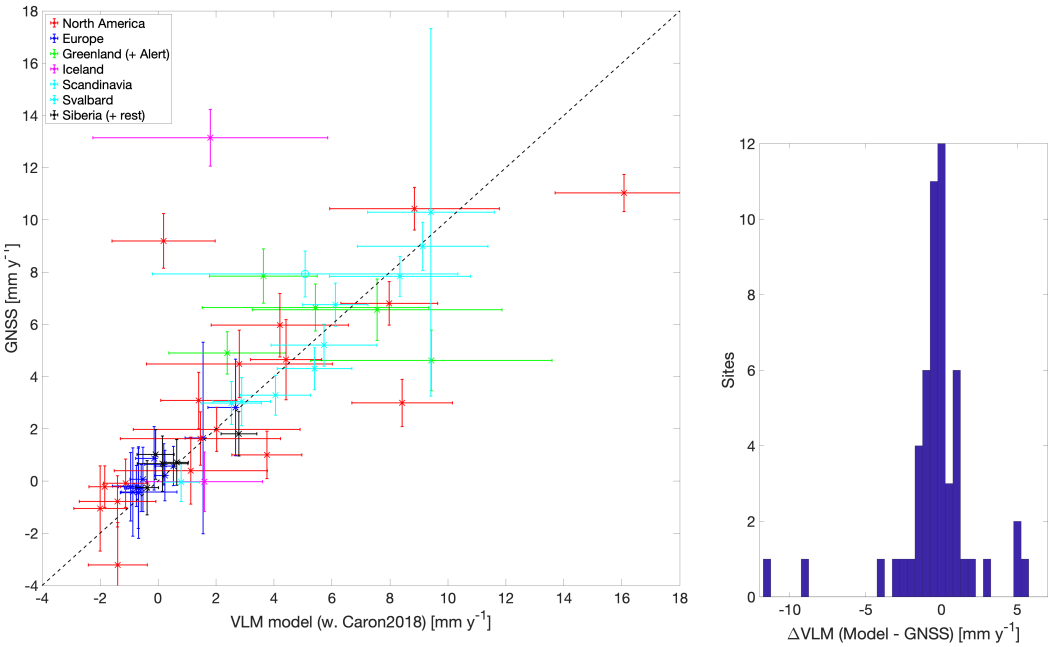

Figure 3. VLM^{CM}_{GNSS} versus $\mathrm{VLM}^{CM}_{model}$ including associated uncertainties for all GNSS-sites. If the cross is above the dashed line the $\mathrm{VLM}^{CM}_{model}$ underestimate compared to VLM^{CM}_{GNSS}. A histogram of the difference between $\mathrm{VLM}^{CM}_{model}$ and VLM^{CM}_{GNSS} (in intervals of 0.5 mm y^{-1}) is shown in the right panel.

tic signal that is much larger than the ones predicted by the GIA-model. A thin crust, also means that the uplift decreases faster with distance to the glacier (Fleming et al., 2007; Sørensen et al., 2017), which could explain why Reykjavik shows little vertical deformation despite being less than 100 km from glaciers.

3.4 Svalbard

The majority of land in Svalbard is covered with ice, and VLM is highly affected by ongoing ice-mass changes. At Ny Ålesund (NYAL), located on the west coast, $\mathrm{VLM}^{CM}_{model}$ is dominated by VLM^{CM}_{ela} of 4.6 ± 5.3 mm yr^{-1} and VLM_{GIA} of 0.5± 0.4 mm yr^{-1}. In total this is 2.6 mm yr^{-1} short of observed VLM^{CM}_{GNSS}. While ICE6G and Caron2018 agree within ± 0.2 mm yr^{-1}, more focused, but older studies predict a slightly higher GIA contribution of around 1.5 mm yr^{-1} (Sato et al., 2006; Kierulf et al., 2009). Also on Svalbard, significant post-LIA deglaciation (Grove, 2001) is likely contributing to an ongoing uplift (Mémin et al., 2014; Rajner, 2018). The effect is still uncertain (Rajner, 2018) and Mémin et al. (2014) estimated the post-LIA rebound to be 2-5 mm yr^{-1} in the beginning of 21st century, which explains the residual of 2.9 mm yr^{-1}.

3.5 Northern Europe and Scandinavia

GIA is dominating the vertical deformation in Scandinavia (Figure 1). Even though small glaciers exist in Norway, the elastic effect is very local and has almost negligible effect on the GNSS-sites in this study. However, VLM^{CM}_{ela} is still significant, and improves the correlation with observed VLM^{CM}_{GNSS} compared to a GIA-only model. This becomes more prominent for GNSS-sites in areas, where GIA is less dominant. Esbjerg (ESBC) on the west coast of Denmark is close to the zero-line of Caron2018 (-0.1 mm yr^{-1}), but

is still measuring an uplift of about 0.6 mm yr^{-1}, which is partly explained by an elastic uplift of 0.3 mm yr^{-1}.

In Northern Europe, Caron2018 models a subsidence, which is mitigated by an elastic uplift caused by present day ice melt. Generally, VLM^{CM}_{model} is consistent with VLM^{CM}_{GNSS} in the North Sea and the Baltic region, while an VLM-model using ICE6G is at odds at several locations.

3.6 Siberia

Only a few available GNSS measurements exist in eastern Europe and Siberia. Caron2018 is also challenged by limited resources of paleo sea-level records, which makes the GIA-model more dependent on the existing GNSS-records. It is commonly anticipated that Siberia had little or no ice during the last glacial cycle (Whitehouse et al., 2007), except north central Siberia and in the shallow waters in the Barents Sea between Svalbard and Novaya Zemlya (Root et al., 2015).

Also VLM^{CM}_{ela} is generally smaller than around 1 mm yr^{-1}. While the VLM^{CM}_{GNSS} is within the uncertainty-range of VLM^{CM}_{model} for the Siberian GNSS-sites (Arti (ARTU), Norilsk (NRIL), Tixi (TIXI) and Magadan (MAG0)), a GIA-only model has a better fit to the GNSS measurements which is likely due to increased dependence on GNSS in Caron2018.

4 Discussion and Conclusion

VLM of the wider Arctic region occurs mainly as a result GIA and elastic VLM. Though this study is limited to the area surrounding the Arctic, VLM caused by deglaciation produces global effects (Riva et al., 2017; Kleinherenbrink et al., 2018; Frederikse et al., 2019). By combining deglaciation that occurred since the last glacial maximum (GIA) and present-day changes in land ice (elastic VLM), the VLM-model provides a realistic estimate of VLM in the Arctic. By evaluating 54 GNSS-sites using a combined VLM-model, we found that measured uplift of GNSS can be explained by either prehistoric or present-day changes in land ice volume. For 46 of the GNSS sites, residuals between GNSS-measured VLM values and the VLM-model were smaller than associated uncertainties.

The 2x2-km spatial resolution of the used ice-model was much higher than similar gravimetric satellite observations from GRACE (Adhikari et al., 2019). Increased spatial resolution improves VLM predictions accuracy in glaciated regions significantly, as local elastic deformation tends to dominate regional averages observed via GRACE (Frederikse et al., 2019). A VLM-model to GNSS comparison also indicated that the VLM-model was inadequate in some regions due to local causes of VLM that were not included in the VLM-model, such as subsurface properties, past seismic activity or 19–20th century ice-loss (Mémin et al., 2014; Rajner, 2018).

In non-glaciated areas, GNSS measurements generally agree well with the VLM-model. Contour lines shown in Figure 1, indicate that elastic uplift is centered around Greenland, except when close to other glaciated regions (e.g. Alaska and Svalbard), despite the fact that total Arctic glaciers mass loss is comparable with that of Greenland. Hence, the elastic uplift caused by ice melt in Greenland significantly affects the entire wider Arctic region, which includes coastlines of Northern Europe and the North American Atlantic.

Riva et al. (2017) showed that elastic uplift caused by ice loss in Greenland causes a subsidence in the Southern Hemisphere. Similar, it is assumed that Antarctic ice loss will cause a subsidence in the Northern Hemisphere. Antarctic ice loss averaged 105 Gt y^{-1} from 2003-2015 (Schröder et al., 2019), and resulted in an elastic subsidence of less than 0.1 mm y^{-1} in the Northern Hemisphere. Since ice loss has the potential to occur

rapidly in the future (Hay et al., 2017; Edwards et al., 2019), VLM caused by Antarctic ice loss will be increasingly significant, and may be important for future coastal sea level projections in the Northern Hemisphere.

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