Response to Reviewer 1.

We thank the reviewer for his or her detailed comments on our manuscript. Below, we respond to the comments in turn.

Comment 1: Title: I have four issues, (1) Scandinavia is part of northern Europe but you miss to mention the Barents Sea, which is largely discussed in your manuscript, (2) abbreviations should not be used in the title except they are well known, (3) although I understand that you want to distinguish the GIA signal you investigate from current climate change-induced GIA signals, "long-term", i.e. its definition, is not the best word to me (see below), and (4) you estimate your signal also with help of GIA models. My suggestion would be: "The glacial isostatic adjustment signal in northern Europe, the British Isles and the Barents Sea estimated from satellite positioning and space gravimetry data, and geophysical modelling".

Response 1: We have modified the title to take into consideration several of the points the reviewer raises. We have removed 'Scandinavia' and 'long-term' from the title and replaced 'GIA' with 'glacial isostatic adjustment'. We agree in general that abbreviations should be introduced upon first usage, however, we think that both 'GPS' and 'GRACE' are well known and they both appear quite often as abbreviations in titles in similar literature. However, we change the title to refer to 'geodetic observations and geophysical models' – hopefully this is an acceptable compromise.

Comment 2: L11/L29-31: it seems "long-term" refers to "ice sheets: : : during the last glaciation" in your introductory lines 29-31. However, parts of this signal can result from previous glaciations, see e.g., Johnston & Lambeck (1999) and Root et al. (2015). This should be either specified or the word "long-term" be dropped.

Response 2: On line 11 in the abstract, and in the introductory paragraph, "long-term" has been removed. We have rewritten a couple of the sentences in the first paragraph to try to clarify the distinction between what we originally termed "long-term" (or paleo GIA) and GIA deformations from shorter-term/more recent processes. We were trying to make the distinction that although we are interested here in the present-day GIA response, that the signal has nothing to do with 'present-day' cryospheric change, such as climate-change enhanced mass losses of ice sheets and glaciers.

Comment 3: L12: suggest change GPS to GNSS and introduce abbreviation; GPS is one of the GNSSs like Galileo, GLONASS or BeiDou. You can specify in the main text that both Kierulf et al. and Blewitt et al. use GPS only.

Response 3: We have replaced GPS here with GNSS and defined the abbreviation. Rather than make a very long first sentence we have added a second sentence where the abbreviations are given explicitly.

Comment 4: L12: explain GRACE abbreviation

Response 4: We have also defined the GRACE abbreviation at first usage in the abstract. See also Response 3.

Comment 5: L12: delete "Scandinavia," (or do you mean northern Central Europe? – but my suggestion would be simply "northern Europe" which includes Scandinavia)

Response 5: Ok, 'Scandinavia' has been removed.

Comment 6: Introduction, i.e. L29-40: this is a rather short introduction that combines a paragraph without any references to a paragraph with references but already specifically focussed on the paper's topic. I suggest mention a few "early" general studies on GIA in the first paragraph, e.g. Peltier & Andrews (1976) and Wu & Peltier (1982). Otherwise it sounds that GIA should be well known for the reader. A reference for the 1 cm/a and the location should be added. I am aware that GIA in Fennoscandia has been extensively studied so that it may be hard to find a good balance in summarizing previous work, however, there are a few review books/papers/reports that summarize many works (Whitehouse, 2009; Ekman, 2010; Steffen & Wu, 2011). These should be the backbones for another paragraph between the two on a brief overview of GIA (investigations) in Fennoscandia.

Response 6: Regarding the overall structure: as a topic, GIA should be reasonably well known to the reader and we feel it is reasonable to have one general introduction paragraph followed by a second paragraph more focussed on our specific interests.

As for the references, we have added a couple of general references which were missing from the paragraph. We have also added Lidberg et al. (2010) and Kierulf et al. (2014) as two of the more recent references for the ~1 cm/yr of maximum uplift around the Gulf of Bothnia (which is already specified as the location, unless by location the GNSS station name is meant, but that might be overly specific for an introduction paragraph). As suggested, we add a paragraph in between the first and second paragraphs which summarizes some forward GIA modelling studies in the region, although we reiterate that forward modelling is not the focus of this paper.

Comment 7: L32f: I suggest remove "that are tectonically quiescent". They are thought to be but there was and is more activity than quiescence, see e.g., Lindblom et al. (2015) and Lund et al. (2017).

Response 7: Ok, this phrase is removed.

Comment 8: L43: introduce abbreviations

Response 8: We have explained the abbreviations here.

Comment 9: L50: I miss Müller et al. (2012) in the references, although they call it land uplift model,while mentioning the study by Zhao et al. (2012) does not seem to fit. They used GNSS data for determination of the subsurface structure.

Comment 9: Ok, we added the Müller et al. (2012) reference. We retain the Zhao et al. (2012) reference.

Comment 10: L52: northern "Central" Europe

Response 10: We change this sentence to refer to regions 'south of Scandinavia' and the British Isles, rather than northern or northern central Europe. It is unclear what clarification comes from adding 'central' here as some of the study area extends into the western and eastern parts of northern Europe.

Comment 11: L61f: please add how many velocity results are taken from those two papers, respectively. Did you use all stations from Kierulf et al. (2014)? Note that especially the many in Norway have short time spans and thus their velocities should be used with care. I would have advised to use only those with at least 5 years of observations and your results in Fig. 8 (top) show differences for many Norwegian stations. Might be that these are the newer stations. Also note that Kierulf et al. point to possible neotectonics along the Norwegian coast emerging in the velocities which should be picked up in the discussion/conclusions.

Response 11: We use 459 GPS velocities in total.

The Midas (Blewitt et al. 2016) data fill out the data coverage south of Scandinavia. Here, the data have been filtered to include only those data with time series duration of ≥10 years. The Midas data also have several sites that are located very close to each other. An additional filter is applied where all points that are within a 30 km radius of each other are collected, and the one with the largest number of usable data epochs is selected. The filtering for geography (i.e. south of the Kierulf dataset), time series duration, and spatial proximity to other sites leaves 309 Midas data points.

The remaining 150 velocities come from Kierulf et al. (2014), which is the full dataset provided in their supplementary material. The Kierulf et al. (2014) data (at least in the supplement from that paper) does not provide the length of the time series for the stations, so these data were not filtered (by us) for times series length. In Kierulf et al. (2014) and an earlier reference therein (Kierulf et al., Journal of Geodesy, 2012, doi:10.1007/s00190-012-0603-2), the authors indicate that although at least a 5 year time series would yield better precision, that they have opted to include data with time series durations of at least 3 years. If the time series duration information were provided we agree it would have been nice to try a cut-off of five years for this data set. Presumably the shorter time series data have larger associated uncertainties which will at least weight them less heavily in the solution.

In summary, the Kierulf et al. (2014) data have time series lengths of at least 3 years, and the Midas data that we have used have time series lengths of at least 10 years. We have added text that clarifies this in the first paragraph of the GPS section. We also add in the discussion/conclusion section a comment about the possible neotectonic signal in Norway mentioned by Kierulf et al. (2014).

Comment 12: Figure 1: the LGM margin is not correct in Denmark, Germany and Poland when compared to Figure 1 in Hughes et al. (2015); also mention that Iceland was glaciated but ice extent is not shown (or cut figure)

Response 12: Ok, we have changed the LGM margin in Figures 1 and 3 to be that of the 21 ka margin from Hughes et al. (2016), which indeed has a slightly different boundary across Denmark (the difference gets harder to distinguish across Germany and Poland). We also add to the caption that ice extent is not shown on Iceland.

Comment 13: L80: Please provide an overview of the 31 common sites and their values. Which station shows the large difference?

Response 13: We include a figure in the appendix that plots the 31 common sites. The site with the large difference is 'HONS' Honningsvaag in northern Norway. The values at station 'KOSG' at Kootwijk in the central Netherlands are also not the same within their uncertainties, although the difference there is smaller (0.194 mm/yr discrepant).

Comment 14: L82: Which uncertainties from Kierulf et al. (2014) did you use? The ones from GAMIT/GLOBK are indeed very low but the authors also provide uncertainties from the time series analysis using CATS where a combination of white noise and flicker noise was assumed. The latter should be preferred in a modelling analysis.

Response 14: It was indeed the latter uncertainties that were used (from the CATS analysis, so combination of white noise and flicker noise). This has been specified in the text.

Comment 15: Section 2.2: Did you add the degree-1 estimates for GRACE?

Response 15: We compute the trends in the CM frame. The GRACE data are already in the CM frame, so degree 1 coefficients are not necessary.

Comment 16: L94: There are quite large uncertainties in the higher degrees, especially from degree 60 and higher. Does the Wiener filter leave high-degree signals at all? If not much is left your spatial resolution is much lower.

Response 16: It is possible that the filter has removed some of the GIA signal, particularly at higher orders where there is more noise; the effective resolution is typically around 300 km (Siemens et al., 2013). We have added a sentence in the text here.

Siemes, C., Ditmar, P., Riva, R.E.M., Slobbe, D.C., Liu, X.L., & Hashemi Farahani, H. (2013). Estimation of mass change trends in the Earth's system on the basis of GRACE satellite data, with application to Greenland. Journal of Geodesy, 87(1), 69-87, doi:10.1007/s00190-012-0580-5.

Comment 17: L98: What about the aliasing effects from tides, see e.g., Ray et al. (2003)? Were these considered?

Response 17: In the level 2 processing of GRACE, several models remove the effects of (high-frequency) atmosphere and ocean signals on the gravity field estimation. In case of CSR release 5 tidal effects are removed with the use of the GOT4.8 model. Since the launch of GRACE in 2002, the removal of tidal aliasing signals became a standard protocol for all GRACE gravity field products. Therefore we did not include it in the description.

Comment 18: Section 2.3: I partially miss some information! How are the corrections calculated? Are they spatially variable in each region? What method is used to calculate the elastic signal in terms of vertical deformation from a mass balance signals? What time steps are used when acceleration is included? What (earth) model (if any) is used to calculate the elastic signal from current ice melt? You explain the input and the result but all intermediate steps are missing!

Response 18: The corrections are indeed spatially variable - this is clearly illustrated in Figures 2 and 3 which show the corrections in the study area. The time steps for the accelerations are annual. The solid Earth elastic signal is calculated (to degree and order 360) by applying the mass balance loads to a spherically symmetric Earth with PREM elastic parameters, computing a trend via least squares, and summing the regional contributions. We have added a couple of sentences in the section that explain this.

Comment 19: L117: Please add that the model considers anthropogenic changes only (as in the conclusions). I wonder why you do not use a global hydrology model like WGHM, which appears to perform OK in northern Europe (see e.g., Wang et al., 2013).

Response 19: We change the wording to indicate that the model considers anthropogenic changes only. In Wang et al. (2013) WGHM is shown to reproduce the peak hydrology signal well, but relative to the estimated separated signal, WGHM's peak signal is extended over a much larger area. In fact, the separated hydrology signal in this paper looks to be closer to ~0 mm/yr than it does the peak signal in much of the study area. Since hydrology models are in general still quite uncertain, and the separated hydrology signal is estimated to be small for much of the study area, it raises the question of whether improvement is achieved by applying a hydrology model at all. We err to the side of caution by only applying a small hydrological correction.

Comment 20: L119: Please specify the glaciated regions, i.e. in Scandinavia. I suppose you do not consider whole Scandinavia as a glaciated region. I also wonder if Scandinavia has glaciers of 2x2 degrees grid size so that the hydrological model has such large gaps? Jostedal Glacier is the largest with 487 km2 – much smaller than a 2x2 degrees grid.

Response 20: No, we do not consider the whole of Scandinavia as a glaciated region. The glaciers here are along the west coast of Norway, depicted by the white shading in Figure 1 (now indicated in the caption) and we have added a line in the text that indicates this. When we apply the correction here, the signal is filtered to be consistent with degree and order 96, the result being that the contributing signal from these glaciers is very small.

Comment 21: L124ff: Please state in the beginning that you use and discuss published estimates. When reading I had the impression you do all the modelling yourself.

Response 21: We add a line clarifying that the modelling comes from published estimates at the beginning (line 183). It is mentioned again in Table 1.

Comment 22: Table 1: I would like to see the detailed contribution from anthropogenic hydrology and glaciers for each area.

Response 22: This request is a bit unclear, since the contributions from the glaciated regions are already shown in Table 1. We describe in the text which of the summarized corrections we apply. It wouldn't be consistent to show the individual glaciers since when the mass loss signal is filtered to be consistent to degree and order 96 (same as the GRACE data) spatial resolution is lost. The combined contribution for hydrology and glacier mass loss is shown in Figure 2c. At any rate, the anthropogenic hydrology signal is quite small. In the Appendix, we have added a figure that separates the glacier and anthropogenic hydrology signals.

Comment 23: L152: altimetry results are also corrected for a GIA effect from GIA models, and those models might be erroneous. It's a bit chasing your own tail. See also Tamisiea (2011).

Response 23: The altimetry results correct for elevation changes due to GIA with a model, and of course there is always uncertainty associated with the application of any GIA model. Altimetry doesn't only measure cryospheric change, but can do so more reliably than GRACE since altimetry estimates are less sensitive to the GIA correction than GRACE. We have reworded the sentences here to make this clearer.

Comment 24: L162: Please refer to Fig. 2c.

Response 24: It is not appropriate to refer to Figure 2c here. The sentence on lines 161-162 state 'However, applying the averaged ice melt corrections to Svalbard and the Russian Arctic creates a large mass gain signal over these two areas and a relatively smaller signal in the central Barents Sea'. We do not show this effect in Figure 2c (or anywhere else); Figure 2c shows larger mass loss over Svalbard and the Russian Arctic than in the Barents Sea – this is expected because of present-day ice mass loss at those 2 locations. The large mass gain signal that is referred to in this sentence is why the ad-hoc filter (discussed below) was applied to the glacier mass loss correction in this region (otherwise it looks like Svalbard and the Russian Arctic gain mass relative to the Barents Sea).

Comment 25: L171ff: This is the weakest part of your study. You are not satisfied with your results as you expect something different. So, you basically tune your corrections, which are an average of published studies, until you end up with a result that you consider reliable based on your expectations. But what if the expectations are wrong or the real situation is much more different from the expectations. Wouldn't it be better to adjust the uncertainty for GRACE based on the, as it appears, rather problematic corrections? It might be that you end up suggesting the GRACE results as not feasible for usage in the semi-empirical model development due to all these issues and likely large uncertainties which would also allow a large range of suitable a priori models. As a matter of fact, Fig. 6 and Table 2 clearly show that the best result is mainly constrained by GNSS data. In the combined solution D3 the GNSS data are much more weighted than GRACE. The contribution from GRACE is minor and much less reliable. Hence, the question arises if GRACE should be used at all in this study and if this point is one of the main conclusions of this study!

Response 25: This is a fair point, and it is one that we also make ourselves in the paper. It is not ideal to perform a tuning of the corrections to fit with expectations. We feel that it is likely that the real situation fits with our expectations in terms of the sign of the response, although the magnitude is indeed more difficult to constrain (i.e., we think that it is a reasonable to expect that when considering the paleo GIA signal there would be more mass gain in the region of the central Barents Ice Sheet than around its periphery). Note also that the VCE does adjust the uncertainty of the GRACE data by increasing it. It is still worth to try to use GRACE in this study, and its use has suggested future avenues that we could pursue to try to improve the reliability of the GRACE contribution. Also, just because the GRACE signal was problematic over the Barents Sea in this case, does not exclude the possibility that it can provide reliable constraint in other parts of the study area.

Comment 26: L196ff: I have difficulties to acknowledge such large corrections especially due to Greenland mass loss knowing that there is a plate boundary in between where already parts of the GIA signal are altered, see e.g. Klemann et al. (2008). Note that I do not question the value which I assume is based on a simple 1D elastic model. Is the value the upper bound or average of different models tested? What earth structure did you use to calculate the effect? Is it similar to the a priori model that best fits your observations?

Response 26: These are the values that are obtained for the solid Earth response using a 1D spherically layered model. It is an interesting comment that some of the elastic response may be altered across the plate boundary. If we understand Klemann et al. (2008), the horizontal velocities are much more sensitive to lateral variations than the vertical velocities (their Figure 8), and it is the vertical rates that we are correcting. At any rate, it is beyond the scope of our study to make an elastic correction using a laterally variable elastic model and it remains true that the 1D elastic models are commonly used to compute the vertical land motion and sea level response to present-day mass change scenarios both locally and globally.

The value of the elastic correction is the sum of the contributions from Greenland, Antarctica, glaciers and ice caps, and hydrology (described in Section 2.3). The elastic correction is not an average of different models. As stated in Section 2.3, the scenarios for Greenland and Antarctica are consistent with the results of Shepherd et al. (2012). The elastic earth model used to calculate the elastic correction is the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981). All of the models in the a priori set also use PREM to describe the elastic structure of the Earth. Otherwise we are unsure what is meant by asking if the model is similar to the best fit model in the a priori set, because all models in the prior set are fully viscoelastic Earth models designed to model the paleo GIA response, whereas these corrections model only the elastic response to present-day load changes.

Comment 27: L212: “mass loss” or “mass changes” or really “mass loss changes” (due to acceleration)?

Response 27: We change the text in the caption here to read ‘mass loss’ (although the Greenland and Antarctic corrections do contain accelerations, see text).

Comment 28: L223: Just wonder why ICE-5G is used while the new ICE-6G_C is available for quite some time now.

Response 28: Yes, we could’ve used ICE-6G instead of ICE-5G. However, we also thought it equally interesting to compare the result of the data-driven model to that of a more recent forward model (ICE-6G). Therefore, using ICE-6G in the prior model set would compromise such a comparison because the data-driven results are to a degree dependent on the input model(s). There are two different ice sheet histories used and they are paired with a variety of viscosity profiles; together, the Earth and ice model combinations should bracket a range of possible GIA signals for the region. We have added a sentence that explains this in Section 2.4.

Comment 29: L237ff: The second paragraph which comes without references. Please check Steffen & Wu (2011) for a list of Fennoscandian GIA model parameter and consider the studies by Zhao et al. (2012), Kierulf et al. (2014), Root et al. (2014), Schmidt et al. (2014 (they also use ANU as you do!)), Nordman et al. (2015) and Root et al. (2015 – for the Barents Sea). Please also refer to some literature for a few words on GIA models and Earth parameter for the British Isles and the Barents Sea.

Response 29: Although forward models are used in the prior input, this is not a forward modelling study. We are also not trying to infer specific values for classical GIA model parameters, we are trying to constrain the present-day GIA when a large range of plausible models are used as input, together with data. Of course, the range of possible parameters in the prior model set is informed by previous modelling studies. We have added a paragraph in Section 2.4 that summarizes some of the main results of these studies – the upper and lower mantle viscosity variations in our *a priori* set fit well with the min/max ranges inferred by these studies (see Response 30 for discussion of the lithospheric thickness).

Comment 30: L237: Why do you use a fixed lithosphere and why 90 km? See references above which partly show quite different best-fitting values. Also, Steffen & Kaufmann (2005) point to differences in the lithosphere thickness in each of the regions you investigate (British Isles, Norwegian coast, Gulf of Bothnia, Barents Sea), further subdivision of (parts of) northern Europe was done in Lambeck et al. (1998) and Steffen et al. (2014).

Response 30: For the study area as a whole, the lithospheric thickness may range from 71 – 160 km (see paragraph added to Section 2.4). The 90 km thickness falls within these value although we acknowledge the study could benefit from a wider use of lithosphere thickness values (a line has been added in the text indicating this). Note, however, that we are not trying to use our predictions to inversely infer Earth model parameters (which we now note in the introduction). If we were, having a range of lithospheric thickness values to choose from would indeed matter more; as it is, we are concerned with having a prior model set to input that contains a wide spread of possible GIA response values (the individual combinations that generate these variations matter less than the presence of the variations themselves). Nordman et al. (2015) as referred to below, also indicate that RSL data in central Fennoscandia cannot distinguish between lithospheric thicknesses (at least between the range of 46 – 146 km). And in general lower mantle viscosity is less well constrained than upper mantle viscosity, which makes the latter parameter probably the most important one.

Comment 31: L239ff: Have a look into Nordman et al. (2015) who discuss this issue.

Response 31: The text has now been edited here due to the added paragraph, but we guess either that the reviewer is referring to the range of mantle viscosity values used, or the idea of fitting an ice sheet model with a mantle viscosity profile. See Response 29 for a discussion of a range of mantle viscosity values. As for the fitting of the ice sheet model to a viscosity profile, ICE-5G is fit to a particular viscosity profile and the ice coverage in the ANU model is iteratively refined in conjunction with Earth model parameters; both ice sheet models are in their own way associated with best-fit viscosity values. In their study, Nordman et al. (2015) use well-constrained RSL data from Ångerman River in Sweden and investigate the fit of a large set of ice/Earth model combinations to the decay times of these data. They concluded similar to other studies that the RSL data are relatively insensitive to the ice sheet model. This may be true in Fennoscandia, but it doesn't necessarily apply in other parts of our study area (British Isles, Barents Sea) – so varying the ice sheet history for this study may still provide meaningful variation to the input model set.

Comment 32: Table 2: Please check if the ratios are correctly calculated.

Response 32: We calculated the ratios, and then rounded all of the numbers to two decimal points, hence the small discrepancy between the values in the table and their ratios. We have edited the ratios to be those generated by using the rounded values in the table.

Comment 33: L329ff: There appears to be a misunderstanding and much information is misleading. It is important to go through the existing documentation (http://www.lantmateriet.se/globalassets/kartor-och-geografisk-information/gps-ochmatning/referenssystem/landhojning/presentation-av-nkg2016lu.pdf). NKG2016LU is not a GIA model, it is as its name says a land uplift model. The observations are not corrected for any motion such elastic contributions from Greenland ice melt, hydrology, tectonics etc. The underlying GIA model is tuned to relative sea-level (RSL) data in northern Europe and GNSS data (with 80% weight on RSL data!), and is used as a gap filler in those areas where observations are not available, i.e. in the Baltic Sea. Hence, on land NKG2016LU represents the observed land motion - which has a very strong GIA component, of course. In addition, one should note that NKG2016LU is quite reliable in Fennoscandia (Norway, Sweden, Finland, Denmark) and performs well in the Baltic countries, but is not much reliable in Germany, Poland and eastern Europe as they are no or just a few observations (both for the semi-empirical and constraining the underlying GIA model). NKG2016LU largely relies here on the GIA model but which is tuned to give the best fit to the observations in Fennoscandia and the Baltic countries. The southern and eastern parts of the model are of less importance for the developers. As an interesting test, the NKG2016LU model could be on land treated as observation where the corrections of this study could be applied, and then used in the least-squares adjustment.

Response 33: We agree that the information as presented may be confusing, and we have reframed the discussion and figure to try to clarify the comparison.

The point here is to evaluate to what extent the presence/absence of an elastic correction in the GPS data influences the predicted model solution. We understand that the NKG2016LU model doesn't include a correction in the GNSS data for elastic/short-term signals. We start by explaining our own prediction from D1, which is a prediction, to the best extent that is possible, of the paleo GIA signal. When the model prediction is compared to the GPS data with the elastic correction, there is a bias of -0.01 mm/yr. Conversely, when the model prediction is compared to the GPS data without an elastic correction, there is a bias of -0.35 mm/yr, which is logical since this is approximately consistent with the magnitude of the elastic correction applied in Scandinavia. If we perform the same comparison with the NKG2016LU model values, the uncorrected GPS data yield a bias of -0.06 mm/yr over Scandinavia, whereas the corrected GPS data yield an average overprediction of +0.42 mm/yr, which is again consistent with expectation given the magnitude of the elastic correction. We could have of course just done this comparison with the D1 model, but it can be helpful to also look at the work of other studies and see a consistent tendency. Maybe a more direct way of looking at this is to compare the NKG2016LU land uplift estimate to the D1 estimate – when we do this, we see over Scandinavia that the average difference is +0.3 mm/yr. This difference is largely explained by the elastic correction on the GPS data applied in D1 – i.e., it is reflecting the difference between the total land uplift and the paleo GIA uplift. The magnitude of this difference may be larger than the uncertainty on the observations and/or the best-fit model prediction.

In the text of our conclusion, we write: *"The prediction of vertical land motion has a small but non-negligible sensitivity to the application of an elastic correction. … Therefore, the presence of such a difference in the vertical motion prediction suggests that while long-term GIA is the dominant contributor to vertical motion in central Scandinavia, that it is still worthwhile to correct GPS land motion rates for present-day elastic signals, so long as these signals are adequately approximated (e.g., Riva et al. 2017)."* This remains true for studies focussed on the paleo GIA signal, and was the essence of the point we were trying to make.

The reviewer also writes "The underlying GIA model is tuned to relative sea-level (RSL) data in northern Europe and GNSS data (with 80% weight on RSL data!)". It is not clear what the reviewer is trying to emphasize with this statement, but it makes sense that the underlying GIA model would also be based on RSL data, and it should be more heavily weighted towards those data since the GNSS data are also going into the semi-empirical solution. Although we haven't tried it, it is an interesting idea to take the NKG2016LU model as an 'observation', correct it for the elastic effect, and include it in the inversion. However, it may also be a bit circular, since the GNSS data used to constrain both NKG2016LU and the models presented here are quite similar over Scandinavia.

Comment 34: L353ff: Of course, the bias is 0.42 mm/a as NKG2016LU is the total observation where no elastic correction has been applied!

Response 34: We are not surprised by this result either – that the difference is due to the presence/absence of the elastic correction is the point we were trying to make. The text has been reworded here now, but the point is that while the elastic correction is small, it can still cause a consistent difference between land uplift predictions and GIA predictions (see Response 33).

Comment 35: Section 3.4: I like this comparison as it nicely shows an important application. However, I wonder why you pick the North Sea where the GIA contribution is small. Would have been nice to see how the model performs in the Baltic Sea and along the Norwegian coast. I also note that in the documentation of NKG2016LU a comparison to tide gauges has been made for Fennoscandia and the Baltic Sea.

Response 35: The GIA signal is generally small in the North Sea (except at sites Hirtshals and Tregde), although different forward GIA models predict both positive and negative rates of sea-level change in the central North Sea indicating there is still uncertainty here - this makes it an interesting place to evaluate the data-driven model.

Based partly on the reviewer's comments, we have modified this section a bit in the revision. For the North Sea, we now use the tide-gauge rates that were presented in Frederikse et al. (2016b, Geophysical Research Letters 43, doi:10.1002/2016GL070750). The main difference here is that the time span over which the trend is calculated is longer (1958-2014 compared to 1980-2013). The method used for calculating the trends over the shorter time span may not be well suited for determining lower frequency signals, and it appears that using the longer time span decreases the inter-station spread of the inferred non-GIA signals. Use of the longer time span also facilitates adding a similar comparison for the Norwegian coast, following the reviewer's suggestion. The sea level trends for the Norwegian coast are also taken from Frederikse et al. (2016b), so the time spans are consistent for the North Sea and Norwegian comparisons. We find that removing the GIA signal decreases much of the inter-station variability for both regions. There is also a difference when the results are compared to the ICE-6G model predictions at these tide gauge locations. We have updated the text and figures throughout Section 3.4 to reflect these changes.

Comment 36: Conclusion: I wonder what the best-fitting Earth structures are for you models. Are they like those used in the generation of ICE-5G and ANU? Although your model is discussed as a data-driven you should mention and discuss how much the contribution of the a priori models is in the final models. According to Table 2 it is quite large at the level of the GNSS data.

Response 36: Table 2 gives the results of the VCE analysis. In model D1, both the GNSS data and prior model information have their uncertainties somewhat scaled down. In model D3, the uncertainties of the GNSS data are almost unscaled (factor of 1.02) while the uncertainties of the prior model are scaled down (by a factor of 0.64). This does not necessarily mean that the prior model contributes more than the GNSS data, since particularly in the former load centre, the original uncertainties are significantly larger than the data uncertainties. We have added a couple of sentences in the text that explains this.

As for the best-fitting Earth structures, yes, we can examine the best-fit empirical model, and then see with which model or models in the *a priori* set it most closely corresponds. We point out again that it was not the main goal of this study to infer Earth structure, in fact, one of the expectations of using a data-driven approach is the minimization of the uncertainty associated with forward models. Nevertheless, when we compare the predicted data-driven prediction(s) to models in the *a priori* set, the suggested upper and lower mantle viscosity values of around 3-6 $\times 10^{20}$ Pa s, and 5-30 $\times 10^{21}$ Pa s, respectively (similar to other studies, the upper mantle viscosity is better constrained than the lower).

These Earth models have a 90 km thick lithosphere, and as discussed in Response 30, if it were a primary goal of our study to infer these parameters, varying the lithospheric thickness would be useful. However, our upper and lower mantle viscosity inferences are quite consistent with those suggested by forward modelling studies whose main goal it is to constrain these parameters.

Comment 37: L419ff: What implications has this for the results of Root et al. (2015)?

Response 37: The study of Root et al. (2015) is a forward modelling study, whereas this is a semi-empirical modelling study. We believe that the GRACE signal we have used may have been aggressively filtered, so it is possible that some of the GIA signal has been lost. It is also the case that estimates of present-day mass loss in the Barents Sea vary over time period and estimation method, complicating the correction to GRACE for this effect. The outcome of the modelling study (for the D2 and D3 models) is thus dependent on the input GRACE signal and the assumed correction applied to it. The same is of course true for Root et al. (2015).

Comment 38: Where can your model be downloaded?

Response 38: We have placed gridded model predictions of vertical land motion and their uncertainties for the D1 model on the 4TU Centre for Research Data repository, https://data.4tu.nl/, doi:10.4121/uuid:4a495bbc-0478-483a-baef-19ff34103dd2. We have added this information at the end of the paper.

Comment 39: L595-598: Please add the website path for the model, http://www.lantmateriet.se/sv/Kartor-och-geografisk-information/GPS-och-geodetiskmatning/Referenssystem/Landhojning/

Response 39: We have added the link.

Response to Reviewer 2.

We thank the reviewer for his or her comments.

Comment 1:
1) The correction of the data for the recent signal is calculated without considering its large variability over the last two decades. More specifically GPS time spans are not uniform and, as I understand, the elastic correction is not computed for each station coherently with its time span. The elastic correction is not constant in time. Greenland mass loss for example has accelerated in the last decades.

Response 1: It is true that the elastic corrections for the GPS are not computed for each station within its time span – the trend is rather computed over the time interval 1993-2014. There is an acceleration for Greenland mass loss considered when the displacements for the elastic effect are computed (see text, Section 2.3). It is true that the computed elastic effect would be larger over shorter or more recent time spans. The full time span that we have used could therefore be considered a moderate elastic correction. It would be nice to try to compute the elastic corrections for each station for the appropriate time span – this would be possible for the data taken from Blewitt et al. (2016) but not possible with the Kierulf et al. (2014) dataset (as given) since the begin and end years of the trends were not provided. It is also this dataset that is centred over Scandinavia, where the elastic correction is largest.

Comment 2:
2) As for the GRCE correction of the mass loss in Svalbard and the Russian arctic, the "large" discrepancies in Table 1 are mostly due to the different time spans and to the fact that the mass loss there has not been constant at all. I understand that from Cryosat is still hard to derive mass changes, so I wouldn't include the range of possible estimate. The most reliable estimates for Svalbard and Russian arctic come from ICESat and GRACE and over the same period they agree well enough. Since you need to extract a long term signal I would simply use the GRACE data over the period for which you have the most reliable corrections.

Response 2: There are some large discrepancies in Table 1, even over the same time spans. For example, the glaciological estimates for Svalbard differ from each other over 2003-2009 and again from the IceSat and GRACE estimates over the same time period. That the mass loss has not been constant means that it is natural that the estimates for different time spans differ from each other. So it may be natural that the Cryosat estimate is larger than the IceSat estimate due to accelerated mass loss, and not due to unreliability of Cryosat estimations. If only IceSat is reliable, then this would mean that we stop the GRACE time series after 2009 and we prefer to use a longer time series.

Comment 3:
3) The re-scaling procedure of the mass loss in Svalbard and Russian is questionable and shows that the filter applied to the GRACE data is way too heavy. In fact Root et al. 2015 (doi.org/10.1002/2015GL063769) perform the same kind of correction on the GRACE data in the Barents Sea without the need to rescale. The authors also recognize that they cannot properly invert for the gravity data and that the initial filtering could have been too strong. So what if more a suitable filter were used on the GRACE data instead? How and how much would the result change? Is the gravity signature of the a priori GIA filtered with the same filter?

Response 3:
We have indicated that the treatment for mass loss in this region was problematic. Note that we applied altimetry-derived corrections, whereas Root et al. (2015) use a correction based on mascons which are smaller than the altimetry estimates. The *a priori* gravity information is unfiltered. The filter may have been too strong in the Barents Sea region, but less aggressive filters show comparable results over Scandinavia, so it is not clear to what extent the use of a different filter would result in a different prediction.

Minor comments

Comment 4: It is not explicitly said that is a semi-empirical study. It is called explicitly "inversion" which is quite misleading at first glance.

Response 4: In the introduction we now refer to the model as a semi-empirical model.

Comment 5: The use of the word “posterior”: I suggest the use of "a posteriori" (if that is what the authors mean), but it is not necessary, it just sounds better to me.

Response 5: Ok, we have changed occurrences of posterior to a posteriori.

Comment 6: L45-46. Forward models are supposed to have formal uncertainties only when the models parameters are well (known and) constrained. The model parameters can have uncertainties depending on the error on the constraints (for the inversion). If a model parameter is unknown or have too large uncertainty then the error on the forward model is meaningless. The sentence is misleading (or incorrect), so I suggest rephrasing it.

Response 6: The inferred model parameters can have uncertainties that depend on the error on the constraints and the model uncertainties can be well or poorly constrained depending on the model’s sensitivity to the data. What we meant also here is that GIA predictions themselves are often provided/discussed/used without uncertainties. The text has been reworded here: “The majority of GIA models are however forward models which can be limited by uncertainties in both the ice sheet model and Earth model. Furthermore, because a best-fit forward GIA model is generally a single Earth-ice model combination, their predictions of GIA deformations are typically provided without uncertainties”.

Comment 7: L153-156. While this can be true, I think the GIA signal from LIA cannot explain large differences. The large differences come from computing the trend over different periods.

Response 7: We have suggested an LIA signal as a possibility, not as a certainty, as indeed there could be other explanations. That the GRACE signal differs from glaciological estimates and to a lesser extent altimetry estimates suggests that the GRACE signal may contain a solid Earth signal in addition to a mass loss signal (which would originate either from paleo GIA or LIA GIA, and spatially a signal from LIA would more likely be centred over the currently glaciated regions than the central Barents Sea region).

Comment 8: L241-244. The sentence is difficult to understand. Mostly because here the use of "... ’tuned’ ice sheet history ..." is rather confusing. At first I believed it referred to the previous sentence so the following didn’t make any sense. ICE5g and ANU for example are in fact ’tuned’ ice histories. Anyway I believe the authors are referring to something else.

Response 8: Yes, we agree that the ICE-5G and ANU models are both in their way tuned ice sheet histories, and that is what we were referring to in this and the previous sentence. The text here has now been somewhat reworded, hopefully this clarifies the meaning. Our meaning was that if an ice sheet history is best fit with a particular viscosity profile then varying the viscosity profile over a wide range of values may make the predicted response variations larger than appropriate for a particular model; however, uncertainty in other parameters not considered would also likely make the uncertainties larger.

The ~~long-term GIA G~~glacial isostatic adjustment signal at present-day in ~~Scandinavia,~~ northern Europe and the British Isles estimated from ~~GPS and GRACE data~~geodetic observations and geophysical models

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Abstract

The ~~long-term~~ glacial isostatic adjustment (GIA) signal at present-day is constrained via joint inversion of ~~GPS vertical land motion rates and GRACE gravity data~~geodetic observations and GIA models for a region encompassing ~~Scandinavia,~~ northern Europe, ~~and~~ the British Isles, and the Barents Sea. The constraining data are ~~Global Positioning System~~GNSS (global navigation satellite system~~GPS~~) vertical ~~surface~~ crustal velocities and ~~gravity data from the~~ GRACE (Gravity Recovery and Climate Experiment~~)~~) ~~t (GRACE)~~ gravity data. When the data are inverted with a set of GIA models, t~~T~~he best-fit model for the vertical motion signal has a χ^2 value of approximately 1 and a maximum *a posteriori* uncertainty of 0.3-0.4 mm/yr. An elastic correction is applied to the vertical land motion rates that accounts for present-day changes to terrestrial hydrology as well as recent mass changes of ice sheets and glaciered regions. Throughout the study area, mass losses from Greenland dominate the elastic vertical signal and combine to give an elastic correction of up to +0.5 mm/yr in central Scandinavia. Neglecting to use an elastic correction may thus introduce a small but persistent bias in model predictions of GIA vertical motion even in central Scandinavia where vertical motion is dominated by ~~long-term~~ GIA due to past glaciations. The predicted gravity signal is generally less well-constrained than the vertical signal, in part due to uncertainties associated with the correction for contemporary ice mass loss in Svalbard and the Russian Arctic. The GRACE-derived gravity trend is corrected for present-day ice mass loss using estimates derived from the ICESat and CryoSat missions, although a difference in magnitude between GRACE-inferred and altimetry-inferred regional

mass loss rates suggests the possibility of a non-negligible GIA response here either from millennial-scale or Little Ice Age GIA.

1. Introduction

~~Long-term glacial isostatic adjustment (GIA) is the process by which the Earth's solid surface and underlying mantle deform in response to loading by the large ice sheets that existed during the last glaciation. Because the time-scale of Earth's viscoelastic relaxation is up to several thousand years, ongoing GIA is usually the dominant present-day deformation signal in formerly glaciated areas that are tectonically quiescent (for example, up to 1 cm/yr land uplift around the northwestern Gulf of Bothnia). Outside formerly glaciated regions, the GIA signal often remains large enough to form a significant component of observed present-day deformation and sea-level change rates. Constraint of the long-term GIA signal at present-day is therefore required for accurate separation of the paleo and the more recent contributions to present-day land deformation and gravity change. This problem is complicated further by the fact that the GIA signal itself is temporally and spatially complex, and poorly constrained by models designed to describe both ice cover during the last glaciation and the structure of the Earth.~~

Glacial isostatic adjustment (GIA) is the process by which the Earth's crust and underlying mantle deform in response to surface loading and unloading by large ice sheets and glaciers (e.g., Peltier and Andrews 1976, Wu and Peltier 1982). Glacial isostatic deformation at present-day can include contributions from both recent (annual, decadal) variations to ice cover as well as contributions from millennial-scale variations in ice cover during Pleistocene and Holocene glaciation cycles, although in this study GIA refers to the latter paleo signal, specifically from the last glaciation. Ongoing GIA is usually the dominant present-day deformation signal in formerly glaciated areas (for example, up to approximately 1 cm/yr land uplift around the northwestern Gulf of Bothnia, Lidberg et al. 2010, Kierulf et al. 2014). Outside formerly glaciated regions, the GIA signal from past glaciations often remains large enough to form a significant component of observed present-day deformation and sea-level change rates. Constraint of the GIA signal at present-day is therefore required for accurate separation of the longer time scale and the more recent contributions to present-day land deformation and gravity change (Peltier 1998, Tamisiea 2011). This problem is complicated further by the fact that the GIA signal itself is temporally and spatially complex, ~~and poorly constrained by~~therefore making it challenging ~~for models~~for models ~~designed~~ to ~~describe~~ constrain some of the fundamental parameters relating to both ice cover during past glaciations and the structure of the Earth~~.~~.

In Scandinavia, the GIA process has been studied extensively and constrained with data including relative sea level indicators, Global Positioning System (GPS) measurements and satellite gravity data (e.g., Lambeck et al. 1998, Milne et al. 2001, Steffen et al. 2010, see also Steffen and Wu (2011) for a review). While the GIA process in the region of the former Fennoscandian Ice Sheet is probably more extensively studied ~~and observationally well-constrained~~ than anywhere else in the world, GIA in the Barents Sea is by comparison less well understood due in part to the lack of observational evidence left behind by a marine-based ice sheet. Auriac et al. (2016) provide a recent summary of GIA models in the Barents Sea region. Studies have also focussed on the smaller British Isles region, which experiences GIA deformation in response to deglaciation of both the local British Isles Ice Sheet and the larger adjacent Fennoscandian Ice Sheet (Bradley et al. 2011, Kuchar et al. 2012). The ice sheet evolution of the region as a whole was recently summarized by Patton et al. (2017). These studies and many others have provided valuable insight into regional GIA processes. The majority of GIA models are however forward models which can be limited by uncertainties in both the ice sheet model and Earth model. Furthermore, because a best-fit forward GIA model is generally a single Earth-ice model combination, their predictions of GIA deformations are typically provided without uncertainties.~~ and typically give no estimation of formal uncertainty.~~

This paper constrains the ~~long-term~~ GIA signal in ~~Scandinavia and~~ northern Europe through the simultaneous inversion of vertical land motion rates from GPS ~~(Global Positioning System)~~ and gravity change rates from ~~the Gravity Recovery and Climate Experiment (~~GRACE~~)~~ (Gravity Recovery and Climate Experiment). The semi-empirical method also estimates c~~C~~orresponding uncertainties ~~are also empirically estimated~~ for the preferred model(s) which relative to forward model studies ~~. Forward GIA model predictions typically have no formal uncertainty estimation although parameter variation suggests that forward model uncertainty can be large. The estimation of formal model uncertainty~~ is ~~therefore~~ a notable advantage of semi-empirical or data-driven methodologies. Similar empirical and semi-empirical approaches have been implemented to estimate regional long-term GIA signals in Antarctica (Riva et al. 2009, Gunter et al. 2014), North America (Sasgen et al. 2012, Simon et al. 2017), Alaska (Jin et al. 2016) and Fennoscandia (Hill et al. 2010, Müller et al. 2012, Zhao et al.

2012). Here, our methodology is based on that of Hill et al. (2010); relative to their previous work, we update both the GPS and GRACE datasets, incorporate a second model ice sheet history into the *a priori* input, ~~-~~and ~~,~~ expand the study area to includ~~e a~~ regions south and west of Scandinavia, ~~e northern Europe and the~~including the British Isles, as well as ~~to the south and~~ the Barents Sea to the north. ~~A, and incorporate a second model of ice sheet history is also incorporated into the *a priori* input.~~ Rather than focus on model parameter estimation, we focus on constraint of the GIA signal at present-day. There are three main goals: i) to model the paleo GIA signal at present-day in a continuous region between Scandinavia and the British Isles, ii) to estimate empirically the uncertainty of the modelled signal, and iii) to assess the importance of applying an elastic correction to the vertical land motion data.

2. Model Inputs and Method

2.1 GPS Data

~~Rates of vertical land motion measured by GPS are taken from both Kierulf et al. (2014) and the Nevada Geodetic Laboratory (Blewitt et al. 2016) (**Figure 1**). The Kierulf et al. (2014) dataset has relatively dense coverage within the region of the former load centre of the Fennoscandian Ice Sheet (FIS), particularly in Norway, but sparse coverage elsewhere. The data from Blewitt et al. (2016) are thus used in the region outside the former ice sheet margin. In total, there are 459 stations. The data span the years 1996-2016; the time series length varies station to station from 3-20 years, with an average time series length of approximately 10 years.~~

Rates of vertical land motion measured by GPS are taken from both Kierulf et al. (2014) and the Nevada Geodetic Laboratory (Blewitt et al. 2016) (**Figure 1**). The Kierulf et al. (2014) dataset has relatively dense coverage within the region of the former load centre of the Fennoscandian Ice Sheet (FIS), particularly in Norway, but sparse coverage elsewhere. The data from Blewitt et al. (2016) are thus used for the region outside the former ice sheet margin. The Kierulf et al. (2014) dataset has 150 stations with time series lengths of at least 3 years. The data from Blewitt et al. (2016) span 1996-2016 and have been limited to sites which have at least 10 years of data. To avoid spatial overlap of sites, the data from Blewitt et al. (2016) have been additionally filtered to include only one site within a 30 km radius (where the site selected within the radius is the one with the largest number of usable data epochs). The subset of data from Blewitt et al. (2016) has 309 stations. Combined with the Kierulf et al. (2014) data, there are 459 ~~stations~~measurements in total.

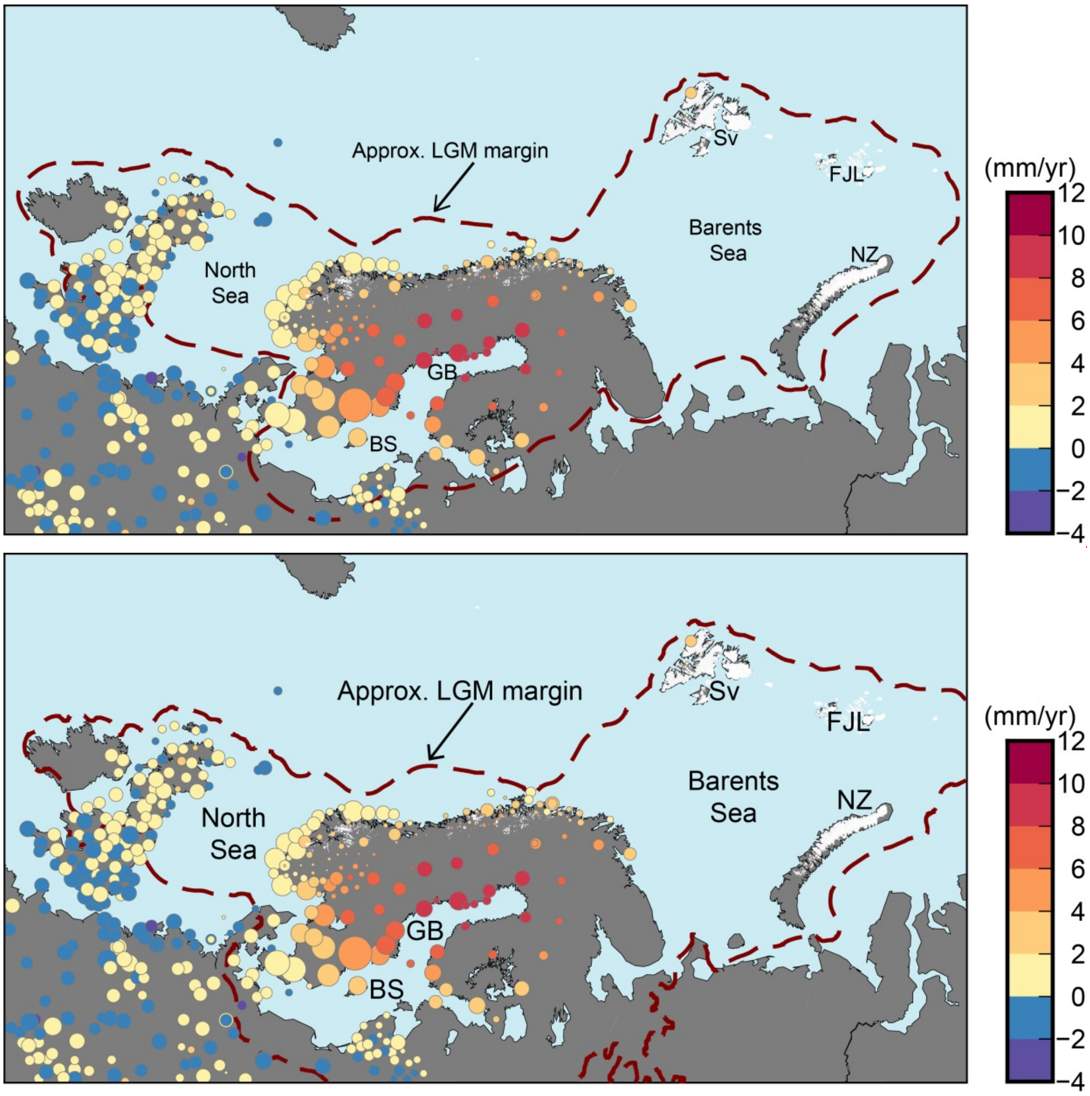


Figure 1. Rates of vertical land motion (mm/yr) for the GPS data used in the inversion, after correction for elastic effects (Section 2.3). BS – Baltic Sea, FJL – Franz Josef Land, GB – Gulf of Bothnia, NZ – Novaya Zemlya, Sv – Svalbard, FJL and NZ = Russian Arctic. Dark red dashed line (Hughes et al. 20~~15~~6) shows the approximate boundary of ice cover at the Last Glacial Maximum (LGM) (ice cover on Iceland not shown). White shading indicates present-day glaciers. The size of the circles is inversely proportional to the measurement uncertainty.

As further described in Kierulf et al. (2014), their rates were derived using the GAMIT/GLOBK GPS analysis software (Herring et al. 2011) and have uncertainties that assume a combination of white noise and flicker noise, while the data from the Nevada Geodetic Laboratory were calculated using the MIDAS trend estimator, an algorithm ~~designed for automatic step detection in~~that is less sensitive to discontinuities in GPS time series (Blewitt et al. 2016). Although the processing technique differs for each dataset, the two datasets are combined in order to achieve the best possible spatial coverage in the study area. Common sites in the two datasets compare within the observational uncertainties at all but two~~one~~ of thirty-one sites, and no apparent bias is observed between the differences at the shared sites (**Figure A1**). Because the uncertainties are consistently larger for the data from the Nevada Geodetic Laboratory than for the data from Kierulf et al. (2014), we use the common sites to determine an average uncertainty scaling factor (~2.25) to apply to the uncertainties in the latter dataset. The scaling avoids significantly biasing the inversion result towards fitting either dataset. Both datasets are aligned in the International Terrestrial Reference Frame 2008 (Altamimi et al. 2011), which is consistent with the CM frame to within ~0.2 mm/yr. As described in Section 2.3, an elastic correction is applied that accounts for recent changes in ice sheet and glacier volumes and terrestrial hydrology.

2.2 GRACE

The GRACE data are processed as in Simon et al. (2017). Rates of gravity change for a 10.5 year period from 2004.02-2014.06 are estimated using 113 GRACE Release-05 (RL05) monthly solutions from the University of Texas at Austin Center for Space Research (CSR). The coefficients are truncated at degree and order 96. Part of the GIA signal may also be lost during the filtering, particularly at higher orders; the typical spatial resolution of the signal is ~300 km (Siemes et al. 2013). ~~(consistent with a spatial resolution of ~200 km).~~ Values estimated from Satellite Laser Ranging (Cheng et al. 2013) replace the C_{20} coefficients. Following Klees et al. (2008), the monthly fields are filtered with a statistically optimal Wiener filter. The optimal filter incorporates the full variance-covariance information of the monthly solutions, and less aggressively filters in regions where signal is stronger. A mass trend is estimated that accounts for bias, annual, and semi-annual variations (**Figure 2**). The signal uncertainty is represented by the full variance-covariance matrix of the trend. Corrections for changes in the terrestrial hydrology cycle and ice mass loss from Svalbard and the Russian Arctic are applied as described in Section 2.3.

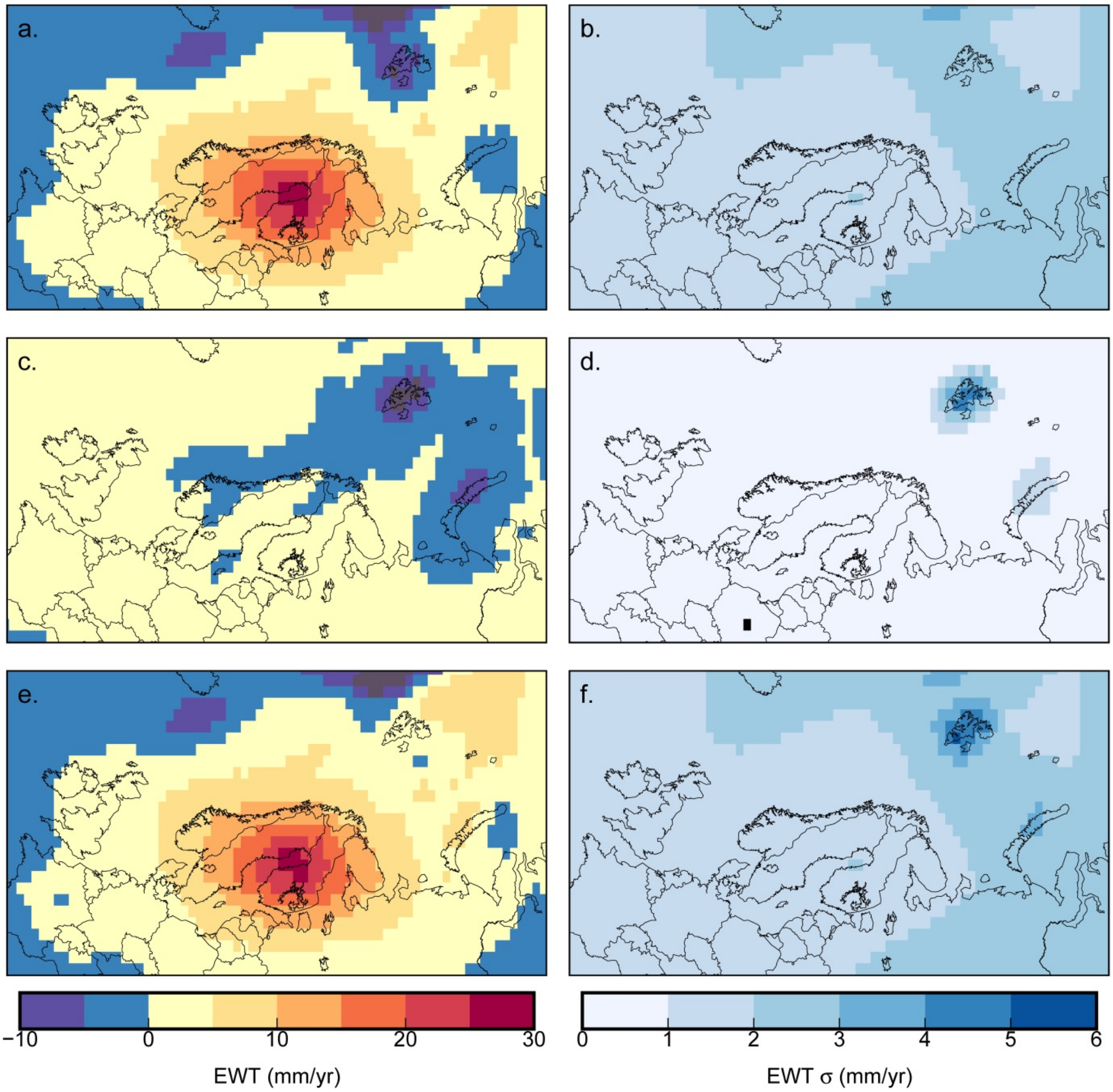


Figure 2. (a) Total gravity change rates measured from GRACE, (c) correction for terrestrial hydrology changes and present-day ice mass loss (Section 2.3), and (e) final corrected rates. (b,d,f) Same as (a,c,e) but rates are the 2σ uncertainties associated with the signal. Units are mm/yr change in equivalent water thickness (EWT).

2.3 Corrections for Terrestrial Hydrology and Present-day Ice Melt

Changes in terrestrial hydrology as well as present-day ice mass loss from Greenland, and glaciers and ice caps in Svalbard, the Russian Arctic, and Scandinavia may form a significant contribution to the total measured gravity change and vertical motion rates within the study area.

GRACE

In the continental region and south of approximately 71.5° N latitude, hydrological changes are the sum of dam retention values (Chao et al. 2008) and anthropogenic groundwater depletion estimated with the model PCR-GLOBWB (Wada et al. 2014~~), which includes considers only changes from anthropogenic groundwater depletion and dam retention)~~~~.~~. The trend is computed for 2004-2014 from 11 annual means on a 2° × 2° grid, consistent with the resolution of the GRACE data~~ (**Figure 2c**)~~. In glaciered regions (Scandinavia, Svalbard and the Russian Arctic), the hydrology model is not used to correct the input rates. Rather, it is assumed that present-day estimates of regional ice melt derived from altimetry observations should more accurately capture the dominant hydrological signals that would be modelled by PCR-GLOBWB. The corrections for mass loss from the glaciers are also filtered to be consistent with the spatial resolution of the GRACE data. The total correction for hydrology and glacial mass loss is shown in **Figure 2c**, the individual contributions are shown in **Figure A2**.

Estimates of present-day mass changes in Scandinavia, the Russian Arctic, and Svalbard are summarized in **Table 1** for various studies, and vary considerably depending on estimation method and time period. Ice m~~M~~ass loss in Scandinavia originates from glaciers in western Norway and is consistently small ~~and generally~~with estimated ~~to be~~rates between -1.2 to -2 Gt/yr. Here, we apply a mass loss rate of -1.3 Gt/yr, determined by glaciological modelling (Marzeion et al. 2012, 2015).

In the Russian Arctic, glaciological estimates of mass change are consistent within uncertainties for the different time periods and suggest mass change between -21.0 to -24.7 Gt/yr. These rates are approximately twice those estimated by the ICESat and CryoSat missions, which estimate mass changes in this region of between -10.5 to -14.9 Gt/yr, with a small acceleration observed after 2010 (Wouters, *pers. comm.*, 2016). The smallest net mass change estimate for the Russian Arctic comes from GRACE, with -5.7 Gt/yr mass change observed between 2003-2013 (Schrama et al. 2014).

In Svalbard, estimated mass change rates are more discrepant. Again, glaciological estimates are the largest, but two estimates of -42.0 Gt/yr and -17.0 Gt/yr between 2003-2009 are not consistent within uncertainties and differ in magnitude by more than a factor of 2. Laser and radar altimetry estimates are smaller, and suggest a clear acceleration in mass loss since 2010 (-4.6 Gt/yr between 2003-2009 and -16.5 Gt/yr between 2010-2014, Wouters, *pers. comm.*, 2016). As with the Russian Arctic, GRACE is the estimation technique that records the smallest net mass change, with -4.0 Gt/yr estimated in Svalbard between 2003-2013 (Schrama et al. 2014).

Study/Source	**Svalbard (Gt/yr)**	**Russian Arctic (Gt/yr)**	**Scandinavia (Gt/yr)**
2003-2009			
Marzeion et al. (~~2012, ~~2015) *(2003-2009)*	-42.0 ± 3.2 (gl)	-22.9 ± 4.7 (gl)	-1.2 ± 0.2 (gl)
Gardner et al. (2013) *(2003-2009)*	-17.0 ± 6.0 (gl) -5.0 ± 2.0 (I, G)	-21.0 ± 13.0 (gl) -11.0 ± 4.0 (I, G)	-2.0 ± 0.0 (gl)
Wouters (2016) *(2003-2009)*	-4.6 ± 1.2 (I)	-10.5 ± 1.3 (I)	-
2010-2014			
Wouters (2016) *(2010-2014)*	-16.5 ± 1.6 (C)	-14.9 ± 1.2 (C)	-
≥10 years time period			
Marzeion et al. (~~2012, ~~2015) *(2004-2013)*	-39.8 ± 2.2 (gl)	-24.7 ± 3.0 (gl)	-1.3 ± 0.1 (gl)
Average Wouters (2016) *(2003-2014)*	-10.6 ± 2.0 (I, C)	-12.7 ± 1.8 (I, C)	-
Schrama et al. (2014) *(2003-2013)*	-4.0 ± 0.7 (G)	-5.7 ± 0.9 (G)	+1.3 ± 0.9 (G)
This study	-10.6 ± 2.0 (I, C)	-12.7 ± 1.8 (I, C)	-1.3 ± 0.1 (gl)
This study, with scaling	-2.7 ± 2.0 (I, C)	-2.5 ± 1.8 (I, C)	-1.3 ± 0.1 (gl)*

Table 1. Estimates of present-day mass change for Svalbard, the Russian Arctic, and Scandinavia for different time periods and from different sources. Letters in parentheses indicate estimation method; gl - glaciological, I - IceSat, G - GRACE, C - CryoSat. All rates are in Gt/yr. *Not scaled.

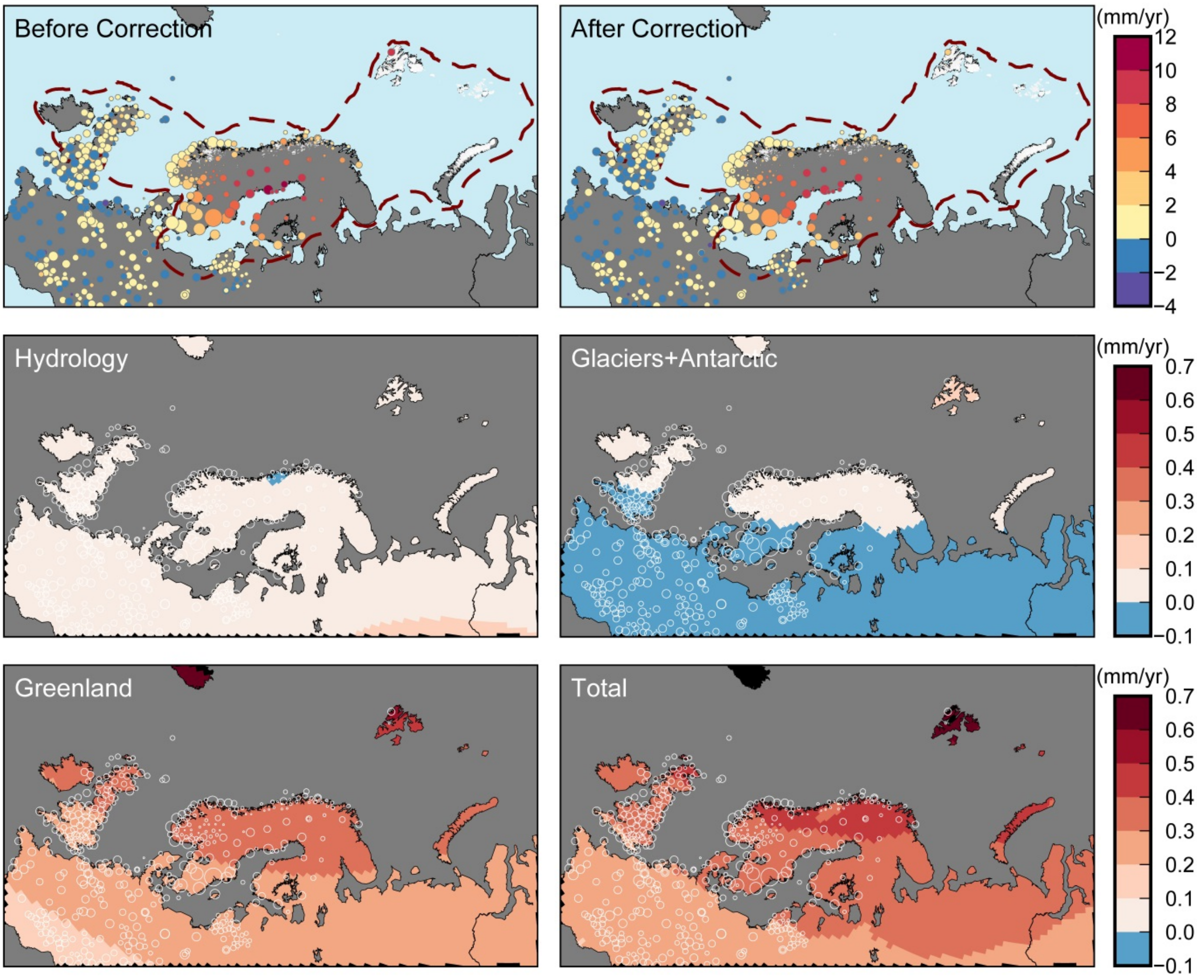
~~The differing mass change estimates among measurement techniques for the Russian Arctic and Svalbard raise the question of which value to use when applying a correction to the total GRACE trend shown in **Figure 2a.**~~ GRACE measures total mass changes (solid Earth plus cryosphere), and thus a correction for one needs to be applied in order to isolate the other. W~~w~~hile the glaciological values and the altimetry ~~methods~~estimates (which ~~have been~~are corrected for crustal uplift due to GIA) are both intended to ~~more accurately~~ ~~isolate~~represent changes to the cryosphere~~ alone,~~ t~~T~~he differing mass change estimates among measurement techniques for the Russian Arctic and Svalbard raise the question of which value to use when applying a correction to the total GRACE trend shown in **Figure 2a**~~.~~. Relative to GRACE, the ~~latter two~~glaciological and altimetry methods both consistently infer larger mass losses, suggesting that GRACE ~~may~~ contains a significant mass gain signal from the solid Earth, either from glacial isostatic adjustment from the last glaciation, or from the Little Ice Age (LIA). For both Svalbard and the Russian Arctic, we choose to apply an estimate that averages the ICESat and CryoSat estimates over the years 2003-2014 (**Table 1**). Subtracting these averaged rates from the total GRACE estimates for a similar time period (2003-2013, Schrama et al. 2014, **Table 1**), infers a reasonably consistent total solid Earth or GIA signal of +6.6-7 Gt/yr in the region.

However, applying the averaged ice melt corrections to Svalbard and the Russian Arctic creates a large mass gain signal over these two areas and a relatively smaller signal in the central Barents Sea; this pattern is generally inconsistent with ice coverage in the Barents Sea region suggested by several different Pleistocene ice sheet reconstructions (Auriac et al. 2016), and therefore inconsistent with the paleo GIA signal that the input signal should represent. Possible explanations for this inconsistency are: i) models of LGM ice cover in the region require thicker ice over Svalbard and the Russian Arctic than in the Barents Sea, ii) there is a large Little Ice Age GIA signal over these two regions, and/or iii) the Wiener filter applied to the GRACE data too aggressively filters signal in these small regions. The first explanation is unlikely because glacial margin chronology suggests that Svalbard and the Russian Arctic were located on or near the margin of the Barents Ice Sheet where ice cover would have been thinnest. To counteract the effect of either of the latter two explanations (LIA rebound or signal loss in GRACE), we apply ad-hoc scaling factors of 0.25 and 0.2 to the ice mass loss estimates in Svalbard and the Russian Arctic (**Table 1**), so that their removal from the total GRACE signal results in a spatial pattern in the residual (i.e., paleo GIA) signal that is approximately consistent with thicker LGM ice cover over the Barents Sea than around its margins (**Figure 2e**). Such a scaling factor approach is certainly not ideal, but serves to provide a GRACE input signal in the Barents Sea region that has a spatial pattern broadly consistent with expectations of the paleo GIA response to loading and unloading from the Barents Ice Sheet.

GPS

Vertical land motion rates may likewise be affected by present-day ice mass loss and the terrestrial hydrology cycle. As with the GRACE data, the GPS data are corrected for changes to terrestrial hydrology south of 71.5° N latitude using predictions from the PCR-GLOBWB model, although here, the hydrology trend has been estimated from 1993-2014 to be more consistent with the length of the GPS time series. North of 71.5° N latitude, the same scaled corrections derived from ICESat and CryoSat are applied for present-day ice mass changes in Svalbard and the Russian Arctic. Throughout the study area, the GPS measurements are also corrected for additional elastic vertical motion from mass loss of the Greenland Ice Sheet, the Antarctic Ice Sheet and glaciers and ice caps in northern Canada. Mass loss of the Greenland Ice Sheet is estimated from 1993-2014 using surface mass balance estimates from RACMO2.3 (Noël et al. 2015) and ice discharge with a constant acceleration of 6.6 Gt/yr^2 (van den Broeke et al. 2016). Mass loss of the Antarctic Ice Sheet is also estimated from 1993-2014 ~~with~~using RACMO2.3p1 and assuming a constant acceleration in ice discharge of 2 Gt/yr^2 (van Wessem et al. 2016). The scenarios for both Greenland and Antarctica are consistent with the mass balance estimates from Shepherd et al. (2012). For the Canadian Arctic, a constant mass loss rate of 60 Gt/yr is used (Gardner et al. 2013). All trends and accelerations are calculated with annual time steps. The vertical elastic response is computed in the CM frame using a pseudo-spectral approach up to degree and order 360 and includes the effect of rotational feedback. T~~by applying t~~he respective loads in each year are applied to a spherically symmetric Earth model (e.g., Farrell 1972) using elastic Earth parameters from the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981)~~ and a maximum spherical harmonic degree and order 360~~. -Linear trends in the calculated vertical motion time series are then estimated by least squares over the years 1993-2014 for each region, and finally summed to yield the total elastic response. All signals combine to yield a total net uplift of approximately 0.2-0.5 mm/yr throughout most of the study area, with Greenland mass loss providing the largest contribution (**Figure 3**). The additional uncertainties are also computed and added in quadrature to the measurement uncertainties; correction of the GPS data for non-GIA signals adds < ±0.05 mm/yr uncertainty in most of the study area and ~±0.1 mm/yr in Svalbard (**Figure 3**).

Finally, in addition to present-day ice mass loss signals, a correction of 4.33 ± 0.40 mm/yr is removed from the vertical motion rates for the two GPS sites on Svalbard (NYAL and LYRS). This value is an average of 3 scenarios from Mémin et al. (2014) which estimate the vertical land motion at Ny-Ålesund due to Pleistocene and Little Ice Age GIA signals; their estimates range from 3.31-4.95 mm/yr; thus the averaged correction of 4.33 mm/yr that is applied assumes that the signal from Pleistocene GIA is small and that most residual land motion here is from LIA rebound. After correction for present-day ice mass changes and approximated LIA uplift, the residual (inferred paleo GIA) vertical uplift rates at NYAL and LYRS are 2.64 ± 0.80 and 1.10 ± 2.64 mm/yr, respectively.

284 
Before Correction
After Correction
(mm/yr)
12
10
8
6
4
2
0
−2
−4
Hydrology
Glaciers+Antarctic
(mm/yr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
Greenland
Total
(mm/yr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1

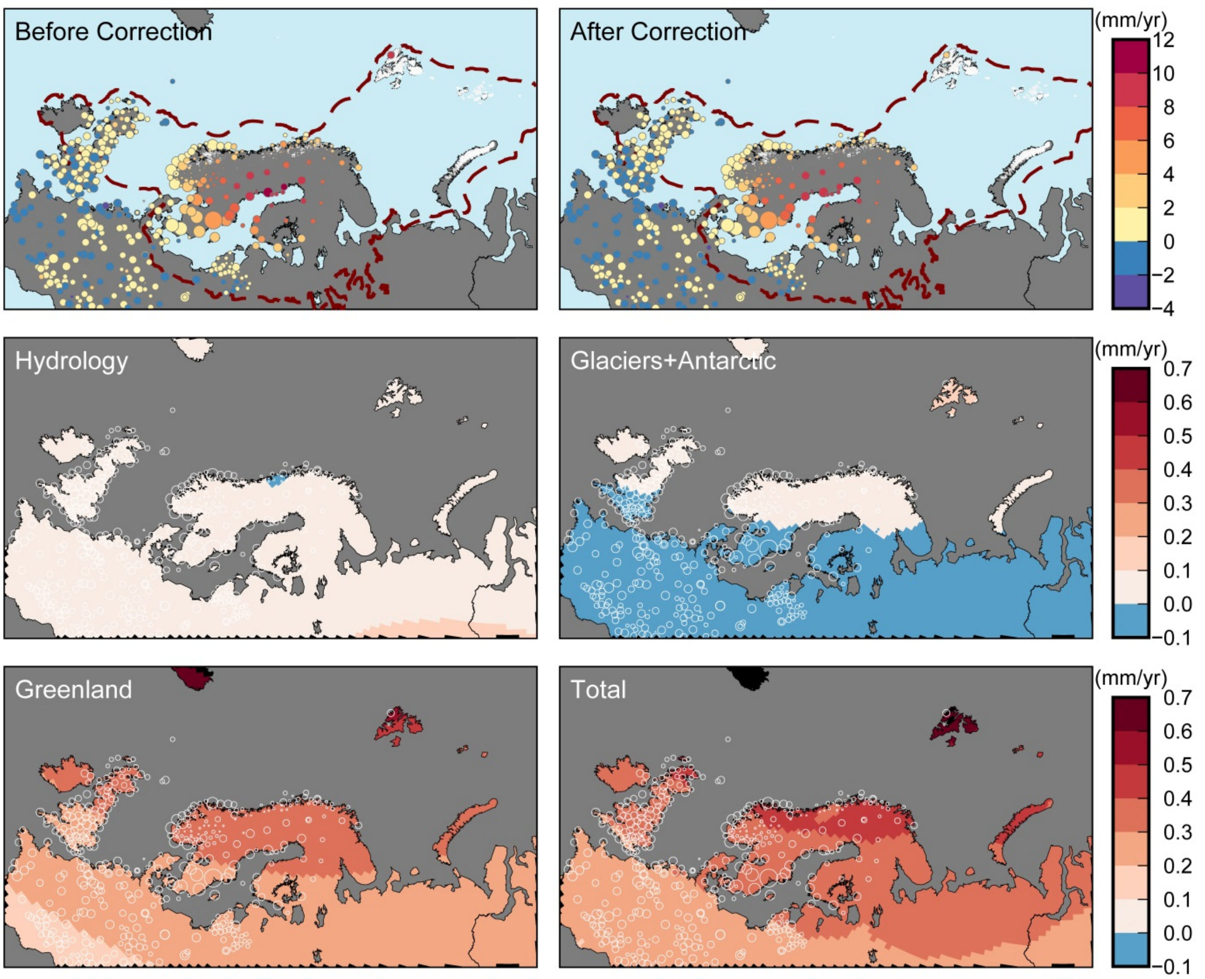


Figure 3. GPS-measured rates of vertical land motion before and after the applied elastic correction (top left and right). An elastic correction is computed for mass loss ~~changes~~ from Greenland, the West Antarctic Ice Sheet (WAIS), glaciers and ice caps in northern Canada, Svalbard and the Russian Arctic, and loading from the terrestrial hydrology cycle. Sites on Svalbard are additionally corrected for LIA uplift as discussed in the text.

2.4 *A Priori* Model Information

The prior model covariance matrix contains predictions from a set of forward GIA models that varies ice sheet history and mantle viscosity and is constructed as described in Hill et al. (2010) and Simon et al. (2017). Here, two different ice sheet histories are coupled to a suite of three-layer Earth models with an elastic lithosphere and varying upper and lower mantle viscosities.

The first ice sheet model is the global ICE-5G model (Peltier 2004). We later compare the data-driven predictions to the more recent ICE-6G forward model (Peltier et al. 2015) (Section 3.3); ~~although ICE-6G is descended from ICE-5G, the comparison is more independent without ICE-6G in the *a priori*~~

~~information.~~without ICE-6G in the *a priori* information, the compared predictions are independent to the extent possible. In the second ice sheet model, the glacial history over Fennoscandia and the British Isles is described by the model(s) from the Australian National University (ANU, Lambeck et al. 2010). This second version of the ice sheet model contains ICE-5G coverage over Greenland and Antarctica and the model of North American coverage presented in Simon et al. (2015, 2016). Tests indicate that varying the ice sheet history over North America has little impact on the predictions in Fennoscandia, although this variation is useful for studies that wish to expand the study area outside of the current study area. Relative to ICE-5G, LGM ice cover in the ANU model is thinner over the Barents Sea, thicker over Svalbard and Scotland, and discontinuous between Scandinavia and the British Isles (**Figure 4**).

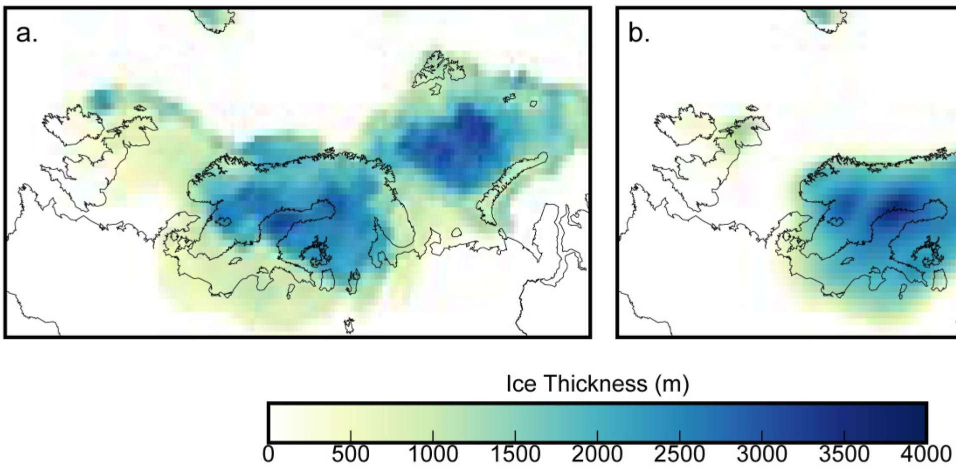


Figure 4. Last glacial maximum (LGM) ice cover in Scandinavia, the Barents Sea and the British Isles from ICE-5G (a) and the ANU model (b).

Previous GIA modelling studies can be used to infer a range of reasonable Earth model parameters for the *a priori* model set. Steffen and Wu (2011) reviewed the results of several GIA modelling studies of the Fennoscandian region and indicated that these analyses suggest regional upper mantle viscosities of between 0.1 – 1 × 10^{21} Pa s and lower mantle viscosities approximately one to two orders of magnitude larger (so 1 – 100 × 10^{21} Pa s). They further indicated that lithospheric thickness in Fennoscandia is likely variable with values ranging from 80 – 200 km (Steffen and Wu 2011). Studies that have followed Steffen and Wu's (2011) review infer slightly narrower ranges for Earth parameters in Fennoscandia. Depending on the ice sheet history and data constraints, the studies of Zhao et al. (2012), Kierulf et al. (2014), Schmidt et al. (2014) and Patton et al. (2017) infer values of upper mantle viscosity, lower mantle viscosity, and lithospheric thickness that may range from (or lie within) 0.34 – 3 × 10^{21} Pa s, 3 – 50 × 10^{21} Pa s, and 93 – 160 km, respectively. In the British Isles, Kuchar et al. (2012) infer upper and lower mantle viscosities of 3 × 10^{21} Pa s and 2 × 10^{22} Pa s respectively, consistent with the values inferred by Bradley et al. (2011). Both studies find a best fit lithospheric thickness of 71 km in this region. In the Barents Sea region, Auriac et al. (2016) summarize the performance of six ice sheet models; the four best-fitting models infer respective upper and lower mantle viscosities of 0.2 – 2 ×10^{21} Pa s and 1 – 50 × 10^{21} Pa s and lithospheric thicknesses of 71 – 120 km. Both the studies of Root et al. (2015) and Patton et al. (2017) infer Earth parameters for this region that are within the ranges given by Auriac et al. (2016).

Considering these three regions as a whole gives minimum to maximum ranges for upper and lower mantle viscosity and lithospheric thickness of 0.2 – 3 × 10^{21} Pa s, 3 – 50 × 10^{21} Pa s and 71 – 160 km. These mantle viscosity ranges are consistent with those used in our prior model set, which range from 0.2 – 2 × 10^{21} Pa s and 1 – 60 × 10^{21} Pa s in the upper and lower mantle. The prior model set uses an elastic lithospheric thickness of 90 km, although future analyses ~~couldmight~~ could benefit from use of a wider range of thicknesses. ~~The Earth models have a 90 km thick elastic lithosphere and the upper and lower mantle viscosities span 0.2 – 2 × 10^{21} Pa s and 1 – 60 × 10^{21} Pa s, respectively. These viscosities span a range of plausible values in the upper and lower mantle. We note however~~With regard to the mantle viscosities, we note that both the ICE-5G and ANU ice sheet models ~~have been fit to a particular viscosity profile~~were not developed independently from a description of mantle viscosity. While the coupling of a set of differing Earth models to a 'tuned' ice sheet history may introduce artificially high variances, this concern may be countered by considering that the variances in such an *a priori* Earth-ice model set could almost certainly be made larger if any combination of 3D Earth structure, non-linear mantle rheology or glaciological and climatological constraints were additionally incorporated. A full covariance matrix is generated that relates the variances of each model prediction relative to the suite's average. All models are represented at spherical harmonic degree and order 256. The average response and uncertainties of the *a priori* set is shown in **Figure 5**.

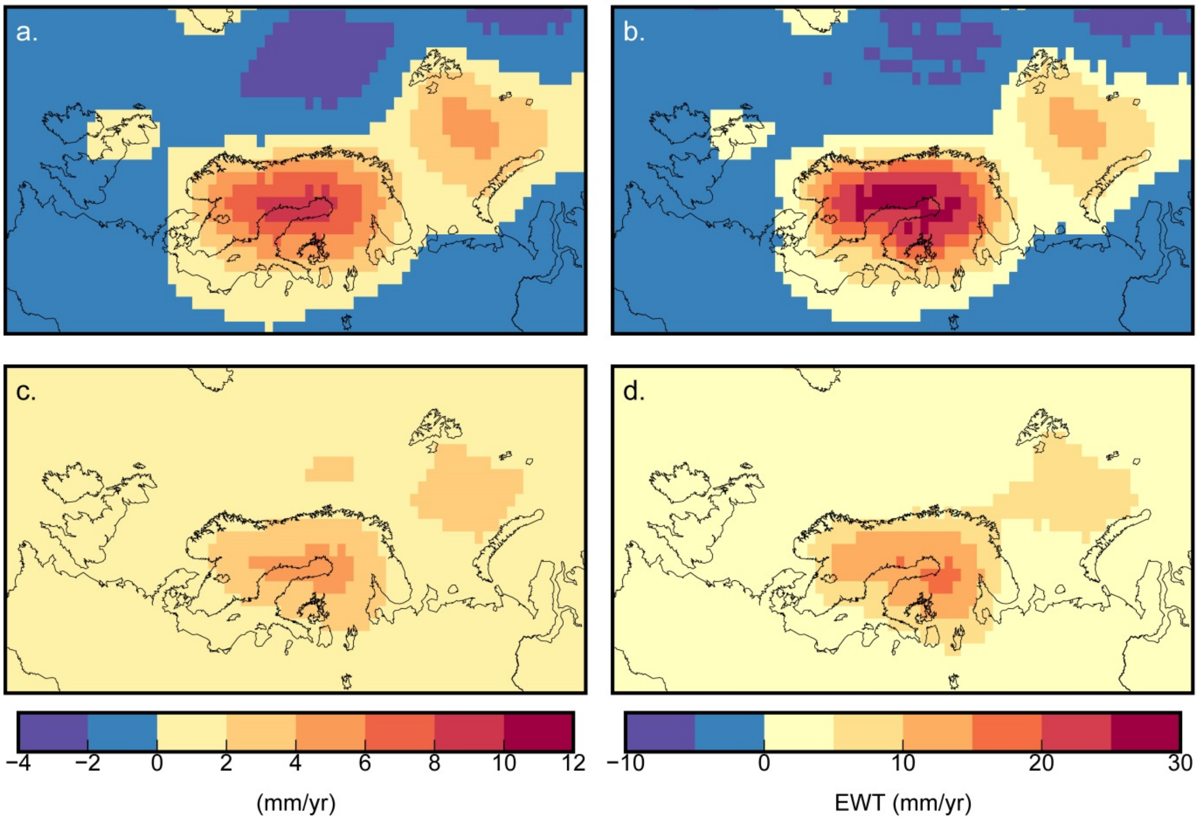


Figure 5. Averaged *a priori* rates of the Earth-ice model set. (a, c) Vertical rates and uncertainties. (b, d) Gravity change rates and uncertainties in units of equivalent water thickness (EWT) change.

2.5 Method

The least-squares adjustment method is based on the methodology of Hill et al. (2010) and extended by Simon et al. (2017). The method simultaneously inverts the data constraints (GPS, GRACE or both) with the *a priori* GIA model information and minimizes the misfit to both input types. As in Simon et al. (2017), variance component estimation (VCE) is also used to weight the input uncertainties. The prior models are combined with the data in three scenarios: inversion with the GPS data alone (D1), inversion with the GRACE data alone (D2), and inversion with both datasets (D3).

3. Results and Discussion

3.1 Prediction of Vertical Motion and Gravity Change

Vertical Motion

The predicted GIA response and uncertainties for the D1-D3 scenarios are shown for vertical land motion (**Figure 6**). The incorporation of the GPS data in scenarios D1 and D3 leads to a similar pattern of regional uplift although relative to D1, the D3 scenario predicts slightly lower rates of uplift over the northern British Isles and in the Barents Sea. D1 and D3 have respective peak uplift rates of 9.8 and 9.2 mm/yr. When only the gravity data are inverted in the D2 scenario, the region of uplift is broader and the peak uplift rate is smaller at 7.1 mm/yr. In all cases, the peak uplift is centred over the northwestern region of the Gulf of Bothnia. The peak (1σ) uncertainty rates are ±0.36, ±0.43 and ±0.28 mm/yr for the D1-D3 cases. Similar to the results of Simon et al. (2017), the predicted uncertainties are largest where the signal is largest (around the Gulf of Bothnia) and/or the data coverage is sparsest and most poorly constrained (around the Barents Sea). In Finland, for example, the relatively large signal and the relatively sparse data coverage combine to create a region of larger uncertainty than in surrounding areas. The inclusion of VCE does not significantly impact the signal prediction but in general somewhat increases the estimated~~tion of~~ *a posteriori* model uncertainty; the weighting factors determined by VCE are shown in **Table 2**. In model D1, ~~the vertical velocities are weighted more heavily than the prior model, whereas in model D3, the prior model information contributes more to the predicted solution than the data.~~both the uncertainties of the vertical velocities and the prior model set are slightly reduced. In model D3, the uncertainties of the vertical velocities are basically unscaled (increased by a factor of 1.02) whereas the covariances of the prior model set are reduced by a factor of 0.64 (note however that the original covariances of the prior model set are still generally larger than those of the vertical data, at least in the region of the former load centre).~~ In both the D2 and D3 models, the uncertainties of the data are increased.~~

Gravity Change

The predicted gravity change rates for D1-D3 are comparable to the predicted vertical motion rates in both the spatial pattern and relative magnitude (not shown). The peak mass change rates are again centred over the northern Gulf of Bothnia, and are 33.7, 24.3, and 32.3 mm/yr of equivalent water thickness change for the D1-D3 scenarios. The peak associated 1σ uncertainties are ±1.59, ±1.59 and ±1.22 mm/yr EWT. In both the D2 and D3 models, the uncertainties of the GRACE data are increased by the VCE analysis (**Table 2**).

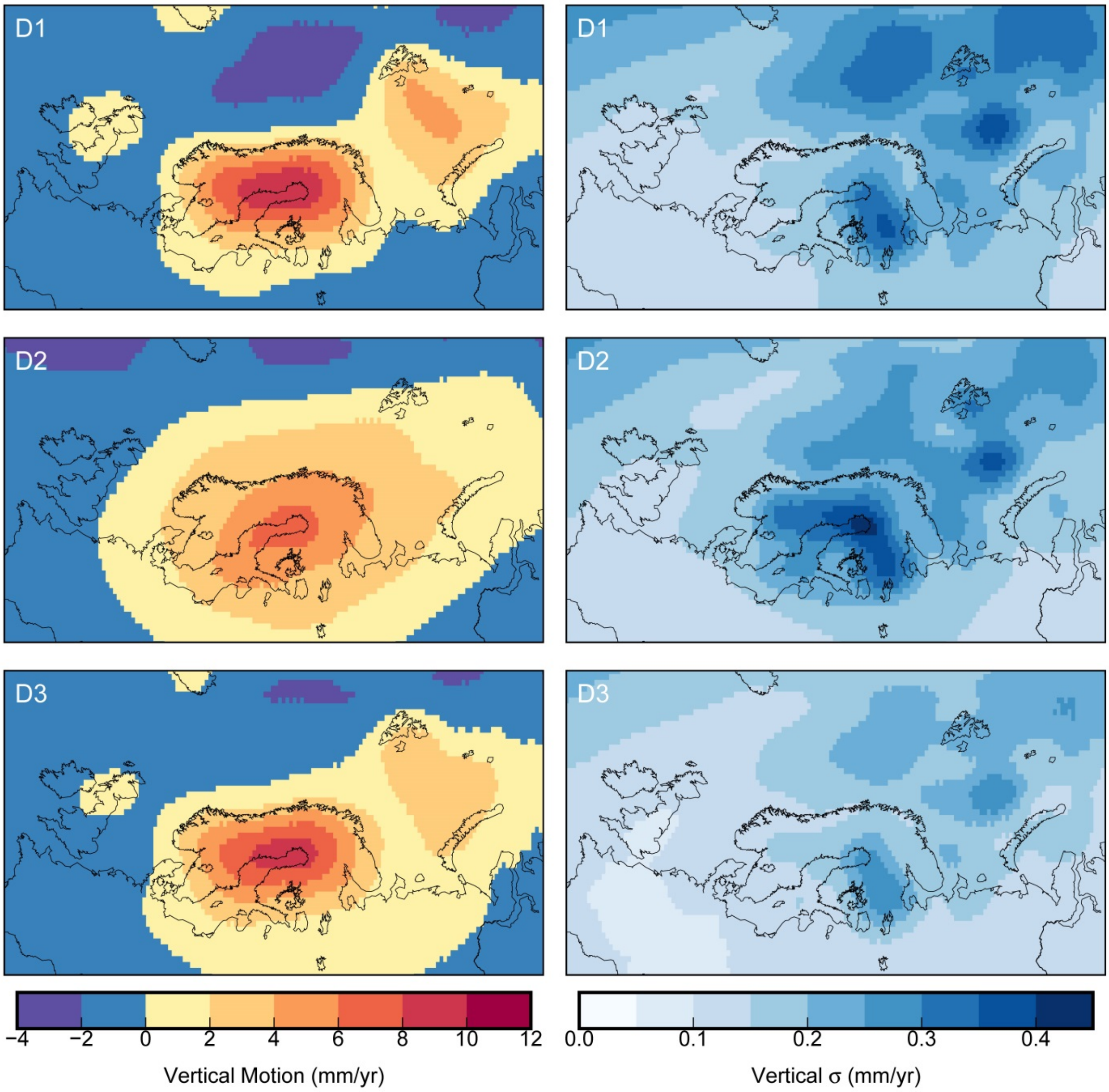


Figure 6. Prediction of present-day vertical land motion (left) and uncertainties (right) due to long-term GIA for the D1-D3 scenarios.

Data Incorporated	σ^2 Squared Value			Ratios	
	σ_1^2 (Vertical)	σ_2^2 (Gravity)	σ_μ^2 (Prior)	σ_1^2/σ_2^2	σ_1^2/σ_μ^2, σ_2^2/σ_μ^2
D1: Vertical only	0.85	-	0.94	-	0.~~92~~90, -
D2: Gravity only	-	13.51	0.61	-	-, 22.~~02~~15
D3: Vertical+Gravity	1.02	20.55	0.64	0.05	1.~~60~~59, 32.~~29~~11

Table 2. Results of the variance component analysis. $\sigma_1^2$and σ_2^2 are the variance factors applied to the vertical motion data (dataset 1) and gravity change data (dataset 2), respectively, and σ_μ^2 is the

variance factor applied to the prior information. The ratios describe how each input covariance matrix is weighted relative to the other(s).

3.2 Misfit Values and Residuals

For both χ^2 and RMS values, the D1 model provides the best fit to the vertical data, the D2 model provides the best fit to the gravity data, and the D3 model provides the best fit overall (**Figure 7**). The χ^2 values of the vertical prediction for both D1 and D3 are approximately equal to 1. The χ^2 values for the gravity data are relatively large with the smallest value of 15.9 obtained for the D2 model. Scaling the gravity data uncertainties by the VCE-determined scaling factors in **Table 2** reduces the overall χ^2 values for the gravity prediction to approximately 1.2 for the D2 and D3 models. However, the statistical fit of the models to the gravity data remains generally worse than the fit to the vertical motion data.

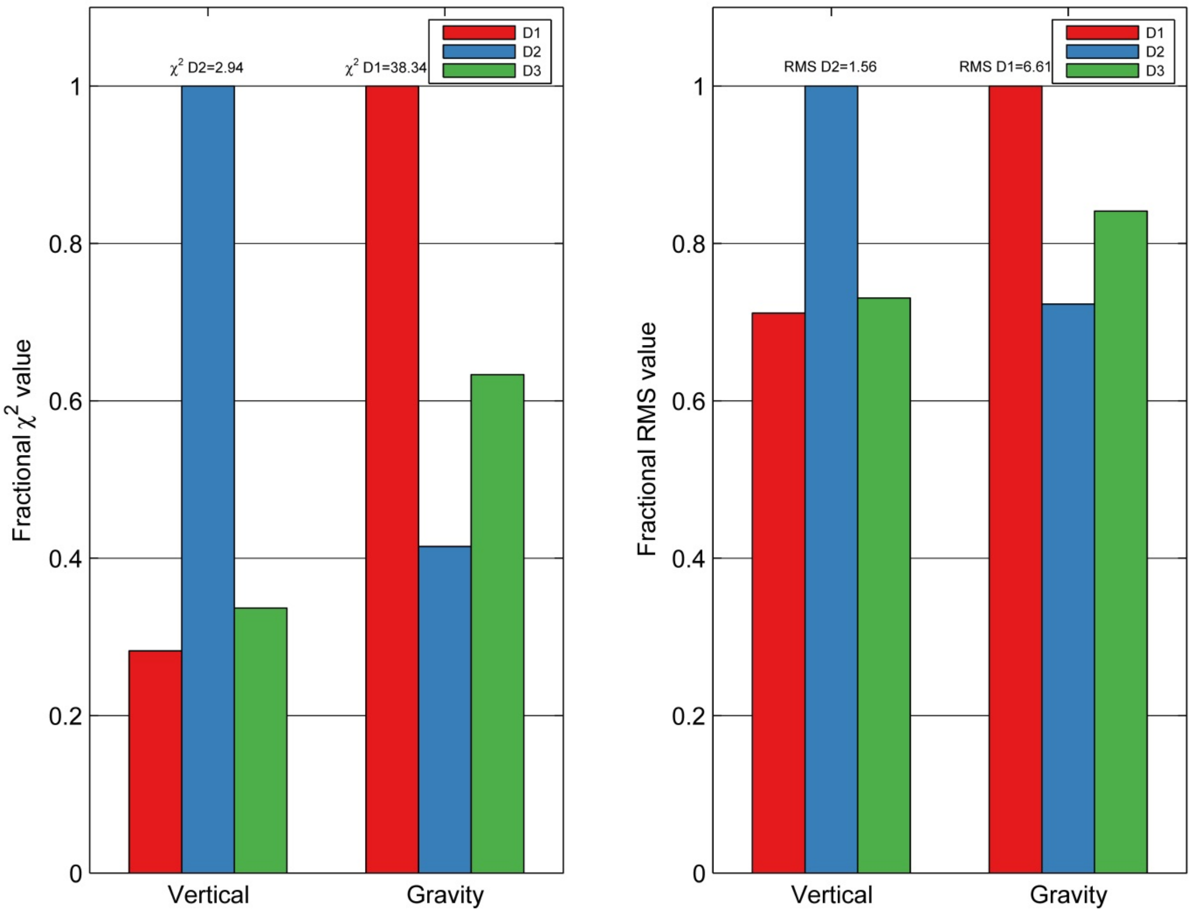


Figure 7. Fractional χ^2 and RMS values for each of the D1-D3 models. Fractional values are determined relative to the value of the worst fitting model for both the vertical motion and gravity change predictions (i.e., fractional χ^2 values of the vertical motion prediction are relative to D2 for

which χ^2 = 2.94). χ^2 values are not VCE-scaled; see **Figure 8** for all χ^2 values including with and without VCE scaling, where applicable.

Figures 8-9 summarize the spatial residuals for the best-fit D3 model and the binned residuals for all models. The vertical motion residuals are unbiased and generally small. Regionally, the D3 model underpredicts vertical motion in Scotland and conversely overpredicts vertical motion along parts of the southern Norwegian coast and the Netherlands. The gravity residuals for D3 are relatively low for much of the study area, although there is noticeable overprediction in central Scandinavia and in the Barents Sea.

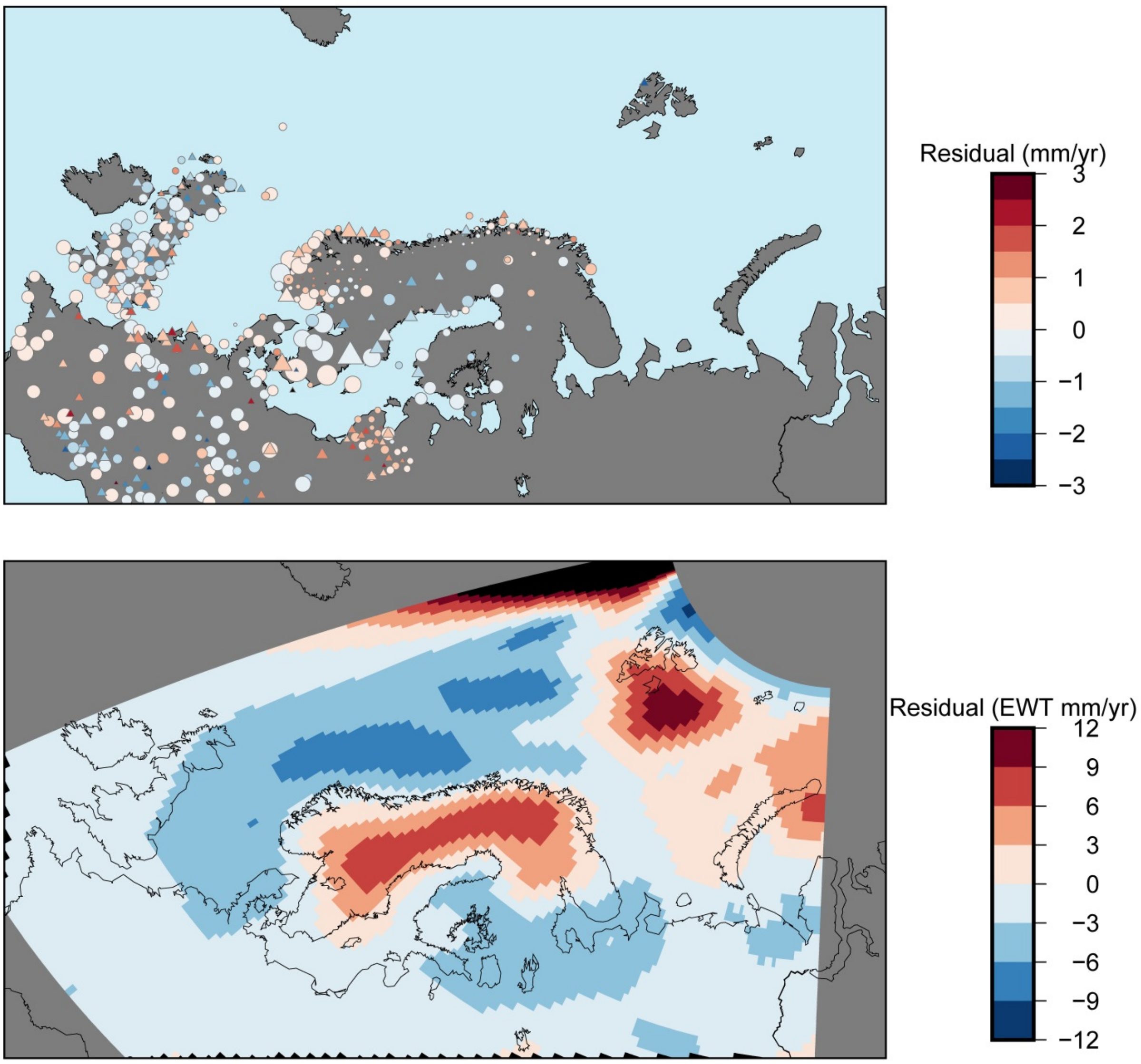


Figure 8. Spatial residuals for the D3 model for vertical motion (top) and gravity change (bottom). In top panel, triangles indicate model prediction is outside the 1σ uncertainty of the measurement, circles indicate model prediction is inside the 1σ uncertainty of the measurement.

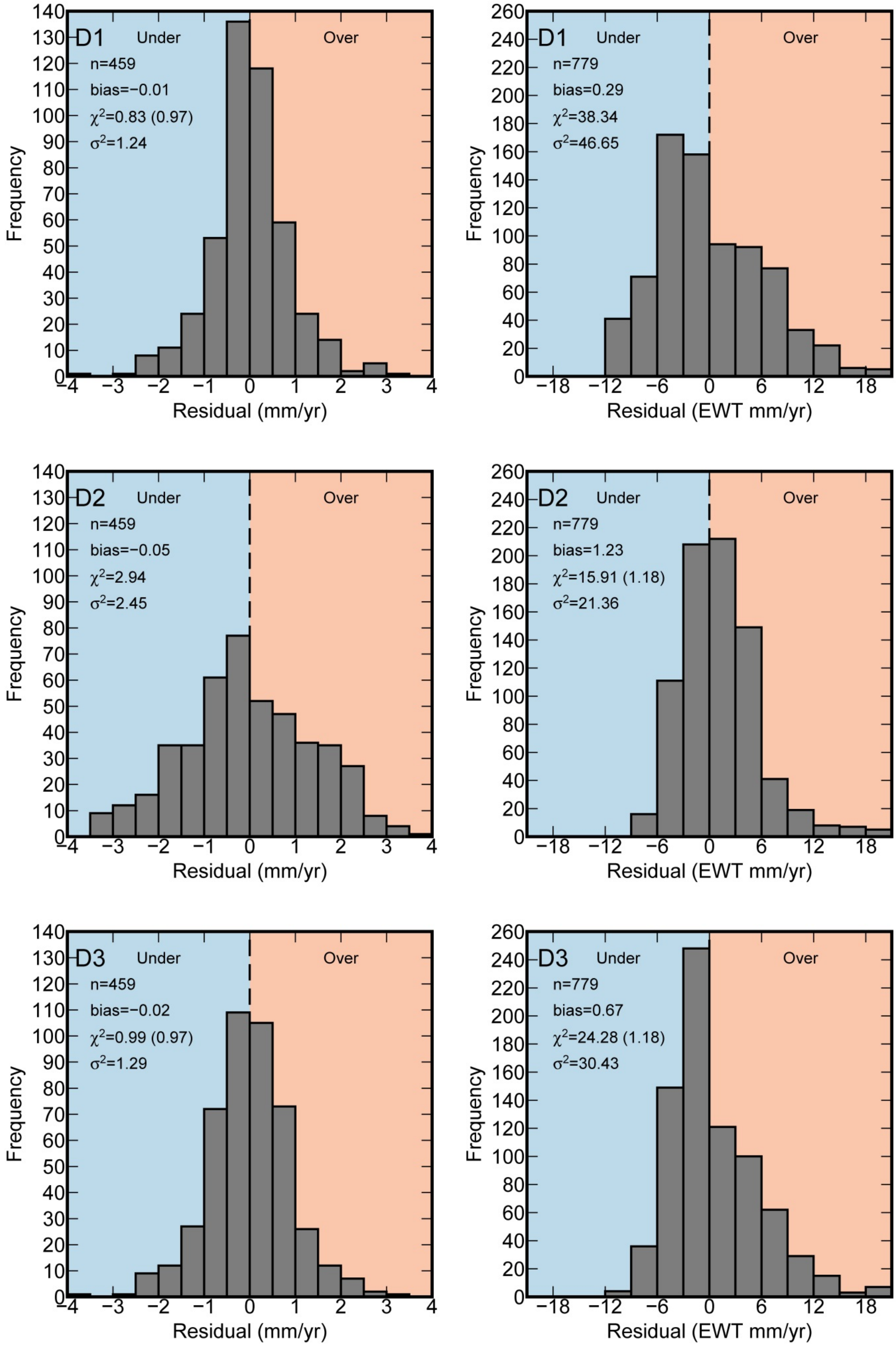

D1
Under
Over
n=459
bias=−0.01
χ2=0.83 (0.97)
σ2=1.24
Frequency
Residual (mm/yr)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
−4 −3 −2 −1 0 1 2 3 4
D1
Under
Over
n=779
bias=0.29
χ2=38.34
σ2=46.65
Frequency
Residual (EWT mm/yr)
0 20 40 60 80 100 120 140 160 180 200 220 240 260
−18 −12 −6 0 6 12 18
D2
Under
Over
n=459
bias=−0.05
χ2=2.94
σ2=2.45
Frequency
Residual (mm/yr)
D2
Under
Over
n=779
bias=1.23
χ2=15.91 (1.18)
σ2=21.36
Frequency
Residual (EWT mm/yr)
D3
Under
Over
n=459
bias=−0.02
χ2=0.99 (0.97)
σ2=1.29
Frequency
Residual (mm/yr)
D3
Under
Over
n=779
bias=0.67
χ2=24.28 (1.18)
σ2=30.43
Frequency
Residual (EWT mm/yr)

Figure 9. Histogram of residuals for models D1-D3, for prediction of vertical motion (left) and gravity change (right). Pink and blue shading indicate model overprediction and underprediction, respectively. Where given, ~~-~~χ^2 values in brackets show the VCE-scaled χ^2 value.

3.3 Comparison of Vertical Motion Prediction to Other Models

We compare the vertical motion prediction of D1 to two other models~~ that estimate the long-term GIA signal at present-day~~. The first model is the forward GIA model ICE-6G (Peltier et al. 2015) which is constrained by a global dataset of vertical land motion measurements. The majority of the these data are GPS measurements from the global solution of JPL; within the study area of Scandinavia and northern Europe, additional measurements come from the BIFROST GPS network as well as a small number of SLR, DORIS and VLBI measurements (Argus et al. 2014, Peltier et al. 2015). The ~~first~~ second model is the semi-empirical land uplift model NKG2016LU (Vestøl et al. 2016) designed by several researchers in collaboration with the Nordic Geodetic Commission (NKG). This model is constrained with GPS-measured vertical land motion rates updated from the dataset of Kierulf et al. (2014), levelling measurements and GIA model predictions and provides a semi-empirical estimate of total present-day vertical land motion. ~~The second model is the forward GIA model ICE-6G (Peltier et al. 2015) which is constrained by a global dataset of vertical land motion measurements. The majority of the these data are GPS measurements from the global solution of JPL; within the study area of Scandinavia and northern Europe, additional measurements come from the BIFROST GPS network as well as a small number of SLR, DORIS and VLBI measurements (Argus et al. 2014, Peltier et al. 2015).~~

Figure 10 compares the vertical land motion predictions of D1, ~~NKG2016LU, and~~ ICE-6G and NKG2016LU. ~~All~~ The ICE-6G comparison~~s~~ is~~are~~ made relative to the vertical motion dataset presented in this paper, although as stated above, ~~both NKG2016LU and ICE-6G were~~it was constrained with a different variant~~s~~ of regional vertical land motion data. As well, NKG2016LU predictions are available on a smaller grid and best fits data from Scandinavia and the Baltic countries~~centred over Scandinavia~~, thus, we limit our comparison with this model to ~~within these bounds~~north of 55°N (reducing the comparison dataset from 459 to ~~280~~ 185 sites).

With no significant bias and a χ^2 value of less than 1, the D1 model provides a good fit to the data. As with the D3 model, the D1 model underpredicts vertical motion over the northern British Isles, and appears also to overpredict vertical motion around the Netherlands. ~~The NKG2016LU model has a χ^2 value of less than 1 and a bias towards overprediction of 0.13 mm/yr. The overall bias towards overprediction is small, but is persistent particularly over Scandinavia (**Figure 10**). For the region north of 55°N (so approximately Scandinavia, 185 sites), the bias of the NKG2016LU model increases to 0.42 mm/yr. This bias is most likely attributable to the elastic correction applied to our GPS dataset, which is approximately +0.2-0.5 mm/yr over Scandinavia (**Figure 3**). Without an elastic correction applied to the GPS data, the NKG2016LU model has a bias of only -0.06 mm/yr in the region north of 55°N.~~ The ICE-6G model underpredicts vertical motion at several sites in Scandinavia and has an overall χ^2 value of 1.33, somewhat higher than that of ~~either~~ D1 ~~or NKG2016LU~~. At station NYAL on Svalbard, both the D1 and ICE-6G models underpredict vertical motion by more than 2 mm/yr, even after the applied corrections for present-day mass loss and possible LIA uplift. When the NKG2016LU model is evaluated relative to the GPS data without an elastic correction applied, the χ^2 value is less than 1, similar to D1. **Figure 10** shows the difference in the prediction of vertical motion between NKG2016LU and D1. The former has consistently higher predicted uplift rates over the study area, with an average difference of +0.3 mm/yr., which is ~~This difference is~~ primarily the result of applying the elastic correction to the data used in the D1 model. ~~;~~ D1 is therefore to the extent that is possible, an estimate of the paleo GIA signal rather than the total uplift signal. That the statistical fit to the data of both D1 and NKG2016LU is slightly better than the fit of the ICE-6G forward model is expected due to the fundamental difference in model type: unlike ICE-6G, both of the semi-empirical models explicitly incorporate the data into the prediction via formal inversion. Conversely, an advantage of ICE-6G and other models of its type is the direct insight they offer into the space-time evolution of the ice sheets, which cannot be inferred from a present-day empirical prediction alone.

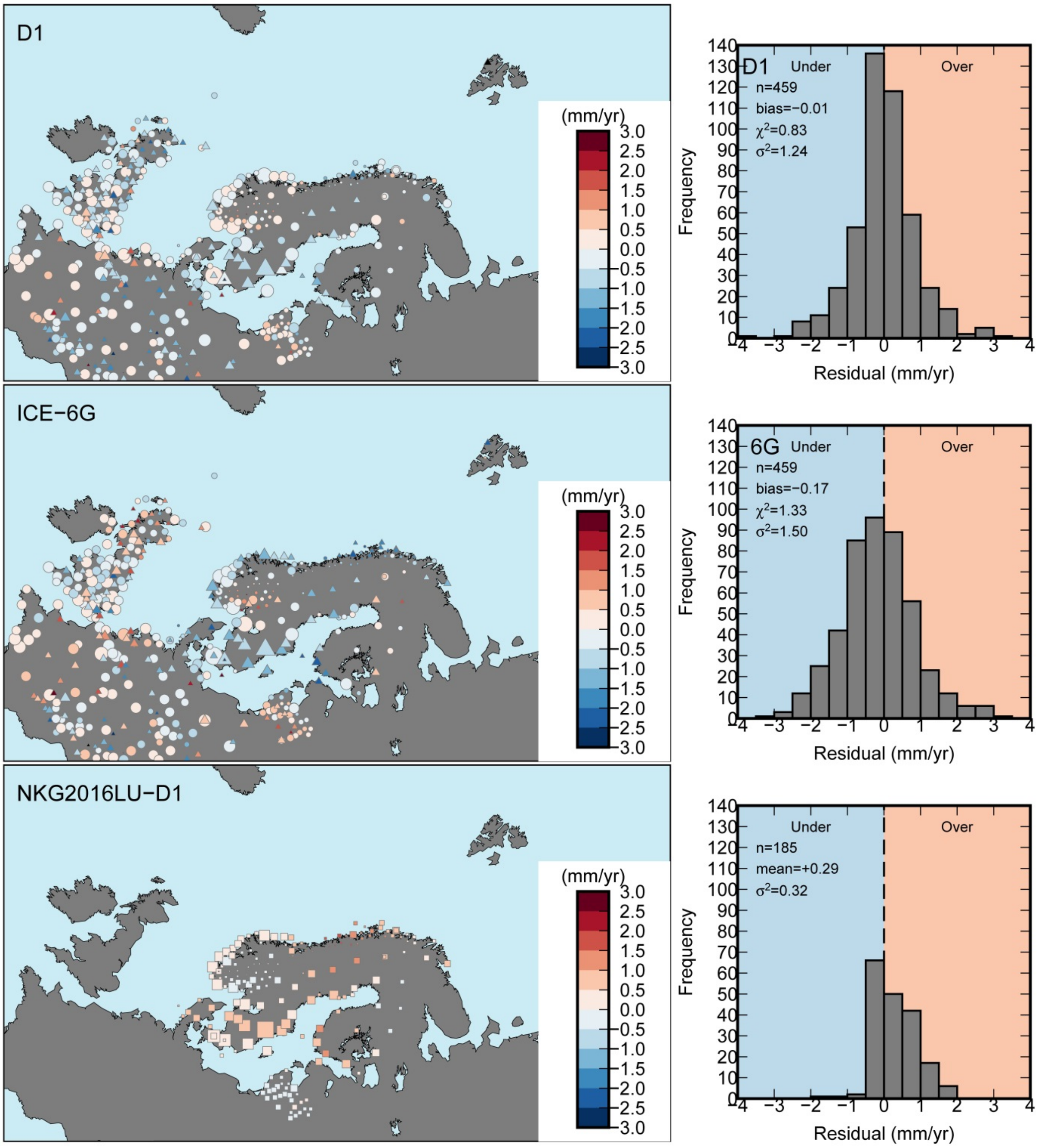


Figure 10. Spatial (left) and binned (right) vertical motion residuals for ~~the~~ D1 and ICE-6G and the difference between the NKG2016LU and D1~~, NKG2016LU and ICE-6G~~ models ~~(the latter two are abbreviated 'NKG' and '6G' in right-hand plots)~~. Triangles indicate model prediction is outside the 1σ uncertainty of the measurement, circles indicate model prediction is inside the 1σ uncertainty of the measurement, squares show the difference between the two models (bottom left).~~.~~

3.4 Tide Gauge Comparison

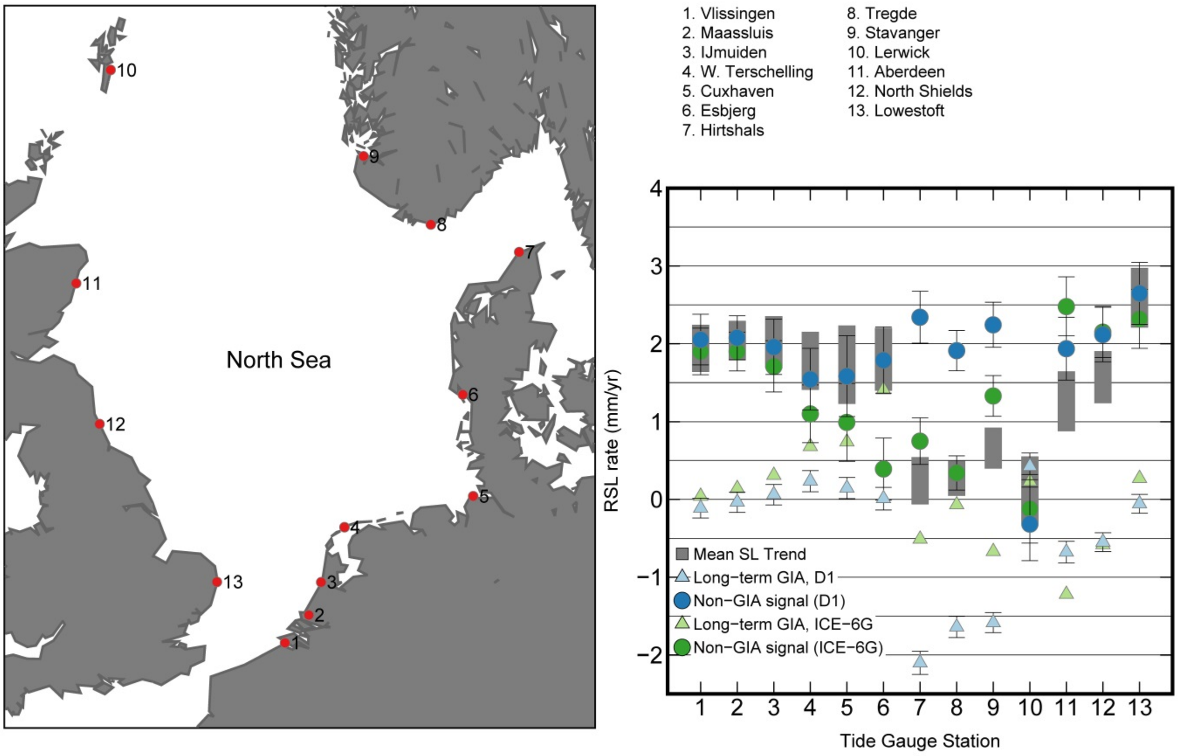
To assess the effect of GIA on regional sea-level change, we remove model D1's predictions of long-term GIA from mean sea-level trends at ~~17~~ 13 tide gauge sites along the coast of the North Sea and 7 tide gauge sites along the Norwegian coast (**Figures 11, 12**). The ~~mean~~ sea-level trends are taken from Frederikse et al. (2016~~a~~) who estimated the rates at ~~for both regions~~Permanent Service for Mean Sea Level (PSMSL) sites over the time interval 1958-2014. We also compare the effect of removing the modelled relative sea-level rates of ICE-6G at the same PSMSL locations. ~~developed a state-space model to compute time-varying trends in tide gauge records, thereby taking into account unexplained (multi-) decadal variability. The rates shown here are for the time interval 1980-2013 and are averaged time-varying trends from Model C of Frederikse et al. (2016a), which removes decadal variability from the tide gauge time series (1980-2013) using a hydrodynamic model developed to predict storm surge heights along the North Sea coast.~~ For both the North Sea and the Norwegian coastline, application of the D1 long-term sea-level trends to the total sea-level trends reduces the interstation variability and infers a similar rate of non-GIA sea-level change (1.89 mm/yr and 1.84 mm/yr respectively).

North Sea

When corrected for the D1 long-term GIA trends, which are assumed to be linear over decadal time-scales, the standard deviation of the trends decreases somewhat from ~~1.08~~0.81 mm/yr to 0.~~89~~71 mm/yr. The D1 GIA correction is small at most sites, and at all sites except ~~10 and 11~~7-9 (Hirtshals, ~~and~~ Tregde and Stavanger), the averaged sea-level trends appear dominated by processes other than long-term GIA (**Figure 11**). At Hirtshals, ~~and~~ Tregde and Stavanger, which are located nearest to the centre of the former FIS, the predicted GIA-induced sea-level trend is more than twice the magnitude of the averaged sea-level trend and removing the GIA signal shifts the original trend at these locations closer to the mean of the ~~17~~ 13 locations. When the ICE-6G rates are removed from the sea-level trends, the interstation variability and standard deviation (from 0.81 mm/yr to 0.83 mm/yr) are relatively unchanged. Regionally, the average D1 GIA model trend is ~-0.45 mm/yr for the North Sea which is larger in magnitude than the ICE-6G GIA trend of ~0.06 mm/yr in the North Sea~~.~~. ~~sea-level analysis of Frederikse et al. (2016b), which was derived from ICE-6G; this~~ This difference may in part be due to the influence of the ANU ice sheet model in the prior model, which predicts stronger subsidence over the North Sea than either ICE-5G or ICE-6G. Accordingly, removal of the GIA signal from all 13 locations changes the North Sea mean sea-level trend from 1.39 mm/yr to 1.84 mm/yr for D1 and to

1.33 mm/yr for ICE-6G. Station Lerwick is particularly ~~problematic~~discrepant; removing it from the comparison decreases the standard deviation of the non-GIA rates to 0.45 mm/yr for D1 and 0.75 mm/yr for ICE-6G.

~~Removal of the GIA signal from all 17~~ 13 ~~locations increases the North Sea mean sea-level trend from 1.31~~ 39 ~~mm/yr to 1.58 mm/yr The GIA-corrected rates at 4 sites along the British Isles coastline (12, 13, 14 and 16) fall outside the standard deviation of the mean corrected rate. In the northern British Isles, around sites 13 and 14 (Wick and Aberdeen), model D1 underpredicts the magnitude of vertical motion and thus also the magnitude of relative sea-level change. However, even if the magnitude of RSL fall were larger in this region by up to 0.5 mm/yr, the GIA-corrected sea-level rates at Wick and Aberdeen would remain outside the standard deviation of the mean. At station Wick, the sea-level trend is particularly variable and non-linear at decadal scales (Frederikse et al. 2016a), suggesting that one averaged time-varying rate cannot be expected to adequately describe sea-level variation at this location. At any rate, such~~The variability at Lerwick is insensitive to application of the relatively small and linear GIA correction for this region and ~~it appears unlikely that the variability in sea-level trends along the British coast~~ cannot be explained by GIA-induced sea-level change. Conversely, the variability in sea-level trends in the northeast North Sea, near the former FIS, is easily attributed to GIA for model D1.



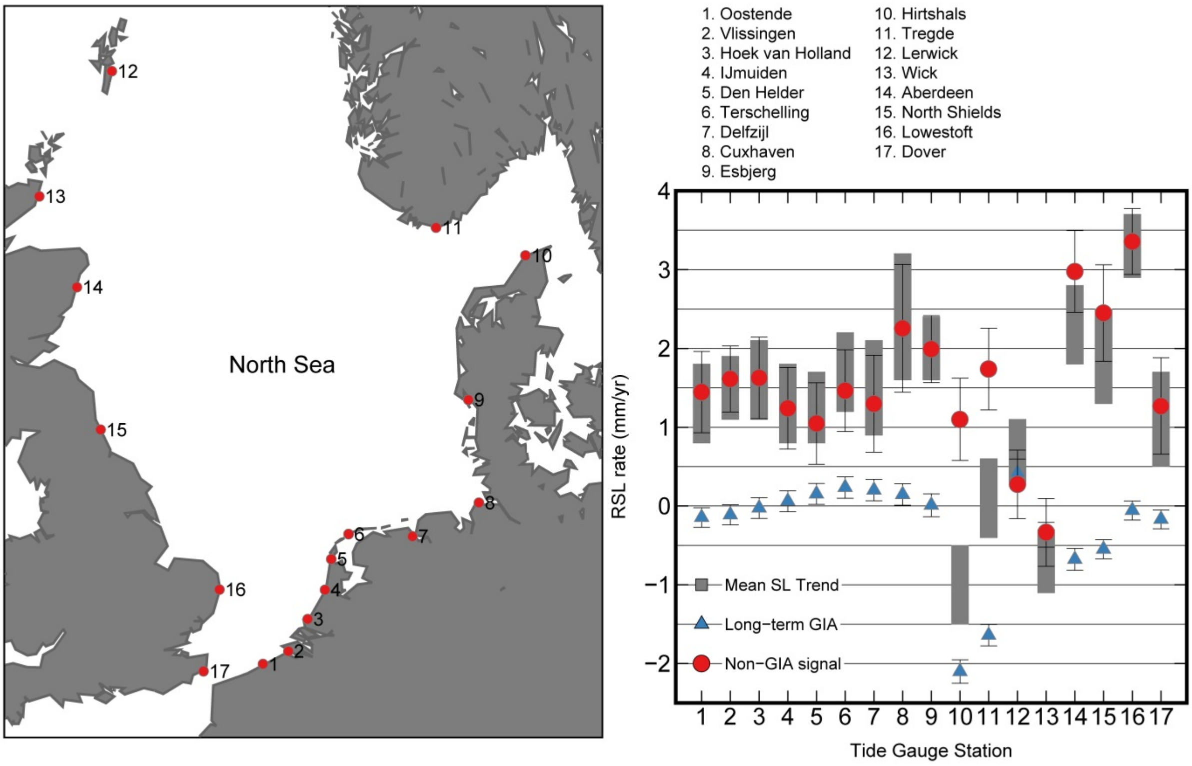


Figure 11. Comparison of mean total, long-term GIA and non-GIA sea-level trends (grey boxes, ~~blue~~ triangles, ~~red~~ circles) for ~~17~~ 13 tide gauge stations in the North Sea. Long-term GIA trends are from model D1 and ICE-6G, mean sea-level trends are from ~~Model C of~~ Frederikse et al. (2016~~a~~).

Norwegian Coast

The average sea-level trend for the 7 sites along the Norwegian coast is -0.22 mm/yr with a standard deviation of 0.87 mm/yr. Removal of the D1 long-term GIA trends increases~~,~~ the average sea-level trend to ~~is~~ 1.89 mm/yr and reduces the interstation variability ~~is reduced~~ (0.44 mm/yr standard deviation) (**Figure 12**). The same is true for ICE-6G, although the magnitude of the changes are smaller (0.44 mm/yr ~~average~~mean, 0.65 mm/yr standard deviation). This difference is owing to the relatively larger average GIA-related relative sea-level change for D1 (-2.11 mm/yr) compared to ICE-6G (-0.66 mm/yr). The gradient of predicted GIA changes across the Norwegian coastline is steep, so the results may also be sensitive to the resolution of the GIA models.

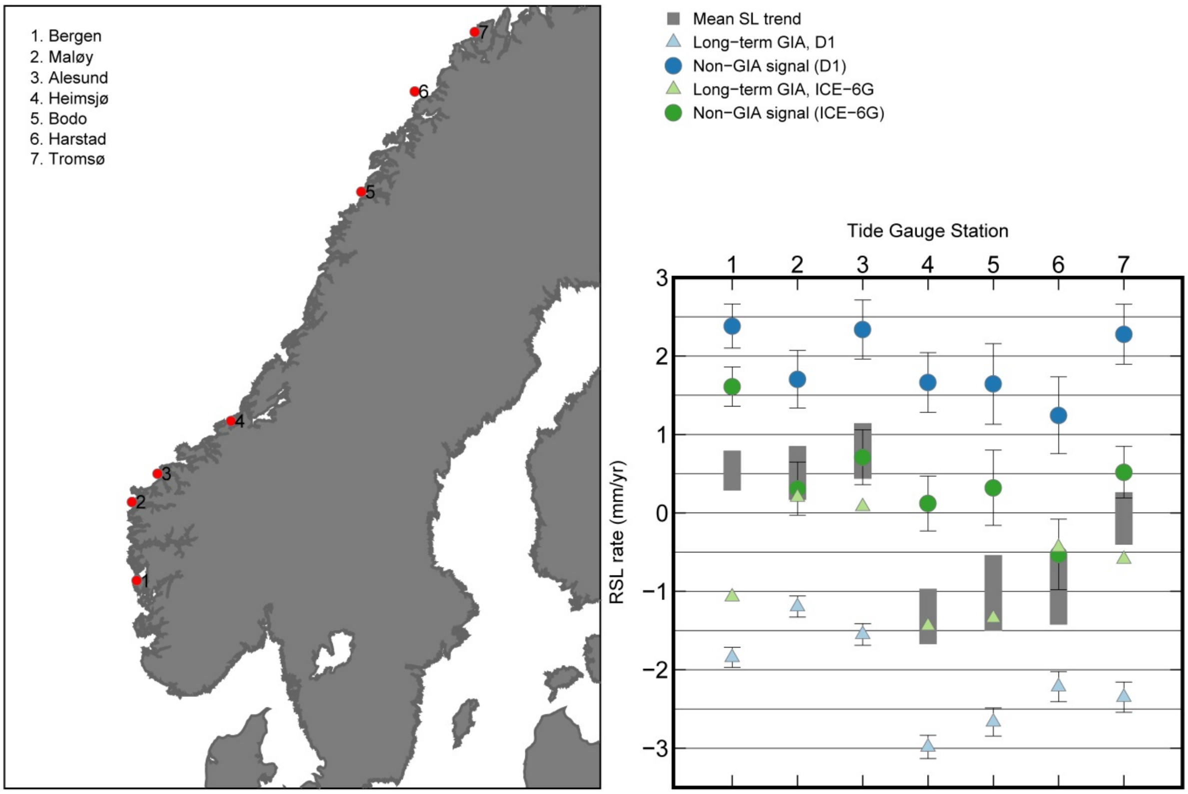


Figure 12. Same as caption for Figure 11, except for tide gauge locations along the Norwegian coastline.

4. Conclusion

We generate a data-driven prediction of the long-term GIA response at present-day in Scandinavia, northern Europe and the Barents Sea through the simultaneous inversion of GPS-measured vertical motion rates, GRACE-measured gravity change rates, and *a priori* GIA model information. In models D1-D3, we predict GIA motions for the inversion of the vertical motion data, the gravity data, and both datasets. In both the χ^2 and RMS sense, the vertical motion data alone have the poorest ability to predict gravity change, and vice versa. Predictions of the D3 model provide the best overall fit to both datasets.

In general, prediction of the gravity signal is problematic, with larger χ^2 values than those obtained for the vertical motion prediction. The poorer prediction of gravity change is in part due to the uncertainty of the present-day mass loss effect in the Barents Sea region. The mass loss signal estimated by GRACE over Svalbard and the Russian Arctic is significantly smaller than estimates obtained from satellite altimetry. This difference may be the result of signal loss in the GRACE data from application of the Wiener filter or may also indicate that there is a non-zero component of ongoing glacial isostatic adjustment from the LIA.

The vertical motion signal is overall better predicted than the gravity signal. Both the D1 and D3 models have χ^2 values of ≤ 1 and predict rates of vertical motion that are within the 1σ uncertainty of the observations throughout most of the study area. Regions of misfit persist in Scotland and around the Netherlands, where the model underpredicts and overpredicts rates of vertical motion, respectively. The misfit in Scotland may be partly due to both positive and negative rates of vertical motion that are present in the data over relatively short distances. Further analysis and filtering of the GPS dataset may be useful in this region. In the Netherlands, Kooi et al. (1998) found that present-day subsidence from sediment compaction as well as tectonic movements may contribute significantly to vertical land motion; correction for these effects may serve to reduce some of the ~~misfit~~ residuals in this region. There may also be significant neotectonic movements in central Norway (Kierulf et al. 2014), which may explain some of the misfits that remain ~~in that region.~~mainly along the central Norwegian coastline (**Figure 8**).

The prediction of vertical land motion has a small but non-negligible sensitivity to the application of an elastic correction. The elastic correction applied in this study is between 0.2-0.5 mm/yr; the largest contribution comes from mass loss of the Greenland Ice Sheet which yields regional uplift with a southeastward decreasing gradient. When the model predictions from another semi-empirical model of ~~GIA~~ vertical motion, NKG2016LU, are compared to ~~the corrected GPS data~~D1, a small but relatively uniform ~~bias~~ difference of +0.~~42~~ 3 mm/yr is present in the model predictions over Scandinavia. ~~Conversely, when D1 model predictions generated with the corrected data are compared to the uncorrected data from the same region, a uniform bias of -0.35 mm/yr is present, consistent with expectations.~~ Both NKG2016LU and D1 (and D3) have vertical motion χ^2 values ≤ 1 over their respective study areas. However, while the magnitude of the ~~bias~~ difference is smaller than the observational uncertainty on many of the measurements, it is generally larger than the estimated *a posteriori* model uncertainty. Also, because only anthropogenic hydrological signals (and not natural hydrological signals) were included in the elastic correction, it is ~~likely~~ possible that the applied elastic correction is conservative in this region.

Therefore, the presence of such a ~~bias~~ difference in the vertical motion prediction suggests that while long-term GIA is the dominant contributor to vertical motion in central Scandinavia, that it is still worthwhile to correct GPS land motion rates for present-day elastic signals, so long as these signals are adequately approximated (e.g., Riva et al. 2017). This conclusion however highlights a fundamental assumption that underpins the data-driven methodology: that the input data can be adequately 'cleaned' for processes not arising from long-term GIA. Even with applied corrections for hydrology and contemporary ice mass loss, this assumption may not always be adequate, especially in regions where model misfits relative to the data are spatially coherent. Thus, the success of data-driven GIA predictions are evaluated by two criteria: i) the estimation of realistic *a posteriori* uncertainties that are smaller than those associated with *a priori* knowledge and measurement uncertainty, and ii) the ability of the final model to provide a good fit to the data. The vertical motion predictions of models D1 and D3 satisfy both criteria for most of the study area and thus can provide a useful tool with which to separate long-term GIA signals from shorter-term forcing.

Data Availability

Gridded vertical land motion predictions for the D1 model are available at the 4TU Centre for Research Data repository, https://data.4tu.nl/, doi:10.4121/uuid:4a495bbc-0478-483a-baef-19ff34103dd2.

Appendix

The 31 GPS measurements that are common to the Kierulf et al. (2014) and Nevada Geodetic Laboratory (Blewitt et al. 2016) datasets are shown in **Figure A1**. The individual anthropogenic hydrology and glacial mass change contributions to the GRACE correction are shown in **Figure A2.**

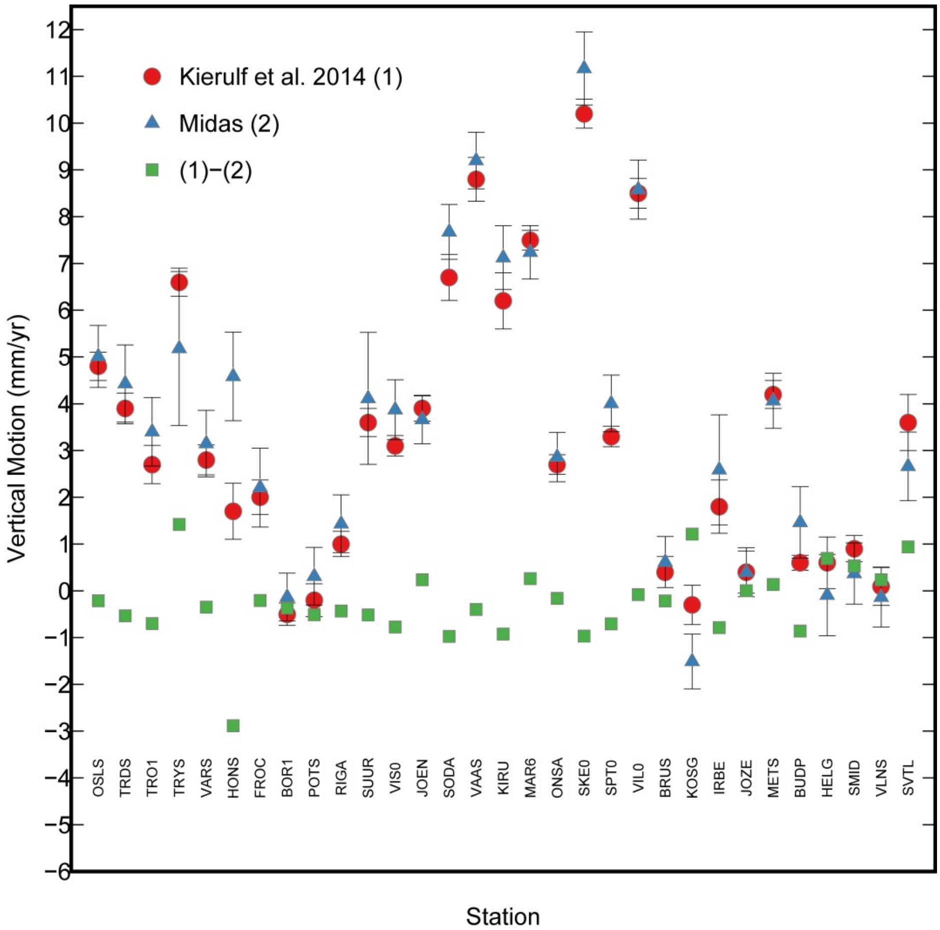


Figure A1. Vertical land motion measurements at 31 sites common to both datasets used in this study.

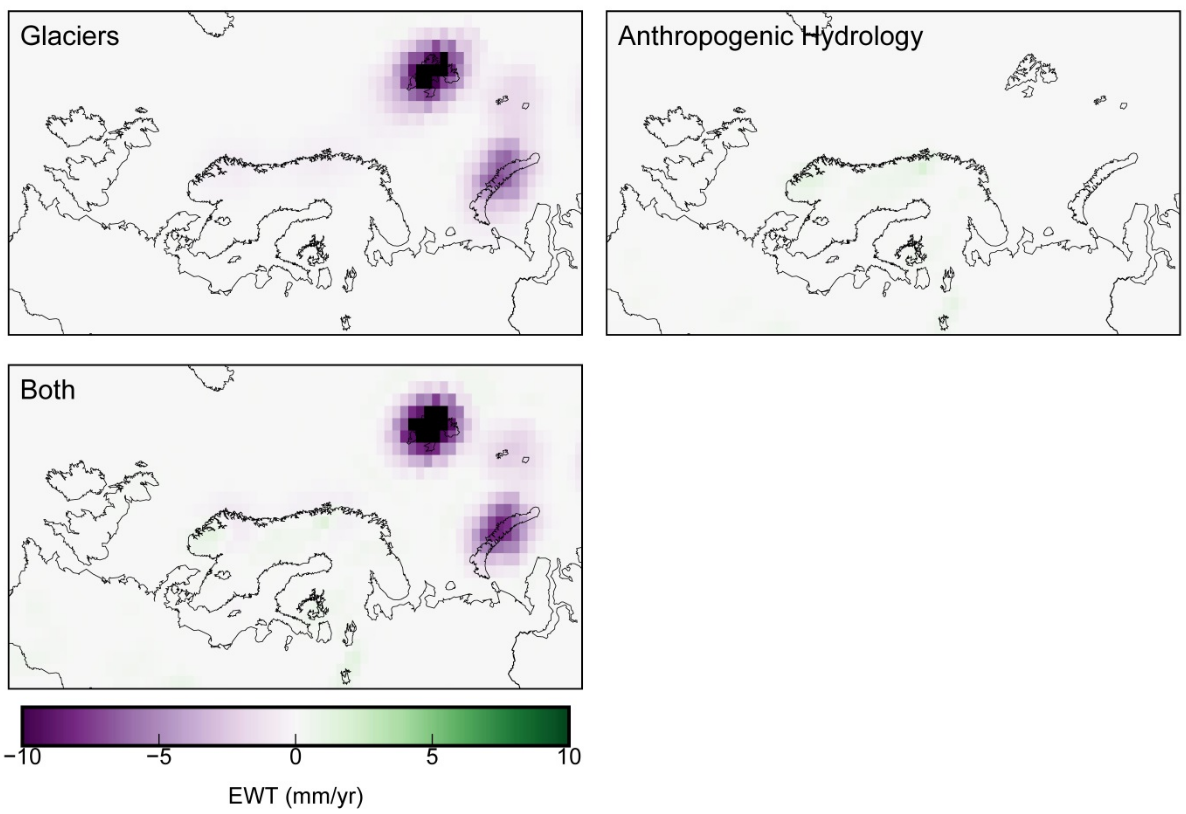


Figure A2. Individual and combined contributions to the correction applied to the GRACE data (combined is the same as **Figure 2c**).

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