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Key Points:

- Early 21st century ice-mass loss generates a global pattern of 3-D crustal motion
- Deformation driven by melting of Greenland Ice Sheet and Arctic glaciers extends across the Northern Hemisphere
- Far-field motions are several tenths of a millimeter per year, with horizontal rates often exceeding vertical rates

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Global Fingerprint of Modern Ice-Mass Loss on 3-D Crustal Motion

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Abstract Crustal motion generated by rapid ice-mass loss from Earth's glaciers and ice sheets has previously been considered in Global Navigational Satellite System (GNSS) analyses and numerical models across regions of ice retreat. However, the fingerprint of ice-mass loss is not limited to glaciated areas, but is characterized by a global pattern of 3-D crustal deformation. We compute “far-field” vertical and horizontal deformation rates that occurred in response to early 21st century mass flux from the Greenland and Antarctic Ice Sheets, global glaciers and ice caps, and associated ocean loading. We demonstrate that mass changes in the Greenland Ice Sheet and high latitude glacier systems each generated average crustal motion of 0.1–0.4 mm/yr across much of the Northern Hemisphere, with significant year-to-year variability in magnitude and direction. Horizontal motions associated with ice-mass loss exceed vertical rates in many far-field areas, and both should be considered in future analysis of GNSS measurements.

Plain Language Summary As ice sheets and glaciers melt and water is redistributed to the global oceans, the Earth's crust deforms, generating a complex pattern of 3-D motions at Earth's surface. In this study, we use satellite-derived constraints on early 21st century ice-mass balance of the Greenland and Antarctic Ice Sheets and a global database of mountain glaciers and ice caps, to predict how the crust has deformed over the last two decades. We show that, rather than only being localized to regions of ice loss, melting of the Greenland Ice Sheet and Arctic glaciers has caused significant horizontal and vertical deformation of the crust that extends over much of the Northern Hemisphere. This 3-D surface motion is on average several tenths of a millimeter per year, and it varies significantly year-to-year. We conclude that future work analyzing measurements of crustal motion (across various fields in Earth science) should correct for the deformation associated with modern ice-mass loss at sites distant from melting ice.

1. Introduction

The global rate of ice-mass loss has increased dramatically since the turn of the century, with loss of grounded ice from the Antarctic Ice Sheet (AIS), the Greenland Ice Sheet (GrIS) and mountain glaciers increasing by ~60% through the 2010s relative to the previous decade (Slater et al., 2020). In addition to being a key contributor to the recent acceleration of global mean sea-level rise (Church et al., 2013) and regional variability in sea-level change (Hay et al., 2015; Mitrovica et al., 2001; Tamisiea et al., 2003), this redistribution of mass between continents and oceans results in significant and time-varying crustal deformation. With the advent and improvement of relatively low-cost Global Navigational Satellite System (GNSS) surveying, it was quickly recognized that geodetic measurements of crustal uplift in the vicinity of ice-mass loss could be an important tool in efforts to monitor the mass balance of ice sheets and glaciers in a progressively warming planet (Hager, 1991).

Following the suggestion of Hager (1991), an extensive body of literature has developed involving the collection and/or analysis of crustal deformation rate measurements at sites proximal to ice sheets (e.g., Barletta et al., 2018; Bevis et al., 2012; Martín-Español et al., 2016, 2017; Nield et al., 2014; Nielsen et al., 2013; Simpson et al., 2011; Spada et al., 2012; Thomas et al., 2011; Zhao et al., 2017), and glaciers (e.g., Auriac et al., 2013; James et al., 2009; Richter et al., 2016; Sato et al., 2011). The goals of these studies have varied, but have commonly ranged from observation-validated modeling of localized uplift (e.g., Martín-Español et al., 2016; Simpson et al., 2011; Spada

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et al., 2012; Thomas et al., 2011), to estimating local mass balance (e.g., Martin-Español et al., 2017; Nielsen et al., 2013). As the field has advanced, studies have elucidated more complex processes; authors have focused on constraining regional viscoelastic Earth structure (e.g., Barletta et al., 2018; James et al., 2009), and disentangling deformation signals driven by modern-day ice-mass loss from those associated with ongoing glacial isostatic adjustment (GIA) in response to the last deglaciation (e.g., King et al., 2010; Spada et al., 2012; Wake et al., 2016).

However, the impacts of ice-mass loss on the Earth system have a global reach. So-called “far-field” effects (which we loosely define as those that occur at a distance beyond ~1000 km from the ice-mass loss) have long been recognized in GIA studies of sea-level change (e.g., Lambeck et al., 2014; Mitrovica & Milne, 2002; Peltier & Andrews, 1976; Wu & Peltier, 1983) and crustal deformation (e.g., James, 1991; James & Lambert, 1993; Latychev et al., 2005; Mitrovica et al., 1994b). Moreover, in the context of modern global change, the rapid melting of ice sheets and glaciers drives significant, global-scale geographic variability in sea-level change (and its two bounding surfaces - the sea surface and solid earth surface) that have come to be known as sea-level fingerprints (e.g., Clark & Lingle, 1977; Mitrovica et al., 2001; Plag & Juettnner, 2001).

The study of Tamisiea et al. (2003) was the first to predict the global scale fingerprints of modern ice-mass loss from the Greenland and Antarctica Ice Sheets on vertical land motion (henceforth VLM). More recently, Riva et al. (2017) compiled estimates of ice-mass changes in Greenland, Antarctica and mountain glaciers through the last century, and predicted VLM of several tenths of a millimeter per year across large continental areas. Patterns of VLM associated with modern ice-mass loss have since been observed in GNSS datasets, and have been estimated and corrected for in these data as well as in tide gauge measurements (Schumacher et al., 2018; Frederikse et al., 2019). Both predictions and observations of VLM from modern ice-mass loss indicate large temporal variability, over time periods of several years, as well as significant spatial variability (Frederikse et al., 2019; Riva et al., 2017). Finally, Ludwigsen et al. (2020) demonstrated that the VLM signal of Arctic ice-mass loss reached amplitudes of 0.5–1.0 mm/yr over the 2003–2015 time period across high latitude polar regions.

Despite the recent emphasis placed on accurately modeling and analyzing VLM driven by modern ice-mass loss, no previous studies have estimated the accompanying horizontal crustal motions. This omission is surprising given that published work on GIA-induced crustal deformation (e.g., James, 1991; James & Lambert, 1993; Latychev et al., 2005; Mitrovica et al., 1994b) indicate that horizontal motions can exceed their vertical counterparts in far-field regions, and, additionally, uncertainties in GNSS estimates of the former are typically a factor of ~2–3 smaller than the latter. Generating models that match observations of horizontal motion due to ongoing GIA has been an outstanding problem in several regions. For example, while calculations in Scandinavia based on 1-D viscoelastic Earth models have accurately reconciled 3-D crustal deformation rates estimated from the BIFROST GNSS network (e.g., Johansson et al., 2002; Milne et al., 2001; Milne et al., 2004), analogous GIA model-data comparisons for North American sites away from tectonic influence have yielded good fits to vertical rates but large misfits in the horizontal component of deformation (Argus et al., 1999; Sella et al., 2007). There is evidence that these misfits may arise from limitations in simplified Earth models used in the GIA simulations (Latychev et al., 2005; Peltier & Drummond, 2008), but a full understanding of the cause of these residuals has yet to emerge.

Herein, we present global predictions of 3-D crustal motions in response to mass changes in polar ice sheets and glaciers over the early 21st century, though we focus our discussion on the far-field signal. Our calculations include the associated sea-level changes in specifying the full surface mass load.

2. Predictions of 3-D Crustal Motion

Our predictions of three-dimensional deformation arising from surface ice-mass and ocean loading adopt a spherically symmetric (i.e., depth varying) Earth model. The calculations are based on elastic Love number theory (Farrell, 1972; Mitrovica et al., 1994a). We adopt the elastic and density structure of the Earth given by the seismic model PREM (Dziewonski & Anderson, 1981) and incorporate rotational effects using now-standard approaches (Milne & Mitrovica, 1998; Mitrovica et al., 2005). Gravitationally self-consistent sea-level changes are included using the pseudo-spectral algorithm described by Kendall et al. (2005) with a truncation at spherical harmonic degree and order 512. Crustal motions are referenced relative to an origin located at the center of mass of the deformed planet (Mitrovica et al., 1994a). To gain insight into the physics of far-field effects, we individually consider horizontal and vertical surface motions generated by recent mass loss from three of the main

contributors to modern-day sea-level rise: GrIS, AIS and a global database of mountain glaciers and ice caps. Total crustal deformation rates can be computed by simply summing these contributions, and are discussed at the end of Section 2.

2.1. Greenland

Figure 1a shows the predicted average annual surface motion in response to recent GrIS mass loss, computed using a published estimate of average mass balance from satellite altimetry datasets. Specifically, we adopt mass changes in GrIS (2003–2018) from an analysis of NASA's ICESat and ICESat-2 data given in Smith et al. (2020). This allows prediction of the average crustal motions due to ice and ocean mass changes over the 16 years time period. As explored in detail in recent literature, within south and west Greenland and bordering the ocean, average crustal uplift rates on the order of several mm/yr are predicted (e.g., Simpson et al., 2011; Spada et al., 2012). In contrast, in northeast Greenland, an area of ice accumulation, sites are predicted to subside at rates up to ~ 1 mm/yr. At slightly further distance, for example, across Iceland, Baffin Island and other sites in Arctic Canada, the average predicted uplift rates lie in the range of 0.4–1.0 mm/yr. There is a further decrease in magnitude, to 0.0–0.4 mm/yr, across the rest of Canada and 0.0–0.2 mm/yr in Fennoscandia and northern Europe. Our global predictions are characterized by minor subsidence (<0.1 mm/yr) across the equator and uplift at high southern latitudes.

Significant tangential motions are predicted across North America, the North Atlantic Ocean and northern Eurasia, with large north-south gradients in magnitude. Tangential motions largely follow an outward spoke-like trend, moving southward in the Atlantic Ocean and turning to the east and west above $\sim 40^\circ\text{N}$. Moving from northeast Canada toward the western US, the magnitude of the average horizontal rates decreases gradually from 0.3 mm/yr to less than 0.05 mm/yr. Similarly, average horizontal rates decrease from maximum values near 0.2 mm/yr in Norway to less than 0.05 mm/yr in southern Europe.

The panels of Figure 1b focus on the variability of these trends through time over North America and Europe. These predictions are calculated using maps of Greenland ice-mass change derived from GRACE gravity field coefficients (CSR, Release 6.0, University Of Texas Center For Space Research (UTCSR), 2018). Following the methodology of Harig and Simons (Bevis et al., 2019; Harig & Simons, 2012), we transform the GRACE geopotential coefficients into surface mass density, subtracting a modeled signal associated with GIA, and project the resulting fields onto a Slepian basis to reduce the signal-to-noise ratio. This allows for the calculation of gridded yearly ice histories for the period 2003–2015.

Figure 1b shows predicted crustal motions for years of relative high (2012) and low (2006) ice-mass loss. In years of high mass loss, VLM rates in northern (mainland) Canada and Scandinavia reach peaks of 0.9 and 0.7 mm/yr respectively, decreasing rapidly to the south. These VLM rates are more than double those predicted in years of low ice-mass loss from Greenland. Tangential motion also varies dramatically, reaching peak rates of 0.45 mm/yr in northernmost regions and magnitudes of 0.2–0.3 mm/yr across large sections of North America and Europe in 2012, as compared to rates of ~ 0.1 mm/yr across both continents in years of low mass loss. We note that for both high and low mass loss years, predicted horizontal motions across most of Canada and parts of Europe exceed the predicted vertical motions that have been a focus of recent geophysical literature (Frederikse et al., 2019; Ludwigsen et al., 2020; Riva et al., 2017).

2.2. Glaciers and Ice Caps

Figures 2 and 3 explore crustal motion generated by global glacier and ice cap ice-mass loss from 2003–2013. The predictions are calculated using a database of yearly mass balance for 17 glacier systems generated from observation-validated climate modeling (Marzeion et al., 2012). We pair the mass balances with static glacier outlines from the Randolph Glacier Inventory (RGI Consortium and others, 2017) to establish a complete history of glacier (and ice cap) evolution, and solve for sea-level variations to specify the full surface mass load. The global crustal motion field predicted from this exercise is largely dominated by ice-mass changes in the Arctic and northern North America.

The pattern of deformation directly surrounding the Arctic glaciers, and their effect on northern Europe, Asia and North America is shown in Figure 2. Outside of regions in close proximity to ice-mass changes, peak crustal

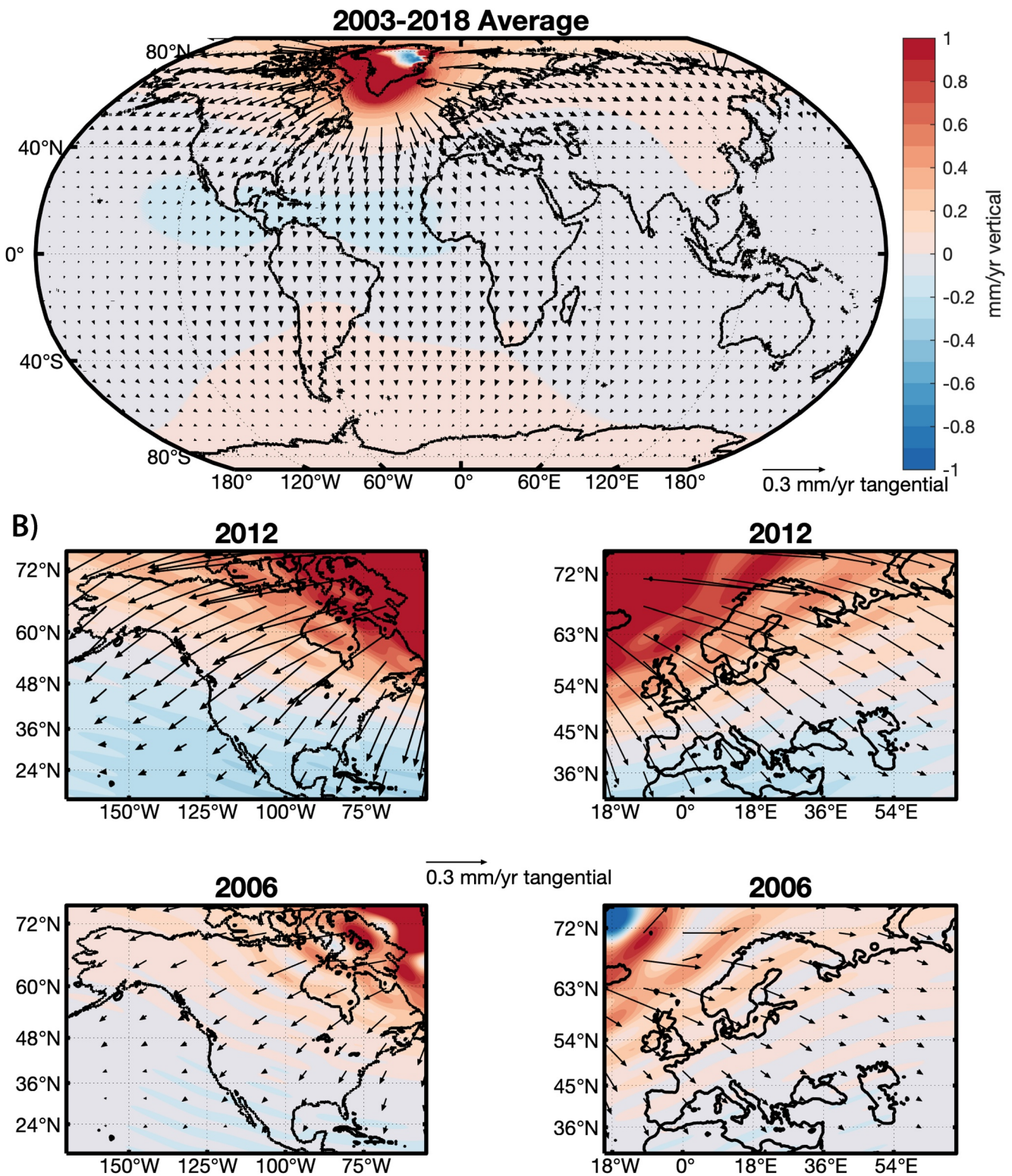


Figure 1. (a) Predicted average crustal deformation rates generated by ice-mass loss across the Greenland Ice Sheet from 2003–2018 (Smith et al., 2020). (b) Predicted crustal deformation rates across North America and Europe, in years of relatively high (2012) and low (2006) mass loss from the Greenland ice sheet. Yearly spatial ice-mass loss is inferred from an analysis of GRACE gravity data (see text). Vertical motion is given by the red-blue color scale and tangential motions are represented as arrow vectors. Tangential motions in the vicinity of Greenland are excluded in order to highlight the far-field response.

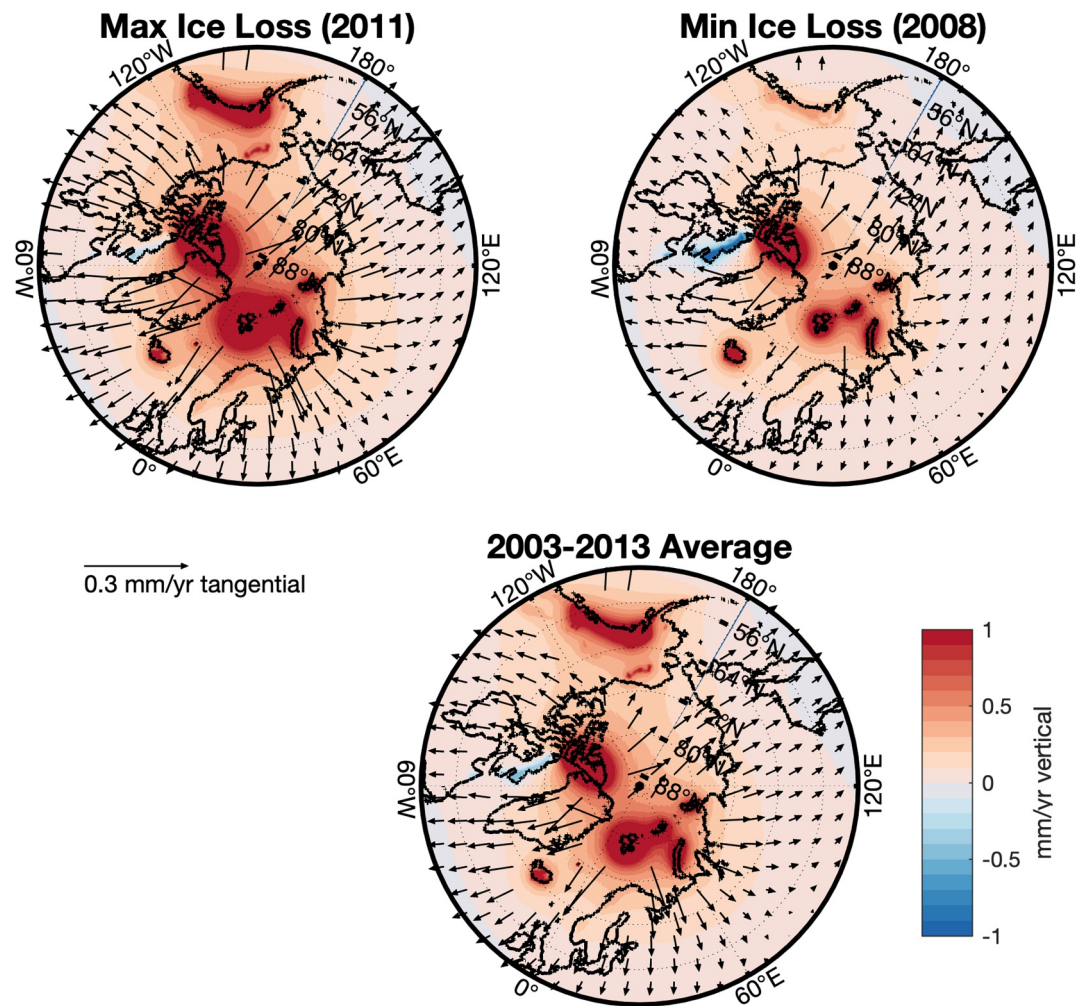


Figure 2. Predicted crustal deformation rates across northern high latitudes in response to ice-mass changes from a global database of glaciers and ice caps. Frames show predictions during the years of maximum (2011) and minimum (2008) mass loss, as well as the 2003–2013 average. Vertical motion is given by the red-blue color scale and tangential motion is represented as arrow vectors. Horizontal motions at sites close to the region of mass loss are excluded. (While this polar projection highlights high latitude glacier systems, deformation from all glacial ice-mass changes globally is included in the predictions.).

uplift rates reach 0.1–0.3 mm/yr across northern North America and Eurasia, depending on the yearly average glacial mass balance of Arctic glaciers. Average tangential motions in these regions are largely directed southward, away from Arctic glaciers, and have magnitudes of ~0.1 mm/yr, although there is some influence of ice-mass loss from Alaskan glaciers (Figure 3). Predictions of horizontal motion show significant year-to-year variations in magnitude and direction. In years of maximum ice-mass loss, tangential motions across North America can reach ~0.15 mm/yr (excluding the region directly surrounding the Alaskan glaciers). All predictions show large north-south gradients in tangential motion across the North American and Eurasian continents.

Patterns of average 3-D crustal motion surrounding the Alaskan, Himalayan and Patagonian glaciers are shown in Figure 3. In southern South America, predicted horizontal motions are characterized by a localized, outward-directed spoke-like pattern typical of post-glacial uplift. In both Alaska and Himalayas, the pattern of horizontal motion reflects the complex ice-mass loss geometries in these regions. Figure 3 demonstrates that outside of the localized regions of mass loss, horizontal motion is largely dominated by southward-directed motion away from the Arctic glacier systems.

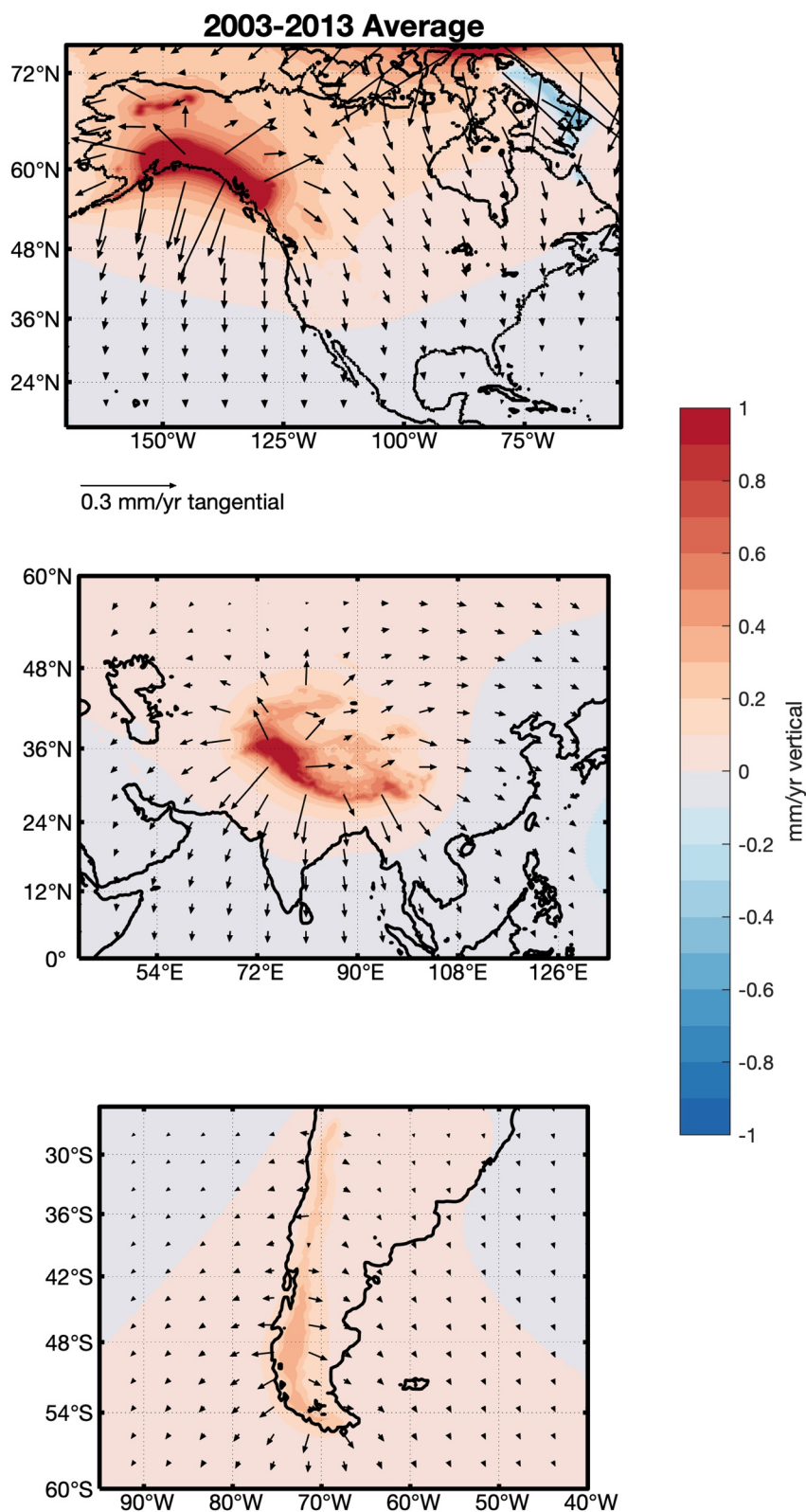


Figure 3. Average crustal deformation rates predicted across North America, southern Asia and southern South America in response to ice-mass changes from a global database of glaciers and ice caps (2003–2013). Vertical motion is given by the red-blue color scale and tangential motion is represented as arrow vectors.

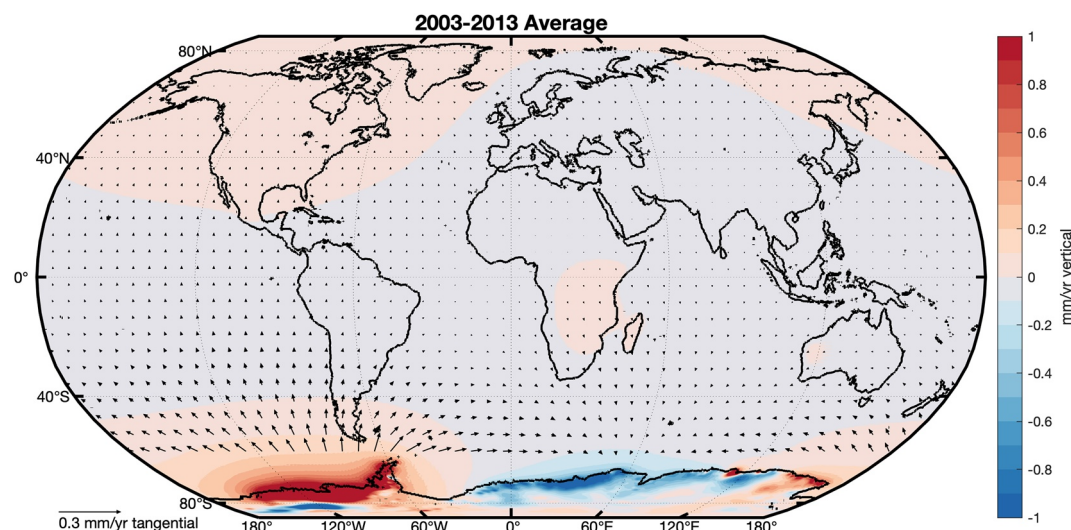


Figure 4. Average crustal deformation rates predicted in response to ice-mass loss from the Antarctic Ice Sheet (2003–2013) (Martín-Español et al., 2016). Vertical motion is given by the red-blue color scale and tangential motion is represented as arrow vectors. Horizontal motions at sites close to the region of mass loss are excluded.

2.3. Antarctica

Finally, we predict crustal deformation rates generated by a mass flux history across the Antarctic Ice Sheet constructed by Martín-Español et al. (2016). These are shown in Figure 4. The Martín-Español et al. (2016) ice history was derived by combining observations of satellite gravimetry and altimetry, as well as surveying using GNSS, over the period 2003–2013. We find that these ice-mass changes led to far-field crustal motions that were smaller than those driven by GrIS or high latitude glacier systems. While relatively significant mass loss from ice sheets and glaciers occurred across West Antarctica and the Antarctic Peninsula, these losses were partially compensated by mass gain in East Antarctica between 2003–2013 (Martín-Español et al., 2016). The variation in geometry and net magnitude of mass change across the AIS was also highly variable through time; for example, while some areas of both the East and West Antarctic ice sheets accumulated mass during years of low net ice-mass loss (e.g., 2005), they experienced significant mass loss during later years (e.g., 2010). The net effect is that the magnitude of predicted crustal motions averaged across the 2003–2013 time period is muted. The largest far-field crustal motions generated by AIS mass changes occur at sites across the southern Pacific Ocean (Figures 4 and 5).

2.4. Summary of Total 3-D Crustal Motion

Sections 2.1–2.3 and the associated figures provide the global 3-D deformation field induced by mass loss from GrIS, AIS and a global database of glaciers and ice caps. Figure 5 shows each of these individual contributions and their total from 2003–2013, for a selection of five sites. The temporal trends in both predicted vertical and tangential motions exhibit considerable year-to-year variability that reflects the mass balance inferred for the various regions of ice. For example, during years of high ice-mass loss from GrIS, predicted horizontal motions at sites across the northern hemisphere are up to a factor of ~ 3 larger than those during low mass loss years.

As demonstrated in Figures 1–4, both horizontal and vertical deformation rates are highest at sites close to the area of mass loss. Deformation rates at Norilsk in Figure 5 illustrate this effect; these rates show a large contribution from glacial mass loss since the site is proximal to the Russian Arctic Island and Svalbard glacier systems, which are experiencing rapid retreat. Crustal rates from 2003–2013 at London, Boston and Norilsk are heavily impacted by the signal from mass loss from GrIS. While GrIS-induced deformation rates decrease towards the equator, these three sites demonstrate the non-negligible sensitivity to GrIS ice-mass loss across the Northern Hemisphere at relatively large distance from the ice sheet. As shown in Figure 4, ice-mass loss from AIS has a relatively muted deformation signal, even at proximal sites (e.g., Falklands).

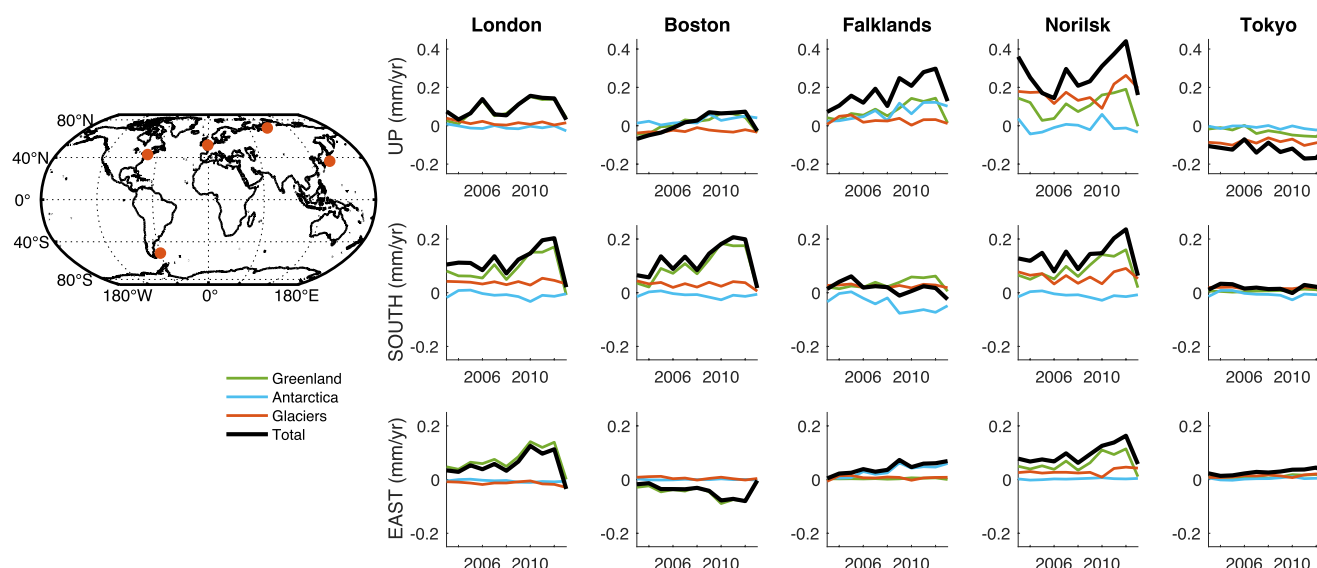


Figure 5. Predicted 3-D crustal deformation through time for selected sites. 3-D motion is separated into up, south and east components. Colored lines show the individual contribution to crustal motion from ice-mass loss from GrIS, AIS and a global database of glaciers and ice caps, as well as the total motion (or sum of contributions; black).

3. Discussion and Conclusions

Crustal motions are a key observable in a multitude of geodynamic applications, including estimating ice-mass changes, constraining Earth models, and isolating GIA signals in the crustal deformation field, as well as in a range of tectonic studies. The predictions presented herein illustrate the range of signals induced by early 21st century ice-mass loss that have previously been overlooked in GNSS and tide gauge studies and therefore have the potential to improve a range of geophysical analyses.

Several studies have investigated the signature of recent ice-mass loss on far-field vertical land motion (e.g., Ludwigsen et al., 2020; Riva et al., 2017). Despite some differences in methodology, our predictions show good agreement with the spatial variation and magnitude of vertical deformation rates presented by Riva et al. (2017). Moreover, our predictions support the earlier study's conclusion that it is important to account for the VLM signal in GNSS data at sites well away from present-day ice cover, particularly in the Northern Hemisphere where motions generated by mass loss from GrIS and Arctic glaciers are large. In the present study, we have extended this earlier work to show the first global predictions of the full 3-D crustal motion field induced by recent ice-mass changes in the polar ice sheets and mountain glaciers and ice caps. Using reconstructions of Greenland ice history over the period 2003–2018, we predict average vertical motions of up to 0.4 mm/yr across the Northern Hemisphere. Tangential rates of 0.05–0.3 mm/yr are predicted across most of Canada and the US, and rates in the range 0.05–0.2 mm/yr are predicted in Fennoscandia and Europe. The ice-mass loss from Arctic glaciers also produces pervasive horizontal motions with magnitude up to 0.15 mm/yr (average 2003–2013) across the high latitudes. Both of these sites of ice-mass change drive large gradients in horizontal and vertical motion across the northern hemisphere, with significant year-to-year variability in their magnitude and direction. These far-field horizontal rates have not been accounted for in any study of GNSS data, despite the higher accuracy of horizontal versus vertical rate determinations.

Crustal motion induced by recent ice-mass loss will have an impact on the terrestrial reference frames derived from global geodetic measurements. A model for these signals is generally not included in the determination of the International Terrestrial Reference Frame (ITRF) (e.g., Altamimi et al., 2011, 2016). Future analyses of GNSS networks must therefore account for reference-frame errors by including adjustments to the a priori reference frame (e.g., Hill et al., 2010; Kierulf et al., 2021).

The magnitude of both horizontal and vertical rates driven by modern ice-mass loss suggests that a reappraisal of some previous results may be warranted. As an example, analyses of GNSS data from sites across the BIFROST network have inferred viscoelastic structure beneath Fennoscandia from the estimated 3-D crustal motion rates

(e.g., Kierulf et al., 2014; Milne et al., 2004) and have used the vertical component of these rates to correct local tide gauge (sea-level) records for the contaminating signal of GIA (e.g., Davis et al., 1999; Johansson et al., 2002). The combined fingerprint of elastic crustal deformation due to recent changes in the mass of the GrIS, AIS and global glaciers and ice caps (shown in Figure S1) shows spatially systematic variations in average deformation rates of ~0.3 mm/yr for the vertical component and 0.1–0.2 mm/yr for the horizontal component, across Fennoscandia. A recent analysis of BIFROST GNSS observations by Kierulf et al. (2021) yields uncertainties for long-term rates at individual stations of comparable or smaller magnitude than these predicted variations (typically < 0.1 mm/yr for the horizontal component and 0.1–0.5 mm/yr for the vertical component). Given the dense distribution of sites, accuracy of the GNSS measurements, and unique spatial and temporal variations in deformation associated with the present-day mass changes, inclusion of both components of this deformation in a network analysis therefore has the potential to significantly alter results of geodetic analyses. This would impact, for example, any inferences of viscoelastic Earth-model parameters. The unique time history of modern ice-mass flux relative to other contributing signals will aid in the detection of these processes in geodetic data.

Data Availability Statement

Datasets for this research are included in the following papers (and their supplementary information files): Smith et al. (2020), Marzeion et al. (2012), Martín-Español et al. (2016), and in the following repositories: University Of Texas Center For Space Research (UTCSR) (2018), <https://doi.org/10.5067/grgsm-20c06>, and RGI Consortium and others (2017), <https://doi.org/10.7265/N5-RGI-60>. Modeled output grids are available online at <http://doi.org/10.5281/zenodo.4632251>.

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Erratum

Because of a plotting error in the originally published version of this article, the figures transposed the north-south directions of horizontal motion vectors. The remaining two components of the 3D crustal motions (east-west, radial) were properly plotted. The article focuses on the magnitudes of the crustal motions associated with recent ice-mass loss from ice sheets and glaciers, and thus none of the conclusions of the study were impacted by the plotting error. These updates have been made, and the present version may be considered the authoritative version of record.