

A Brief History of GIA Research and Recent Advances via Remote Sensing

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4 A Brief History of GIA Research and Recent Advances via Remote Sensing

*Bramha Dutt Vishwakarma, Holger Steffen,
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4.1 INTRODUCTION – THE DISCOVERY OF GLACIAL ISOSTATIC ADJUSTMENT

One of the prime research areas in geophysics is understanding the changes in solid Earth and their drivers. Apart from planetary evolution processes, natural climate variability plays a major role in changing the shape of the Earth's crust. The eccentricity of the Earth's orbit around the Sun, axial tilt, and precession alters the Earth's energy budget to induce warm and cold phases that can last thousands of years. They are known as the glacial cycles. They explain the long-term climate variability and the occurrence and recession of the cold phase, also known as the ice age. During the cold phase, ocean water is slowly transported via precipitation to the land and remains there as large continental ice sheets. In the past, this has led to a global mean sea level drop of more than 100 m (e.g., Peltier et al., 2022). The ice mass on the surface of the Earth exerts a significant load that deforms the shape of the Earth. After the onset of the warm phase, the ice sheets start to melt, returning the water to the oceans and removing the load on continents. The sea level rises, and the continents rebound slowly to about their original state. This deformation and rebound of the Earth's solid surface in response to glacial cycles is known as glacial isostatic adjustment or GIA (Peltier, 1999).

The sea level perceived by an observer at a coast that itself may move with respect to a fixed benchmark, usually the center of mass of the Earth, is called relative sea level (Gregory et al., 2019). If the sea-level changes while the coast does not, relative sea-level change is equal to the absolute sea-level change. When the land is sinking while the absolute sea level is rising, the sea level appears to rise very quickly, as was recently reported for California, where land subsidence is driven by groundwater pumping and exceptional drought (e.g., Ojha et al., 2018). On the other hand, if the coastal land is rebounding (vertical uplift) but at a faster rate than the absolute sea-level rise, the relative sea level would appear to be falling. GIA makes the relative sea level fall in several places. As of now, parts of Canada, Alaska, and the northern Baltic Sea coast are experiencing a relative sea-level decline (e.g., Frederikse et al., 2019) while the global mean sea level is reported to rise at close to $3.3 \pm 0.3 \text{ mm yr}^{-1}$ (Guérou et al., 2023). Observations of sea level falling at one place while rising at the other are responsible for advancing the GIA research in the last 300 years (Ekman, 2009), with Fennoscandia, due to its good infrastructure, inspiring scientific inquiry (Steffen and Wu, 2011).

GIA effects have been recognized in Fennoscandia for centuries, impacting human settlements (e.g., Ekman, 2009; Schmitt et al., 2009). Early observations, such as the relocation of the port of Östhammar in 1491 due to rising land, indicated awareness of GIA effects (Ekman, 2009). Scientific investigations began in the late 17th century when Urban Hjärne conducted surveys on water levels. By the early 18th century, Anders Celsius and Carl von Linné theorized that the sinking water levels were due to evaporation and absorption by plants (Bergsten, 1954).

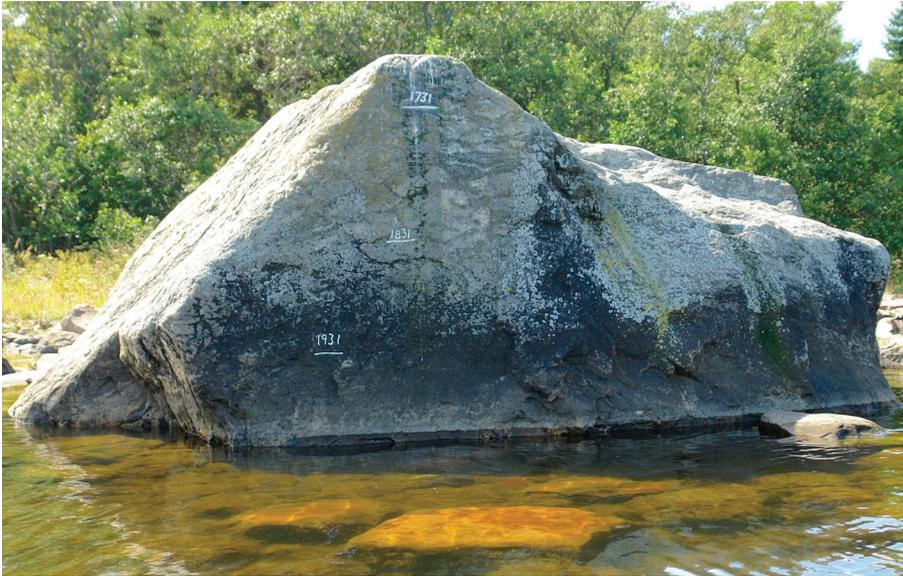


FIGURE 4.1 Celsius Rock on Lövgrund island in the Bay of Gävle in August 2015. The 1731 mark near its top was initiated by Anders Celsius. The present sea level is more than 2 m lower. (Photo courtesy of Holger Steffen.)

In 1731, Celsius instructed Rudman, a math teacher in Gävle about 170 km north of Stockholm, to cut a waterline mark in an erratic block on Lövgrund island in the Bay of Gävle (Bergsten, 1954). This block is known as Celsius Rock today (Fig. 4.1). It may be seen as the beginning of geodetic GIA investigations. A few earlier water marks around the Baltic Sea are believed to be due to Hjärke's influence (Ekman, 2009). These water marks, while imprecise by modern standards, fit well with contemporary results when corrected for current barystatic sea-level rise (Ekman, 2009; Steffen and Wu, 2011).

Celsius' work was foundational in linking historical records (dating back to the year 1563) to sea-level changes, calculating that the sea level in the Gulf of Bothnia was falling at 1.4 cm/yr relative to land height (Celsius, 1743). This initiated a debate on whether the change was due to falling sea levels or land uplift. Playfair (1802) and Lyell (1835) contributed to this debate, with Lyell concluding that the varied rates of sea-level change across Sweden indicated land uplift.

The idea of land uplift was independently proposed in 1765 by Ephraim Runeberg and Bengt Ferner, who found evidence in the bedrock structure (Ekman, 2009). The dissemination of the Ice Age discovery by Agassiz (1837) led to the theory of land uplift due to the weight of ice depressing the surface and subsequent rising during deglaciation. Jamieson (1865) proposed that ice sheets depressed coastal land below sea level, preventing flooding in interior areas, a theory gaining traction among field scientists but debated by theoreticians due to uncertainties about Earth's interior structure. Croll (1875) theorized repeated glacial cycles affecting global mass distribution and sea levels, though his dismissal of solid Earth deformation and lack of understanding of mass redistribution impacts limited his conclusions (Whitehouse, 2018). Woodward (1888) improved upon this by considering geoid perturbations from ice mass changes but did not fully account for Earth's deformation. Jamieson's theory, however, was supported by De Geer's (1888) map of land uplift isobases in Scandinavia. Wright (1914) further differentiated between isostatic land uplift and barystatic sea-level changes.

One important key to understanding GIA was developing a conceptual model, including physically reliable subsurface structures, to explain the land uplift phenomenon. Nansen (1922, 1928)

introduced the idea of a rigid lithosphere over a viscous upper mantle, explaining the formation of forebulges around ice caps. Daly (1925) further explored Earth's elastic and viscous responses to surface loading, highlighting little-known Rudzki's (1899) work on geoid changes due to ice melting (Whitehouse, 2018). Haskell (1935) determined a mantle viscosity of 10^{21} Pa s beneath Fennoscandia, while van Bemmelen and Berlage (1935) proposed a 100 km thick asthenosphere with a lower viscosity of 1.3×10^{19} Pa s. These early Earth models already illustrated the complexity of subsurface (Earth) models and how their different setups can provide (almost) identical results.

Another important key to understanding GIA was a deeper understanding of the spatiotemporal evolution of the ice load that triggered GIA, how the water transfer from ocean to land and back can be described best, and a comprehensive and high-quality database of GIA observations. These parts relied, among others, on geological observations and sophisticated dating methods to achieve a timestamp of a certain process. It was not until the 1970s that dedicated GIA modeling could be pursued. This development is illuminated in the next section.

4.2 MODELING GLACIAL ISOSTATIC ADJUSTMENT

GIA models consist of an ice model, i.e., a representation of the ice-mass changes over time, and an Earth model, which depicts changes in the material parameters. The ice model itself can include the paleo ice-sheet history, recent century ice mass variations (e.g., during the Little Ice Age), and/or contemporary changes in ice heights. The Earth model is described by changes in the mantle viscosity, thicknesses of the elastic and viscoelastic layers (lithosphere and mantle), rheological parameters (Poisson's ratio, elastic modulus, density), and the rheological model (e.g., Maxwell, Burgers, Kelvin-Voigt). The first three components can change with depth but also in the lateral directions.

Setting up a GIA model requires solving various equations (see Wu et al., 2021, for a detailed description). The Earth model has to solve the linearized elastic equation of motion, linearized continuity equation, and Poisson's equation. These equations depend on the displacement vector, density, gravity, gravitational potential, and stress (Wu et al., 2021). Some equations depend on a perturbed density field, which exists when compressible material is used, as only compressible material changes its density when pressure is applied. Thus, when incompressible material is used (Poisson's ratio is equal to 0.5), the governing equations of GIA are reduced. These equations also come with a specific set of boundary conditions, which must be considered in the setup of the Earth model. In addition to the governing equations for the Earth model, the sea-level equation needs to be solved, which describes changes in the ocean height induced by the ice model and the accompanying deformation and geoidal variations (Farrell and Clark, 1976). Most recent advances in the sea-level equation consider moving coastlines (Kendall et al., 2005), floating ice (Lambeck et al., 2003), rotational feedback (Wu and Peltier, 1984; Milne and Mitrovica, 1998) as well as water flux across sills (Coulson et al., 2021). Once an ice load with an accompanying ocean load is applied to an Earth model, the induced pressure leads to changes in displacement, gravitational potential (geoid height changes), and stresses. The displacements, in turn, affect the topography as well as the ocean heights, which are obtained via the sea-level equation. Thus, GIA models have to be solved iteratively.

The comparison to observations (3D land motion, gravity changes, Earth rotation changes, relative sea level and ice extent, lake levels, and seismicity) helps to get a better understanding of the GIA process itself as well as to get constraints on the Earth rheology and surface mass redistribution. Several 1D GIA model codes (e.g., SELEN (Spada and Melini, 2019)) are available, which assume that the material parameters of the Earth vary only along the radial direction. But as the Earth has viscosity, thickness, density, and elastic moduli variations in the lateral directions as well, 3D Earth models are more realistic. The first results from a 3D GIA model code were presented by Wu (1992), and since then several other 3D GIA modeling codes have been developed (e.g., Latychev

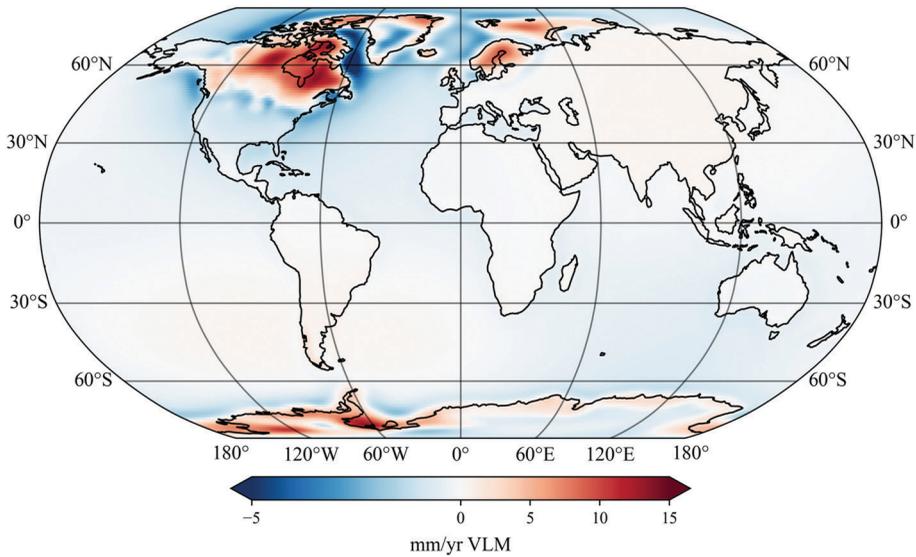


FIGURE 4.2 GIA VLM rates, as predicted by the ICE-6G_D model by Peltier et al. (2018).

et al., 2005; Martinec, 2000; Zhong et al., 2022). Most recent 3D GIA modeling codes include self-gravitation and compressibility in a spherical model setup (e.g., Huang et al., 2023), solving the sea-level equation, including moving coastlines, floating ice, and rotational feedback.

GIA models largely depend on the ice-sheet history as well as the Earth model parameters. These two input parameters come with uncertainties, which are described by various models that can be incorporated into GIA models (e.g., different paleo ice-sheet histories for the ice model component, and seismic tomography models for the Earth model component). Thus, results from GIA models can have a large spread of possible estimates to be used in further studies, especially when only one observation is used to constrain the GIA model. Whitehouse (2018) showed that the same uplift rate (as observed by the Global Navigation Satellite System, GNSS) could be produced by a large ice loss and weak Earth (low mantle viscosity) or by a small ice loss and strong Earth (high mantle viscosity). Thus, the usage of as much as possible GIA observations is necessary to constrain the GIA models. In addition, a range of possible GIA models needs to be provided, as not only one GIA model will be able to describe all GIA observations equally well. An additional uncertainty of GIA models comes from missing model physics, simplifications/errors in the model setup, as well as numerical errors. For example, compressible GIA models yield a different horizontal velocity field than incompressible GIA models (Reusen et al., 2023). Their differences are larger than the uncertainties of the GNSS observations. In geodesy, GIA model outputs, such as ICE-6G_D model predicted vertical land motion (VLM) rates (Fig. 4.2), are usually applied as a correction model when looking at other signals (e.g., those coming from terrestrial water storage changes). It is necessary to use a range of GIA modeling estimates (e.g., Eicker et al., 2024; Parang et al., 2024) when doing the corrections due to the large uncertainties existing in the input parameters as well as the numerical uncertainties of GIA models. GIA observations used to constrain the models are discussed in the next section, with a focus on geodetic techniques.

4.3 OBSERVATIONS FOR ESTIMATING GIA

The most obvious observable for GIA is the paleo-strandlines and contemporary land deformation with respect to a standard reference. Several geodetic observations provide changes in the shape of the Earth, which are useful for GIA research. For example, in the 1930s, analysis of tide gauge

records around the US revealed land tilting in the Great Lakes region, with an upward tilt of about 10 cm per 100 km per century in a northerly direction, while areas south of Portland were sinking (Gutenberg, 1933). These observations were attributed to GIA. Estimating the rate of GIA accurately was a challenge because solid Earth deformations also carry the elastic signal from local processes and contemporary mass changes, such as those due to water storage changes over the Great Lakes in this case. Furthermore, GIA is a global phenomenon, and the lack of a consistent vertical datum across countries and continents also impeded GIA research in those days. Furthermore, tide gauges contain signals from VLM due to solid Earth deformations and sea level change and to estimate GIA, other sources should be accounted for (Gregory et al., 2019). Some of these issues were resolved to a large extent by the launch of the Global Positioning System (GPS), which provided VLM with respect to the Geocenter. With more countries launching satellite systems for precise positioning, the technique became known as GNSS. The next logical step was to install a GNSS station near a tide gauge, but that provided only a partial solution, as the tide gauge network was not global and could only cover coastal regions.

Another observable that helps in estimating GIA is the secular gravity change. The redistribution of mass due to mantle relaxation and the VLM leads to a change in the gravity on the Earth's surface. This information is also valuable for constraining the GIA models. Therefore, studying the ratio between the rate of change in gravity \dot{g} , and the rate of vertical land deformation \dot{h} has been an additional tool for geodesists (Olsson et al., 2019). Due to an excellent network of terrestrial gravimeters and GNSS stations, the GIA estimates over Fennoscandia are probably the most accurate ones. However, to determine the ratio, the observed \dot{g} from the network of terrestrial gravimeters must be corrected for contemporary water storage changes, which is generally done with hydrology models. The ratio $\frac{\dot{g}}{\dot{h}}$ varies between -0.15 to -0.21 for Fennoscandia, for which uncertainties in hydrological models are responsible to a large extent.

Analyzing the rate of change in gravity with respect to the rate of VLM to infer the GIA-related mantle mass change is one of the most robust methods for analyzing GIA. However, having GNSS stations all over the globe, along with dedicated gravimeters, was never a feasible solution due to economic and political reasons. The global GNSS network of the International GNSS Service (IGS) with heterogeneous coverage was established with efforts from the International Association of Geodesy (IAG), but it was the launch of the Gravity Recovery and Climate Experiment (GRACE) satellite mission that helped gain new insights into GIA. The recent developments in remote sensing that have fueled the GIA research are discussed next.

4.4 HOW GRACE PUSHED GIA RESEARCH

In March 2002, the GRACE satellite mission was launched with a vision to map monthly variations in the Earth's gravity field. GRACE consists of two satellites, one following the other, in a near-polar orbit at an altitude of nearly 500 km (Tapley et al., 2004). The idea was to measure the changes in the distance between the two satellites with micrometer precision and use it to infer the gravity field of the Earth, which is supposed to vary from one month to the other due to surface mass changes within and on the Earth (Wahr et al., 1998). Since the dominant and dynamic month-to-month surface mass change is driven by hydrology, the GRACE mission was expected to map water mass transport with much better resolution and accuracy than before (Tapley et al., 2004). Since GRACE would also see solid Earth mass changes, GIA was expected to appear in GRACE products, and estimates of GIA trends are required to be removed from the GRACE time series to study hydrology, ice-sheet mass balance, and sea-level budgets (Lehmann et al., 2022, Vishwakarma et al., 2020). Usually, GIA modeling estimates are used to correct for GIA while using GRACE for the analysis of the hydrosphere and cryosphere. If one changes the applied GIA model, the water mass trends also change (Vishwakarma et al., 2022; Eicker et al., 2024). In fact, the uncertainty in GRACE mass

trend estimates over Antarctica is dominated by the GIA model uncertainties (Sasgen et al., 2017). This issue was known prior to the launch of GRACE and Wahr et al. (1998) suggested that instead of correcting GRACE for GIA, one may use it with surface displacement measured by satellite altimeters to estimate GIA.

4.4.1 THE PROBLEM OF SOURCE SEPARATION

The combination of gravity and surface displacement observations relies on the fact that the GIA signal originates deep inside the Earth, where viscoelastic relaxation occurs (cf. Fig. 4.3). While surface deformation cannot distinguish between the magnitude and the depth of the signal source (e.g., the same surface signal could originate from a weak shallow or a strong deep source), the gravitational signature of mass movements inside the Earth will carry additional information because rock density changes with depth. At the same time, gravity observations alone are not enough, because also, in this case, different mass movements could cause the same surface signal. However, in most cases, there will be only a single source that can simultaneously produce both the observed deformation and gravity patterns. In practice, the problem is still not simple, mainly because of the uncertainties in the observations, particularly the fact that the signal is contaminated by other processes than GIA.

After the launch of the GRACE satellite mission, the first attempt at producing such a data-driven GIA model at a regional scale was published by Riva et al. (2009), where GRACE and ICESat (satellite altimetry) data were combined to separate Antarctic GIA from present-day ice mass changes. The first global solution was published by Wu et al. (2010), where a model-independent framework was developed to separate GIA from land hydrology (including ice mass changes), by combining GRACE gravity observations, displacement observation from various space-geodetic techniques (satellite laser ranging, very long baseline interferometry, GPS) and data from an ocean bottom pressure model. Those studies revealed large discrepancies between GIA signals produced by the numerical models discussed in the previous section (based on ice sheet history reconstructions and highly simplified mechanical models of the Earth's interior) and GIA signals derived from space-geodetic observations.

While such discrepancies were expected, considering that physical models are mostly based on sparser and often more uncertain geological evidence, the need to accurately account for GIA when quantifying ongoing changes in oceans, ice sheets, and land hydrology led to increased efforts to capitalize on space-geodetic observations.

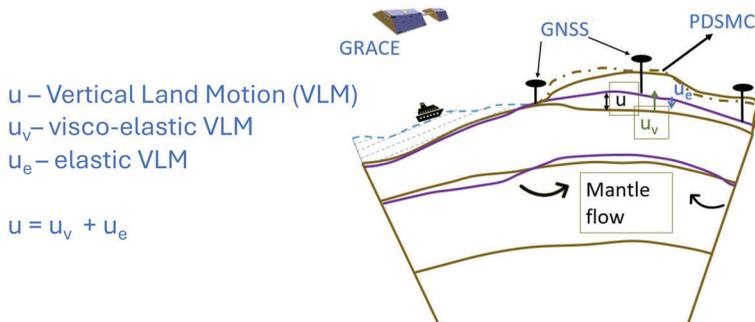


FIGURE 4.3 Sketch illustrating surface processes and GIA along with observations. u is the total VLM observed by the GNSS station, which can be decomposed into elastic VLM u_e , driven by present-day mass changes and viscoelastic VLM u_v , which is the GIA. (Adapted from Vishwakarma et al., 2023, under the terms of the Creative Commons Attribution License 4.0, CC-BY.)

Several geodetic techniques are available, each characterized by its measurement accuracy, as well as specific spatial and temporal resolution. GNSS is providing by far the most accurate observation, allowing positioning at a millimeter scale if several years of continuous observations are available. However, observations are mostly limited to continental areas and the station distribution is spatially highly heterogeneous. For GIA studies, the data are very sparse over crucial regions, such as the lowly populated northern Canada, or the interior of Greenland and Antarctica, because of the limited number of locations where rocks are exposed to allow the installation of geodetic stations.

The other major remote sensing tool for GIA studies, as mentioned above, is the GRACE and GRACE Follow-on (GRACE-FO) missions, which have been mapping the Earth's gravity field since 2002 with a monthly temporal resolution and a spatial resolution of about 300 km (Vishwakarma et al., 2018). Compared with GNSS, GRACE provides global coverage, and the spatial resolution is more than adequate for capturing the GIA signal. However, gravity observations also contain mass redistribution due to the water cycle and other processes within and on the Earth, where many processes occur at even smaller spatial and temporal scales than what is observed. It should be noted that those processes also affect the vertical motions observed by GNSS.

For both GNSS and GRACE-FO, if accurate models of water and ice redistribution were available, their effect could be modeled and removed from the observations, which would allow for the extraction of the underlying solid Earth signals (Van Dam et al., 2001). However, such models are generally not reliable. Scanlon et al. (2018) showed that nearly all the hydrology models misrepresent the water storage trends, which would affect the GIA estimates by combining model-based VLM or gravity perturbations with GNSS and GRACE, respectively. This is the reason most studies need to combine different observations to simultaneously estimate both GIA and mass redistribution in the hydrosphere (oceans, land hydrology, glaciers, and ice sheets).

Besides accounting for the effect of present-day surface mass changes, another challenge in using space geodetic observations is represented by the need to accurately determine global-scale deformation, in particular, changes in the flattening of the Earth. The GIA-driven signal is of the order of one millimeter per year of reduced flattening, so tiny, but when its effect is integrated over entire continents, it becomes an important contributor to the error budget (Frederikse et al., 2019). Observations of the Earth's flattening are largely based on Satellite Laser Ranging (SLR), which then becomes an important additional technique to observe the total GIA signal (Wu et al., 2010). Notably, SLR has been used since the 1980s to constrain viscosity values for the lower mantle. Currently, SLR results for Earth flattening are directly incorporated into GRACE observations, as well as implicitly present in GNSS results through their role in the definition of the International Terrestrial Reference Frame. GIA also affects Earth's rotation and day length. These observations cover periods from decades to several thousand years. Combined with data on ice-sheet retreat and barostatic sea-level fall since the Last Glacial Maximum approximately 20,000 years ago, these observations provide a comprehensive view of past and ongoing deformation and ice thickness variations. In the following, we will focus on the key remote sensing observations for GIA, i.e., GNSS and space gravimetry.

4.4.2 INSIGHTS INTO GIA FROM REMOTE SENSING IN THE LAST DECADE

The large uncertainties in GIA estimates obtained from Wu et al. (2010) and Riva et al. (2009), required improvements as the uncertainties of the models were propagated in subsequent analyses. A semi-empirical approach was initially proposed by Rietbroek et al. (2012) to study sea-level change, then adapted by Sun et al. (2019) to study changes in the Earth's flattening, and further developed by Sun and Riva (2020) to isolate GIA from GRACE data (cf. Fig. 4.4a). This approach is based on the use of pre-computed geoid change patterns for GIA and present-day mass redistribution in the Earth's water layer, where those patterns are usually called "fingerprints" because they

are unique for each mass change source. The method works as follows: For the effect of present-day mass redistribution, areas where large mass changes occur are defined based on input from physical models, while for GIA, the former ice sheets are divided into a few regional components, each one with their history of growth and retreat; the second step is to generate geoid fingerprints for each of the sources, by solving the sea-level equation discussed earlier, on an elastic Earth for present-day signals and a viscoelastic Earth for GIA; finally, those fingerprints are used as basis functions (eigenvectors) to reproduce observed gravity changes. In other words, the original fingerprints are multiplied by individual scaling factors and added together, where a standard inversion procedure that minimizes the least-square error makes sure that all scaling factors are optimally determined. From a statistical point of view, it is always possible to obtain a solution if the fingerprints are different enough and their number is smaller than the number of observations. The main challenge is to produce realistic fingerprints: For present-day sources, by selecting significant regions of change in ice cover or surface/ground waters content to reproduce most of the observed variations, for the GIA sources by combining the regional ice histories with enough viscoelastic Earth models to allow for different possible GIA contributions to be evaluated. It should be noted that this approach is solely based on GRACE gravity data: Using a single dataset has the advantage of reducing the risk of inconsistencies that might arise when combining different datasets, which always require some form of calibration. At the same time, this limits the accuracy of the solution: For example, the GIA contribution to present-day sea-level change estimates is found to be equal to -0.8 ± 0.8 mm/yr (90% confidence). On the other hand, Martín-Español et al. (2016) developed a Bayesian hierarchical framework to ingest satellite altimetry, gravimetry, and elastic-corrected GPS data over Antarctica to simultaneously determine annual trends in surface mass balance anomalies, ice dynamics, and GIA trend. The study was the first attempt to separate geophysical processes at different spatio-temporal scales without depending heavily on forward models of GIA. Their GIA estimate agreed with most of the GIA models in terms of mean rate over Antarctica but had significant deviations at the regional scale. They predicted a stronger GIA over the Antarctic Peninsula and the Pine Island Glacier.

The importance of a GIA correction is highlighted by the fact that the ice-mass balance over Antarctica has huge uncertainty, and most of that comes from uncertainties in GIA. Since Antarctica has the potential to contribute significantly to the mean sea level change, obtaining better GIA estimates over Antarctica has been a priority. Sasgen et al. (2018) expressed the trends in observed geoid height, surface elevation, and bedrock uplift as a function of past mass change that caused GIA, present-day mass change, and firn compaction over the snow. This system of equations can be solved for locations where the three data types (altimetry, gravimetry, and GNSS uplift rates) are available. Since GNSS data are sparse, a two-step approach was used where first the gravity and altimetry trends are combined by assuming the elevation rates are purely caused by present-day mass changes. Then, in the second step, obtained estimates of present-day mass change are iteratively updated until the bedrock uplift rates match GNSS uplift rates. The problem is ill-posed and requires regularization to stabilize (Sasgen et al., 2018). These studies provided GIA rates only over Antarctica but convinced the community that one can estimate GIA from remote sensing data while being independent of models.

A comprehensive global inversion was attempted in Vishwakarma et al. (2023), where they combined global GNSS rates and GRACE data to separate GIA and present-day mass change. They worked in the frequency domain, i.e., in terms of Stokes' coefficients, instead of the spatial domain. They expressed the rate of geoid height change as a linear sum of geoid height rate due to present-day mass change and GIA. However, they expressed the rate of bedrock uplift as a linear sum of 1) geoid height rate due to present-day mass change multiplied with a transfer function that converts geoid rate into elastic uplift rate, and 2) geoid height rate due to GIA multiplied by a transfer function that accounts for the viscoelastic response to past changes in ice load. Then, they combined the two equations to solve for GIA geoid rates. To tackle the sparsity of GNSS data, they generated

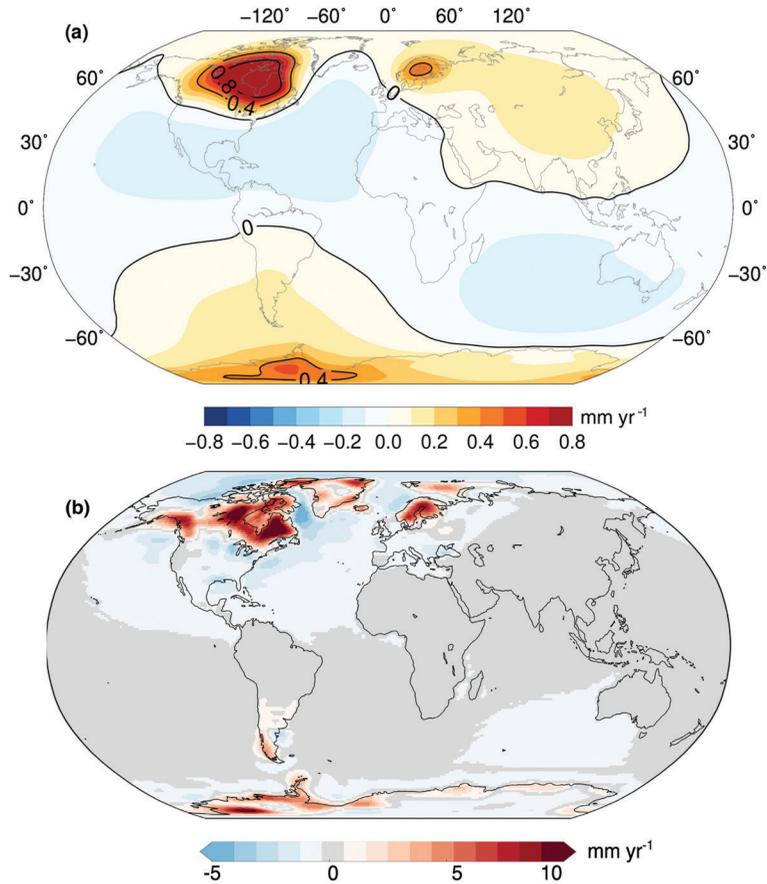


FIGURE 4.4 GIA outputs from Sun and Riva, 2020 (a) and Vishwakarma et al., 2023 (b). Please note the difference in units: (a) is in mm/yr of geoid height rate and (b) is the rate of vertical land motion (VLM) in mm/yr . (Sun and Riva, 2020; and Vishwakarma et al., 2023, under the Creative Commons Attribution 4.0 License, CC-BY.)

synthetic fields to fill the data gaps. Since most of the regions known to have a strong GIA signal have a decent GNSS coverage, the impact of synthetic data was a minimum. They could solve for Stokes coefficients up to degree and order 35, which also needed filtering to reduce noise, which resulted in a spatial grid resolution of ~ 700 km. To improve the resolution, they used the forward modeling approach by Chen et al. 2015 (cf. Fig. 4.4). They reported that the models overestimated GIA in central Canada and underestimated Alaska and Greenland. Their GIA estimates are the only global GIA estimates that put a vertical land uplift of approx. 5 mm/yr over Alaska, which has also been reported by several regional studies.

4.5 WHAT CAN WE EXPECT IN THE FUTURE?

Interferometric Synthetic Aperture Radar (InSAR) data has been used recently for mapping land subsidence and has been explored to tackle the sparse GNSS coverage (Wang et al., 2024). The major issue with employing InSAR is the relatively smaller time-series length of InSAR data, which results in higher uncertainty in the trends obtained. However, with the operational Sentinel series and upcoming SAR satellite missions, the time series will get extended and InSAR could be a potential tool for GIA research in the future. Similarly, Machine Learning (ML) has also seen a surge

in its application to solve problems in Earth sciences. Running GIA models, especially the 3-D models, are computationally very expensive (Whitehouse et al., 2018). ML has been used to train over a large set of parameters for various viscosity and ice-history profiles; then they could be used to quickly predict several thousand realizations of GIA (Lin et al., 2023). The mean of these GIA fields is very close to the mean GIA one would obtain by running several hundreds of computationally expensive model simulations. It is expected that advanced ML tools, such as Physics Informed Neural Networks (PINNs) and Long Short-Term Memory (LSTM), could be employed to ingest the large volume of Earth observation data and provide novel insights into GIA. Nevertheless, the role of remote sensing in GIA research is only going to become more important with upcoming satellite missions for gravimetry, altimetry, and InSAR.

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