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A data-driven model for constraint of present-day glacial isostatic adjustment in North America

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ABSTRACT

Geodetic measurements of vertical land motion and gravity change are incorporated into an *a priori* model of present-day glacial isostatic adjustment (GIA) in North America via least-squares adjustment. The result is an updated GIA model wherein the final predicted signal is informed by both observational data, and prior knowledge (or intuition) of GIA inferred from models. The data-driven method allows calculation of the uncertainties of predicted GIA fields, and thus offers a significant advantage over predictions from purely forward GIA models. In order to assess the influence each dataset has on the final GIA prediction, the vertical land motion and GRACE-measured gravity data are incorporated into the model first independently (i.e., one dataset only), then simultaneously. The relative weighting of the datasets and the prior input is iteratively determined by variance component estimation in order to achieve the most statistically appropriate fit to the data. The best-fit model is obtained when both datasets are inverted and gives respective RMS misfits to the GPS and GRACE data of 1.3 mm/yr and 0.8 mm/yr equivalent water layer change. Non-GIA signals (e.g., hydrology) are removed from the datasets prior to inversion. The post-fit residuals between the model predictions and the vertical motion and gravity datasets, however, suggest particular regions where significant non-GIA signals may still be present in the data, including unmodeled hydrological changes in the central Prairies west of Lake Winnipeg. Outside of these regions of misfit, the posterior uncertainty of the predicted model provides a measure of the formal uncertainty associated with the GIA process; results indicate that this quantity is sensitive to the uncertainty and spatial distribution of the input data as well as that of the prior model information. In the study area, the predicted uncertainty of the present-day GIA signal ranges from ~0.2–1.2 mm/yr for rates of vertical land motion, and from ~3–4 mm/yr of equivalent water layer change for gravity variations.

1. Introduction and previous modeling studies

Glacial isostatic adjustment (GIA) is the Earth's ongoing long-term (kyr-scale) viscoelastic response to surface loading and unloading by the ice sheets that existed during past glacial cycles. GIA causes deformation of the Earth's solid surface and gravitational potential field, and these deformations in turn result in sea-level changes via the redistribution of water in the global ocean (e.g., Peltier, 1974; Farrell and Clark, 1976; Peltier and Andrews, 1976; Clark et al., 1978; Mitrovica and Peltier, 1991). The absolute magnitude of the long-term GIA contribution to present-day observables (crustal deformation, gravity field perturbations, sea-level change) is largest in regions proximal to the former ice sheets. However, at all locations on the globe, ongoing GIA from the last glacial cycle can represent a significant fraction of the total value of observed present-day change. Consequently, constraining the contribution of shorter time-scale processes (contemporary ice mass loss, continental hydrology variations, oceanographic changes) to total present-day rates of crustal deformation, gravity change, and sea-level variation, requires an estimate of the GIA response at present day (e.g., Peltier and Tushingham, 1989; Tamisiea and Mitrovica, 2011).

Because glacial isostatic adjustment can seldom be measured directly, the present-day GIA response is often estimated by forward models (e.g., Lambeck et al., 1998; Peltier, 2004; Spada et al., 2006; Peltier et al., 2015). Forward modeled GIA is sensitive to several poorly constrained variables, including ice sheet history, elastic lithospheric thickness, the magnitude and parameterization of mantle viscosity, and the effects of lateral changes in Earth structure (e.g., Tushingham and Peltier, 1991; Lambeck et al., 1998;

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Latychev et al., 2005; van der Wal et al., 2010; Tamisiea, 2011; Peltier et al., 2015), although forward model predictions typically lack any formal quantification of the uncertainties associated with the input model combinations. However, variation of input model parameters within a reasonable range of values can result in significant changes to the magnitude (and sometimes the sign) of the predicted GIA response, indicating GIA uncertainty is large. This observation holds even in far-field regions, which are characterized by much smaller GIA signals than near-field regions. For example, Mitrovica and Davis (1995) found that estimates of the GIA contribution to far-field sea-level change varied by as much as ∼0.3–0.5 mm/yr for a range of GIA models, a value which represents ∼10–20% uncertainty in the GIA contribution relative to their mean total far-field sea-level rate estimated from tide gauge measurements (∼1.4 mm/yr).

As datasets from satellite geodesy missions have increased both in quantity and duration of observation, increasing emphasis has been placed on the use of data-driven methods to constrain better the individual components of total measured present-day change rates (Riva et al., 2009; Hill et al., 2010; X. Wu et al., 2010; Rietbroek et al., 2012; Sasgen et al., 2012; Lambert et al., 2013; Wang et al., 2013, 2015; Zhao, 2013; Gunter et al., 2014). A main limitation of these types of models is that they typically focus on present-day GIA signals, and therefore offer little insight into the time-varying GIA response or ice sheet evolution. However, while the method, study area, and quantity of primary interest vary by study, all of these studies either eliminate or reduce the uncertainty associated with forward modeled GIA (through the use of separation approaches, or data-driven inversion approaches, respectively).

In North America, separation approaches that use a combination of GPS measurements and observations from the Gravity Recovery and Climate Experiment (GRACE) have been employed to estimate recent continental hydrology changes (Lambert et al., 2013; Wang et al., 2013, 2015). Although Lambert et al. (2013) and Wang et al. (2013, 2015) use different methodologies, both methods assume a relationship between GIA-induced changes to vertical land motion and gravity change that can be used to separate and remove the GIA effect from total measured rates (e.g., Wahr et al., 1995), and thus avoid the use of forward modeled GIA predictions. Data-model combination approaches involving the simultaneous adjustment of geodetic measurements with *a priori* forward modeled GIA information have been applied globally (X. Wu et al., 2010), in North America (Sasgen et al., 2012; Zhao, 2013), Antarctica (Sasgen et al., 2013), and Fennoscandia (Hill et al., 2010). These data combination approaches yield updated models of present-day GIA informed by both observational data and prior expectation of GIA motions derived from models, although in the North American studies, the focus was not placed on quantifying GIA uncertainty. The methodology of Hill et al. (2010) was also used to obtain the GIA model used for the Stable North American Reference Frame (SNARF) (https://www.unavco.org/projects/past-projects/snarf/snarf.html).

In this study, we extend the data-driven combination method of Hill et al. (2010) to obtain a prediction of present-day GIA in North America. Relative to the SNARF project, which used a similar methodology, we include GRACE data, as well as use updated vertical land motion data and an updated North American ice sheet reconstruction to generate the prior GIA information. We also use variance component estimation to weight the contributions of the data and prior input to the final model prediction. Our goal is to obtain a present-day GIA solution for the study region that adequately predicts available observational constraints, minimizes the uncertainty associated with the forward modeled GIA inputs, and includes a realistic estimation of formal model error.

2. Methodology

The GIA response is solved for by least-squares adjustment, following the methods described by Hill et al. (2010). The final predicted GIA model response is represented by vector m^*, where the response represents the GIA-related deformation type(s) of interest. Here, the predicted deformation types are rates of vertical crustal motion and gravity change. A solution for m^* is obtained by minimizing the objective function of the data misfits and the *a priori* model misfits (e.g., Tarantola, 2005)

$$\varphi(m^*) = (d - A \cdot m^*)^T C_d^{-1} (d - A \cdot m^*) + (m^* - m)^T C_m^{-1} (m^* - m), \qquad (2.1)$$

where d is a vector of GIA-induced observations, A is the design matrix, C_d is the data covariance matrix, m is a vector of *a priori* GIA predictions, and C_m is the prior model covariance matrix.

2.1. Observational inputs

The observation vector d contains N measurements of GIA-related observations. In this study, depending on the combination of data that is inverted, d contains observed vertical land motion rates, GRACE-measured gravity change rates, or both. N is the total number of input observations used to constrain the solution. For example, if n_{GPS} vertical land motion data and n_{GRACE} GRACE data points are inverted simultaneously, then $N = n_{GPS} + n_{GRACE}$. The data covariance matrix C_d is an $N \times N$ matrix containing the covariances associated with the observations. The component of C_d associated with the vertical land motion data is assumed to be diagonal (variances only), while the component of C_d associated with the GRACE gravity data includes the full covariance matrix of the trend. The data are described further in Sections 3.1–3.3.

2.2. Model inputs

The *a priori* model vector m contains the mean of a suite of forward-modeled GIA predictions. Each model deformation type is predicted at each of the input observation sites, as well as on a grid of the study area. The length of vector m is thus the sum of the total number of predictions at observation sites and the total number of predictions at grid locations, or $M = M_{obs} + M_{grid}$. For two model deformation quantities (vertical motion and gravity change) and a grid of n_{grid} locations, $M_{grid} = 2n_{grid}$ and $M_{obs} = 2N$.

There are no formal uncertainties associated with forward GIA models. However, for a suite of GIA models that spans a reasonable range of parameter space, an input model covariance matrix can be constructed using

$$C_m^{ij} = \frac{1}{\Omega} \sum_{k=1}^{\Omega} (m_i^k - m_i)(m_j^k - m_j) \quad i, j = 1, \ldots, M, \qquad (2.2)$$

where $k = 1, \ldots, \Omega$ represents the suite of Ω forward models, m_i^k is the model prediction at the ith spatial location in the kth GIA model, m_i is the average prediction of Ω models at the ith location, and here i and j are the indices of the model covariance matrix. The *a priori* model averages and the associated suite of GIA model predictions are discussed further in Section 3.4.

2.3. Design matrix

The $N \times M$ design matrix A consists of the partial derivatives of the observations with respect to the model parameters according to

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