Application of GIA for computing physical quantities – surface mass landing

We develop a 3-D finite-element model to study the viscoelastic response of a compressible Earth to surface loads. The effects of centre of mass motion, polar wander feedback, and self-consistent ocean loading are implemented. To assess the model's accuracy, we benchmark the numerical results against a semi-analytic solution for spherically symmetric structure. We force our model with the ICE-5G global ice loading history to study the effects of laterally varying viscosity structure on several glacial isostatic adjustment (GIA) observables, including relative sea-level (RSL) measurements in Canada, and present-day time-variable gravity and uplift rates in Antarctica. Canadian RSL observations have been used to determine the Earth's globally averaged viscosity profile. Antarctic GPS uplift rates have been used to constrain Antarctic GIA models. And GIA time-variable gravity and uplift signals are error sources for GRACE and altimeter estimates of present-day Antarctic ice mass loss, and must be modelled and removed from those estimates. Computing GIA results for a 3-D viscosity profile derived from a realistic seismic tomography model, and comparing with results computed for 1-D averages of that 3-D profile, we conclude that: (1) a GIA viscosity model based on Canadian relative sea-level data is more likely to represent a Canadian average than a true global average; (2) the effects of 3-D viscosity structure on GRACE estimates of present-day Antarctic mass loss are probably smaller than the difference between GIA models based on different Antarctic deglaciation histories and (3) the effects of 3-D viscosity structure on Antarctic GPS observations of present-day uplift rate can be significant, and can complicate efforts to use GPS observations to constrain 1-D GIA models.

Using different GIA models – different estimates

The changing distribution of surface mass (oceans, atmospheric pressure, continental water storage, groundwater, lakes, snow and ice) causes detectable changes in the shape of the solid Earth, on time scales ranging from hours to millennia. Transient changes in the Earth's shape can, regardless of cause, be readily separated from steady secular variation in surface mass loading, but other secular changes due to plate tectonics and **glacial isostatic adjustment (GIA) cannot.** We estimate secular station velocities from almost 11 years of high quality combined GPS position solutions (GPS weeks 1,000-1,570) submitted as part of the first international global navigation satellite system service reprocessing campaign. Individual station velocities are estimated as a linear fit, paying careful attention to outliers and offsets. We remove a suite of a priori GIA models, each with an associated set of plate tectonic Euler vectors estimated by us; the latter are shown to be insensitive to the a priori GIA model. From the coordinate time series residuals after removing the GIA models and corresponding plate tectonic velocities, we use mass-conserving continental basis functions to estimate surface mass loading including the secular term. **The different GIA models lead to significant differences in the estimates of loading in selected regions**. Although our loading estimates are broadly comparable with independent estimates from other satellite missions, their range highlights the **need for better, more robust GIA models that incorporate 3D Earth structure and accurately represent 3D surface displacements**.

Sea level budget to constrain GIA

From the IPCC 4th Assessment Report published in 2007, ocean thermal expansion contributed by similar to 50% to the 3.1 mm/yr observed global mean sea level rise during the 1993-2003 decade, the remaining rate of rise being essentially explained by shrinking of land ice. Recently published results suggest that since about 2003, ocean thermal expansion change, based on the newly deployed Argo system, is showing a plateau while sea level is still rising, although at a reduced rate (similar to 2.5 mm/yr). Using space gravimetry observations from GRACE, we show that recent years sea level rise can be mostly explained by an increase of the mass of the oceans. Estimating GRACE-based ice sheet mass balance and using published estimates for glaciers melting, we further show that ocean mass increase since 2003 results by about half from an enhanced contribution of the polar ice sheets - compared to the previous decade - and half from mountain glaciers melting. Taking also into account the small GRACE-based contribution from continental waters (<0.2 mm/yr), we find a total ocean mass contribution of similar to 2 mm/yr over 2003-2008. Such a value represents similar to 80% of the altimetry-based rate of sea level rise over that period. We next estimate the steric sea level (i.e., ocean thermal expansion plus salinity effects) contribution from: (1) the difference between altimetry-based sea level and ocean mass change and (2) Argo data. Inferred steric sea level rate from (1) (similar to 0.3 mm/yr over 2003-2008) agrees well with the Argo-based value also estimated here (0.37 mm/yr over 2004-2008). Furthermore, the sea level budget approach presented in this study allows us to constrain independent estimates of the **Glacial Isostatic Adjustment (GIA) correction applied to GRACE-based ocean and ice sheet mass changes**, as well as of glaciers melting. Values for the CIA correction and glacier contribution needed to close the sea level budget and explain GRACE-based mass estimates over the recent years agree well with totally independent determinations.

Empirical estimate of GIA at Antarctica

This study explores an approach that s**imultaneously estimates Antarctic mass balance and glacial isostatic adjustment (GIA)** through the combination of **satellite gravity and altimetry data sets**. The results improve upon previous efforts by incorporating a firn densification model to account for firn compaction and surface processes as well as reprocessed data sets over a slightly longer period of time. A range of different Gravity Recovery and Climate Experiment (GRACE) gravity models were evaluated and a new Ice, Cloud, and Land Elevation Satellite (ICESat) surface height trend map computed using an overlapping footprint approach. When the GIA models created from the combination approach were compared to in situ GPS ground station displacements, the vertical rates estimated showed consistently better agreement than recent conventional GIA models. The new empirically derived GIA rates suggest the presence of strong uplift in the Amundsen Sea sector in West Antarctica (WA) and the Philippi/Denman sectors, as well as subsidence in large parts of East Antarctica (EA). The total GIA-related mass change estimates for the entire Antarctic ice sheet ranged from 53 to 103 Gt yr(-1), depending on the GRACE solution used, with an estimated uncertainty of +/- 40 Gt yr(-1). Over the time frame February 2003-October 2009, the corresponding ice mass change showed an average value of -100 +/- 44 Gt yr(-1) (EA: 5 +/- 38, WA: -105 +/- 22), consistent with other recent estimates in the literature, with regional mass loss mostly concentrated in WA. The refined approach presented in this study shows the contribution that such data combinations can make towards improving estimates of present-day GIA and ice mass change, particularly with respect to determining more reliable uncertainties.

Improved GIA estimates for GRACE using a model and high-quality GPS data

Antarctic volume changes during the past 21 thousand years are smaller than previously thought, and here we construct an ice sheet history that **drives a forward model prediction of the glacial isostatic adjustment (GIA) gravity** signal. The new model, in turn, should give predictions that are constrained with recent uplift data. The impact of the GIA signal on a Gravity Recovery and Climate Experiment (GRACE) Antarctic mass balance estimate depends on the specific GRACE analysis method used. For the method described in this paper, the GIA contribution to the apparent surface mass change is re-evaluated to be +55±13 Gt/yr by considering a revised ice history model **and a parameter search for vertical motion predictions that best fit the GPS observations at 18 high-quality stations**. Although the GIA model spans a range of possible Earth rheological structure values, the data are not yet sufficient for solving for a preferred value of upper and lower mantle viscosity nor for a preferred lithospheric thickness. GRACE monthly solutions from the Center for Space Research Release 04 (CSR-RL04) release time series from January 2003 to the beginning of January 2012, uncorrected for GIA, yield an ice mass rate of +2.9± 29 Gt/yr. The new GIA correction increases the solved-for ice mass imbalance of Antarctica to −57±34 Gt/yr. The revised GIA correction is smaller than past GRACE estimates by about 50 to 90 Gt/yr. The new upper bound to the sea level rise from the Antarctic ice sheet, averaged over the time span 2003.0–2012.0, is about 0.16±0.09 mm/yr.

GIA estimates from GPS in Antarctica

In this work we assess the most recent estimates of glacial isostatic adjustment (GIA) for Antarctica, including those from both **forward and inverse methods**. The assessment is based on a comparison of the estimated uplift rates **with a set of elastic-corrected GPS vertical velocities**. These have been observed from an extensive GPS network and computed using data over the period 2009–2014. We find systematic underestimations of the observed uplift rates in both inverse and forward methods over specific regions of Antarctica characterized by low mantle viscosities and thin lithosphere, such as the northern Antarctic Peninsula and the Amundsen Sea Embayment, where its recent ice discharge history is likely to be playing a role in current GIA. Uplift estimates for regions where many GIA models have traditionally placed their uplift maxima, such as the margins of Filchner-Ronne and Ross ice shelves, are found to be overestimated. GIA estimates show large variability over the interior of East Antarctica which results in increased uncertainties on the ice-sheet mass balance derived from gravimetry methods.

We present spatiotemporal mass balance trends for the Antarctic Ice Sheet from **a statistical inversion** of satellite altimetry, gravimetry, and elastic-corrected GPS data for the period 2003–2013. Our method simultaneously determines annual trends in ice dynamics, surface mass balance anomalies, and **a time-invariant solution for glacio-isostatic adjustment** while remaining largely independent of forward models. We establish that over the period 2003–2013, Antarctica has been losing mass at a rate of −84 ± 22 Gt yr−1, with a sustained negative mean trend of dynamic imbalance of −111 ± 13 Gt yr−1. West Antarctica is the largest contributor with −112 ± 10 Gt yr−1, mainly triggered by high thinning rates of glaciers draining into the Amundsen Sea Embayment. The Antarctic Peninsula has experienced a dramatic increase in mass loss in the last decade, with a mean rate of −28 ± 7 Gt yr−1 and significantly higher values for the most recent years following the destabilization of the Southern Antarctic Peninsula around 2010. The total mass loss is partly compensated by a significant mass gain of 56 ± 18 Gt yr−1 in East Antarctica due to a positive trend of surface mass balance anomalies.

A comprehensive analysis of satellite datasets has estimated that the ice sheets of Greenland, West Antarctica, the Antarctic Peninsula, and East Antarctica experienced a net mass loss of ?100 ± 92 Gt yr?1 over the period 1992?2000 and ?298 ± 58 Gt yr?1 over the period 2000?11, representing an increase of ?198 ± 109 Gt yr?1 between the two epochs. The authors demonstrate that the time rate of change of the degree-four zonal harmonic of Earth's gravitational potential provides an independent check on these mass balances that is less sensitive to uncertainties that have contaminated previous analyses of the degree-2 zonal harmonic [e.g., due to ongoing glacial isostatic adjustment (GIA), solid Earth body tides, and core?mantle coupling]. For the period 2000?11, the signal implied by the ice sheet mass flux cited above is (3.8 ± 0.6) ? 10?11 yr?1, whereas the change in the harmonic across the two epochs is (2.3 ± 1.1) ? 10?11 yr?1. In comparison, using satellite laser ranging (SLR) data, the authors **estimate a GIA-corrected value o**f (3.8 ± 0.6) ? 10?11 yr?1 for the epoch 2000?11 and a change across the two epochs of (5.3 ± 1.6) ? 10?11 yr?1. The authors conclude that the former supports recent estimates of melting over the last decade, whereas the latter suggests either that estimated melt rates for the earlier epoch were too high or that the uncertainty associated with the SLR-based inference of during the earlier epoch is underestimated.

We have studied the ability of the GRACE gravimetry mission and Jason-1 altimetry to resolve ice and glacier induced contributions to sea level rise, by means of **a fingerprint method**. Here, the signals from ice sheet and land glacier changes, steric changes, **glacial isostatic adjustment** and terrestrial hydrology are **assumed to have fixed spatial patterns.** In a joint inversion using GRACE and Jason-1 data the unknown temporal components can then be estimated by least-squares. In total, we estimate temporal components for up to similar to 80 individual patterns. From a propagation of the full error-covariance from GRACE and a diagonal error-covariance from Jason-1 altimetry we find that: (1) GRACE almost entirely explains the mass related parameters in the joint inversion, (2) an inversion using only Jason-1 data has a marginal ability to estimate the mass related parameters, while the steric parameters have much better formal accuracy. In terms of mean sea level rise the steric patterns have a maximum formal accuracy of 0.01 mm for an 11 week running mean. In general, strong negative error correlations (rho < -0.9) exists between the high and low elevation parts of the ice sheet drainage basins, when those are estimated independently. The largest formal errors found are in the order of 40 Gton for small high elevation sub-basins in the southern Greenland ice sheet, which are difficult to separate. In a simplified joint inversion, merging high and low elevation basins, we have investigated the ability of the GRACE and Jason-1 data to separate the geocenter motion into a present-day contribution and a contribution from glacial isostatic adjustment (CIA). We find that the CIA related signal is larger than the present-day component with a maximum of -0.71 mm/year in the Z direction. Total geocenter motion rates are found to be -0.28, 0.43. -1.08 mm/year for the X, Y and Z components, respectively. The inversion results have been propagated to the Jason-1 along-track measurements. Over the time period considered, we see that a large part of the variability in the Pacific, Atlantic and Indian ocean can be explained by our inversion results. The applied **inversion method therefore seems a feasible way to separate steric from mass induced sea level changes.** At the same time, the joint inversion would benefit from more advanced parameterizations, which may aid in fitting remaining signal from altimetry.

**Glacial Isostatic Adjustment over Antarctica from combined ICESat and GRACE satellite data**

The glacial history of Antarctica during the most recent Milankovitch cycles is poorly constrained relative to the Northern Hemisphere. As a consequence, the contribution of mass changes in the Antarctic ice sheet to global sea-level change and the prediction of its future evolution remain uncertain. The process of **Glacial Isostatic Adjustment** (GIA) represents the ongoing response of the solid Earth to the Late-Pleistocene deglaciation and, therefore, provides information about Antarctic glacial history. Moreover, **insufficient knowledge of GIA hampers the determination of present-day changes in the Antarctic mass balance through satellite gravity measurements**. Previous studies have laid the theoretical foundation for distinguishing between signals of ongoing GIA and contemporary ice mass change **through the combination of satellite gravimetry and satellite altimetry**. This distinction is made possible by the fact the GIA-induced changes (involving relatively dense rock) will produce a different combination of topography and gravity change than those produced by variations in ice or firn thickness (due to the lower density of these materials); however, no conclusive results have been produced to date. Here we show that, by **combining laser altimetry and gravity data from the ICESat and GRACE satellite missions over the period March 2003–March 2008, the GIA contribution can indeed be isolated.** The inferred GIA signal over the Antarctic continent, which represents the first result derived from direct observations by satellite techniques, strongly supports Late-Pleistocene ice models derived from glacio-geologic studies. The GIA impact on GRACE-derived estimates of mass balance is found to be 100 ± 67 Gt/yr.

Schoen, AZM 2015

The Antarctic Ice Sheet is the largest potential source of future sea-level rise. Mass loss has been increasing over the last 2 decades for the West Antarctic Ice Sheet (WAIS) but with significant discrepancies between estimates, especially for the Antarctic Peninsula. Most of these **estimates utilise geophysical models to explicitly correct** the observations for (unobserved) processes. Systematic errors in these models introduce biases in the results which are difficult to quantify. In this study, we provide a **statistically rigorous error-bounded trend** estimate of ice mass loss over the WAIS from 2003 to 2009 which is almost entirely data driven. Using **altimetry, gravimetry, and GPS data** in **a hierarchical Bayesian framework**, we derive spatial fields for ice mass change, surface mass balance, and **glacial isostatic adjustment (GIA) without relying explicitly on forward models**. The approach we use separates mass and height change contributions from different processes, reproducing spatial features found in, for example, regional climate and GIA forward models, and provides an independent estimate which can be used to validate and test the models. In addition, spatial error estimates are derived for each field. The mass loss estimates we obtain are smaller than some recent results, with a time-averaged mean rate of −76 ± 15 Gt yr−1 for the WAIS and Antarctic Peninsula, including the major Antarctic islands. The GIA estimate compares well with results obtained from recent forward models (IJ05-R2) and inverse methods (AGE-1). The Bayesian framework is sufficiently flexible that it can, eventually, be used for the whole of Antarctica, be adapted for other ice sheets and utilise data from other sources such as ice cores, accumulation radar data, and other measurements that contain information about any of the processes that are solved for.

We study the spatial patterns of the mass and steric components of sea-level change during the “altimetry era” (1992–today), and we characterize them at different scales by the **orthonormal functions** method. The spectrum of the altimetry-derived rate of sea-level rise is red and decays with increasing wavenumber nearly following a power law with exponent ≈ 2. By analyzing the degree correlation and the admittance function, we find that the altimetric rate of sea-level change is coherent with the total steric field in the whole range of wavelengths considered (down to ≈ 1000 km), but particularly for wavelengths exceeding ≈ 2000 km. Thermosteric and halosteric components are moderately anti-correlated within the range of wavelengths 1000–4000 km. Their power spectrum varies significantly with the wavelength and, for ≈ 2000 km, it is equally partitioned between the two components. The power of regional sea-level variations driven by **Glacial Isostatic Adjustment** and the melting of continental ice sheets **is small** compared to that held by the steric component, which explains most of the regional variability shown by the altimetry record. This causes the elusiveness of the “static” sea-level fingerprints, which at present are hidden in the pattern of the residual sea-level (i.e., the altimetry-derived sea-level minus the steric component). However, we find that at harmonic degree 2, mainly associated with rotational variations, the power of glacial melting is significant and it will progressively increase during next century in response to global warming. We also estimate that at the end of the Mid-Holocene the strength of the glacial isostatic readjustment fingerprints was ≈ 10 times larger than today, well above the long-wavelength component of residual sea-level.

Compare GIA corrections

**Glacial isostatic adjustment (GIA) represents a source of uncertainty for ice sheet mass balance estimates from the Gravity Recovery and Climate Experiment (GRACE) time-variable gravity measurements**. We evaluate Greenland GIA corrections from Simpson et al (2009 Quat. Sci. Rev. 28 1631-57), A et al (2013 Geophys. J. Int. 192 557-72) and Wu et al (2010 Nature Geosci. 3 642-6) by **comparing the spatial patterns of GRACE-derived ice mass trends calculated using the three corrections with volume changes** from ICESat (Ice, Cloud, and land Elevation Satellite) and OIB (Operation IceBridge) altimetry missions, and surface mass balance products from the Regional Atmospheric Climate Model (RACMO). During the period September 2003-August 2011, GRACE ice mass changes obtained using the Simpson et al (2009 Quat. Sci. Rev. 28 1631-57) and A et al (2013 Geophys. J. Int. 192 557-72) GIA corrections yield similar spatial patterns and amplitudes, and are consistent with altimetry observations and surface mass balance data. The two GRACE estimates agree within 2% on average over the entire ice sheet, and better than 15% in four subdivisions of Greenland. The third GRACE estimate corrected using the (Wu et al 2010 Nature Geosci. 3 642-6)) GIA shows similar spatial patterns, but produces an average ice mass loss for the entire ice sheet that is 64 67 Gt yr(-1) smaller. In the Northeast the recovered ice mass change is 46-49 Gt yr(-1) (245-270%) more positive than that deduced from the other two corrections. By comparing the spatial and temporal variability of the GRACE estimates with trends of volume changes from altimetry and surface mass balance from RACMO, we show that the Wu et al (2010 Nature Geosci. 3 642-6) correction leads to a large mass increase in the Northeast that is inconsistent with independent observations.

Studies determining the contribution of water fluxes to sea level rise typically remove the ongoing effects of glacial isostatic adjustment (GIA). Unfortunately, use of inconsistent terminology between various disciplines has caused confusion as to **how contributions from GIA should be removed from altimetry and GRACE measurements**. In this paper, we **review the physics of the GIA corrections applicable** to these measurements and discuss the differing nomenclature between the GIA literature and other studies of sea level change. We then **examine a range of estimates for the GIA contribution derived by varying the Earth and ice models** employed in the prediction. We find, similar to early studies, that **GIA produces a small (compared to the observed value) but systematic contribution to the altimetry estimates**, with a maximum range of −0.15 to −0.5 mm yr−1. Moreover, we also find that the **GIA contribution to the mass change measured by GRACE over the ocean is significant**. In this regard, we demonstrate that confusion in nomenclature between the terms ‘absolute sea level’ and ‘geoid’ has led to an overestimation of this contribution in some previous studies. A component of this overestimation is the incorrect inclusion of the direct effect of the contemporaneous perturbations of the rotation vector, which leads to a factor of ∼two larger value of the degree two, order one spherical harmonic component of the model results. Aside from this confusion, uncertainties in Earth model structure and ice sheet history yield a spread of up to 1.4 mm yr−1 in the estimates of this contribution. However, even if the ice and Earth models were perfectly known, the processing techniques used in GRACE data analysis can introduce variations of up to 0.4 mm yr−1. Thus, we conclude that a **single-valued ‘GIA correction’ is not appropriate for sea level studies based on gravity data; each study must estimate a bound on the GIA correction consistent with the adopted data-analysis scheme.**

Seismic data indicate that there are **large viscosity variations** in the mantle beneath Antarctica. Consideration of such variations would **affect predictions of models of Glacial Isostatic Adjustment (GIA),** which are used to correct satellite measurements of ice mass change. However, most GIA models used for that purpose have **assumed the mantle to be uniformly stratified in terms of viscosity**. The goal of this study is to estimate the effect of lateral variations in viscosity on Antarctic mass balance estimates derived from the Gravity Recovery and Climate Experiment (GRACE) data. To this end, recently-developed **global GIA models based on lateral variations** in mantle temperature are tuned to fit constraints in the northern hemisphere and then **compared to GPS-derived uplift rates** in Antarctica. We find that these models can provide a better fit to GPS uplift rates in Antarctica than existing GIA models with a radially-varying (1D) rheology. When 3D viscosity models in combination with specific ice loading histories are used to correct GRACE measurements, mass loss in Antarctica is smaller than previously found for the same ice loading histories and their preferred 1D viscosity profiles. The variation in mass balance estimates arising from using different plausible realizations of 3D viscosity amounts to 20 Gt/yr for the ICE-5G ice model and 16 Gt/yr for the W12a ice model; these values are larger than the GRACE measurement error, but smaller than the variation arising from unknown ice history. While there exist 1D Earth models that can reproduce the total mass balance estimates derived using 3D Earth models, the spatial pattern of gravity rates can be significantly affected by 3D viscosity in a way that cannot be reproduced by GIA models with 1D viscosity. As an example, models with 1D viscosity always predict maximum gravity rates in the Ross Sea for the ICE-5G ice model, however, for one of the three preferred 3D models the maximum (for the same ice model) is found near the Weddell Sea. This demonstrates that 3D variations in viscosity affect the sensitivity of present-day uplift and gravity rates to changes in the timing of the ice history. In particular, low viscosities ( &lt; 10 19   Pa s ) found in West Antarctica make the mantle very sensitive to recent changes in ice thickness.

We present **a glacial isostatic adjustment (GIA) model for Antarctica**. This is driven by a new deglaciation history that has been developed using a numerical ice-sheet model, and is constrained to fit observations of past ice extent. We test the sensitivity of the GIA model to uncertainties in the deglaciation history, and seek earth model parameters that minimize the misfit of model predictions to relative sea-level observations from Antarctica. We find that the relative sea-level predictions are fairly insensitive to changes in lithospheric thickness and lower mantle viscosity, but show high sensitivity to changes in upper mantle viscosity and constrain this value (95 per cent confidence) to lie in the range 0.8–2.0 × 1021 Pa s. Significant misfits at several sites may be due to errors in the deglaciation history, or unmodelled effects of lateral variations in Earth structure. When we **compare our GIA model predictions with elastic-corrected GPS uplift rates** we find that the predicted rates are biased high (weighted mean bias = 1.8 mm yr–1) and there is a weighted root-mean-square (WRMS) error of 2.9 mm yr–1. In particular, our model systematically over-predicts uplift rates in the Antarctica Peninsula, and we attempt to address this by adjusting the Late Holocene loading history in this region, within the bounds of uncertainty of the deglaciation model. Using this adjusted model the weighted mean bias improves from 1.8 to 1.2 mm yr–1, and the WRMS error is reduced to 2.3 mm yr–1, compared with 4.9 mm yr–1 for ICE-5G v1.2 and 5.0 mm yr–1 for IJ05. Finally, we place spatially variable error bars on our GIA uplift rate predictions, taking into account uncertainties in both the deglaciation history and modelled Earth viscosity structure. This work provides a new GIA correction for the GRACE data in Antarctica, thus permitting more accurate constraints to be placed on current ice-mass change.

***Objective 2: Data driven solution for global Glacio-Isostatic Ajustment (GIA) that is consistent with the full suite of observations and processes***. GIA affects estimates of barystatic SLR from GRACE, GPS measurements of bedrock vertical motion, the global gravity field, and GMSL (*Tamisiea*, 2011). In general, estimates of global GIA have been obtained by forward modelling (simulating) the solid Earth response to changes in ice loading that have taken place since ~ the Last Glacial Maximum (*Argus et al.*, 2014; *Paulson et al.*, 2007; *Peltier*, 2004)}. There are three difficulties with this approach: i) uncertainties in lower mantle viscosity; ii) uncertainties in ice loading histories and iii) the 3-D structure of the Earth. All of these issues present major challenges for the simulators. As a consequence, significant uncertainties remain in determining the impact of GIA on global sea level, either directly, or on the estimates of mass change of the oceans obtained by GRACE (*Tamisiea*, 2011). To date, there has been one attempt at a data-driven solution for global GIA (*Wu et al.*, 2010). That approach bears some similarity to **what I propose here: it used GRACE, GPS and modelled ocean bottom pressure estimates to solve simultaneously for GIA and mass exchange between land and ocean**. However, the solution for GIA, in particular for Greenland, was not physically reasonable (*Tyler et al.*, 2014) and the methodology I propose here is fundamentally different. Further, I am not just solving for GIA and land/ocean mass exchange but am solving for all the processes shown in Fig. 1, while including physical constraints and other priors. **GIA can be considered to be stationary over decadal timescales**, and we will solve for it over the epoch 2005-2016 as this maximises data density (in space and time) for all observations, including the GNET and POLENET GPS stations in Greenland and Antarctica (*Bevis et al.*, 2009; *Bevis et al.*, 2012). This is an important step in achieving objectives 3-5: because **GIA is time-invariant**, once it has been determined it is then an input (with associated posterior uncertainty) into the BHM. This reduces the number of latent processes to four (c.f. Fig 1), which, in turn, further improves source separation. This solution must be consistent with all the observations and constraints including, for example, RSL from tide gauges and GMSL from altimetry, the residual mass signal from GRACE (after ocean mass has been accounted for) and **GPS vertical bedrock velocities**.

**First results from an integrated approach for estimating GIA, land ice, hydrology and ocean mass trends within a complete coupled Earth system framework**

Correctly separating the sources of sea level rise (SLR) is crucial for improving future SLR predictions. Traditionally, changes in each component of the integrated signal have been tackled separately, which has often lead to inconsistencies between the sum of these components and the integral as measured by satellite altimetry. To address these issues, the European Research Council has funded a five year project aimed at producing the first physically-based and data-driven solution for the complete coupled land-ocean-solid Earth system that is consistent with the full suite of observations, prior knowledge and fundamental geophysical constraints. This project is called "GlobalMass" based at the Bristol Glaciology Centre and Department of Maths, University of Bristol.

**Observed mass movement from the Gravity Recovery And Climate Experiment (GRACE) mission and vertical land motions from a global network of permanent GPS stations are used in a data-driven approach to estimate the glacial isostatic adjustment (GIA) without introducing any assumptions about the Earth structure or ice loading history**. A Bayesian Hierarchical Model (BHM) is used as the framework to combine the satellite and in-situ observations alongside prior information that incorporates the physics of the coupled system such as conservation of mass and characteristic length scales of different processes in both space and time. The BHM enables dimensional reduction of the observations so that a simultaneous solution can be obtained at a global scale. It will be used to produce a consistent partitioning of the integrated SLR signal into its steric (temperature and salinity) and barystatic component for the satellite era. The latter component is caused by land hydrology and melting ice sheets and glaciers, all of which are solved for simultaneously. The BHM was developed and tested on Antarctica, where it has been used to separate surface, ice dynamic and GIA signals simultaneously.  We illustrate the approach and concepts with examples from this test case and present the first results where we **assess the consistency of the ICE-6G GIA model** against the integral of sea surface height anomalies, ARGO-derived steric variations and GRACE-derived mass exchange.