Widespread low rates of Antarctic glacial isostatic adjustment revealed by GPS observations

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[1] Bedrock uplift in Antarctica is dominated by a combination of glacial isostatic adjustment (GIA) and elastic response to contemporary mass change. Here, we present spatially extensive GPS observations of Antarctic bedrock uplift, using 52% more stations than previous studies, giving enhanced coverage, and with improved precision. We observe rapid elastic uplift in the northern Antarctic Peninsula. After considering elastic rebound, the GPS data suggests that modeled or empirical GIA uplift signals are often over-estimated, particularly the magnitudes of the signal maxima. Our observation that GIA uplift is misrepresented by modeling (weighted root-mean-squares of observation-model differences: 4.9–5.0 mm/yr) suggests that, apart from a few regions where large ice mass loss is occurring, the spatial pattern of secular ice mass change derived from Gravity Recovery and Climate Experiment (GRACE) data and GIA models may be unreliable, and that several recent secular Antarctic ice mass loss estimates are systematically biased, mainly too high. **Citation:** Thomas, I. D., et al. (2011), Widespread low rates of Antarctic glacial isostatic adjustment revealed by GPS observations, *Geophys. Res. Lett.*, *38*, L22302, doi:10.1029/2011GL049277.

1. Introduction

[2] Estimates of Antarctica's recent rate of ice mass contribution to sea level change differ by amounts that cannot all be reconciled within their formal errors partly due to the existence of substantial technique-specific systematic errors [*Shepherd and Wingham*, 2007]. While monthly measurements of the gravity field by GRACE are heavily contributing to knowledge of changes at non-secular time-scales [*Chen et al.*, 2009; *Velicogna*, 2009], they have been limited in their direct contribution to improving our understanding of secular Antarctic ice mass change ($\dot{M}_{ice}^{Ant}$). This is mainly because separating *ice* mass change from *total* mass change, uniquely measured by GRACE, critically requires the accurate subtraction of the gravitational signature of mass movement in the mantle due to GIA, which is a secular signal. However, large discrepancies exist between models of Antarctic GIA (compare Figures 1a and 1b) due to a reliance on poorly constrained knowledge of the spatio-temporal evolution of the ice sheet since the Last Glacial Maximum [*Anderson et al.*, 2002] and of Earth mechanical properties [*Ritzwoller et al.*, 2001]. Estimates of $\dot{M}_{ice}^{Ant}$ are dominated by the consequent GIA uncertainty [*Velicogna and Wahr*, 2006]. Importantly, an error in a GIA model is seen as a systematic error in GRACE-derived $\dot{M}_{ice}^{Ant}$; it is not a random error. Due to a lack of independent data, the error in a given GIA model is presently impossible to quantify robustly, with some authors resorting to differencing two models [*Velicogna and Wahr*, 2006] and others [*Chen et al.*, 2009] electing not to quantify the error at all. This large uncertainty has led to empirical estimates [*Riva et al.*, 2009] or adjustments to existing models [*Sasgen et al.*, 2007; *Wu et al.*, 2010] of GIA-related uplift, but they also show large and systematic differences.

[3] GIA has a secular surface expression and hence GPS surface velocity field measurements provide an independent assessment of the accuracy of GIA models [*Bevis et al.*, 2009; *Dietrich and Rülke*, 2008; *Donnellan and Luyendyk*, 2004] provided that the elastic signal due to contemporaneous mass change is accounted for. To date, only *Bevis et al.* [2009] and *Argus et al.* [2011] have provided detailed comparison between GPS vertical velocities and Antarctic GIA models. They were limited to comparisons at about 20 sites across all of Antarctica and *Bevis et al.* [2009] in particular did not account for temporal correlations in their velocity uncertainties.

[4] Here, we present a GPS velocity field with improved spatial coverage of both inland and coastal East and West Antarctica, and, in most cases, improved velocity precision through improved temporal sampling. We compare the GPS observed vertical velocities to recent model and empirical uplift estimates.

2. Data Analysis and Models

2.1. GPS Velocities

[5] We assembled raw GPS data from 52 individual Antarctic stations (Table S1 of the auxiliary material), and computed coordinate time series as part of a self-consistent global reanalysis.[1] Raw GPS data from ~80 sites globally were processed on a daily basis from 1995.0 to 2011.0,

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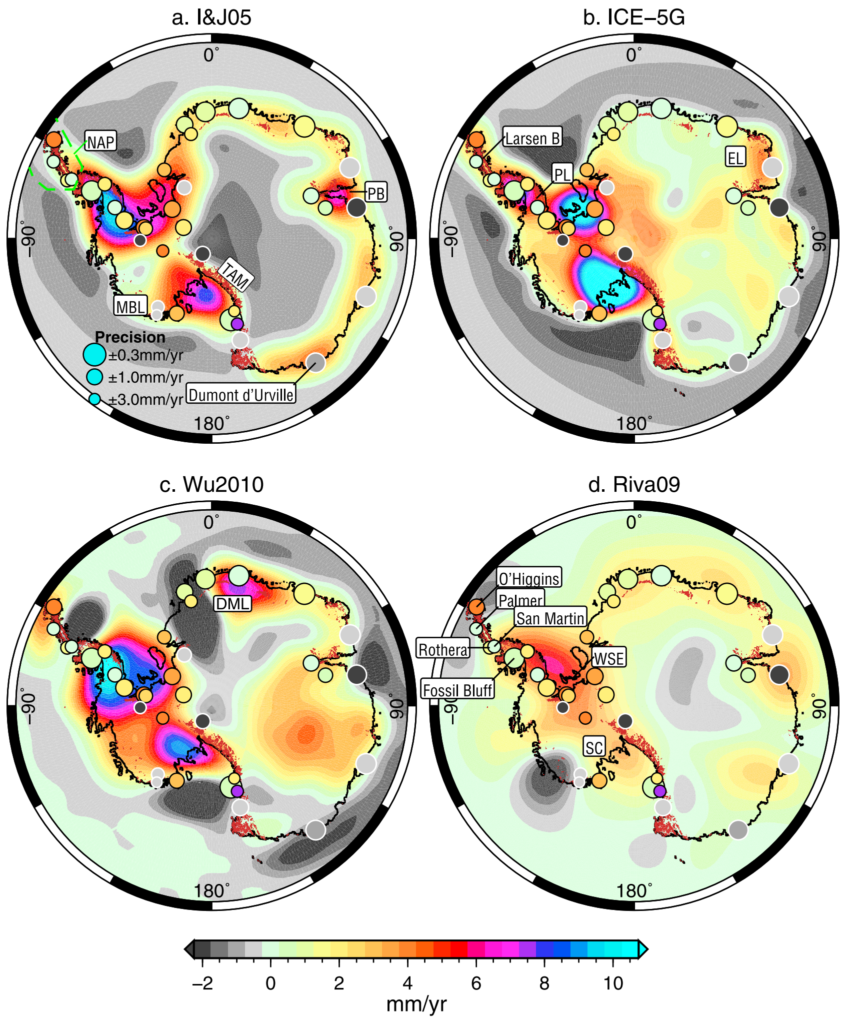

Figure 1. Model/empirical (background) and GPS observed velocities (filled circles), the latter after elastic correction. Symbol size increases with increased precision. The Weddell Sea Embayment (WSE), Palmer Land (PL), Dronning Maud Land (DML), Marie Byrd Land (MBL), Siple Coast (SC), Transantarctic Mountains (TAM), Enderby Land (EL) and Prydz Bay (PB) are marked. The dashed green line demarks the Northern Antarctic Peninsula (NAP). Rock outcrops are shown in brown.

computing satellite orbits, Earth orientation parameters and station coordinates using homogeneous observation modeling. Antarctic sites not included in the global analysis were added on a point-wise basis. From the Antarctic time series we obtained vertical site velocities for 35 distinct locations (Figure 1 and Table S1 of the auxiliary material), representing at least a 52% increase over the largest previous studies [*Argus et al.*, 2011; *Bevis et al.*, 2009; *Dietrich and Rülke*, 2008] with particularly improved spatial coverage in the mid-to-southern Antarctic Peninsula and inland East Antarctica (notably the Prydz Bay region). Site velocities were determined from coordinate time series in the International Terrestrial Reference Frame 2005 (ITRF2005, International GNSS Service realization). See auxiliary material for further information.

[6] We determined robust velocity uncertainties [cf. *Bevis et al.*, 2009; *Dietrich and Rülke*, 2008] as follows. Velocity uncertainties for the longest (over 1000 daily epochs) continuous GPS sites were calculated using the CATS software [*Williams*, 2008] which simultaneously solves for power-law noise plus variable white noise parameters. For the shorter continuous and episodic data we used the average noise parameters estimated (15.6 mm yr$^{-0.25}$ of flicker noise and a scale factor of 1.5 for the formal errors) from the longer series and estimated the uncertainties by propagation of errors. For the episodic sites we also added a component of noise that compensated for additional noise due to antenna/receiver replacement/removal for each campaign (1 mm). The noise was assumed to be independent and normally distributed between campaigns but identical within a campaign.

2.2. Model and Empirical Estimates of Uplift Due to GIA

[7] The GPS velocities are compared with two predictions of present-day GIA which have been used elsewhere in determining the ice mass balance of Antarctica but which are based on different ice history and Earth models (ICE-5G v1.2 [*Peltier*, 2004] and I&J05, using the *Simon et al.* [2010] revision of *Ivins and James* [2005] with the full sea-level equation and global ocean loading). The ICE-5G deglacial history and the accompanying VM2 viscosity model [*Peltier*, 2004], are input to the sea level equation,

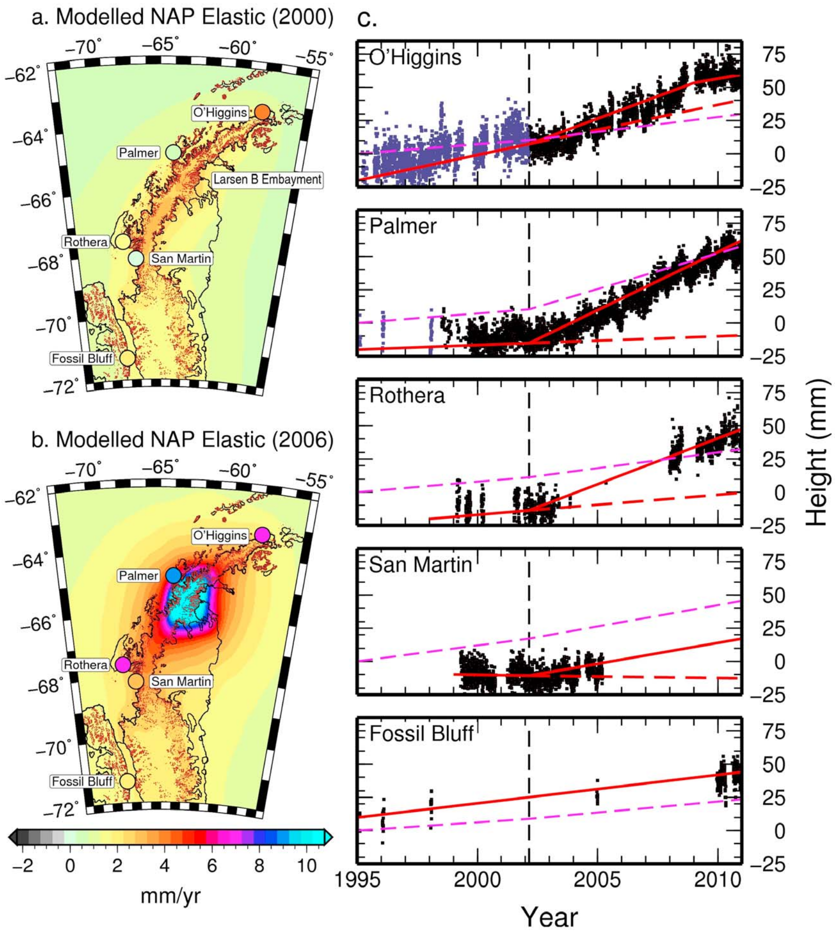

Figure 2. (a) Map of modeled elastic signal (background) and GPS observations (filled circles) for NAP before and (b) after the breakup of Larsen B Ice Shelf in March 2002 dashed vertical line in (c) site time series (without elastic correction) showing mean vertical velocities (red) and modeled elastic signal (magenta). O'Higgins, Rothera, and Palmer are a compilation of two records each and these are shown in blue and black. Neither modeled elastic signal is applied to these sites' velocities, other than Fossil Bluff, where the model (Figure 2b) was subtracted (see main text).

which is solved in terms of present-day uplift rates, considering rotational feedback [*Mitrovica et al.*, 2005]. The I&J05 deglacial history with no Antarctic deglaciation beyond 800 yr B.P. is combined with their 'average' mantle viscosity profile [*Ivins and James*, 2005; *Simon et al.*, 2010] and a Maxwell rheology. However, since I&J05 is not bound to a specific Earth model, large variations in uplift rates could be generated with the use of a different viscosity layering and alternative rheologies. We also compare the observed uplift to an empirical adjustment of the uplift signal of I&J05 (Wu2010 [*Wu et al.*, 2010]), and one entirely independent empirical estimate of uplift based on a combination of GRACE and satellite altimetry data (Riva09 [*Riva et al.*, 2009]). The Wu2010 and Riva09 estimates are used as described in the cited papers; we note these empirical estimates cannot be used to correct GRACE data external to those studies.

2.3. Reference Frames

[8] GIA models are produced in a reference frame where the origin lies at the centre-of-mass of the solid Earth (CE), whereas our GPS velocities are in ITRF2005 which is, at secular timescales, a centre-of-mass of the entire Earth system reference frame (CM). We estimated the difference between vertical velocities in our CM frame and the CE frame of ICE-5G [*Peltier*, 2004] and found negligible differences in X, Y and Z of −0.2 ± 0.1, 0.0 ± 0.1 and −0.1 ± 0.1 mm/yr, respectively [cf. *Argus et al.*, 2011, Figure S3c]; see Text S1 of the auxiliary material. Within uncertainties, these are consistent with the lower end of independent estimates [*Métivier et al.*, 2011] of the secular trend in CM relative to CE over the past 2–3 decades (as is appropriate for ITRF2005). We regard the model and GPS velocities as being self-consistent at the ~0.1 mm/yr level; the Wu2010 and Riva09 estimates are in reference frames which are variants of ITRF2005.

3. Results

3.1. Estimates of Uplift Due to Contemporaneous Ice Mass Change

[9] The GPS velocities include the elastic response of the solid Earth to contemporaneous ice mass change. In our dataset, this is greatest in the northern Antarctic Peninsula (NAP) where increased mass loss has occurred [*Rignot et al.*, 2008] since early 2002 following the breakup of the Larsen B Ice Shelf. Elastic effects are evident in our GPS time series in this region (Figure 2c) where we observe significant

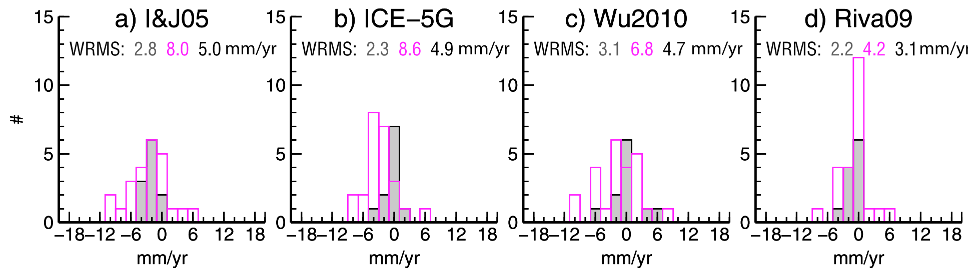

Figure 3. Histograms of GPS observed (elastic corrected) minus model/empirical uplift rates for East (grey) and West (magenta) Antarctica. Weighted Root-Mean-Square (WRMS, weights based on uncertainties in Table S1) values are also given, including the WRMS for all sites (black). Particularly in West Antarctica, the WRMS values are dominated by the high precision sites (Figure 1).

nonlinearity with an inflection near the time of the breakup. At Palmer we observe an increase from 0.1 mm/yr to a sustained 8.8 mm/yr after the breakup, suggesting mass loss from glaciers formerly feeding Larsen B Ice Shelf is ongoing at similar levels since 2002, with decreasing magnitude at greater distances (Figure 2). O'Higgins is particularly sensitive to mass loss related to the collapse in 1995 of the Larsen A and Prince Gustav ice shelves, and we observe varying uplift rates ranging from ~4 mm/yr to ~7 mm/yr, suggesting localized time-variable mass loss rates [*Glasser et al.*, 2011]. Further south in the Peninsula (e.g., Fossil Bluff, Figure 2), and elsewhere in Antarctica, the time series exhibit no sign of substantial nonlinearity.

[10] We modeled elastic effects by adopting ice mass flux estimates for 2000 and updated for 2006 where available [*Rignot et al.*, 2008]; see Text S1 of the auxiliary material. We included a correction for the Bellingshausen Sea (E. Rignot, personal communication, 2011). The spatial pattern of the mass flux for each sector was reconstructed as being proportional to the spatial gradient in glacier balance velocities [*Bamber et al.*, 2000], although our site distribution means the exact distribution of mass change is not critical outwith the NAP as we discuss later. Due to limits in our knowledge of balance velocities and mass flux resolution over the NAP, we distributed the mass loss at year 2000 uniformly and concentrated all increased 2006 mass loss on the former Larsen B glaciers. To produce modeled elastic rates (Figure S1 and Table S1 of the auxiliary material), the mass change field was expanded to spherical harmonic degree 600 (0.3°) and used as input into a rebound model that solves the sea level equation for a compressible PREM Earth, considering rotational feedback [*Mitrovica et al.*, 2005]. We examined the result of adopting a completely different input mass field (Figure S1 of the auxiliary material) and found the difference unimportant to our conclusions here (see Text S1 and Table S1 of the auxiliary material).

[11] Due to the proximity of the NAP sites (O'Higgins, Palmer, Rothera and San Martin) to glaciers losing mass, the near-field elastic model accuracy depends critically on the spatial pattern of NAP mass loss and the maximum harmonic degree used [*Barletta et al.*, 2006]. However, NAP mass loss magnitude and pattern is not completely known. For the near-field NAP sites we therefore found the modeled elastic rebound unsatisfactory and instead used the observed vertical velocities from before early 2002 without any elastic correction. Some mass loss did occur in the NAP pre-2002 [*Glasser et al.*, 2011; *Pritchard and Vaughan*, 2007], notably in the far north, so the pre-2002 GPS velocities are considered to represent an upper bound on GIA for the NAP, especially at O'Higgins where the true uplift due to GIA may be closer to ~1 mm/yr.

3.2. Comparison of GPS Uplift With Modeled/Empirical Estimates

[12] In Figure 1 we show our GPS estimates of GIA uplift (after elastic correction/assumption) compared with the vertical rates predicted by the model and empirical estimates. Differences with GPS uplifts are summarized in Figure 3, and range from −10.2 to +8.1 mm/yr and −6.1 to +6.7 mm/yr in West and East Antarctica, respectively. Comparing our velocity field with I&J05 predictions (Figures 1a and 3a) reveals large disagreement in Palmer Land where the observations give no more than 2.0 ± 1.6 mm/yr uplift. In the NAP, our pre-2002 GPS velocities are in agreement with I&J05 in showing small or negligible uplift around the Larsen B embayment (apart from O'Higgins where the GPS-derived uplift is ~4 mm/yr higher). Our velocities in the Weddell Sea Embayment (WSE) and Marie Byrd Land (MBL) are also substantially lower than I&J05 predictions. In the latter case, our GPS velocities are a significant re-evaluation of previously reported values [*Donnellan and Luyendyk*, 2004] which suggested substantial uplift in this region. There is general agreement with I&J05 of little uplift along the Transantarctic Mountains (TAM) and further south, and a subsiding interior East Antarctica. A lack of bedrock along the Siple Coast prevents confirmation of the predicted uplift there. In coastal East Antarctica the model and GPS agree generally to within 1–2 mm/yr, although I&J05 predictions are systematically higher, most notably at Dumont d'Urville. We observe close to zero uplift in the Prydz Bay region in contrast to an I&J05 uplift prediction of up to 4.1 mm/yr.

[13] Figure 1b reveals closer agreement between GPS and ICE-5G predictions along coastal East Antarctica than for I&J05, with the exception of larger predicted uplift in Enderby Land. Our southernmost GPS site along the TAM suggests subsidence there, in disagreement with overall uplift in the interior of East Antarctica in ICE-5G. The differences are systematic in West Antarctica (Figure 3b), with predictions consistently higher than the GPS velocities. In particular, our observations do not agree with the large uplift predictions in Palmer Land and the WSE, and the predictions for the NAP are systematically high by ~2 mm/yr.

[14] Our observations show that the Wu2010 adjustment to I&J05 uplift has quantitatively improved the agreement in general in West Antarctica (Figures 1c and 3c), however, the alternating patterns of high and low signal in Wu2010 often do not appear glaciologically reasonable and could suggest the presence of artifacts. If so, this improved agreement is at least partly coincidental. The contrastingly smoother Riva09 estimates produce the closest quantitative and qualitative agreement with the GPS observations (Figures 1d and 3d). However, the magnitude of the uplift pattern in Palmer Land is not supported by our observations, neither is the uplift in Prydz Bay. We are unable to test the large subsidence prediction in eastern MBL but our observations further west are not in disagreement. We note that the Riva09 estimate was smoothed (400 km Gaussian) in its generation.

4. Discussion and Conclusions

[15] Our finding of systematically lower present-day rates of GIA, particularly at the uplift centers, than predicted in I&J05 and ICE-5G is likely predominantly due to errors in the ice histories and Earth rheologies of these models; alternative elastic rebound values (Table S1) do not alter our overall findings. GPS observation of lower-than-predicted uplift rates in the WSE is in agreement with recent independent geological evidence that the ice elevation at the Last Glacial Maximum (LGM) was substantially lower than previously understood in these regions [*Bentley et al.*, 2010; *Bevis et al.*, 2009; *Hein et al.*, 2011]. Low rates of observed GIA near the Larsen B embayment and Palmer Land are surprising, especially so considering our estimates near Larsen B may be an upper bound due to unaccounted elastic signal, since independent evidence suggests substantial additional ice mass in these regions at the LGM [*Anderson et al.*, 2002; *Bentley et al.*, 2006; *Domack et al.*, 2005]. This may be indicative of low-viscosity upper mantle in this former subduction zone, and/or that deglaciation was largely complete earlier than in the models. In East Antarctica, our GPS data do not support extensive thick ice across the continental shelf, in agreement with *Anderson et al.* [2002], and imply little LGM advance in Prdyz Bay, unlike that included in I&J05. Our observation of little uplift along the TAM is in agreement with a doubling of accumulation in interior East Antarctica since the LGM [*Lorius et al.*, 1984], although the exact location of the nodal line depends on the pattern of Siple Coast uplift which we cannot verify.

[16] Regardless of the origin(s) of the disagreements we observe, over-prediction of GIA in I&J05 and ICE-5G, when applied to GRACE data, results in spatially-averaged estimates of ice mass loss that are an over-prediction. Biases such as these should be accounted for through bounded estimates [e.g., *Barletta et al.*, 2008] rather than increasing $\dot{M}_{ice}^{Ant}$ uncertainties. To date, the I&J05 model has been most frequently applied to GRACE data to obtain estimates of $\dot{M}_{ice}^{Ant}$, and significant GIA over-estimation is evident in the presented model, most clearly in West Antarctica. Taking the GPS and independent ice core data [*Lorius et al.*, 1984] together suggests that none of the models has all large scale East Antarctic features correct, including low coastal uplift and expected widespread interior subsidence. Spatial variations in model-data disagreement imply that, apart from a few regions where $\dot{M}_{ice}^{Ant}$ is large, the spatial pattern of $\dot{M}_{ice}^{Ant}$, when estimated from GRACE data, may be being masked by GIA modeling errors.

[17] Before GRACE data can be fully exploited for determining $\dot{M}_{ice}^{Ant}$ accurately a more accurate GIA model is required. New POLENET (www.polenet.org) observations of spatially varying Earth structure and surface velocity, together with new developments in ice sheet model sophistication and new ice history constraints, will allow substantial improvements in the future.

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