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Geodetic measurements of vertical crustal velocity in West Antarctica and the implications for ice mass balance

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[1] We present preliminary geodetic estimates for vertical bedrock velocity at twelve survey GPS stations in the West Antarctic GPS Network, an additional survey station in the northern Antarctic Peninsula, and eleven continuous GPS stations distributed across the continent. The spatial pattern of these velocities is not consistent with any postglacial rebound (PGR) model known to us. Four leading PGR models appear to be overpredicting uplift rates in the Transantarctic Mountains and West Antarctica and underpredicting them in the peninsula north of 65°. This discrepancy cannot be explained in terms of an elastic response to modern ice loss (except, perhaps, in part of the peninsula). Therefore, our initial geodetic results suggest that most GRACE ice mass rate estimates, which are critically dependent on a PGR correction, are systematically biased and are overpredicting ice loss for the continent as a whole.

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1. Introduction

[2] The GRACE satellite mission, which measures temporal changes in Earth's gravity field, can infer near-surface mass changes with unprecedented precision, but in Antarctica (as in Greenland) these estimates are unusually ambiguous, because GRACE cannot distinguish between changes in ice mass and nearby changes in rock mass associated with postglacial rebound (PGR) [*Le Meur and Huybrechts*, 2001; *Velicogna and Wahr*, 2002]. Therefore, numerical models of PGR are used during or after the analysis of GRACE observations to account for the viscous influx of rock mass into the study area, and thereby isolate the changes in ice mass [*Velicogna and Wahr*, 2006; *Chen et al.*, 2006; *Ramillien et al.*, 2006, *Sasgen et al.*, 2007a]. Over much of Antarctica, this "PGR correction" is larger than the resulting estimate of ice mass change, sometimes much larger [*Velicogna and Wahr*, 2006]. This vulnerability is worrying because there are many disparate predictions for contemporary uplift rates in Antarctica, and little really firm basis for choosing between them. For example, we contrast the predictions of PGR models ICE-5G (VM2) [*Peltier*, 2004] and IJ05 (6A) [*Ivins and James*, 2005, see Figure 6A] in Figure 1. These disagreements are not surprising, since PGR models are based on (1) an ice history model and (2) a geomechanical model (parameterized in terms of the thickness of the lithosphere, the underlying mantle viscosity structure, etc.), neither of which are strongly constrained by observations. Indeed, because PGR beneath and adjacent to an actively evolving ice sheet is sensitive to the details of crustal and mantle rheology, and these details are not known with the necessary level of accuracy, many theorists produce suites of PGR predictions by combining a single ice history model with a set of geomechanical scenarios [*Ivins and James*, 2005; *Wang et al.*, 2008]. Predictions of PGR can be improved by reducing the underlying uncertainties in rock rheology (e.g., using seismology) and ice history (e.g., using glacial geomorphology and stratigraphy). They can also be tested and improved by utilizing geodetic observations of crustal motion [*Milne et al.*, 2004], which is our approach.

2. Geodetic Measurements

[3] Between late 2001 and early 2006, the West Antarctic GPS Network (WAGN, also known as Project WAGN) constructed a network of 18 bedrock GPS stations (W01–W18) on nunataks across various parts of West Antarctica and along the Transantarctic Mountains (TAM) between the Ross and Weddell seas. It also reoccupied preexisting survey markers MBL1 [*Donnellan and Luyendyk*, 2004] (near W12) and HAAG (near W15) (Figures 2 and 3). We use the term "WAGN area" to describe the extent of this network, i.e., to indicate the TAM plus West Antarctica minus the Antarctic Peninsula. Two survey markers were installed at all WAGN sites, except at sites W06, W12 and W15, and both monuments (designated A and B) were observed simultaneously whenever circumstances allowed. The WAGN survey marker, a level steel plate bolted into bedrock, serves as an oriented mounting surface for a custom-designed, fixed height antenna mast. This design reduces antenna setup noise to negligible levels, and allows any WAGN station to be upgraded to a continuous reference station without changing the position of the GPS antenna. This upgrade process began during the 2007/08 field season as part of the new Polar Earth Observing Network (POLENET) project. So far only twelve of the WAGN sites (including HAAG and MBL1) have been observed over a total time span of 3 years or more, thereby allowing useful vertical velocity estimates to be formed.

[4] All WAGN data were incorporated into a much larger time series of observations from >240 continuous GPS (CGPS) stations selected from the

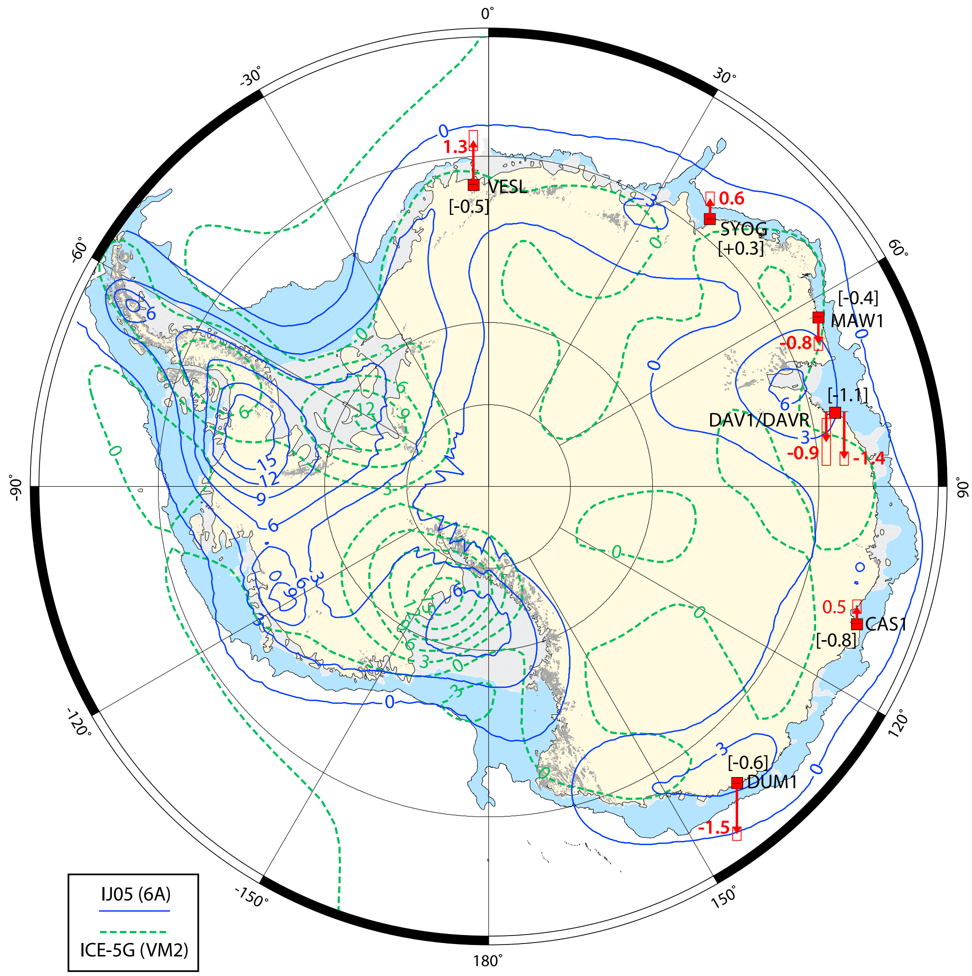

Figure 1. The rates of crustal uplift predicted by the PGR models IJ05 (6A) and ICE-5G (VM2). The red arrows and boxes depict the geodetic vertical velocity solutions (in mm/yr) and their 95% confidence intervals. The rates of purely elastic uplift (mm/yr) predicted for each site are shown in brackets. The blue area shows the continent to a depth of 2000 m. The gray areas indicate floating ice sheets.

global tracking network of the International GNSS Service. This global time series extended from January 1996 through March 2008. We used GAMIT/GLOBK software [*Herring et al.*, 2006] to estimate a daily network polyhedron and a consistent set of GPS satellite orbital solutions, both expressed in the ITRF 2005 reference frame. This software incorporates "absolute" models of phase center variation for each satellite antenna. We then used a generalized Helmhert transformation [*Kendrick et al.*, 2001] to shift our station position time series into a reference frame which was realized by simultaneously minimizing (1) the horizontal velocities of a set (HREF) of 11 CGPS stations located within the Antarctic plate and (2) the vertical velocities of a set (VREF) of 202 CGPS stations almost entirely located between 60° N and 60° S (Figure 2). After this transformation is achieved, the RMS horizontal velocity of the HREF stations is 1.0 mm/yr, and the RMS vertical velocity of the VREF stations is 0.6 mm/yr.

[5] The vertical reference set VREF was selected because nearly all global PGR models indicate that very little net vertical motion occurs in the area (the "VREF zone") sampled by these stations. Even though northern North America, Greenland, northern Eurasia, southern Patagonia and Antarctica are all moving upward on average (due to PGR), and so there must be a net downward movement in the intervening areas, the total area of continent undergoing moderate or rapid rates of uplift is so small in relation to that of the rest of the world that subsidence typically occurs with a velocity which is small compared to the peak rates of uplift. In particular, the average vertical velocity predicted

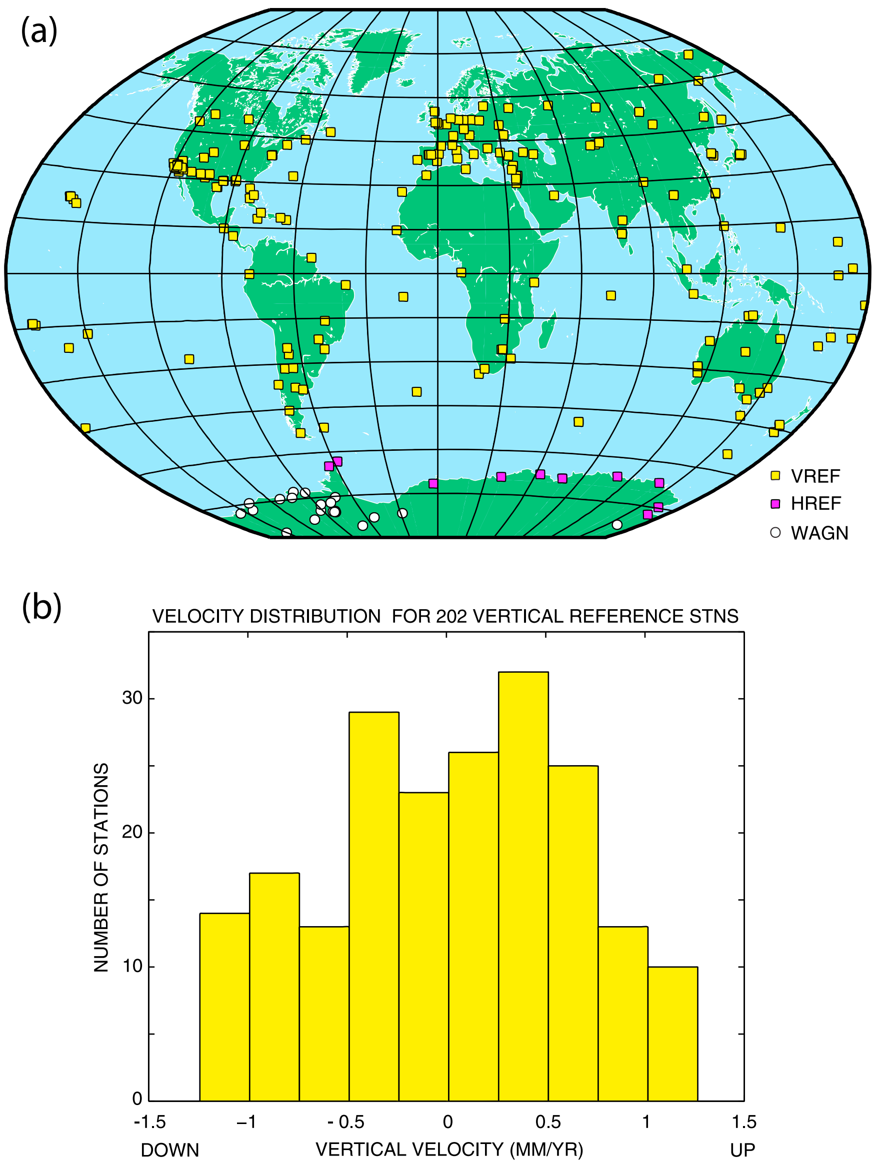

Figure 2. (a) A map showing the sets VREF and HREF used to impose our reference frame. Also shown are the stations of the WAGN network. (b) The vertical velocity distribution for the stations in set VREF.

for the VREF zone is barely distinguishable from zero. For example, the average vertical velocity at 201 of the 202 VREF sites is -0.12 ± 0.06 mm/yr according to the global PGR model ICE5G (VM2). The corresponding statistic for the global model RF3S20 (β = 0.2) [*Wang et al.*, 2008] is 0.03 ± 0.03 mm/yr. The mean vertical velocity of the VREF stations in our GPS solution is 0.01 ± 0.04 mm/yr. Even though we realized our reference frame in a purely geometrical way, and yet wish to compare our geodetic velocities with the predictions of PGR models associated with physically defined reference frames, the comparison of these average rates implies that the vertical velocity biases imposed on our solutions by our choice of reference frame are of magnitude $\sim$0.1 mm/yr, which we consider to be negligible.

[6] The vertical velocities of the WAGN stations and many of the Antarctic CGPS stations in our preferred reference frame are listed in Table 1, along with their nominal 95% confidence intervals. The vertical velocities obtained for the CGPS stations in East Antarctica all lie within the range -1.5 to $+1.3$ mm/yr, in reasonable agreement with the predictions of most modern PGR models (Figure 1). We did not include these stations in the group VREF used to impose the vertical reference frame, but had we done so none of our vertical velocity solutions in Antarctica would have

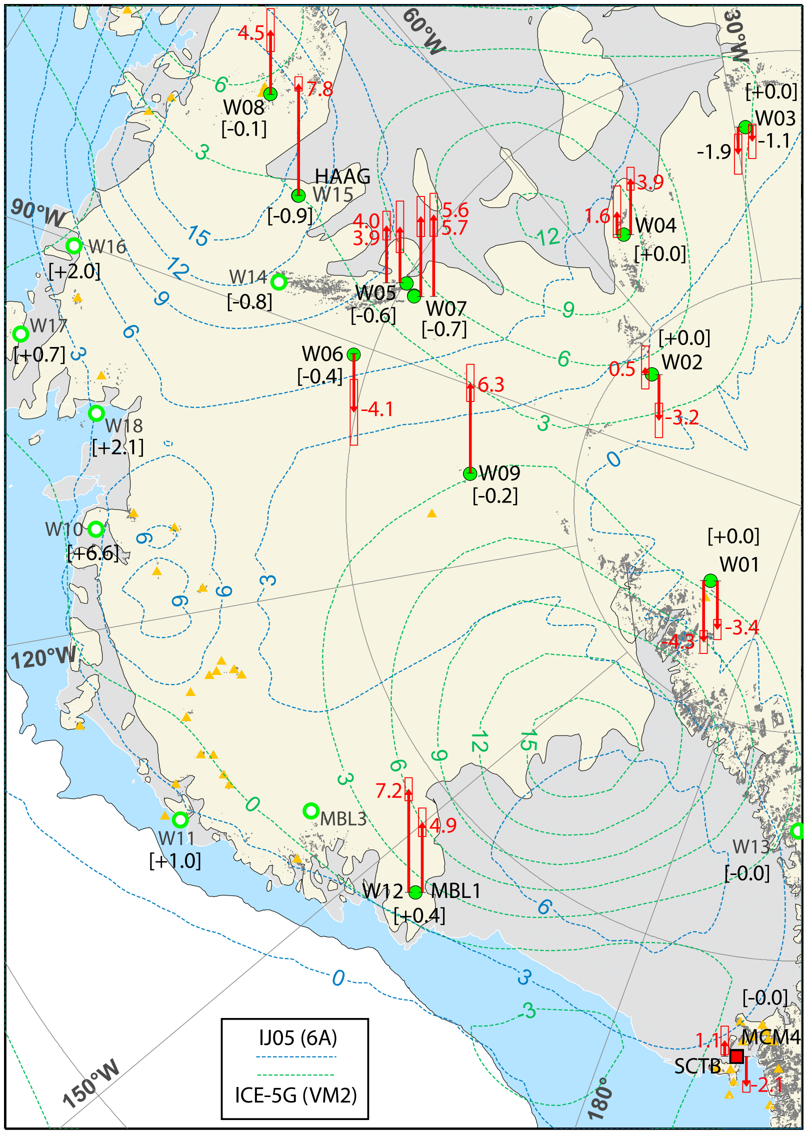

Figure 3. The vertical velocity solutions (mm/yr) presently available for WAGN survey stations (filled green circles) and two nearly collocated CGPS stations MCM4 and SCTB (red square). The open green circles indicate WAGN stations that must be reoccupied before they can deliver a useful velocity estimate. The contours indicate the model predictions shown in Figure 1. Predicted elastic uplift rates (mm/yr) are shown in brackets. Yellow triangles indicate volcanoes. Other symbols are as in Figure 1.

changed by more than 0.1 mm/yr. In this sense our vertical reference frame is robust. It is gratifying, if somewhat surprising, to note that if we utilized a local (“cratonic”) reference frame “attached” to East Antarctica, our vertical velocity estimates would remain almost unchanged.

[7] The horizontal velocities observed at the WAGN stations, HAAG, and MBL1 are everywhere small (their RMS value is just 1.6 mm/yr) supporting previous suggestions that almost the entire Antarctic continent constitutes part of a single tectonic plate [*Donnellan and Luyendyk*, 2004; *Dietrich et al.*, 2004]. We shall discuss these modest horizontal movements elsewhere. We note that all nearly collocated (“A” and “B”) stations have no significant relative horizontal velocities, implying that the rocks into which these monuments were set are not locally unstable. The A and B monuments are typically 5–15 m apart.

[8] Redundant determinations of vertical velocity were made at sites W01–W05, and W07, and these all agree well except for the pair at W02 (Pecora Escarpment). The stations MBL1 and W12A are nearly colocated, and only slightly discrepant. We suspect that the velocity estimate at W02B was biased downward because the second (and last)

Table 1. Geodetic Solution for the WAGN Stations and Various CGPS Stations in Antarctica[a]

Stnm	Latitude	Longitude	Tspan	Epochs	$\mathbf{v}_u$	σ_u	$\mathbf{v}_{el}$	Station Name
				East Antarctic Stations				
DAV1	−68.58	77.97	11.5	2361	−1.4	0.2	−1.1	Davis
DAVR	−68.58	77.97	5.0	623	−0.9	0.7	−1.1	Davis (same antenna as DAV1)
DUM1	−66.67	140.00	9.4	2515	−1.5	0.2	−0.6	Dumont d'Urville
MAW1	−67.60	62.87	12.2	2489	−0.8	0.2	−0.4	Mawson
SYOG	−69.01	39.58	12.2	2638	0.6	0.2	0.3	Syowa
VESL	−71.67	−2.84	9.4	1898	1.3	0.3	−0.5	Vesleskarvet
CAS1	−66.28	110.52	12.2	2489	0.5	0.2	−0.8	Casey Base
				Antarctic Peninsula Stations and Frei Base				
OHIG	−63.32	−57.90	6.1	629	7.6	1.0	0.9	O'Higgins
OHI2	−63.32	−57.90	6.1	1600	7.0	0.7	0.9	O'Higgins
OHI3	−63.32	−57.90	5.1	1208	6.5	0.8	0.9	O'Higgins
PALM	−64.78	−64.05	9.3	2563	4.8	0.3	4.1	Palmer Station
SPPT	−64.29	−61.05	4.0	5	7.5	1.8	4.5	Spring Point (survey station)
FREI	−62.19	−58.98	4.8	744	−2.9	0.7	0.6	Frei (not in Antarctic plate)
				West Antarctica and the Transantarctic Mountains				
MCM4	−77.84	166.67	12.2	2694	−2.1	0.4	−0.0	McMurdo CGPS
SCTB	−77.85	166.76	3.3	1167	1.1	1.0	−0.0	Scott Base CGPS
W01A	−87.42	−149.43	4.0	16	−4.3	0.8	0.0	Mount Howe
W01B	−87.42	−149.44	4.0	18	−3.4	0.7	0.0	Mount Howe
W02A	−85.61	−68.56	6.0	17	0.5	1.5	0.0	Pecora Escarpment
W02B	−85.61	−68.56	3.9	7	−3.2	1.2	0.0	Pecora Escarpment
W03A	−81.58	−28.40	3.9	7	−1.9	1.4	0.0	Whichaway Nunataks
W03B	−81.58	−28.40	3.9	7	−1.1	1.2	0.0	Whichaway Nunataks
W04A	−82.86	−53.20	3.0	13	1.6	1.8	0.0	Cordiner Peaks
W04B	−82.86	−53.20	5.1	18	3.9	0.8	0.0	Cordiner Peaks
W05A	−80.04	−80.56	5.1	54	4.0	1.0	−0.6	Wilson Nunataks
W05B	−80.04	−80.56	3.0	32	3.9	1.8	−0.6	Wilson Nunataks
W06A	−79.63	−91.28	3.0	10	−4.1	2.3	−0.4	Mount Johns
W07A	−80.32	−81.43	5.1	50	5.6	1.4	−0.7	Patriot Hills
W07B	−80.32	−81.54	5.0	18	5.7	1.5	−0.7	Patriot Hills
W08A	−75.28	−72.18	5.0	23	4.5	1.5	−0.1	Mount Suggs aka Behrendt Mountains
W09A	−82.68	−104.40	3.0	25	6.3	1.3	−0.2	Whitmore Mountains
W12A	−78.03	−155.02	4.1	17	7.2	0.8	0.4	Mount Paterson
MBL1	−78.03	−155.02	7.1	39	4.9	1.0	0.4	Mount Paterson (JPL), near W12A
HAAG	−77.04	−78.29	12.0	18	7.8	0.5	−0.9	Haag Nunatak (BAS), near W15
				WAGN Sites Presently Without Velocity Solutions				
W10	−74.55	−111.88					6.6	Bear Peninsula
W11	−74.78	−136.79					1.0	Cape Burks
W13	−83.13	159.51					−0.0	Moody Nunatak
W14	−77.52	−86.77					−0.8	Howard Nunataks
W15	−77.04	−78.29					−0.9	Haag Nunatak
W16	−73.11	−90.30					2.0	Lepley Nunatak
W17	−72.53	−97.56					0.7	Thurston Island
W18	−74.43	−102.48					2.1	Backer Islands

[a] Listed are the station code, its latitude and longitude, the time span between the first and last station occupations, the number of measurement epochs, the vertical velocity in mm/yr (positive upward), and its uncertainty (the half-width of the nominal 95% confidence level). Also listed is the estimated rate of purely elastic rebound ($\mathbf{v}_{el}$) in mm/yr. Stnm, four-letter station code.

occupation of this station occurred much earlier in the summer than did the first occupation, and so the annual oscillation in station height driven by seasonal snow and ice loads "leaked" into the secular velocity estimate. This aliasing problem can be significant when the station has been occupied only twice, the total observational time span is 4 years or less, and the phase shifts between occupation dates are appreciable (∼1 month). This combination of factors has occurred at two additional stations (W09A and W012) though the seasonal phase shifts there were considerably smaller. If our aliasing hypothesis is correct, then the velocity at W12A and W09A could be biased by as much as +1.5 and −1.0 mm/yr, respectively. We will get further insights into this process as

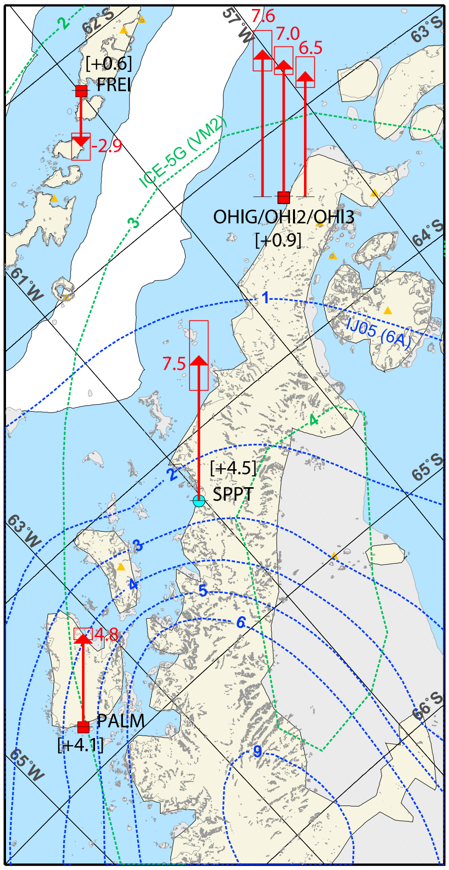

Figure 4. Vertical velocity solutions (mm/yr) available at CGPS stations (red squares) and the survey station SPPT (green circle) in the northern Antarctic Peninsula, together with the model predictions (contours) from Figure 1. Note that three separate solutions are available for Base O'Higgins. Predicted elastic uplift rates (mm/yr) are shown in brackets. Other symbols are as in Figure 1.

more WAGN stations are converted to CPGS stations. Because strong seasonal (elastic) signals are often driven by local environmental load cycles [e.g., *Bevis et al.*, 2005], it is not practical to use remote CGPS stations (i.e., the IGS stations) to assess the potential impact of seasonal signal aliasing at WAGN stations occupied only in survey mode.

[9] The CGPS stations at Scott Base (SCTB) and McMurdo Station (MCM4) are both located on the volcanically active Ross Island. Although they are only ~2.4 km apart, their vertical velocities are significantly different. We infer that MCM4, built on a mound of basaltic gravel, which appears to be engineering fill, is subject to local subsidence. Since SCTB was constructed on bedrock, we prefer this solution despite its shorter observational time span.

[10] The vertical velocity solutions obtained within the WAGN area (Figure 3) are rather surprising. Four stations (W01, W02, W03 and W06) appear to be subsiding in areas where nearly all PGR models predict uplift or no appreciable movement, and the uplift rates observed at W04, though positive, are substantially lower than most model predictions for this location. The same situation occurs at CGPS station SCTB at Scott Base. In contrast, two stations (W12/MBL1 and W09) are uplifting at rates that substantially exceed nearly all model predictions. No PGR model known to us matches our geodetic results. For example, ICE-5G (VM2) greatly overpredicts the uplift rate observed at W04, and IJ05 (6A) greatly overpredicts the uplift rate observed at stations W08 and HAAG.

[11] We present several velocity solutions for stations located in the northern Antarctic Peninsula, including the CGPS station PALM at Palmer Station, and several CGPS stations (OHIG, OHI2, OHI3) at O'Higgins Base. We have obtained an additional result for the survey station SPPT at Spring Point, and for the CGPS station FREI that is not part of the peninsula nor the Antarctic plate [*Dietrich et al.*, 2004; *Taylor et al.*, 2008]. All PGR models known to us underestimate the geodetic uplift rates at O'Higgins, SPPT, and FREI, and some of them also underestimate the uplift rate at PALM (Figure 4).

3. Comparing the GPS Results With PGR Model Predictions

[12] We have compared our initial vertical velocity estimates with the predictions of four numerical models for PGR: ICE-5G (VM2), IJ05 (6A), RF3S20 (β = 0.2) and HUY09m [*Sasgen et al.*, 2007a]. The first two model predictions are depicted in Figures 1, 3, and 4. We have computed the differences between all four predictions and our geodetic estimates for each WAGN station listed in Table 1 (including all nearly colocated measurements). We have computed the empirical cumulative distribution functions (CDFs), for the predicted minus observed (P-O) uplift rates for each of the PGR models, and we have computed an ensemble CDF by combining the (P-O) residuals for all four models (Figure 5). The ensemble or composite CDF curve has been color coded so as to indicate the contributions of (1) the East Antarctic stations, (2) the WAGN stations, (3) the northern peninsula stations, and (4) station FREI, which lies just outside the Antarctic plate. We see that all PGR models tend to overpredict the rebound rates in the

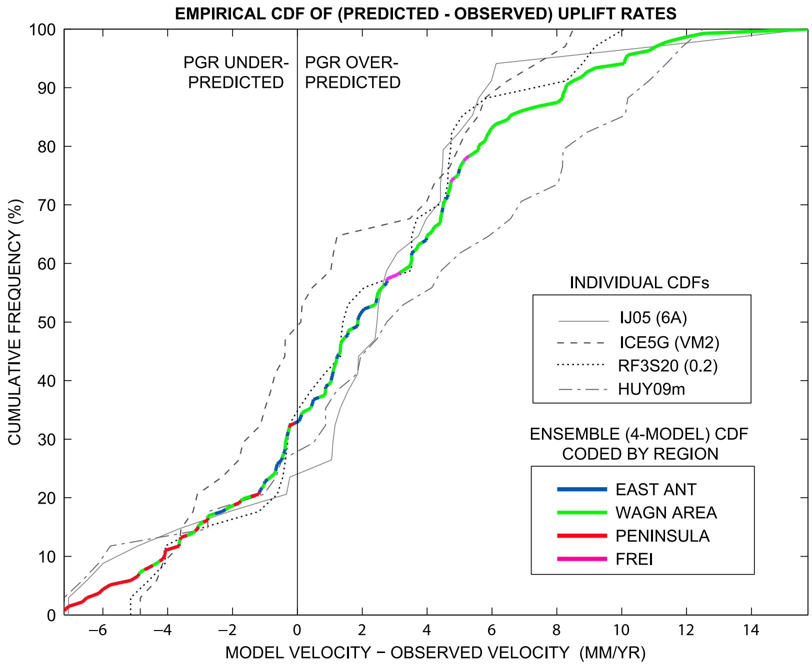

Figure 5. The four gray curves are empirical CDFs for the predicted minus observed values for uplift rate for the PGR models IJ05 (6A), ICE-5G (VM2), RF3S20 ($\beta = 0.2$), and HUY09m (see the top inset key). The colored curve indicates the ensemble CDF for all four models, color coded according to the spatial location of the GPS stations (see bottom inset key). All geodetic velocity solutions (Table 1) are represented, including the three separate solutions available at O'Higgins Base and both the A and B solutions available at six of the WAGN stations.

WAGN area, and underpredict them in the northern peninsula (a much smaller area).

4. Elastic Rebound

[13] We now make the case that the discrepancy between the measured uplift velocities and PGR predictions cannot be accounted for by the Earth's instantaneous elastic response to contemporary changes in ice mass, except, possibly, in parts of the northern peninsula. Estimates of the elastic response to modern changes in ice loading are imprecise because near-field elastic responses are sensitive to the details of shallow elastic structure [*Bevis et al.*, 2005], which are not well known, and, even more importantly, because *all* published estimates of recent ice mass rates of change involve large uncertainties [e.g., *Rignot et al.*, 2008; *Helsen et al.*, 2008; *Wingham et al.*, 2006]. For example, a recent and highly regarded study [*Rignot et al.*, 2008] divided Antarctica into 19 sectors, each consisting of one or more drainage basins, and estimated the annual rate of change of ice mass ($\dot{M}$) in each sector, nominally for the year 2000. The associated formal error estimates, σ, for $\dot{M}$ are sufficiently large that for 14 of the 19 sectors $|\dot{M}| \leq \sigma$, and of the remaining 5 sectors in only two cases is $|\dot{M}| > 2\,\sigma$. Nevertheless, we can estimate the probable magnitude of elastic rebound rates and assess their potential impact. While the net mass rate $\dot{M}$ per sector is of interest, it is also relevant to consider the spatial intensity of this loading, i.e., each sector's average value of ice mass change per unit area. If we express this rate in terms of an equivalent change in water depth, $\dot{D}$, then 3 sectors have $+8 < \dot{D} < +40$ mm/yr, 10 sectors have $-16 < \dot{D} < 0$ mm/yr, 5 sectors have $-190 < \dot{D} < -71$ mm/yr, and one (Ferrigno-Abbot) has $\dot{D} = -628$ mm/yr, though this last sector represents just 0.6% of Antarctica's total area. As a result, pronounced elastic uplift rates are expected only over limited parts of the continent, and these areas are all located near the coast of West Antarctica (Amundsen Sea), where we have no geodetic velocity solutions as yet, or in the northern peninsula [*Rignot et al.*, 2008].

[14] We have computed estimates of the elastic uplift rates using a loading grid, with a resolution of 0.25°, based on an analysis [*Helsen et al.*, 2008] which attributes observed ice sheet elevation changes in the period 1995–2003 to a combination of ice mass changes and ice density changes. The latter are due to changes in firn depth caused by space-time variations in accumulation and temper-

ature [*Helsen et al.*, 2008]. We modified this loading field in the northern peninsula by substituting the mass rates estimated by *Rignot et al.* [2004]. Using this loading grid, designated H08+, the Earth's elastic response was computed using the spectral method of *Sasgen et al.* [2007b]. For this study we used a spherical harmonic expansion truncated at degree and order 512, and we adopted the purely radial structure of PREM [*Dziewonski and Anderson*, 1981] to represent Earth's elastic structure.

[15] The predicted rates of elastic rebound are indicated for each GPS station in Figures 1, 3, and 4. The elastic rebound rates predicted for the East Antarctic stations fall in the range −1.1 to +0.3 mm/yr. For the WAGN stations with geodetic velocity estimates the predicted elastic rates fall between extremes of −0.9 mm/yr at HAAG and +0.4 mm/yr at station MBL1 (+0.4 mm/yr), though more than half of the predictions fall in the range −0.17 to +0.03 mm/yr. Clearly our elastic rebound predictions cannot account for the several mm/yr bias between the geodetic velocities and the PGR predictions for East Antarctica and the WAGN area (Figure 5), even if we assume that average rebound rates increased by a factor of two or three between the period 1995–2003, for which our loading grid applies, and for 2002–2005/7 when the observed displacements accumulated. Elastic rebound may be a much more important component of vertical crustal velocity in parts of the northern peninsula. We predict elastic uplift rates of 4.1 mm/yr at PALM and 4.5 mm/yr at SPPT, though only 0.9 mm/yr at O'Higgins Base near the tip of the peninsula.

[16] It is difficult to assess how elastic rebound rates have varied since 1995. Net ice mass loss in the peninsula accelerated from −25 ± 45 Gt/yr in 1996, to −28 ± 45 Gt/yr in 2000 and −60 ± 46 Gt/yr in 2006 [*Rignot et al.*, 2008]. However, the individual formal errors are so large that the implied rate of acceleration (−3.6 ± 6.4 Gt/yr) is not significantly different from zero. We note that our geodetic measurements at O'Higgins Base imply no significant increase in its vertical velocity, since the estimate of 7.6 ± 1.0 mm/yr for OHIG was obtained in 1996.3–2002.1, whereas the velocity estimates of 7.0 ± 0.7 mm/yr for OHI2 and 6.5 ± 0.8 mm/yr for OHI3 represent the time periods 2002.1–2008.3 and 2003.2–2008.3, respectively.

5. Discussion

[17] The most uncertain element in most geodetic solutions is the formal estimate of its uncertainty. Could our measurement errors at the WAGN stations be larger than our formal error estimates (Table 1) by say ∼1 mm/yr, and perhaps by ∼2 mm/yr at a small number of stations? Certainly that is possible. But it is extremely unlikely that errors in our geodetic solutions can account for systematic biases with absolute magnitudes of >4 mm/yr in the northern peninsula and >7 mm/yr in the WAGN area (Figure 5). We have been using survey GPS to measure the vertical crustal velocity field at about two dozen stations in southern Patagonia for many years, and we have noticed that our latest velocity solution, which is based on total observational time spans of 6–12 years at most stations, does not differ by more than ∼2 mm/yr from our first vertical velocity solution, which was obtained using time spans of 4–5 years at most stations.

[18] We conclude that all four PGR models considered here tend to underpredict geodetic uplift rates in the northern peninsula, and overpredict them in the WAGN area. Elastic rebound signals can account for part of the discrepancy in the peninsula, but cannot explain the PGR prediction bias detected elsewhere. Significant elastic signals are expected for stations W10, W11, and W16–W18, which we are still waiting to reobserve. Since the PGR models are positively biased outside of the peninsula, the suggestion is that most recent GRACE-based studies of ice mass balance in Antarctica have overestimated recent rates of ice loss. This systematic bias would be amplified in studies that used a spatial averaging filter that deemphasizes the northern peninsula.

[19] We can estimate the potential magnitude of the ice mass biases by noting that if the average velocity prediction bias of ∼5 mm/yr evident in Figure 5 is developed over $\sim 2 \times 10^6$ km^2, an area somewhat smaller than that of West Antarctica, this would cause an apparent but spurious ice loss of ∼33 Gt yr^{-1}, which is a significant fraction of all published ice mass rates derived from GRACE [*Velicogna and Wahr*, 2006; *Chen et al.*, 2006; *Ramillien et al.*, 2006; *Sasgen et al.*, 2007a]. However, it is not possible to arrive at an accurate numerical estimate of the impact of our geodetic measurements on GRACE ice mass change solutions without finding a reliable means to interpolate between our point measurements of vertical crustal velocity. Clearly, the most reasonable basis for doing this is to assimilate our geodetic results into the leading classes of PGR models, and allow these sophisticated models to perform the interpolation based on their model physics.

[20] As POLENET fieldwork proceeds our geodetic solutions will improve, and become more numerous. Given continuous time series at most of these stations, we will obtain deeper insights into elastic loading by observing the bedrock response to seasonal loading cycles. We expect that the substantial differences between Antarctica ice mass rate estimates already derived from GRACE observations [*Velicogna and Wahr*, 2006; *Chen et al.*, 2006; *Ramillien et al.*, 2006; *Sasgen et al.*, 2007a] will steadily diminish as these analyses are repeated using later generations of PGR models that are better constrained by direct crustal velocity measurements.

[21] At present, inadequate knowledge of the PGR fields in Antarctica limits our ability to gauge linear (in time) trends in ice mass using GRACE. However, any sudden increase in the rate of ice loss will be resolved unambiguously by GRACE since the mass rates associated with PGR do not change significantly over several years. Rapidly accelerating changes in ice mass can also be detected, completely independently of GRACE, by growing networks of GPS stations. In effect, Earth's instantaneous elastic response to surface loading changes will allow us to ''weigh'' the ice sheets using GPS [*Hager*, 1991; *Khan et al.*, 2007]. While observed vertical velocities are a mixture of PGR and the elastic response to modern load changes, any sudden increase in vertical crustal velocity will unambiguously reveal an increase in the rate of ice loss.

[22] Higher than expected rates of PGR in the peninsula, and lower than expected rates in the WAGN area, can be explained, in part, by imperfections in our ice history models [e.g., *Bentley*, 2009]. But we suspect that the influence that neotectonic setting has on isostatic response times, already demonstrated in Patagonia [*Ivins and James*, 2004], is also a key factor in Antarctica.

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