Rise of the Ellsworth mountains and parts of the East Antarctic coast observed with GPS

Donald F. Argus,[1] Geoffrey Blewitt,[2] W. Richard Peltier,[3] and Corné Kreemer[2]

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[1] Using GPS observations from 1996 to 2011, we constrain postglacial rebound in Antarctica. Sites in the Ellsworth mountains, West Antarctica, are rising at ≈5 ± 4 mm/yr (95% confidence limits), as in the postglacial rebound model of Peltier, but ≈10 mm/yr slower than in the model of Ivins and James. Therefore significant ice loss from the Ellsworth mountains ended by 4 ka, and current ice loss there is less than inferred from GRACE gravity observations in studies assuming the model of Ivins and James. Three sites along the coast of East Antarctica are rising at 3 to 4 ± 2 mm/yr, in viscous response to Holocene unloading of ice along the Queen Maud Land coast and elsewhere. Kerguelen island and seven sites along the coast of East Antarctic are part of a rigid Antarctica plate. O'Higgins, northern Antarctic peninsula, is moving southeast at 2.3 ± 0.6 mm/yr relative to the Antarctic plate.

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1. Introduction

[2] Antarctica's viscous response to late Pleistocene unloading of ice is poorly constrained because there are few Holocene relative sea level histories available [e.g., *Bassett et al.*, 2007]. Hence estimates of the contribution of Antarctic ice loss to Holocene global sea level rise vary greatly: 10 m [*Ivins and James*, 2005], 14 m [*Denton and Hughes*, 2002], 18 m (ICE-5G v1.3a [*Peltier*, 2007]), and 37 m [*Nakada and Lambeck*, 1988].

[3] Geological observations constrain the start of significant Antarctic deglaciation to be after 14.2 ka, the time of Meltwater Pulse 1A [*Bentley et al.*, 2010]. Radiocarbon dating of sediment cores shows that marine sedimentation beneath the Larsen B ice shelf began at 10.5 ka [*Domack et al.*, 2005]; radiocarbon dating shows that deposition of varved sediments on calving bay reentrants along the East Antarctic coast began at 11 ka [*Leventer et al.*, 2006]. The observation that relative sea level on tropical Pacific islands was at a 2 m high stand at 4 ka requires ice sheet loss from Antarctic and elsewhere to have ended by 4 ka [*Peltier et al.*, 2002]. *Mackintosh et al.* [2011] find that ice loss from Mac Robertson Land, East Antarctica, started slowly at 14 ka, increased greatly at ≈12 ka, and ended by 7 ka. In ICE-5G v1.3a [*Peltier*, 2007] Antarctic ice loss begins abruptly at 11.5 ka, the time of Meltwater Pulse 1B [*Peltier and Fairbanks*, 2006], and ends at 4 ka.

[4] In this study we evaluate the fit of two postglacial rebound models to space geodetic estimates of uplift of solid Earth's surface (Figure 1). The model of *Peltier* [2007] is based on deglaciation history ICE-5G v1.3a and mantle viscosity profile VM2 and has an elastic lithosphere 90 km thick. The model of *Simon et al.* [2010] is based on deglaciation history IJ05 [*Ivins and James*, 2005] and a three-layer mantle viscosity profile and also has an elastic lithosphere 90 km thick. Because postglacial rebound of West Antarctica depends mostly on the viscosity of the upper mantle (see Fréchet kernels in Figure 5 of *Peltier* [2004], with West Antarctica being about the same size as Fennoscandia), and because the mean upper mantle viscosity is nearly equal in the models of *Peltier* [2007] and *Simon et al.* [2010], differences between the predictions of the two models are due mainly to differences in deglaciation history. *Argus and Peltier* [2010] assess the fit of the model of *Peltier* [2007] to space geodetic observations.

[5] In Antarctica the model of *Peltier* [2007] predicts current uplift to have three local maxima: (Figure 2a, R) 10 mm/yr in the southern Antarctic peninsula, (S) 10 mm/yr along the southern margin of the Ronne ice shelf, and (T) 14 mm/yr along the southeast margin of Ross ice shelf. The model of *Simon et al.* [2010], which is nearly identical to that of *Ivins and James* [2005], predicts current uplift to be a maximum of (Figure 2b, U) 20 mm/yr in the southern Antarctic peninsula. Herein we find that sites in the Ellsworth mountains are rising at ≈5 ± 4 mm/yr (95% confidence limits), as in the model of *Peltier* [2007], but ≈10 mm/yr slower than in the model of *Simon et al.* [2010].

2. Data and Methods

[6] From GPS observations we estimate position-time series from 1996 to 2011 (Text S1 in the auxiliary material).[1] Eleven permanent GPS sites along the Antarctic coast have 8 to 15 yr of data [*Dow et al.*, 2009], yielding tight velocity estimates (Figure S1). Scientists established the (WAGN) West Antarctic Campaign Network in four consecutive summers beginning in January 2002; at six sites *Bevis et al.* [2009] placed a permanent (ANET) Antarctic NETwork GPS receiver at the WAGN mark, allowing us to estimate the velocity of each site without solving for an offset (Figure S2).

[7] Following the method of *Argus et al.* [2010] we invert estimates of velocity from GPS, VLBI, SLR, and DORIS for the velocity of Earth's center and the velocity of the plates.

[1]Satellite Geodesy and Geodynamics, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

[2]Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, Reno, Nevada, USA.

[3]Department of Physics, University of Toronto, Toronto, Ontario, Canada.

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL048025.

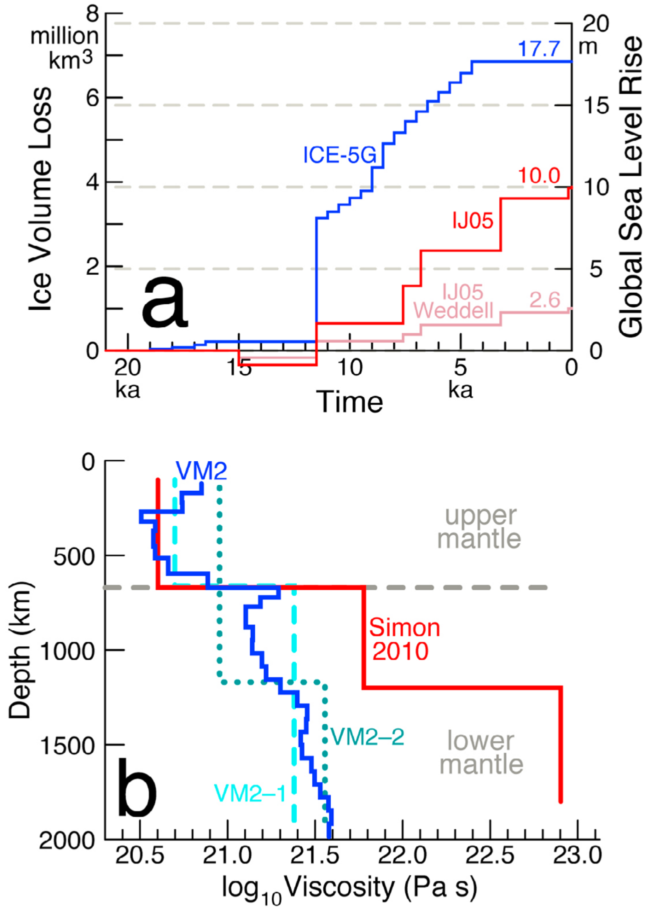

Figure 1. (a) Antarctic ice loss as a function of time in models ICE-5G v1.3a [*Peltier*, 2007] and IJ05 [*Ivins and James*, 2005]. The contribution to global sea level rise in m is given along the right-hand axis. (b) Mantle viscosity as a function of depth in models VM2 [*Peltier*, 2004], the model of *Simon et al.* [2010], and models VM2–1 and VM2–2 [*Paulson et al.*, 2007].

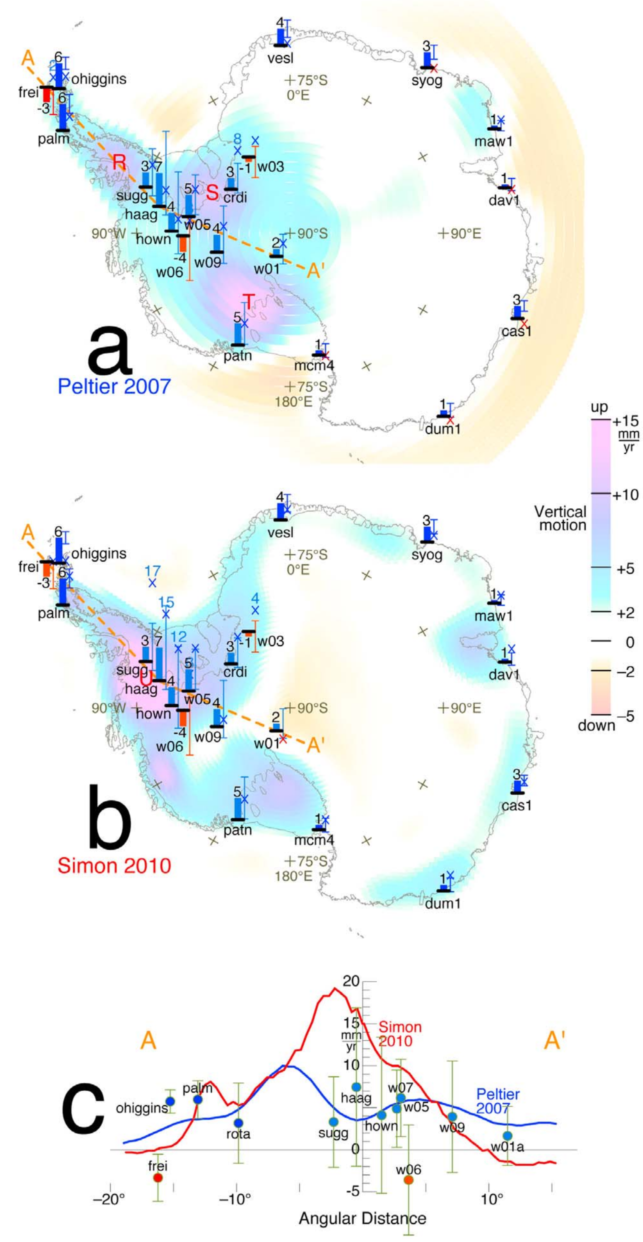

Figure 2. Observations of uplift (vertical blue bars) and subsidence (vertical red bars) are compared to the predictions of the postglacial rebound models of (a) *Peltier* [2007] and (b) *Simon et al.* [2010]. Observed vertical rates are given (in black) in mm/yr; error bars are 95% confidence limits; the (small blue) 'X's are the model predictions; predicted uplift rates are given (in light blue) where they exceed observed rates by more than 5 mm/yr. The color gradations show, as the legend specifies, the model predictions. The uplift maxima of *Peltier* [2007] are shown (in red) as 'R', 'S', and 'T'; the uplift maximum of *Simon et al.* [2010] is shown (in red) as 'U'. (c) Observations of uplift and subsidence as a function of distance along profile A–A′ are compared to the predictions of the postglacial rebound models of (blue) *Peltier* [2007] and (red) *Simon et al.* [2010].

Velocity models for VLBI, SLR, and DORIS are identical to those of *Argus et al.* [2010].

3. Results

3.1. Earth's Center

[8] The velocity of Earth's center transforms 1 to 1 into all estimates of site velocity [*Argus et al.*, 1999]. Herein we define Earth's center to be (CE) the mass center of solid Earth and simultaneously estimate the velocity of CE assuming that, besides plate motion, the parts of the plates not near the late Pleistocene ice sheets are moving negligibly in the horizontal relative to CE [*Argus*, 2007; *Argus et al.*, 2010]. (*Kogan and Steblov* [2008] do so also, but describe the definition of Earth's center differently.) We minimize the sum of the squares of the weighted differences between the observed and predicted horizontal site velocities. The horizontal components of site velocity constrain the velocity of CE because changing the velocity of CE changes the horizontal component of site velocity by a different amount at different places and, if the velocity of CE were wrong, then the plates would appear to be deforming. (*Blewitt*

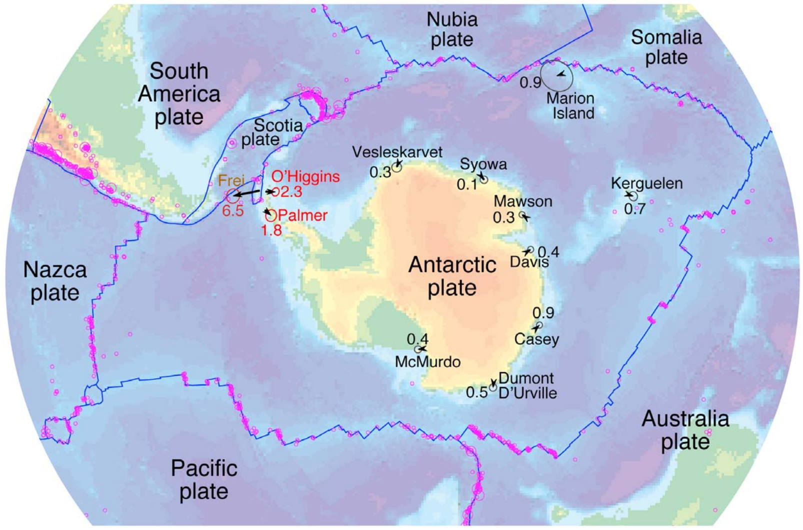

Figure 3. Observations of horizontal velocity and two-dimensional 95% confidence limits. The color of each ellipse and site name designate the category to which the site is assigned: (black) on the Antarctic plate and moving insignificantly in glacial isostatic adjustment, (red) on the Antarctic plate but moving in glacial isostatic adjustment, (brown) on the Shetland plate. Earthquakes with body or moment magnitude greater than 5.2 from 1964 to 1995 are from *Engdahl et al.* [1998].

[2003] defines this constraint to be the (CL) center of lateral movement of Earth's surface.) We maintain that no phenomenon can sustain a significant velocity between CE and the (CM) center of mass of solid Earth, oceans, and atmosphere [*Argus*, 2007; *Argus et al.*, 2010, Appendix A]. The inversion yields estimates of vertical motion that do not depend on a postglacial rebound model.

[9] The velocity of CE that we estimate is nearly identical to the velocity that *Argus et al.* [2010] estimate in an identical manner (Figure S3). But our estimate of the velocity of CE differs from the velocity of CM in ITRF2008 [*Altamimi et al.*, 2011] along Z by 1.1 mm/yr. Therefore our estimates of vertical rates in Antarctic have 1.0 mm/yr more uplift than do those in ITRF2008 (Figure S4).

3.2. Vertical

[10] Five sites in the Ellsworth mountains (sugg, haag, hown, w07, and w05) are rising at ≈5 mm/yr, consistent with the uplift predicted by the model of *Peltier* [2007], but a significant 5–12 mm/yr slower than predicted by the model of *Simon et al.* [2010] (Figure 2 and Table S1). We infer that significant ice loss from the Ellsworth mountains ended by 4 ka, as in the model of *Peltier* [2007]. If there were current ice loss from the Ellsworth mountains, then the disagreement with the model of *Simon et al.* [2010] would increase.

[11] Three sites along the East Antarctica coast (Vesleskarvet, Syowa, and Casey) are rising at 3–4 ± 2 mm/yr, in viscous response to Holocene unloading of ice. GRACE gravity observations near the three sites suggest current ice loss to be small [*Chen et al.*, 2009; *Horwath and Dietrich*, 2009]. We infer that there was more ice in these places at 11.5 ka than in ICE-5G.

[12] O'Higgins, in the northern Antarctic peninsula, is rising at 5.7 ± 1.3 mm/yr, 3 mm/yr faster than predicted by the model of *Peltier* [2007]. Palmer is rising at 6.0 ± 2.2 mm/yr, 3 mm/yr faster than the prediction. From GRACE gravity observations *Peltier* [2009] infers there to be current ice loss from the northern Antarctic peninsula, which would produce uplift that lessens the difference between the GPS observation and the postglacial rebound prediction. Frei is, however, falling at 3.4 ± 2.8 mm/yr, bringing some doubt to that interpretation.

3.3. Horizontal

[13] Kerguelen island and seven sites along the East Antarctic coast (Vesleskarvet, Syowa, Mawson, Davis, Casey, Dumont D' Urville, and McMurdo) are moving as part of the rigid Antarctic plate (Figure 3). The weighted root mean square of the eight residual speeds is 0.5 mm/yr.

[14] O'Higgins, along the northern coast of the Antarctic peninsula, is moving relative to the Antarctic plate southeast at 2.3 ± 0.6 mm/yr (95% confidence limits). This direction is opposite that expected due to current or Holocene ice loss from the peninsula. O'Higgins is 110 km south of Bransfield basin, the continental rift between the Antarctic and Shetland plates [*Bird*, 2003], far enough for the site to be on the Antarctic plate. Palmer is moving relative to the Antarctic plate south at 1.8 ± 1.0 mm/yr.

[15] Frei, on the Shetland plate just north of Bransfield basin, is moving relative to the Antarctic plate northwest at 6.5 ± 1.3 mm/yr, consistent with the observation of *Taylor et al.* [2008] that Frei and three campaign sites are moving northwest at ≈7 mm/yr as part of the Shetland plate.

4. Discussion

[16] Estimates of current Antarctic ice mass loss from GRACE gravity observations depend strongly on the postglacial rebound model corrected for. *Chen et al.* [2009] estimate Antarctica to be losing ice at 190 Gt/yr (equivalent to a global sea level rise of 0.52 mm/yr), which they determine to be the gravity decrease observed by GRACE (−112 Gt/yr) minus the gravity increase due to postglacial rebound (+78 Gt/yr). If *Chen et al.* [2009] were to instead correct for the model of *Paulson et al.* [2007], then they

would estimate Antarctic ice loss to be 250 Gt/yr (global sea level rise 0.69 mm/yr). (The model of *Paulson et al.* [2007] consists of deglaciation history ICE-5G and mantle viscosity profile VM2-2.) The estimates of Antarctic ice loss of *Velicogna and Wahr* [2006] (global sea level rise of 0.38 mm/yr), *Horwath and Dietrich* [2009] (0.30 mm/yr), and *Peltier* [2009] (0.34 mm/yr) also depend on the postglacial rebound model corrected for.

[17] The Ellsworth mountains are rising at ≈5 ± 4 mm/yr, as in the model of *Peltier* [2007], but ≈10 mm/yr slower than in the model of *Simon et al.* [2010]. Substituting the model of *Peltier* [2007] for that of *Ivins and James* [2005], we infer less current ice loss (or more current ice gain) near the south coast of Ronne ice shelf than do *Chen et al.* [2009] and *Horwath and Dietrich* [2009].

[18] Using cosmogenic ^{10}Be dating of exposure of the trim line in the Heritage range, Ellsworth mountains, *Bentley et al.* [2010] conclude that the ice sheet there thinned by 230 to 480 m since 15 ka and that 80% of this thinning occurred since 8 ka. In the Weddell Sea model of *Bentley et al.* [2010] ice loss near the Ellsworth mountains is 800 to 1200 m, consistent with the 1000 to 1500 m ice loss in ICE-5G v3.1a.

5. Conclusion

[19] The Ellsworth mountains are rising at ≈5 ± 4 mm/yr (95% confidence limits), as in the postglacial rebound model of Peltier, but ≈10 mm/yr slower than in the model of Ivins and James. Significant ice loss from the Ellsworth mountains ended by 4 ka. Current ice loss there is less than inferred from GRACE gravity observations in studies assuming the model of *Ivins and James* [2005]. GPS observations of uplift in more places and GRACE observations of gravity will distinguish between current ice loss and postglacial rebound elsewhere in Antarctica.

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D. F. Argus, Satellite Geodesy and Geodynamics, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., MS 238-600, Pasadena, CA 91109-8099, USA. (donald.f.argus@jpl.nasa.gov)

G. Blewitt and C. Kreemer, Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, 1664 N. Virginia St., MS 178, Reno, NV 89557-0088, USA.

W. R. Peltier, Department of Physics, University of Toronto, 60 St. George St., Toronto, ON M5S 1A7, Canada.