Revised History and Anticipated Future of the West Antarctic Ice Sheet Based on Recent Results on Mantle Viscosity and Satellite Measurements of Current Mass Changes

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ABSTRACT: Previously (Zwally et. al. (2021) utilized results from simultaneous measurement of ice volume-mass changes by ICESat laser altimetry and ice-mass changes by GRACE gravimetry, deriving compatible corrections respectively for the vertical motion of the Earth's crust and changes in the mass of the Earth's viscous mantle underlying the elastic-plastic crust.

Modeled gravimetry corrections were 5.22 times altimetry corrections over East Antarctica (EA) and 4.51 times over West Antarctica (WA), with inferred mantle densities 4.75 and 4.11 g cm^{-3}.

Derived sensitivities (S_g,S_a) to bedrock motion enabled calculation of motion (δB_0) needed to equalize GRACE and ICESat mass changes during 2003-2008.

For EA, δB_0 is -2.2 mm a^{-1} subsidence with mass matching at 150 Gt a^{-1}, inland WA is -3.5mm a^{-1} at 66 Gt a^{-1}, and coastal WA is only -0.35 mm a^{-1} at -95 Gt a^{-1}.

The EA subsidence was attributed to Holocene dynamic thickening due to a post-glacial increase in precipitation.

The WA subsidence was attributed to low mantle viscosity with faster responses to post-LGM deglaciation and to ice growth during Holocene grounding-line re-advance.

Supporting evidence for low viscosity in WA comes from measurements of faster than expected crustal response to grounded ice mass losses in coastal WA by Barletta et. al. (2018), and deductions that the low mantle viscosity extends inland to the Trans-Antarctic mountain range separating WA from EA, which has the higher viscosity used in GIA models.

The purpose of this poster is to discuss the implications of the lower-viscosity WA mantle on the time response of WA to the post-glacial loss of ice in inner WA and the past and current ice advances into the Ross and Filchner-Ronne ice shelves

Zwally HJ, Robbins JW, Luthcke SB, Loomis BD, Rémy F (2021). Mass balance of the Antarctic ice sheet 1992–2016: reconciling results from GRACE gravimetry with ICESat, ERS1/2 and Envisat altimetry. J. of Glaciology 67(263), 533–559. https://doi.org/10.1017/jog.2021.8

Barletta VR and 16 others (2018) Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability. Science, 360 (6395) 1335-1339 (doi:10.1126/science.aao1447)

The **GIA Models showing uplift in West Antarctica have driven the current prevailing view** in the community **that the bedrock is still rising** from the large mass loss following the Last Glacial Maximum (LGM).

That view raised **serious concerns that the rising bedrock would cause the ice shelf grounding lines** of both the Ross Ice Shelf and the Filchner-Ronne Ice Shelves to advance thereby **significantly increasing the rate of ice discharge into the ocean causing a rapid increase in the rise of global sea level**.

Importantly, **our findings of substantial bedrock subsidence throughout West Antarctica are consistent with**:

a) a lower mantle-viscosity in most of West Antarctica that caused the Post-LGM bedrock uplift to very-rapidly diminish in several thousand years (i.e. early Holocene).

b) post-2013 results showing mid-to-late Holocene ice-sheet thickening and grounding-line advance (e.g. Kingslake et al., 2018; Price et al. 2007; Bentley et al., 2014; Pollard et al., 2016 & 2017).

The **consequent effect of the ice thickening and the bedrock lowering is to stabilize the West Antarctic Ice Sheet** and therefore diminish previous concerns about rapid West Antarctic ice loss and consequent large increase in global sea-level rise.

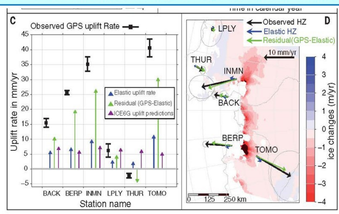
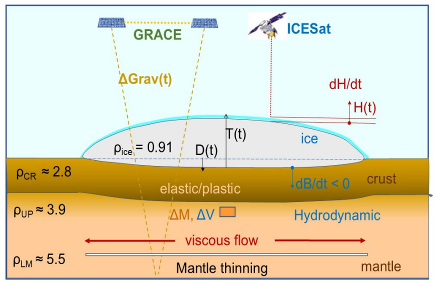


Fig. 1. Observations of bedrock motions and ice changes. (A) The average trend of ice mass

"The bedrock response to ice mass loss, …(GIA) was thought to occur on a time scale of 10,000 years."

"We found a much lower viscosity (4 x 10^{18} pascal-sec) than global average, and this shortens the GIA response to decades up to a century."

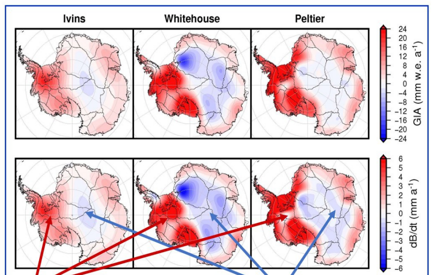
GRACE Senses Gravity Changes and ICESat Senses Ice-Height Changes



- In above, gravity is increasing with increasing ice mass and requiring negative correction for decreasing gravity from viscous outflow of mantle mass (ΔM.) .
- Ice elevation/thickness/volume are increasing requiring positive correction for downward motion of the crust from viscous mantle outflow (ΔV.).

dh/dt = rate of surface elevation change mapped by ICESat repeat passes
dB/dt = bedrock-motion current rate from long-term GIA (Glacial Isostatic Adj.)

GIA and dB/dt from Three Models of Viscous Response of Mantle to Ice Loading



Uplift in West Antarctica from post LGM **ice unloading**. **(Incorrect in sign and magnitude)**

Bedrock **subsidence** in East Antarctica from post LGM **ice growth**.. **(Correct in sign but not magnitude)**

GIA models depend on **history of ice unloading for ~10K years**, which is not well known, and the use of a **global value of mantle viscosity.**

Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability

Science 360 (2018)

Valentina R. Barletta[1,2*], Michael Bevis[2], Benjamin E. Smith[3], Terry Wilson[2], Abel Brown[2], Andrea Bordoni[4], Michael Willis[5], Shfaqat Abbas Khan[1], Marc Rovira-Navarro[1,6], Ian Dalziel[7], Robert Smalley Jr.[8], Eric Kendrick[2], Stephanie Konfal[2], Dana J. Caccamise II[2], Richard C. Aster[9], Andy Nyblade[10], Douglas A. Wiens[11]

The marine portion of the West Antarctic Ice Sheet (WAIS) in the Amundsen Sea Embayment (ASE) accounts for one-fourth of the cryospheric contribution to global sea-level rise and is vulnerable to catastrophic collapse. The bedrock response to ice mass loss, glacial isostatic adjustment (GIA), was thought to occur on a time scale of 10,000 years. We used new GPS measurements, which show a rapid (41 millimeters per year) uplift of the ASE, to estimate the viscosity of the mantle underneath. We found a much lower viscosity (4 × 10^{18} pascal-second) than global average, and this shortens the GIA response time scale to decades up to a century. Our finding requires an upward revision of ice mass loss from gravity data of 10% and increases the potential stability of the WAIS against catastrophic collapse.

Antarctic Regions and Drainage Systems

Novel Method of Zwally et al., 2021 Derived the dB/dt Bedrock Motion from Simultaneous ICESat Laser Altimetry Data and GRACE Gravimetry Data

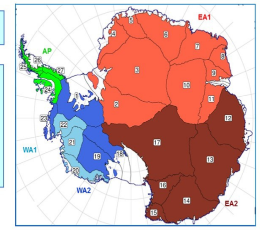
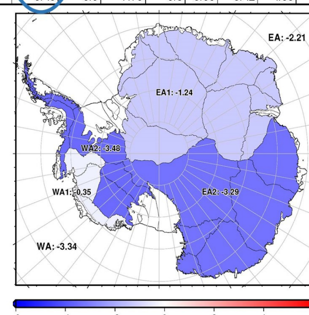


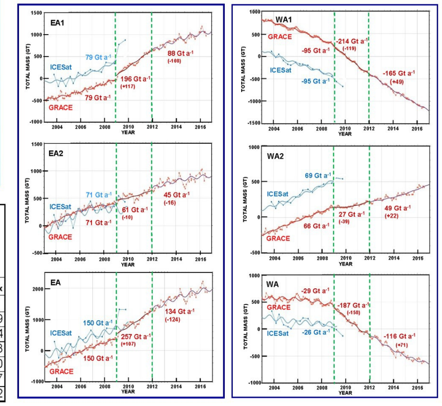
Table 5. Bedrock motions $\delta B_{0\text{-avg}}$ and $\delta B_{md\text{-avg}}$ with their corresponding dB_{cor} that bring ICESat and GRACE dM/dt into agreement, dB/dt from Ivins, Peltier,and Whitehouse models, maximum difference, $\delta(dB/dt)_{max}$, among models

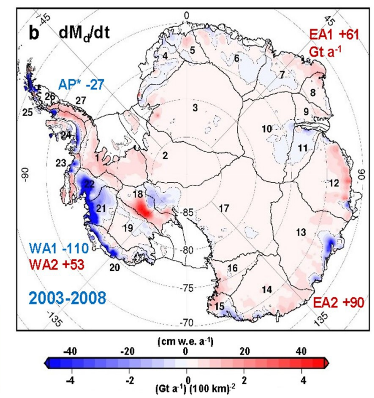
	$\delta B_{0\text{-avg}}$ &	dB_{cor}	$\delta B_{md\text{-avg}}$ &	dB_{cor}	dB/dt (mm a^{-1})			$\delta(dB/dt)_{max}$
Region	(mm a^{-1})	(Gt a^{-1})	(mm a^{-1})	(Gt a^{-1})	Ivins	Peltier	Wthse	(mm a^{-1})
EA	-2.21	-20.5	-2.49	-23.1	0.42	0.60	-0.19	0.79
EA1	-1.24	-6.1	-0.86	-4.2	0.51	0.66	-0.49	1.14
EA2	-3.29	-14.3	-3.62	-15.8	0.33	0.53	0.14	0.38
WA	-3.34	-5.7	-7.20	-12.3	2.76	4.76	4.07	2.00
WA1	-0.35	-0.2	-3.34	-1.9	2.28	3.45	3.23	1.17
WA2	-3.48	-3.9	-7.79	-8.8	3.00	5.42	4.50	2.42



In East Antarctica, the bedrock subsidence derived from satellite data is larger than from the three GIA models all resulting from post LGM ice growth. **In West Antarctica**, the overall subsidence is from ice growth following the uplift after the post LGM ice unloading that decayed quickly due to the lower mantle viscosity.

GRACE and ICESat Mass Changes During 2003-08 Were Equalized by Selecting Appropriate Values of Bedrock Motion (dB/dt) Correction to Mass and Volume





Conclusions from above: a) derivation of significant on-going bedrock subsidence and b) current ice-elevation increase in inner West Antarctica

1. **The rising bedrock shown in the three global-viscosity GIA models is not occurring in the measured GIA, which shows wide-spread subsidence. This result implies that the response to large post LGM ice unloading must have been faster than modeled, as would have occurred using a lower-viscosity mantle.**
2. **The increasing ice elevation in inner West Antarctica (in DS 1, 18, & 19 and the inner portions of the coastal 20, 21, & 22) is likely to be an on-going continuation of the mid-to-late Holocene ice thickening and bedrock subsidence.**
3. **These conclusions suggest that the low viscosity mantle in the coastal region of West Antarctica found by Barletta et al., 2018 very likely extends throughout West Antarctica to the Trans-Antarctic mountains.**

Potential Future Related Work

1. **Repeat the above method of calculation of the bedrock motion (dB/dt) correction (i.e. the GIA) to mass and volume needed to equalizing GRACE and ICESat mass changes during 2003-08 with higher spatial resolution (e.g. 50 km).**
2. **This would provide a widely-useful accurate GIA map with resolution comparable to that from the GIA models.**