Estimation of Antarctic Peninsula Earth structure from viscoelastic modelling constrained by GPS observations

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Summary

The collapse of Antarctic Peninsula ice shelves during the past few decades has resulted in increased ice mass loss from tributary glaciers due to removal of the buttressing ice shelf [*De Angelis and Skvarca*, 2003; *Rignot et al.*, 2004]. Most notably the collapse of the Larsen B ice shelf in 2002 has led to continued acceleration and thinning of glaciers flowing into this embayment [*Berthier et al.*, 2012]. Ice mass changes in this region induce a solid Earth response, which, due to the low viscosity nature of the Earth [*Ivins et al.*, 2011], occurs on a decadal timescale and may be observed as uplift in GPS records.

Using the long term GPS record from Palmer Station (Figures 1 and 3) located close to the Larsen B embayment, we show that ongoing elastic effects of present-day ice mass loss from Prince Gustav, Larsen A, and Larsen B tributary glaciers alone are not enough to explain the observed uplift. The uplift time series can be used to constrain a high resolution viscous model to obtain a range of Earth models that fit the data. We then use six LARISSA (LARsen Ice Shelf System, Antarctica) GPS stations installed in 2009-2010, which are ideally located close to the site of mass loss, to place tighter constraints on the Earth's structure in this region.

The range of rheological parameters that fit the GPS observations using the current ice loss data are a lithospheric thickness of 40 – 100km and an upper mantle viscosity of 1 – 3.2 x 10^{18} Pa s, which will be further refined with improved mass loss datasets and a compressible Earth model.

1. Data

GPS Locations

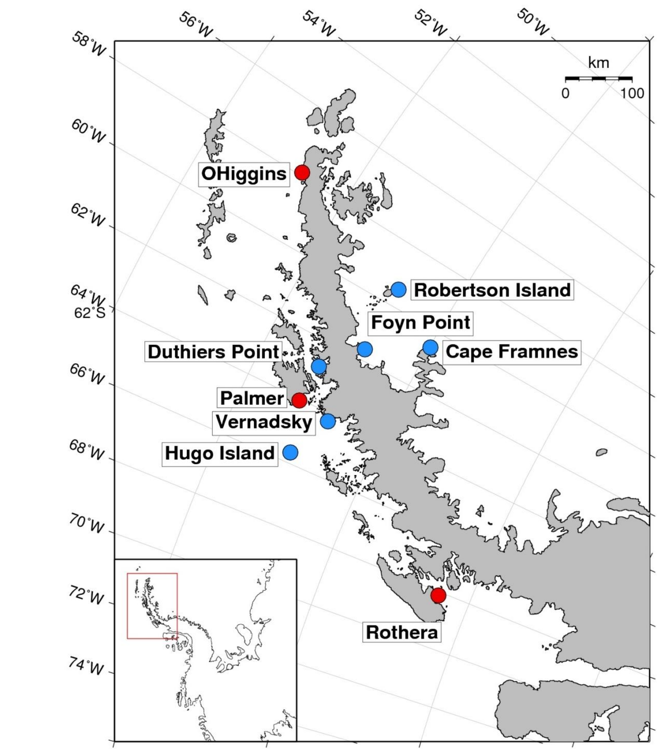

Figure 1: GPS Locations in the Northern Antarctic Peninsula. Red locations are the long term GPS records: O'Higgins and Rothera 1995 to 2013, Palmer 1998 to 2013. Blue are LARISSA GPS 2009-2010 to 2013

Present-day ice loss from ice shelf break-up

- Prince Gustav (Jan 1995): Rohss, Sjorgren, Boydell glaciers
- Larsen A (Jan/Feb 1995): Drygalski, Dinsmoor, Bombardier, Edgeworth glaciers
- Larsen B (Feb 2002): Hektoria, Green, Evans, Jorum, Punchbowl, Crane, Mapple, Melville, Pequod
- Assume mass loss continues at the same rate to present-day

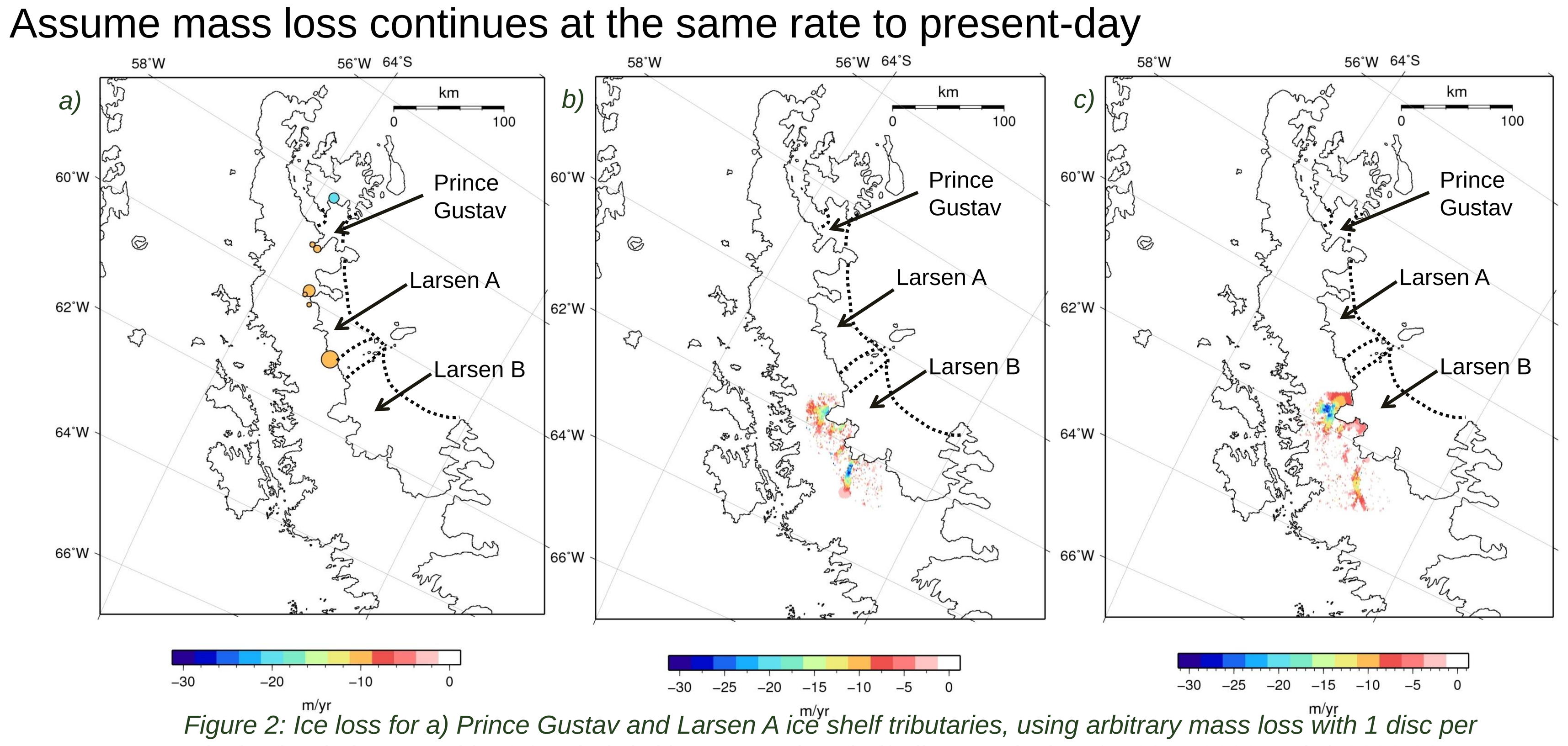

Figure 2: Ice loss for a) Prince Gustav and Larsen A ice shelf tributaries, using arbitrary mass loss with 1 disc per glacier (scale increased by 3 for clarity); b) Larsen B ice shelf tributary glaciers for 2001-2006 and c) 2006-2011. b) and c) from Berthier et al. [2012] and Shuman et al. [2011].

2. High Resolution Model

- The viscoelastic model used is described in *Barletta et al.* [2006]
- The fine spatial detail of the Northern Antarctic Peninsula requires a high resolution approach, we calculate up to harmonic degree 3754.
- The ice loss is treated as a set of disc loads with the possibility of a high number of discs with very small radii.
- We use an incompressible Earth model, however a compressible Earth model will be used in the near future.

3. Elastic only response?

Is the uplift seen at Palmer due to the elastic response of the Earth to present-day ice mass change? (Ice history in Figure 2)

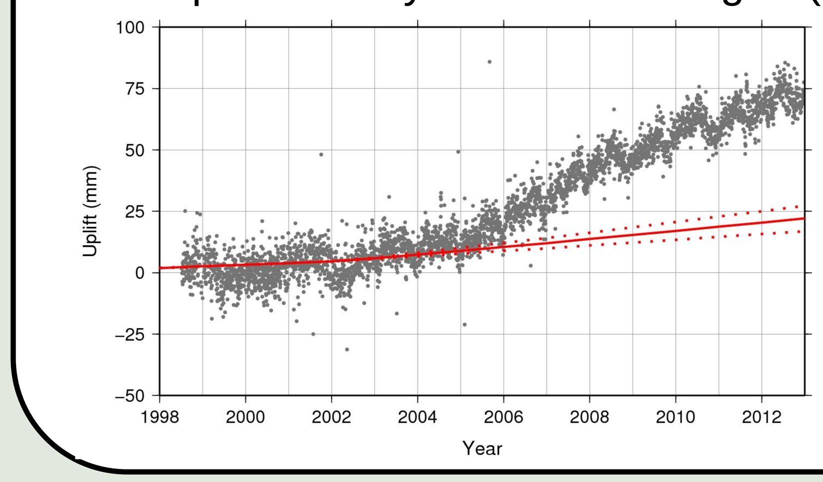

Figure 3: GPS observations at Palmer (grey dots) with modelled elastic uplift due to ice loss since 1995 (red line). Red dots show modelled elastic uplift with ±50% of the ice loss. Includes an estimate of the pre-1995 uplift rate.

4. Viscoelastic response?

The elastic response alone cannot reproduce the uplift seen at Palmer, suggesting there must also be a viscous component. A wide range of Earth models can reasonably reproduce the uplift time series, however a typical Earth model for Antarctica cannot (see Figure 4).

Layer	Depth to base (km)	Viscosity (Pa s)
Lithosphere	**10 – 170**	1 x 10^{51}
Upper Mantle	400	**1 x 10^{15} – 1 x 10^{20}**
Transition Zone	670	4 x 10^{20}(no sensitivity)
Lower Mantle	-	1 x 10^{22} (no sensitivity)

Table 1: Input viscous model parameters

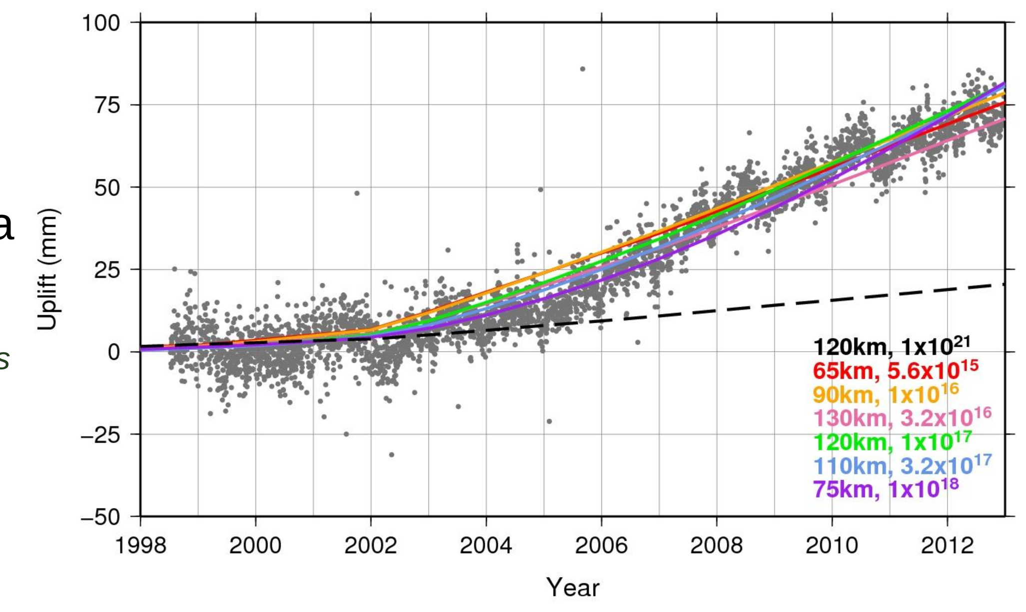

Figure 4: GPS observations at Palmer (grey dots) with combined modelled elastic and viscous uplift for a selection of Earth models. Includes an estimate of the pre-1995 uplift rate.

5. Constraining the Earth Model

- A wide range of Earth models can produce an uplift time series similar to that observed at Palmer (Figure 4 and 5).
- The addition of the LARISSA GPS uplift rates can help to constrain the spatial pattern of the uplift, particularly close to the centre of the mass loss near the Larsen B embayment, and hence provide tighter constraints for the Earth model (Figure 6).

RMS: Palmer time series

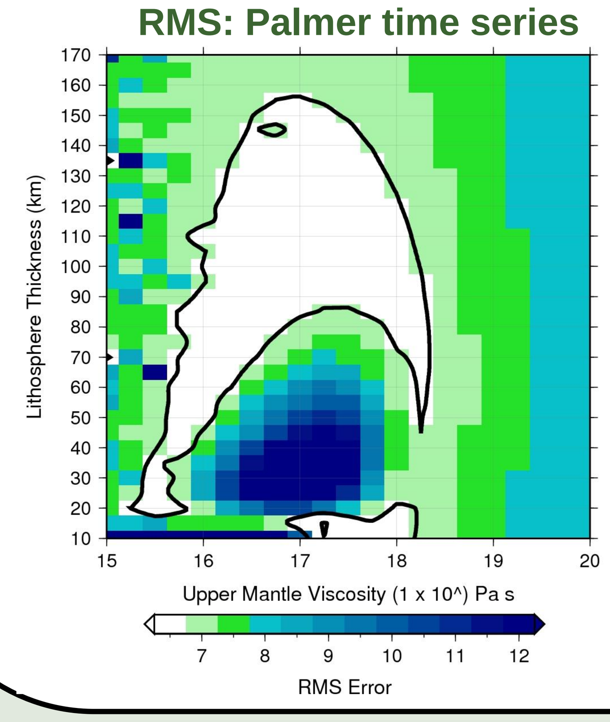

Figure 5: RMS of combined elastic and viscous modelled uplift time series to observed GPS time series at Palmer for each viscous model tested. Includes estimate of pre-1995 uplift rate.

RMS: 2011 rates for all sites

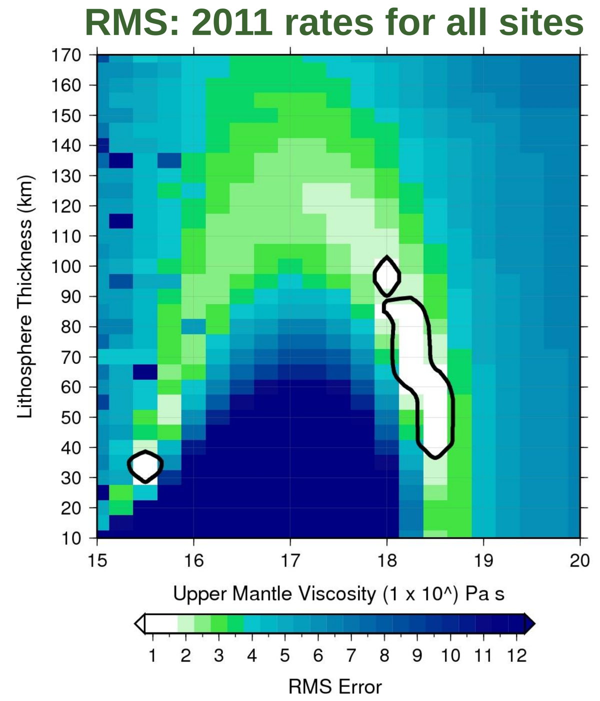

Figure 6: As for Figure 5 but using the Palmer and LARISSA GPS velocities.

6. Conclusions

- The range of rheological parameters that fit the GPS observations using the current ice loss data are a lithospheric thickness of 40 – 100km and an upper mantle viscosity of 1 – 3.2 x 10^{18} Pa s.
- Figure 7 shows the elastic, viscous and combined uplift for an Earth model in this range, (lithosphere 60km, upper mantle viscosity 1.8 x 10^{18} Pa s).
- Regions with similar values: Alaska: lithosphere 54km, upper mantle viscosity 5.58 x 10^18 Pa s [*Sato et al.*, 2011], Patagonia lithosphere 45-65km, upper mantle viscosity 4-8 x 10 ^18 Pa s [*Dietrich et al.*, 2010].

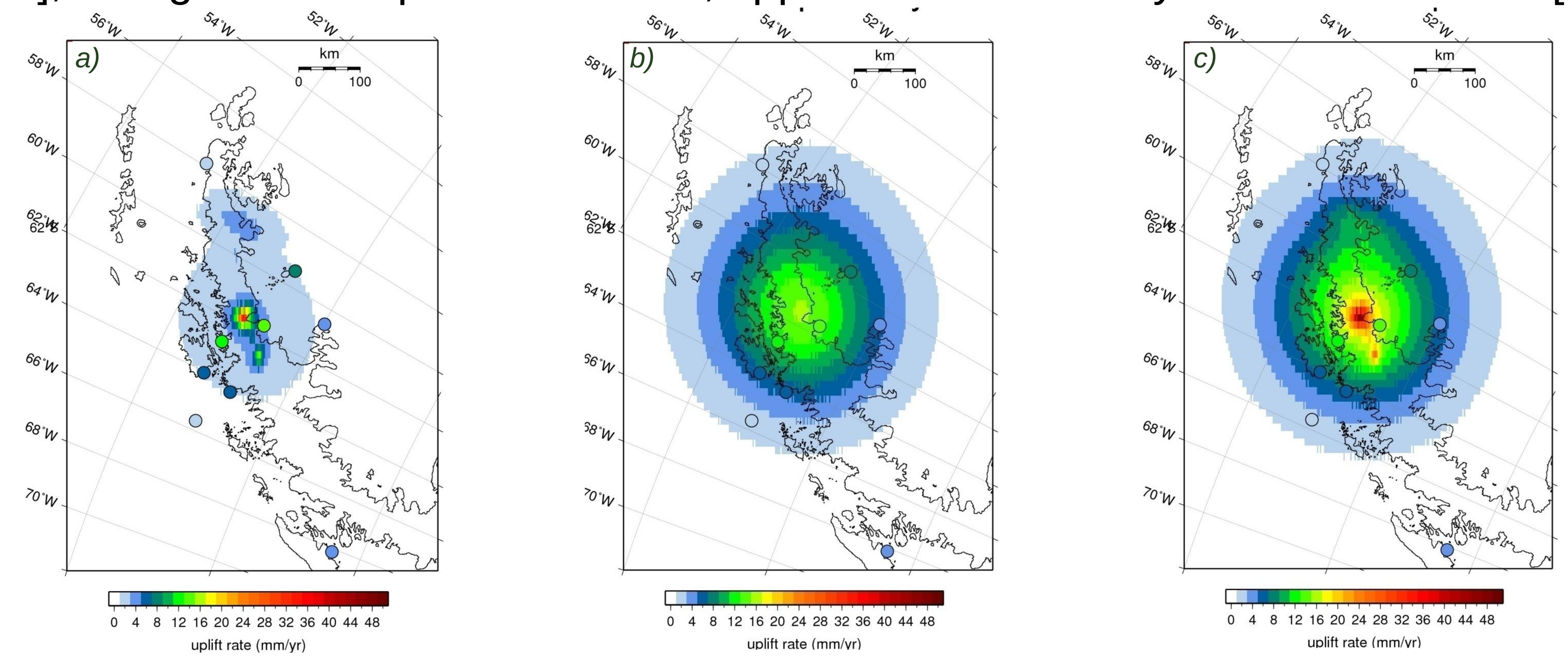

Figure 7: Spatial pattern of modelled uplift for the a) elastic, b) viscous, and c) combined components for a well fitting Earth model (including the pre-1995 rate). GPS observed uplift rates are shown in the circles on the same colour scale.

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