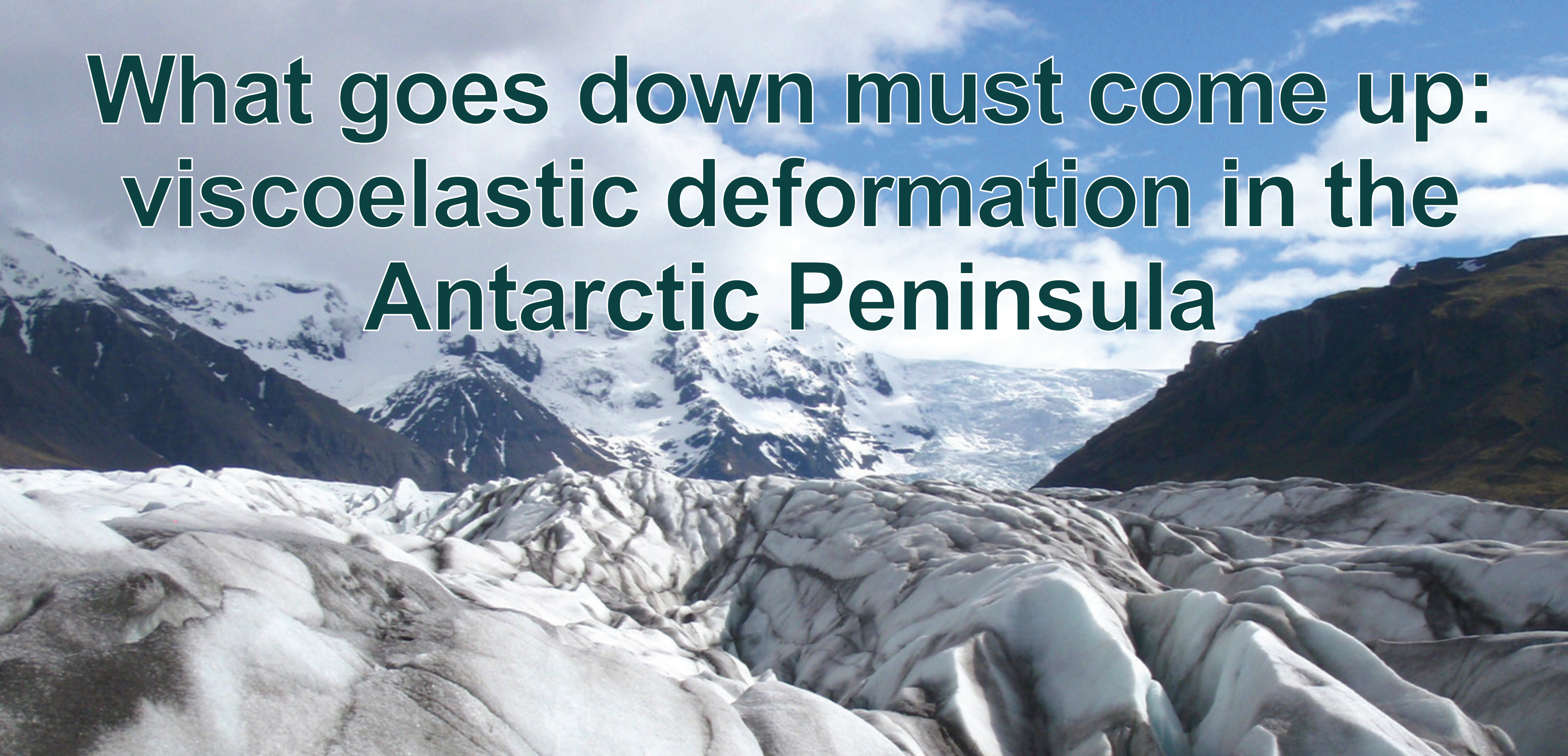
What goes down must come up: viscoelastic deformation in the Antarctic Peninsula



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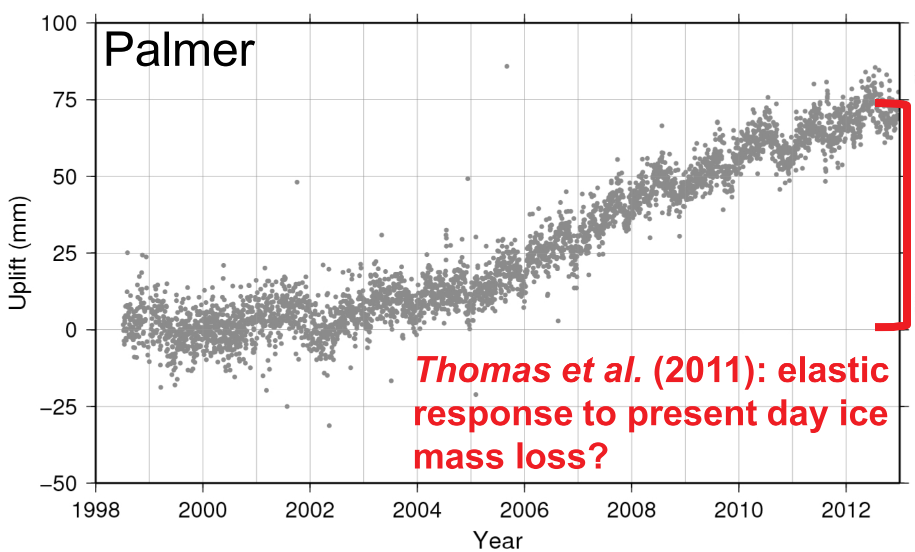
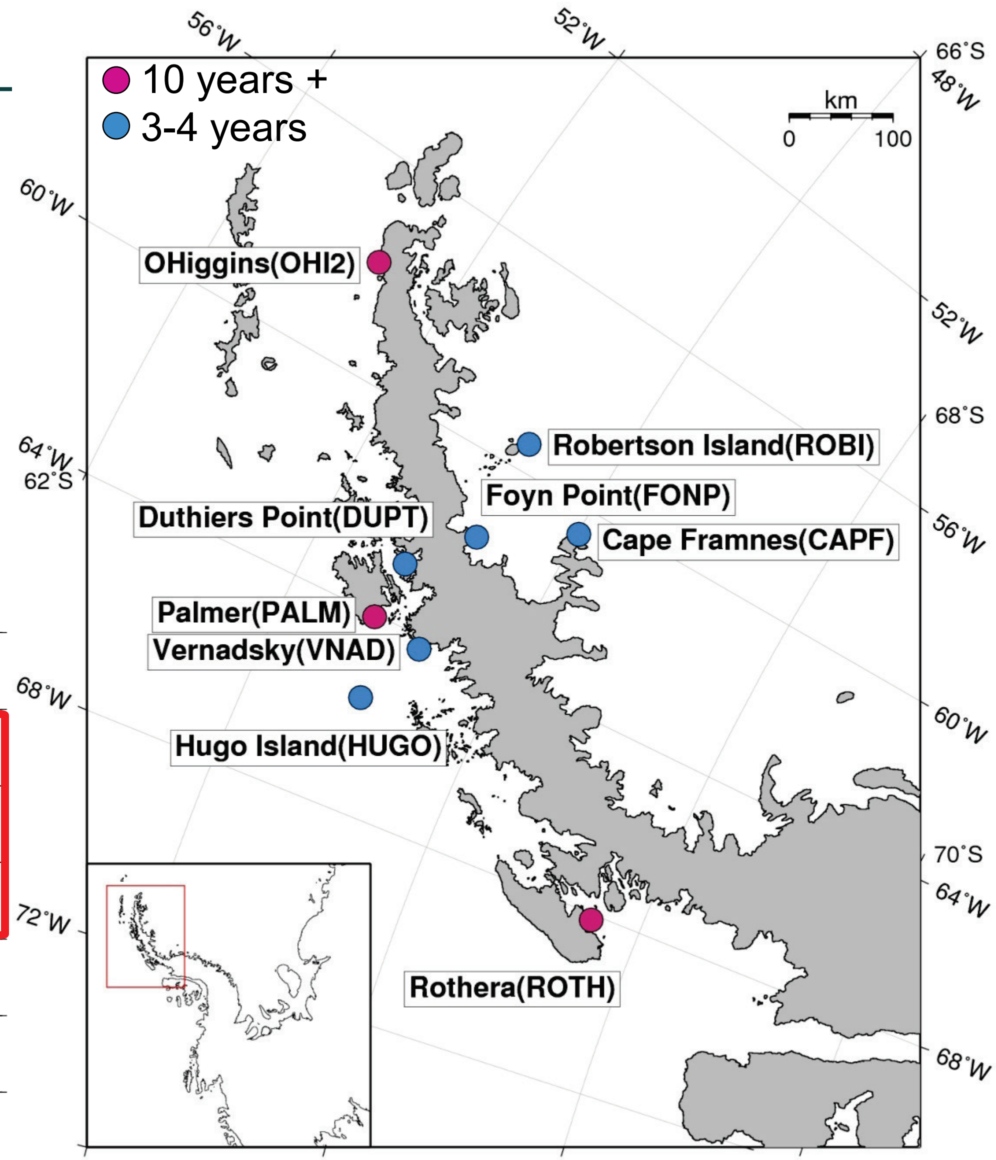
Motivation

- How is Antarctica responding to millenial/centennial/decadal scale unloading?
- How can we explain the rapid GPS-observed uplift in the Antarctic Peninsula since ~2002?
- Well observed unloading may provide unique insight into Earth rheology (noting all GIA modelling use linear Maxwell)

GPS Observations

- Palmer Station
  1998 – present
- LARISSA
  2009/2010 - present





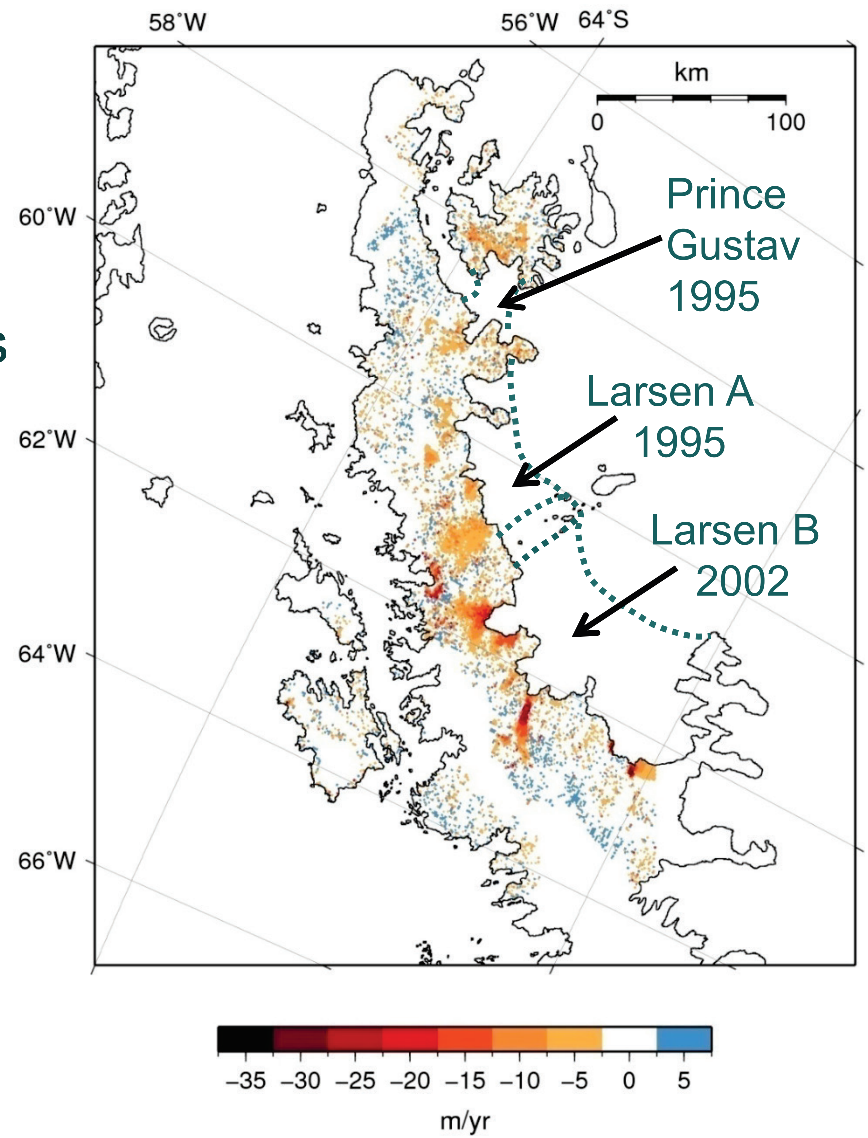
Recent Ice Mass Changes

Data:

- Elevation change from DEM differencing/ICESat 2003-2008
- *Berthier et al.*, 2012 GRL; *Shuman et al.*, 2011 J. Glaciology; Scambos et al. (in prep)

Assumptions for model input:

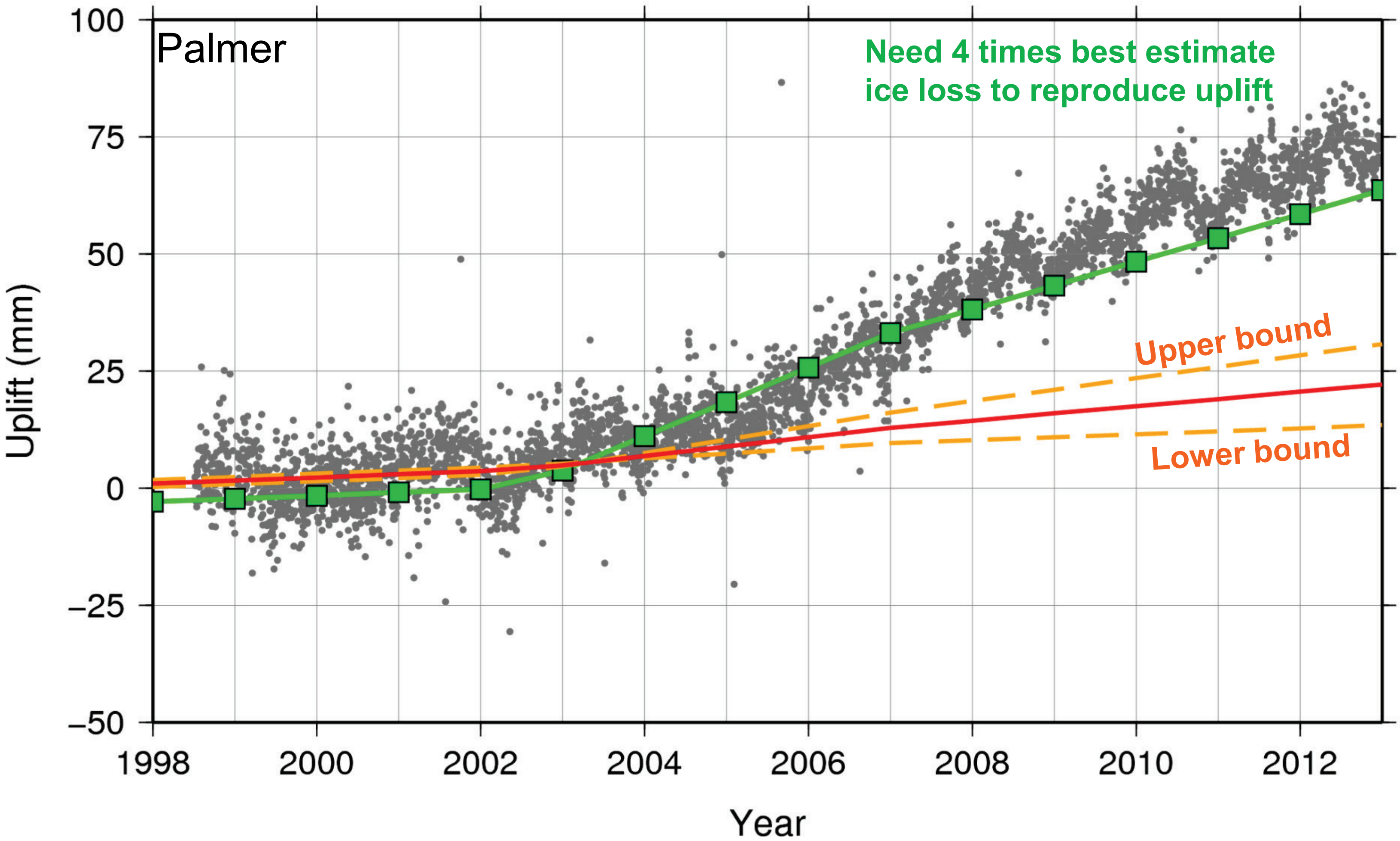
- Ice loss onset few months after collapse, negligible before this
- Mass loss continues at the same rate to present day
- Mass changes away from these glaciers is constant/long term trend



Modelling approach

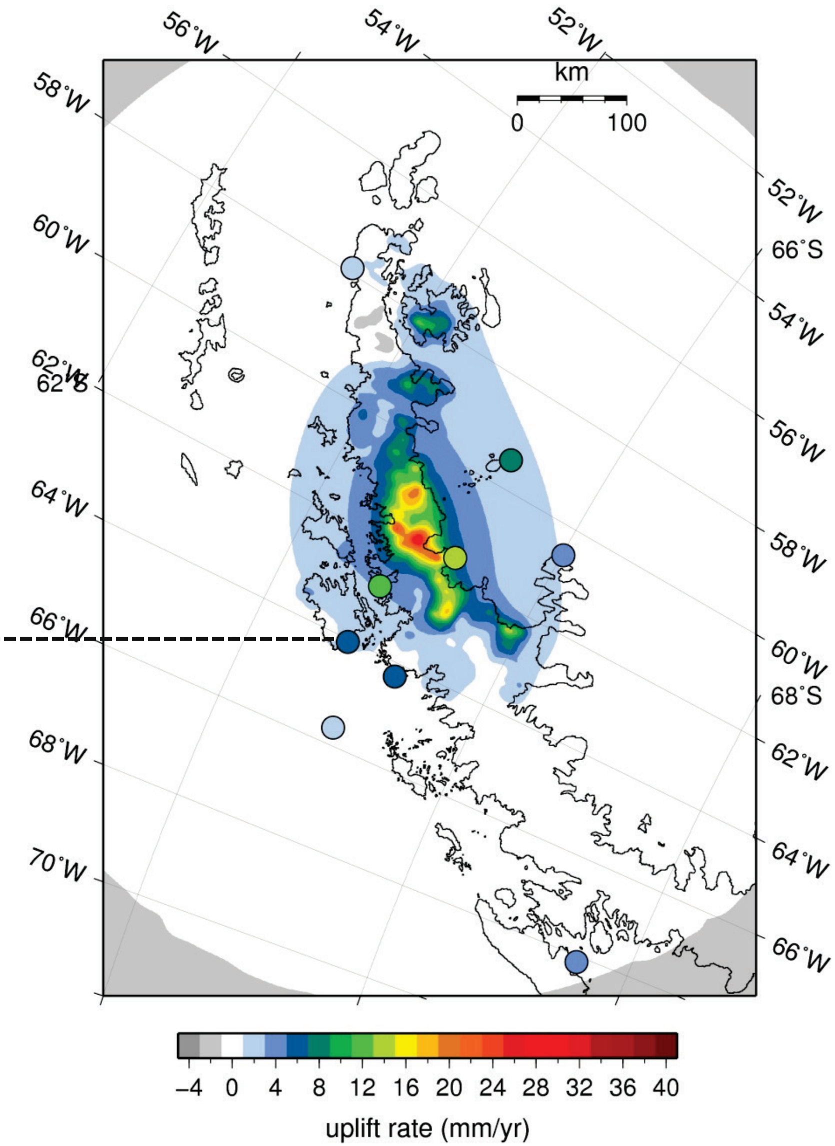
- Model solid Earth response to ice loss 1995-2013
  - Elastic response only?
  - Low viscosity mantle – viscoelastic response over ~15 years?
- Use GPS observed uplift to constrain the modelling
- Make estimate of the background rate
- Model – HresV2 - *Barletta et al.*, 2006 (GRL)

Elastic Model - PREM



Elastic Model – 2011 uplift rates

Modelled to spherical harmonic degree 3754

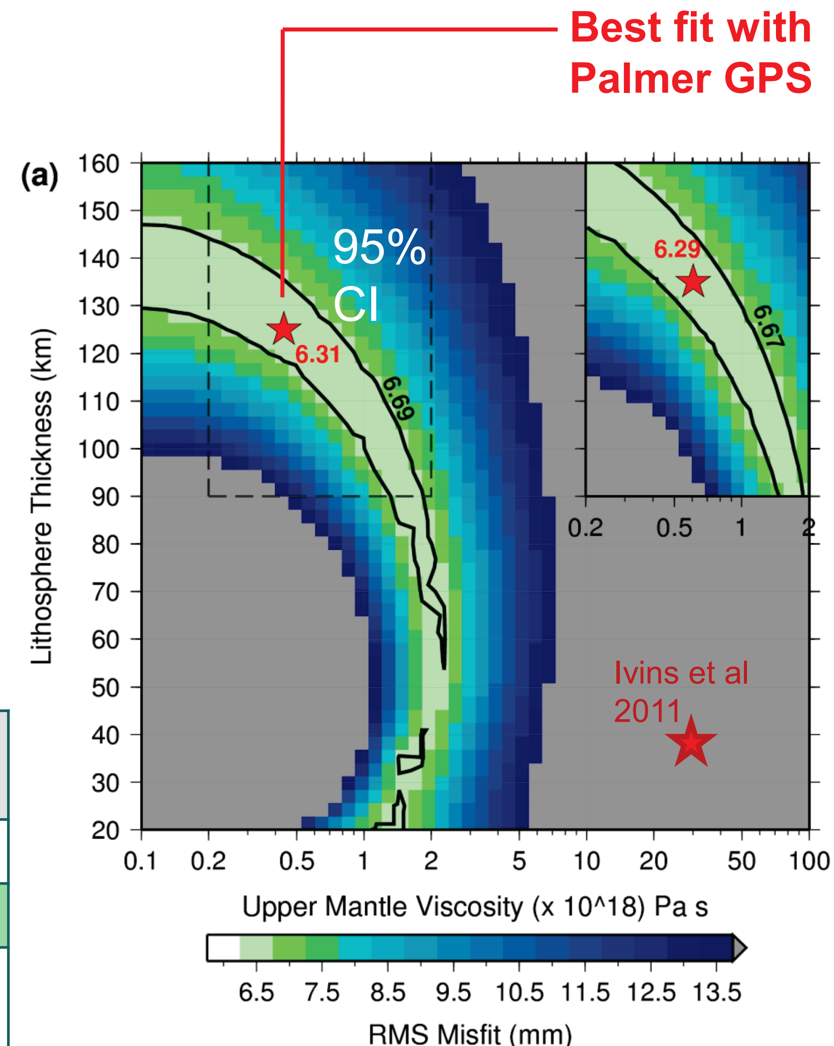


Palmer
Modelled: 2.23 mm/yr
Observed: 6.56 mm/yr

Viscoelastic Model

- Model a viscous component
- Compute RMS misfit between modelled time series (elastic+viscous+background) and Palmer timeseries
- Incompressible Earth, with further compressible estimates shown as inset – shifts +10 to +15km

Layer	Depth to base (km)	Viscosity (Pa s)
Lithosphere	**20 – 160**	1×10^{51}
Upper Mantle	400	**$1 \times 10^{17} – 1 \times 10^{20}$**
Transition Zone	670	4×10^{20}(no sensitivity)
Lower Mantle	-	1×10^{22} (no sensitivity)



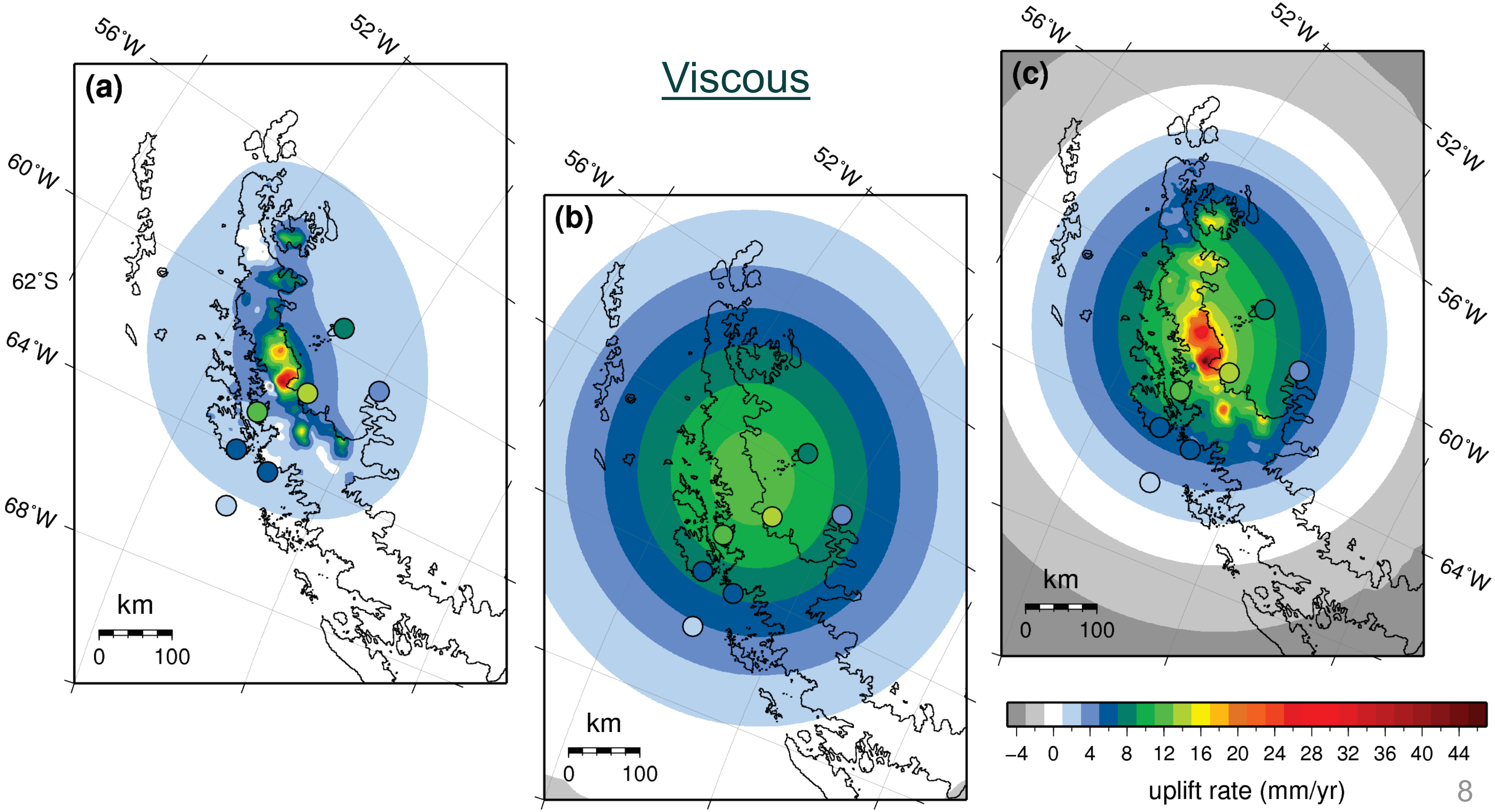
Uplift rates for best model

Pre-1995 background rate = -2.5 mm/yr

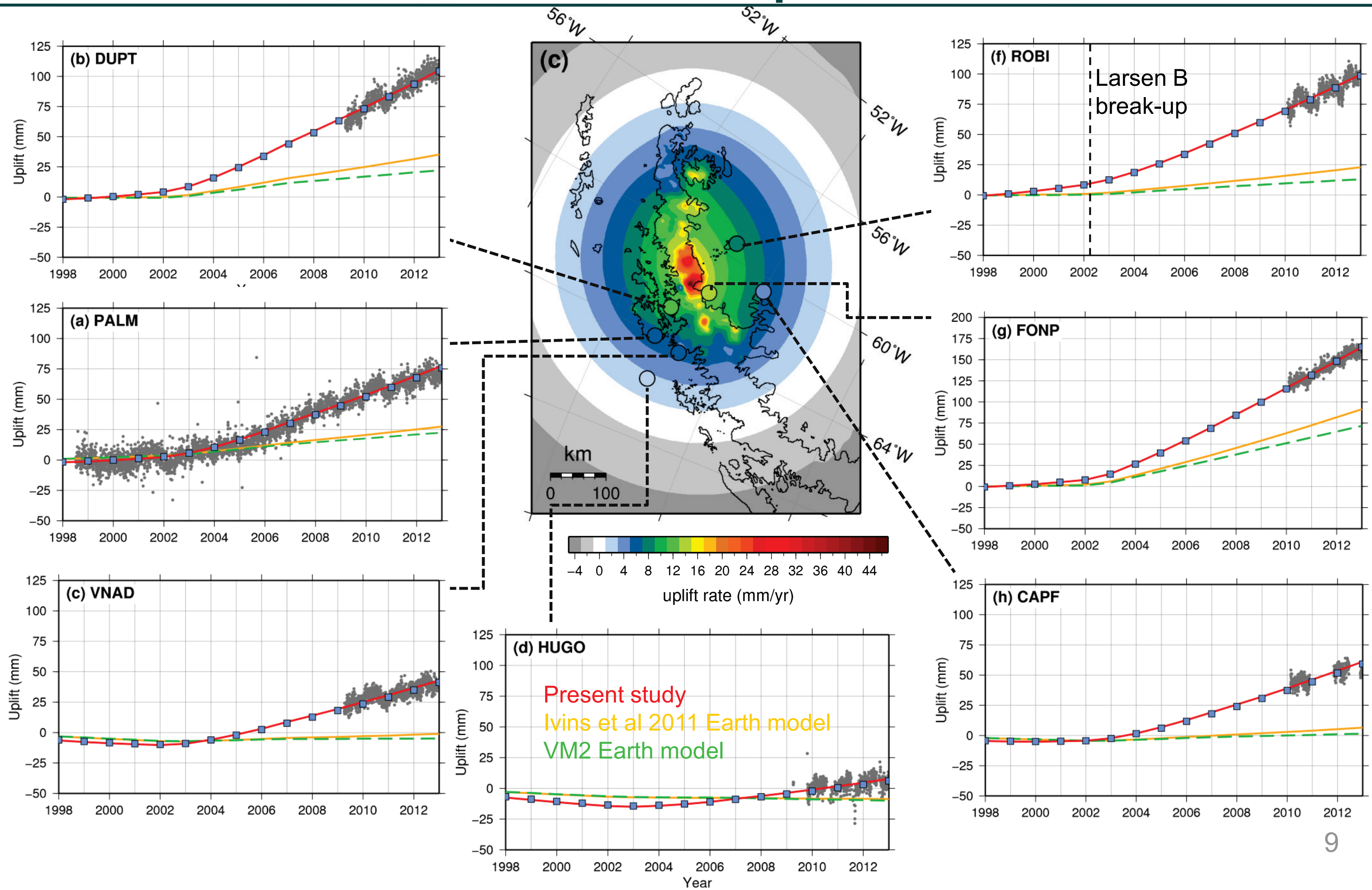
Elastic

Visco-elastic + background rate

Viscous

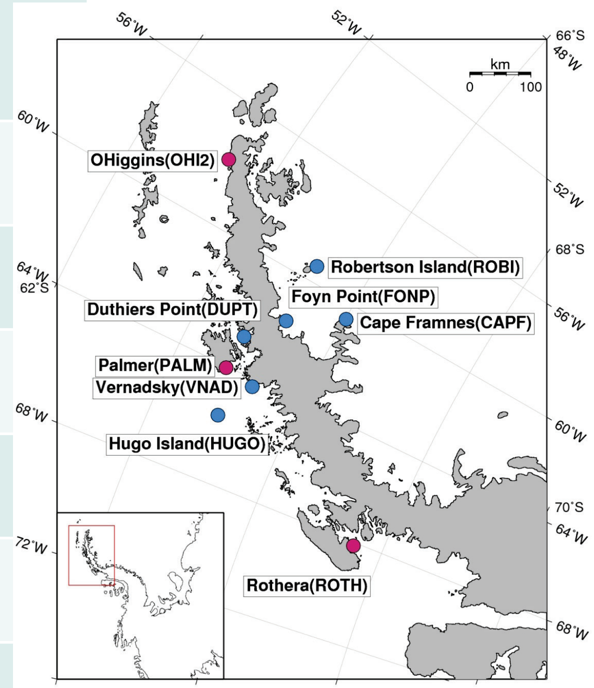


Modelled vs. GPS uplift time series

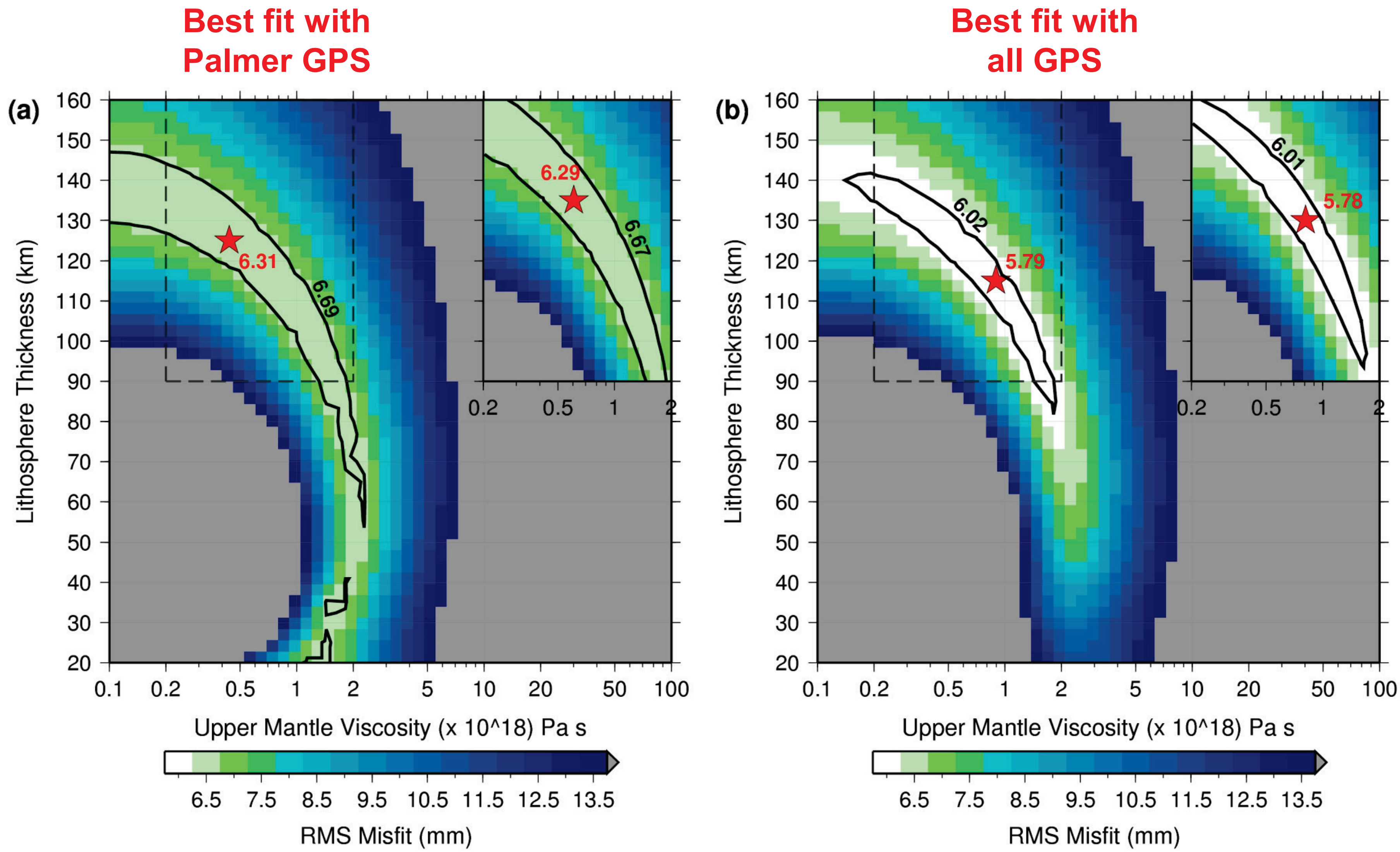


Uplift residuals

Site	GPS Observed Uplift (mm/yr)	Viscoelastic Modelled Uplift (mm/yr)	Residual (GPS minus viscoelastic model) (mm/yr)
PALM	6.56 ± 1.07 (using 2009.0 to 2013.0)	7.77	-1.21 ± 1.07
CAPF	4.50 ± 1.45	7.09	-2.60± 1.45
DUPT	12.84 ± 1.06	10.08	2.76± 1.06
FONP	14.89 ± 1.35	15.98	-1.08± 1.35
HUGO	1.69 ± 1.66	2.82	-1.13± 1.66
ROBI	7.79 ± 1.45	9.52	-1.73± 1.45
VNAD	5.78 ± 1.21	5.77	0.01± 1.21

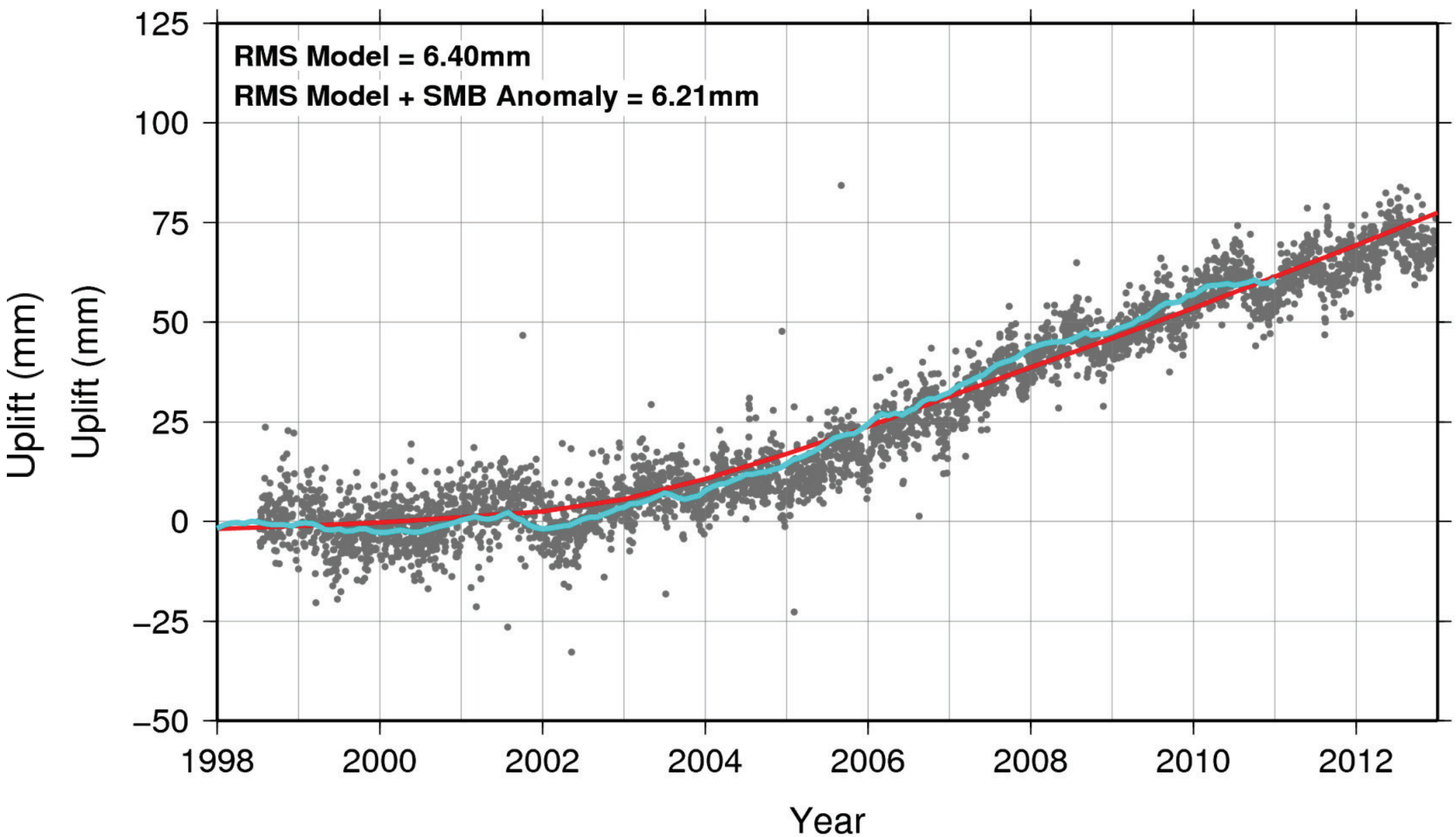


Viscoelastic Model



Local time-variable elastic effects?

- SMB anomalies may cause an additional elastic effect.
- Test using RACMO2.1/ANT (Lenaerts et al., 2012) SMB, anomaly to 1979 - 2011.0 mean

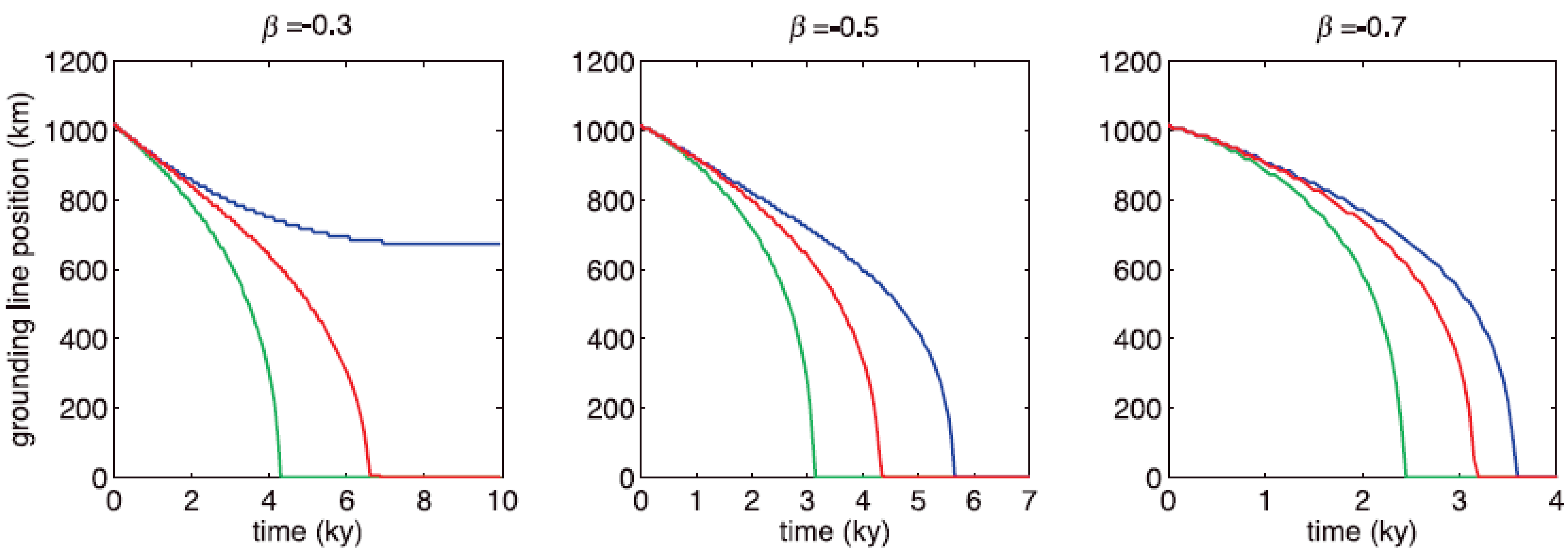


Summary

- A unique experiment – needs to be ongoing [dh/dt and new GPS to capture before/after future events e.g., SCAR inlet]
- Elastic response alone cannot explain the observed uplift & viscous component is required
- Modelling suggests the range of parameters that fit the GPS observations are:
  - Lithospheric thickness: ~70-135km
  - Upper mantle viscosity: < 2 x 10^{18} Pa s
- Pre-2002 uplift at PALM very low. Pre-1995 uplift likely negative [-2.5mm/yr]
- Earth models of Peltier (VM2) and Ivins et al 2011 do not provide good fits to the GPS when combined with post-1995 unloading – is time-dependent rheology at play?

Rapid viscous uplift and WAIS

- Gomez et al 2012 highlighted importance of viscoelastic (blue) response to reverse slope beds (β= slope m/km) cf not considering (green)
- Elastic component (red) dominates for first several centuries



Rapid viscous response and grounding line stabilisation

- But Gomez et al adopted globally typical η_{UM}=5x10^{20}Pa s (t_m=236y) and elastic lithosphere 120km
- Weaker Earth model may apply in WAIS, possibly locally very weak
- Examine PIG-like scenario – 80x20km region thinning at 2m/yr from t=0 & ongoing
- Semi-infinite half-space with elastic lid of 50km and various η and linear and power-law within RELAX

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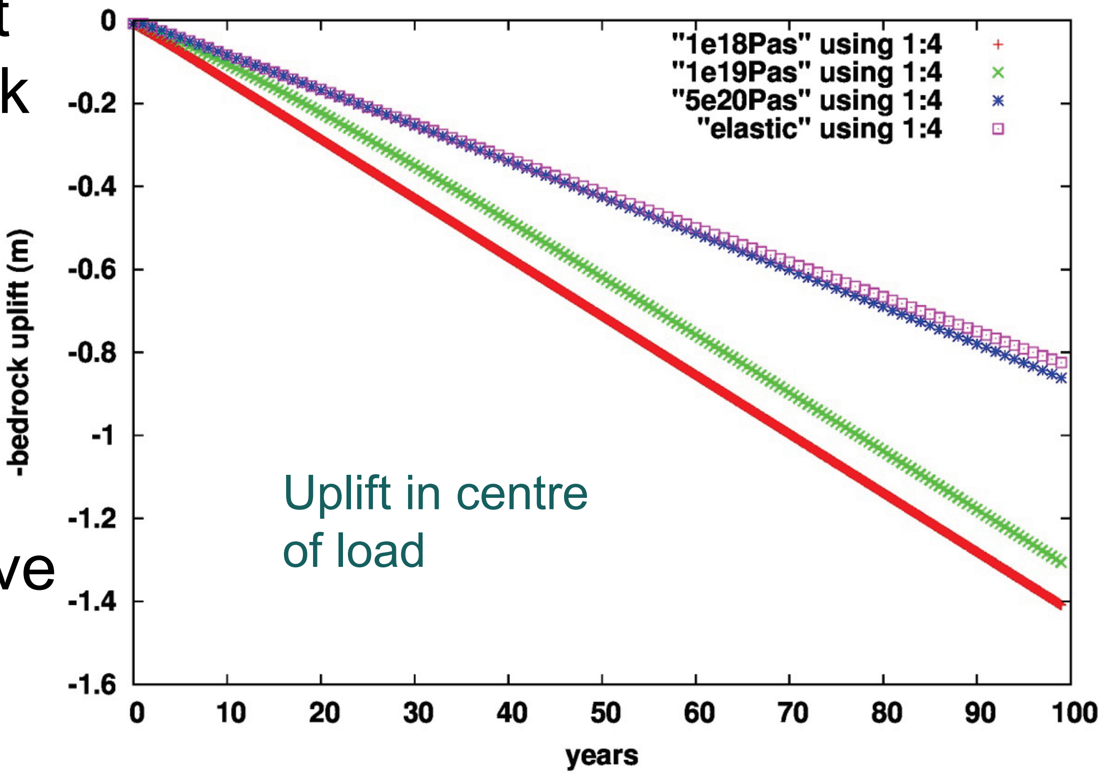
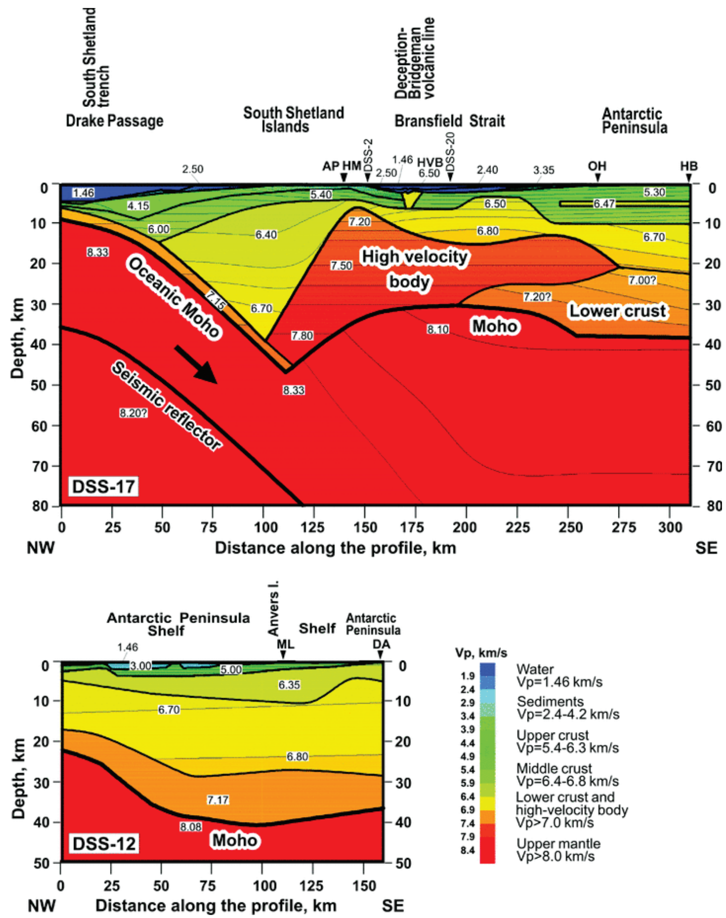
Rapid viscous response and grounding line stabilisation

- Weak Earth could result in ~50% greater bedrock adjustment within years to decades cf elastic or high viscosity model
- not shown: Power-law rheology concentrates uplift temporally (effective viscosity reduction) and spatially near to load change so important for bedrock slopes



Joint geophysical and petrological models for the lithosphere structure of the Antarctic Peninsula continental margin



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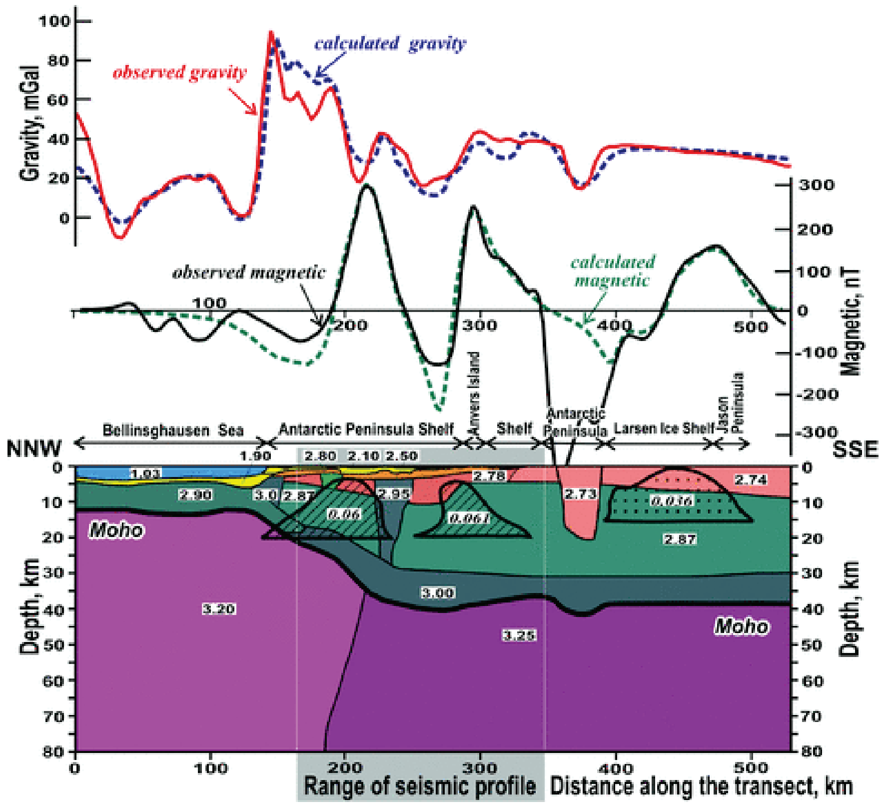

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