Exploration of Combination of GRACE, ICESat, and GPS Data over Antarctica

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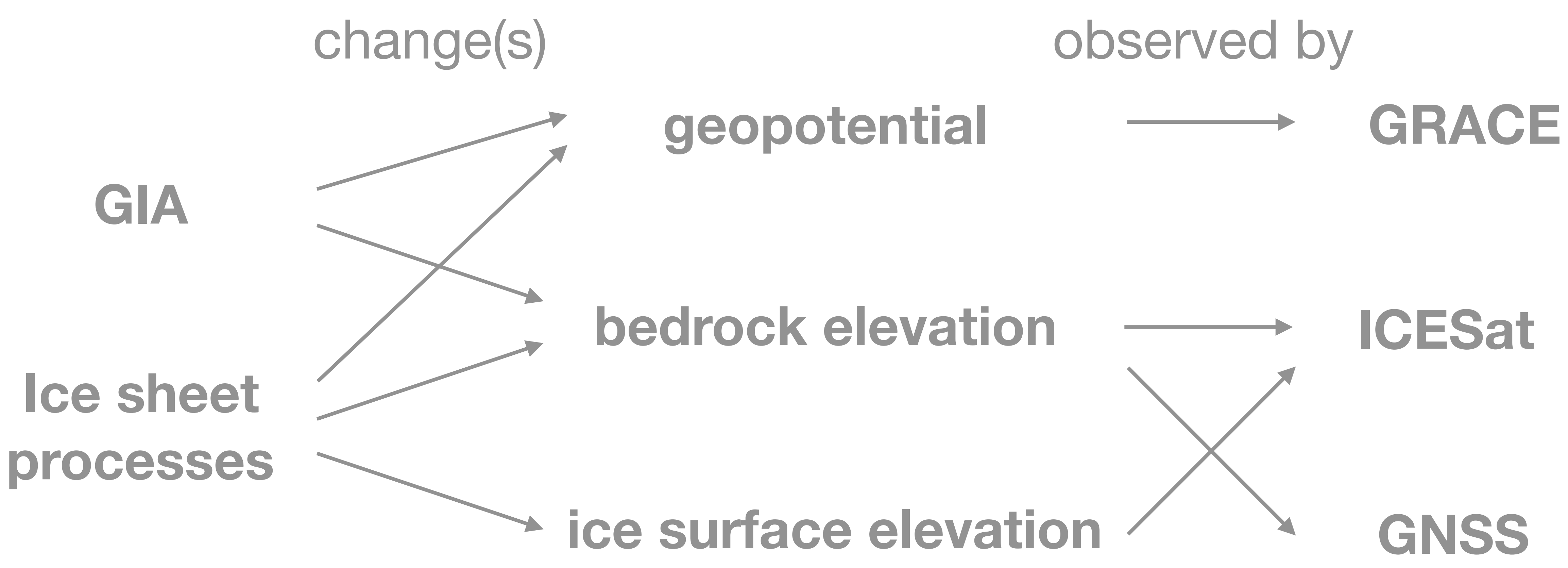
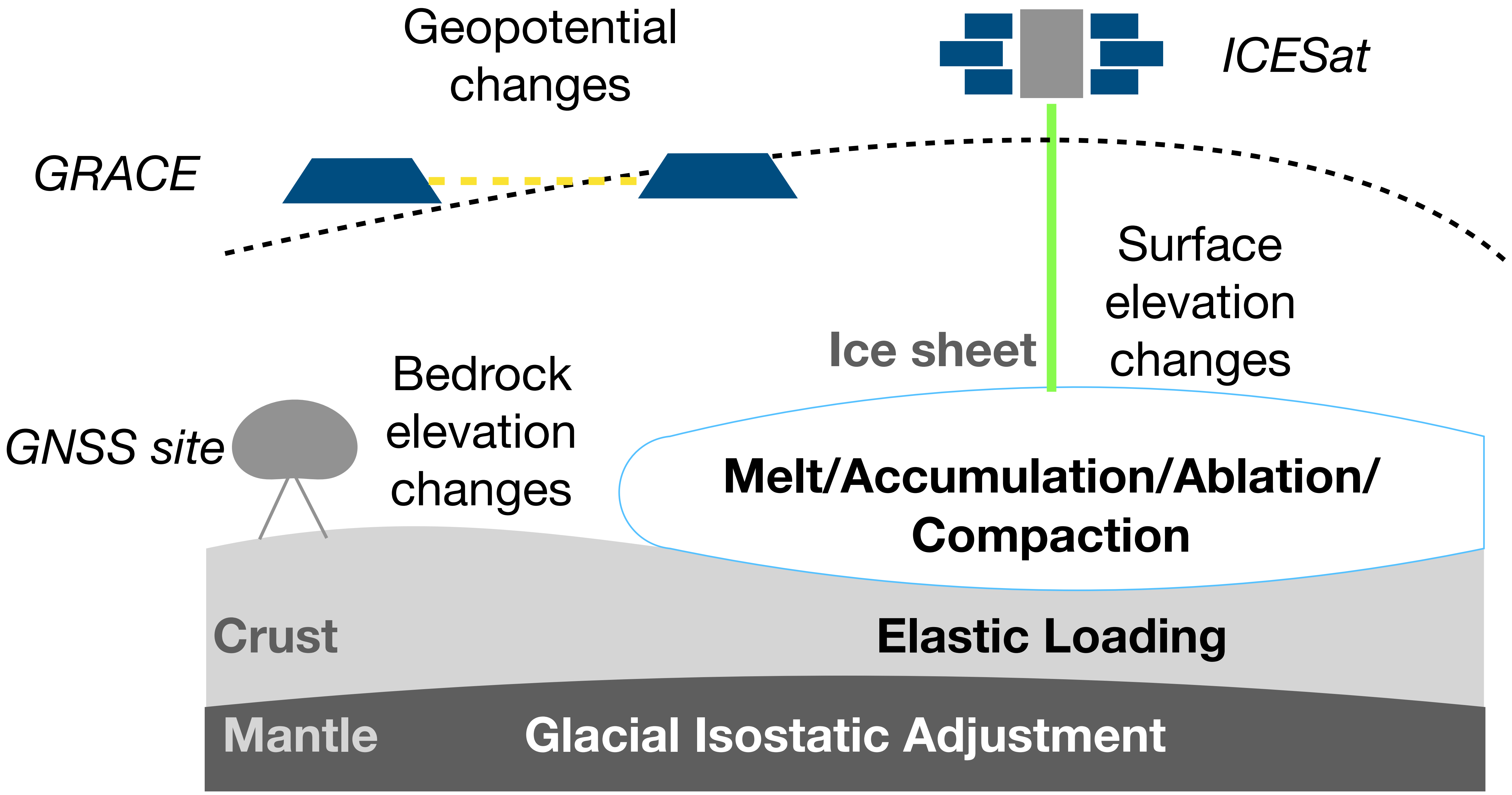
Introduction

- Geodetic monitoring of Antarctica enables tracking of mass distribution in both space and time
- GRACE Follow-On and ICESat-2 are expected to run concurrently starting in 2018

	Launch date
GRACE Follow-On	March 2018
ICESat-2	2018





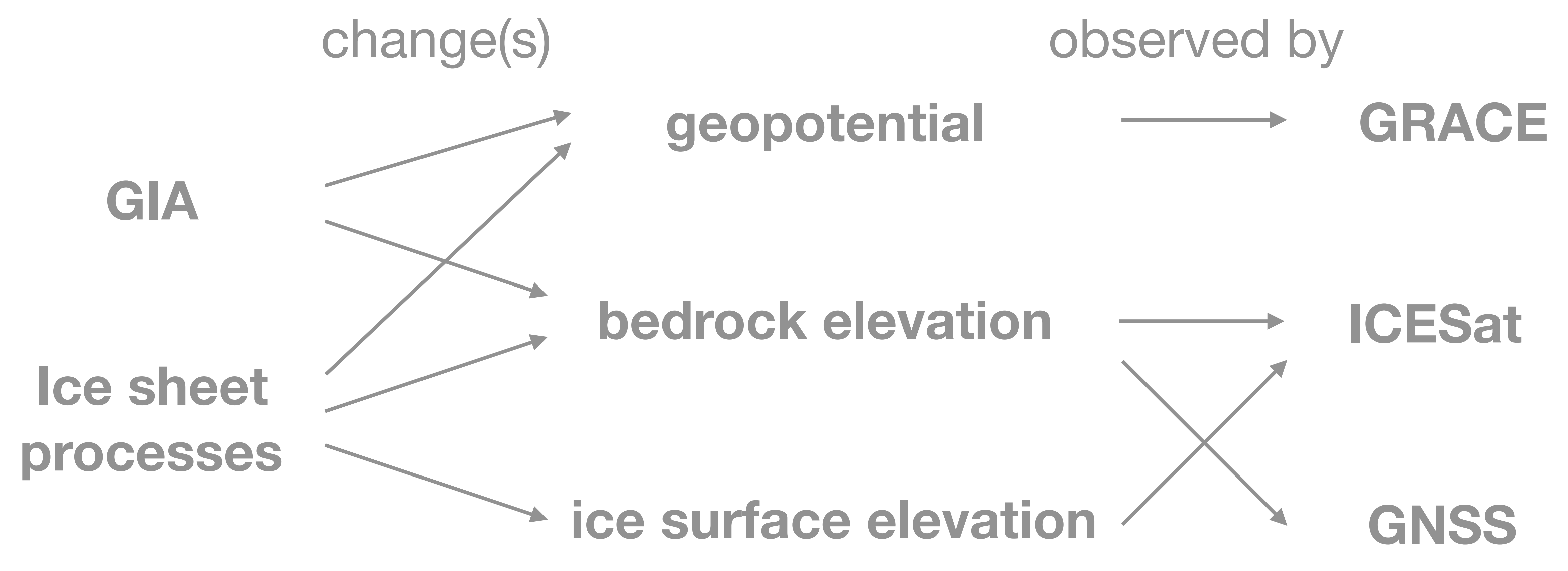
Goals

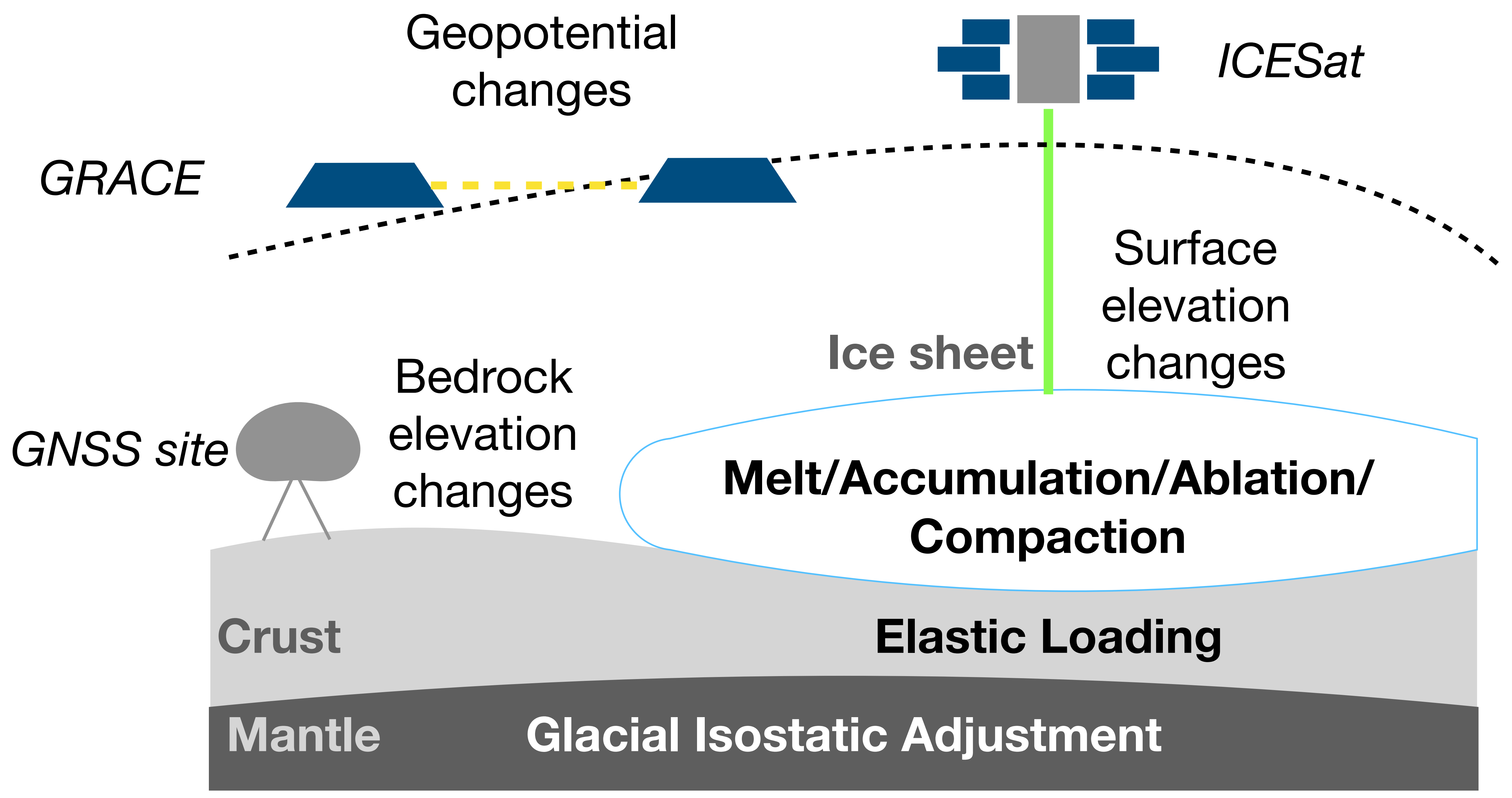
1. Assimilate GNSS, altimetry, and gravimetry data into model of mass variability in Antarctica

2. Disaggregate sources of mass change
   - glacial isostatic adjustment (GIA)
   - ice dynamics
   - surface mass balance

3. Increase spatial resolution of Antarctic mass transport at monthly timescales

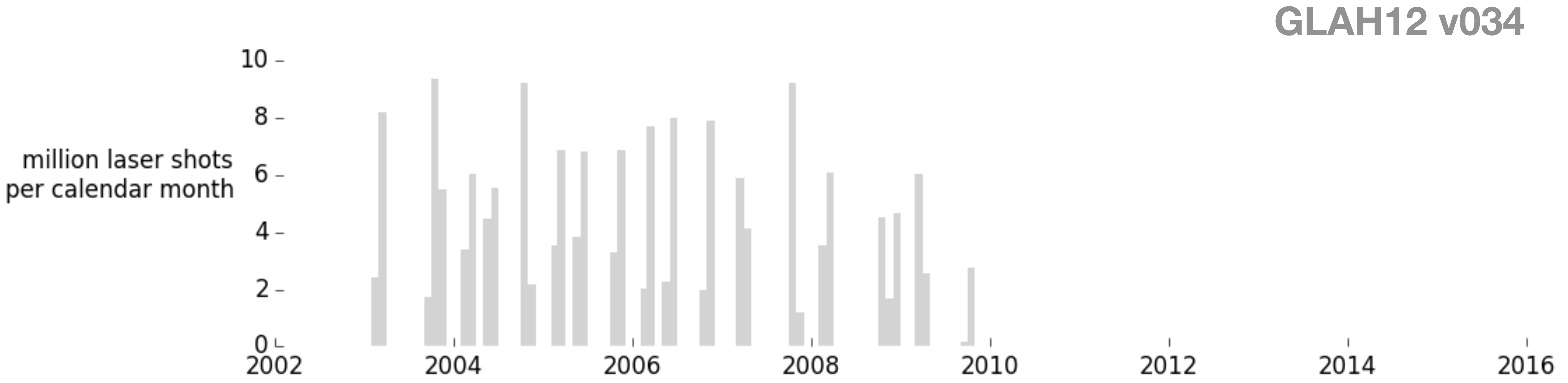
	Launch date
GRACE Follow-On	January 2018
ICESat-2	2018





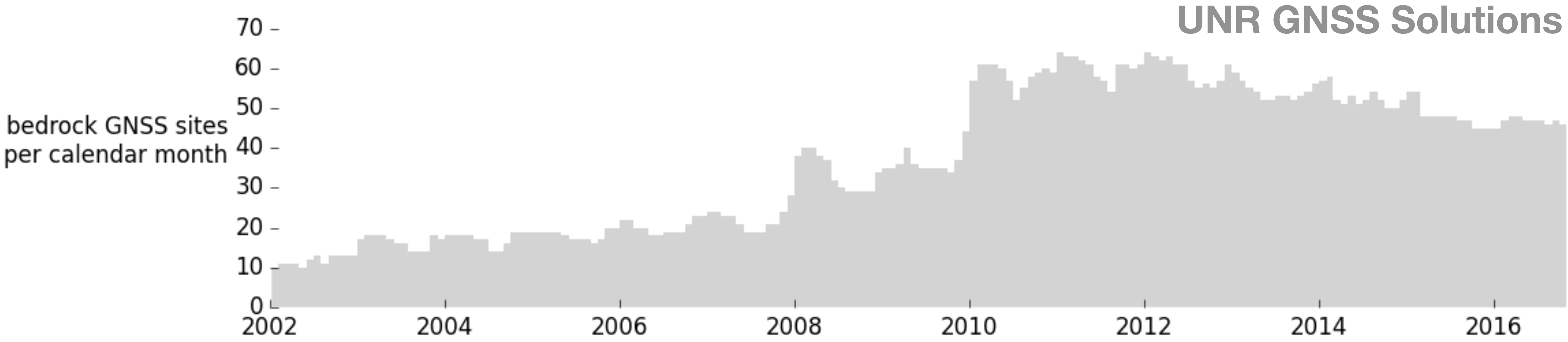
Data

ICESat



GRACE

GNSS



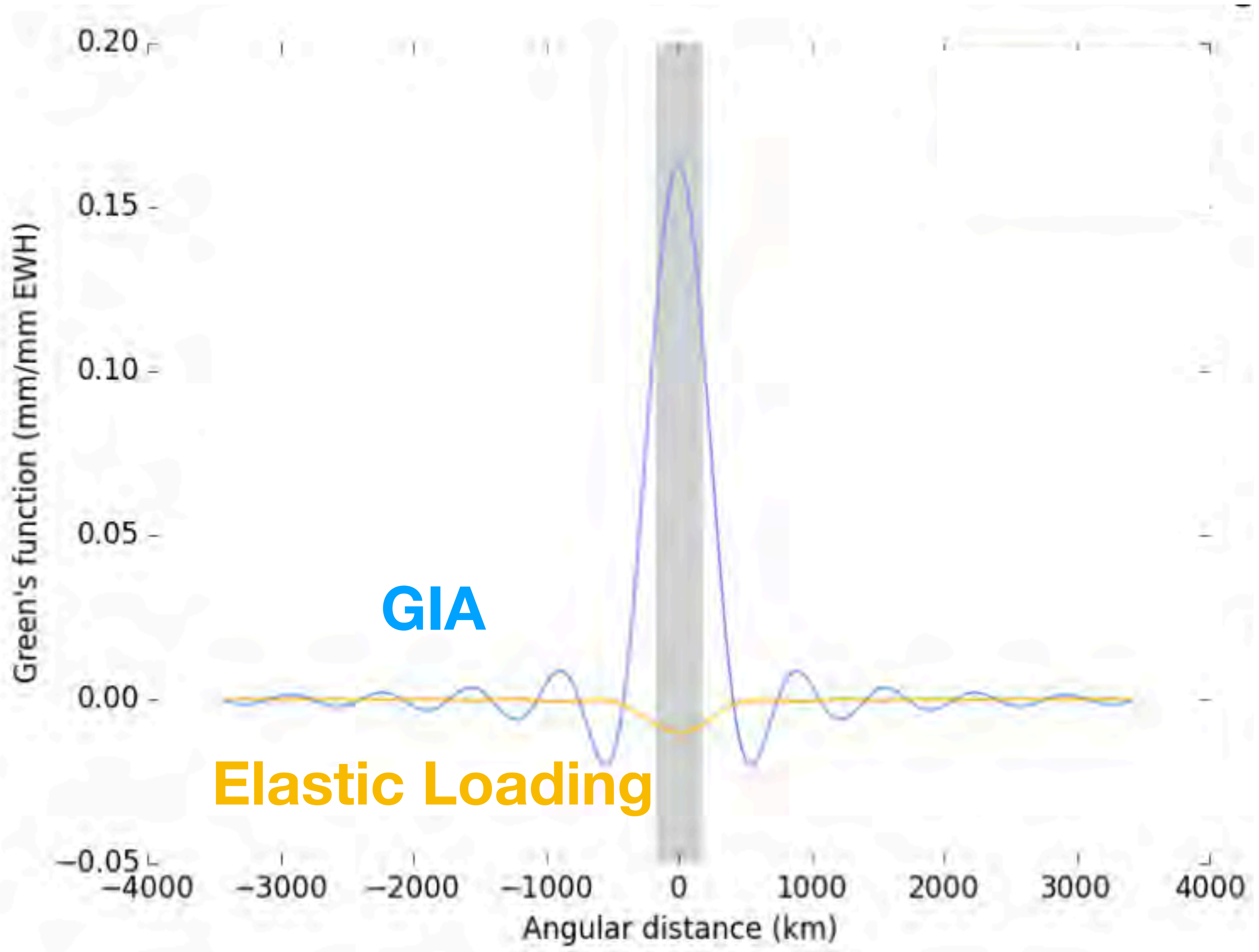
Current Approaches

Combination of GRACE and GNSS data

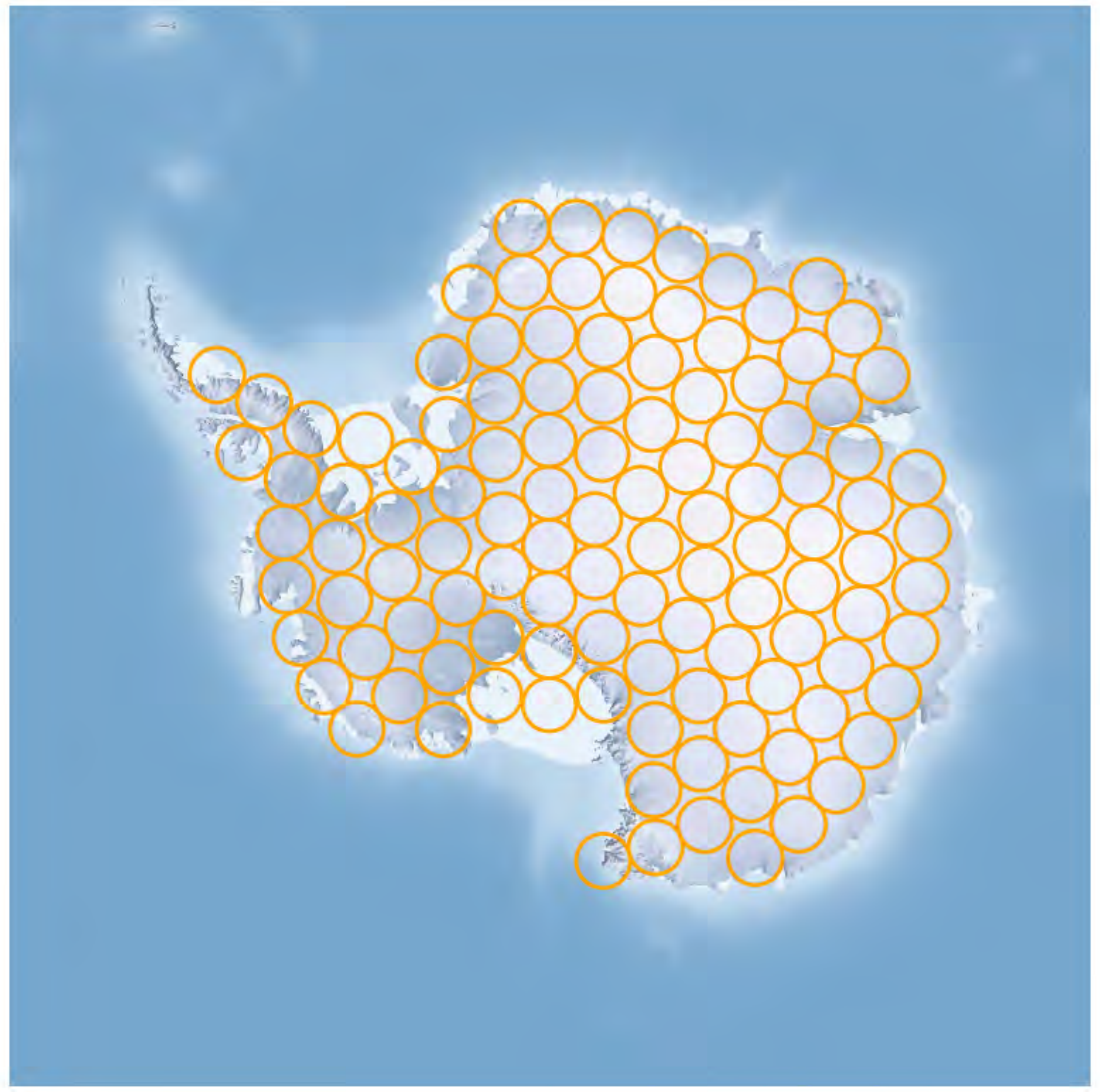
Combination of GRACE and ICESat

Combining GRACE and GNSS

- Use CSR RL05 spherical harmonic trends and GNSS trends from 2002-2016
- Decompose Antarctica into 114 3° spherical caps representing ice sheet mass and GIA
- Predict effects of elastic loading and GIA from spherical caps with spherical harmonics
- Hold total mass change fixed and solve for adjustments to GIA models



Uplift per unit equivalent water height change (truncated to degree 60)

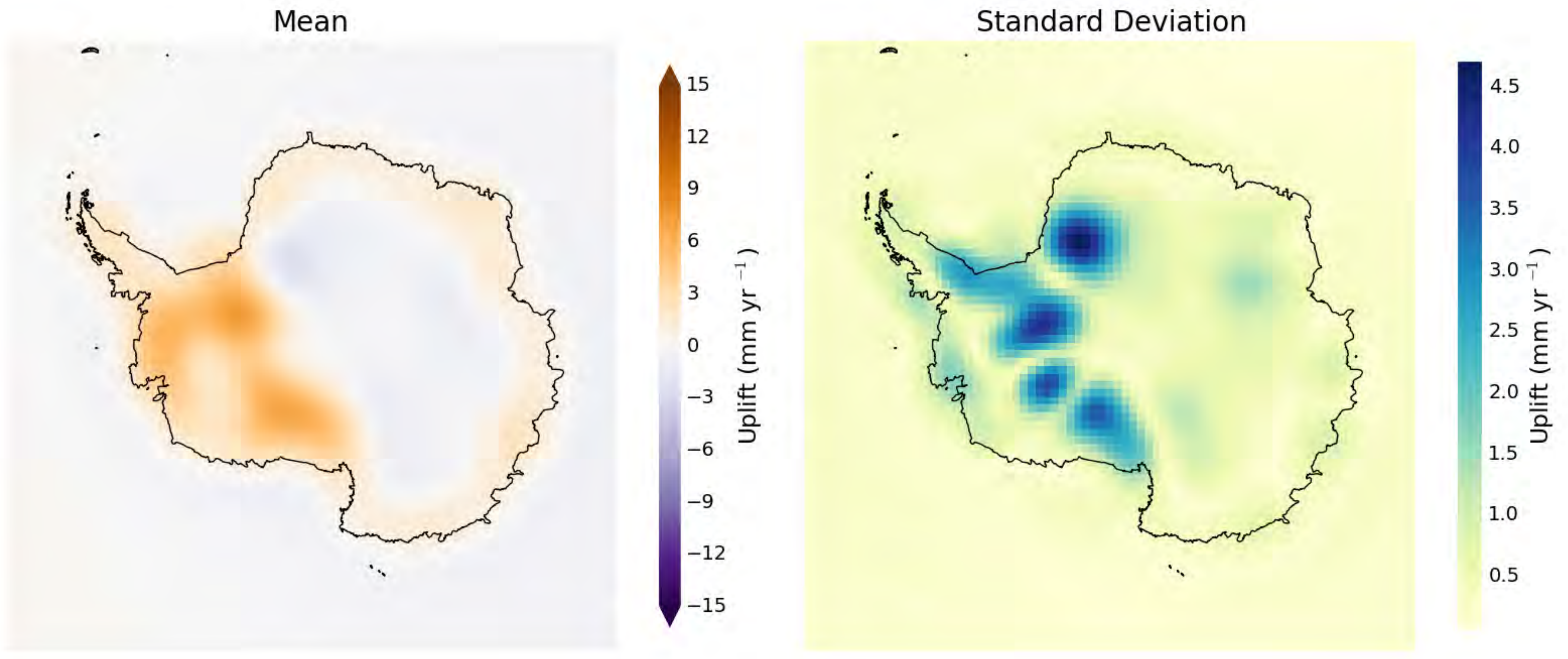


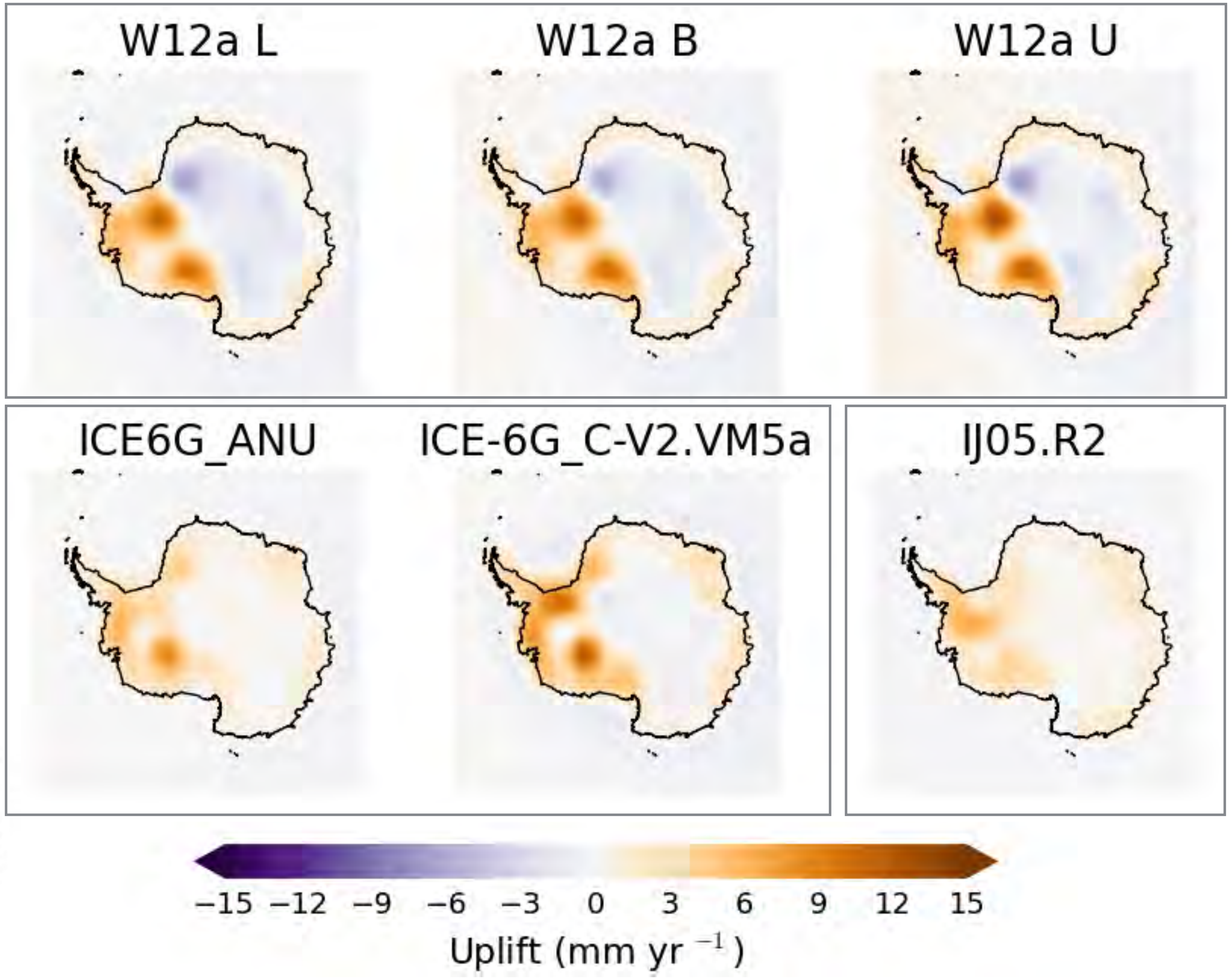
If total mass measured by GRACE is held fixed, uplift Green's functions may be combined into a single function to solve for GIA

GIA Ensembles

- Adjustment of GIA models requires GIA covariance estimate

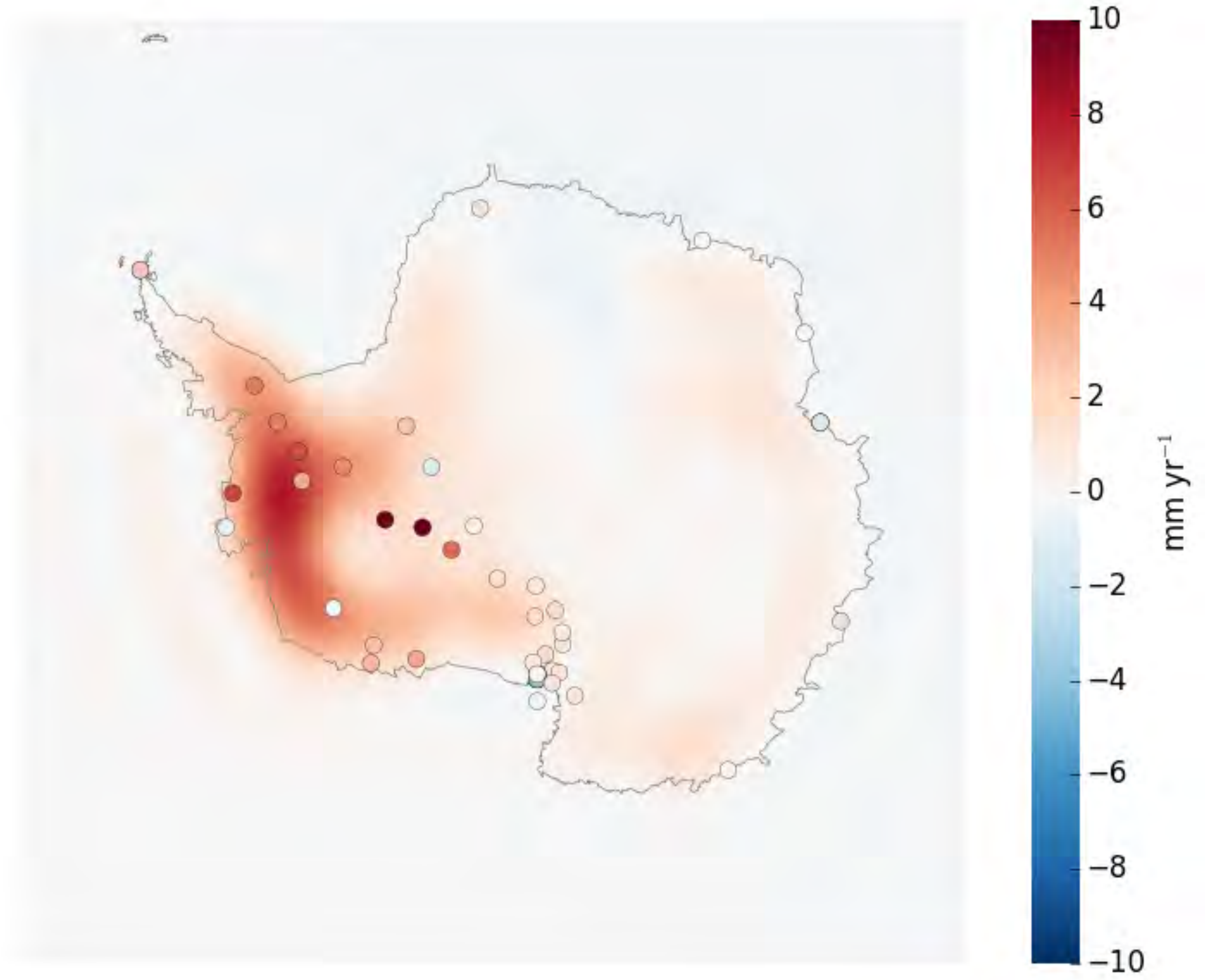
- We use an ensemble of six recent models representing three different load histories



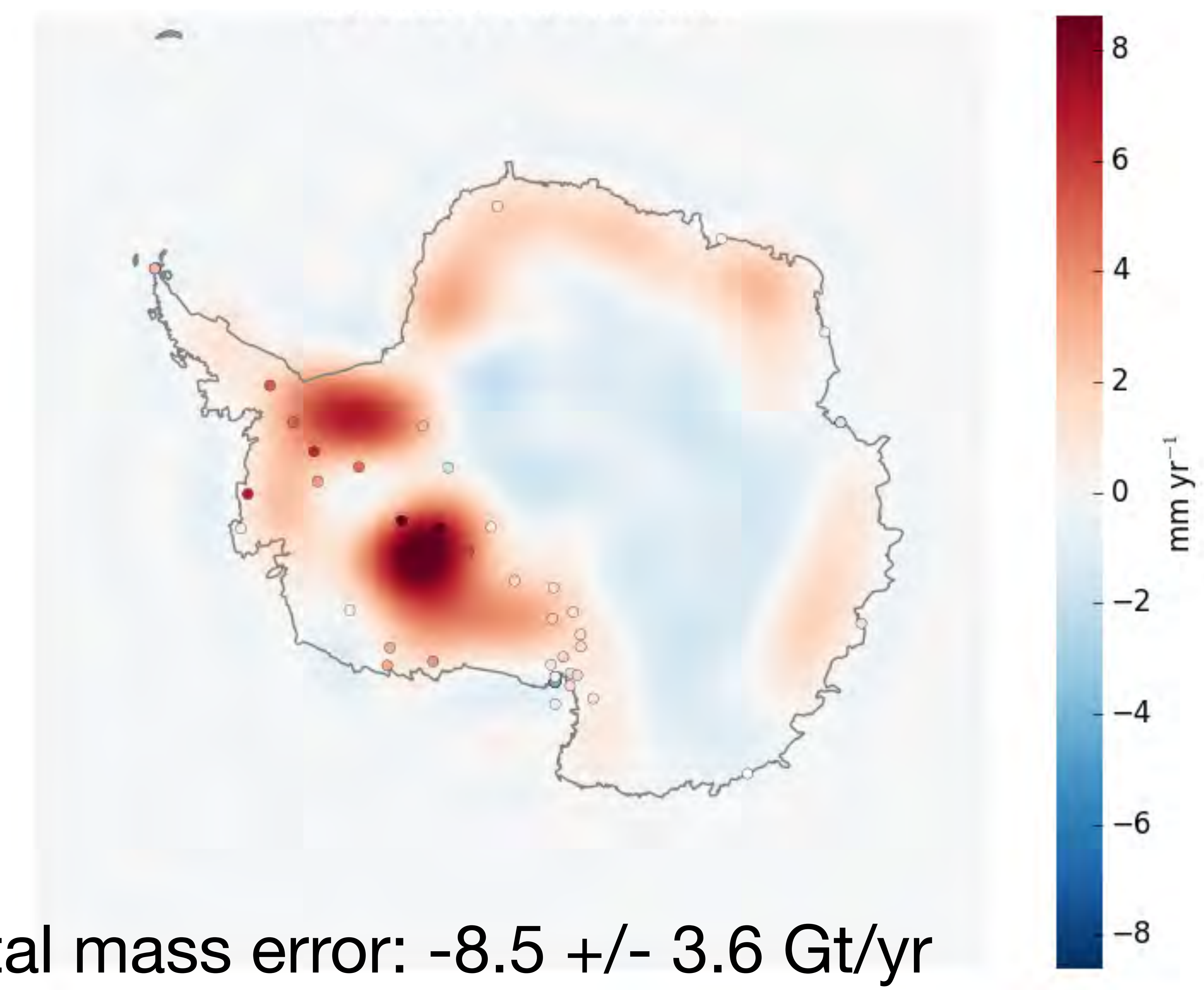


Results

***A priori* combined elastic loading and GIA uplift effects**



Post-adjustment uplift prediction

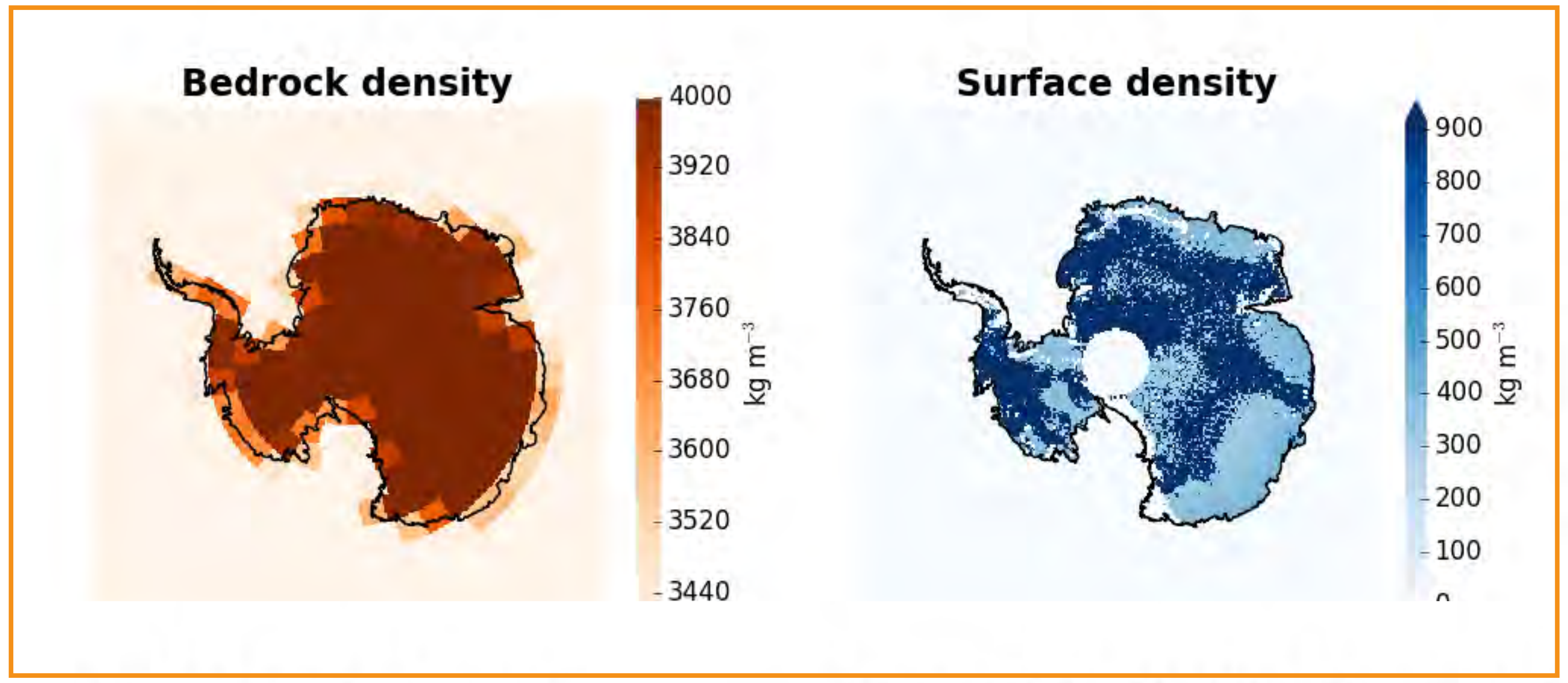


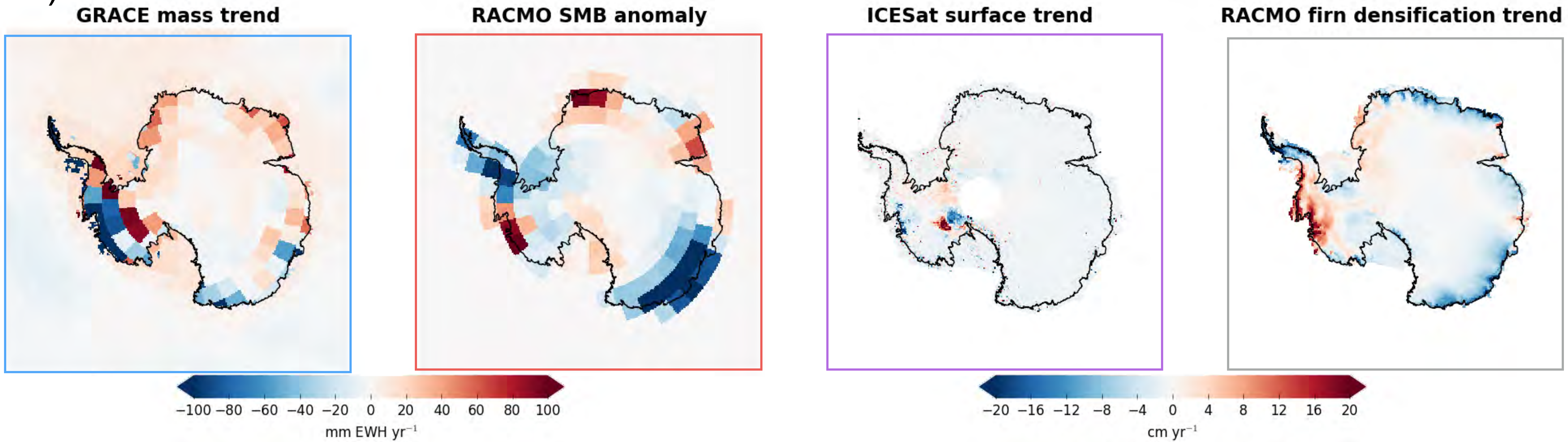
Total mass error: -8.5 +/- 3.6 Gt/yr
Weighted RMS residuals: 1.0 mm/yr
Variance explained: 47%

Combining GRACE and ICESat

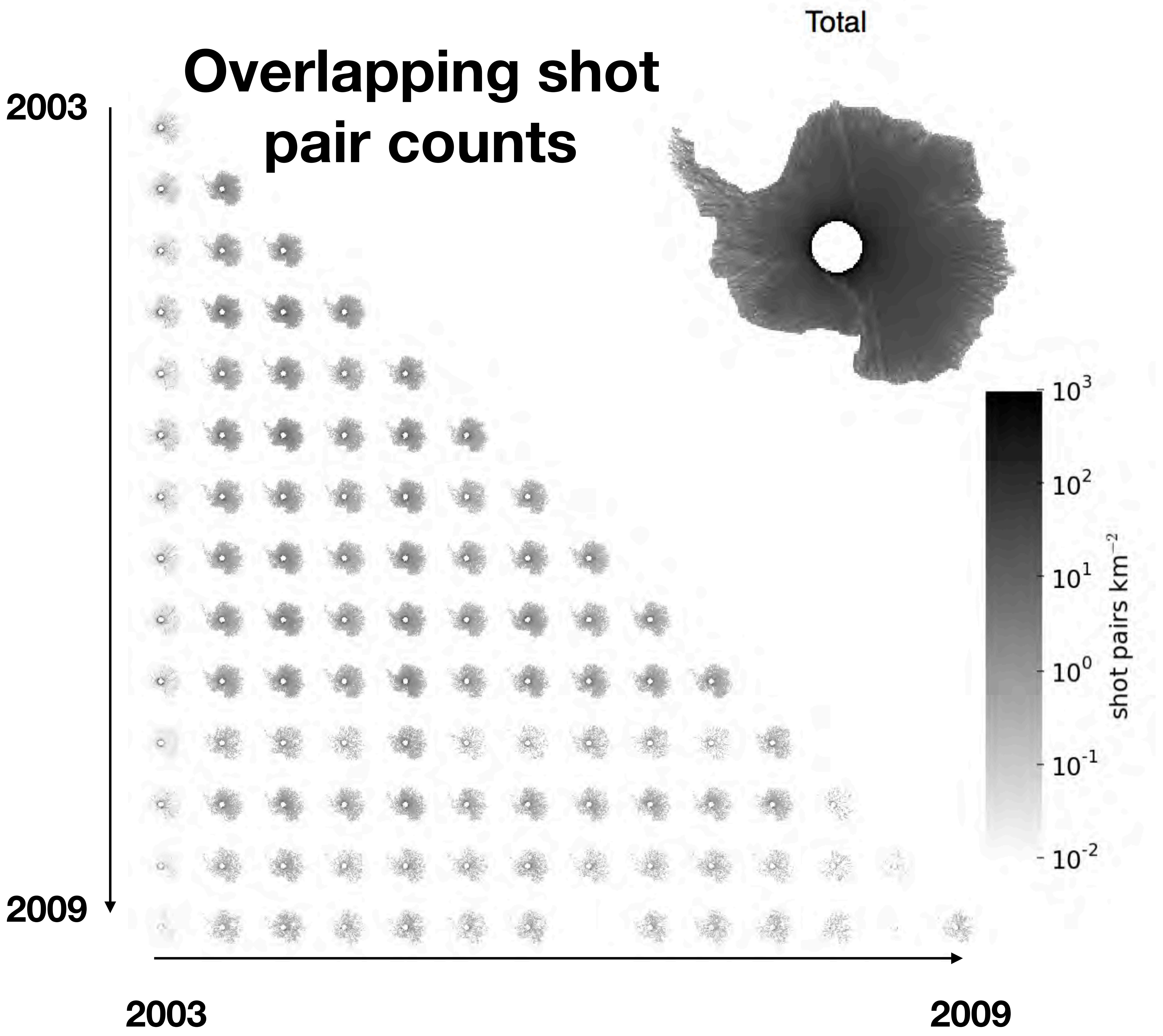
$$\text{Bedrock Velocity} = \frac{(\text{GRACE} - \text{SMB}) - (\text{ICESat} - \text{Firn}) \times (\text{Surface Density})}{\text{Bedrock Density} - \text{Surface Density}}$$

- Direct combination of GRACE and ICESat after Gunter et al. (2014) and Riva et al. (2009)
- Using JPL RL05.1M mascons instead of spherical-harmonic products
- SMB and firn compaction models obtained from RACMO (Ligtenberg et al., 2013)



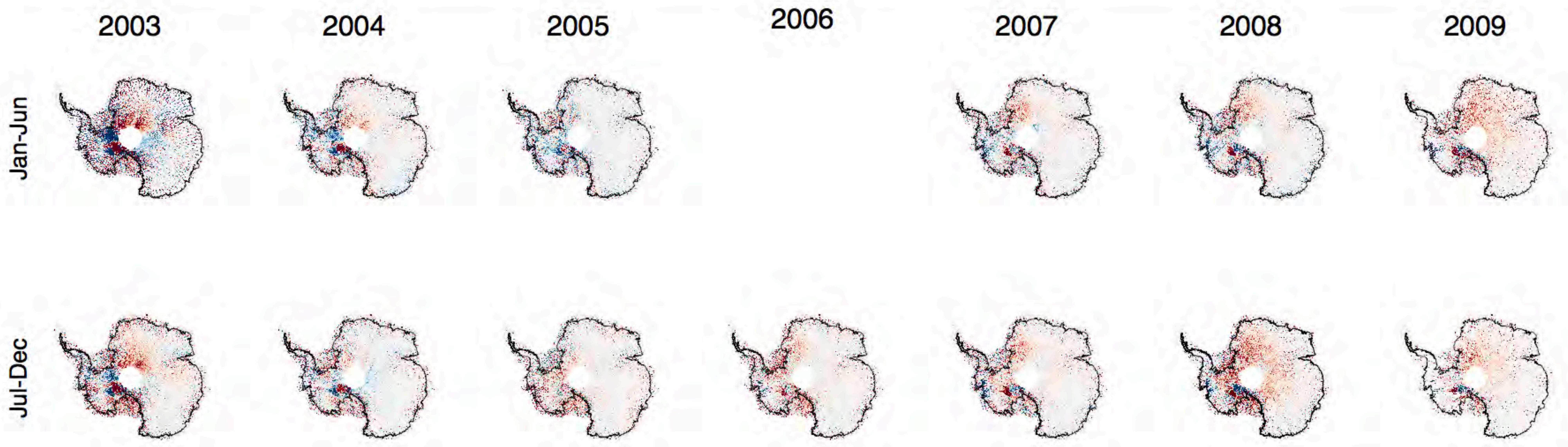


Overlapping Footprints

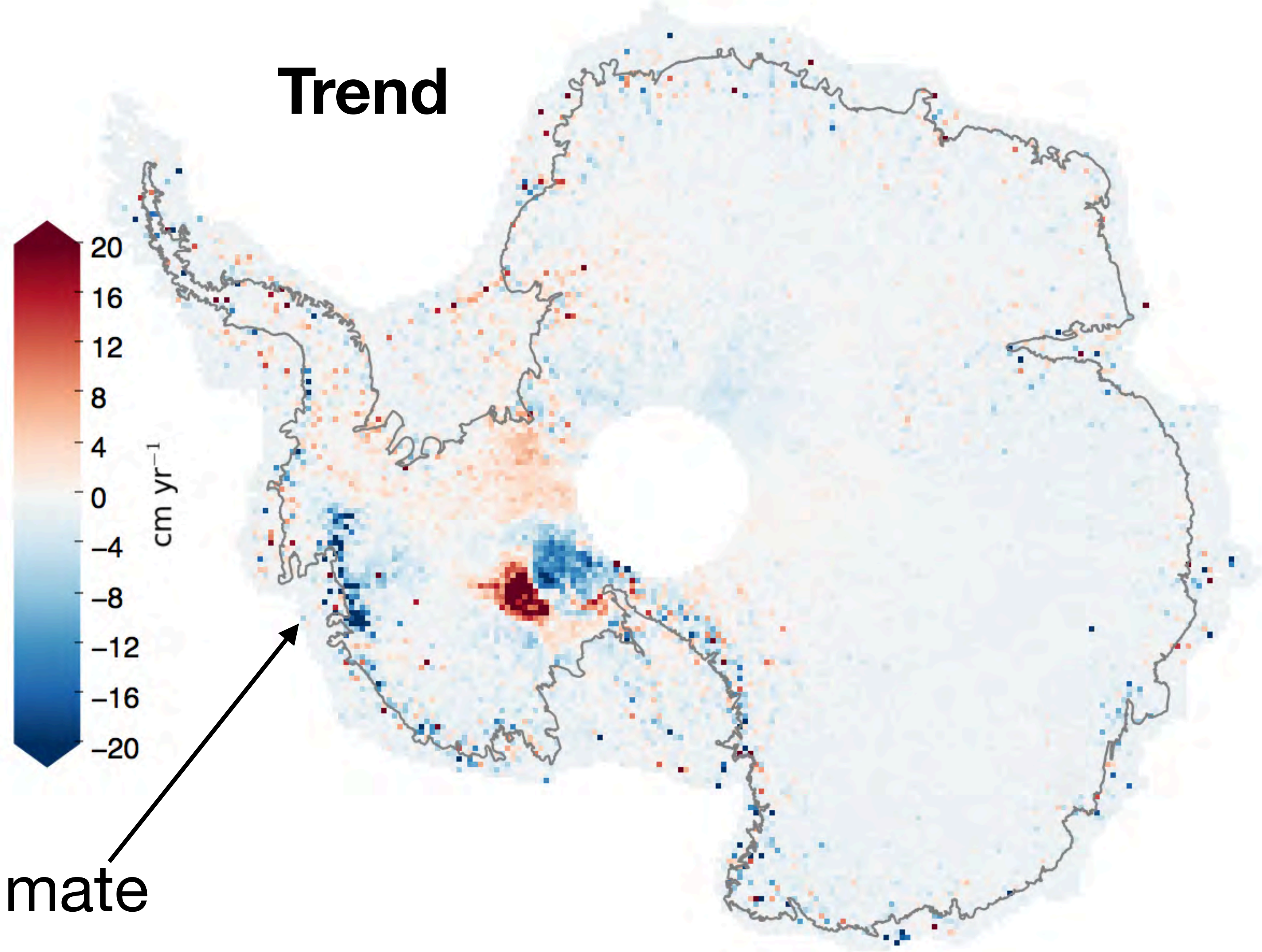


- Following Gunter et al. (2014) and Riva et al. (2009)
- Brute-force approach maximizes spatial resolution
- Algorithm
    - Find all Antarctic overlapping footprint pairs in GLAH12
    - Apply saturation correction; filter by co-elevation, apparent elevation rate, peak counts, standard flags, etc.
    - Assign footprint pairs to ~27 km grid cells
    - Solve for timestamped elevation grids and trends using Laser 3e (Feb-Mar 2006) as reference epoch

Overlapping Footprints



(Laser 3k not shown)



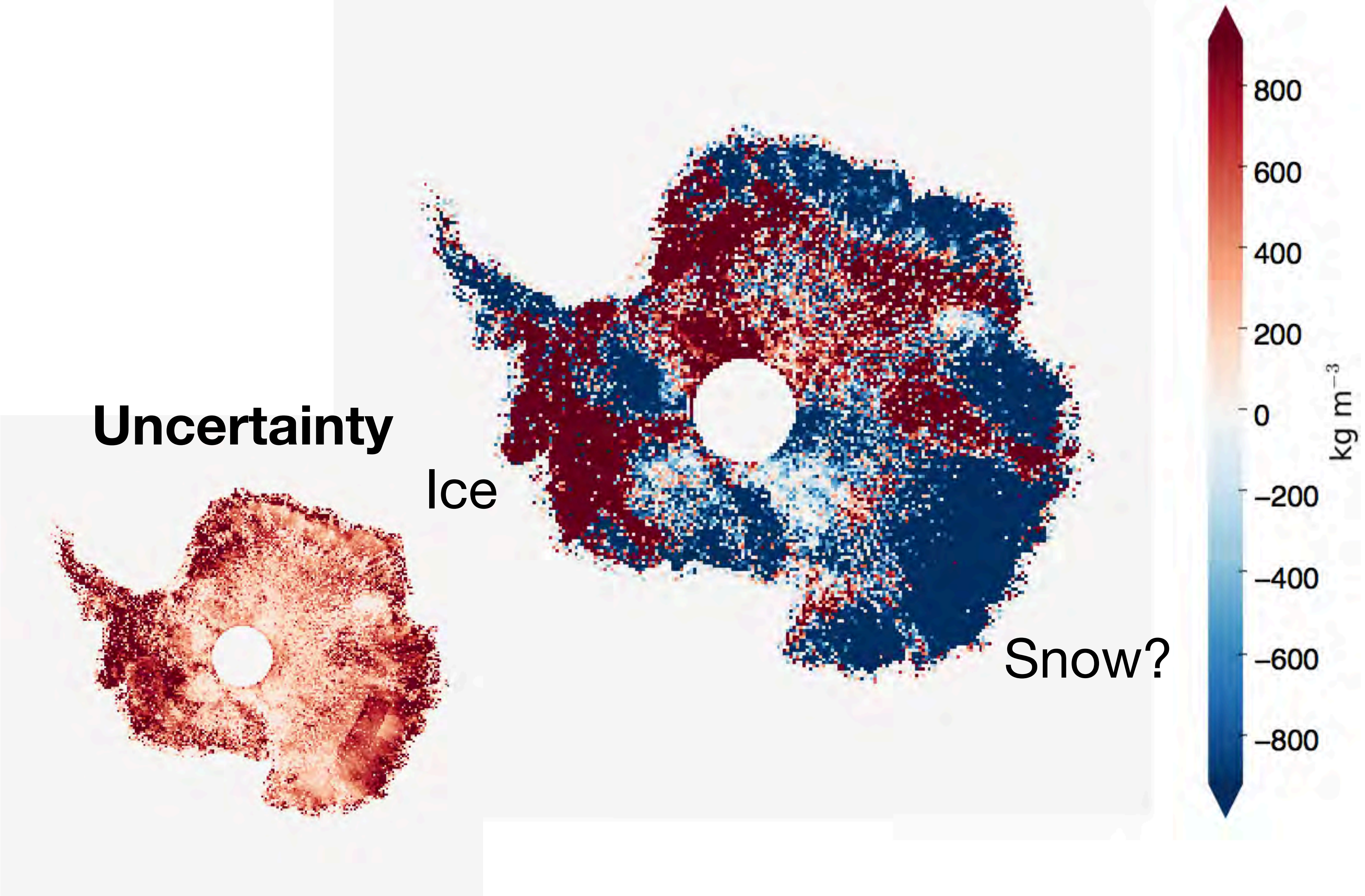
- Found over 500 million overlapping shots
- Applied low-precipitation zone bias correction after Gunter et al. (2014)

Surface Density Estimation

Least-squares combination with GRACE

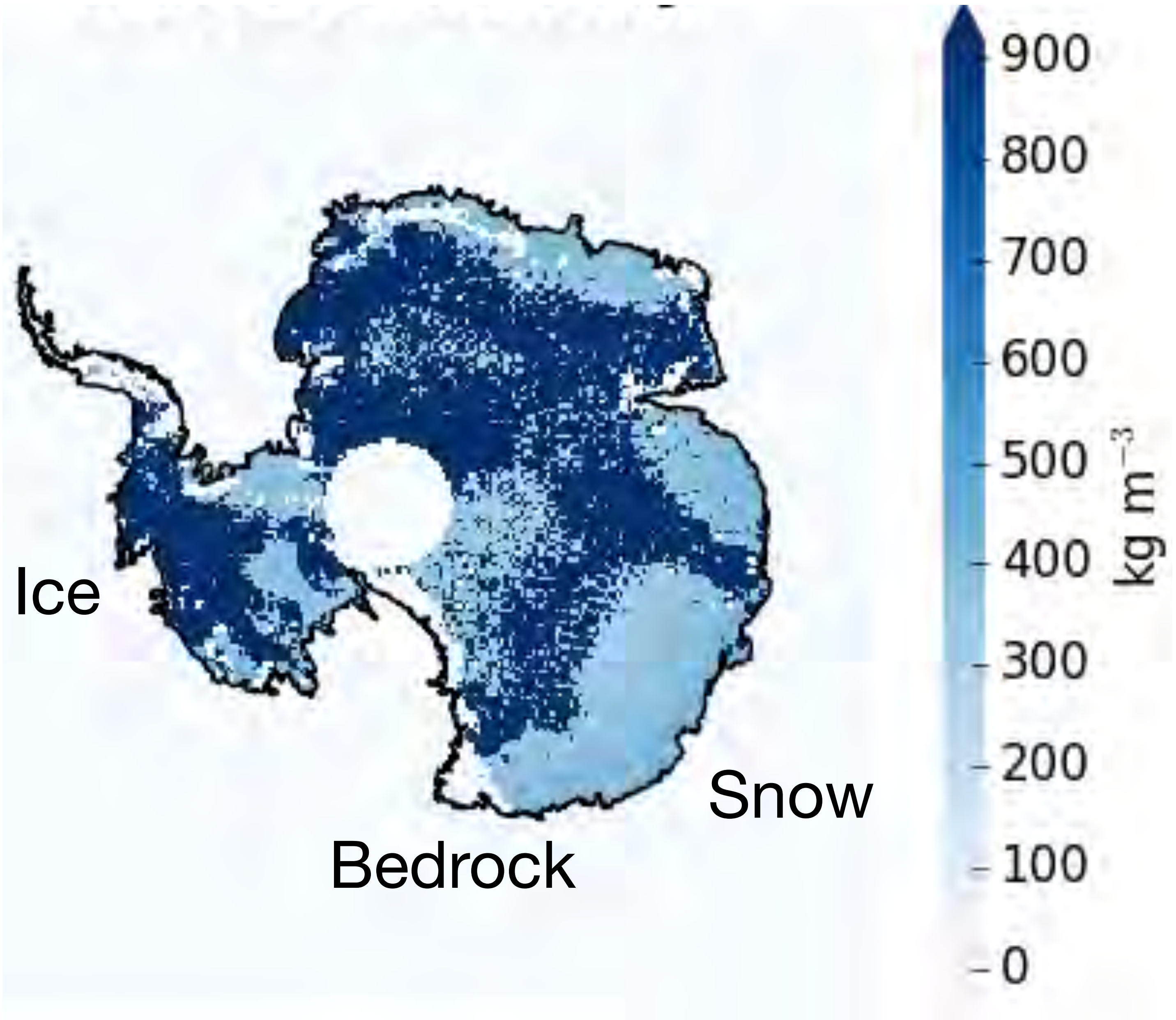
- GRACE (minus SMB) and ICESat (minus firn) grids are detrended and fit together to estimate density

- Estimates may inform classification

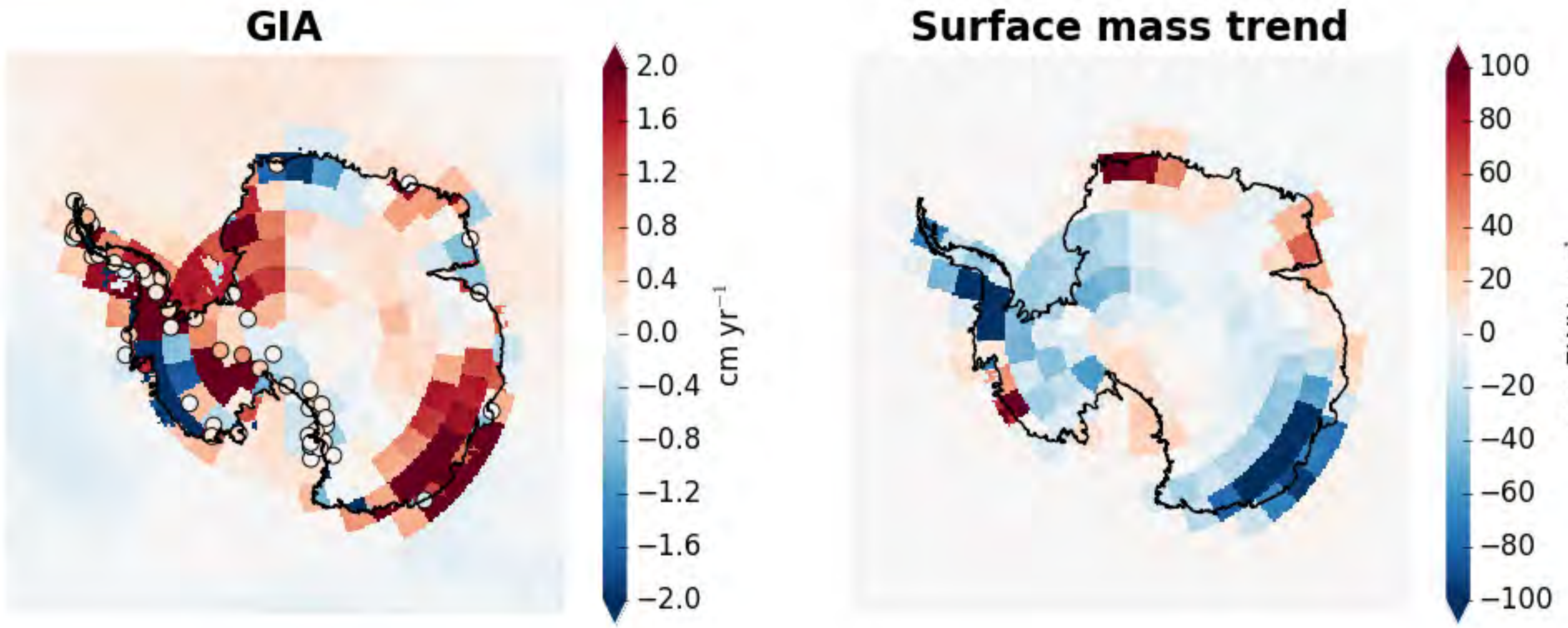


Non-firn surface elevation rate

- Difference between ICESat and firn elevation rate informs choice of surface density
  - Density of ice (917 kg m^{-3})
  - Density of snow (300-600 kg m^{-3})
  - Zero
- Density set to zero according to BEDMAP2 exposed rock mask



Results

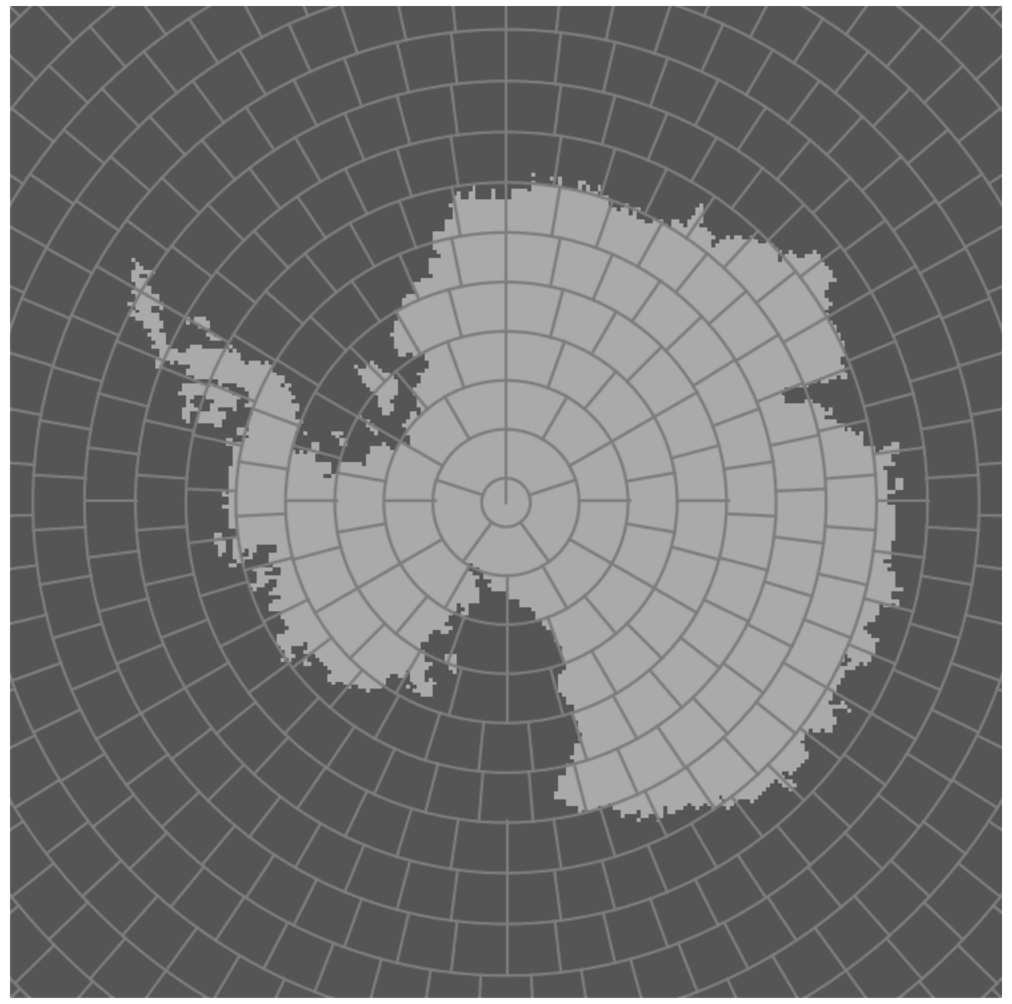


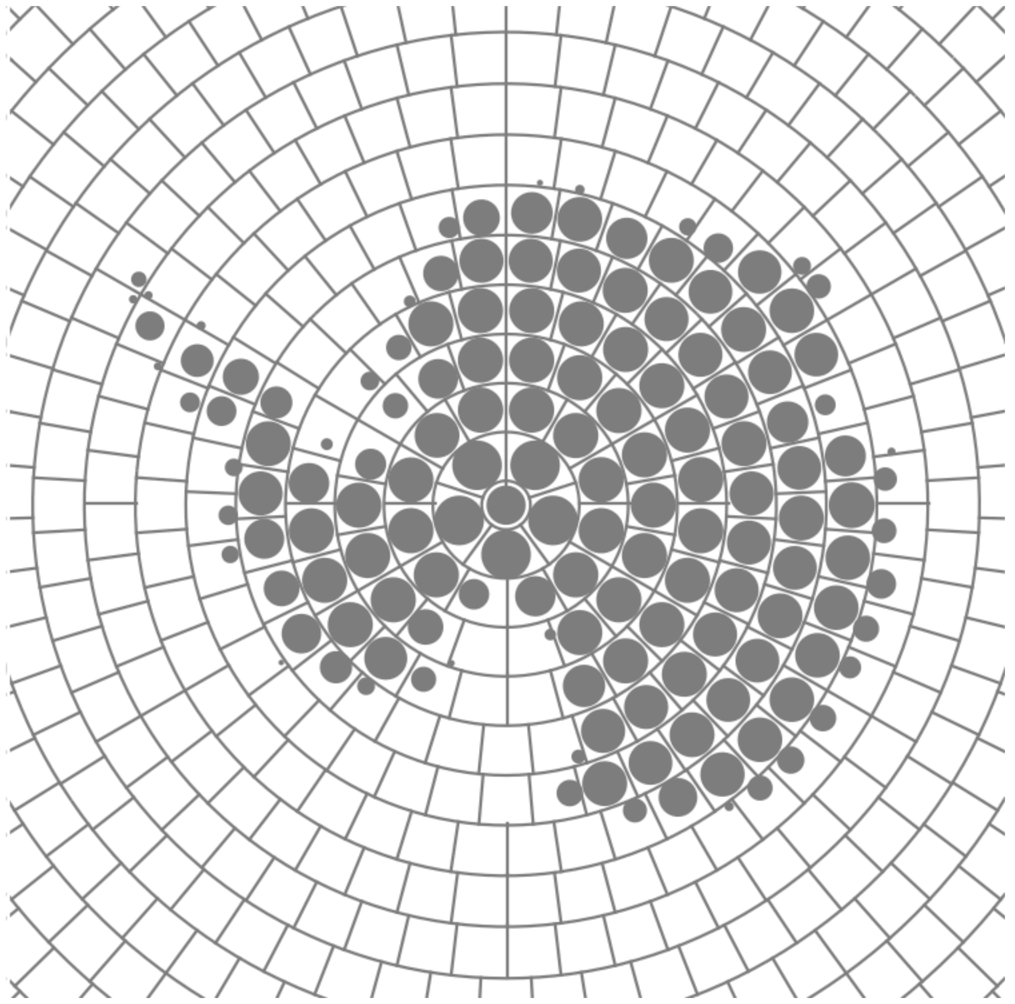
GIA
2.0
1.6
1.2
0.8
0.4
0.0
−0.4
−0.8
−1.2
−1.6
−2.0
cm yr^{-1}
Surface mass trend
100
80
60
40
20
0
−20
−40
−60
−80
−100
mm EWH yr^{-1}

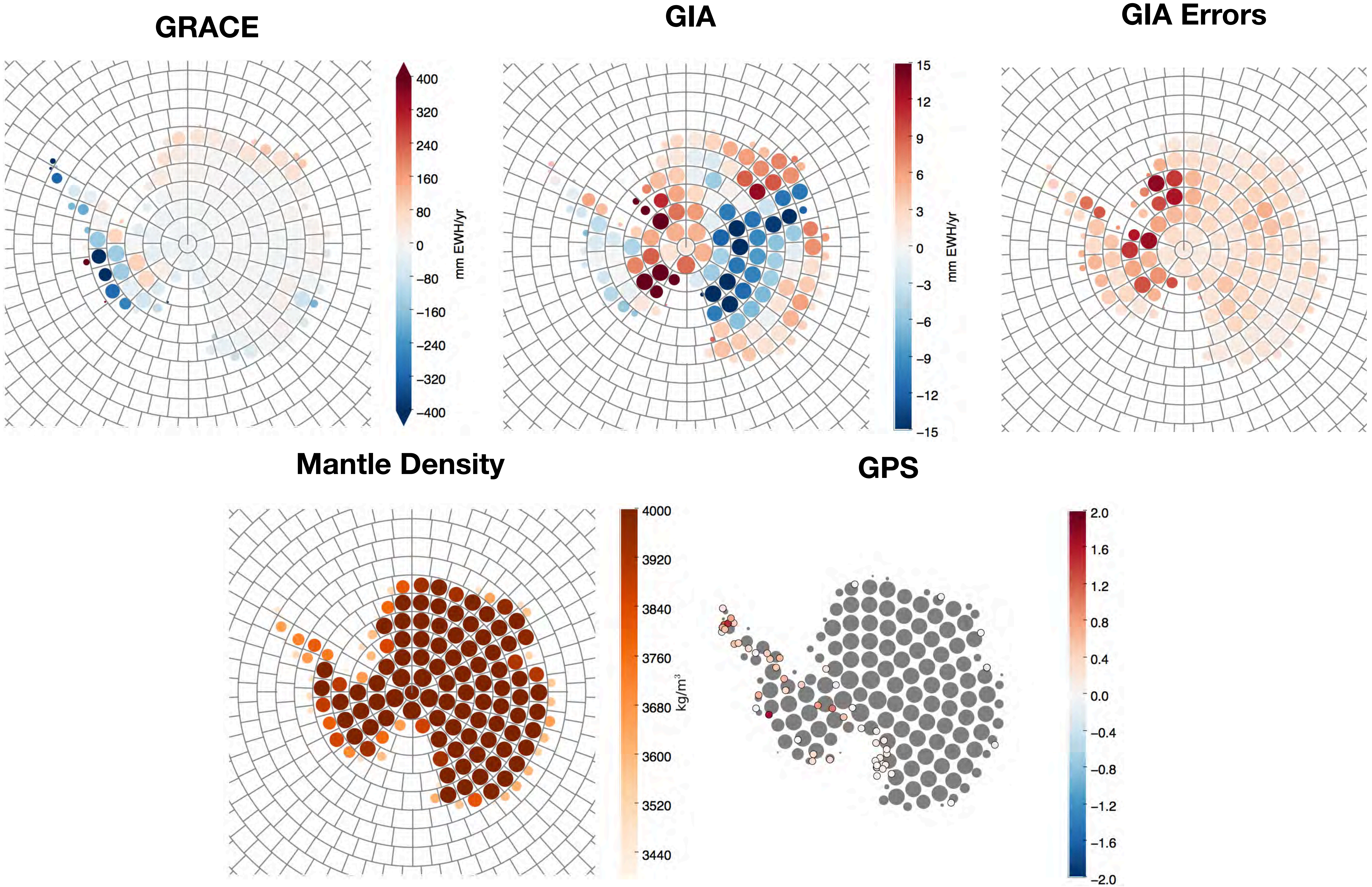
Direct Filtering

Fit all data at once

- Decompose CRI-filtered land mascons into discrete elements
- Model:
    - GIA effects as uniform over mascon
    - Elastic loading with spherical caps
    - Effective snow/ice density uniform within cap
- Subtract GRACE and GIA from all other data
- Simultaneously fit GIA for entire time period and mass solutions for individual months
- Use GIA ensemble for spatial constraints

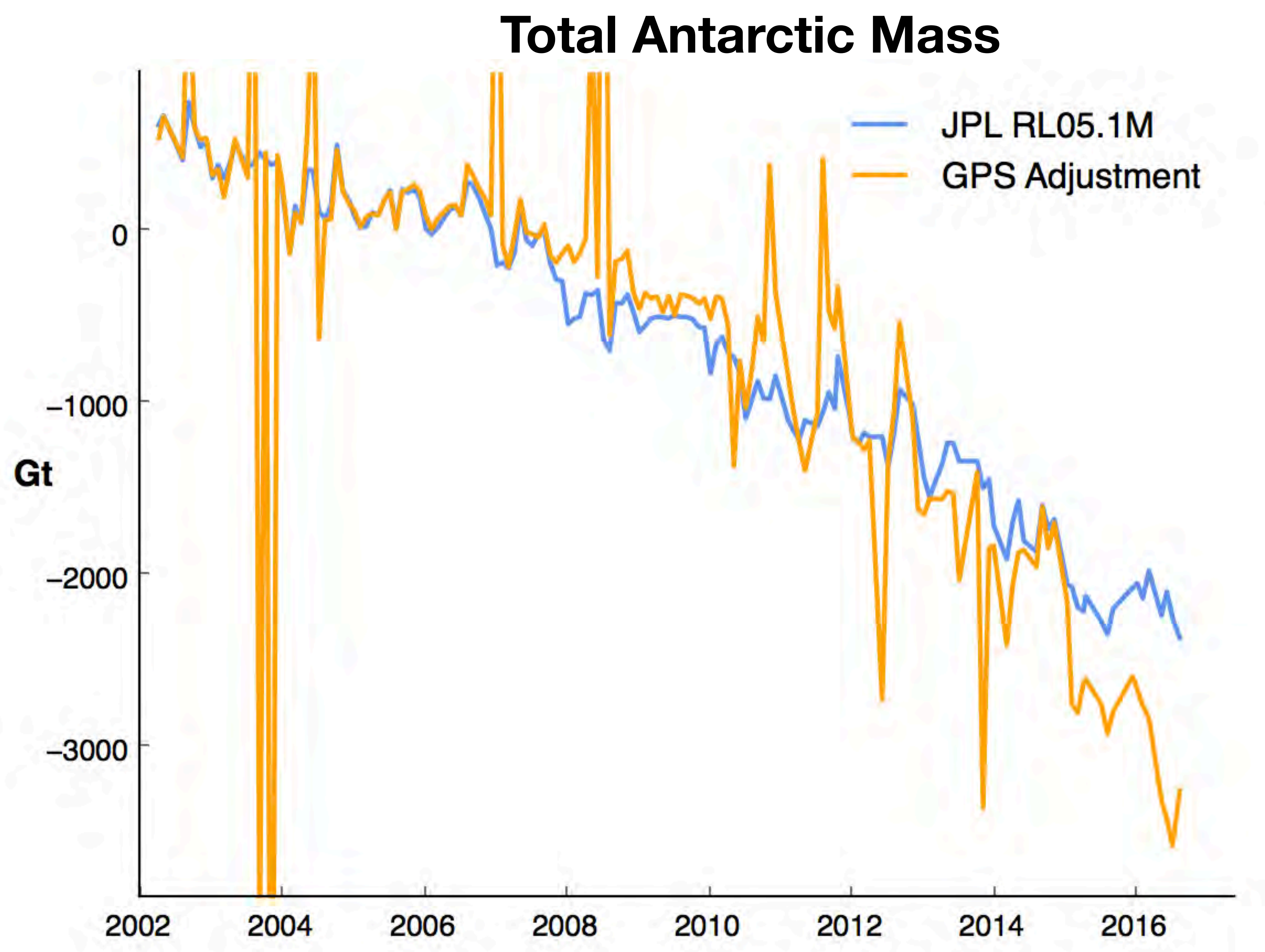


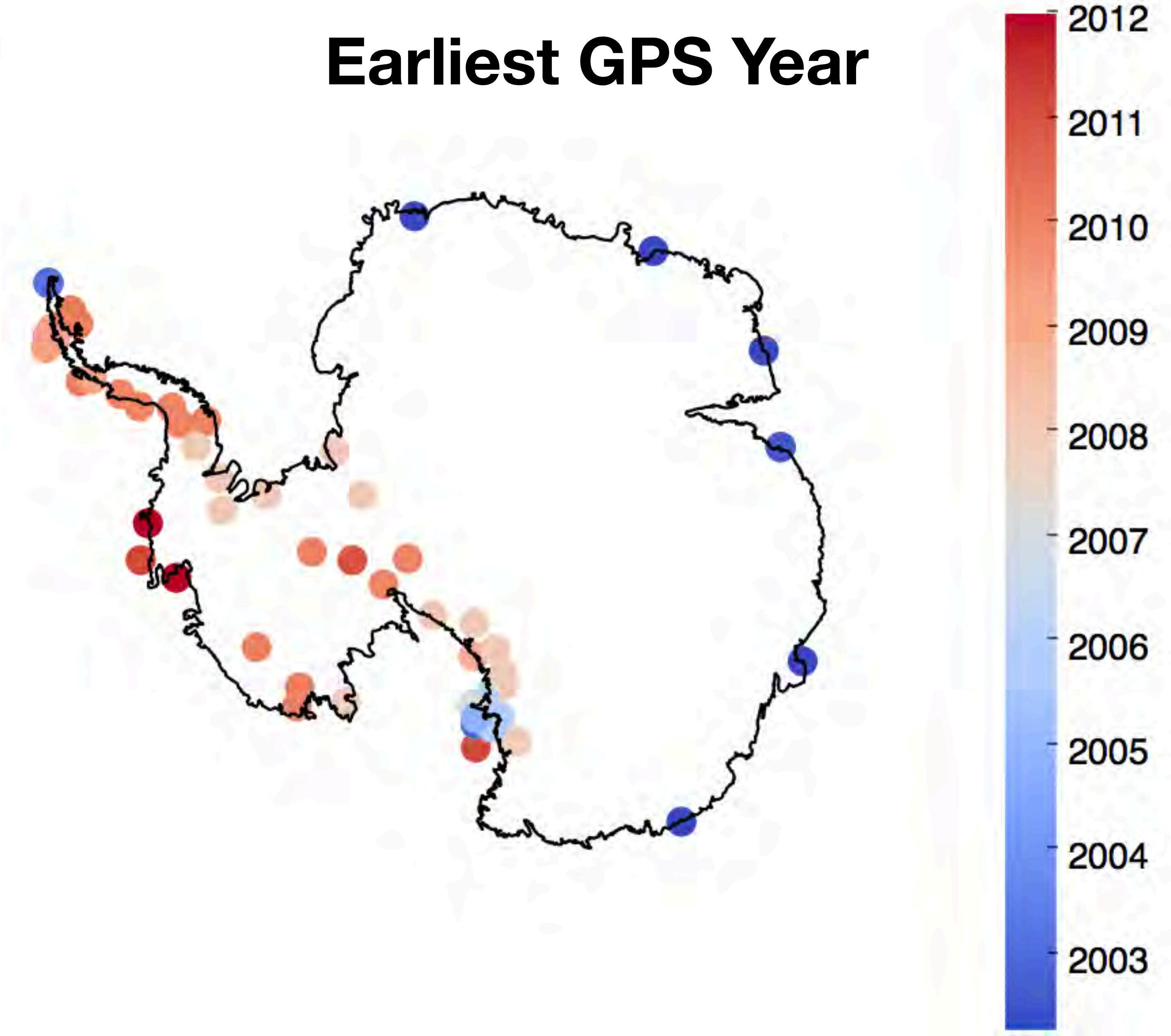



GRACE
400
320
240
160
80
0
−80
−160
−240
−320
−400
mm EWH/yr
GIA
15
12
9
6
3
0
−3
−6
−9
−12
−15
mm EWH/yr
GIA Errors
Mantle Density
4000
3920
3840
3760
3680
3600
3520
3440
kg/m³
GPS
2.0
1.6
1.2
0.8
0.4
0.0
−0.4
−0.8
−1.2
−1.6
−2.0

Results

- Additional 40 Gt/yr of mass loss introduced by recent GPS data
- Inadequate combination of GRACE and ICESat
- GIA solution saturated. Need better a priori constraints.

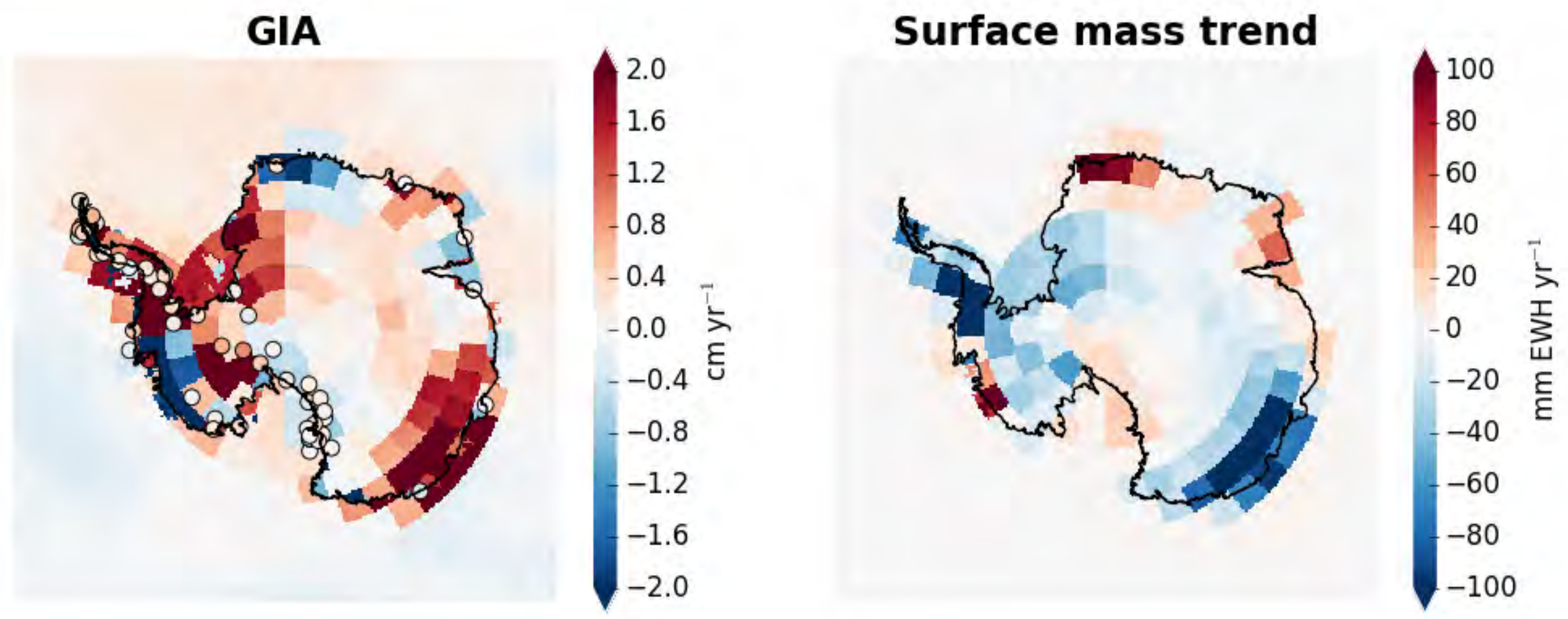




Summary

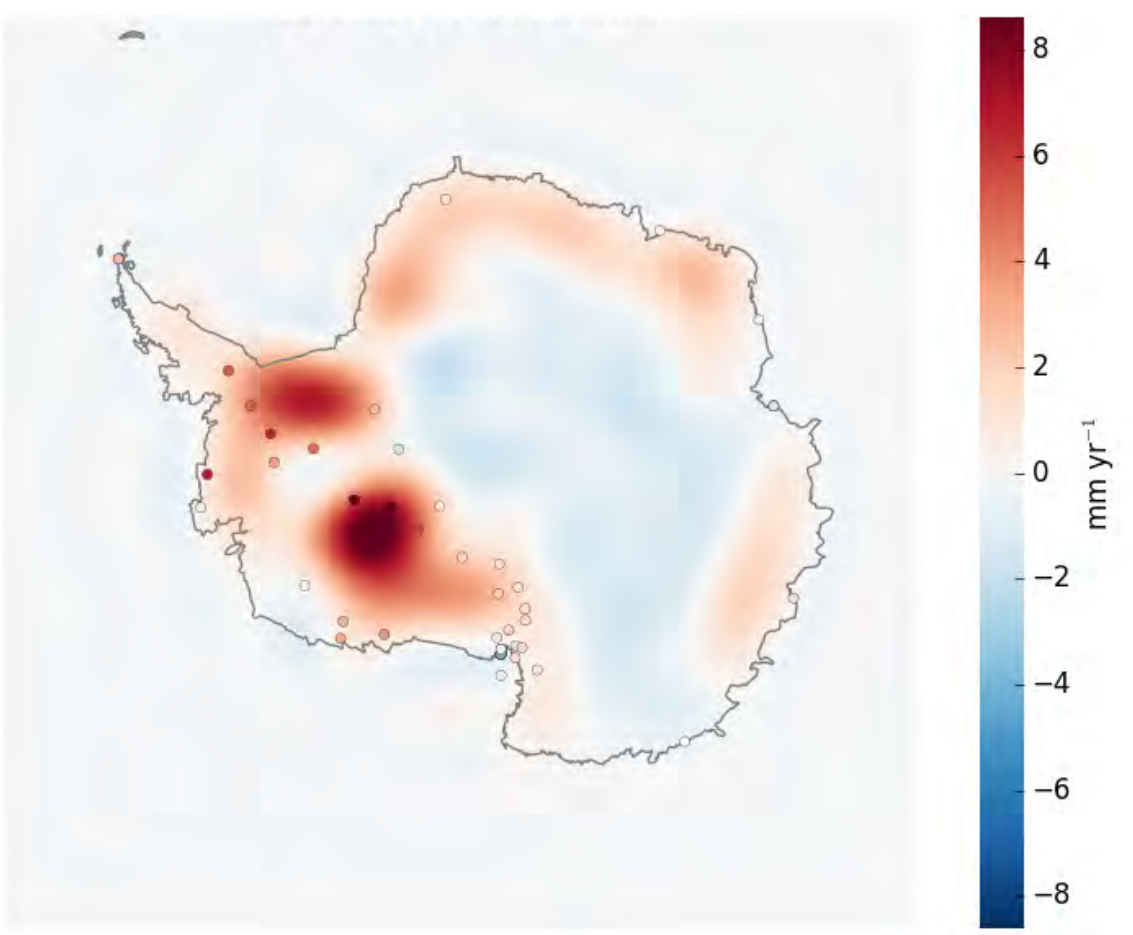
- Obtained adjustments to GIA and ice sheet trends via combination of GRACE with GNSS and ICESat
- No final mass balance figures at present
- Results presented here are consistent with ice mass loss of 90—160 Gt/yr

Combination of GRACE and ICESat



Combination of GRACE and GNSS

GIA



Future Work

Data Reduction

- Revisit ICESat trend estimation
- Fully explore ICESat bias corrections

New Data Sources

- Radar altimetry
- Horizontal GNSS motion
- InSAR
- Operation IceBridge data
- Photogrammetry

Modeling

- Produce solutions on monthly timescales
- Combine all three measurement types
- Explore temporal constraints
- Explore combination of all three data sources via Kalman filter
- Use SMB and ice velocity models for constraints