Challenges of GRACE Data Processing

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The Earth's Gravity Field

The geopotential field is determined by mass distribution within the Earth's system, and is conveniently expressed in spherical harmonic expansion as,

$$U(r,\phi,\lambda) = \frac{GM_e}{r}\left[1 + \sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{R_e}{r}\right)^l \cdot (C_{lm}\cos m\lambda + S_{lm}m\lambda)P_{lm}(\sin\phi)\right]$$

where,

r, ϕ, λ are the geocentric distance, latitude, and longitude;

G is the gravitational constant;

M_e, R_e are the mass and equatorial radius of the Earth;

C_{lm} , S_{lm} are the spherical harmonics of degree l and order m;

P_{lm} (sinϕ) are the Legendre polynomials of degree l and order m.

The Earth's Time-Variable Gravity

C_{lm} & S_{lm} **are computed from mass changes as**

$$C_{lm} = \frac{1}{M_e R_e^l} \frac{(2-\delta_{0m})(l-m)!}{(l+m)!} \int_M r^l \cdot P_{lm}(\sin\phi) \cdot \cos m\lambda \cdot dM$$

$$S_{lm} = \frac{1}{M_e R_e^l} \frac{(2-\delta_{0m})(l-m)!}{(l+m)!} \int_M r^l \cdot P_{lm}(\sin\phi) \cdot \sin m\lambda \cdot dM$$

Monthly C_{lm} & S_{lm} variations, or so called Stokes Coefficients are provided by GRACE, which can be used to infer surface mass variation or geoid height change.

Three Representations:

- Spherical Harmonics ΔC_{lm} & ΔS_{lm}
- Surface mass load change $\Delta\sigma$

$$\Delta\sigma(\theta,\phi) = \frac{R_e \rho_{ave}}{3} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{2l+1}{1+k_l} W_l \tilde{P}_{lm}(\cos\theta) \times [\Delta C_{lm}\cos(m\phi) + \Delta S_{lm}\sin(m\phi)]$$

- Geoid height change ΔN

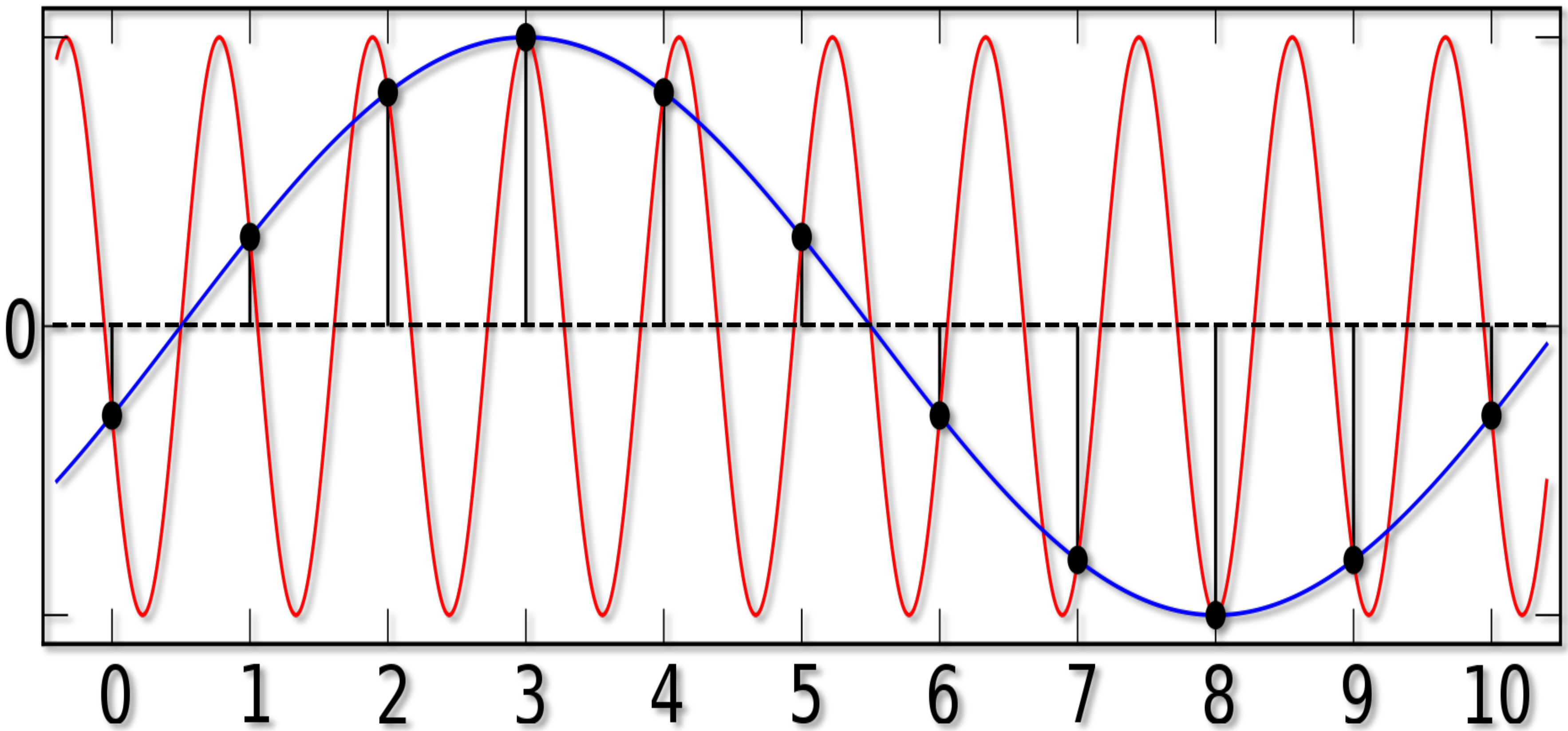
$$\Delta N(\theta,\phi) = R_e \sum_{l=0}^{\infty} \sum_{m=0}^{l} W_l \tilde{P}_{lm}(\cos\theta) \times [\Delta C_{lm}\cos(m\phi) + \Delta S_{lm}\sin(m\phi)]$$

$W_l = W_l(r)$ is the Gaussian weighting as a function of spatial radius, r.

GRACE Main Products

- Time-variable gravity field solutions at approximately monthly intervals.
- Static mean gravity fields (e.g., GGM01C, GGM02C, …).
- In forms of fully normalized spherical harmonics (or Stokes coefficients) up to degree and order 60 (or 100).
- From three processing centers, CSR, GFZ, and JPL.
- Supporting data products, GAC, GAB, GAA, and etc.

What is Aliasing?



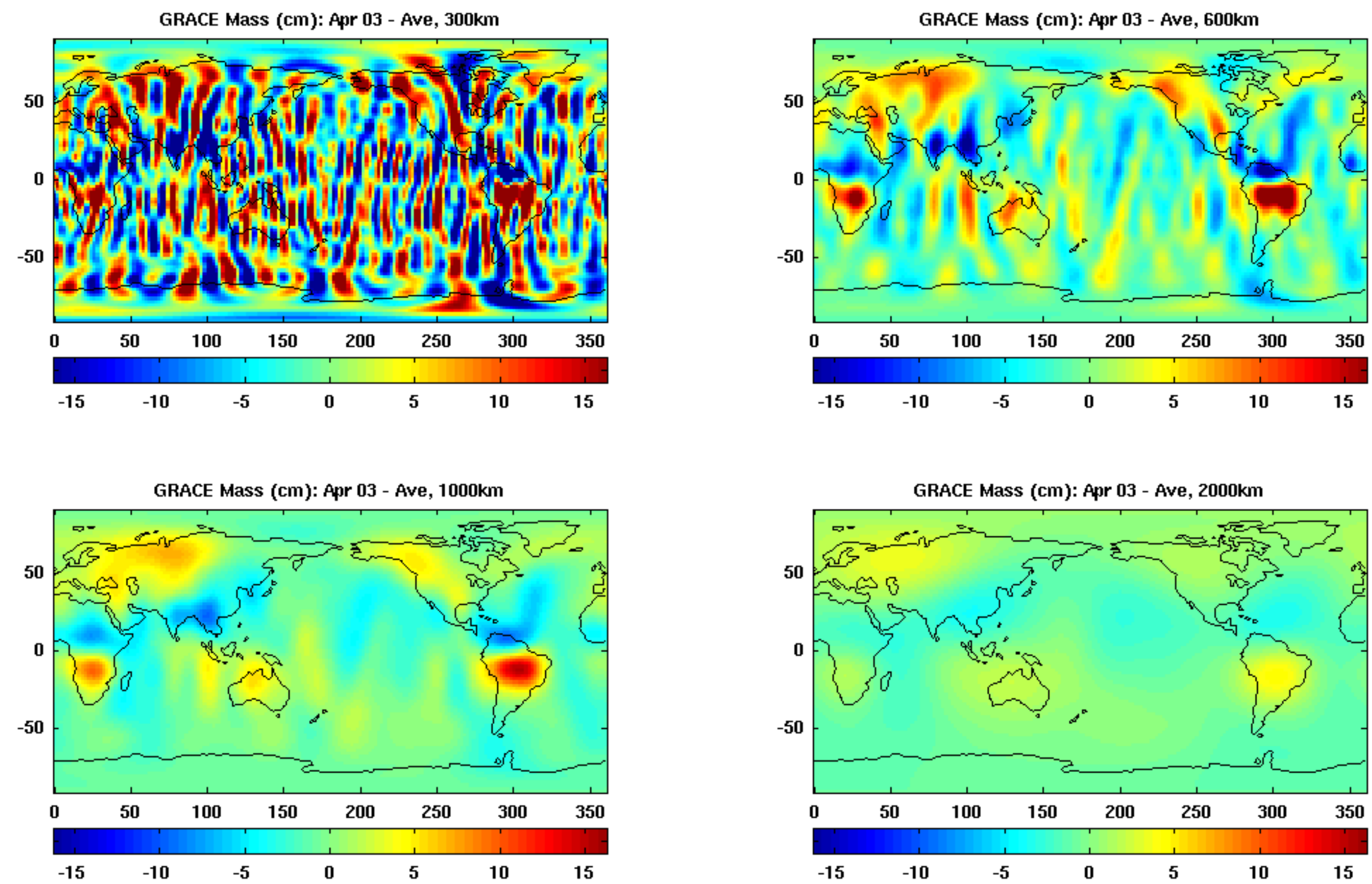
Everyday Example

Surface Mass Changes from GRACE

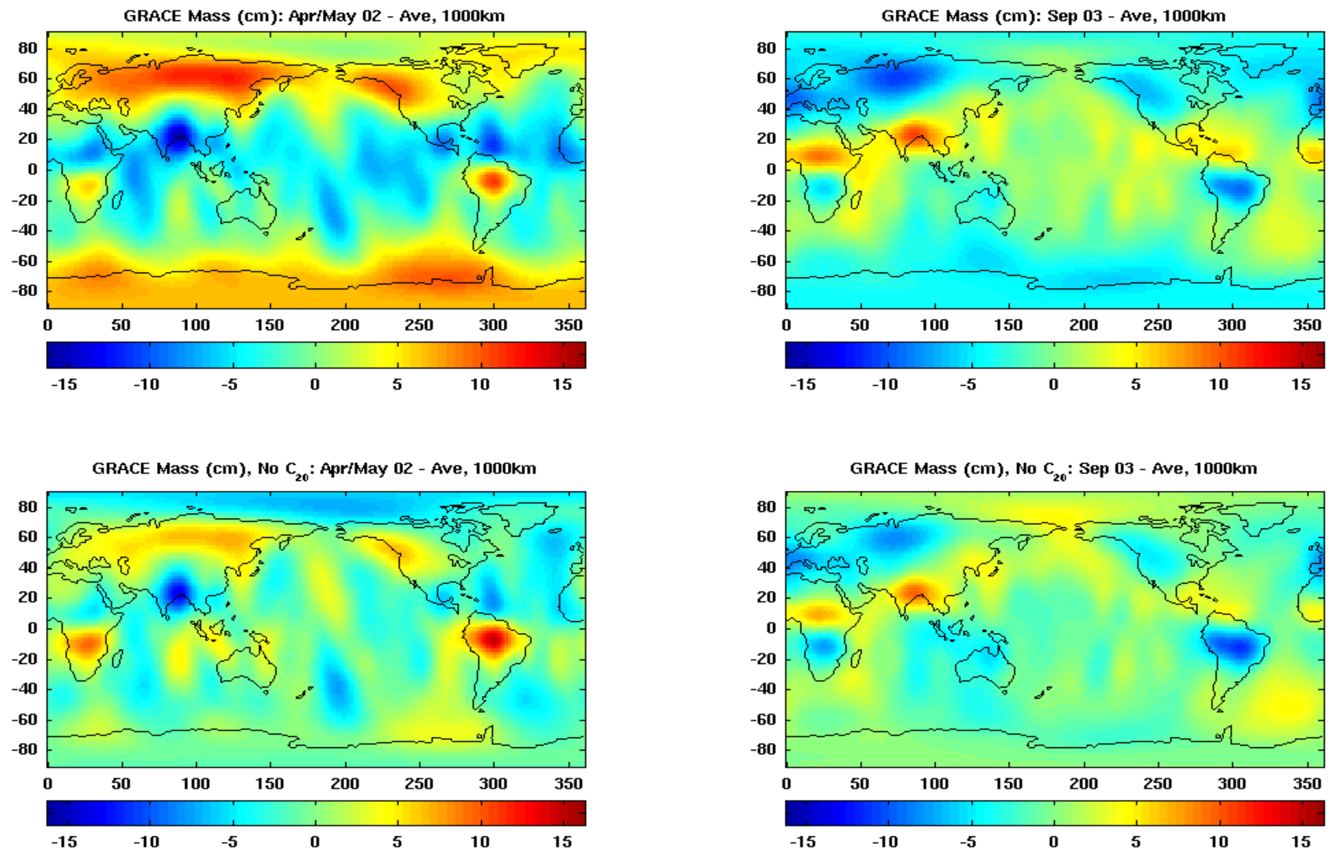
Main issues to solve:

- Spatial smoothing or filtering is needed as high degree and order terms are dominated by noise.
- Appropriate treatments of low degree harmonics (e.g., the large uncertainty of C20 in GRACE solutions, and the missing geocenter, degree-1 terms in GRACE data).
- Residual aliasing effects (from ocean and air tide model errors).
- How to minimize leakage effects due to the spatial smoothing?
- How to validate GRACE estimates?
- What is the effective spatial resolution of GRACE?

Challenges of GRACE Data Filtering



The Challenge of Low Degree Terms



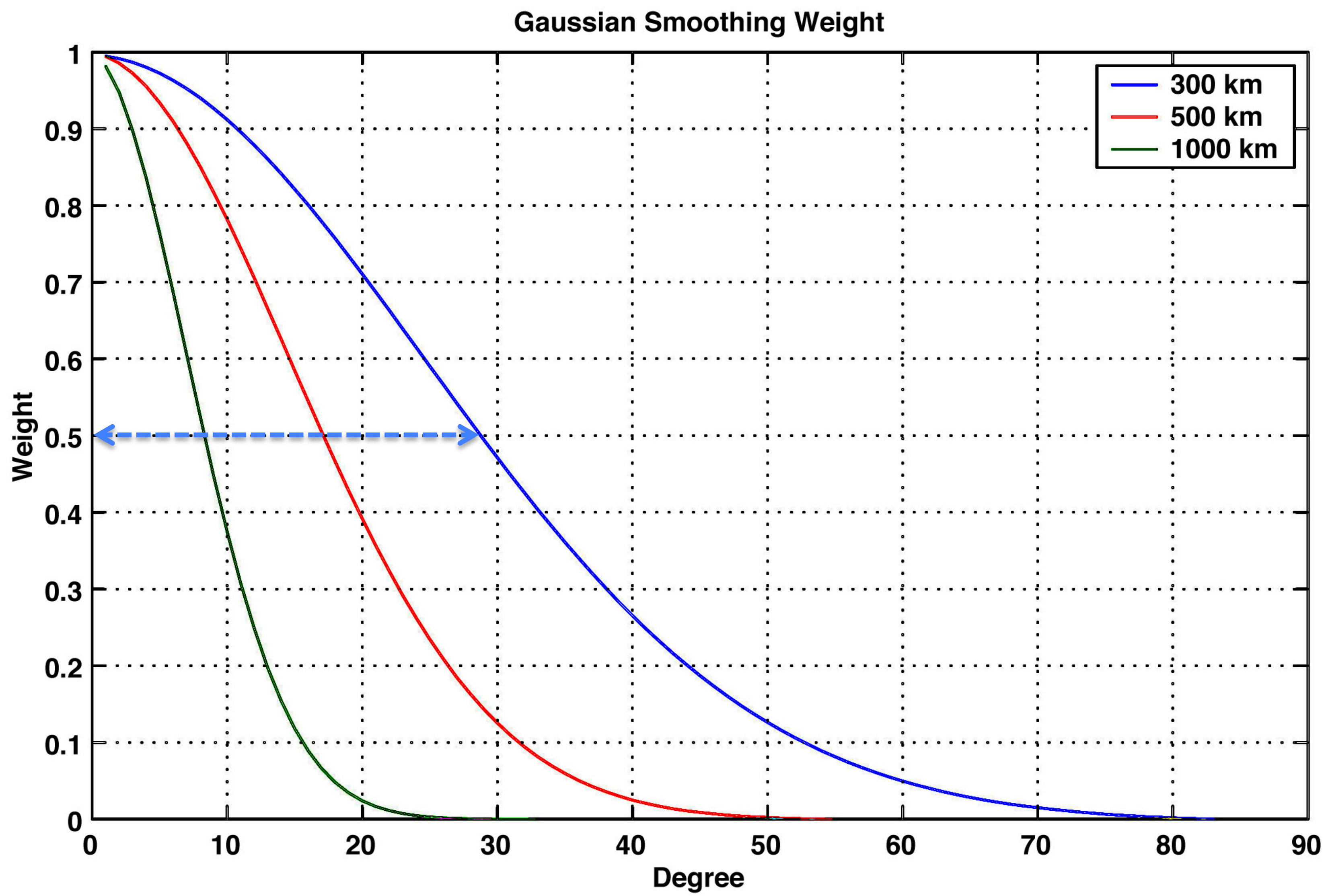
Spatial Filterings of GRACE Data

- Gaussian filtering (Jekeli 1981, Wahr et al. 1998)
- Non-isotropic Gaussian filtering (Han et al. 2005)
- Optimized filtering (signal-to-noise ratio) (Chen et al. 2006)
- Decorrelation + Gaussian filtering (Swenson and Wahr 2006)
- Wiener optimal filtering (Sasgen et al. 2006)
- Statistical filtering (Davis et al. 2008)
- Wavelets & EOFs
- …

How does spatial filtering work?

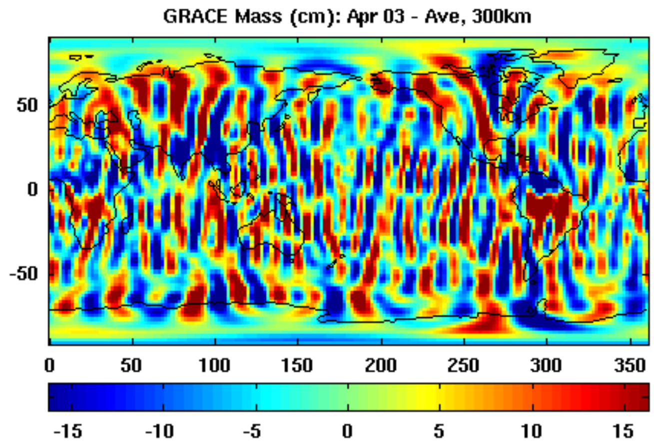
$$\Delta\sigma(\theta,\phi) = \frac{R_e\rho_{ave}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\tilde{P}_{lm}(\cos\theta)\times[\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)]$$

$$\Delta\sigma(\theta,\phi) = \frac{R_E\rho_{ave}}{3}\sum_{l=0}^{N}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}W_l\tilde{P}_{lm}(\cos\theta)$$
$$\times[\Delta C_{lm}\cos(m\phi)+\Delta S_{lm}\sin(m\phi)],$$

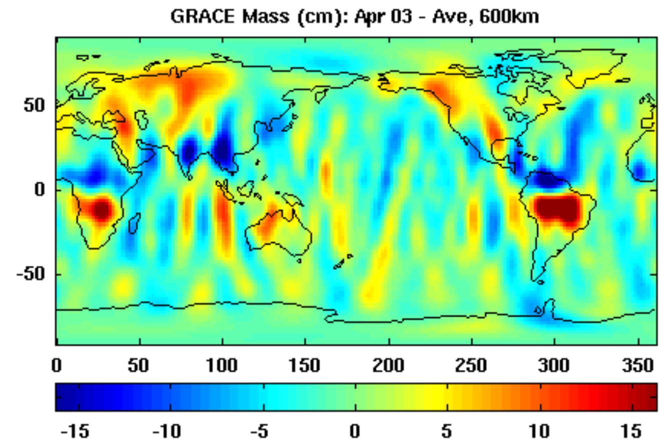

Gaussian Smoothing Weight
300 km
500 km
1000 km
Weight
Degree
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90

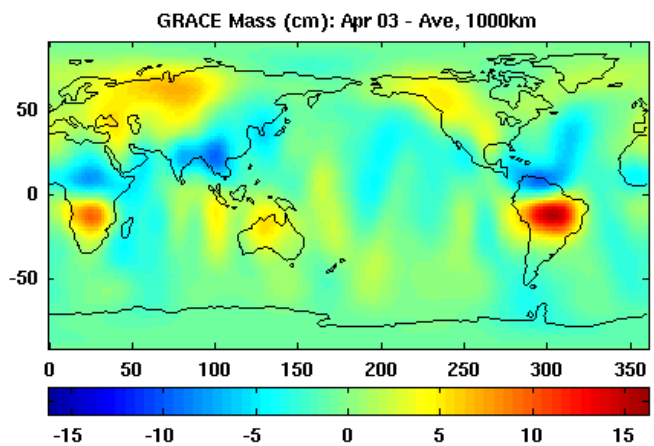
Gaussian Smoothing

300 km

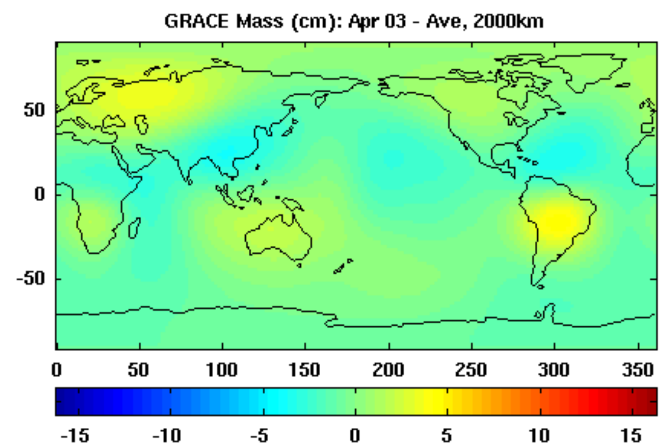


600 km

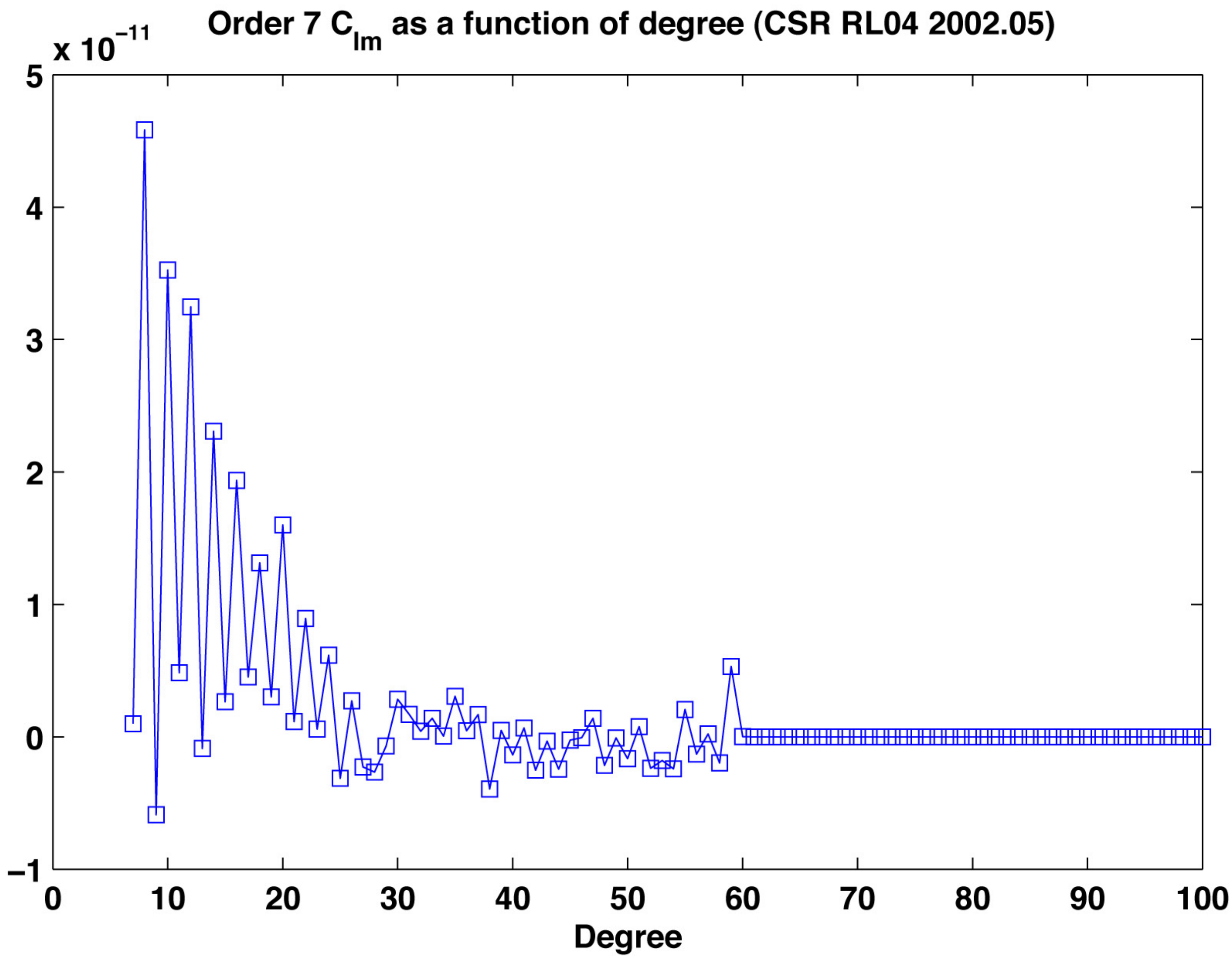




1000 km

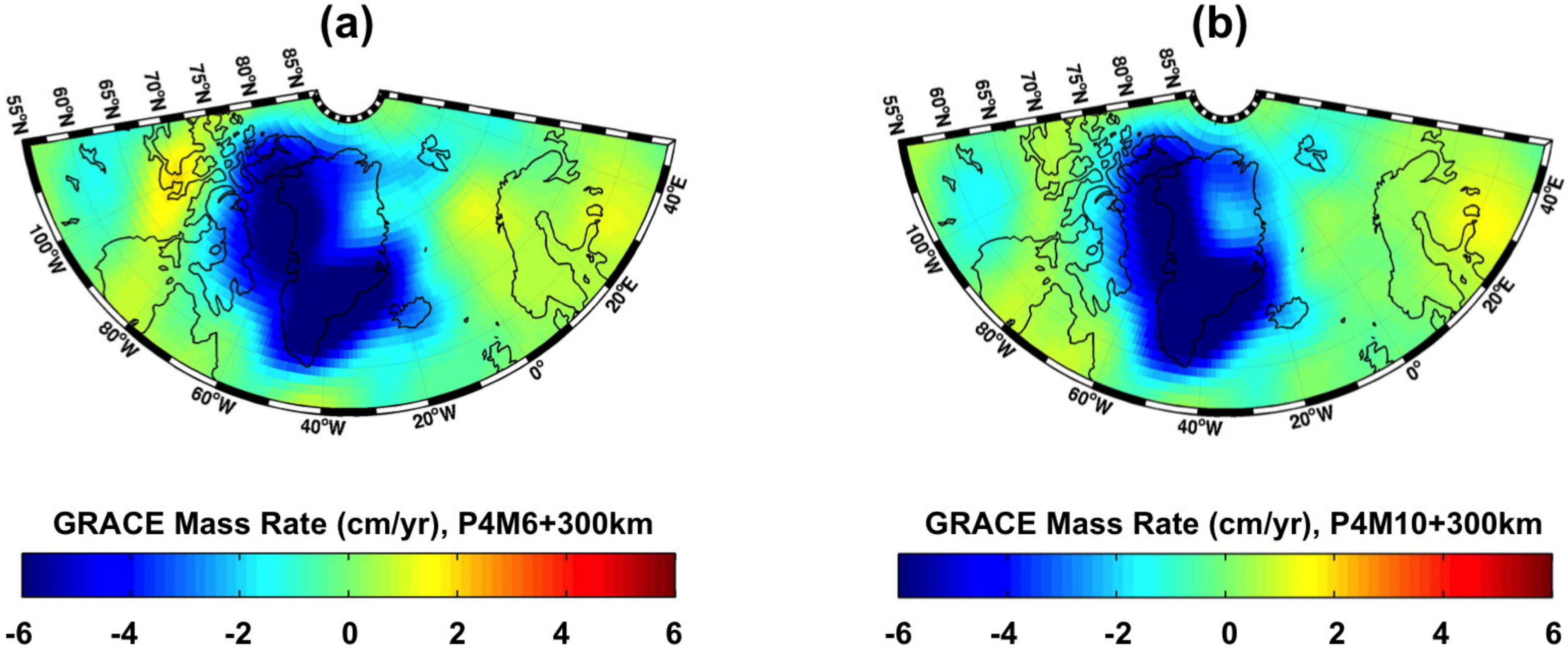


2000 km



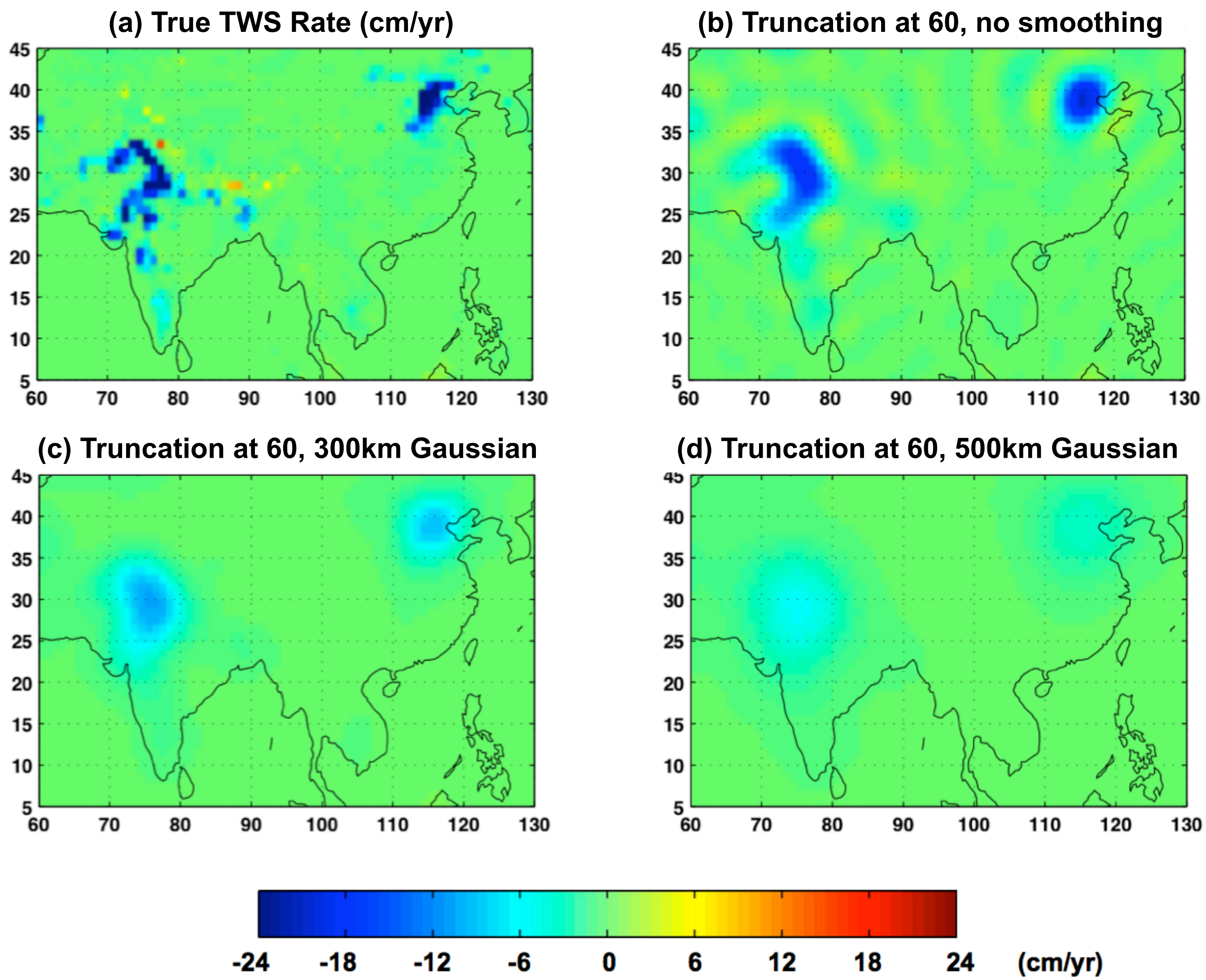
Order 7 C_{lm} as a function of degree (CSR RL04 2002.05)
x 10^{-11}
5
4
3
2
1
0
−1
0
10
20
30
40
50
60
70
80
90
100
Degree

Decorrelation Filterings

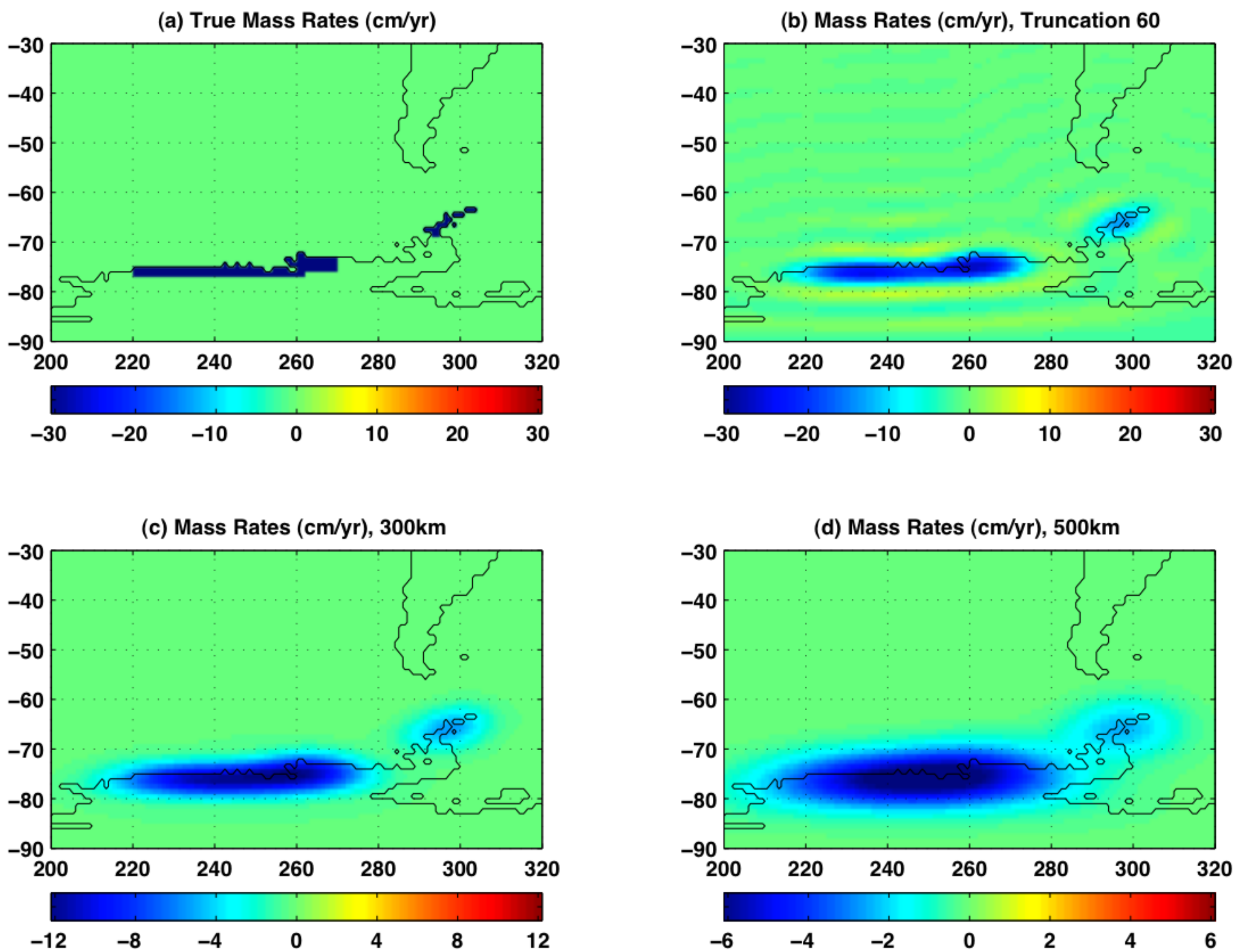


Addressing Leakage Error of GRACE Gravity Measurements

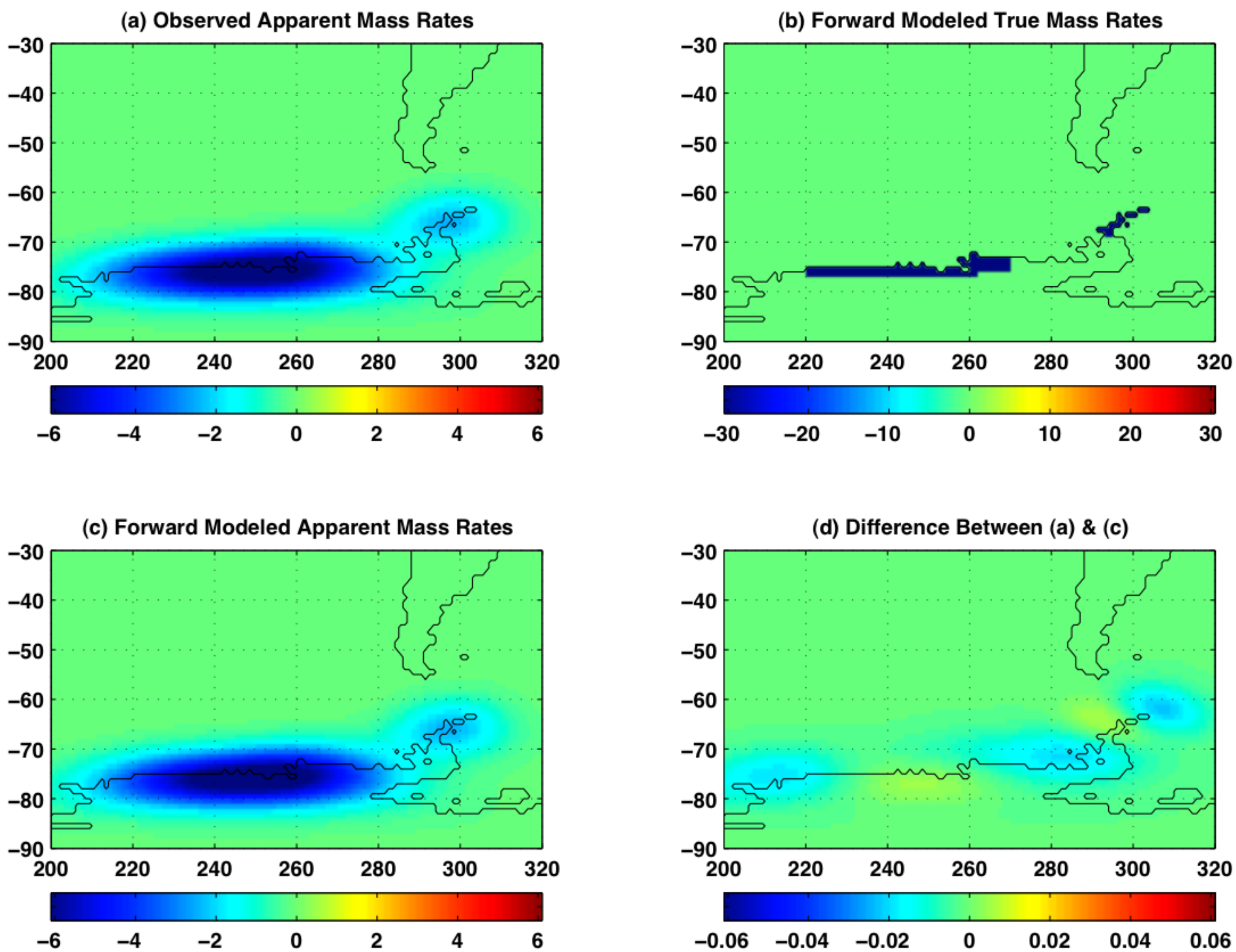
Leakage Effects of GRACE Gravity Measurements



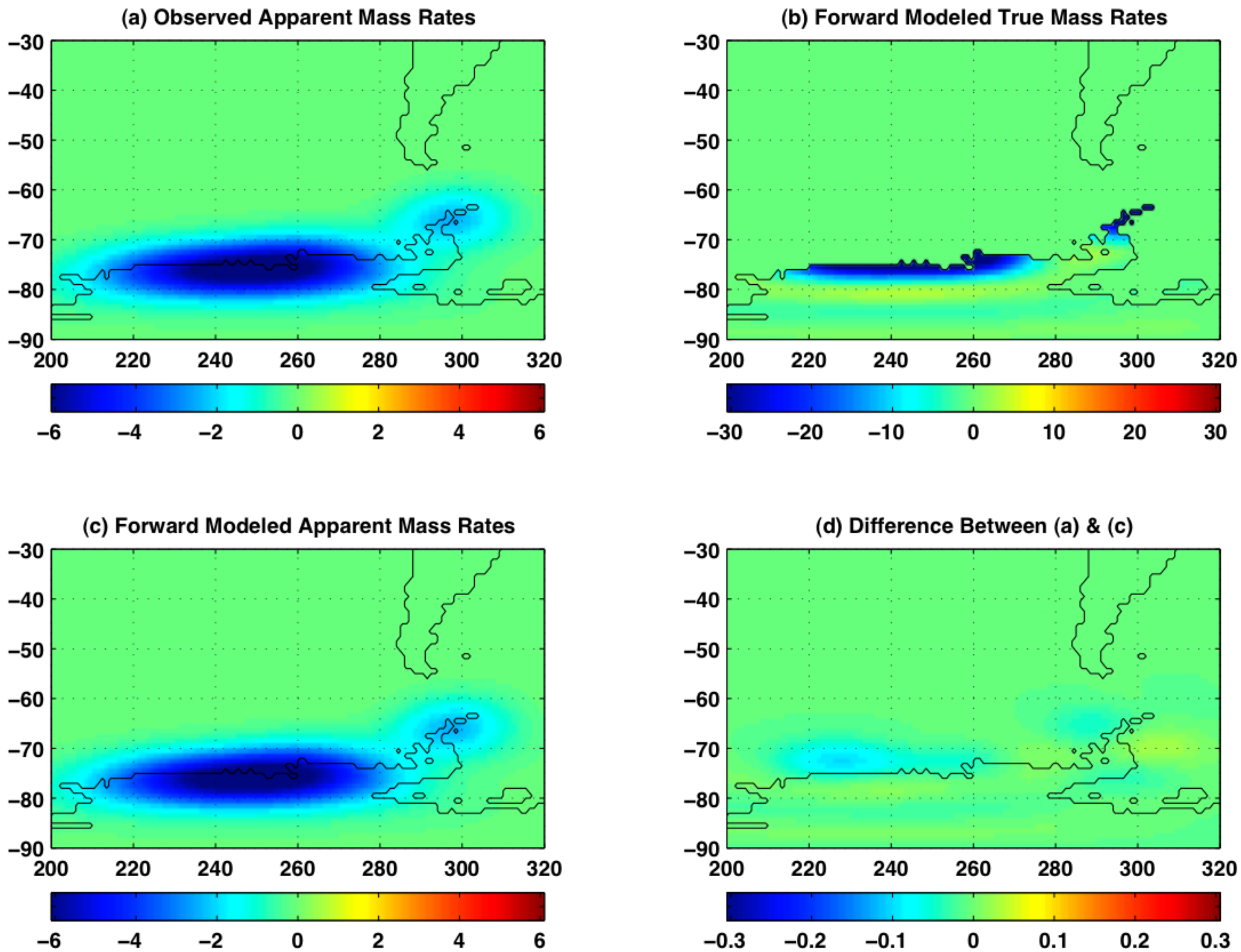
Leakage Effects of GRACE Satellite Gravity Data

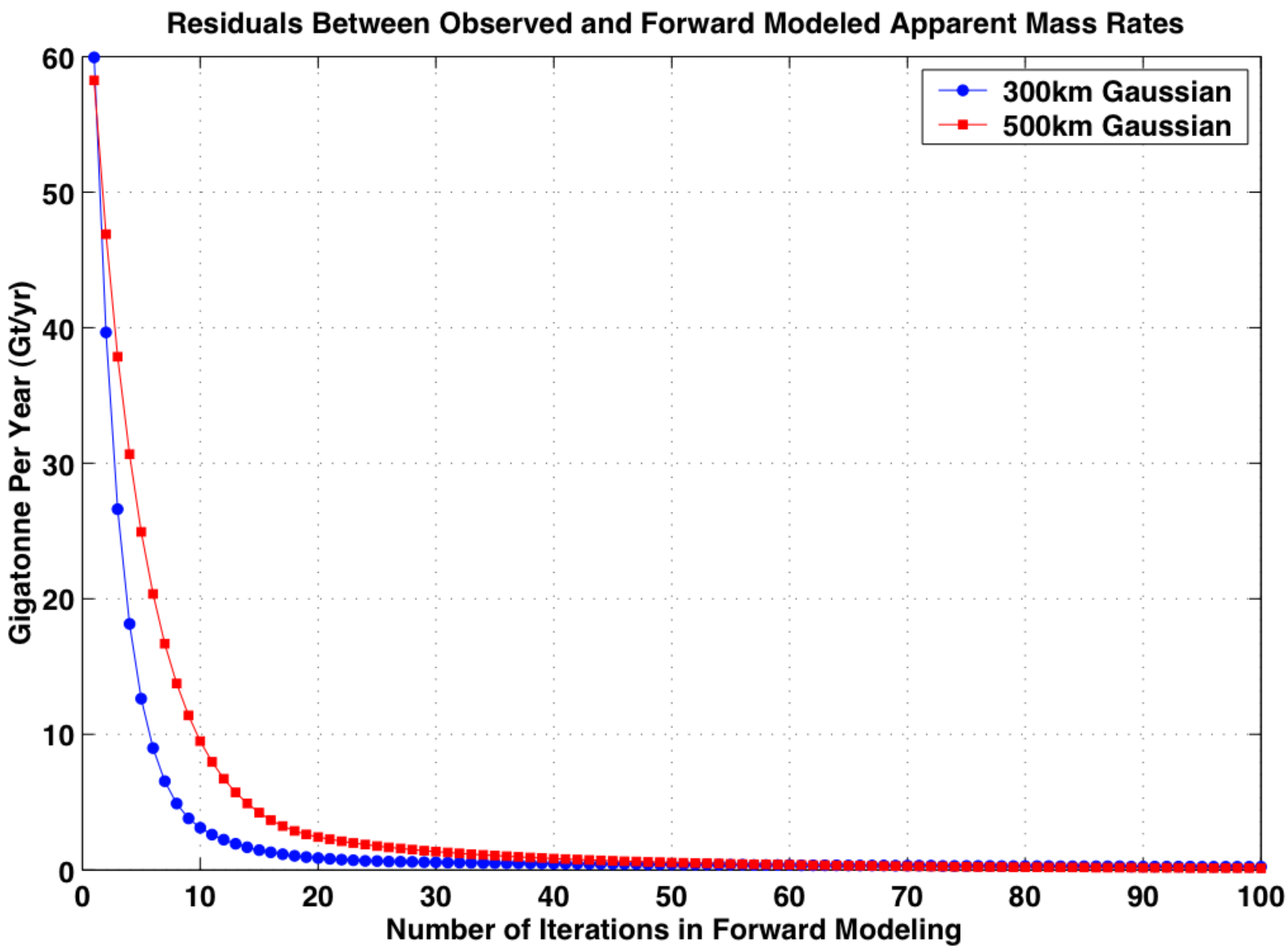


Leakage Correction Using Constrained Forward Modeling



Leakage Correction Using Unconstrained Forward Modeling





Residuals Between Observed and Forward Modeled Apparent Mass Rates
300km Gaussian
500km Gaussian
Gigatonne Per Year (Gt/yr)
Number of Iterations in Forward Modeling
0
10
20
30
40
50
60
70
80
90
100

Table 1. Estimated ice mass rates (Gt/yr) over the Antarctic Peninsula, Amundsen Sea Embayment (ASE) coastal regions, and the entire Antarctic using synthetic data. For both constrained and un-constrained forward modeling, two separate estimates are shown for 100 iterations, without (w/o) or with (w/t) considerations of OBP and TWS rates using models and ice melting over Greenland and CAA (noted as OBP/TWS/GC).

Experiment	Peninsula (Gt/yr)	ASE Coastal (Gt/yr)	Antarctica (Gt/yr)
True Mass Rates	-30	-120	-150
Truncation at 60, No Smoothing	-9.64	-91.26	-92.91
Truncation at 60, 300km Gaussian	-5.34	-69.89	-69.05
Truncation at 60, 500km Gaussian	-3.60	-55.12	-55.15
Forward Modeling (Constrained, w/o OBP/TWS/GC)	-29.83	-119.99	-149.83
Forward Modeling (Un-constrained, w/o OBP/TWS/GC)	-30.44	-121.96	-149.54
Forward Modeling (Constrained, w/t OBP/TWS/GC)	-27.99	-117.96	-145.95
Forward Modeling (Un-constrained, w/t OBP/TWS/GC)	-28.66	-118.42	-127.98