



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 ;

$P_{lm}(\sin \phi)$ are the Legendre polynomials of degree l and order m .



How to understand GRACE spatial resolution?

Geopotential field and spherical harmonic expansion

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

Corresponding spatial resolution as a function of degree l : $\sim \frac{20000}{l}$ km

Truncation at degree 60 : ~ 330 km

Truncation at degree 30 : ~ 670 km

Truncation at degree 20 : ~ 1000 km

These are the true spatial resolutions (by definition)!



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 .

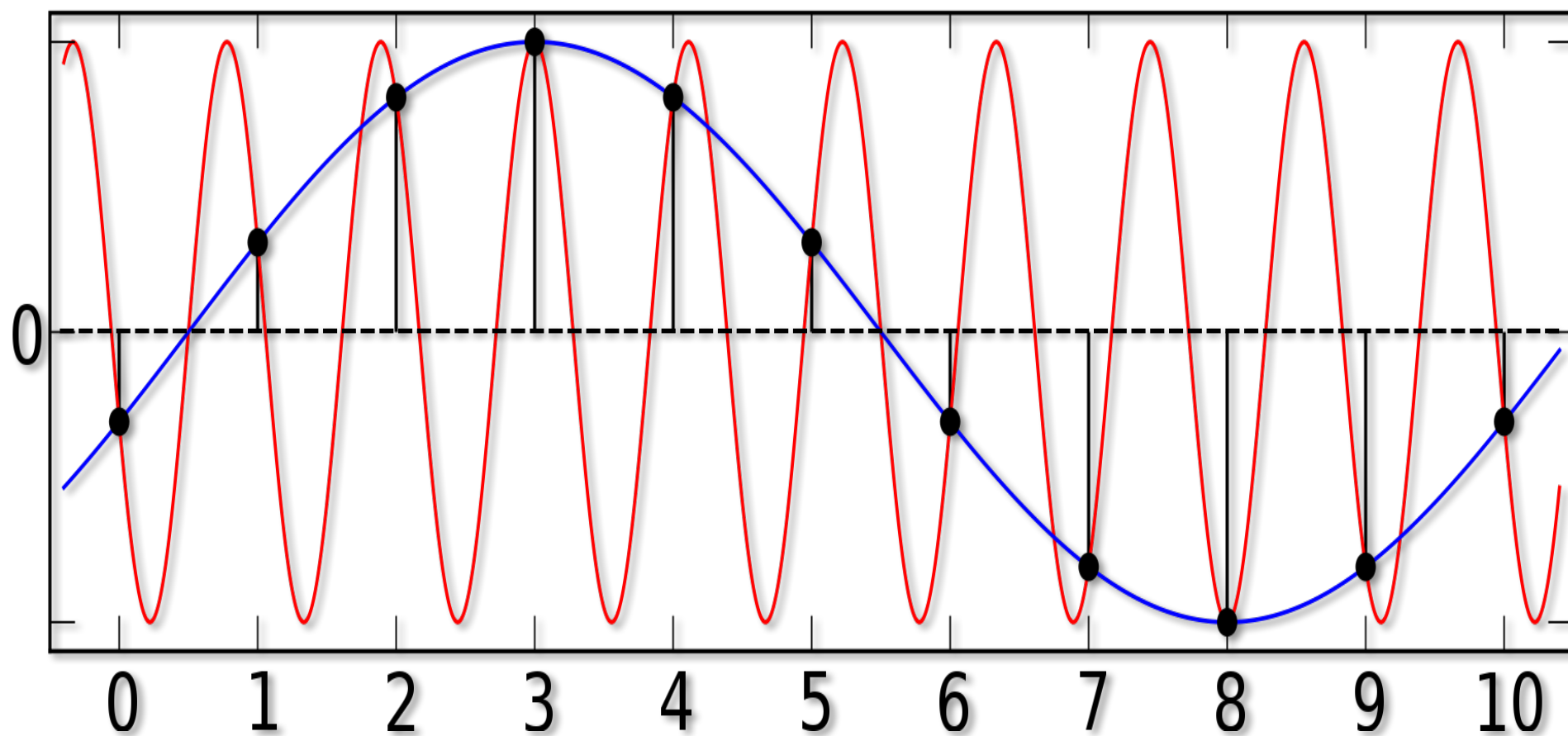


GRACE Main Products

- ❑ 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





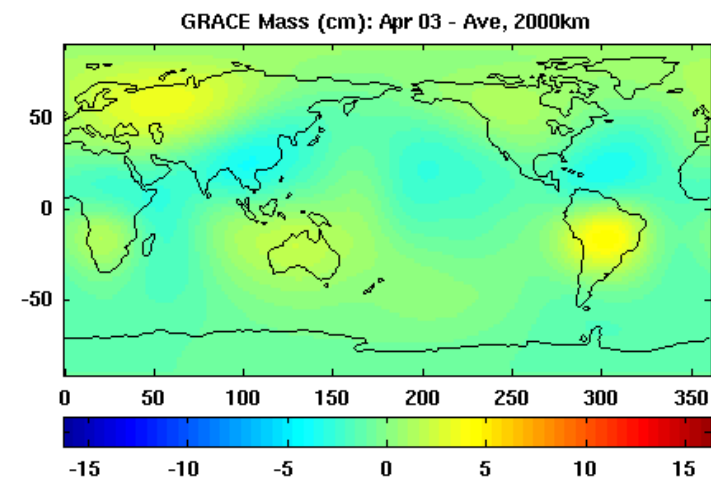
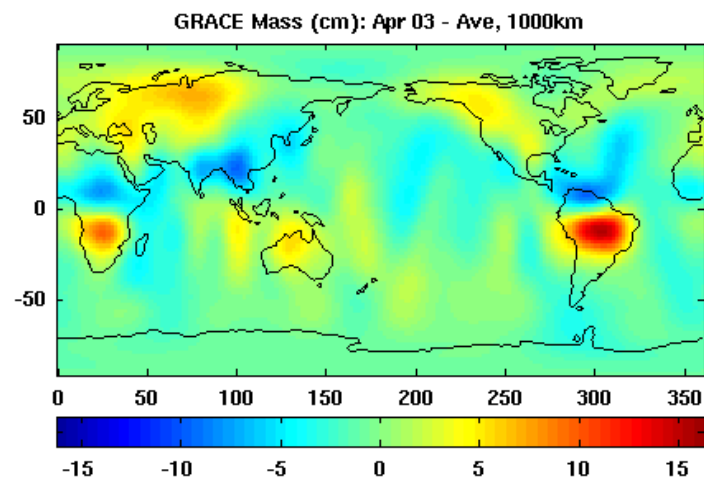
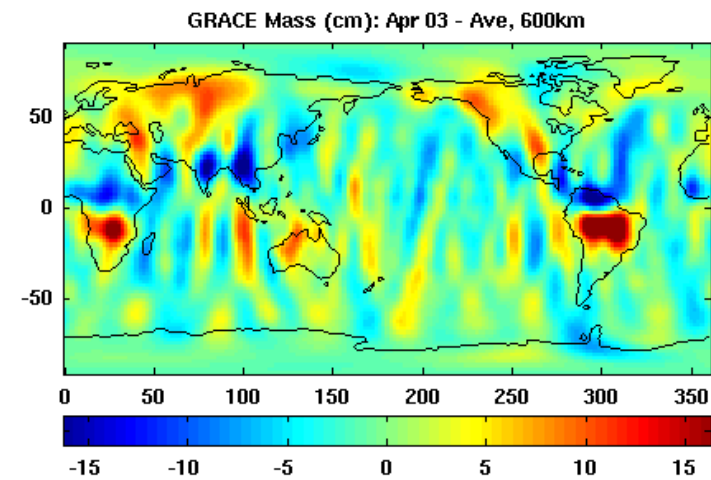
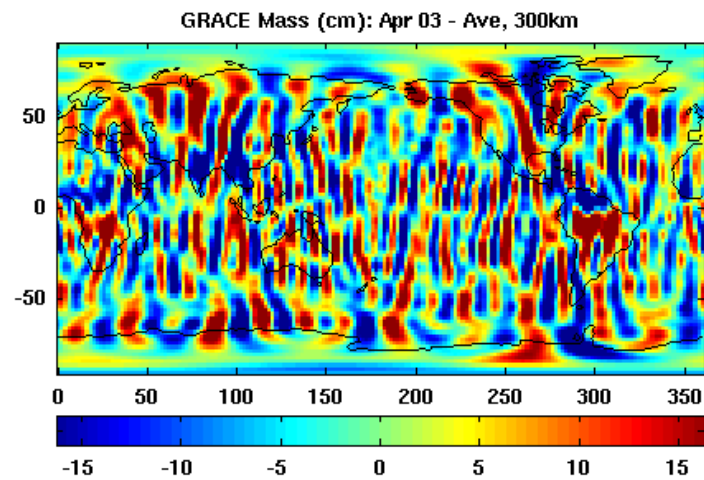
Surface Mass Changes from GRACE

Main issues to solve:

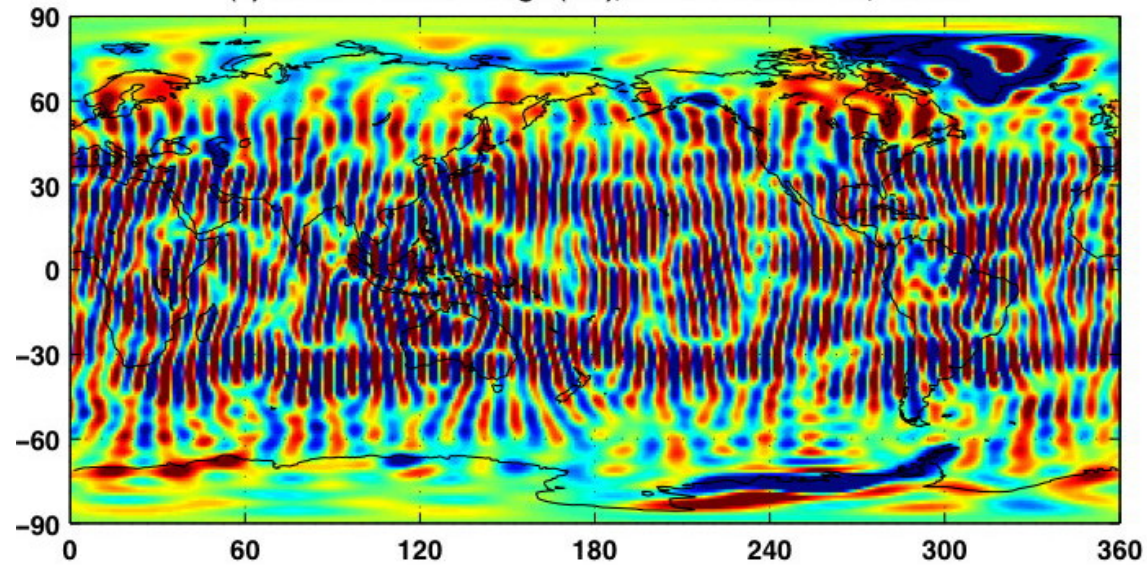
- ❑ Spatial smoothing or filtering is needed as high degree and order terms are dominated by noise.
- ❑ Appropriate treatments of low degree harmonics (e.g., the large uncertainty of C20 in GRACE solutions, and the missing geocenter, degree-1 terms in GRACE data).
- ❑ Residual aliasing effects (from 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

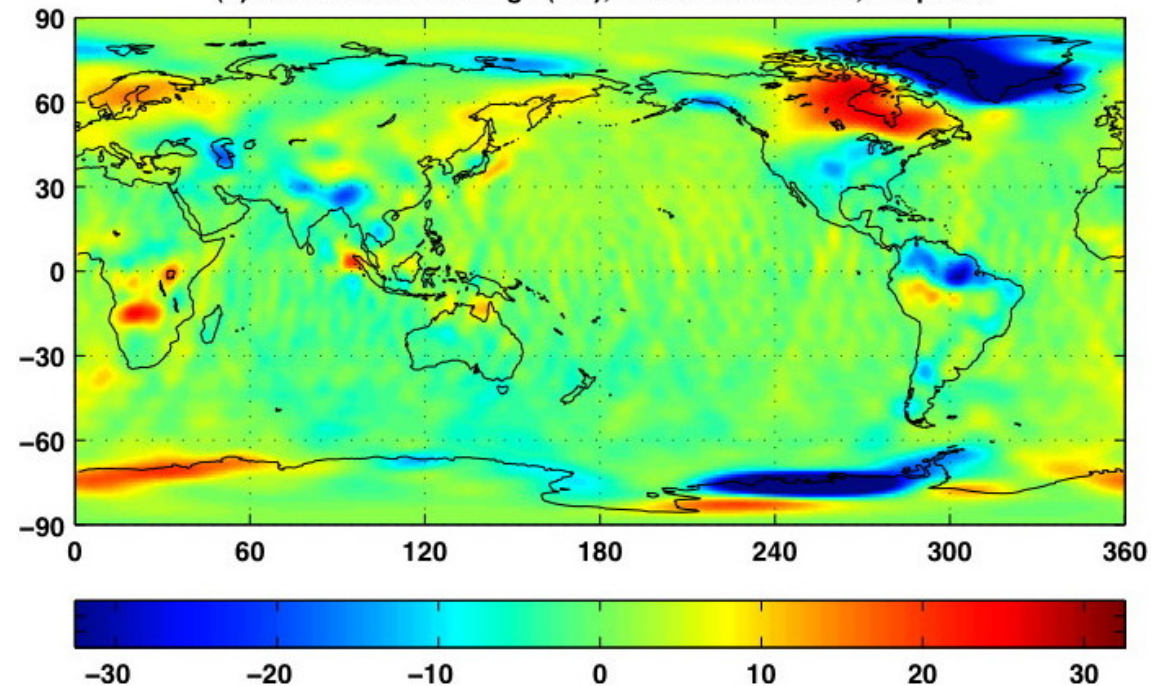


(a) GRACE Mass Change (cm), 2003.01 CSR RL05, NOSM



No filtering
or smoothing

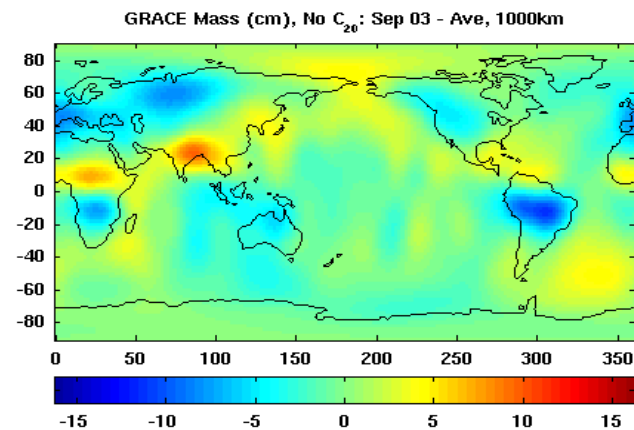
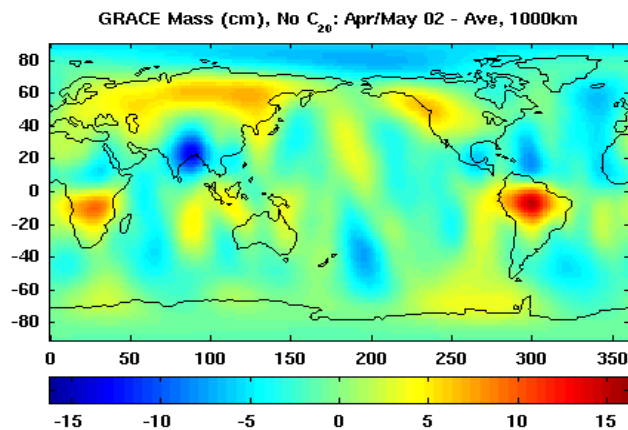
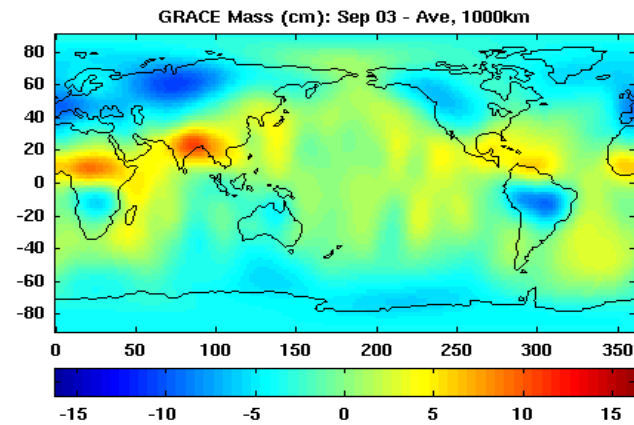
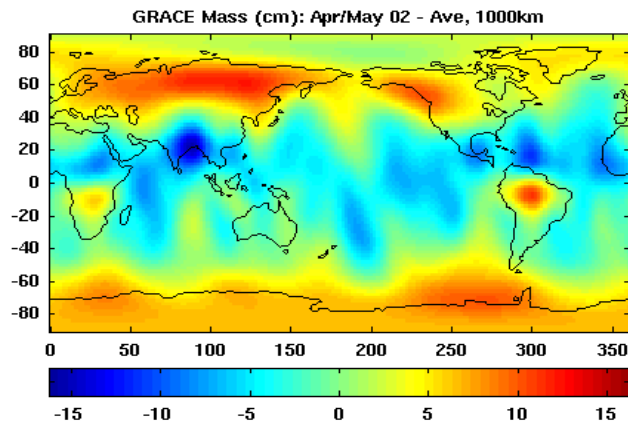
(b) GRACE Mass Change (cm), 2003.01 CSR RL05, 300p4m6



Decorrelation +
300 km Gaussian



The Challenge of Low Degree Terms





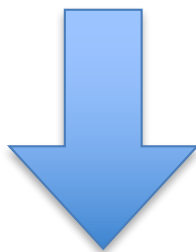
Spatial Filterings of GRACE Data

- ❑ **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**
- ❑ ...

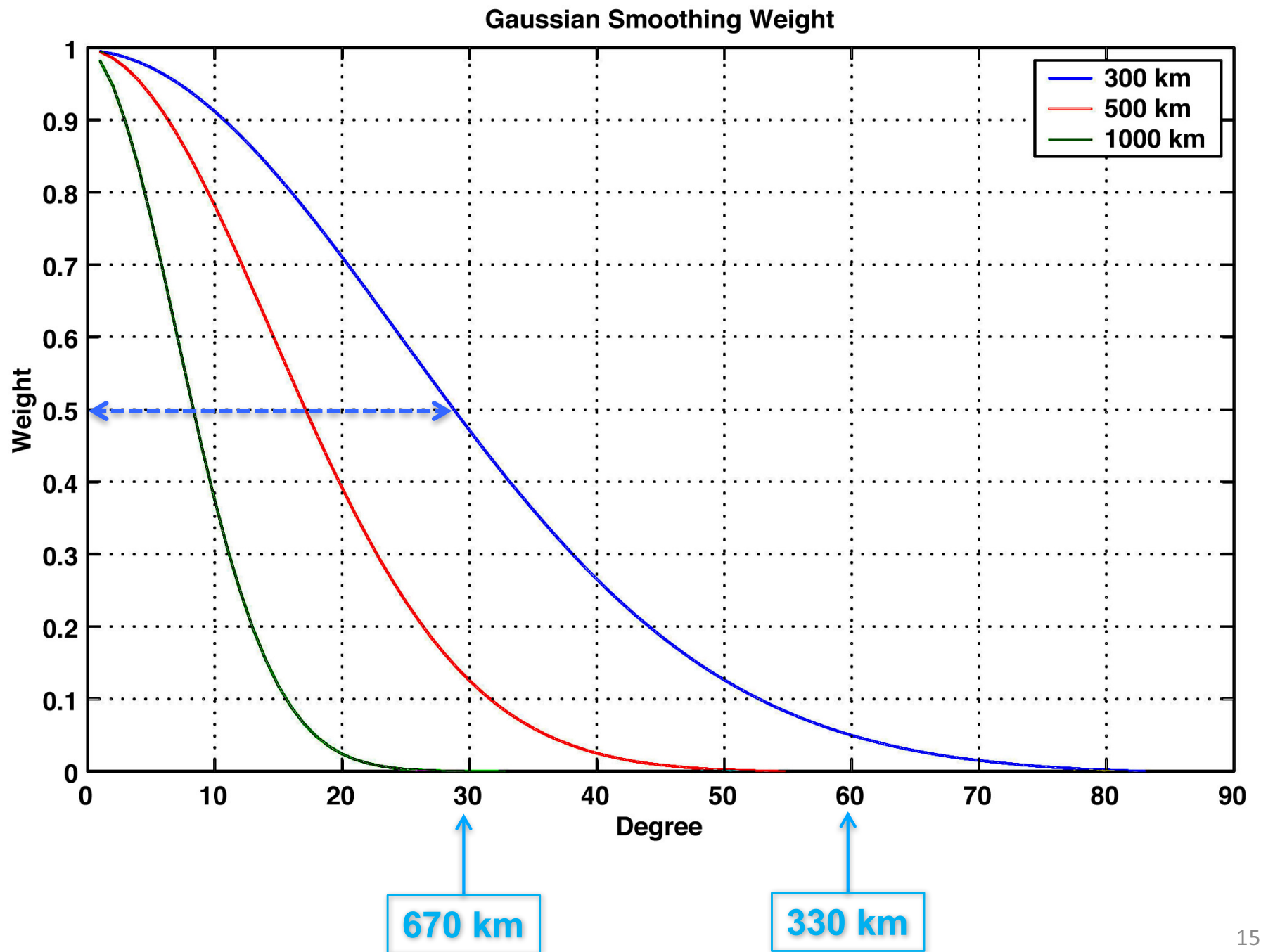


How does spatial filtering work?

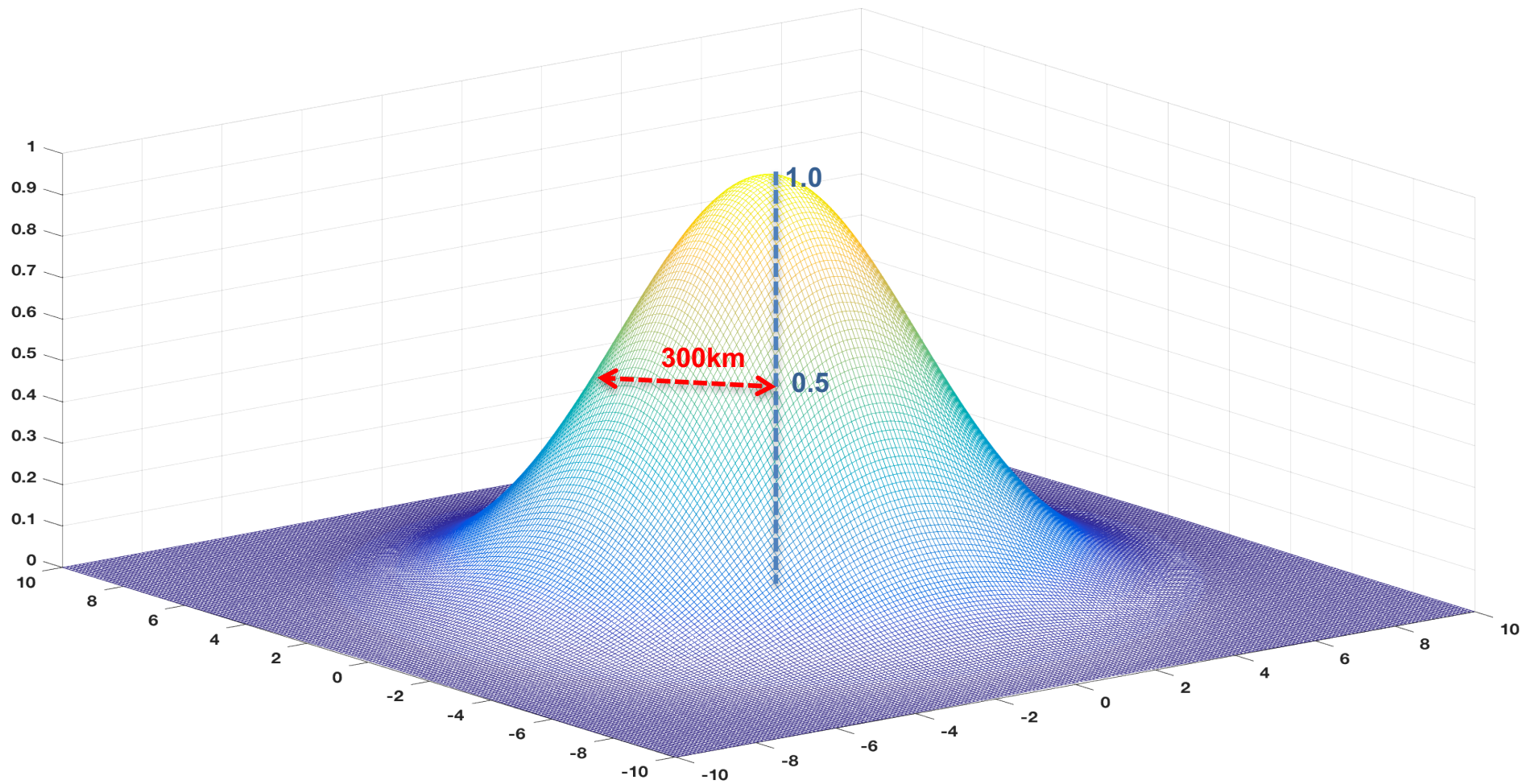
$$\Delta\sigma(\theta, \phi) = \frac{R_e \rho_{ave}}{3} \sum_{l=0}^N \sum_{m=0}^l \frac{2l+1}{1+k_l} \tilde{P}_{lm}(\cos\theta) \times [\Delta C_{lm} \cos(m\phi) + \Delta S_{lm} \sin(m\phi)]$$



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

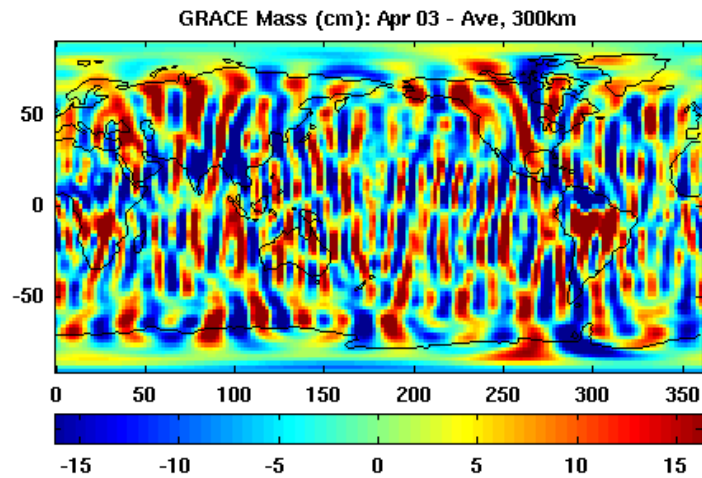


300 km Gaussian Smoothing

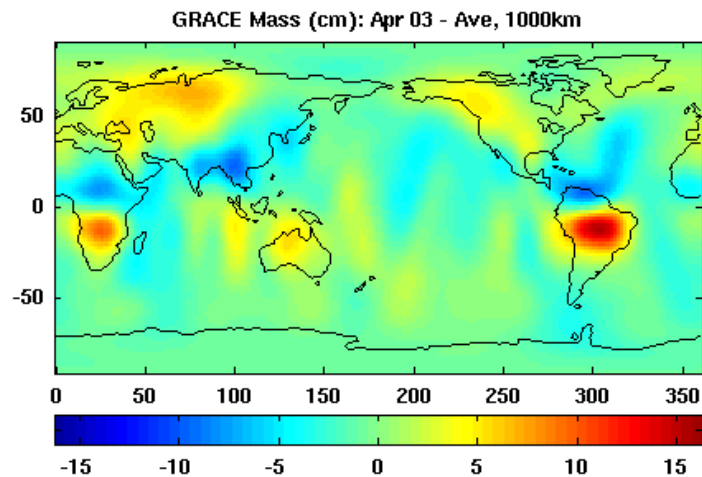
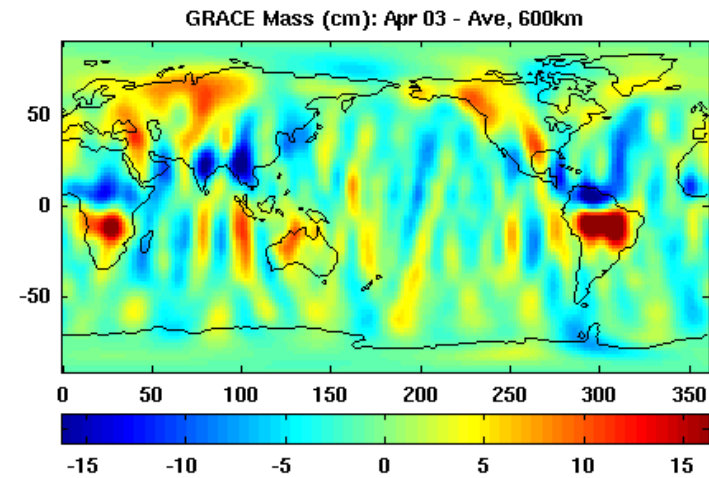


Gaussian Smoothing

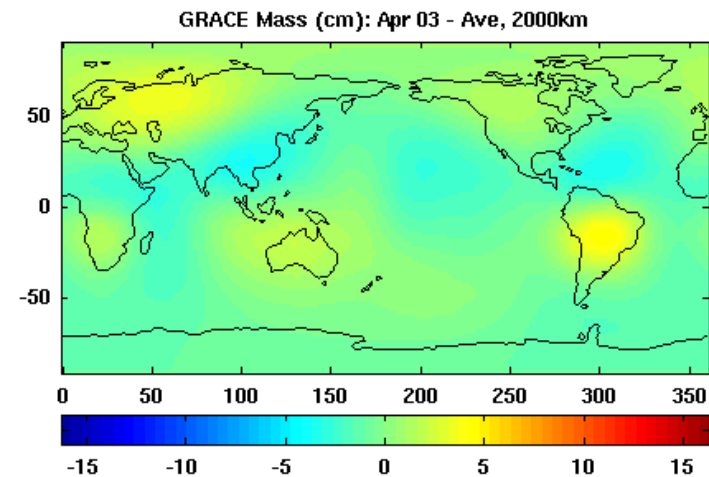
300 km



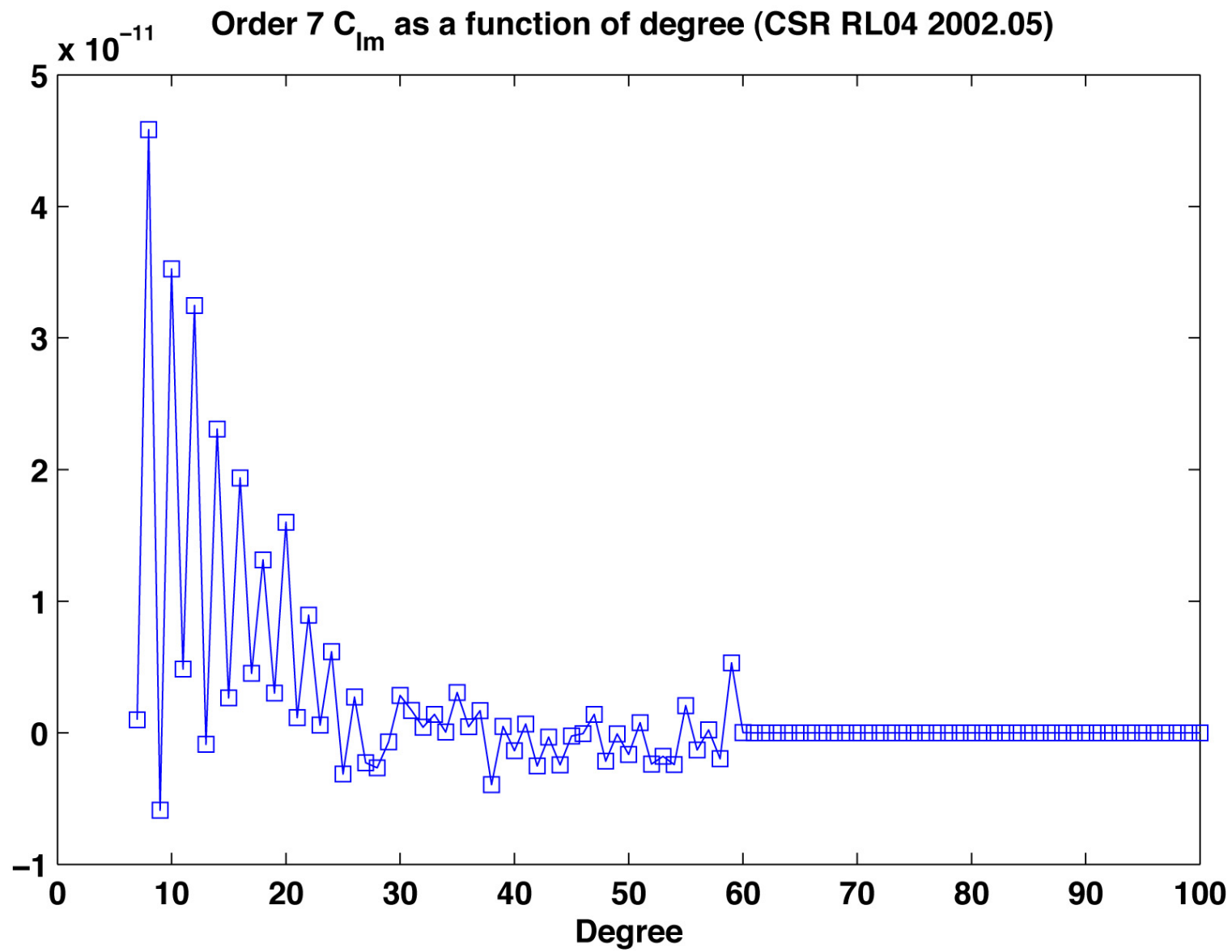
600 km



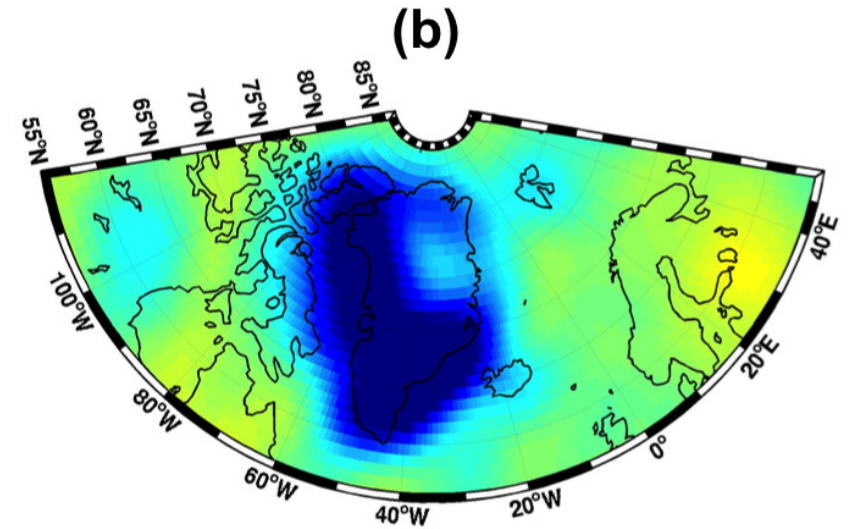
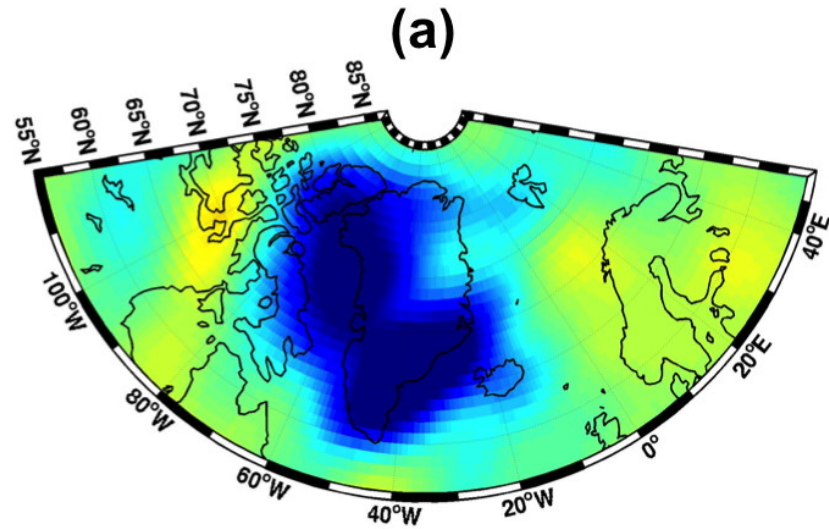
1000 km



2000 km

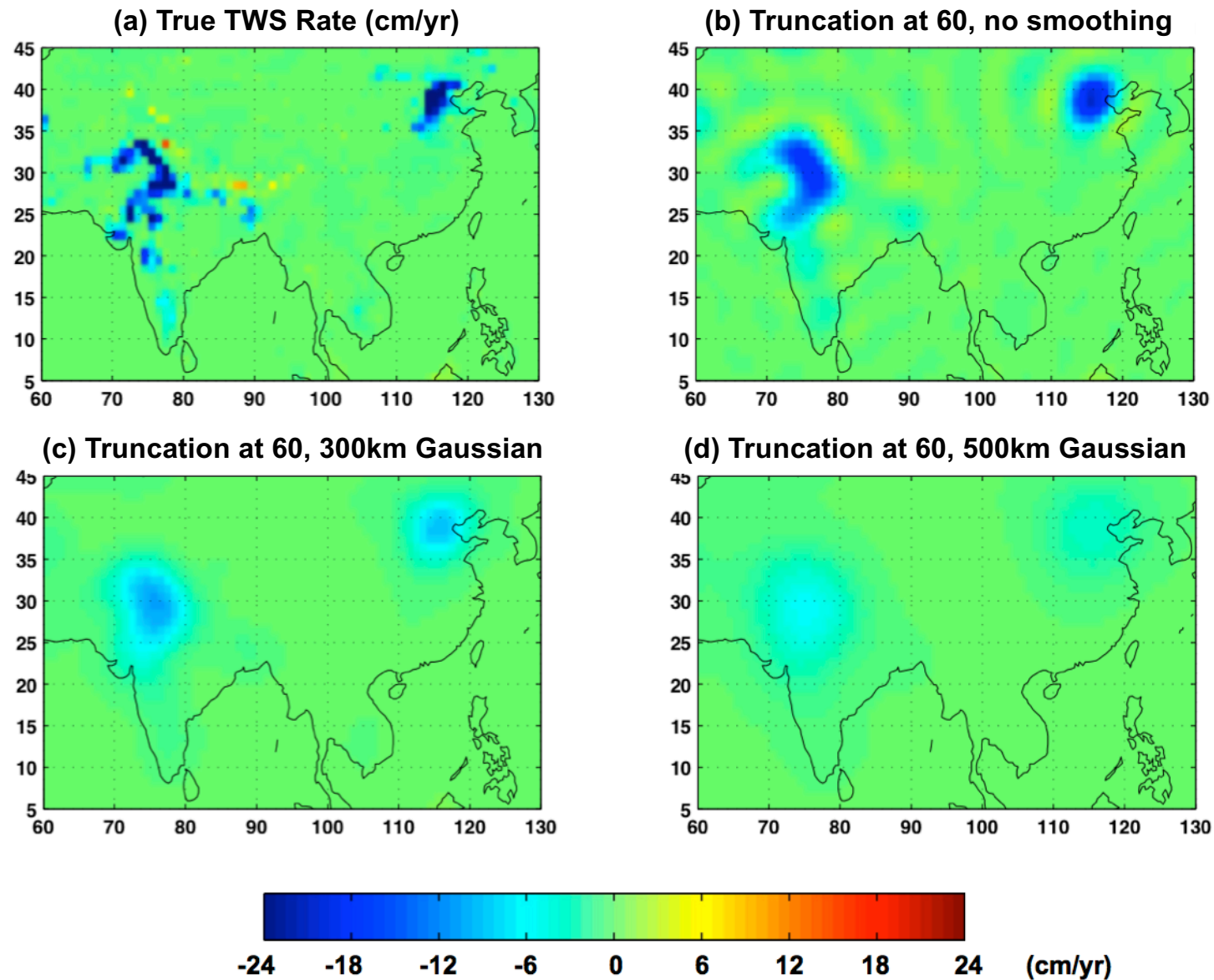


Decorrelation Filterings



Addressing Leakage Error of GRACE Gravity Measurements

Leakage Effects of GRACE Gravity Measurements



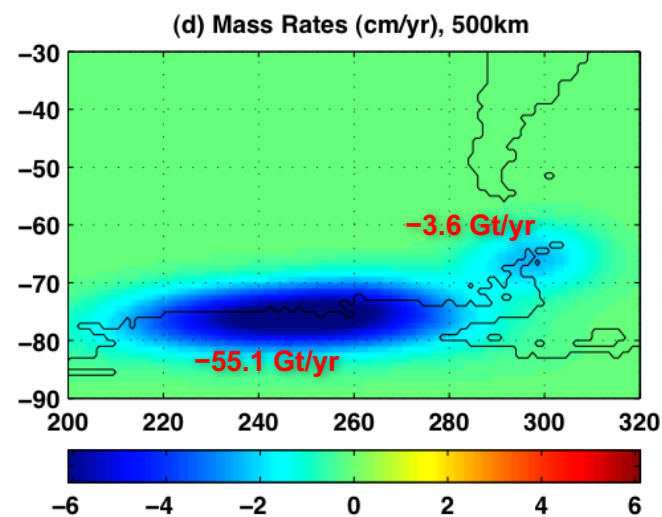
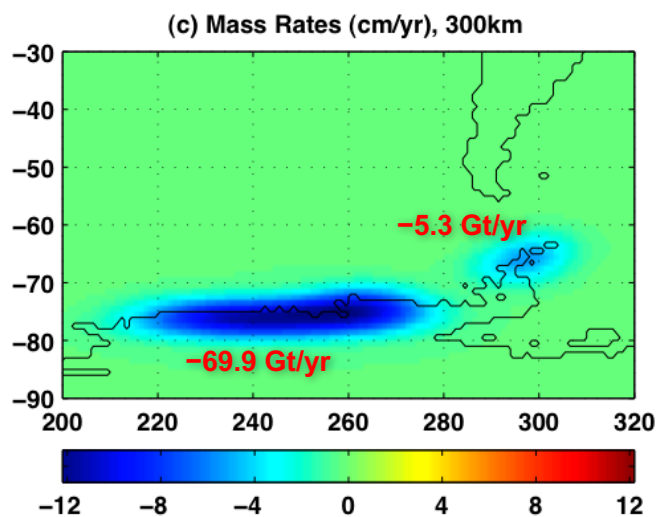
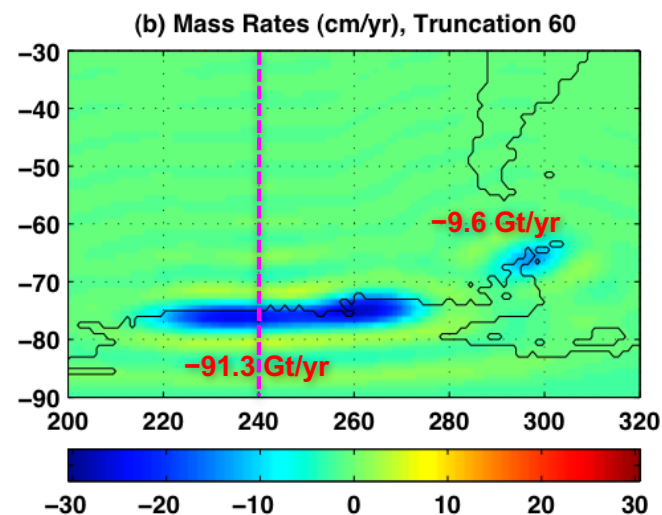
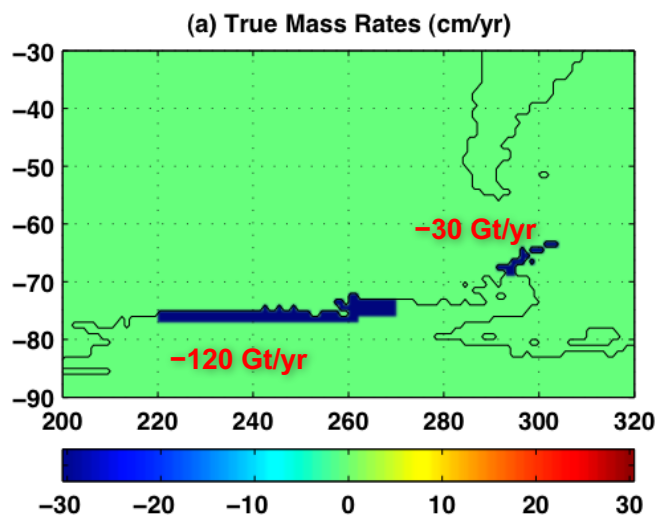


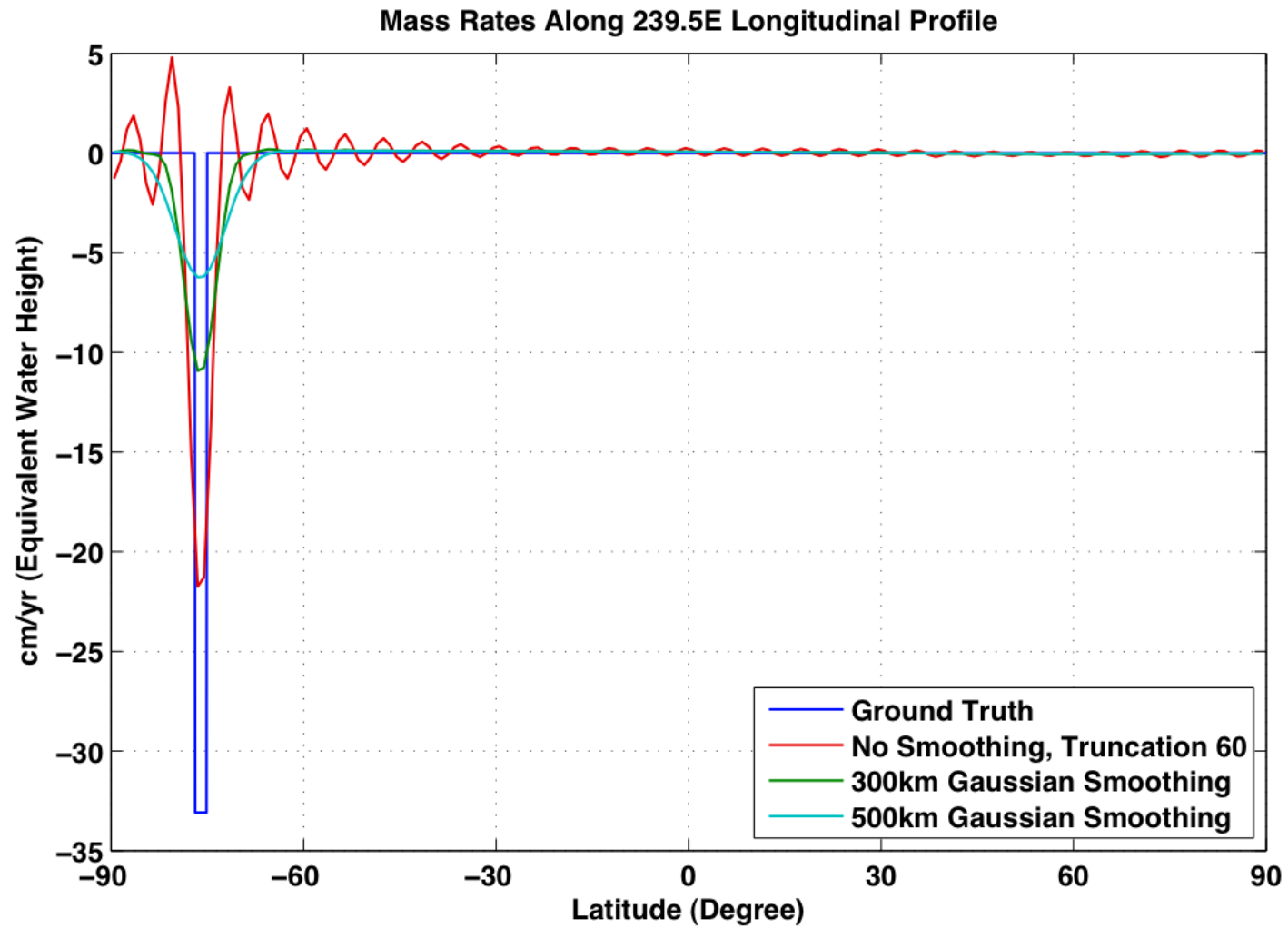
How to remove or reduce leakage biases in GRACE estimated long-term mass rate?

- ☐ **Synthetic mass change over West Antarctica**
- ☐ **Model predicted terrestrial water storage (TWS) over land**
- ☐ **Model predicted ocean bottom pressure (OBP) over the ocean**
- ☐ **Synthetic mass change for Greenland and Canadian Arctic Archipelago (CAA)**
- ☐ **Proxy spatial noise from GRACE**

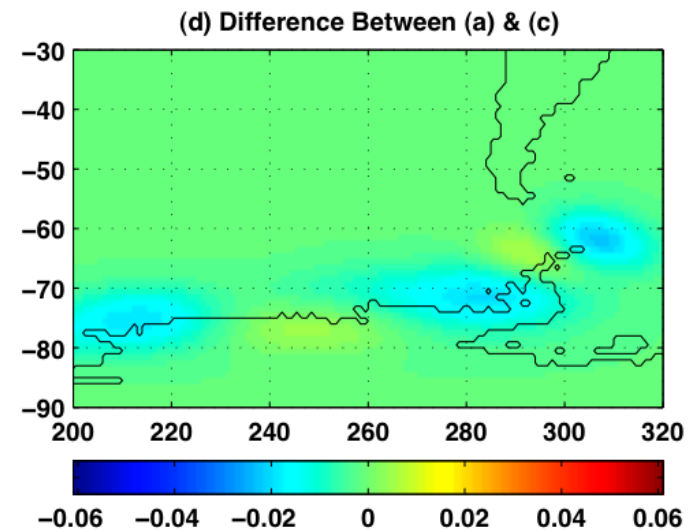
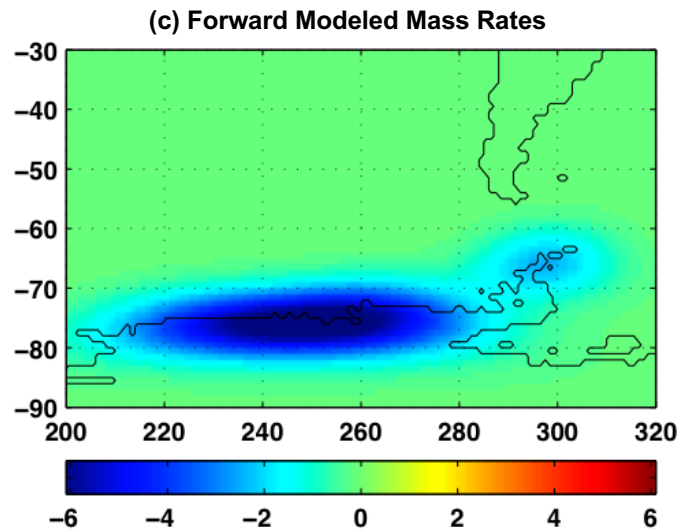
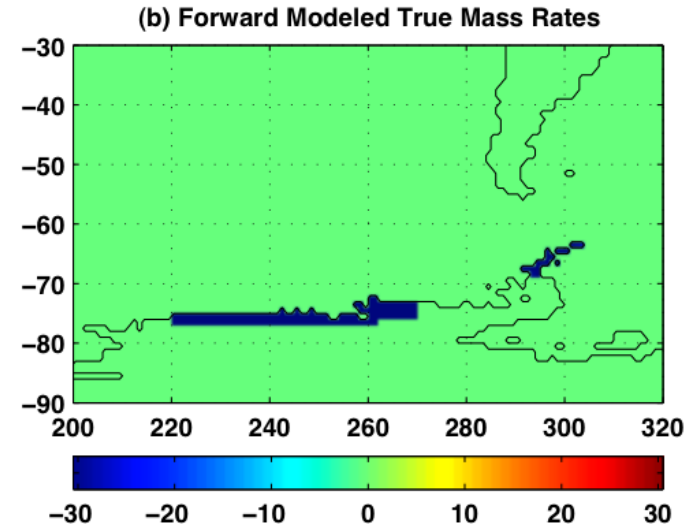
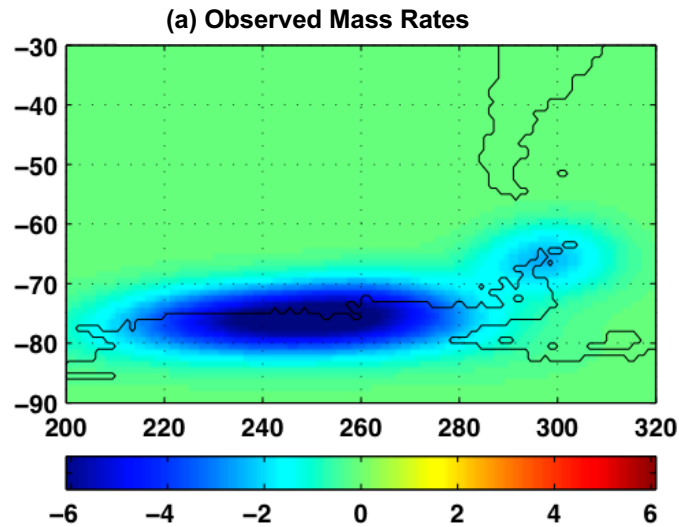


Example of Leakage Bias From Truncation and Filtering



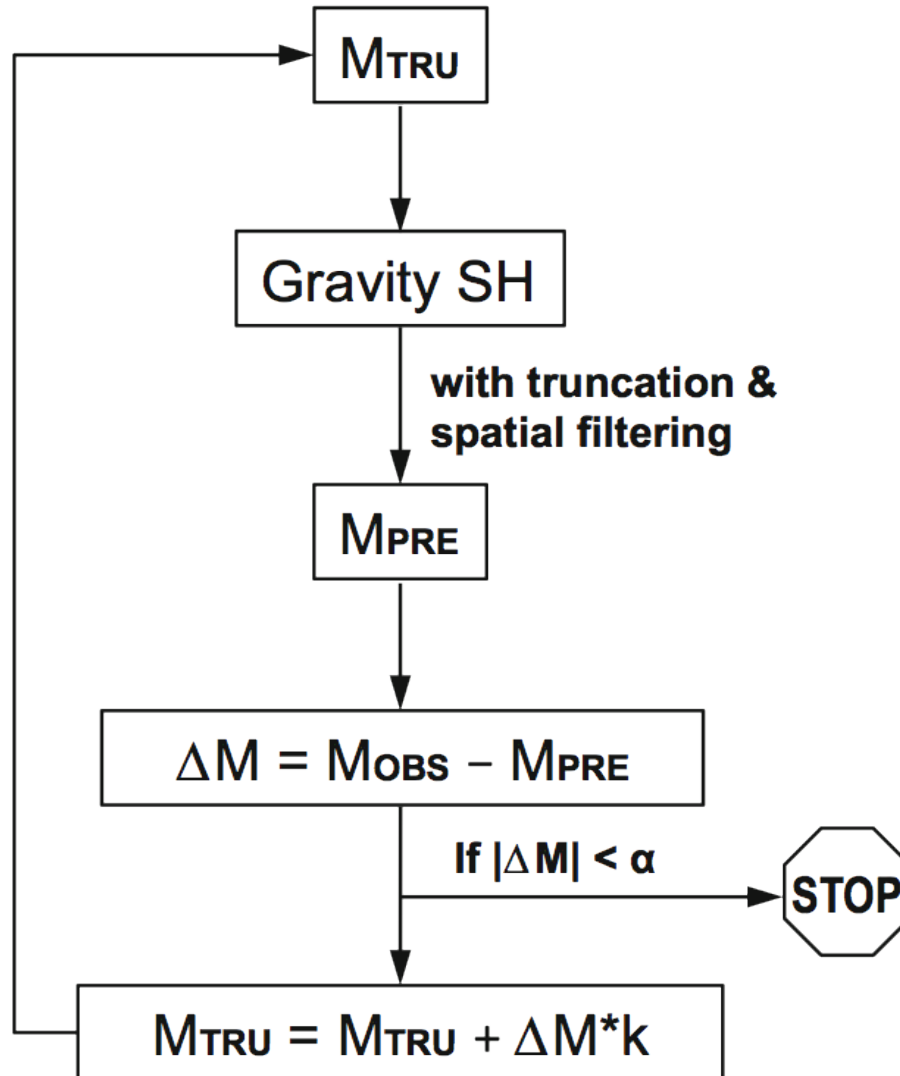


Constrained Global Forward Modeling





Schematic Diagram of Forward Modeling



M_{TRU} : True Mass Model

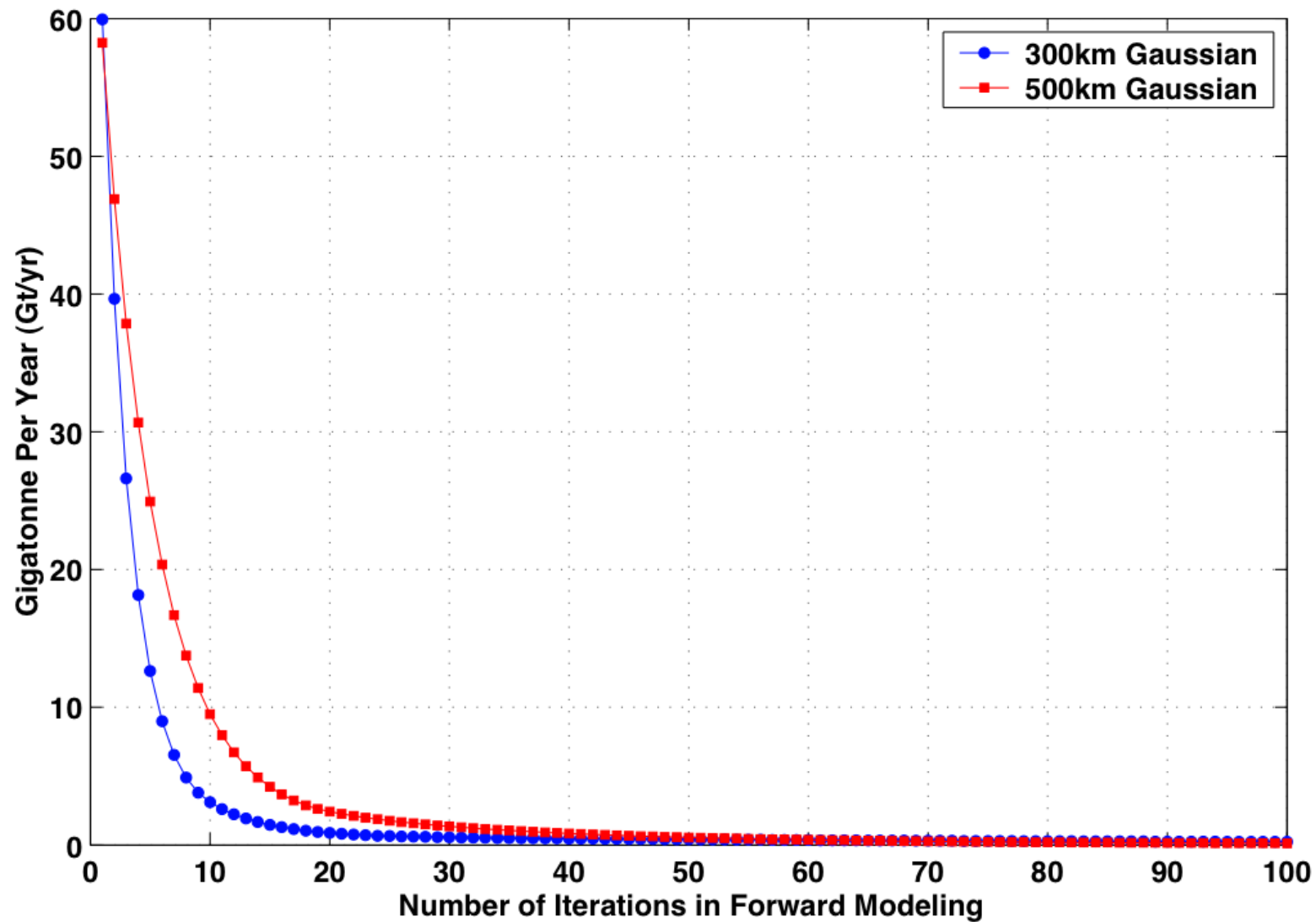
M_{PRE} : Predicted Mass Model

M_{OBS} : Observed Mass Model

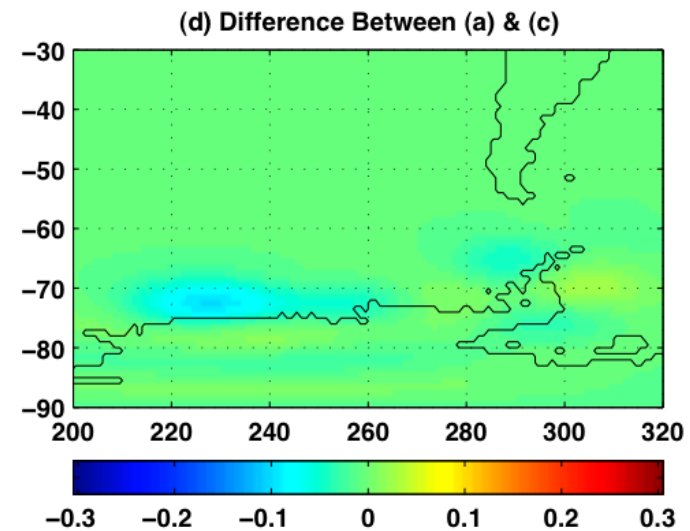
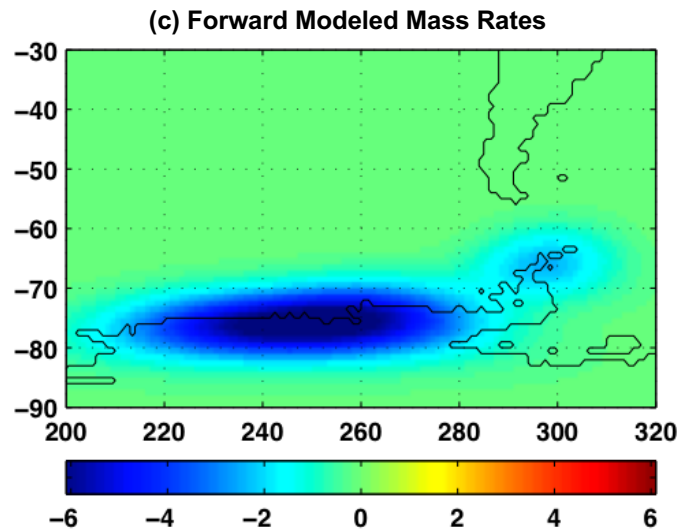
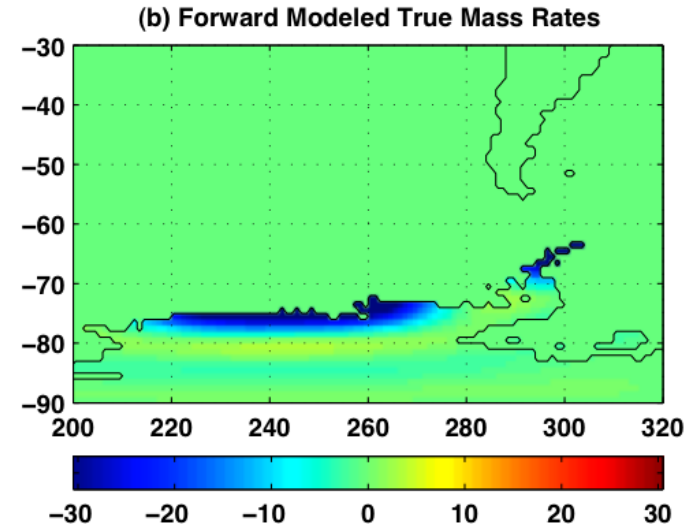
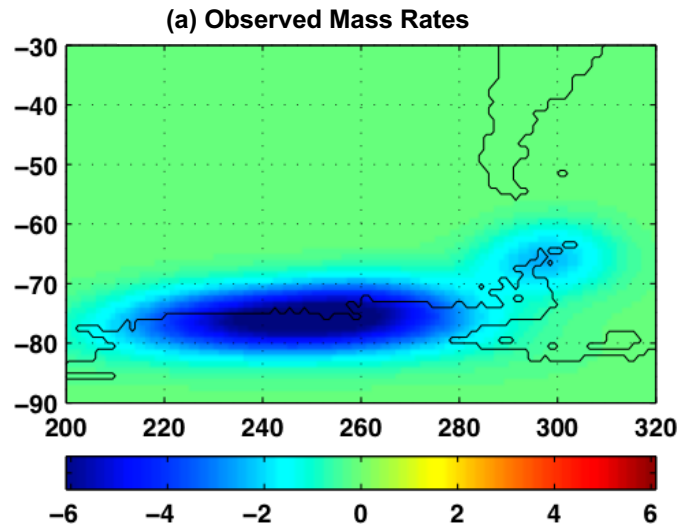
Constrained Global Forward Modeling



Residuals Between Observed and Forward Modeled Mass Rates



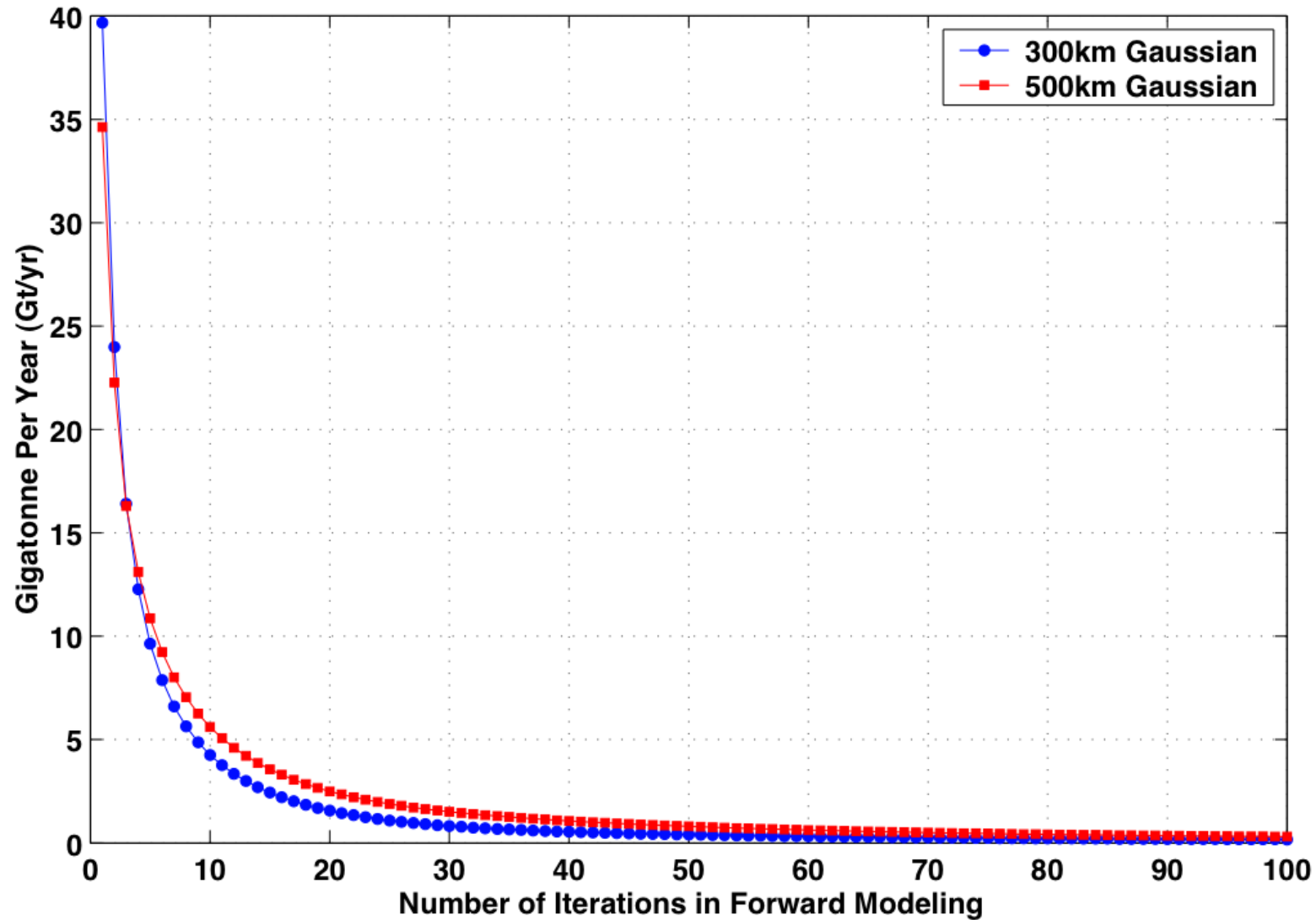
Unconstrained Global Forward Modeling





Unconstrained Global Forward Modeling

Residuals Between Observed and Forward Modeled Mass Rates



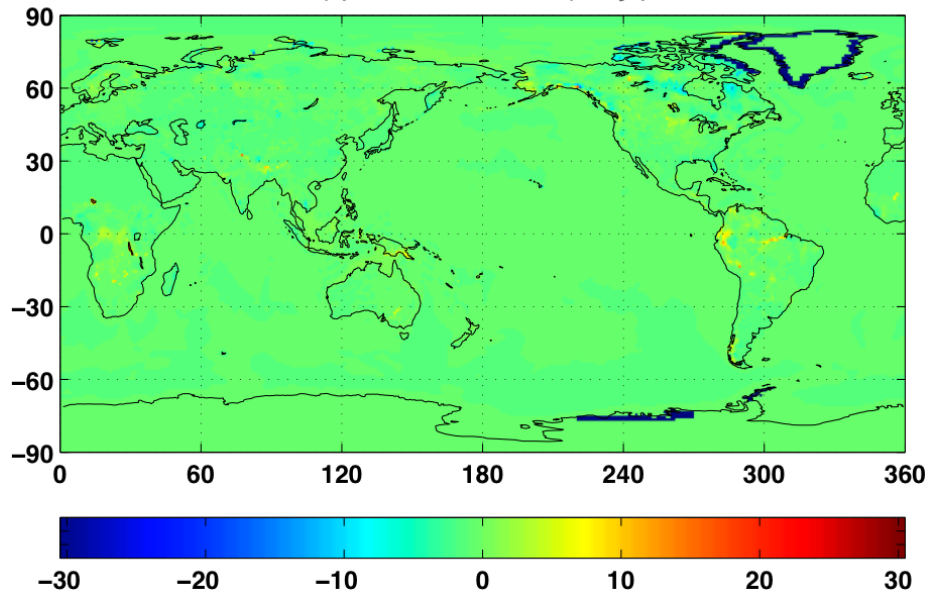


True Antarctic mass rates and mass rates recovered from constrained and unconstrained global forward modeling

Experiments	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
Constrained Forward Modeling (60 iterations)	-29.57	-119.62	-149.19
Constrained Forward Modeling (100 iterations)	-29.83	-119.99	-149.83
Unconstrained Forward Modeling (60 iterations)	-30.53	-120.01	-148.21
Unconstrained Forward Modeling (100 iterations)	-30.44	-121.96	-149.54



(a) True Mass Rates (cm/yr)



TWS rate from GLDAS (2003-2012)

OBP Rate from GAC (2003-2012)

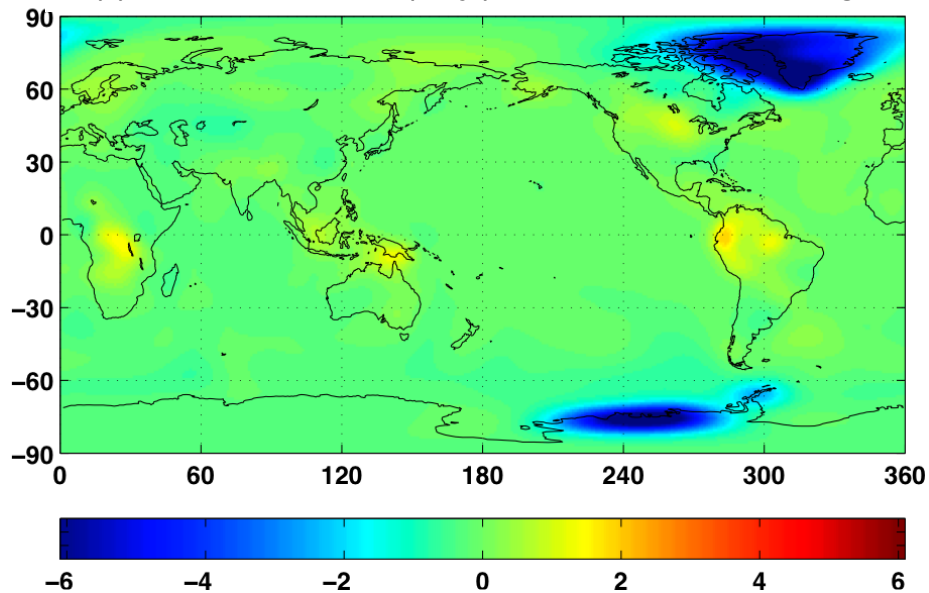
Greenland: - 260 Gt/yr

CAA: -80 Gt/yr

ASE: -120 Gt/yr

Antarctic Peninsula: -30 Gt/yr

(b) Observed Mass Rates (cm/yr), 500km, Gaussian Smoothing





Constructing Proxy GRACE Spatial Noise

$$M_{obs} = M_{signal} + S_{noise}$$

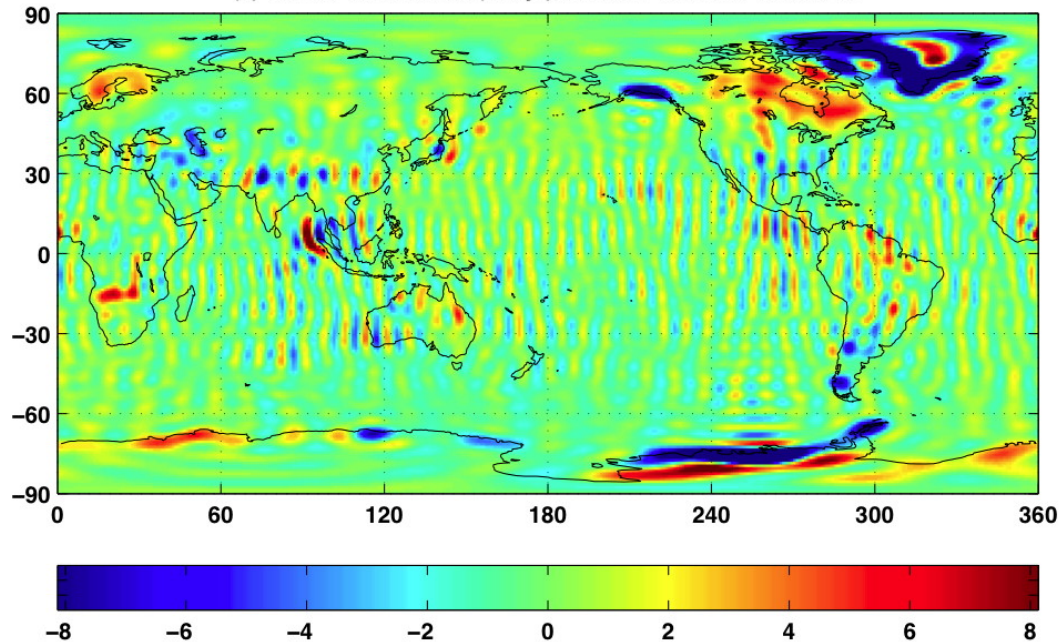
Using “double difference” to avoid systematic biases between different GRACE solutions.

$$[CSR_{Apr03} - CSR_{Oct03}] - [JPL_{Apr03} - JPL_{Oct03}]$$

Scaling of the proxy noise field



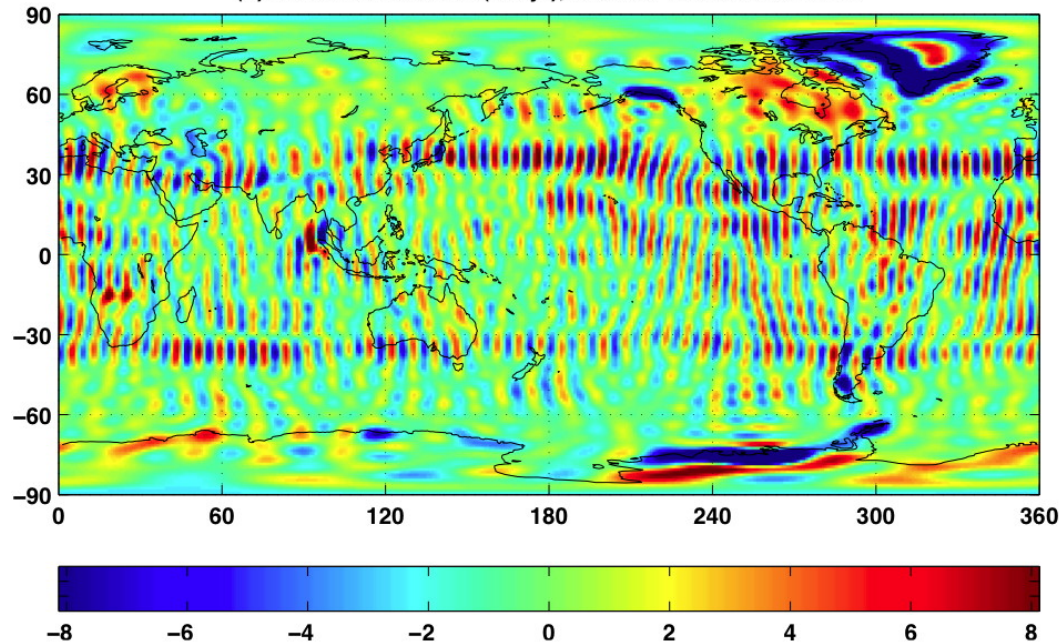
(a) GRACE Mass Rate (cm/yr), 2003.01–2012.12 CSR RL05



CSR 10-years mass rate (2003.01-2012.12)

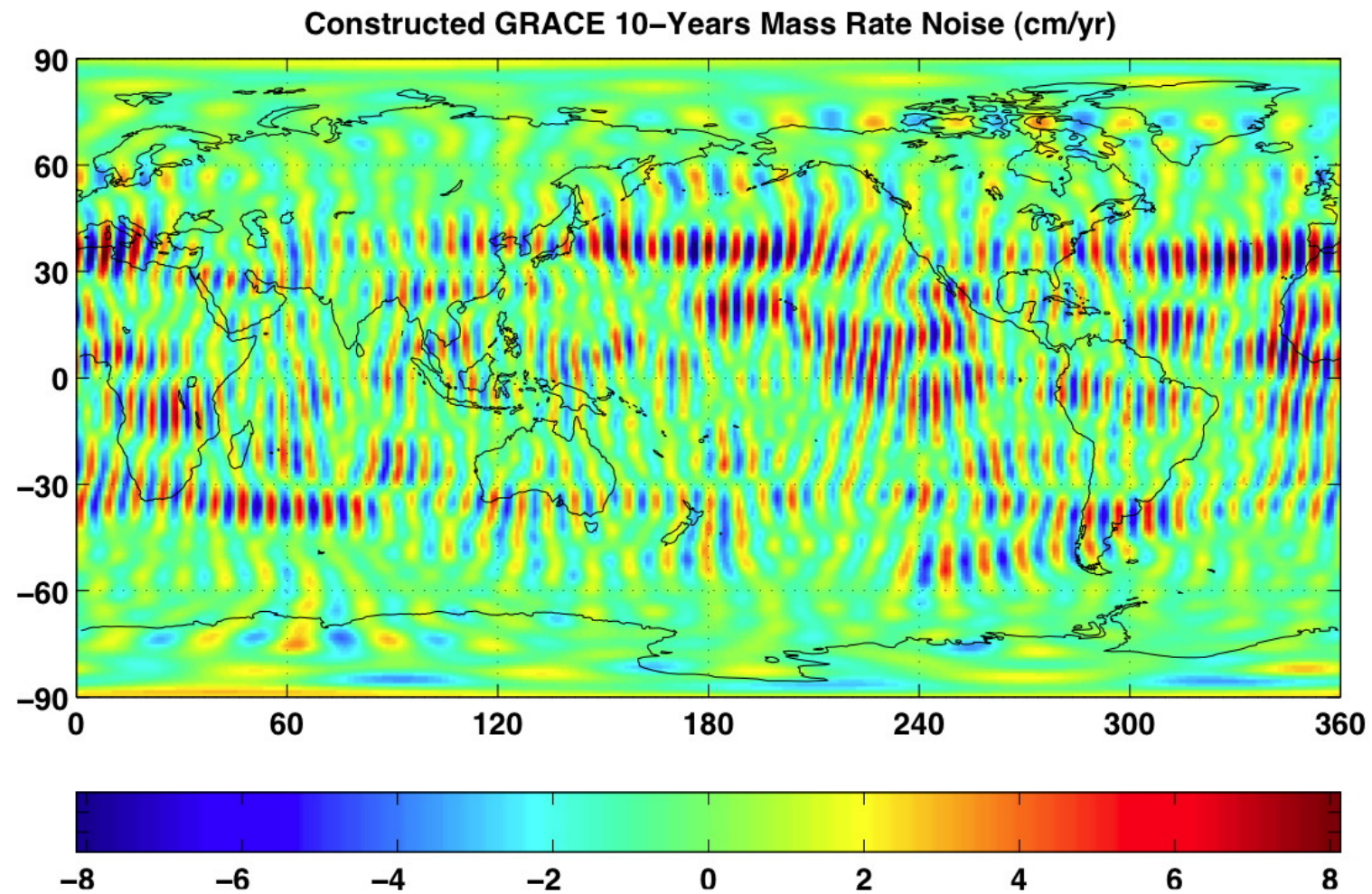
**Ocean residuals RMS: 1.27 cm/yr
(excluding 500 km from the coast)**

(b) GRACE Mass Rate (cm/yr), 2003.01–2012.12 JPL RL05



**JPL 10-years mass rate
(2003.01-2012.12)**

**Ocean residuals RMS: 2.22 cm/yr
(excluding 500 km from the coast)**



CSR-JPL Ocean RMS is ~ 2.0 cm/yr.

Mean ocean RMS of CSR, JPL and GFZ's 10-years mass rates is ~ 2.0 cm/yr.

Recovered mass rates from constrained and unconstrained global forward modeling

Experiments	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
Constrained Forward Modeling	-29.57	-119.62	-149.19
Unconstrained Forward Modeling	-30.53	-120.01	-148.21
Constrained Forward Modeling (OBP/TWS/GC)	-27.99	-117.96	-145.95
Unconstrained Forward Modeling (OBP/TWS/GC)	-28.66	-118.42	-127.98
Constrained Forward Modeling (OBP/TWS/GC + Noise)	-28.74	-122.07	-150.81
Unconstrained Forward Modeling (OBP/TWS/GCGC + Noise)	-29.55	-122.99	-143.17



Conclusions

- ❑ **Spatial leakage can significantly attenuate the magnitude of GRACE observed mass change signal, especially for small regional scale variations (e.g., Antarctic Peninsula).**
- ❑ **Experiments based on synthetic data indicate that both constrained and unconstrained global forward modeling can successfully remove the leakage bias in GRACE Antarctic mass rate estimates.**
- ❑ **Uncertainty of long-term ocean bottom pressure in the Antarctic Circumpolar Current regions may bias Antarctica mass rate estimates by up to 20 Gt/yr.**
- ❑ **Contribution from spatial noise (stripes) on forward modeling recovered Antarctic mass rates appears insignificant (< 3 Gt/yr) at 10-years or longer time scales.**