Progress towards high resolution mass grid solutions from GRACE for global applications

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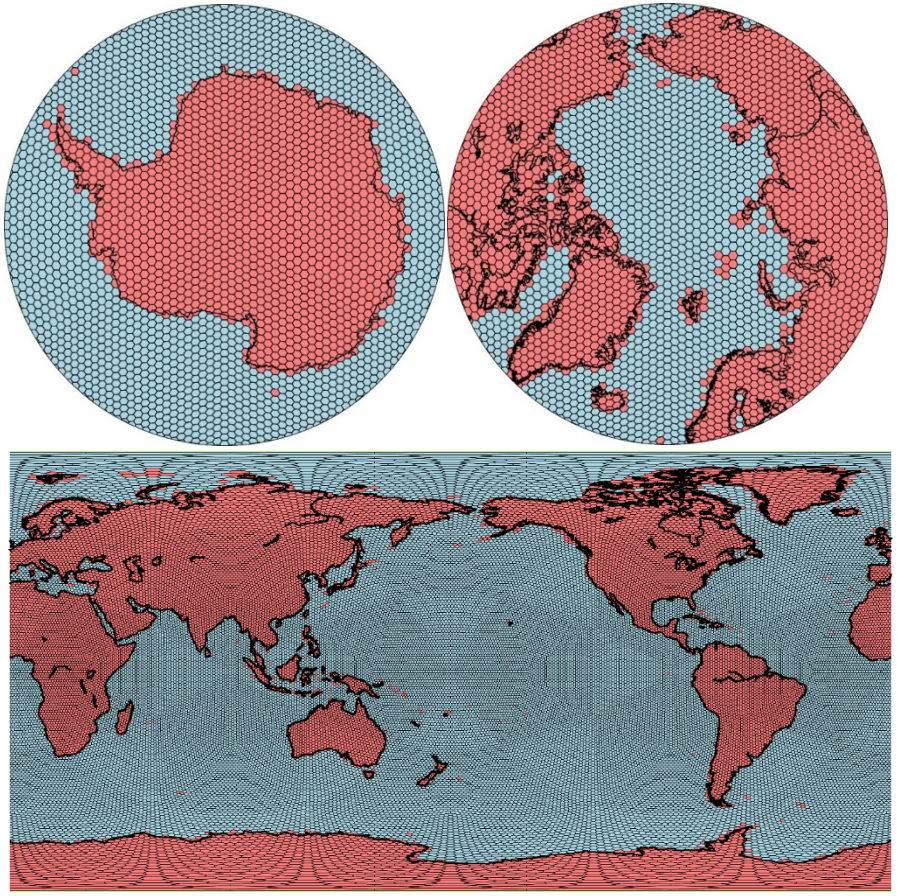
Geodesic Grid

- Geodesic grid technique* used to model the surface of the earth
- Equal area gridded (approximate) representation of the earth
- 40962 Cells (40950 Hexagons + 12 Pentagons)
- Size of each cell is about equatorial 1^o
- Number of cells along the equator : 320
- Average area of each cell : 12,400 km^2
- 120 km average distance between cell centers
- Does not suffer from over-sampling at the poles like equi-angular grid
- No single point of contact between neighboring cells



** Ringler et. al., 1999*

Mass Grid inversion

Define a Transformation *T* to convert *z* (mass grid) to *x* (SHC) $x = Tz$

Use *R* and *b* from the orthogonal transformation computed during SHC inversion setup

$Rx = b$ Where, $QH = R$ and $Qy = b$

Thus with $\overline{H}z = b$ Where, $\overline{H} = RT$

Mass grid estimate can be computed using Tikhonov regularization as

$$\hat{z} = (\overline{H}^T \overline{H} + \mu M^T M)^{-1} \overline{H}^T b$$

The transformation matrix ***T*** is defined by discretizing the following integral equations over the defined grid

$$\Delta C_{jlm}(t) = \frac{\sigma_j(t)(1+k_j')R^2}{(2l+1)M} \int \overline{P}_{lm}(\sin\upsilon)(\cos m\lambda)d\Omega$$

$$\Delta S_{jlm}(t) = \frac{\sigma_j(t)(1+k_j')R^2}{(2l+1)M} \int \overline{P}_{lm}(\sin\upsilon)(\sin m\lambda)d\Omega$$

Where, $\overline{P}_{lm}$ is Legendre associated polynomial, $\sigma(t)$ is the is the mass of the layer over a unit of surface area at the epoch, t, for region, j, k_j is the load love number, l is degree and m is order

Tikhonov Regularization

$$\hat{z} = (\overline{H}^T \overline{H} + \mu M^T M)^{-1} \overline{H}^T b$$

GRACE information equations mapped into geodesic grid

Regularization parameter

Regularization Matrix/Constraint Matrix

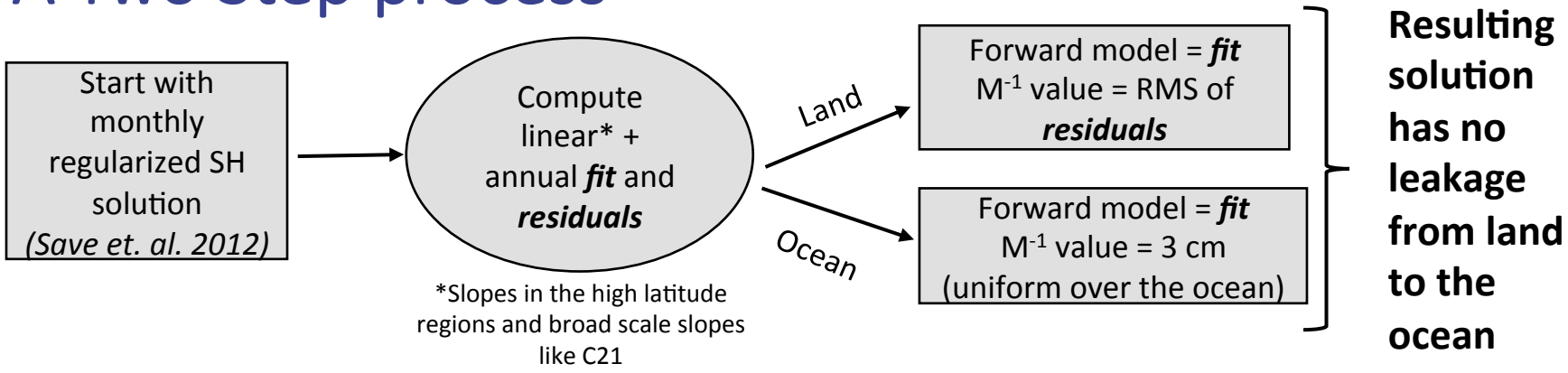
GRACE observations

- Variable regularization matrix is designed for each monthly solution separately
- The regularization parameter is computed for each solution using L-curve method to balance the signal and noise in the solution*

* Described in Save et. at. 2012

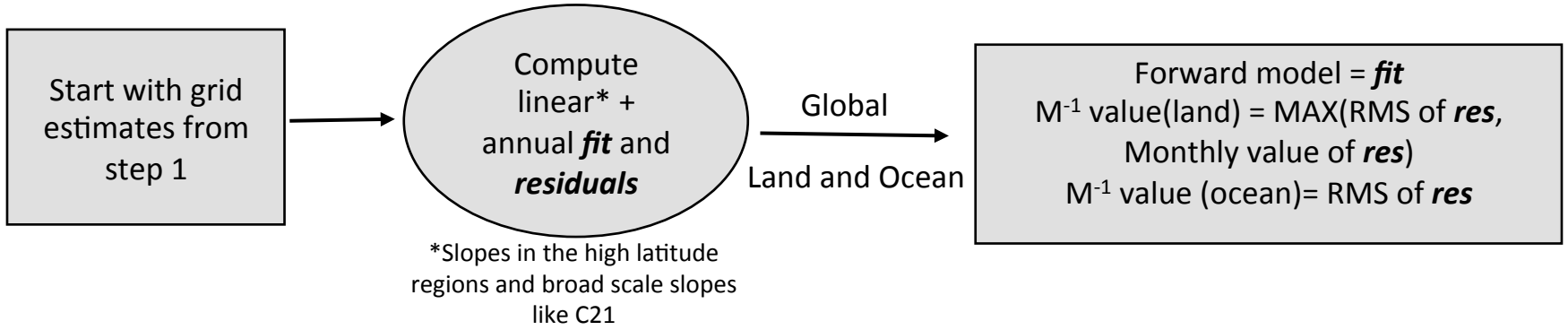
Regularization Matrix (M^{-1}) Design: A Two Step process

Step 1



Step 1 is only used to localize the GRACE signal to land areas

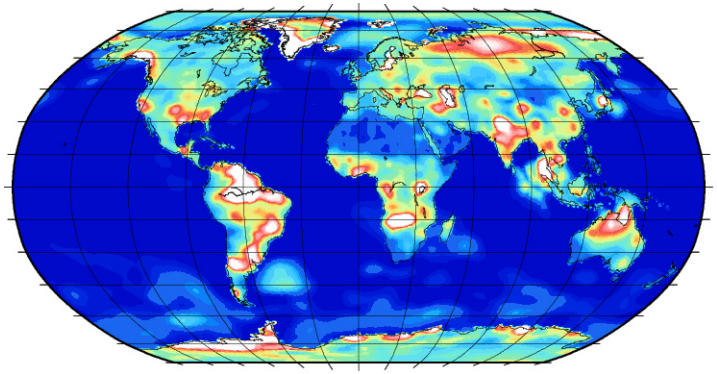
Step 2



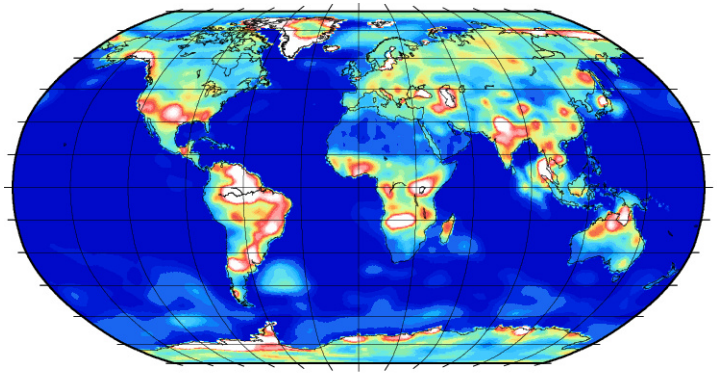
- The grid mass estimates are the correction to the linear + annual fit forward model
- linear + annual fit forward model is added back

Variable Regularization Matrix (M^{-1})

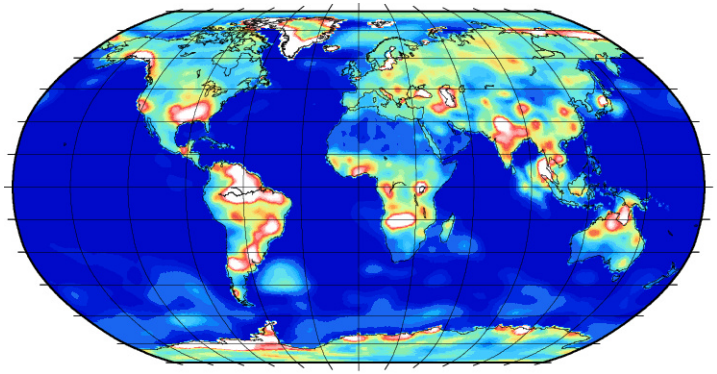
May 2008



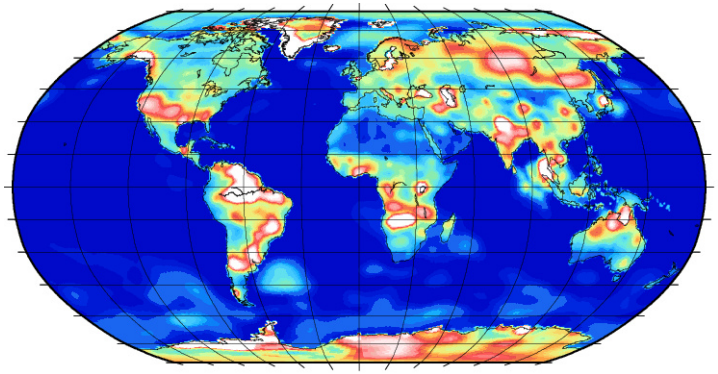
May 2013

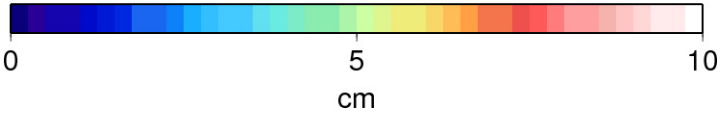


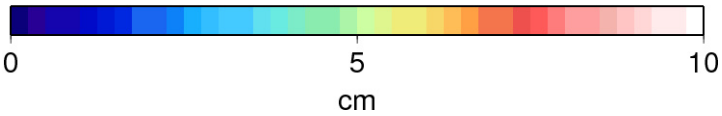
Dec 2004



Jan 2014



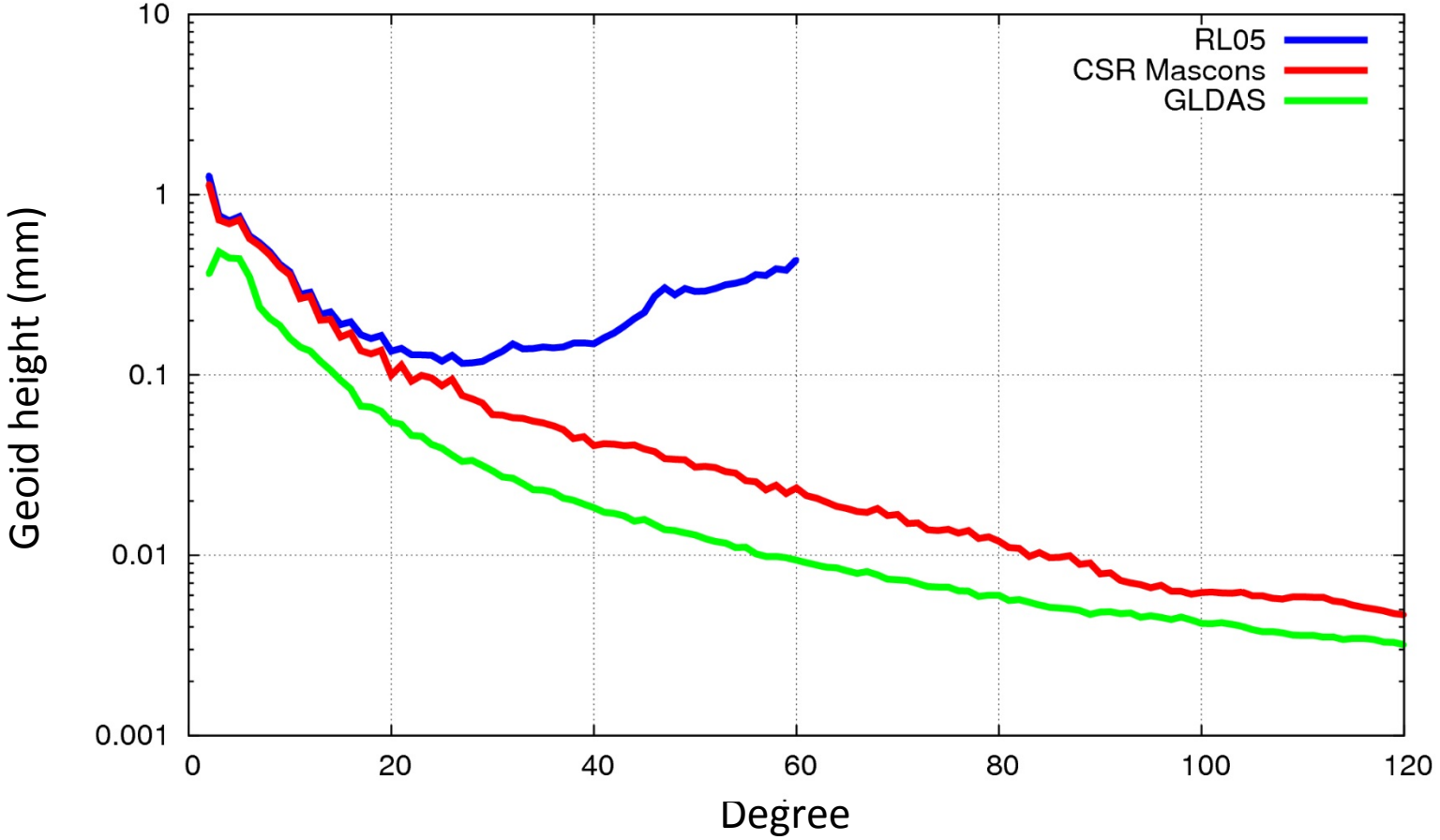




Regularization Matrix (M^{-1})

- Regularization matrix is variable and is computed for each month independently
- No model information or independent data information was used to define the regularization matrix
- These global mascon solutions are purely driven by GRACE information without any influence from the hydrological/ocean models or other data
- Regularization Matrix is diagonal – No land/ocean correlations have been used

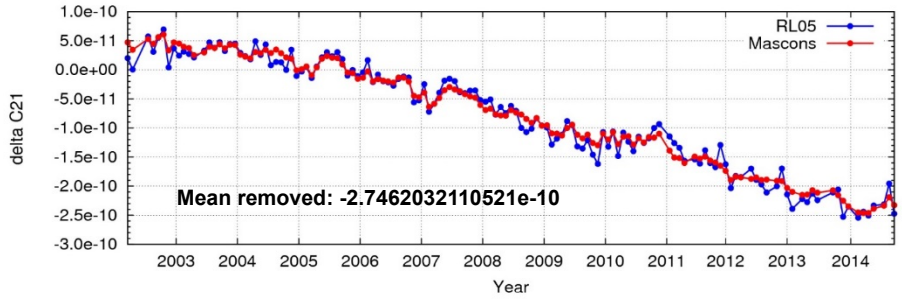
Degree Variance



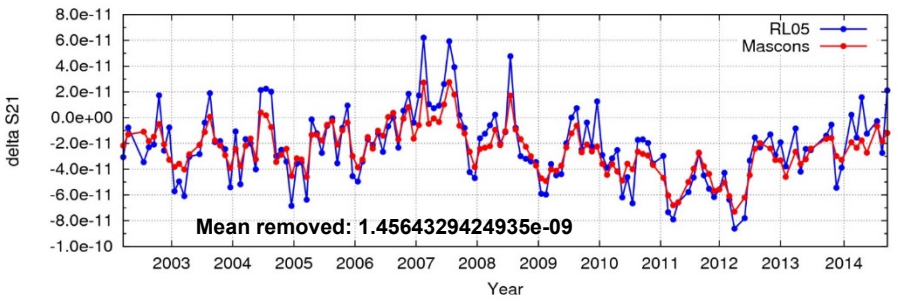
Degree Variance scatter shows that global mascon solutions capture all the low degree signal and deviate from RL05 solutions at degree 14

Degree 2 Harmonics

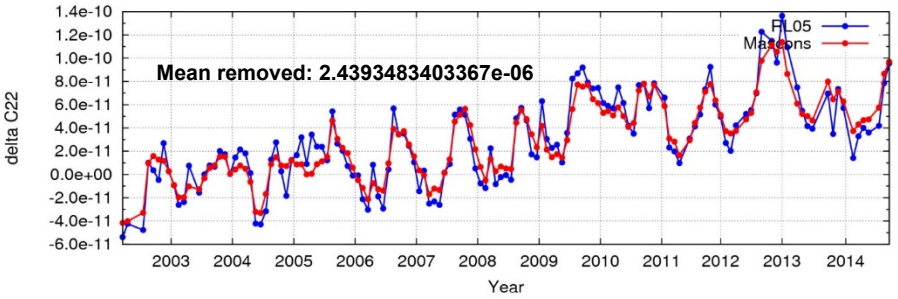
C21



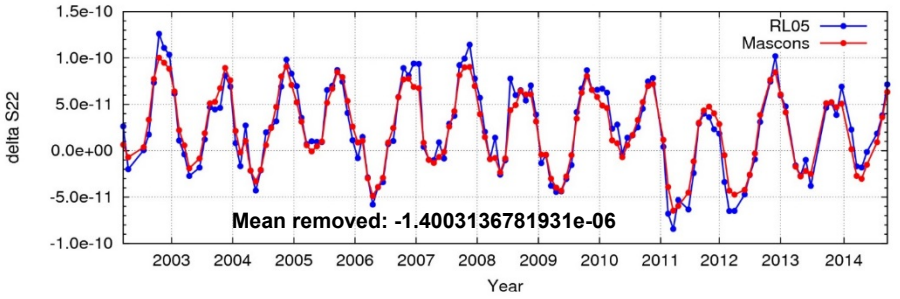
S21



C22

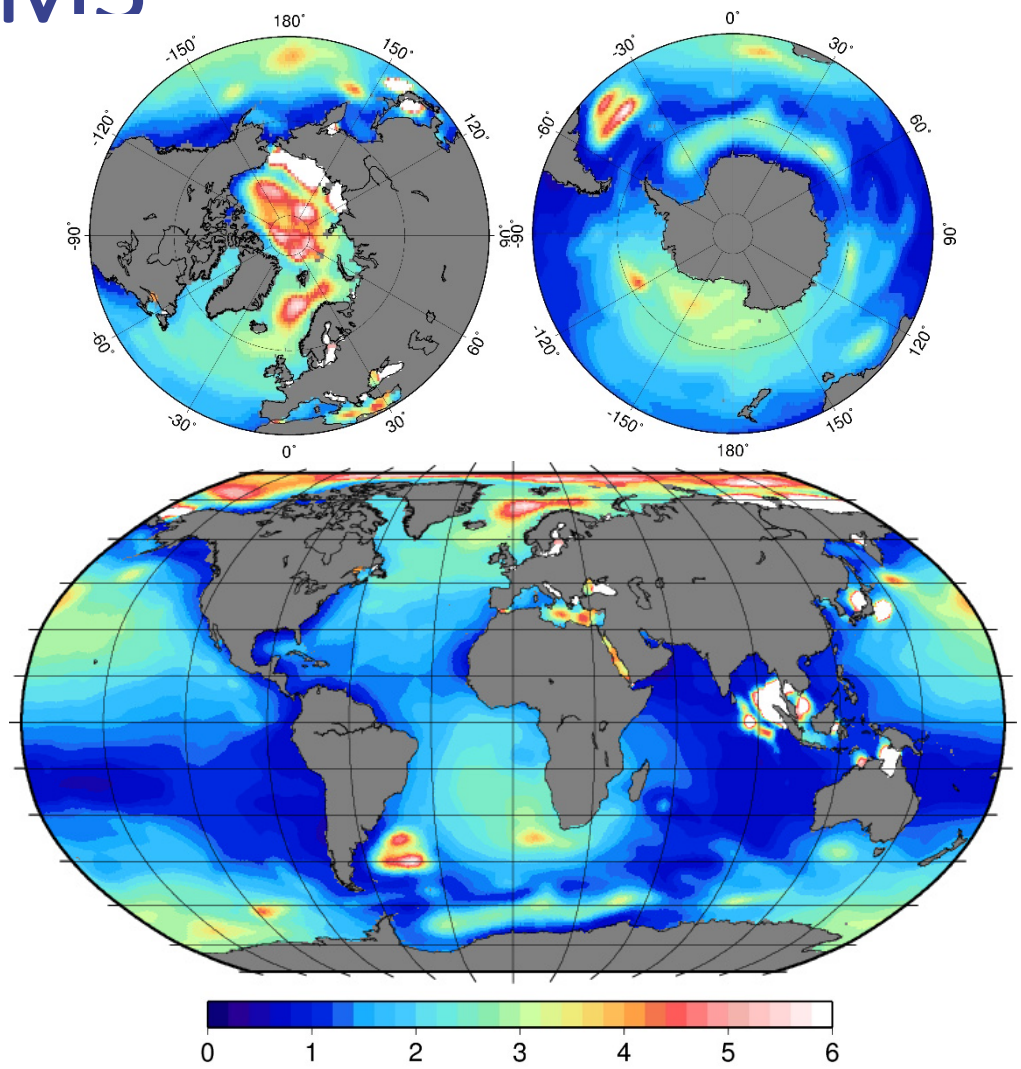


S22



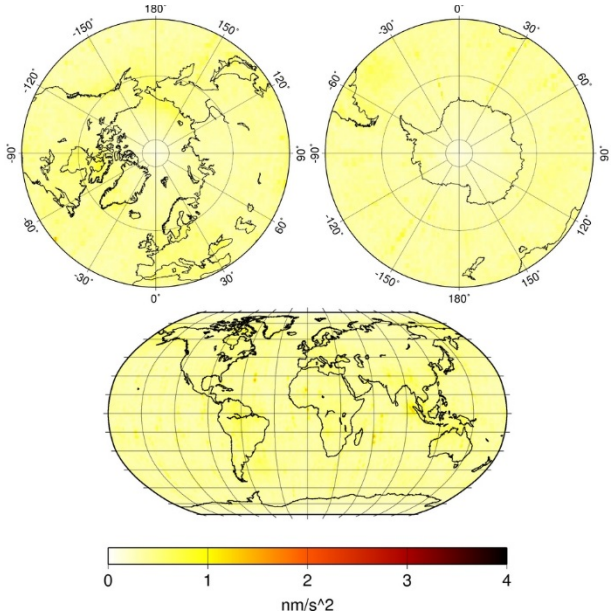
Global Ocean RMS

Global RMS show significantly reduced noise over the ocean for the mass grid solutions. The corrections to the background de-aliasing model are in the expected regions.



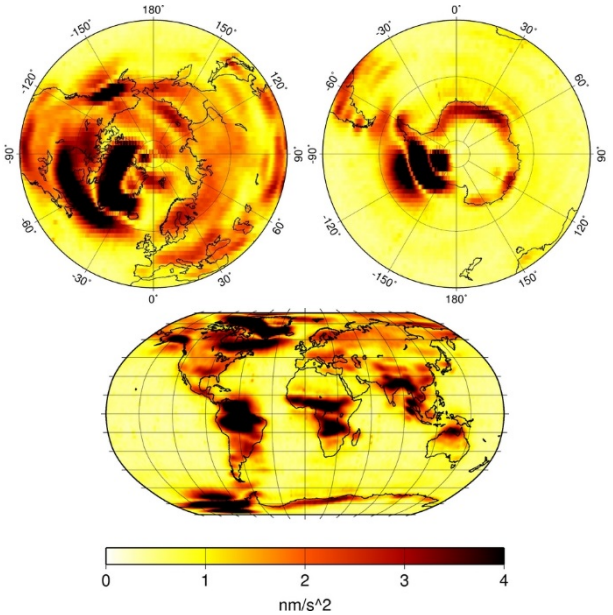
Post-fit residual analysis

Residual range accelerations after fitting the GRACE range rate data to global mascon solutions **(post-fit)**



Min:0.09633 nm/s^2, **Max: 2.04631 nm/s^2**

Residual range accelerations of the full signal **(RL05 prefit)**

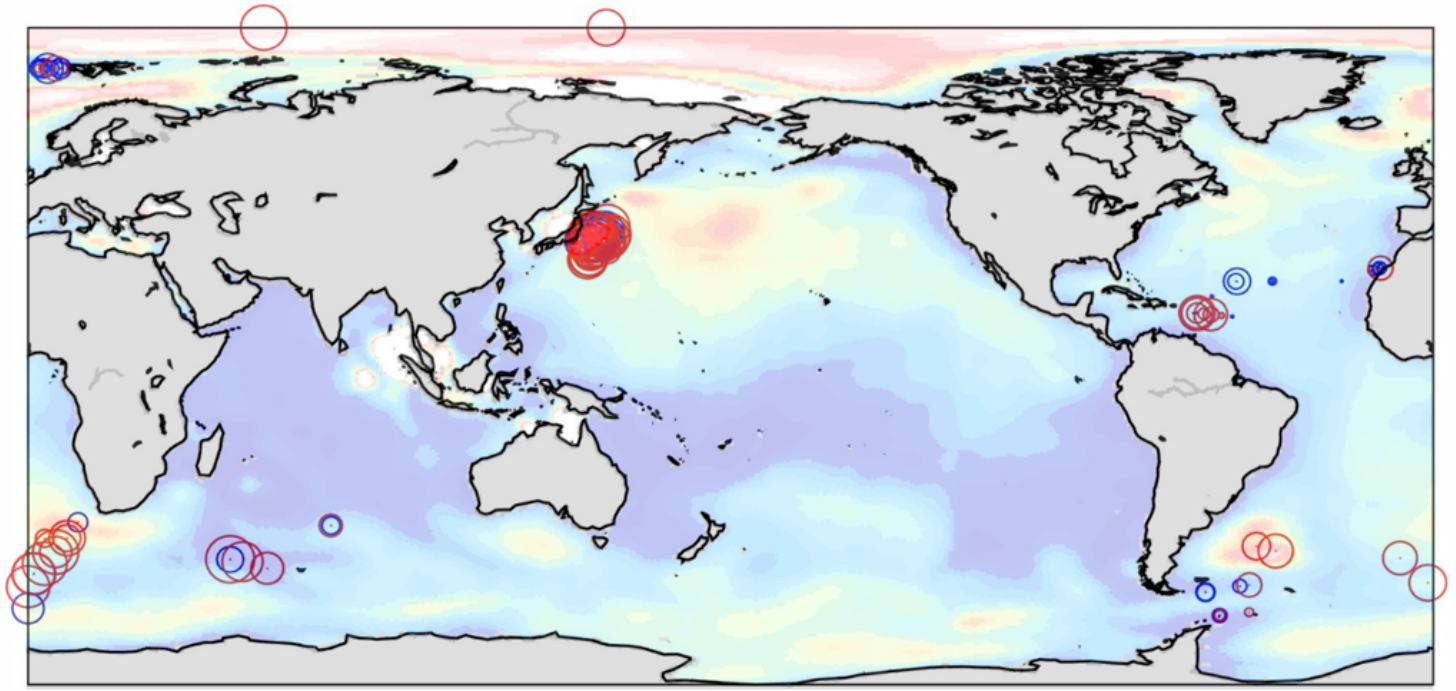


Min: 0.28076 nm/s^2, **Max: 24.4754 nm/s^2**

No geo-spatial correlation in the range-acceleration residuals

The post-fit residuals are smaller than the GRACE errors of 3-4 nm/s^2. The solutions meet the necessary condition and all the signal is captured in the solutions within the GRACE error levels

Ocean Bottom Pressure Comparison



Background image is the RMS over the ocean of the mascon solutions.

Blue circle: OBPR corr w/ mascon+GAD < only GAD

Red circle: OBPR corr w/ mascon+GAD > only GAD

Key for Correlation coefficient

Point wise comparison of the ocean bottom pressure recorder (OBPR)* data and mascon cell mass estimate time series

** Macrander et. al., 2010.*

Ocean Bottom Pressure

Latitude	Longitude	Corr w/ JPL Mascons	Corr w/CSR Mascons
-50.25	1.42	0.85	0.75
47.66	4.26	0.81	0.83
-41.13	9.94	0.51	0.52
15.5	308.5	0.55	0.58
16.5	302.5	0.63	0.51
34.83	145.04	0.65	0.71
36.35	145.99	0.83	0.6
36.35	146.92	0.72	0.66
36.35	148.85	0.72	0.74
37.11	144.57	0.58	0.58
37.81	147.87	0.70	0.70
38.51	148.34	0.80	0.80
89.43	60.31	0.86	0.80

Thanks to Carmen Boening for the OBPR comparisons

Comparison with published result

The mass anomaly computed in the Amundsen sea sector from CSR global mascon solutions, without any post processing, reproduces the results published by *Sutterly et. at., 2014.*

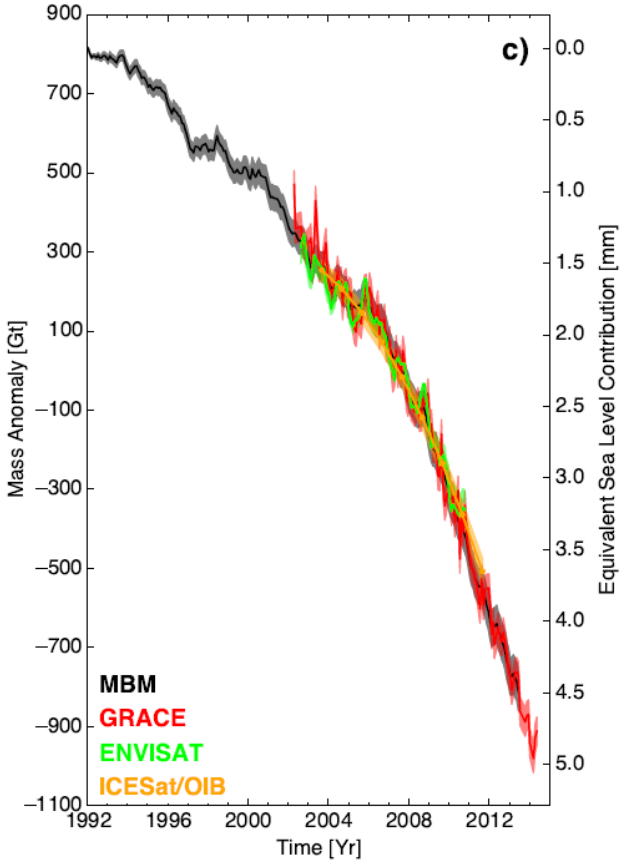
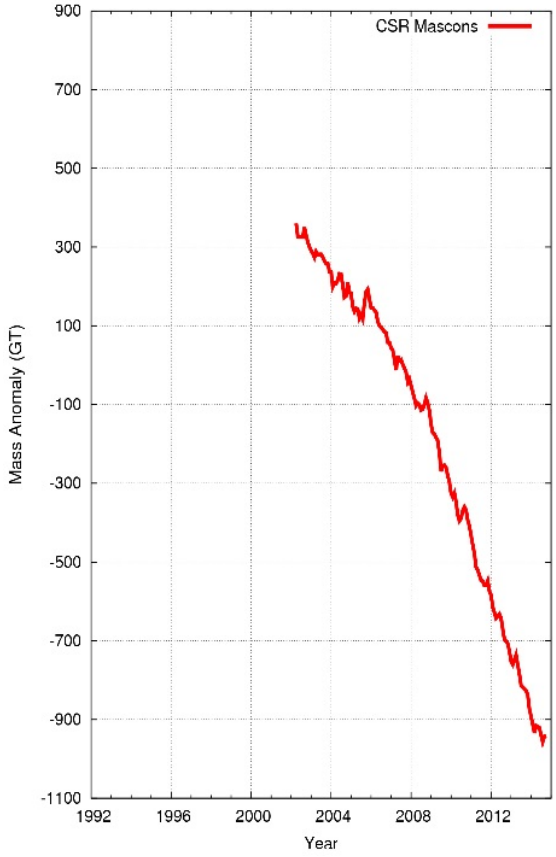
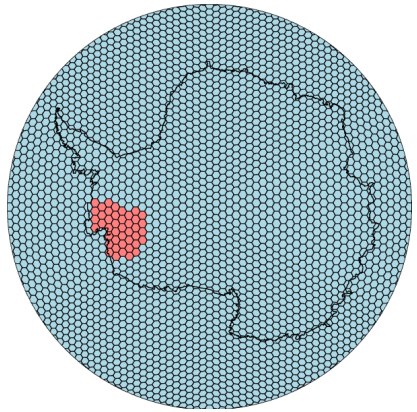


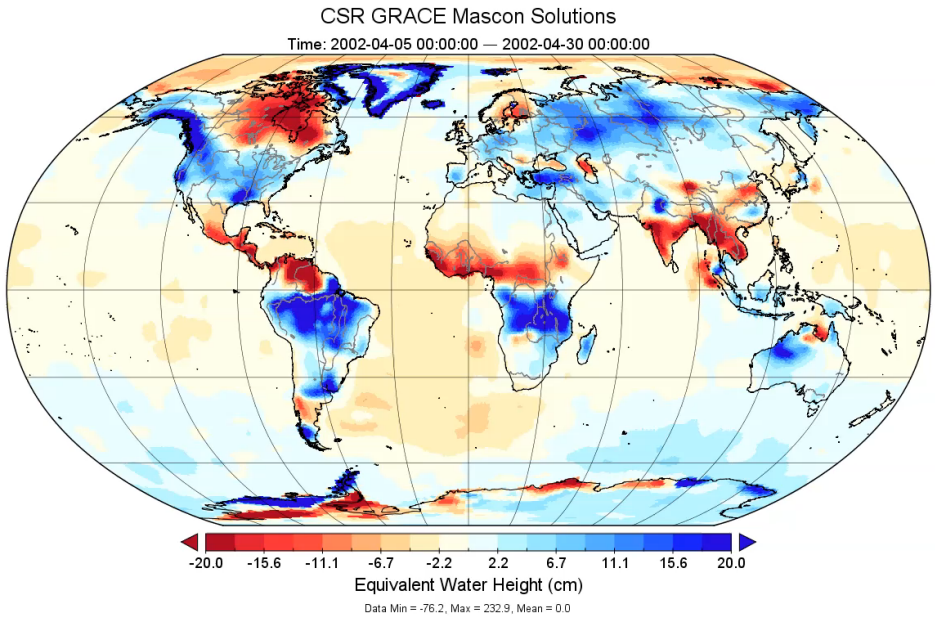
Image from Sutterley et. at. 2014





CSR mascon solutions summary (1/2)

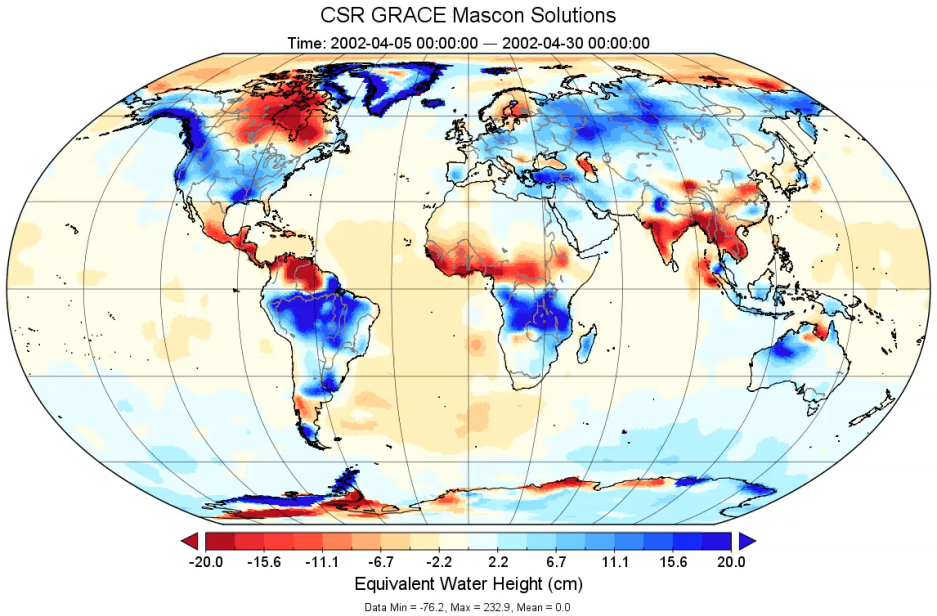
- The regularization is purely driven by GRACE and no model information is used in the computation.
- These solutions meet the necessary condition that the post-fit residuals show no geo-physical correlations and all the signal is captured with-in the noise level of GRACE.
- These solutions have excellent correlation with independent OBPR data.



- These solutions reproduce ice mass loss estimates without any need for post-processing.

CSR mascon solutions summary (2/2)

- These solutions will be released to the user community soon.
  - C20 estimate will be replaced by the C20 estimate from SLR
  - Degree 1 component will be added
  - A GIA model will be removed
  - GAD will be added back for ocean applications
- Solutions will be available as 0.5^{o} equi-angular grids
- No post-processing should be applied when using these solutions



- Single solution file will be available for use with global applications like Cryosphere, Oceanography and Hydrology etc.
- Please watch the space at http://www.csr.utexas.edu/grace/ for upcoming release

Thank you

Please contact

Himanshu Save (save@csr.utexas.edu)

with any questions.

Special thanks to Texas Advanced Computing Center (TACC) for providing access to their supercomputing resources

1. Ringler, T., Heikes, R. P. and Randall, D. A. (1999): "Modeling the Atmospheric General Circulation Using a Spherical Geodesic Grid: A New Class of Dynamical Cores", NCAR CGD Seminar Series, May 6, 1999.
2. Save, H., Bettadpur, S. and Tapley,.B. D. (2012):"Reducing errors in the GRACE gravity solutions using regularization." *Journal of Geodesy,* 1-17.
3. Macrander, A. , Böning, C. , Boebel, O. and Schröter, J. (2010): Validation of GRACE Gravity Fields by in-situ Data of Ocean Bottom Pressure , System Earth via Geodetic-Geophysical Space Techniques / edited by Frank M. Flechtner, Thomas Gruber, Andreas Güntner, Mioara Mandea, Markus Rothacher, Tilo Schöne, Jens Wickert Berlin, Heidelberg : Springer-Verlag Berlin Heidelberg, 169-185. (Advanced Te, ISBN: 978-3-642-10227-1 . doi: 10.1007/978-3-642-10228-8_14
4. Sutterley, T., Velicogna, I., Rignot, E., Mouginot, J., Flament, T., van den Broeke, M., van Wessem, J and Reijmer, C., (2014): "Mass loss of the Amundsen Sea Embayment of West Antarctica from four independent techniques", Geophysical Research Letters