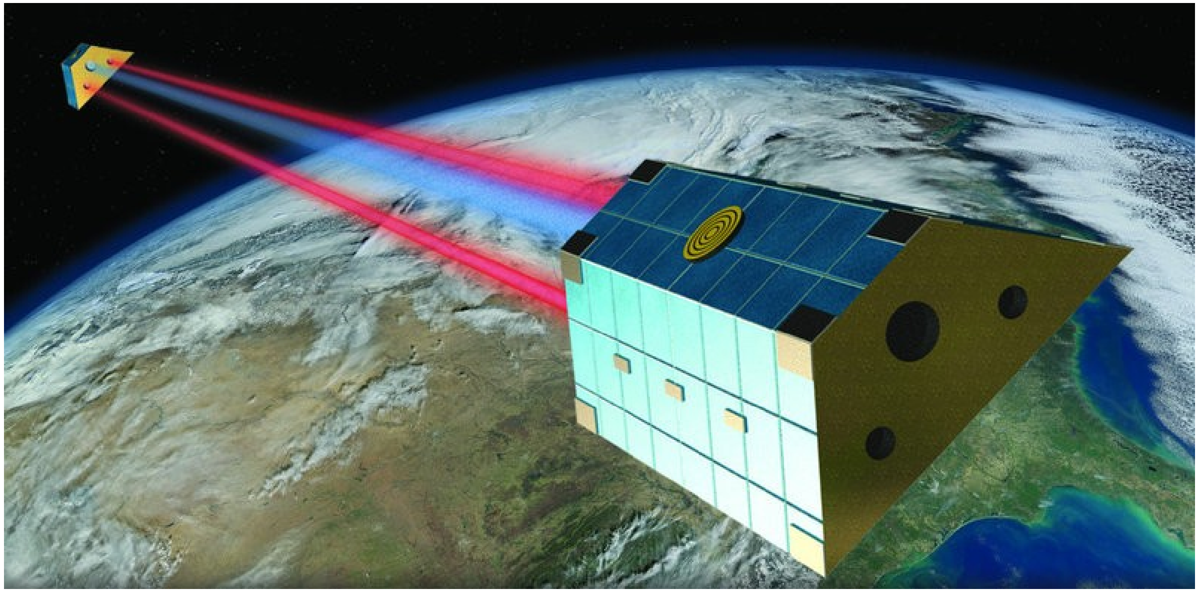
Introduction to GRACE/FO and working with their data



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April 14, 2022

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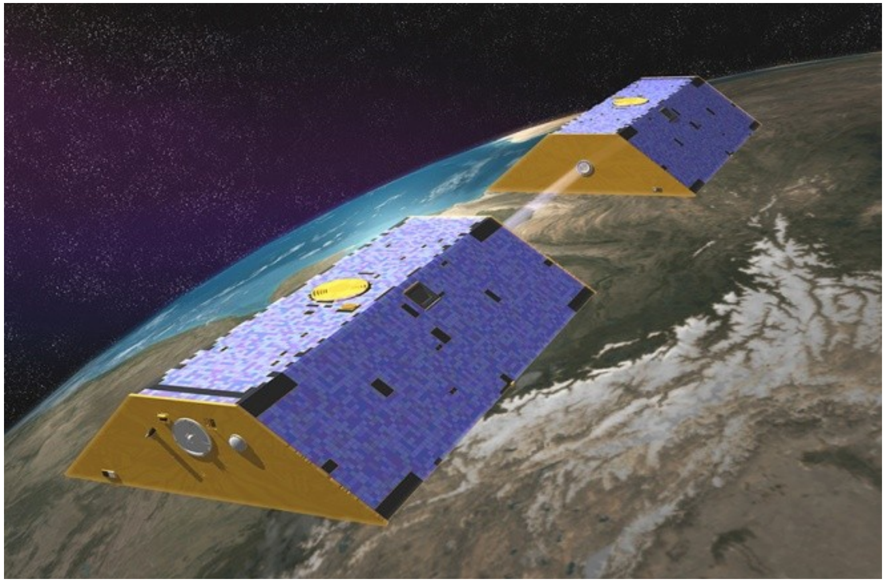
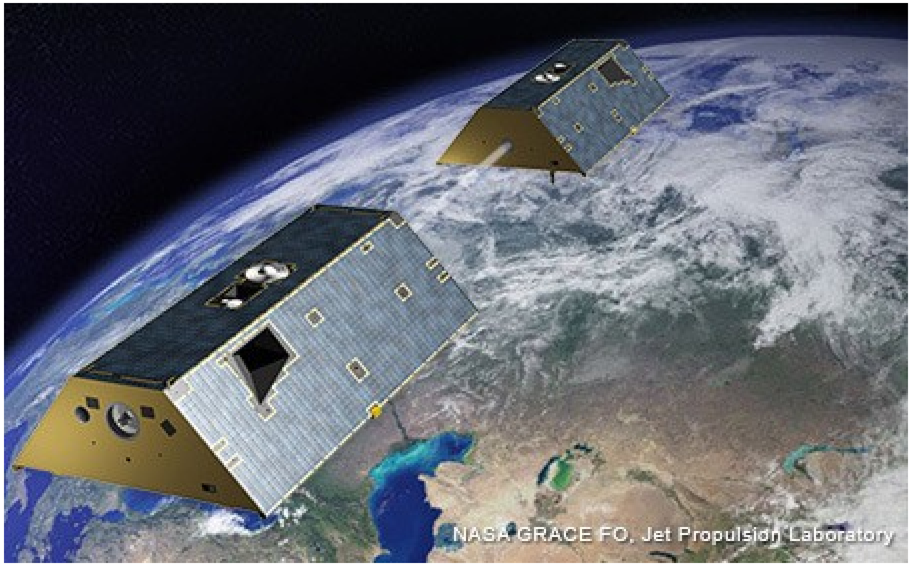
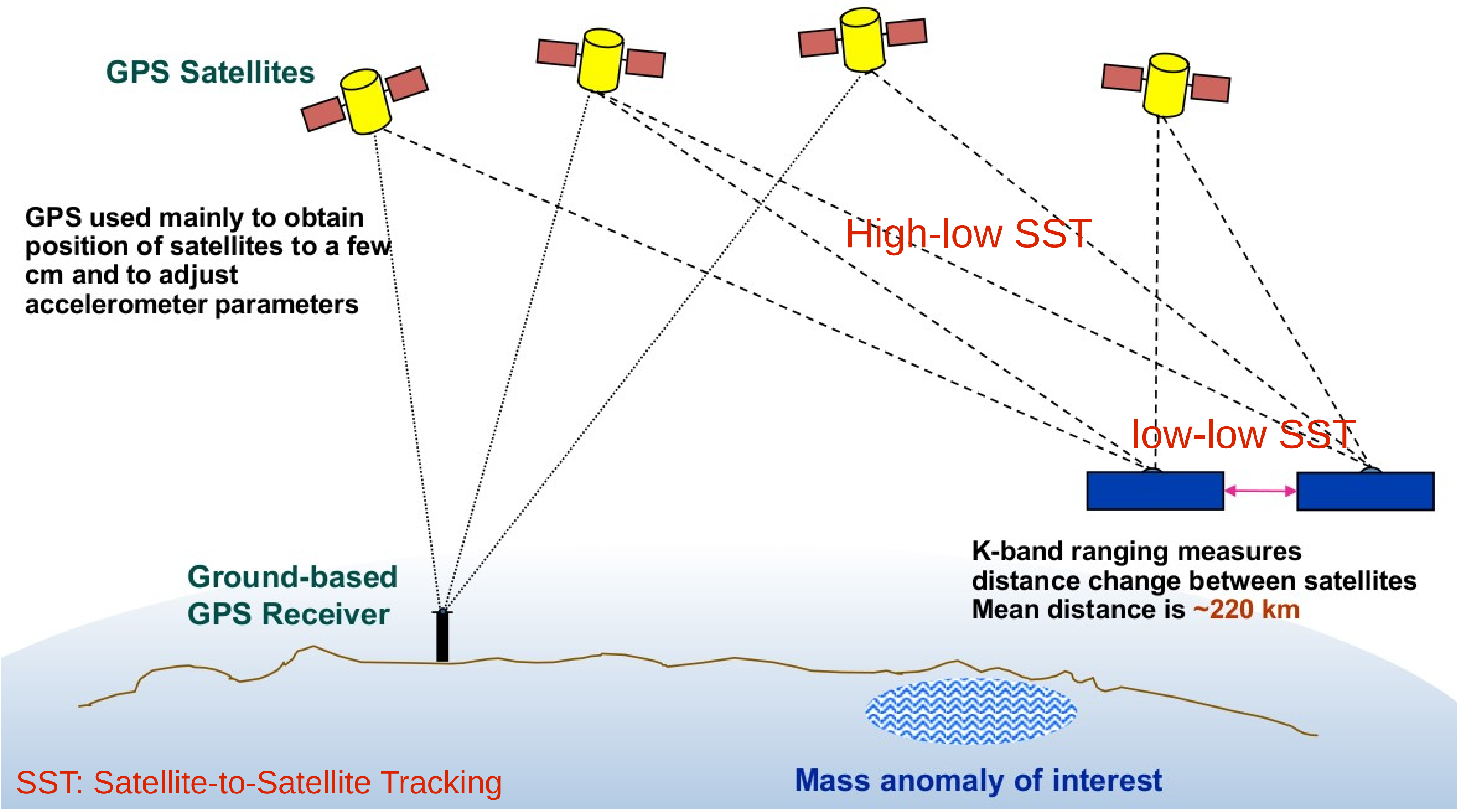
Joint NASA and DLR mission launched in March 2002 and terminated in October 2017 (GRACE-FO since May 2018) with a goal to measure time variable gravity field due to changes in land water storage and ocean circulations and movements.



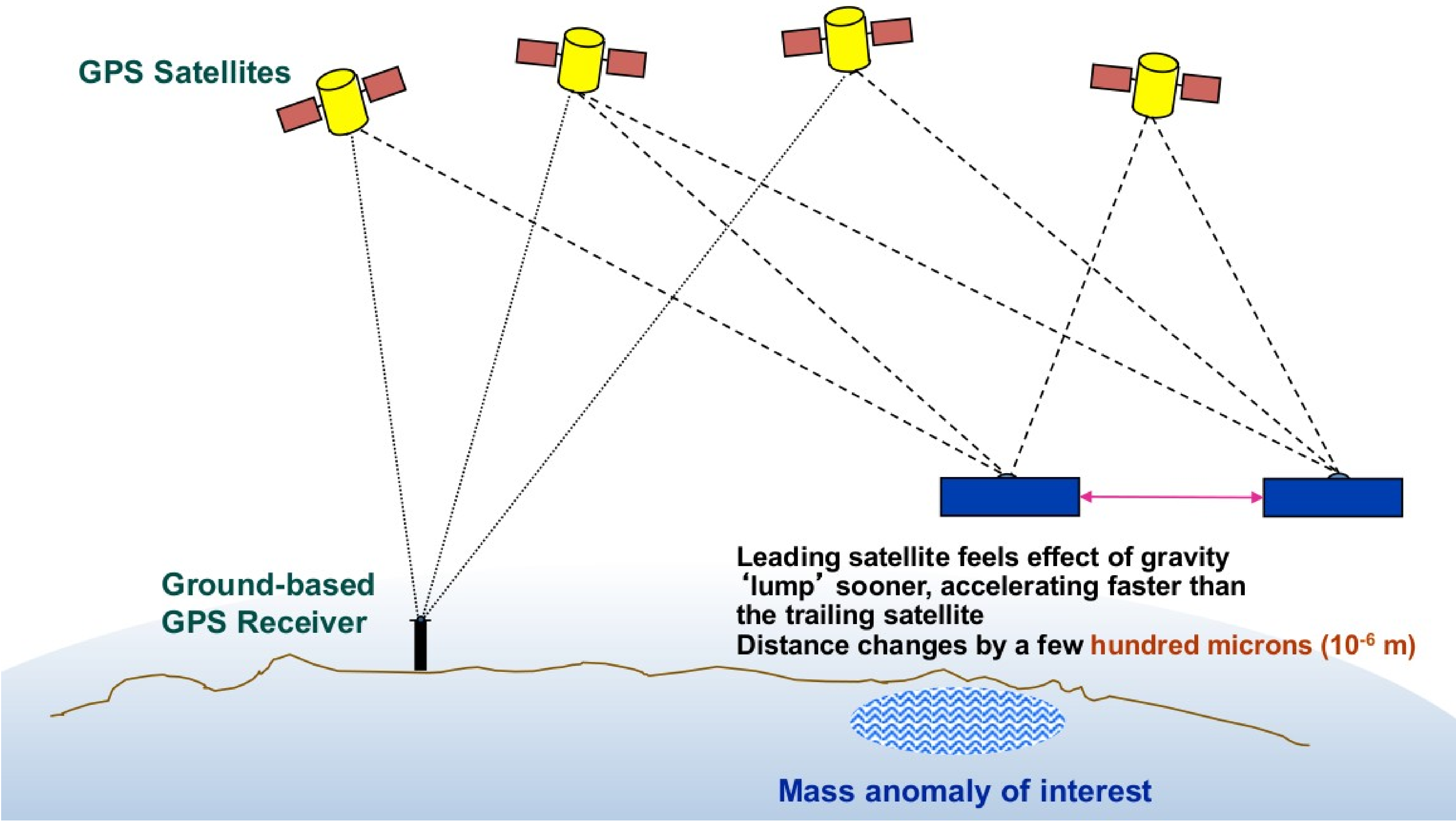


Concepts

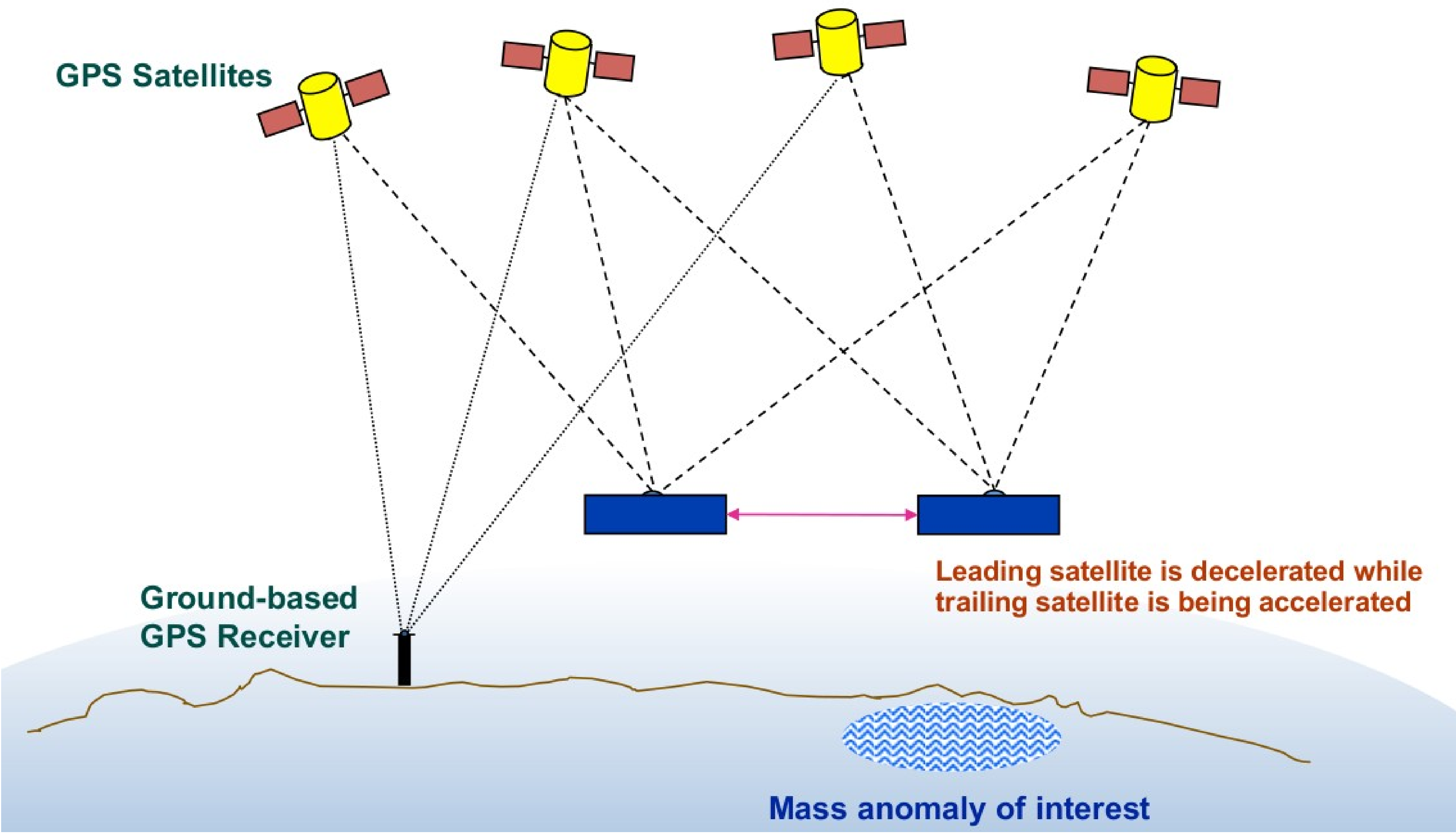


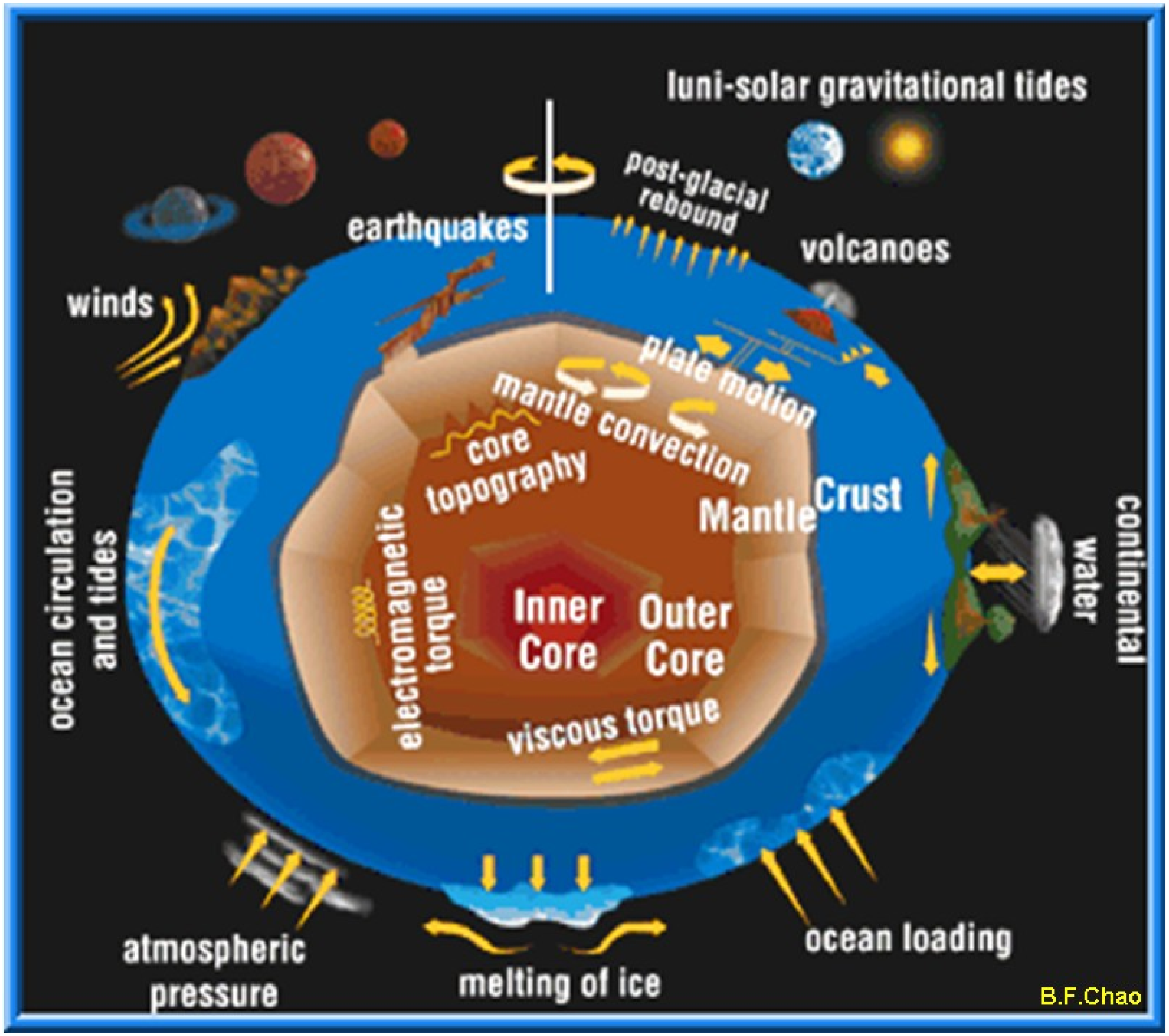
SST: Satellite-to-Satellite Tracking

Concepts


GPS Satellites
Ground-based
GPS Receiver
Leading satellite feels effect of gravity
'lump' sooner, accelerating faster than
the trailing satellite
Distance changes by a few hundred microns (10-6 m)
Mass anomaly of interest

Concepts


GPS Satellites
Ground-based
GPS Receiver
Leading satellite is decelerated while
trailing satellite is being accelerated
Mass anomaly of interest



Mass density is changing at different time and spatial scales.

Newton's integral for gravitational potential:

$$V(\mathbf{x}, t) = G \int_{\mathcal{V}} \frac{\rho(\mathbf{x}', t)}{l} dv$$

Any changes in mass density results in potential or gravity Changes (eq. 1-12 in Hofmann & Moritz, 2006)

$$\rho(\mathbf{x}', t)$$

4D density distribution

G Newtonian gravitational constant

dv an element of volume

l* distance between *x* and *x'

Most of mass variability concentrated within a thin layer of thickness H (~ 10 km) near the surface of Earth containing *atmosphere, oceans, ice sheets, and land water storage*. This layer is subject to significant mass fluctuations.

$$\Delta V'(r,\lambda,\theta) = G\int_{\Omega}\frac{\Delta\sigma(\lambda',\theta')}{l}d\omega$$

Let's expand surface density over sphere with SH coefficients of ΔC^{σ}_{lm} & ΔS^{σ}_{lm}

$$\Delta\sigma(\lambda,\theta) = a\rho_w\sum_{l,m}\left(\Delta C^{\sigma}_{lm}\cos m\lambda + \Delta S^{\sigma}_{lm}\sin m\lambda\right)\overline{P}_{lm}(\cos\theta)$$

ρ_w
Density of water 1000 kg/m³

And expand the reciprocal distance (1/*l*) to Legendre's polynomial (Hofmann & Moritz 2006, Section 1.11, eq. 1-108)

$$\frac{1}{l} = \left(r^2 + r_E^2 - 2rr_E\cos\psi\right)^{-\frac{1}{2}} = \frac{1}{r}\sum_{n=0}^{\infty}\left(\frac{r_E}{r}\right)^n P_n(\cos\psi)$$

P_n can be expanded to SH (eq. 1-105)
or Lecture Note 2, P 21

After putting SH expression of 1/*l* and SH formula of surface density in the Newton's integral, we get the potential variation in terms of SHCs of surface density ΔC^{σ}_{lm} & ΔS^{σ}_{lm}

$$\Delta V'(r,\lambda,\theta) = 4\pi G\frac{r_E^3\rho_w}{r}\sum_{n=0}^{\infty}\left(\frac{r_E}{r}\right)^n\frac{1}{2n+1}\sum_{m=0}^{n}\left(\Delta c^{\sigma}_{nm}\cos m\lambda + \Delta s^{\sigma}_{nm}\sin m\lambda\right)P_{nm}(\cos\theta)$$

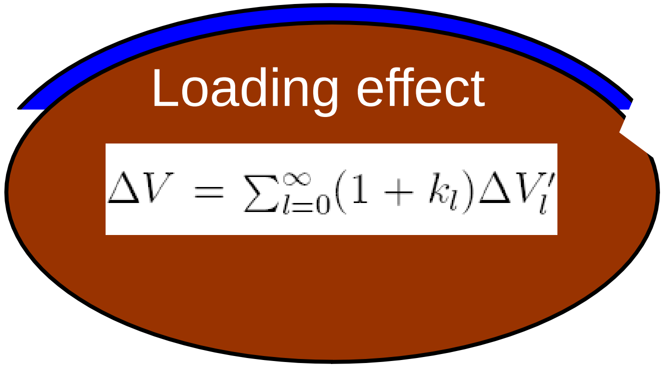
Surface density change to potential change: effect of solid Earth deformation

* Any change in surface density will cause <u>deformation</u> within the solid Earth, leading to an additional surface density change.

* The gravity change caused by these “solid Earth mass anomalies” is up to 30% of the gravity caused by the surface mass itself.

* It can be represented in terms of load Love numbers: k_l

$$\left\{ \begin{array}{c} \Delta C_{lm}^{\text{solid Earth}} \\ \Delta S_{lm}^{\text{solid Earth}} \end{array} \right\} = k_l \left\{ \begin{array}{c} \Delta C_{lm}^{\text{surf mass}} \\ \Delta S_{lm}^{\text{surf mass}} \end{array} \right\}$$



$$\Delta V(r,\lambda,\theta) = 4\pi G \frac{r_E^3 \rho_w}{r} \sum_{n=0}^{\infty} \left(\frac{r_E}{r}\right)^n \frac{1+k_l}{2n+1} \sum_{m=0}^{n} (\Delta c_{nm}^{\sigma} \cos m\lambda + \Delta s_{nm}^{\sigma} \sin m\lambda) P_{nm}(\cos\theta)$$

satellite gravimetry measures mass effect + its elastic response

Thin layer assumption

R: mean radius of the Earth,
H: thickness of thin leyer where most of mass changes occur (~ 10 km)
r = R and r_E = R + H

binomial expansion: $[r_E/r]^n = [(R + H)/R]^n =$
$1 + H/R + 2*H/R + ...+ n_{max}*H/R$

Suppose H is thin enough so $[r_E/r]^n = 1$
** max committing error 10/6378 = 0.001

$$\Delta V(r,\lambda,\theta) = 4\pi G \frac{r_E^3 \rho_w}{r} \sum_{n=0}^{\infty} \left(\frac{r_E}{r}\right)^n \frac{1+k_l}{2n+1} \sum_{m=0}^{n} (\Delta c_{nm}^{\sigma} \cos m\lambda + \Delta s_{nm}^{\sigma} \sin m\lambda) P_{nm}(\cos\theta)$$

changes in potential in terms of SHCs of surface density

$$\Delta V(r,\lambda,\theta) = 4\pi G \rho_w r^2 \sum_{n=0}^{\infty} \frac{1+k_l}{2n+1} \sum_{m=0}^{n} (\Delta c_{nm}^{\sigma} \cos m\lambda + \Delta s_{nm}^{\sigma} \sin m\lambda) P_{nm}(\cos\theta)$$

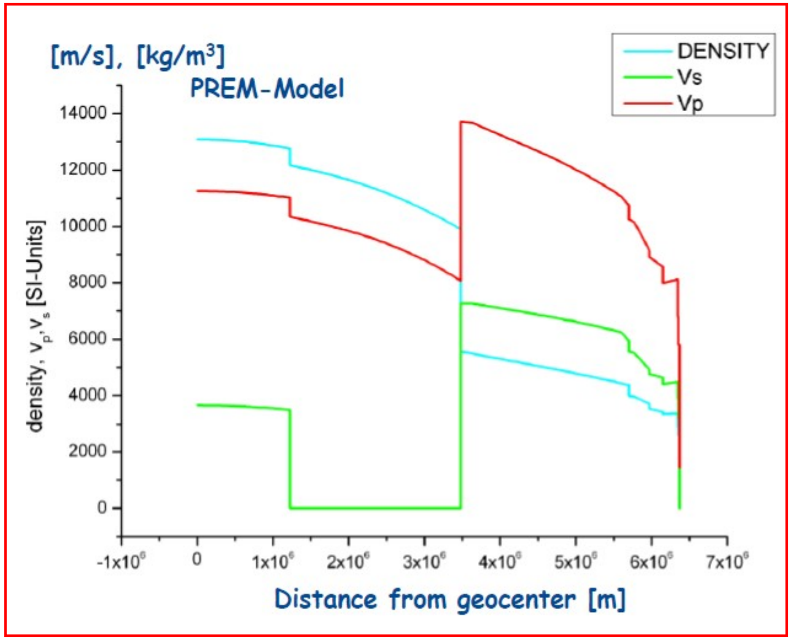
Relationship between potential and surface density SHCs

Potential (geoid height) SHCs ↔ Mass density SHCs

What GRACE delivers

$$\begin{Bmatrix} \Delta C_{lm}^N \\ \Delta S_{lm}^N \end{Bmatrix} = \frac{3\rho_w}{\rho_e} \frac{1+k_l}{2l+1} \begin{Bmatrix} \Delta C_{lm}^\sigma \\ \Delta S_{lm}^\sigma \end{Bmatrix}$$

degree n	h'_n	$1+k'_n$	l'_n
2	-1.001	0.692	0.0295
3	-1.052	0.805	0.0743
4	-1.053	0.868	0.0617
5	-1.088	0.897	0.0486
6	-1.147	0.911	0.0408
7	-1.219	0.919	0.0367
8	-1.291	0.924	0.0336
9	-1.362	0.929	0.0318
10	-1.433	0.932	0.0303
100	-3.058	0.985	0.00973
1000	-4.906	0.998	0.00162



More in lecture 4

Equivalent water thickness (total water storage)

The dominant mass changes are related to movement of water in the oceans, on land and through the atmosphere. Therefore one can scale by water density (ρ_w) to get equivalent water thickness (EWT, or total water storage) change over land and ocean and compute the water storage term over large-scales:

EWT = surface density / p_w >>> EWT in m SI unit

$$S(\phi,\lambda,t)=\frac{a_E\rho_E}{3\rho_W}\sum_{l=0}^{120}\sum_{m=0}^{l}\frac{(2l+1)}{(1+k_l)}P_{lm}(\sin\phi)\left\{\Delta C_{lm}(t)\cos m\lambda+\Delta S_{lm}(t)\sin m\lambda\right\}$$

Basic Earth parameters (radius, avg. density, Love Load numbers)

Time-Variable Gravity Coefficients from GRACE Project

GRACE will measure all gravitational variations, even those that have time scales much shorter than one month.

In order to get the monthly variation correct, we have to model and remove

* Ocean tides * Solid Earth tides

* Atmospheric mass changes (namely tidal and non-tidal atmospheric loading)

* Post glacial rebound (GIA) – for contemporary mass change

GRACE estimates are non-tidal ocean mass variations, land hydrology, and cryospheric changes.

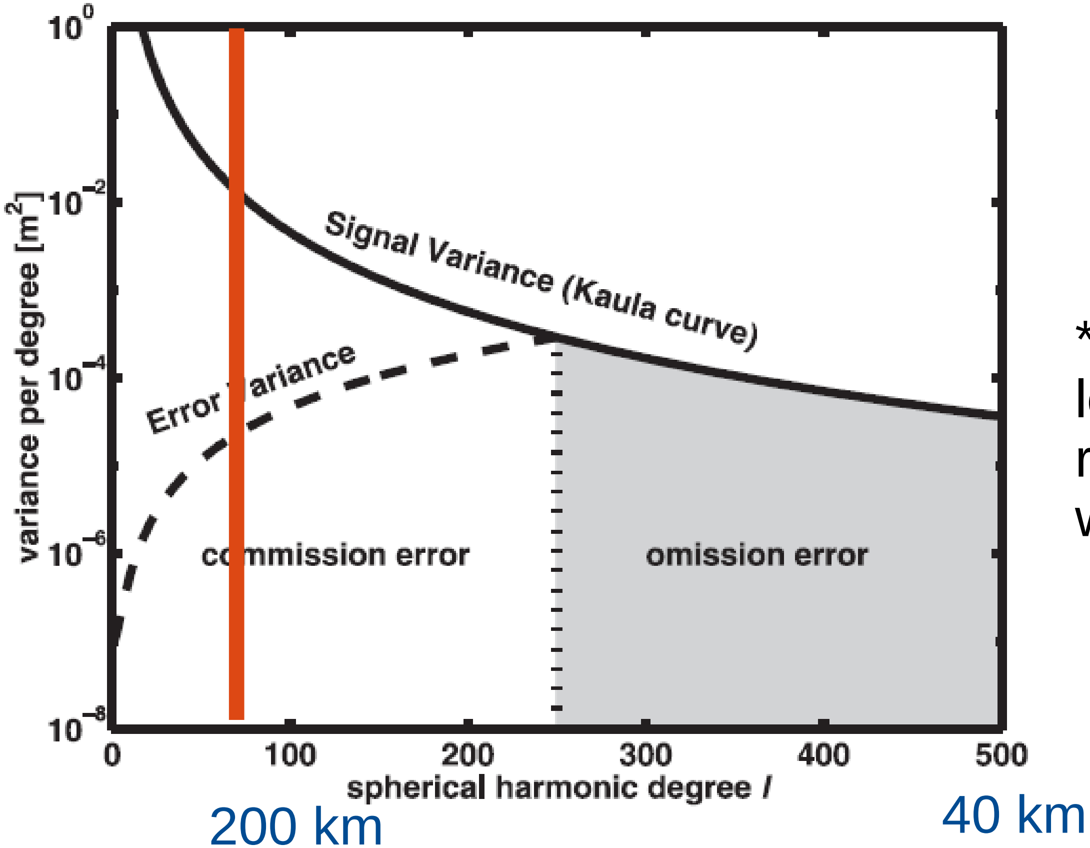
Atmosphere and Ocean De-aliasing Level-1B (AOD1B) products from GFZ. AOD1B products are 3-hourly series of spherical harmonic coefficients up to degree and order 180 at:

https://www.gfz-potsdam.de/en/aod1b/

Commission error vs. omission error

Spectrum of mean and time-variable gravity field

$$S_{vv}(n) = \frac{GM}{R}(2n+1)\bar{c}_n^2 \qquad \bar{c}_n^2 = \frac{1}{2n+1}\sum_{m=0}^{n}\left(\bar{c}_{nm}^2 + \bar{s}_{nm}^2\right)$$



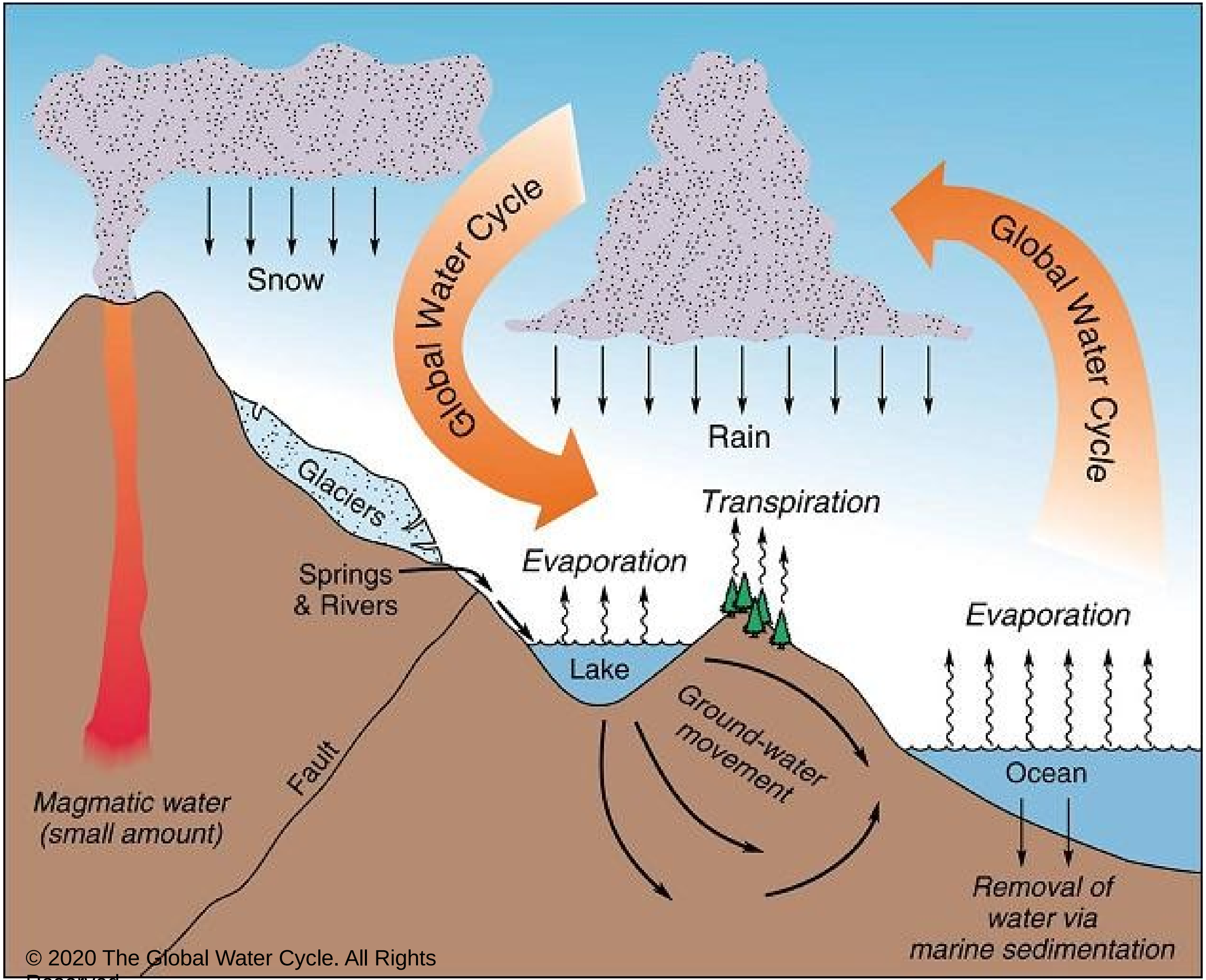
Spatial resolution and max of SH expansion:

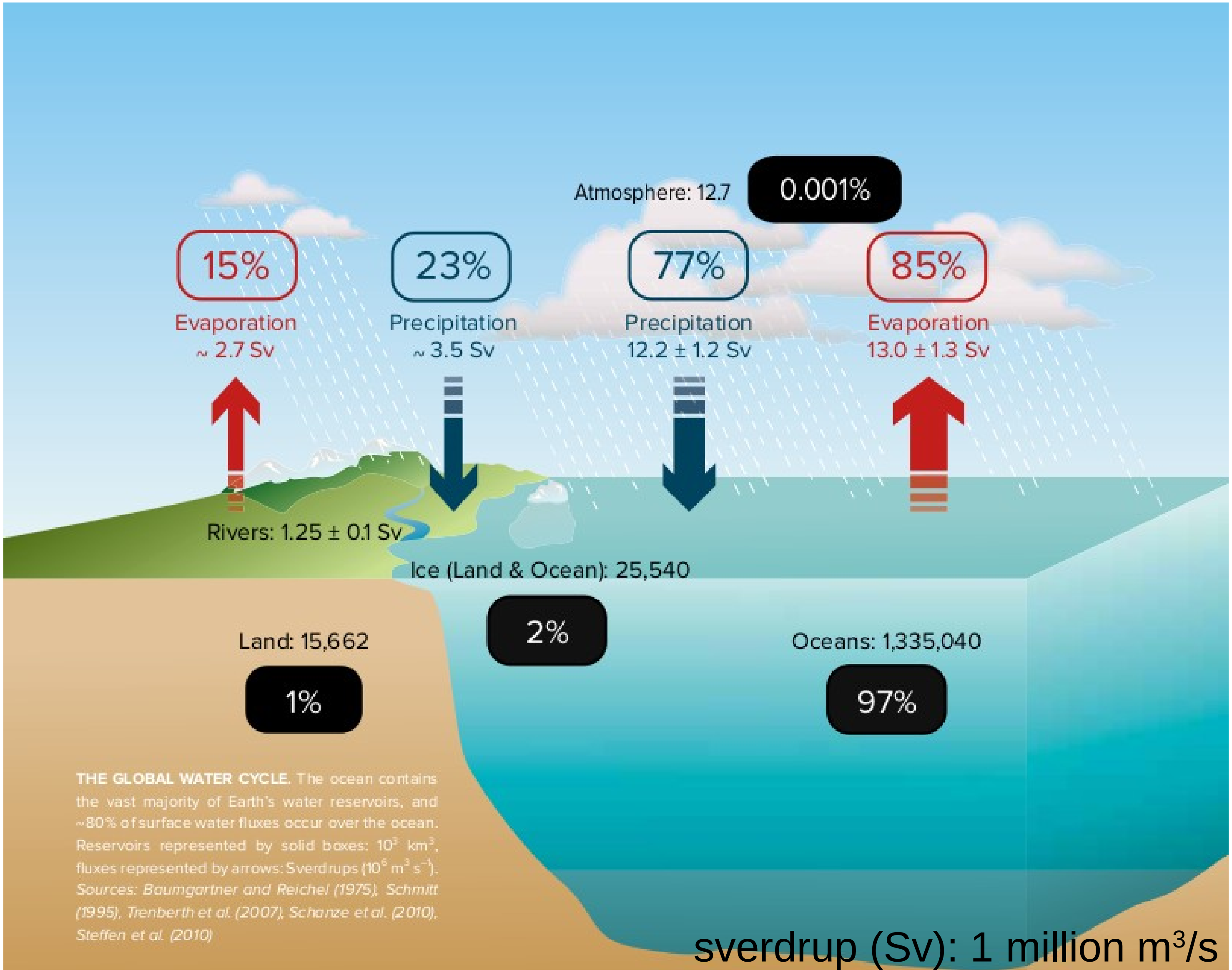
L ~ 20,000 km / n_{max}

* GRACE is most sensitive to long-wavelengths and has higher random error at shorter wavelengths.

* The inherent GRACE resolution is caused by the height of the satellites above the Earth (~300-400 km) and the separation between them (~200 km)

Global water cycle





sverdrup (Sv): 1 million m^3/s

Durack (2015)

On land, water storage changes due to:

* surface water (rivers, lakes, reservoirs flooding)

* soil moisture

* snow

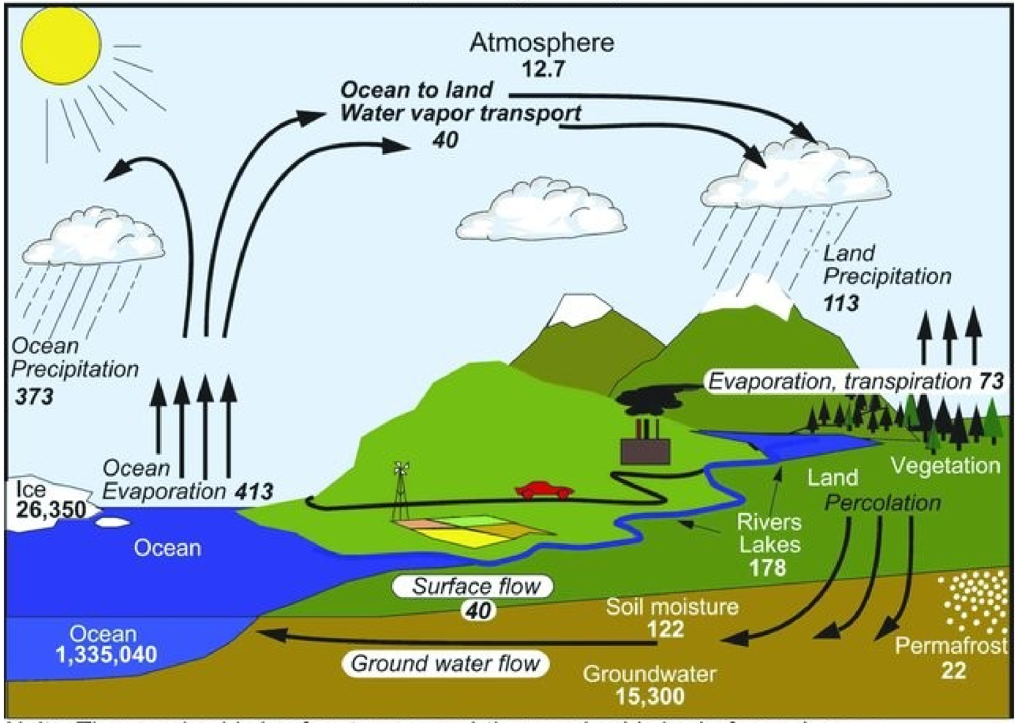
* ground water

On ocean, changes due to:

* mass fluxes in and out

* Circulation changes due to winds

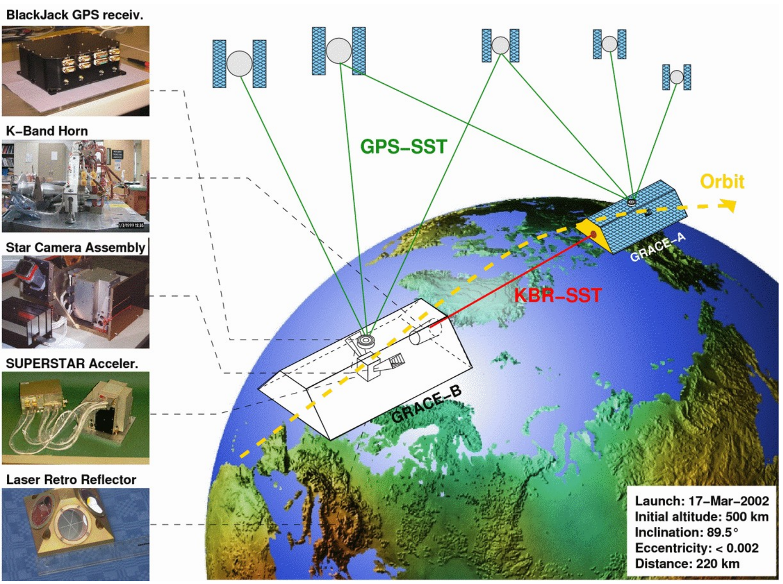
Hydrological Cycle



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

[Trenberth et al., 2007].

GRACE data: three levels of data



Level 1

- Ranging + GPS data
- Very difficult to work with

Level 2

- Spherical harmonic coefficients (SHCs) that describe monthly gravity potential, worldwide
- Difficult for non-specialists but doable
- Contain all information

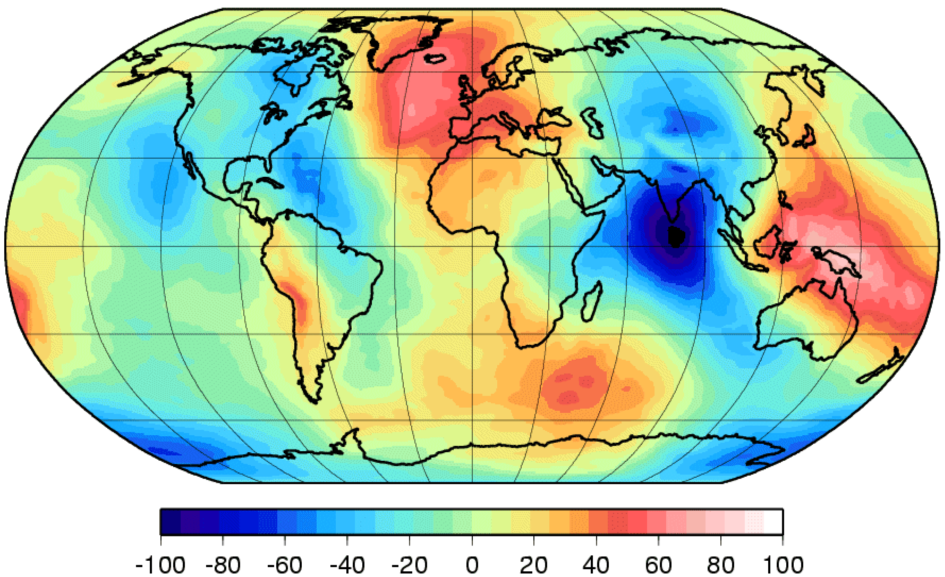
Level 3

- Monthly maps of water storage anomalies (1x1 deg)
- Easy to work with for non-specialists
- Does not contain all info

(what you have to do when working with the SHCs from the data centers)

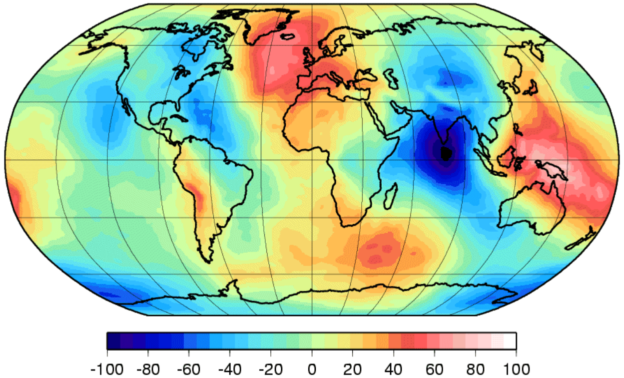
$$V(r,\theta,\lambda,t) = \frac{GM}{r}$$
$$+ \frac{GM}{r} \sum_{n=2}^{\bar{n}} \left(\frac{R}{r}\right)^n \sum_{m=0}^{n} P_{nm}(\cos\theta) \left(\bar{C}_{nm}(t) \cos m\lambda + \bar{S}_{nm}(t) \sin m\lambda\right)$$

Data centers provide each month (since ~4/2002) gravity SHCs



GRACE data: SH coefficients

$$V(r,\theta,\lambda,t) = \frac{GM}{r} + \frac{GM}{r}\sum_{n=2}^{\bar{n}}\left(\frac{R}{r}\right)^{n}\sum_{m=0}^{n} P_{nm}(\cos\theta)\left(\bar{C}_{nm}(t)\cos m\lambda + \bar{S}_{nm}(t)\sin m\lambda\right)$$



Normalized SH coefficients

```
3.986004415e14
6.3781363e+06
360
   0    0   1.0000000000000000e+00   0.0000000000000000e+00
   1    0   0.0000000000000000e+00   0.0000000000000000e+00
   1    1   0.0000000000000000e+00   0.0000000000000000e+00
   2    0   4.8416537173600000e-04   0.0000000000000000e+00
   2    1  -1.8698763595500000e-10   1.1952801203099999e-09
   2    2   2.4391435239799998e-06  -1.4001668365399999e-06
   3    0   9.5725417379199997e-07   0.0000000000000000e+00
   3    1   2.0299888218400001e-06   2.4851315871599998e-07
   3    2   9.0462776860499998e-07  -6.1902594420499998e-07
   3    3   7.2107265705700001e-07   1.4143562695799999e-06
   4    0   5.3987386378900003e-07   0.0000000000000000e+00
   4    1  -5.3632161697100004e-07  -4.7344026585300002e-07
   4    2   3.5069410578500000e-07   6.6267157254000005e-07
   4    3   9.9077180382900004e-07  -2.0092836917700000e-07
   4    4  -1.8856080273499999e-07   3.0885316933300002e-07
   5    0   6.8532347563000006e-08   0.0000000000000000e+00
   5    1  -6.2101212852799994e-08  -9.4422612752500001e-08
   5    2   6.5243829761200005e-07  -3.2334961266800000e-07
   5    3  -4.5195540607099999e-07  -2.1484719062400001e-07
   5    4  -2.9530164765400001e-07   4.9665887676899997e-08
```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<R>6.37813700000000e+06</R>
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<cnm degree="0" order="0">1.00000000000000e+00</cnm>
<cnm degree="2" order="0">-4.84165532804000e-04</cnm>
<cnm degree="2" order="1">8.57179552165000e-13</cnm>
<snm degree="2" order="1">2.89607376372000e-12</snm>
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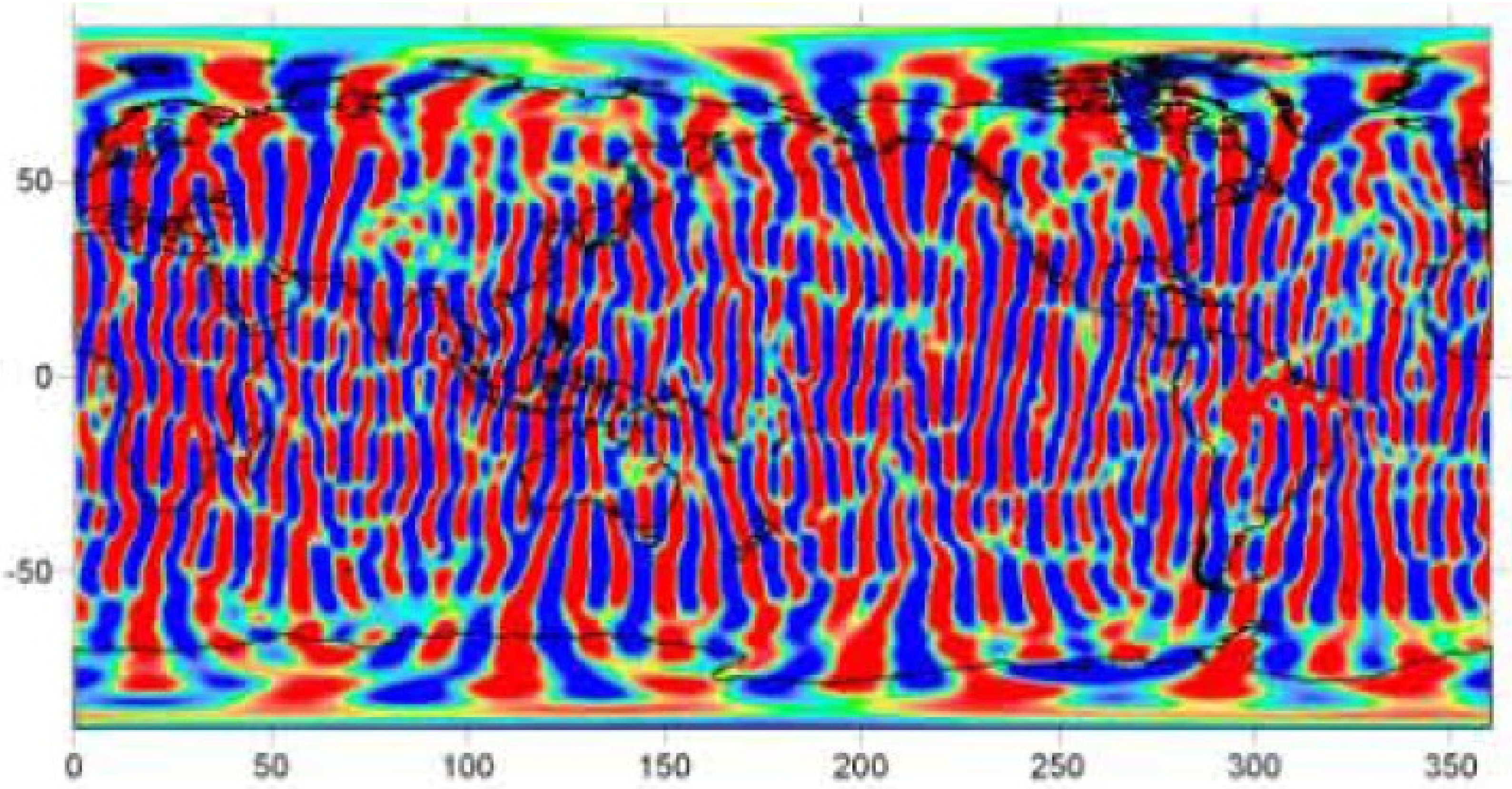
<snm degree="2" order="2">-1.39990174643000e-06</snm>
<cnm degree="3" order="0">9.57139401177000e-07</cnm>
<cnm degree="3" order="1">2.02968777310000e-06</cnm>
<snm degree="3" order="1">2.49431310090000e-07</snm>
<cnm degree="3" order="2">9.04648670700000e-07</cnm>
```

Unfiltered GRACE data looks very noise: example here – total water storage



$$F_W(\lambda,\theta)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n} w_n \bar{f}_{nm}\bar{Y}(\lambda,\theta)$$

Spatial Averaging to Improve Accuracy

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. B9, 2193, doi:10.1029/2001JB000576, 2002

Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity

Sean Swenson and John Wahr
Department of Physics and Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, USA

Received 8 May 2001; revised 9 March 2002; accepted 14 March 2002; published 19 September 2002.

[1] The Gravity Recovery and Climate Experiment, GRACE, will deliver monthly averages of the spherical harmonic coefficients describing the Earth's gravity field, from which we expect to infer time-variable changes in mass, averaged over arbitrary regions having length scales of a few hundred kilometers and larger, to accuracies of better than 1 cm of equivalent water thickness. These data will be useful for examining changes in the distribution of water in the ocean, in snow and ice on polar ice sheets, and in continental water and snow storage. We describe methods of extracting regional mass anomalies from GRACE gravity coefficients. Spatial averaging kernels were created to isolate the gravity signal of individual regions while simultaneously minimizing the effects of GRACE observational errors and contamination from surrounding glacial, hydrological, and oceanic gravity signals. We then estimated the probable accuracy of averaging kernels for regions of arbitrary shape and size. *INDEX TERMS:* 1836 Hydrology: Hydrologic budget (1655); 4283 Oceanography: General: Water masses; 1655 Global Change: Water cycles (1836); 1243 Geodesy and Gravity: Space geodetic surveys; 1640 Global Change: Remote sensing; *KEYWORDS:* GRACE, satellite gravity, hydrology, time-variable gravity, regional water storage

Citation: Swenson, S., and J. Wahr, Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity, *J. Geophys. Res.*, *107*(B9), 2193, doi:10.1029/2001JB000576, 2002.

1. Introduction

[2] Time-variable gravity changes are caused by a combination of postglacial rebound, fluctuations in atmospheric mass, and the redistribution of water, snow, and ice on land heat storage, as well as deep ocean currents. In polar regions, GRACE data can be used to study postglacial rebound and, in conjunction with laser altimetry, to constrain the mass balance of ice sheets.

For example your kernel could be:

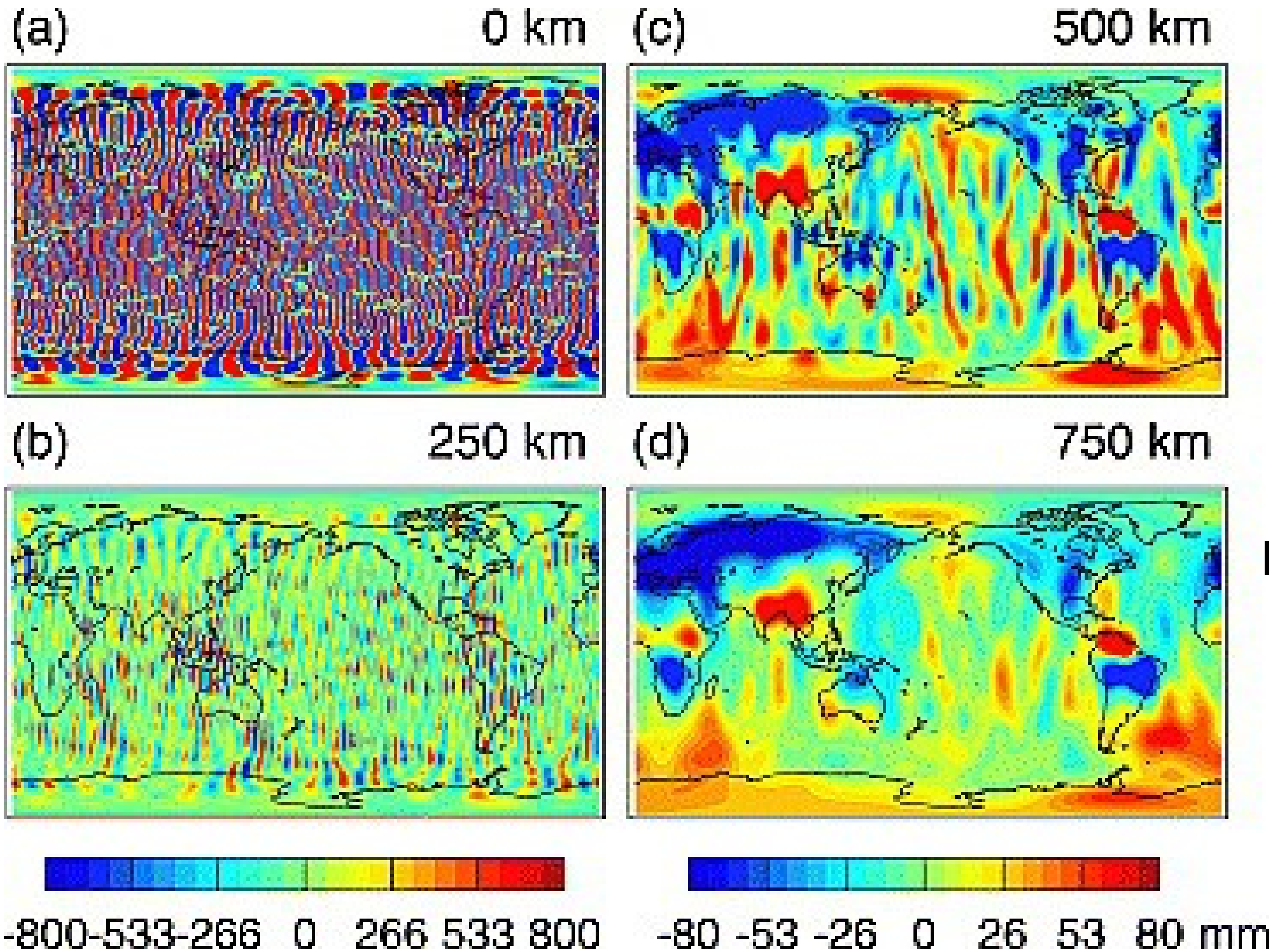
$$\vartheta(\theta,\phi) = \begin{cases} 0 & \text{outside the basin} \\ 1 & \text{inside the basin} \end{cases}$$

$$\overline{\Delta\sigma}_{\text{region}} = \frac{1}{\Omega_{\text{region}}} \int \Delta\sigma(\theta,\phi)\,\vartheta(\theta,\phi)\,d\Omega,$$

radius of spatial filtering

$$\overline{\Delta\sigma}_{\text{region}} = \frac{a\,\rho_E}{3\,\Omega_{\text{region}}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{(2l+1)}{(1+k_l)} \left(\vartheta^c_{lm}\Delta C_{lm} + \vartheta^s_{lm}\Delta S_{lm}\right),$$

Filtering: two steps – spatial average or smoothing



Isotropic Gaussian filter

GRACE-derived maps of monthly anomaly of water storage, smoothed with **Gaussian (isotropic)** filters of different radius. (a) Unsmoothed; (b) 250 km radius; (c) 500 km radius; (d) 750 km radius. (Swenson & Wahr, 2007)

Filtering: two steps – decorrelation/Destriping filter

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L08402, doi:10.1029/2005GL025285, 2006

Post-processing removal of correlated errors in GRACE data

Sean Swenson[1] and John Wahr[1]

Received 21 November 2005; revised 7 February 2006; accepted 1 March 2006; published 25 April 2006.

[1] Gravity fields produced by the Gravity Recovery and Climate Experiment (GRACE) satellite mission require smoothing to reduce the effects of errors present in short wavelength components. As the smoothing radius decreases, these errors manifest themselves in maps of surface mass variability as long, linear features generally oriented north to south (i.e., stripes). The presence of stripes implies correlations in the gravity field coefficients. Here we examine the spectral signature of these correlated errors, and present a method to remove them. Finally, we apply the filter to a model of surface-mass variability to show that the filter has relatively little degradation of the underlying geophysical signals we seek to recover. **Citation:** Swenson, S., and J. Wahr (2006), Post-processing removal of correlated errors in GRACE data, *Geophys. Res. Lett.*, *33*, L08402, doi:10.1029/2005GL025285.

1. Introduction

[2] Monthly estimates of the Earth's gravity field produced by the Gravity Recovery and Climate Experiment (GRACE) mission [*Tapley et al.*, 2004a] can be used to infer changes in mass at and below the surface of the Earth [*Wahr et al.*, 1998]. A number of studies have exploited this relationship to make estimates of water storage variability, both on land and in the oceans [*Swenson and Milly*, 2006; *Ramillien et al.*, 2005; *Chen et al.*, 2005; *Velicogna and Wahr*, 2005; *Tamisiea et al.*, 2005; *Chambers et al.*, 2004; *Tapley et al.*, 2004b; *Wahr et al.*, 2004]. The water storage estimates used in these studies are typically presented as spatial averages over regions having scales of a few long, linear features, commonly referred to as "stripes". As the level of smoothing is increased the amplitude of the stripes decreases, until geophysical signals become apparent, typically at averaging scales of a few hundred km or larger [*Chen et al.*, 2005].

[5] The presence of stripes indicates a high degree of spatial correlation in the GRACE errors. Here, we identify the spectral signature of the correlations between spherical harmonic coefficients that is manifested in the striped patterns seen in GRACE maps. We then design a filter to remove correlated errors in the Stokes coefficients, and apply the filter to GRACE data. Finally, we apply the filter to a model of surface-mass variability to estimate the extent to which the filter degrades the geophysical signals of interest.

2. Correlated Errors

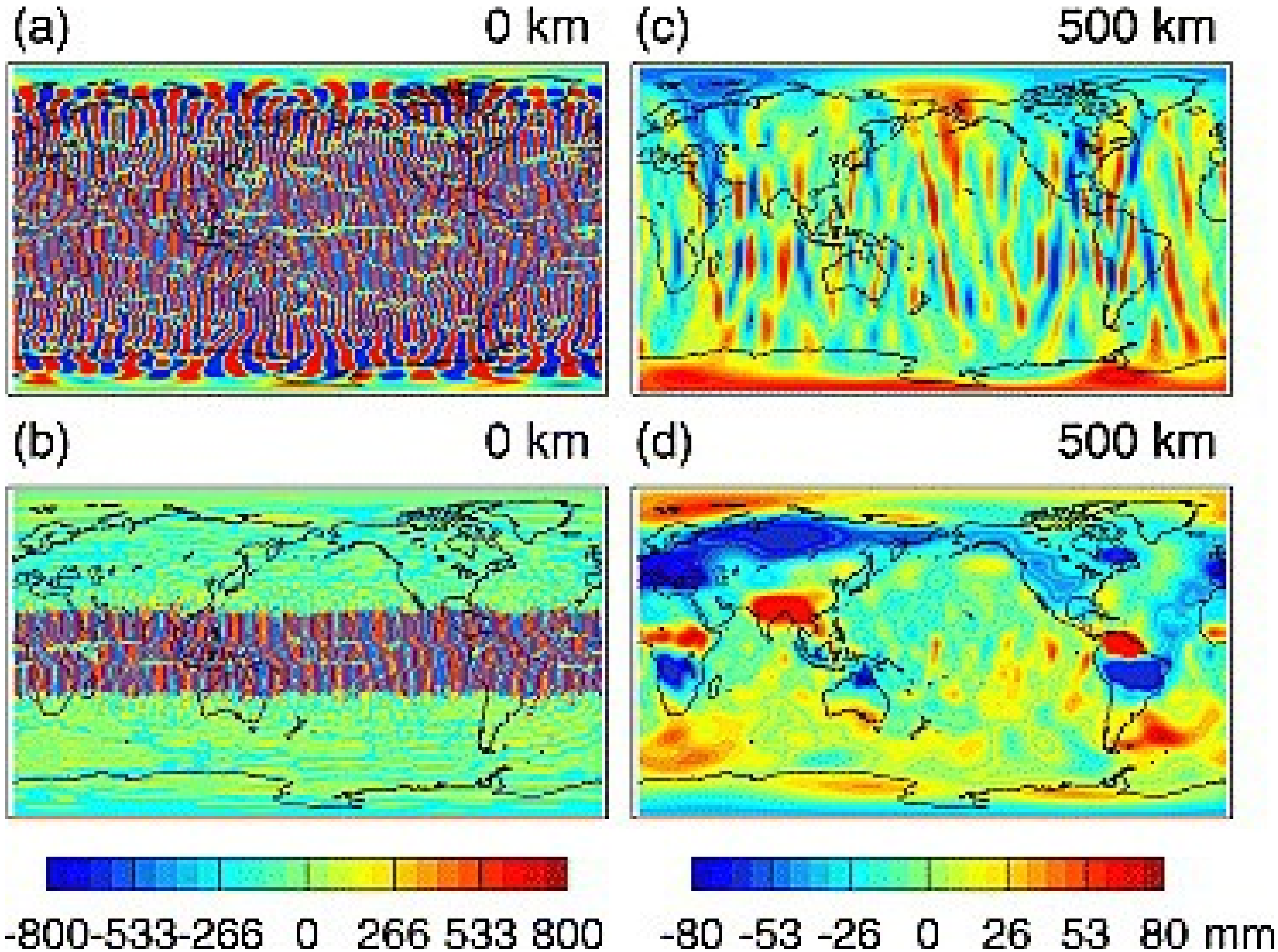
2.1. Spatial Domain

[6] Because of the absence of suitable ground-truth observations, preliminary validation of GRACE data has taken the form of comparisons between GRACE-derived and model-derived estimates of surface-mass variability. Studies such as *Wahr et al.* [2004] and *Tapley et al.* [2004b] have shown good agreement between estimates of water storage changes from GRACE and those from models. Error analyses based on internal consistency tests provide model-independent upper bounds on the errors in the GRACE fields; these analyses indicate root-mean-square errors of approximately 1 cm for surface-mass estimates smoothed with a 1000 km Gaussian filter [*Wahr*

Monthly SHCs are correlated due to sensor errors, orbit geometry, and errors in background model.

Swenson & Wahr suggested to smooth the SHCs for a particular order (m) with a quadratic polynomial

Filtering: two steps – decorrelation + smoothing



GRACE-derived maps of monthly anomaly of water storage. (a) Unfiltered, no smoothing; (b) filtered with correlated-error filter, no smoothing; (c) unfiltered and smoothed with 500 km Gaussian; (d) filtered with correlated-error filter and smoothed with 500 km Gaussian. (Swenson & Wahr, 2007)

Filtering: two steps – DDK filter

J Geod (2007) 81:733–749
DOI 10.1007/s00190-007-0143-3

ORIGINAL ARTICLE

Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-type gravity field models

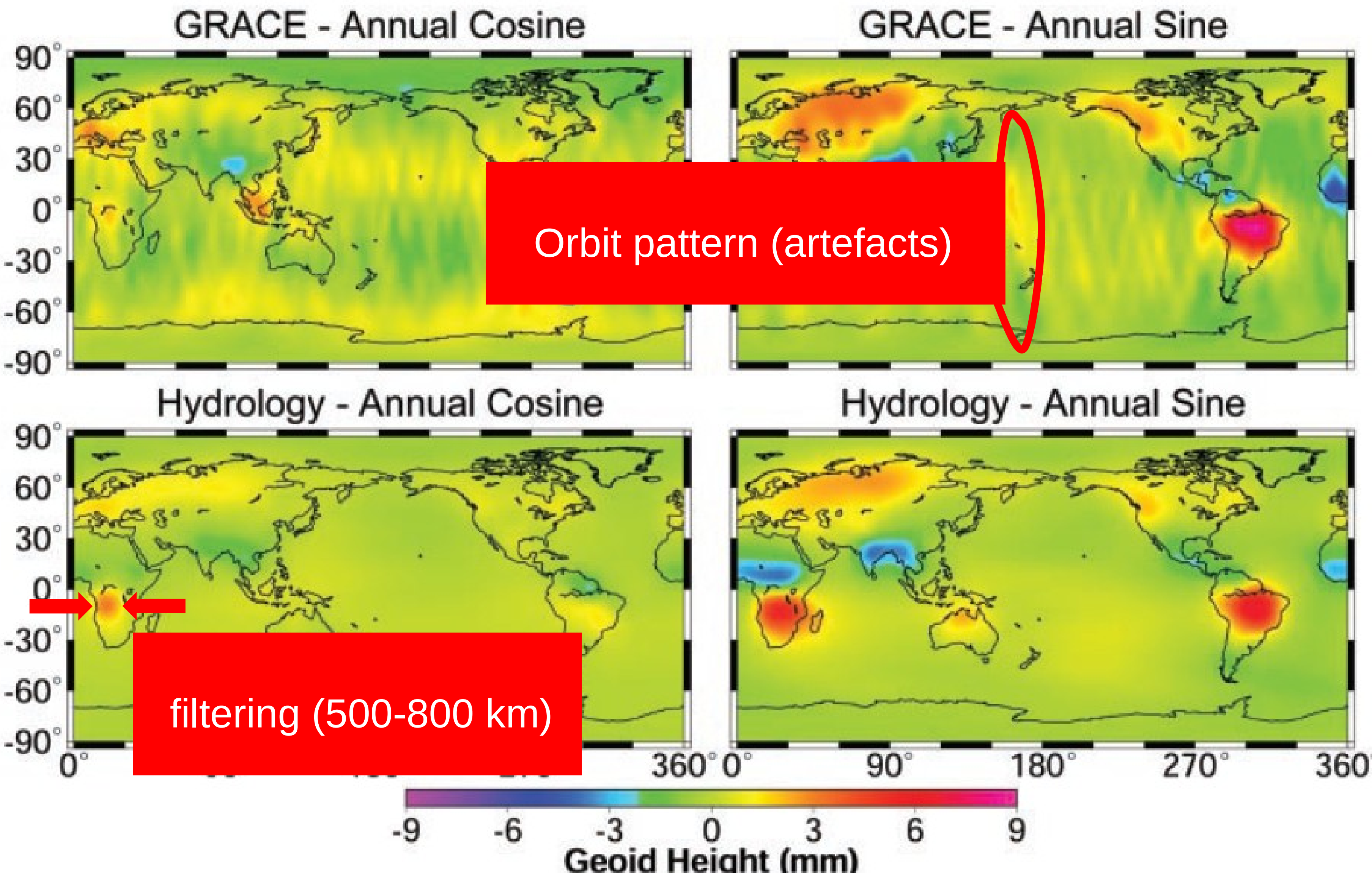
Jürgen Kusche

Received: 15 August 2006 / Accepted: 4 February 2007 / Published online: 27 February 2007

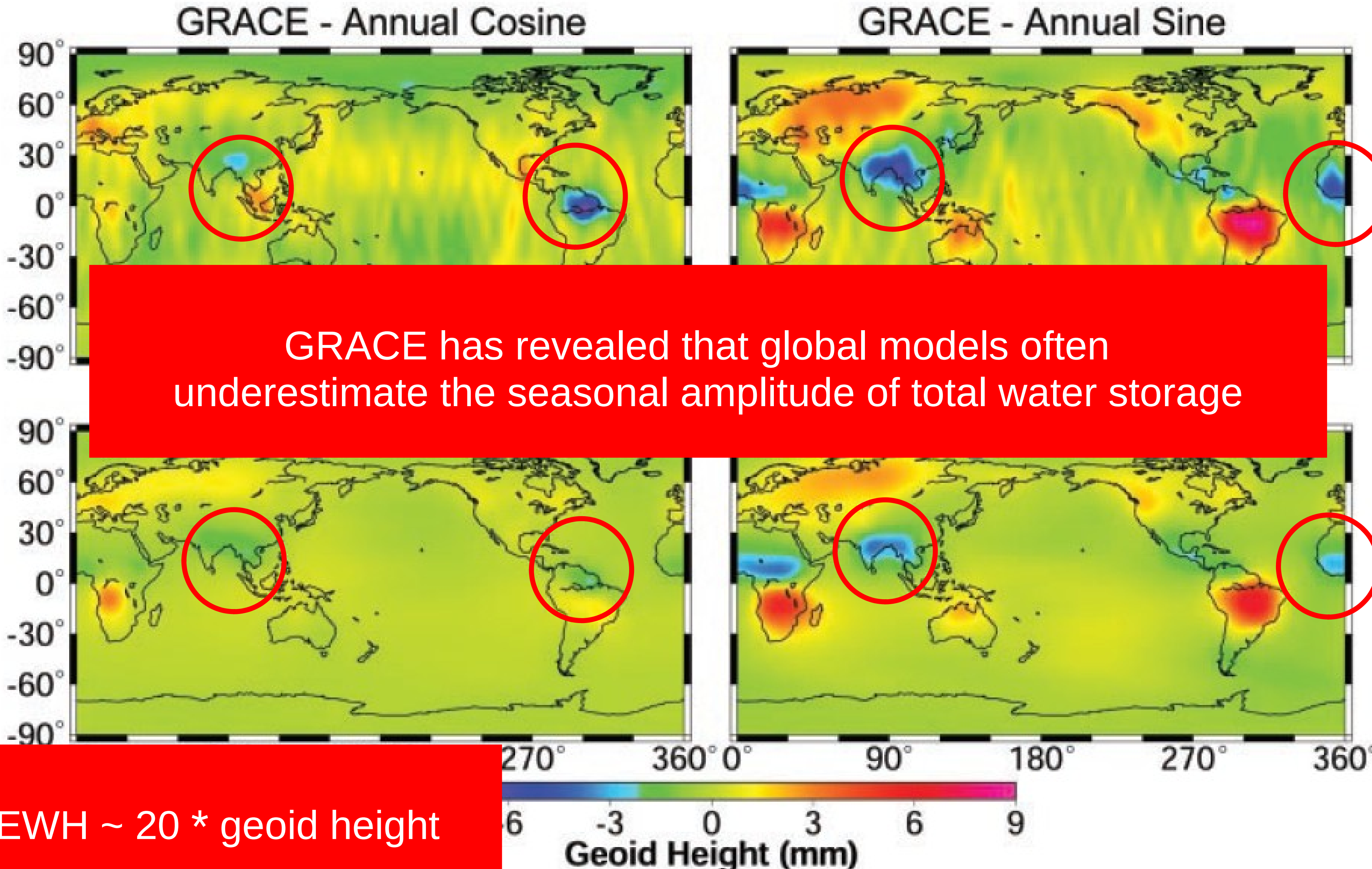
Abstract We discuss a new method for approximately decorrelating and non-isotropically filtering the monthly gravity fields provided by the gravity recovery and climate experiment (GRACE) twin-satellite mission. The procedure is more efficient than conventional Gaussian-type isotropic filters in reducing stripes and spurious patterns, while retaining the signal magnitudes. One of the problems that users of GRACE level 2 monthly gravity field solutions fight is the effect of increasing noise in higher frequencies. Simply truncating the spherical harmonic solution at low degrees causes the loss of a significant portion of signal, which is not an option if one is interested in geophysical phenomena on a scale of few hundred to few thousand km. The common approach is to filter the published solutions, that is to convolve them transformations applied to the monthly solutions, which enable a successive smoothing to reduce the noise in the higher frequencies. This smoothing effect may be used to generate solutions that behave, on average over all possible directions, very close to Gaussian-type filtered ones. The localizing and smoothing properties of our non-isotropic kernels are compared with Gaussian kernels in terms of the kernel variance and the resulting amplitude bias for a standard signal. Examples involving real GRACE level 2 fields as well as geophysical models are used to demonstrate the techniques. With the new method, we find that the characteristic striping pattern in the GRACE solutions are much more reduced than Gaussian-filtered solutions of comparable signal amplitude and root mean square.

Kusche designed a filter for GRACE SHCs using the a prior information about the unfiltered coefficients, that is GRACE error covariance matrix and signal covariance estimated from geophysical models

GRACE early results (Tapley et al., 2004, Science)



GRACE early results (Tapley et al., 2004, Science)



GRACE has revealed that global models often underestimate the seasonal amplitude of total water storage

EWH ~ 20 * geoid height

Issues with GRACE data

- Accuracy varies over mission lifetime (due to instrument aging and orbital pattern)
- For some months, data is missing (due to instrument problems)
- Level 2 data (SHCs): several corrections are required, some depend on application
- GRACE data has increasing noise at shorter scales → filtering of SHCs (level 2 data) is required
- Working with level 2 data may require seeking aid

- Level 2 data (SHCs) provided by 3 official data centres NASA JPL, CSR U Texas, GFZ Potsdam (GRACE SDS Science Data System)

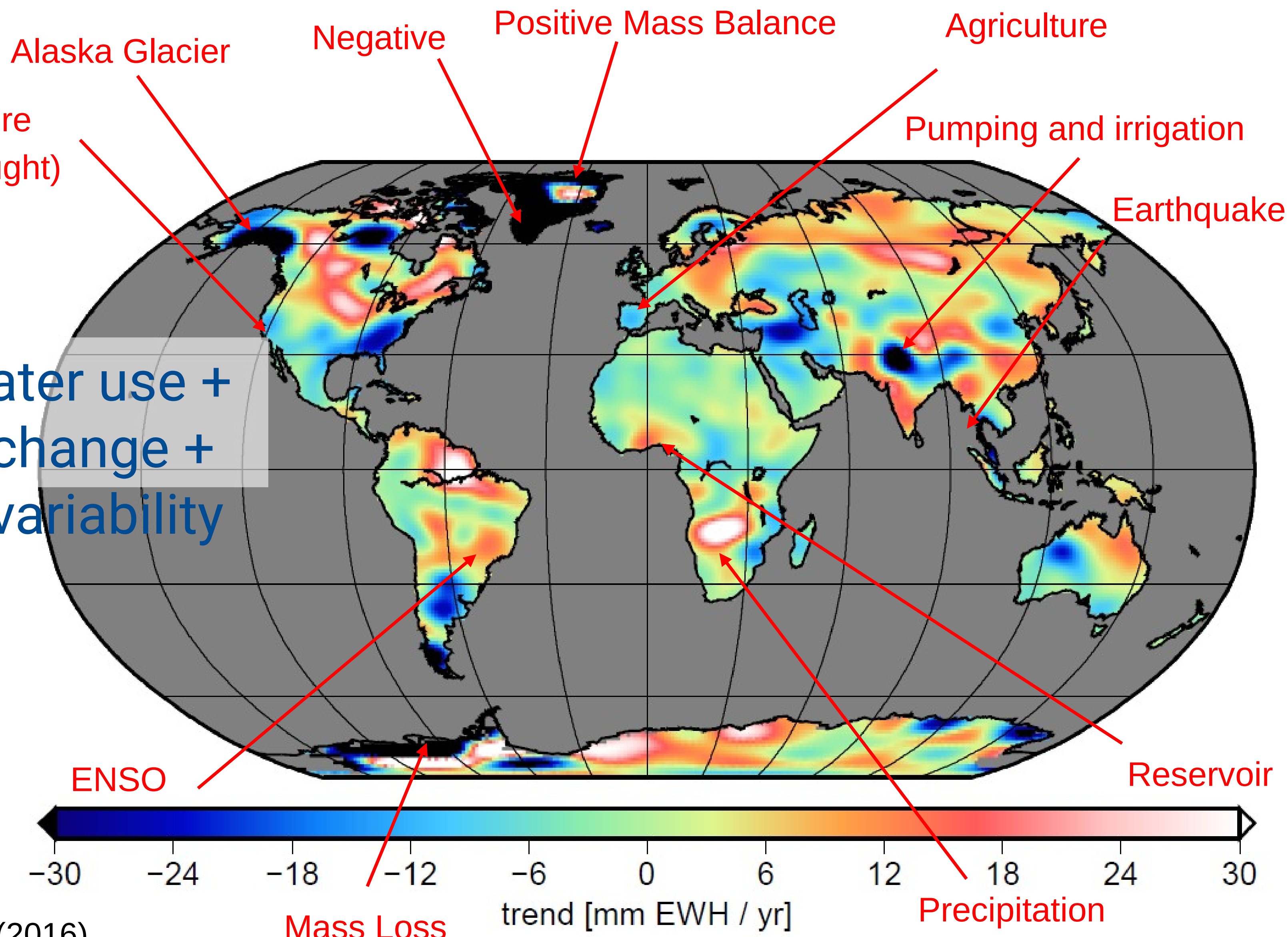
- several unofficial solutions (CNES/GRDS, Universities) available

- Several alternative data products available: mascon solutions, daily solutions, …

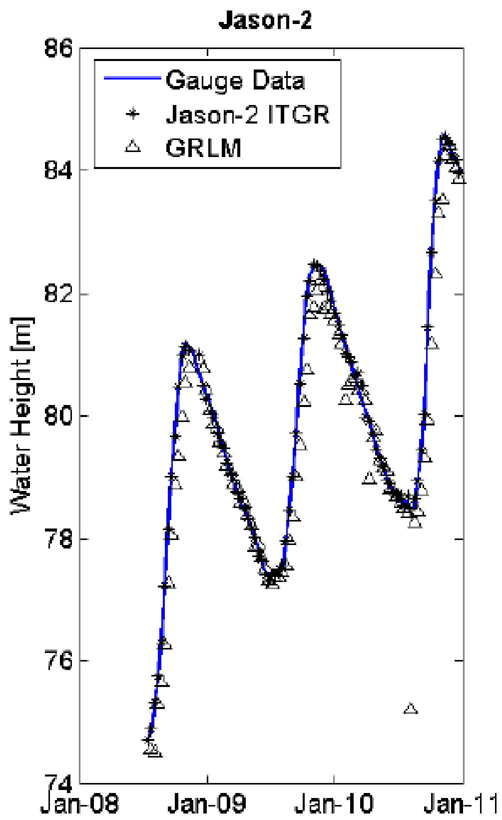
- Level 3 data (total water mass grids) are easy to use

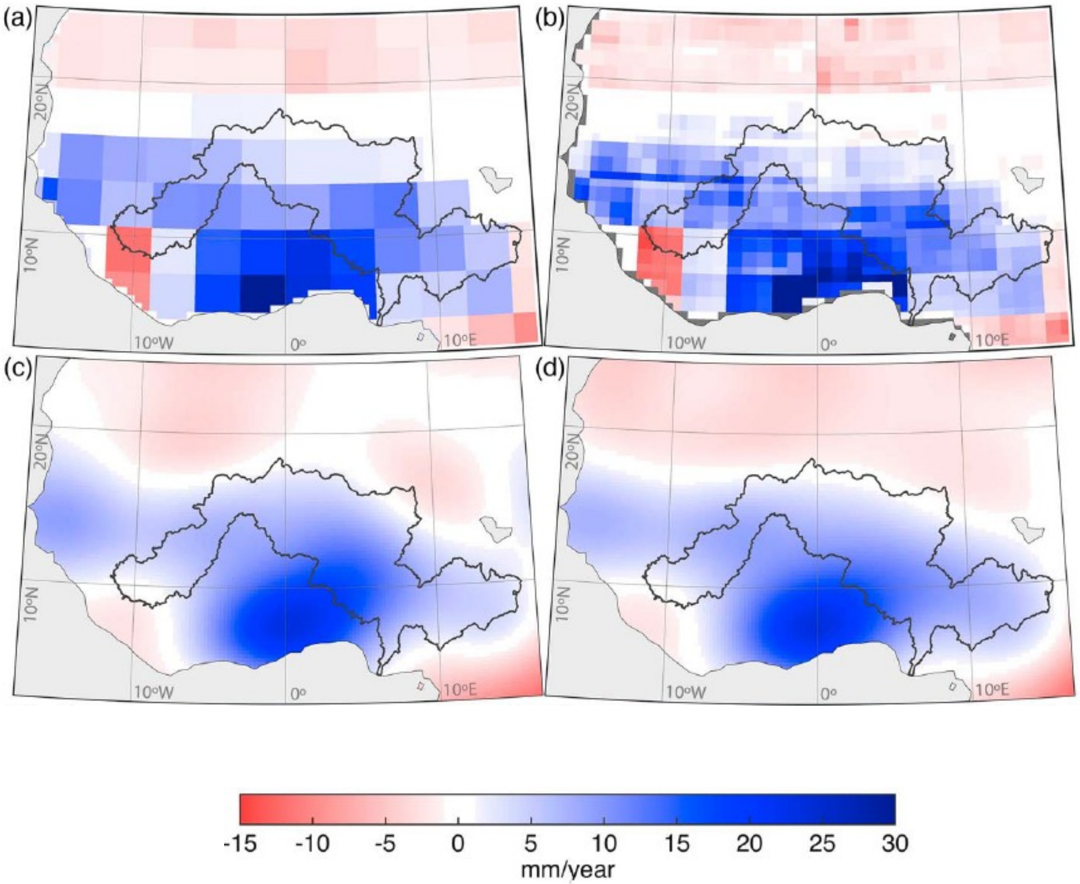
Applications: Land hydrology / water storage

direct water use +
climate change +
climate variability



Eicker et al. (2016)

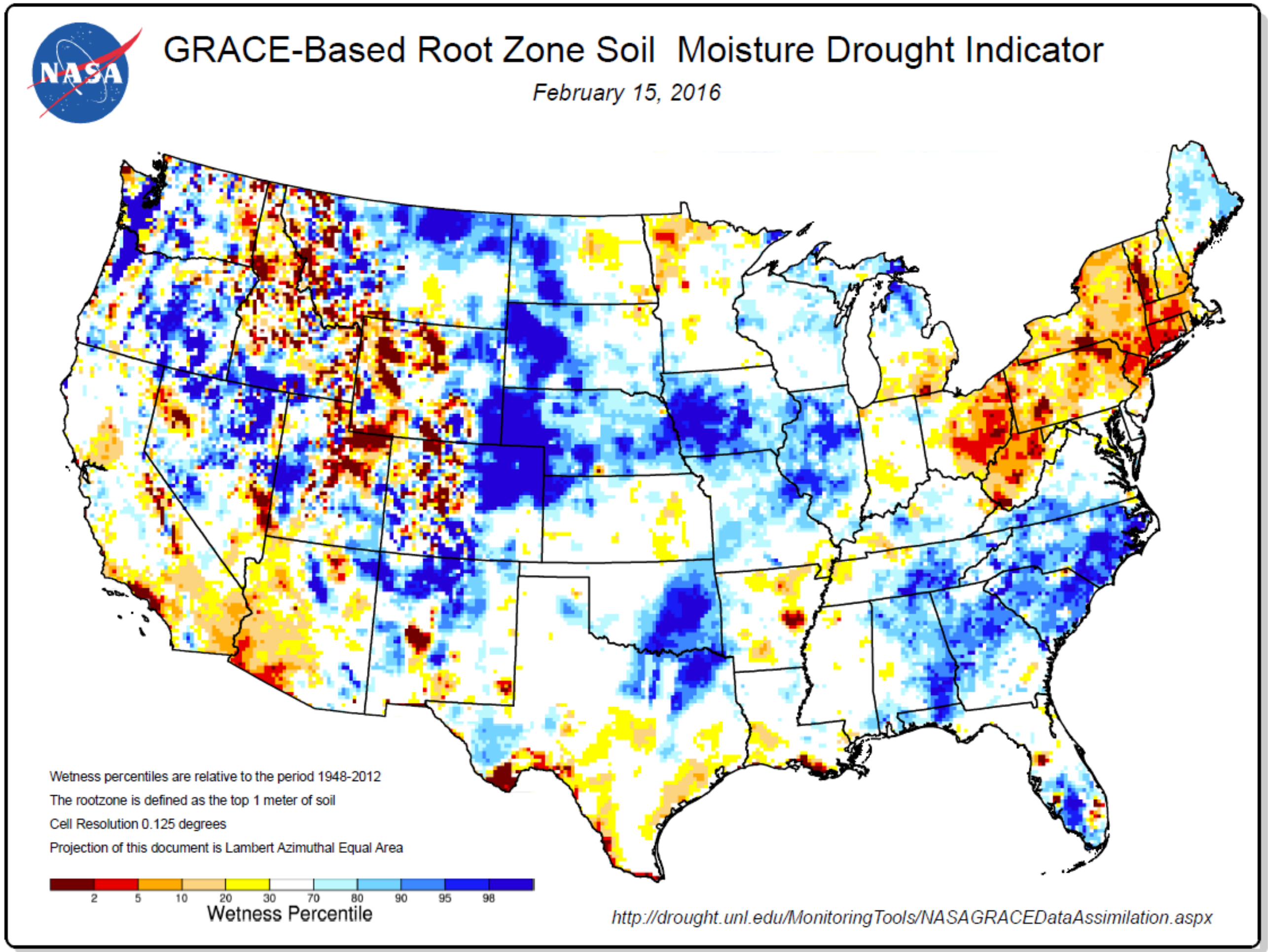




Werth et al., 2018:

Assimilation of GRACE data into hydrological models

- e.g. for drought monitoring



Data assimilation (DA) minimizes

$$\mathcal{J}(\mathbf{z}) = (\mathbf{z}-\mathbf{z}^*)^T \mathbf{C}_{\mathbf{z}^*\mathbf{z}^*}^{-1} (\mathbf{z}-\mathbf{z}^*) + (H(\mathbf{z})-\mathbf{y})^T \mathbf{C}_{\mathbf{ee}}^{-1} (H(\mathbf{z})-\mathbf{y})$$

Hydrological model:

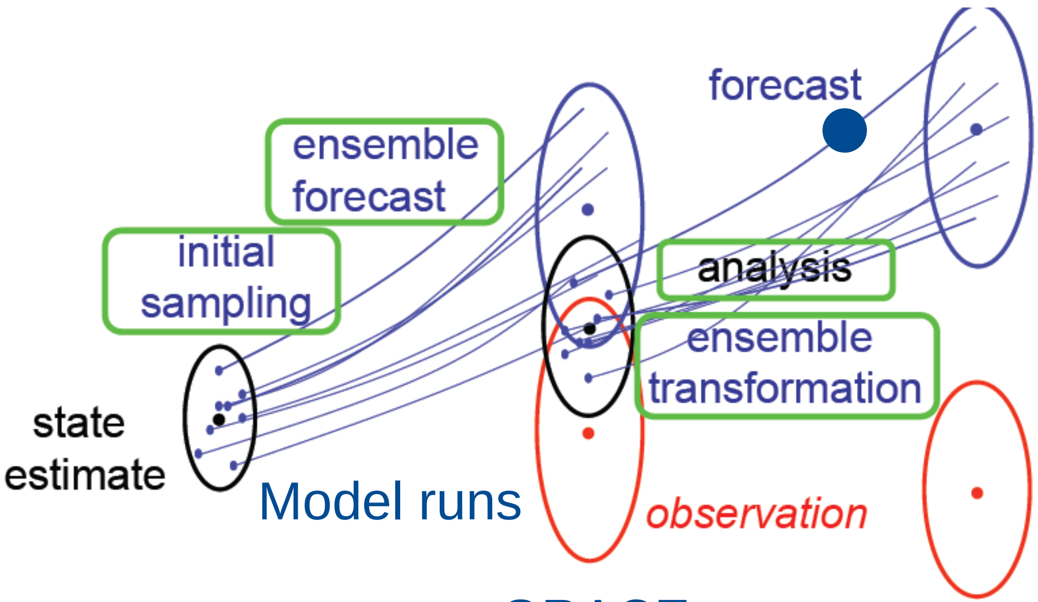
- storage (soil layers, surface water, groundwater…)
- grid cells
- E.g. daily time steps
- Calibration parameters

GRACE: total water storage anomalies (TWSA)

Döll et al (2003):

DA minimizes

$$\mathcal{J}(\mathbf{z}) = (\mathbf{z}-\mathbf{z}^*)^T \mathbf{C}_{\mathbf{z}^*\mathbf{z}^*}^{-1} (\mathbf{z}-\mathbf{z}^*) + (H(\mathbf{z})-\mathbf{y})^T \mathbf{C}_{\mathbf{ee}}^{-1} (H(\mathbf{z})-\mathbf{y})$$

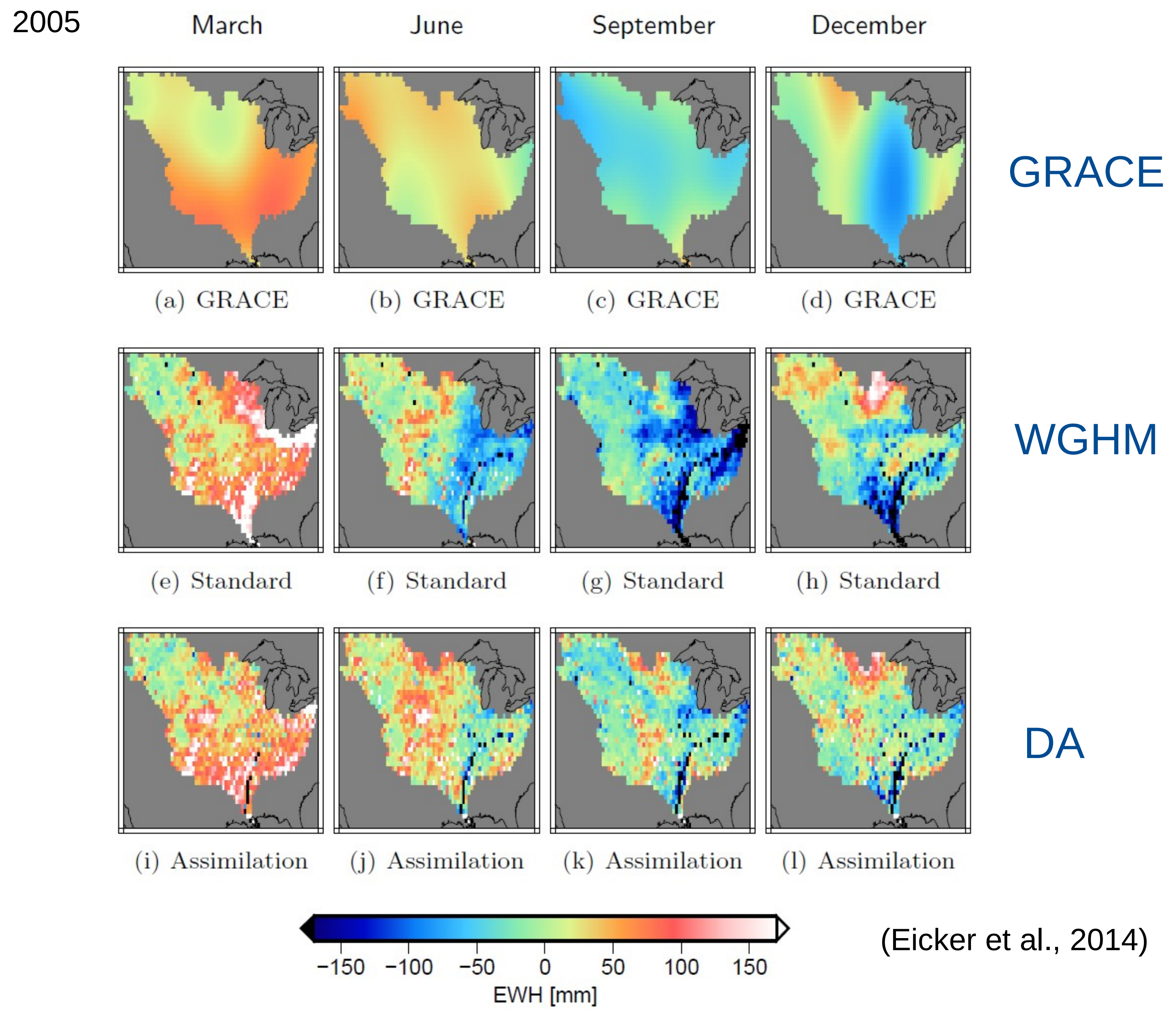


GRACE: Error variance covariance matrix for gridded EWH

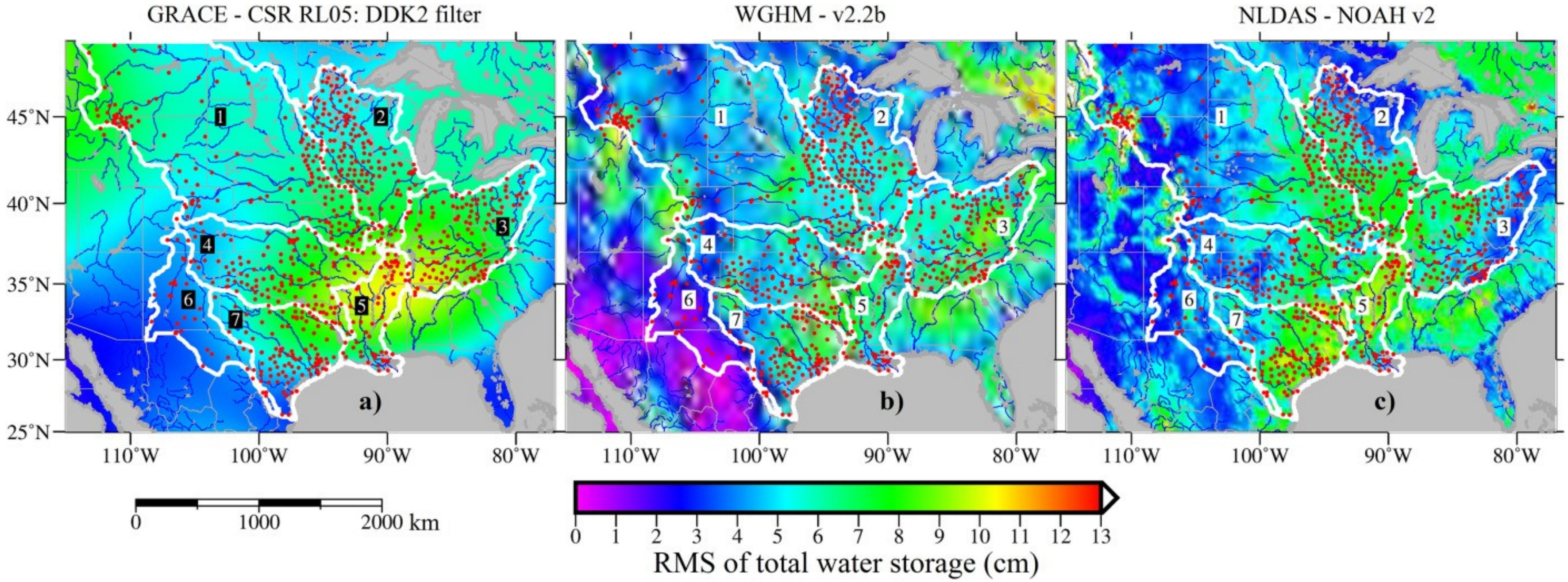
GRACE

Ensemble Kalman Filter

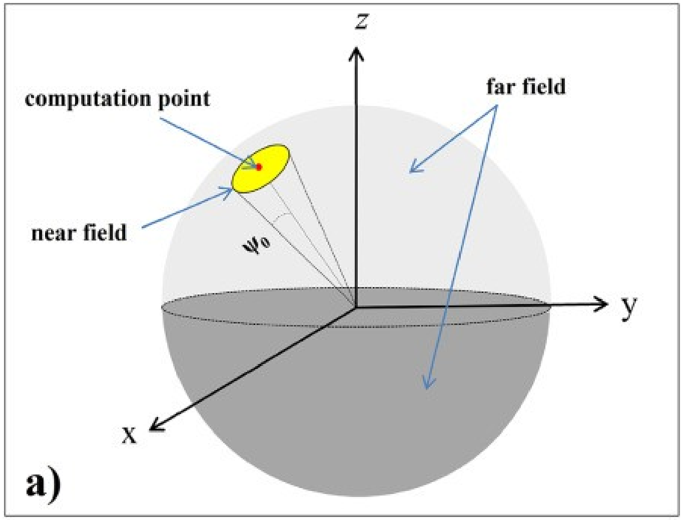
Integration of GRACE data into models by data assimilation



(Eicker et al., 2014)

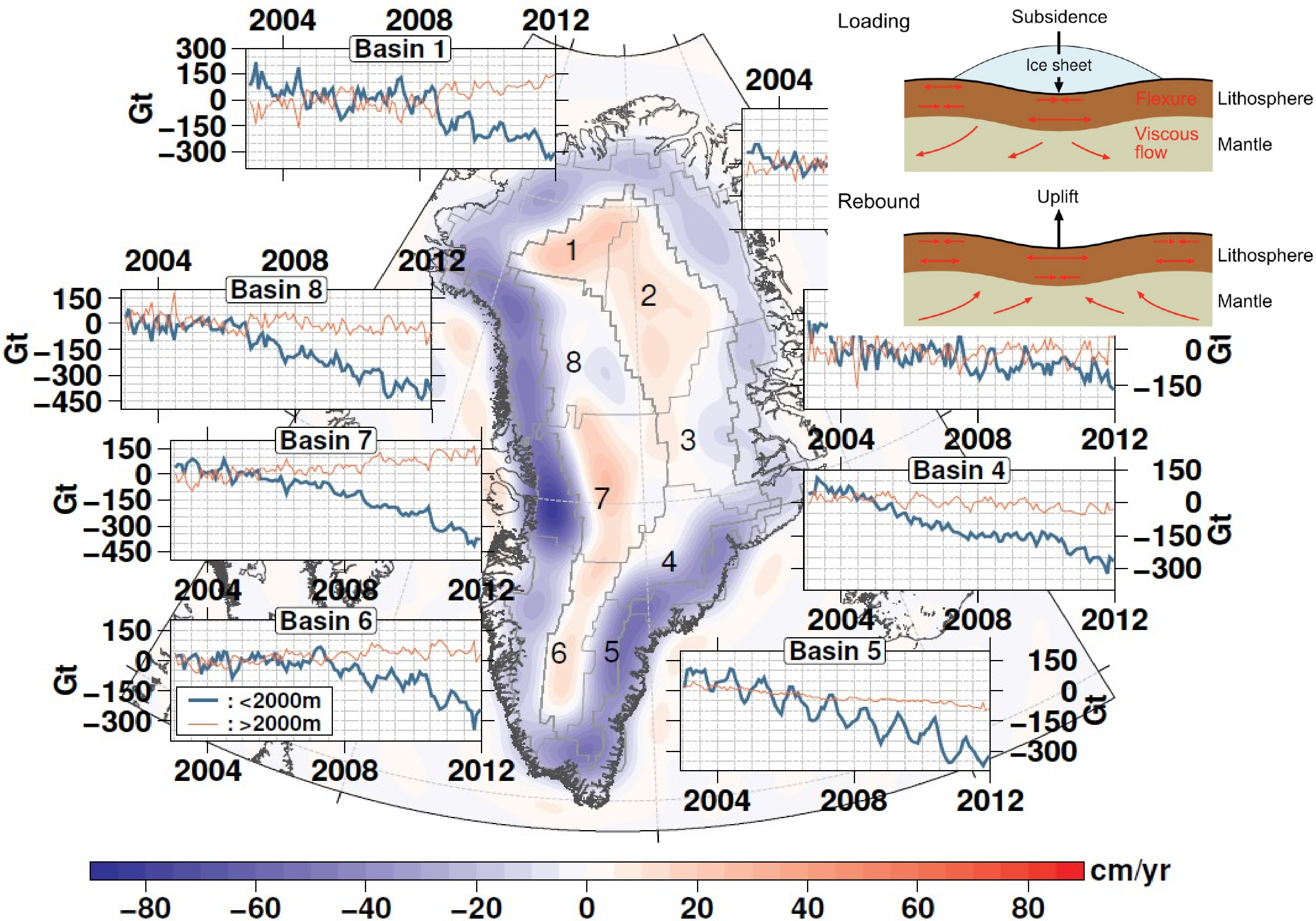


Hydrological model provides TWS with higher spatial resolutions than GRACE. A hybrid approach was suggested to combine GRACE and hydro model in order to better estimate hydrological loading deformation (more in the next lecture)



(Karegar et al., 2018)

Greenland ice mass imbalance due to global warming



Comprehensive archive:

http://icgem.gfz-potsdam.de/home

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 360

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   3    1  2.0299888218400001e-06  2.4851315871599998e-07
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   4    2  3.5069410578500000e-07  6.6267157254000005e-07
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   5    2  6.5243829761200005e-07 -3.2334961266800000e-07
   5    3 -4.5195540607099999e-07 -2.1484719062400001e-07
   5    4 -2.9530164765400001e-07  4.9665887676899997e-08
```

Gravity Field Solutions for dedicated Time Periods

The following gravity field time series are presently available:

GRACE and Grace-FO solutions from the Science Data System centers CSR, GFZ and JPL — collapse all

- **CSR**				**Center for Space Research at University of Texas, Austin**
CSR Release 05		monthly		UTCSR Level-2 Processing Standards Document, Rev 4.0 May 29, 2012
CSR Release 06	DOI	monthly		UTCSR Level-2 Processing Standards Document, Rev 5.0 April 18, 2018
CSR Release 06 (GFO)	DOI	monthly		UTCSR Level-2 Processing Standards Document, V 1.1 June 6, 2019
- **GFZ**				**Helmholtz Centre Potsdam German Research Centre for Geosciences**
GFZ Release 05		monthly	weekly	GFZ GRACE Level-2 Processing, Revised Edition, January 2013
GFZ Release 06	DOI	monthly		GFZ GRACE Level-2 Processing Standards Document for Level-2 Products, Rev. 1.0, October 26, 2018
GFZ Release 06 (GFO)	DOI	monthly		GFZ GRACE Level-2 Processing Standards Document for Level-2 Products, Rev. 1.0, June 3, 2019
- **JPL**				**Jet Propulsion Laboratory**
JPL Release 05		monthly		JPL Level-2 Processing Standards Document, Release 05.1 November 3, 2014
JPL Release 06	DOI	monthly		JPL Level-2 Processing Standards Document, Release 06.0 June 1, 2018
JPL Release 06 (GFO)	DOI	monthly		JPL Level-2 Processing Standards Document, v 1.0 May 28, 2019

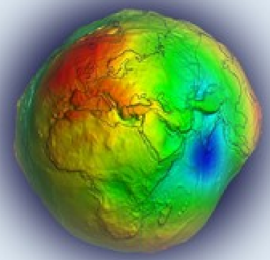
The processing standards to generate the GRACE Level-2 products of CSR, GFZ and JPL
are also available in the Document Section of the GRACE archives at GFZ ISDC or JPL PO.DAAC

COST-G (International Combination Service for Time-variable Gravity Field) — collapse all

GRACE		monthly
Swarm	DOI	monthly

GRACE / CHAMP solutions from other groups — expand all

+ AIUB	Astronomical Institute University Bern
+ CNES	Centre national d'études spatiales
+ EGSIEM	European Gravity Service for Improved Emergency Project
+ geo-Q	Leibniz Universität Hannover
+ HUST	Huazhong University of Science and Technology, Wuhan, PR China
+ IGG	Institute of Geodesy and Geophysics, Chinese Academy of Sciences, China
+ ITG	Institute of Geodesy and Geoinformation, Universität Bonn
+ ITSG	Institute of Geodesy at Graz University of Technology (ITSG)



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GFZ
Helmholtz Centr
POTSDAM

Gravity Field Solutions for dedicated Time Periods

JPL / JPL Release 05

You can download all the models in this set as zip (138.2 MiB) or you can find subsets and single model files below.
It can take a moment to generate the zip file for you.
You can also find these files at ftp://icgem.gfz-potsdam.de/01_GRACE/JPL/JPL Release 05.

DDK1	zip	(15.4 MiB)
DDK2	zip	(15.4 MiB)
DDK3	zip	(15.4 MiB)
DDK4	zip	(15.4 MiB)
DDK5	zip	(15.4 MiB)
DDK6	zip	(15.4 MiB)
DDK7	zip	(15.4 MiB)
DDK8	zip	(15.3 MiB)
non-iso	zip	(22 Bytes)
unfiltered	zip	(15.0 MiB)

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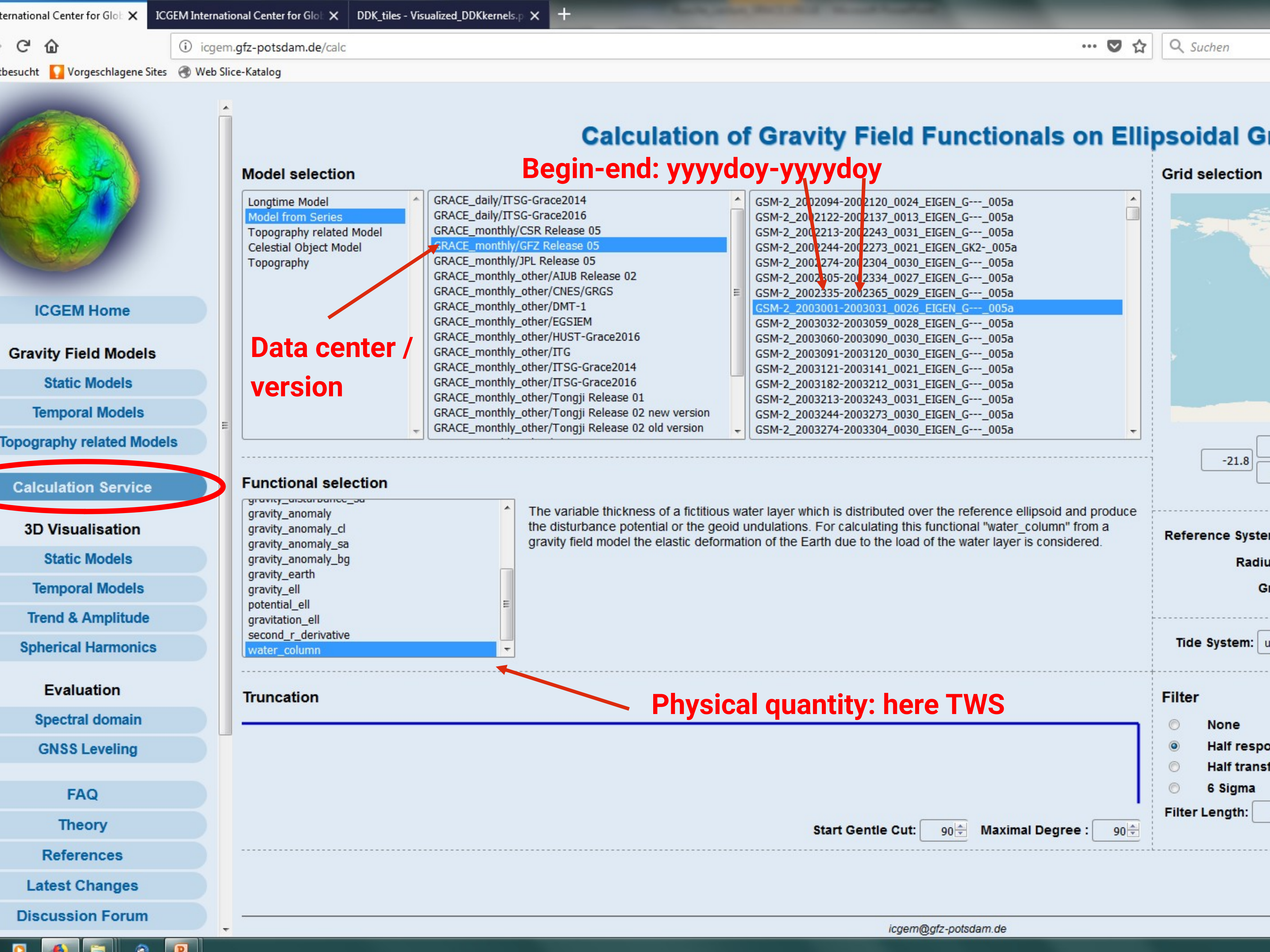

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Grid selection
Longtime Model
Model from Series
Topography related Model
Celestial Object Model
Topography
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GRACE_daily/ITSG-Grace2016
GRACE_monthly/CSR Release 05
GRACE_monthly/GFZ Release 05
GRACE_monthly/JPL Release 05
GRACE_monthly_other/AIUB Release 02
GRACE_monthly_other/CNES/GRGS
GRACE_monthly_other/DMT-1
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GRACE_monthly_other/HUST-Grace2016
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Functional selection
gravity_anomaly
gravity_anomaly_cl
gravity_anomaly_sa
gravity_anomaly_bg
gravity_earth
gravity_ell
potential_ell
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water_column
The variable thickness of a fictitious water layer which is distributed over the reference ellipsoid and produce the disturbance potential or the geoid undulations. For calculating this functional "water_column" from a gravity field model the elastic deformation of the Earth due to the load of the water layer is considered.
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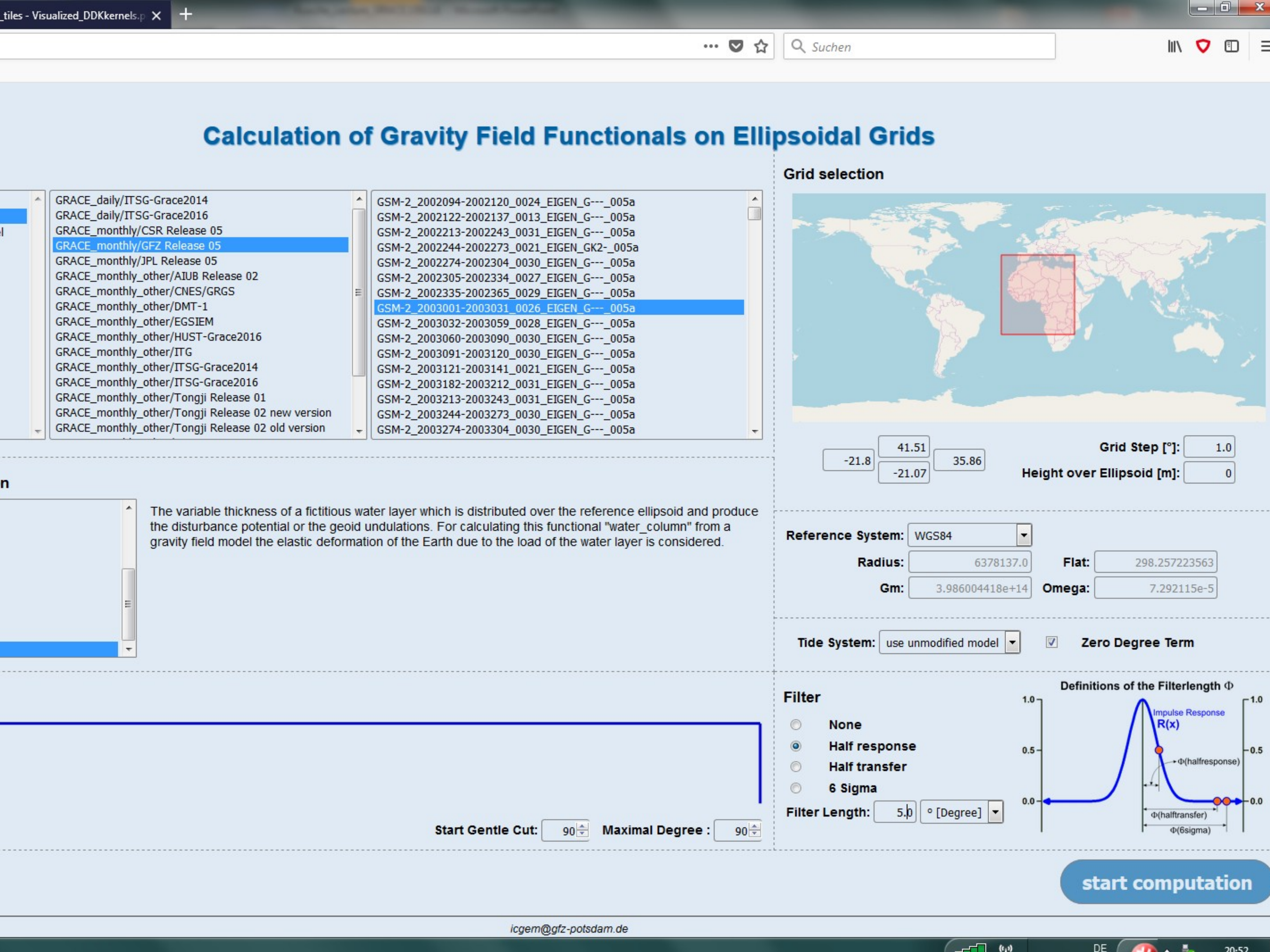
Maximal Degree : 90
icgem@gfz-potsdam.de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Suchen
Calculation of Gravity Field Functionals on Ellipsoidal Grids
GRACE_daily/ITSG-Grace2014
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GRACE_monthly/CSR Release 05
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GRACE_monthly_other/AIUB Release 02
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GRACE_monthly_other/Tongji Release 02 new version
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The variable thickness of a fictitious water layer which is distributed over the reference ellipsoid and produce the disturbance potential or the geoid undulations. For calculating this functional "water_column" from a gravity field model the elastic deformation of the Earth due to the load of the water layer is considered.
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Flat: 298.257223563
Gm: 3.986004418e+14
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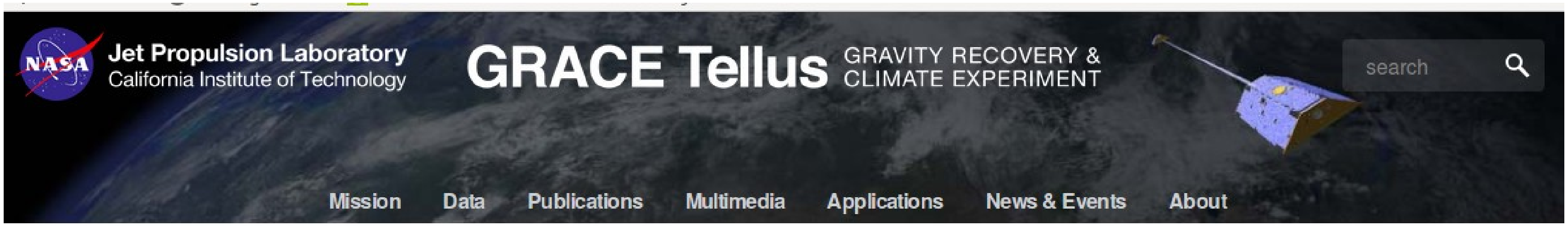
icgem@gfz-potsdam.de



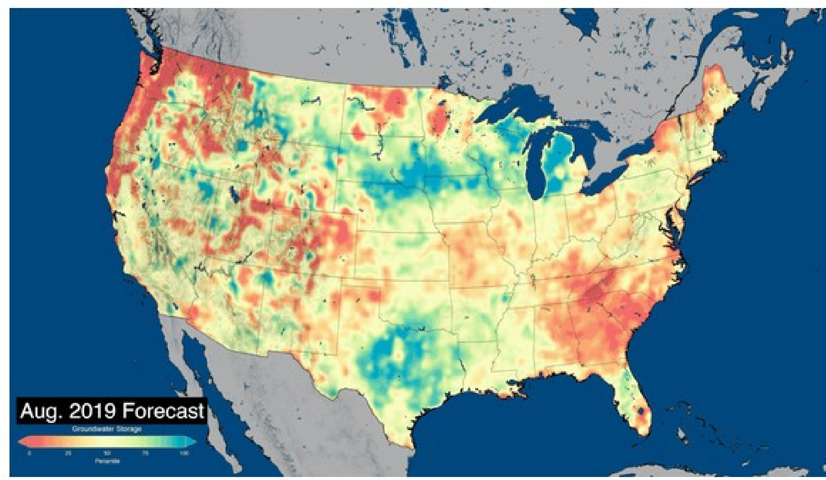
Measuring Earth's Surface Mass and Water Changes

NASA, University of Nebraska Release New Global Groundwater Maps and U.S. Drought Forecasts

During the exceptionally warm Arctic summer of 2019, Greenland lost 600 billion tons of ice - enough to raise global sea levels by nearly a tenth of an inch (2.2 millimeters) in just two months, a new study shows.

› Full Story

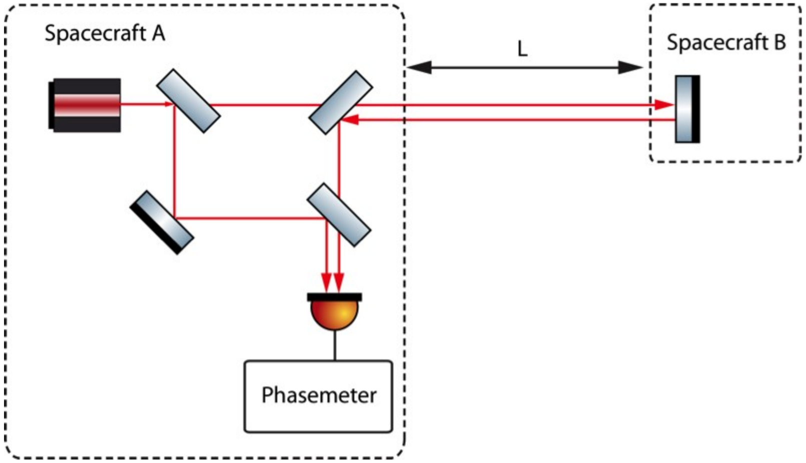
› All News

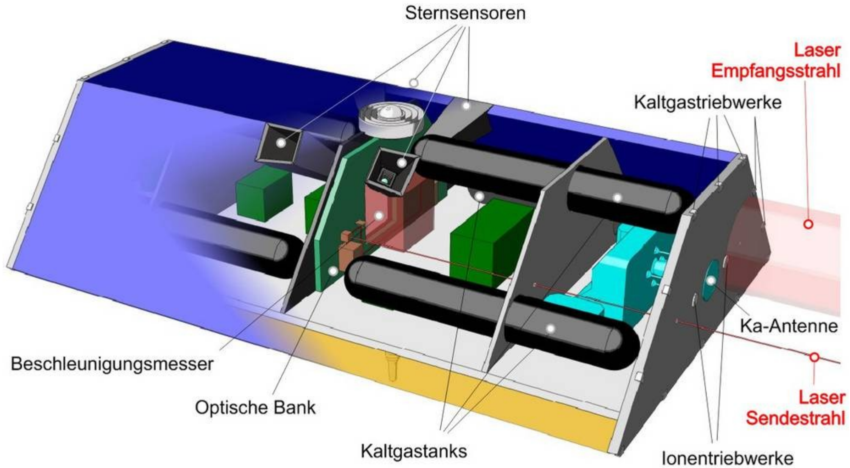


- https://grace.jpl.nasa.gov/
- 1*1 degree grids of TWS anomaly (with respect to long-term mean)
- all corrections applied
- comes with error grids
- JPL, CSR and GFZ solutions

Upcoming mission: GRACE-FO (4/2018)

- FO = “Follow-On”
- NASA/GFZ, launch April 2018
- Like GRACE but in addition carries technology demonstrator Laser Range Interference instrument,
- Uncertainty 10 to 20 times better than GRACE (theoretically)
- With lessons learnt, somewhat better resolution than GRACE will be obtained
- Same data products, same formats
- With some luck we may soon have a 30-year time series of water storage variability





Take-home message

* GRACE provides total (vertically integrated water storage), beginning 2002 until end of 2017.

* Data is freely available.

* Latency ~ 6 weeks, but some products are available with reduced accuracy

* Resolution is ~300 km at monthly scale, around 600 km at daily scale

* Groundwater storage change can be derived from TWS minus modeled soil moisture change from hydrological models.

* Higher spatial resolution through assimilation into hydrological models

* Can not measure the total mass of the ocean or land water

* Can not separate it from the solid Earth mass