



GRACE & The Global Water Cycle

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Outline

- ❑ **About GRACE**
- ❑ **Time-Variable Gravity**
- ❑ **The Global Water Cycle**
- ❑ **GRACE & The Global Water Cycle**

GRACE MISSION

Science Goals

High resolution, mean and time variable gravity field for Earth System Science applications.

Mission Systems

Instruments

- HAIRS (JPL/SSL/APL)
- SuperSTAR (ONERA)
- Star Cameras (DTU)
- GPS Receiver (JPL)

Satellite (JPL/Astrium)

Launcher (DLR/Eurockot)

Operations (DLR/GSOC)

Science (CSR/JPL/GFZ)

Orbit

Launched: March 17, 2002

Initial Altitude: 500 km

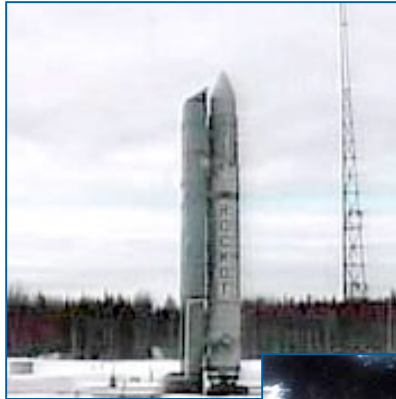
Inclination: 89 deg

Eccentricity: ~0.001

Separation Distance: ~220 km

Nominal Mission : 5 (extended to 8) years

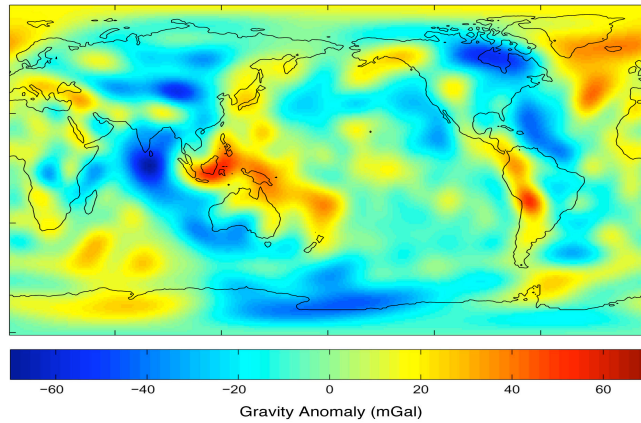




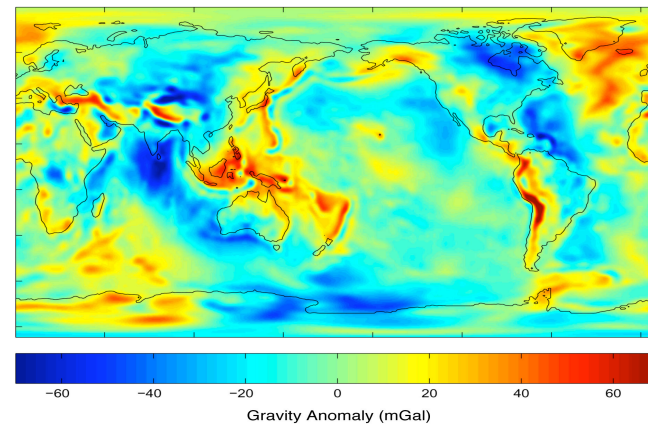
obj-99991 02y76d10h49m20s Time: 15.426 s Copyright[C] FGAN

Progress in Gravity Field Resolution

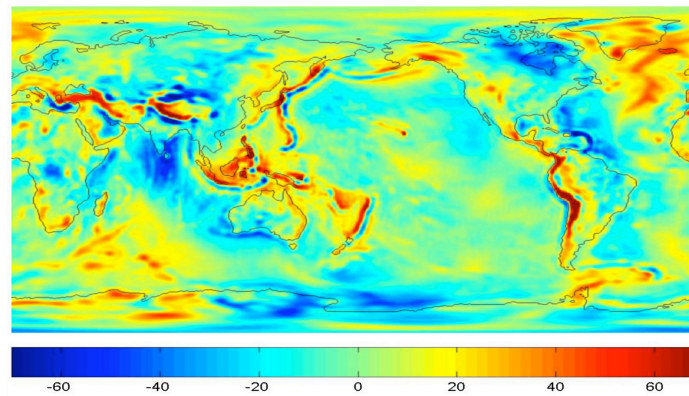
Decades of tracking to geodetic satellites



111 days of GRACE data



13 months of GRACE data





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 120.
- ❑ From three processing centers, CSR, GFZ, and JPL.
- ❑ Supporting data products, GAC, GAB, GAA, and etc.



- [illegible]



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The Earth's Time-Variable Gravity

The geopotential field is determined by mass distribution within the Earth's system, and is conveniently expressed in a 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 .



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 changes of C_{lm} & S_{lm} are provided by GRACE, which can be used to infer mass variations in the Earth system.



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 .



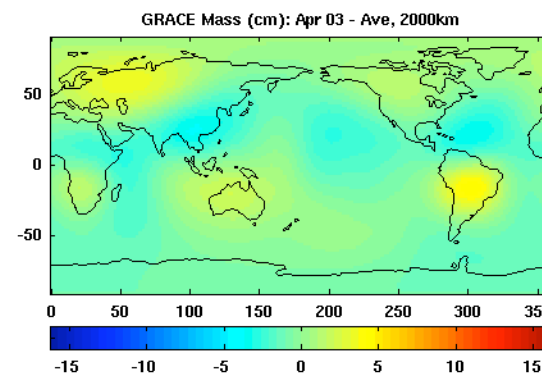
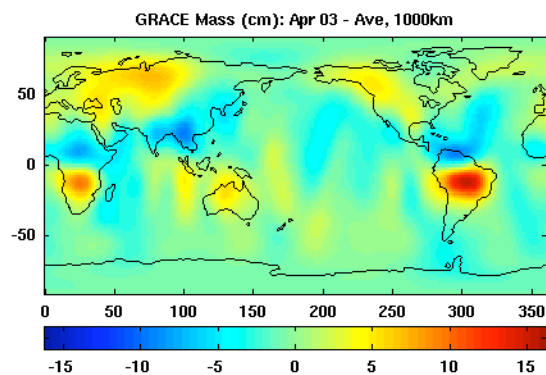
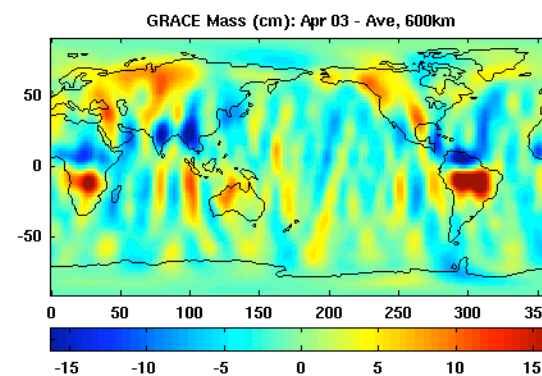
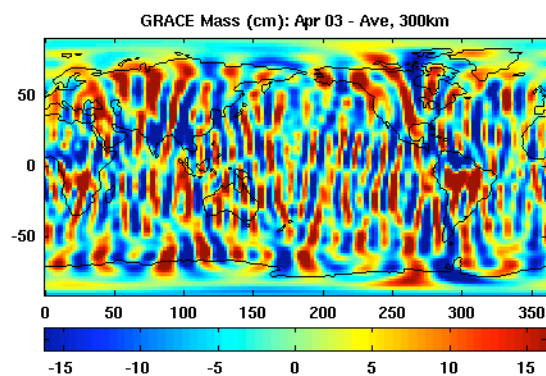
Surface Mass Changes from GRACE

Main issues to solve:

- ❑ Spatial smoothing 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 RL01 solutions, and the missing geocenter, degree-1 terms in GRACE data).
- ❑ How to validate GRACE estimates?
- ❑ How to minimize leakage effects due to the spatial smoothing?
- ❑ What is the effective spatial resolution of GRACE?

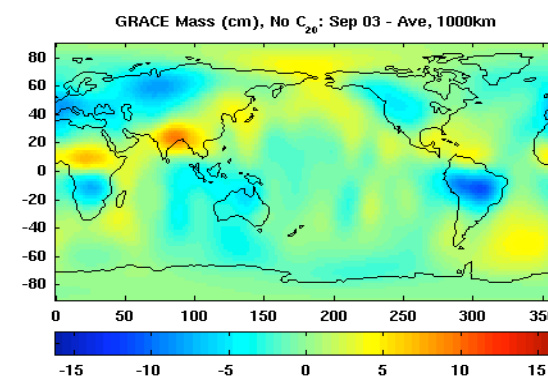
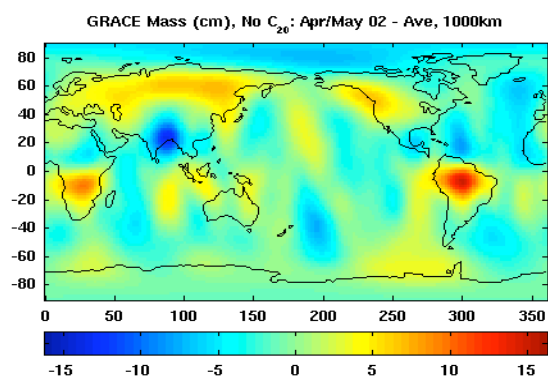
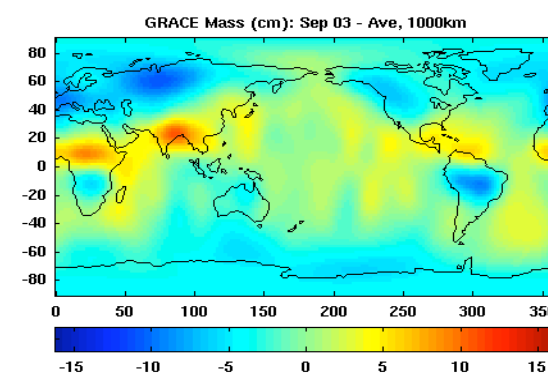
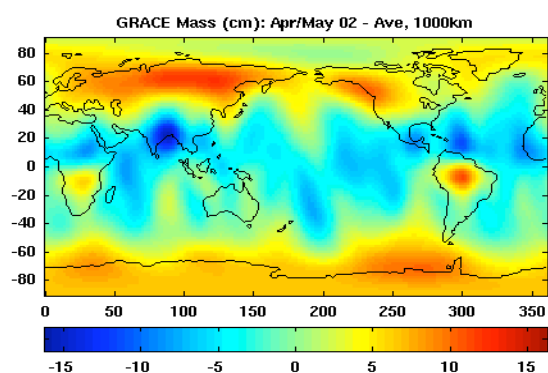


The Challenge of Spatial Smoothing





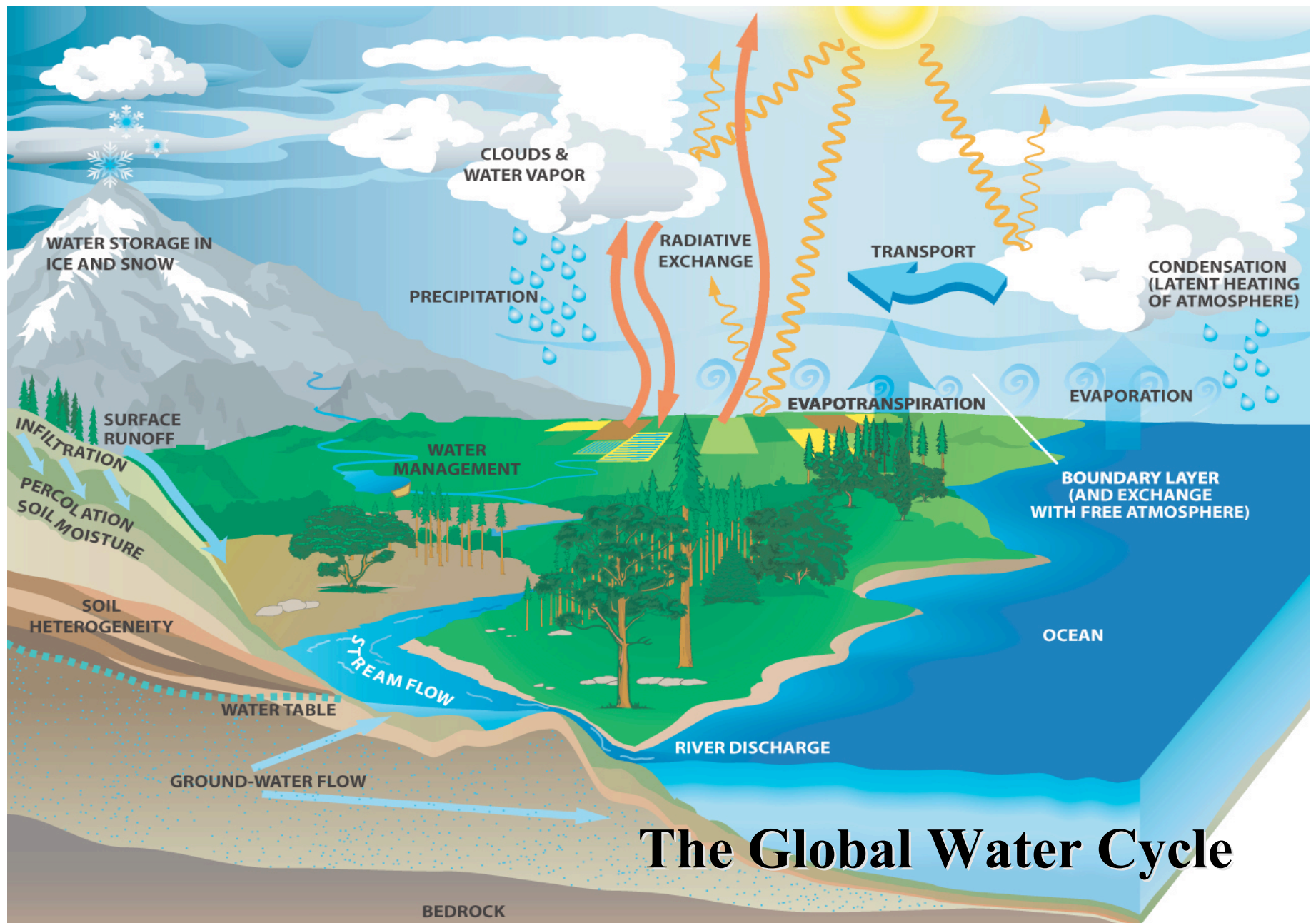
The Challenge of Low Degree Terms





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The Global Water Cycle

The Global Water Cycle



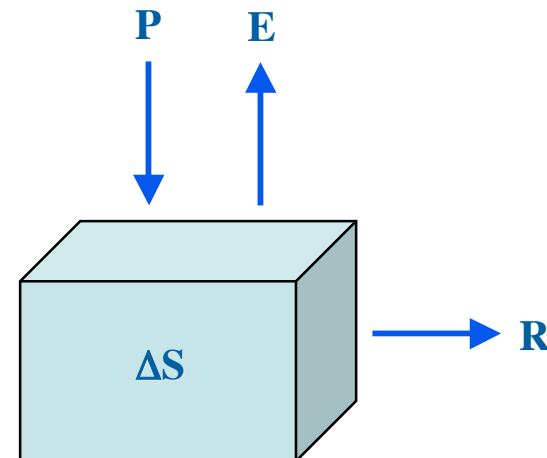
(Courtesy of NASA Water and Energy Cycle Project)



The Global Water Cycle

Hydrological Cycle -

- ❑ Precipitation (P)
- ❑ Evapotranspiration (E)
- ❑ Runoff (R)
- ❑ Water storage change (ΔS)
- ❑ Basic Conservation Equation $\Delta S = P - E - R$





Hydrological Interests

- ❑ **Terrestrial water storage change (ΔS) - soil moisture & ground water**

- ❑ $\Delta S = P - E - R$

- ❑ **Polar ice sheet mass balance (ΔS)**

- ❑ $\Delta S = P - E - R$

- ❑ **Snow water equivalent (ΔSWE)**

- ❑ $\Delta SWE = P - E - R - \Delta S$

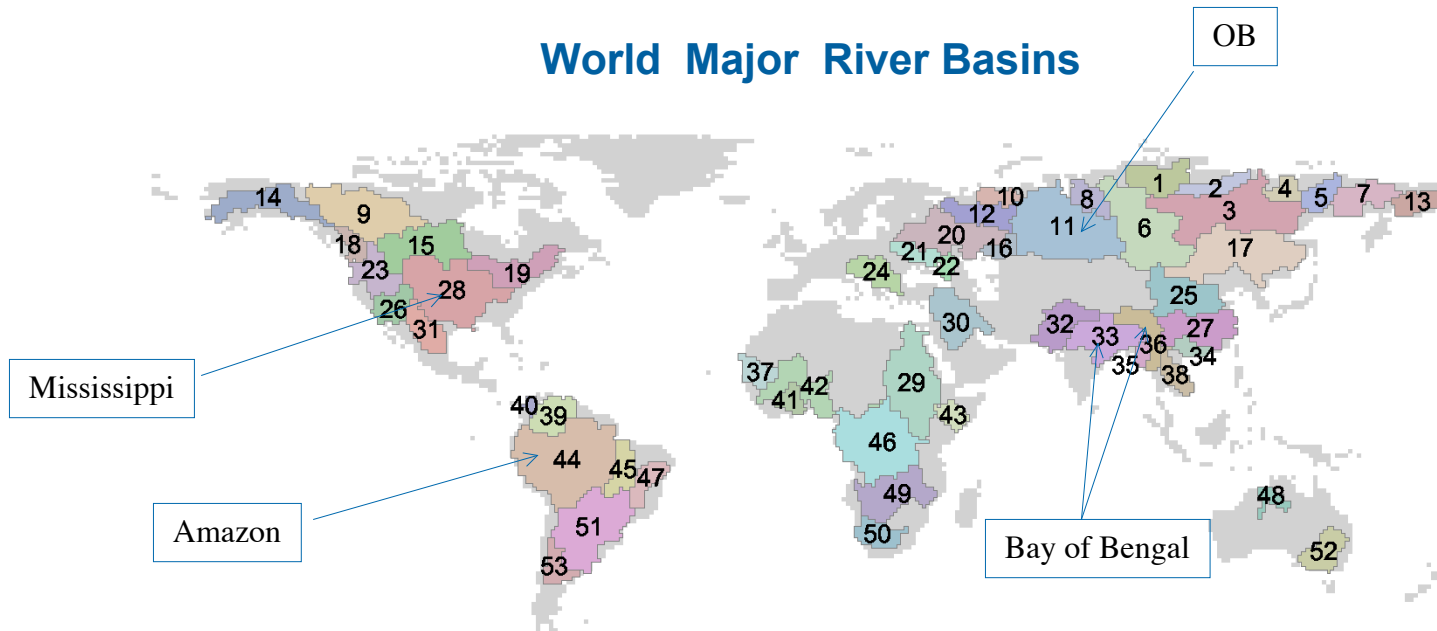
- ❑ **Evapotranspiration (E)**

- ❑ $E = P - R - \Delta S$

- ❑ **Runoff (R)**

- ❑ $R = P - E - \Delta S$

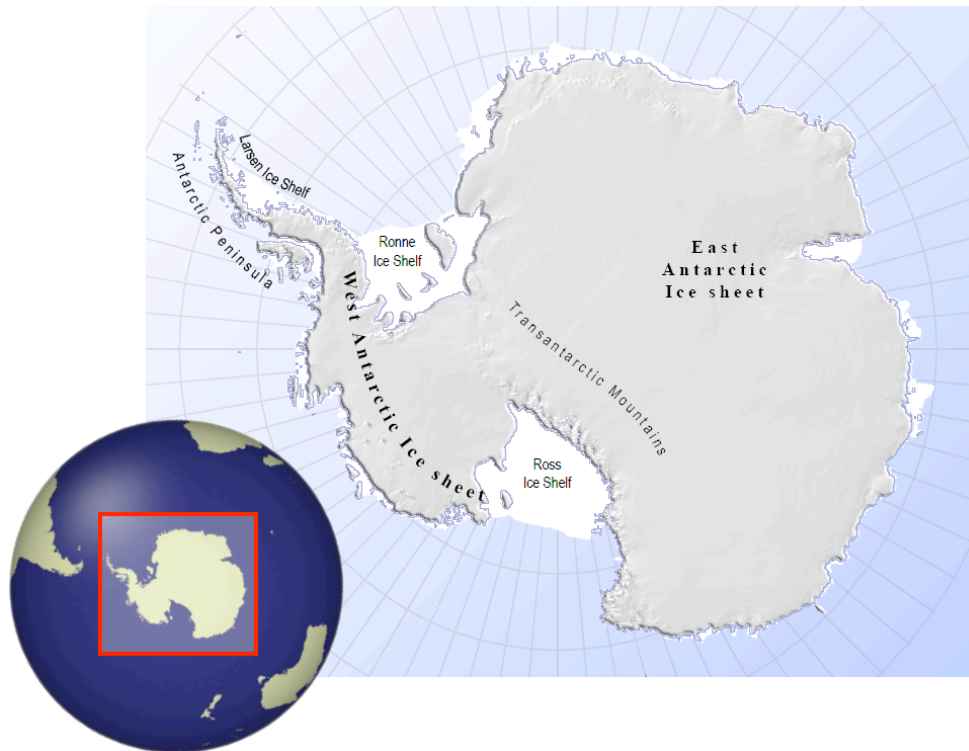
World Major River Basins



River Name	ID	River Name	ID	River Name	ID
Khatanga-Popigay	1	Fraser	18	Salween	36
Olenek	2	Saint Lawrence	19	Senegal	37
Lena	3	Volga	20	Mekong	38
Yana	4	Dnieper	21	Orinoco	39
Indigirka	5	Don	22	Magdalena	40
Yenisei	6	Columbia	23	Volta	41
Kolyma	7	Danube	24	Niger	42
Taz	8	Huang He (Yellow)	25	Juba	43
MacKenzie	9	Colorado	26	Amazon	44
Pechora	10	Chang Jiang (Yangtze)	27	Tocantins	45
Ob	11	Mississippi	28	Zaire(Congo)	46
Severnaya Dvina	12	Nile	29	Sao Francisco	47
Anadyr	13	Shatt-al-Arab(Tigris/Euphrates)	30	Victoria	48
Yukon	14	Rio Grande	31	Zambezi	49
Churchill 2	15	Indus	32	Oranje	50
Nelson	15	Ganges/Brahmaputra	33	Parana (Plata) and Uruguay	51
Ural	16	Xi (Zhu Jiang) (Pearl)	34	Mumay 1	52
Amur	17	Imawaddy	35	Colorado	53



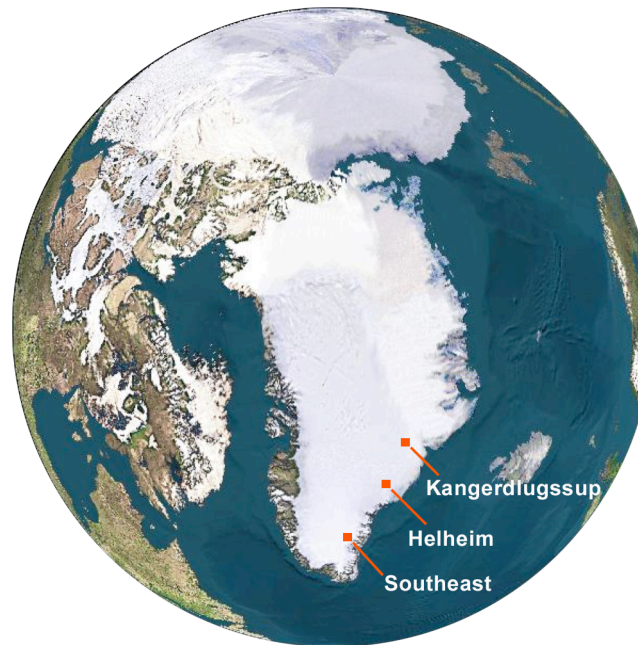
Antarctica Ice Sheet



The Antarctic ice sheet has a total area of $\sim 14,000,000 \text{ km}^2$ and averaged ice sheet thickness of $\sim 2.16 \text{ km}$, accounts for 90% of the world's ice and 75% of the world's fresh water resources, and has the potential to raise the global sea level by over 70 meters if completely melt.



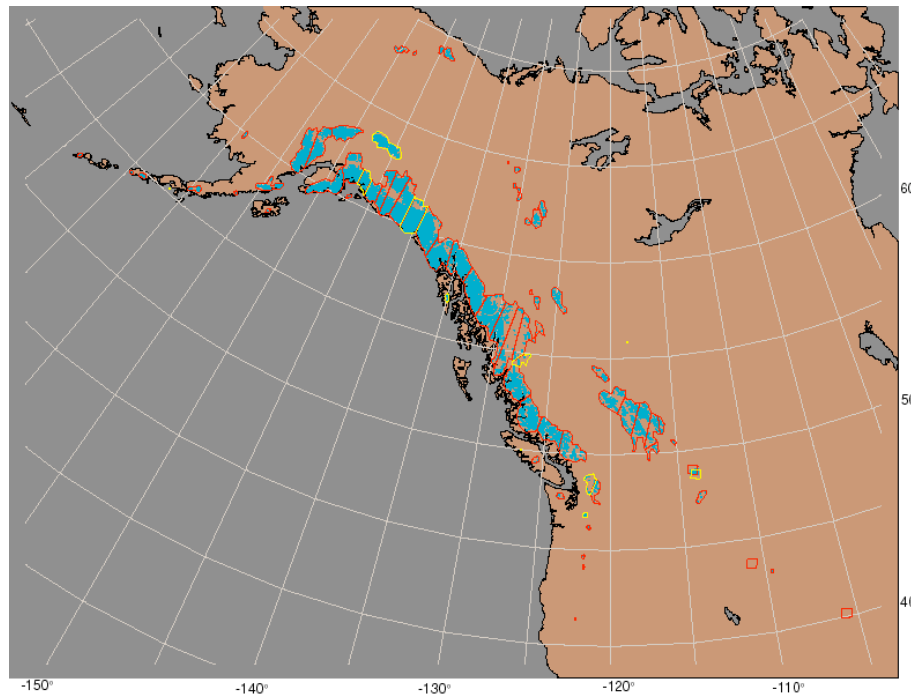
Greenland Ice Sheet



The Greenland ice sheet is the 2nd largest ice cap on Earth, and contains ~ 2.5 million cubic kilometers or 10% of total global ice mass. The glacial complex in southeast Greenland is among the most active glaciers.



Mountain Glaciers



Mountain glaciers (e.g., those in the Gulf of Alaska region) only hold a small portion of the world's ice. However, they are more vulnerable to the global warming and regional climate change, and thus may have comparable amount of melting (as compared with polar ice sheets) and contribute significantly to the global sea level rise.



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GRACE Applications in Hydrology

- ❑ **Terrestrial water storage (TWS) change**
 - ❑ Global, continental, & basin scales
 - ❑ Comparison between GRACE and model estimates
- ❑ **Basin scale evapotranspiration (E)**
 - ❑ $E = P - R - \Delta S$
 - ❑ ΔS from GRACE, P-R from model & gauge measurements
- ❑ **Basin scale surface runoff (R)**
 - ❑ $R = P - E - \Delta S$
 - ❑ ΔS from GRACE & P-E from models
- ❑ **Ground water (ΔGWS)**
 - ❑ $\Delta GWS = \Delta S(\text{GRACE}) - \Delta S_{\text{soil_snow_water}}(\text{model})$



GRACE Applications in Climate Change

- ❑ **Polar ice sheet mass balance**
 - ❑ Continental & drainage basin scales
 - ❑ Comparison between GRACE and remote sensing
- ❑ **Mountain glacial mass balance**
 - ❑ Alaskan and other glacial complexes
 - ❑ Comparison between GRACE and remote sensing or available mass balance data
- ❑ **Reconstruction of ice history at Last Glacial Maximum**
 - ❑ $\text{GRACE} = (\text{Ice}) \text{ Mass Balance} - \text{Postglacial Rebound (PGR)}$
 - ❑ $\text{PGR} = \text{GRACE} - \text{Ice Mass Balance}$
- ❑ **Global mean sea level rise**
- ❑ **Long-term ground water storage change**



GRACE Application Examples

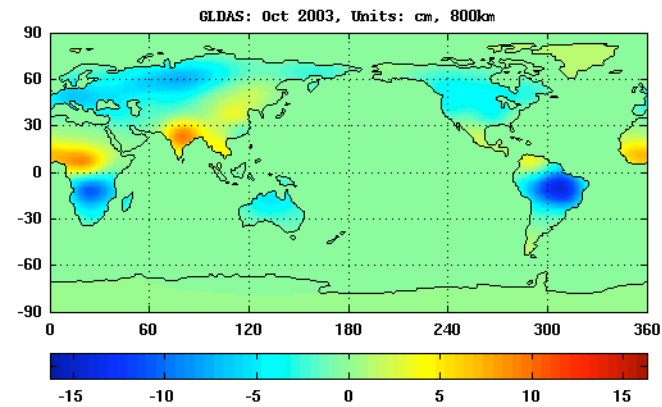
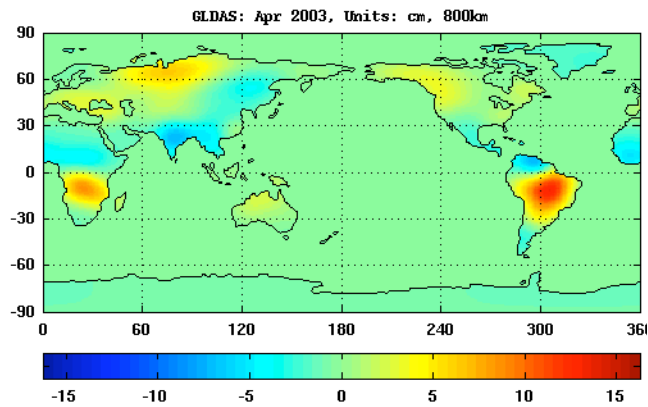
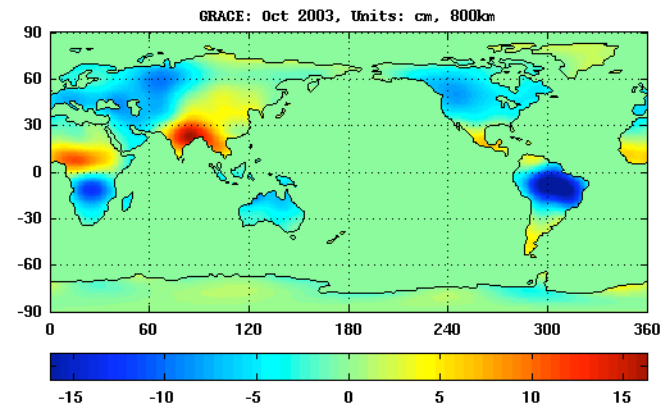
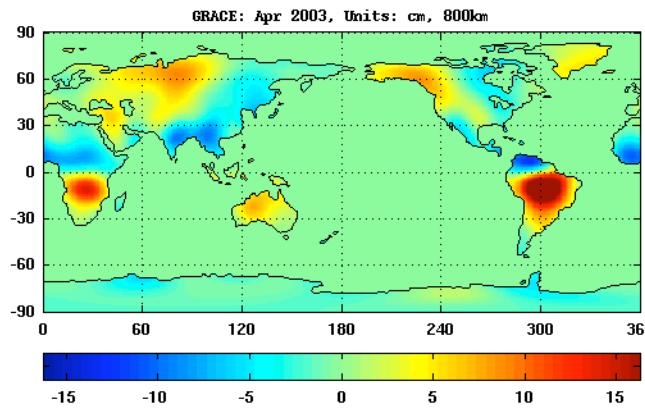
- ❑ **Global water storage change from GRACE**
- ❑ **GRACE estimated river runoff in the Amazon basin**
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- ❑ **Mountain glacial melting from GRACE**
- ❑ **GRACE confirms accelerated melting over Greenland**



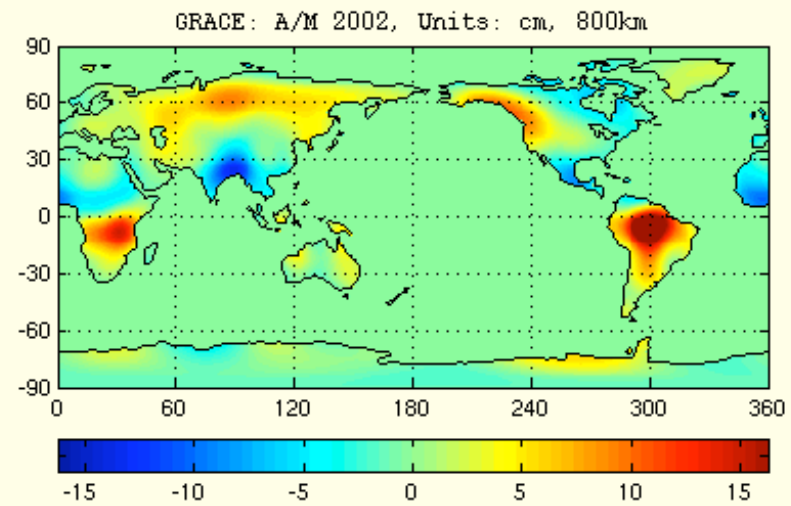
Global Water Storage Change from GRACE

- ❑ **GRACE time-variable gravity data**
 - ❑ CSR constrained RL01 solutions up to degree 120
 - ❑ 35 monthly solutions covering the period April 2002 - June 2005
 - ❑ C20 excluded, truncation at degree 60
 - ❑ 800 km Gaussian smoothing
- ❑ **Global land data assimilation system (GLDAS)**
 - ❑ GLDAS estimated TWS changes
 - ❑ Converted into spherical harmonics of degree 100
 - ❑ Drop C20 and geocenter terms (to be consistent with GRACE)
 - ❑ 800 km Gaussian smoothing & truncation at degree 60
- ❑ **Comparisons**
 - ❑ Global scale
 - ❑ Basin scale

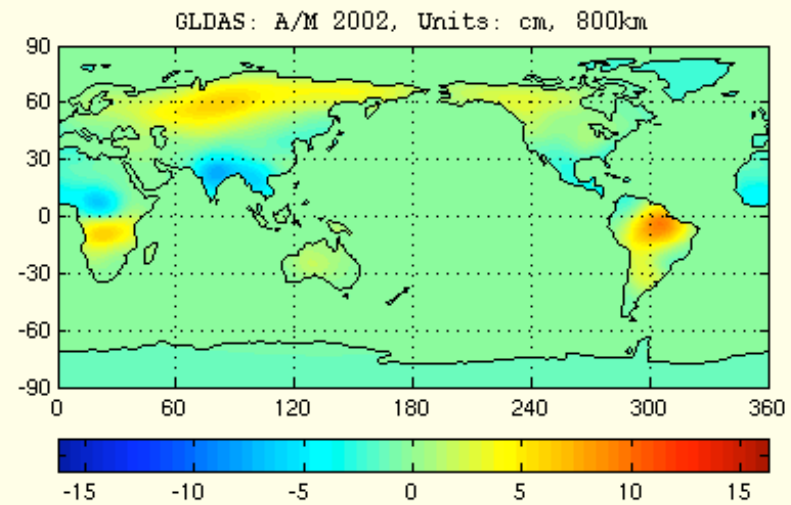
Global Water Storage Change from GRACE



GRACE

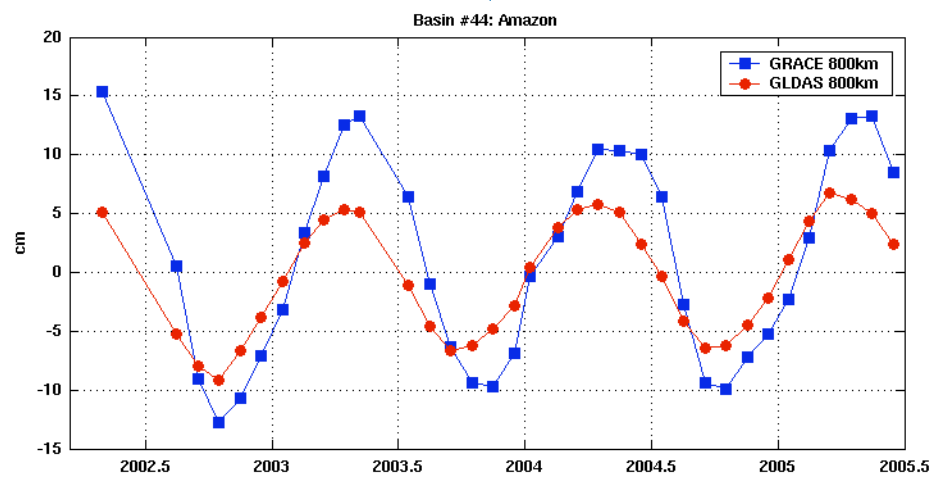
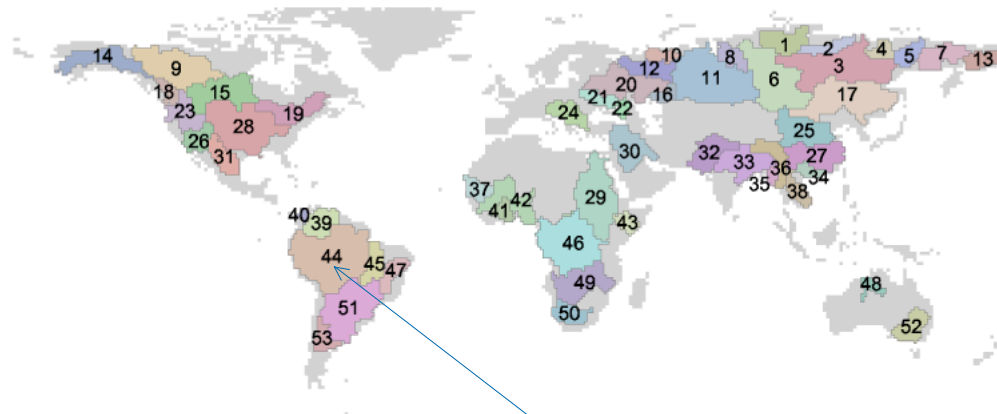


GLDAS

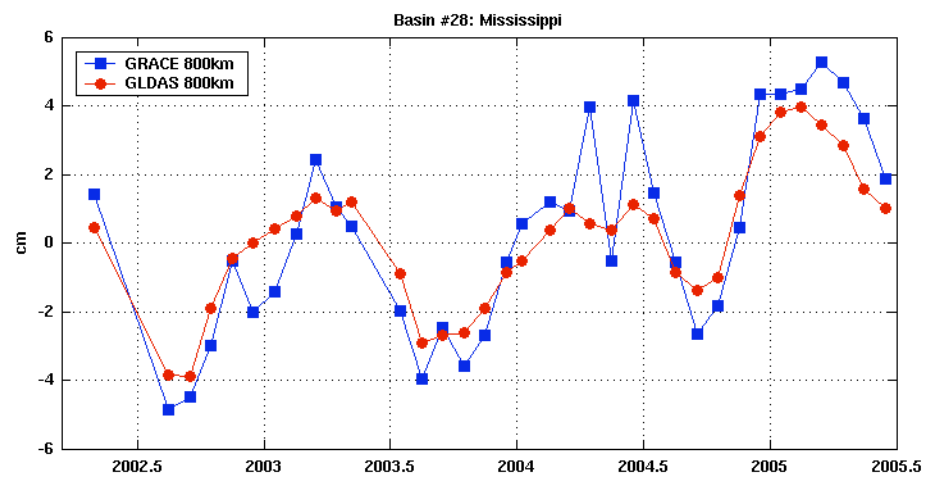
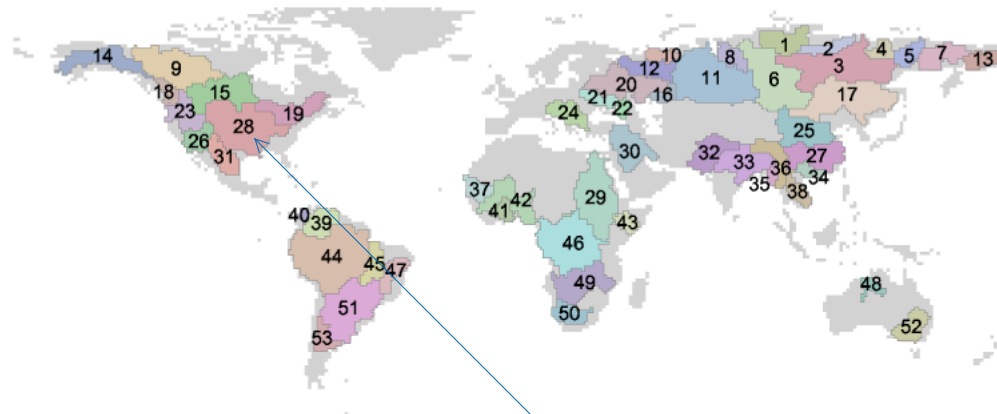


800 Gaussian

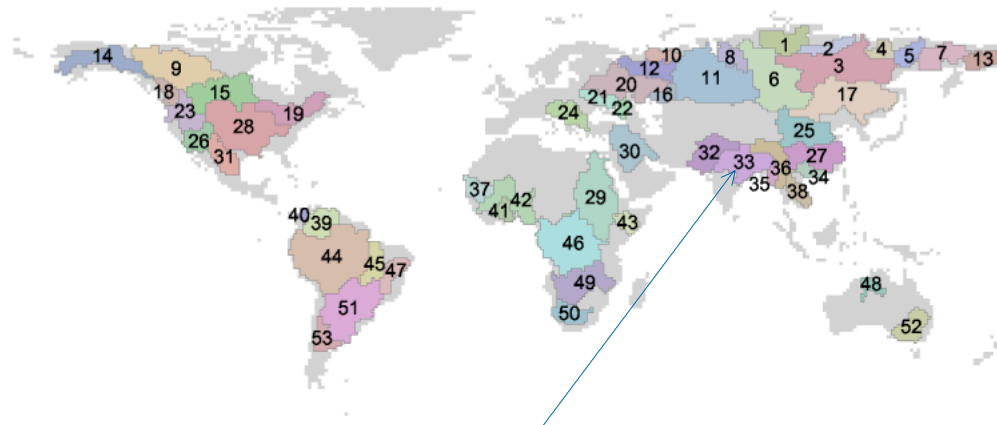
GRACE/GLDAS Comparison in Amazon



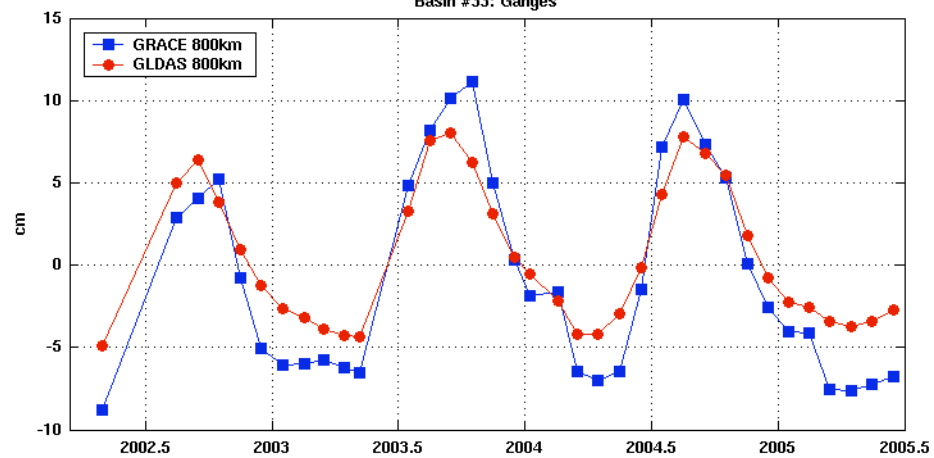
GRACE/GLDAS Comparison in Mississippi



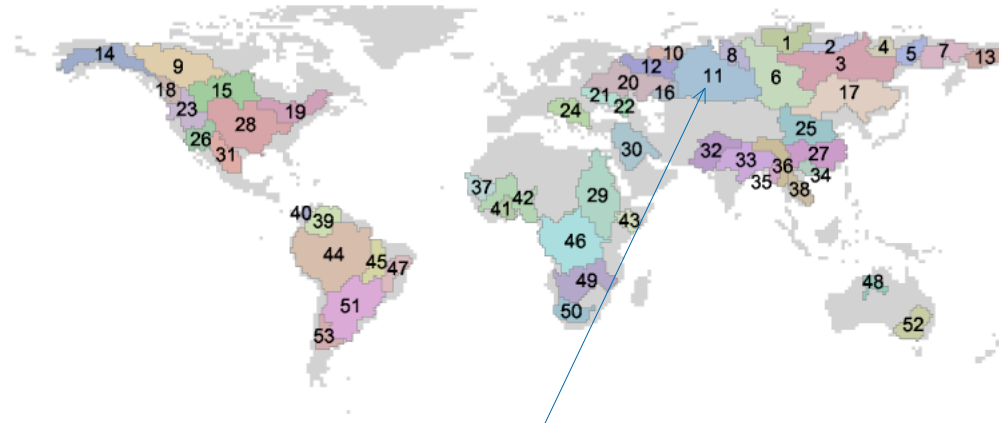
GRACE/GLDAS Comparison in Ganges



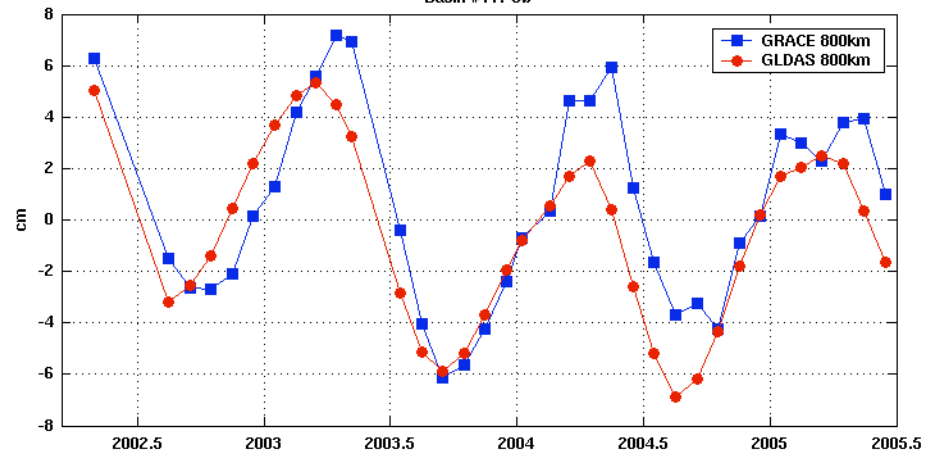
Basin #33: Ganges



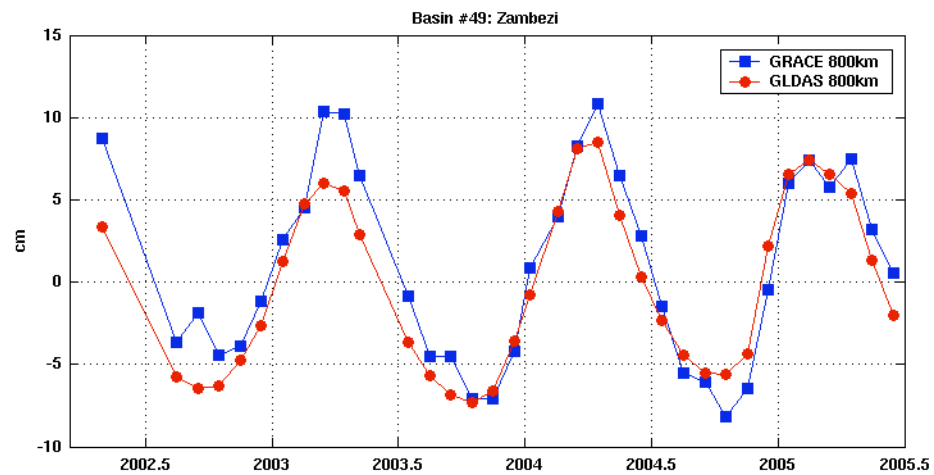
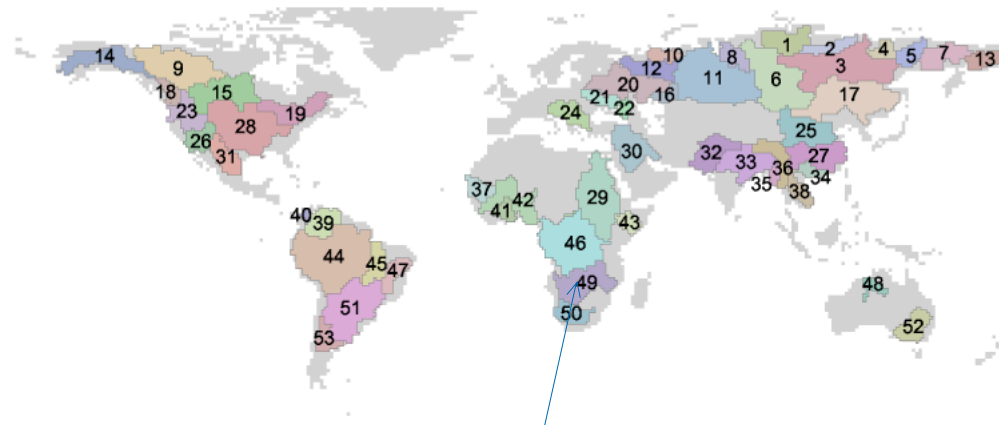
GRACE/GLDAS Comparison in Ob



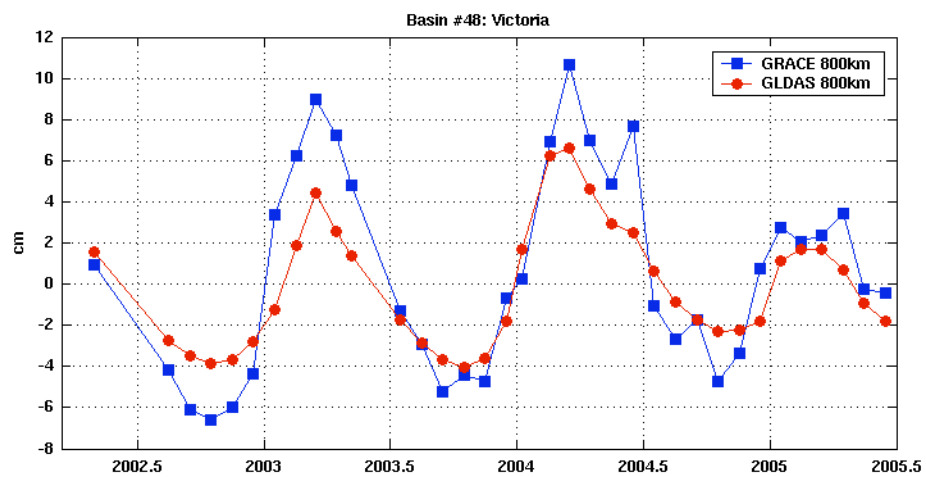
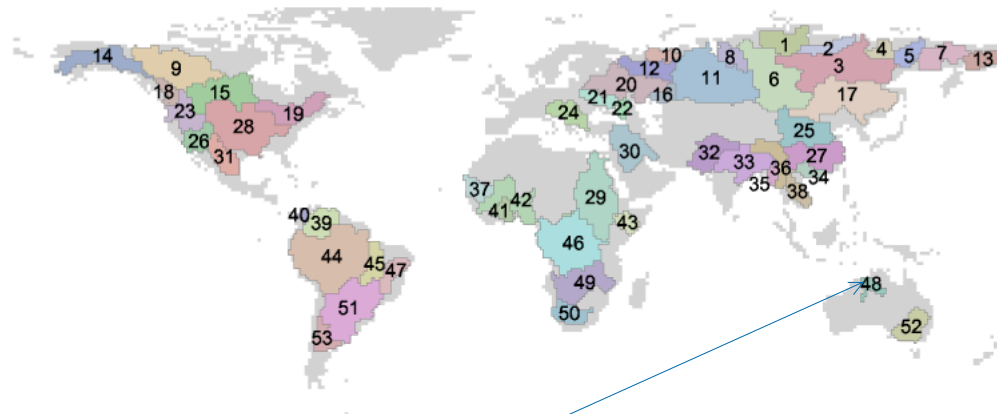
Basin #11: Ob



GRACE/GLDAS Comparison in Zambezi



GRACE/GLDAS Comparison in Victoria





GRACE Application Examples

- ☑ Global water storage change from GRACE
- ☐ GRACE estimated river runoff in the Amazon basin
- ☐ Antarctic long-term mass change from GRACE
- ☐ Mountain glacial melting from GRACE
- ☐ GRACE confirms accelerated melting over Greenland



GRACE Estimated River Runoff in the Amazon Basin

- ❑ **Basic equation: $R = (P - E) - \Delta S$**
- ❑ **ΔS from GRACE time-variable gravity**
 - ❑ 22 CSR RL01 unconstrained solutions April 2002 - July 2004
 - ❑ C20 excluded
 - ❑ 1000 km Gaussian smoothing
- ❑ **P-E from ECMWF model estimates**
 - ❑ Based on land-atmosphere water mass balance
- ❑ **Comparison with gauge measurements (at Obidos, Brazil)**



Land-Atmosphere Water Mass Balance

- For land water mass balance

$$\frac{\partial S}{\partial t} = P - E - R$$

- For atmosphere water mass balance

$$\frac{\partial W}{\partial t} = E - P - \text{div}Q$$

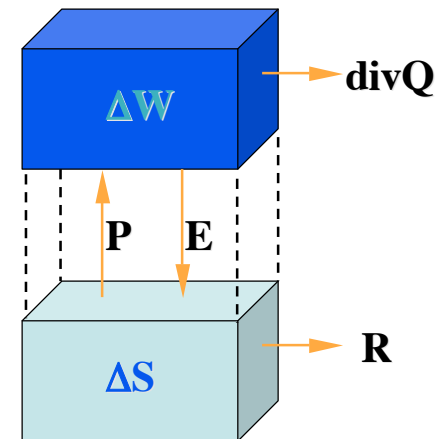
- For combined land-atmosphere water mass balance

$$R = -\frac{\partial S}{\partial t} - \frac{\partial W}{\partial t} - \text{div}Q$$

W - Vertically-integrated precipitable water (ECMWF)

Q - Divergence of the vertically-integrated average atmospheric moisture flux vector (ECMWF)

S - Water storage (GRACE)





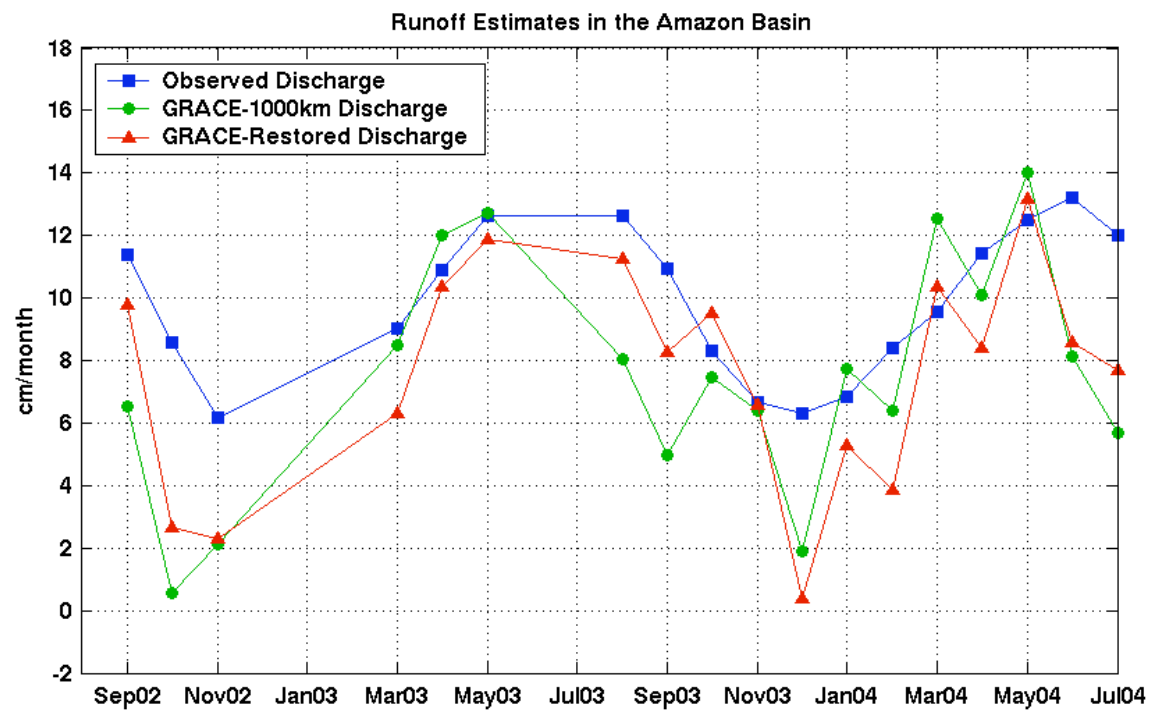
Land-Atmosphere Water Mass Balance

Details of this land-atmosphere water mass balance methodology and some related results are presented in

Syed, T.H., J.S. Famiglietti, J.L. Chen, M. Rodell, S.I. Seneviratne, P. Viterbo, C.R. Wilson, Amazon and Mississippi River Discharge Estimated from GRACE and a Land-Atmosphere Water Balance, *Geophys. Res. Lett.*, 32, L24404, doi:10.1029/2005GL024851, 2005.

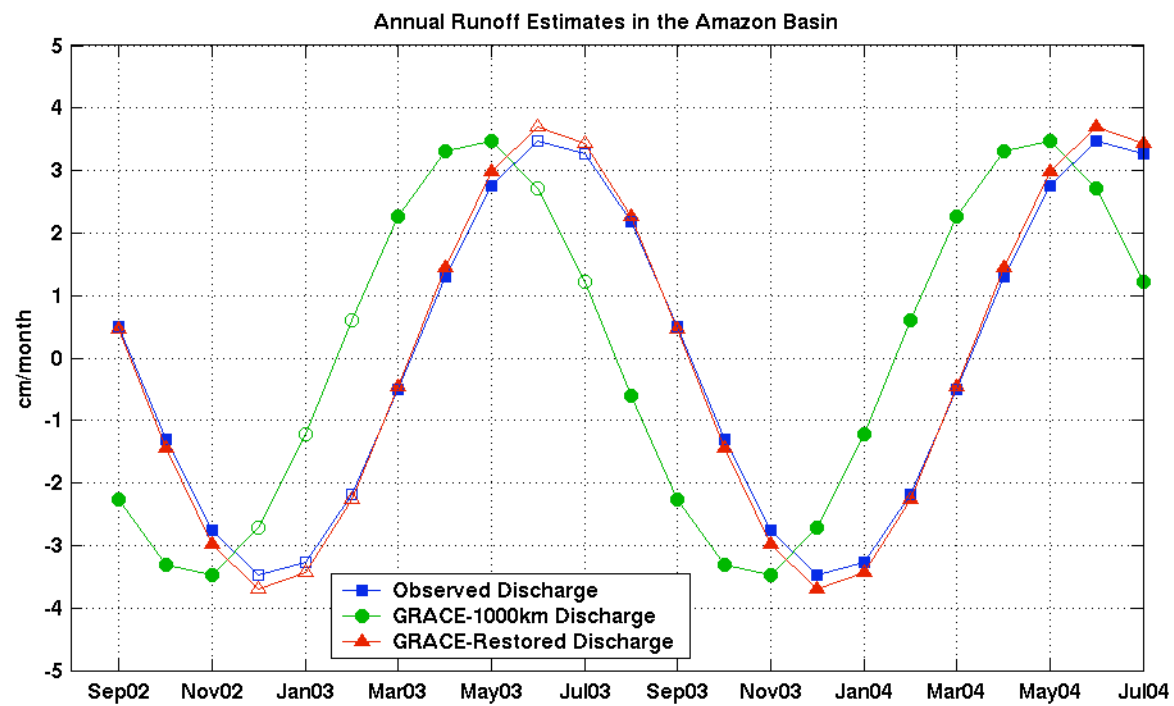


Runoff Estimates in the Amazon River Basin





Annual Runoff Estimates in the Amazon River Basin





GRACE Application Examples

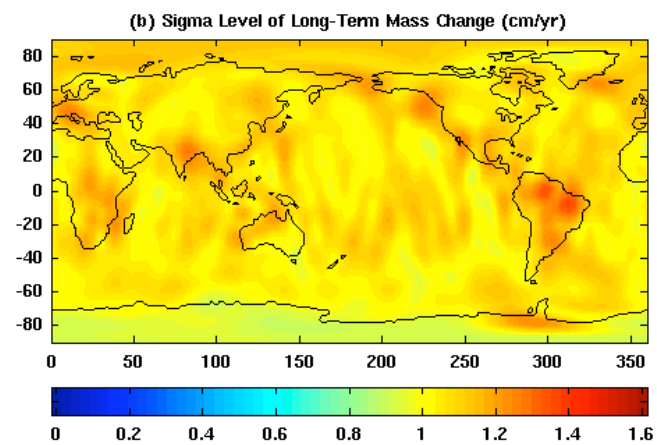
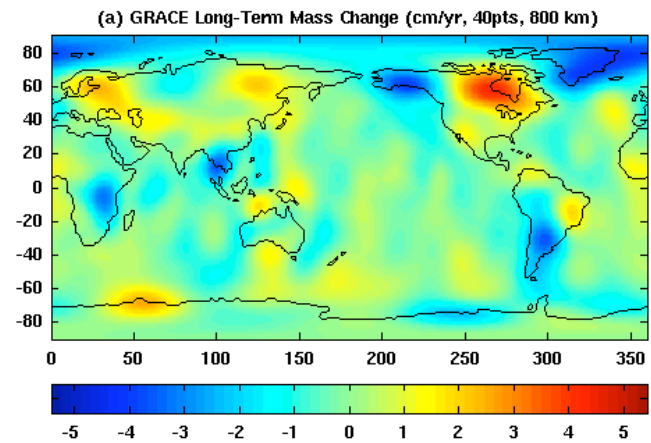
- ✓ Global water storage change from GRACE
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- Antarctic long-term mass change from GRACE
- Mountain glacial melting from GRACE
- GRACE confirms accelerated Greenland ice melting



Antarctic Long-Term Mass Change From GRACE

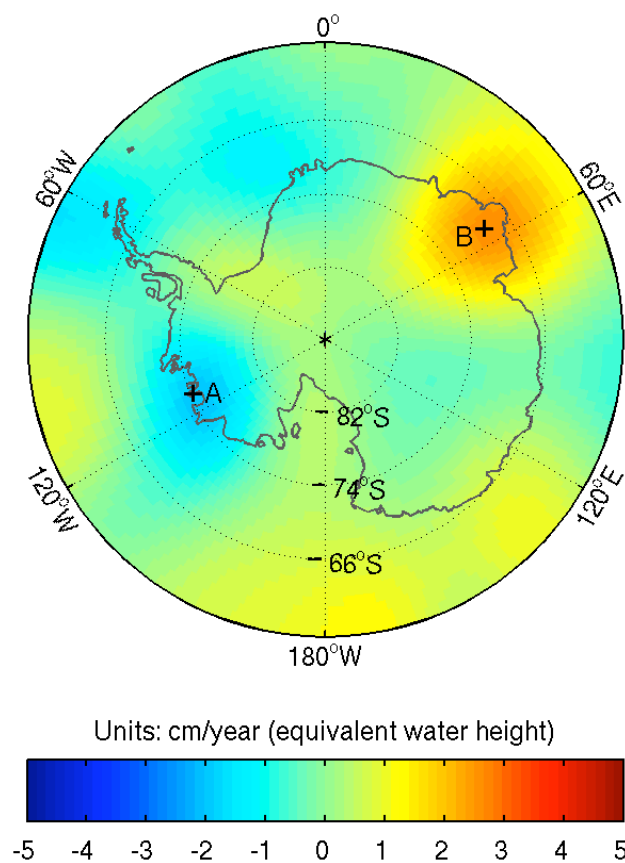
- ❑ **GRACE time-variable gravity data**
 - ❑ CSR constrained RL01 solutions up to degree 120
 - ❑ 40 monthly solutions covering the period Apr 2002 - Nov 2005
 - ❑ C20 excluded, truncation at degree 60
 - ❑ 500, 800, 1000 km Gaussian smoothing
- ❑ **Forward Modeling**
 - ❑ A numerical simulation technique to more effectively quantify leakage effects from smoothing.
 - ❑ Successfully applied in a number of recent studies.
 - ❑ The main purpose is to determine what original mass change signals could generate the changes observed by GRACE.
- ❑ **Postglacial rebound (PGR) effects**
- ❑ **Comparison with remote sensing measurements**

Global Long-Term Mass Change Rates From GRACE



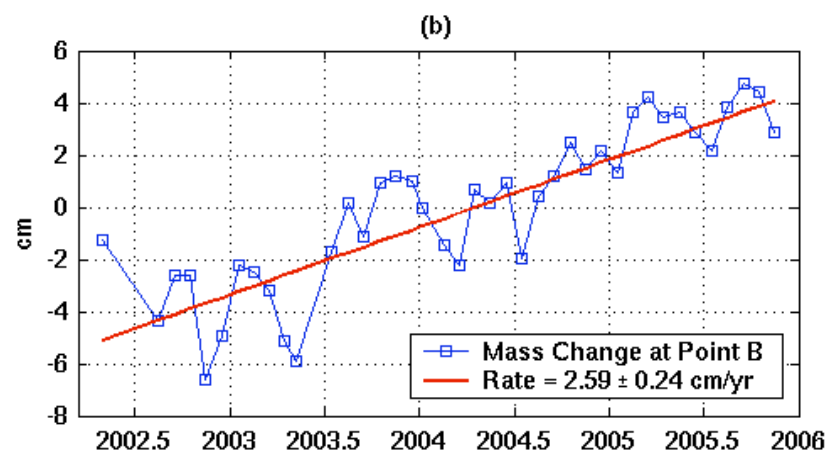
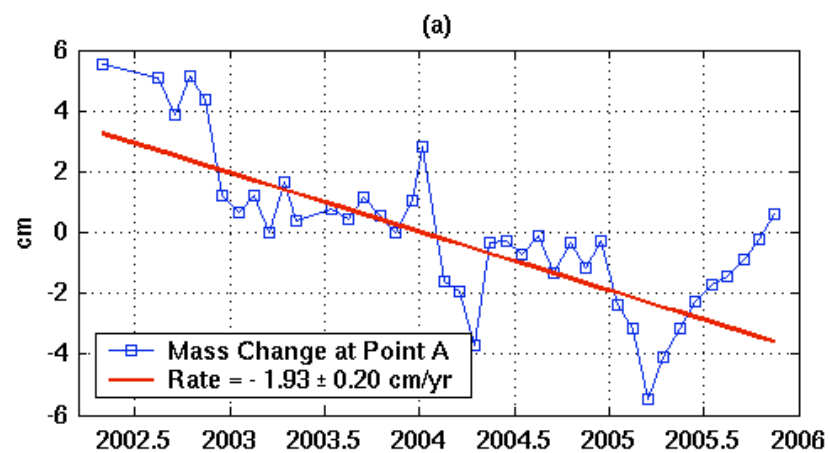


Antarctic Mass Rates From GRACE (Apr 2002 - Nov 2005)



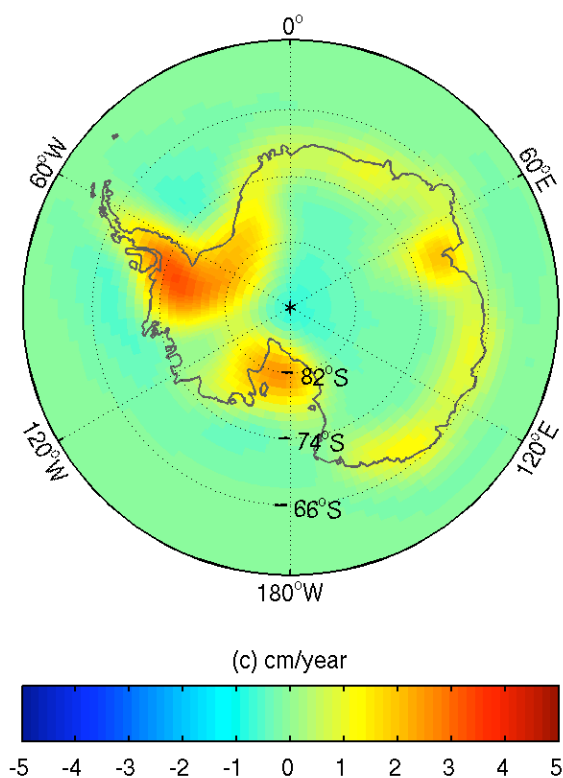


Antarctic mass changes at points A & B from GRACE

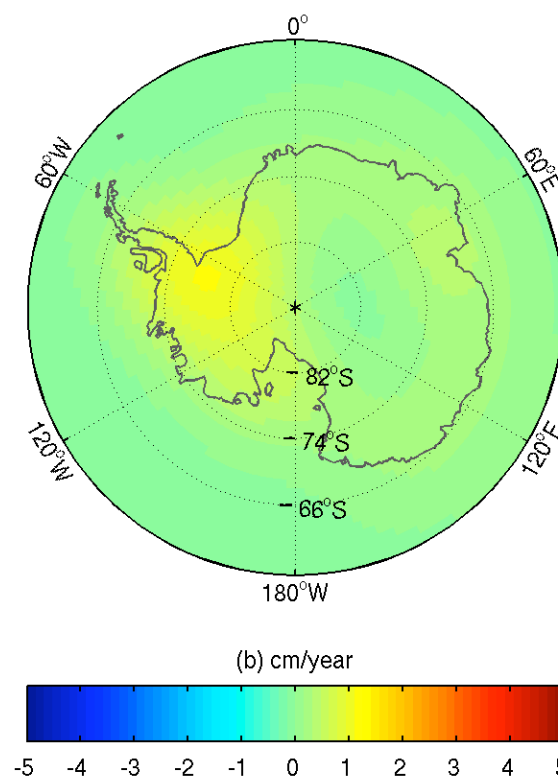




PGR effects (in mass equivalent) over Antarctica from the IJ05 PGR model [Ivins and James, 2005], No smoothing.

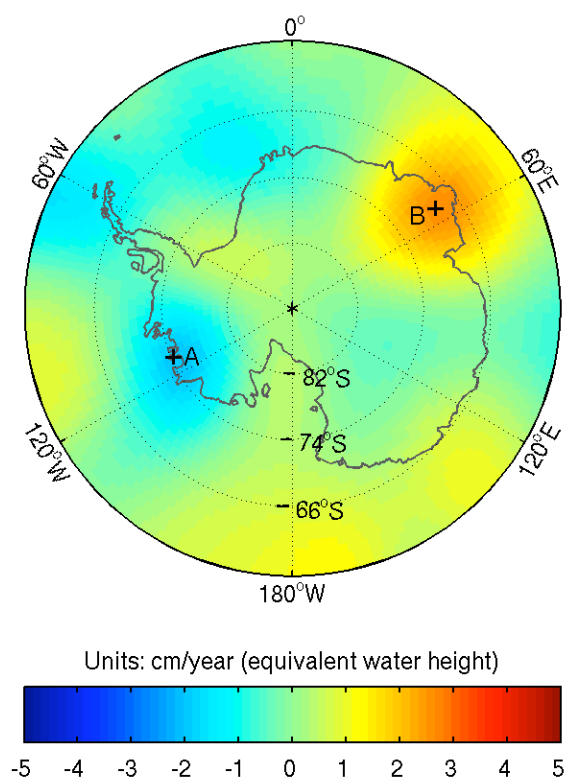


PGR effects (in mass equivalent) over Antarctica from the IJ05 PGR model, 800 km Gaussian smoothing.

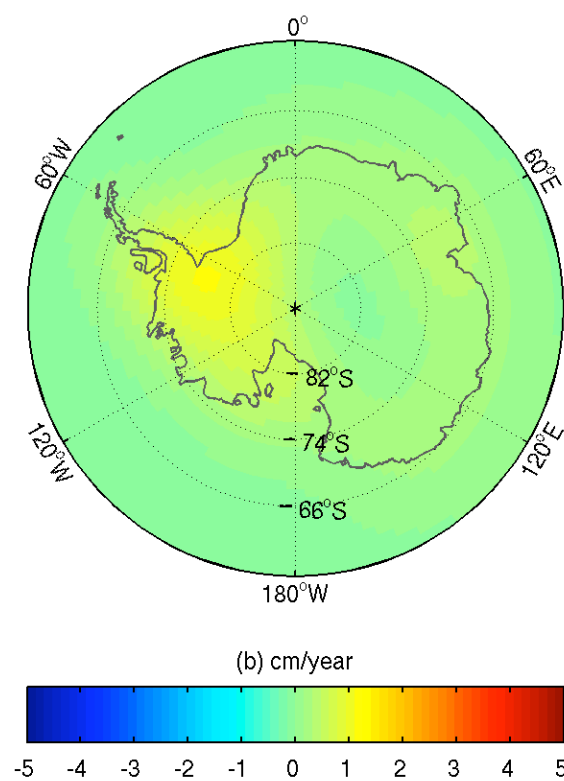




GRACE mass rates over Antarctica,
800 km Gaussian smoothing.

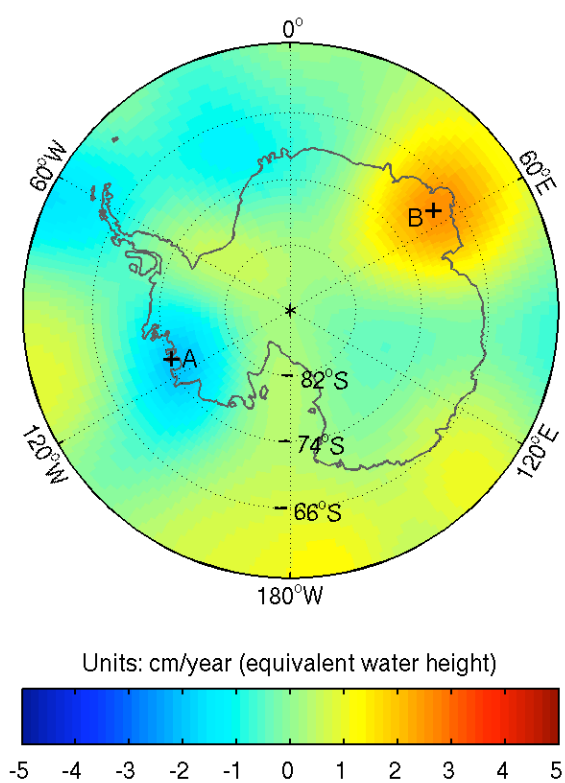


PGR effects over Antarctica (IJ05)
800 km Gaussian smoothing.

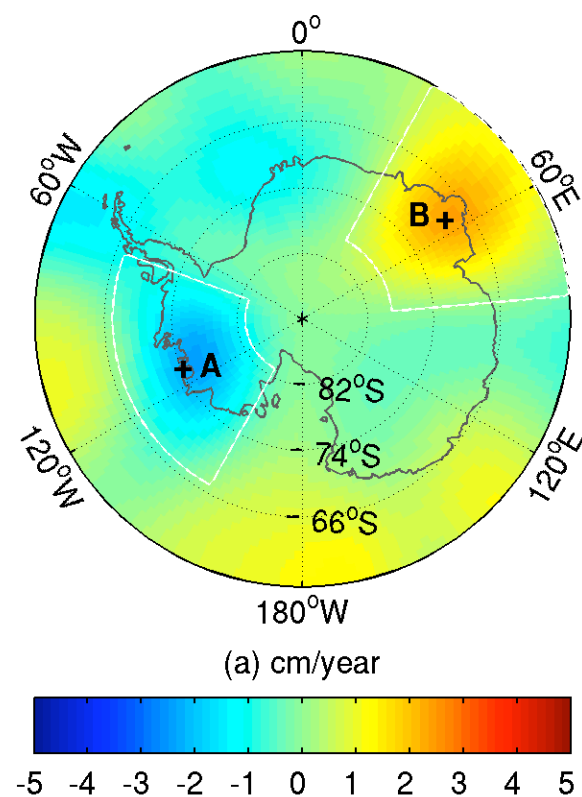




GRACE mass rates over Antarctica,
800 km Gaussian smoothing.



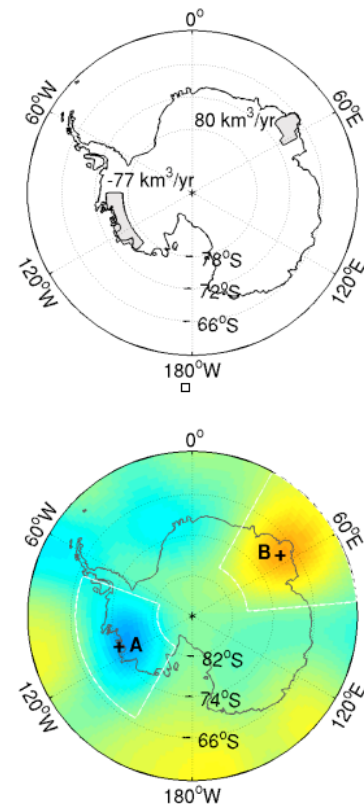
GRACE - PGR (IJ05) over Antarctica,
800 km Gaussian smoothing.





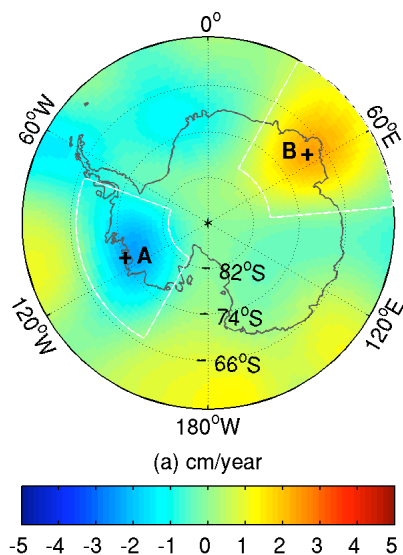
Forward Modeling

- ❑ **Step-1:** To calculate the total variance in the two predefined regions (circled by white lines).
- ❑ **Step-2:** To place the two calculated total mass rates evenly distributed in the two shaded areas in West and East Antarctic, & convert into spherical harmonics.
- ❑ **Step-3:** To replicate procedures (used to transform GRACE data) to compute surface mass changes (no C20 & degree-1 terms, same truncation and smoothing, ...).
- ❑ **Step-4:** To compute the total variance of the simulated mass rates in the same regions (circled by white lines).
- ❑ **Step-5:** To adjust the total mass rates and the sizes and locations of the two simulated areas, and repeat steps 1-4, until the simulated total mass rates 'best' match GRACE estimates.

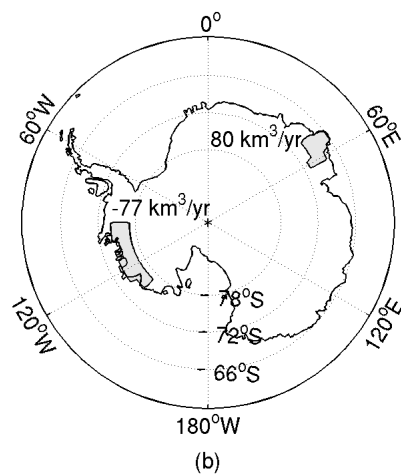




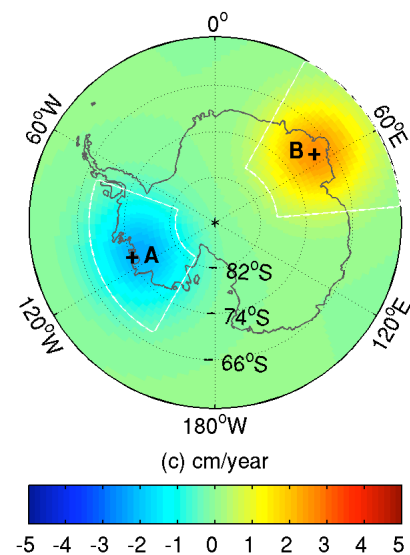
GRACE - PGR (IJ05) 800 km Gaussian



Simulation Scheme



Forward modeling 800 km Gaussian





Sensitivity of Spatial Radii on GRACE Estimates

Table 1. Long-term snow/ice mass change rates (in km³/yr) in West (W.) and East (E.) Antarctica estimated from numerical simulations in 3 cases when using 500 km, 800 km, and 1000 km Gaussian smoothings.

Cases	W. Antarctica	E. Antarctica
500 km	$- 85 \pm 21$	$+ 88 \pm 23$
800 km	$- 77 \pm 14$	$+ 80 \pm 16$
1000 km	$- 73 \pm 14$	$+ 77 \pm 15$
Average	$- 78 \pm 10$	$+ 82 \pm 11$



What do we learn over Antarctica from GRACE?

Conclusions:

- ❑ The first 3.5 years of GRACE data show two prominent features, a region of mass loss along the coast of Amundsen Sea Embayment in West Antarctica, and one of accumulation in Enderby Land in East Antarctica.
- ❑ Through forward modeling to quantify attenuation effects and leakage errors from spatial smoothing, and removing PGR effects, the rate in West Antarctica is $-77 \pm 14 \text{ km}^3/\text{year}$, consistent with recent assessment from satellite altimetry and remote sensing data.
- ❑ The accumulation rate in the Enderby Land region is $\sim +80 \pm 16 \text{ km}^3/\text{year}$, contrary to estimates from remote sensing data, which show approximate ice mass balance in this region, suggesting that this feature is either from unquantified snow accumulation in this region or more likely due to unmodeled PGR.
- ❑ The surprisingly steady increasing trend in the Enderby Land region appears to support the PGR hypothesis. Longer GRACE time series will provide a more convincing conclusion in the future.



Antarctic Mass Change Rates From GRACE

Details of the forward modeling methodology and related results on Antarctic mass rates have been published in

Chen, J.L., C.R. Wilson, D.D. Blankenship, and B.D. Tapley (2006), Antarctic Mass Change Rates From GRACE, *Geophys. Res. Lett.*, 33, L11502, doi:10.1029/2006GL026369.

Reprints are available (chen@csr.utexas.edu).



GRACE Application Examples

- ☒ **Global water storage change from GRACE**
- ☒ **GRACE estimated river runoff in the Amazon basin**
- ☒ **Antarctic long-term mass change from GRACE**
- ☐ **Mountain glacial melting from GRACE**
- ☐ **GRACE confirms accelerated Greenland ice melting**



Alaskan Mountain Glacial Melting From GRACE

❑ GRACE time-variable gravity data

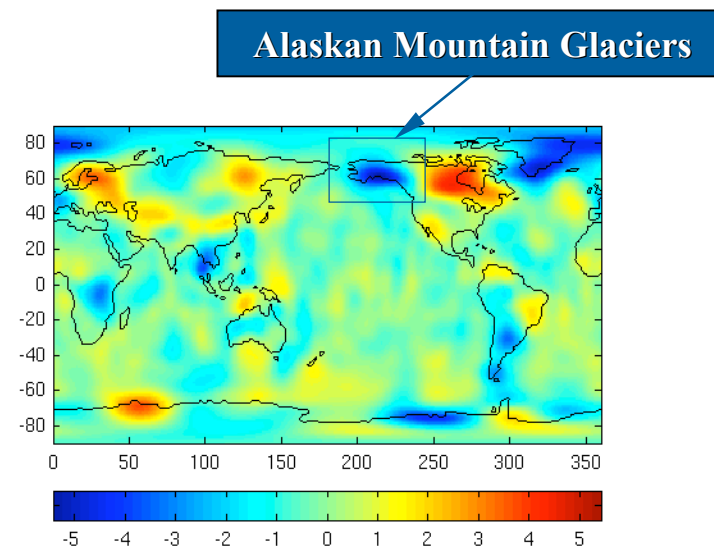
- ❑ 40 CSR constrained RL01 solutions (Apr 2002 - Nov 2005)
- ❑ 2-Step optimized smoothing (to maximize signal-to-noise ratio)

❑ Similar Forward Modeling

- ❑ Glacial melting
- ❑ Water storage change
- ❑ PGR effects

❑ Comparisons

- ❑ GRACE estimates
- ❑ Remote sensing
- ❑ USGS glacial mass balance

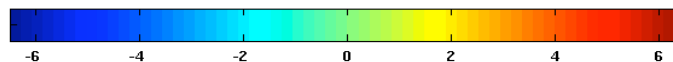
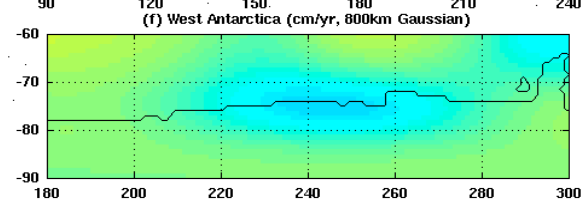
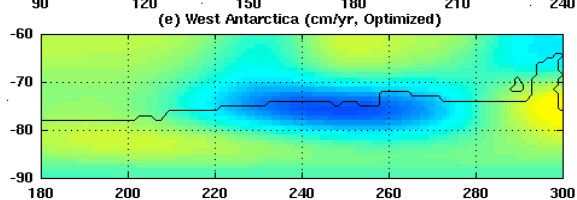
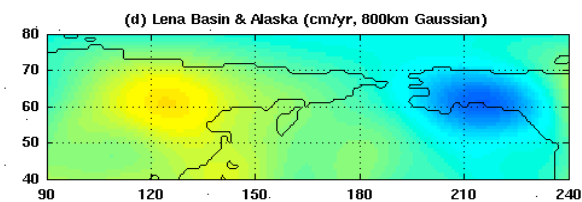
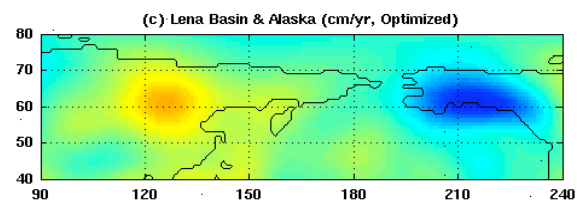
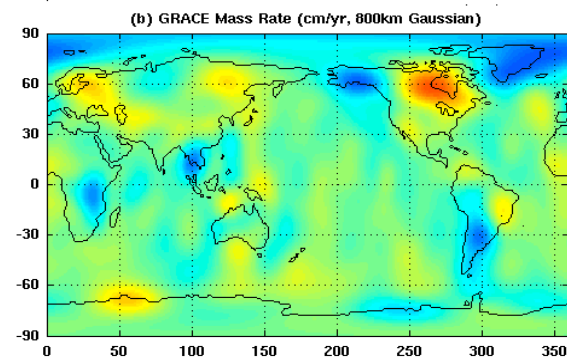
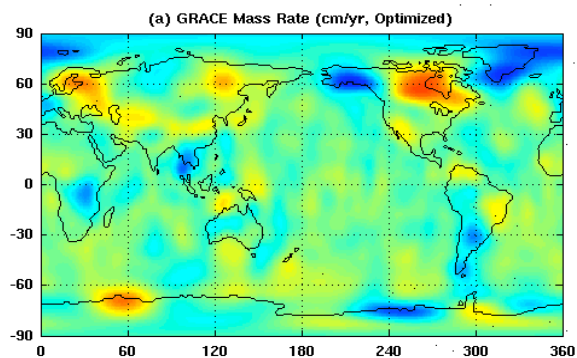


2-Step Optimized Smoothing of GRACE Data



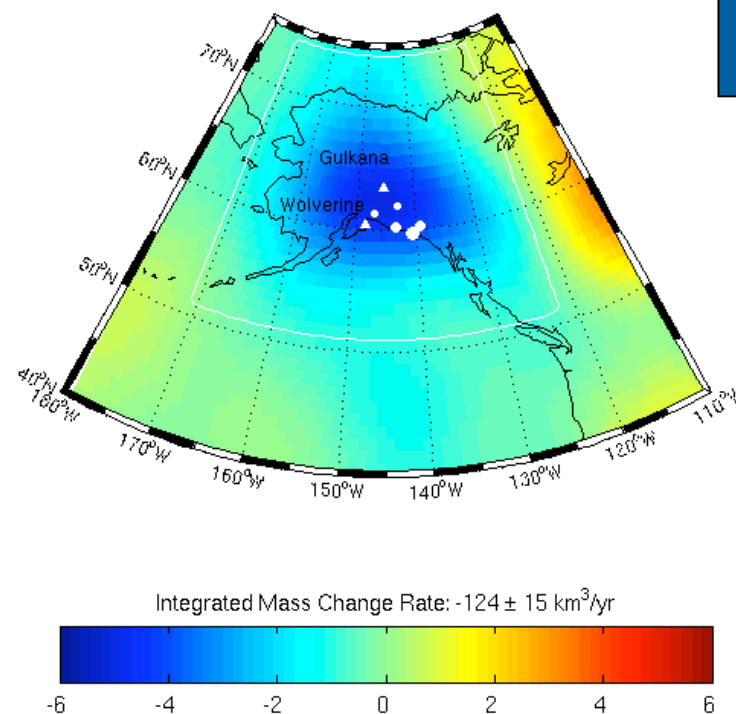
Optimized

Gaussian





Alaskan Glacial Melting Observed by GRACE



▲ Gulkana & Wolverine - Two USGS Benchmark Glaciers

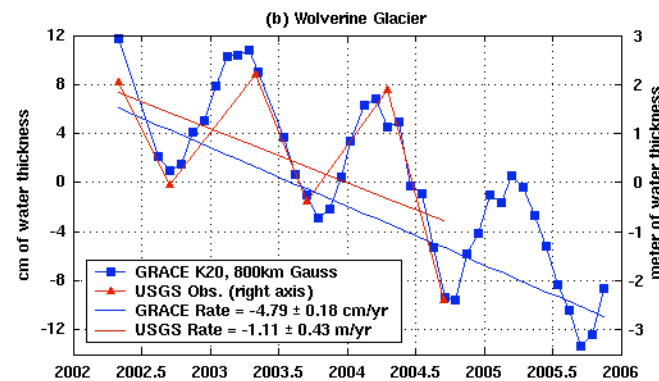
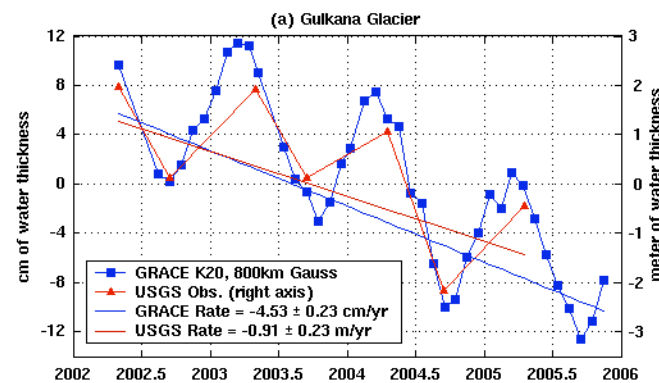
● Major Alaskan Glaciers with area $\geq 1000 \text{ km}^2$

PGR Leakage Effect
A Big Challenge

Land Water Storage
A Big Challenge



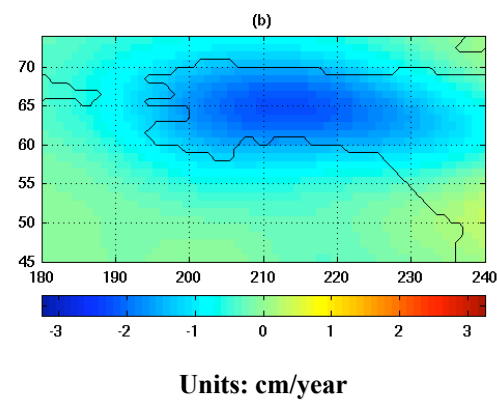
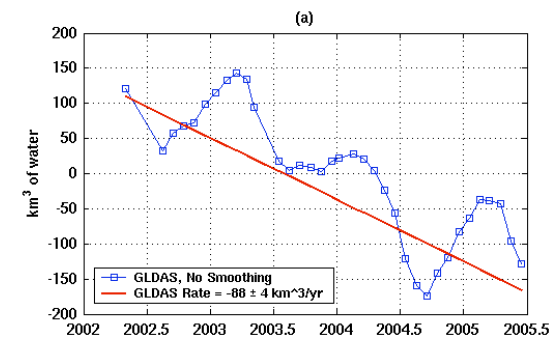
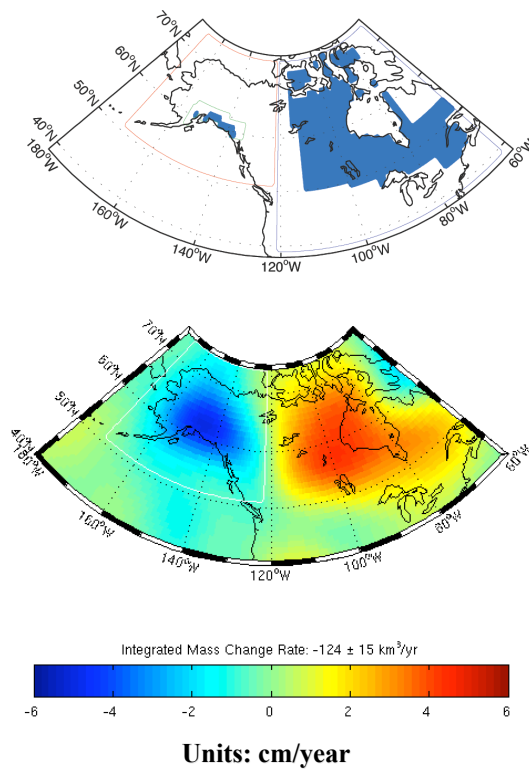
Comparison Between GRACE & USGS Mass Balance Data at Two Benchmark Glaciers





Forward Modeling of Alaskan Glacial Melting

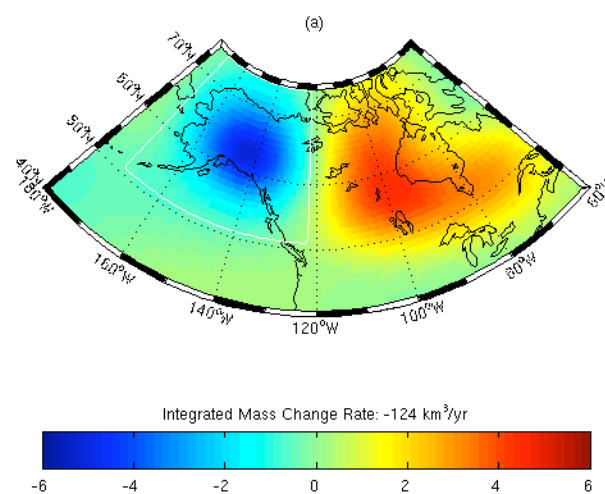
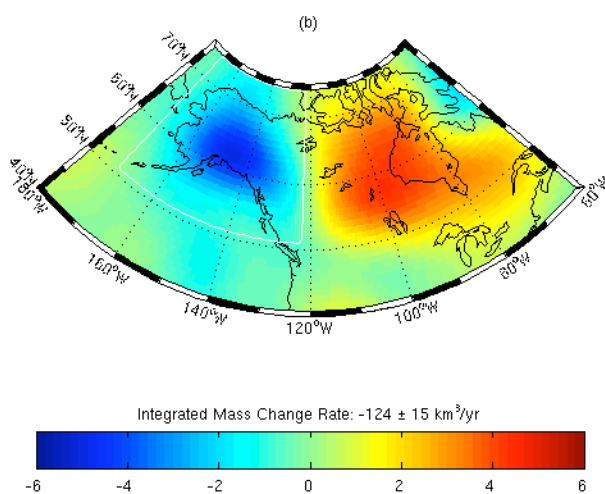
Glacial Melting + GLDAS Water Storage = GRACE





GRACE Estimates in Alaskan & Hudson Bay Area

Forward Modeling of Mass Rates in Alaskan & Hudson Bay Area



Glacial Melting: $-101 \text{ km}^3/\text{year}$
GLDAS Water Storage: $-79 \text{ km}^3/\text{year}$



Conclusions (Mountain Glacial Melting From GRACE):

- ❑ The first 3.5 years of GRACE data suggest significant mountain glacial melting in the Gulf of Alaska region.
- ❑ Through forward modeling to quantify attenuation effects and leakage errors from spatial smoothing, and removing PGR leakage effects, the melting rate is $\sim -101 \pm 22 \text{ km}^3/\text{year}$.
- ❑ This estimate agrees remarkably well with the airborne laser altimetry measurement of $\sim -96 \pm 35 \text{ km}^3/\text{year}$ [Arendt et al. 2002], consistent with an independent estimate of $\sim -115 \pm 20 \text{ km}^3/\text{year}$ based on the first 2 years of GRACE data [Tamisiea et al. 2005].
- ❑ Terrestrial water storage change may account for a significant portion of GRACE observed mass loss in the Alaskan region.
- ❑ The forward modeling technique is proved to be successful in quantifying leakage effects from spatial smoothing.



Alaskan Glacial Melting Observed by GRACE

Details of the above analysis (e.g., the 2-step optimized smoothing methodology, forward modeling of Alaskan glacial melting, land water storage change, and PGR leakage effects) are being published in,

Chen, J.L., B.D. Tapley, C.R. Wilson, Alaskan Mountain Glacial Melting Observed by Satellite Gravimetry, *Earth and Planetary Science Letters*, 2006 (in press).

Preprints are available (chen@csr.utexas.edu).



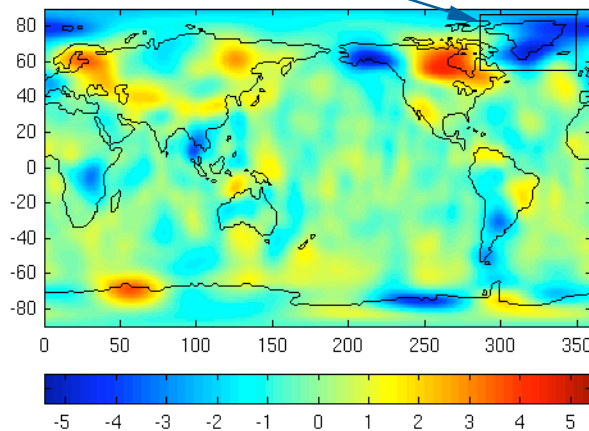
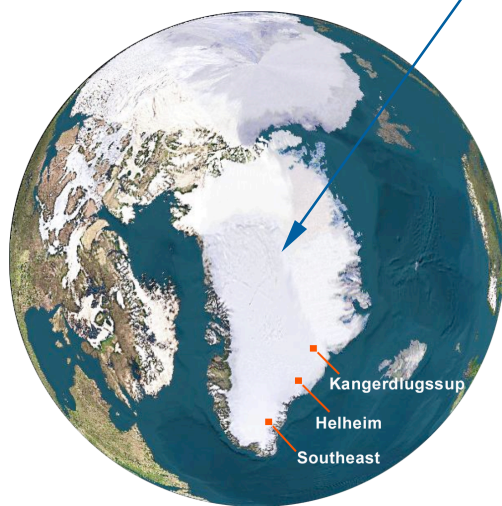
GRACE Application Examples

- ☑ Global water storage change from GRACE
- ☑ GRACE estimated river runoff in the Amazon basin
- ☑ Antarctic long-term mass change from GRACE
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GRACE Confirms Accelerated Greenland Ice Melting



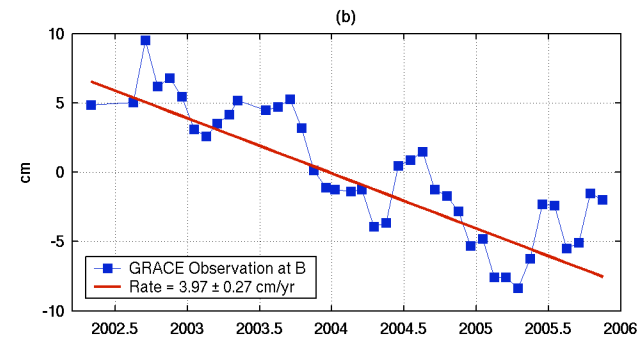
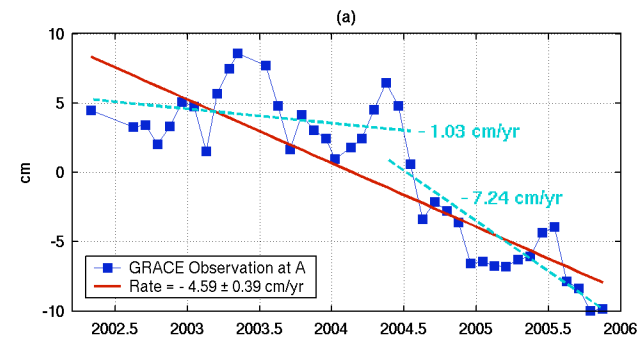
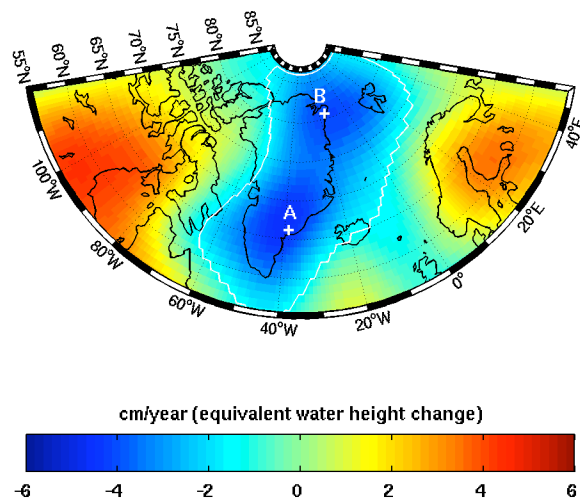
Greenland Ice Sheet



GRACE Confirms Accelerated Greenland Ice Melting



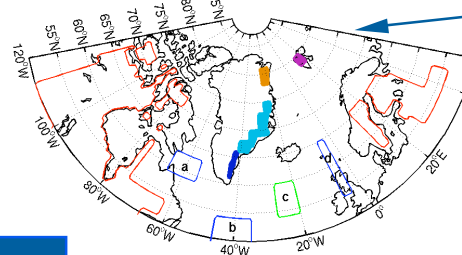
- 40 CSR RL01 constrained solutions
- 3.5 years (Apr 2002 - Nov 2005)
- 2-step optimized filtering



GRACE Confirms Accelerated Greenland Ice Melting

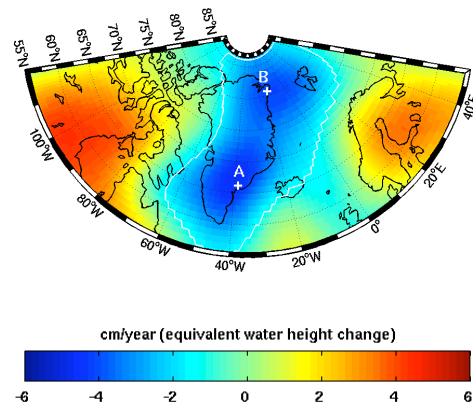


Simulation Scheme

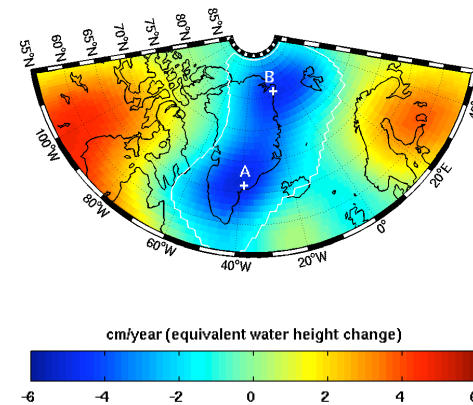


Involving more complicated simulation scheme than previous studies.

GRACE Estimates



Forward modeling



GRACE Confirms Accelerated Greenland Ice Melting



Main Conclusions:

- ❑ The first 3.5 years of GRACE gravity measurements show prominent ice melting over Greenland. After correcting leakage effects through forward modeling, the Greenland ice loss rate is $\sim -239 \pm 23 \text{ km}^3/\text{year}$.
- ❑ This assessment is consistent with a very recent estimate of $-224 \pm 41 \text{ km}^3/\text{year}$ from satellite radar interferometry [Rignot and Kanagaratnam, 2006, *Science*].
- ❑ Our analysis indicates that most of the $-239 \pm 23 \text{ km}^3/\text{year}$ is from East Greenland, with $\sim -90 \text{ km}^3/\text{year}$ in the Southeast Glacier, which are also consistent with the recent satellite radar interferometry estimates.
- ❑ Our forward modeling also suggests significant ice mass loss ($\sim -75 \text{ km}^3/\text{year}$) in Svalbard, supported by a recent study based on superconducting gravimeter and GPS measurements in that region.
- ❑ PGR leakage effect is significant, although direct PGR effect over Greenland is negligible ($-5 \text{ km}^3/\text{year}$).

GRACE Confirms Accelerated Greenland Ice Melting



The above results are presented in,

Chen, J.L., C.R. Wilson, B.D. Tapley, Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet, *Science*, 2006 (under in-depth review).

Reprints & preprints of our GRACE related studies is available at

<http://www.csr.utexas.edu/personal/chen/publication.html>

Comments: chen@csr.utexas.edu



So, what do we learn from GRACE?

- ☑ Global water storage change from GRACE**
- ☑ GRACE estimated river runoff in the Amazon basin**
- ☑ Antarctic long-term mass change from GRACE**
- ☑ Mountain glacial melting from GRACE**
- ☑ GRACE confirms accelerated Greenland ice melting**



What else can we learn from GRACE?

- ☐ **PGR & Reconstruction of Ice History at LGM**
- ☐ **Global Warming & Sea Level Rise**
- ☐ **Drought & Flooding**
- ☐ **Oceanography**
- ☐ **Atmosphere**
- ☐ **Solid Earth**
- ☐ **...**
- ☐ **Or, you name it.**



Amazing GRACE !





Thanks !

GRACE Web Links:

PODAAC GRACE Webpage: <http://podaac.jpl.nasa.gov/grace/>

CSR GRACE Webpage: <http://www.csr.utexas.edu/grace/>

GFZ GRACE: <http://www.gfz-potsdam.de/grace/>

