



GRACE Satellite Gravity Measurements and Geophysical Applications

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Amazing GRACE

Launched: **March 17, 2002**

Initial Altitude: 500 km

Inclination: 89 deg

Eccentricity: ~ 0.001

Separation Distance: ~ 220 km

Nominal Mission : **5 years**

Decommissioned in Nov., 2017

Over 15 years in space!!!



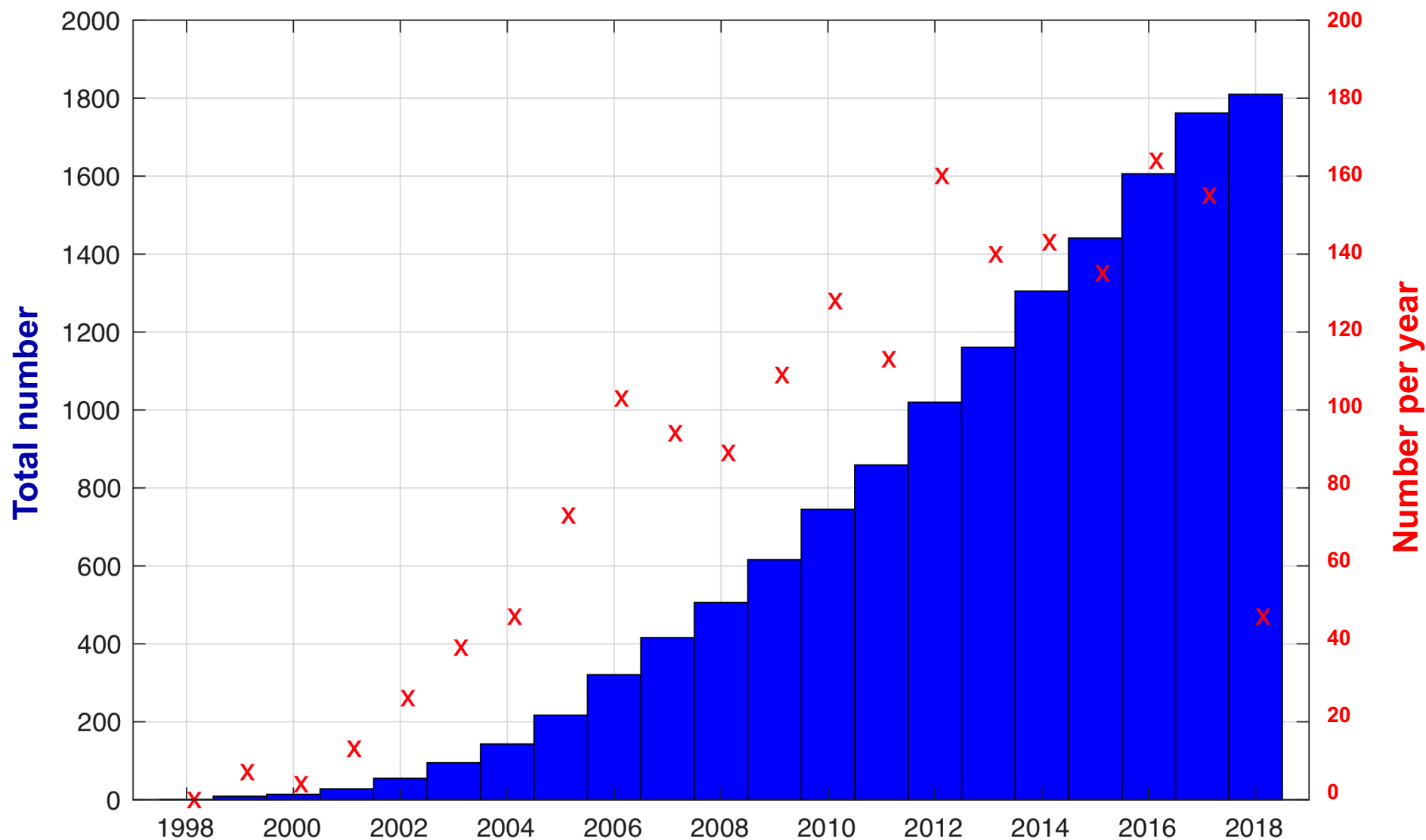
GRACE Follow-On

Launched on 2018.05.22





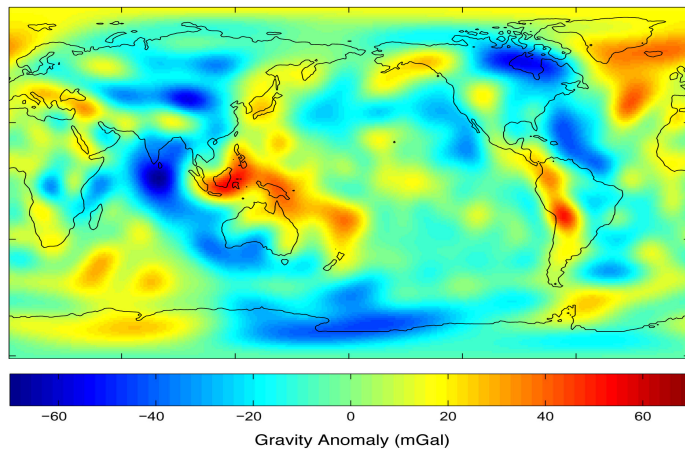
GRACE Publication Statistics (> 1800 by June of 2018)



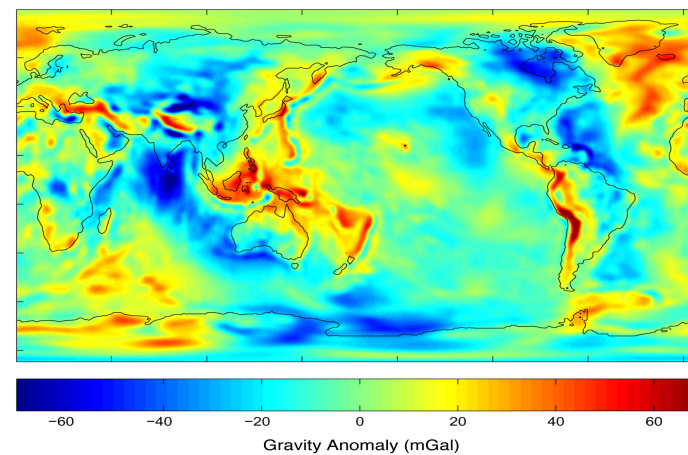
(http://www-app2.gfz-potsdam.de/pb1/op/grace//references/sort_date.html)

Progress in Gravity Field Resolutions

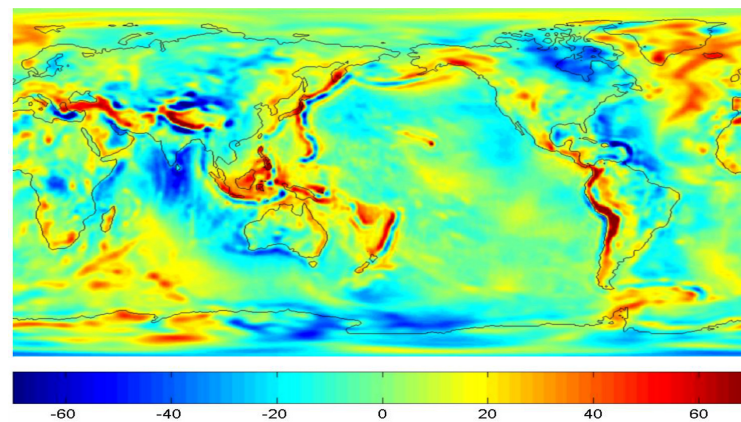
Decades of tracking to geodetic satellites



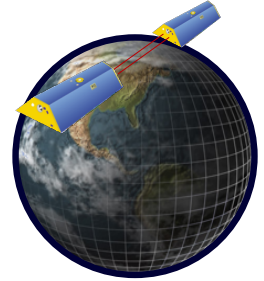
111 days of GRACE data



13 months of GRACE data



GRACE and Global Climate Change



□ Hydrosphere

- Land water storage**
- Precipitation**
- Evapotranspiration**
- Runoff**
- Ground water**
- Droughts**
- Floodings**

□ Ocean

- Global sea level change**
- Ocean heat content variation**

□ Cryosphere

- Polar ice sheets mass balance**
- Mountain glaciers mass balance**

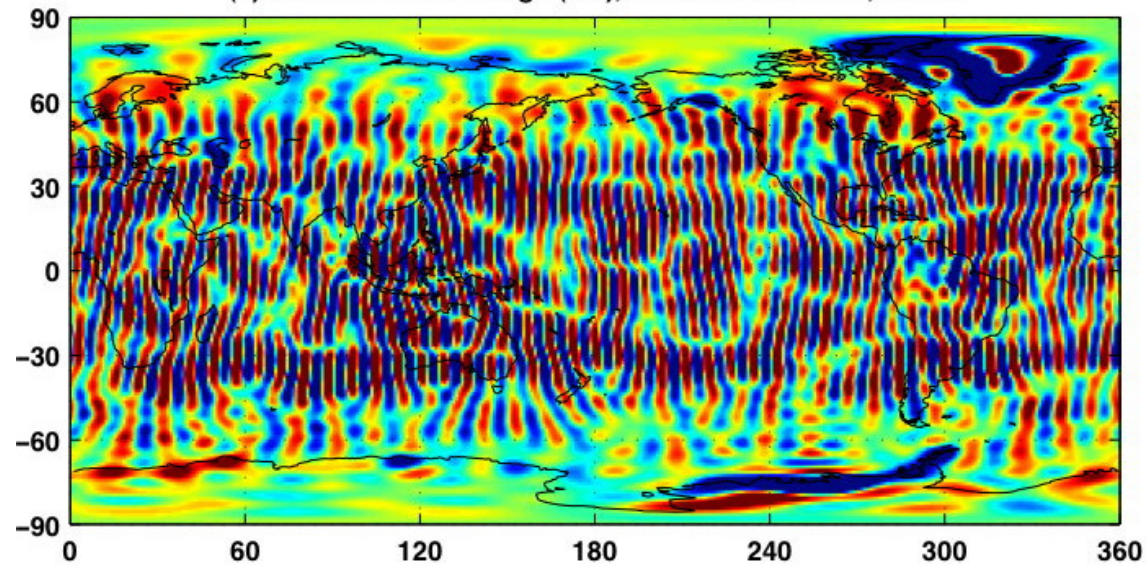




Major Challenges in GRACE Mass Estimation

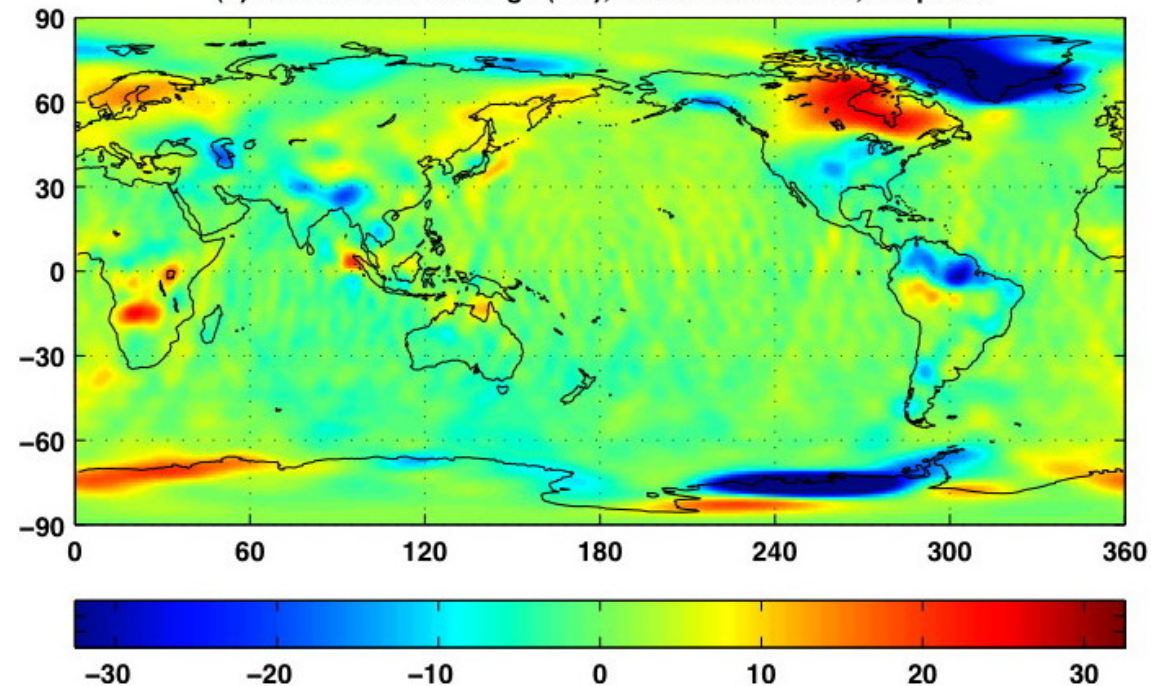
- ❑ Low spatial resolution (300 – 500 km)
- ❑ Leakage bias of GRACE estimates, especially for small basin or regional mass change
- ❑ Uncertainty of low-degree gravitational changes (ΔC_{20} or ΔJ_2)
- ❑ Uncertainty of geocenter center motion (ΔC_{11} , ΔS_{11} , ΔC_{10})
- ❑ Uncertainty of solid earth geophysical signal (GIA)
- ❑ Uncertainty of atmospheric and ocean model predictions (GAC)
- ❑ Lack of adequate independent observations to validate GRACE estimates

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



No filtering
or smoothing

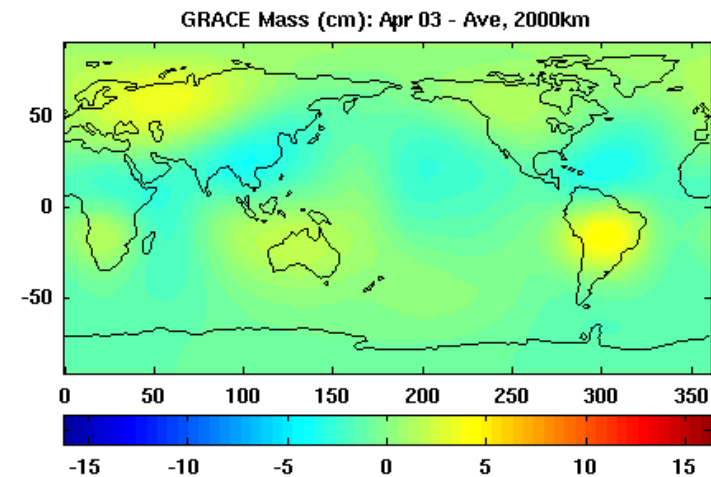
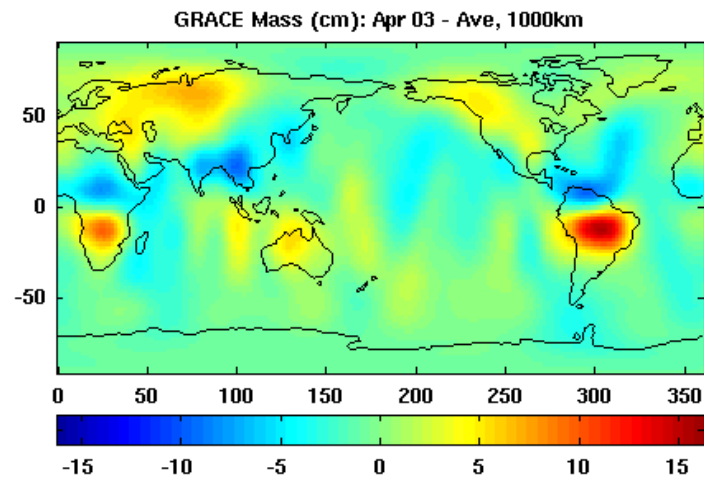
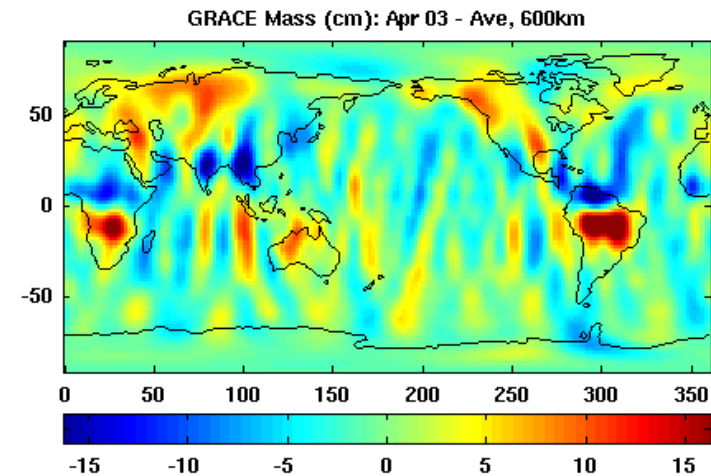
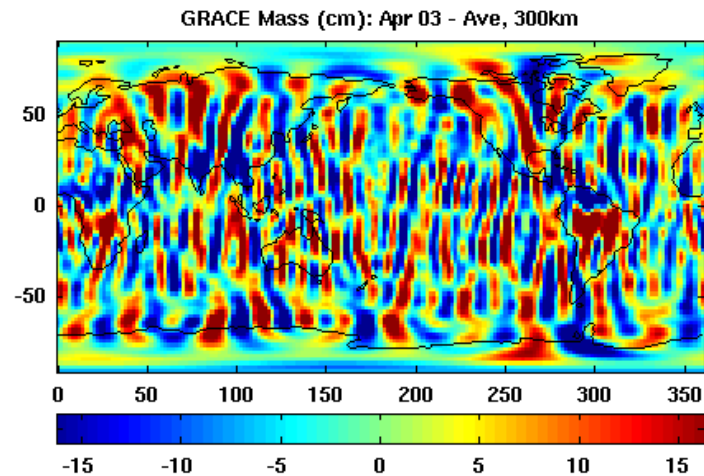
(b) GRACE Mass Change (cm), 2003.01 CSR RL05, 300p4m6



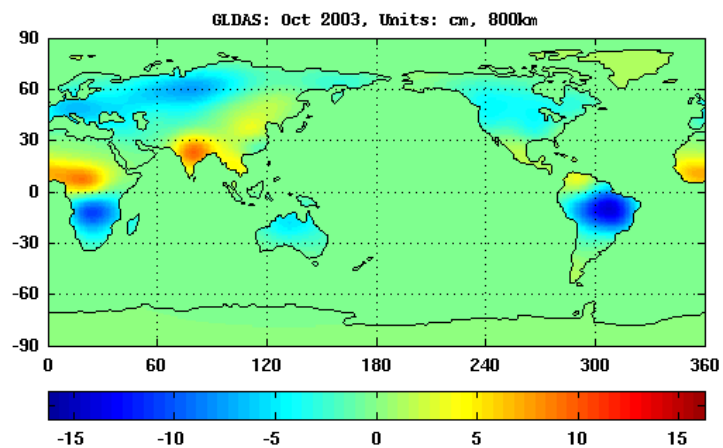
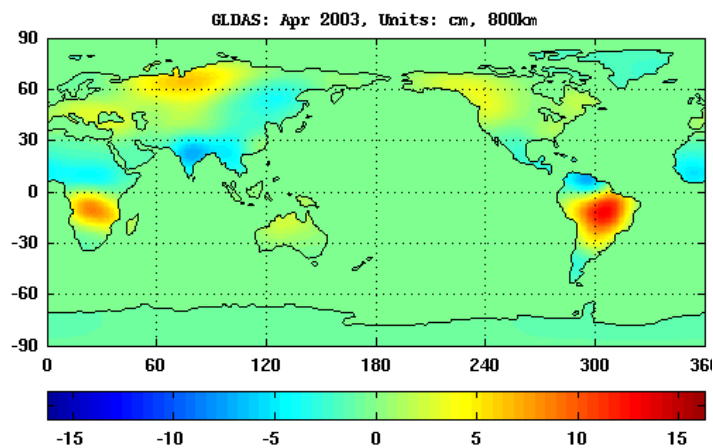
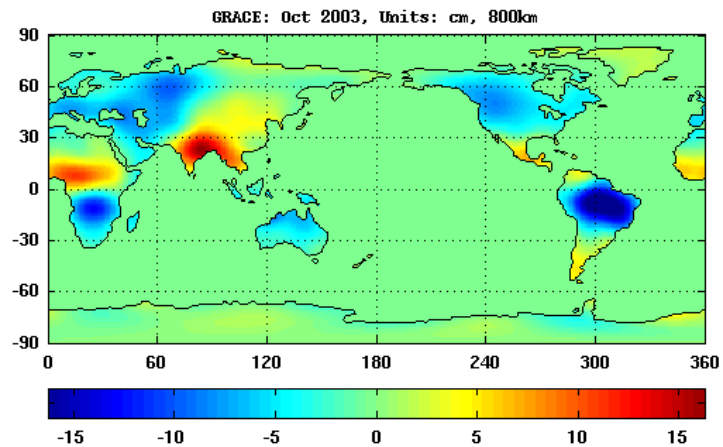
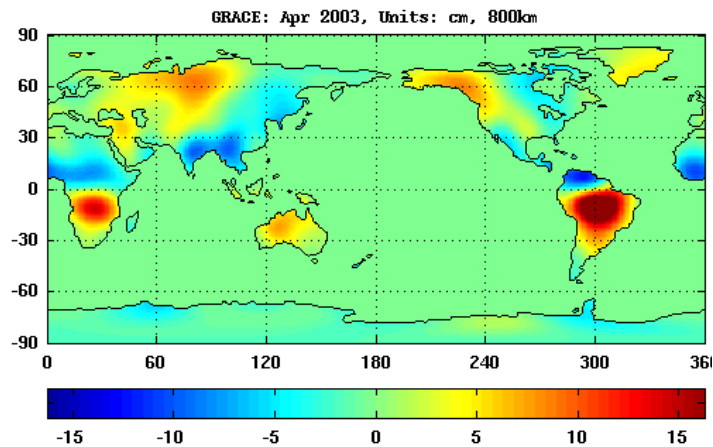
Decorrelation +
300 km Gaussian



Challenges of GRACE Data Processing

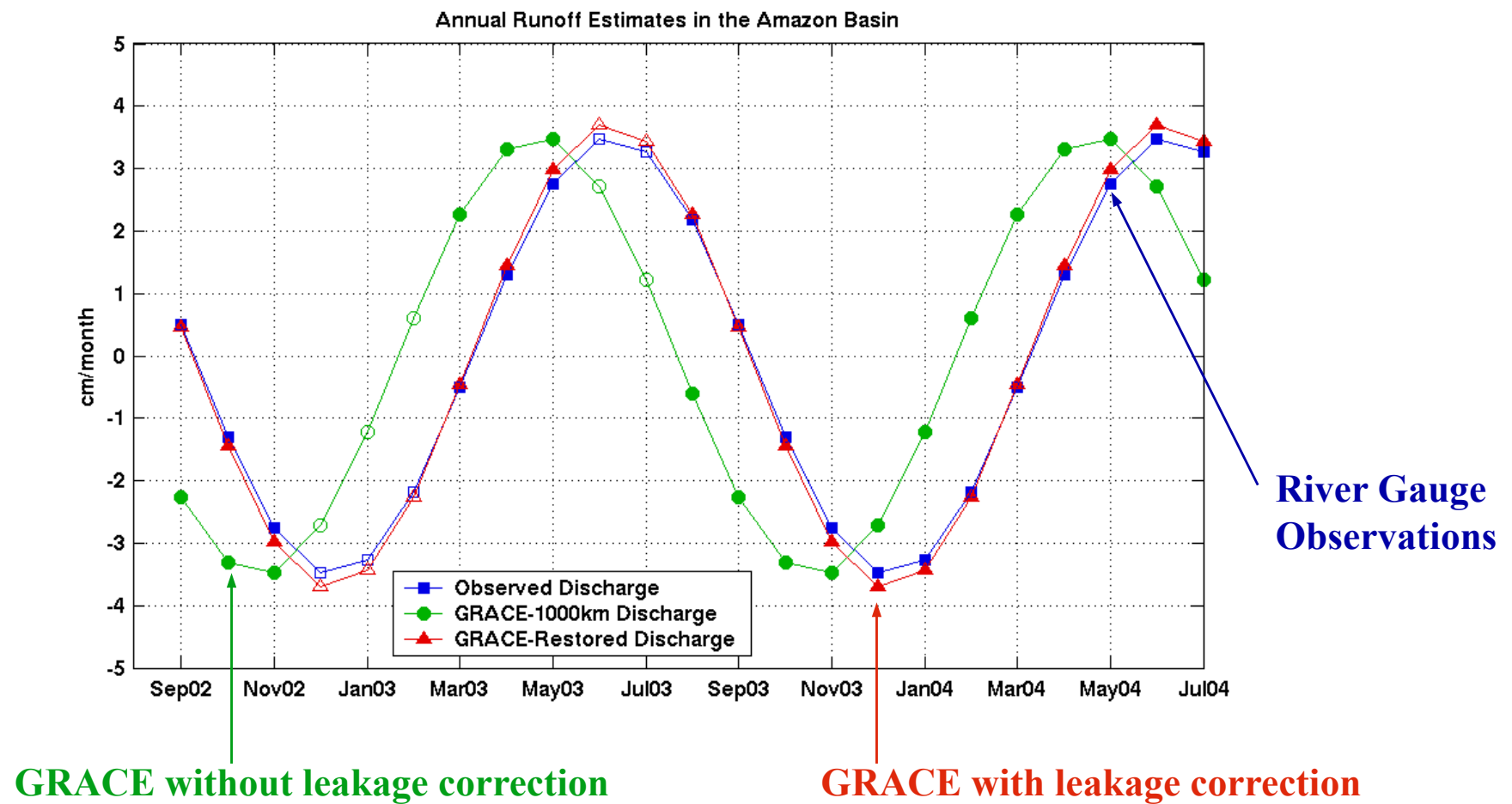


Global Water Storage Change from GRACE



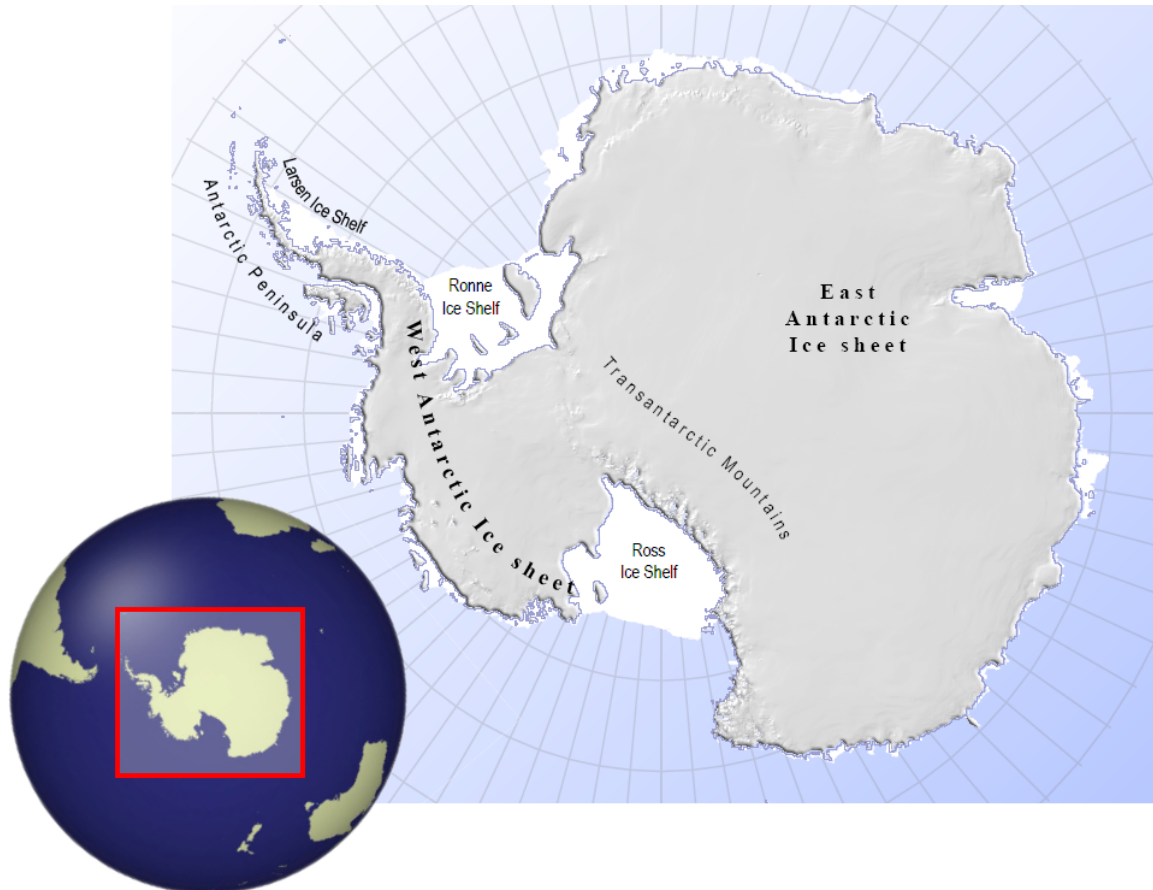


Annual Runoff Estimates in Amazon Basin



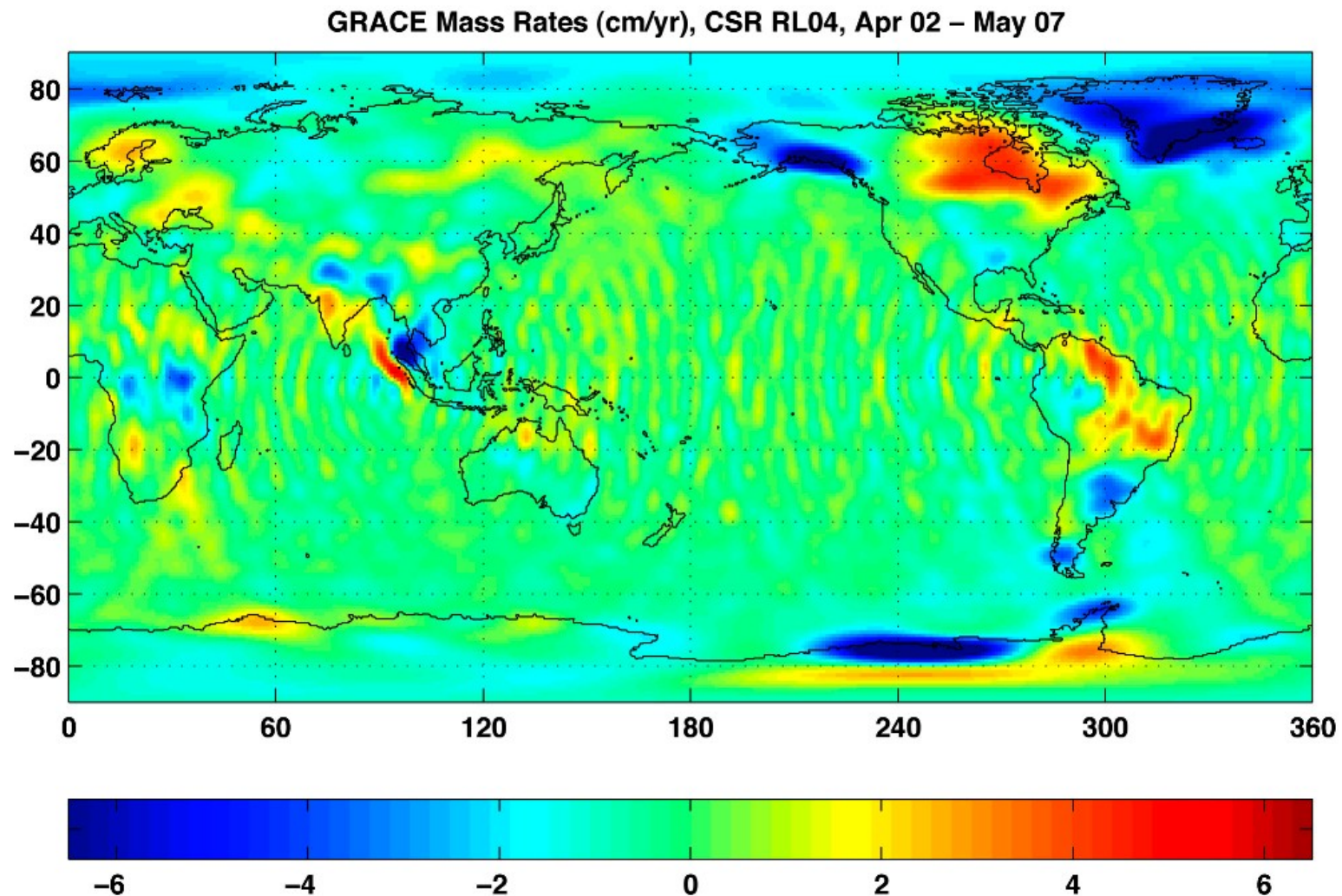


Antarctic Ice Sheet Mass Balance From GRACE



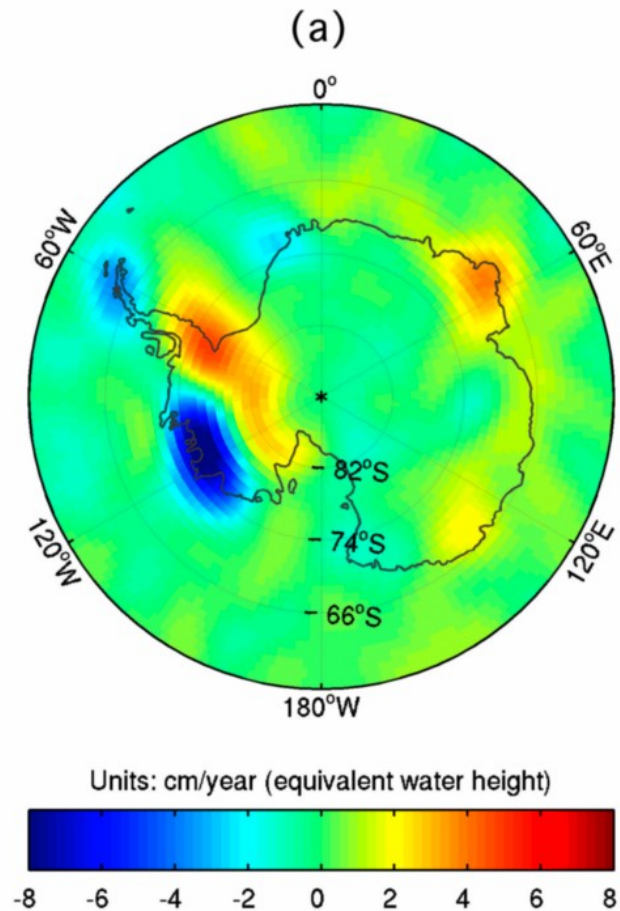
The Antarctic ice sheet has a total area of $\sim 14,000,000 \text{ km}^2$ and averaged ice sheet thickness of $\sim 2.16 \text{ km}$, accounts for 90% of the world's ice and 75% of the world's fresh water resources, and has the potential to raise the global sea level by over 70 meters if completely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

Global long-term mass change rates from GRACE

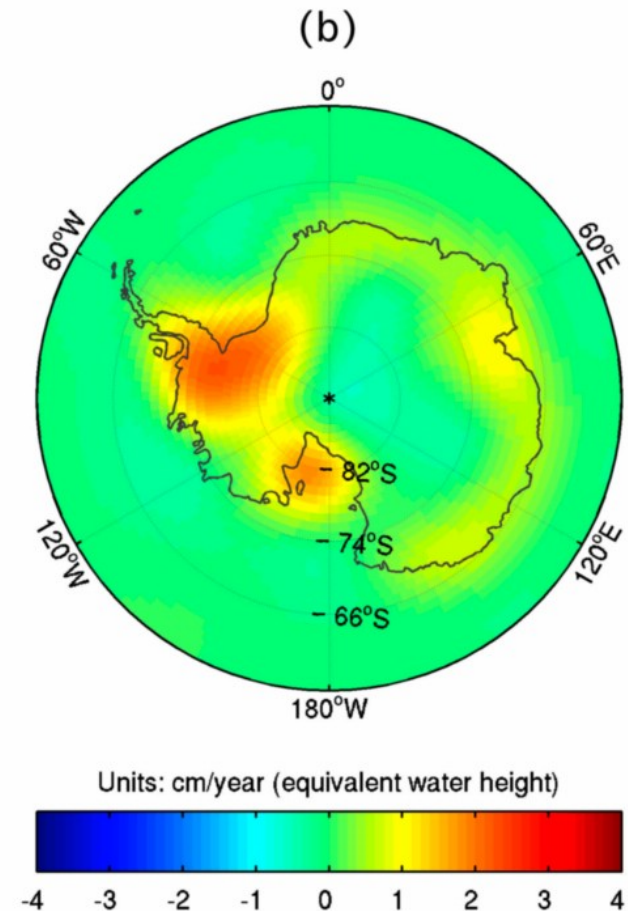


Based on 58 CSR RL04 monthly gravity solutions from April 2002 to May 2007.

GRACE-observed mass change rates (in cm/year of water height) over Antarctica, P4M6 + 300 km Gaussian smoothing.

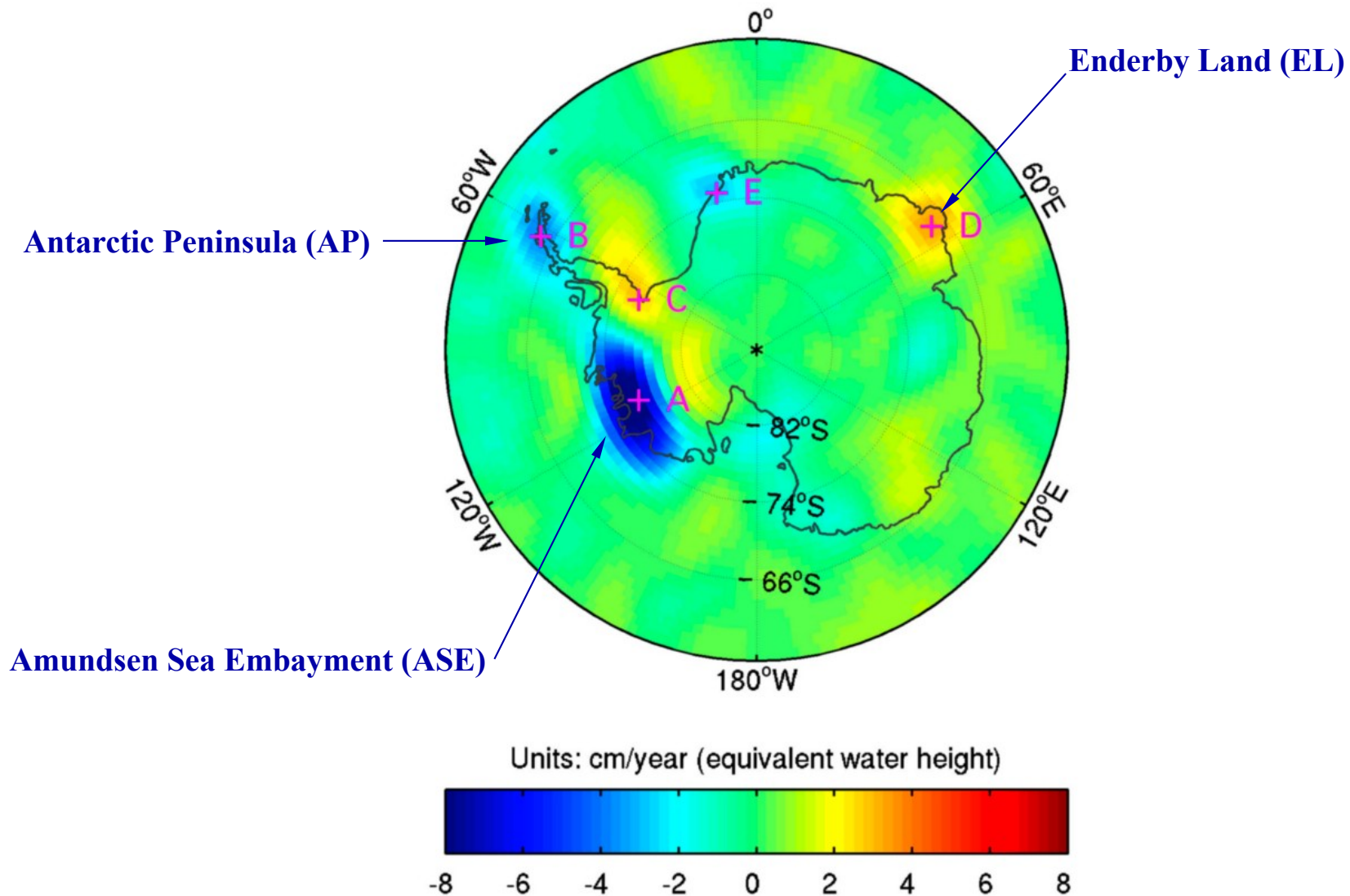


PGR effects (in mass equivalent) over Antarctica from the IJ05 PGR model, P4M6 + 300 km Gaussian smoothing.



(Please note the different color scales, ± 8 vs. ± 4 .)

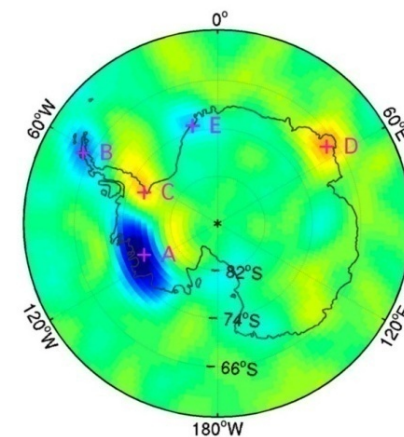
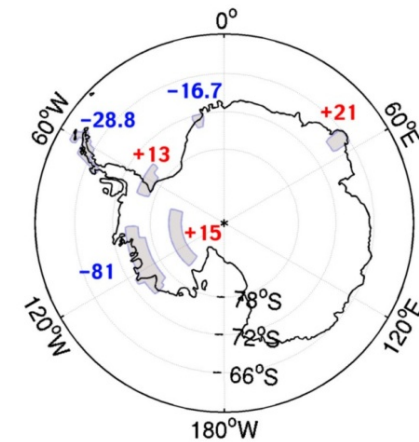
Antarctic long-term ice mass change rates (GRACE - PGR)



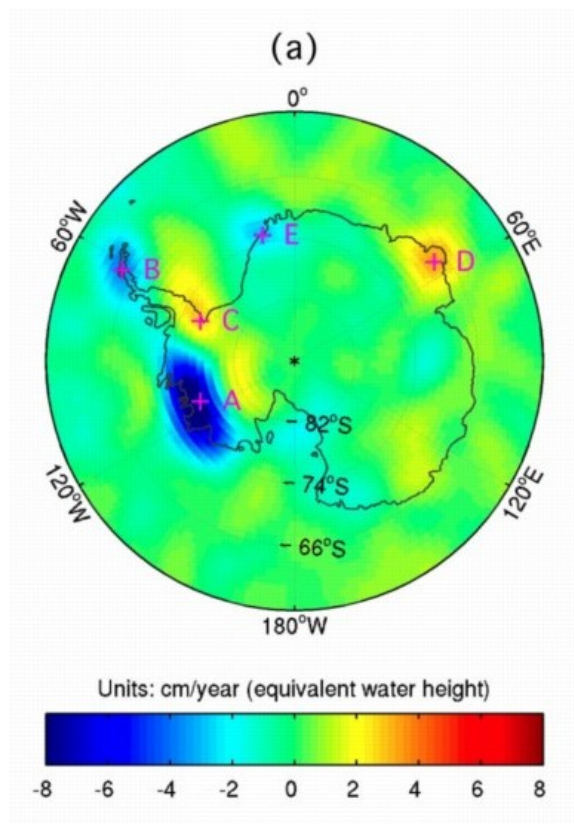
Forward Modeling



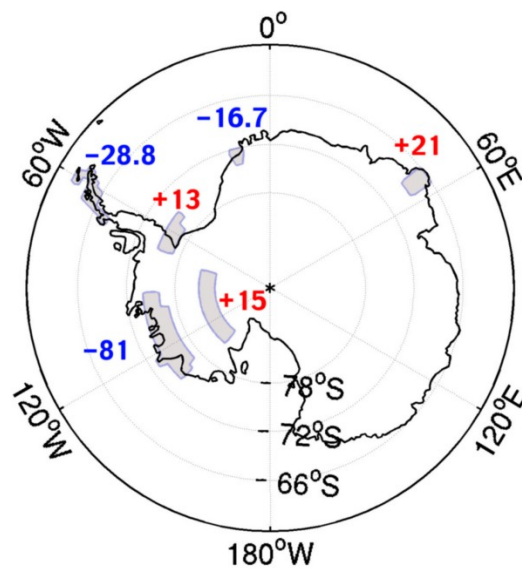
- ❑ **Step-1:** To choose six regions (shaded) where GRACE data show prominent signals. In each region (on $1^\circ \times 1^\circ$ grid), a trial mass rate (in units of km^3/yr) is distributed uniformly. The remainder of the grid (outside Antarctica) retains GRACE mass rates. Therefore, spatial leakage from the 6 regions to areas outside Antarctica should be evident when comparing the model and GRACE rate maps. This is a variation of the forward modeling technique in our previous studies.
- ❑ **Step-2:** To convert the constructed mass rate grids into spherical harmonics.
- ❑ **Step-3:** To replicate procedures (used to transform GRACE data) to compute surface mass changes (no degree-1 terms, same truncation and same 2-steps filtering, ...).
- ❑ **Step-4:** To adjust model rates and region shapes until there is general agreement with the GRACE map. As a final constraint, we force model integrated mass rate for each region (sum over grid points with cosine of latitude weights within boundaries where magnitude exceeds 1 cm/year) to agree with the GRACE map.



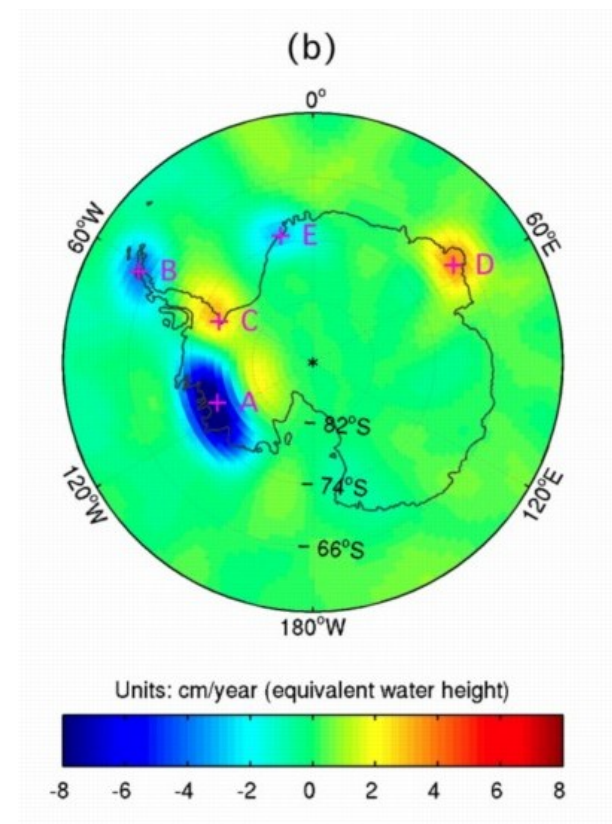
GRACE Observations (GRACE-PGR)



Modeling Scheme



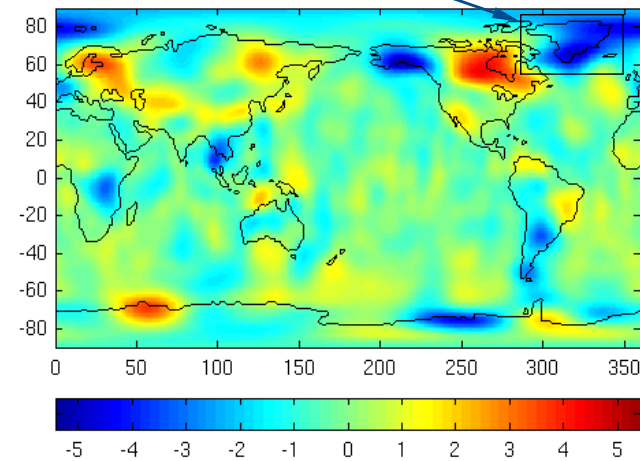
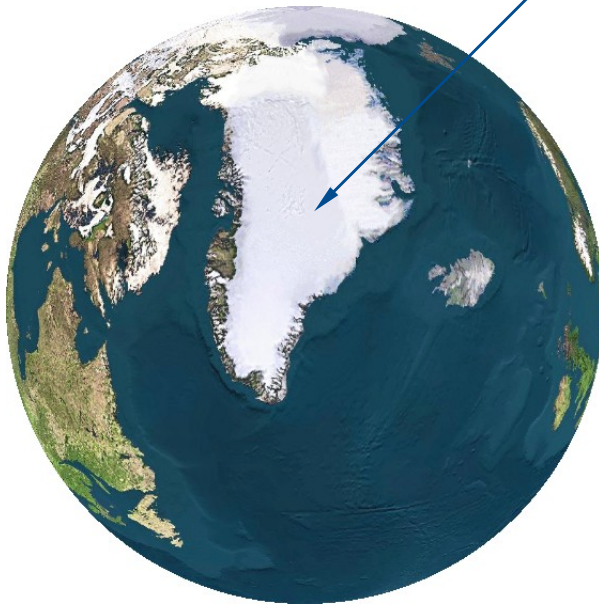
Forward Modeling Estimates



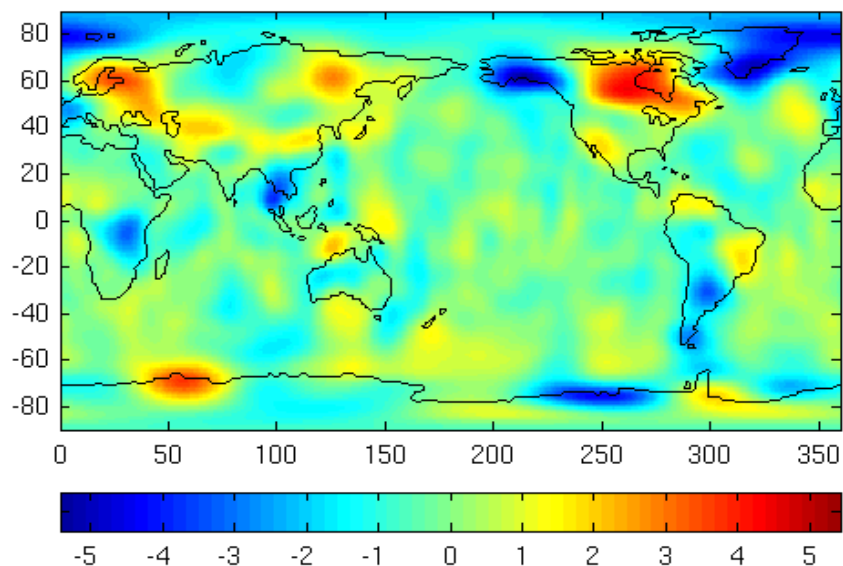


Climate Change and Greenland Ice Loss

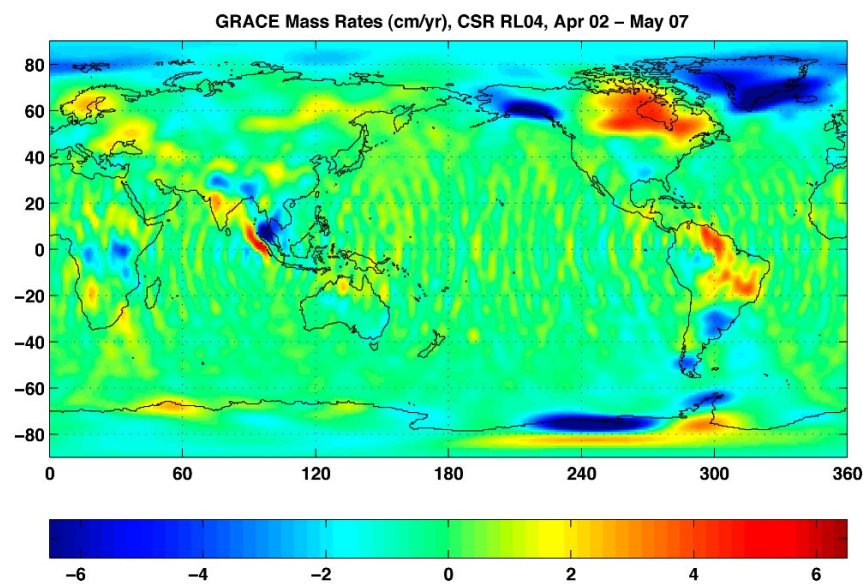
Greenland Ice Sheet



The Changing Climate & Greenland Ice Mass Change



**RL01 - 3.5 Years
(Apr 2002 - Nov 2005)**



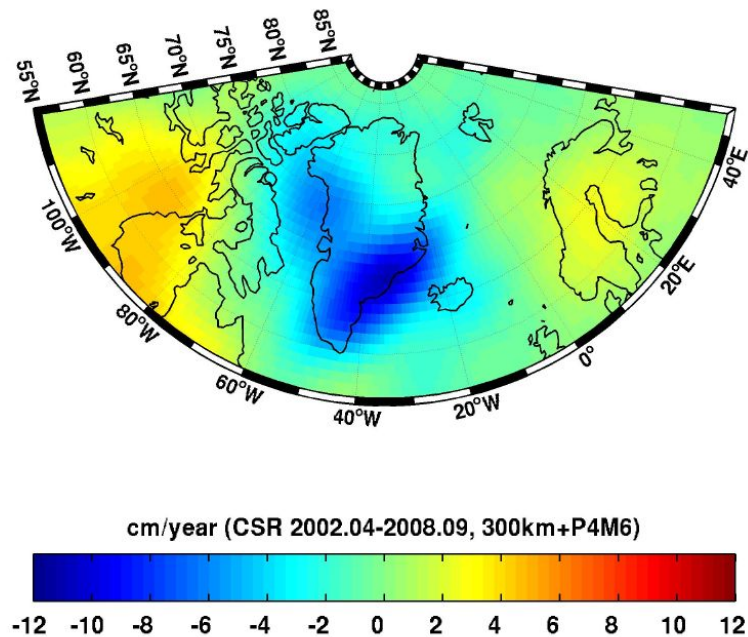
**RL04 - 5 Years
(Apr 2002 - May 2007)**



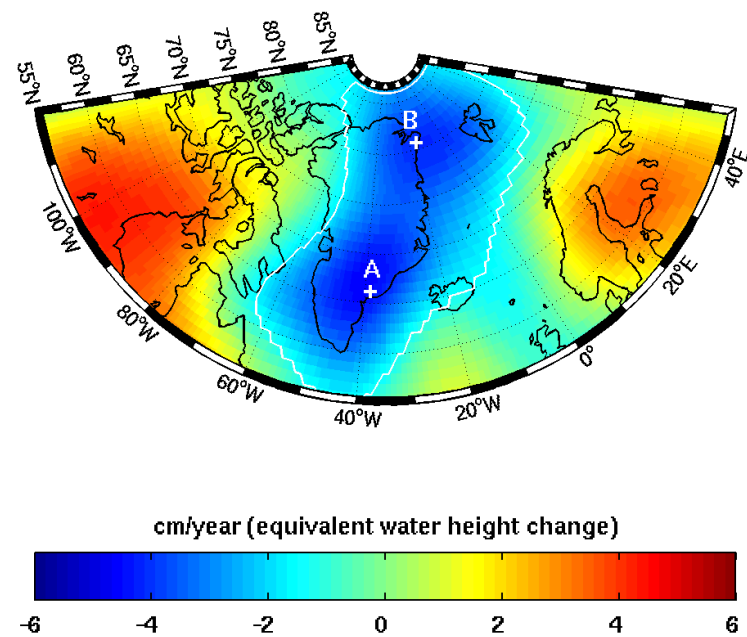
The Changing Climate & Greenland Ice Mass Change



GRACE RL04 - 6.5 Years
2002.04 - 2008.09



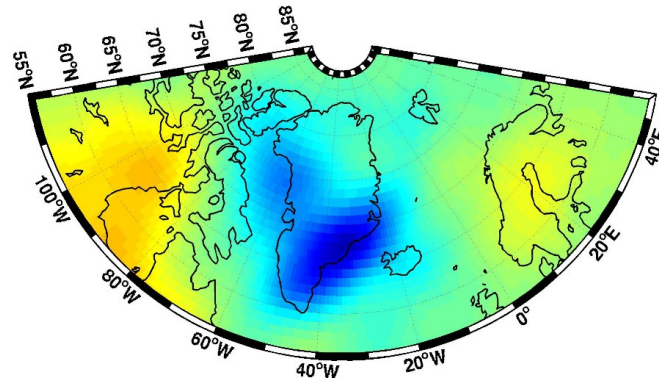
GRACE RL01 - 3.5 Years
2002.04 - 2005.11



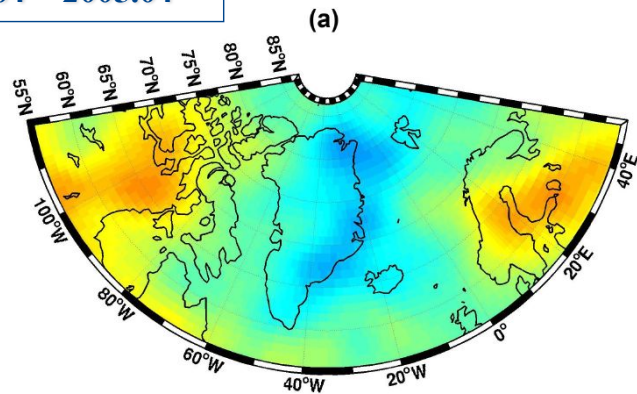
The Changing Climate & Greenland Ice Mass Change



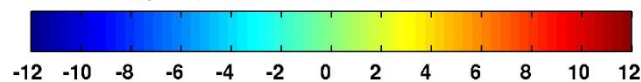
GRACE RL04 - 6.5 Years
2002.04 - 2008.09



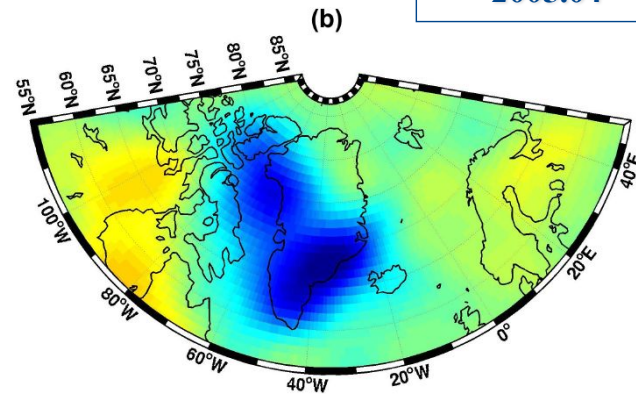
RL04 - First 3 Years
2002.04 - 2005.04



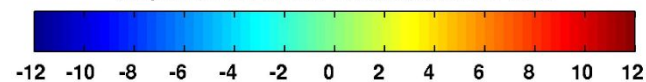
cm/year (CSR 2002.04-2005.04, 300km+P4M6)



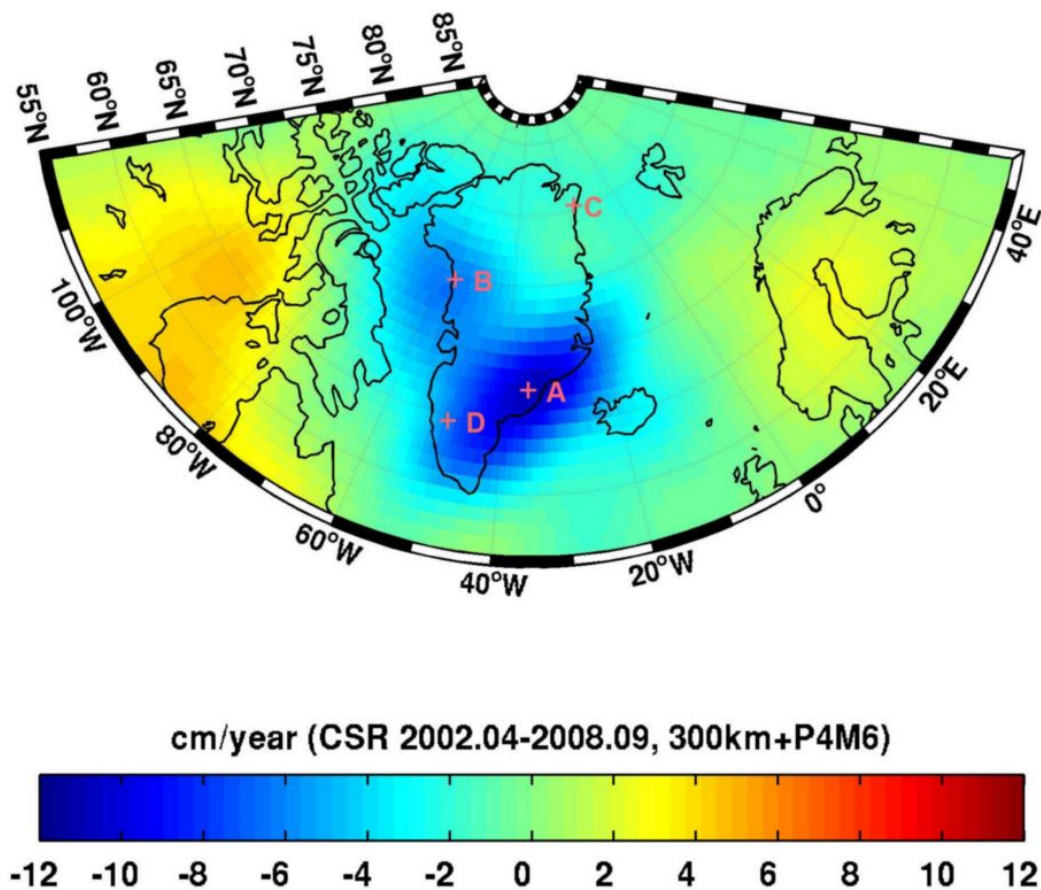
RL04 - Recent 3.5 Years
2005.04 - 2008.09



cm/year (CSR 2005.04-2008.09, 300km+P4M6)

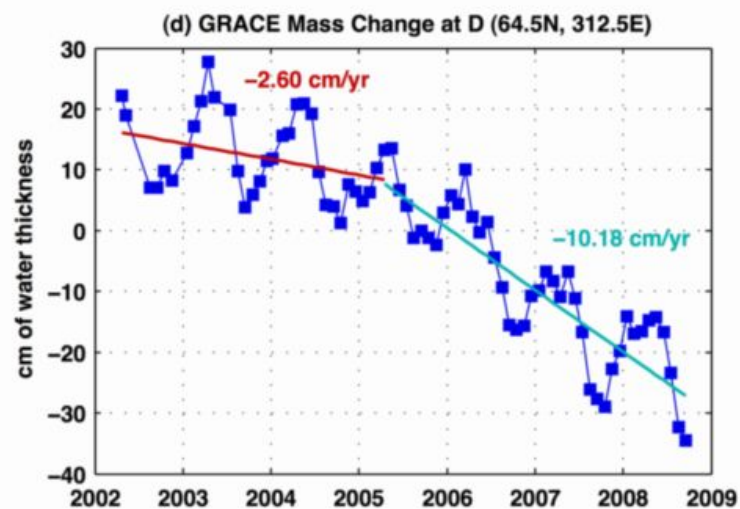
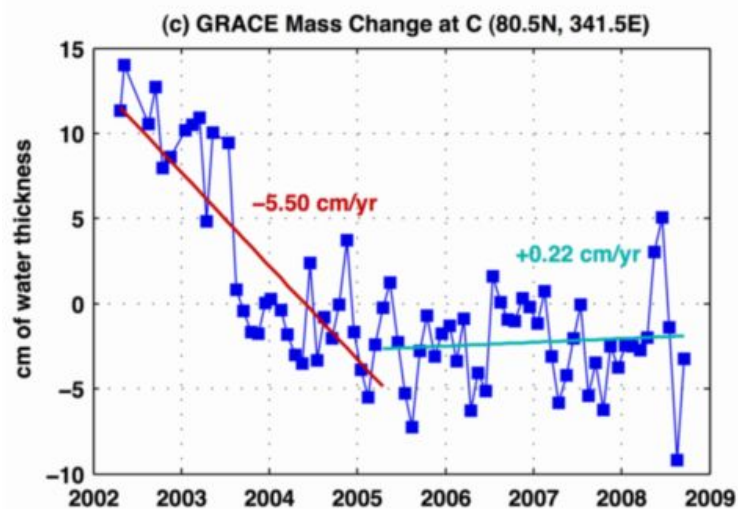
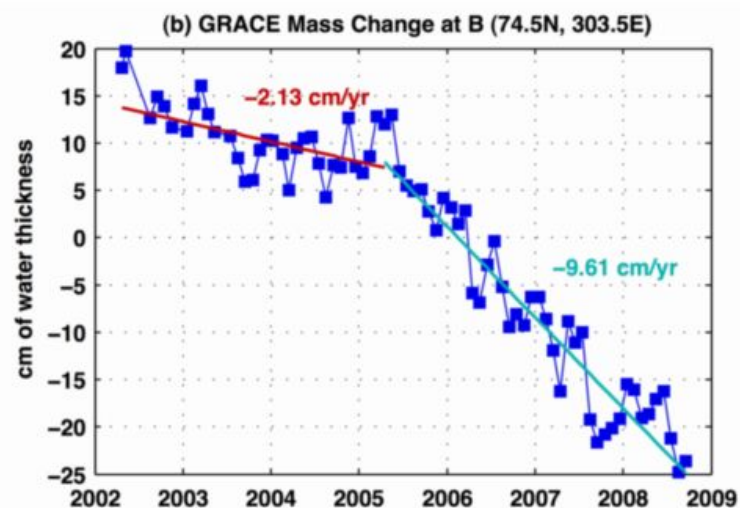
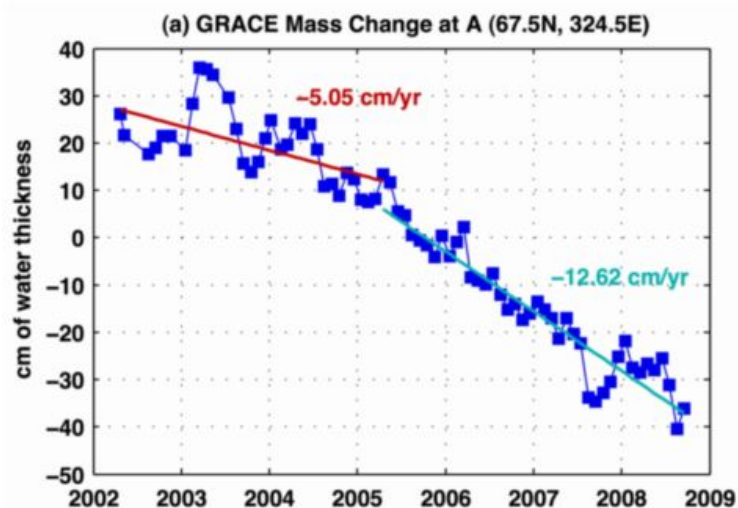


GRACE Time Series at 4 Selected Locations (A, B, C, D)



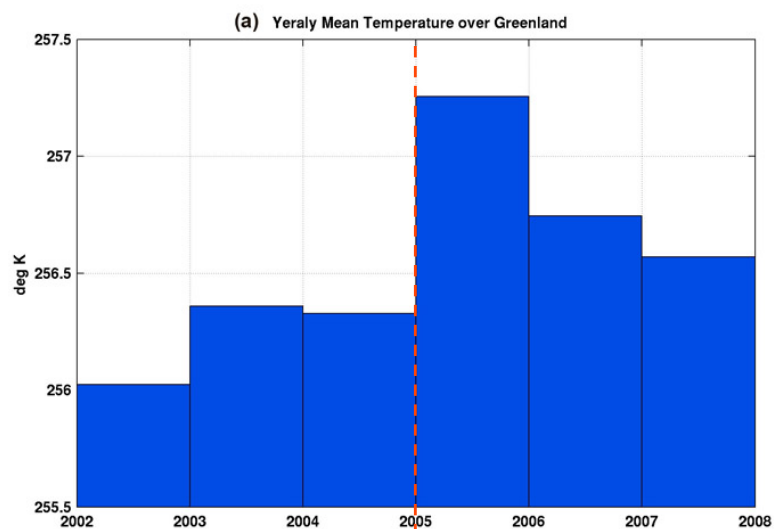


GRACE Time Series at 4 Selected Grids (A, B, C, D)

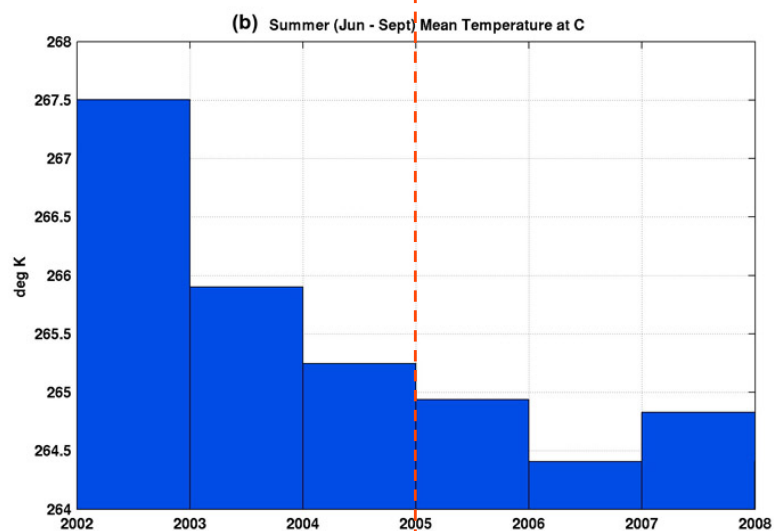




The Changing Climate in Greenland



Yearly Mean Temperature (2m)
Over Greenland

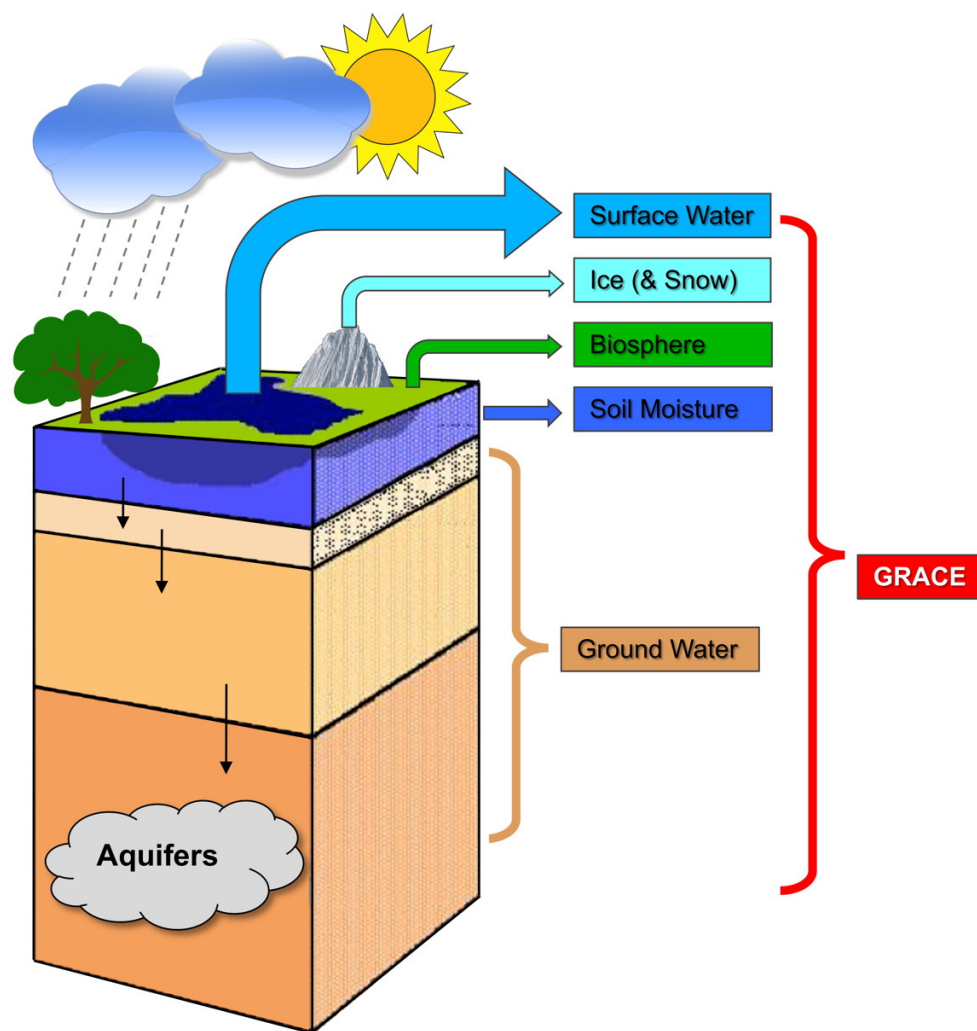


Summer (Jun - Sept) Mean
Temperature (2m) at Point C

2005



GRACE Groundwater Monitoring



(From Cazenave and Chen, 2009)



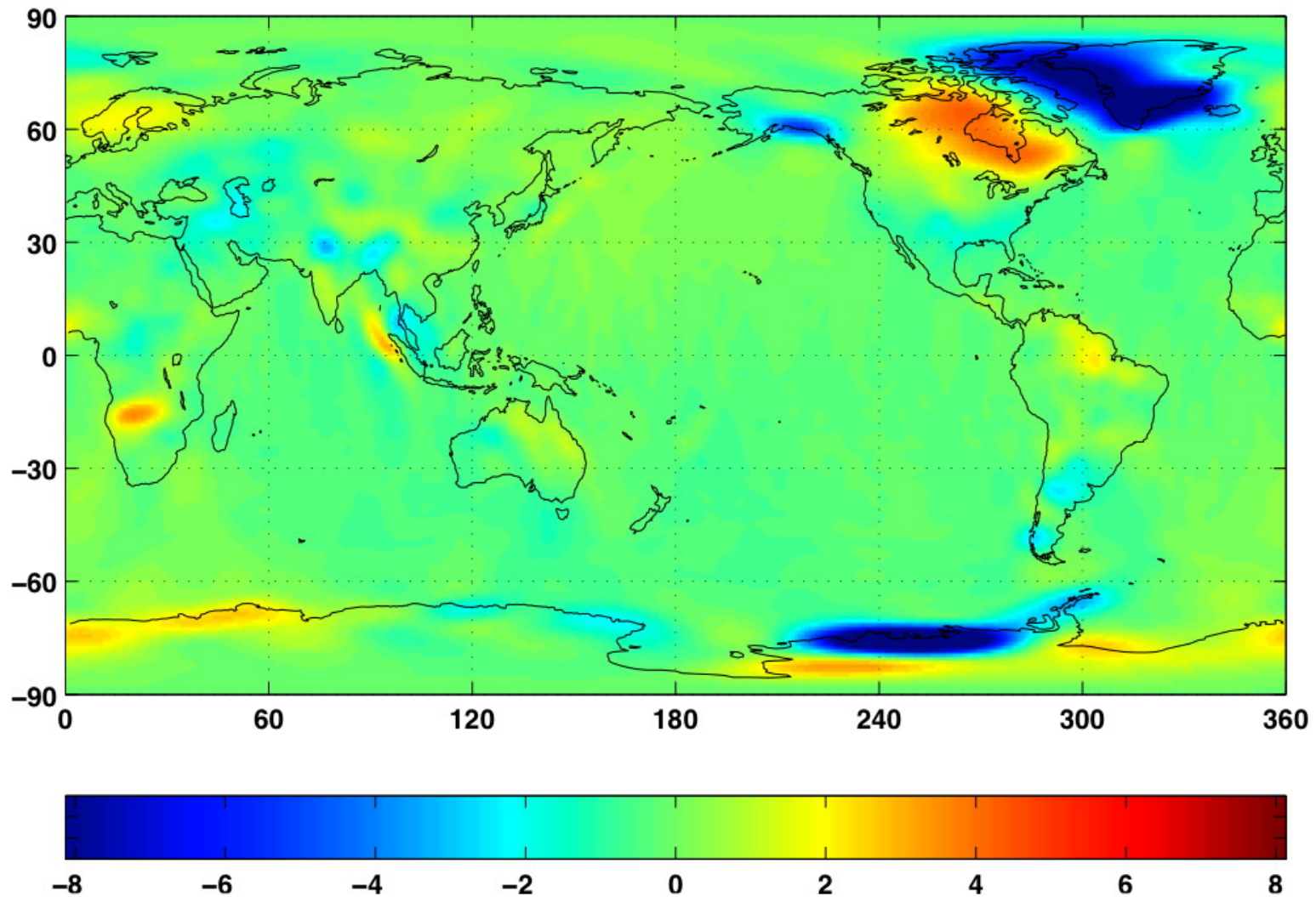


Challenges in GRACE groundwater monitoring

- ❑ Low spatial resolution (300 – 500 km)
- ❑ Leakage bias of GRACE estimates, especially for small basin or regional groundwater change
- ❑ Uncertainty of model estimated surface water storage (soil, snow & surface reservoirs) change
- ❑ Uncertainty of long-term solid earth geophysical signal
- ❑ Contamination from nearby glaciers signal (such as in Northwest India)
- ❑ Uncertainty assessment for GRACE groundwater estimates
- ❑ Lack of adequate *in situ* groundwater data to validate GRACE estimates

Global Long-Term Mass Rate From GRACE

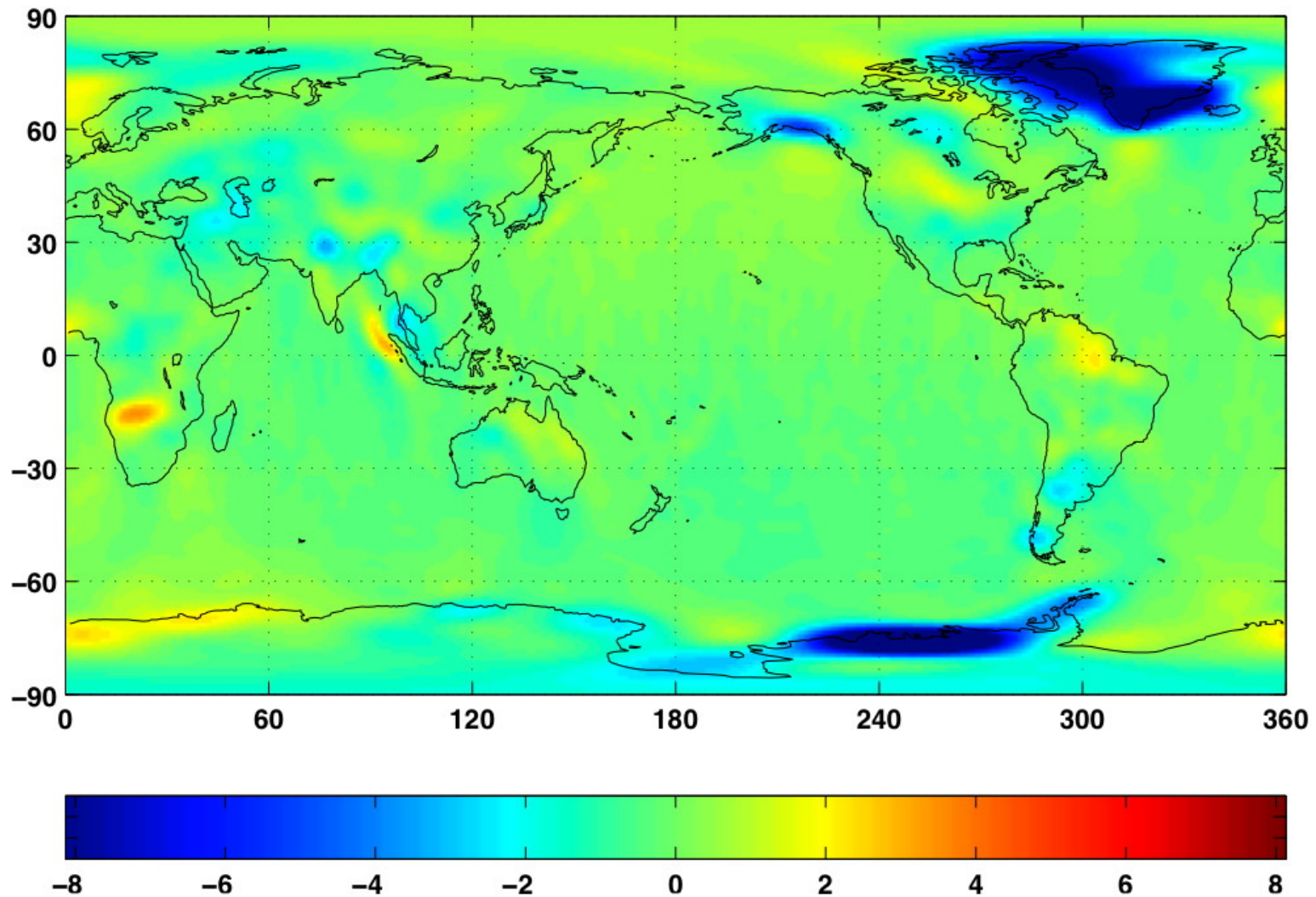
(2003.01- 2012.12, CSR RL05, Decorrelation + 300km)



cm/yr (equivalent water height)

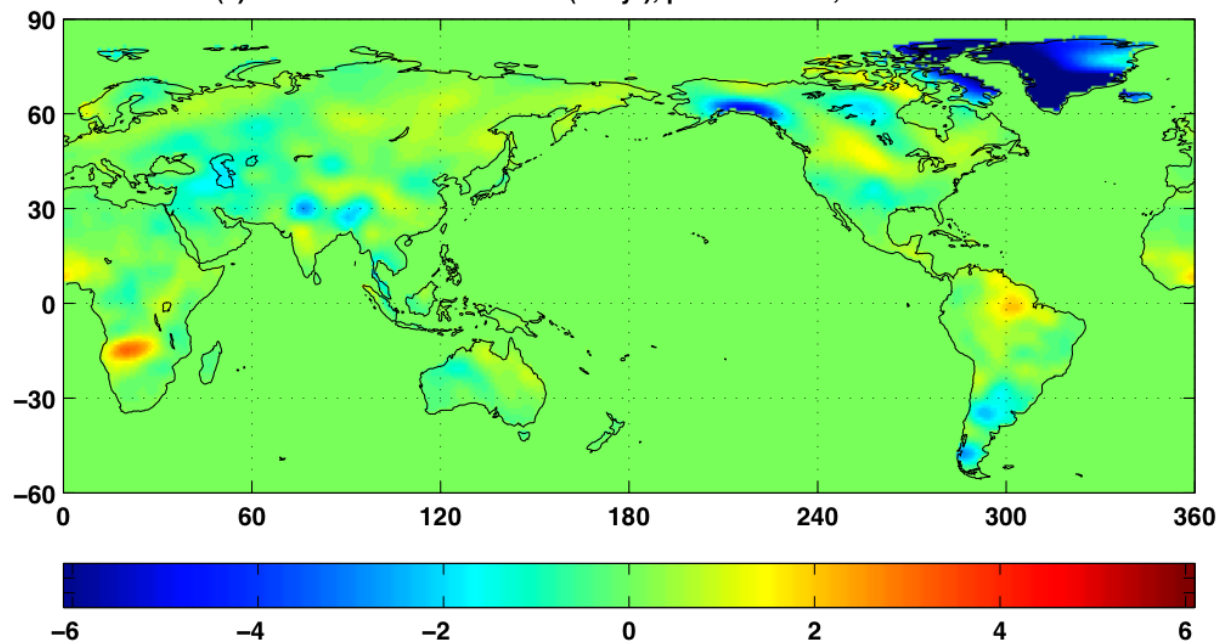
Global Long-Term Mass Rate From GRACE

(2003.01- 2012.12, CSR RL05, PGR Removed, A et al., 2013)



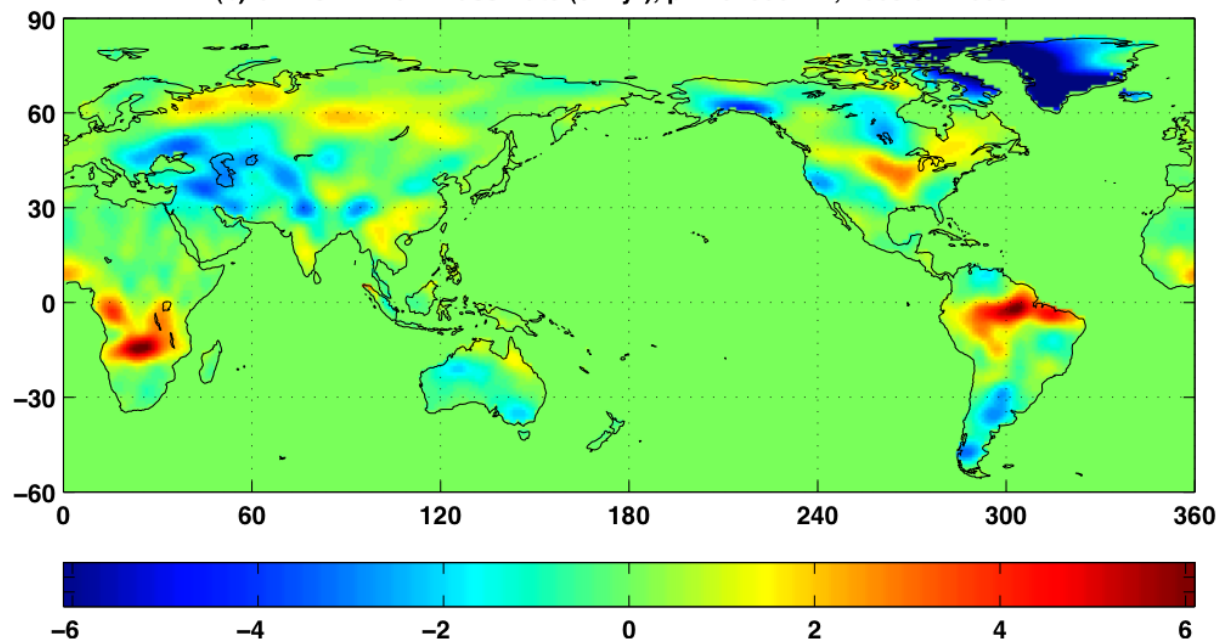
cm/yr (equivalent water height)

(a) GRACE – PGR Mass Rate (cm/yr), p4m6+300 km, 2002.04–2014.08



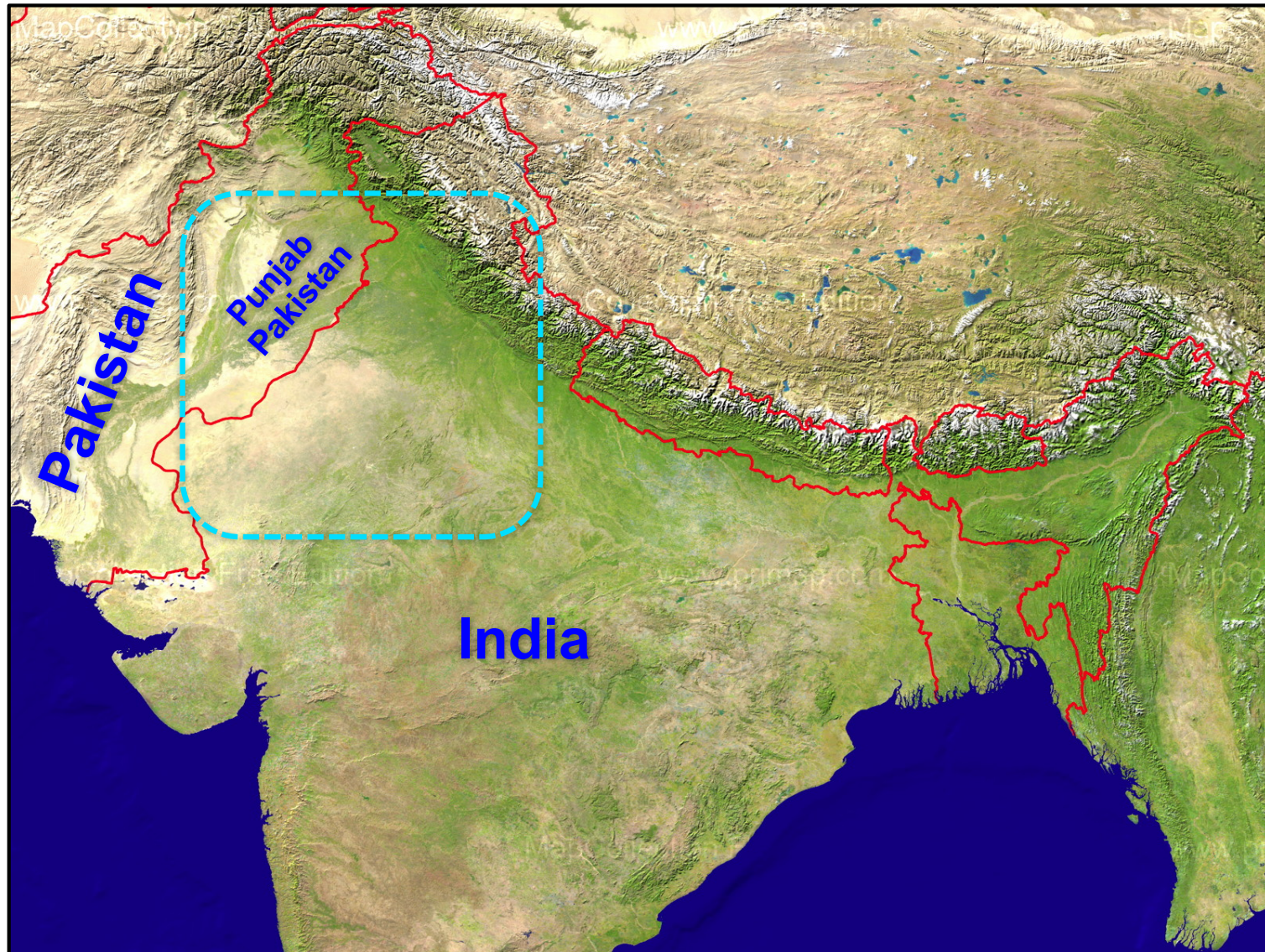
12+ Years
2002.04-2014.08

(b) GRACE – PGR Mass Rate (cm/yr), p4m6+300 km, 2005.01–2009.12

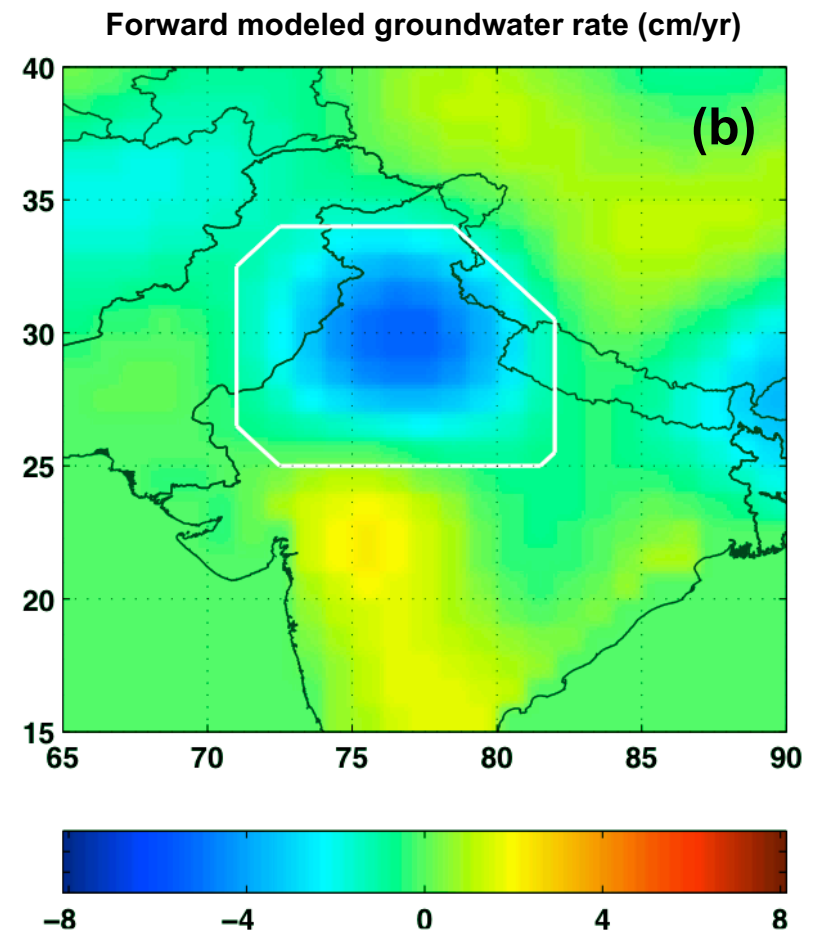
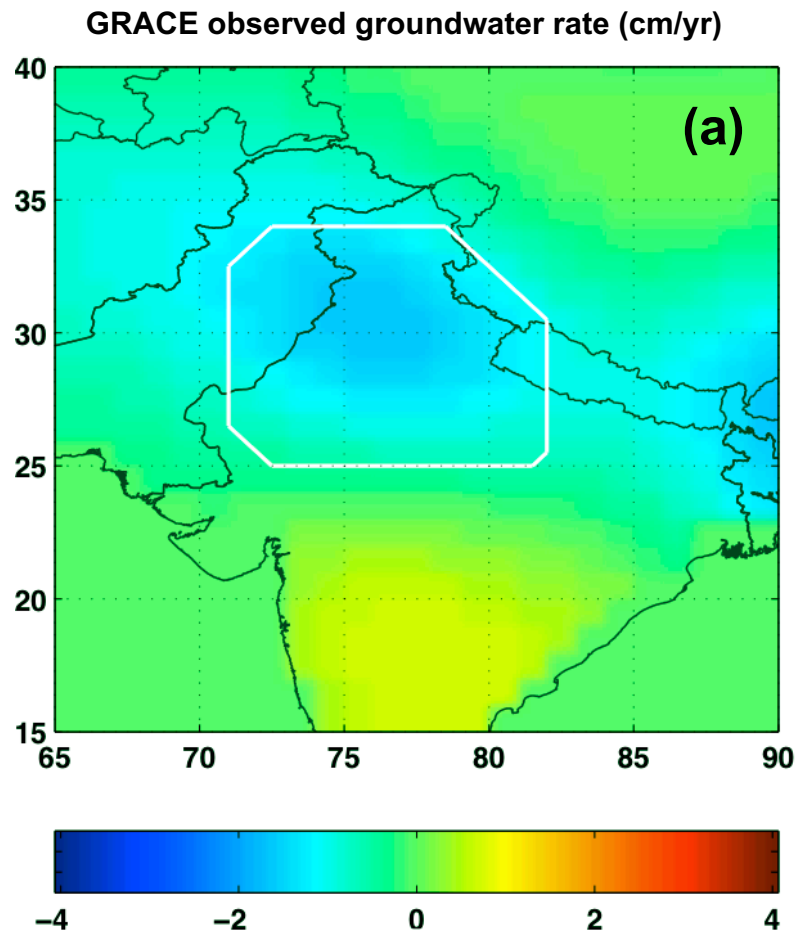


5 Years
2005.01-2009.12

Case Study 1: Groundwater Depletion in Northwest India (+ Punjab, Pakistan)

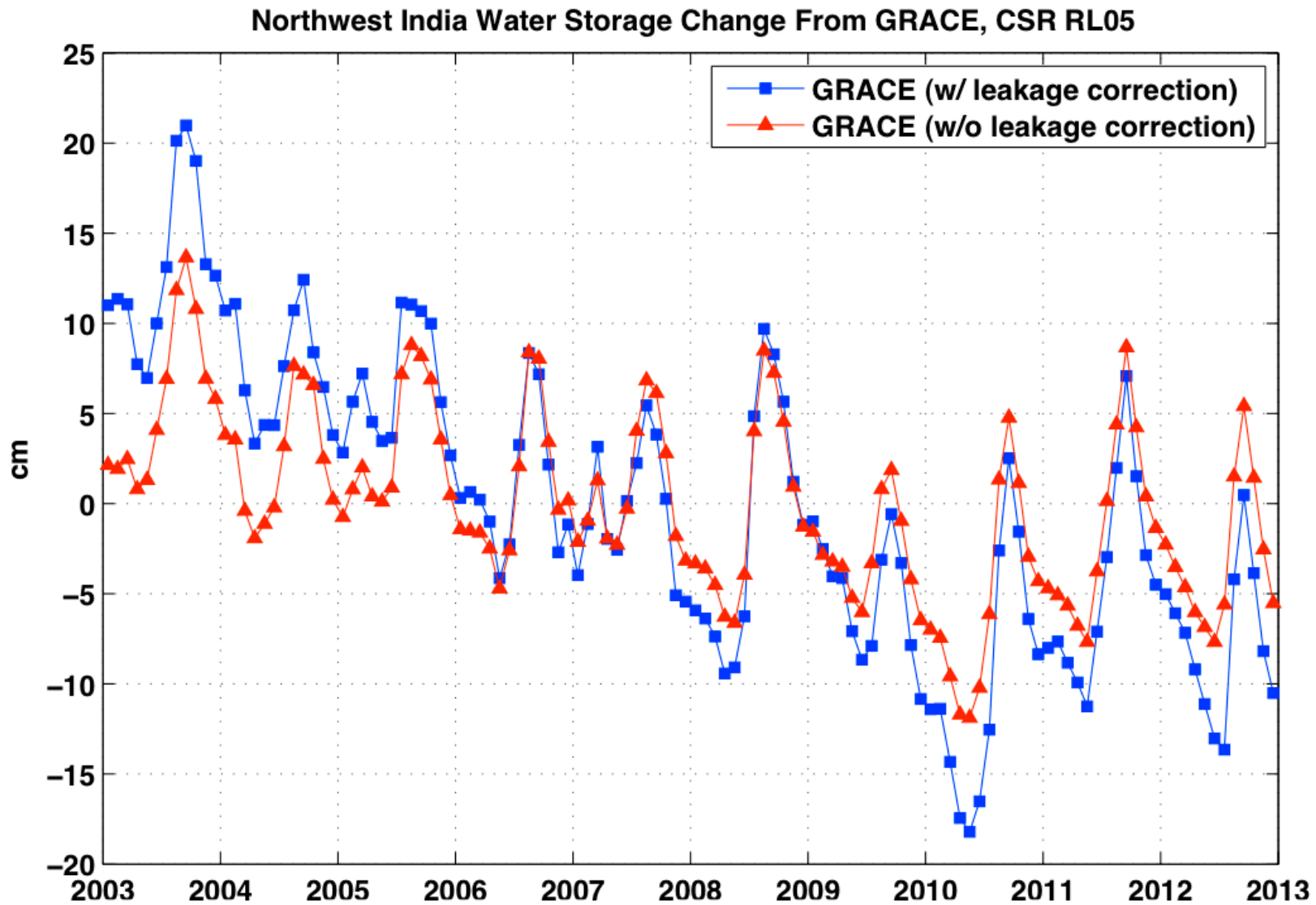


GRACE observed and forward modeled long-term groundwater rate (cm/yr), 2003.01 - 2012.12

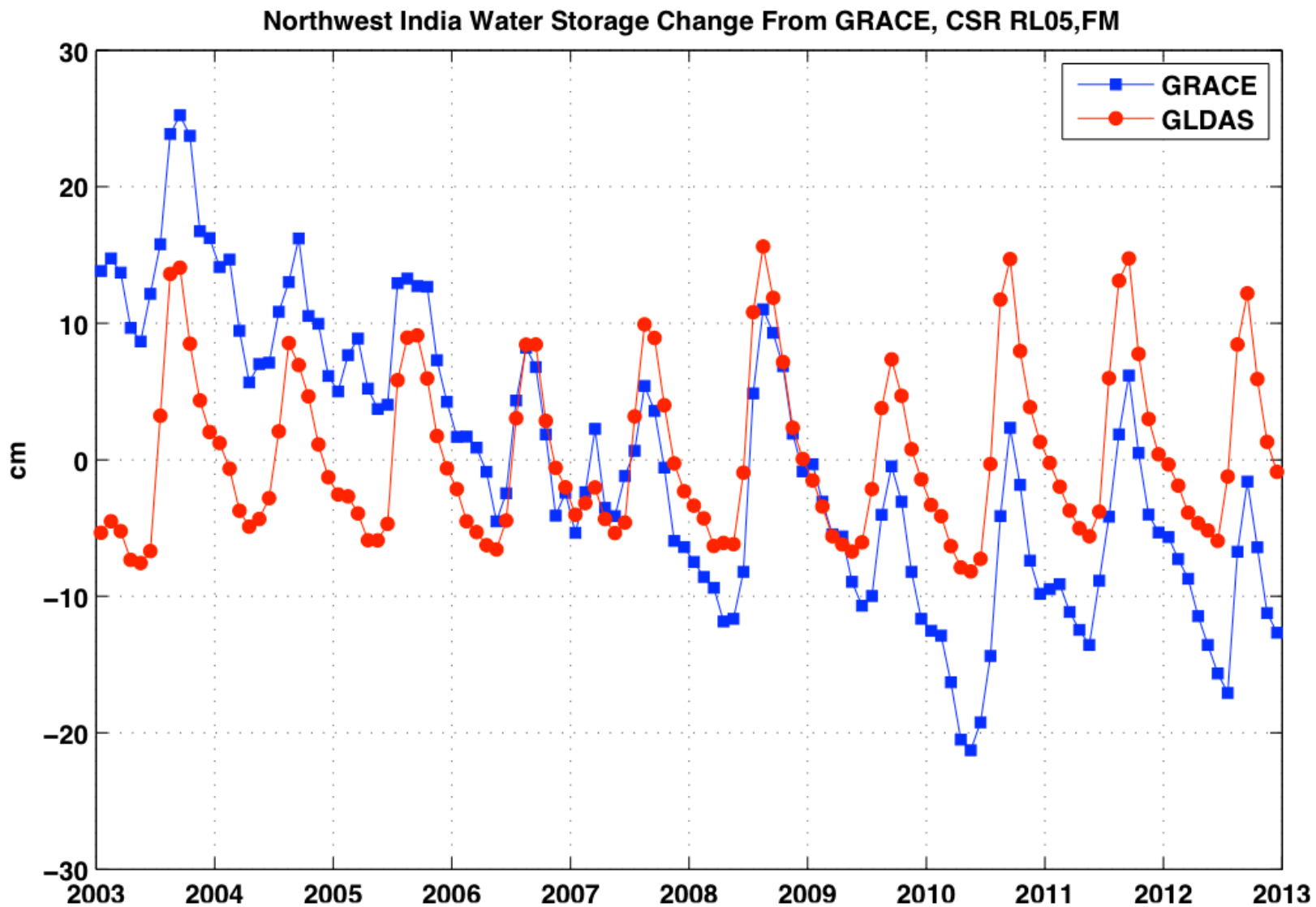


(Chen et al., 2014)

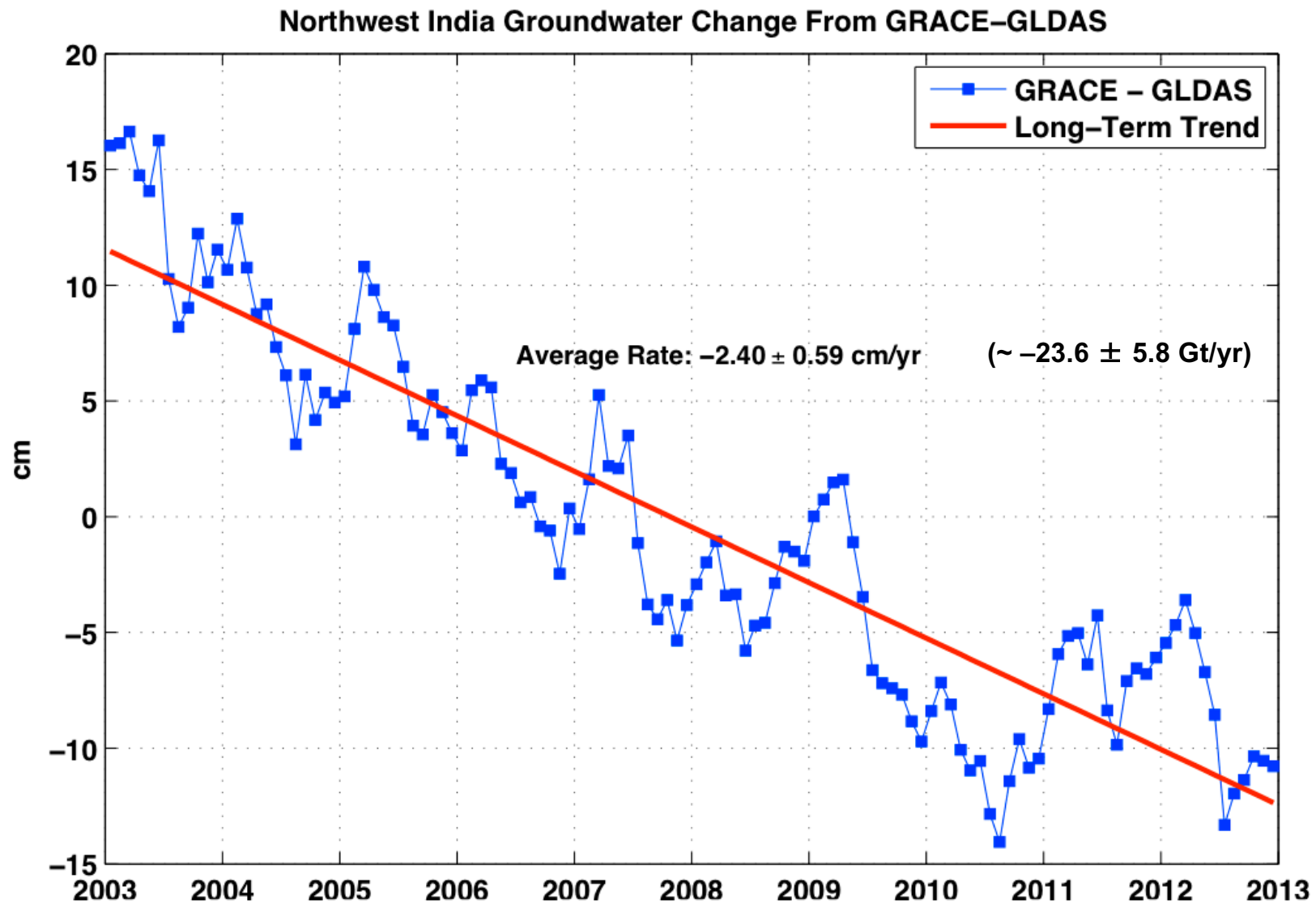
GRACE observed terrestrial water storage change



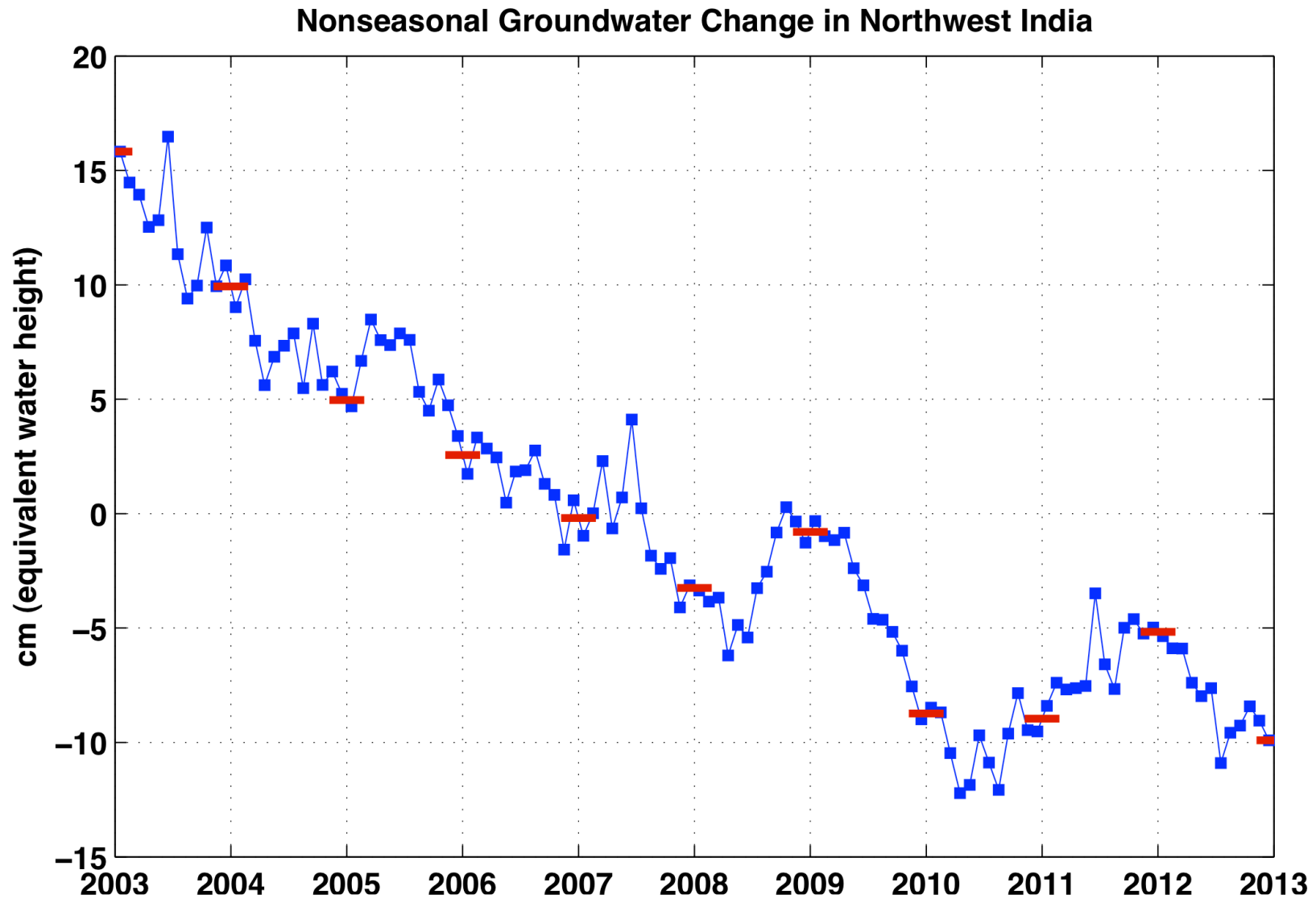
Comparison of GRACE terrestrial water storage change with GLDAS soil/snow water



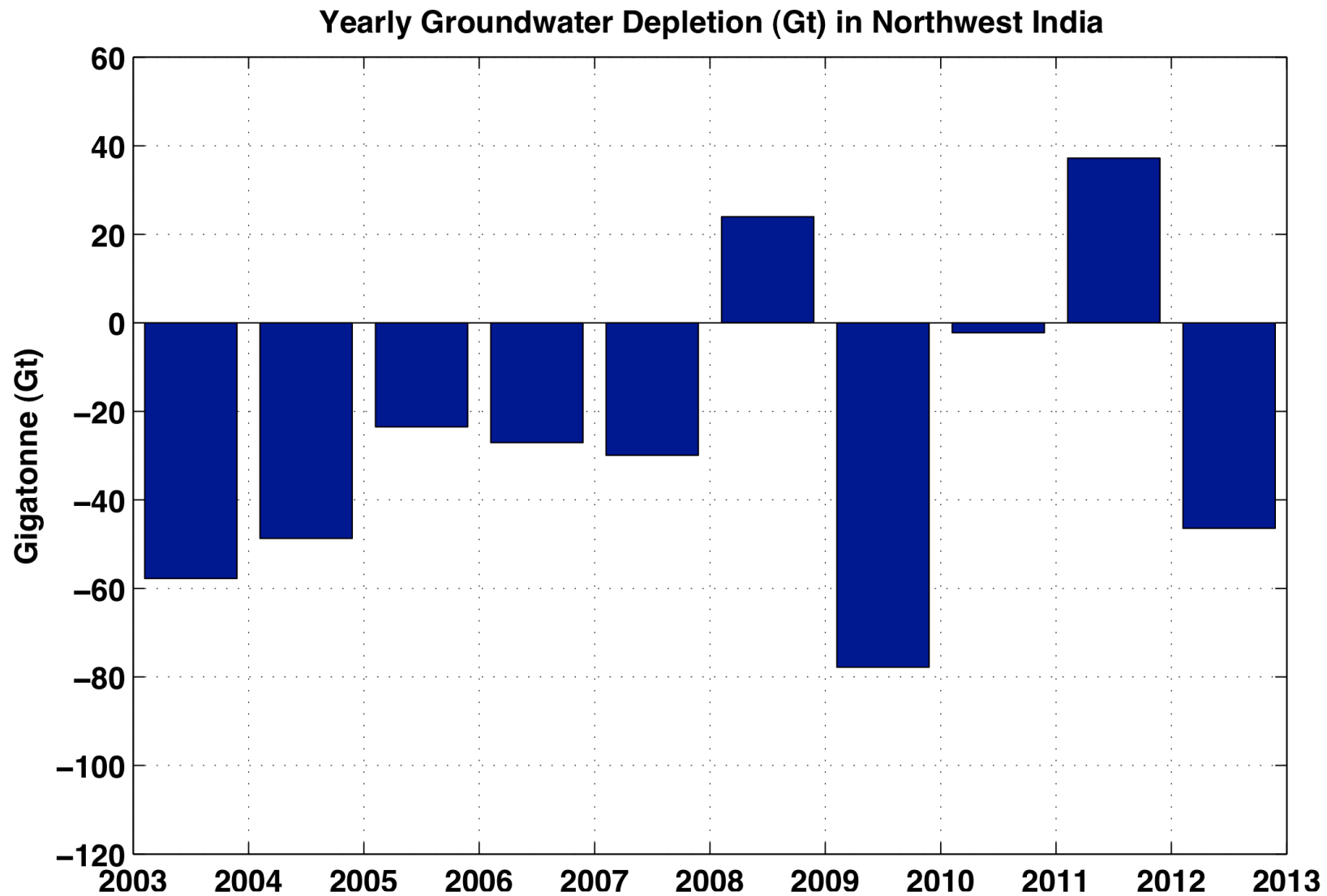
NWI Groundwater Change From GRACE - GLDAS



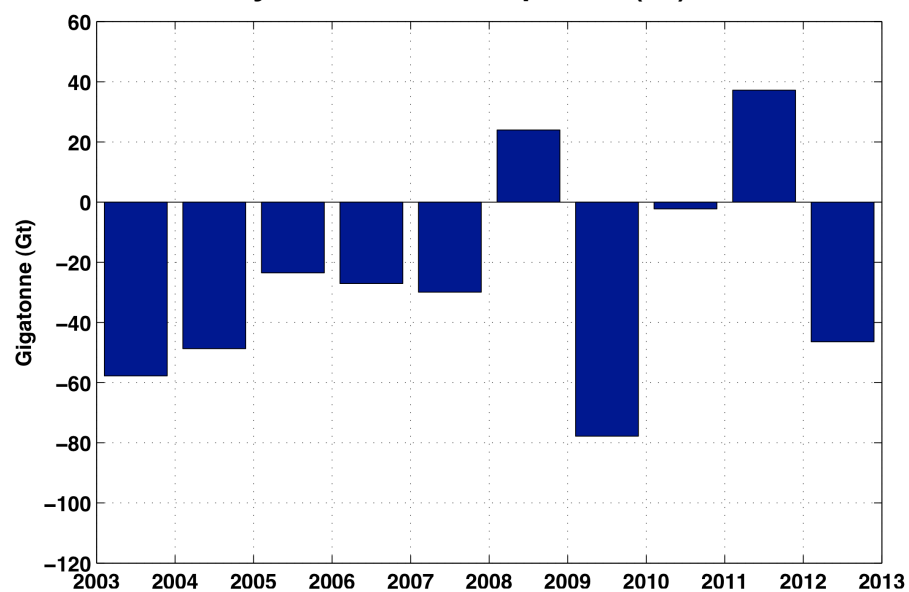
Non-seasonal NWI Groundwater Change From GRACE - GLDAS



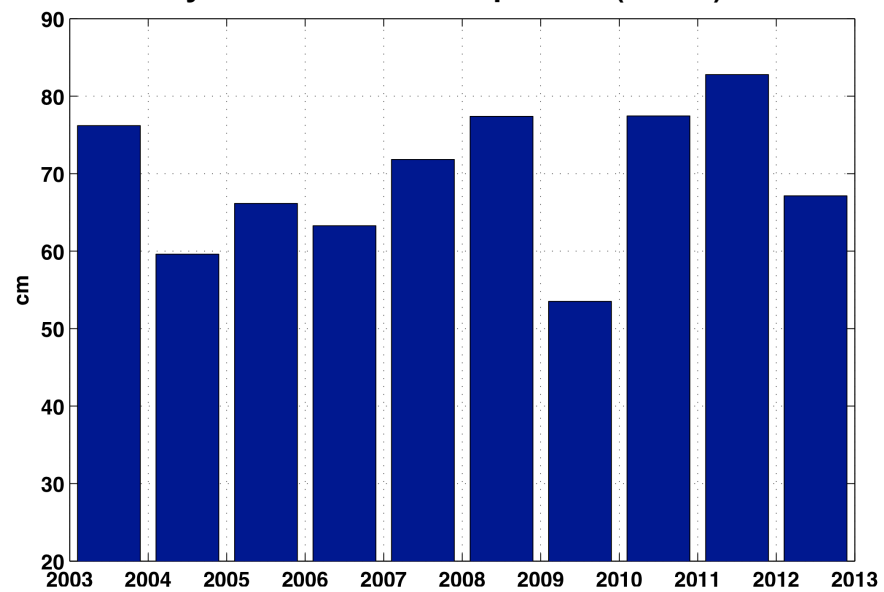
Yearly Groundwater Change From GRACE - GLDAS



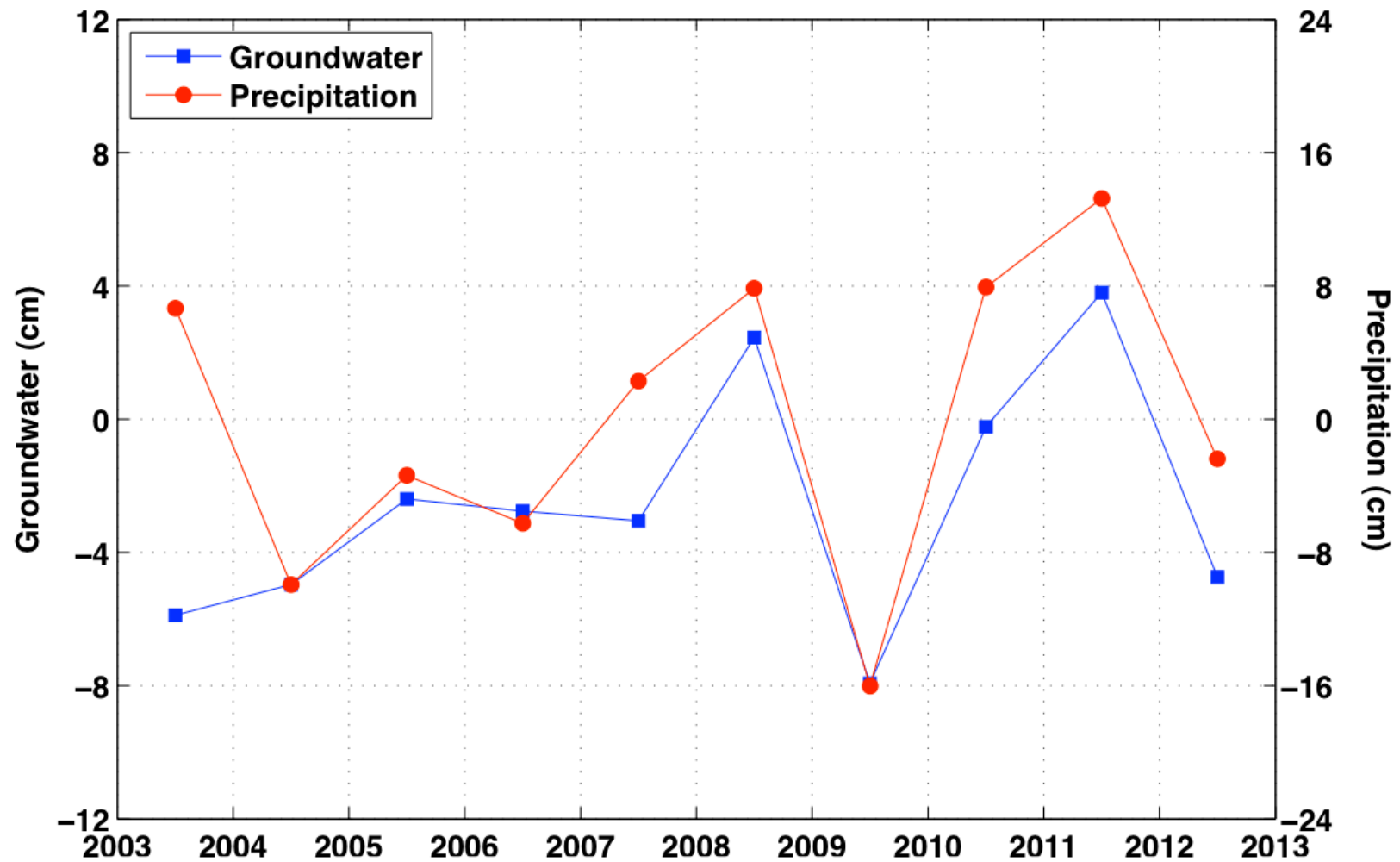
Yearly Groundwater Depletion (Gt) in NWI



Yearly Accumulated Precipitation (GPCP) in NWI



Yearly Groundwater Change vs. Precipitation Anomaly





Uncertainty Assessment

- ❑ GRACE residual measurement error is estimated using the RMS of residuals over an open ocean area (25N–35N, 170E–220E) at about the same latitudes (~ 0.48 cm/yr or ± 4.6 Gt/yr after leakage correction).
- ❑ Leakage from glaciers melting is ~ -2.8 Gt/yr (Rodell et al., 2009), with an assumed uncertainty of 100% of the leakage signal.
- ❑ Least squares fitting error is ~ 20 of the trend (-23.6 ± 5.8 Gt/yr).
- ❑ Other error sources (e.g., GLDAS TWS trends, atmospheric model's pressure trends, ...) are neglected.
- ❑ Total uncertainty for the estimated NWI groundwater depletion rate is $\sim \pm 7.1$ Gt/yr.



Summary – NW India

- ❑ Over the 10-years period (2003.01 – 2012.12), GRACE-observed groundwater depletion rate in the NWI (plus Punjab, Pakistan) region is 20.4 ± 7.1 Gt/yr.
- ❑ However, for the first 5-years period (2003-2007), the groundwater depletion rate reached to 29.4 ± 8.4 Gt/yr.
- ❑ Yearly groundwater storage changes in the NWI region are strongly correlated with yearly precipitation anomalies.
- ❑ In the driest season (2009) of the decade, the groundwater depletion reached nearly 80 Gt, while in the two relatively wet seasons (2008 and 2011), the groundwater storages even showed net increases of ~ 24 and 35 Gt, respectively.
- ❑ Reducing leakage bias plays an important role in quantifying regional groundwater storage change.

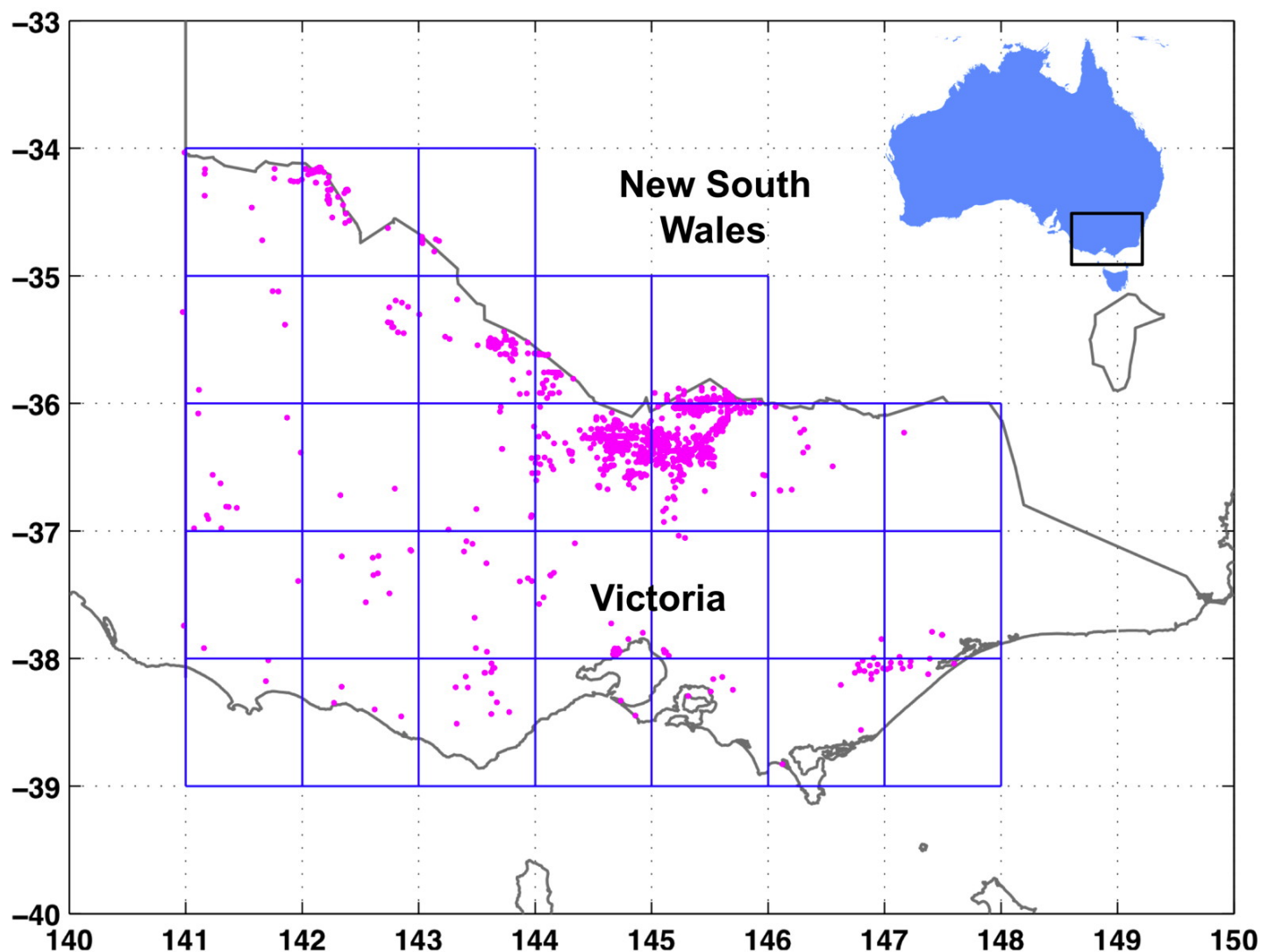
Case Study 2: Decadal-Scale Groundwater Storage Change in South Murray-Darling Basin (MDB), 1993-2012

The Murray-Darling River Basin



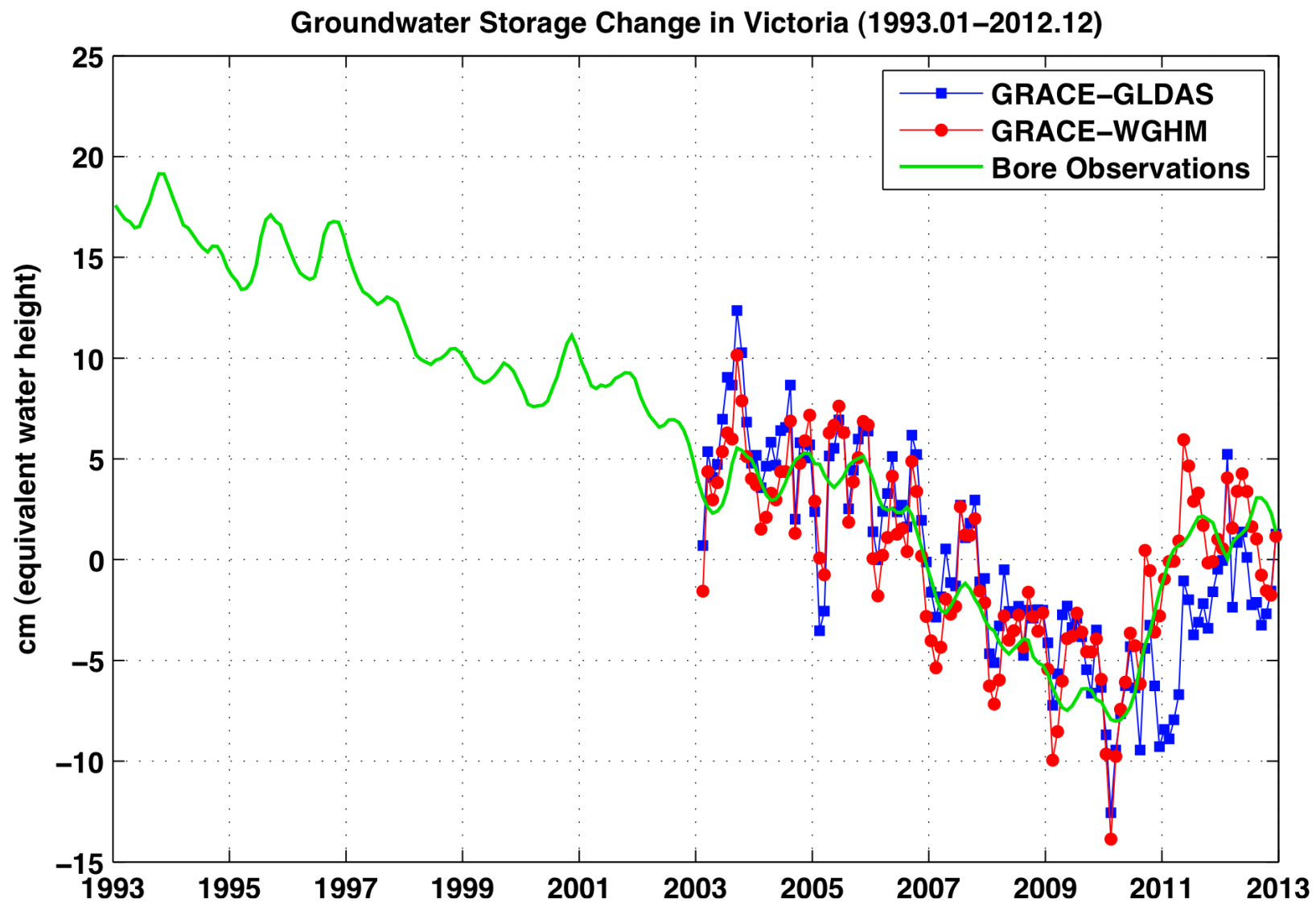
Australia is the 2nd driest continent, next to the Antarctica.

Distribution Map of Wells in Victoria (1395 Wells, 1993.01 – 2012.12)

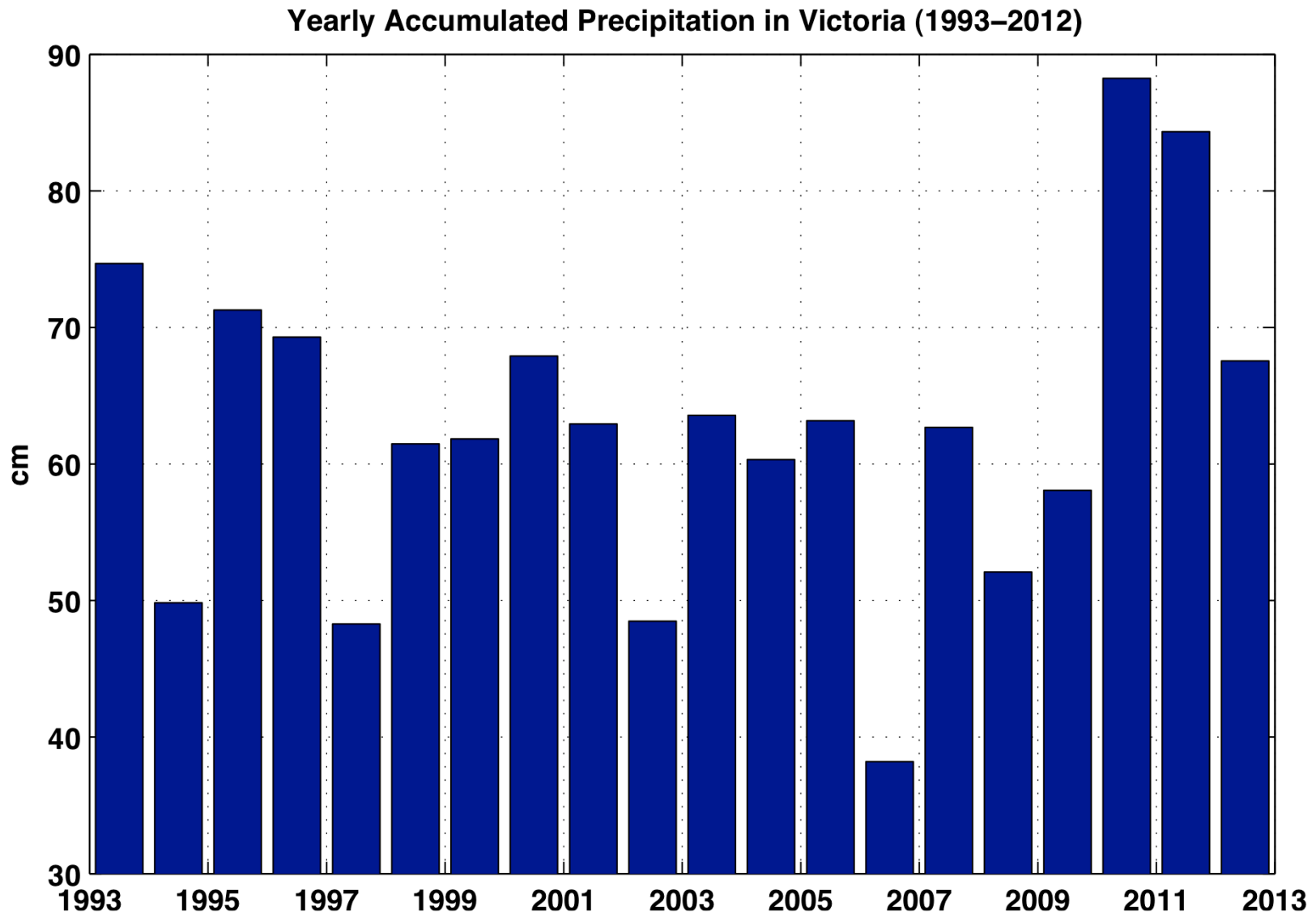


Well groundwater level data are provided by the Department of Environment and Primary Industries (<http://www.depi.vic.gov.au/>) of Victoria, Australia.

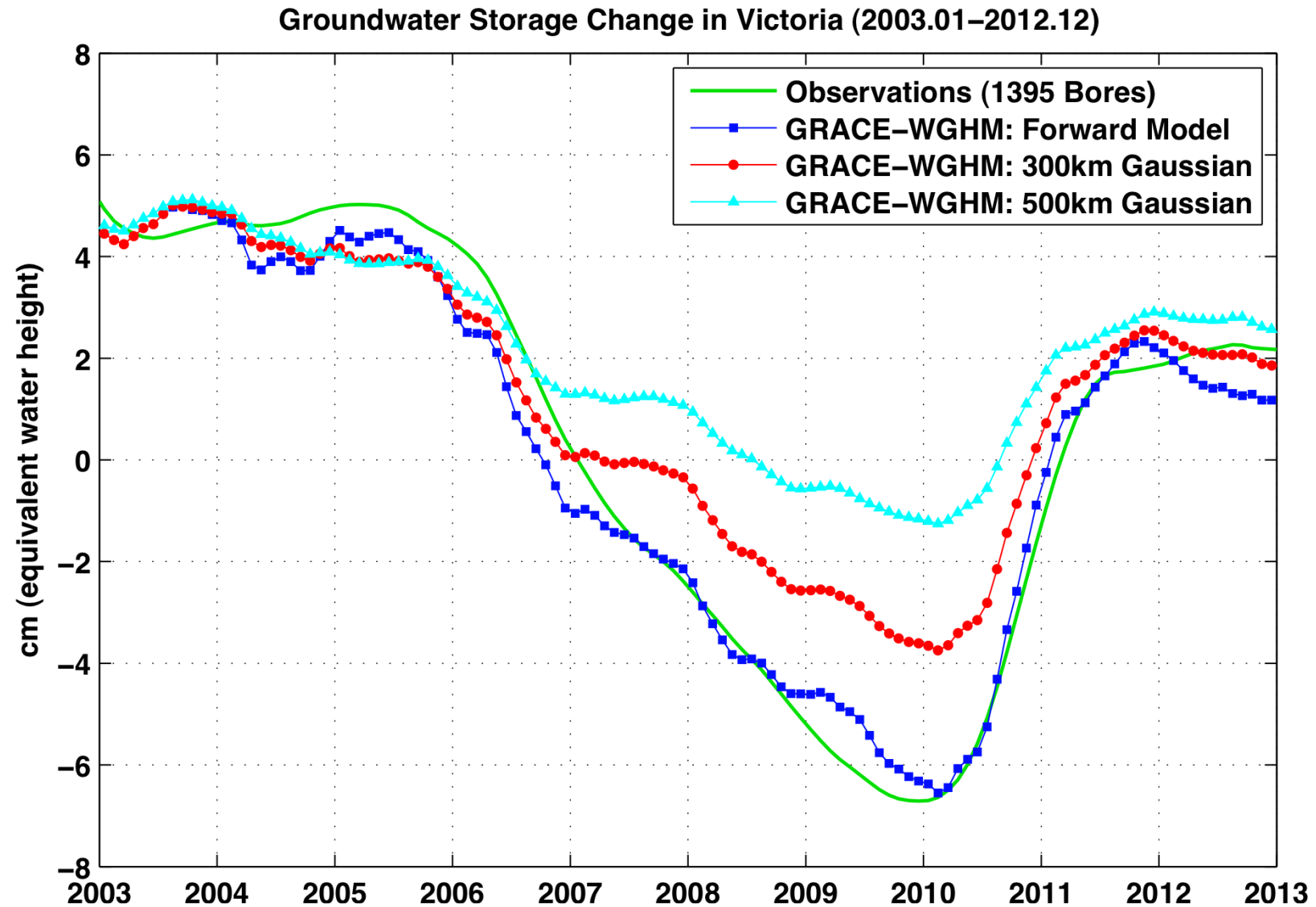
Groundwater Storage Change in South MDB/Victoria



Yearly Accumulated Precipitation (GPCP) in South MDB/Victoria

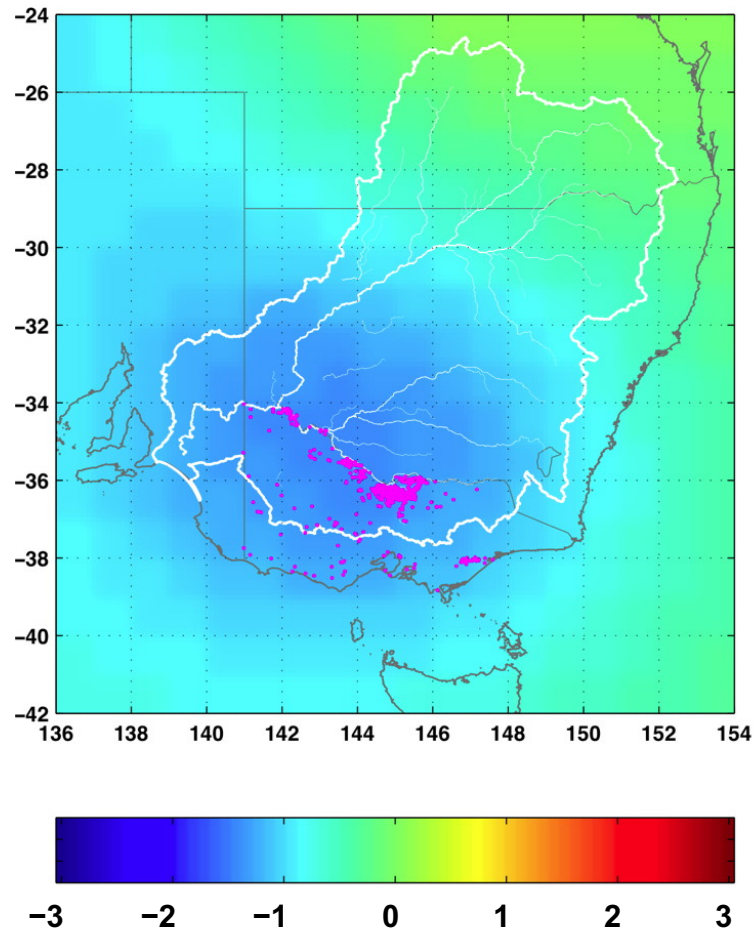


GRACE-Derived Groundwater Storage Change in South MDB/Victoria

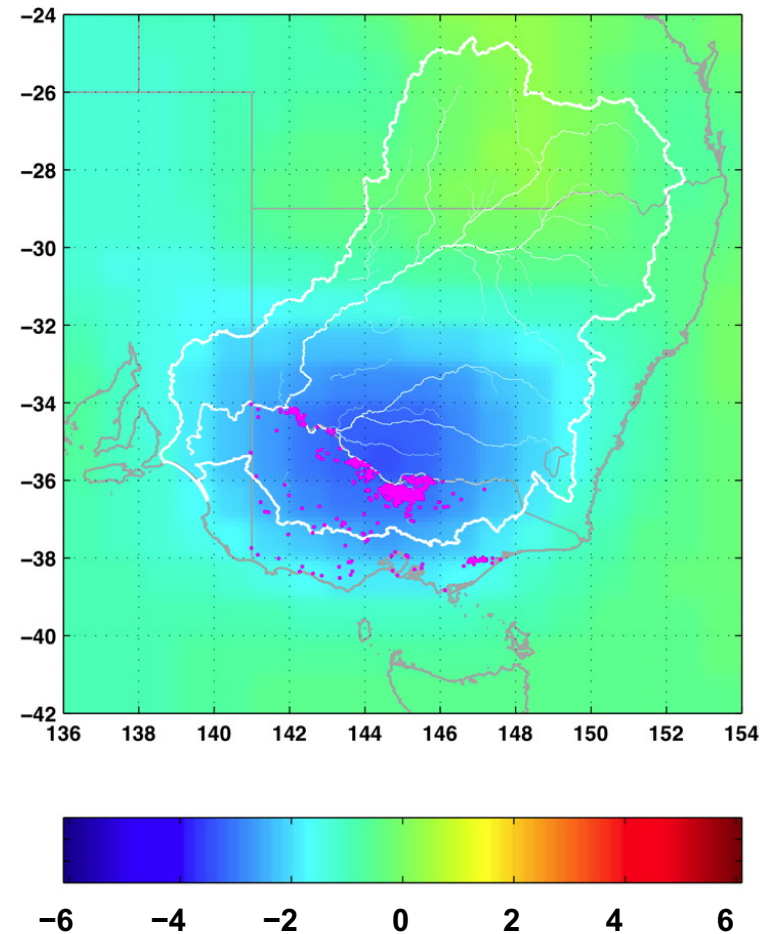


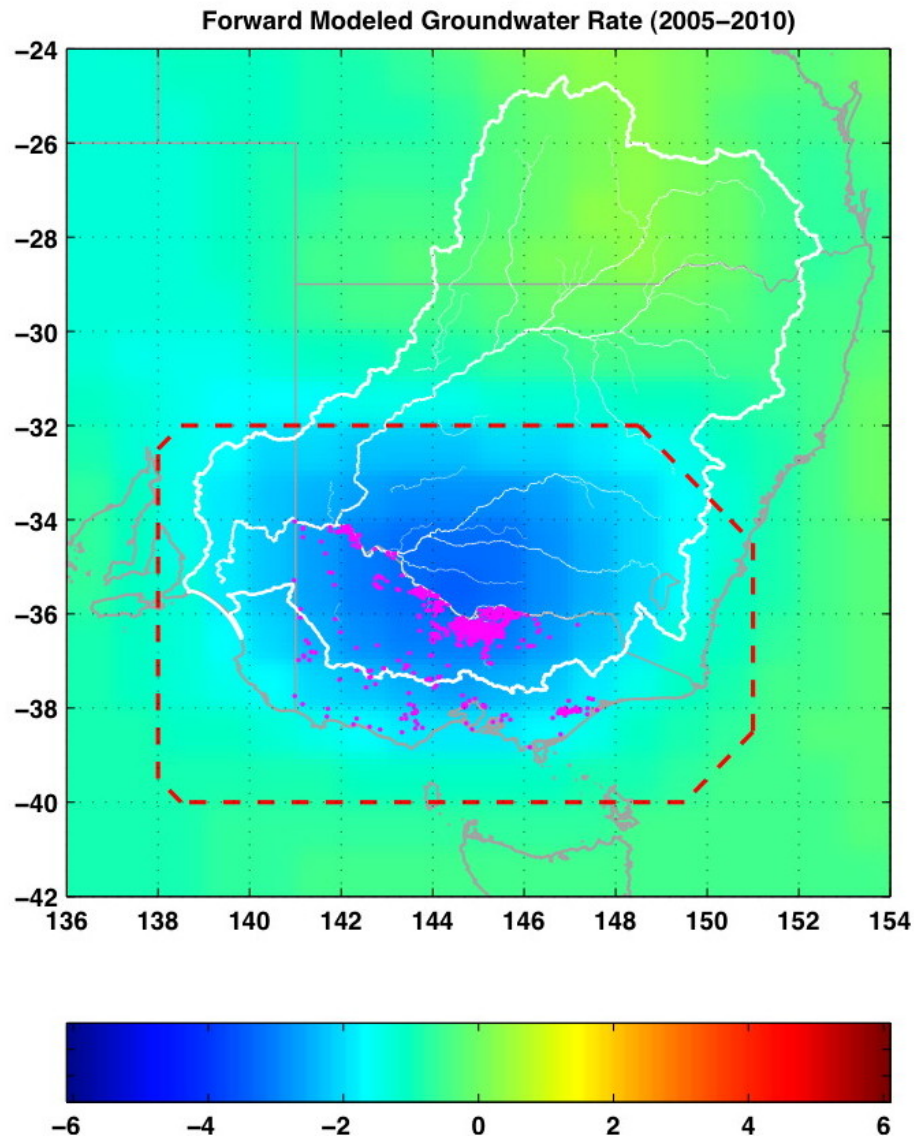
GRACE-Observed vs. Forward Modeled Groundwater Rate (cm/yr)

(a) GRACE-Observed GW Rate



(b) Forward-Modeled GW Rate





5-Years Period (2005-2009)

Victoria Groundwater Rate:

Wells Data: $\sim -8.3 \pm 0.9$ Gt/yr

GRACE-WGHM: $\sim -7.0 \pm 1.2$ Gt/yr

GRACE-WGHM: $\sim -8.0 \pm 1.3$ Gt/yr
(if add 100km buffer zone to the south)

Over the entire south
MDB/Victoria Region (within red
contour line):

GRACE: $\sim -17 \pm 3.6$ Gt/yr



Summary – Southern MDB

- ❑ Over the 20-years period (1993.01 – 2012.12), *in situ* groundwater level measurements from 1395 wells in Victoria, Australia indicate a steady decrease of groundwater storage in the south MDB/Victoria region until the arrival of two significantly wet seasons at the end (2010 & 2011).
- ❑ After removing leakage bias through fully unconstrained global forward modeling, GRACE-derived groundwater changes in the Victoria region agree remarkably well with *in situ* measurements for the 10-years period overlapped with GRCAE.
- ❑ Over the period 2005 – 2009, average groundwater depletion rates in the Victoria region are -8.3 ± 0.9 Gt/yr from well data, and -8.0 ± 1.3 Gt/yr from GRACE – WGHM.
- ❑ Again, reducing leakage bias plays an important role in quantifying regional groundwater storage change.



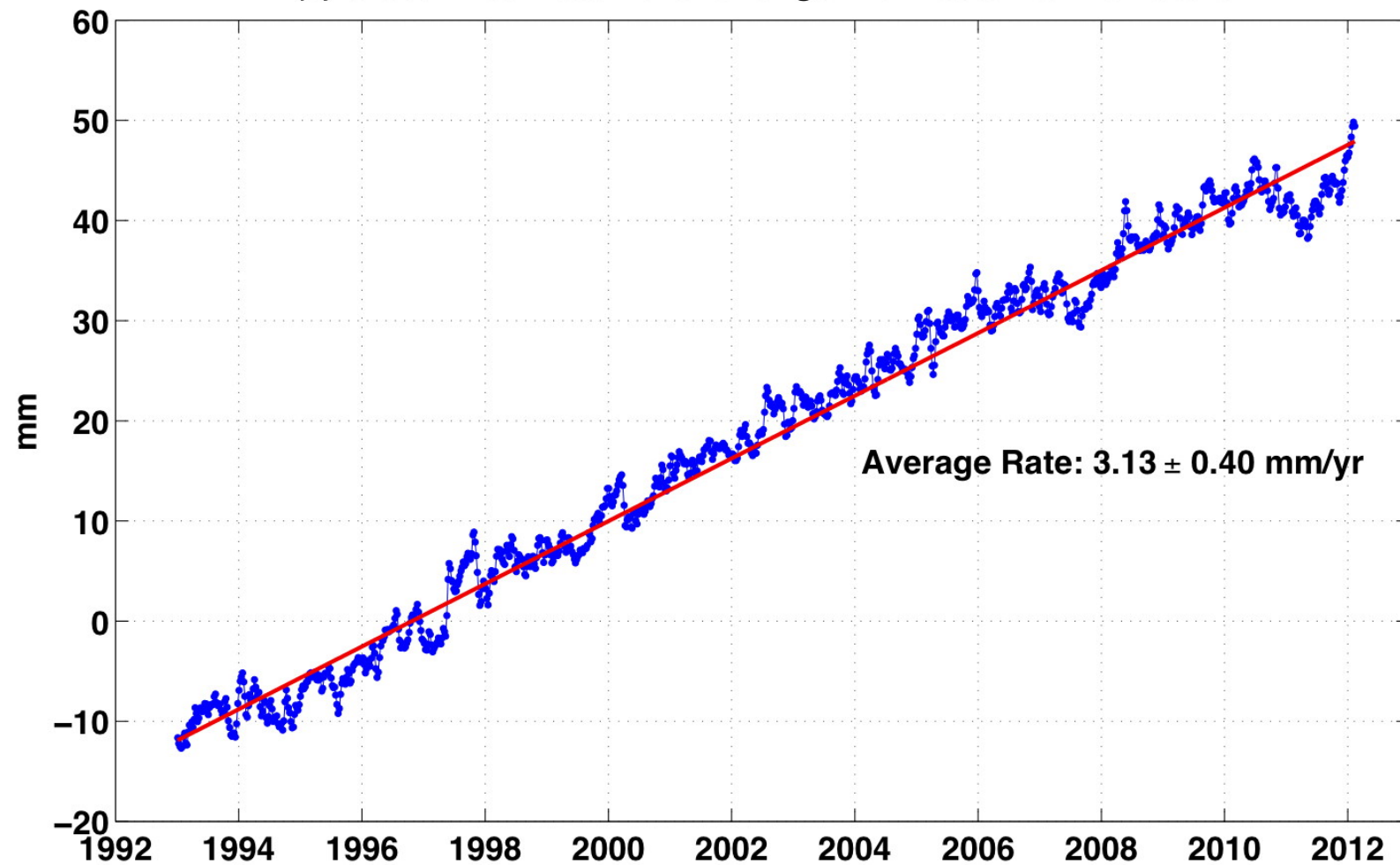
Closing the global mean sea level rise budget



Closing the global mean sea level rise budget

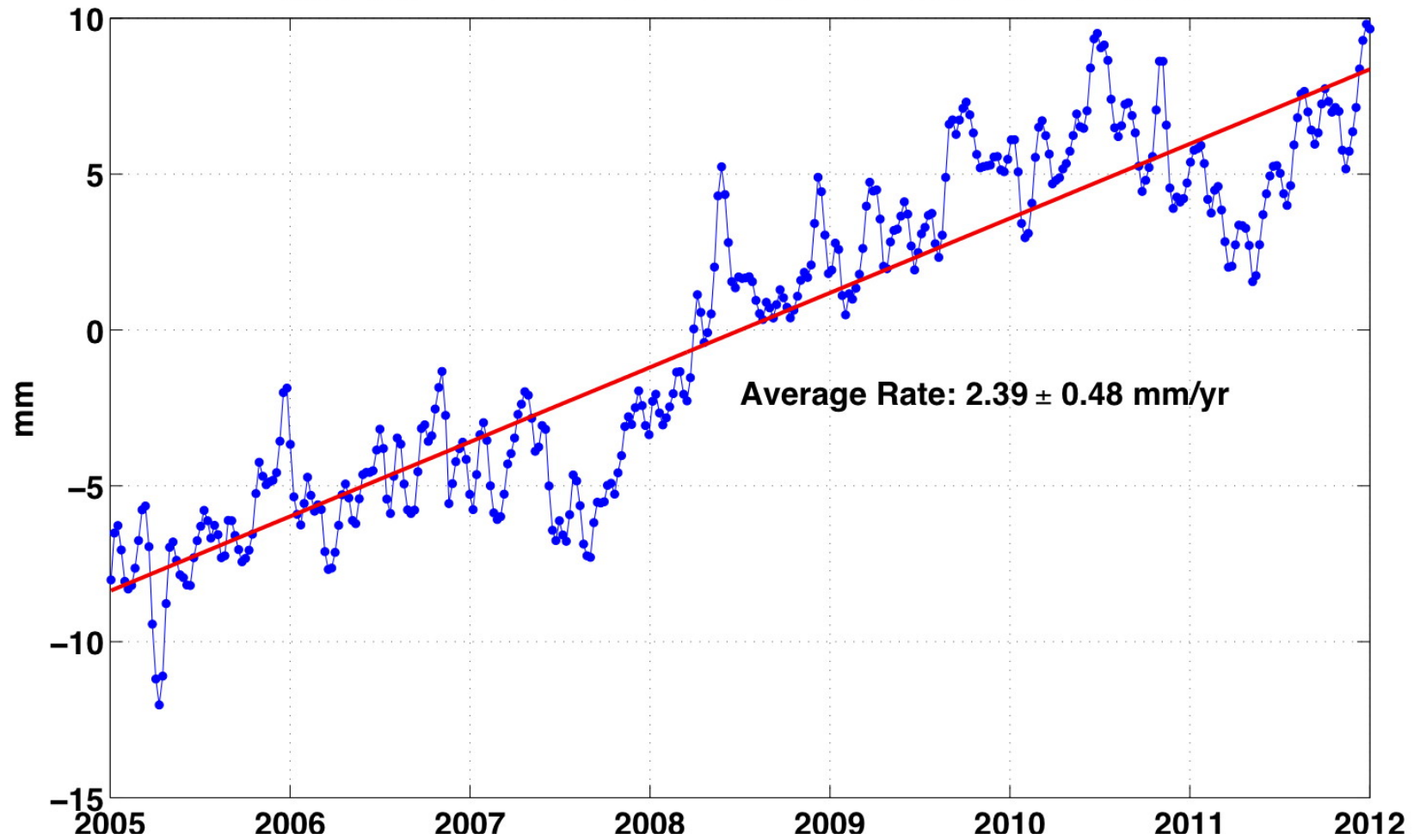


(a) Global Mean Sea Level Change From Satellite Altimeters





(b) Global Mean Sea Level Change From Satellite Altimeters





Three Main Contributors to Observed Sea Level Change

**Ocean Mass
Change**

Non-Steric

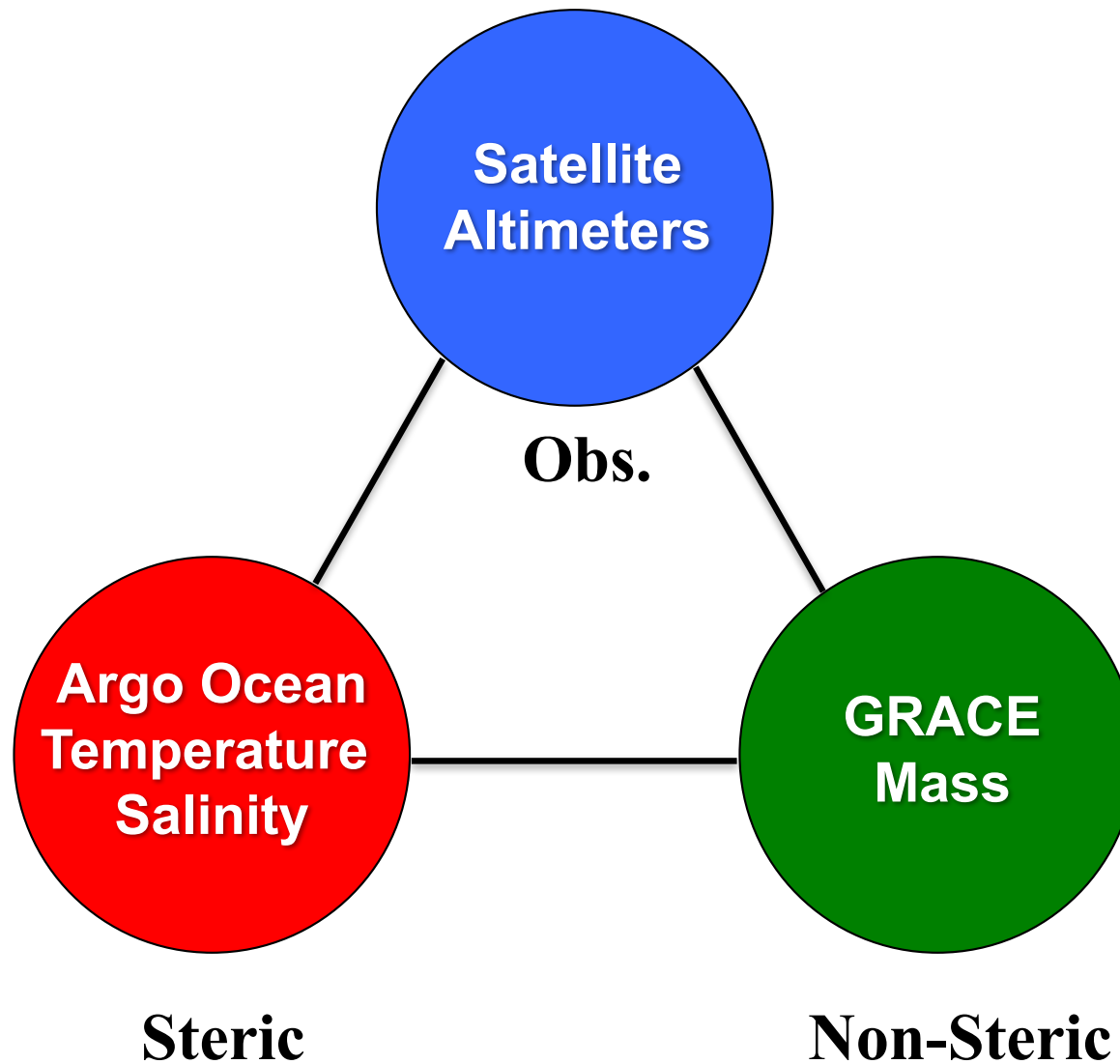
**Ocean Temperature
& Salinity Change**

Steric

**Ocean Basin Volume
Change (GIA)**

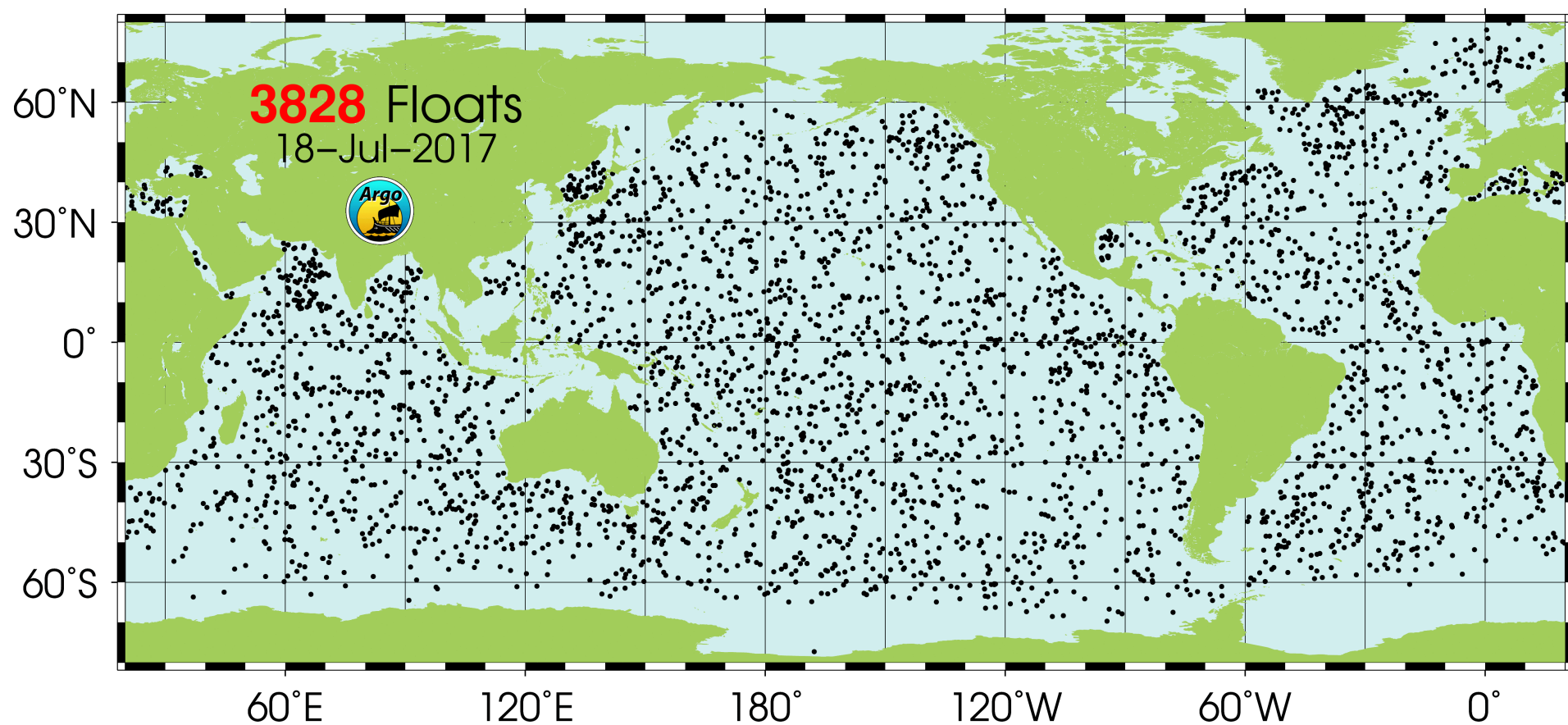


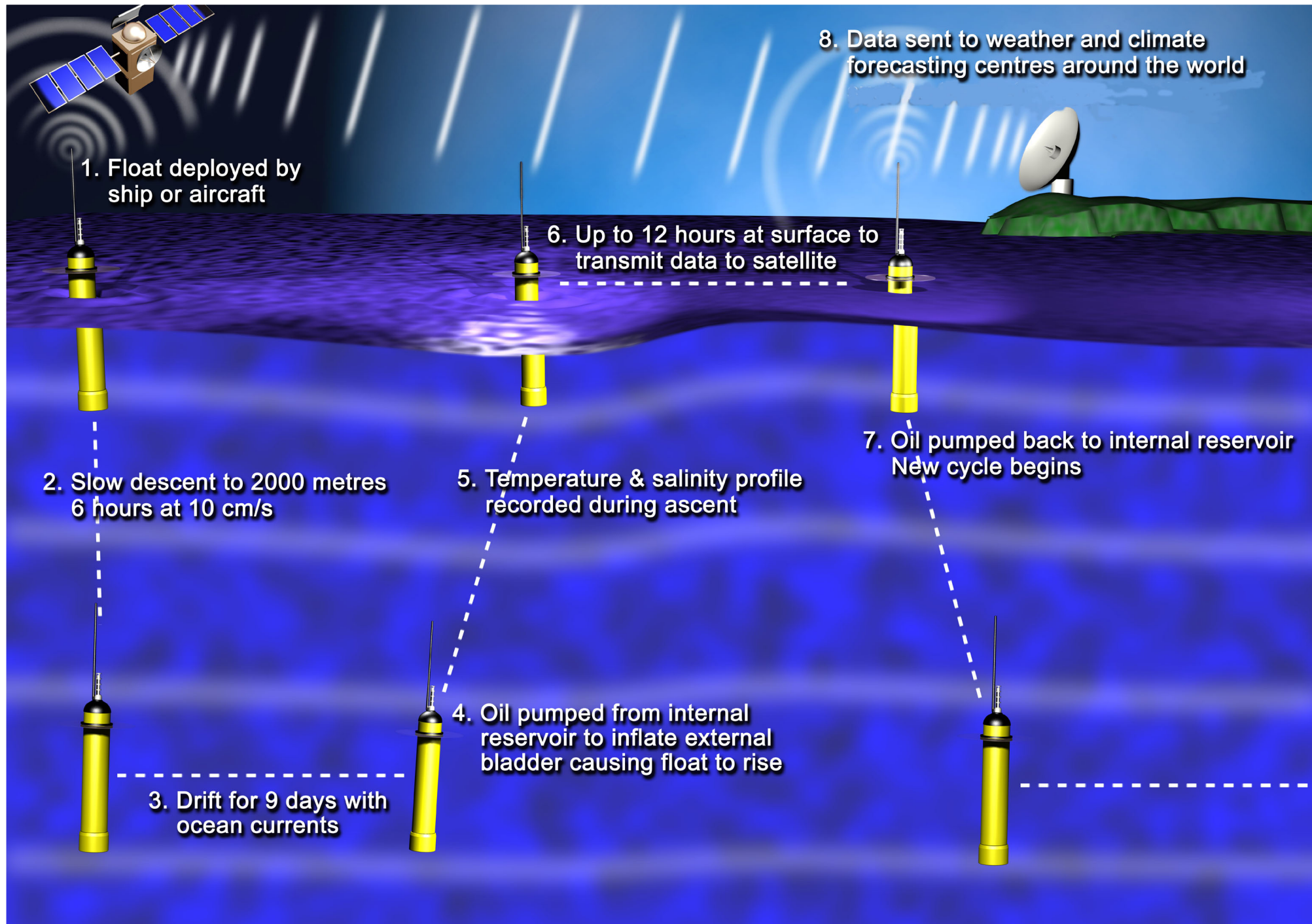
Reconciling the Three Components





The Argo Floats Network

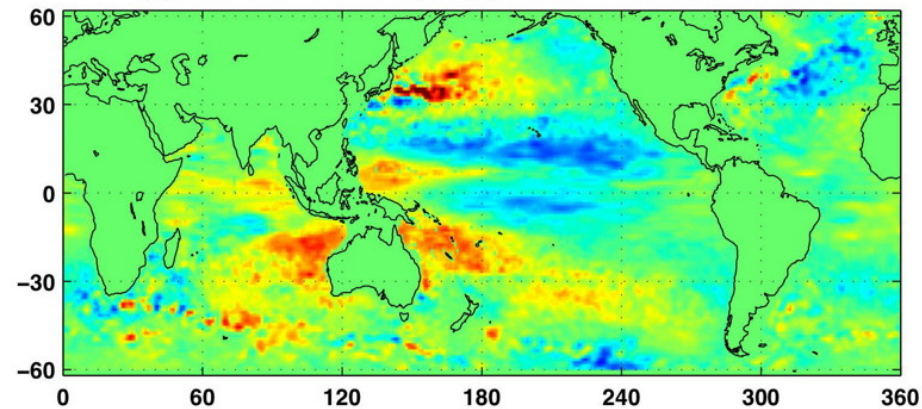




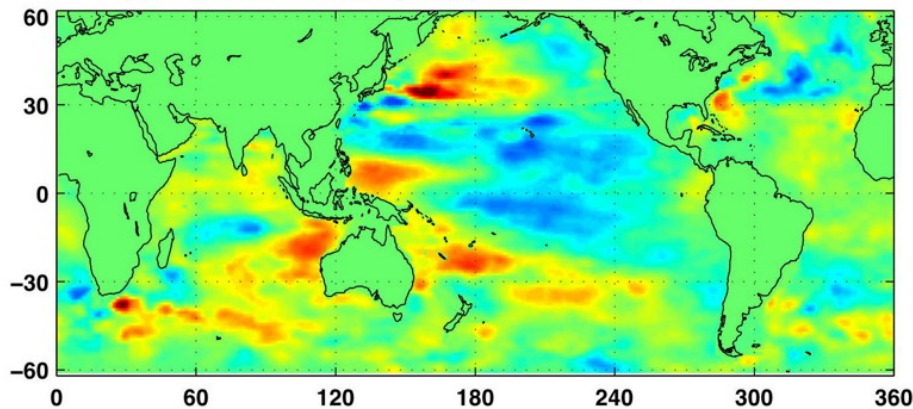
Global Steric Sea Level Rates From Argo



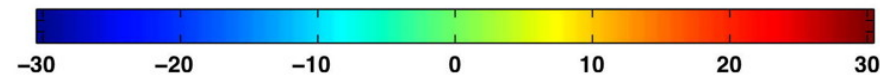
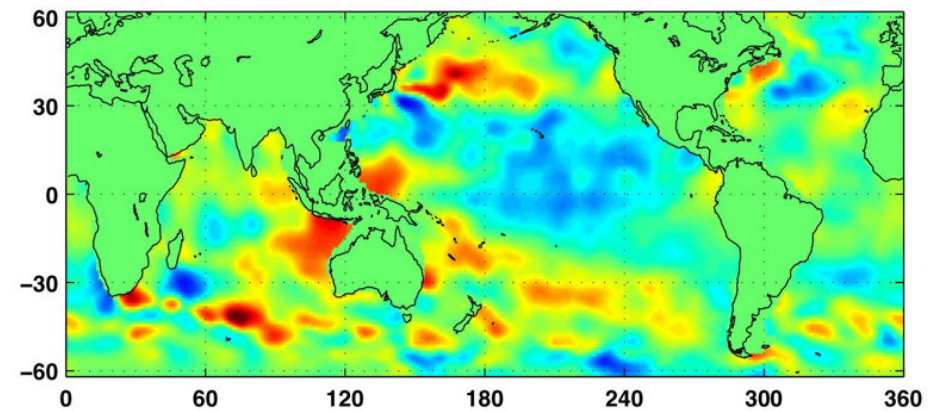
(a) Steric Sea Level Rate (mm/yr): ARGO-SIO, 2005.01-2011.12

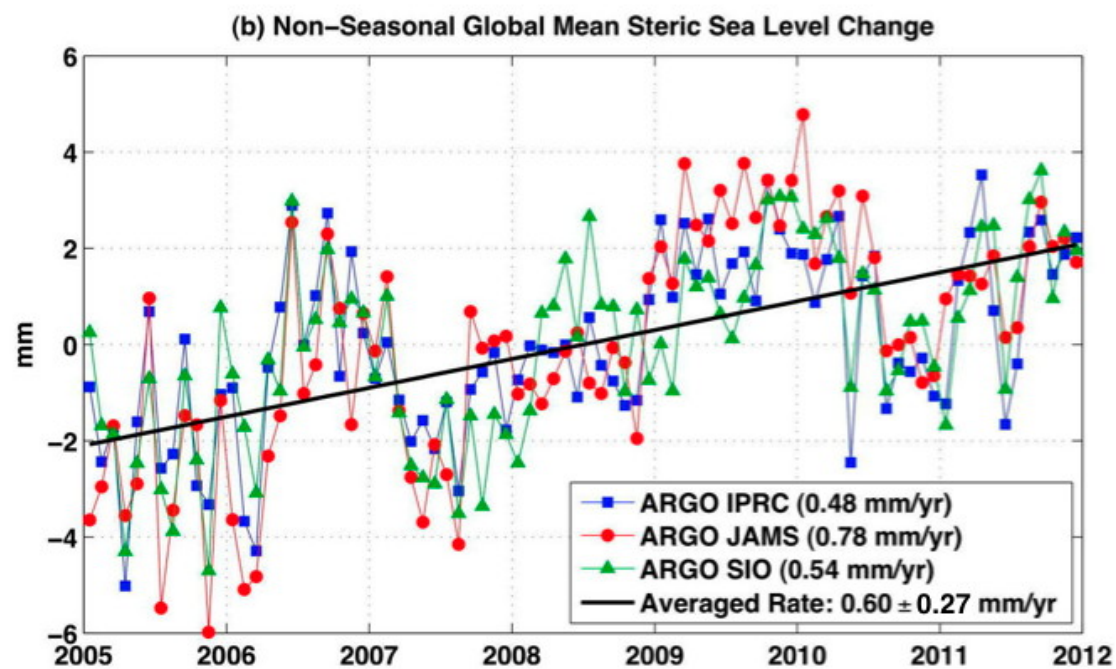
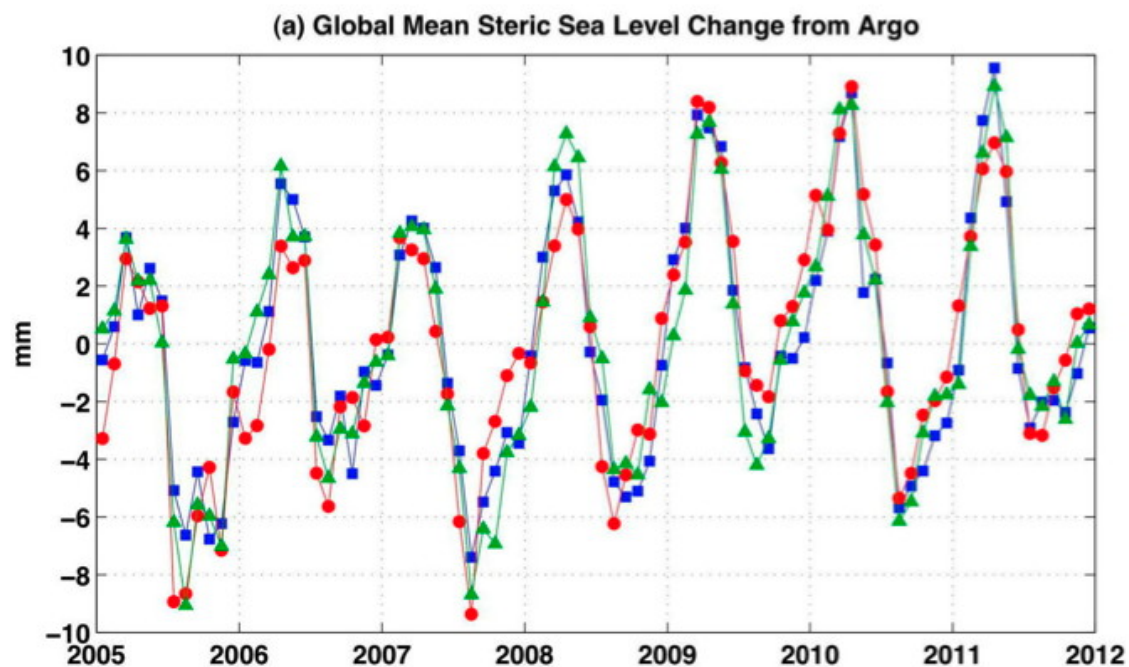


(b) Steric Sea Level Rate (mm/yr): ARGO-JAMS, 2005.01-2011.12



(c) Steric Sea Level Rate (mm/yr): ARGO-IPRC, 2005.01-2011.12

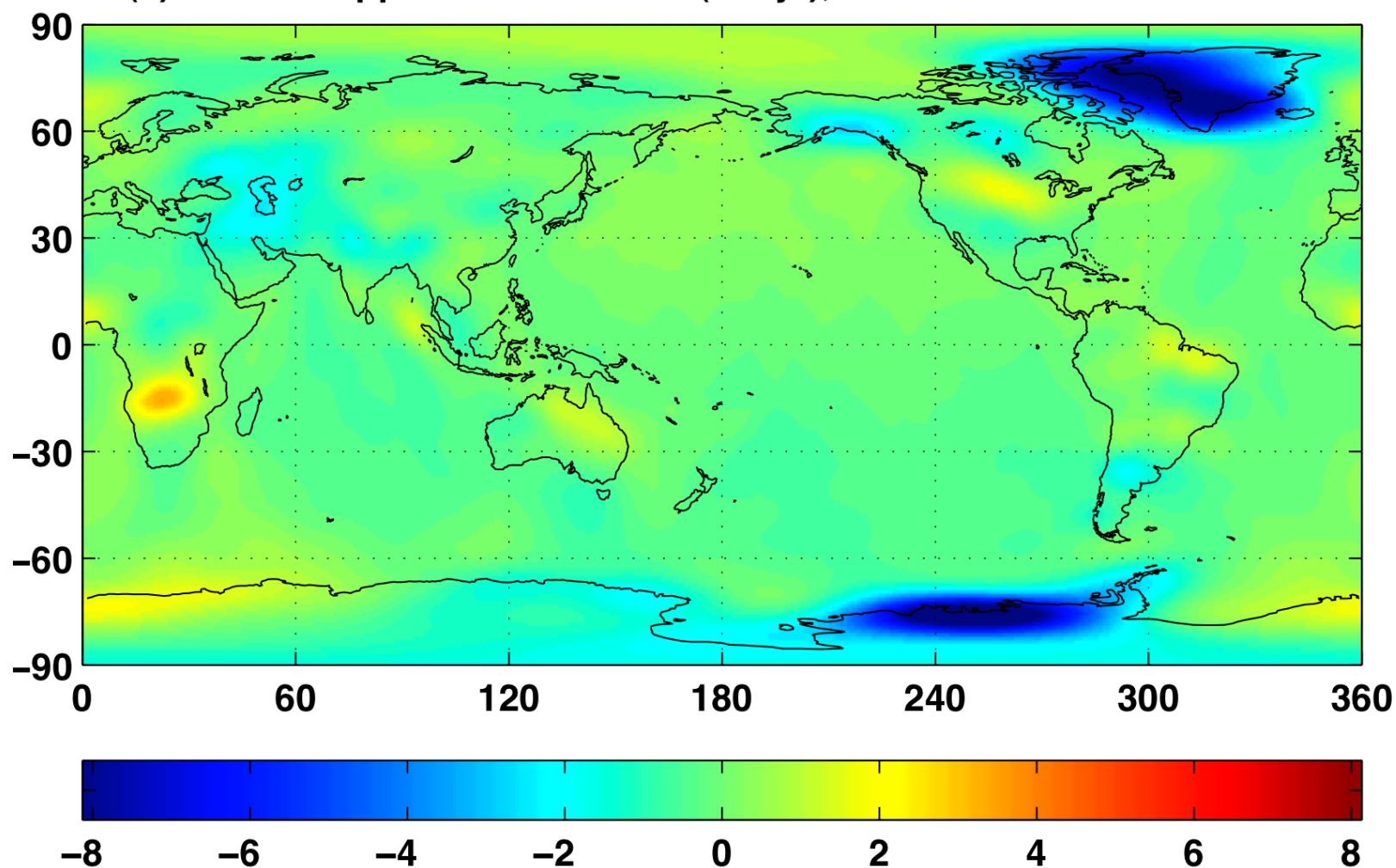




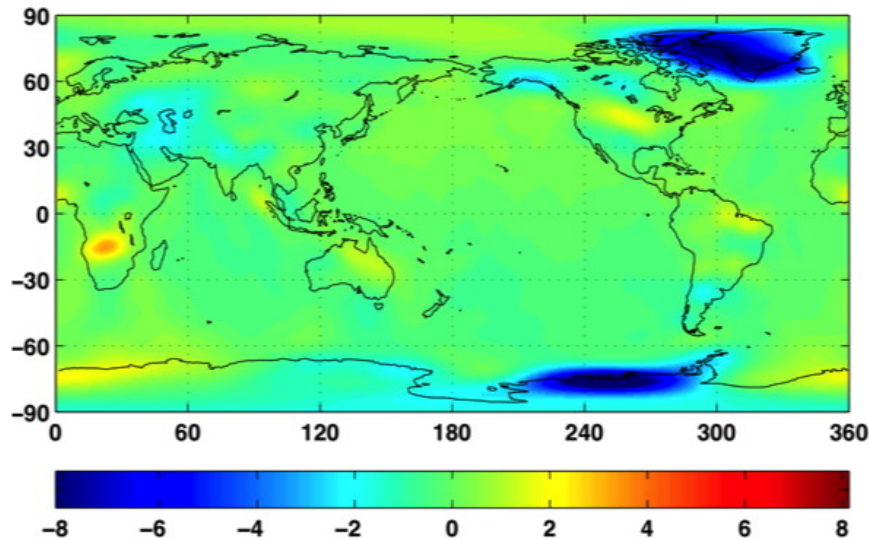
Measuring Global Mass Change From GRACE



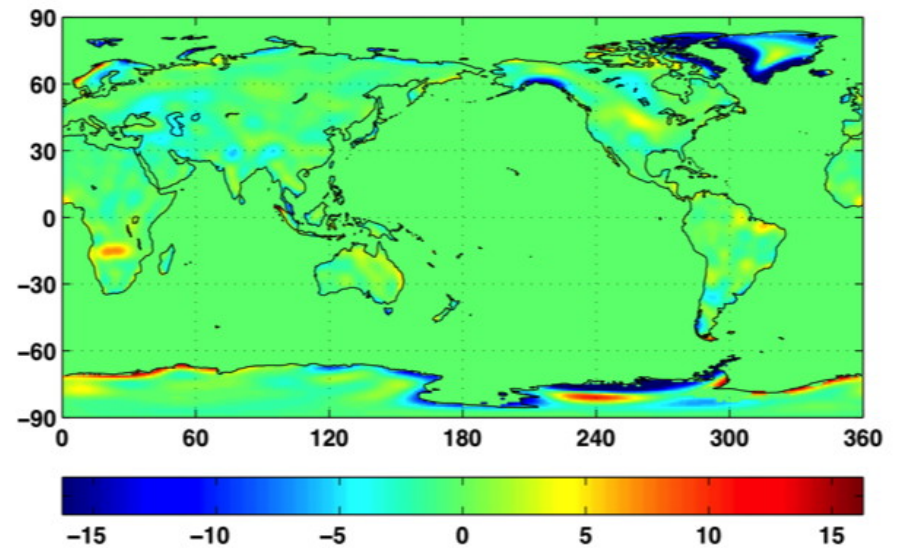
(a) GRACE Apparent Mass Rate (cm/yr), CSR RL05 2005.01–2011.12



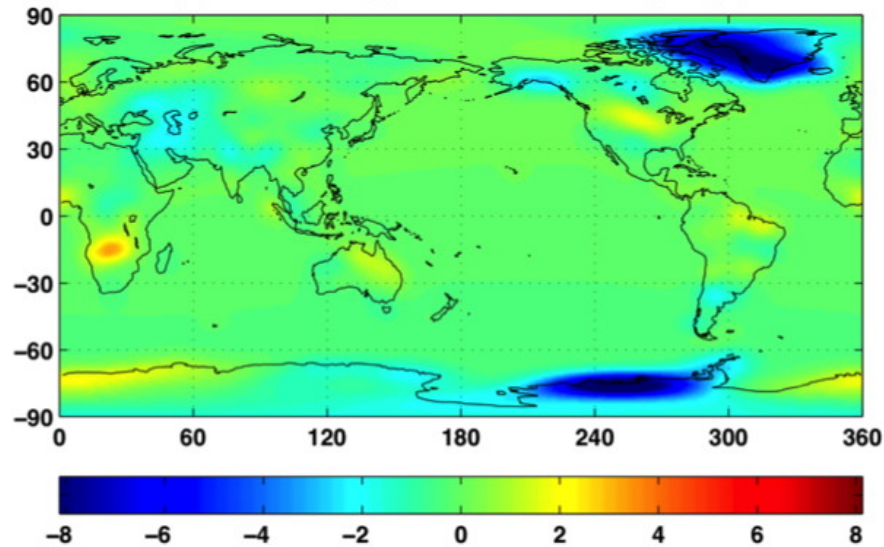
(a) GRACE Apparent Mass Rate (cm/yr)



(b) Modeled True Mass Rate (cm/yr)



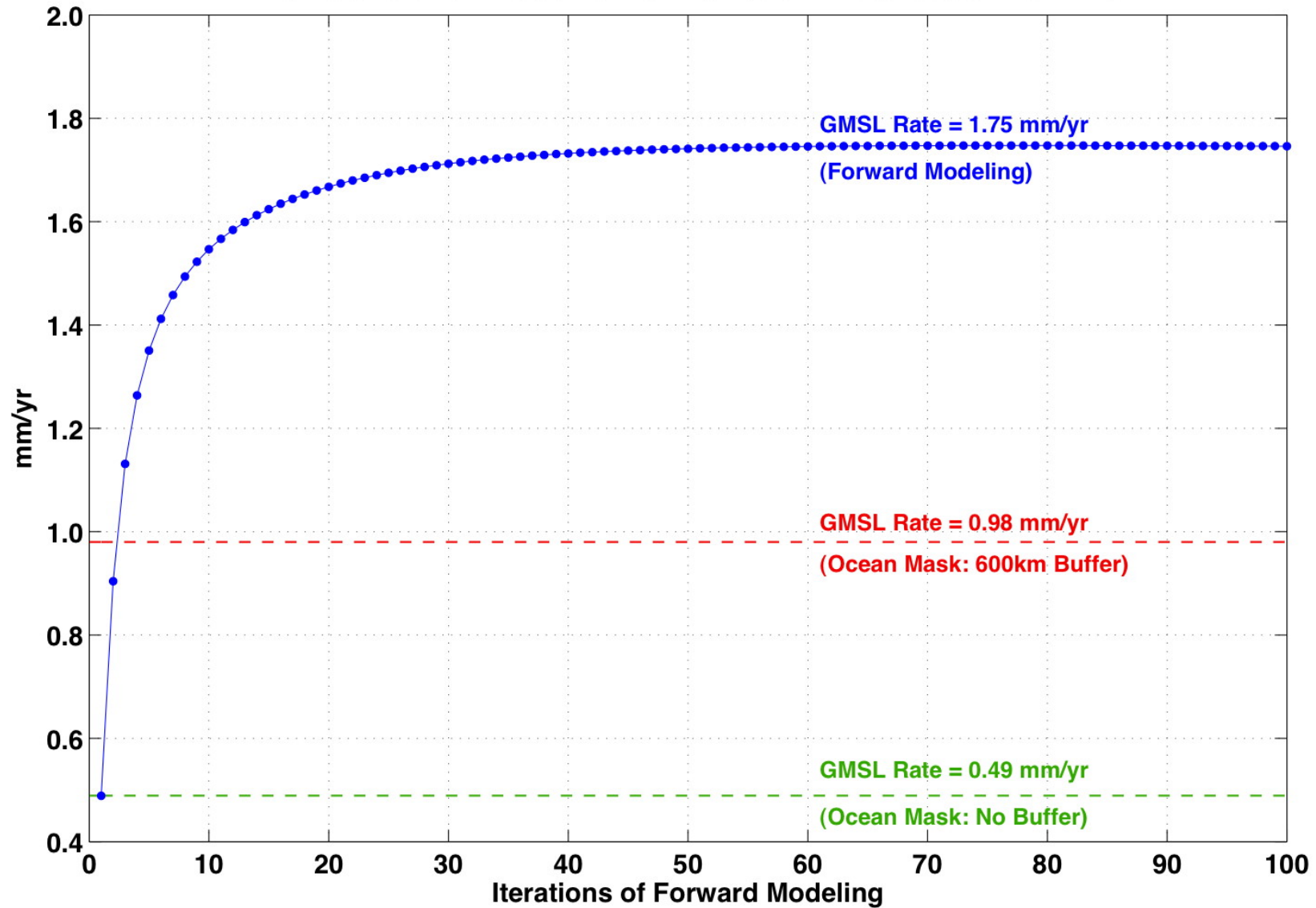
(c) Modeled Apparent Mass Rate (cm/yr)



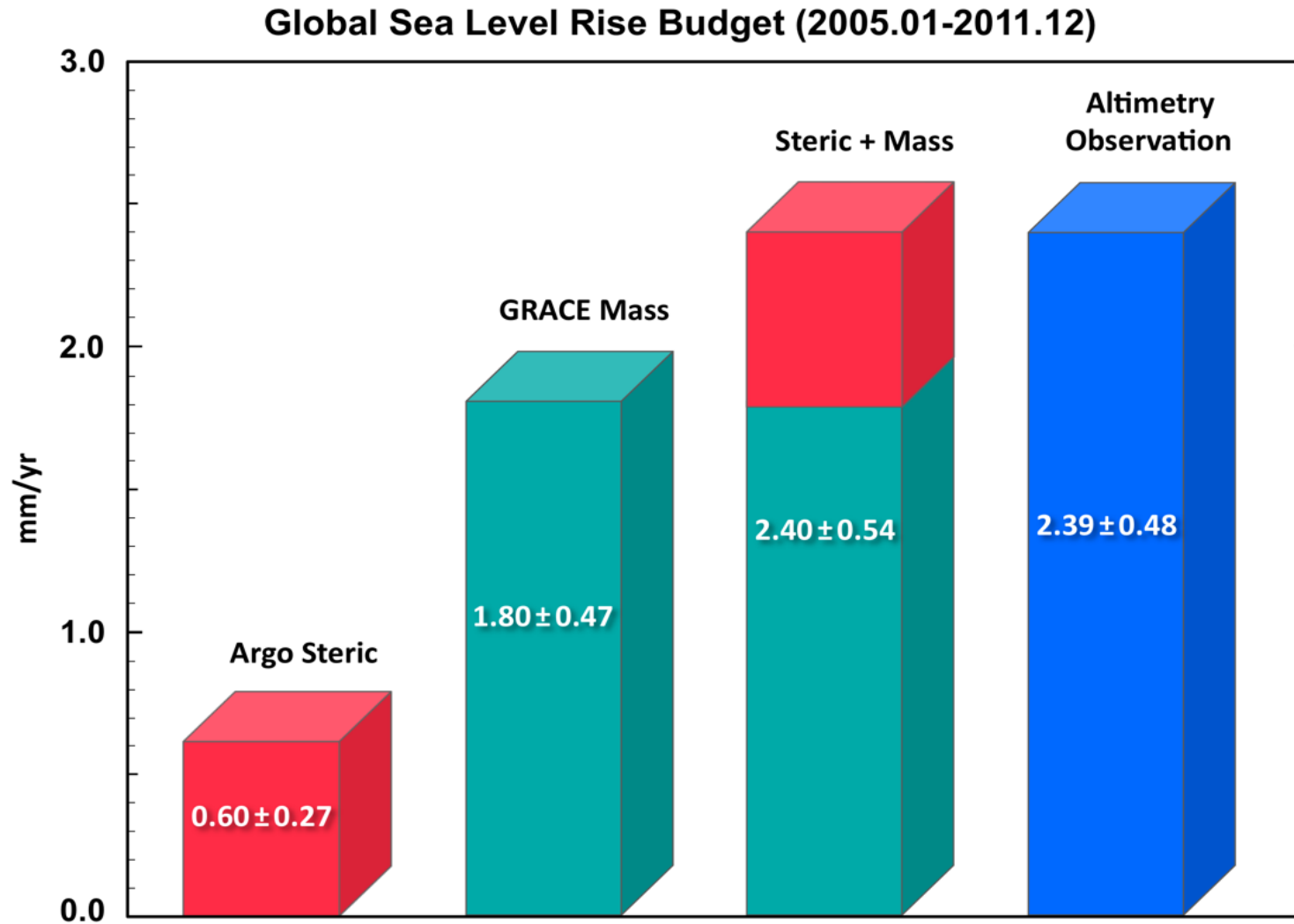
**Recovering GRACE “True”
Global Mass Rates Using
Global Forward Modeling**



Non-steric GMSL Rates from GRACE (CSR RL05, 2005.01–2011.12)



Closing the global mean sea level rise budget



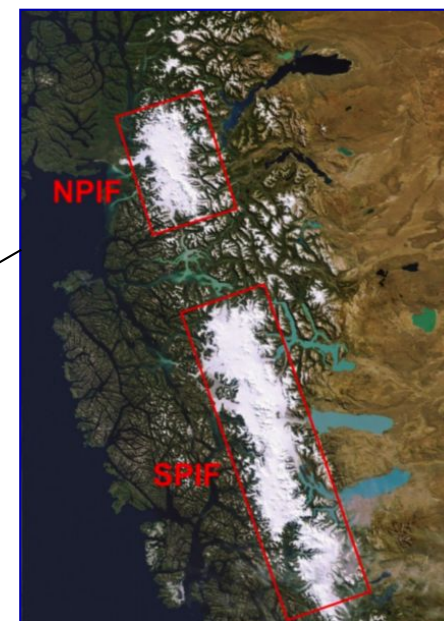
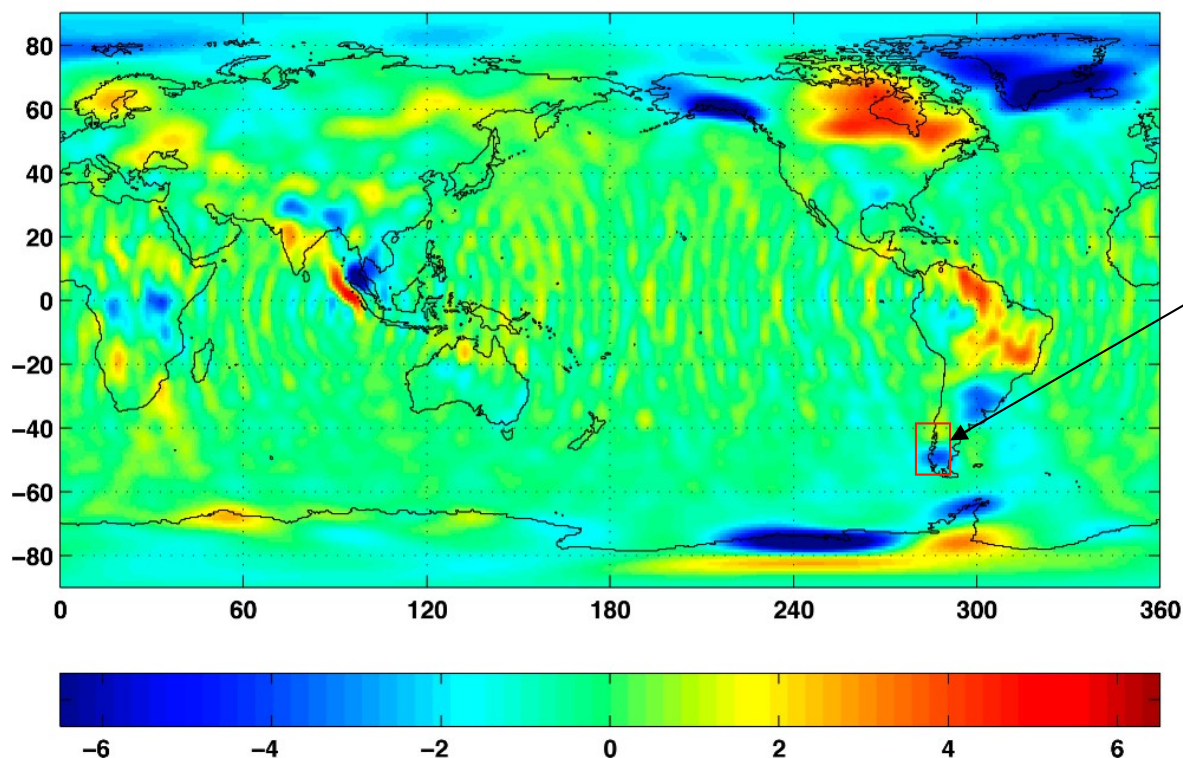
Chen et al., Contribution of polar and mountain glacier melt to recent sea level rise, *Nature Geoscience*, 6, 549-552, DOI: 10.1038/NGEO1829, 2013.

GRACE Other Applications - Mountain Glaciers

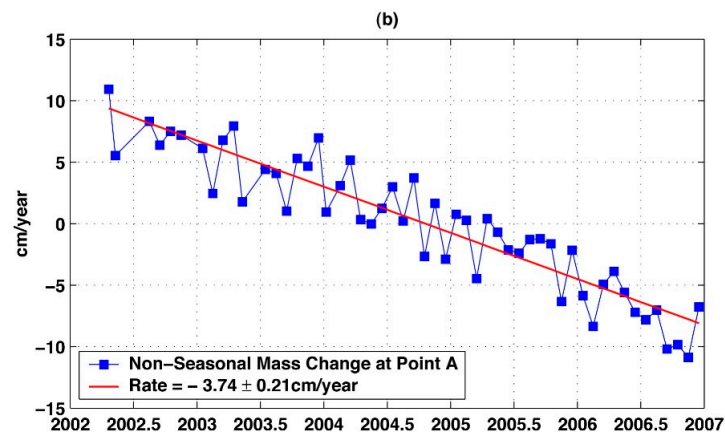
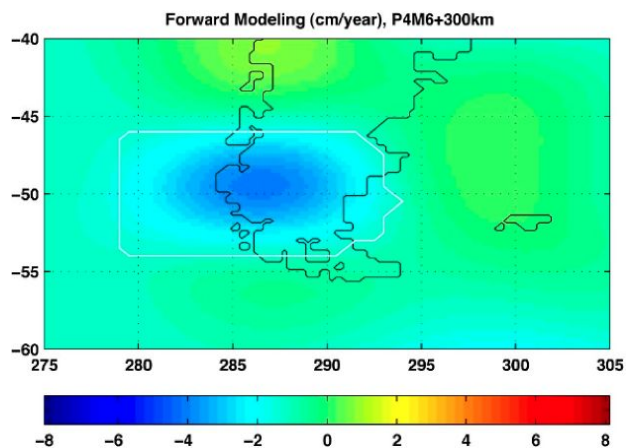
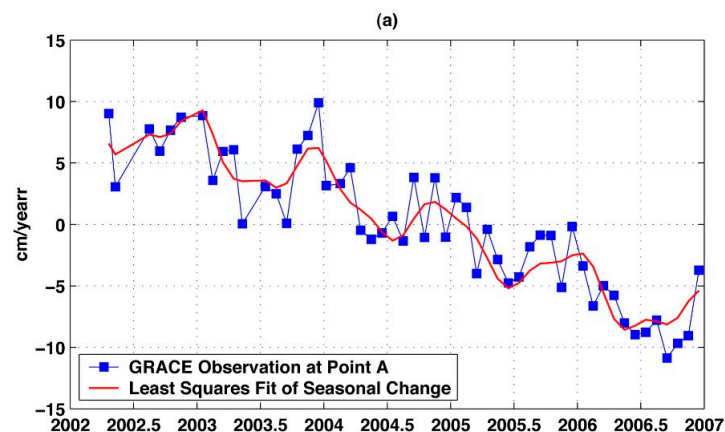
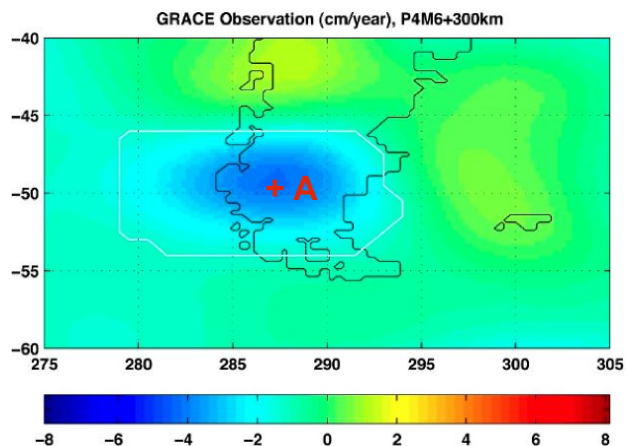


Patagonia Ice Fields Melting From GRACE

GRACE Mass Rates (cm/yr), CSR RL04, Apr 02 – May 07



GRACE Observed Mass Rates in the PIF Region



GRACE estimated PIF ice melting rate based on forward modeling is 25.0 ± 9.2 km³/year - first successful 'direct' measurement of PIF mass balance of recent years [Chen et al. 2007, GRL].

Thanks!