The GRACE Satellite Mission: Using Time-Variable Gravity to Study the Earth

With help from Sean Swenson, Thomas Jacob,
Isabella Velicogna, and Geruo A

- Map the Earth's gravity field at monthly time intervals.
- The results provide information about month-to-month variations in the Earth's mass distribution.
- Has applications for hydrology, oceanography, glaciers and polar ice sheets, and the solid Earth.

The structure of this talk

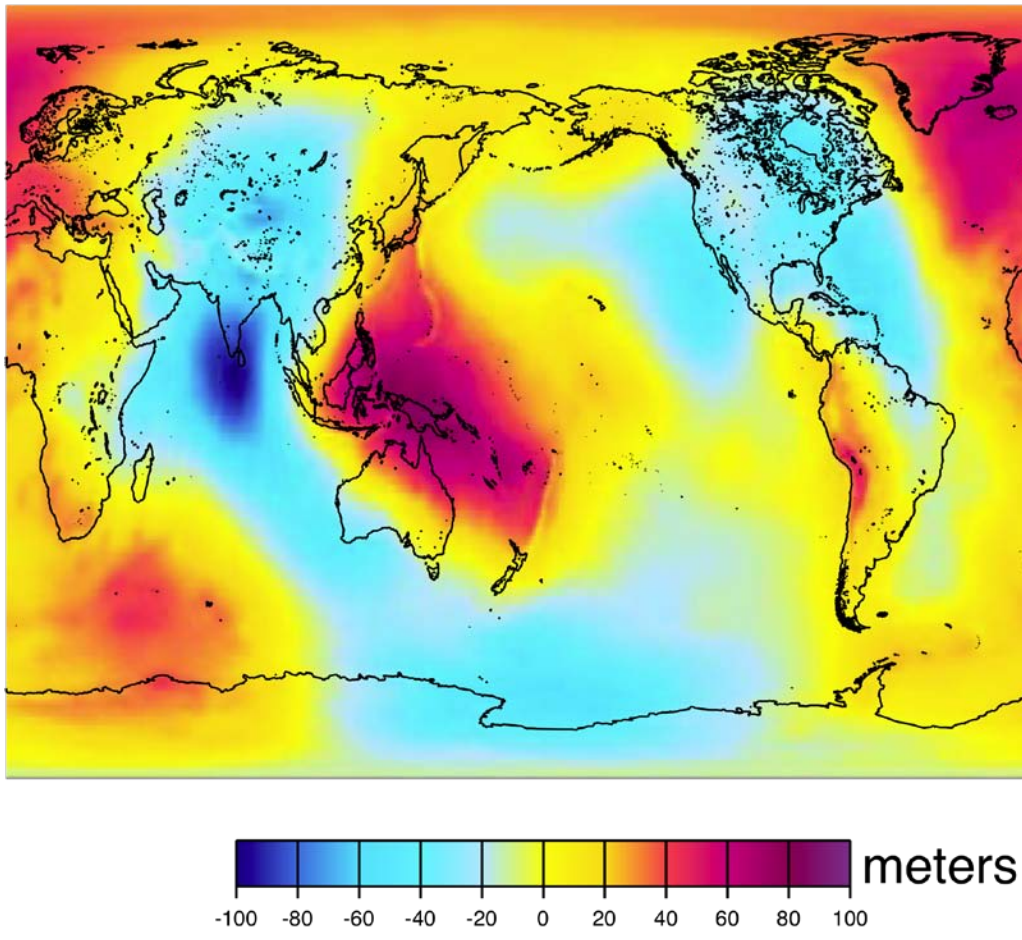
(1) General comments about satellite gravity, and GRACE.

(2) A few representative climate-related GRACE results.

The Earth's mass distribution causes its gravity field.

But the mass distribution cannot be uniquely determined from the gravity field.

The mean (time-averaged) geoid



- The inversion for time variations in mass is easier.

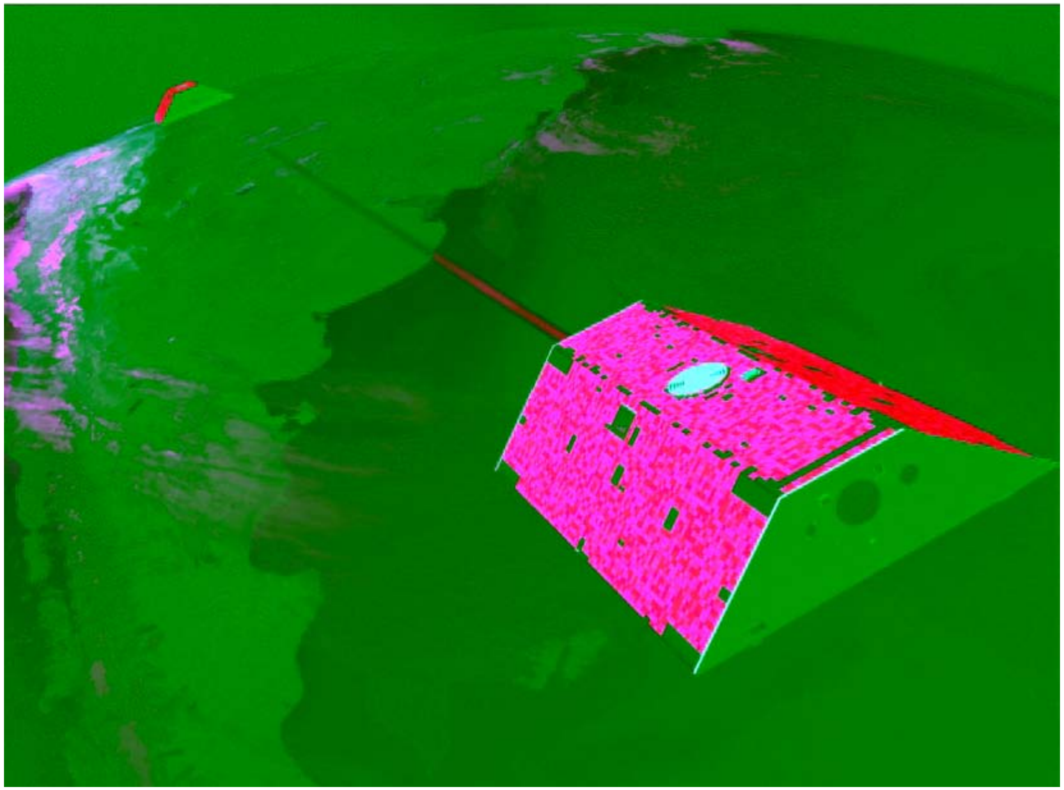
  Example: SEASONAL VARIATIONS in gravity originate at the Earth’s surface (the atmosphere, the oceans, the water and snow stored on land).

- But time variable signals are small: the amplitude of the annual cycle in the geoid is about 10 mm.

GRACE

Launched March, 2002. A NASA/DLR mission. Managed by U Texas, JPL, and GFZ. Anticipated lifetime: Through 2015-2016.

Objective: map out the gravity field to high accuracy every month



Two spacecraft. Altitude 450-500 km. Separation ~200 km.

GRACE Analysis

$$\text{Geoid height} = a\sum_{l=2}^{\infty}\sum_{m=0}^{l} P_{lm}(\cos\theta)\ (C_{lm}\cos m\phi + S_{lm}\sin m\phi)$$

- The P_{lm} are Legendre functions, a is the Earth's radius.
- The C_{lm} , S_{lm} are Stokes coefficients.
- Terms with small *l* have large horizontal scales.

- Large scales (small *l*) are determined more accurately than small scales.

- GRACE provides monthly sets of Stokes coefficients to $l \leq 60$ (or greater).

$$\text{Geoid height} = a \sum_{l=2}^{\infty} \sum_{m=0}^{l} P_{lm}(\cos\theta)\,(C_{lm}\cos m\phi + S_{lm}\sin m\phi)$$

- 116 monthly fields, between April, 2002 and April, 2012, are now available.

Time-Variable Gravity:

a) Remove a mean to get monthly changes in gravity.
b) Use these to estimate changes in surface mass.

Limitation #1

The mass results must be averaged over scales of several hundred km or larger, to be accurate.

Limitation #2

The mass results have no vertical resolution.

(1) can't distinguish between water on the surface and in the ground.

(2) or between water storage, and mass in the atmosphere or in the solid Earth.

The atmosphere: ECMWF meteorological fields are used to remove atmospheric contributions.

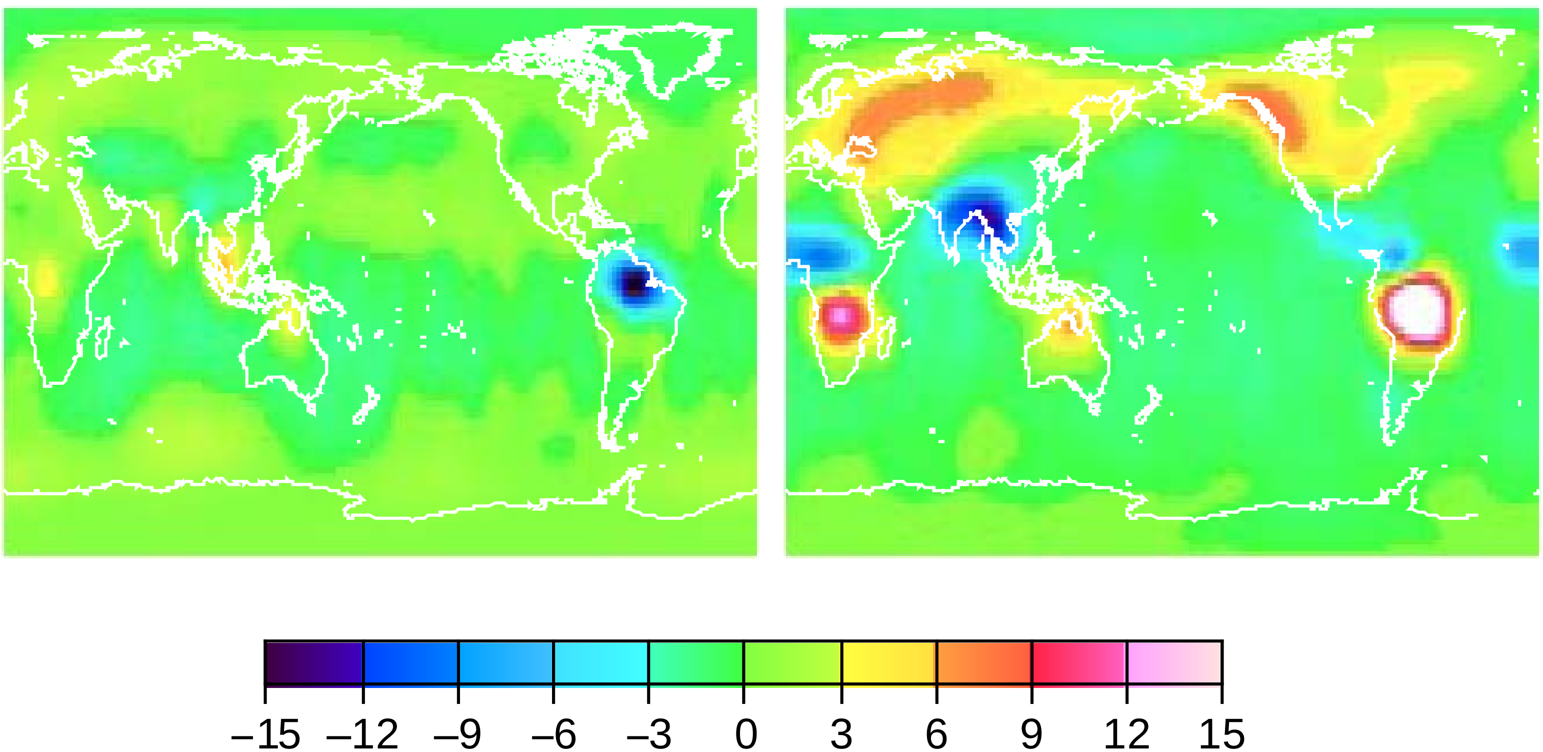
Solid Earth: Post-glacial-rebound causes secular trends.
Earthquakes cause step function offsets.

[Ocean signals have also been removed, using a baroclinic ocean model. Must be added back to study the ocean.]

Annual Mass Cycle From GRACE

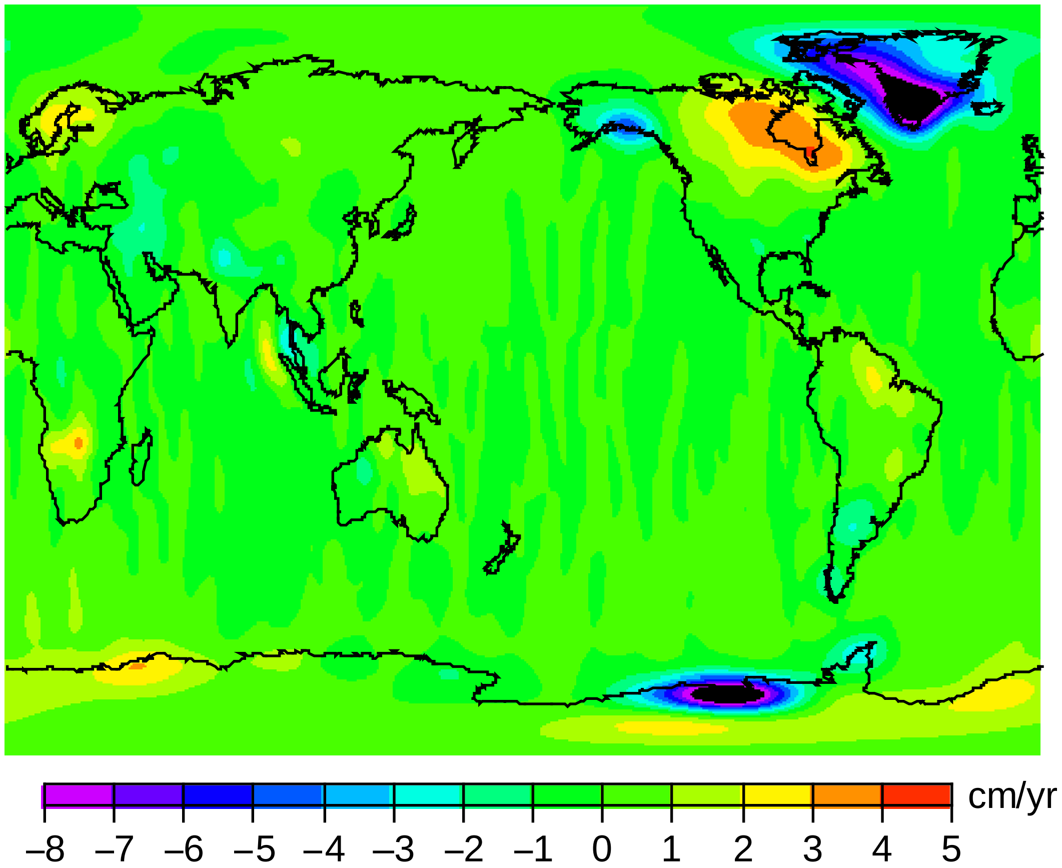
Annual cycle: $A*\cos(2\pi t/T) + B*\sin(2\pi t/T)$
where $T = 1$ year, and $t=0$ on Jan 1.
Cosine is max on Jan 1; Sine is max on April 1.

Cosine Sine

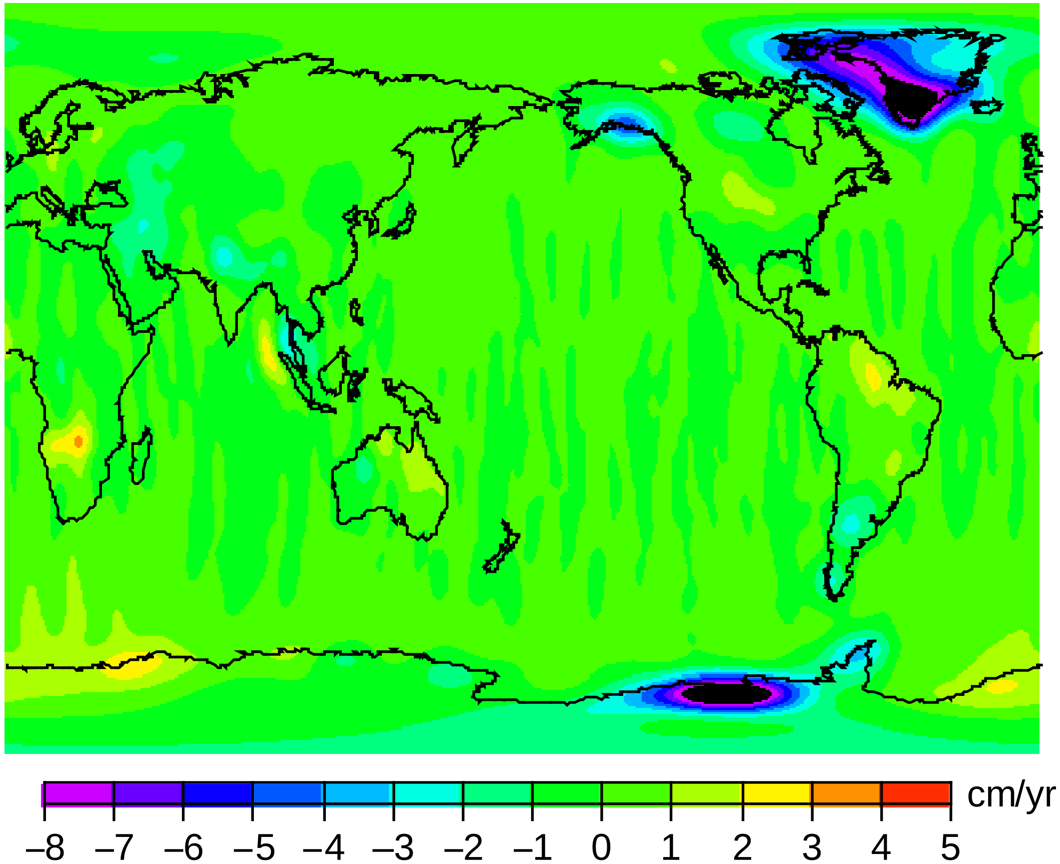


cm of water

Secular trend in mass. April, 2002-April, 2012



Secular trends with rebound model removed



Post-glacial-rebound model: from Geruo A (based on Peltier's (2004) ICE5G deglaciation history and VM2 viscosity profile).

The rest of this talk will include:

(1) A few hydrological and oceanographic applications.

(2) Greenland & Antarctica.

(3) A study of all the world's mountain glacier systems and ice caps.

Hydrology

What are hydrologists doing with GRACE?

(1) Assess and improve water storage models, and assess hydrological data.

(2) Estimate groundwater variations:

groundwater = total water (from GRACE) – soil moisture – snow mass – surface water

(3) Use mass balance equation:

Rate of water storage change = precip –evapotranspiration – runoff

$$dS/dt = P - ET - R$$

Possible Applications:

$P - ET = dS/dt$ (S from GRACE) $+ R$ (from river discharge)

$$ET = P - dS/dt - R$$

$$R = P - ET - dS/dt$$

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Possible Applications:

P - ET = dS/dt (S from GRACE) + R (from river discharge)

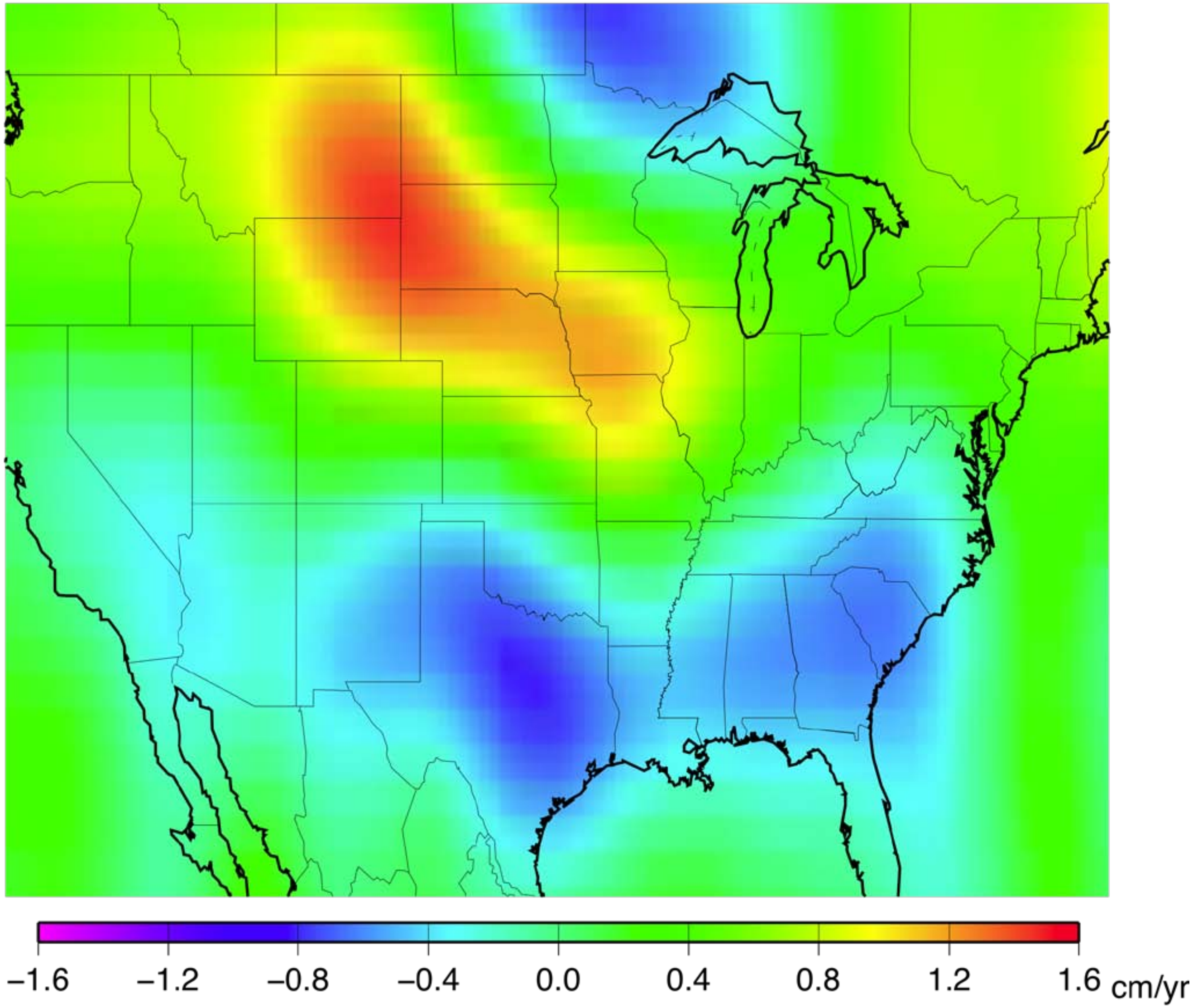
$$ET = P - dS/dt - R$$

$$R = P - ET - dS/dt$$

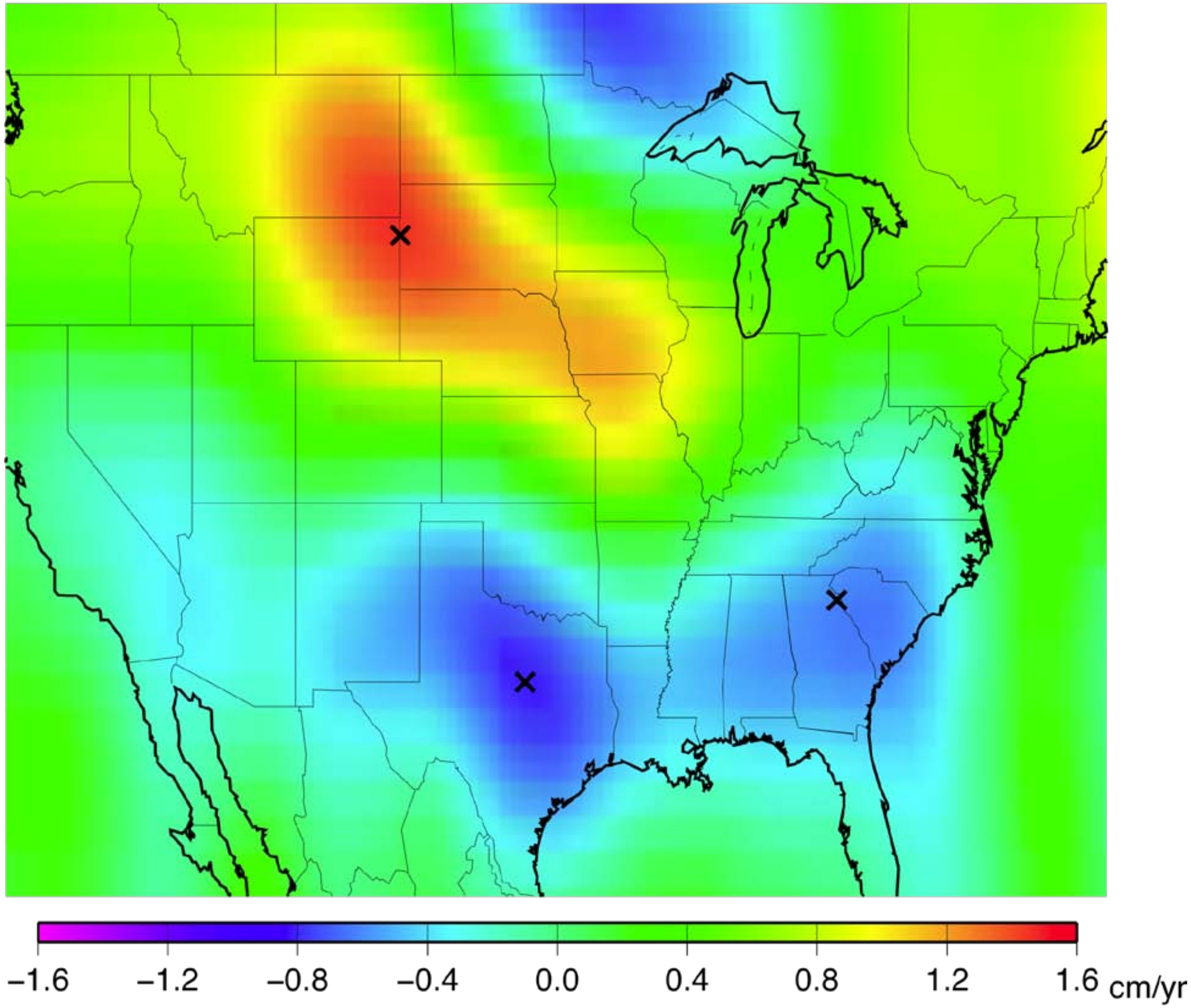
In the following: examples of (1) and (2).

A brief illustration of water storage signals in the United States

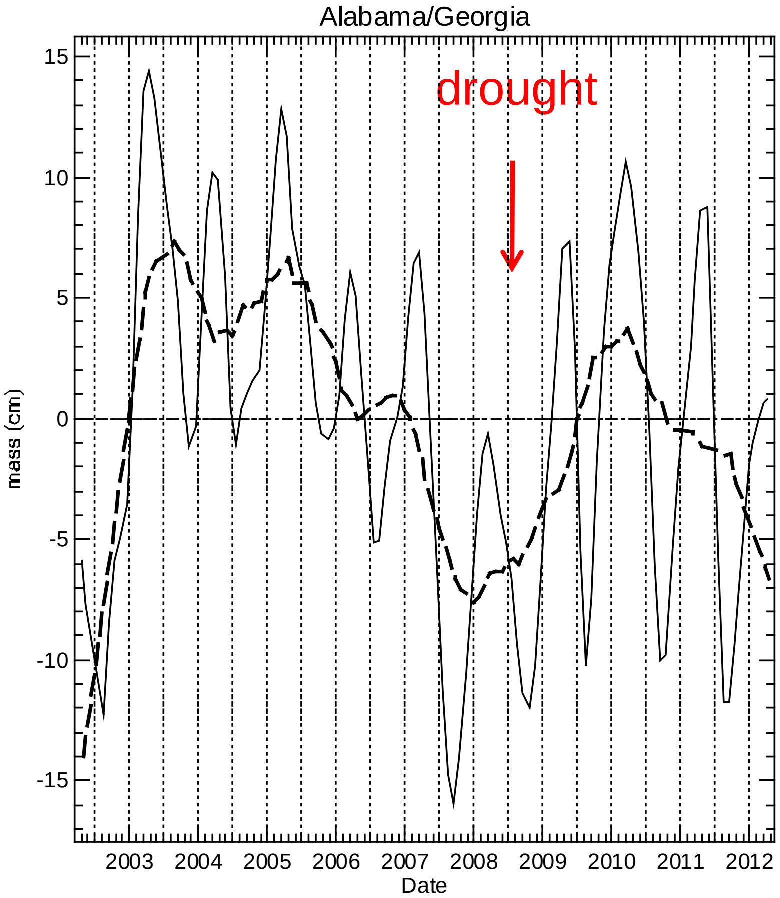
Secular trend. April, 2002 through April, 2012

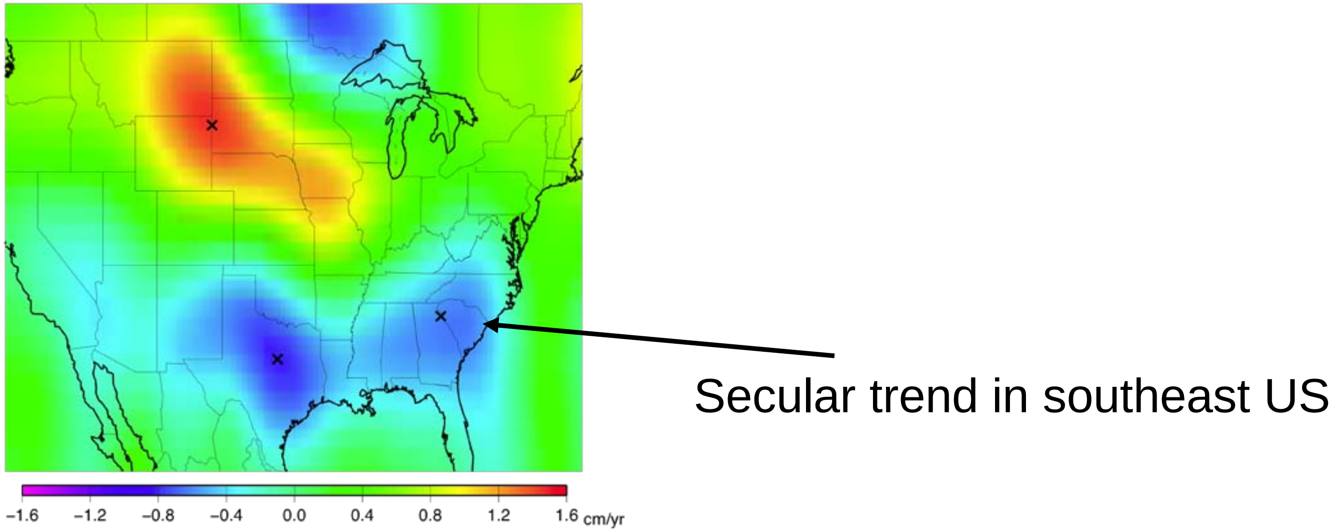


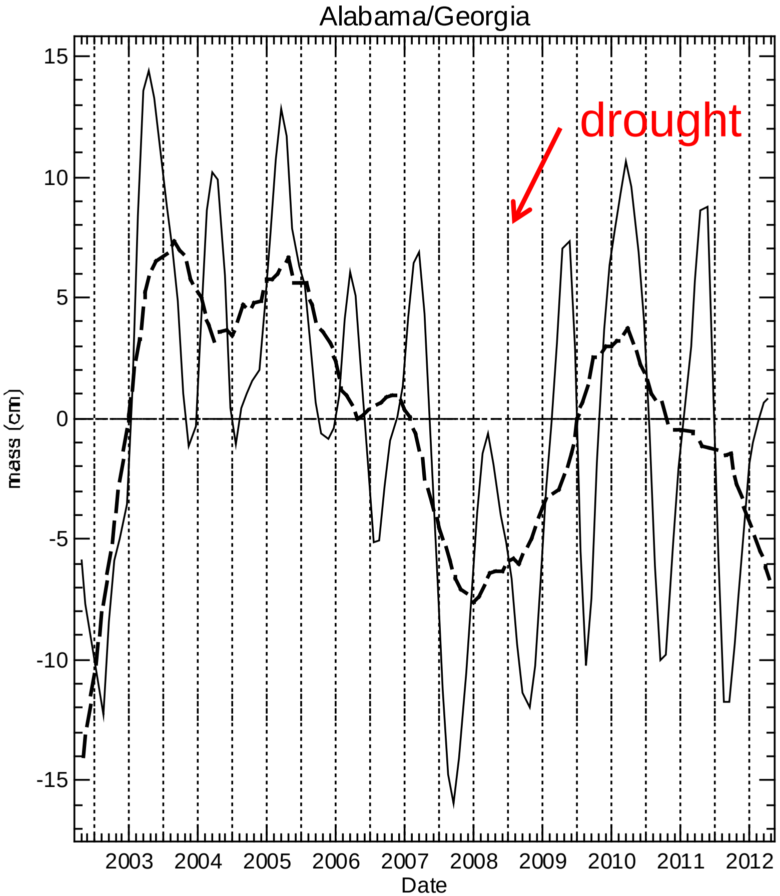
Secular trend. April, 2002 through April, 2012

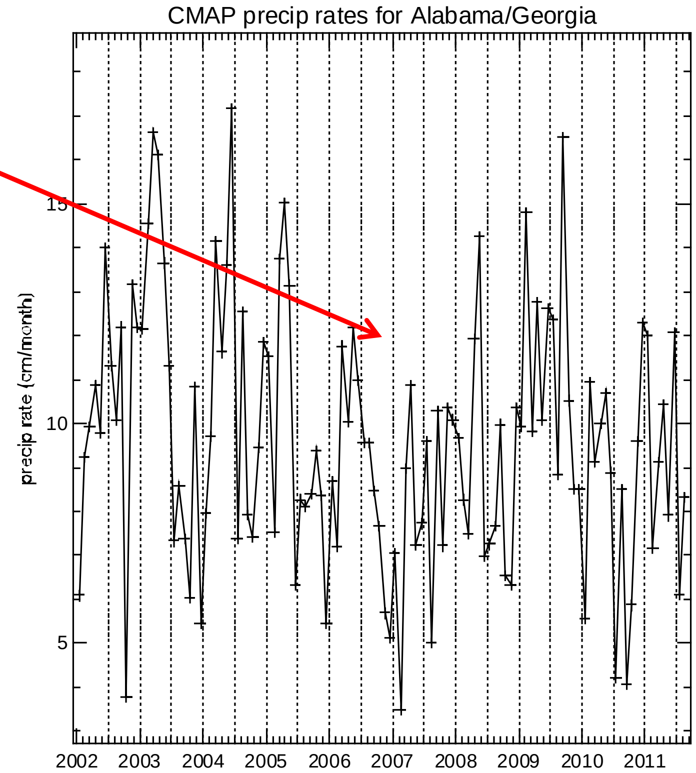


The x's mark locations shown in the following slides.

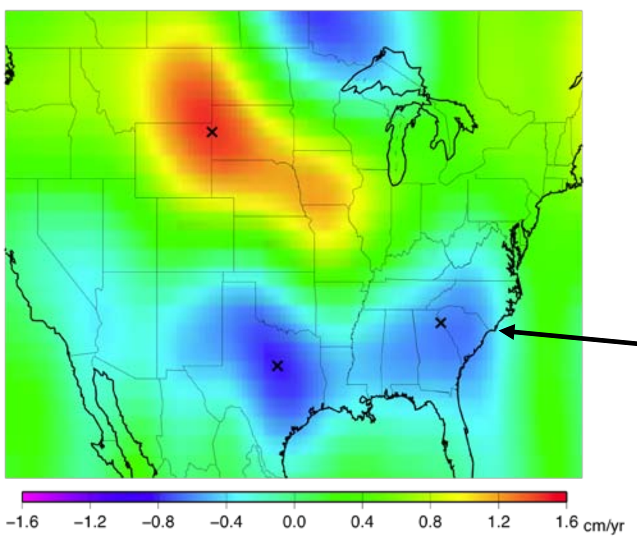

Alabama/Georgia
drought
mass (cm)
15
10
5
0
-5
-10
-15
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Date


−1.6
−1.2
−0.8
−0.4
0.0
0.4
0.8
1.2
1.6
cm/yr
Secular trend in southeast US

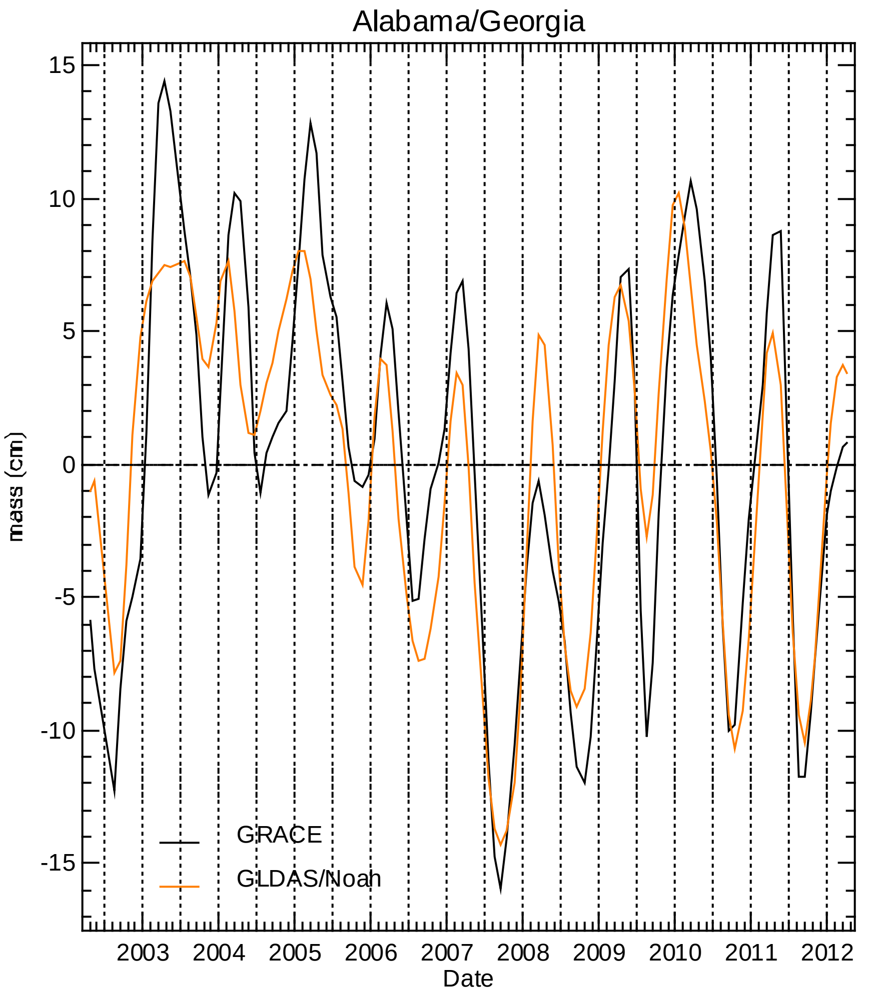




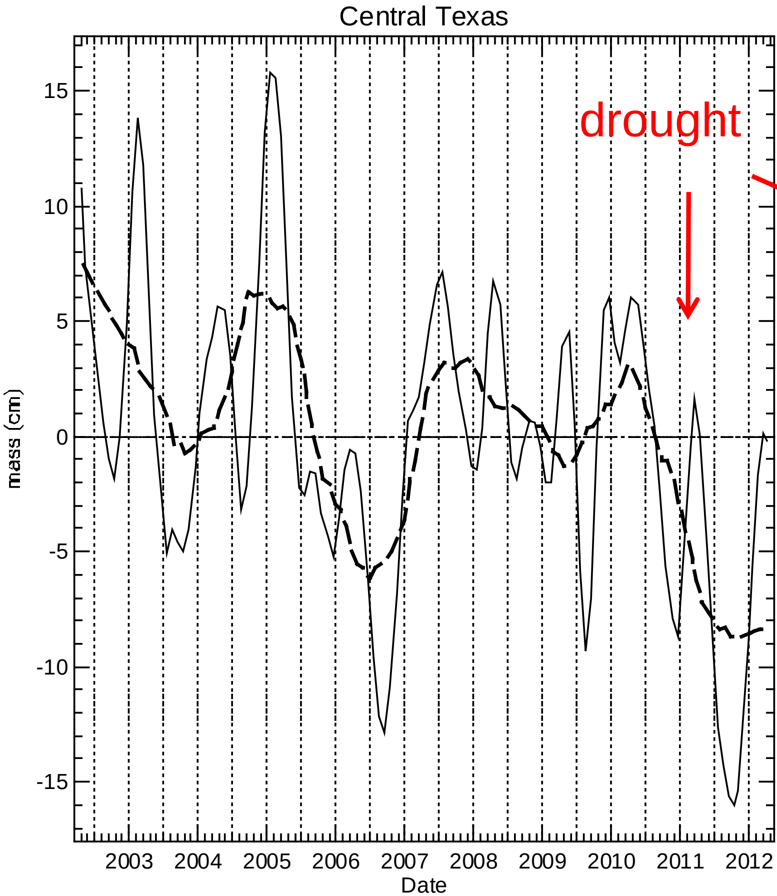
CMAP (CPC Merged Analysis of Precipitation) precipitation rate (Xie and Arkin, 1997), from NOAA

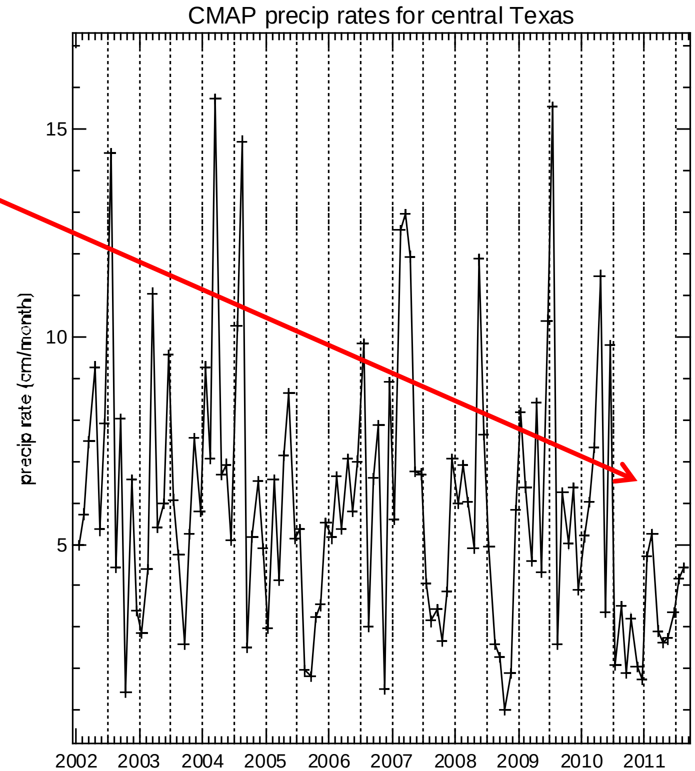


Secular trend in southeast US



Orange = GLDAS/Noah model (Rodell et al, 2004). Model includes soil moisture and snow, but not groundwater or surface water.





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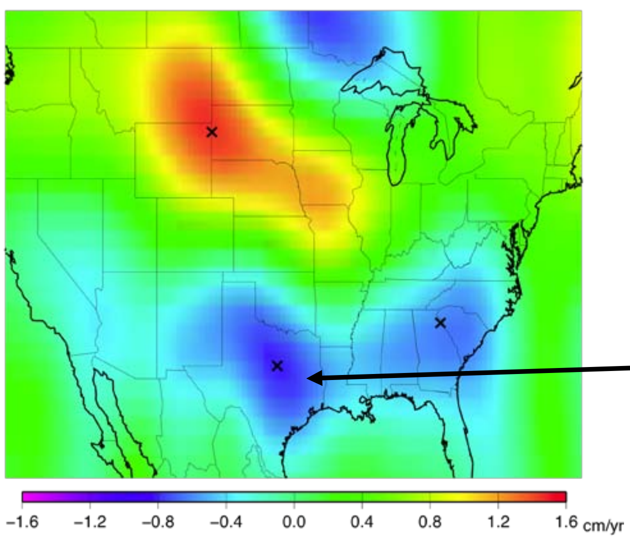
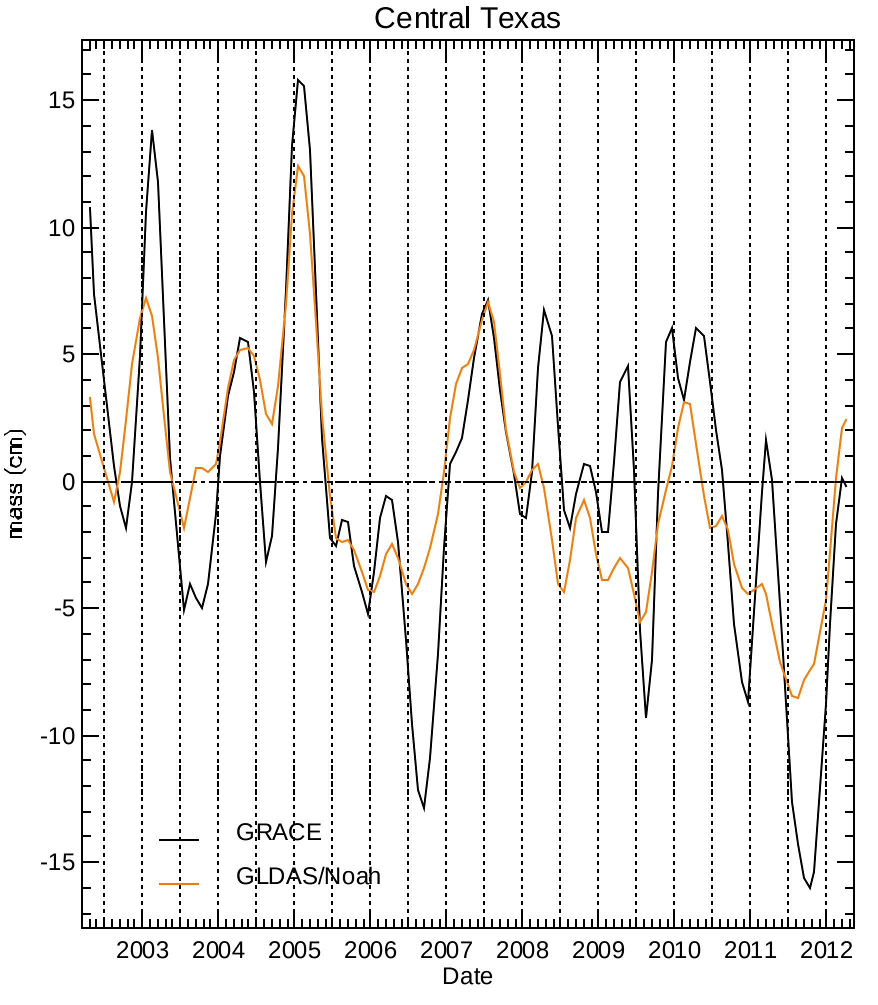
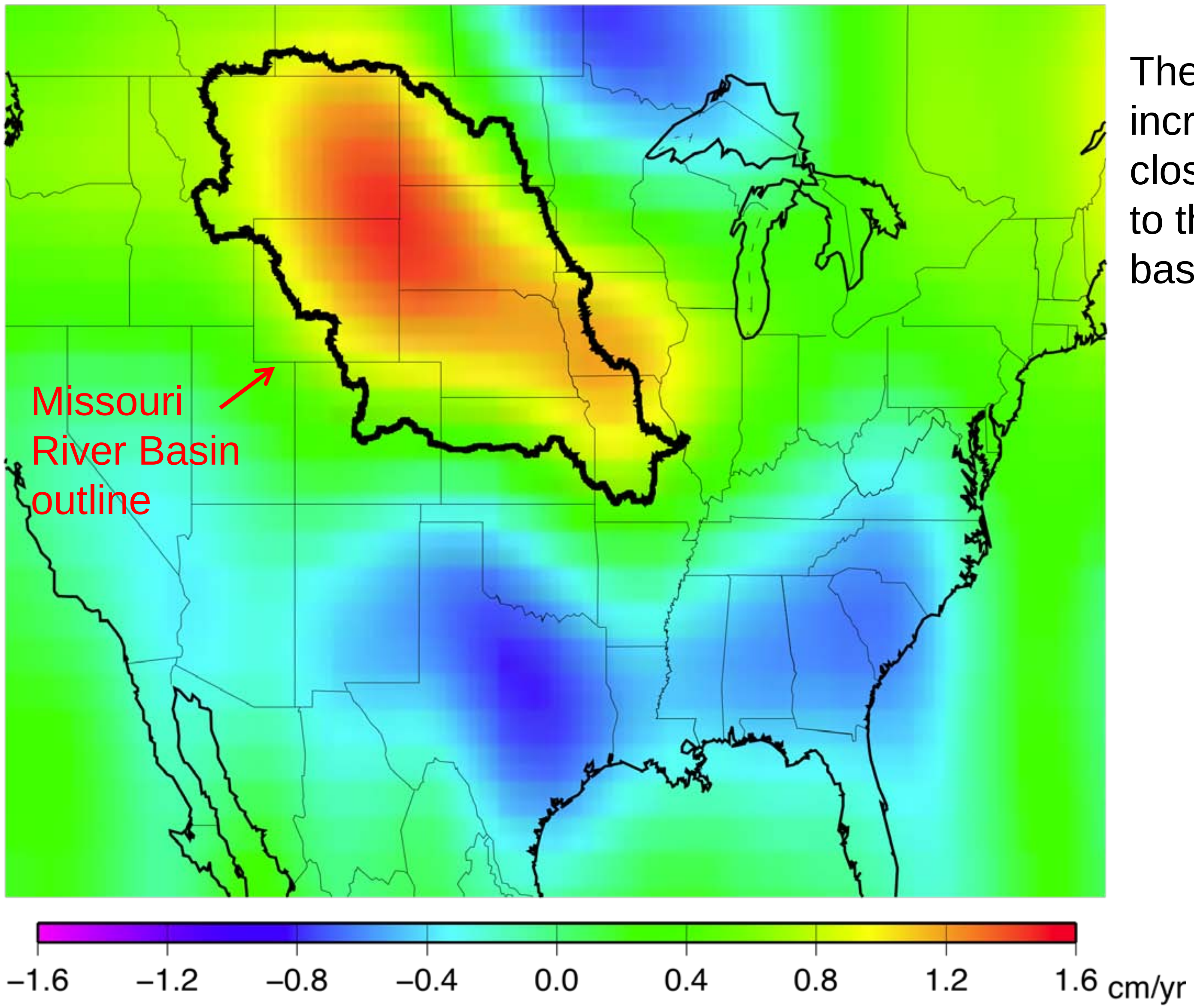


Secular trend in Texas

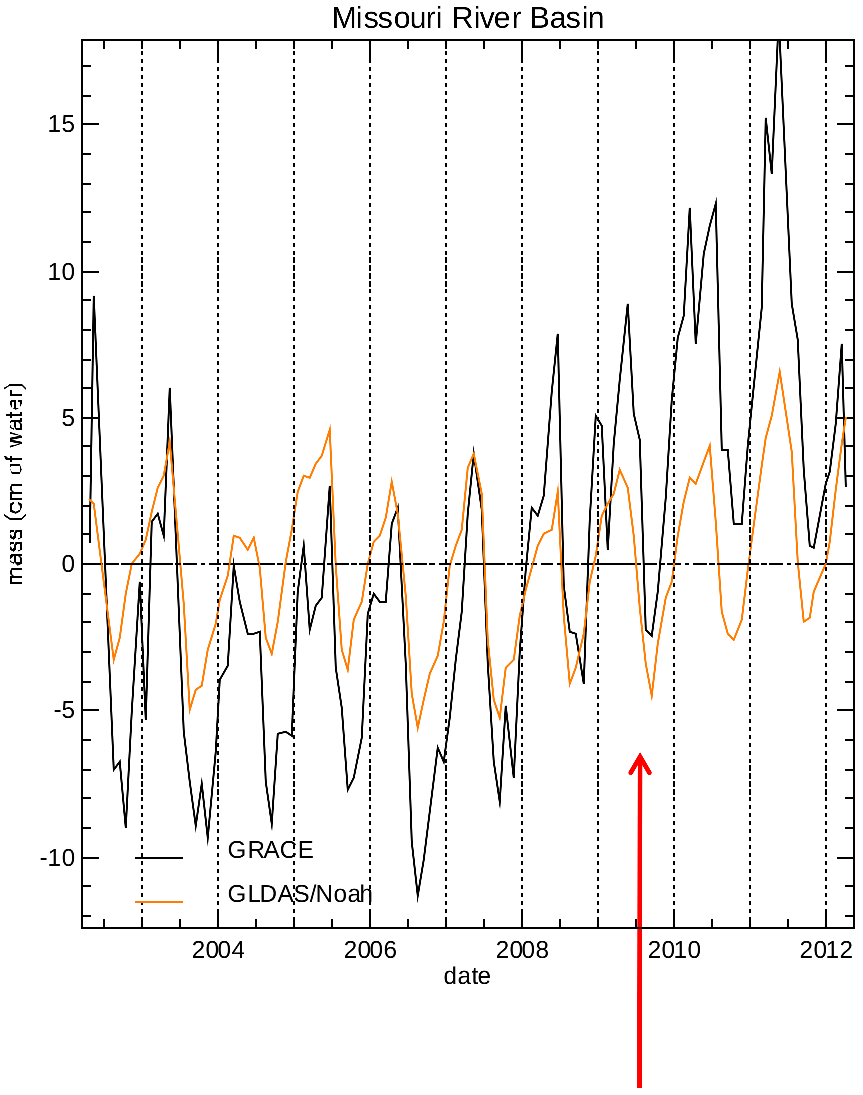


Orange = GLDAS/Noah model. Model includes soil moisture and snow, but not groundwater or surface water.

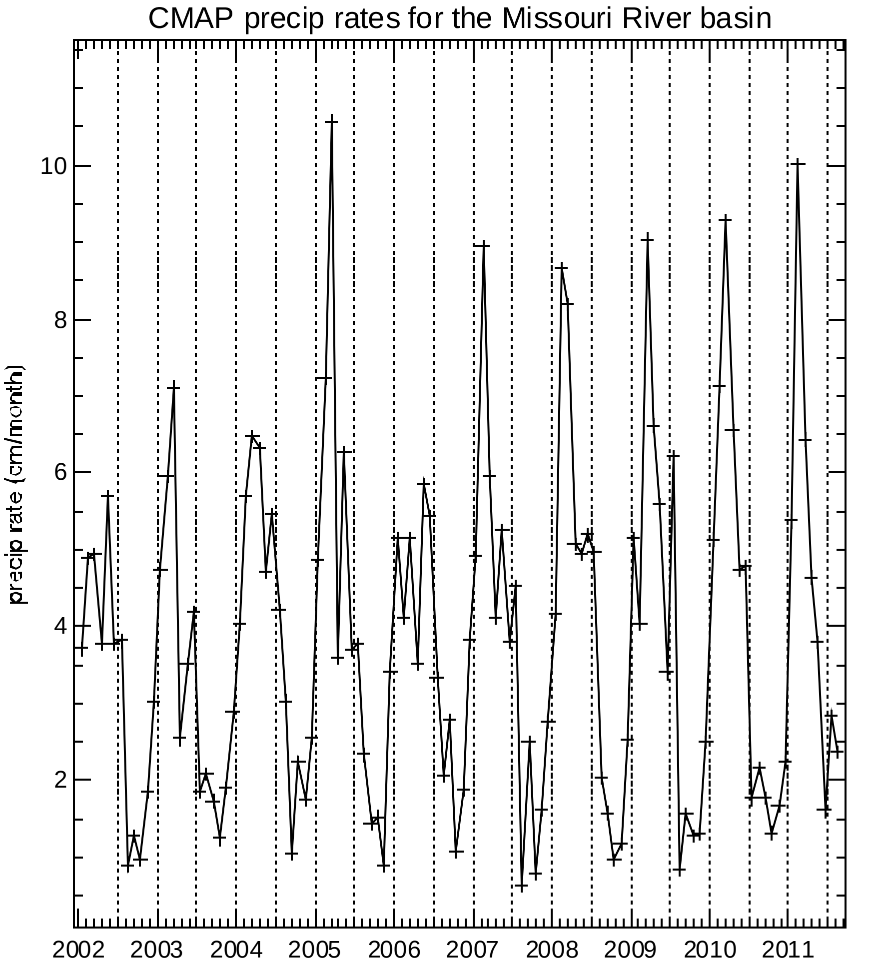
Secular trend. April, 2002 through April, 2012



The region of increasing mass closely corresponds to the Missouri River basin.



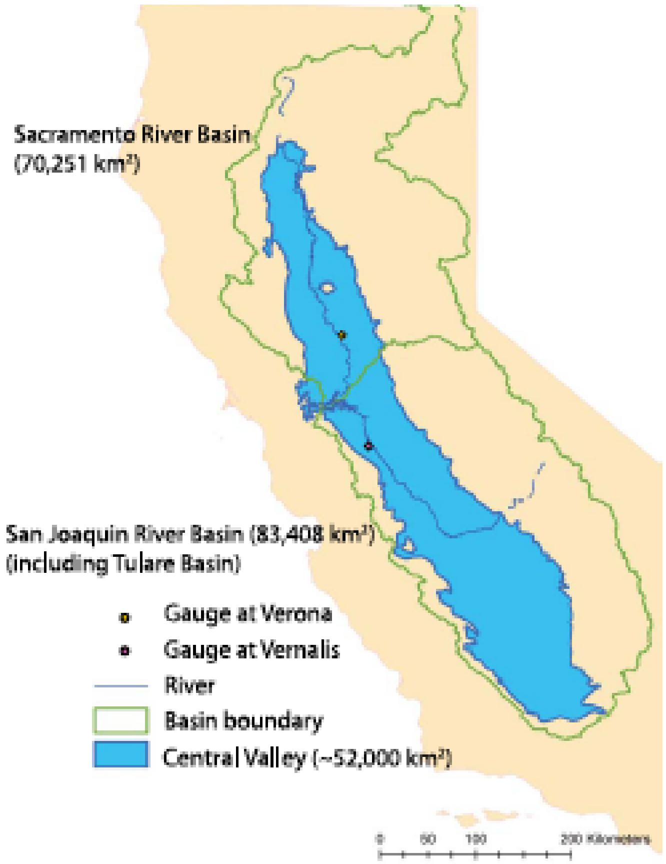
Mass increase began in 2008/2009. Much more prominent in GRACE than in the model, suggesting it is largely a groundwater signal.



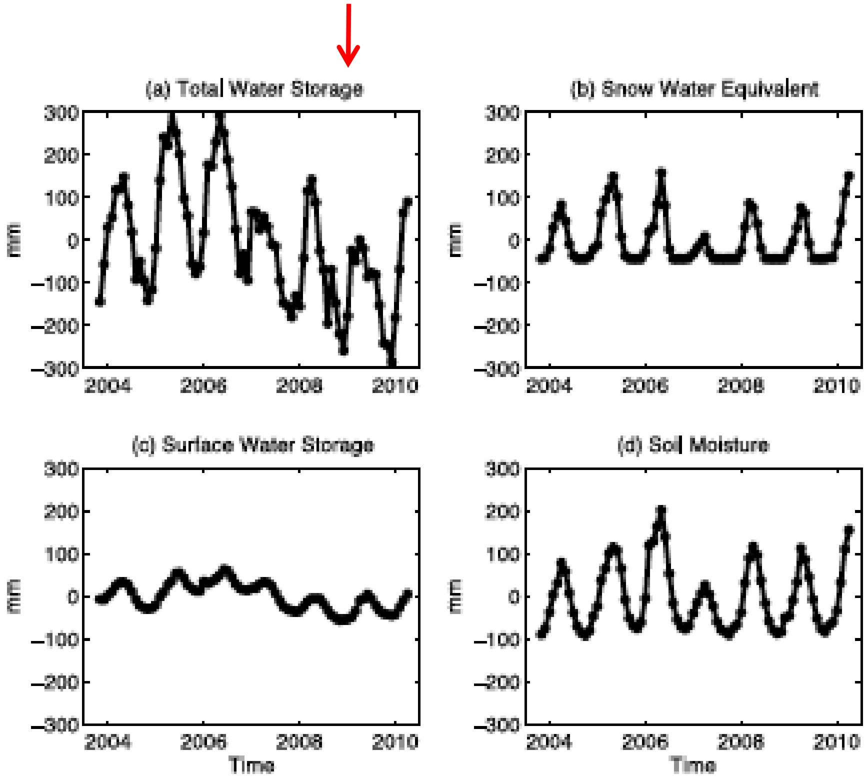
Precipitation rates have been larger after 2007 than before.

Groundwater Depletion in California's Central Valley

Famiglietti et al (2011)



Subtract soil moisture, snow, and surface water from GRACE total storage



to get groundwater

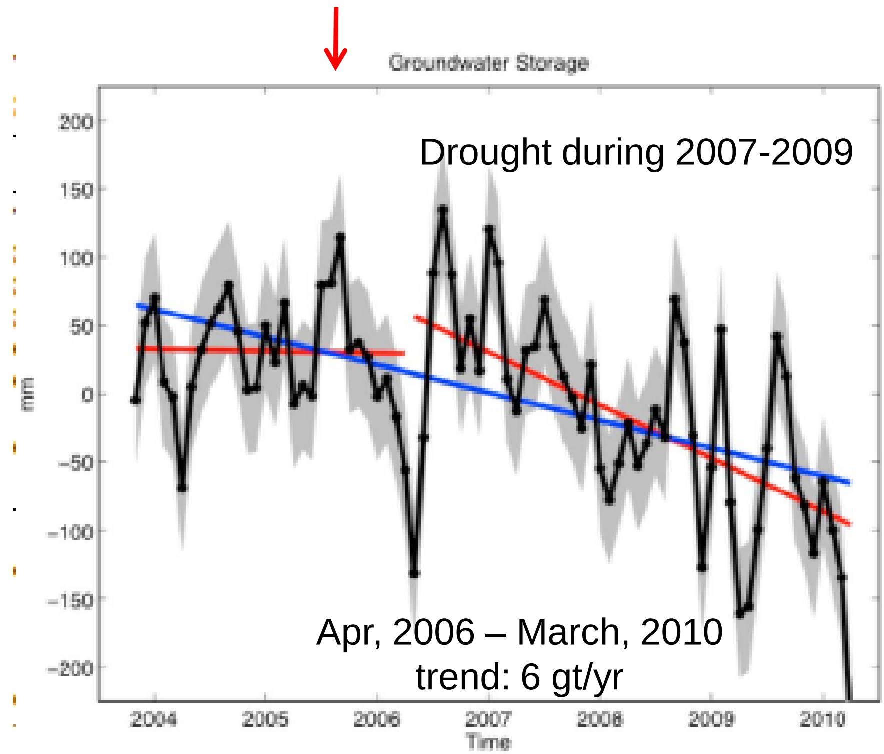


Figure 4. Monthly groundwater storage anomalies for the Sacramento and San Joaquin River Basins in mm, from October 2003 to March 2010. Monthly errors shown by gray shading. The blue line represents the overall trend in groundwater storage changes for the 78-month period. The red lines represent the trends from October 2003 and March 2006 and April 2006 through March 2010.

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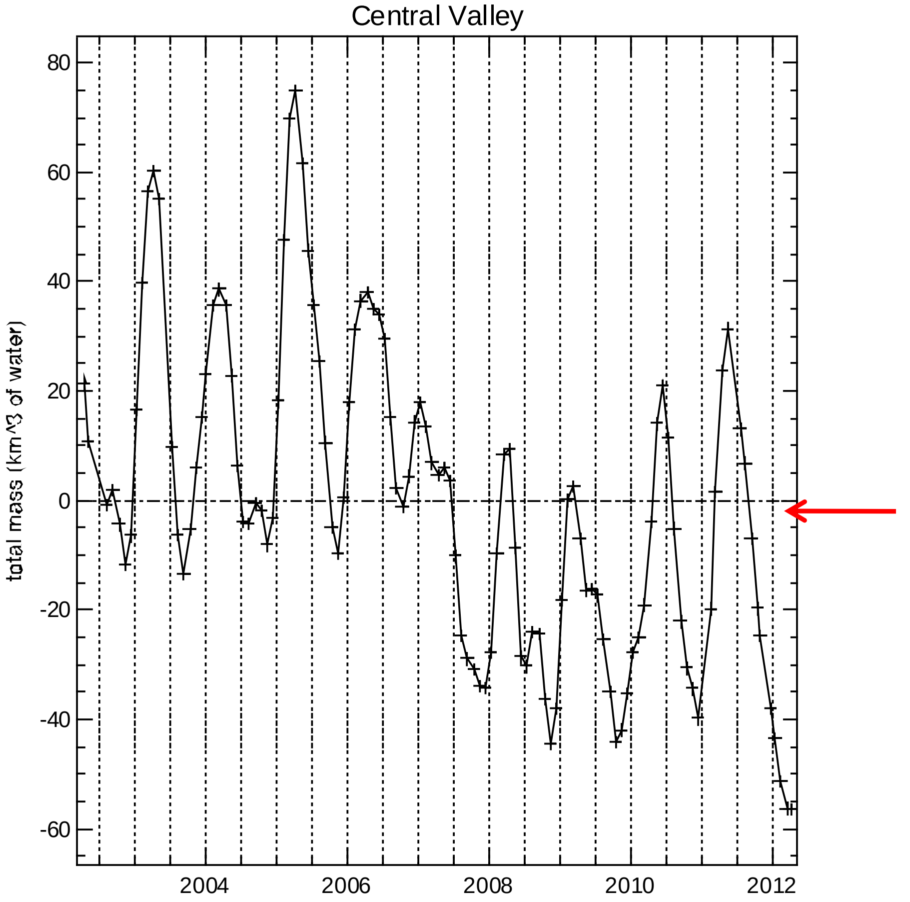
Famiglietti et al (2011)

Time series extended through April, 2012



Groundwater appears to have stabilized

Oceanography

What can oceanographers do with GRACE?

(1) Assess ocean general circulation models. (GRACE provides changes in ocean bottom pressure.)

(2) Sea level change = change in water mass

+ steric change (thermal expansion + salinity change)

Steric = sea level (from altimetry) – mass (from GRACE).

Steric effects can be used to determine changes in ocean heat content.

(3) Partition global sea level change into mass and steric contributions.

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Steric effects can be used to determine changes in ocean heat content.

(3) Partition global sea level rise into mass and steric contributions.

In the following: an example of (3).

Global Sea Level Rise

Global sea level rise = change in ocean mass + steric effects

Sea level: from satellite altimetry.

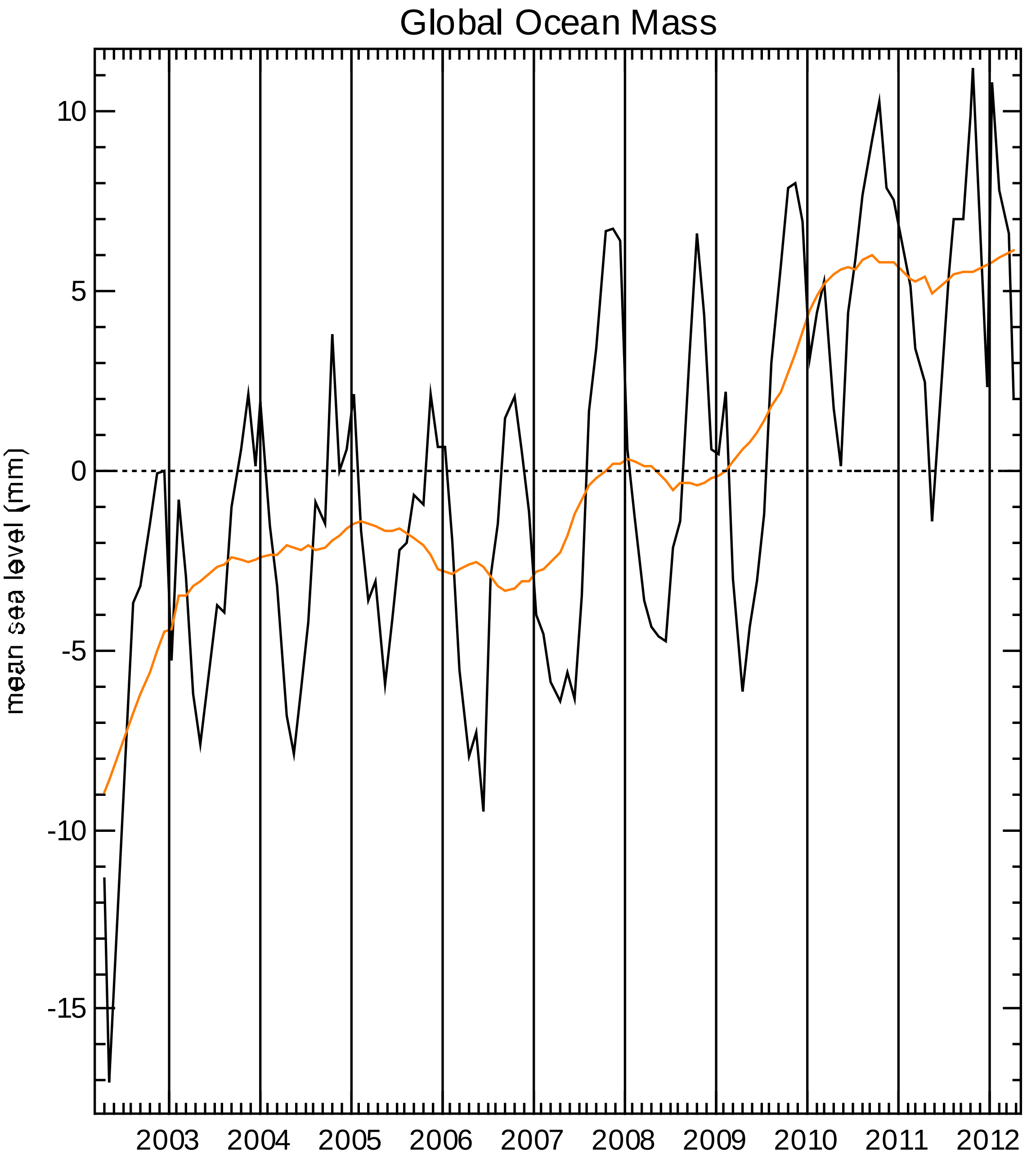
Ocean mass: from GRACE.

Steric effects: ocean temperature and salinity from Argo float network.

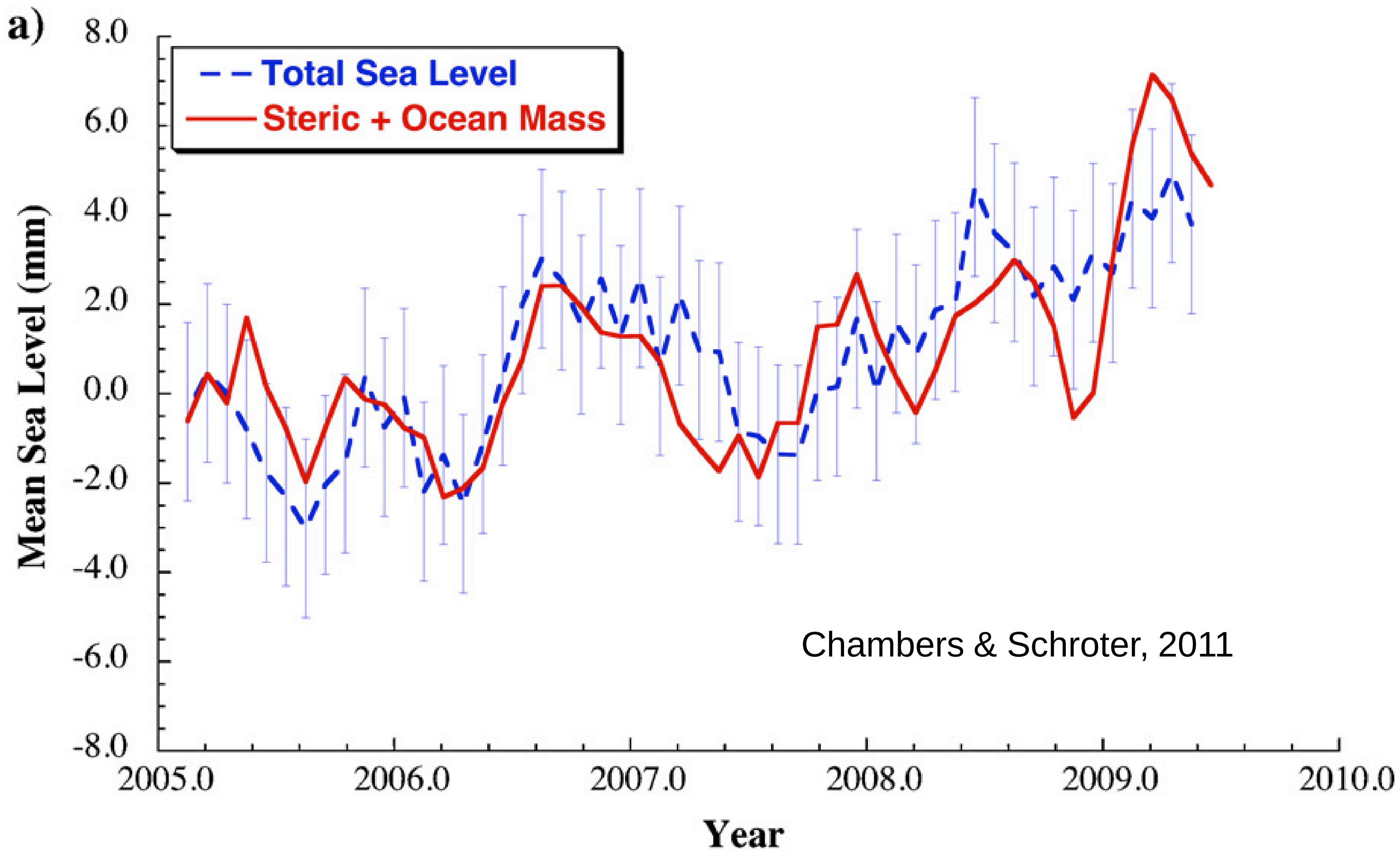
Questions:

(a) Do the altimeter estimates agree with the GRACE plus Argo estimates?

(b) What are the mass and steric contributions to global sea level change?


Global Ocean Mass
mean sea level (mm)
10
5
0
-5
-10
-15
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

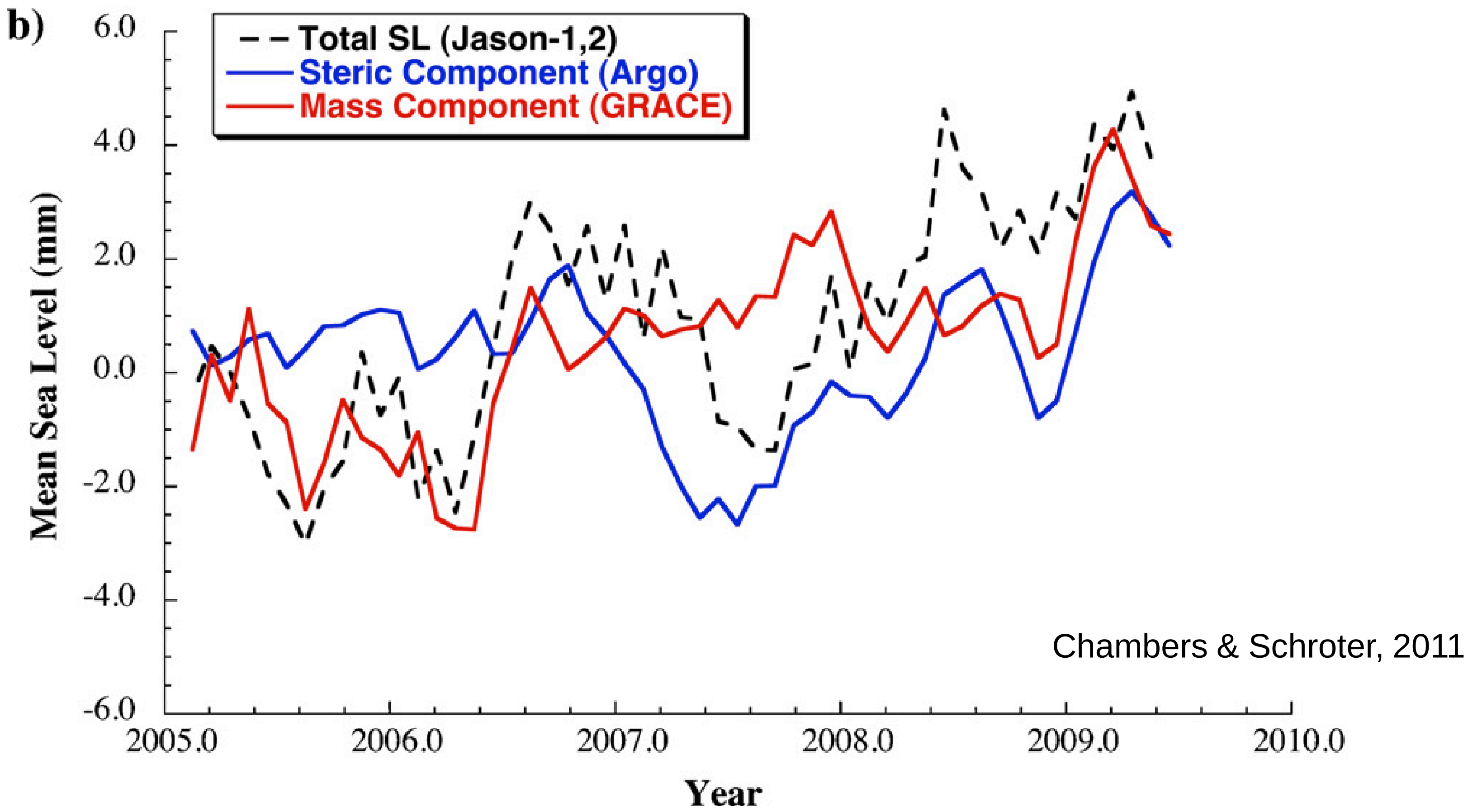
Do the altimeter estimates agree with the GRACE plus Argo estimates?



Seasonal terms removed.

There's a good match between sea level from altimetry, and sea level from GRACE (mass) + Argo (steric)

What are the mass and steric contributions?



The steric and mass signals have ~same amplitudes but otherwise don't look similar.

.

2005.0-2011.0 trends (Don Chambers, personal communication):

total sea level rise: 2.3 ± 0.6 mm/yr

mass contribution: 1.2 ± 0.4 mm/yr

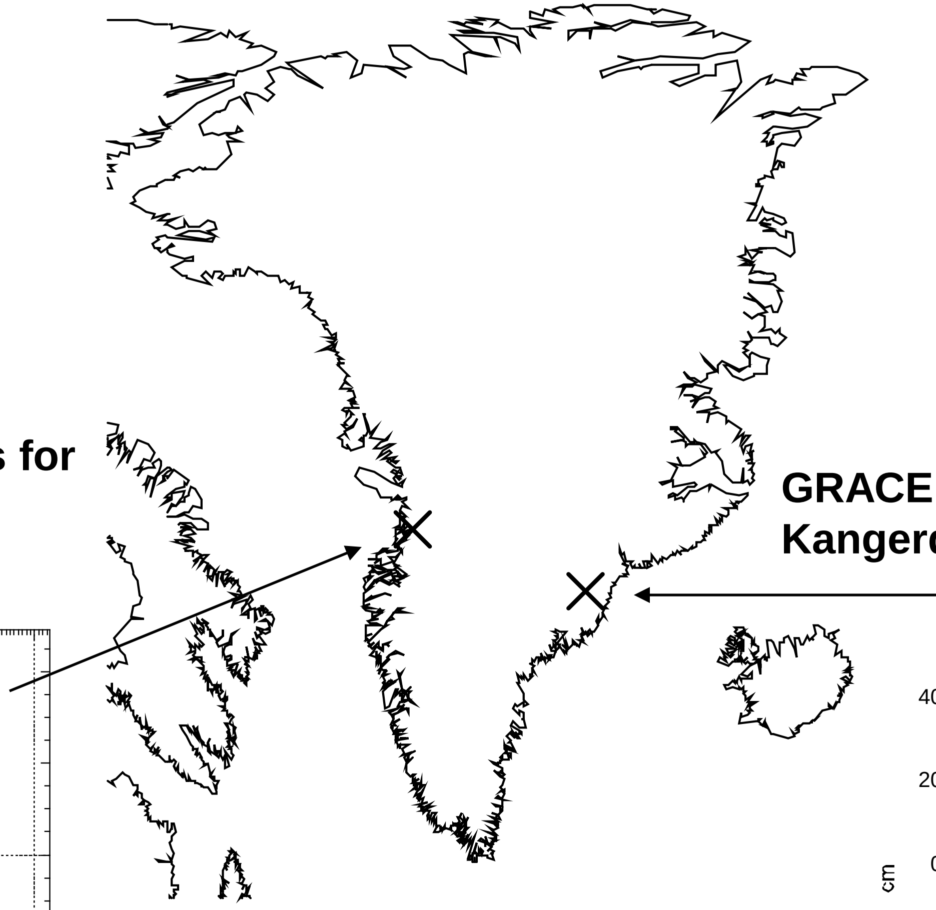
steric contribution: 0.8 ± 0.3 mm/yr

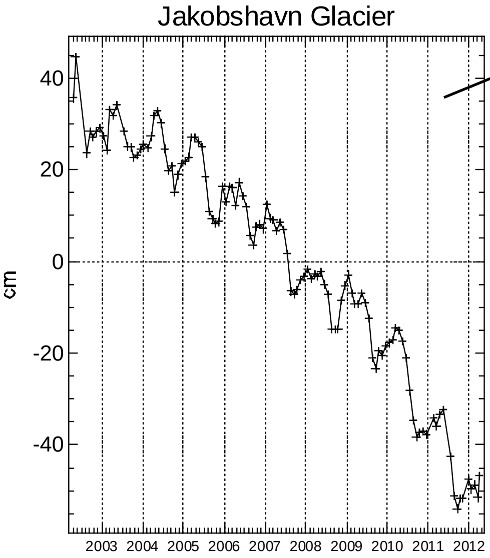
Greenland

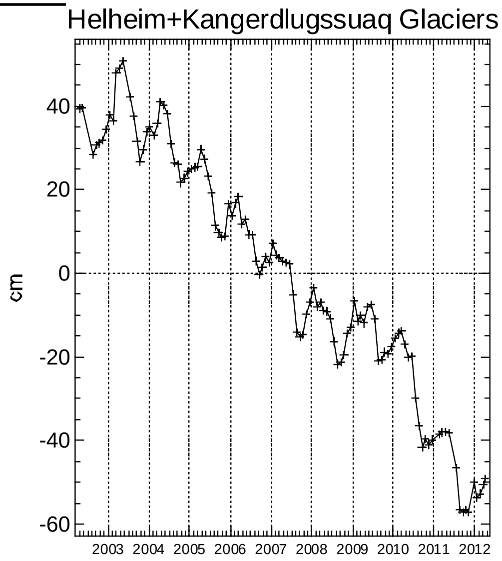

Jakobshavn Glacier
Helheim +
Kangerdlugssuaq
Glaciers

GRACE mass results for Jakobshavn Glacier

GRACE results for Helheim + Kangerdlugssuaq Glaciers

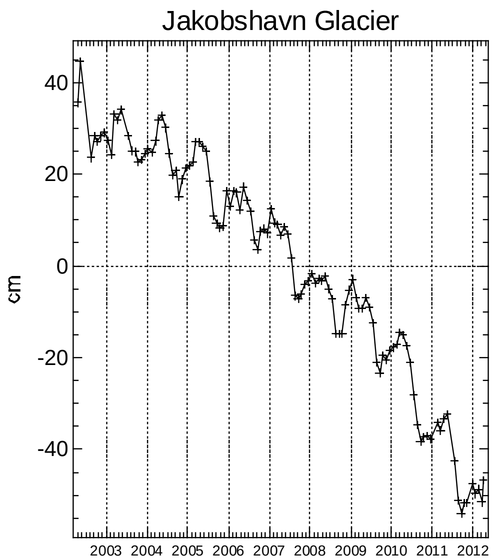


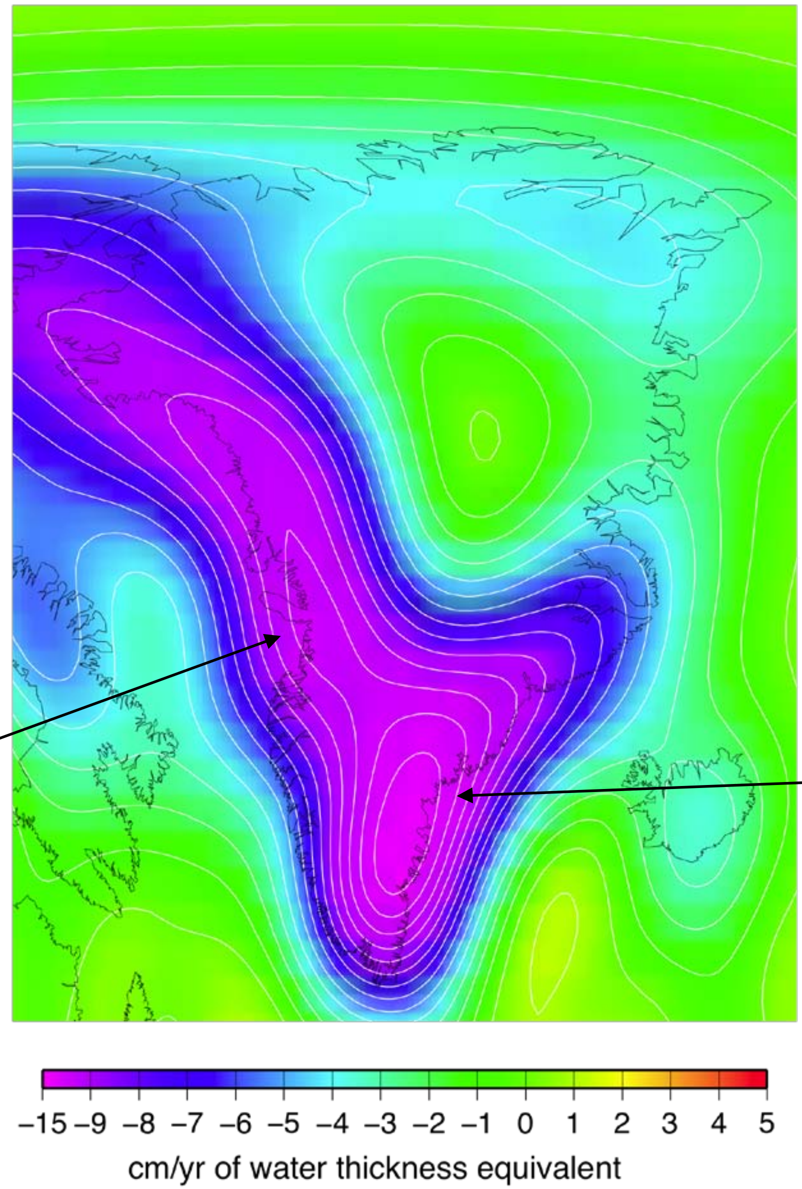




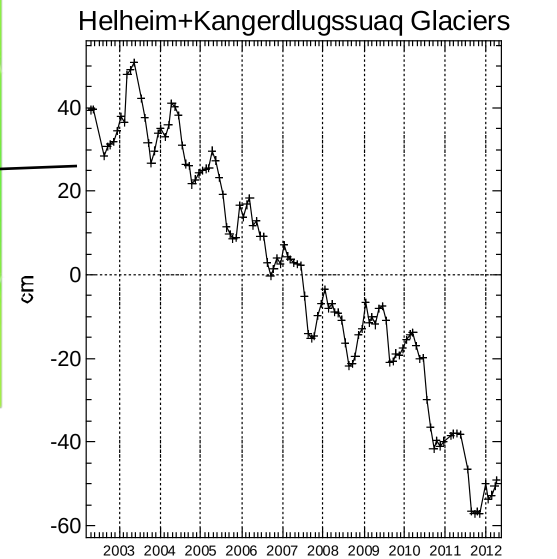
Rate of mass change between April 2002 and April 2012

GRACE results for Jakobshavn Glacier





Kangerdlugssuaq + Helheim Glaciers

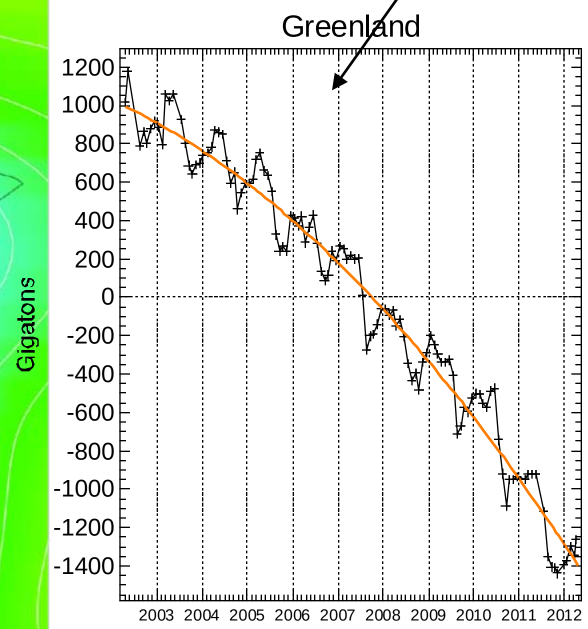


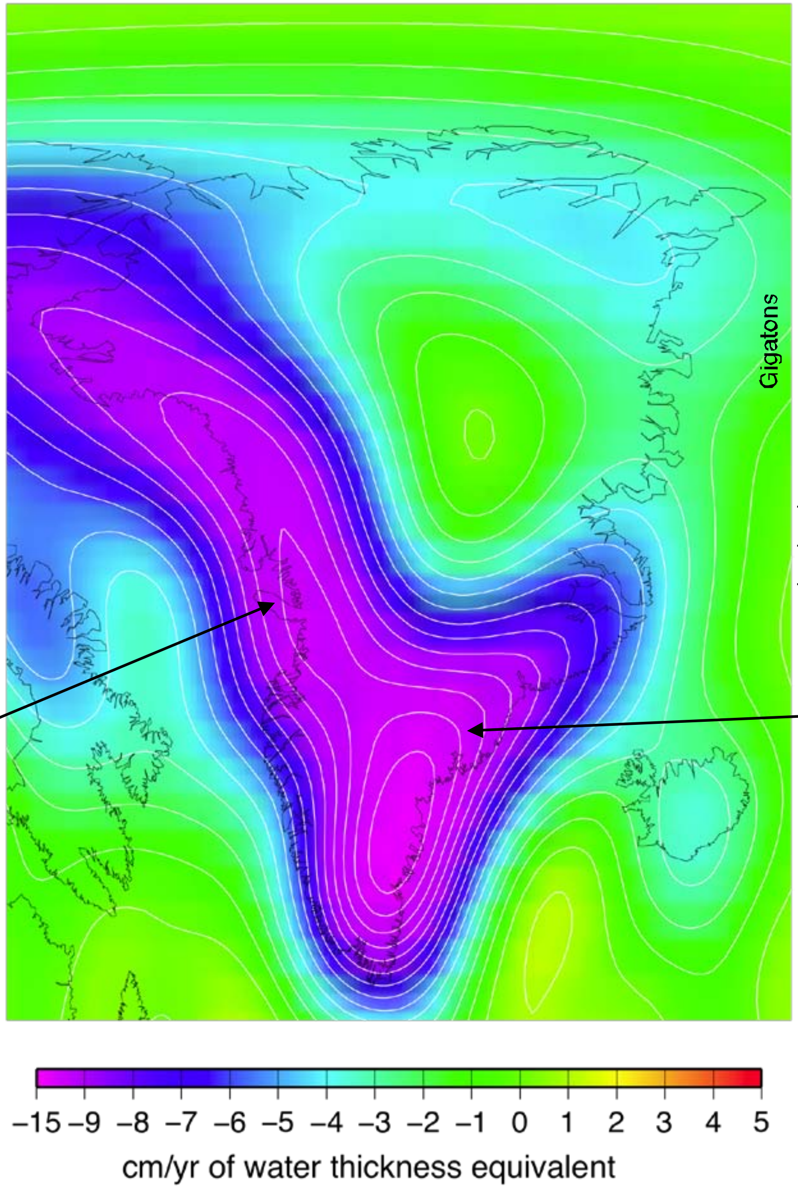
April 2002 - Apr 2012

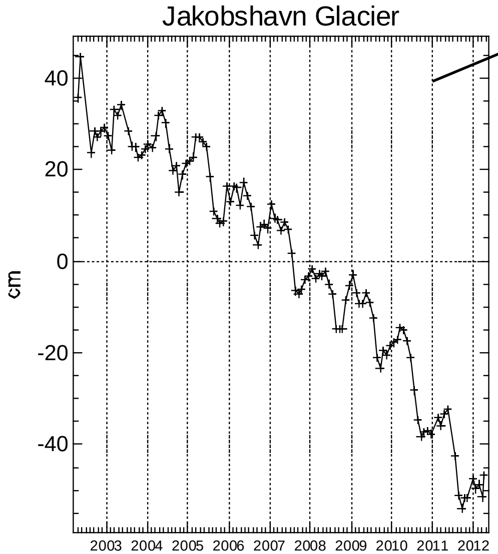
Rate of total Greenland mass change: -241 Gigatons/yr

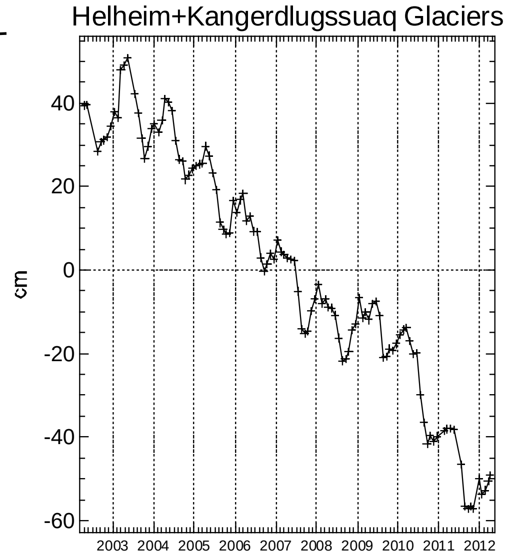
= 0.7 mm/yr sea level rise

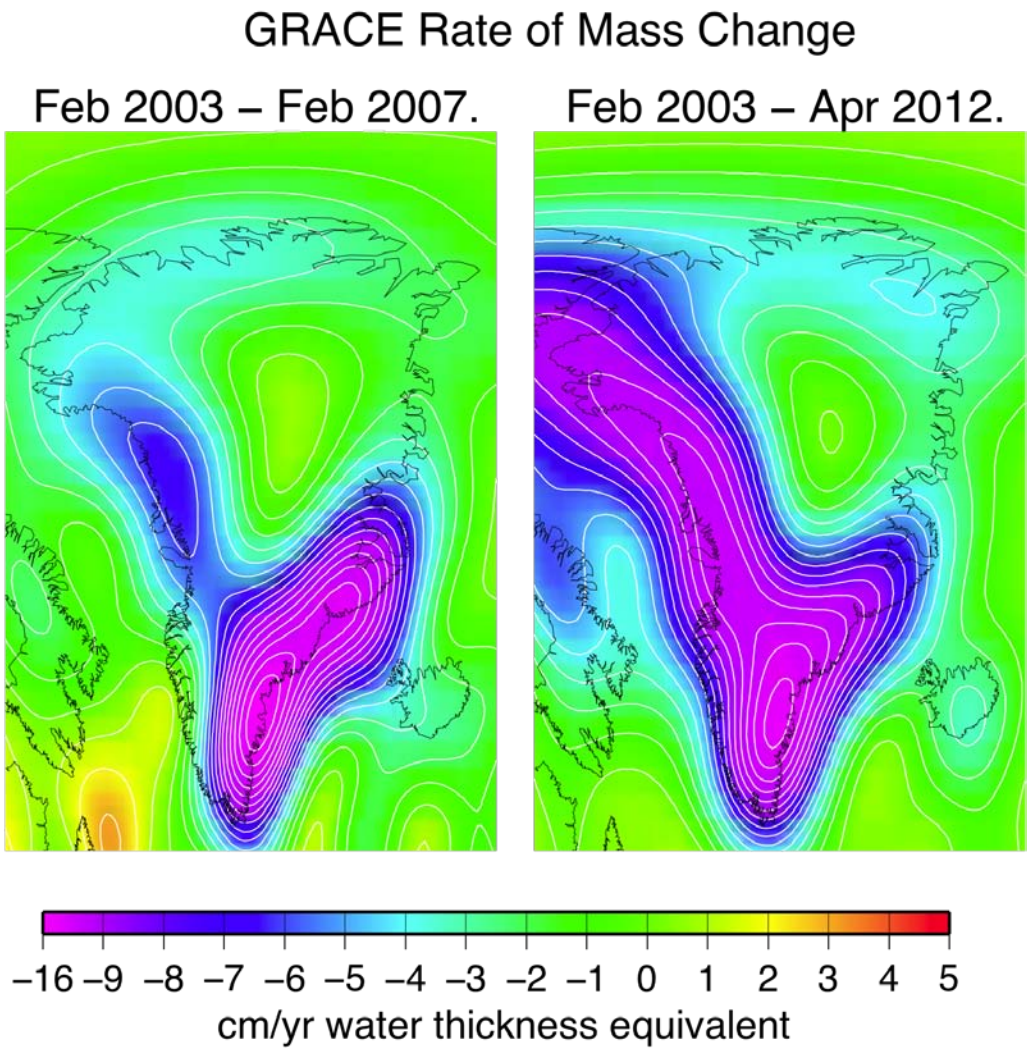
Total Greenland ice volume



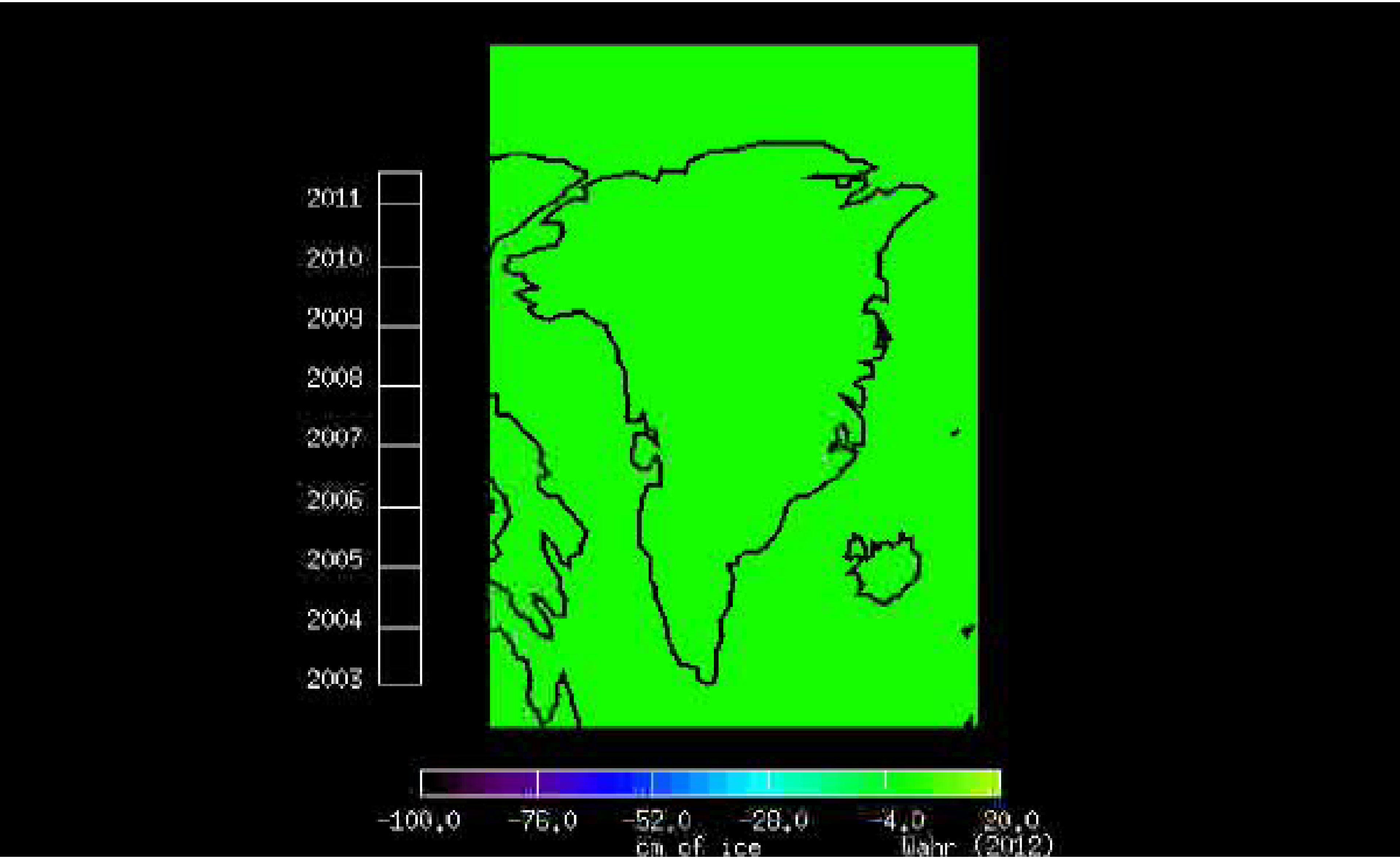








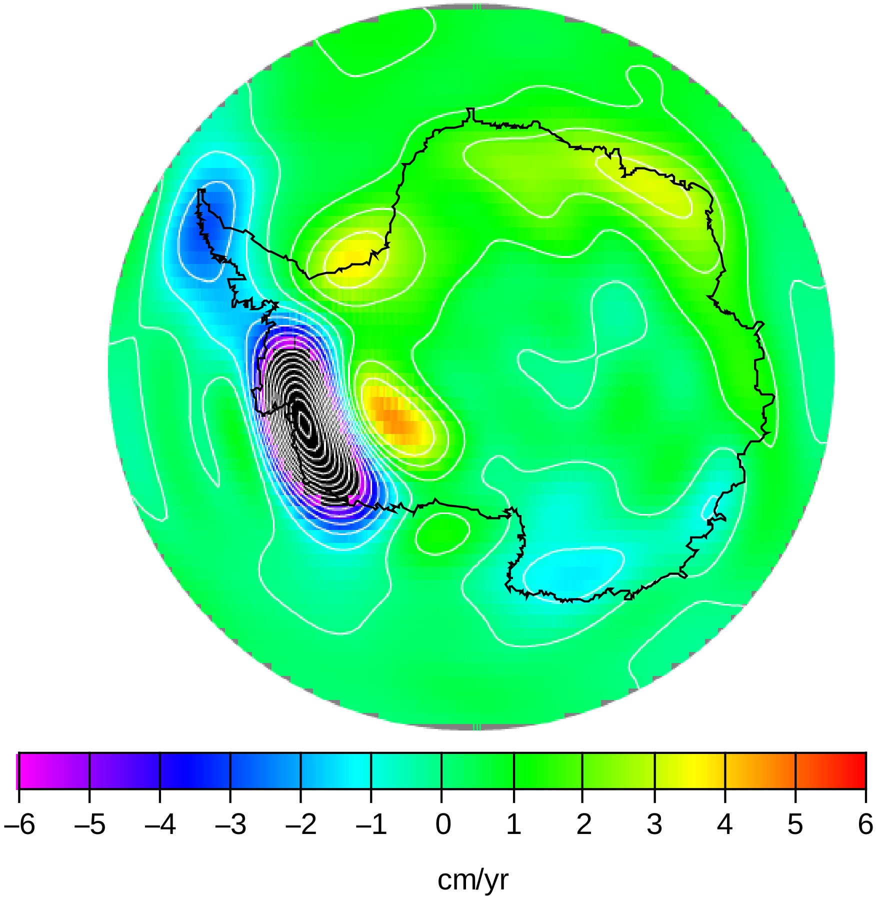
The mass loss has been spreading up the northwest coast the last few years.


2011
2010
2009
2008
2007
2006
2005
2004
2003
-100.0
-76.0
-52.0
-28.0
-4.0
20.0
cm of ice
Wahr (2012)

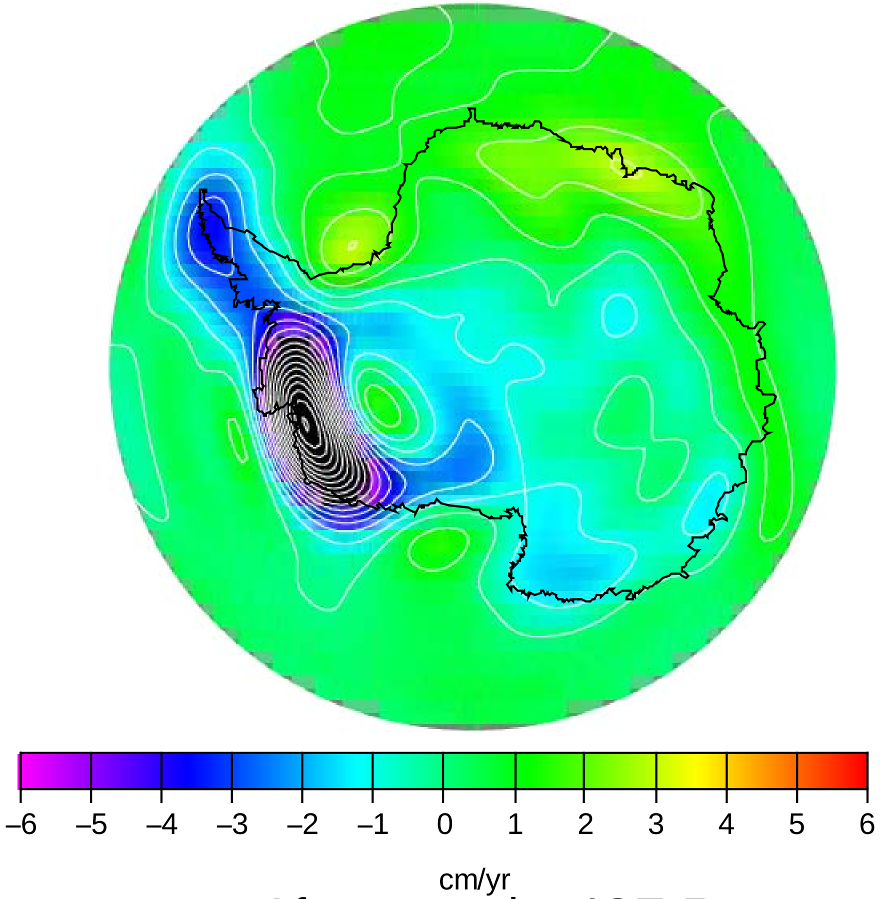
Antarctica

Antarctica

Rate of mass loss between April, 2002 and April, 2012.



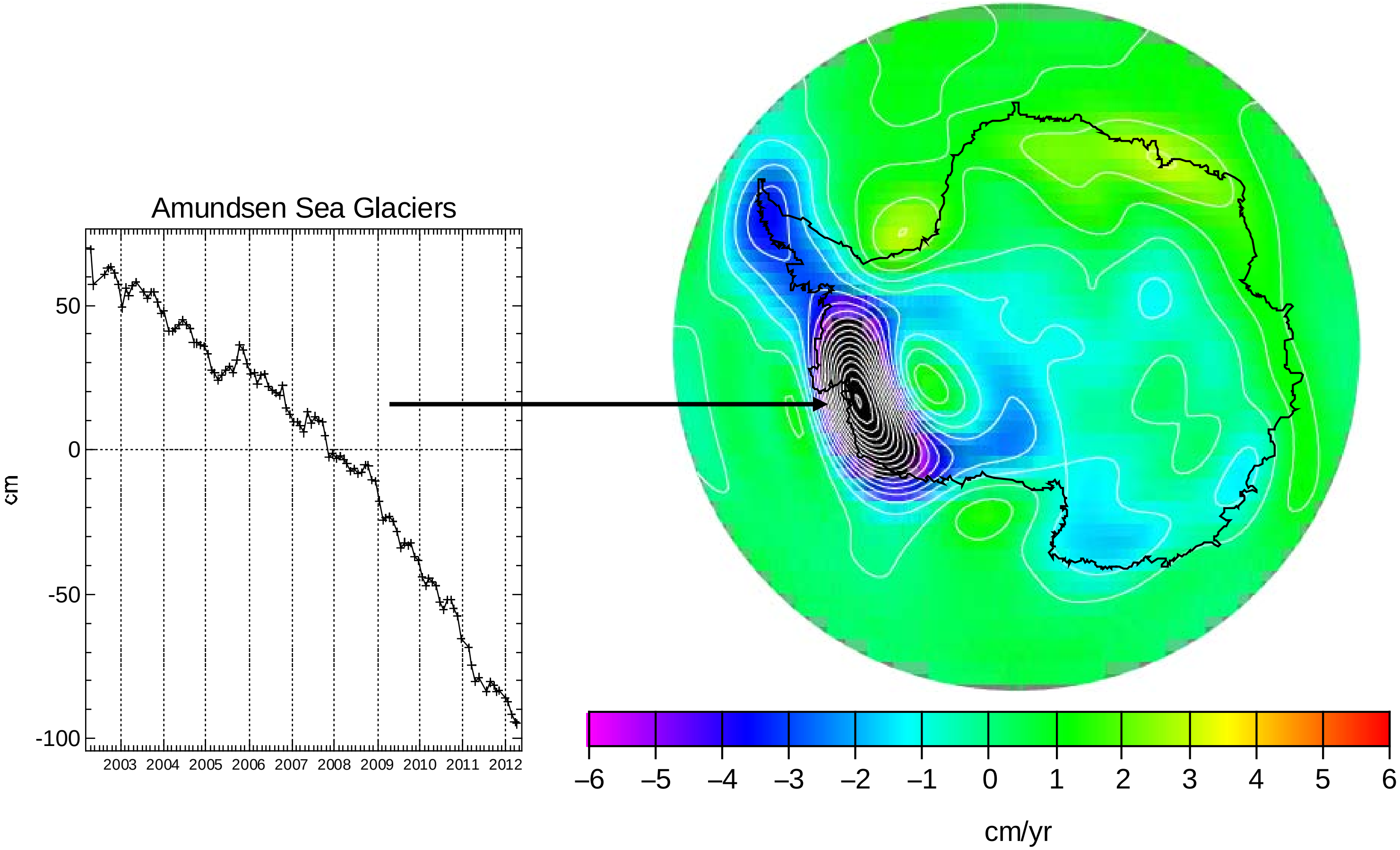
Before correcting for post-glacial-rebound.

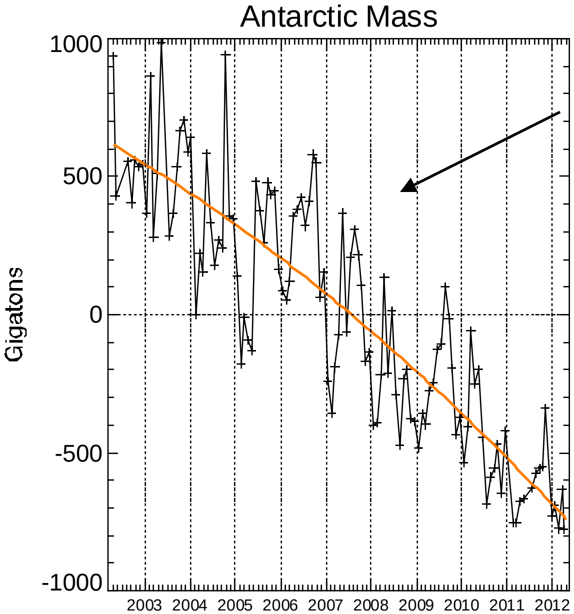


After removing ICE-5 post-glacial-rebound prediction.

Antarctica

Ice mass change between April, 2002 and April, 2012.





Total Antarctic ice mass.

(noisy because of atmospheric pressure errors)

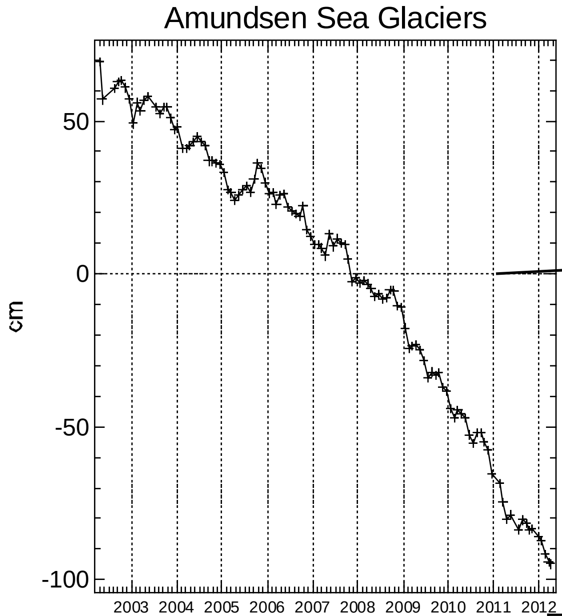
April, 2002 – April, 2012

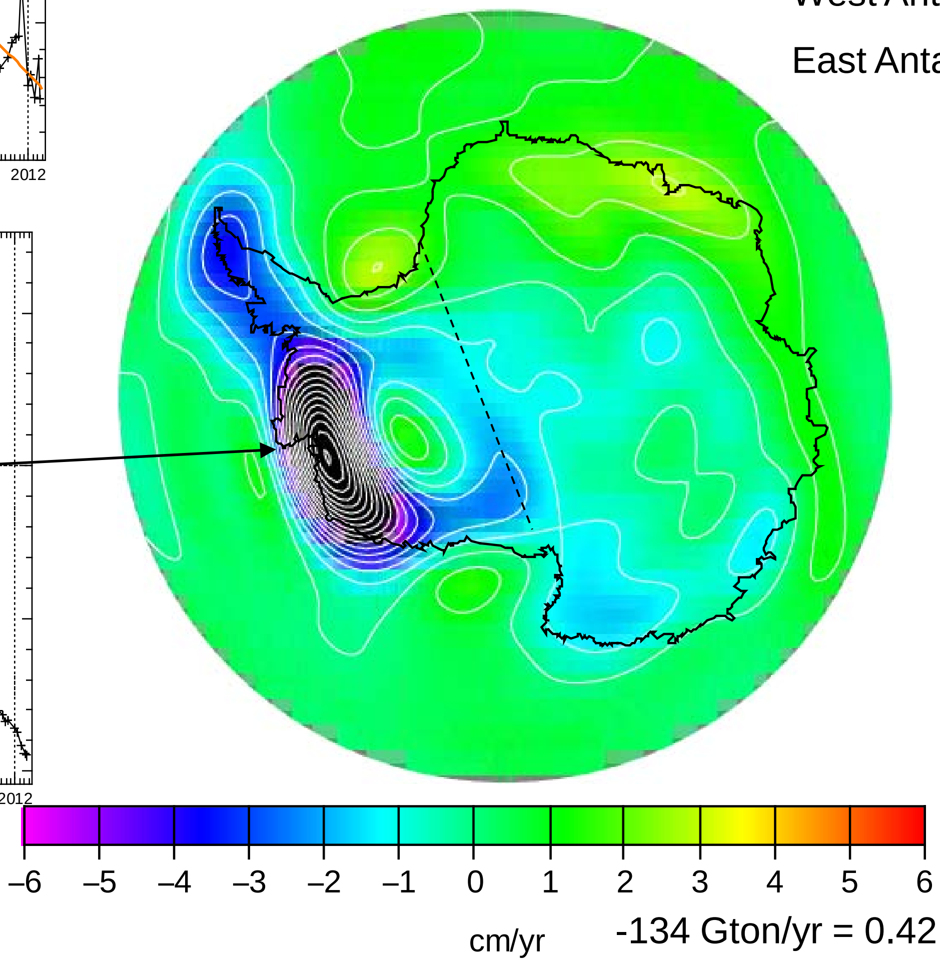
Rate of ice mass change:

All Antarctica: -134 Gton/yr

West Antarctica: -166 Gton//yr

East Antarctica: +40 Gton/yr



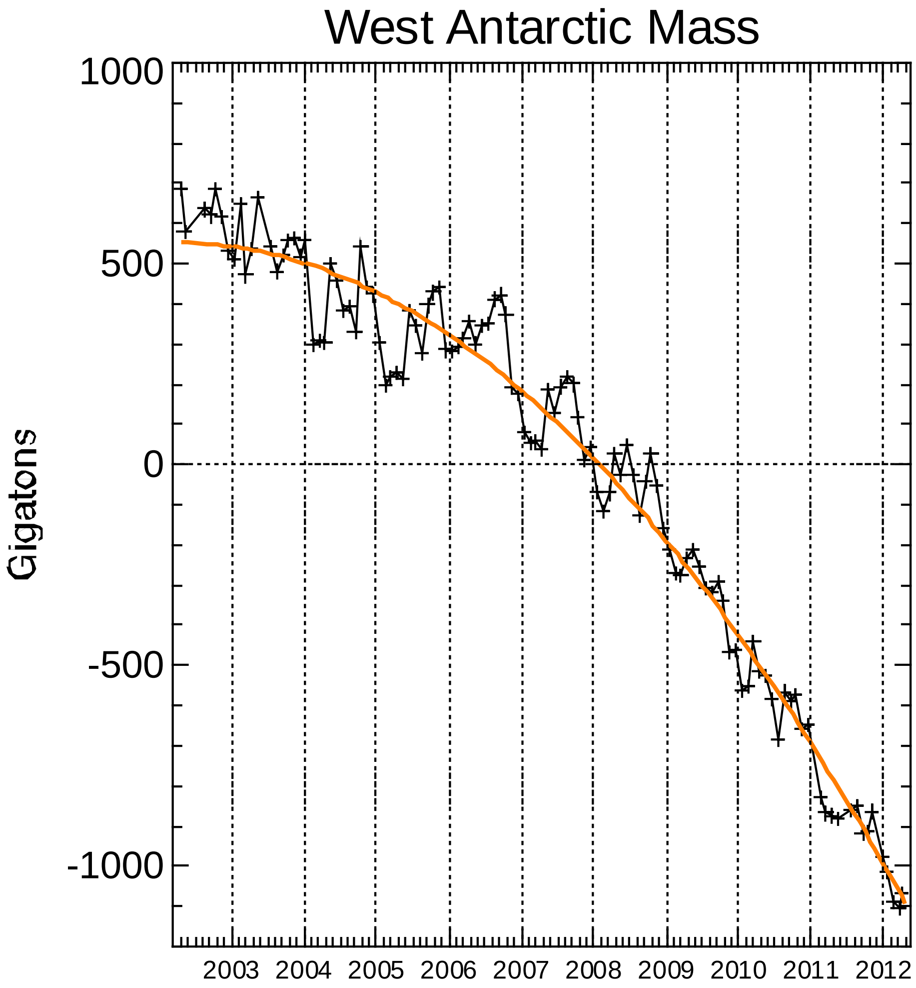


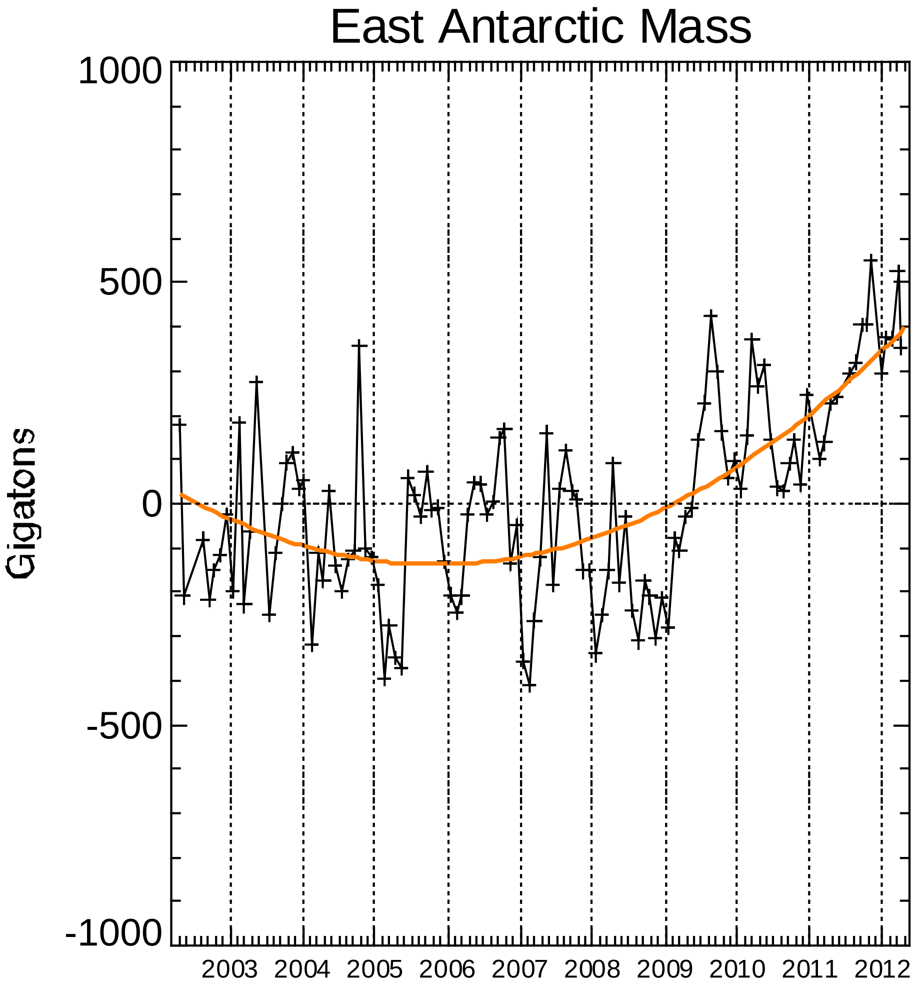
-134 Gton/yr = 0.42 mm/yr sea level rise

Is the Antarctic mass loss rate holding steady?

Orange: Best-fitting linear and quadratic terms.

Changes in mass loss rate are not affected by PGR errors.





The rate seems to be increasing.

The upward swing of the orange curve is due to increased snowfall.

A study of all the world's mountain glacier systems and ice caps, between Jan, 2003 and December, 2010 (Jacob et al, 2012)

(1)Overlay all ice-covered areas with small regions ("mascons"). Solve for monthly mass variability of each area by fitting the mascons to the GRACE data.

(2) Before fitting, remove hydrology and post-glacial-rebound models from GRACE:

Hydrology models:

(A) GLDAS/Noah (Rodell et al, 2004). (B) CLM4 (Oleson et al, 2010)

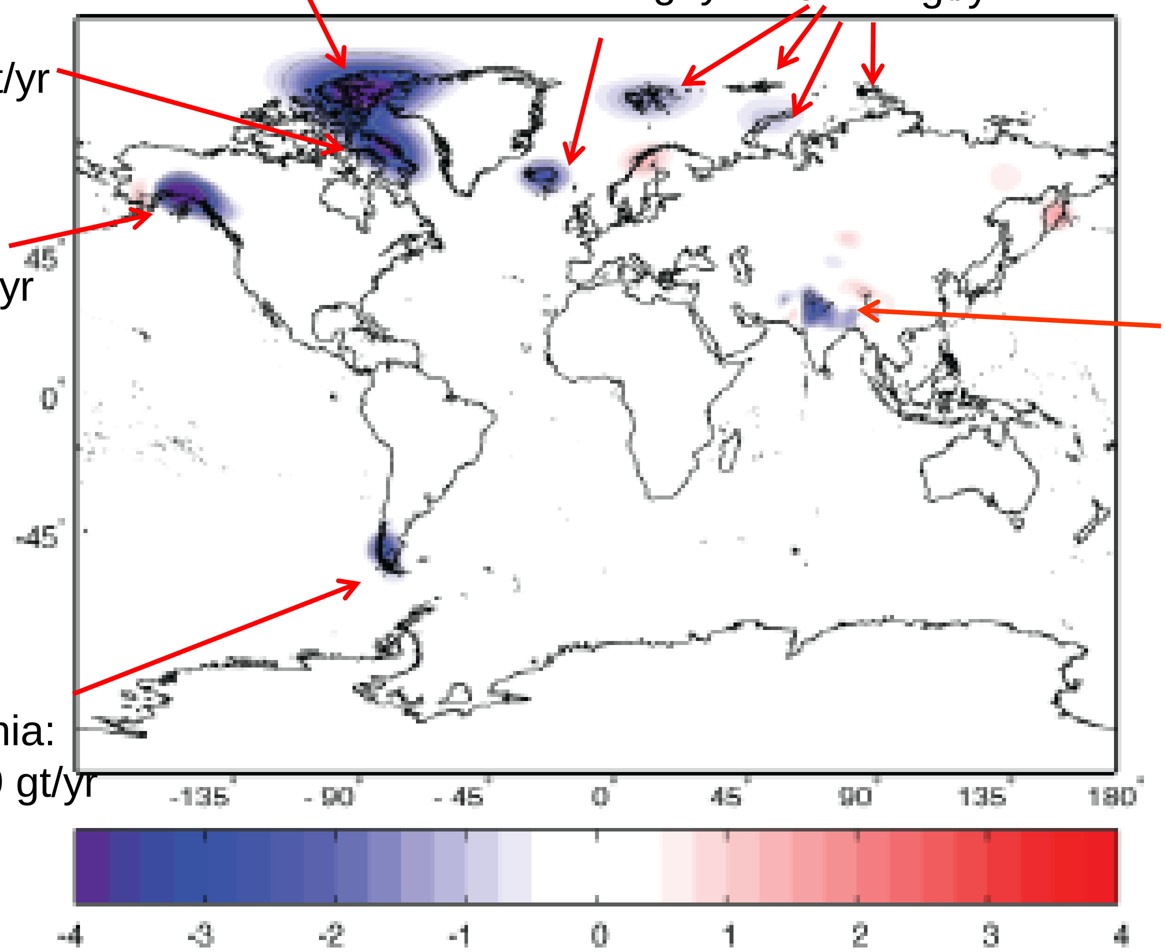
Post-glacial-rebound model: from Geruo A (based on Peltier's (2004) ICE5G deglaciation history and VM2 viscosity profile).

Total uncertainty estimate: Sum (in quadrature) the following:

Measurement error: ± 2-σ of scatter in time series

Hydrology error: ± |difference between the 2 hydrology models|

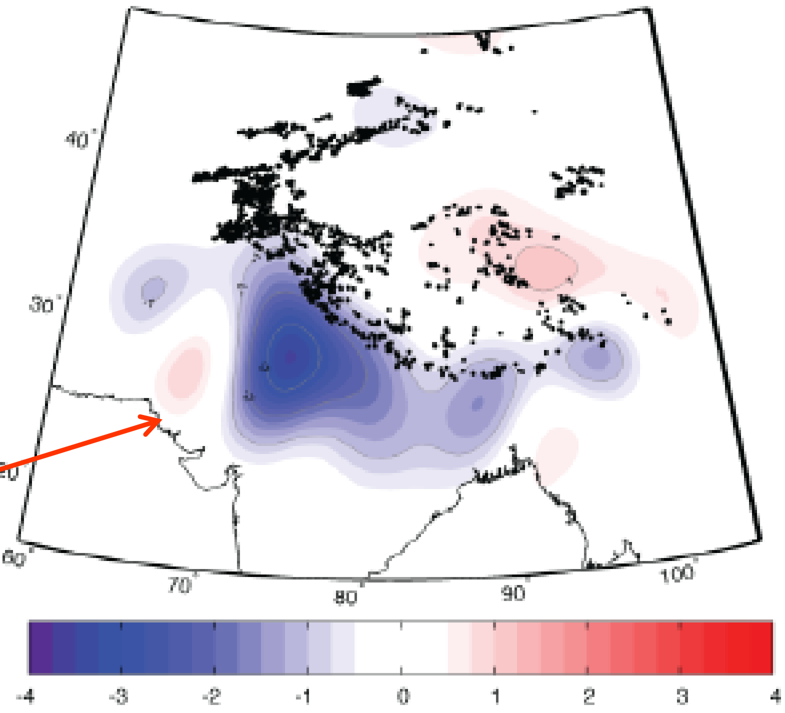
Rebound error: ± ½ |rebound correction|



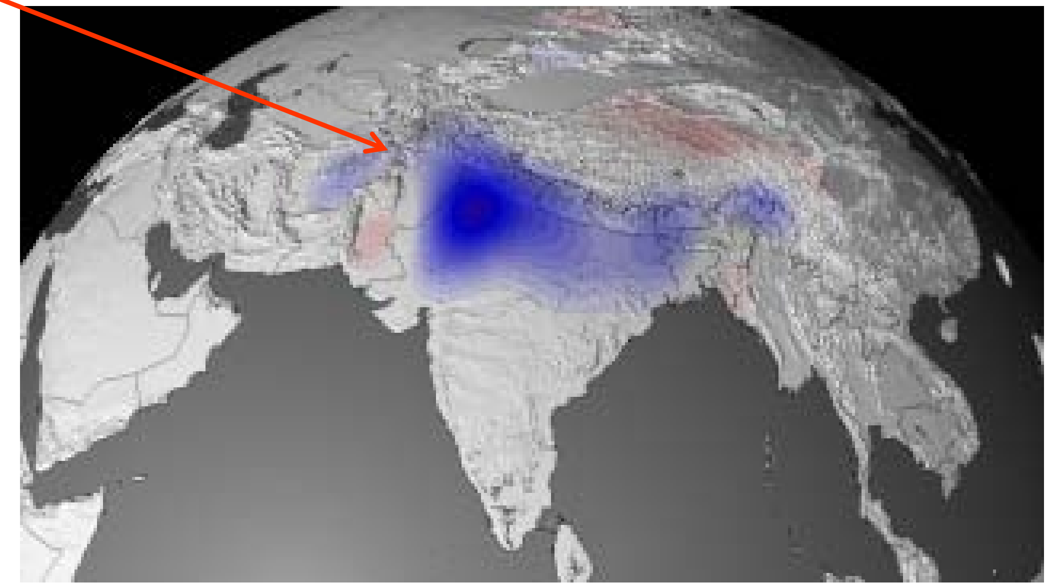
Average Mass Loss Rates During Jan, 2003 – Dec, 2010.

For comparison: Greenland = -222 ± 9 gt/yr, Antarctica = -165 ± 72 gt/yr

The mass loss is concentrated south of the glaciers,

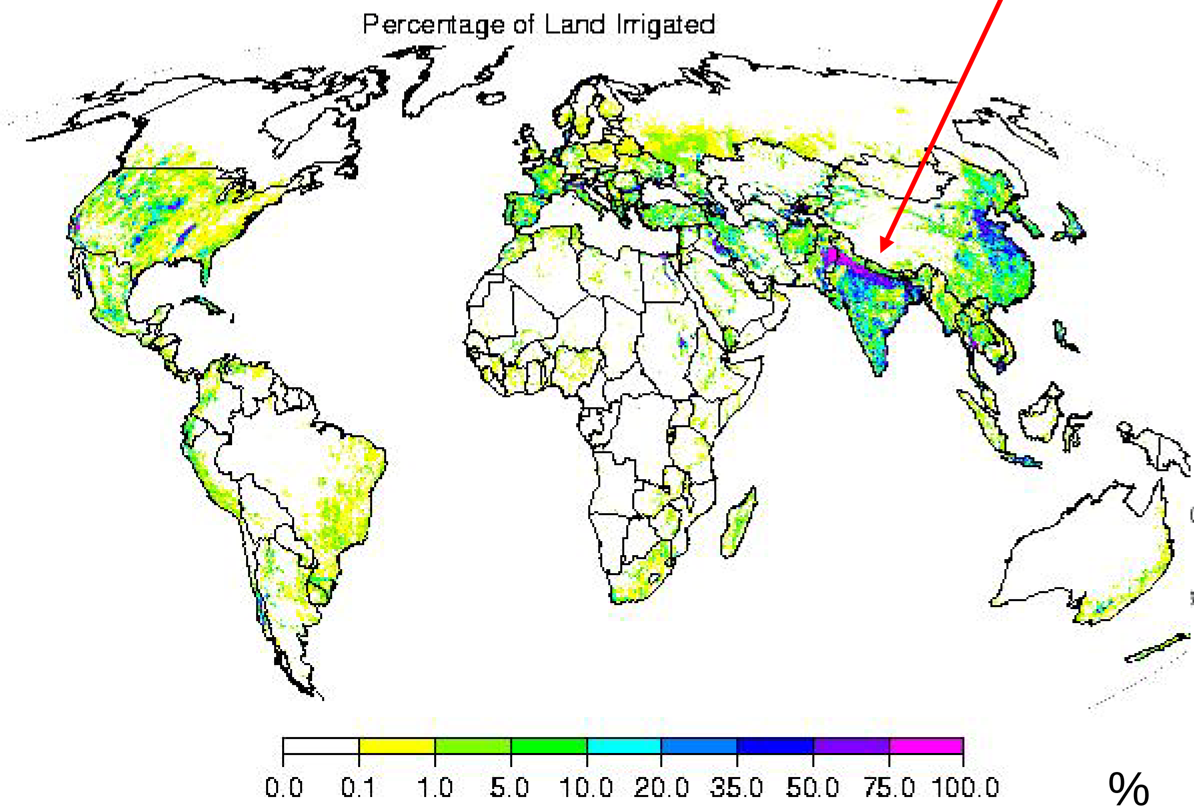


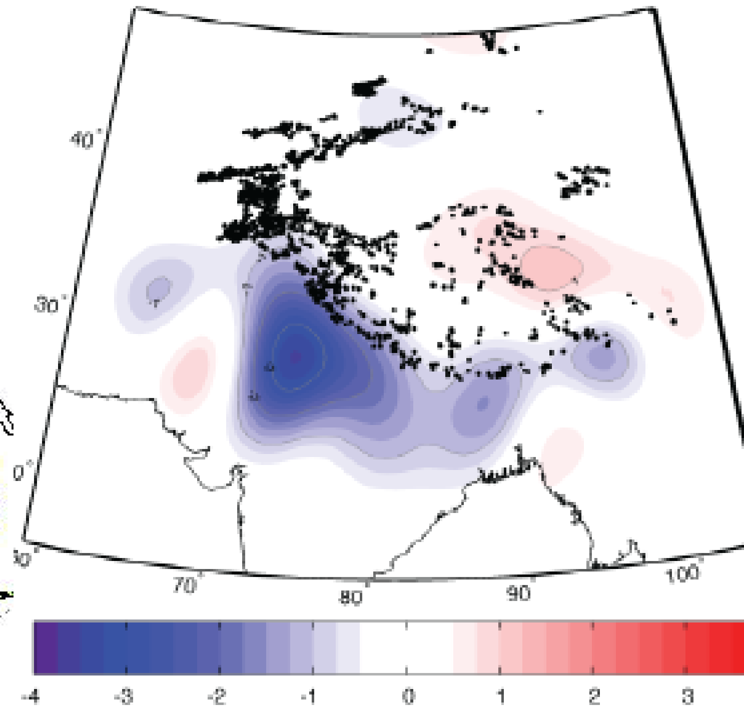
and even south of the mountains.



Anthropogenic groundwater depletion (Rodell et al, 2009; Tiwari et al, 2009).

Northern India, Bangladesh, and Pakistan is the most heavily irrigated region on earth.



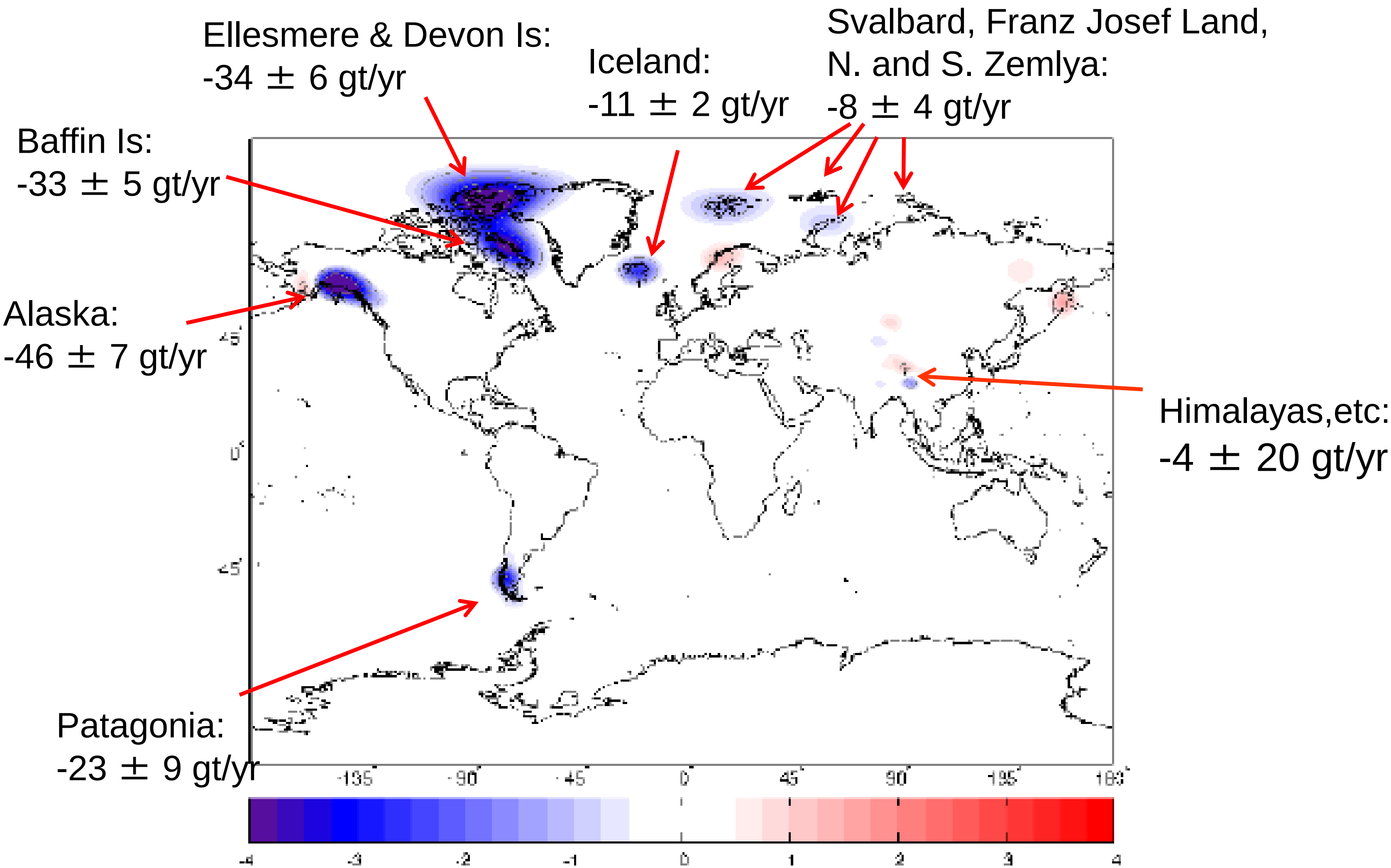


Data from the Food And Agriculture
Organizations of the United Nations

We obtain, for all the HMA glaciers: trend = -4 ± 20 gt/yr (for 2003-2010).

[The plains groundwater trend is –35 ± 21 gt/yr.]

The large uncertainty comes mostly from the uncertainty in the hydrology correction.



Average Mass Loss Rates During Jan, 2003 – Dec, 2010

For comparison: Greenland = -222 ± 9 gt/yr, Antarctica = -165 ± 72 gt/yr

Summary of Ice Results

Between January 2003 and December 2010:

All mountain glacier systems and ice caps: -148 ± 30 gt/yr.

Greenland: -222 ± 9 gt/yr.

Antarctica: -165 ± 72 gt/yr.

Total: -536 ± 93 gt/yr, equivalent to 1.5 mm/yr sea level rise (~1/2 the observed rate of sea level rise during the past decade).

536 gt/yr × 8 yrs = 4288 gt would cover the entire US with 1.5 ft of water

The Future

- GRACE lifetime expected to run at least through 2015-2016.

- NASA and DLR (German space agency) have approved a GRACE follow-on mission, for launch in 2017.

The End