Détermination des variations de masse en surface par la géodésie spatiale

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(UMR 7516 CNRS/Univ. de Strasbourg)

Mass variations from space geodesy

Introduction
  - Gravity Recovery And Climate Experiment (GRACE)
  - Global hydrology models

Ice-sheet mass balance

Continental hydrology
  - Groundwater
  - Surface water
  - Assimilation of GRACE in hydrology models

Hydrology from GPS measurements
  - Multi-paths
  - Deformation

Conclusion and Perspectives

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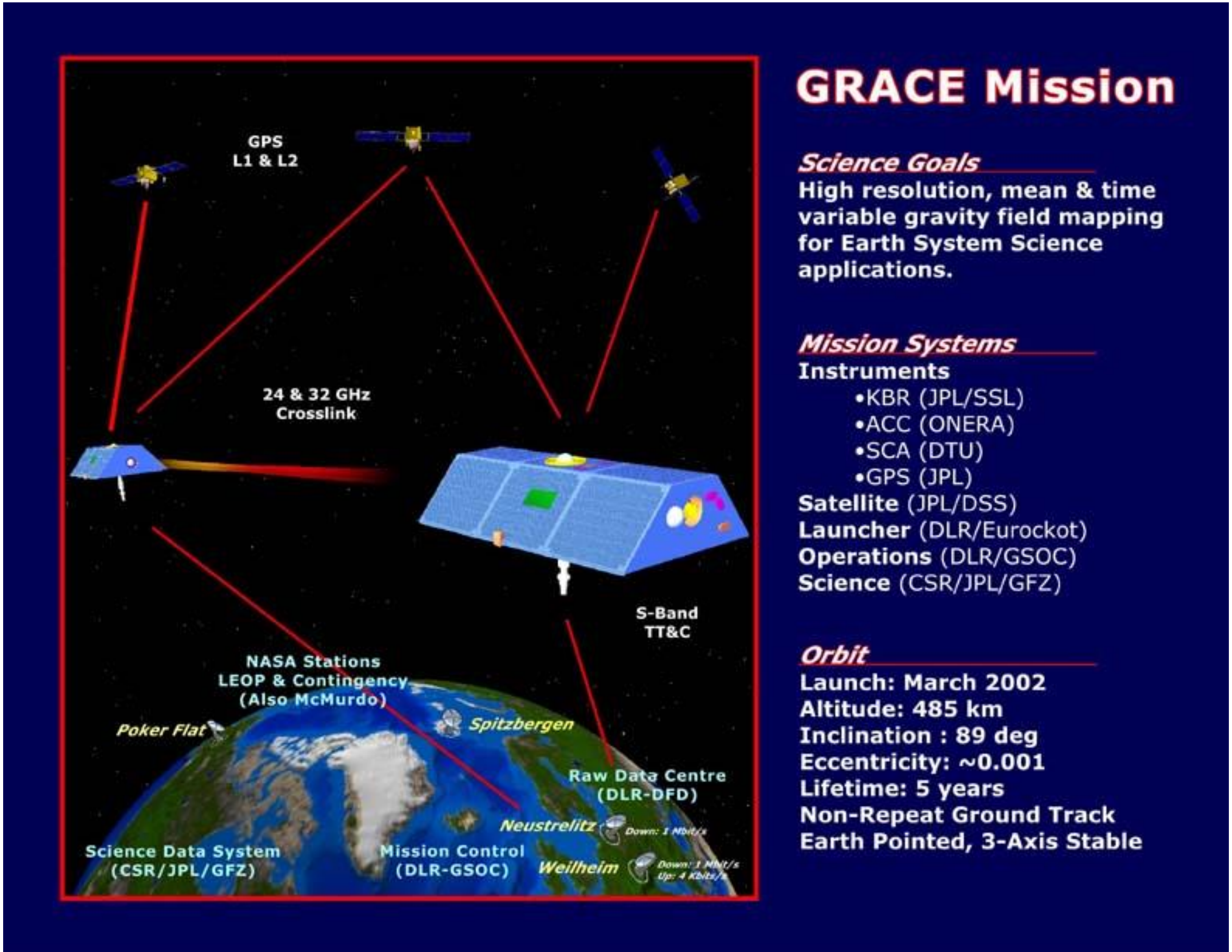
Gravity Recovery And Climate Experiment



GRACE Mission

Science Goals

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

Mission Systems

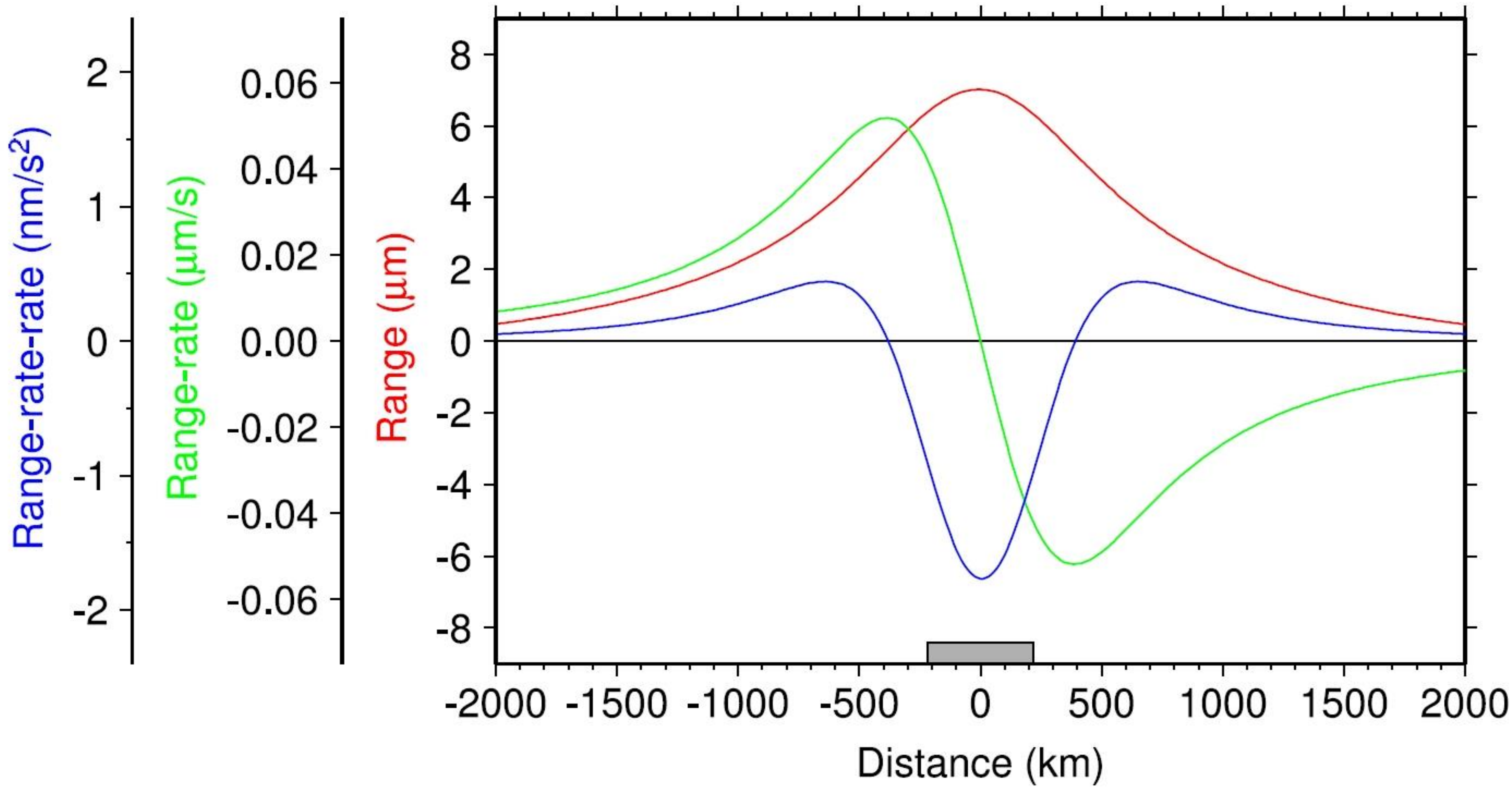
Instruments
- KBR (JPL/SSL)
- ACC (ONERA)
- SCA (DTU)
- GPS (JPL)

Satellite (JPL/DSS)
Launcher (DLR/Eurockot)
Operations (DLR/GSOC)
Science (CSR/JPL/GFZ)

Orbit

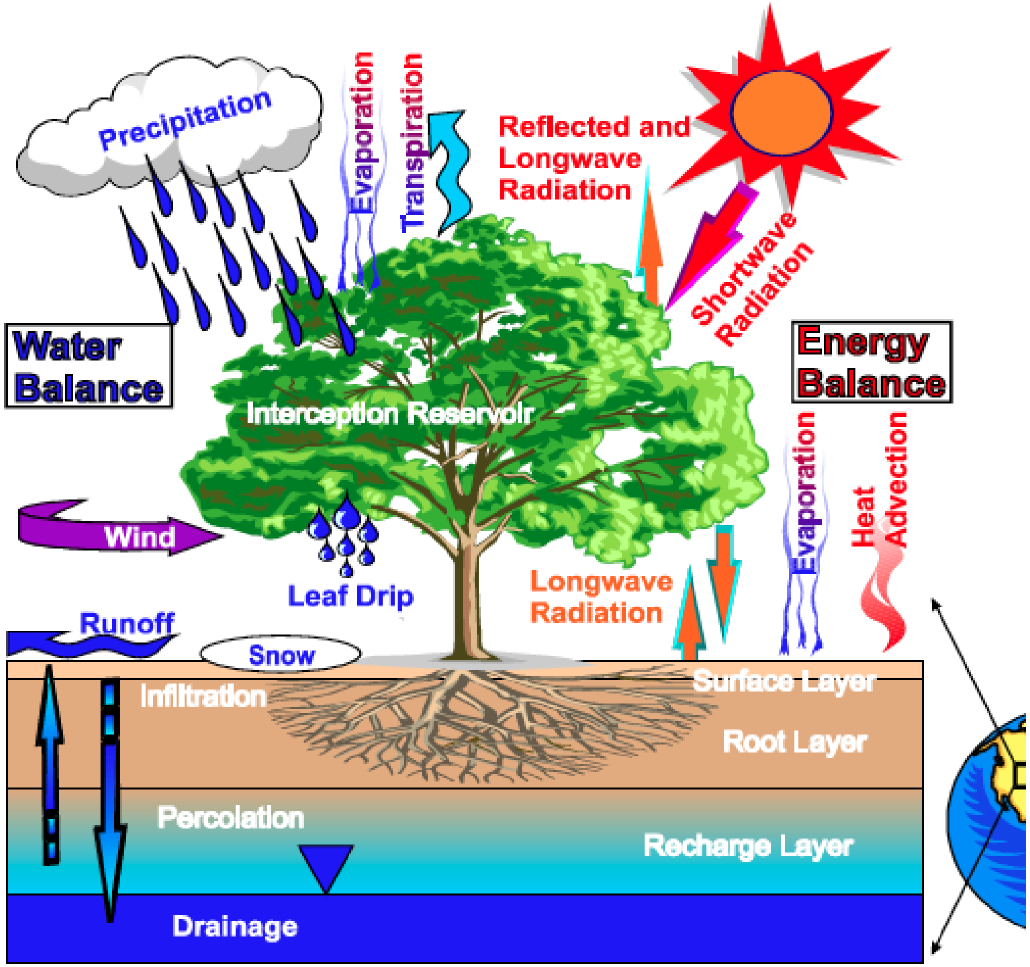
Launch: March 2002
Altitude: 485 km
Inclination : 89 deg
Eccentricity: ~0.001
Lifetime: 5 years
Non-Repeat Ground Track
Earth Pointed, 3-Axis Stable

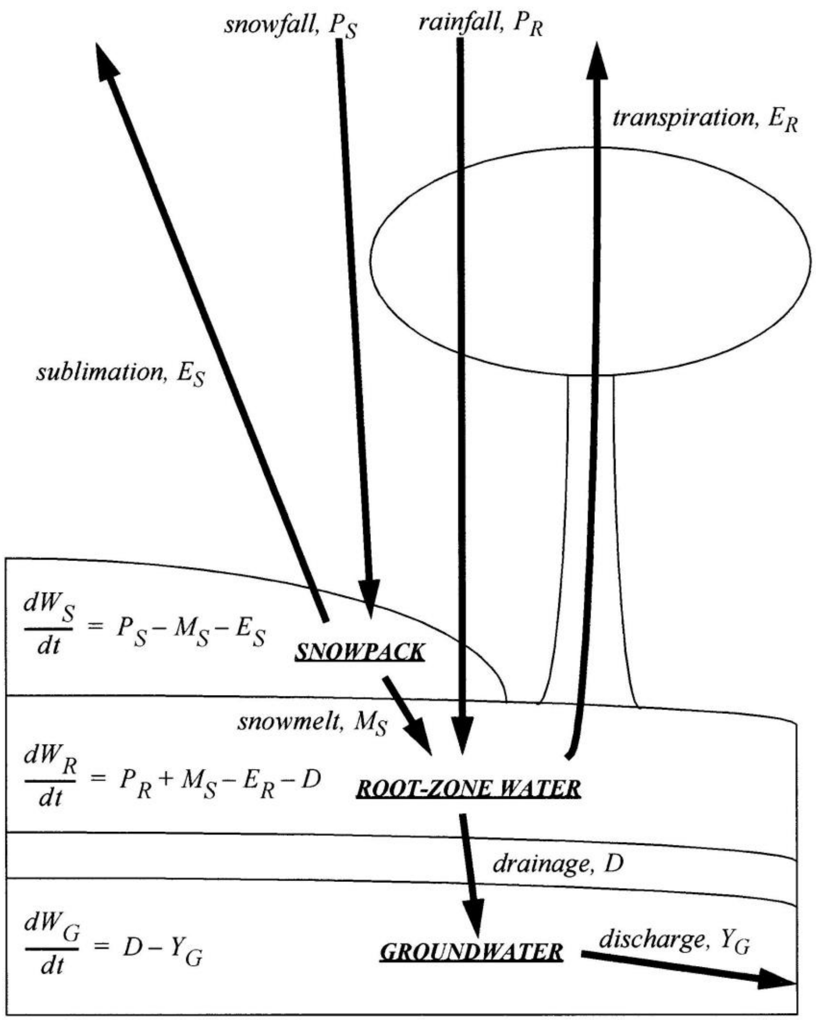
Simulation of an overflight of a 4x4 degree block with 10-cm eq. water height at the equator



from Ray et al., JGR, 2009.

General principals of global hydrology models





$$\frac{\partial W}{\partial t} = \left(P - E\right) - Y$$

from Milly & Shmakin, 2002.

From orbitography to mass changes

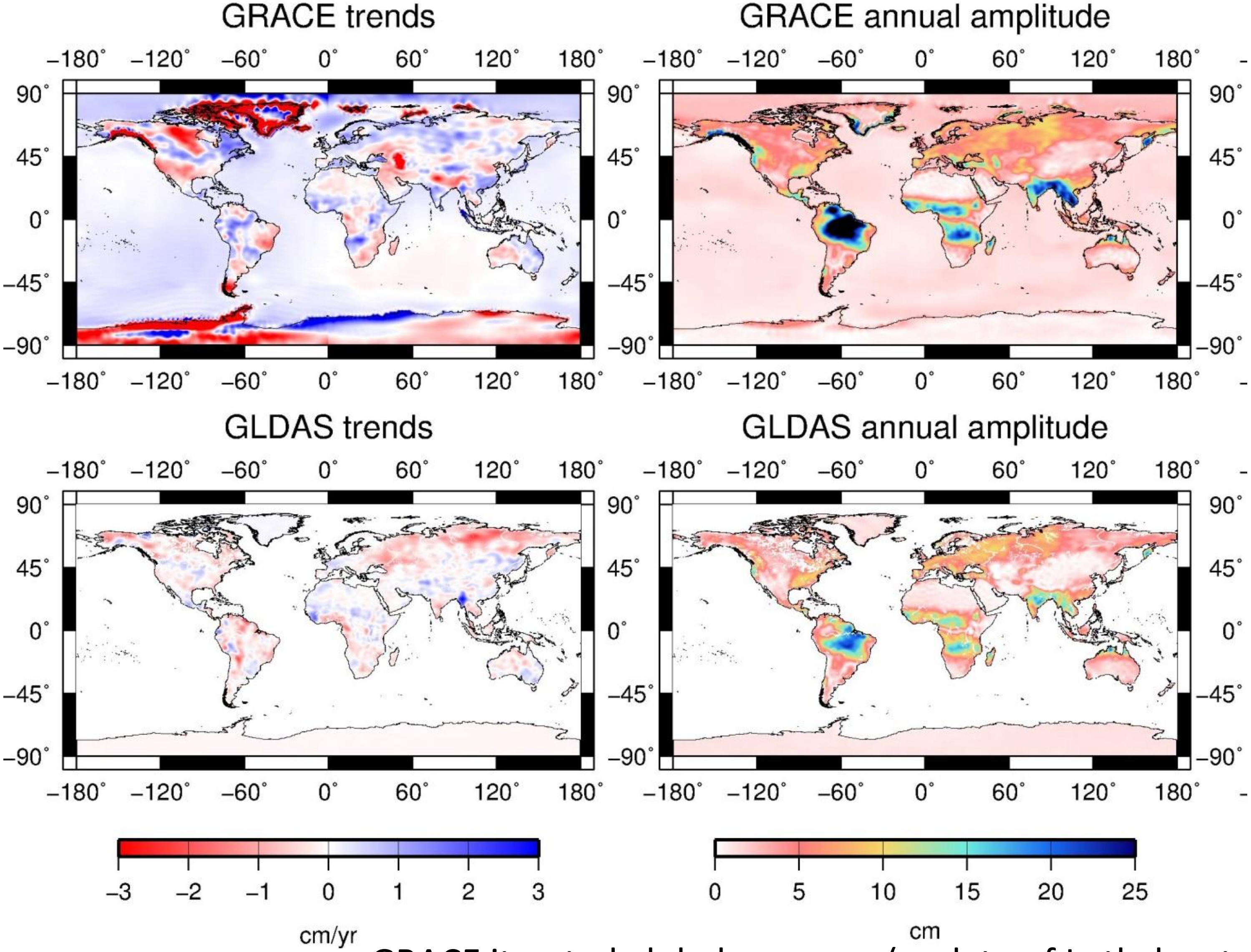
$$V(r,\theta,\lambda)=\frac{GM}{r}\left(1+\sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^{n}\sum_{m=0}^{n}P_n^m\left(\cos\theta\right)\left(C_n^m\cos m\lambda+S_n^m\sin\lambda\right)\right)$$

$$h(r,\theta,\lambda)=\frac{a\rho_E}{3\rho_W}\sum_{n=0}^{\infty}\frac{2n+1}{1+k'_n}\sum_{m=0}^{n}P_n^m\left(\cos\theta\right)\left(C_n^m\cos m\lambda+S_n^m\sin\lambda\right)$$

GRACE “measures” the total water storage at the Earth’s surface (if other effects, such as GIA, are corrected).

The separation between all storage (surface water, snow, soil-moisture, groundwater, etc.) can only be done with the help of other space or ground observations or models.

GRACE trends & annual variations compared to GLDAS/Noah global hydrology model



GRACE iterated global mascons (update of Luthcke et al., 2013).

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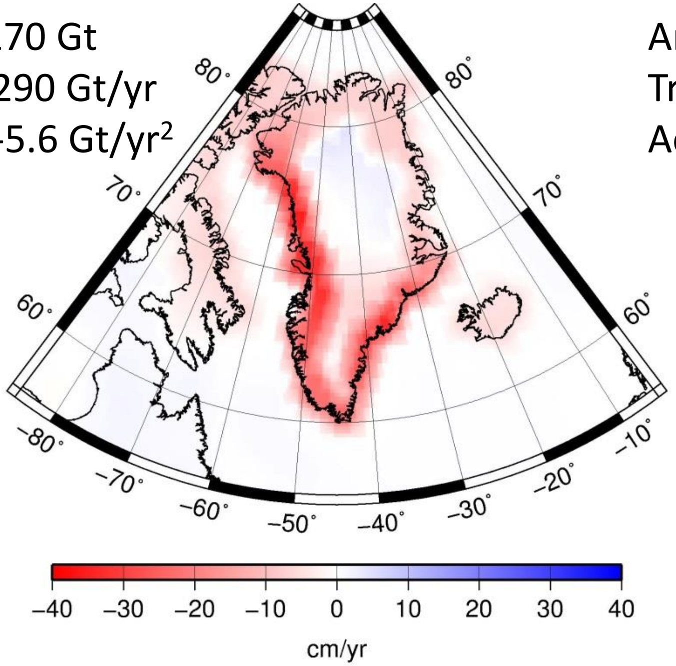
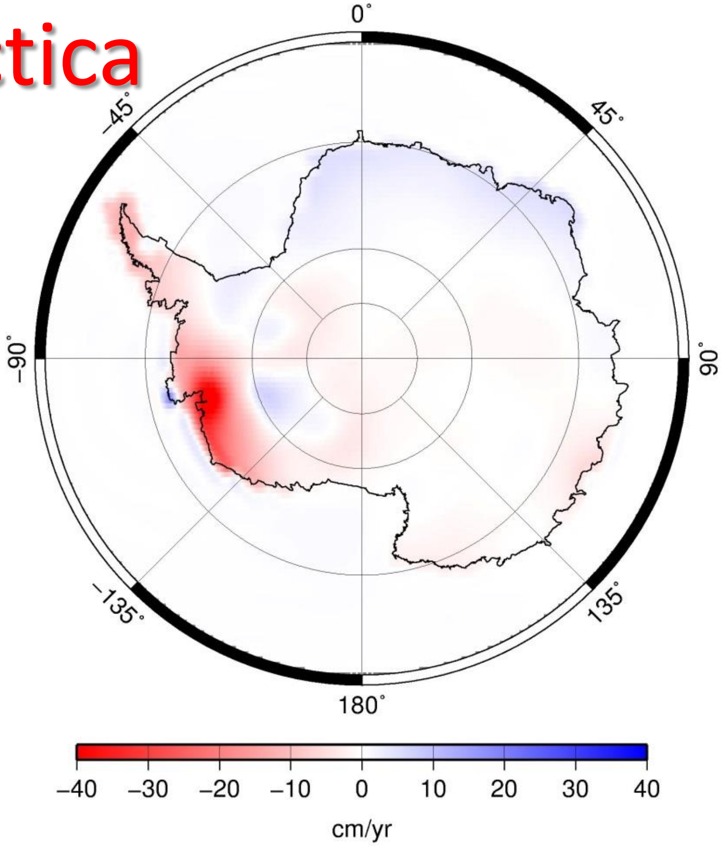
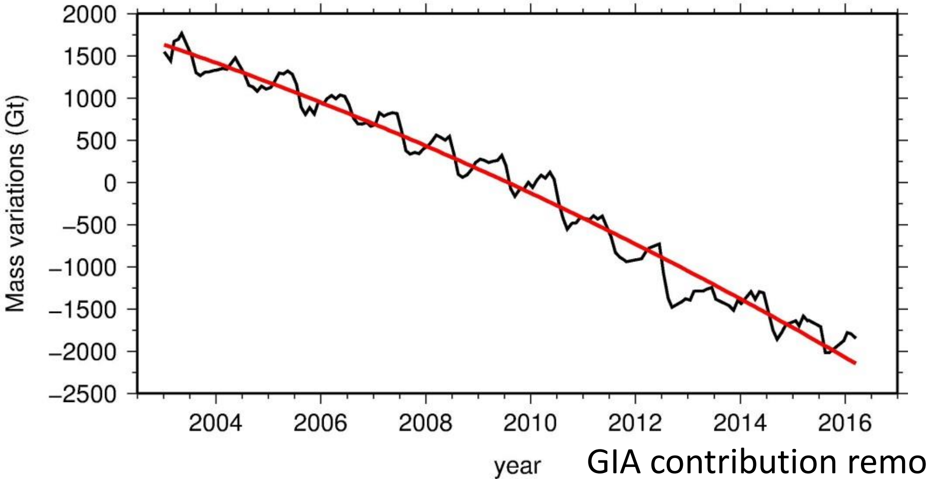
Greenland and Antarctica

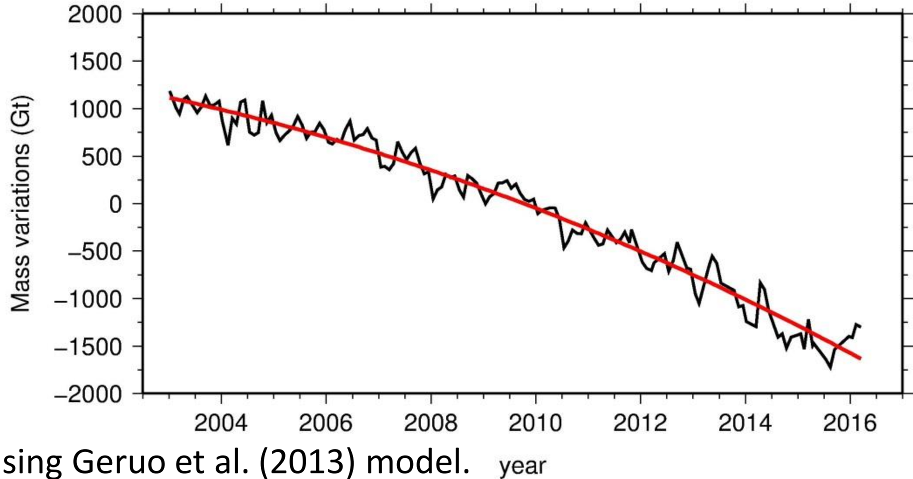
Annual: 170 Gt
Trend: -290 Gt/yr
Accel.: -5.6 Gt/yr^2



Annual: 39.9 Gt
Trend: -213 Gt/yr
Accel.: -6.7 Gt/yr^2

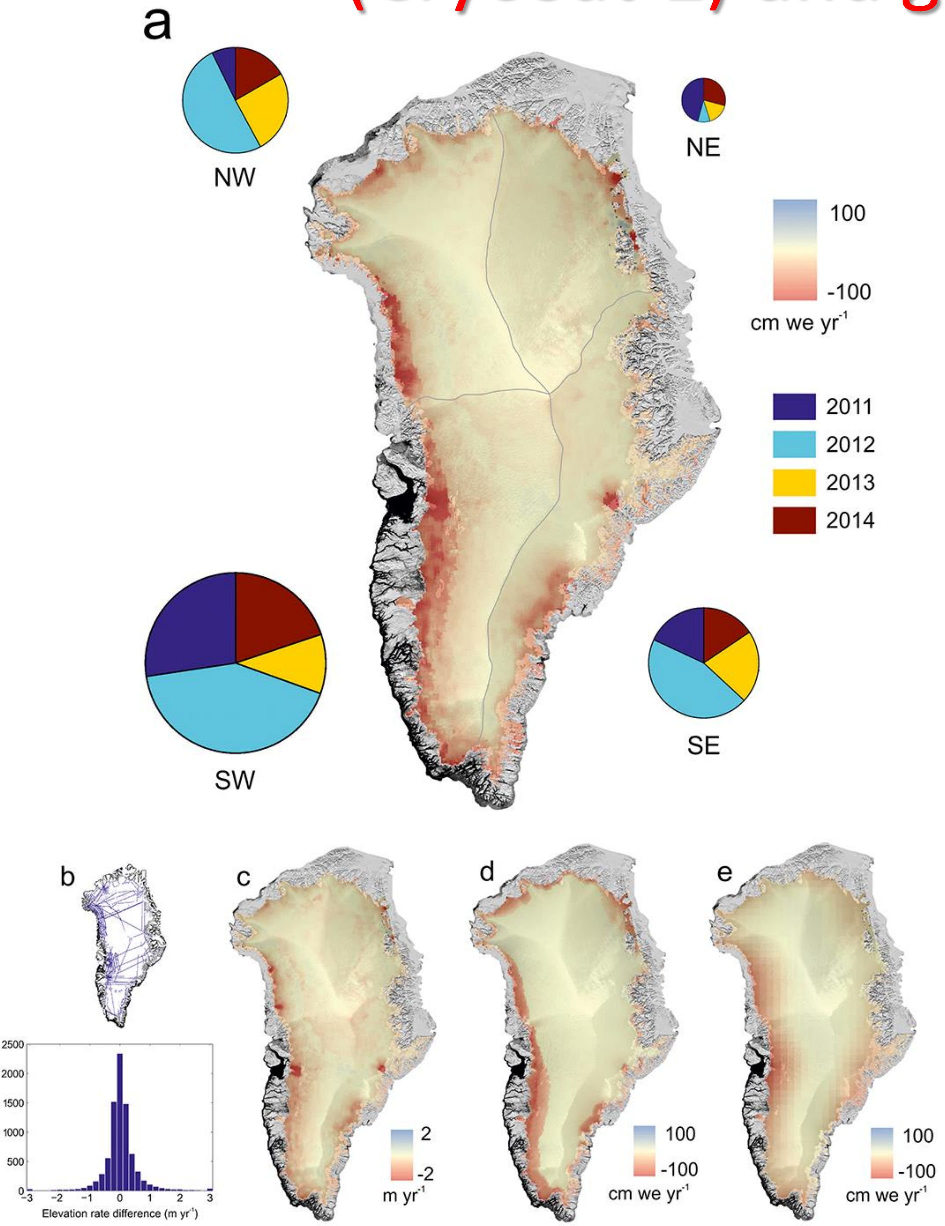






GIA contribution removed using Geruo et al. (2013) model.

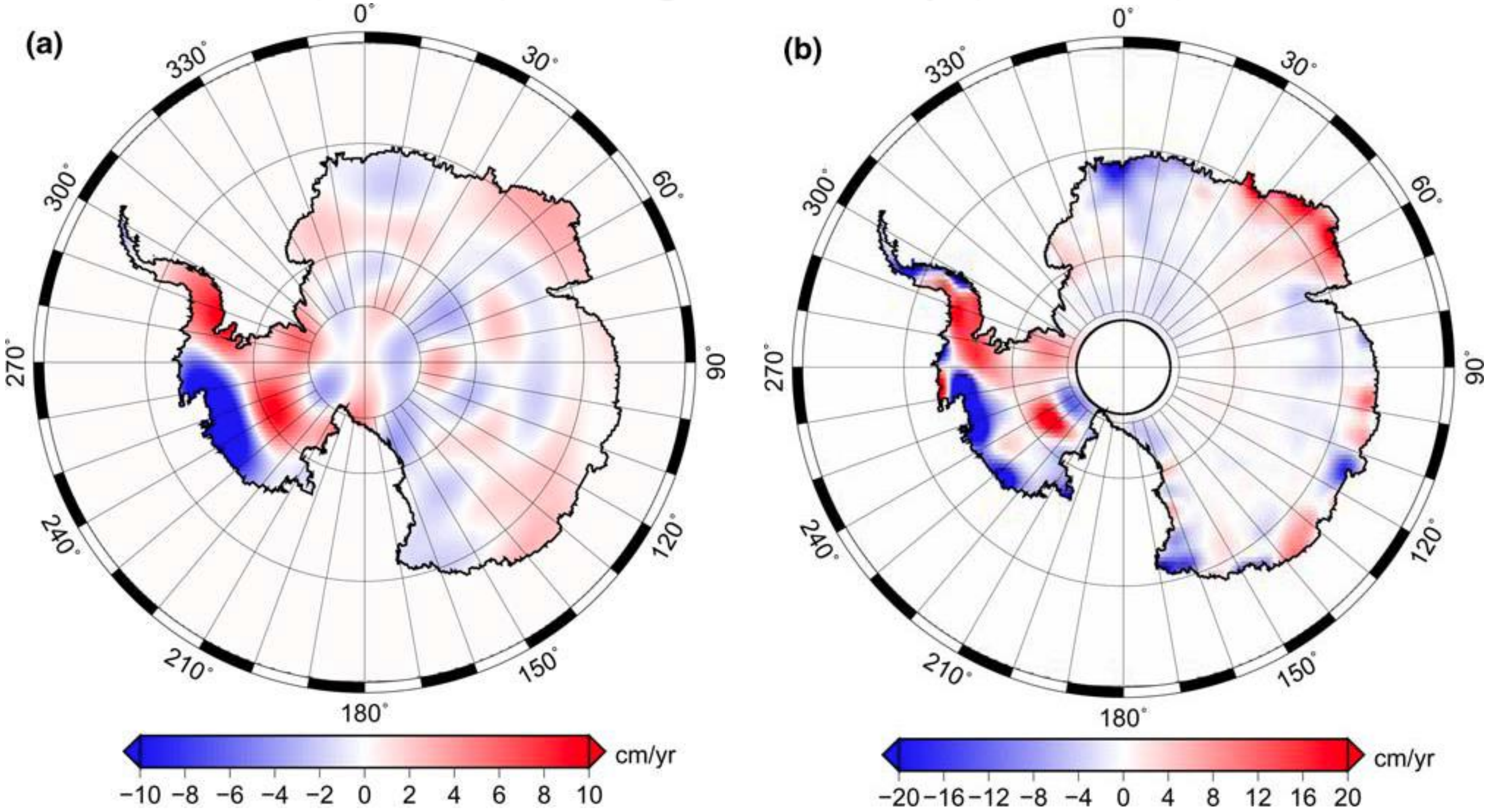
Comparison between altimetry (CryoSat-2) and gravimetry (GRACE)



(a) Rate of mass change from 2011/01 and 2014/12 from CryoSat-2 and firn modeling.
(b) IceBridge airborne altimetry ground tracks.
(c) Rate of elevation change from 2011 and 2014 from CryoSat-2 radar altimetry.
(d) Simulated 2011–2014 rate of mass change from RACMO2.3.
(e) Rate of mass change between 2011 and 2014 from GRACE.

from McMillan et al., 2016.

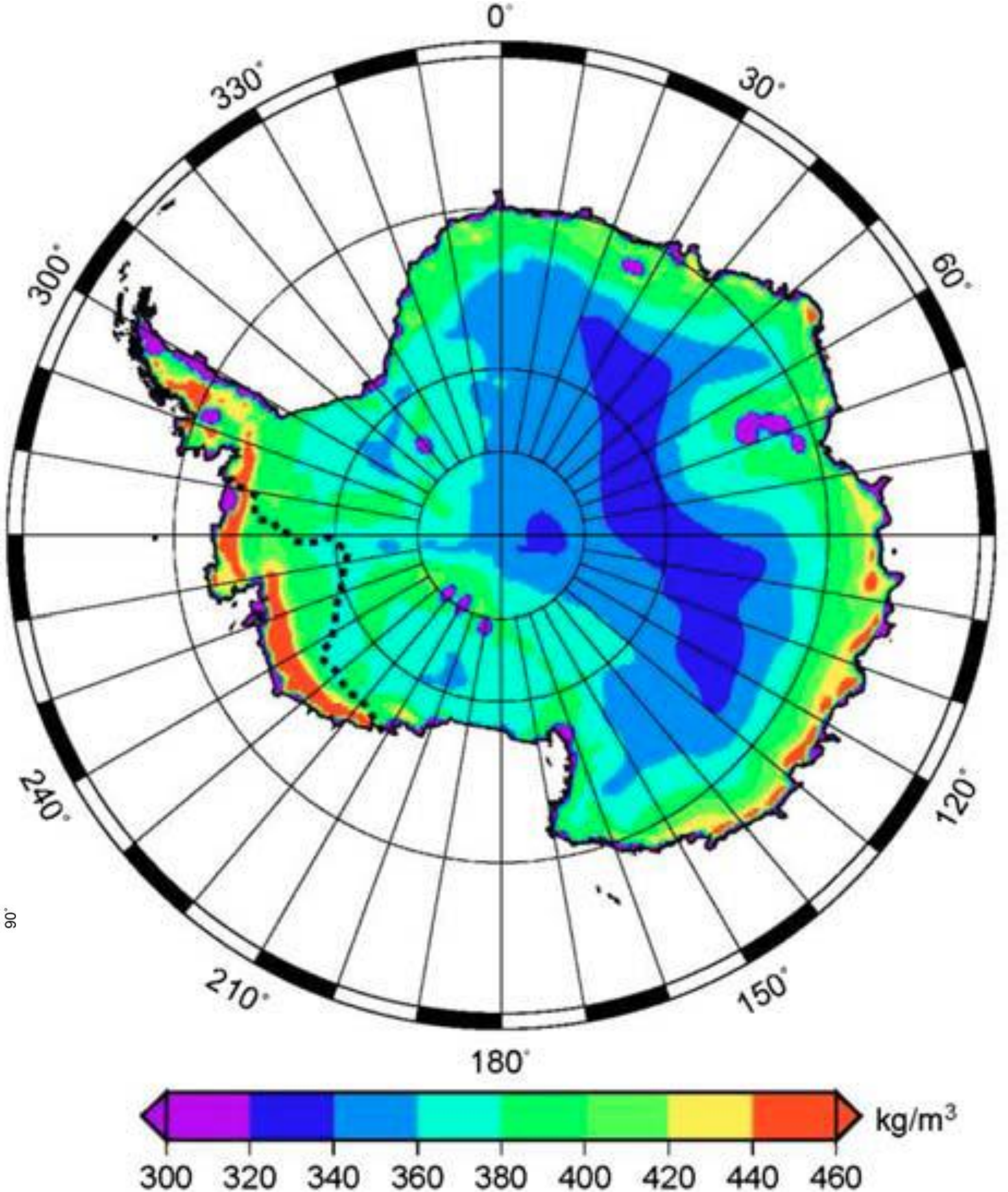
Comparison between altimetry (ICESat) and gravimetry (GRACE)



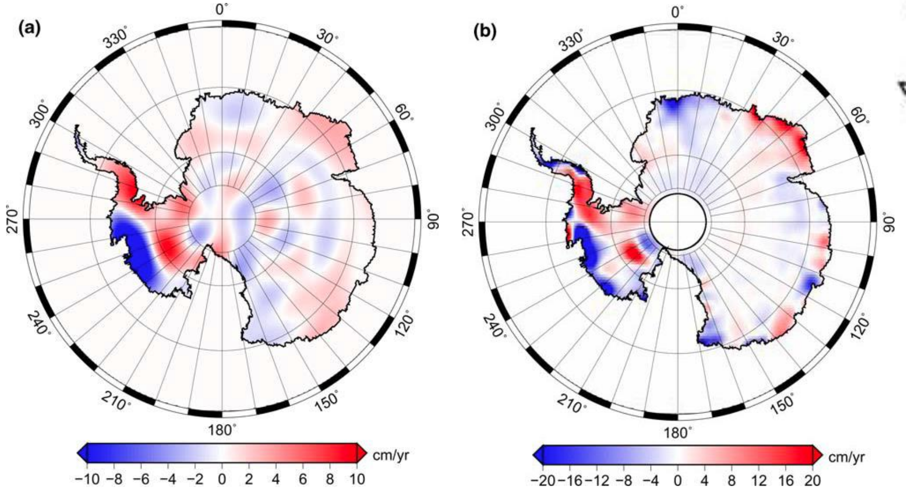
Comparison between mass variations from GRACE (left) and derived from ICEsat (right), from Gunter et al. (2009) for the 2003-2007 period.

Comparison between altimetry (ICESat) and gravimetry (GRACE)

Density model used for the conversion of elevation into mass, from Gunter et al. (2009).

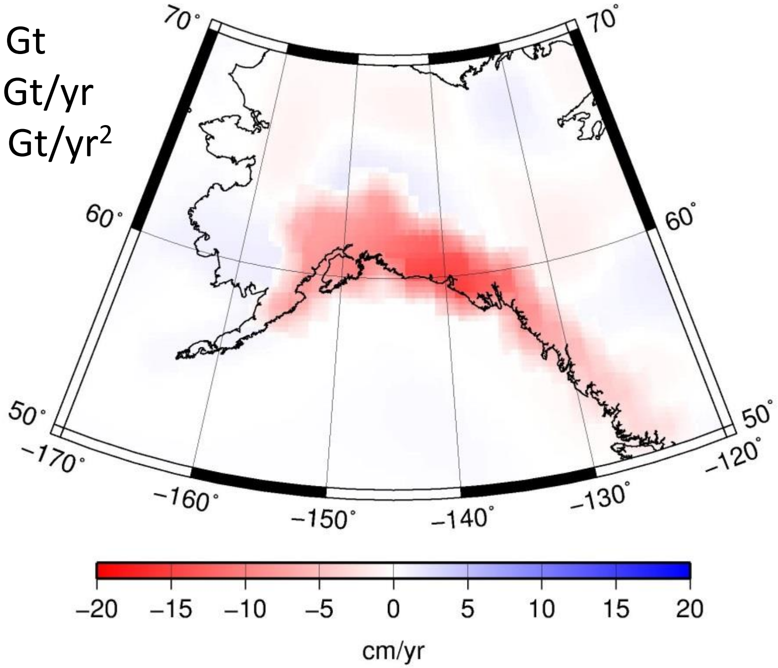


Comparison between mass variations from GRACE (a) and derived from ICEsat (b), for 2003-2007.



Alaska

Annual: 226 Gt
Trend: -66 Gt/yr
Accel.: -1.7 Gt/yr^2



GIA contribution removed using
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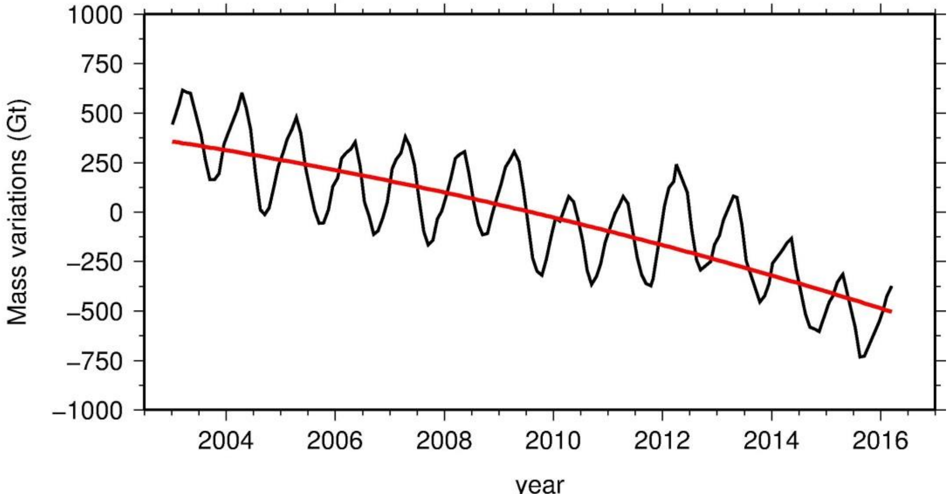

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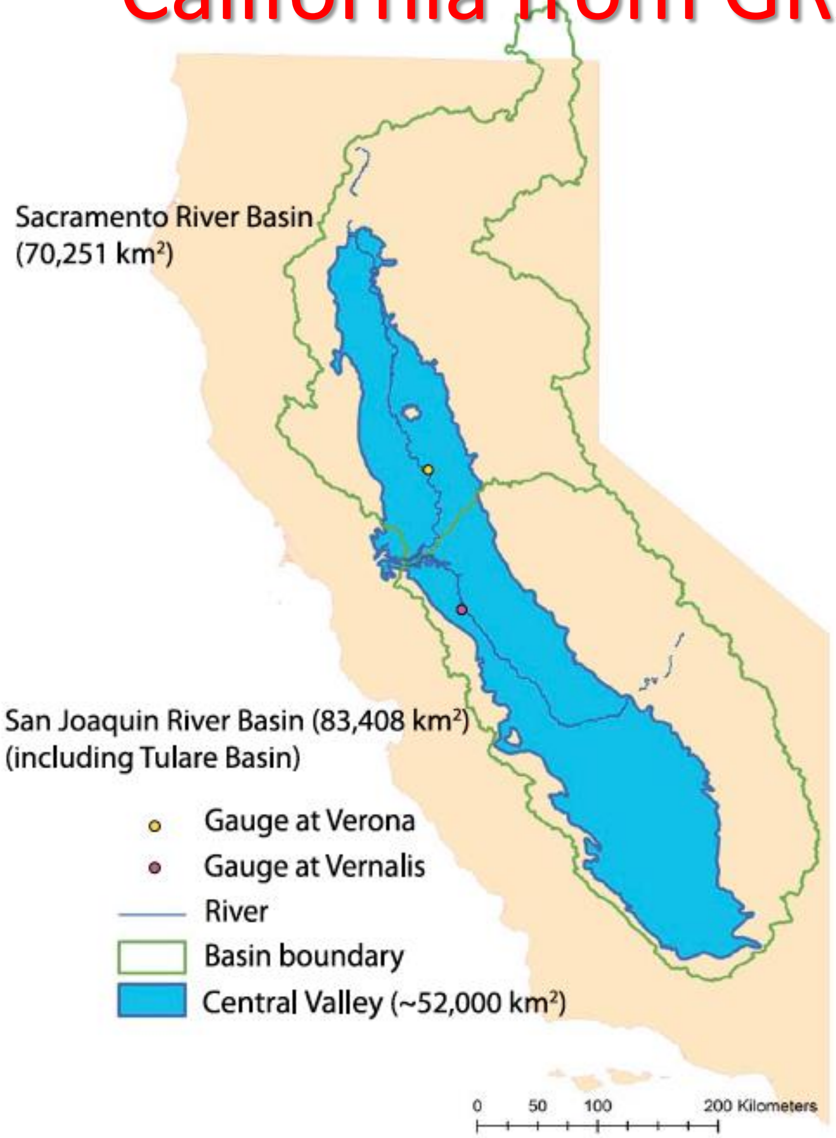
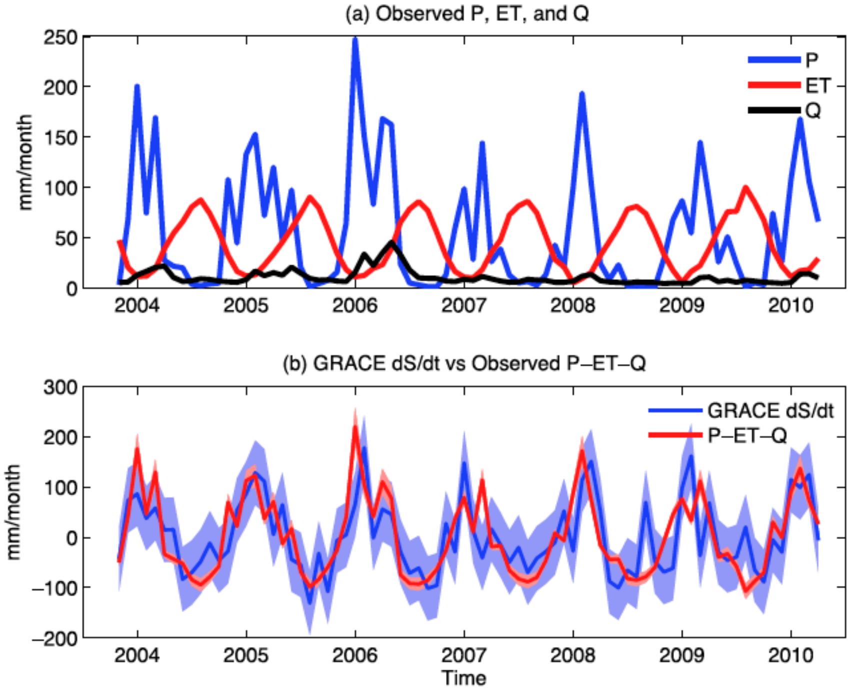
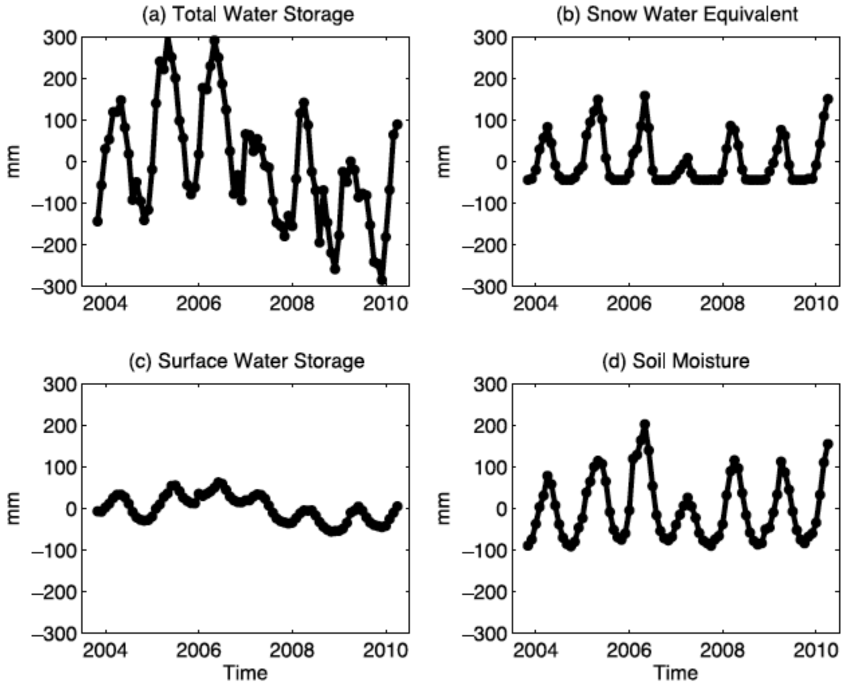
Water table loss in California from GRACE

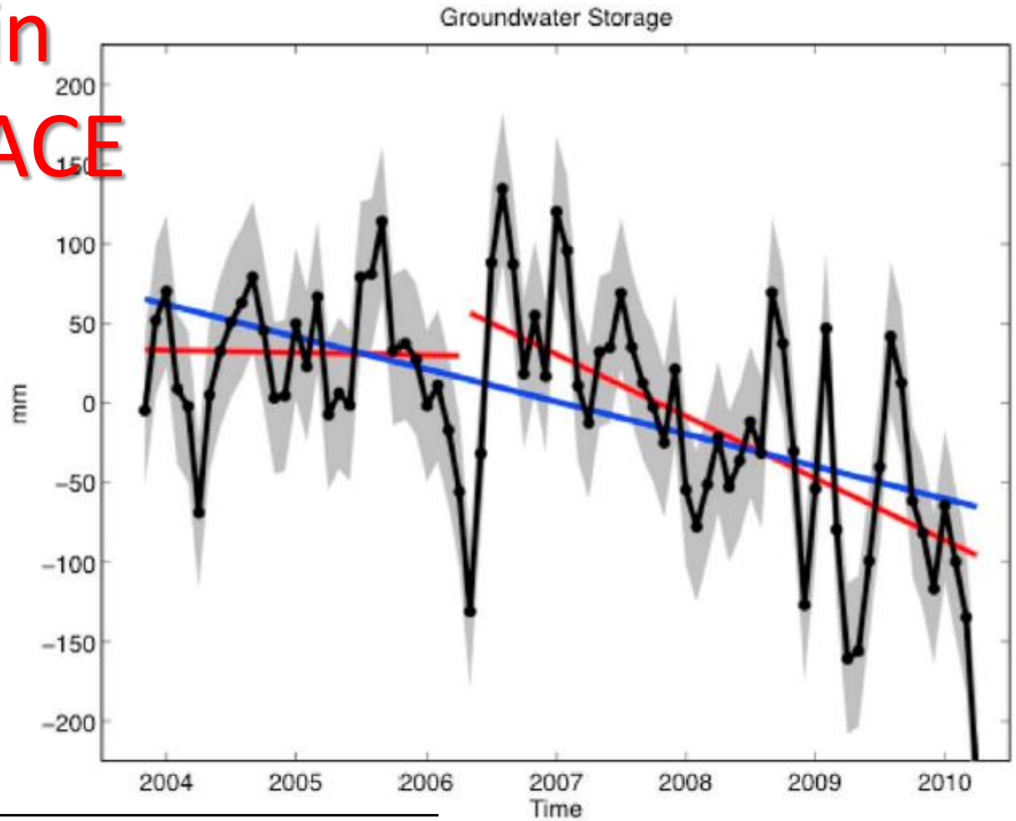


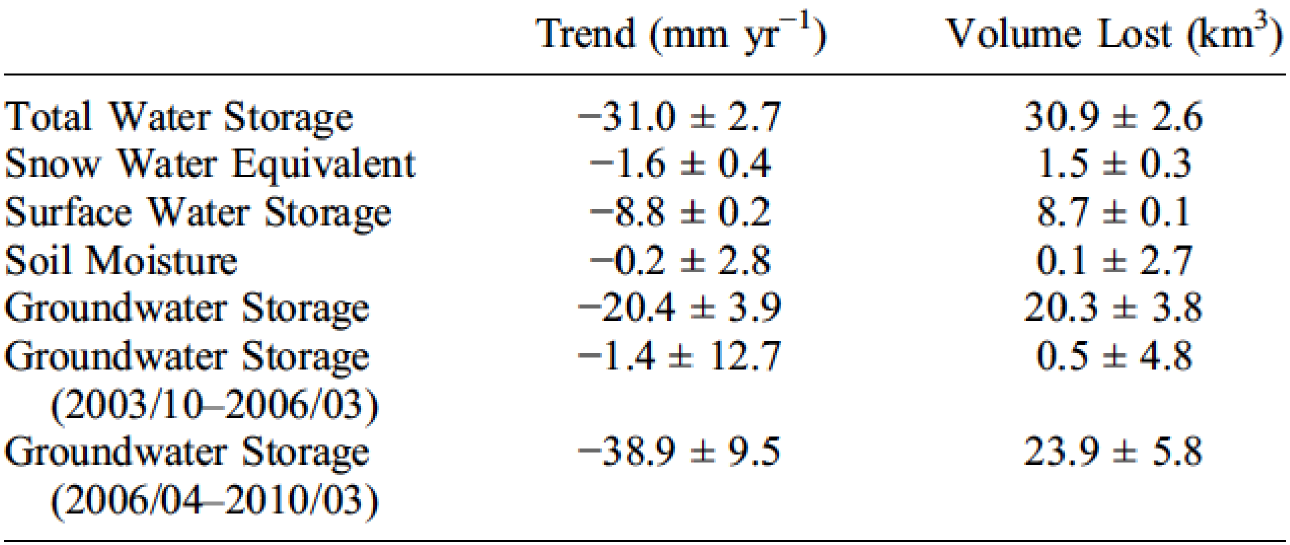




from Famiglietti et al., 2011.

Water table loss in California from GRACE

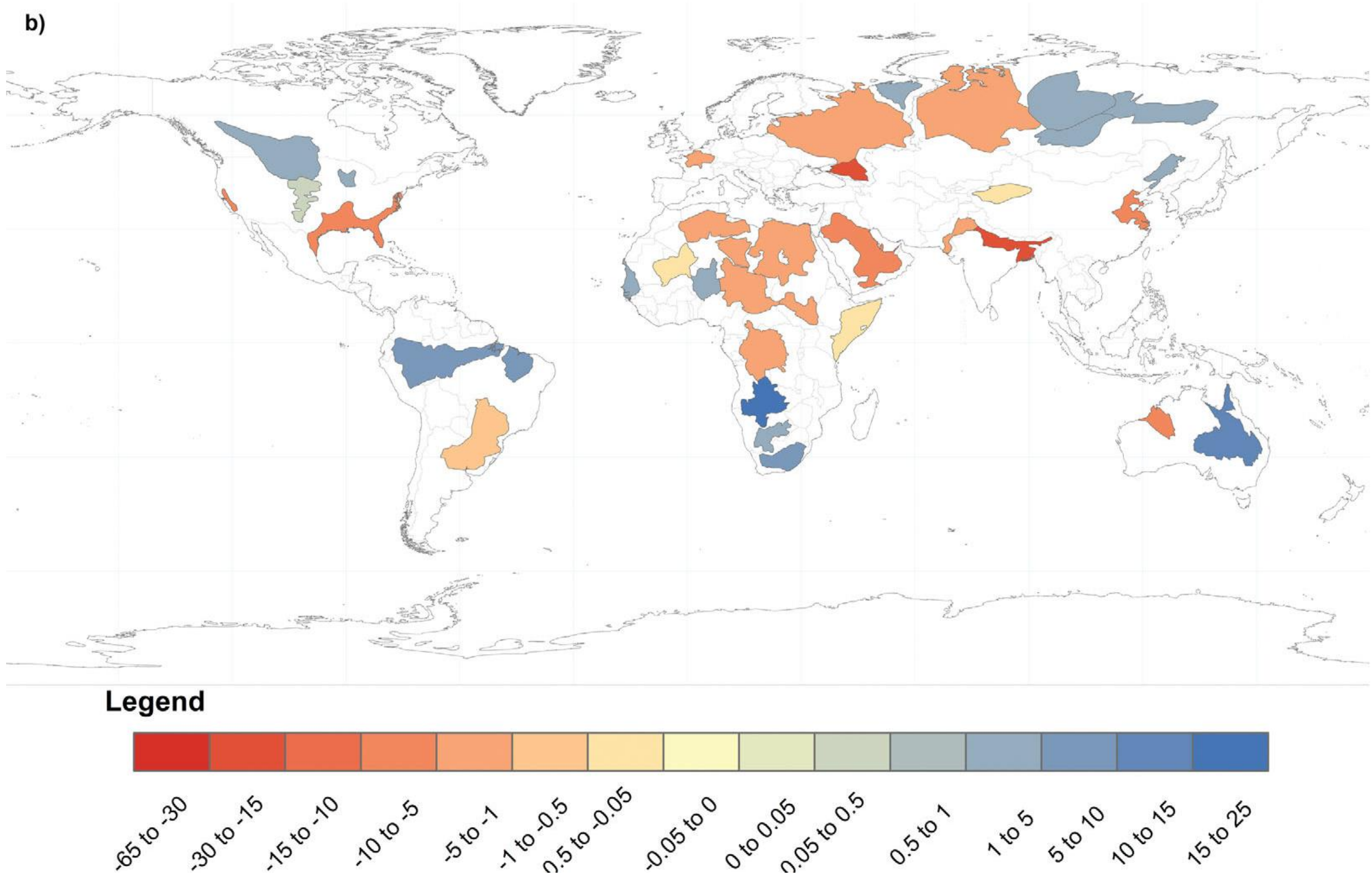




	Trend (mm yr^{-1})	Volume Lost (km^{3})
Total Water Storage	−31.0 ± 2.7	30.9 ± 2.6
Snow Water Equivalent	−1.6 ± 0.4	1.5 ± 0.3
Surface Water Storage	−8.8 ± 0.2	8.7 ± 0.1
Soil Moisture	−0.2 ± 2.8	0.1 ± 2.7
Groundwater Storage	−20.4 ± 3.9	20.3 ± 3.8
Groundwater Storage (2003/10–2006/03)	−1.4 ± 12.7	0.5 ± 4.8
Groundwater Storage (2006/04–2010/03)	−38.9 ± 9.5	23.9 ± 5.8

from Famiglietti et al., 2011.

Global groundwater depletion



GRACE-derived depletion in millimeters per year, from Richey et al., 2015.

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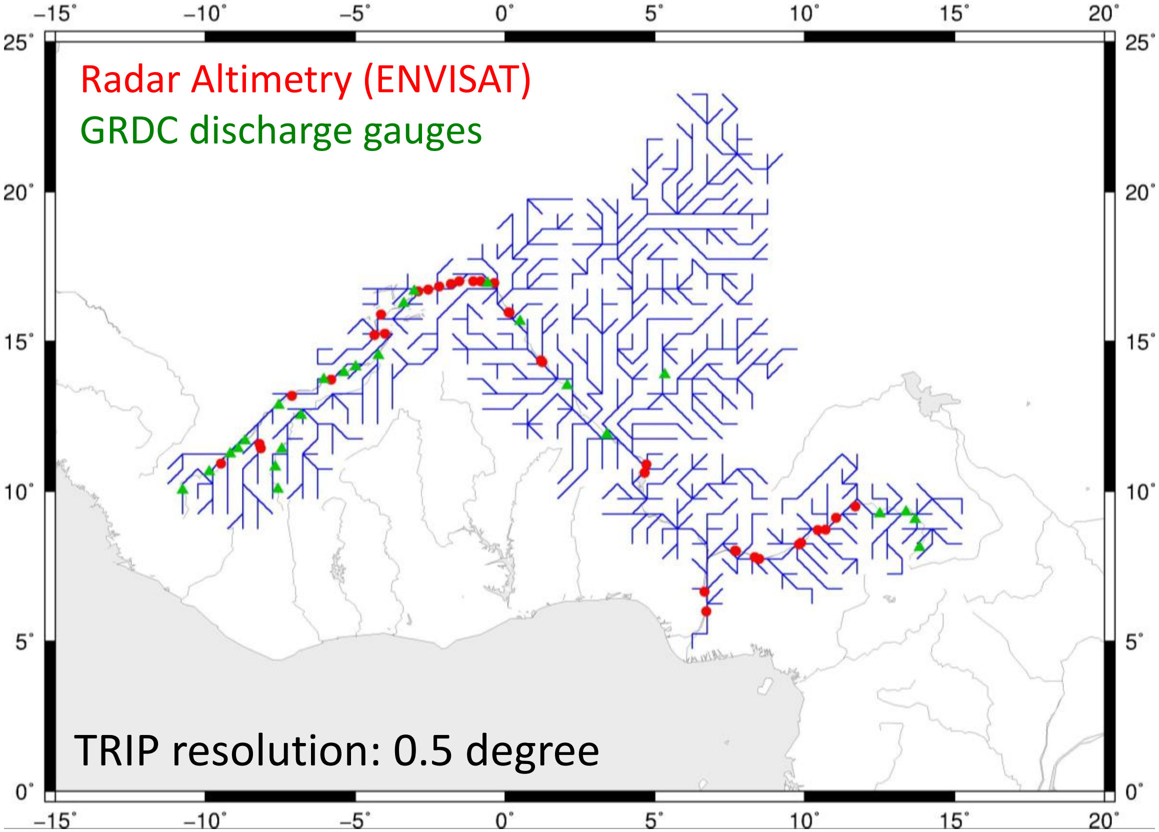
River routing: continuity equation

Niger river

$$\frac{\partial h}{\partial t} = q_{upstream} - q_{downstream} + q_{hydro}$$

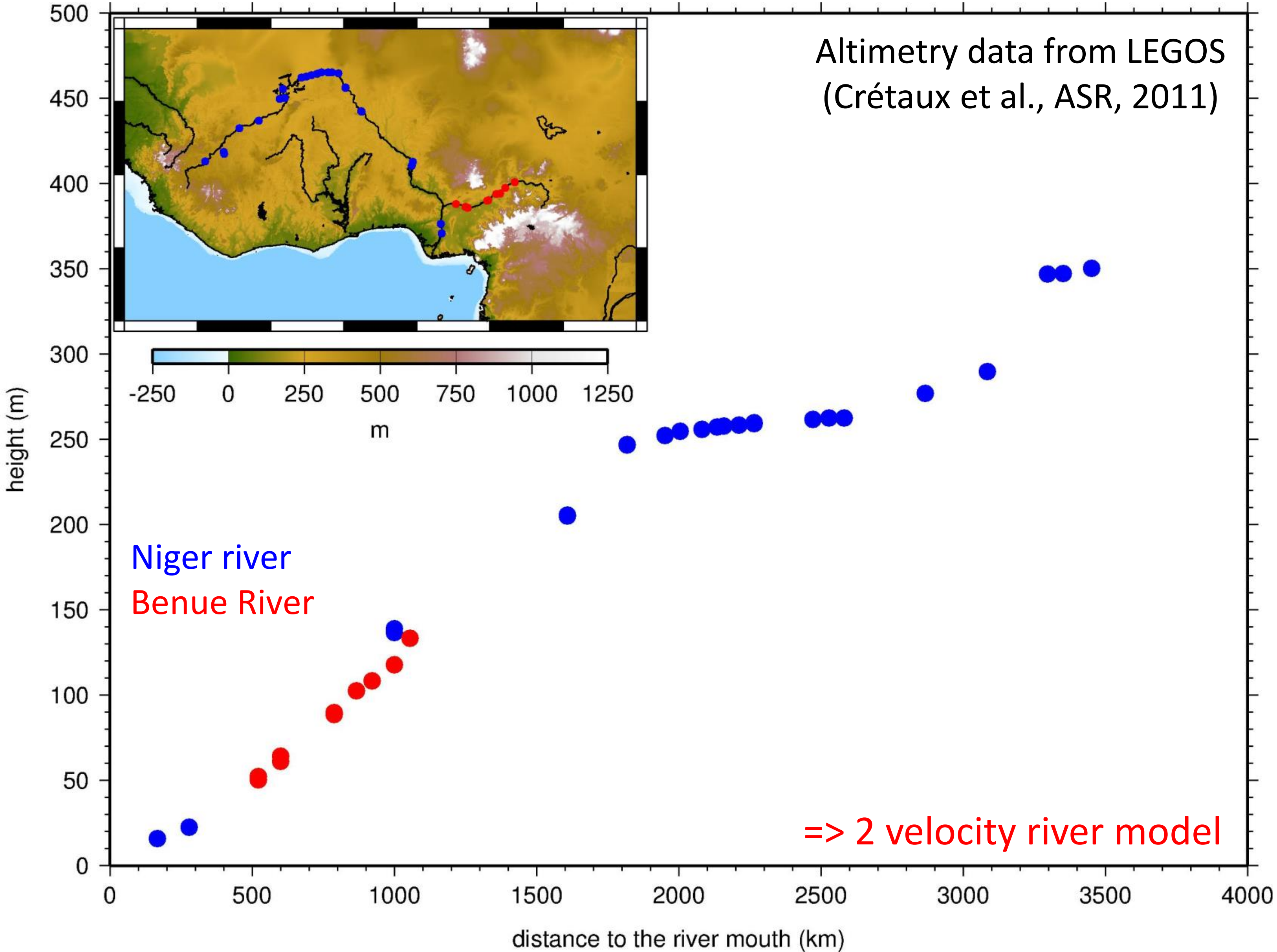
$$q_{upstream} = \sum_i \frac{u_i}{L_i} h_i \; ; \; q_{downstream} = \frac{u}{L} h$$

with u flow velocity & L distance between cells



=> The river flow velocity is the only free parameter.

Niger and Benue River profiles



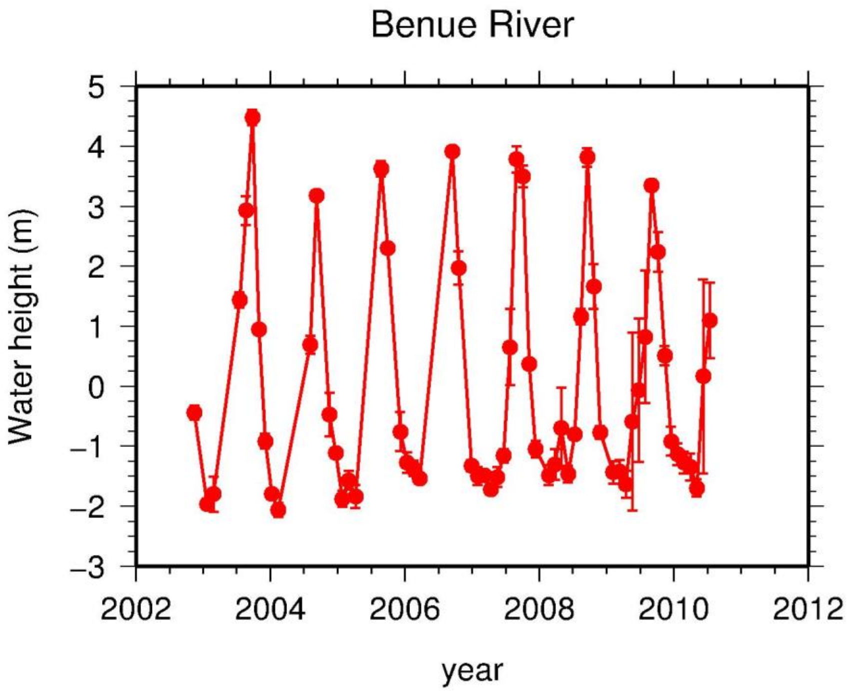
Altimetry data from LEGOS (Crétaux et al., ASR, 2011)

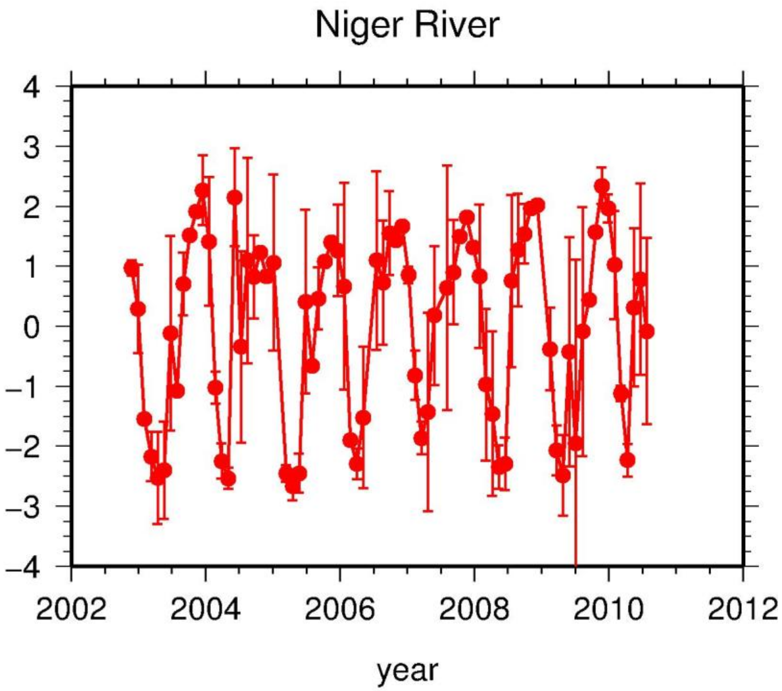
Niger river

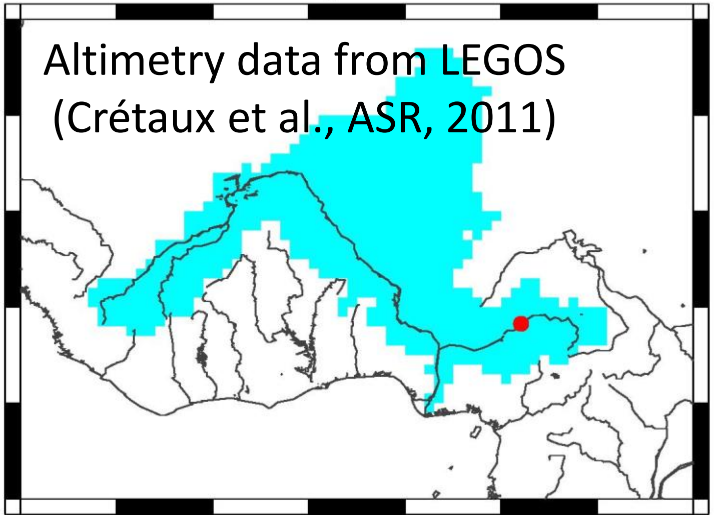
Benue River

=> 2 velocity river model

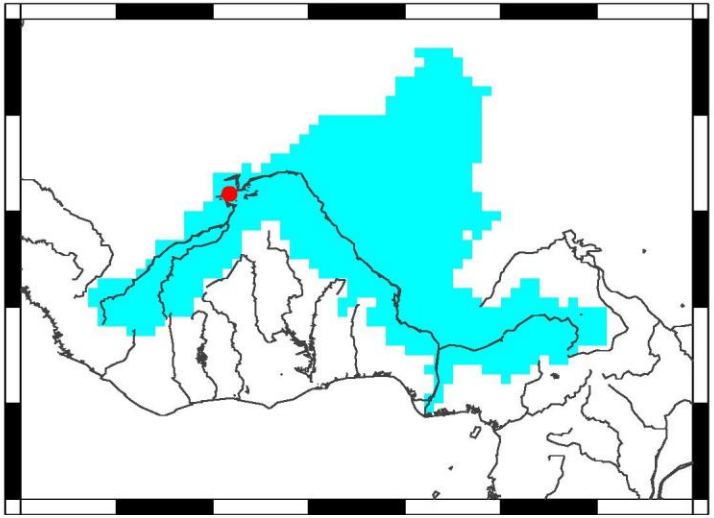
Water height variations from ENVISAT



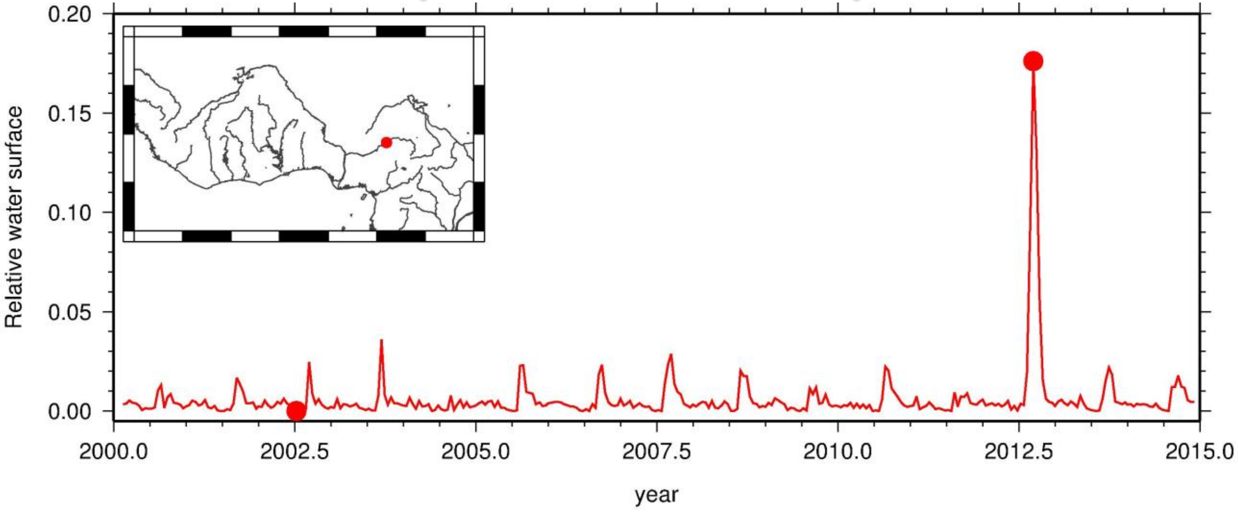


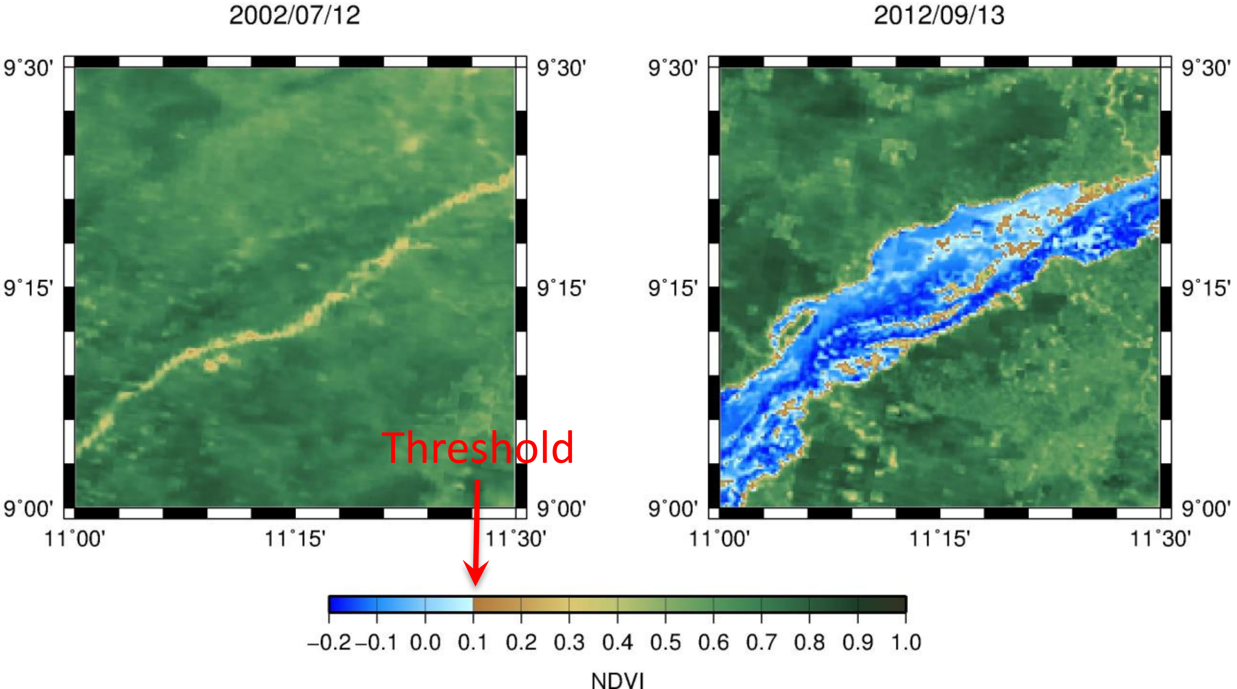


Altimetry data from LEGOS
(Crétaux et al., ASR, 2011)

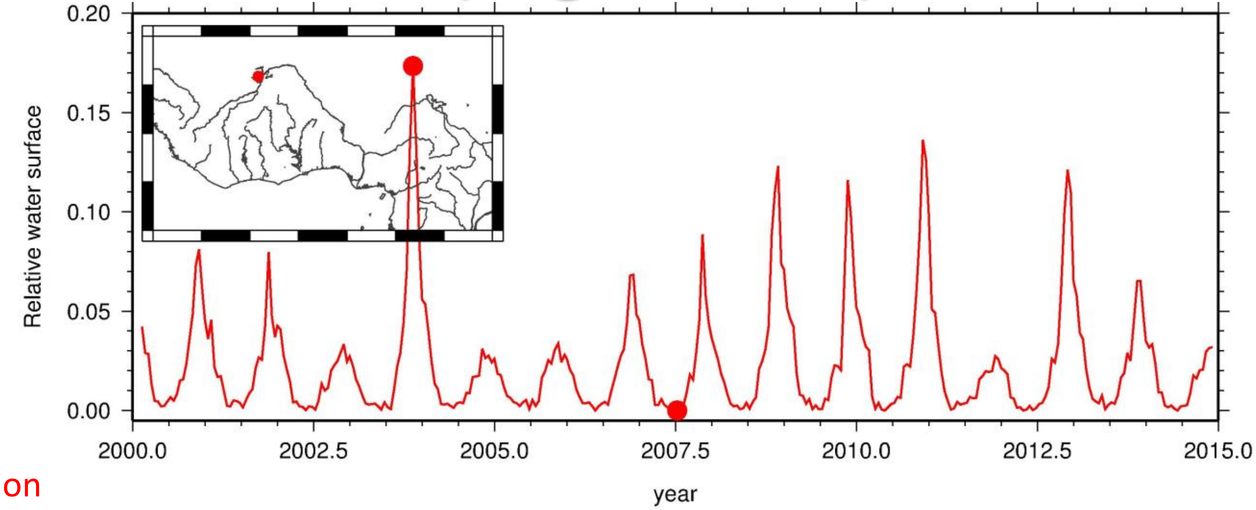


Water surface from MODIS NDVI (Benue River)

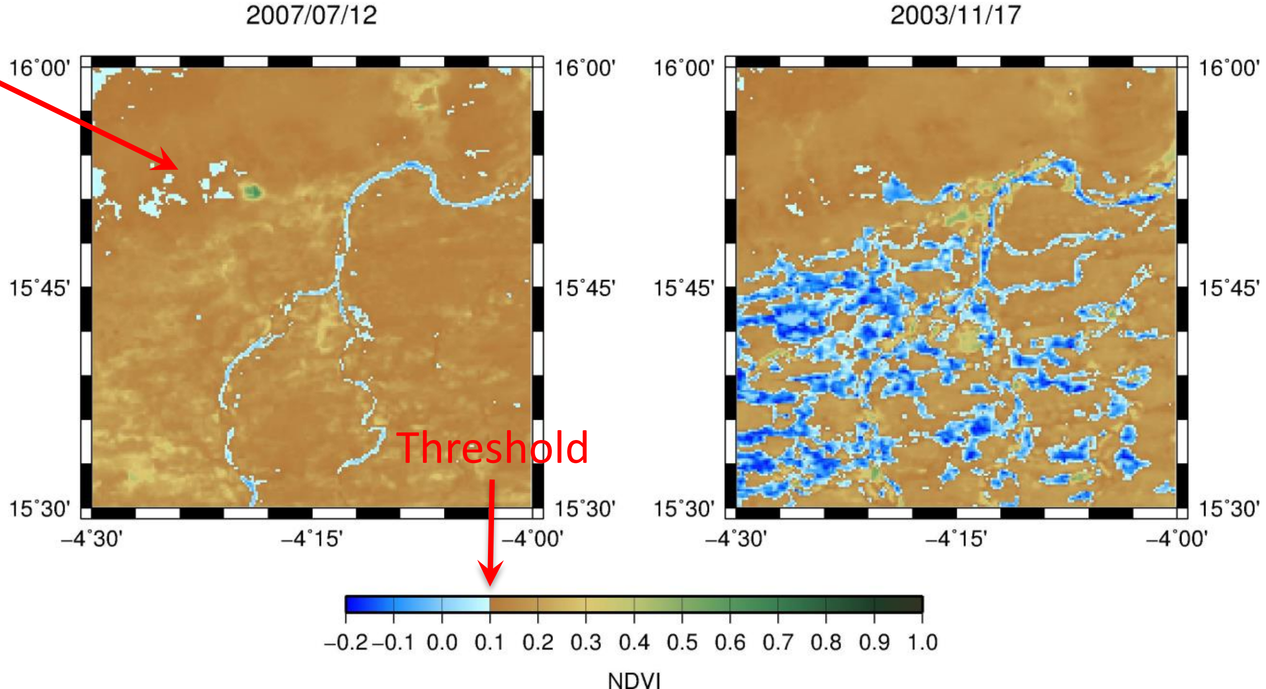




Water surface from MODIS NDVI (Niger River)

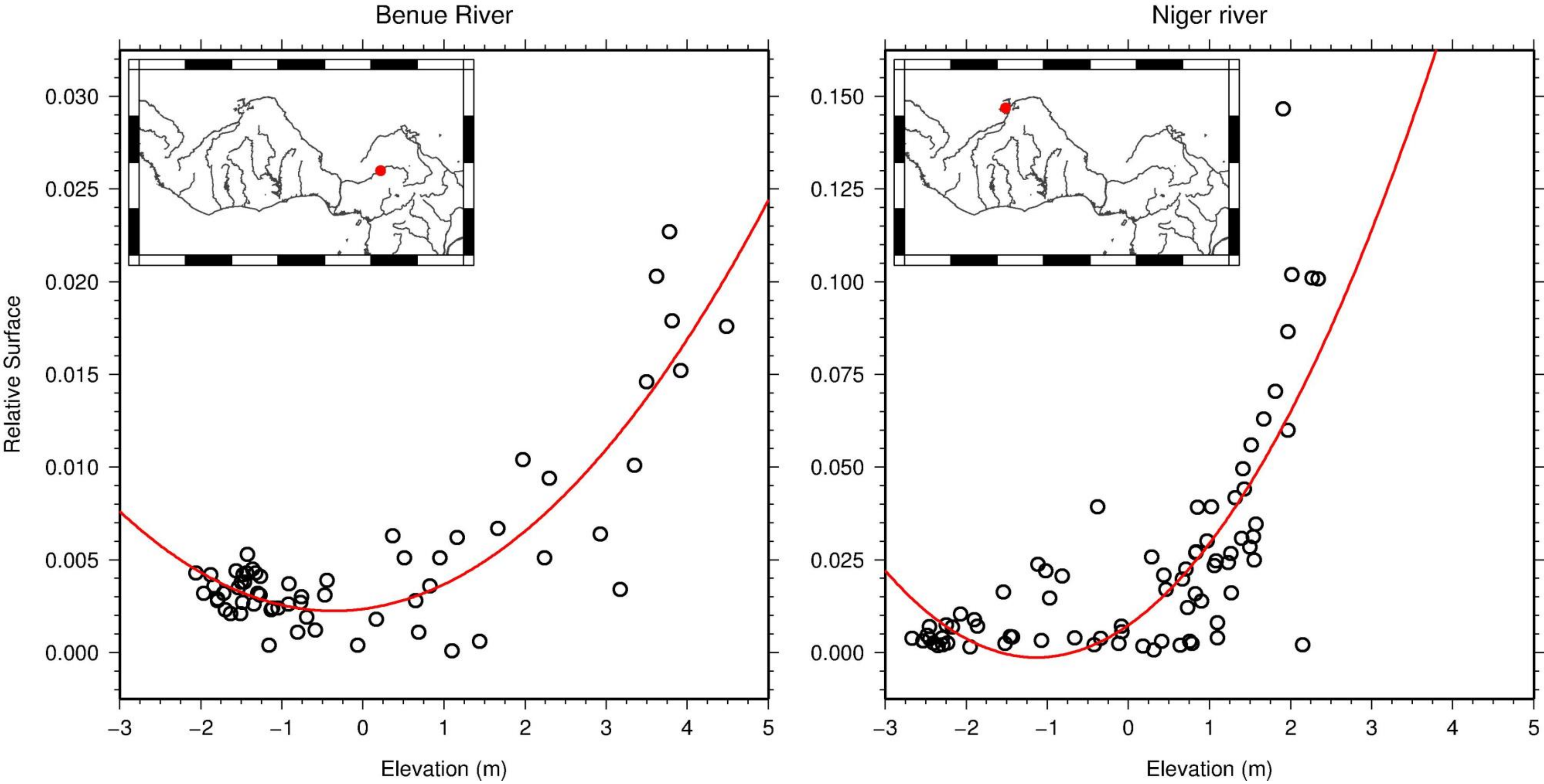


Removed with another threshold on the NIR reflectance



Threshold

Relation between water surface & height



Validation using GRDC mean annual discharge (GLDAS/Noah)

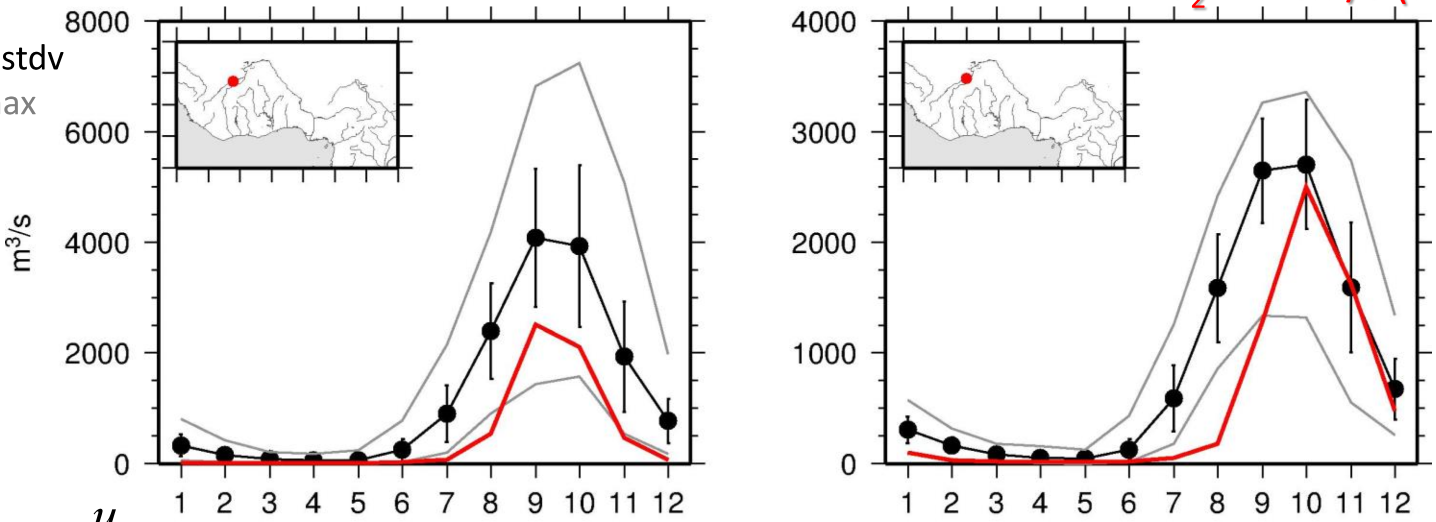
u_1 = 33 cm/s

u_2 = 7 cm/s (Inner Delta)

GRDC mean & stdv

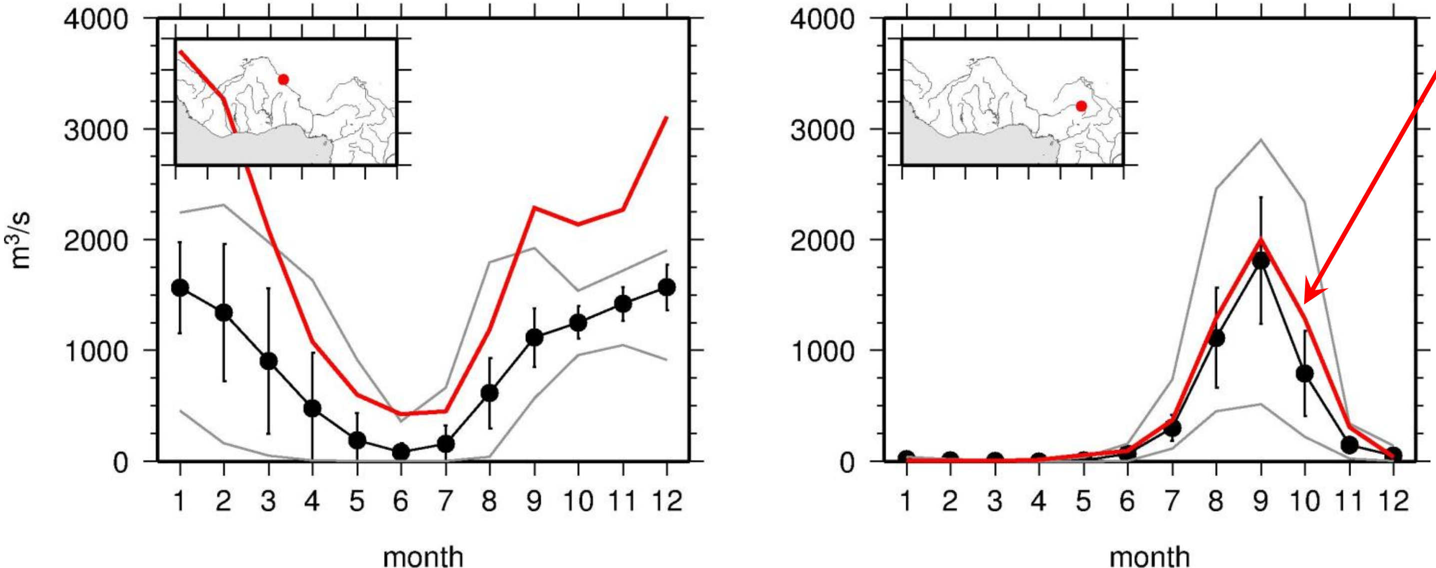
GRDC min & max

River model

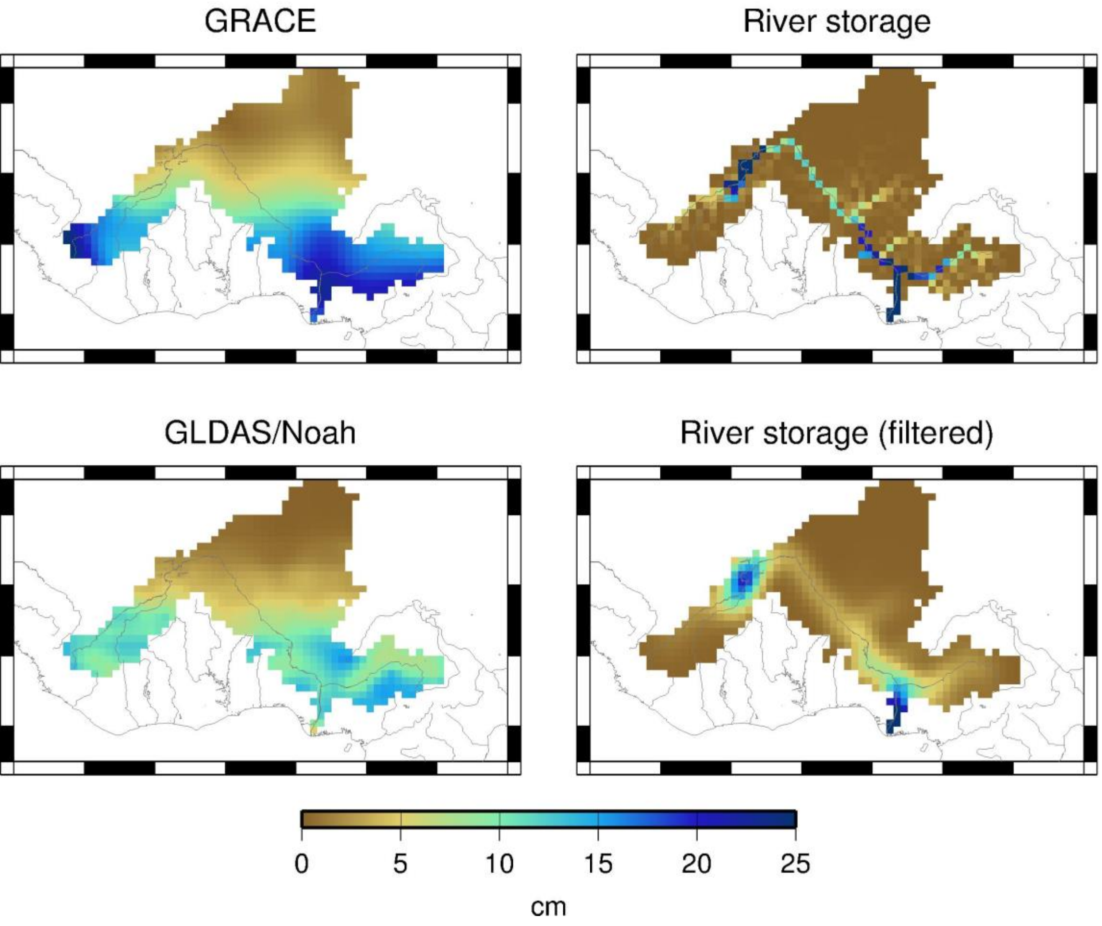


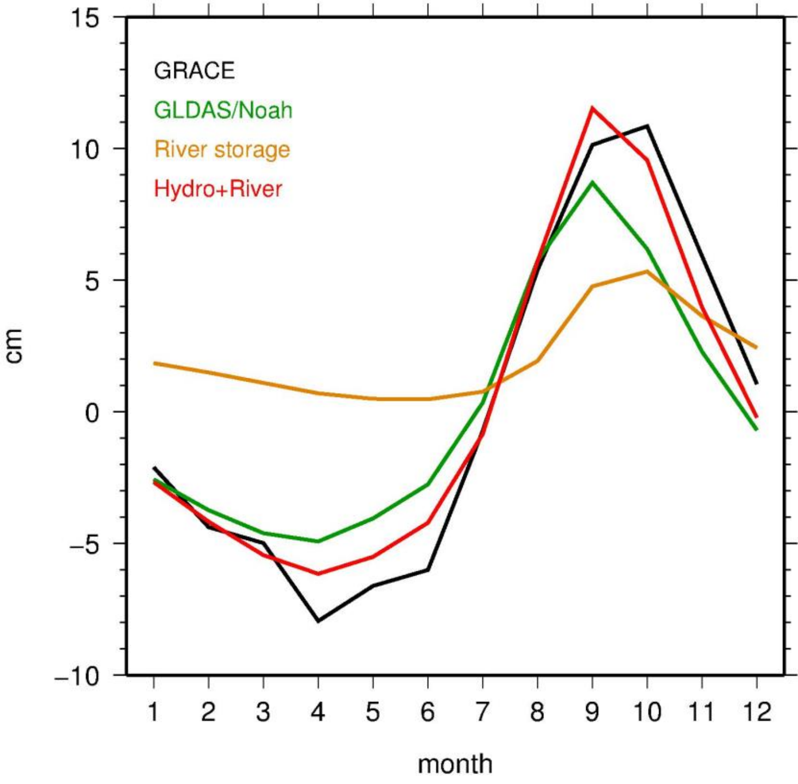
$$\text{discharge} \ : q = \frac{u}{L} h$$

Need to reduce the amplitude with a simple evaporation scheme…



Seasonal variations (GLDAS/Noah)





u_1 = 33 cm/s
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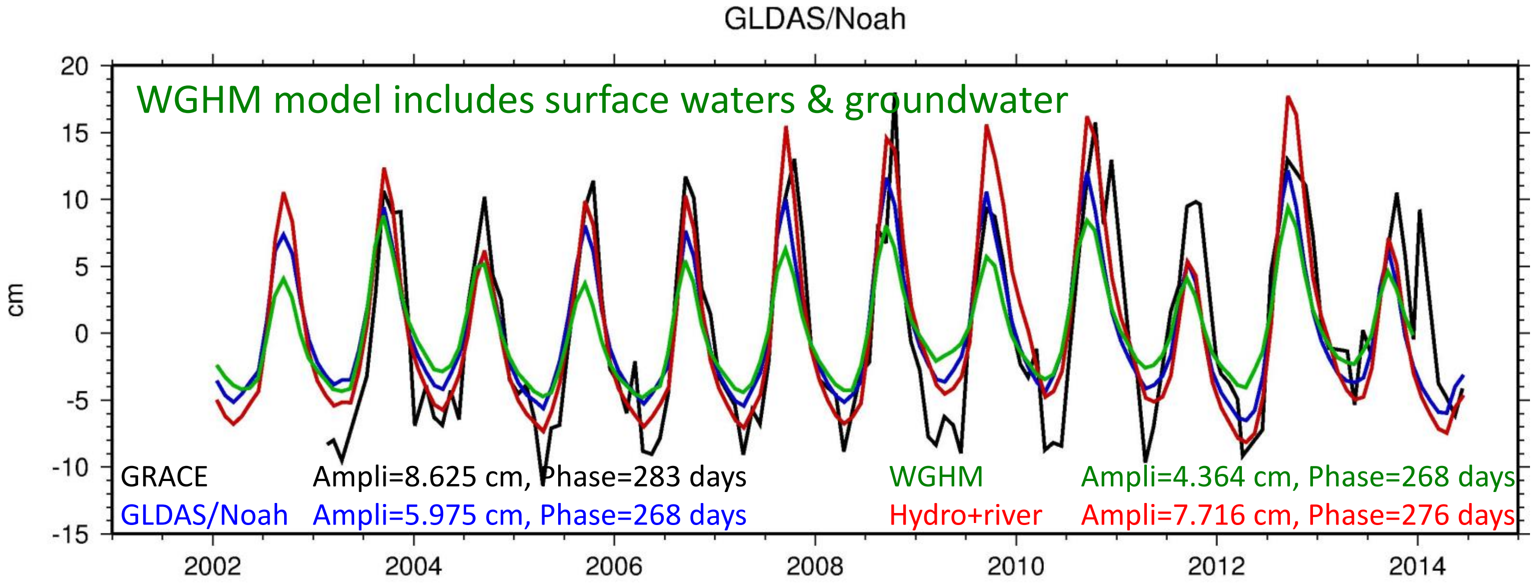
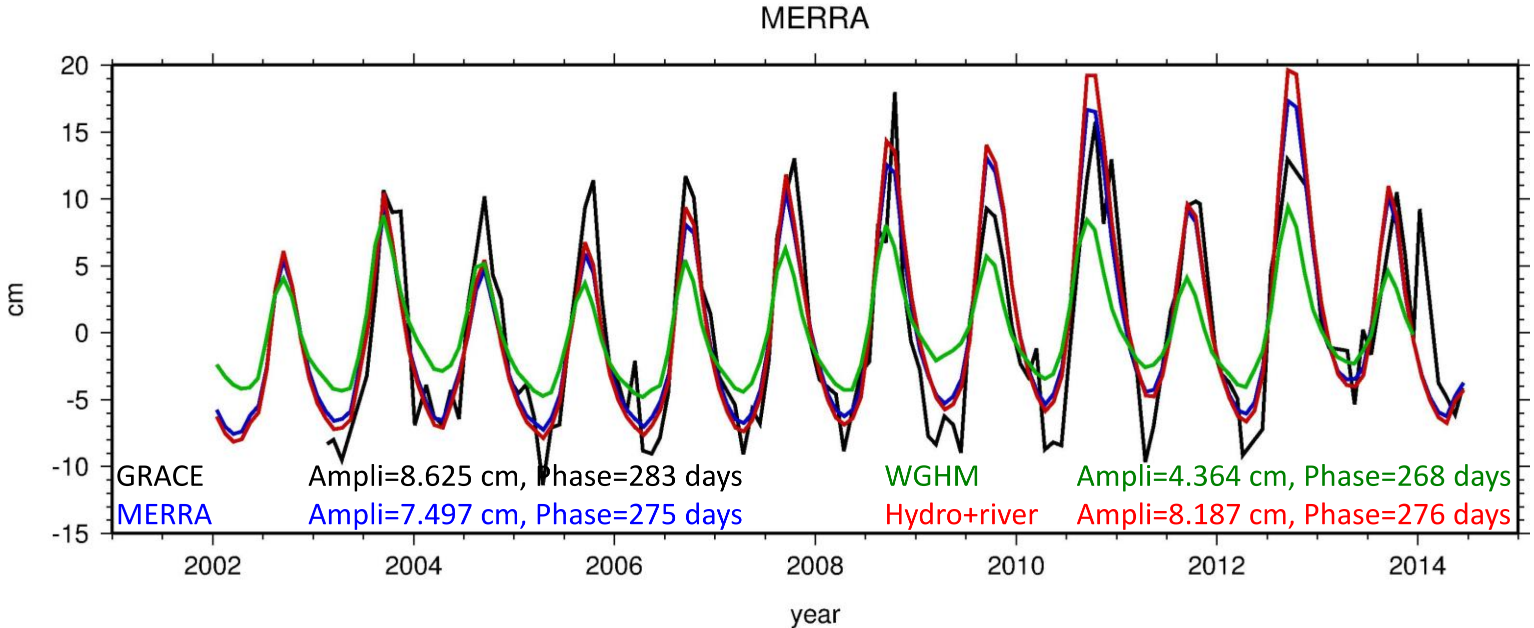
Water storage time series


WGHM model includes surface waters & groundwater



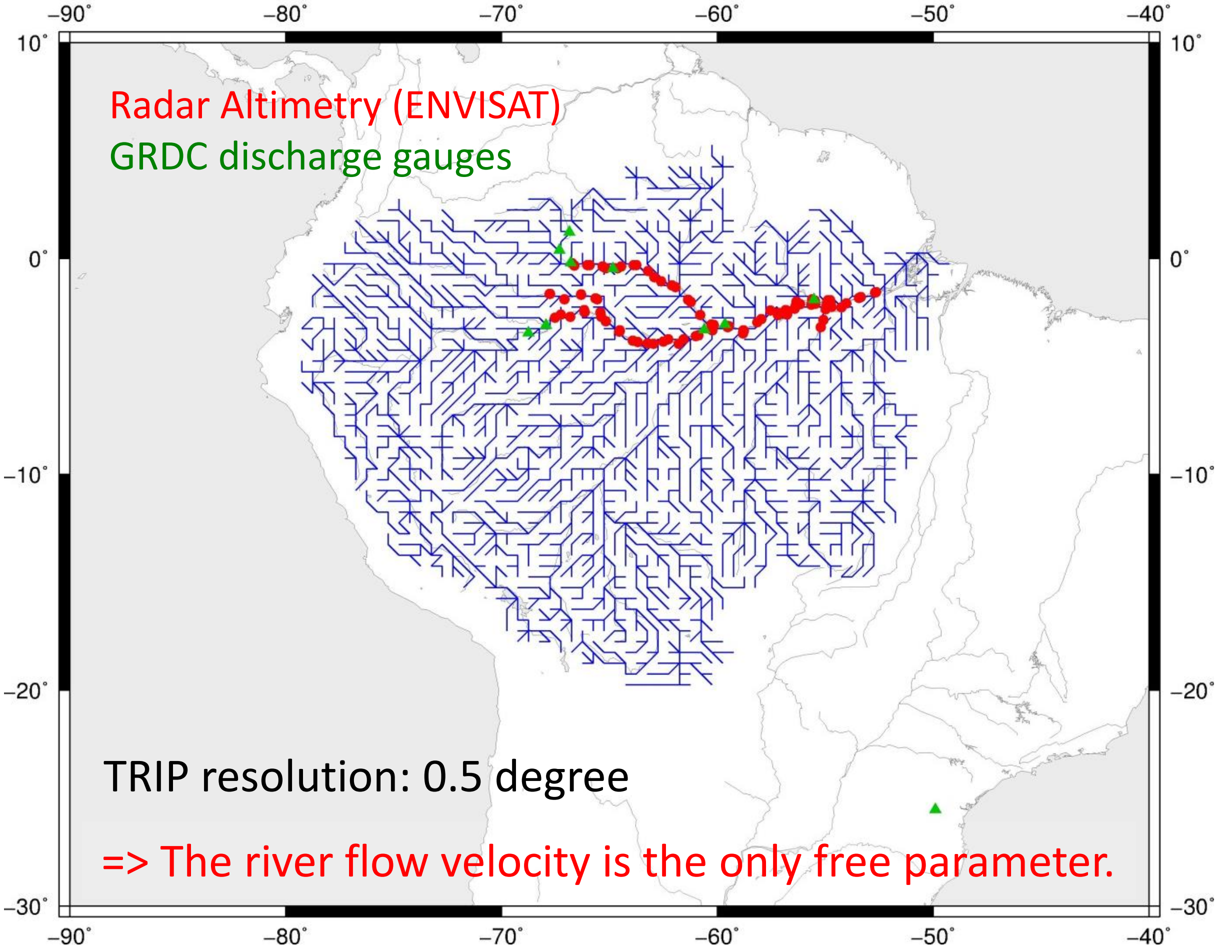
River routing: continuity equation

Amazon river

$$\frac{\partial h}{\partial t} = q_{upstream} - q_{downstream} + q_{hydro}$$

$$q_{upstream} = \sum_i \frac{u_i}{L_i} h_i \; ; \; q_{downstream} = \frac{u}{L} h$$

with u flow velocity & L distance between cells



TRIP resolution: 0.5 degree

=> The river flow velocity is the only free parameter.

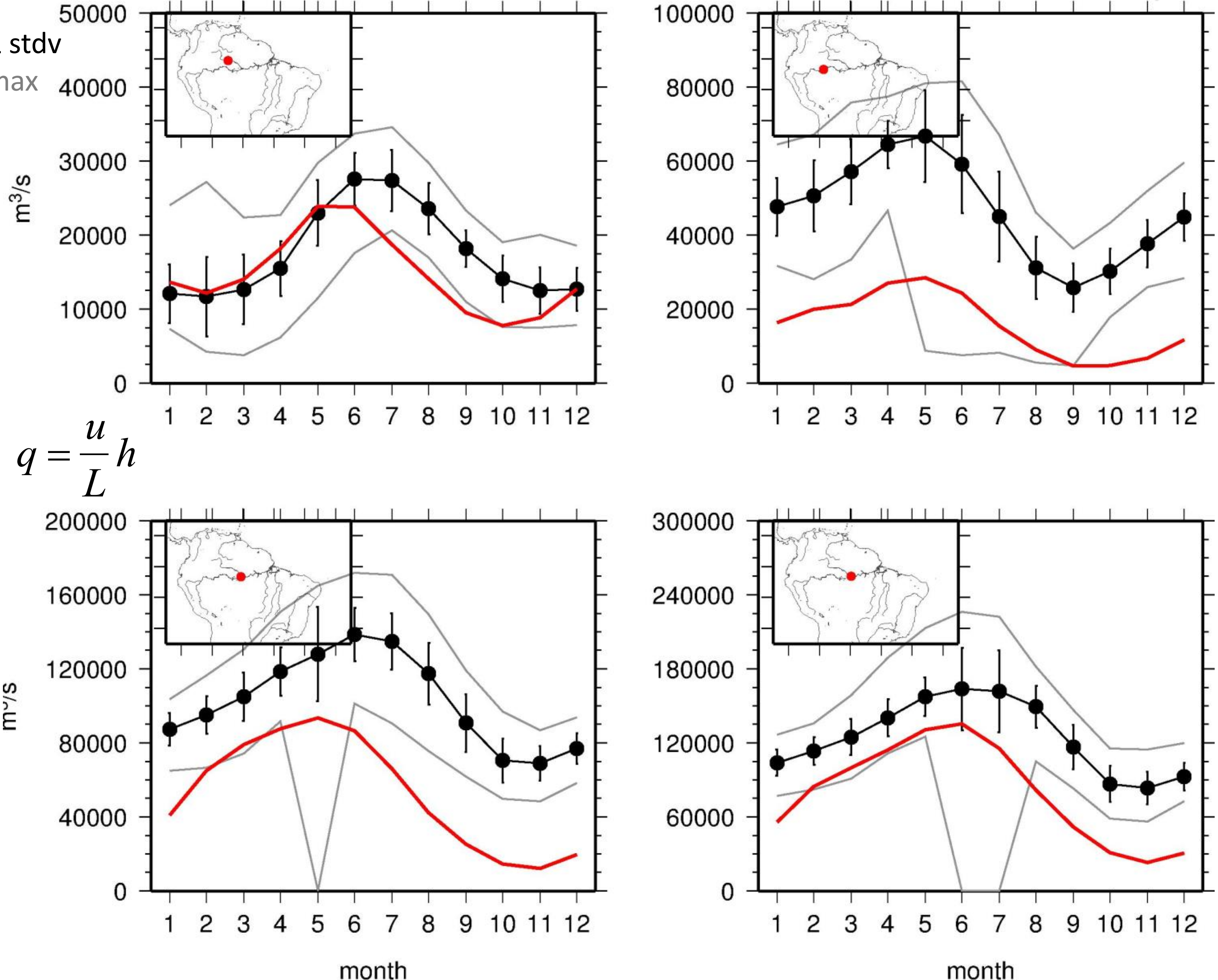
Validation using GRDC mean annual discharge (GLDAS/Noah)

u = 29 cm/s

GRDC mean & stdv

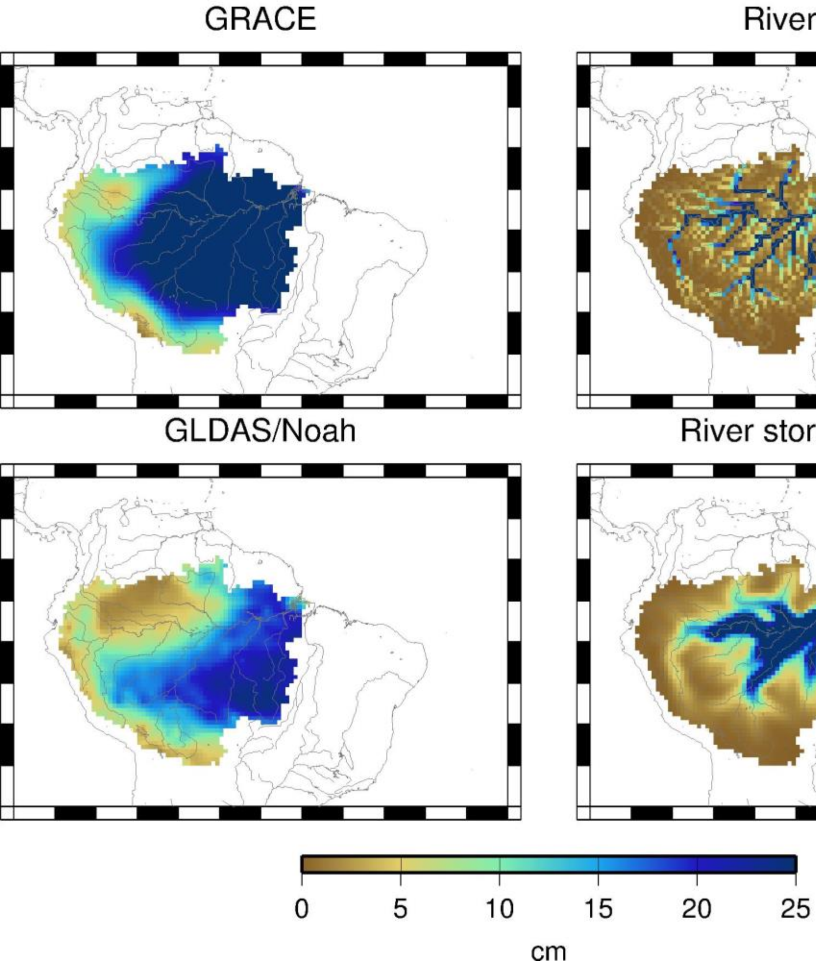
GRDC min & max

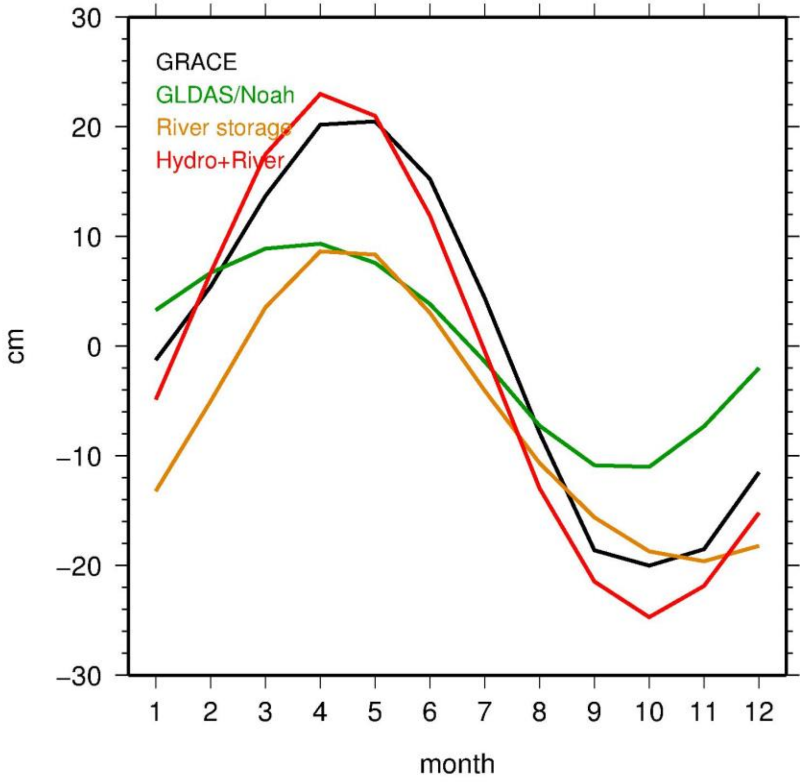
River model



discharge : $q = \frac{u}{L} h$

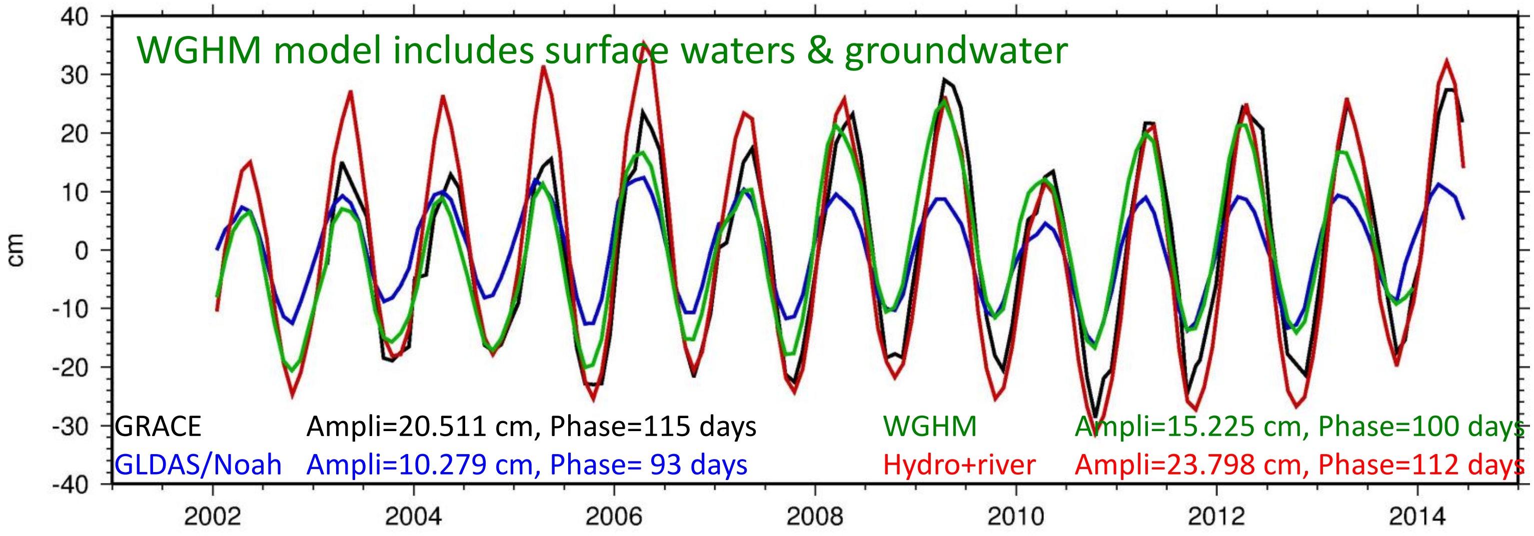
Seasonal variations (GLDAS/Noah)





u = 29 cm/s

Water storage time series


GLDAS/Noah

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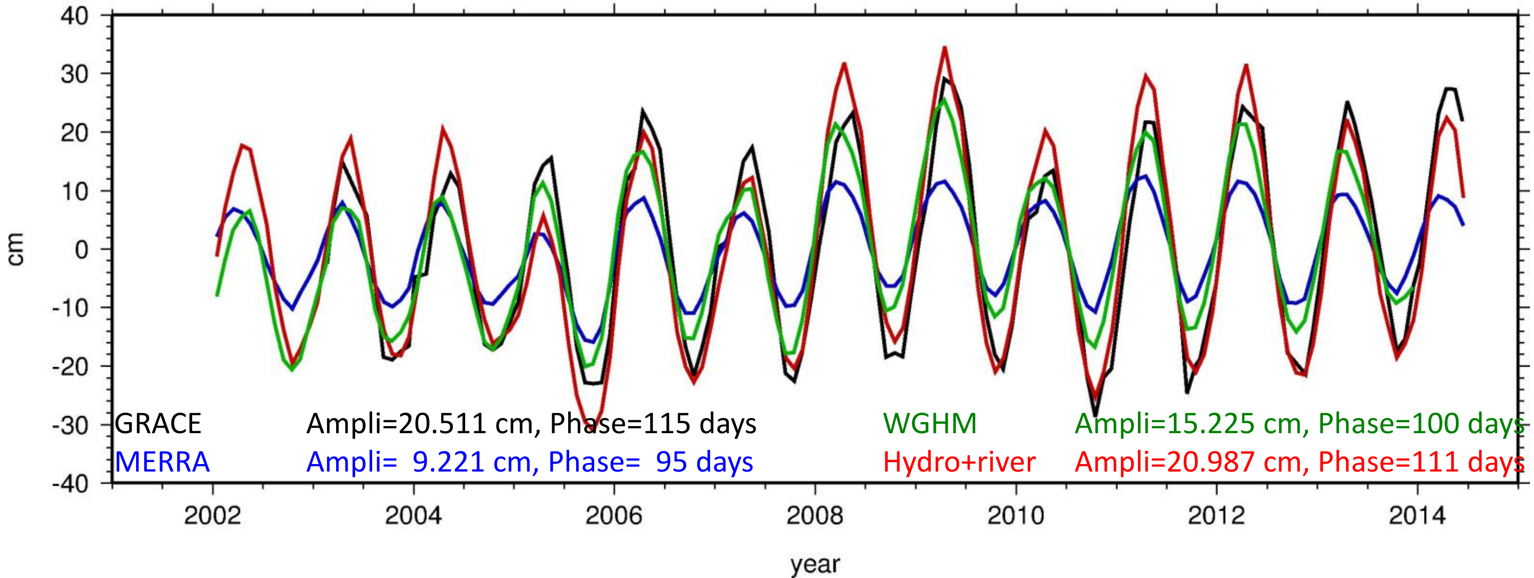
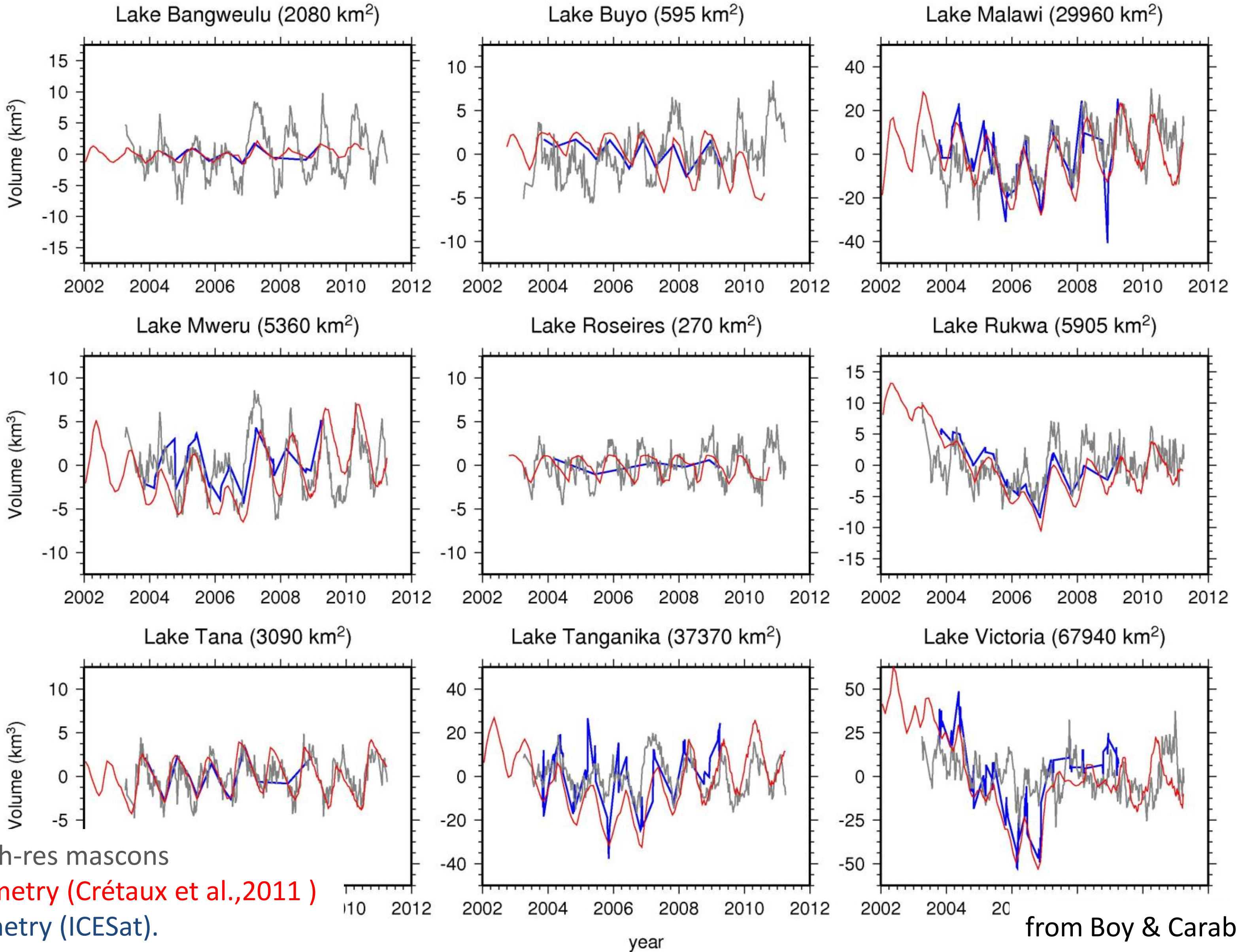

MERRA

Mass variations of lakes in Africa and ASIA from GRACE, radar and laser altimetry



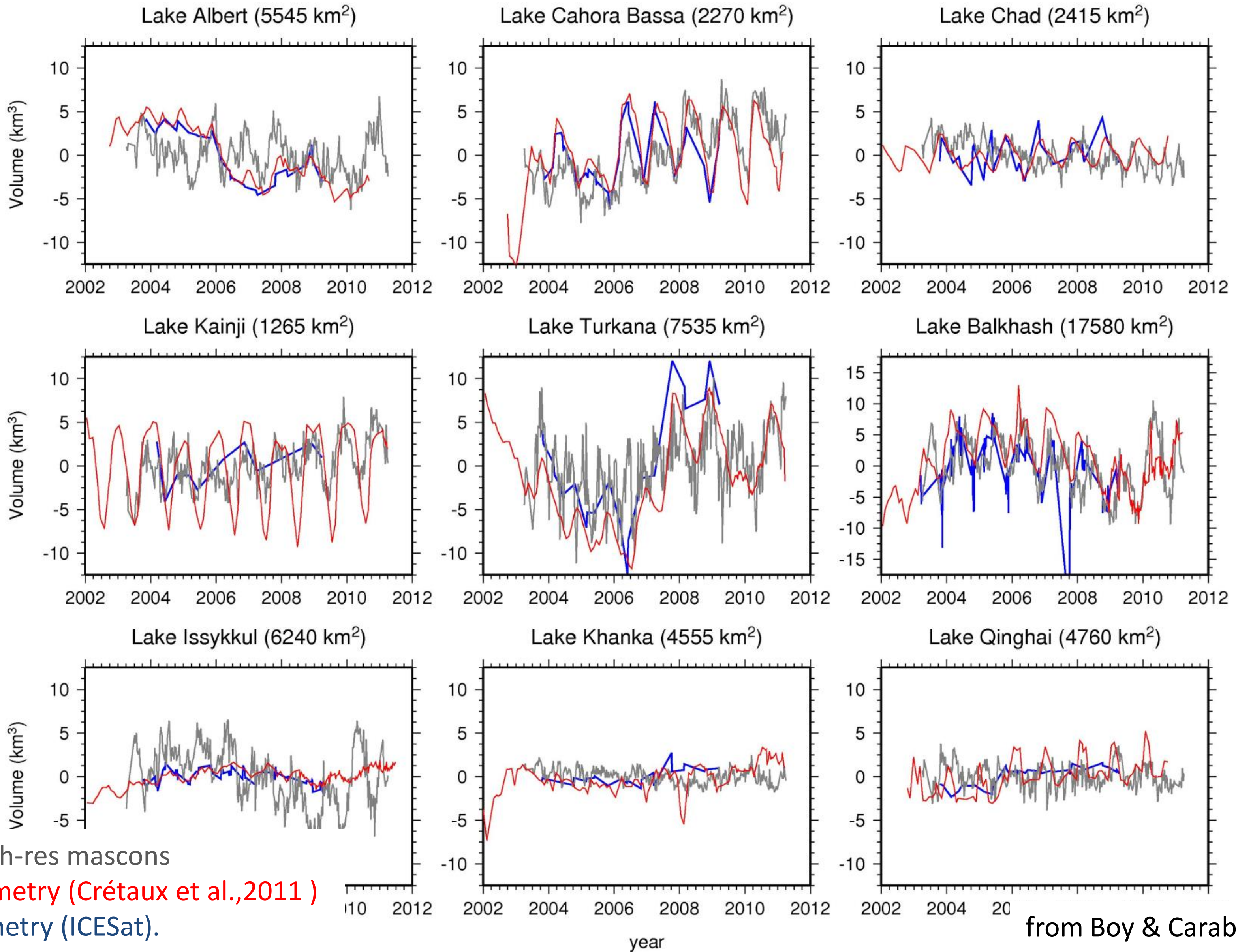
GRACE high-res mascons

Radar altimetry (Crétaux et al.,2011)

Laser altimetry (ICESat).

from Boy & Carabajal, 2011.

Mass variations of lakes in Africa and ASIA from GRACE, radar and laser altimetry



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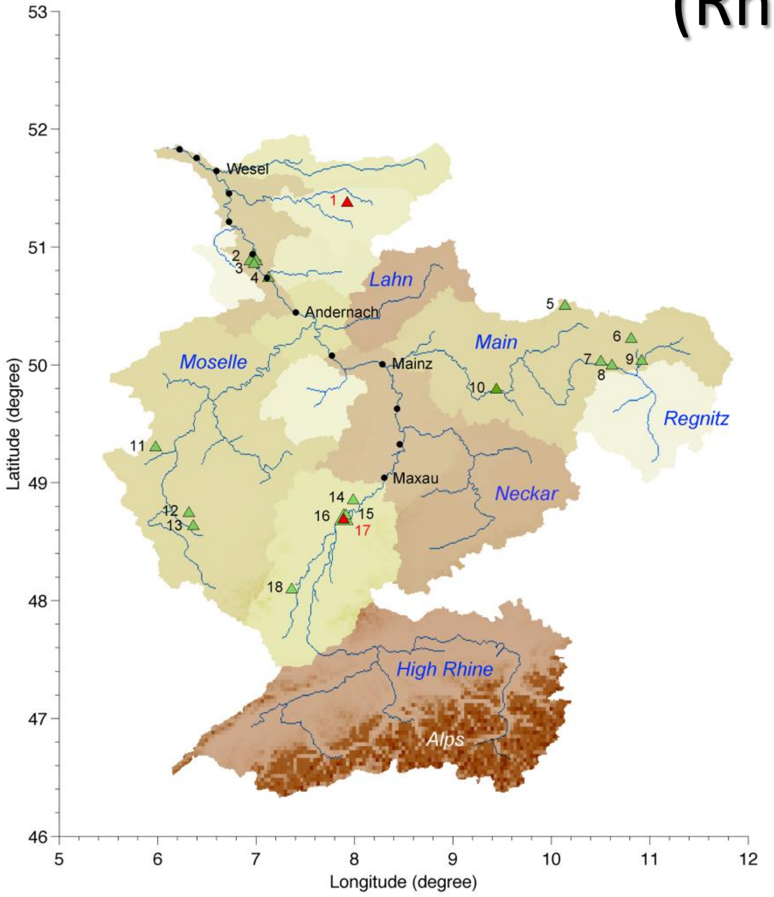
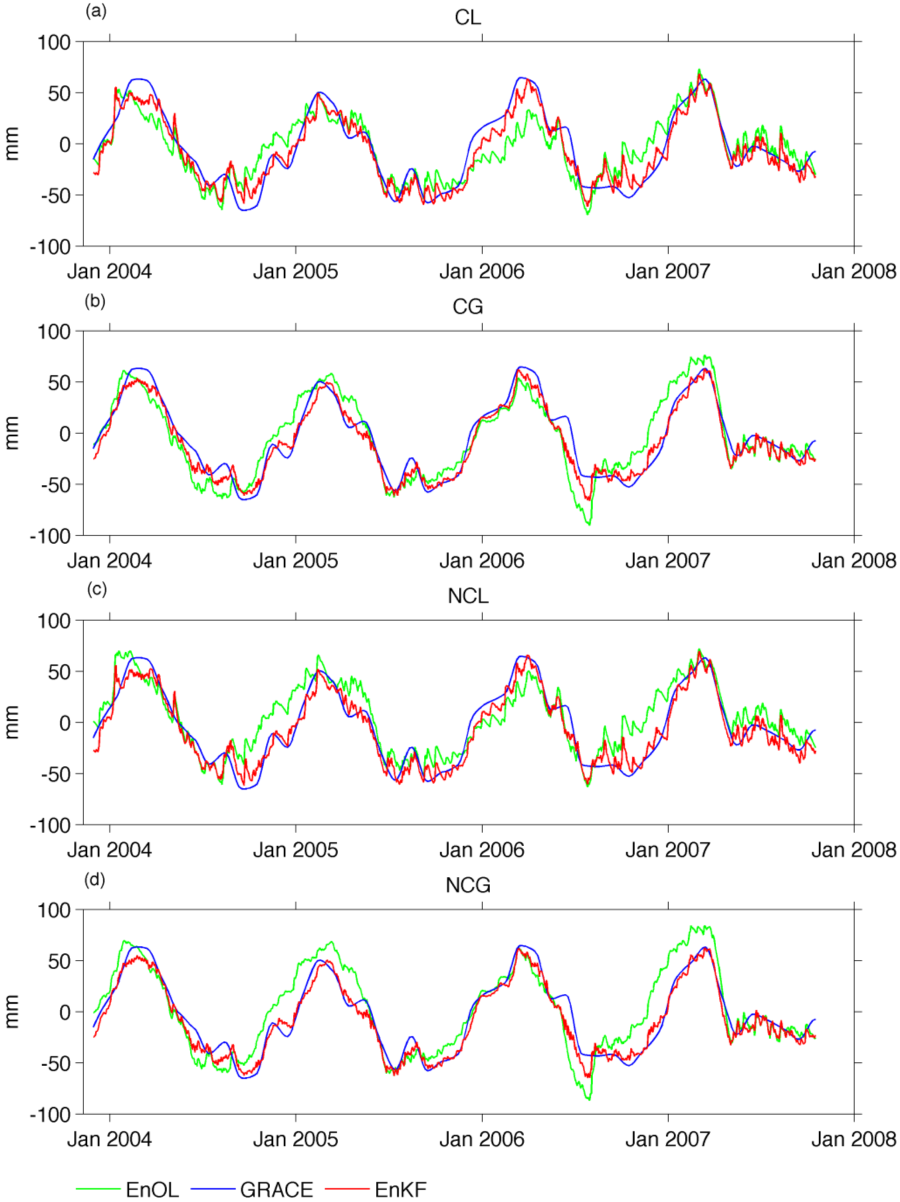
Assimilation of GRACE in a hydrology model

(Rhine River)



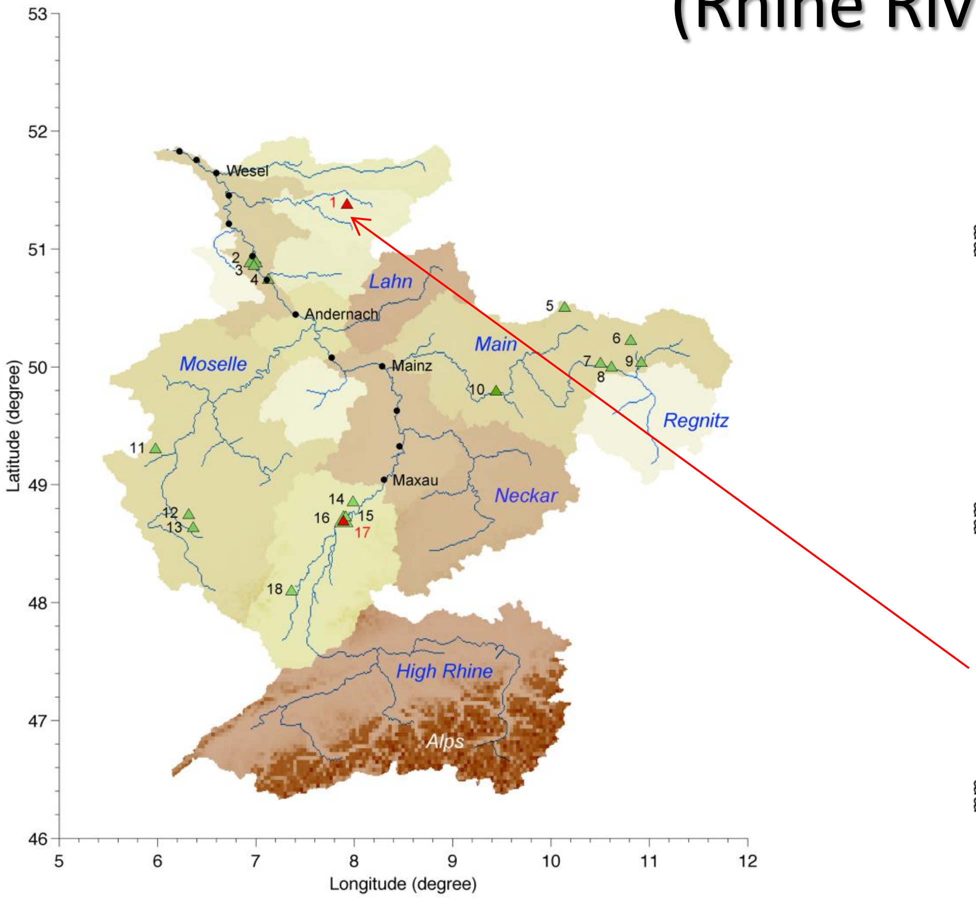


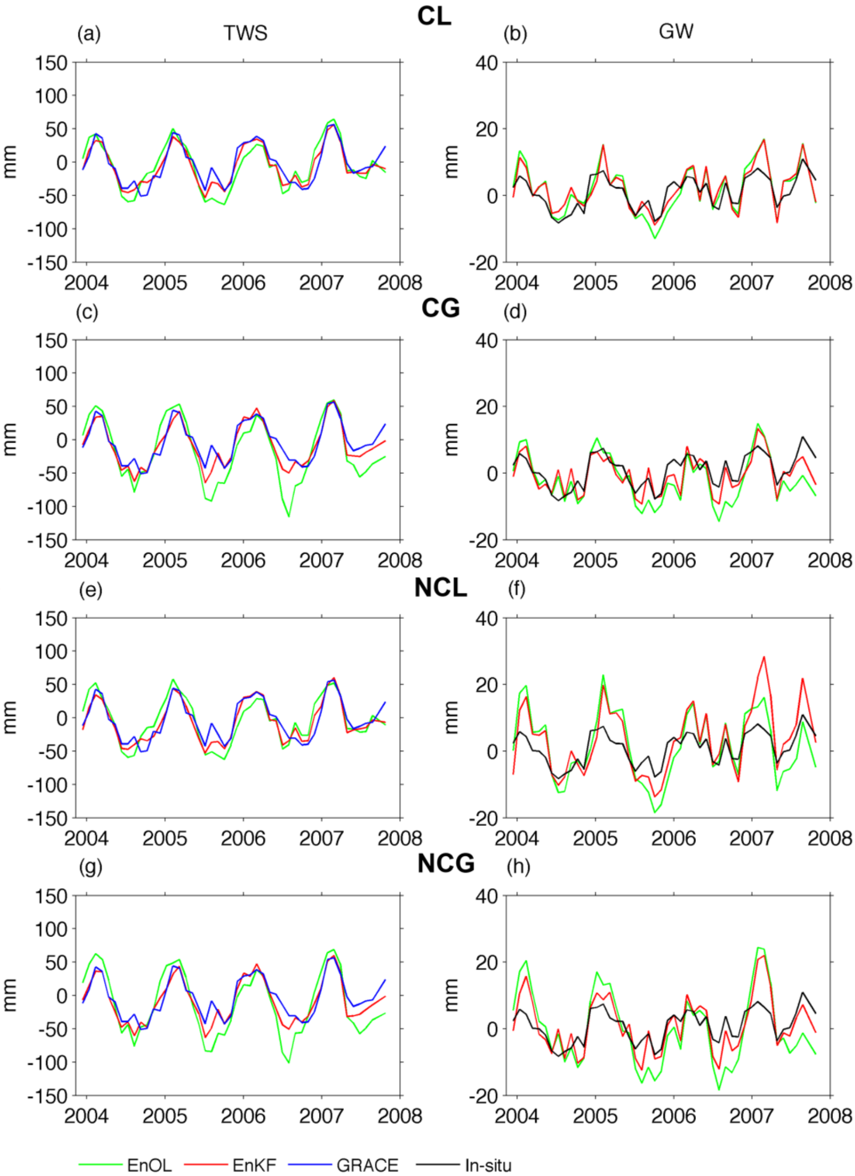
Area-averaged mean terrestrial water storage over the Rhine River basin from the EnOL, EnKF, and GRACE observations (4 different scenarios).

from Tangdamrongsub et al., 2015.

Assimilation of GRACE in a hydrology model

(Rhine River)



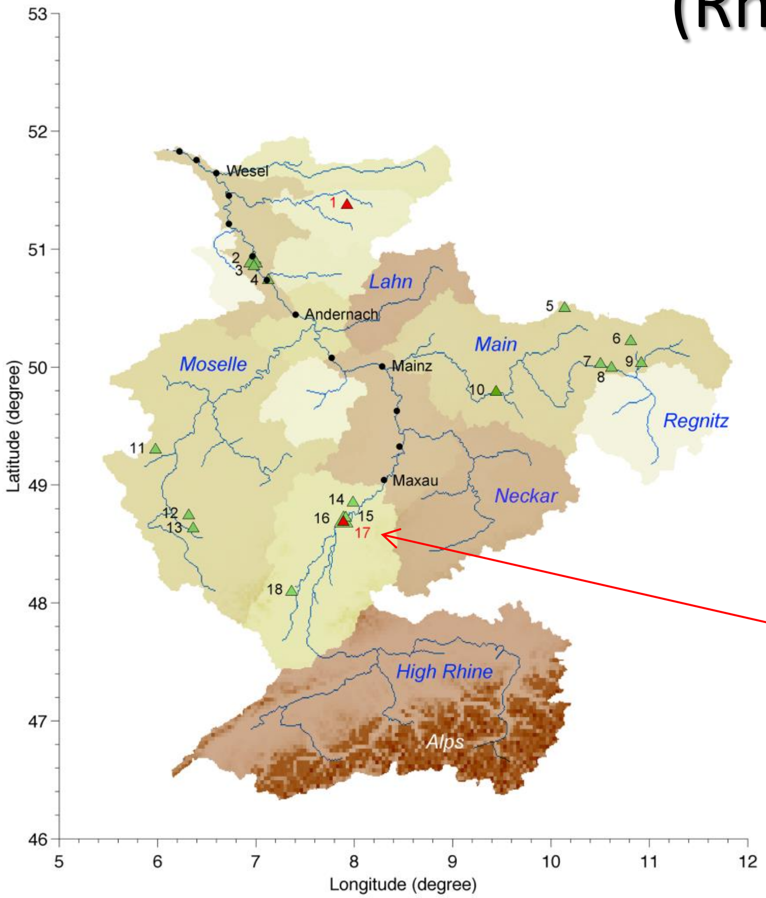


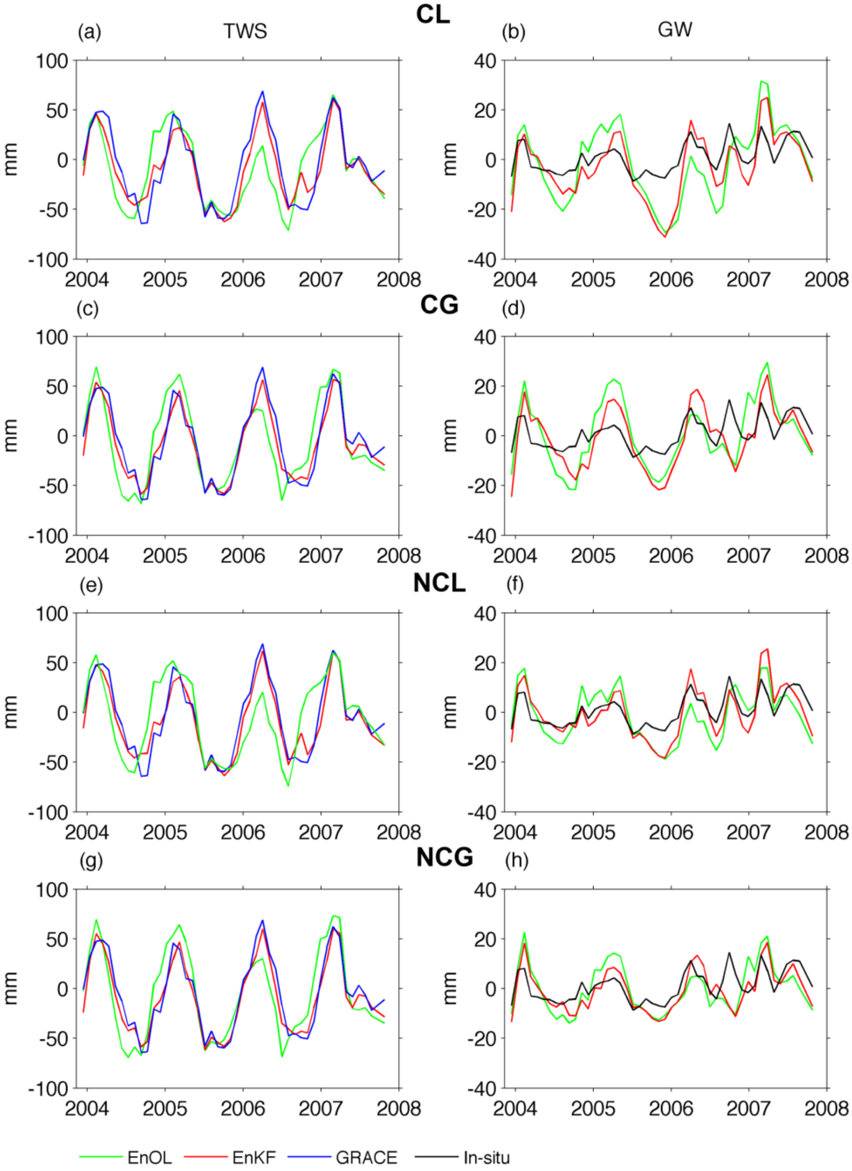
TWS variation (left panels) and GW variation (right panels) at the Sundern well location(4 different scenarios).

from Tangdamrongsub et al., 2015.

Assimilation of GRACE in a hydrology model

(Rhine River)





TWS variation (left panels) and GW variation (right panels) at the A319C well location(4 different scenarios).

from Tangdamrongsub et al., 2015.

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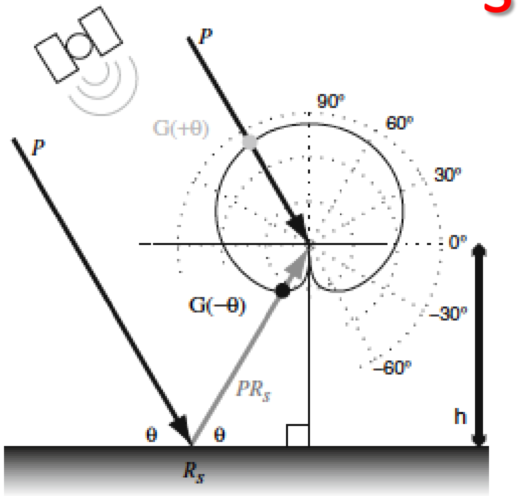
Using GPS multi-paths to measure soil-moisture and snow



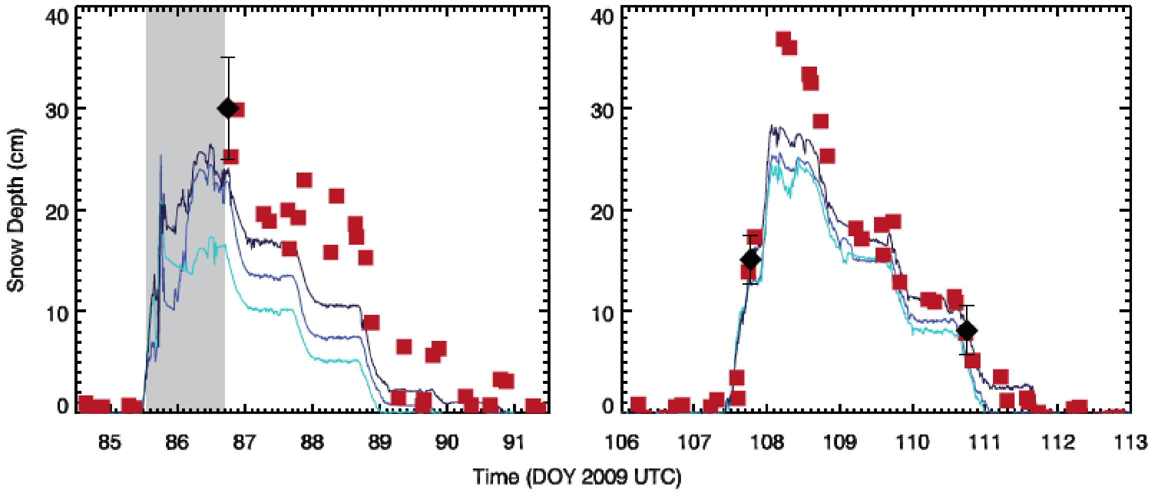


Figure 3. Snow depth derived from GPS (red squares), the three ultrasonic sonic snow depth sensors (blue lines) and field measurements (black diamonds). Bars on field observations are one standard deviation. GPS snow depth estimates during the first storm (doy 85.5–86.5) are not shown (gray region) because the SNR data indicate that snow was on top of the antenna.

from Larson et al., 2008; 2009.

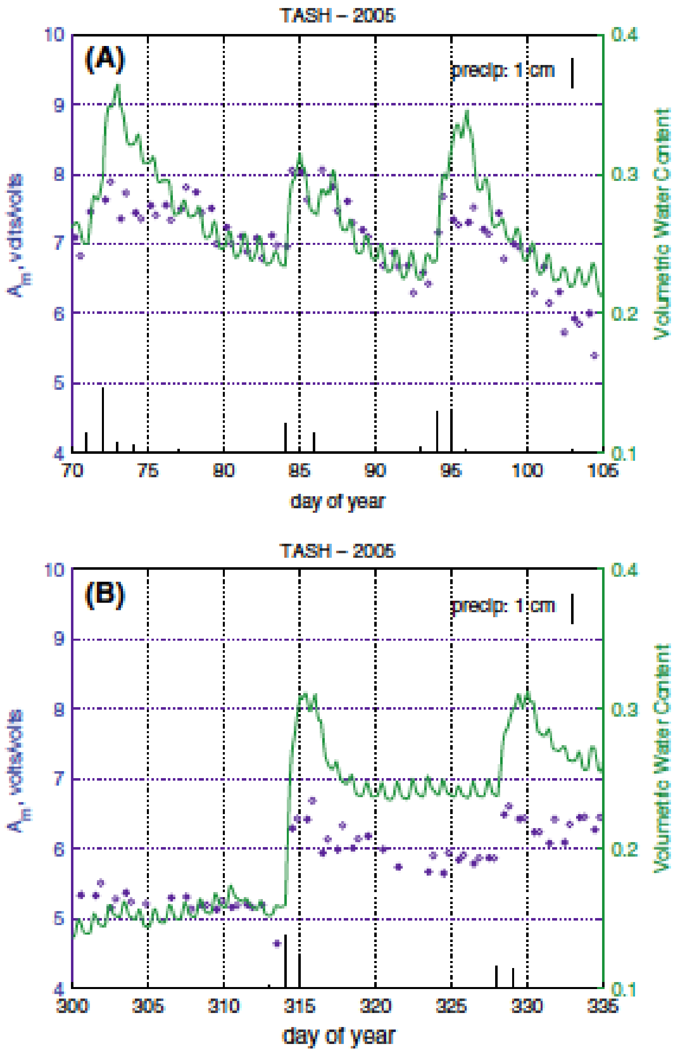
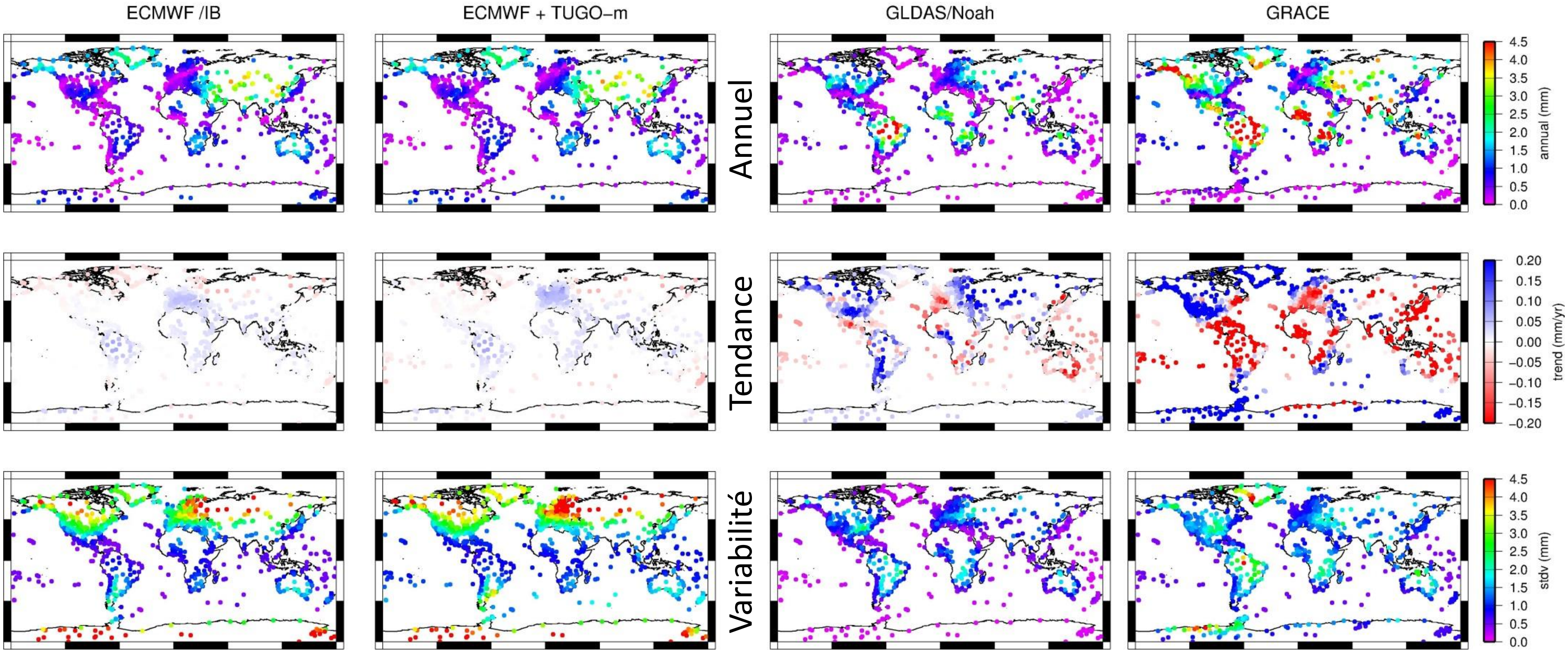


Fig. 5 Comparison of GPS multipath amplitudes and volumetric water content. *Open circles* are PRN 1 and *closed circles* are PRN 9. Daily precipitation values from a nearby airport are shown for comparison. **a** days 70–105; **b** days 300–335

Vertical displacements due to atmospheric & hydrological loading



Atmospheric loading with different ocean responses (IB vs TUGO-m)

Hydrological loading from GLDAS/Noah and GRACE

Time-series available at: http://loading.u-strasbg.fr

Vertical displacements and precipitation

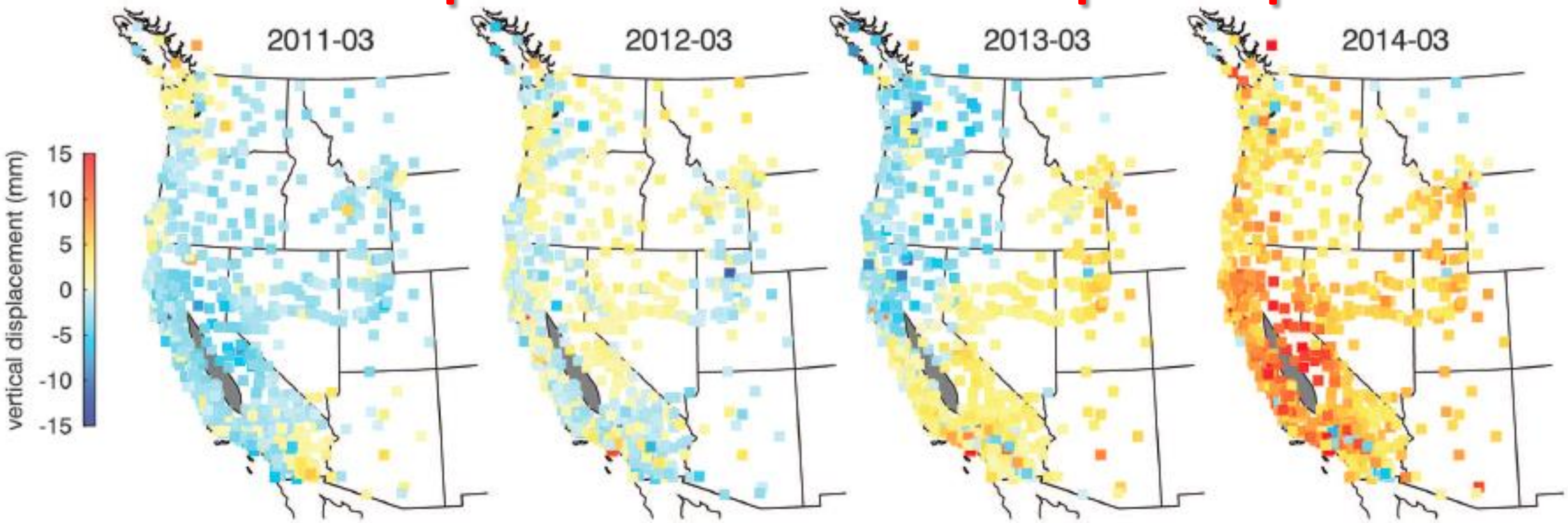


Fig. 2. Maps of vertical GPS displacements. Spatial distribution of displacements from the time series in Fig. 1, from 1 March 2011 through 2014. Uplift is indicated by yellow-red colors and subsidence by shades of blue. The gray region is where stations were excluded in the Central Valley of California.

from Borsa et al., 2014.

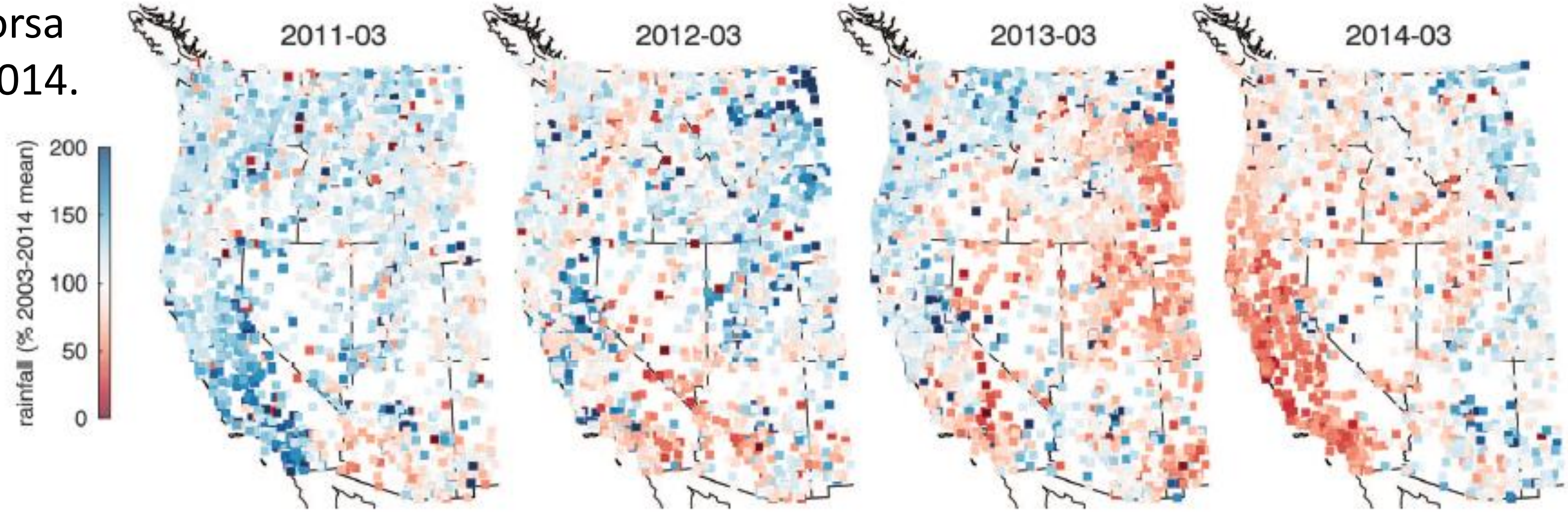


Fig. 4. Maps of annual precipitation anomalies. Deviation of annual precipitation from the 2003-to-2013 mean at meteorological stations in the National Oceanic and Atmospheric Administration's Global Historical Climatology Network, for 2011 to 2014. The pattern of precipitation—in particular, the surplus in California in 2011 and the deficit in 2014—mirrors the pattern of uplift seen in the GPS data.

Mass variations in California estimated from a dense GPS network

from Argus et al., 2014.

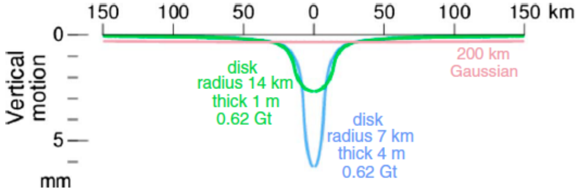


Figure 1. (Green curve) Vertical motion in elastic response to unloading of a disk with a radius of 14 km and a water thickness of 1 m. This disk has the same area as a pixel at 36°N that we estimate water thickness for (1/4° latitude by 1/4° longitude). (Blue curve) Vertical motion in elastic response to unloading of a disk with a radius of 7 km and a water thickness of 4 m. This disk has the same area as 1 NLDAS pixel at 36°N (1/8° latitude by 1/8° longitude). The Green's functions for PREM are used [*Wang et al.*, 2012]. (Pink curve) Vertical motion that would be inferred by GRACE is approximated by a Gaussian distribution with a half width of 200 km. "Gt" is gigatons (10^{12} kg).

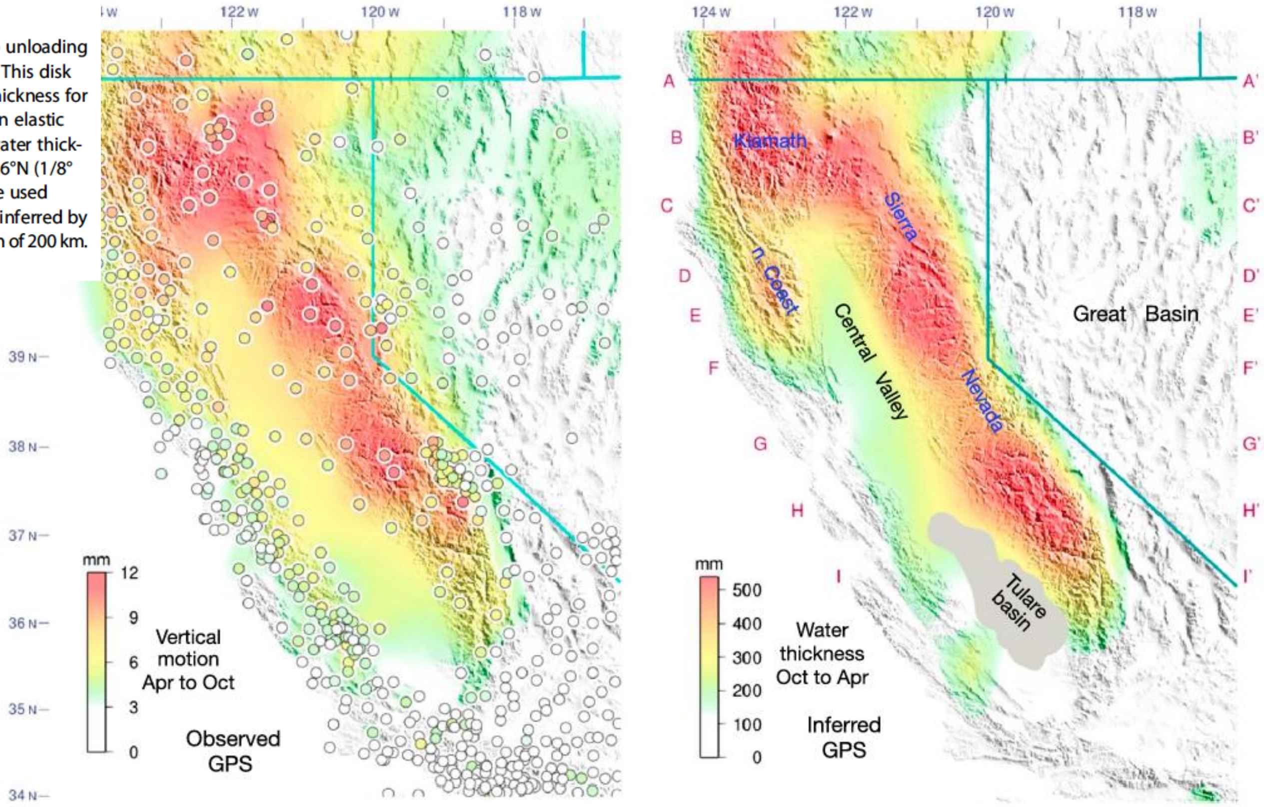
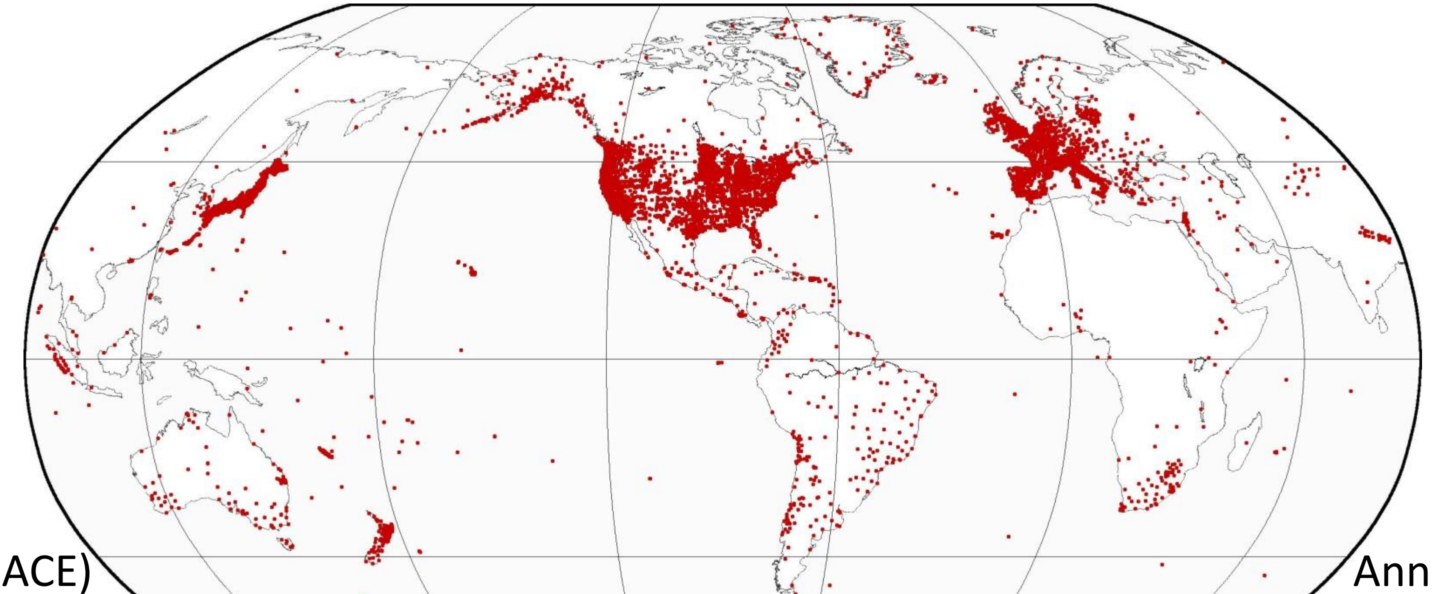


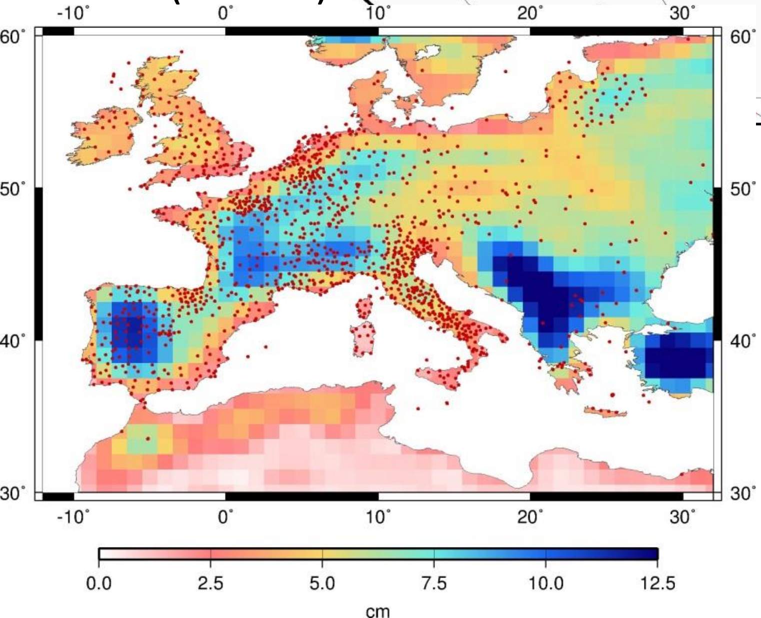
Figure 2. (left) Average uplift in the spring and summer observed with GPS is compared with (right) the inferred average increase in equivalent water thickness in the fall and winter. (Figure 2, left) Average uplift at GPS sites (circles) from 1 April to 1 October. The colors of the circles indicate the value of uplift. Seasonal uplift throughout California and Nevada (color gradations) is inferred by fitting a continuous, curved surface to the GPS estimates using GMT program Surface. (Figure 2, right) Average increase in equivalent water thickness (color gradations) from 1 October to 1 April is inferred by inverting the GPS vertical estimates as described in the main text. Seasonal water change in the Tulare basin (shaded gray) is poorly constrained by GPS. The letters (A through I) are at the endpoints of the cross sections along lines of constant latitude in Figure 4 and S4.

Permanent GPS stations

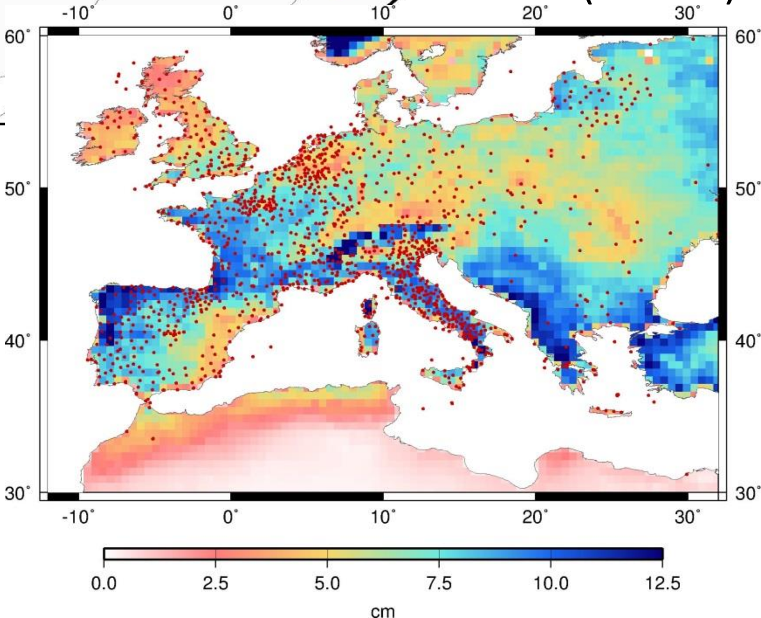
(duration ≥ 5 years)



Annual (GRACE)



Annual (GLDAS)



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Mass variations from space geodesy

- In spite of its limitations (10-day to monthly and a few 100s of km sampling), GRACE is the unique tool to measure mass variations from space.
- Precise estimation of ice-sheet mass changes, in addition to radar/laser altimetry measurements.
- For continental hydrology, the separation of the different storage components (surface water, snow, soil-moisture, groundwater) requires additional space and/or in-situ measurements & hydro. models.
- We are moving towards assimilating GRACE into hydro. models.

Mass variations from space geodesy

- GPS measurements can give additional assessments of continental water storage variations; the multi-path method gives local “surface” soil-moisture estimates and snow height.
- Inversion of vertical (and horizontal) displacements observed by GPS provides valuable mass estimates supplementary to GRACE (resolutions of typically 1-day and 10s of kms).
- However, very dense networks are required (only Continental US, Europe and Japan currently possible). Processing so many stations is not trivial!
- Next step is a joint inversion of GPS and GRACE…