Supplementary files for

GRACE Water Storage Estimates for the Middle East and Other Regions with Significant Reservoir and Lake Storage

Submitted to HESS

In discussion in HESSD

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1. Numerical Experiment 1

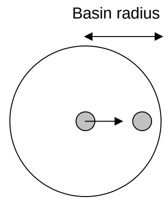
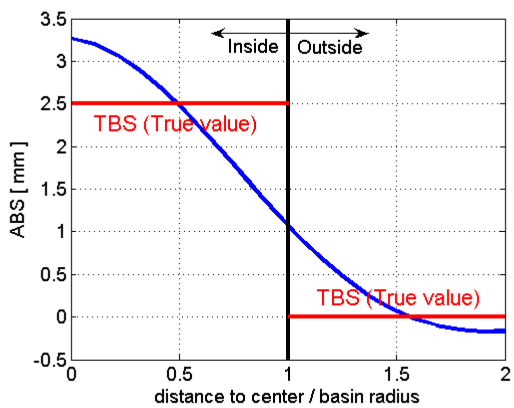
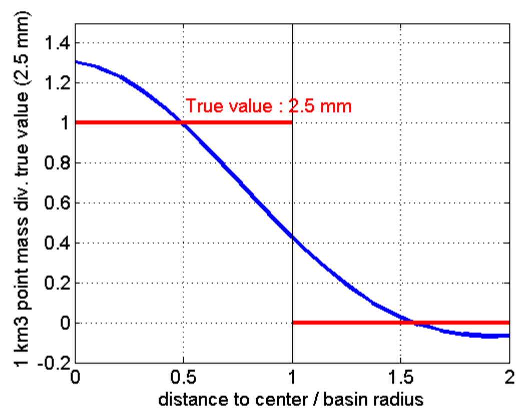


Figure S1 : Experiment 1: Contours of ABS (apparent basin storage) in mm of water due to a 1 km^3 point mass within a circular basin as a function of location relative to basin center (Ratio distance to center versus basin radius) and basin area (M km^2, horizontal axis). TBS (true basin storage, distributing the mass uniformly on the basin) is provided on top of the graphs. ABS is given as [mm] on the left to estimate detectability of point masses on GRACE, and as reduced to TBS on the right, to investigate the apparent amplification or damping of point masses on GRACE compared to TBS

Degree 50, no smoothing, basin size 0.4 M km²





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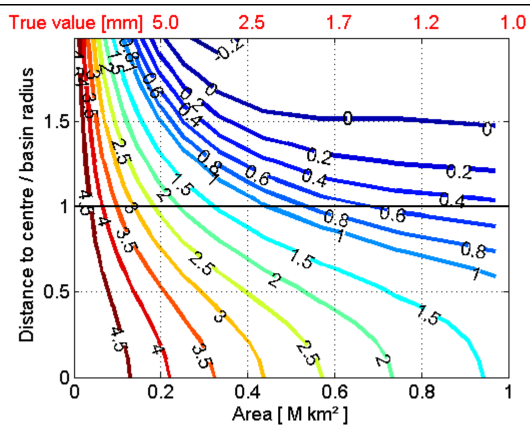

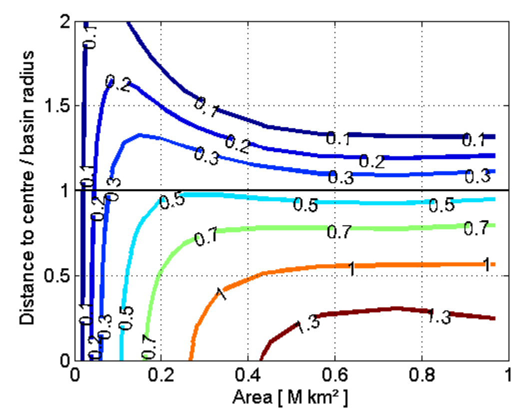

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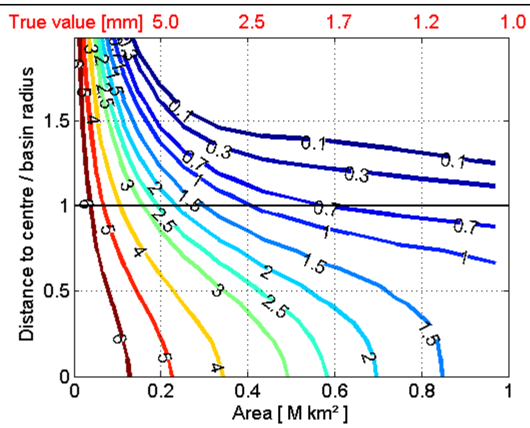

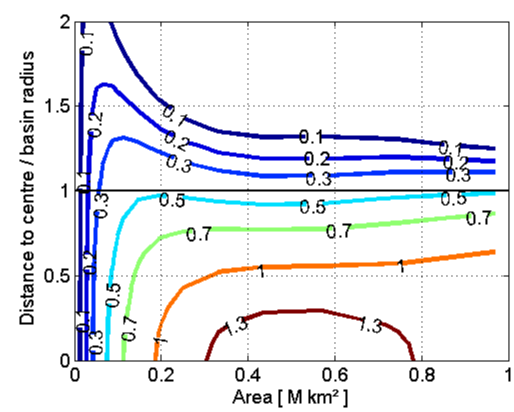

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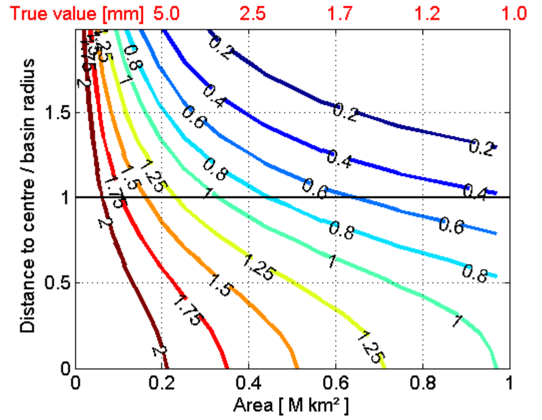
<td>
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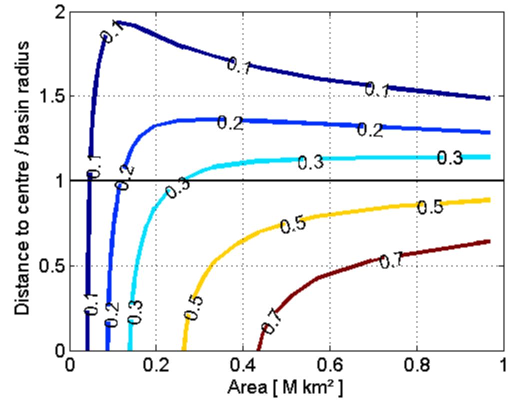
<td>
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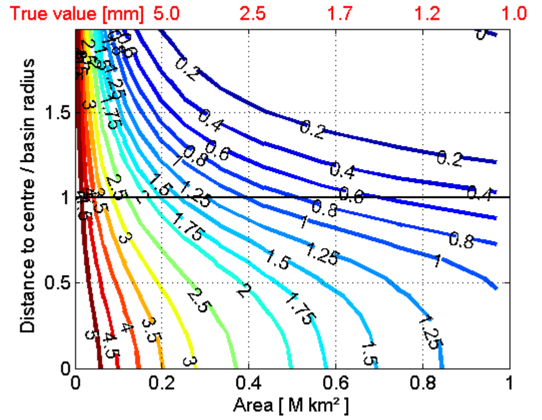
<td>
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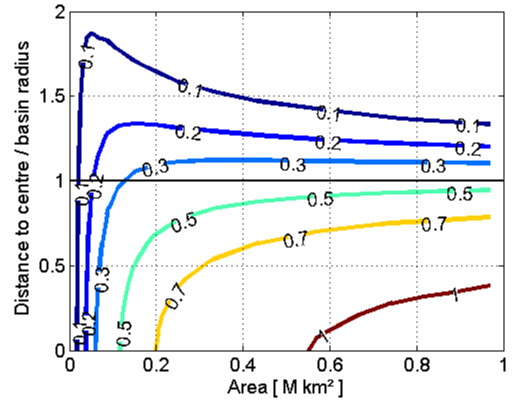
<td>
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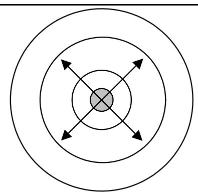
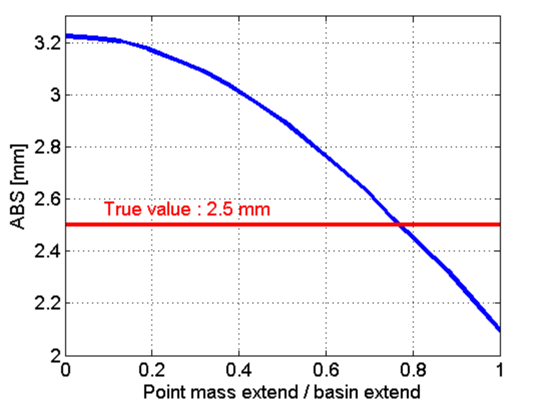
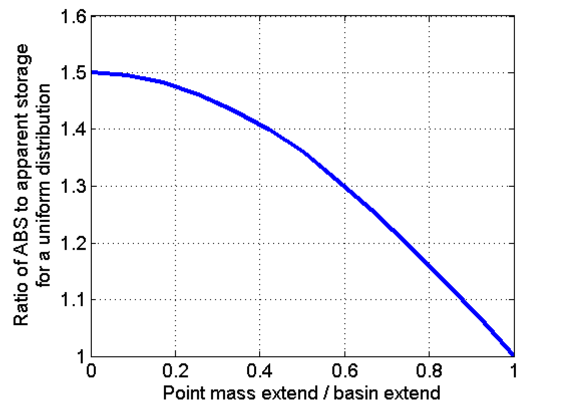
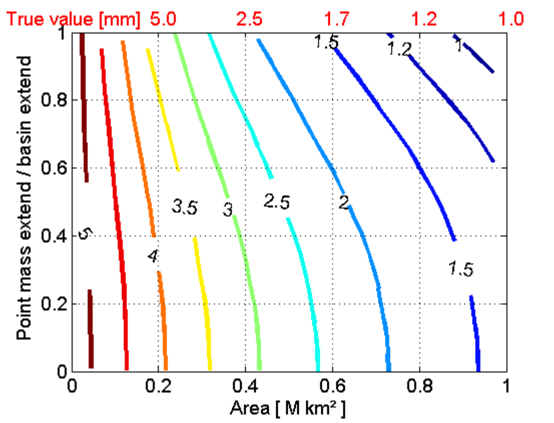
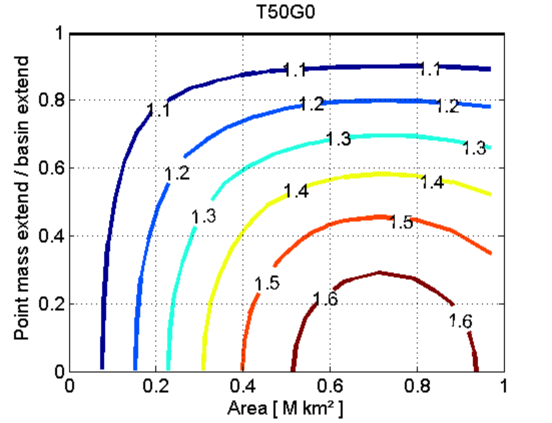
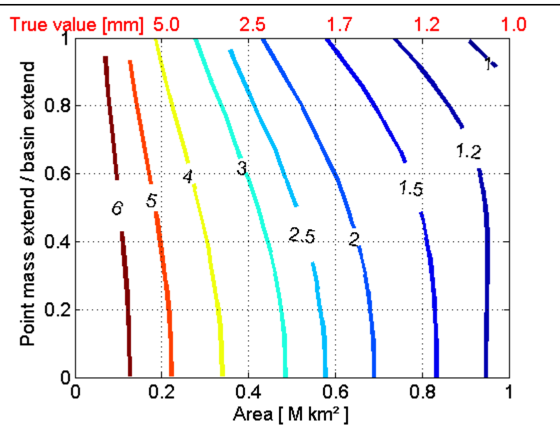
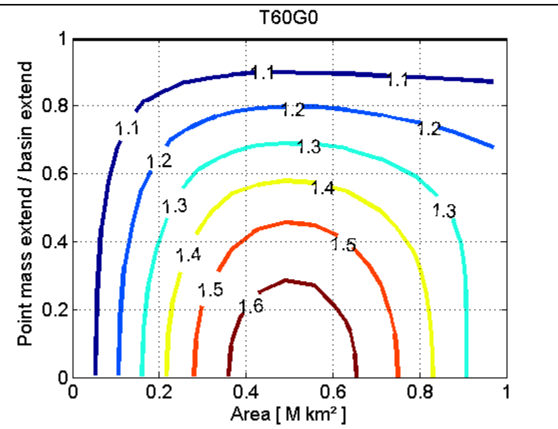
2. Numerical Experiment 2

	Figure S2: Experiment 2: Mass is focused at the basin center, but its size is varied symmetrically. Contours give ABS of the impact of a 1 km^3 mass uniformly distributed, in [mm] on the left, reduced to the impact on GRACE of the same mass distributed over the basin on the right. The upper axis includes the corresponding true basin storage (1 km3 storage volume divided by corresponding basin area). T50G0 refers to truncation to degree 50 and zero Gaussian smoothing.	
Degree 50, no smoothing, basin size 0.4 M km²		
Degree 50, no smoothing		
Degree 60, no smoothing		

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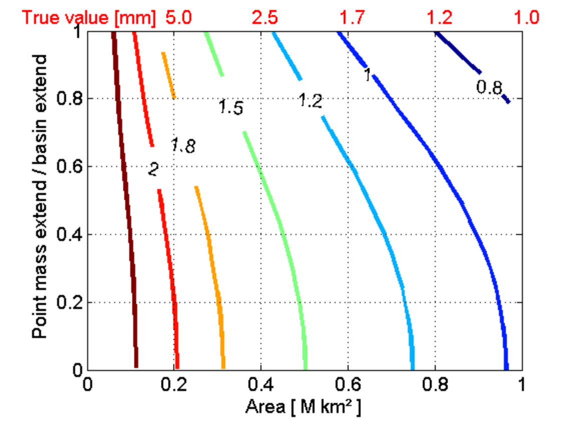
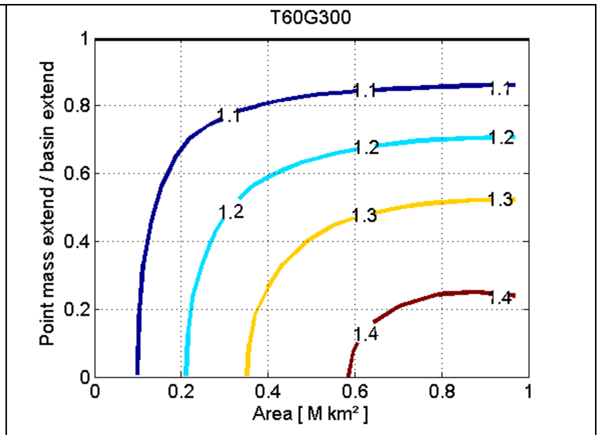
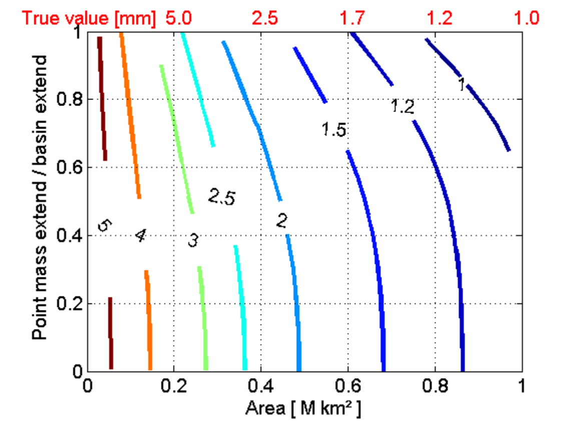
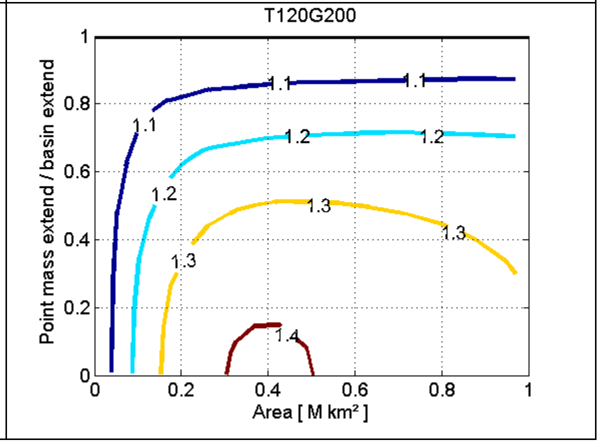




Degree 120, 200-km Gaussian smoother





3. Table S1: Lake and Reservoir Data Summary.

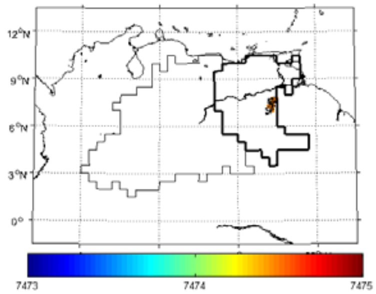
Region	Lake name	Area [km^2]	Variability [km^3]	Volume / Level data
Lower Nile (410 000 km^2)	**Aswan**	**6200 km^2**	**16 km^3**	**Level**
Lower Orinoco (350 000 km^2)	**Guri**	**3919 km^2**	**23 km^3**	
Tigris-Euphrates (790 000 km^2)	**TOTAL**	**15300 km^2**	**24 km^3**	
	Asad	447	0.30	Level
	Ataturk	707	1.6	Level
	Daryace	5200	3.7	Volume
	Mossoul	285	1.8	Level
	Qadisiyah	415	3.3	Volume
	Razazah	1501	1.9	Level
	Saksak	458	1.7	Volume
	Tharthar	2500	8.3	Level
	Van	3755	1.0	Level
East Africa (1 125 000 km^2)	**TOTAL**	**175144 km^2**	**86 km^3**	
	Albert	5270	2.9	Level
	Bangwelu	9840	3.9	Level
	Cahora Bassa	2739	5.6	Level
	Edouard	2150	0.48	Volume
	Kariba	5400	10.6	Level
	Kivu	2700	0.63	Level
	Kyoga	1720	1.2	Level
	Malawi	29500	14	Level
	Mweru	5120	3.0	Level
	Rukwa	2600	2.3	Level
	Tanganyka	32900	12	Level
	Turkana	6405	4.6	Level
	Victoria	68800	25	

4. Tigris-Euphrates Basin – Land Surface Model (LSM) Estimates

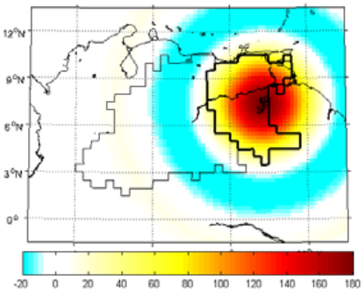
Table S2: Comparison between GRACE TWS, ΔSMS+ΔSWES from CLM, NOAH, MOSAIC, and VIC *LSMs and ΔRESS for Tigris-Euphrates basin. In all cases, adding predicted ΔRESS contribution to LSM output results in better agreement with GRACE data*

	GRACE CSR	CLM	CLM + ΔRESS	MOSAIC	MOSAIC + ΔRESS	NOAH	NOAH + ΔRESS	VIC	VIC + ΔRESS	WGHM	WGHM + ΔRESS
Amplitude of seasonal variations [mm]	**63.1**	22.7	**23.4**	56.6	**62.9**	44.2	**45.2**	47.7	**49.1**	39.7	**40.8**
Phase (seasonal) [days]	**Ref.**	-36	**-15**	-16	**-1.2**	-29	**-17**	-26	**-16**	-29	**-16**
Correlation	**Ref.**	0.80	**0.89**	0.93	**0.95**	0.88	**0.93**	0.82	**0.93**	0.86	**0.92**
RMS with GRACE [mm]	**Ref.**	47	**38**	25	**20**	34	**25**	37	**27**	36	**28**
Trend (2002/10 - 2009/09) [mm/yr]	**-11**	- 3.2	**-7.3**	- 8.4	**-12**	-6.0	**-11**	-3.2	**-7.3**	-5.2	**-9.2**
Trend (2006/10 – 2009/09) [mm/yr]	**-39**	-7	**-26**	-21	**-39**	-18	**-37**	-7.9	**-27**	-14	**-33**

5. Lower Orinoco - Guri Dam



a)



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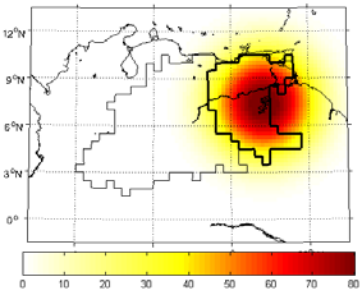
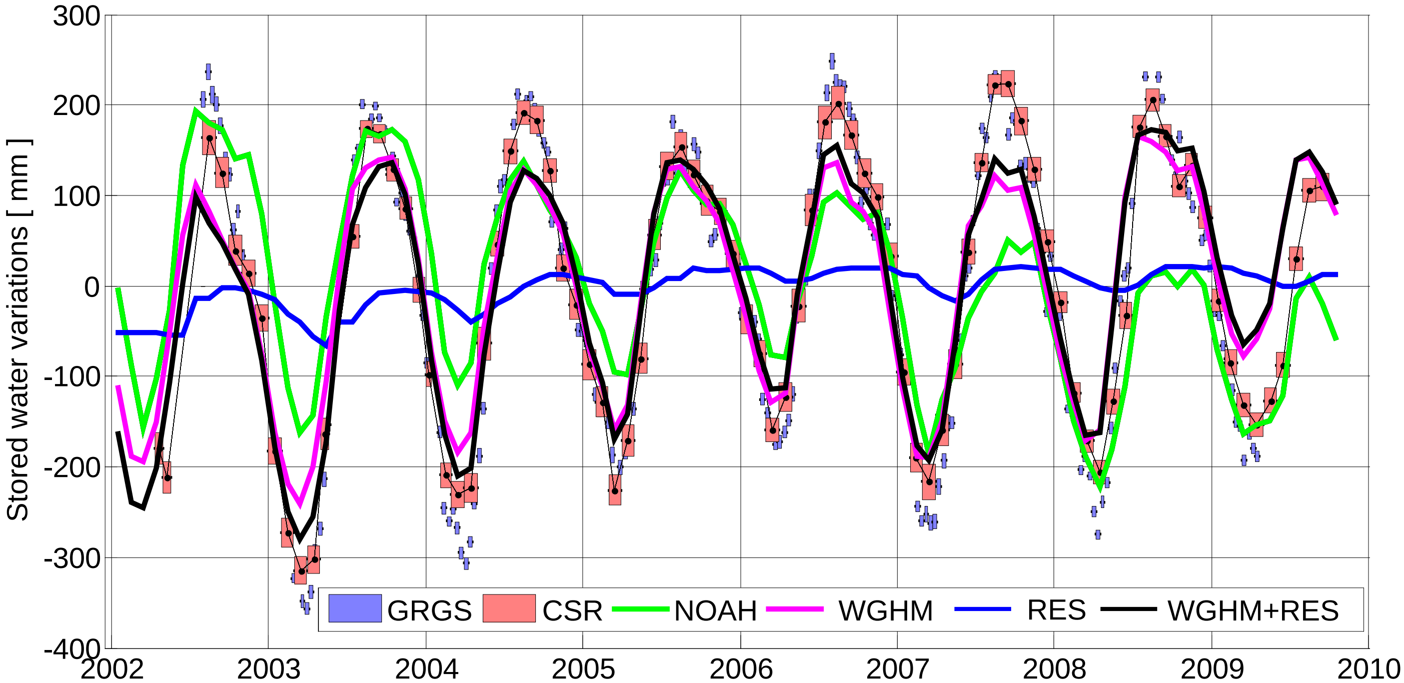
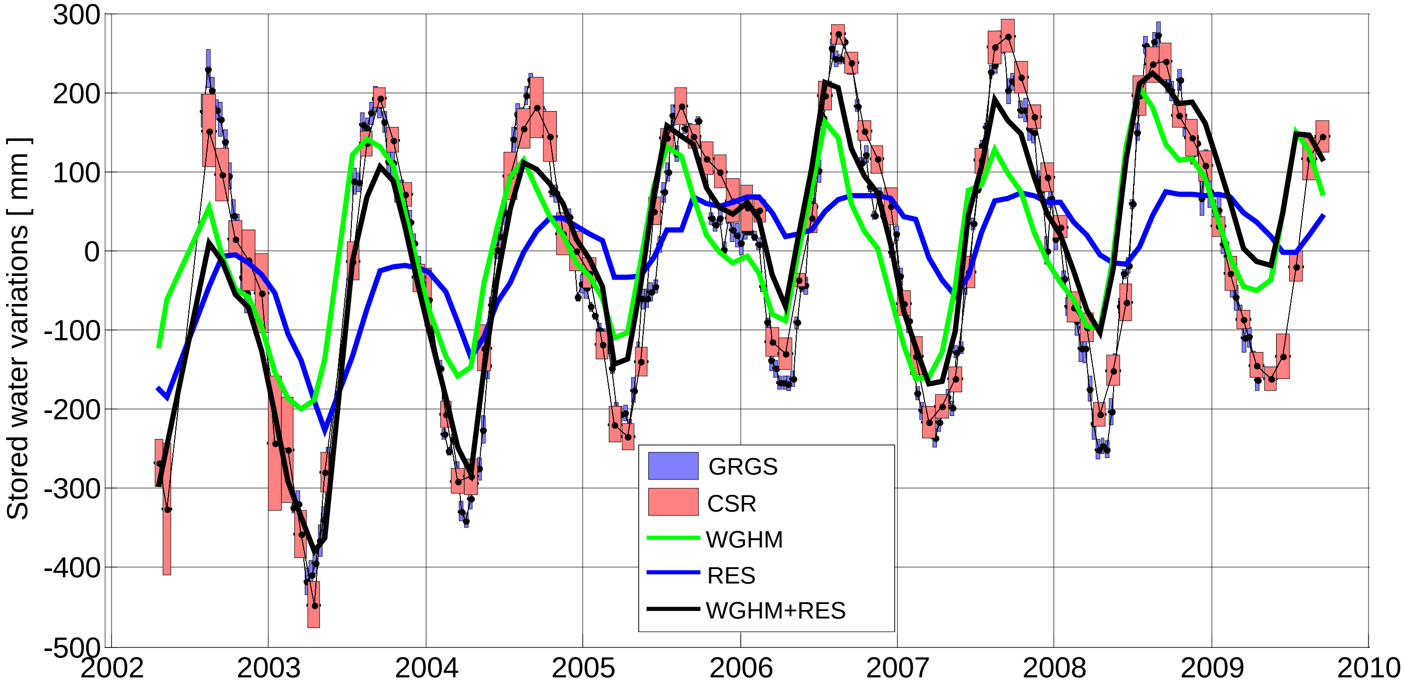


c)

d) Orinoco basin *(1 M km²)*



e) Lower Orinoco basin *(350 000 km²)*



f) Lower Orinoco Basin *(350 000 km²)*

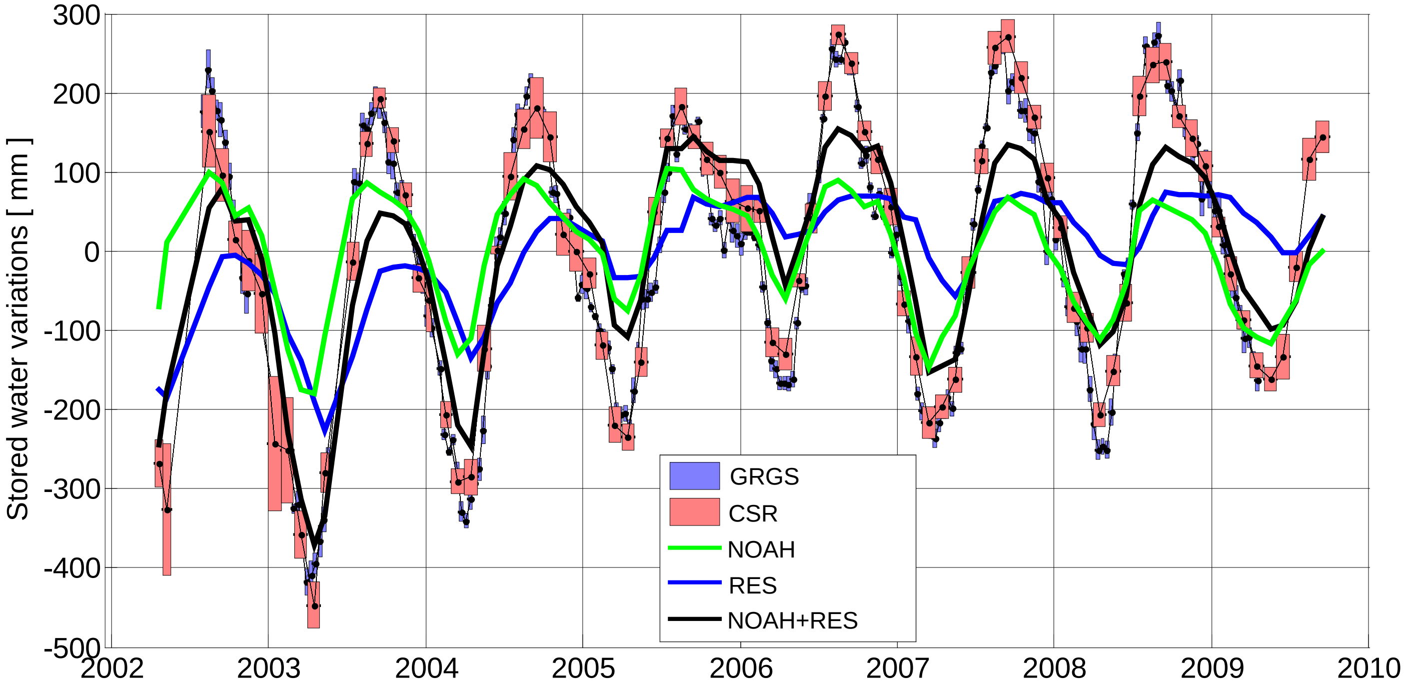


Figure S4: Lower Orinoco and Guri lake contribution. The Guri dam impounds the Caroni River (Venezuela) and creates a lake of 3919 km². The first stage of the facility was completed in 1969 and completed in 1986, as a 162-m high earth and rockfill dam with a crest length of 11 km. It is mainly used for hydropower purposes (capacity of 10 300 MW) and supplies ~50% of Venezuela's electricity. In contrast to Lake Nasser, Guri lake is located in a tropical climate with large natural storage fluctuations.

(a) Reservoir and standard deviation of Guri lake level variation within the basin,
(b) same map after truncation at degree 50 similar to GRGS processing,
(c) same map after truncation at degree 60 and 300-km Gaussian smoother applied, similar to CSR processing. The thick line represents the lower Orinoco basin, the thin line shows the Oricono basin;
(d) GRACE Water storage variations in the Orinoco basin (1 M km²) compared to GLDAS, WGHM and RESS from Guri dam,
(e) GRACE water storage variations in the Lower Orinoco basin (350 000 km²) compared to WGHM
(f) same as e but comparison with NOAH SMS . Water storage variations from the inundated area along the course of the river are not modeled in GLDAS and may explain remaining discrepancy with GRACE.

The contribution of this single reservoir is significant, similar to the soil moisture contribution modeled by NOAH, and explains 25% (50 mm) of seasonal variations in the lower Orinoco basin (350 000 km²) and shifts the phase by 15 to 20 days (Table S2). This single lake explains nearly entirely the positive trend on the investigated period (20 mm/year; 7 km3/yr), while NOAH models a decreasing trend (Table S3). At the scale of the Orinoco basin as a whole (1 M km²), the Guri lake still contributes ~ 10% of the seasonal variations in water storage, and 65% of the trend at the scale of the basin

Table S3: Comparison between GRACE, ΔSMS and ΔRESS for the Lower Orinoco basin (350 000 km^2)

	GRACE CSR	ΔRES Contribution to GRACE	NOAH	NOAH + ΔRESS	WGHM	WGHM + ΔRESS
Seasonal amplitude [mm]	**199**	51 (25%)	85	**129**	116	**143**
Phase (seasonal) [days]	**Ref.**	+39	-14	**0**	-28	**-8**
Correlation	**Ref.**		0.87	**0.93**	0.84	**0.91**
Trend [mm/yr]	**22**	20	-4.6	**16**	16	**36**
Trend [km^3/yr]	**7.7**	7	-1.6	**5.6**	5.6	**12.6**

Table S4: Comparison between GRACE, ΔSMS and ΔRES for Orinoco basin (1 M km^2)

	GRACE CSR	ΔRES Contribution to GRACE	NOAH	NOAH + ΔRESS	WGHM	WGHM + ΔRESS
Seasonal amplitude [mm]	**185**	16.5 (9%)	113	**127**	146	**156**
Phase (seasonal) [days]	**Ref.**	+44	+7	**+11**	-10	**-5**
Correlation	**Ref.**		0.78	**0.83**	0.93	**0.95**
Trend [mm/yr]	**8.1**	5.3	-23	**-18**	10	**16**
Trend [km^3/yr]	**8.1**	5.3	-23	**-18**	10	**16**

1. East African Lakes

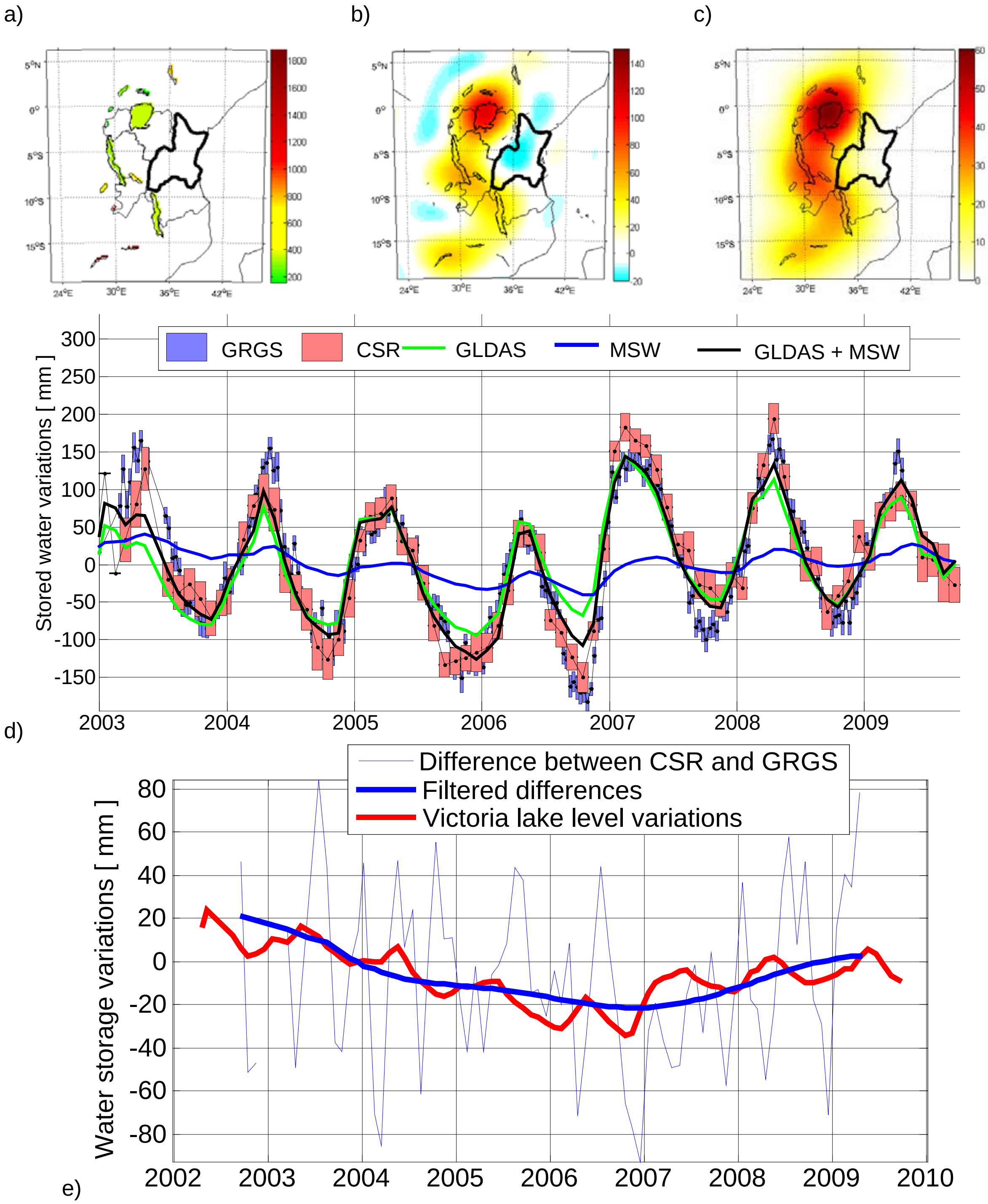


Figure S5: This example illustrate the East African lake contribution to GRACE from Xie et al.,[2012].

(a) Reservoir distribution and mass variations for each of the 34 lakes, the thin outline shows Tanzania (1 125 000 km²), the thick outline shows the North Tanzanian Coastal Basin (355 000 km²). Note that most of the lakes are located at the edge or outside Tanzania. No lake is located within the North Tanzanian Coastal Basin

(b) Associated mass variations after truncation to degree 50, similar to GRGS processing,

(c) Mass variations after truncation at degree 60 with 300-km Gaussian smoothing, similar to CSR processing. Note that the predicted lake effect on GRGS and CSR shows different leakage amplitudes and signs in the North Tanzanian Coastal Basin.

(d) Comparison between lake storage, GLDAS NOAH SMS, and GRACE over Tanzania as a whole. While most of the lakes are located at the edge or outside Tanzania, the inter-annual lake contribution is significant and reaches 80 mm (min-max) over this large basin.

e) Difference between CSR and GRGS solution over the North Tanzanian Coastal Basin. As predicted, the lake effect on CSR and GRGS has different leakage signs in this region, this should show up in the data. RMS difference between CSR and GRGS is ~39 mm. After filtering high-frequency noise, the long-term residuals show a clear correlation with Lake Victoria level variations (r=0.88). While Lake Victoria is more than 300 km from the outline of the North Tanzanian Coastal basin, leakage from this lake is still important, and explains the differences between the two different GRACE processing strategies (CSR and GRGS).