

1 **Auxiliary material for paper 2011WR011312**

2 **Ground Referencing GRACE Satellite Estimates of Groundwater Storage Changes in the**
3 **California Central Valley, US**

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11 **Introduction**

12 The auxiliary material includes five sections: Section 1, information on regular GRACE
13 processing, Section 2, a list of the 26 major reservoirs in the Sacramento and San Joaquin
14 River Basins, Section 3, Comparison of Different Filters to Remove Seasonal Signals and High
15 Frequency Noise, Section 4, Comparison of Groundwater Storage Changes from CSR and
16 GRGS, and Section 5 Spatial Analysis of Mass Anomaly.

17 **Section 1. Regular Processing of Total Water Storage Changes**

18 A regular processing approach was used to estimate changes in TWS as shown in Fig. 3
19 and described in Longuevergne et al. (2010). Changes in TWS were not used to calculate
20 changes in GWS in this study but were calculated to compare CSR and GRGS data and to
21 compare TWS changes with precipitation. Changes in TWS were estimated by applying
22 spherical harmonics (SH) to GRACE data and filtering the SH. Filtering refers to truncation to
23 degree 50 for GRGS data and truncation to degree 60 for CSR data, followed by application of a
24 destriping filter to remove north-south stripes in CSR data and a Gaussian smoothing filter at
25 300 km for CSR data only. Because filtering removes signal along with high frequency noise,
26 the signal needs to be restored. The terminology used to restore the signal amplitude varies
27 among studies. Longuevergne et al. (2010) distinguish bias corrections relative to masses within
28 a basin from leakage corrections related to variations in masses outside the basin. However,
29 Wahr et al. [1998] and Swenson and Wahr [2002] consider “leakage” to include effects of both
30 variations within the basin and variations external to the basin. Bias and leakage corrections
31 were applied to restore signal amplitude for TWS following procedures outlined in
32 Longuevergne et al. (2010). The theoretical basin function should be 1 inside the basin and 0
33 outside. Because of filtering, the basin function is generally less than 1 inside the basin or is

34 biased and is often greater than 1 outside the basin. Bias correction inside the basin was
35 calculated by filtering the theoretical function using the different filtering approaches described
36 previously for CSR and GRGS data. A rescaling or multiplicative factor was then calculated from
37 the ratio of the filtered versus unfiltered theoretical function. Leakage of signal into the basin
38 requires use of a-priori information, mainly National Land Data Assimilation System (NLDAS) for
39 soil moisture storage (SMS), SNODAS for snow water equivalent (SWE), and reservoir storage
40 (RESS) and USGS Central Valley hydrologic model for groundwater storage (GWS) as a-priori
41 data.

42 Uncertainty in total water storage (TWS) changes was estimated from GRACE
43 measurement uncertainties and propagation of LSM errors into the bias and leakage processing
44 step. GRACE measurement error was estimated from residuals over the Pacific Ocean at the
45 same latitude as the Sacramento and San Joaquin River Basins (Chen et al. 2009), ~ 14 mm
46 (2.2 km^3) for CSR and GRGS solutions. The resultant error in TWS changes is 18 mm (10 d,
47 GRGS) to 22 mm (monthly, CSR) ($2.8 - 3.4 \text{ km}^3$) after propagation of LSMs error into the
48 bias/leakage mathematical process. The root mean square difference between CSR and GRGS
49 solutions (~27 mm, 4.2 km^3) based on propagation of LSMs error may be underestimated.

50 **References:**

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- 54 Longuevergne, L., B. R. Scanlon, and C. R. Wilson (2010), GRACE Hydrological estimates for
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56 *Resources Research*, 46.
- 57 Swenson, S., and J. Wahr (2002), Methods for inferring regional surface-mass anomalies from
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59 *Journal of Geophysical Research-Solid Earth*, 107(B9).
- 60 Wahr, J., M. Molenaar, and F. Bryan (1998), Time variability of the earth's gravity field: Hydrologic
61 and oceanic effects and their possible detection using GRACE, *J. Geophys. Res.*, 103,
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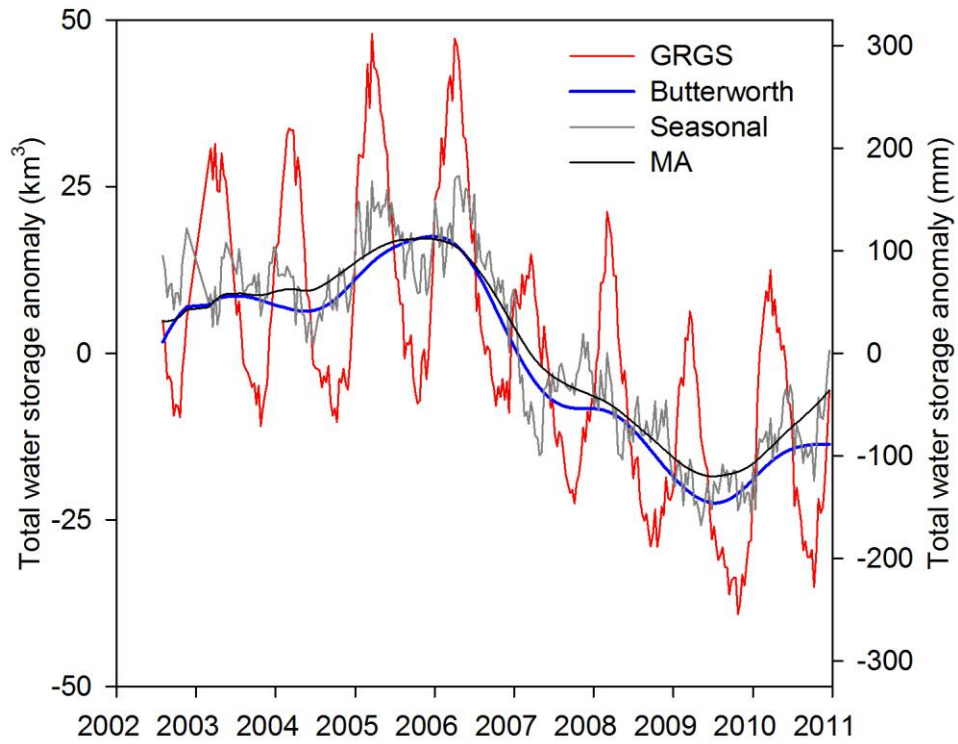
66 **Section 2. Distribution of Major Reservoirs in the Sacramento/San Joaquin River Basins.**

67 2011WR011312-ts01.txt; Table S1. Major reservoirs (26) used to calculate reservoir storage
68 changes in the Sacramento/San Joaquin river basins (www.water.ca.gov).

Reservoir	Storage Capacity	Reservoir	Storage Capacity
	km ³		km ³
Shasta	5.61	Warm Springs	0.47
Oroville	4.36	Hetch/Hetchy	0.44
Trinity	3.02	Castaic	0.40
Melones	2.98	New Hogan	0.39
San Luis	2.51	Whiskeytown	0.30
Don Pedro	2.50	Pardee	0.24
Exchequer	1.26	Kaweah	0.23
Pine Flat	1.23	Pyramid	0.21
Folsom	1.20	Buchanan	0.18
Bullards	1.19	Black Butte	0.17
Isabella	0.70	Coyote	0.15
Millerton	0.64	Beardsley	0.12
Camanche	0.51	Lake Davis	0.10

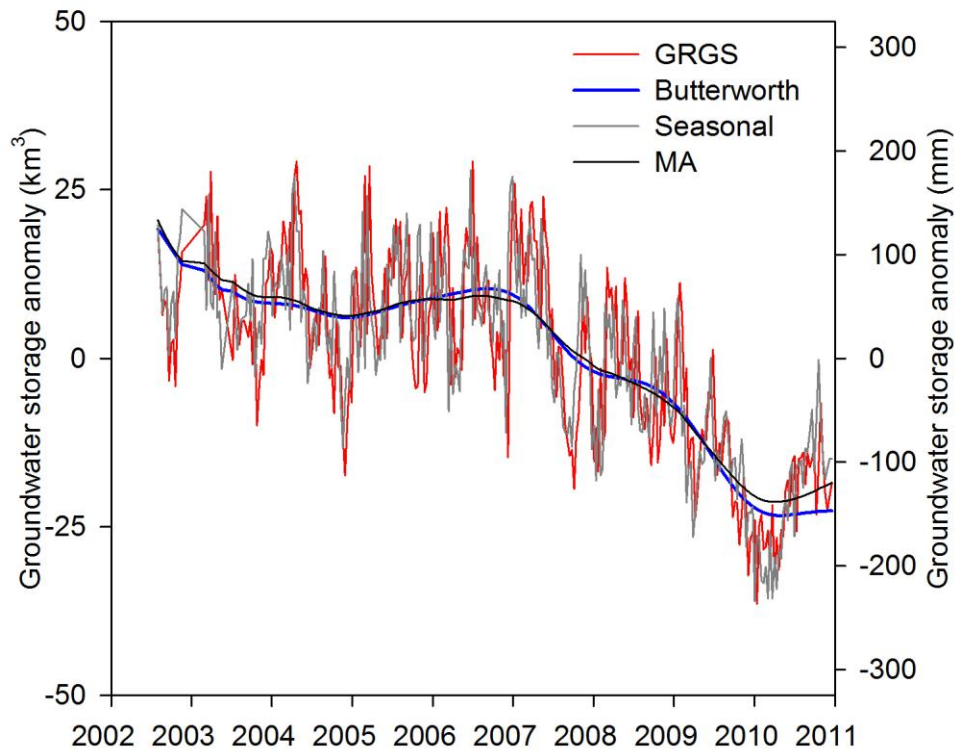
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70 **Section 3. Comparison of Different Filters to Remove Seasonal Signals and High**
71 **Frequency Noise**

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73 Trends and magnitudes in water storage changes can be calculated from the raw data or
74 from temporally filtered data to remove seasonal fluctuations and high frequency noise. Results
75 of applications of a seasonal filter (6 term sine/cosine filter), Butterworth filter, and centered 12
76 month moving average filter are shown for GRGS TWS (Fig. S1) and GRGS GWS (Fig. S2).
77 The seasonal filter is more variable and the Butterworth and 12 month moving average filters
78 are similar for TWS and GWS. Maximum depletion in TWS from Jan 2006 through July 2009 is
79 43.6 ± 1.8 km³ for the seasonal filter, 40.8 ± 0.9 km³ for the Butterworth filter, and 39.9 ± 0.9 km³ for
80 the 12 mo moving average filter. Maximum depletions in GWS for Oct 2006 through Mar 2010
81 are similar for all three filters (31.2 ± 5.0 km³ seasonal; 31.0 ± 3.0 km³ Butterworth; 31.3 ± 3.0 km³
82 moving average); however, the error is greatest for the seasonal filter. Results for the seasonal
83 filter plot close to the raw data for GWS changes.



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85 2011WR011312-fs01.jpeg Figure S1 . Application of Butterworth, seasonal sine/cosine, and
 86 centered 12 month moving average temporal filters to total water storage (TWS) changes from
 87 GRGS data. Precipitation anomalies from PRISM database.



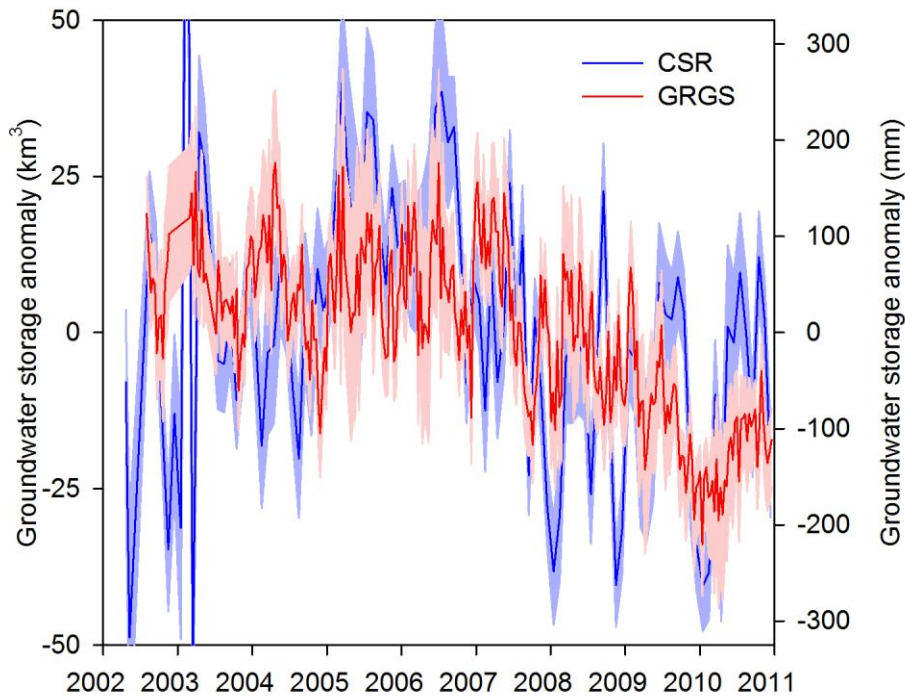
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89 2011WR011312-fs02.jpeg Figure S2 . Application of Butterworth, seasonal sine/cosine, and
 90 centered 12 month moving average temporal filters to groundwater storage (GWS) changes
 91 from GRGS data. Precipitation anomalies from PRISM database.

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93 **Section 4. Comparison of Groundwater Storage Changes from CSR and GRGS**

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2011WR011312-

96 fs03.jpeg Figure S3. Comparison of CSR and GRGS groundwater storage changes.
97 Precipitation anomaly from PRISM data.

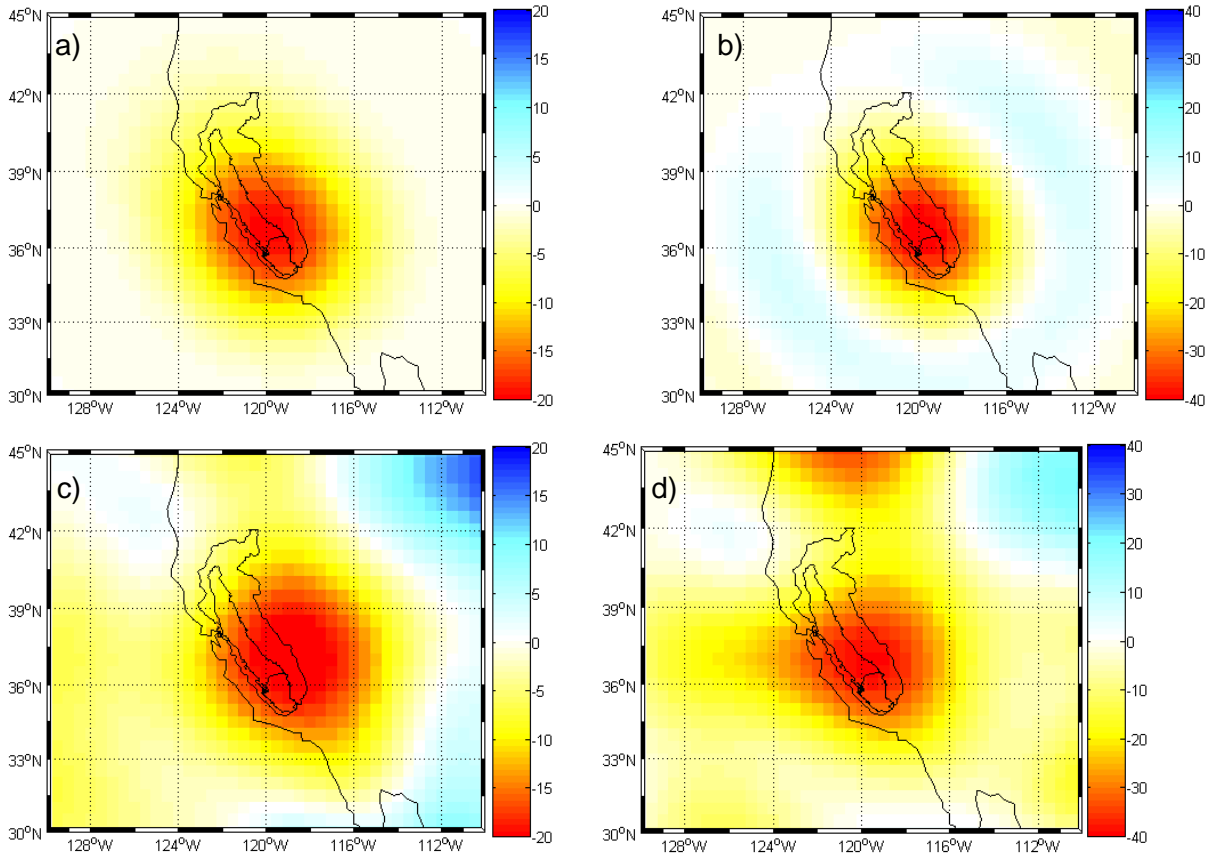
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99 **Section 5: Spatial Analysis of Mass Anomaly**

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101 **Section 5: Spatial Analysis of Mass Anomaly**

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104 2011WR011312-fs04.jpeg Figure S4. Spatial variability in the mass anomaly based on (a)
105 forward modeling of groundwater storage changes (truncation to degree 60 plus 300 km
106 Gaussian smoother) for comparison with CSR data, (b), forward modeling of GWS changes
107 (truncation to degree 50) for comparison with GRGS data, (c) GRACE GWS changes from CSR
108 data, and (d) GRACE GWS changes from GRGS data.