“Model-data Fusion of Hydrologic Simulations and Satellite Observations to Estimate Changes in Water Table Depth”

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Groundwater: key strategic reserve that ensures global water and food security

- 96% of all liquid freshwater
- Important source of water for public water systems and private wells
- Essential for irrigation and agricultural activities as well as industrial facilities
- Central role in sustaining ecosystems

Groundwater: one of the most reliable sources of freshwater globally, but now under pressure

Naturally occurring spatial heterogeneity

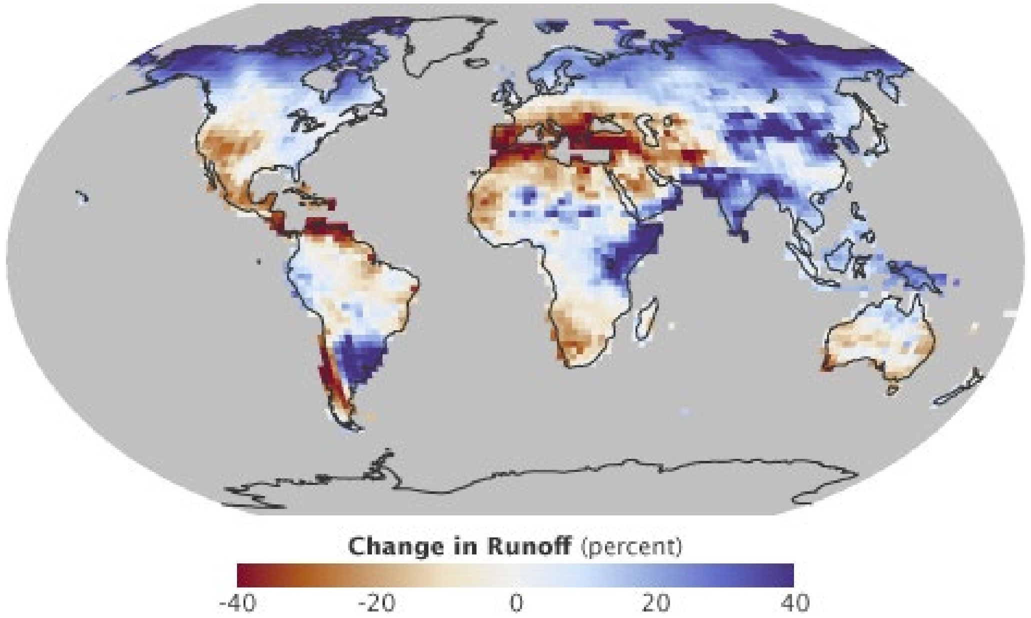
Unsustainable groundwater pumping

Rising population

Intensification of Hydrologic Cycle

Increase in frequency of extreme hydrologic events

More droughts/floods that impact agriculture, ecosystems, economy, and human health

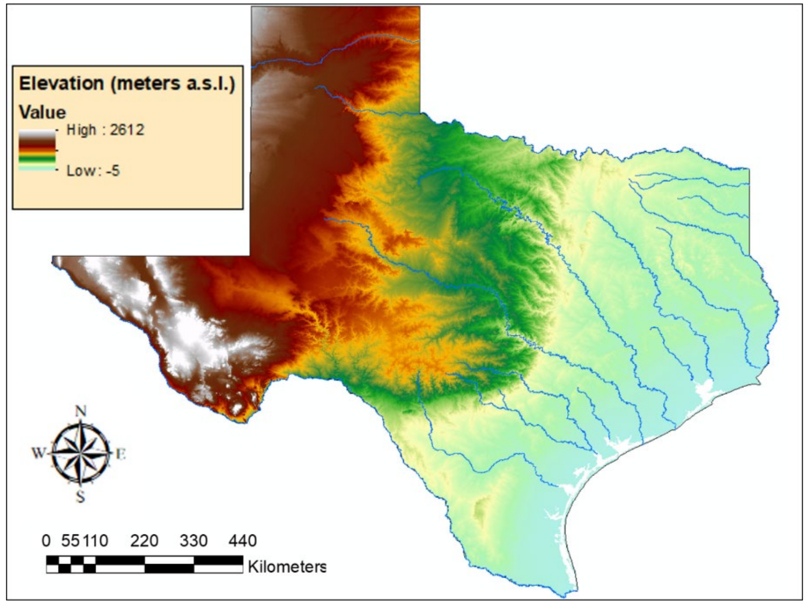


Direct human interventions (e.g. dams)

Increasing water usage to meet human needs

The accurate quantification and monitoring of groundwater dynamics is of paramount importance for a sustainable groundwater resources management

Water supply has been changing in many regions across the globe, with severe implications to the environment, food security, and economic prosperity.



Hydrologically vulnerable regions, such as those with limited resources for mitigation and adaptation will be disproportionally impacted.

Reproducing groundwater variability – state-of-the-art approaches and relative challenges

- Land Surface Models (LSMs)
  - no explicit representation of the free water table
  - bucket model behavior
- Coupling LSMs and groundwater models
  - disparity in spatial scales and resolutions
  - shallow groundwater compartment
  - high demands in terms of computation times
- Ground-based observations (observation or monitoring wells)
  - lack of sufficiently extensive networks of observation wells
  - inconsistencies in well data due to spatial and/or temporal data gaps, human errors
  - high installation and maintenance cost
- Remote sensing observations (GRACE)
  - coarse spatial resolution (~300 km)
  - data account for multiple water storage components

Objective

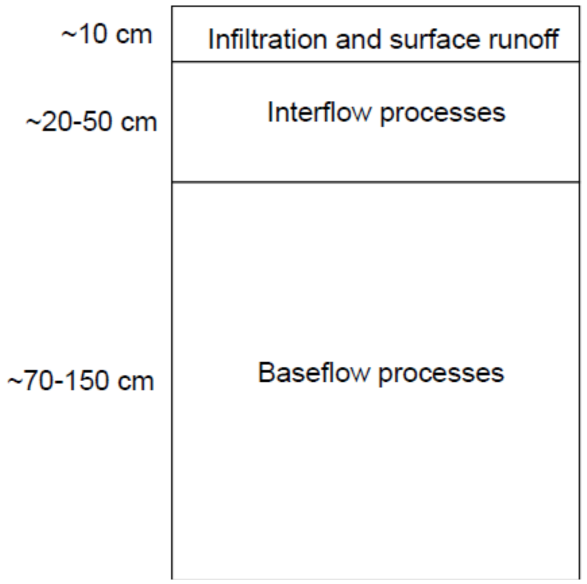
1) **Reproduce groundwater variability at high spatio-temporal scales**

2) **Improve the accuracy of modeled groundwater estimates**

3) **Allow the representation of water table depth at finer spatial scales**

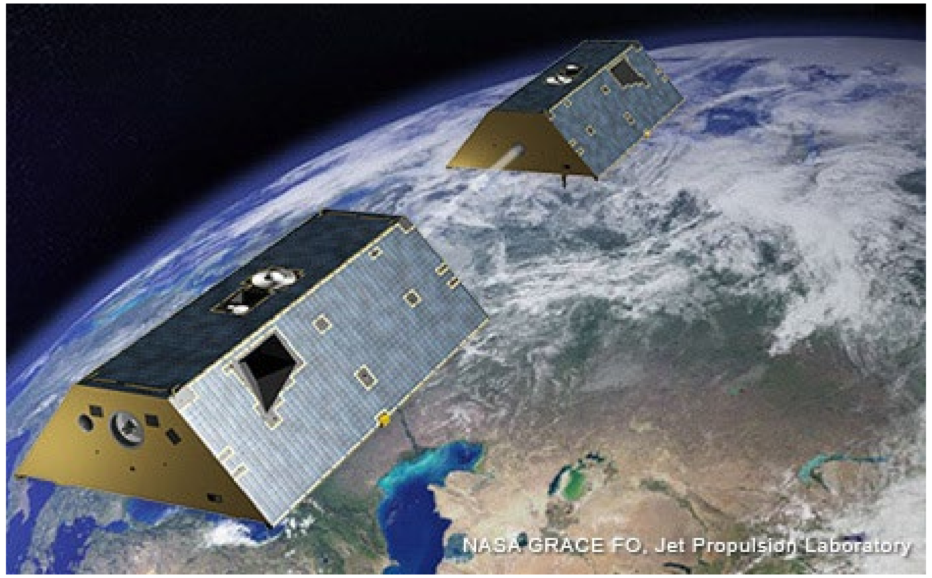
Variable Infiltration Capacity (VIC) model

- Widely used and robust macroscale hydrologic model
- Solves full water and energy balances to simulate major elements of Earth's water cycle.
- The subsurface is represented as **3 layers** that control the generation of surface runoff and baseflow.
- Outputs a variety of variables, including soil moisture, evaporation, snow cover, snow water equivalent, runoff, among others.
- Characterized by a lack of sufficient subsurface characterization to capture groundwater responses
- VIC.4.2.d



GRACE

- Consists of 2 twin satellites at a distance of ~220km launched in 2002
- Their orbits are monitored to produce monthly estimates of the Earth's gravity field.
- The changes in these estimates over land are in turn converted to changes in Total Water Storage (TWS), which reflect groundwater dynamics
- JPL-RL05M TWS change estimates at 0.5^0 resolution (http://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/)



Methodology

VIC augmentation

Incorporating a fourth soil layer in the model as the bottom groundwater layer

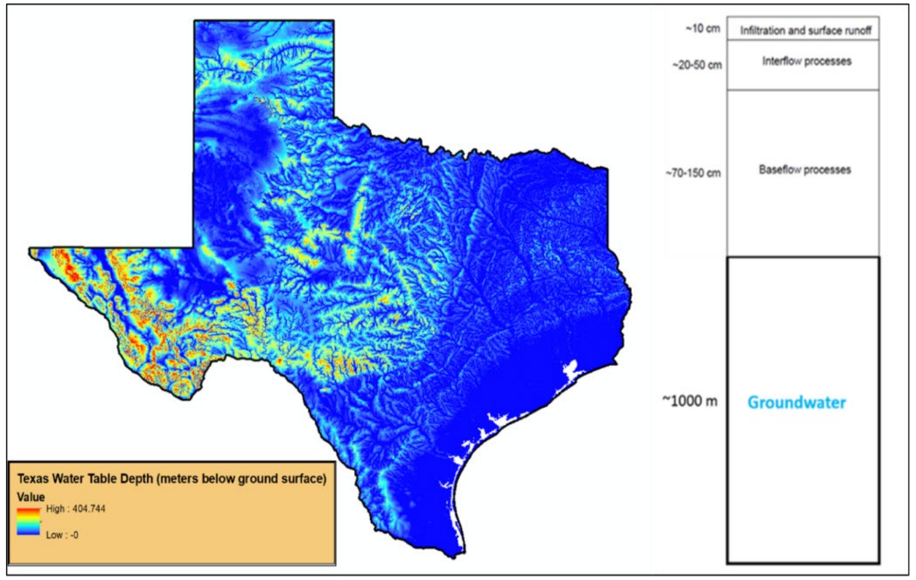
Updated model (**VIC4L**) reproduces water storage variability in both shallow soils and deeper groundwater

Model augmentation allows the integration of GRACE-data

Development of assimilation scheme that integrates the high temporal and spatial resolution model outputs with the high-fidelity GRACE satellite observations.

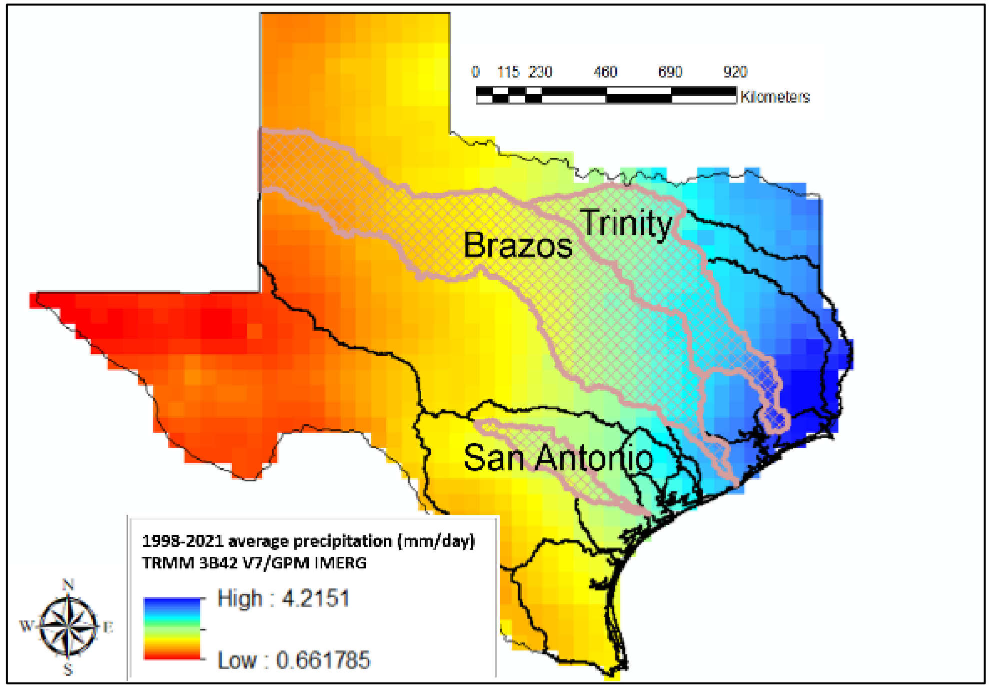
Robust representation of **changes in water table depth**

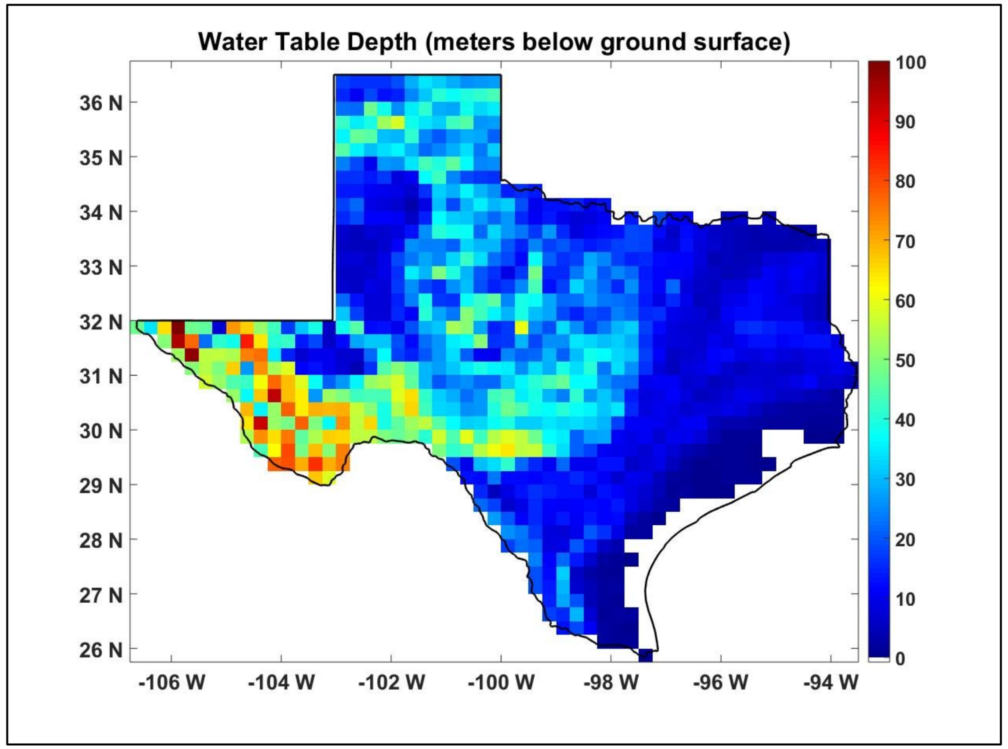
More accurate representation of the spatial heterogeneity and temporal variations of the interlinked **surface and subsurface water dynamics**



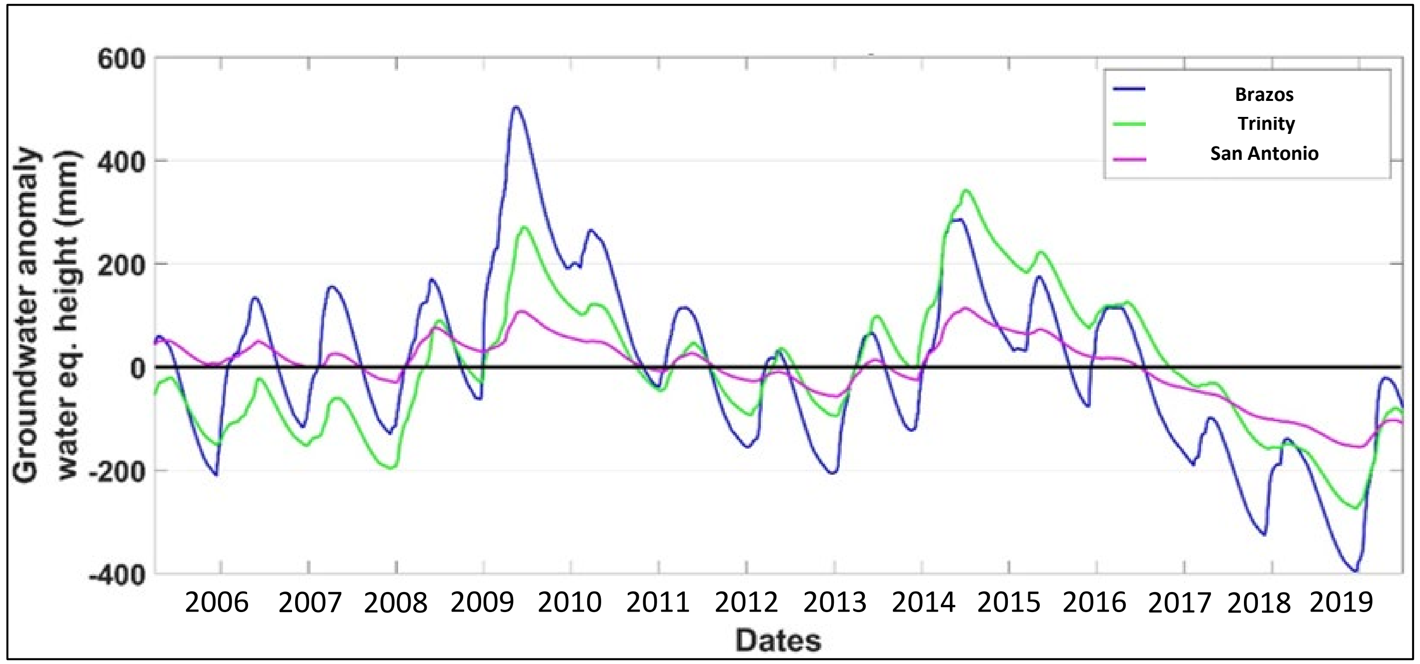
Gridded (~1km) water table depth data derived from observations at two million well sites and groundwater model simulations (Fan et al., 2013) used to initialize a water table in the Variable Infiltration Capacity hydrology model, by adding a fourth deep layer. Right panel: a schematic of the updated subsurface structural representation of VIC4L-GRACE that allows for the integration of GRACE data.

VIC4L



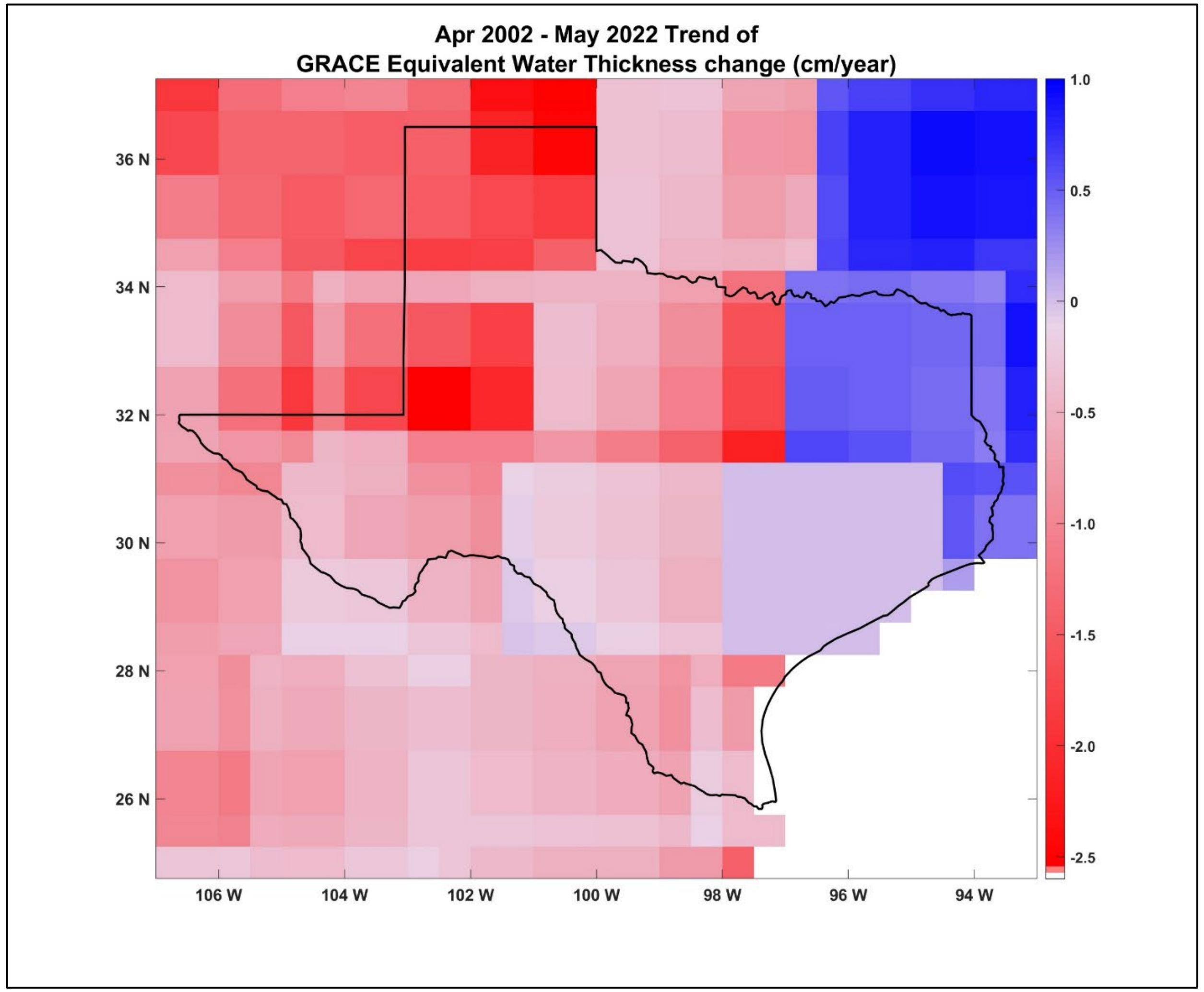


Temporally averaged

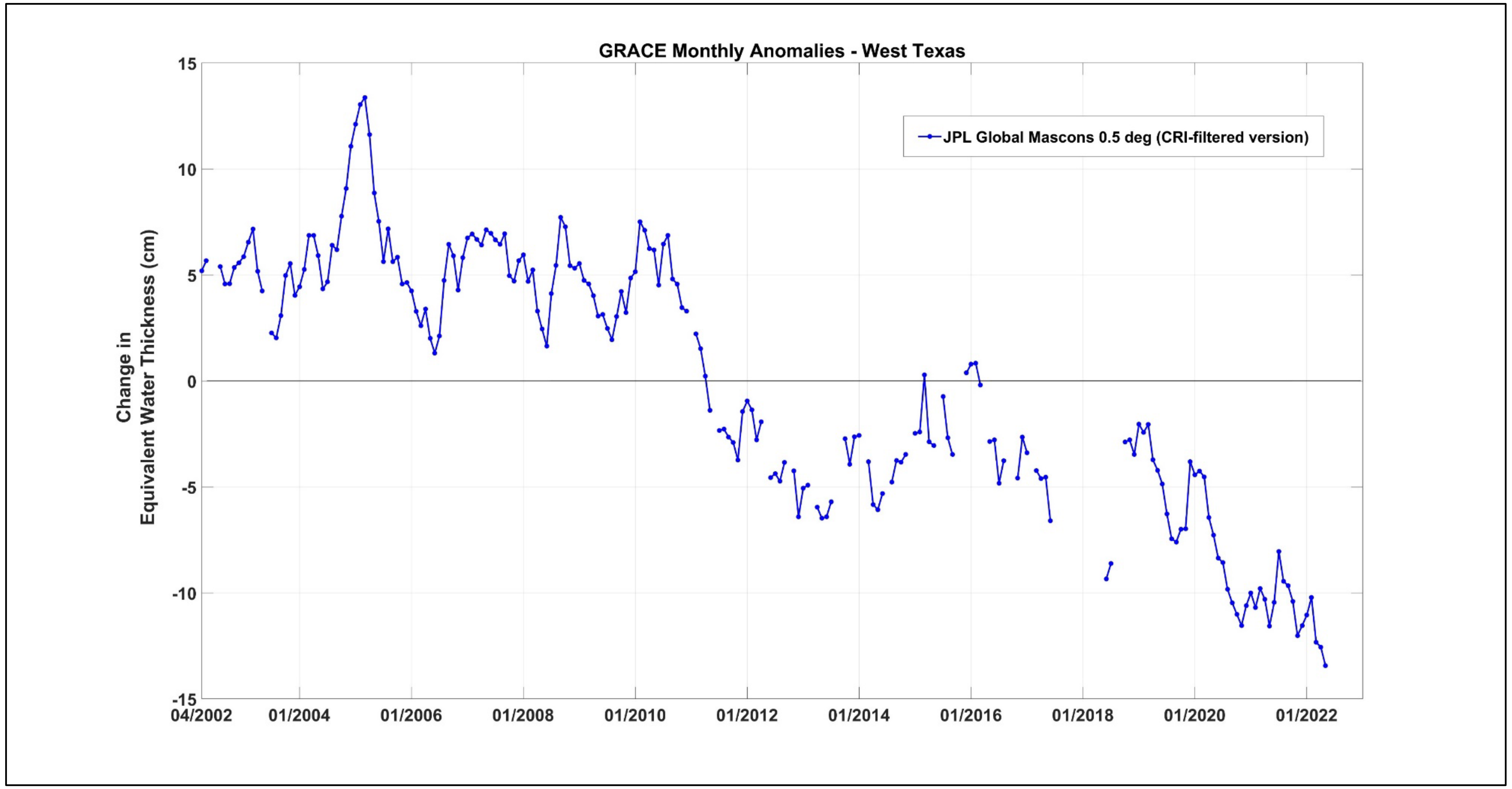


Spatially averaged

GRACE



Apr 2002 - May 2022 Trend of
GRACE Equivalent Water Thickness change (cm/year)
36 N
34 N
32 N
30 N
28 N
26 N
106 W
104 W
102 W
100 W
98 W
96 W
94 W
1.0
0.5
0
-0.5
-1.0
-1.5
-2.0
-2.5

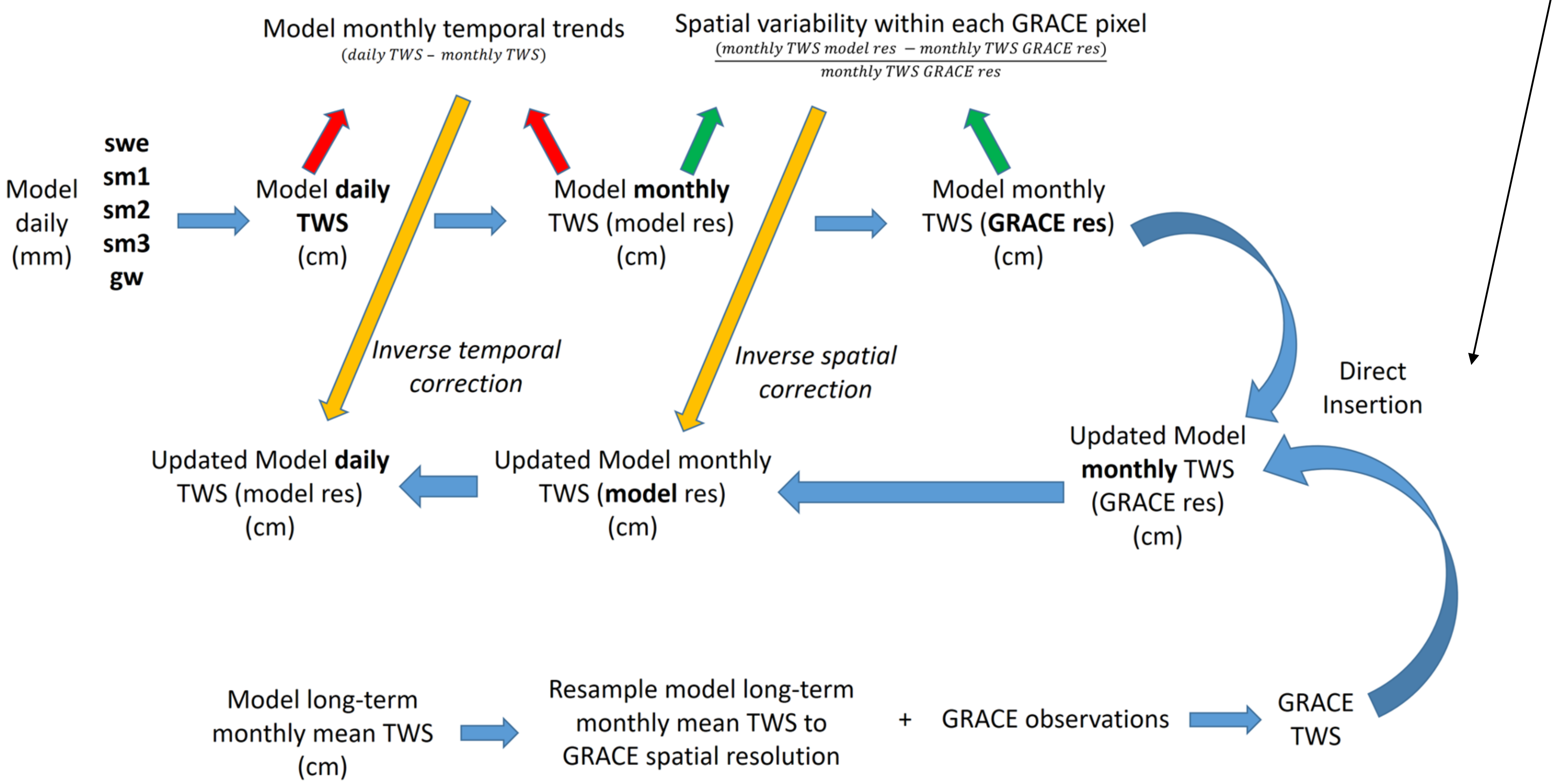


GRACE Monthly Anomalies - West Texas
JPL Global Mascons 0.5 deg (CRI-filtered version)
Change in
Equivalent Water Thickness (cm)
15
10
5
0
-5
-10
-15
04/2002
01/2004
01/2006
01/2008
01/2010
01/2012
01/2014
01/2016
01/2018
01/2020
01/2022

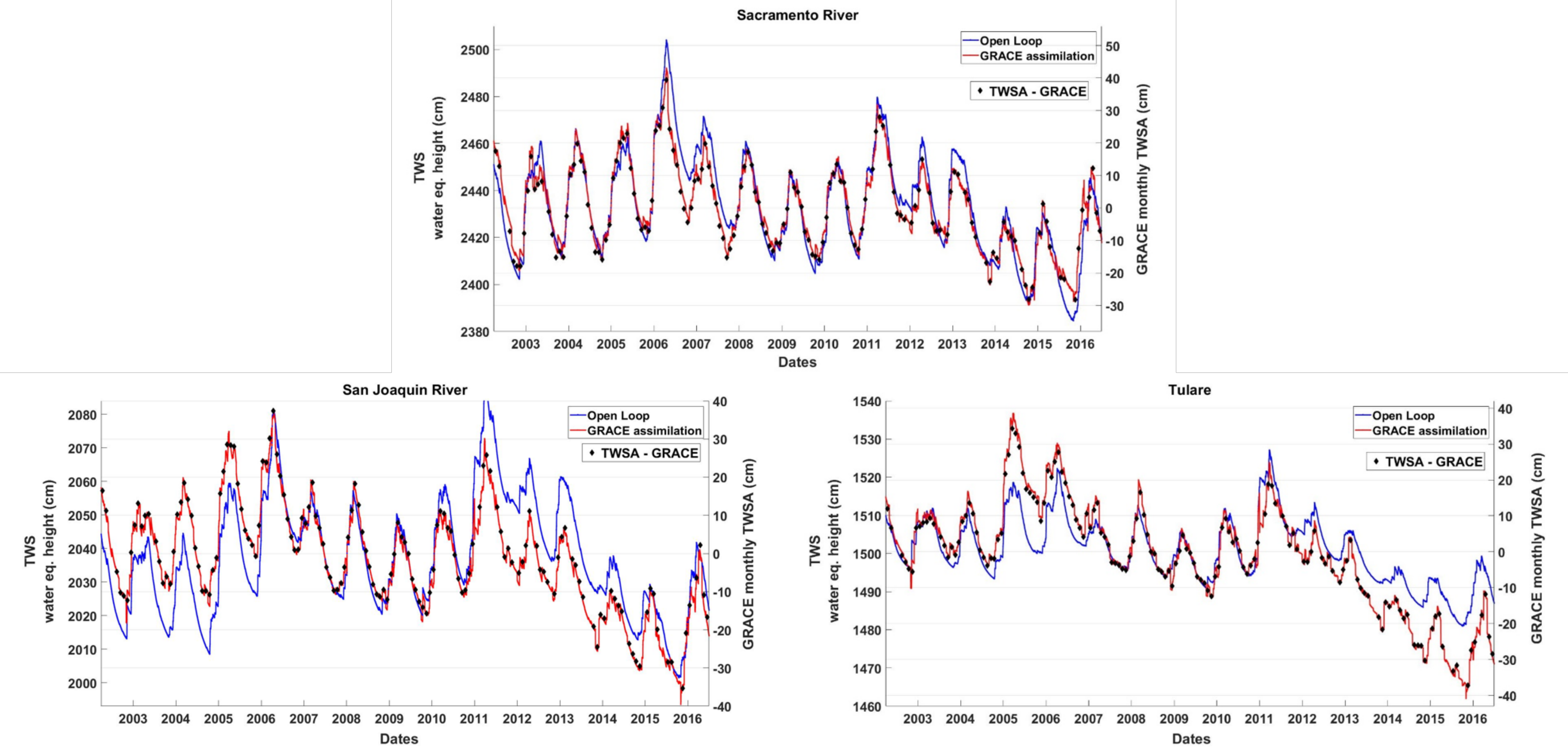
Schematic of VIC4L-GRACE fusion

(assimilation module in progress)

- $TWS_{vic} = TWSA_{vic} + TWSmean\_vic$
- $TWS_{vic_{updated}} = TWSA_{grace} + TWSmean\_vic$

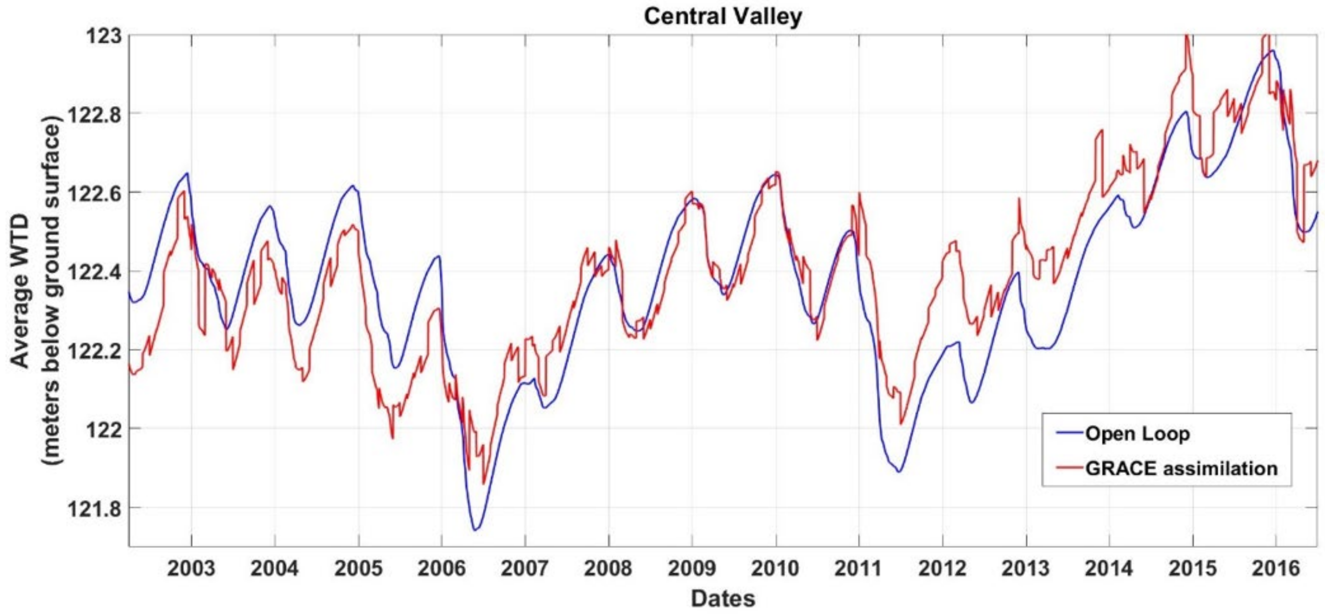


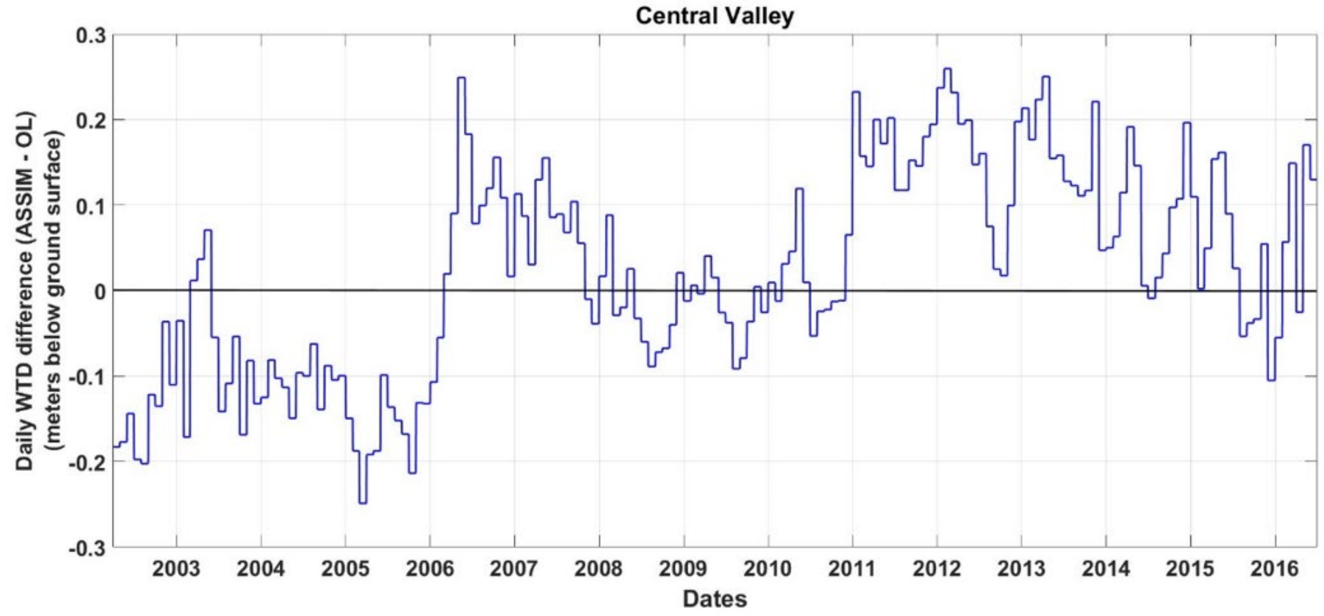
Methodological approach previously tested and validated over Central Valley, California

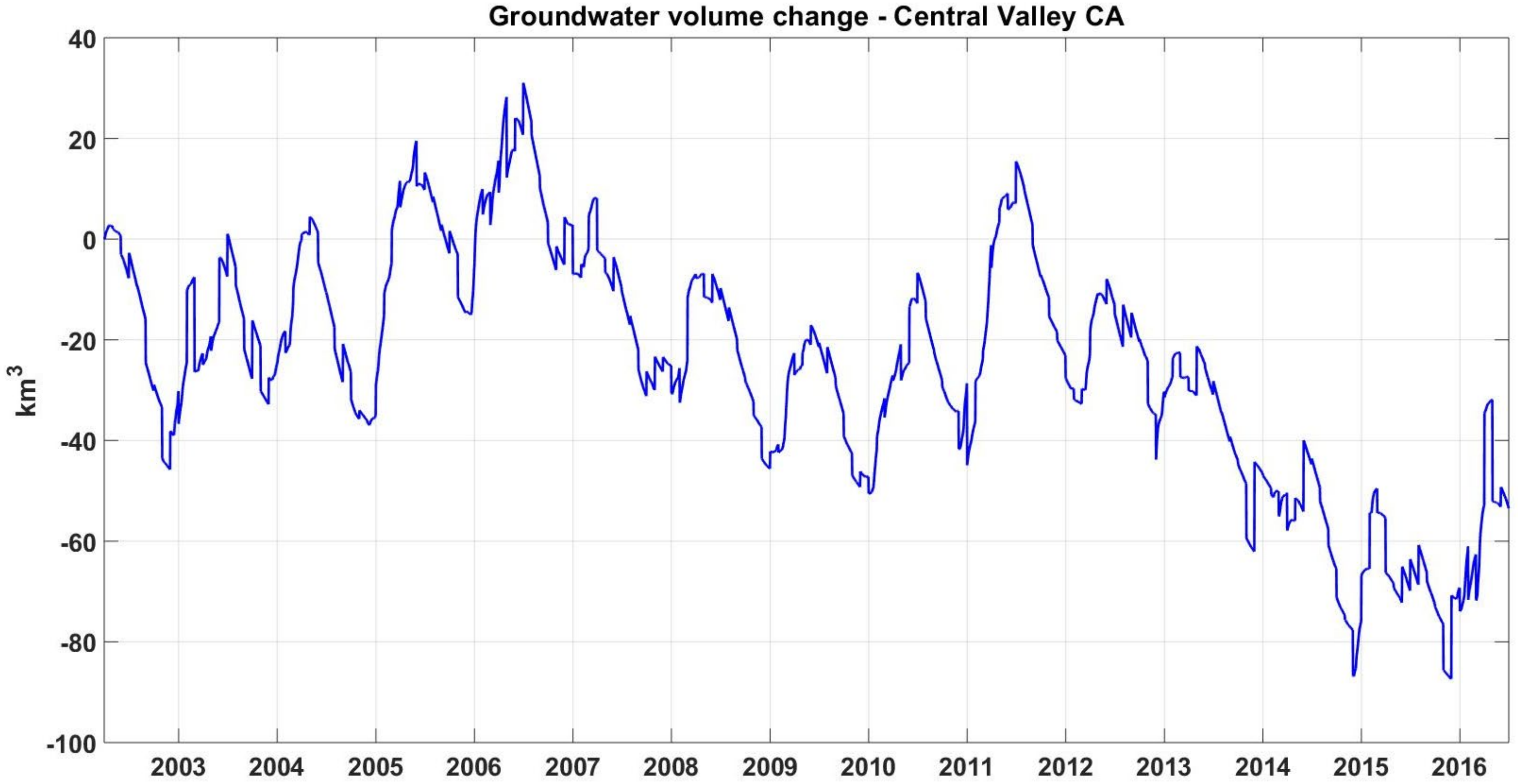


Stampoulis, D., Reager, J. T., David, C. H., Andreadis, K. M., Famiglietti, J. S., Farr T. G., Trangsrud A. R., Basilio R. R., Sabo J. L., Osterman G. B., Lundgren P. R., Liu Z. (2019). Model-data fusion of hydrologic simulations and GRACE Terrestrial Water Storage observations to estimate changes in water table depth. *Advances in Water Resources* (https://doi.org/10.1016/j.advwatres.2019.04.004)

Change of Groundwater Volume over Central Valley





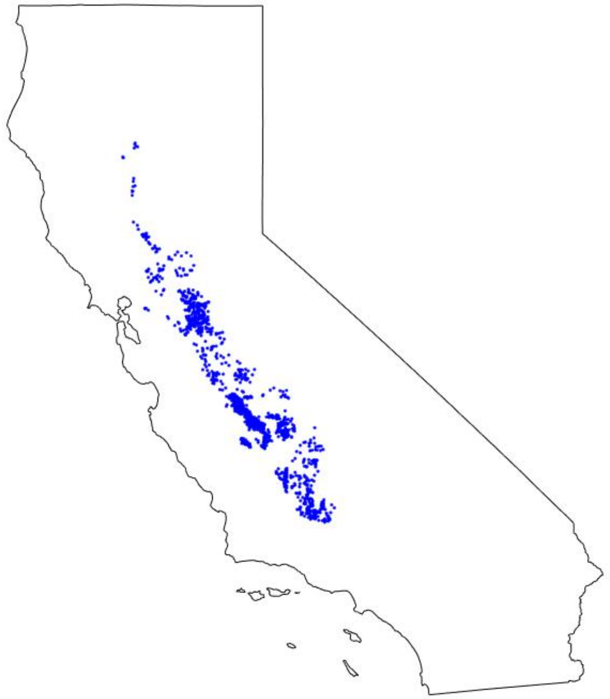


Validation using well observations - California Department of Water Resources (DWR)

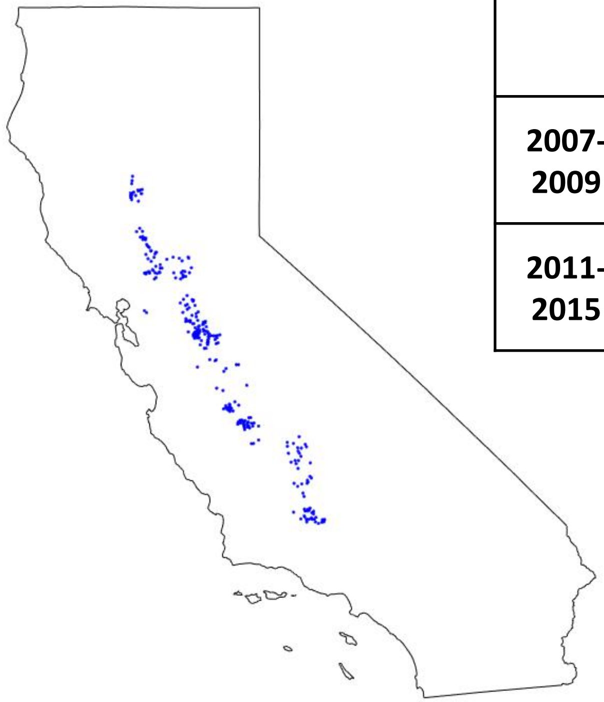
$$WTD_{change} = WTD_{enddate} - WTD_{startdate}$$

$$WTD_{slope} = linear\ least\ squares\ slope\ of\ WTD\ time\ series$$

1,285 wells with annual data for 2007-2009



292 wells with annual data for 2011-2015



		WTD Change (meters)			WTD Slope			WTD Correlation Coefficient	
		Wells	Open-Loop	GRACE assim.	Wells	Open-Loop	GRACE assim.	Wells - Open-Loop	Wells - GRACE assim.
2007-2009	Sacramento River	0.696	0.0825	0.288	0.348	0.0413	0.144	0.0887	0.9437
	San Joaquin River	0.7864	0.0736	0.1063	0.3932	0.0368	0.0532	0.9794	0.8687
	Tulare	3.5711	0.0467	1.7011	1.7855	0.0233	0.8506	0.9896	0.9994
2011-2015	Sacramento River	5.9621	0.286	2.682	1.5176	0.0727	0.6844	0.9069	0.9961
	San Joaquin River	4.4325	0.1573	1.4954	1.1414	0.0387	0.3954	0.9779	0.9922
	Tulare	22.8972	0.0925	2.3864	5.7728	0.0231	0.5781	0.957	0.9865

Model's skill significantly improved after GRACE data assimilation

Final remarks

- ✓ Novel methodology that enables data integration of GRACE observations to the augmented version of a macroscale hydrologic model, VIC4L, ultimately allowing an improved representation of the long period variability in the WTD at the local scale.
- ✓ This work provides a holistic insight into reproducing water storage variability not only in shallow soils, but also in deeper groundwater , by jointly assessing the temporal fluctuations of water in both surface as well as deep aquifers at high spatial resolution.
- ✓ Improvement in the model's skill after GRACE data integration
- ✓ Corrections due to GRACE observations are of greater magnitude during periods characterized by stronger deviations from the average hydrologic conditions.
- ✓ GRACE observations present significant value in accounting for large-scale groundwater depletion in heavily irrigated regions, especially during drought periods.


Thank you!

- Changes in input model files (Global Parameter file, Soil Parameter file, etc.) to account for the addition of the new layer

- To initialize a WTD in the model:

Water table depth

Grid cell area

Volume of saturated soil column

$$porosity = \left(1 - \left(\frac{bulk\ density}{particle\ density}\right)\right) \times 100\%$$

Water equivalent height in 4^{th} layer