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Groundwater Estimates from the Gravity Recovery and Climate Experiment (GRACE) Applications to the State of California in support of California Footprints

Felix W. Landerer
Jet Propulsion Laboratory / California Institute of Technology
with support from Vance Fong, Don Hodge (EPA-Region 9)

An EPA GEOSS/AMI Project

SWRR meeting, December 7, UC Davis

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JPL: From Caltech students testing rockets to exploring the planets in our lifetime

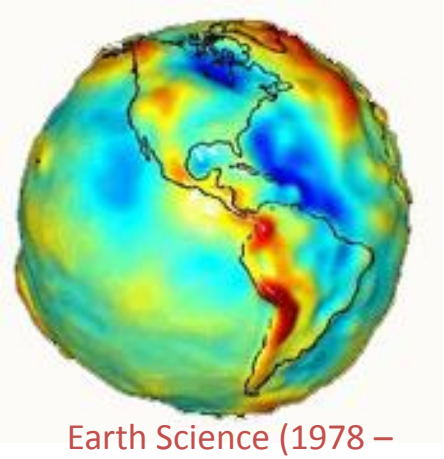
Caltech students (1936)

Missiles (1940s)

Explorer 1 (1958)

Mars Exploration Rovers (2004 – present)

Spitzer Space Telescope (2004 – present)



Earth Science (1978 – now)

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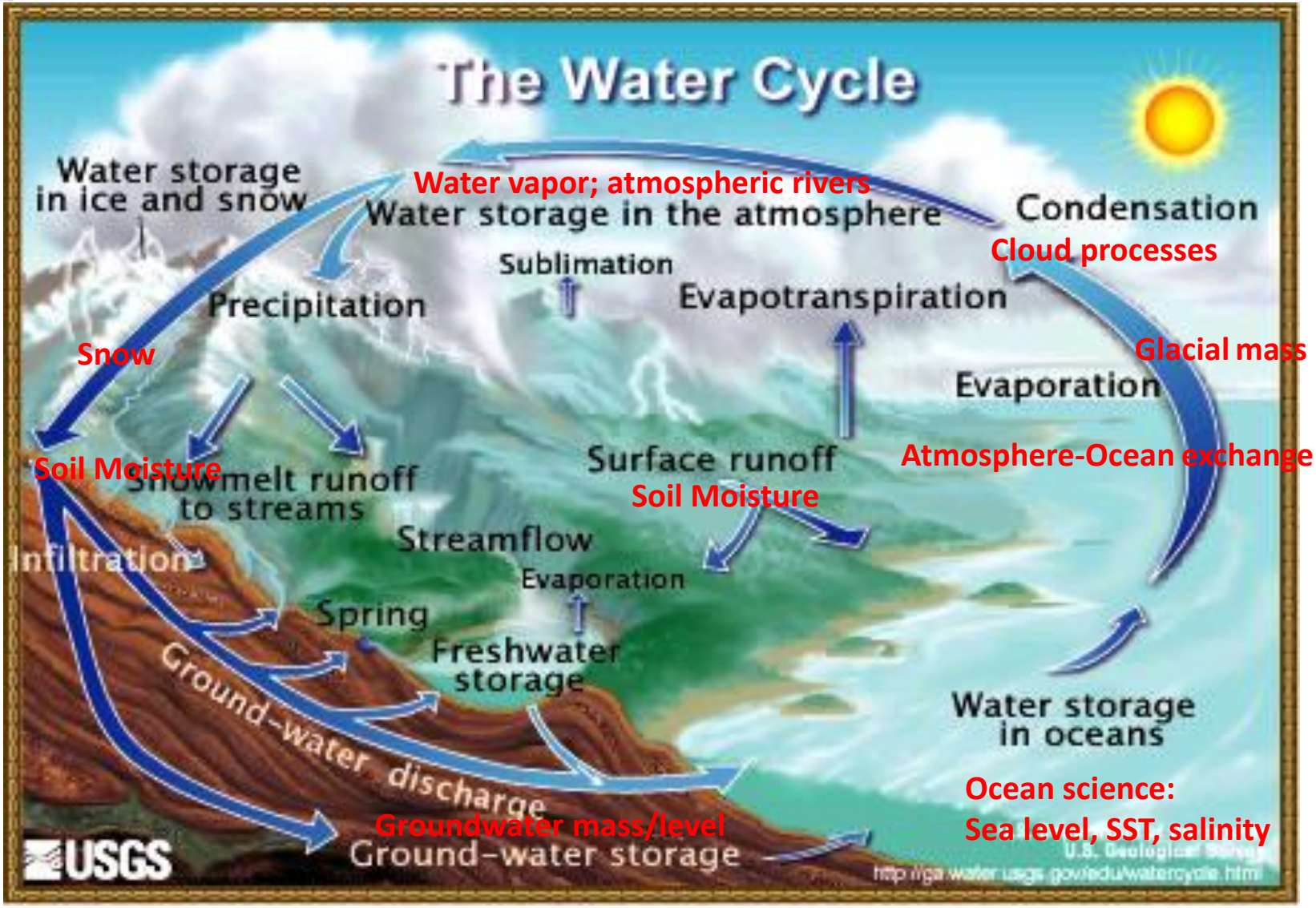
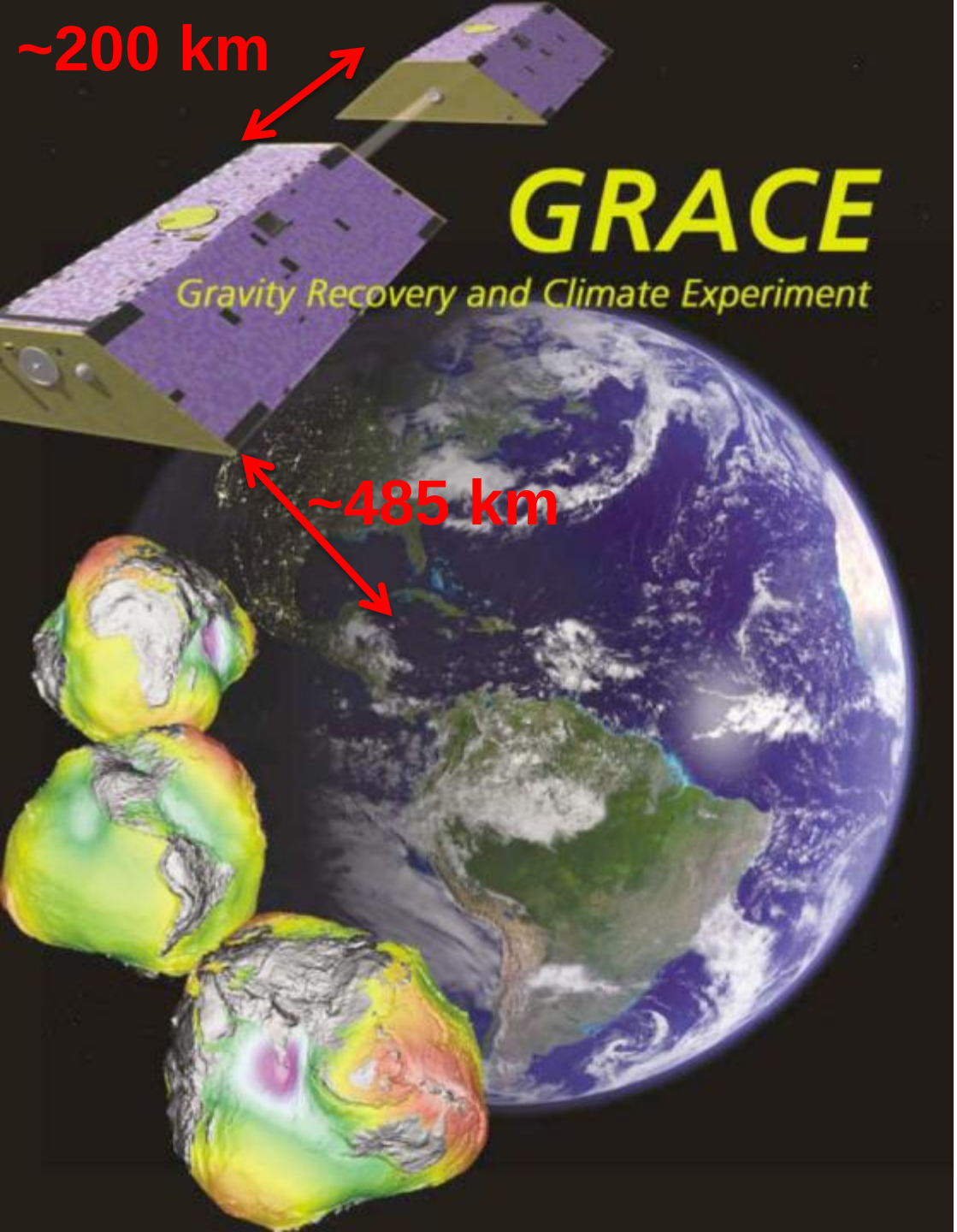
NASA/JPL strength in observing the Water cycle





- ***Measurement:*** distance between the two satellites
- ***Infer*** monthly gravity anomalies (GRACE, GPS)
- Correct for tides, alias signals, atmospheric loading, (GIA)
- Over land: surface mass changes related to **hydrology**, **ice sheets & glaciers**, earthquakes
- Over oceans: **ocean mass (bottom pressure)**
- Typical unit: **equivalent-water-height [cmH2O]**

GRACE: Measurement principle

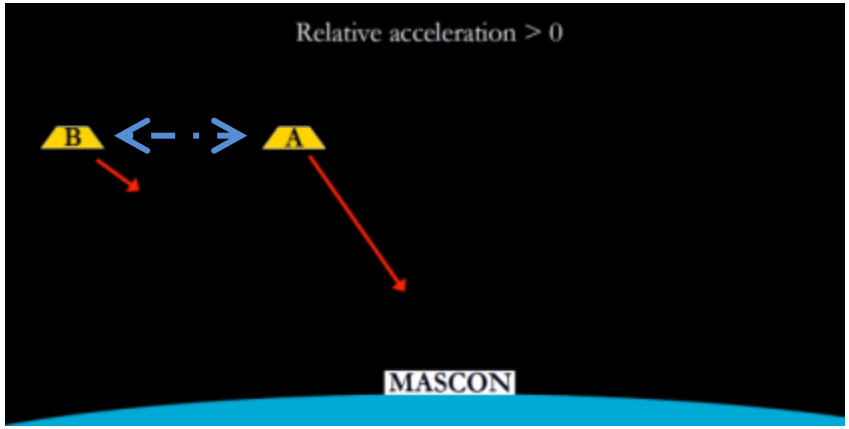
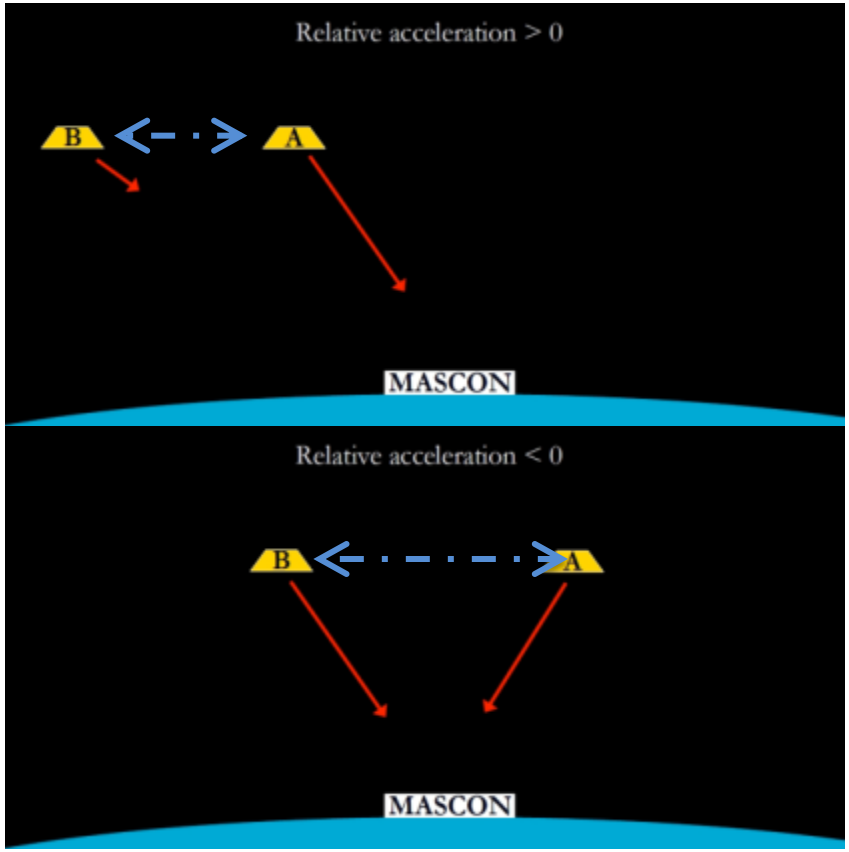


Fig. by
Brian Killett

GRACE: Measurement principle



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GRACE: Measurement principle

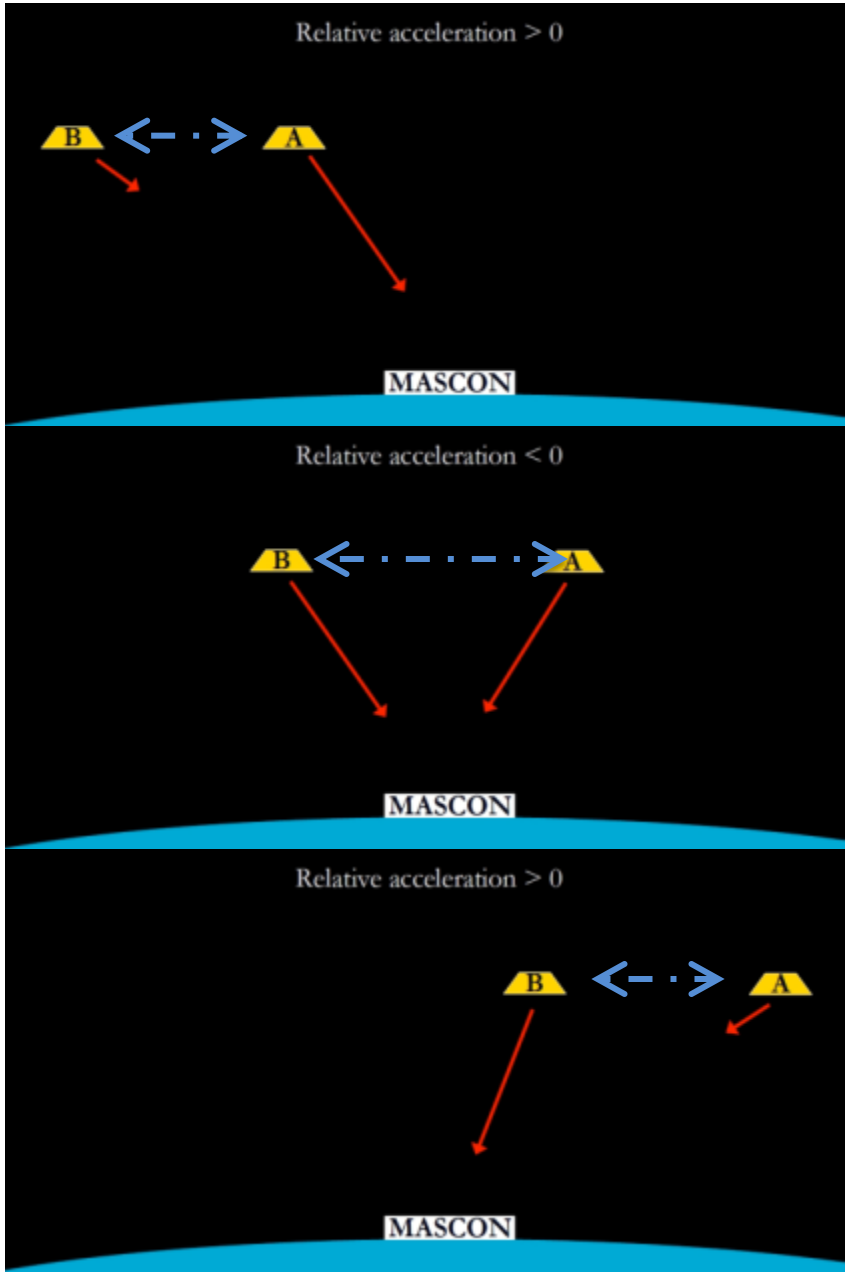

Fig. by
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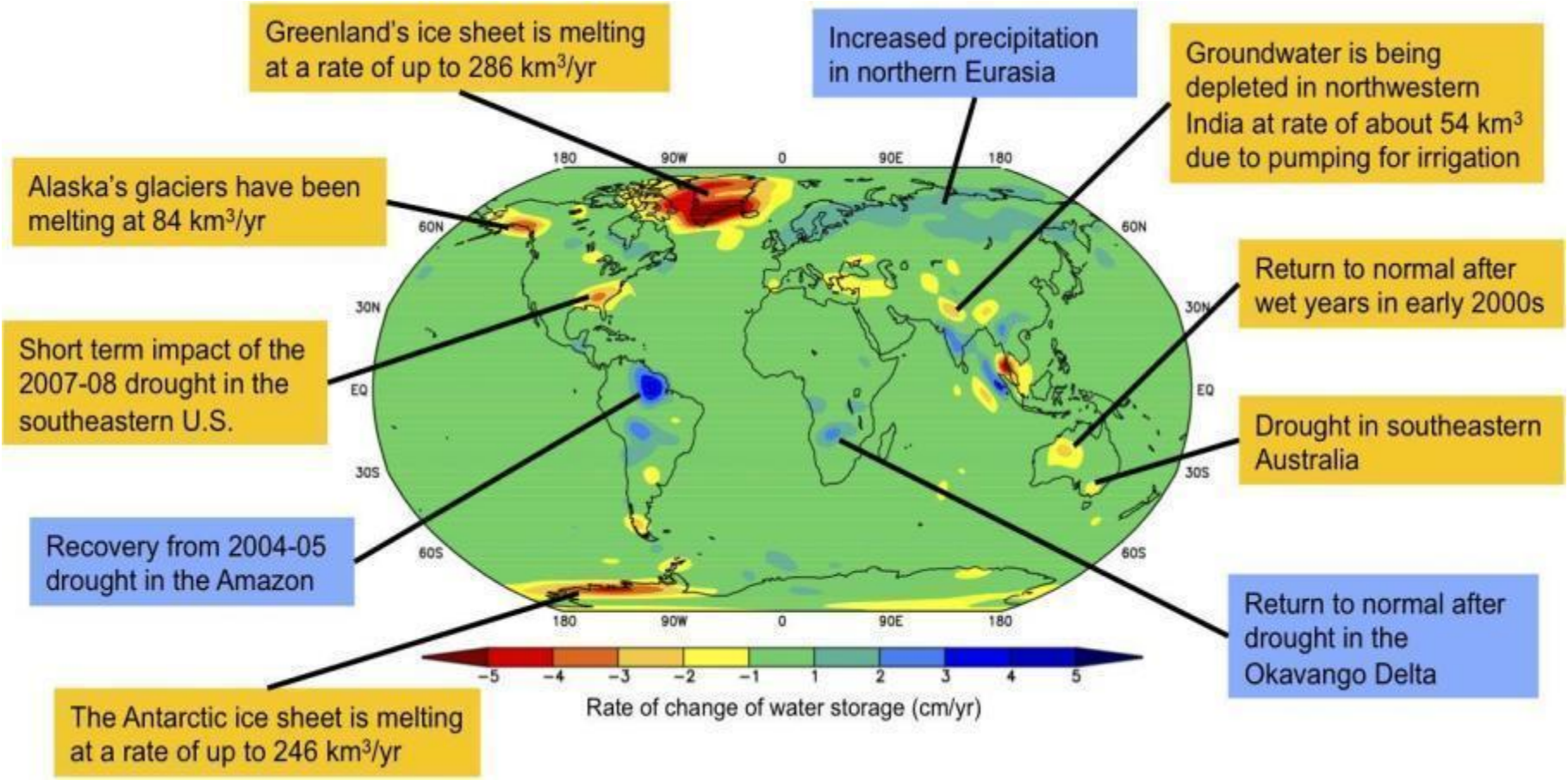
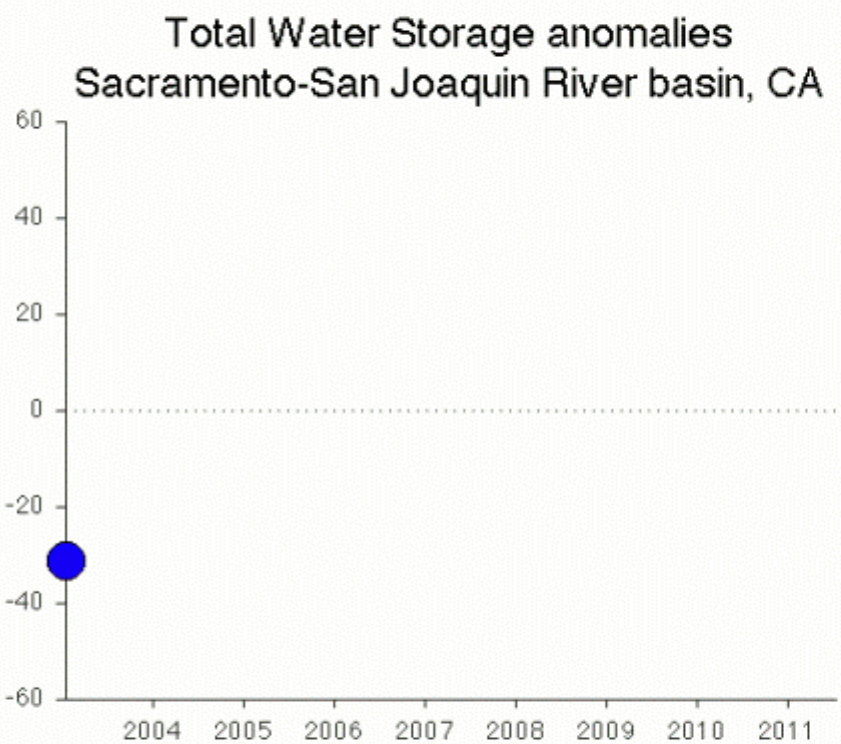
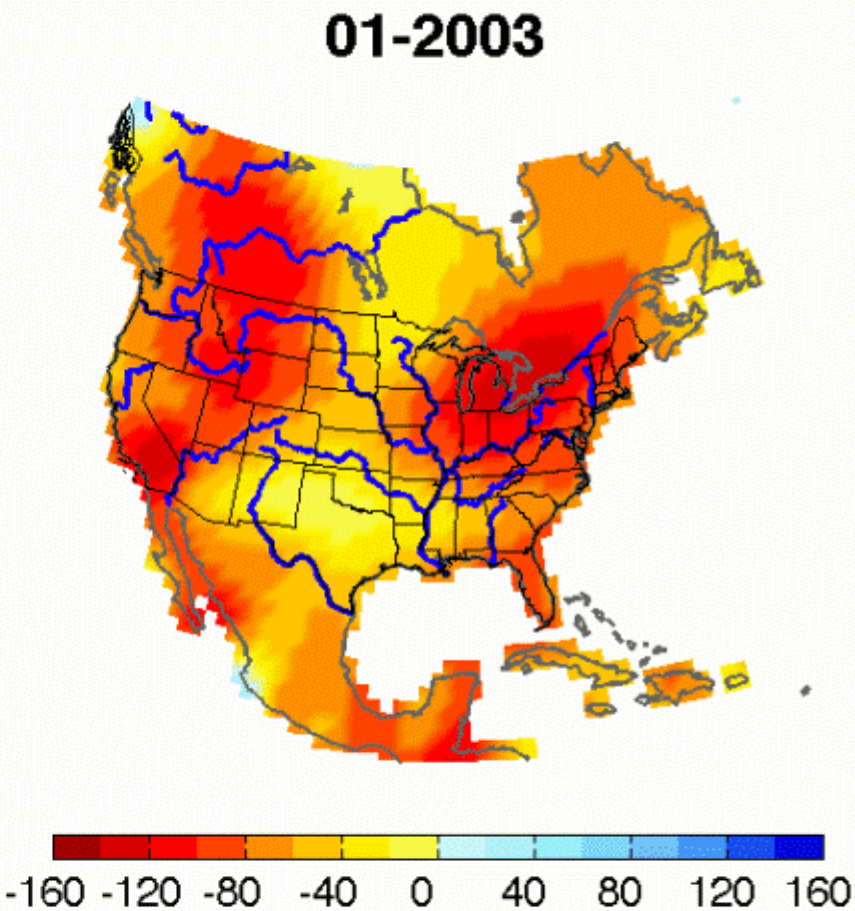
The World As Seen by GRACE 2002-2010

Trends



Total terrestrial water storage changes
GRACE 01-2003 to 05-2011





California's Central Valley: Terrestrial Water Storage changes measured from GRACE 2003 - 2011

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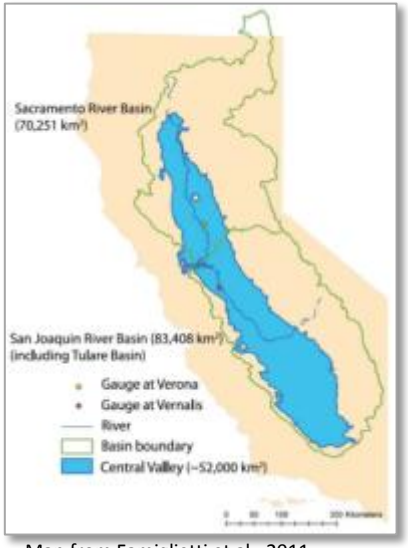
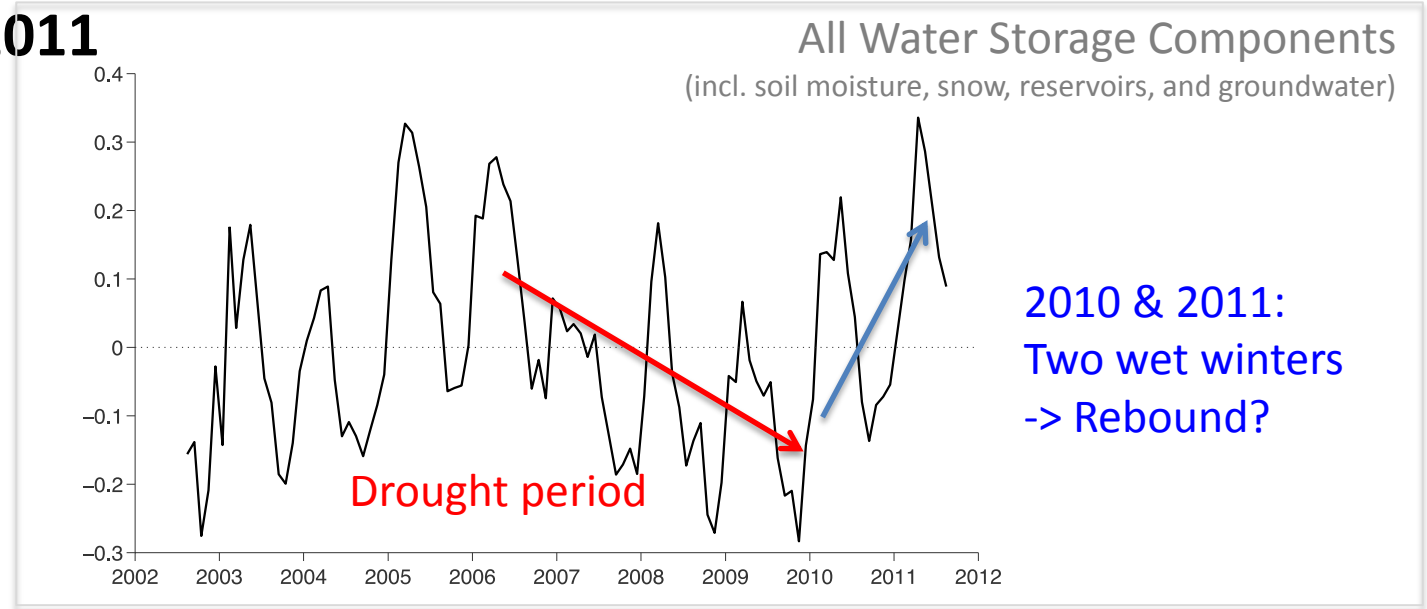
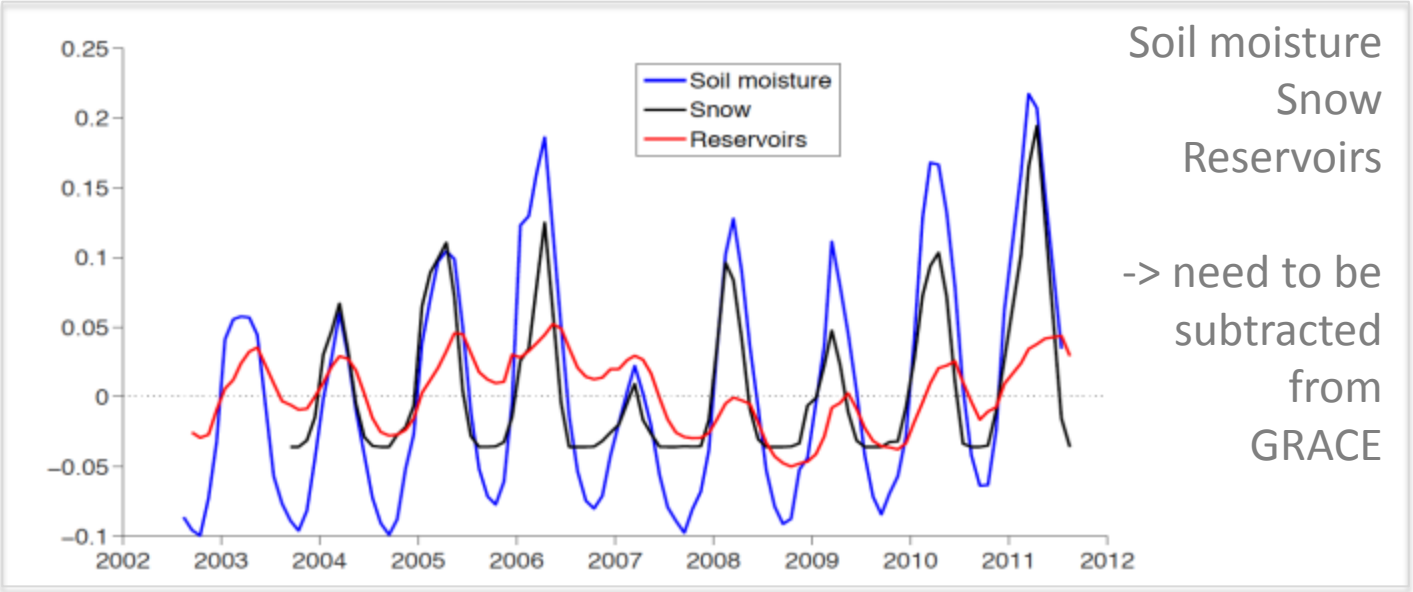


Map from Famiglietti et al., 2011





Units: Meters H_2O

Felix W. Landerer, JPL
Nov-29, 2011

California's Central Valley: Terrestrial Water Storage changes measured from GRACE 2003 - 2011

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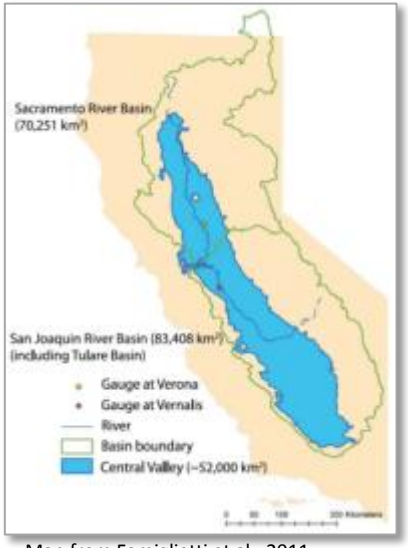

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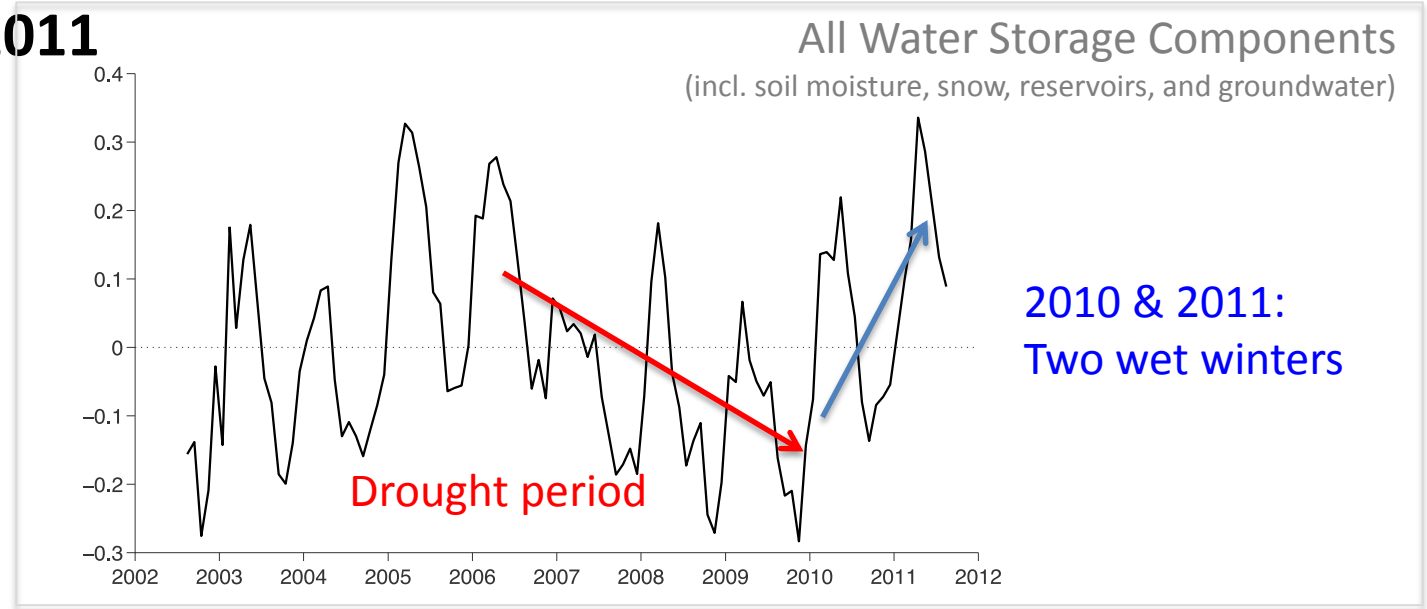

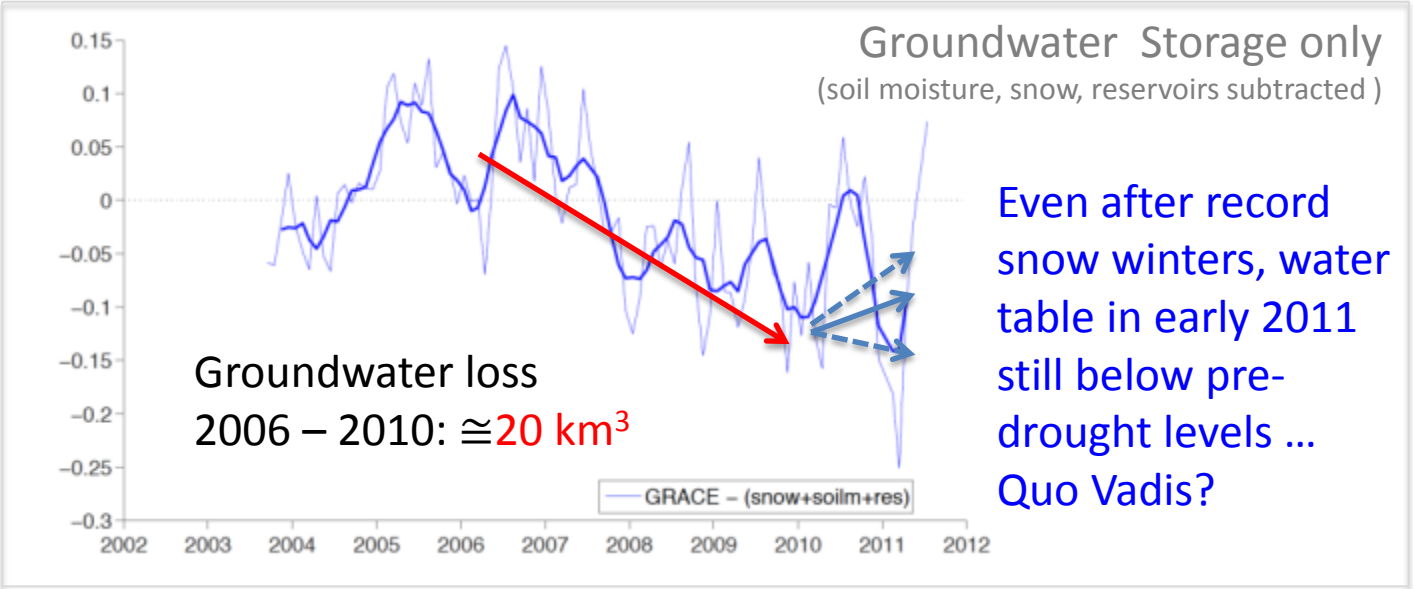

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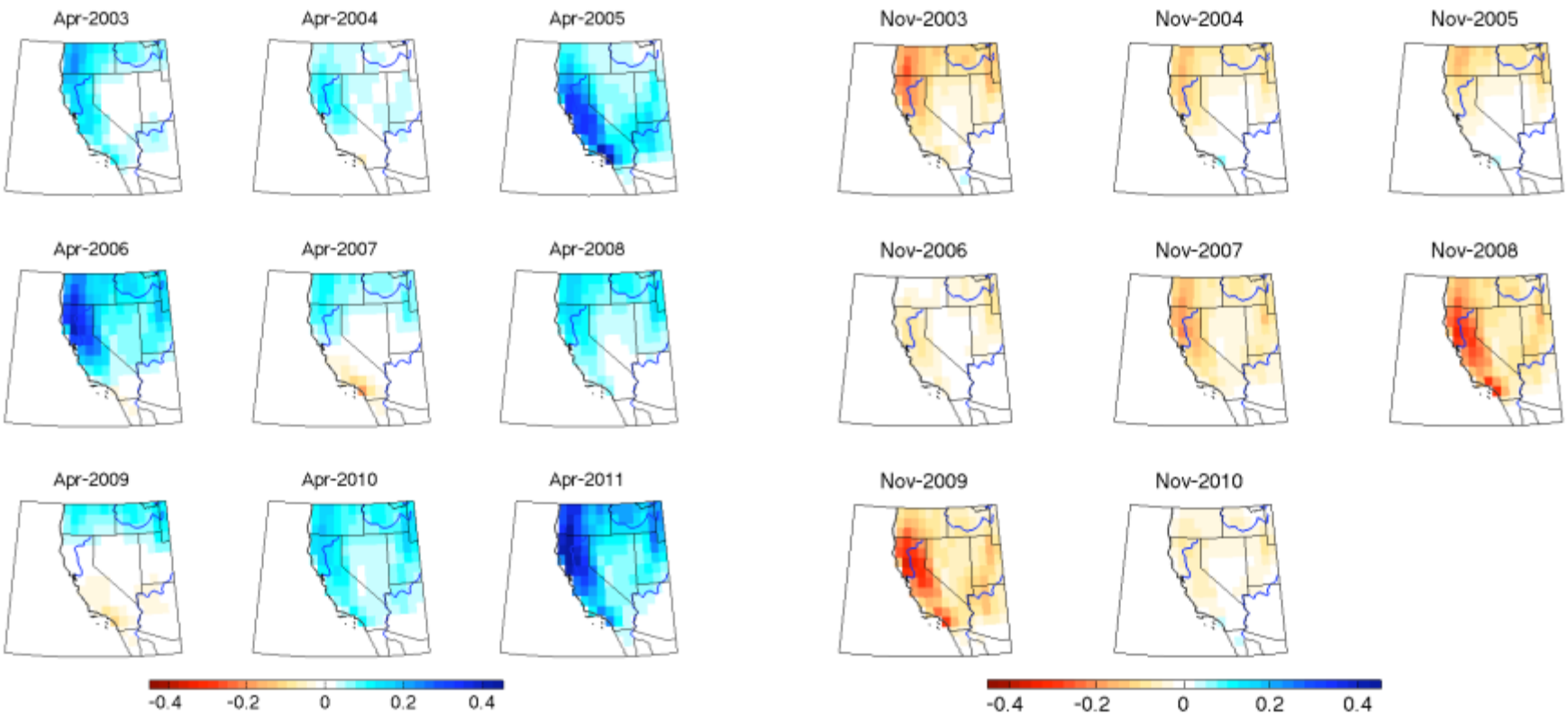
Zooming into sub-regions of the Sacramento - San Joaquin basin

Total Water Storage



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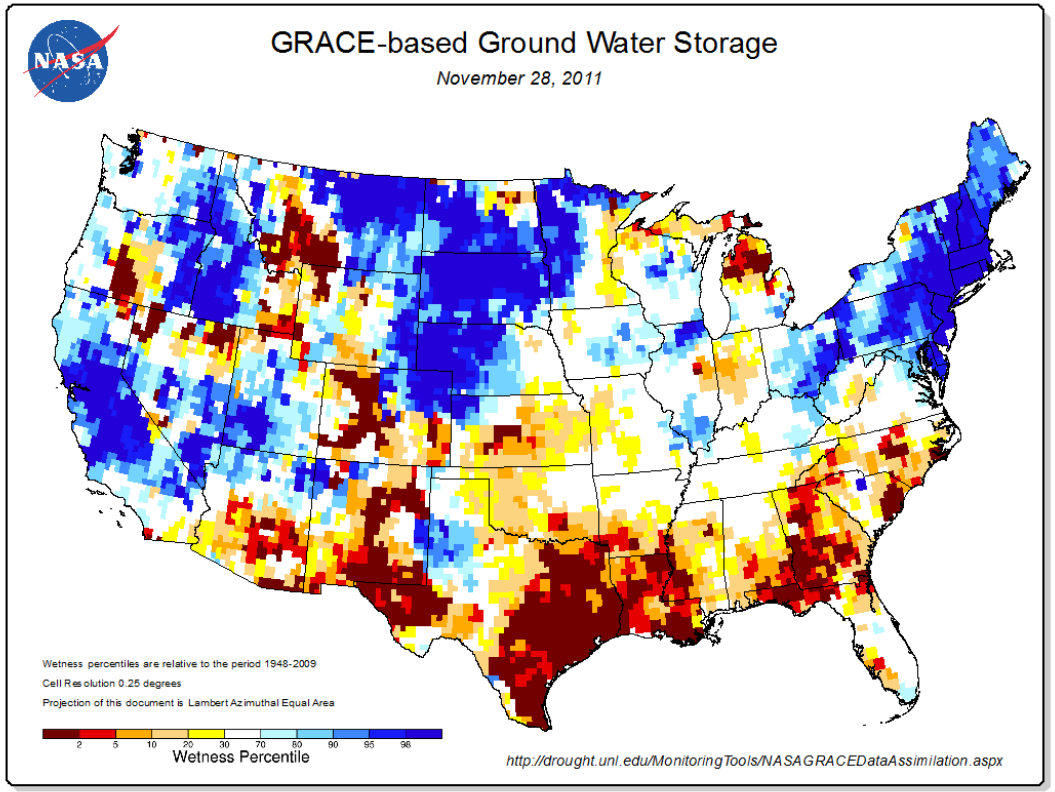
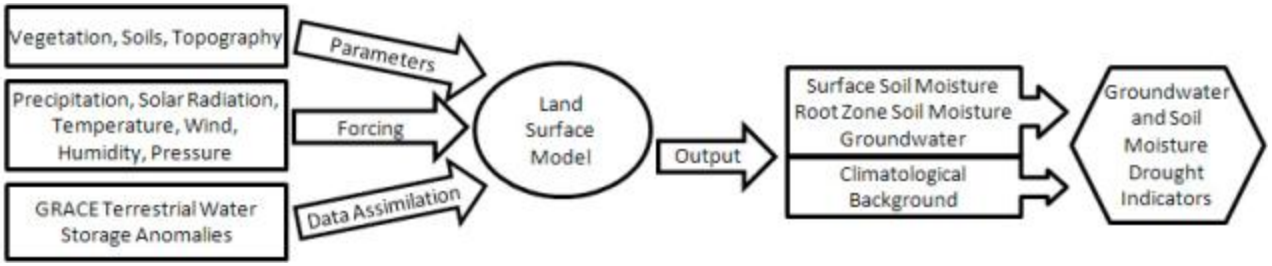
National Drought Mitigation Center

Monitoring Tools 〉 NASA GRACE Data Assimilation

Register Login

Groundwater and Soil Moisture Conditions from GRACE Data Assimilation





Summary & Outlook

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- GRACE can clearly observe water storage changes over CA's Central Valley
- Spatial resolution still challenging, but improvements have been made
- From 2006 to 2010, about 20 km^3 of groundwater were depleted
- After 2010, total water storage increased again close to pre-drought levels, but groundwater (as of May-2011) appears to be still below 2006 levels

Outlook:

- DEVELOP program: collaboration with NASA Ames & DWR
- New snow-water estimates from JPL in-house product
- Needed: compare GRACE-derived groundwater estimates with in-situ observations
- Downscaling (e.g., Drought Monitor)
- Release-05 GRACE data
- GRACE Follow-on

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Back-up slides

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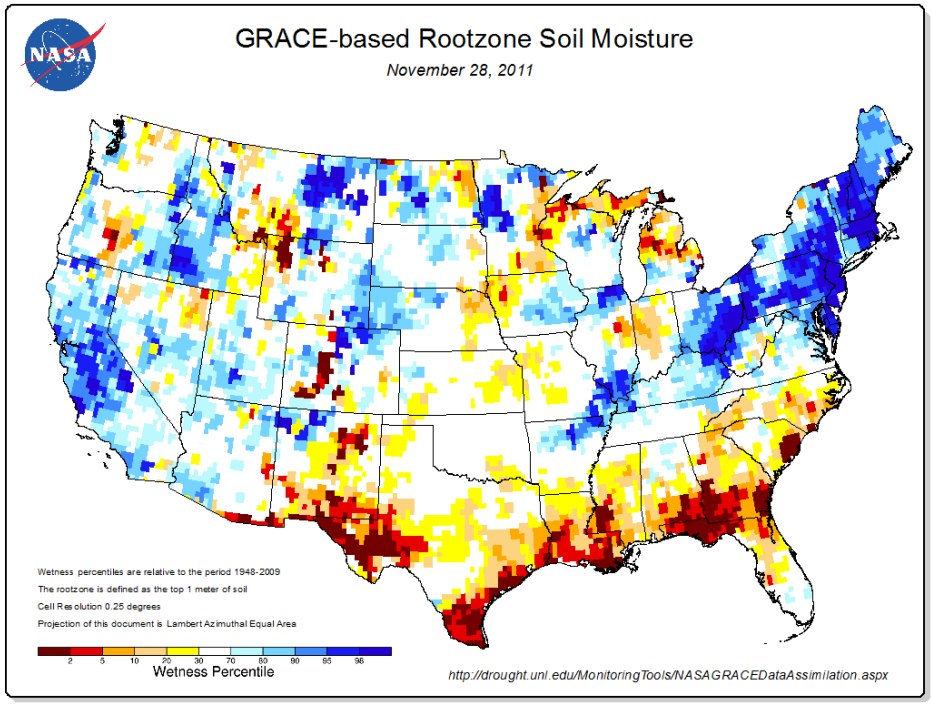

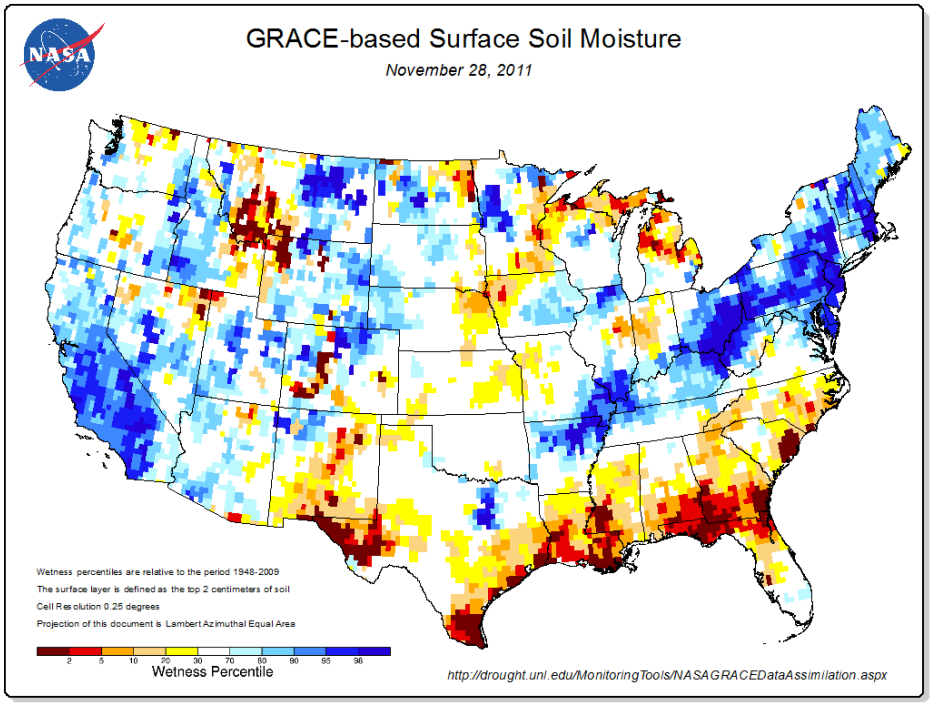

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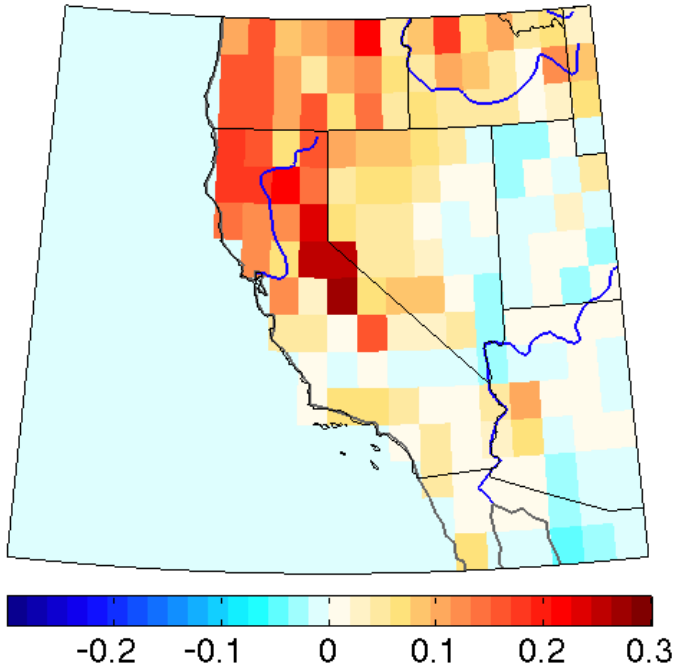
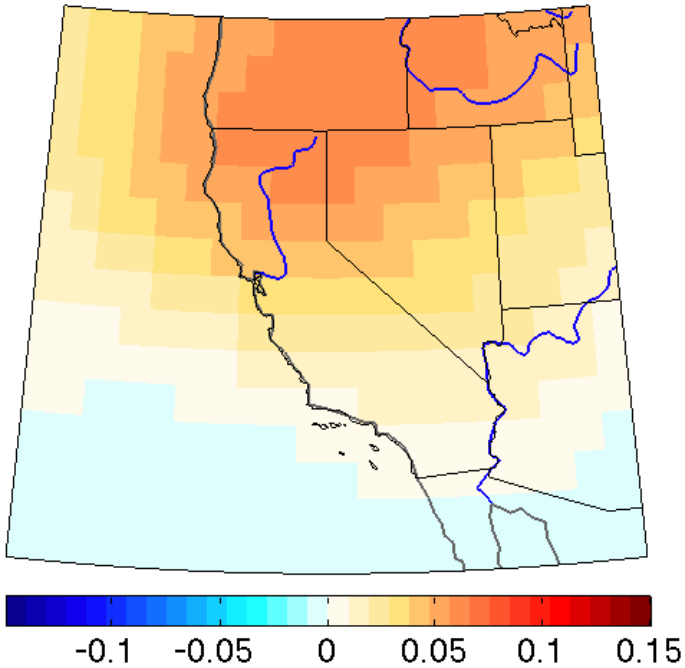
GRACE: Resolution & Footprint





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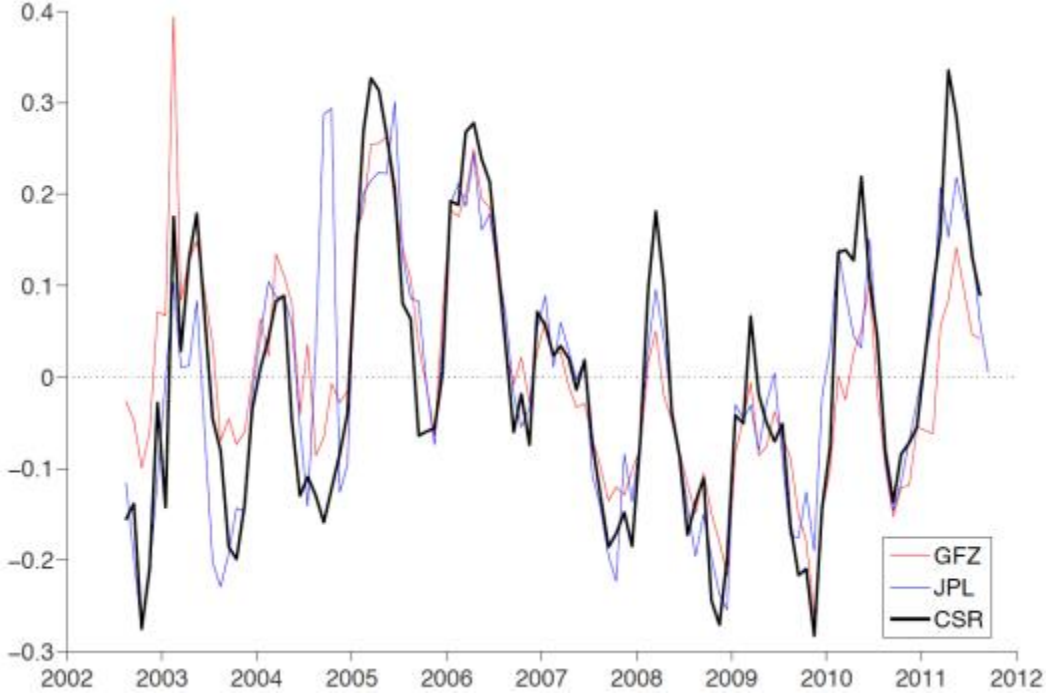
Accuracy of GRACE-based water storage estimates

Error of monthly TWS value: +/- 46 mmH_2O

(TD: draw error bar into plot!)

Discuss: different data center solutions



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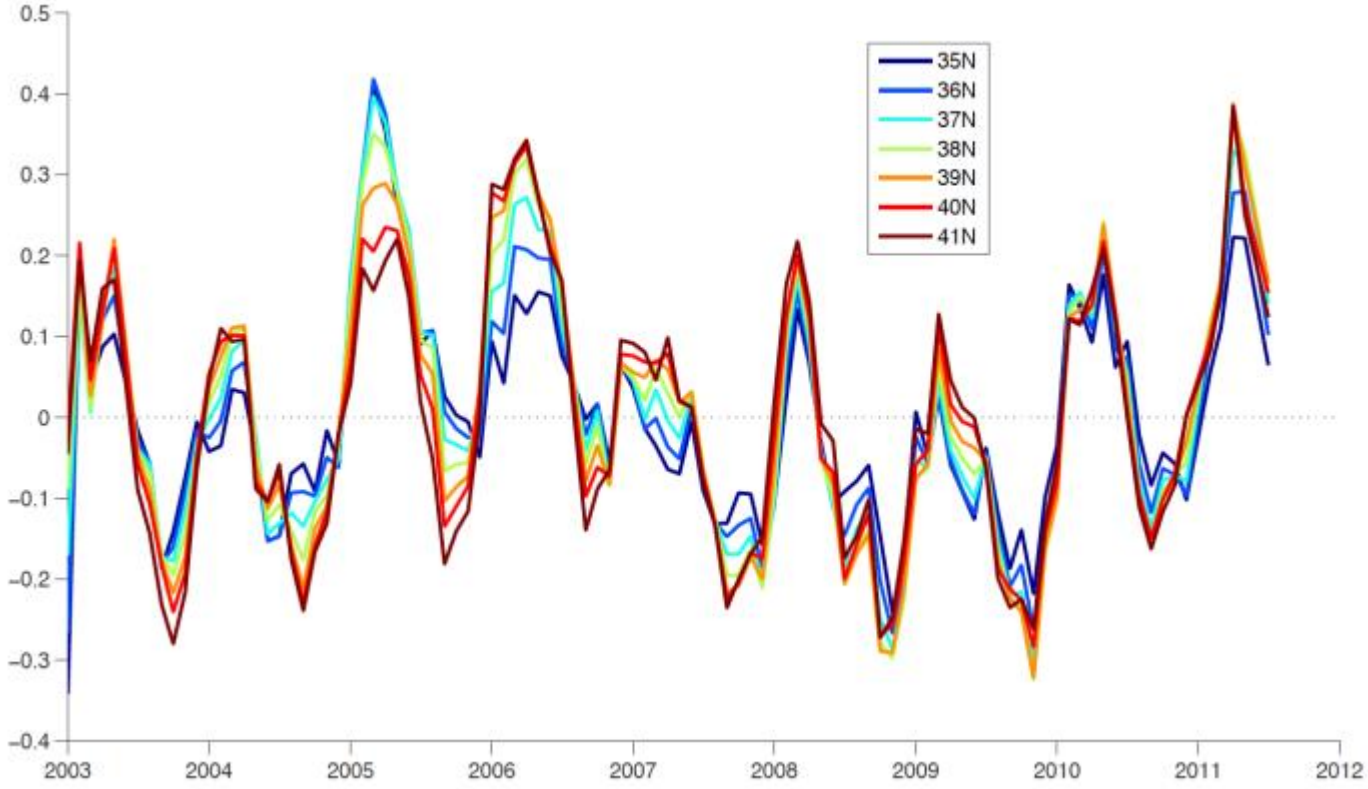

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Ancillary water storage data used:

1. Soil moisture:
   - GLDAS-NOAH, a forward land surface model (LSM).
2. Snow-water equivalent
   - Snow Data Assimilation System (SNODAS) from NOAA's National Weather Service National Operational Hydrologic Remote Sensing Center (NOHRSC)
3. Reservoir storage
   - 20 largest reservoirs in the Sacramento-San Joaquin basin (CDEC: http://cdec/water.ca.gov).

Table 1: Surface reservoirs used in the analysis. Data source: California Department of Water Resources; http://cdec.water.ca.gov.

Name	CDEC code	capacity [af]
Shasta	SHA	
Oroville	ORO	
New Melones	NML	
San Luis	SNL	
Don Pedro	DNP	
Montecello	BER	
Canyon	ALM	
San Luis	LUS	
New Excherquer	EXC	
Pine Flat	PNF	
Folsom	FOL	
San Luis	SLF	
New Bullards Bar	BUL	
Isabella	ISB	
Clear Lake	CLK	
Friant	MIL	
Camanche	CMN	
O Shanessey	HTG	
New Hogan	NHG	
Clear Lake Imp	CLA	

NASA/JPL Missions and Data: Water

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Outcomes	*Spaceborne*	*Airborne*	*Ground*	*DSS*	*Future*
Flow and flood	Terra, Aqua, TOPEX/Poseiden, Jason-1, GRACE, QuikSCAT, TRMM, CloudSAT, CALIPSO, LandSat	AVIRIS, POLSCAT, PALS, UAVSAR	Surface radars, Weather Station	RiverWare EPA SWMM 5 VIC, Mike-xxx	Aquarius NPOES SWOT GPM GRACE-II
Drought	Terra, Aqua, TRMM, QuikSCAT, LandSat, GRACE	AVIRIS, PALS, UAVSAR	SNOTEL, SCAN, Surface radar, Weather station	WSF NIDIS, Mike-xxx	SMAP DESDynI
Water Delivery and Irrigation	Terra, Aqua, GRACE, AMSR-E, QuikSCAT, LandSat	PALS, GLISTIN, UAVSAR	SNOTEL	AWARDS WEAP CalSimII, Mike-xxx	SMAP DESDynI SWOT SCLP
Water Quality	Terra, Aqua, GRACE, SRTM, ASTER	AVIRIS, UAVSAR, MASTER, HyTES, AMS	Temperature Sediment Chlorophyll	BASINS	SMAP GPM, HyspIRI, SWOT

Snow Water Equivalent (SWE)

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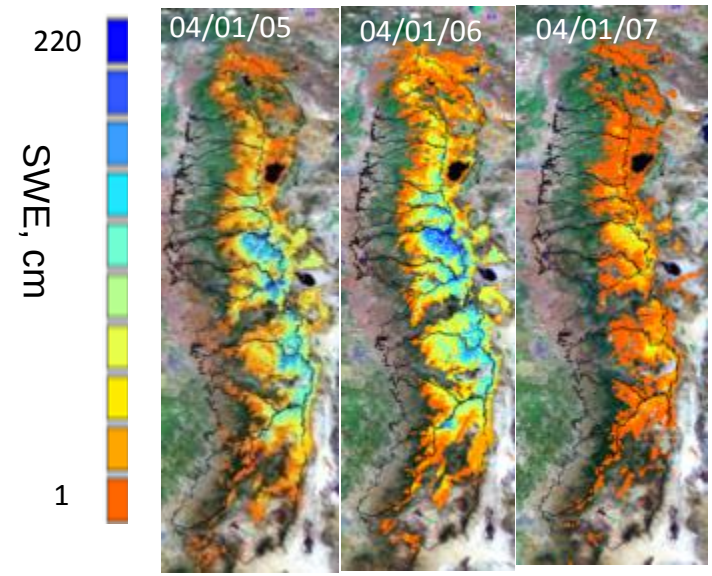
- Objective: Combine observations from NASA satellite data and ground-based snow sensors into distributed models to estimate SWE.
- Focus: Snow water equivalent mapping using NASA satellite data for water supply forecasts.
- Data: MODIS; CADWR, NRCS and other snow sensor data; stream gauges.
- Team: Noah Molotch, NASA/JPL, CU Boulder, Leanne Lestak, CU Boulder

Customers and Needs:

- Practitioners: CADWR, NRCS, and the California Cooperative Snow Survey (consortium of ~50 agencies and utilities).
- Needs: Decision makers are seeking alternate sources of data due to inconsistent measurements, lack of data at high elevations, and loss of stations because of budget cuts.

Maturity of the Algorithms and Technology:

- Algorithms for SWE are fully developed and vetted through a series of peer-reviewed publications.
- SWE product data delivery system under development and near completion.
- Validation sites in the southern, central, and northern Sierra Nevada provide confidence in data products.



MODIS-model estimates of snow water equivalent in Sierra Nevada reveal extreme inter-annual variability.

Noah.P.Molotch@jpl.nasa.gov

Groundwater storage changes in the Sacramento-San Joaquin River Basins from GRACE and supplementary data, Oct2003 – Mar2010

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UCCHM

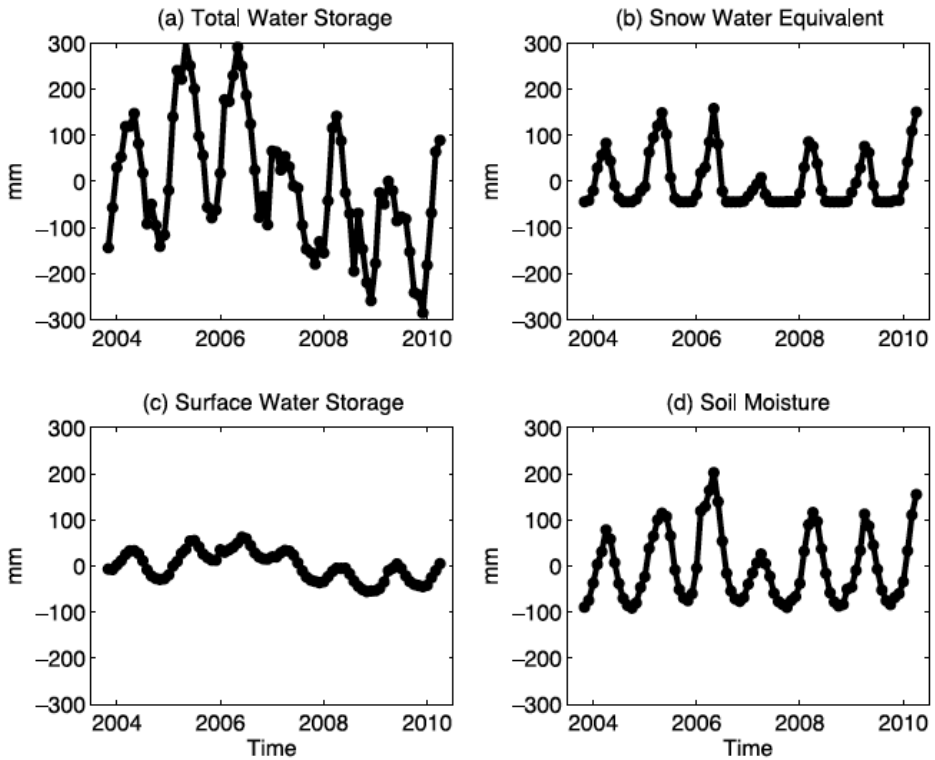
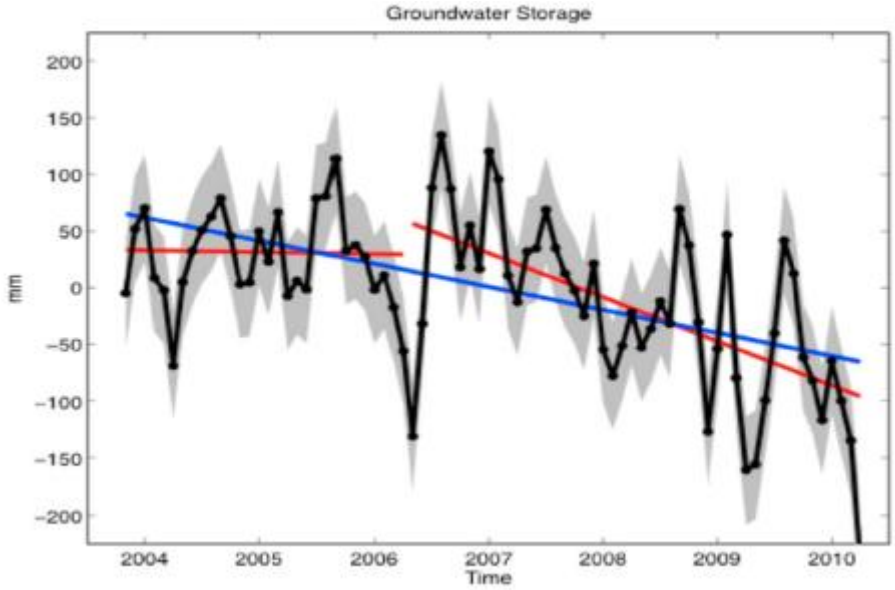


Table 1. Trends in Water Storage for the Combined Sacramento-San Joaquin River Basins[a]

	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

[a]Trends and volumes are for October, 2003–March, 2010 unless otherwise noted.



- In the 78 month period analyzed, the water stored in the combined Sacramento-San Joaquin River Basin decreased by over 31 km^3, or nearly the volume of Lake Mead
- Nearly two-thirds of this, or roughly 20 km^3, came from changes in groundwater storage, primarily from the Central Valley