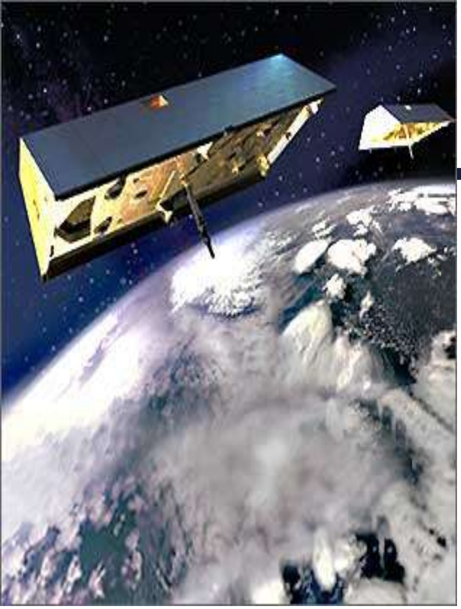


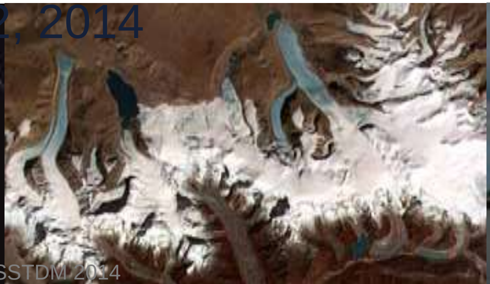
Monitoring Terrestrial Hydrology with GRACE Satellites

Alys Thomas

University of California, Irvine USA

International Workshop on Small Satellite and Sensor Technology for Disaster Management

April 2, 2014



University of California Center for Hydrologic Modeling
(UCCHM)

- Mission: provide state-of-the-art integrated water cycle modeling tools to support research, explore environmental solutions, and to provide highly reliable information to decision makers

- We address pressing issues including **how water availability will change** in response to climate change and a diminishing snowpack; **how resources will vary** in response to climate oscillations; and **how the frequency of hydrologic extremes** such as flooding and drought will affect resources.

- A key component of the Center's research uses data from NASA's **GRACE** (Gravity Recovery and Climate Experiment) mission to track changes in freshwater availability in large aquifers and river basins.

www.ucchm.org

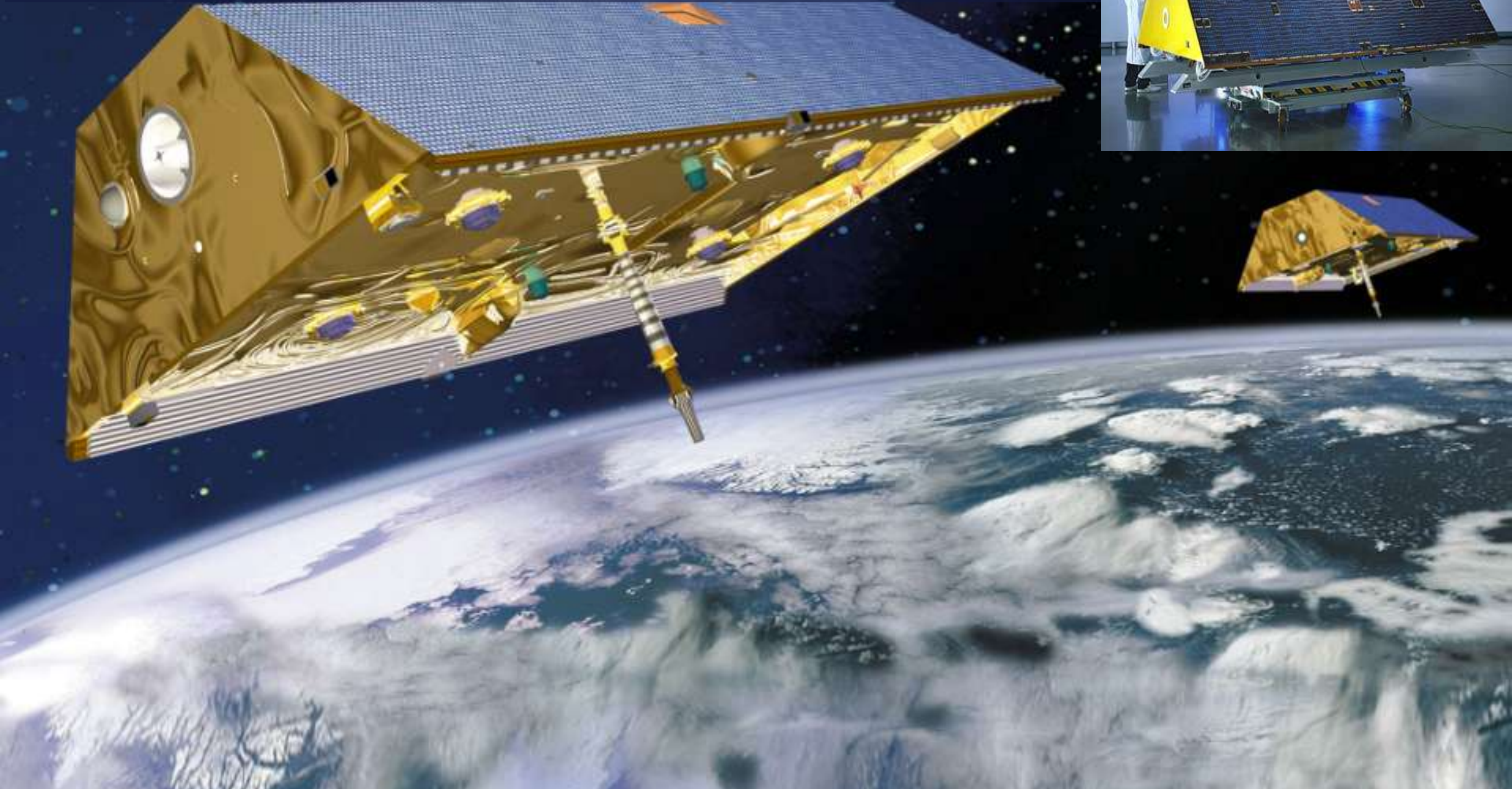
UCCHM
University of California
Center for Hydrologic Modeling

Presentation Overview

1. The Gravity Recovery and Climate Experiment (GRACE) Satellite Mission
2. GRACE for:
   1. Observations of Regional Water Storage Change
   2. Groundwater Estimates
   3. Characterizing Hydrological Extremes
3. Use of GRACE data in land surface models
4. Future?
   1. GRACE contributions for monitoring terrestrial water cycle, climatic extremes, and water/disaster management

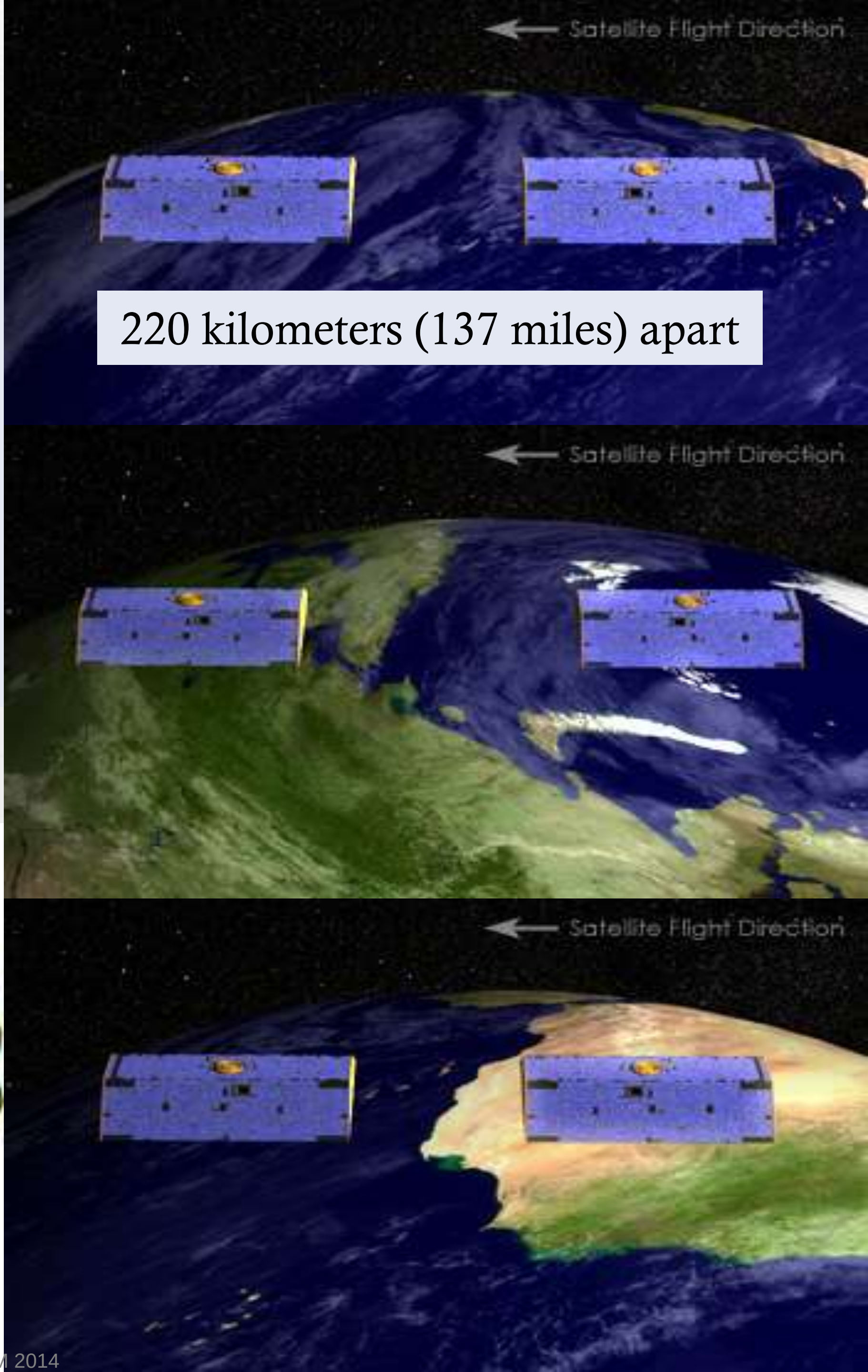
NASA Gravity Recovery and Climate Experiment (GRACE)

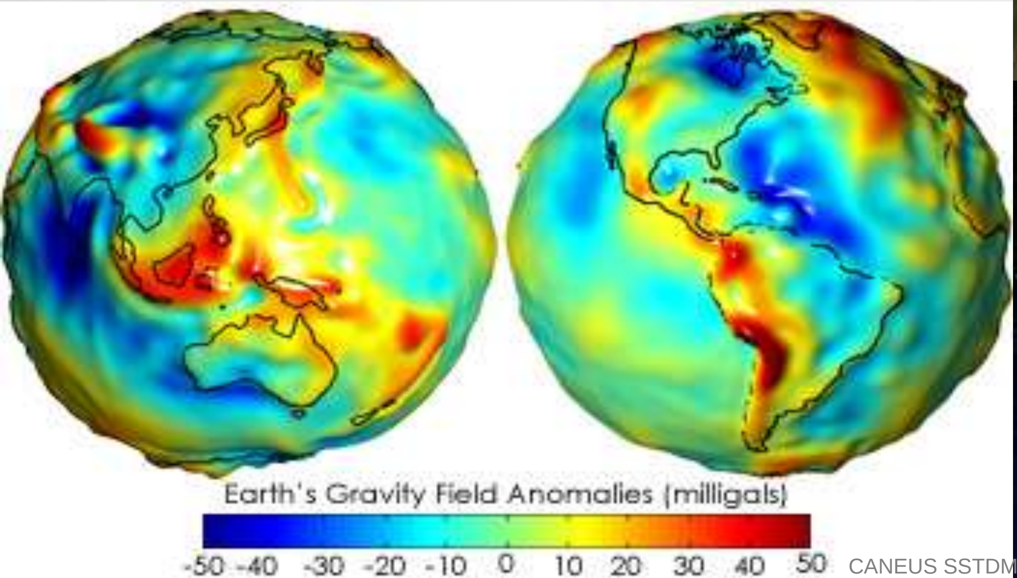
- Launched in 2002
- GRACE maps the Earth's gravity fields by making accurate measurements of the distance between the two satellites, using GPS and a microwave ranging system.



The two GRACE satellites themselves act in unison as the primary instrument.

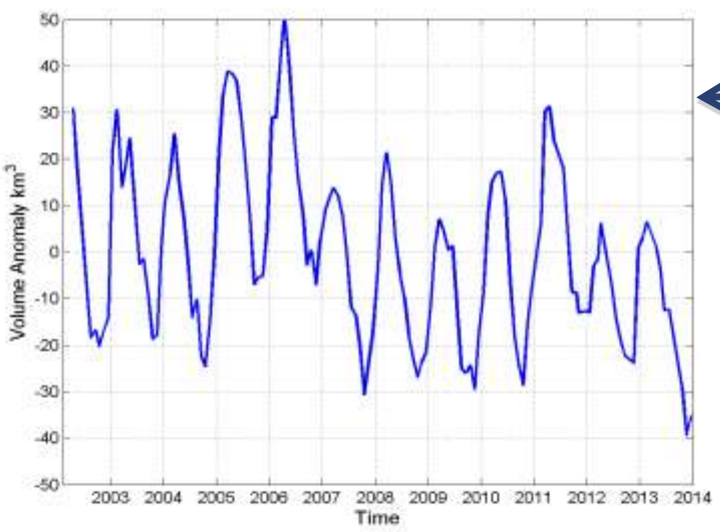
Changes in the distance between the twin satellites are used to make gravitational field measurements.

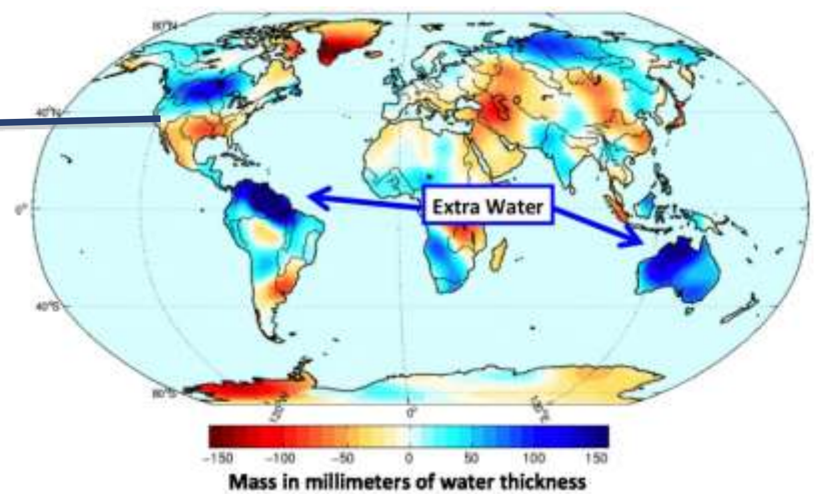




Estimating water storage changes with GRACE

- The difference between two GRACE global gravity fields yields a time-variable component.
- The main contributors to time variations in the gravity field are changes in water storage in the ocean, the atmosphere and on land.
- Why? Because water is REALLY HEAVY!
- Consequently, the GRACE time-variable signal on land is dominated by changes in terrestrial water storage, i.e. GRACE monitors changes in all of the water stored on land, ***the change in total water storage*** (all of the snow, surface waters, soil moisture and groundwater), at monthly and longer timescales
- Given the extremely high precision of GRACE, the resulting errors are ~1.5 cm for monthly storage anomalies at the 150,000 km^2 scale (~2.25 km^3)





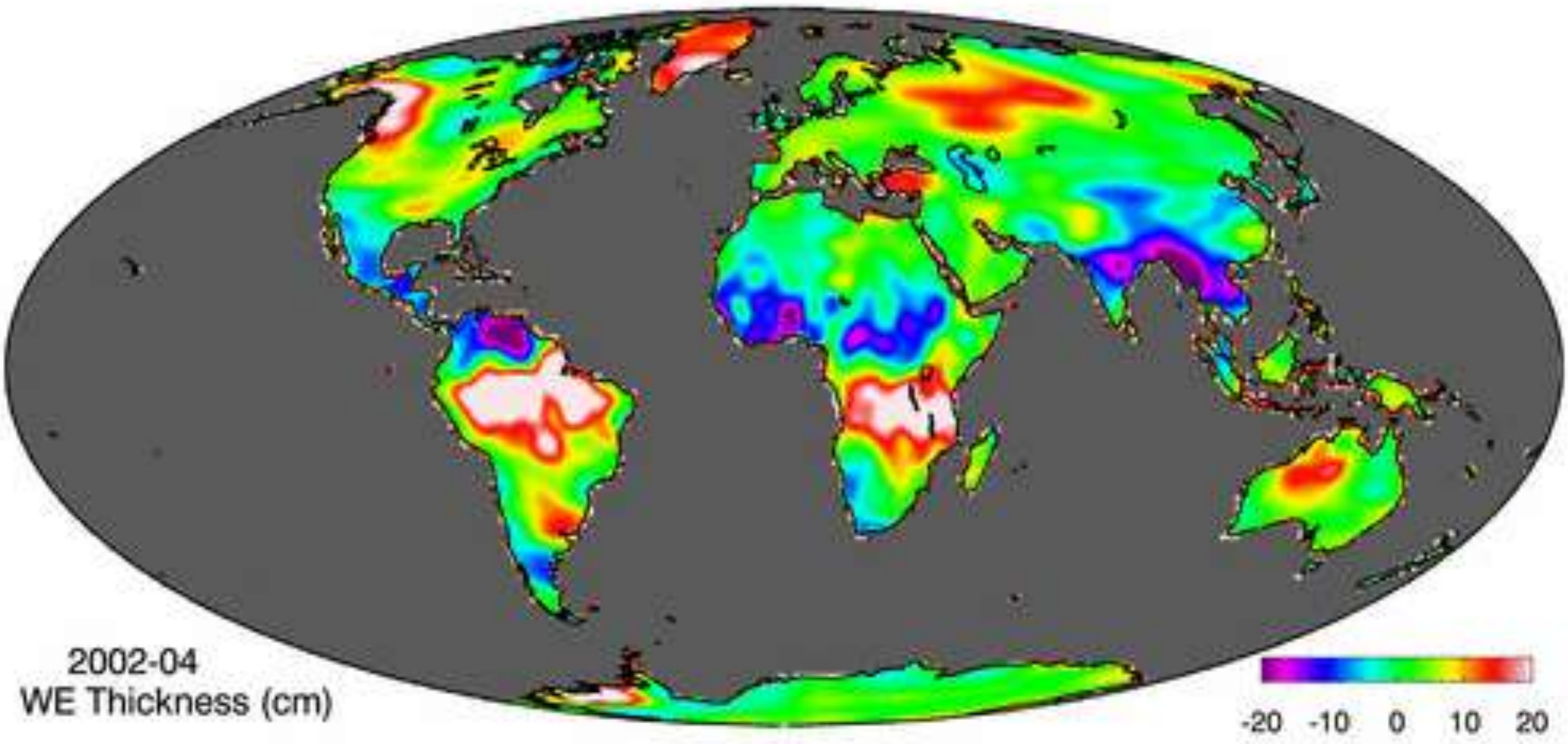
2010 (January-February-March average) to mid 2011 (March-April-May average)
from Boening et al., 2012

Mean gravity field + monthly maps of the time-variable gravity field useful tools for scientists as they study the Earth's changing climate:

- **The mean gravity field helps scientists better understand the structure of the solid Earth and learn about ocean circulation.**
- **Scientists use time-variable gravity to study ground water fluctuations, sea ice, sea level rise, deep ocean currents, ocean bottom pressure, and ocean heat flux.**

GRACE is like a giant scale in the sky that tells you how much weight you've gained or lost each month

Estimating water storage changes with GRACE cont.

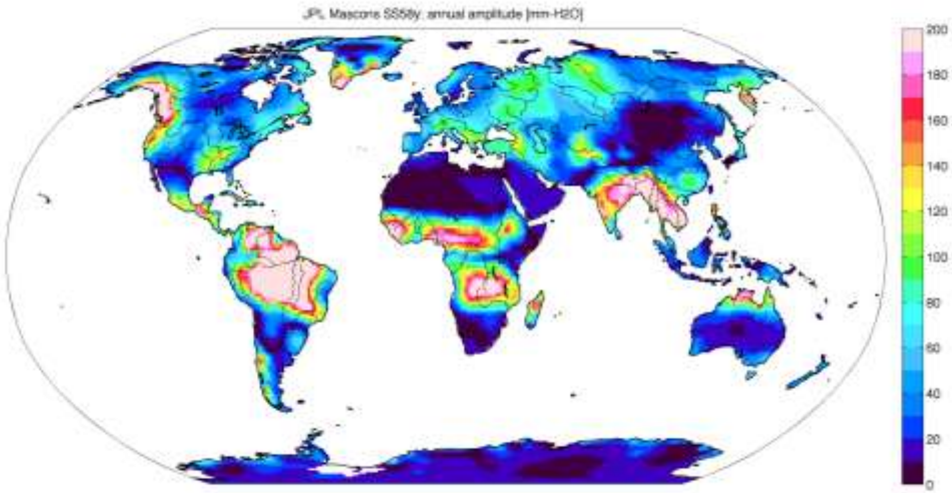


GRACE is unique in its ability to detect variations in all components of water storage, no matter the depth

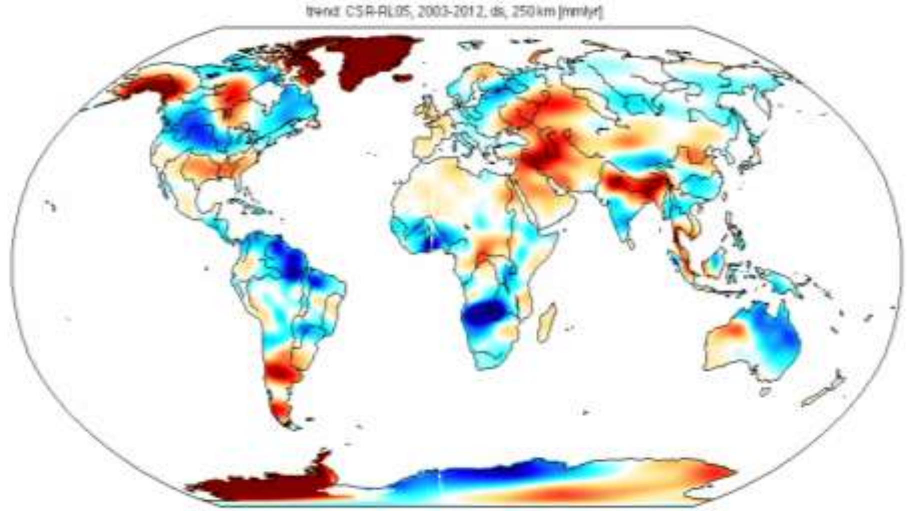
Estimating water storage changes with GRACE cont.

Inter-annual variations and emerging trends from GRACE, 2003-2012

Annual Amplitude (mm)



Trend (mm/yr.)

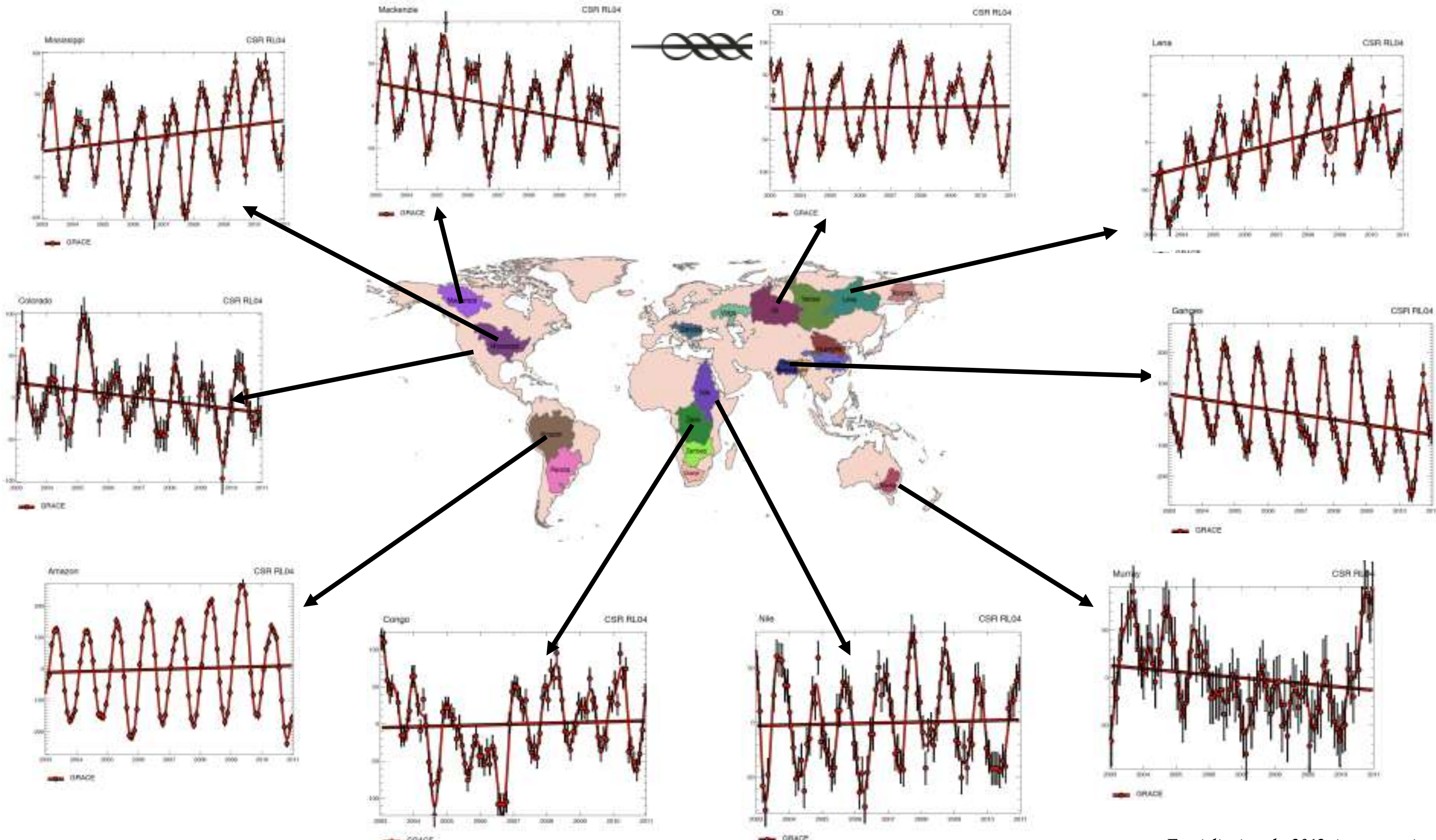


Famiglietti et al., 2013

- First global look at magnitude of water storage variations
- Reveal important information on storage that is typically not captured by models: glacial melt, reservoir release, groundwater mining, etc.
- Amplitude is a measure of water cycle **strength** and **variability**
- Important trends emerging
- Data are ripe for understanding hydro-climatological variations, for understanding human impacts, for data assimilation, for pointing to model enhancements, and for informing sustainable water management

Estimating water storage changes with GRACE cont.

Inter-annual variations and emerging trends in large river basins 2003-2011



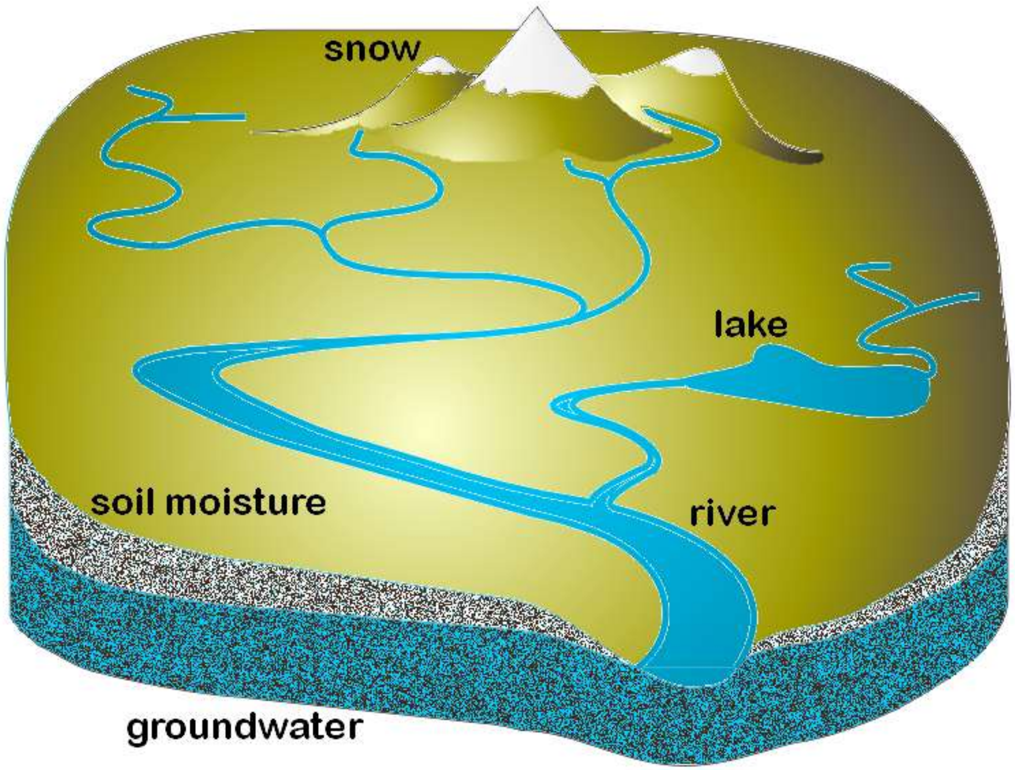
Famiglietti et al., 2012, in preparation

Estimating groundwater storage changes with GRACE

$$\Delta S_{LAND} = \Delta S_{SNOW} + \Delta S_{SW} + \Delta S_{SM} + \Delta S_{GW}$$

$$\Delta S_{GW} = \Delta S_{LAND} - \Delta S_{SNOW} - \Delta S_{SW} - \Delta S_{SM}$$

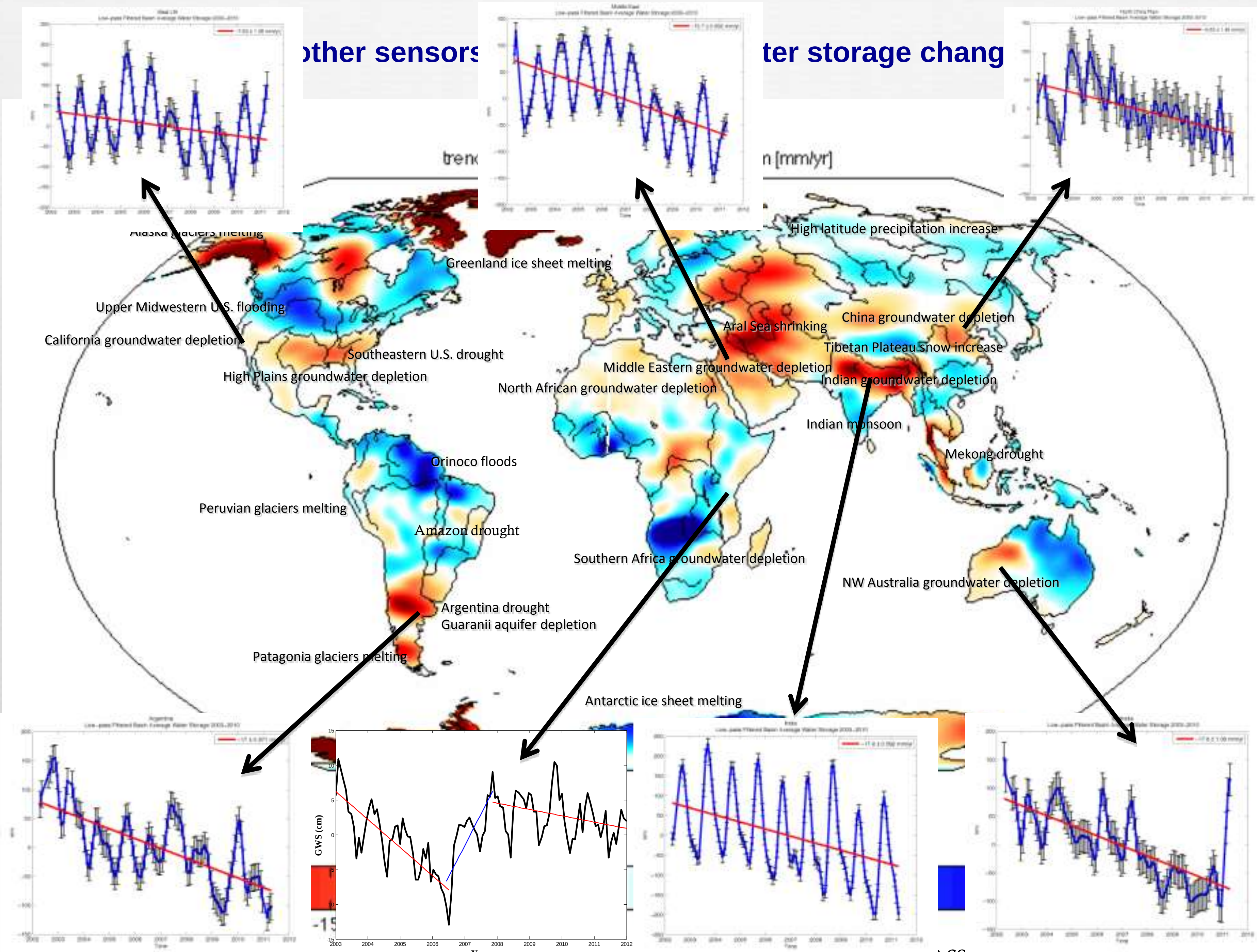
ΔS_{LAND}

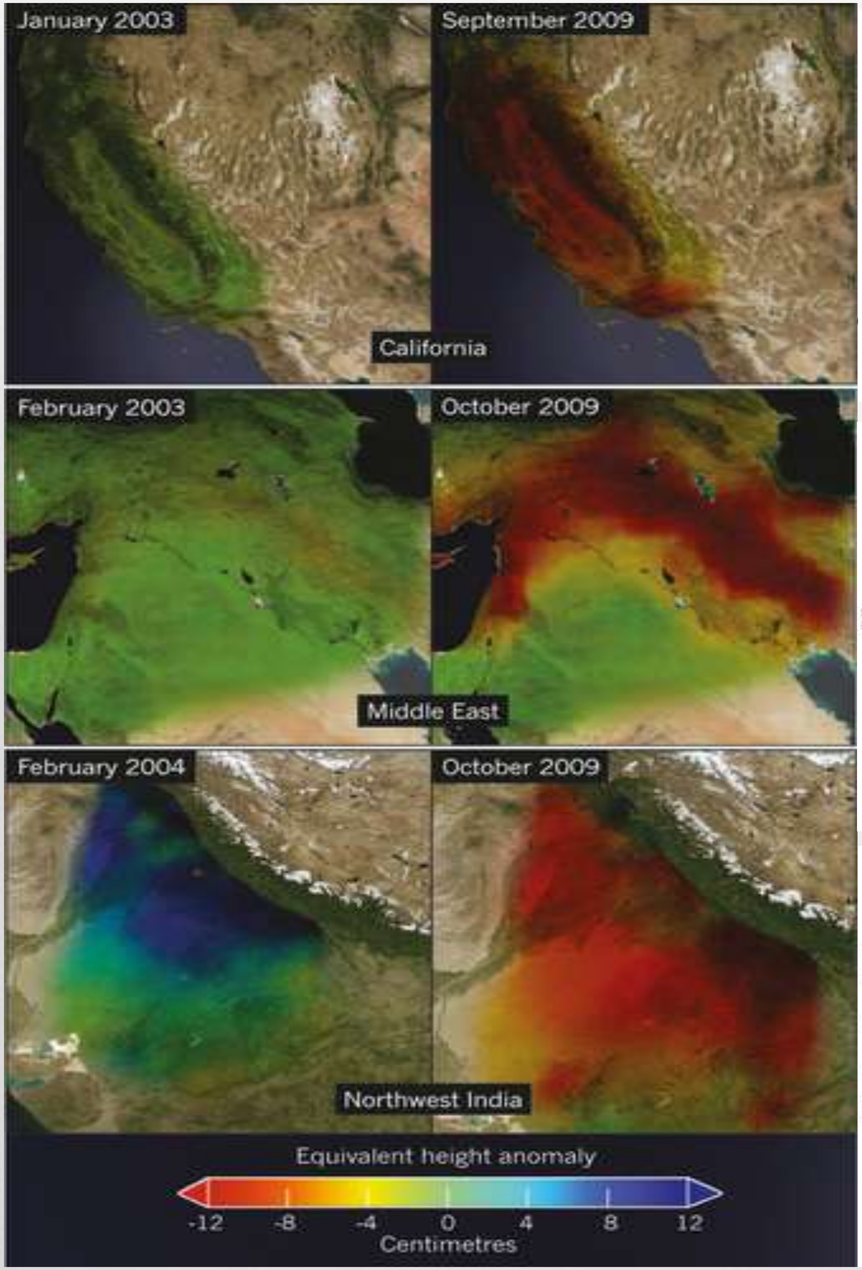


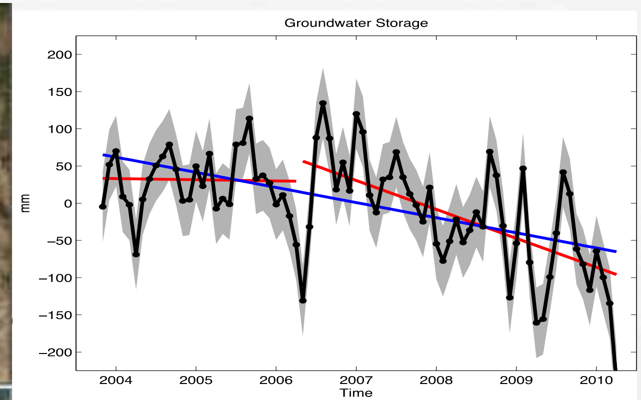
Remove this ($\Delta S_{SNOW} + \Delta S_{SW} + \Delta S_{SM}$) from

ΔS_{LAND}…

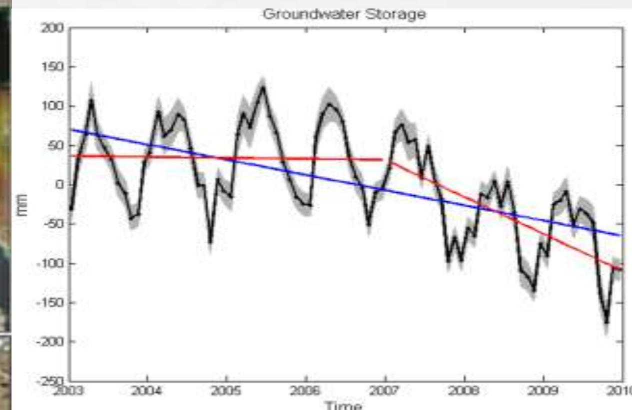
To isolate this (ΔS_{GW})


ther sensors
ter storage chang
trend
n [mm/yr]
Alaska glaciers melting
Greenland ice sheet melting
High latitude precipitation increase
Upper Midwestern U.S. flooding
California groundwater depletion
Southeastern U.S. drought
High Plains groundwater depletion
Aral Sea shrinking
China groundwater depletion
Tibetan Plateau snow increase
Middle Eastern groundwater depletion
Indian groundwater depletion
North African groundwater depletion
Indian monsoon
Mekong drought
Orinoco floods
Peruvian glaciers melting
Amazon drought
Southern Africa groundwater depletion
NW Australia groundwater depletion
Argentina drought
Guaranii aquifer depletion
Patagonia glaciers melting
Antarctic ice sheet melting
GWS (cm)
Year

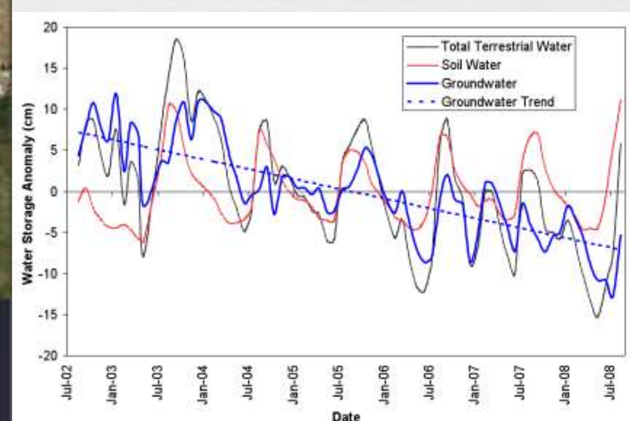




Famiglietti et al., 2011
~30 km³/yr.
(Oct '03-Mar '10)



Voss et al., 2013
~93 km³/yr.
(Jan '03-Dec '09)

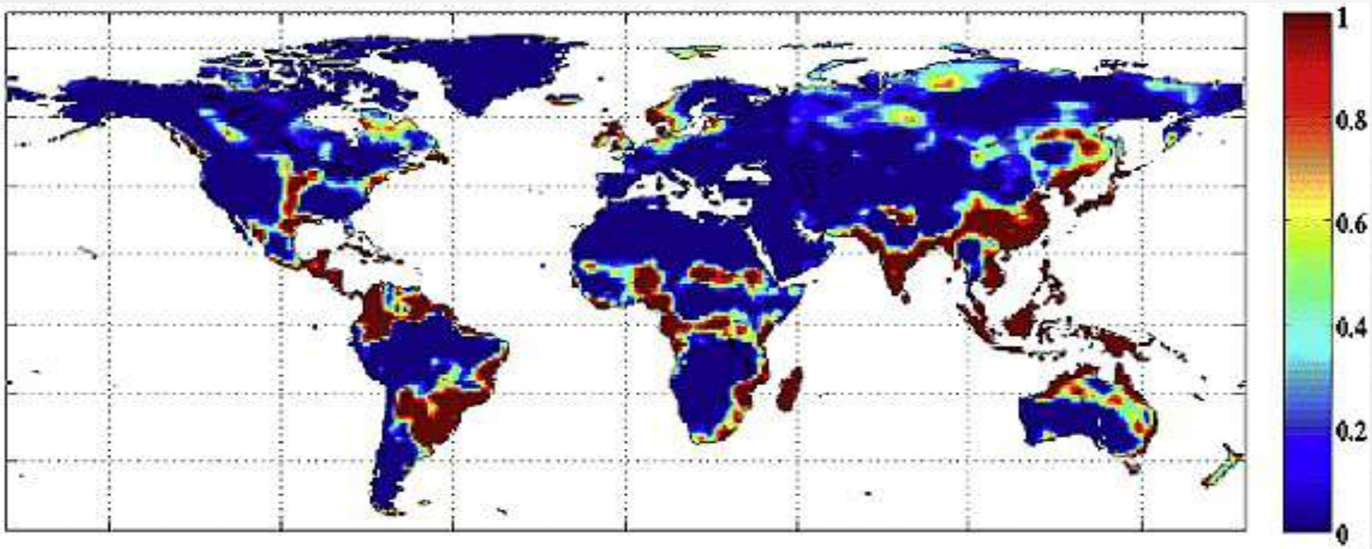


Rodell et al., 2009
~18 km³/yr.
(Aug '02-Oct '08)

over the Indian states of Rajasthan, Punjab and Haryana (including Delhi)

Bourzac, 2013; after Rodell et al., 2009; Famiglietti et al. 2011; Voss et al., 2013

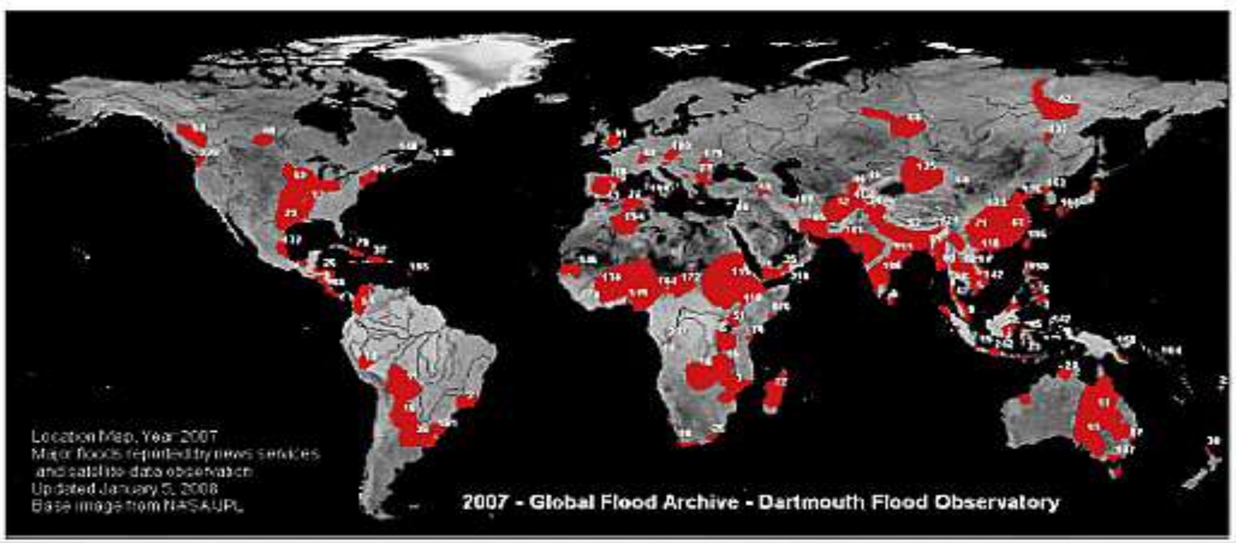
GRACE: Potential for flood prediction



GRACE-based Flood Index Maxima May, 2007

$$S_{DEF} = S_{MAX} - S(t\text{-}1)$$

$$F(t) = P_{MON}(t) - S_{DEF}$$



Recorded floods, Dartmouth Flood Observatory, May, 2007

Quantity of incoming water that cannot enter storage for the current month based on the regionally observed storage anomaly maxima

Reager and Famiglietti, 2009

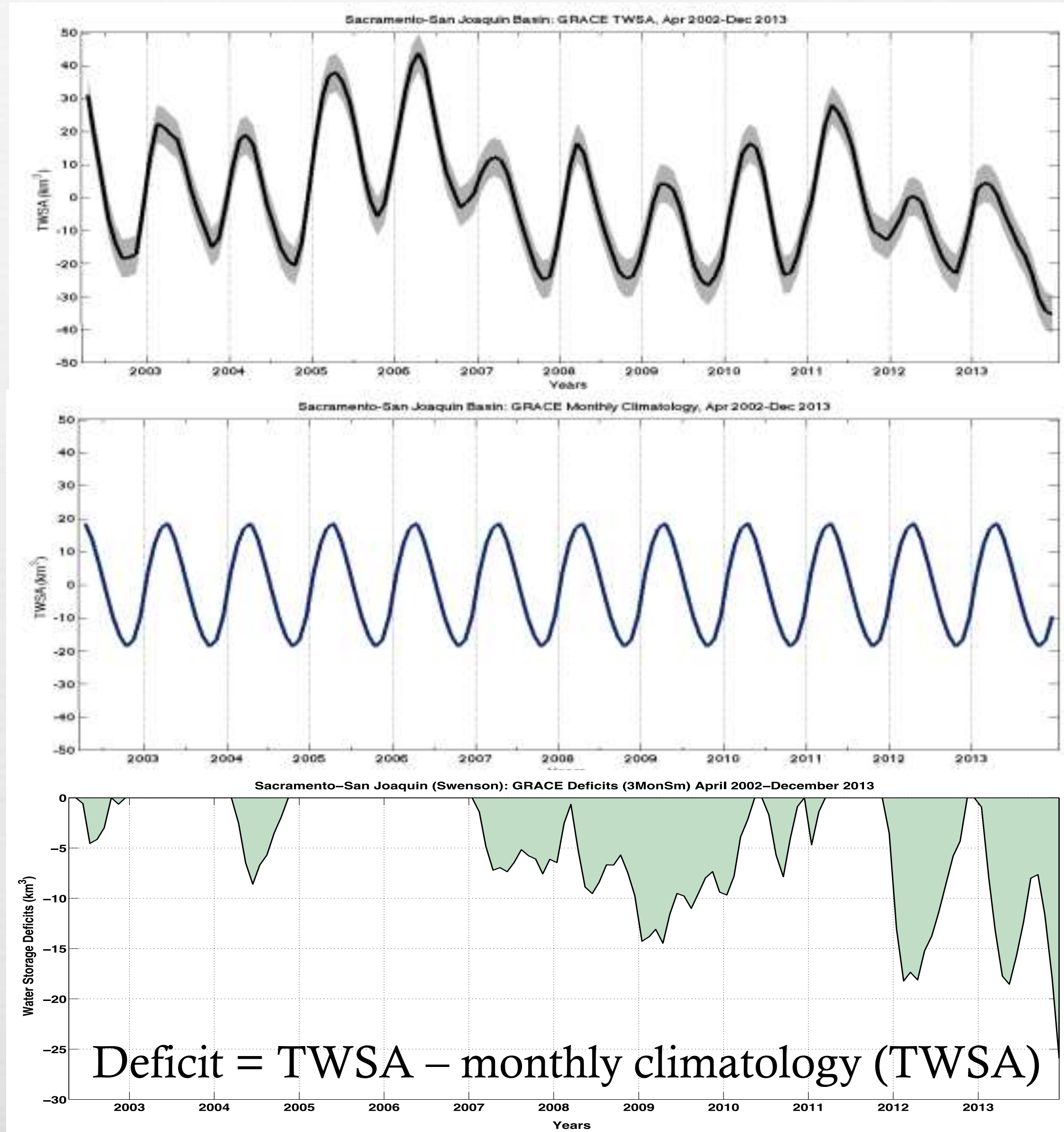
An example of water cycle change from GRACE

Increasing Extremes in California

Monthly changes in total water storage

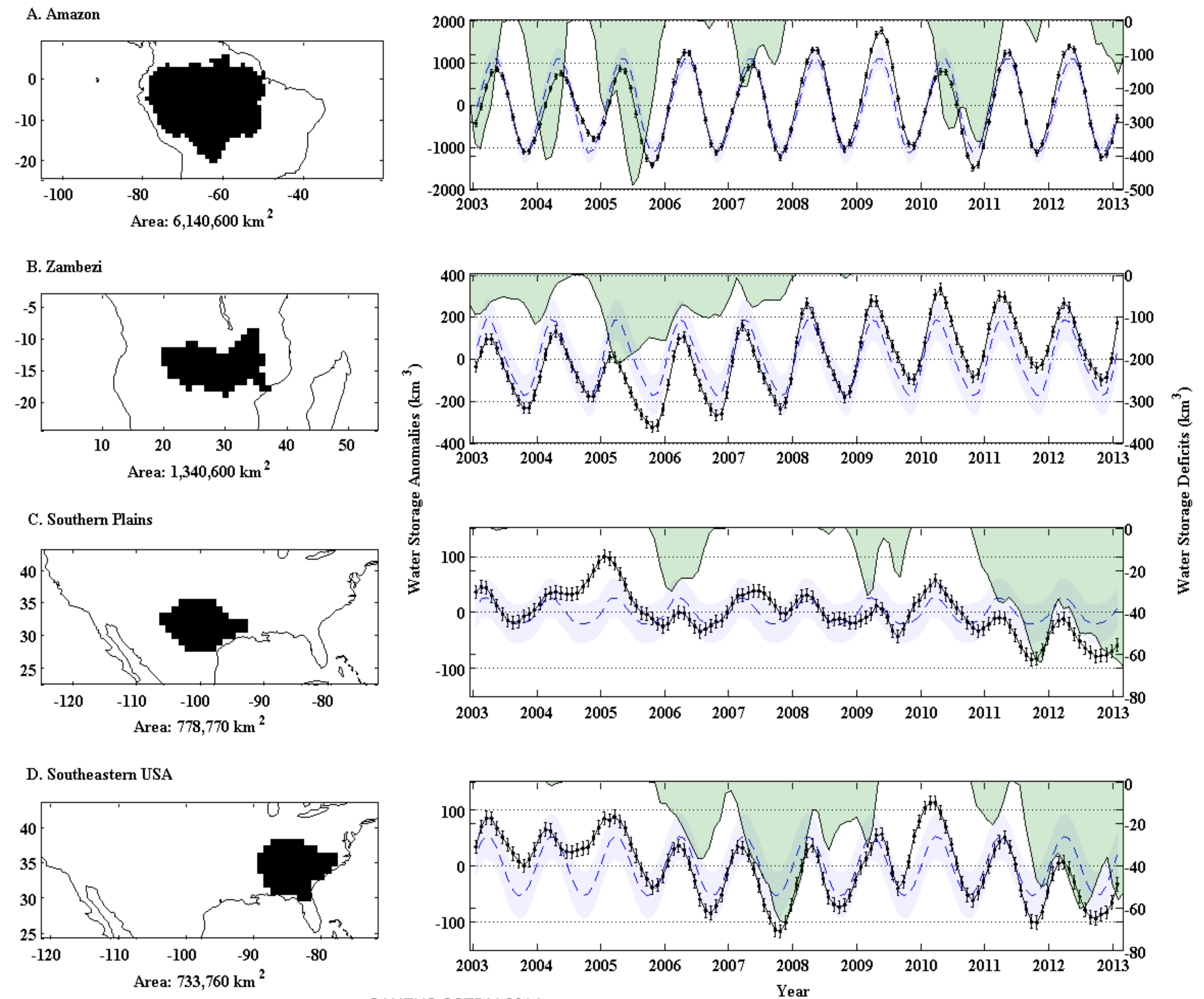
Average changes in total water storage

Negative deviations from average water storage conditons



Thomas et al., 2014

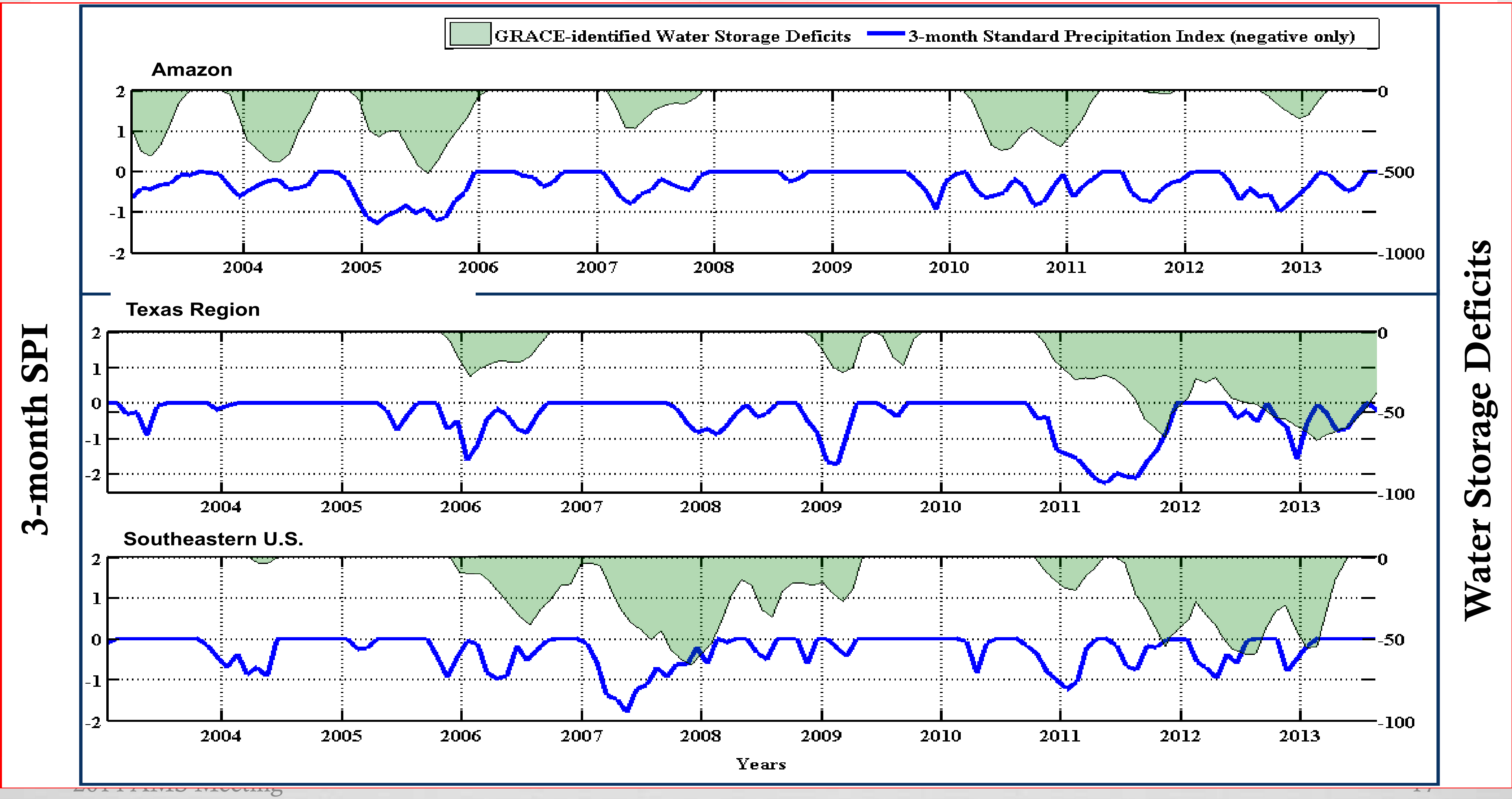
GRACE: Potential for drought monitoring



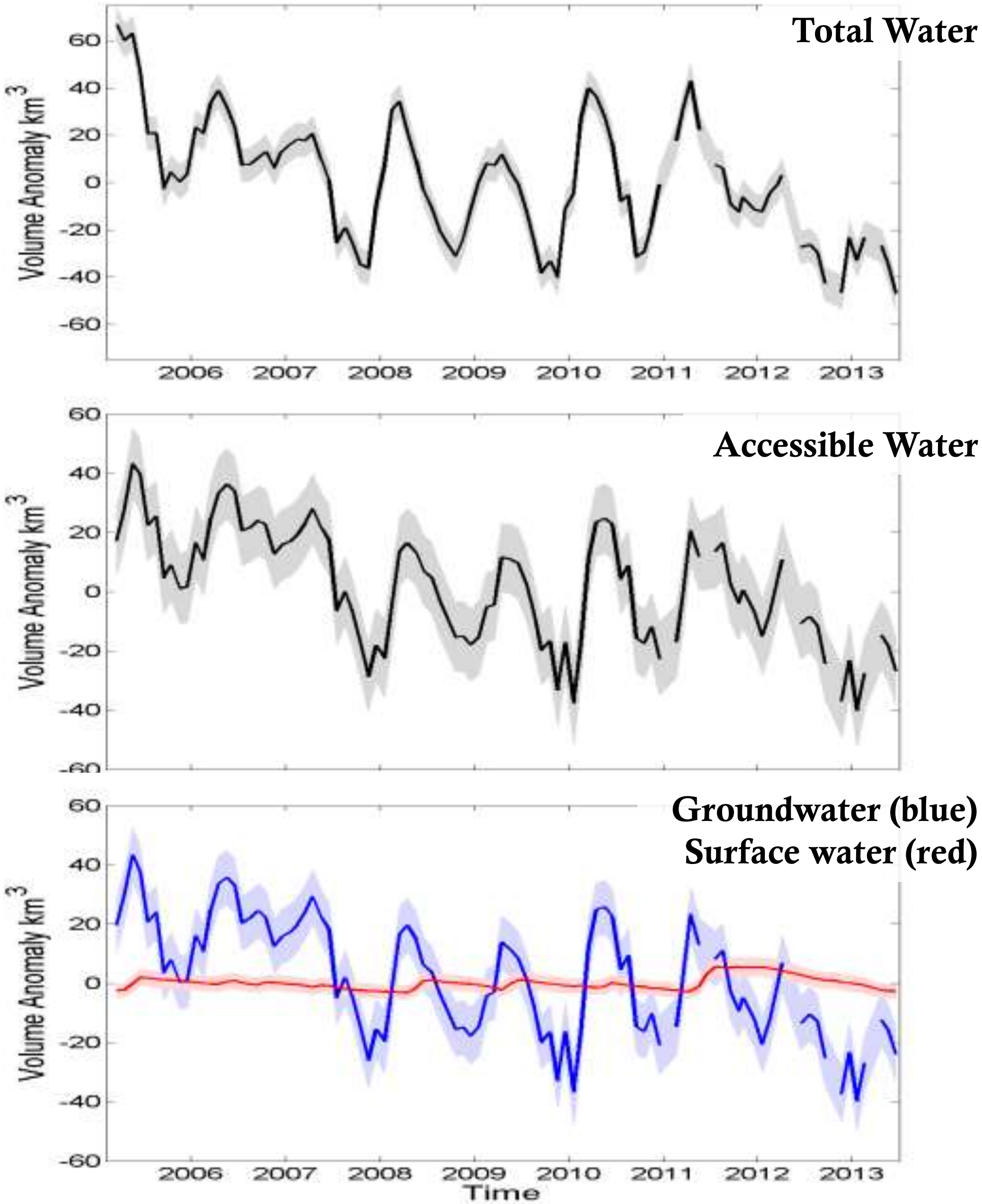
Thomas et al., 2013

Implications for Water Resources

- The severity metric (S) is most associated with reports of widespread, catastrophic meteorological drought.

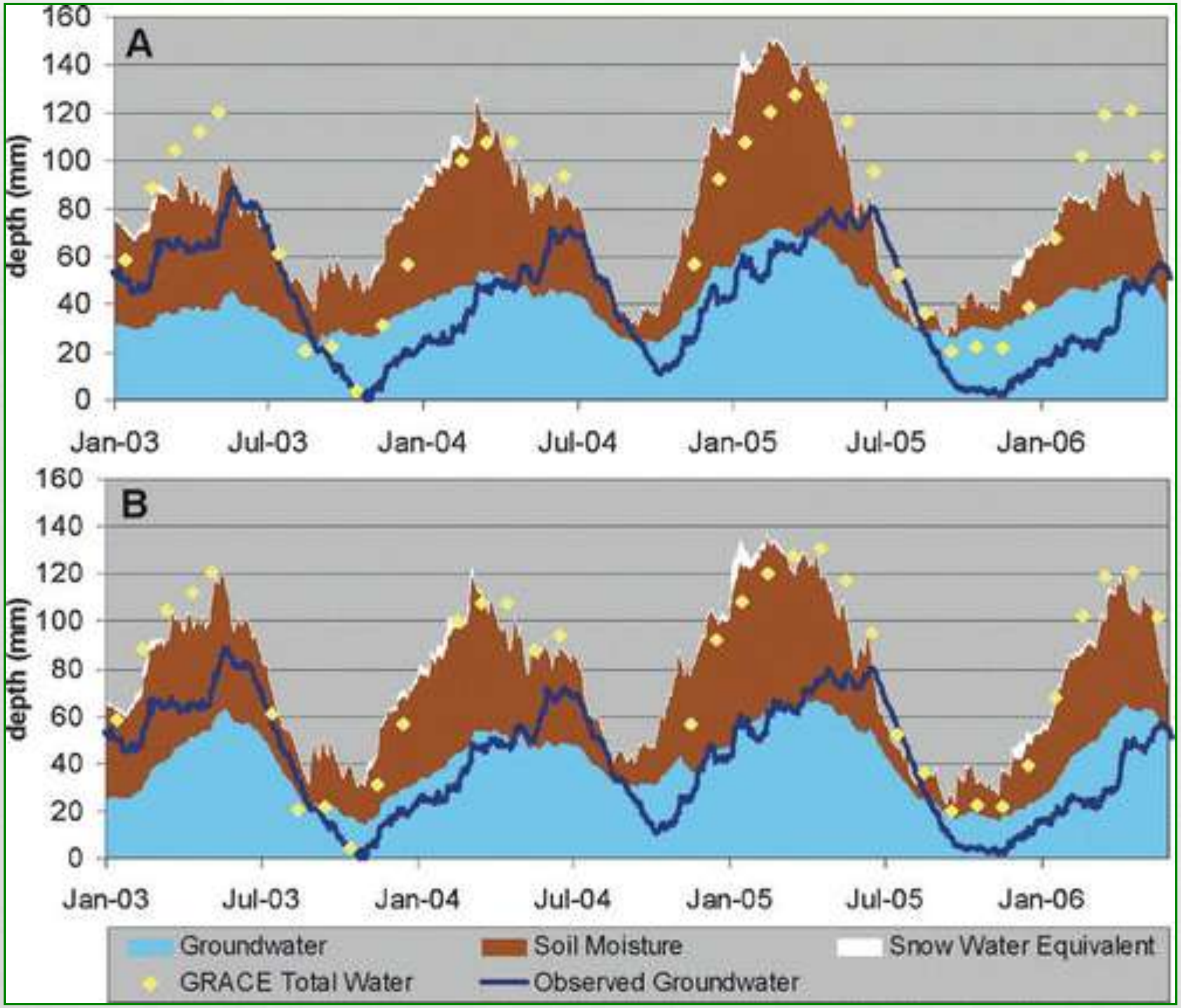


Groundwater use in the Colorado River Basin during drought (2005-2013)



Castle et al. 2014, in review

Using GRACE for Calibration, Validation, Model Diagnostics and Improvement

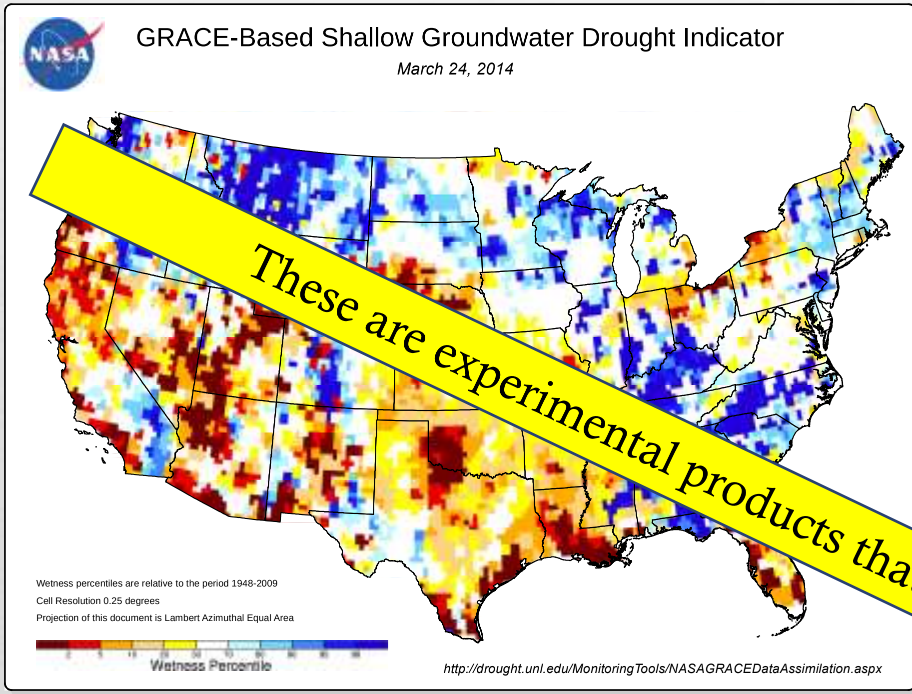


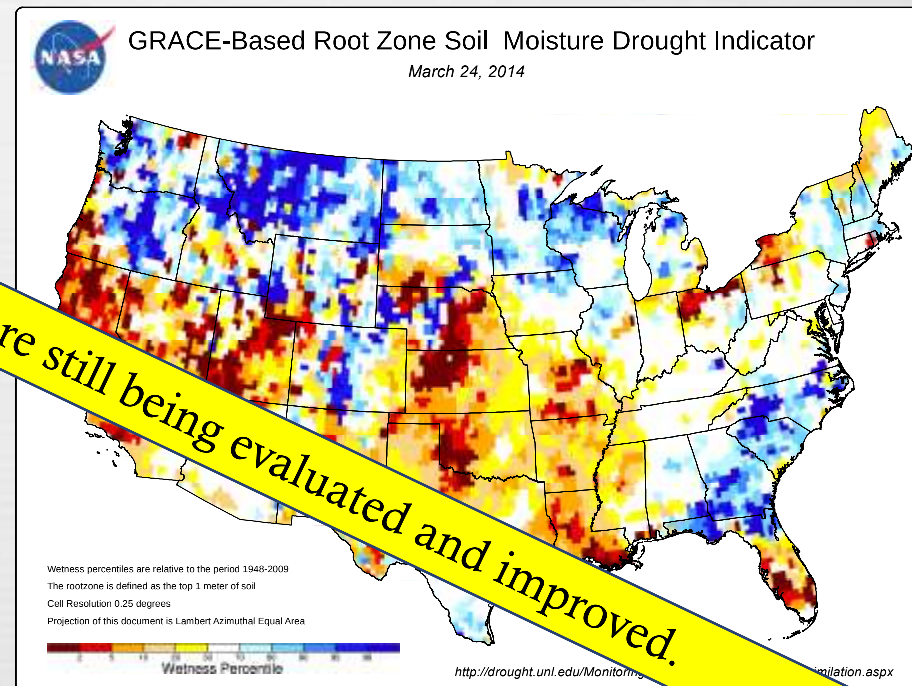
Simulated groundwater, soil moisture, and snow water equivalent for the Mississippi river basin for
(A) open loop
(B) GRACE assimilation.

Daily observed groundwater and monthly GRACE-derived TWS anomalies.

GRACE and modeled TWS are adjusted to a common mean, as are observed and modeled groundwater.

Zaitchik et al. (2007)

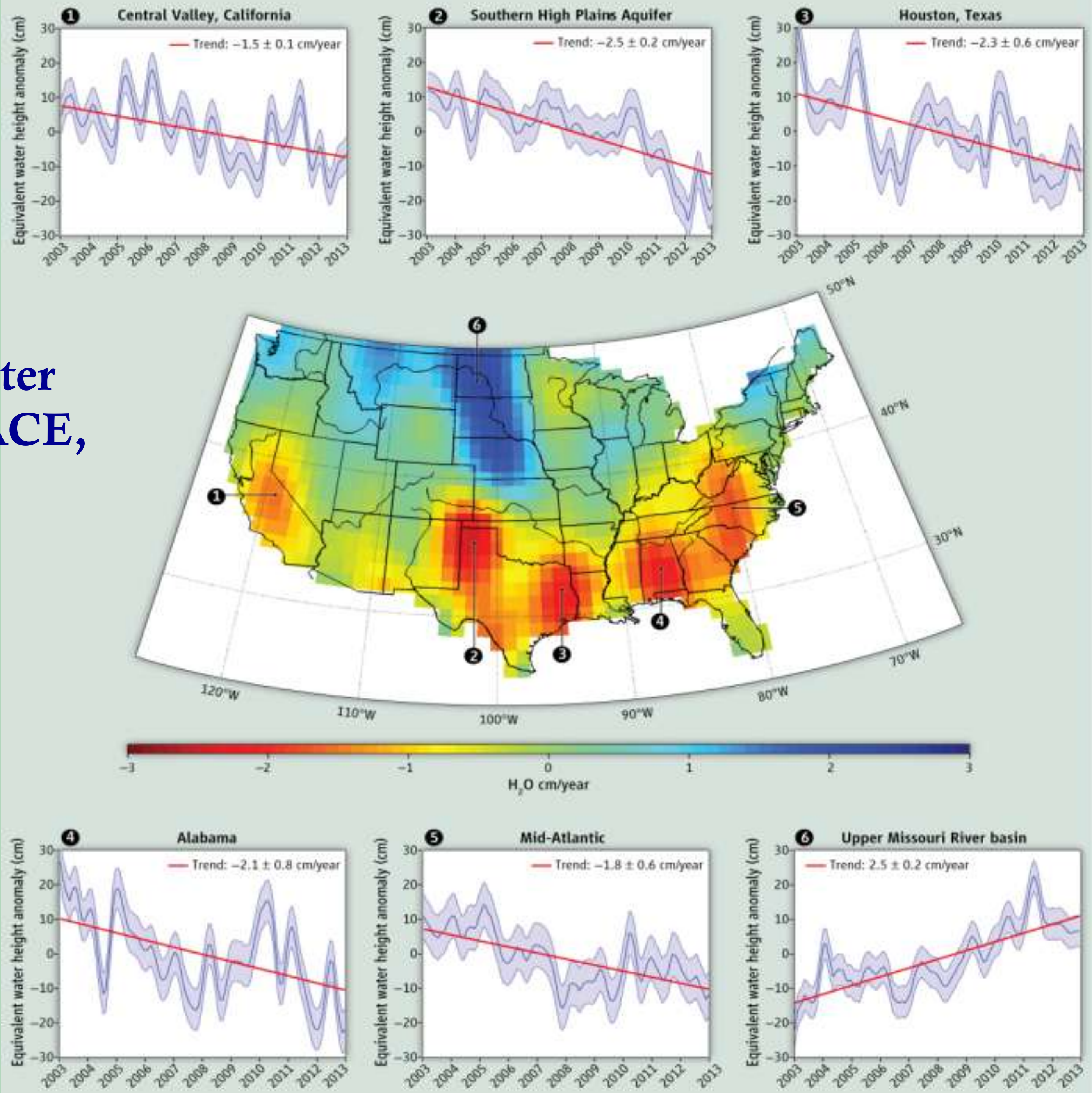




These are experimental products that are still being evaluated and improved.

Houborg et al 2012

Trends in Freshwater Storage from GRACE, 2003-2012



From 'Water in the Balance,' Famiglietti and Rodell, 2013

A short list of how GRACE can help with water and water management issues in climate models

- **Amplitude**: Variability, extremes, changing storage
- **Trend**: climate change, human water management
- **Calibration**: residence times, baseflow
- Understanding and parameterization of process: persistence of anomalies, changes in active layer thickness, effective storage
- **Water balance closure**: independent estimates of river discharge, evapotranspiration, and groundwater storage
- **Data assimilation**: large-scale constraints, model-based downscaling
- **Predictive capability**: significant memory in certain regions, perhaps due to more slowly changing groundwater storage
- **Feedbacks**: e.g. to water management practices like irrigation

Summary

- Tremendous information content in the GRACE data for improving climate and hydrologic prediction
- Contributions to improved understanding of how terrestrial water storage responds to climate change and variability
- Capturing amplitude is important for predicting extremes and inter-annual variability
- Reproducing trends is important to capturing climate change and human signal of water management
- Lots and lots of work to be done on climate models in terms of datasets of unknown properties, key natural and human water cycle components not yet parameterized, multi-sensor assimilation, etc.
- ‘Doing hydrology backwards’ – in a good way -- thanks to availability of GRACE
- Exposing the importance of groundwater, both natural and managed

Contact Information

- **Presenter**
  - Alys Thomas: thomasac@uci.edu
- **Professor & Director of the UCCHM**
  - **Jay Famiglietti**: jfamigli@uci.edu
- **Collaborators**
  - J.T. Reager: jreager@uci.edu
  - Matt Rodell: matthew.rodell@nasa.gov
  - Stephanie Castle: castles@uci.edu

UCCHM
University of California
Center for Hydrologic Modeling

http://www.ucchm.org/
http://blog.ucchm.org/

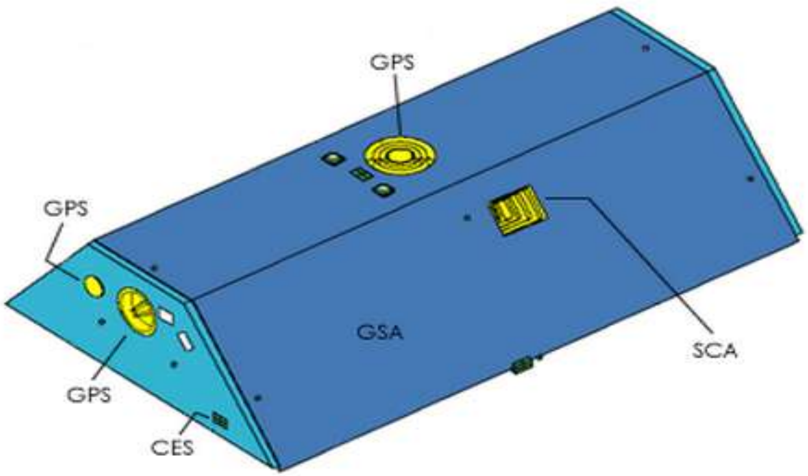
GRACE Animation

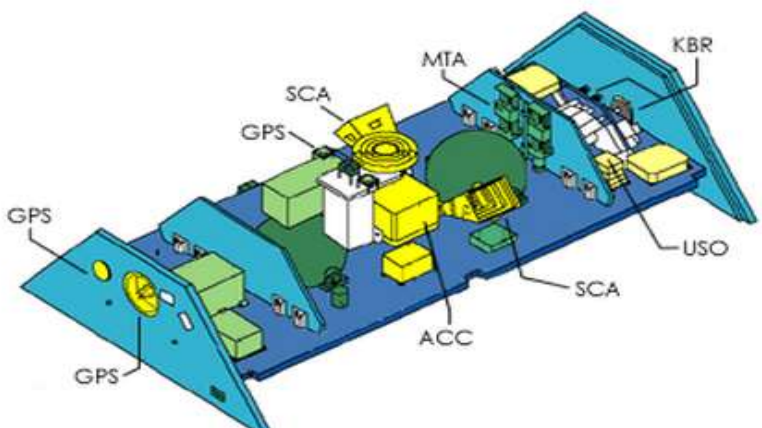
- **Tapley** et al. (2004), Geophys. Res. Lett. 31, L09607, doi:10.1029/2004GL019920.
- **Tapley**, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins, GRACE Measurements of Mass Variability in the Earth System, Science 23 July 2004: 305 (5683), 503-505. doi:10.1126/science.1099192.
- **Landerer**, F. W., and S. C. Swenson. "Accuracy of scaled GRACE terrestrial water storage estimates." Water Resources Research 48.4 (2012).
- **Syed**, T. H., J. S. Famiglietti, M. Rodell, J. Chen, and C. R. Wilson (2008), Analysis of terrestrial water storage changes from GRACE and GLDAS, Water Resour. Res., 44, W02433, doi:10.1029/2006WR005779.
- **Famiglietti**, J. S., M. Lo, S. L. Ho, J. Bethune, K. J. Anderson, T. H. Syed, S. C. Swenson, C. R. de Linage, and M. Rodell. (2011): Satellites measure recent rates of groundwater depletion in California's Central Valley, 38, L03403, doi:10.1029/2010GL046442.
- **Rodell**, M., and J. S. Famiglietti. (2002): The potential for satellite-based monitoring of groundwater storage changes using GRACE: the High Plains aquifer, Central US, Journal of Hydrology, 263(1-4), 245–256.
- **Rodell**, M., I. Velicogna, and J. S. Famiglietti. "Satellite-based estimates of groundwater depletion in India." Nature 460.7258 (2009): 999-1002.
- **Voss**, K. A., J. S. Famiglietti, M. Lo, C. de Linage, M. Rodell, and S. C. Swenson (2013), Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region, Water Resour. Res., 49, doi:10.1002/wrcr.20078.
- **Famiglietti and Rodell** (2013), Science, 14 June 2013: Vol. 340 no. 6138 pp. 1300-1301, doi: 10.1126/science.1236460.
- **Reager and Famiglietti** (2009), Global terrestrial water storage capacity and flood potential using GRACE, Geophys. Res. Lett., 36, L23402, doi:10.1029/2009GL040826.
- **Thomas**, A. C., J. T. Reager, J. S. Famiglietti, and M. Rodell (2014), A GRACE-based water storage deficit approach for hydrological drought characterization, Geophys. Res. Lett., 41, doi:10.1002/2014GL059323.
- **Zaitchik**, B. F., M. Rodell, and R. H. Reichle. "Assimilation of GRACE Terrestrial Water Storage Data into a Land Surface Model: Results for the Mississippi River Basin." Journal of Hydrometeorology 9.3 (2008).
- **Houborg**, R., M. Rodell, B. Li, R. Reichle, and B. Zaitchik, Drought indicators based on model assimilated GRACE terrestrial water storage observations, Wat. Resour. Res., 48, W07525, doi:10.1029/2011WR011291, 2012.
- **Lo**, M.-H., J. S. Famiglietti, P. J.-F. Yeh, and T. H. Syed (2010), Improving Parameter Estimation and Water Table Depth Simulation in a Land Surface Model Using GRACE Water Storage and Estimated Baseflow Data, Water Resour. Res., 46, W05517, doi:10.1029/2009WR007855.

Gravity Recovery And Climate Experiment (GRACE)

Key Spacecraft Components

Now that we have an idea how GRACE works, let's peer "under the hood" of this high-tech wonder and understand some of the component parts of GRACE. These components can be seen in the photos on pages 2 and 4; the letters following the name of each component in parentheses correspond to the labels on the diagrams below each photo.





K-band Ranging System (KBR). Provides precise (within 10 μm) measurements of the distance change between the two satellites needed to measure fluctuations in gravity.

Ultra Stable Oscillator (USO). Provides frequency generation for the K-band ranging system.

SuperSTAR Accelorometers (ACC). Precisely measures the non-gravitational accelerations acting on the satellite.

Star Camera Assembly (SCA). Precisely determines the two satellites' orientation by tracking them relative to the position of the stars.

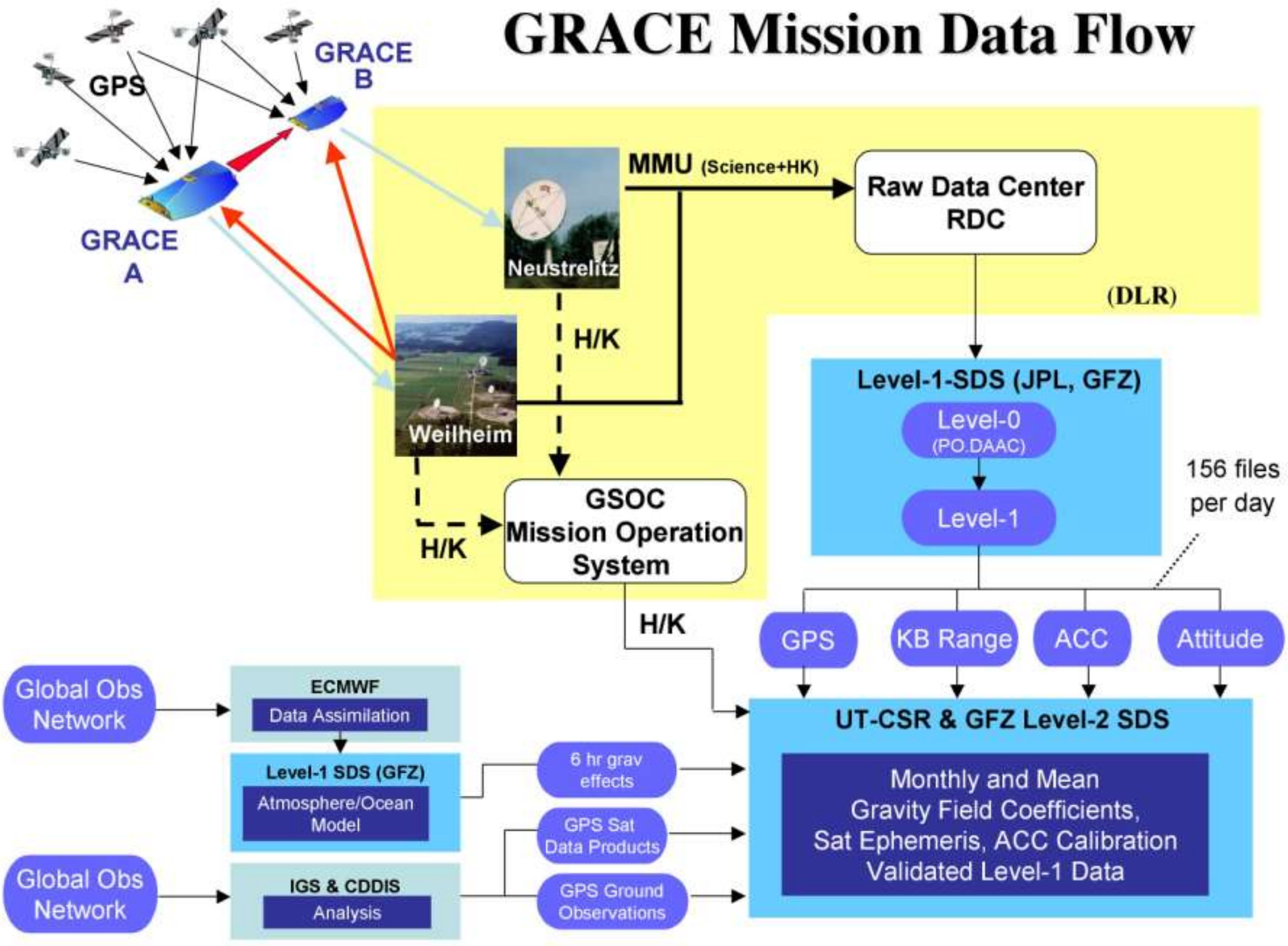
Coarse Earth and Sun Sensor (CES). Provides omnidirectional, reliable, and robust, but fairly coarse, Earth and Sun tracking. Used during initial acquisition and whenever GRACE operates in safe mode.

Center of Mass Trim Assembly (MTA). Precisely measures the offset between the satellite's center of mass and the "acceleration-proof" mass and adjusts center of mass as needed during the flight.

Black-Jack GPS Receiver and Instrument Processing Unit (GPS). Provides digital signal processing; measures the distance change relative to the GPS satellite constellation.

Globalstar Silicon Solar Cell Arrays (GSA). Covers the outer shell of the spacecraft and generates power.

GRACE Mission Data Flow



http://www.csr.utexas.edu/grace/asdp.html

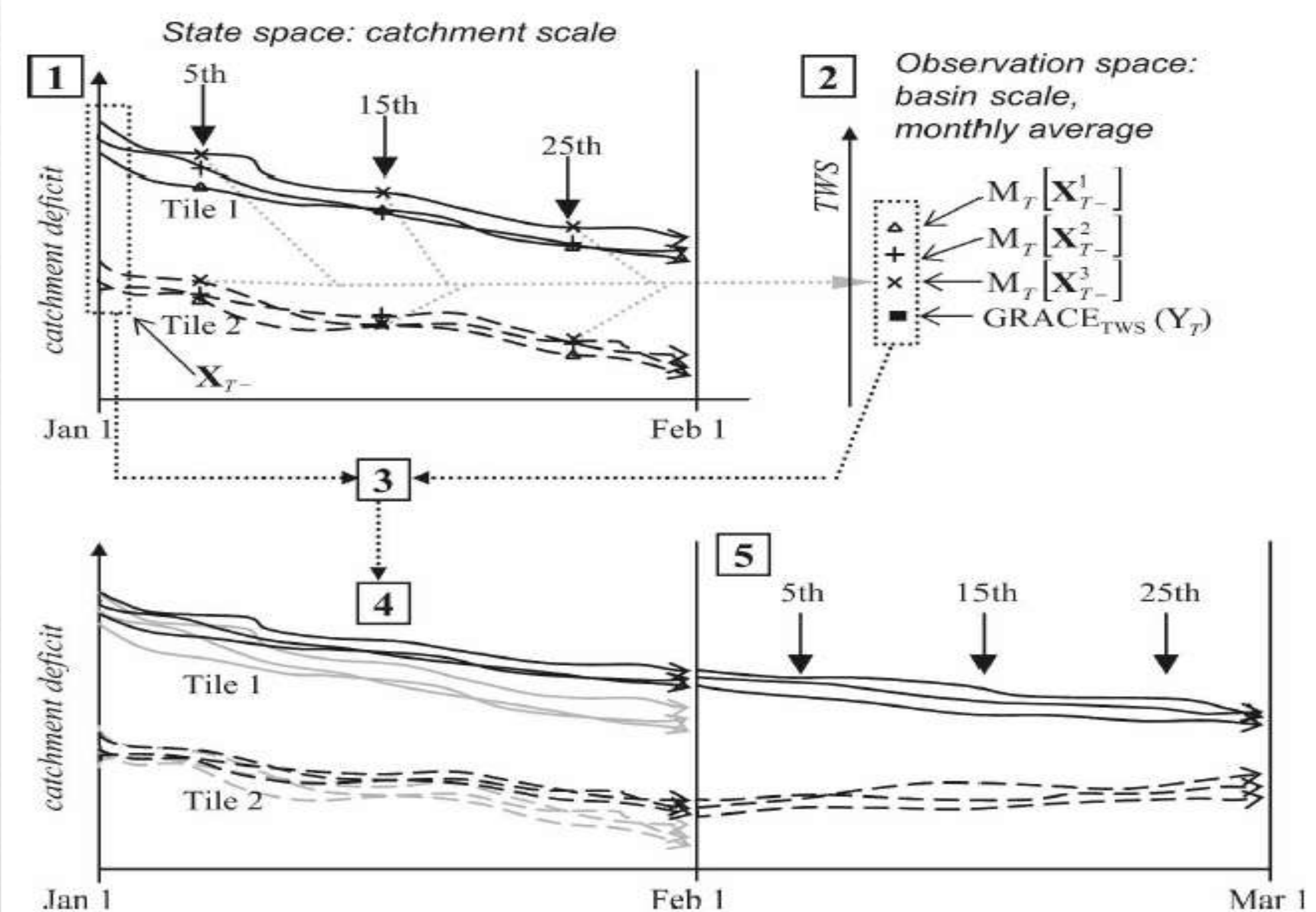
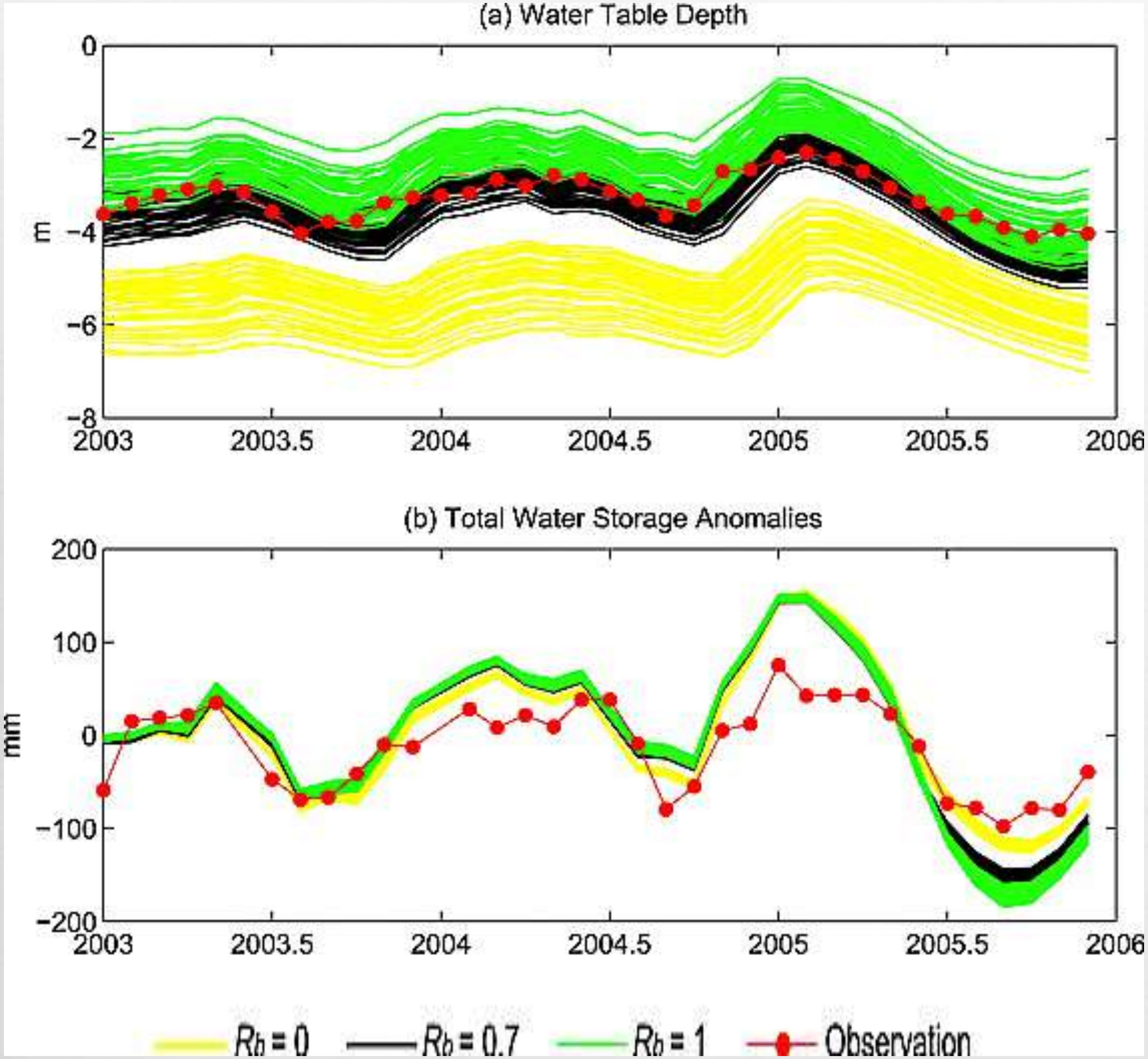


FIG. 5. Ensemble smoother. Consider one subbasin with two snow-free CLSM tiles and three ensemble members. For simplicity, root zone excess moisture is not included in this schematic. [1] One-month forecast ensemble integration without assimilation. Store catchment deficit for the 5th, 15th, and 25th of the month. [2] Calculate model prediction of GRACE observation—$\mathbf{M}_T[\mathbf{X}^i_{T-}]$—by converting stored catchment deficit values into basin-scale, time-average TWS. [3] Use Eq. (1) to compute analysis increments for catchment deficits on the 1st of the month (state vector $\mathbf{X}^i_T$). [4] Integrate CLSM again from the 1st of the month and apply analysis increments evenly distributed over all days of the month. [5] Proceed with ensemble forecast and repeat process.

Using GRACE for Calibrating LSM Groundwater Depth



R_b = 0 (total water storage calibration alone)
R_b = 1 (base flow calibration alone)

Lo et al, 2010