

89th Annual Meeting of the American Meteorological Society
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***Assimilation of GRACE terrestrial water
storage data into a land surface model***

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1 – Global Modeling and Assimilation Office, NASA/GSFC

2 – Johns Hopkins University

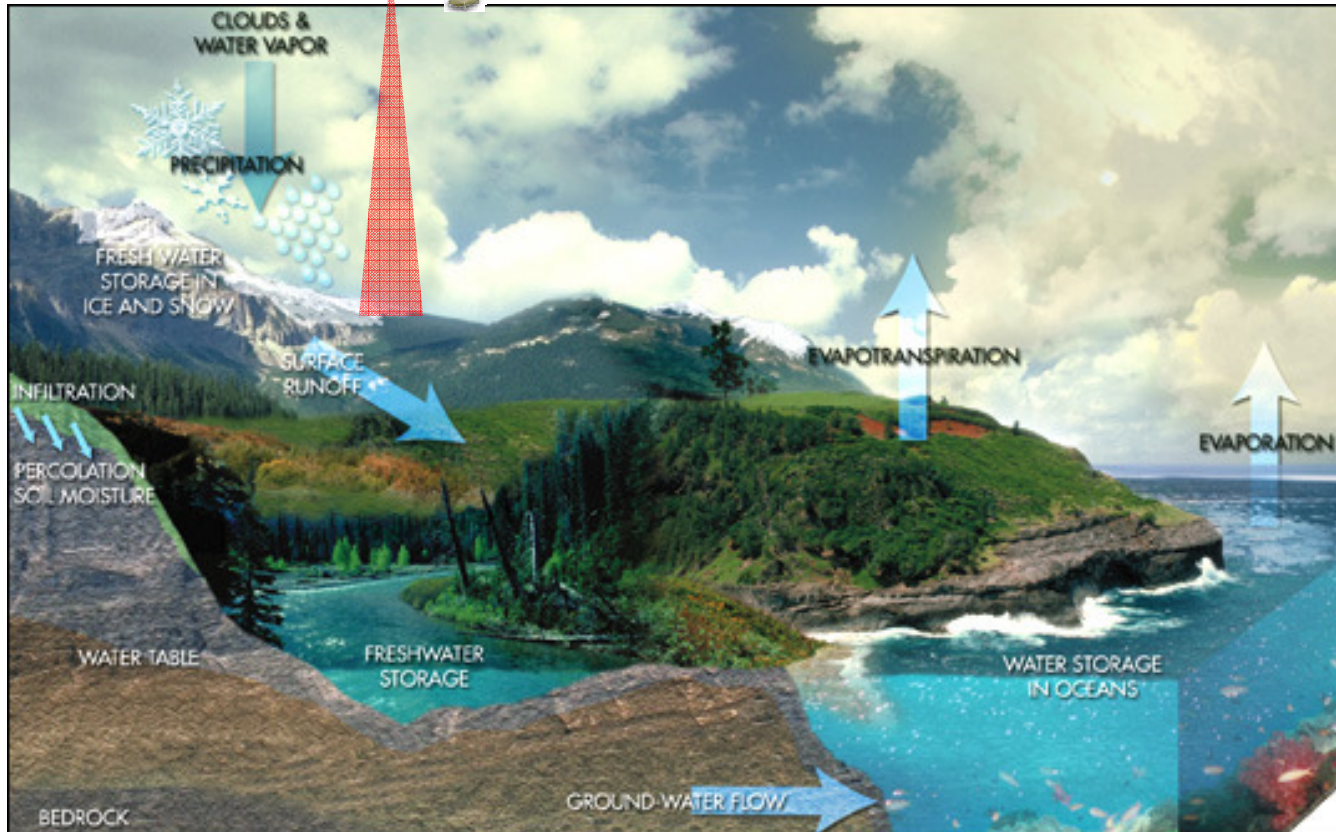
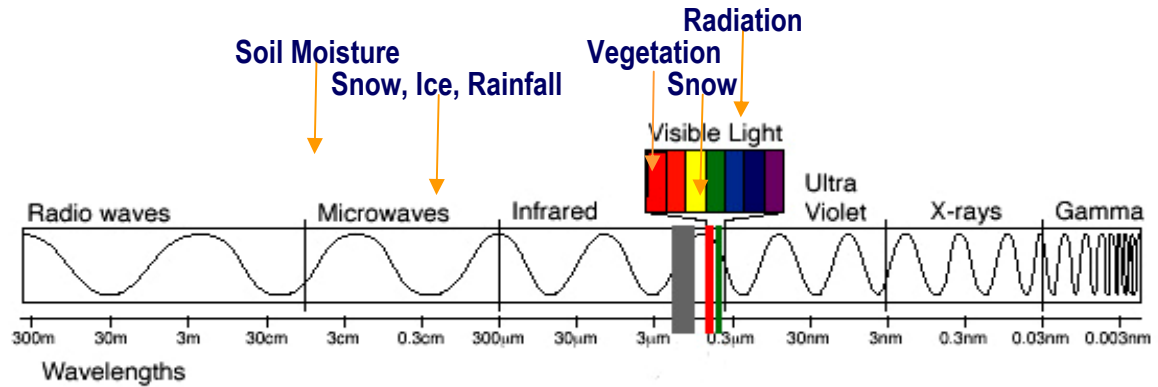
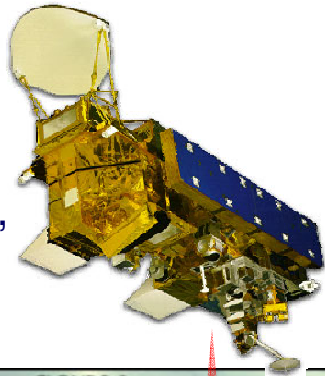
3 – Hydrological Sciences Branch, NASA/GSFC

4 – SAIC



Remote sensing of the water cycle

Aqua:
MODIS,
AMSR-E,
etc.

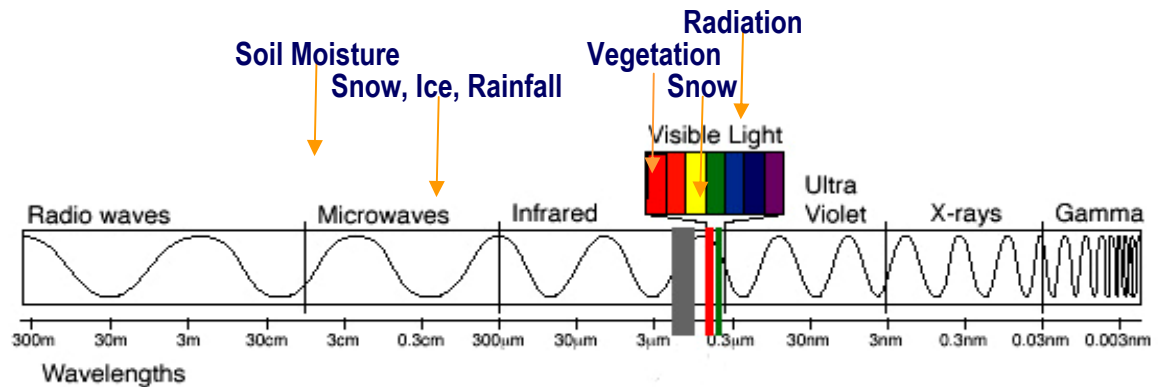
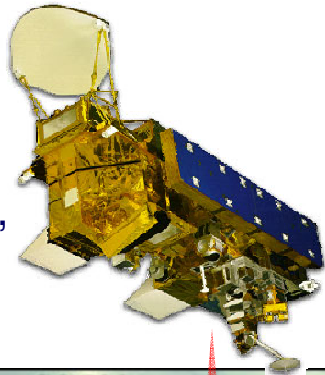


Traditional remote sensing (using electro-magnetic radiation) can only measure water in the top few cm of the soil.



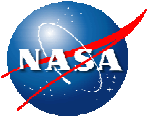
Remote sensing of the water cycle

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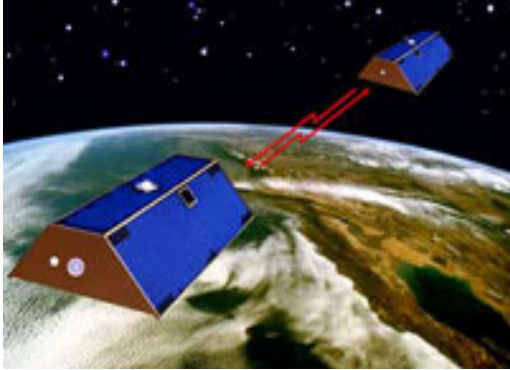


GRACE

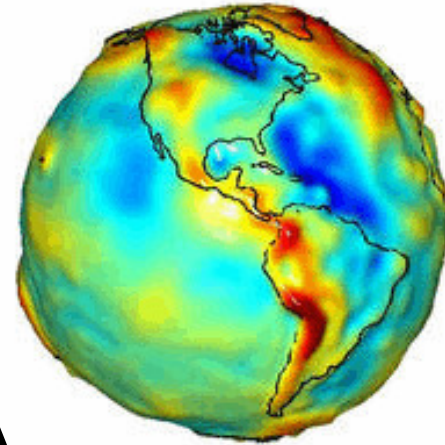
GRACE is unique in its ability to monitor water at all levels, down to the deepest aquifer



GRACE measurements

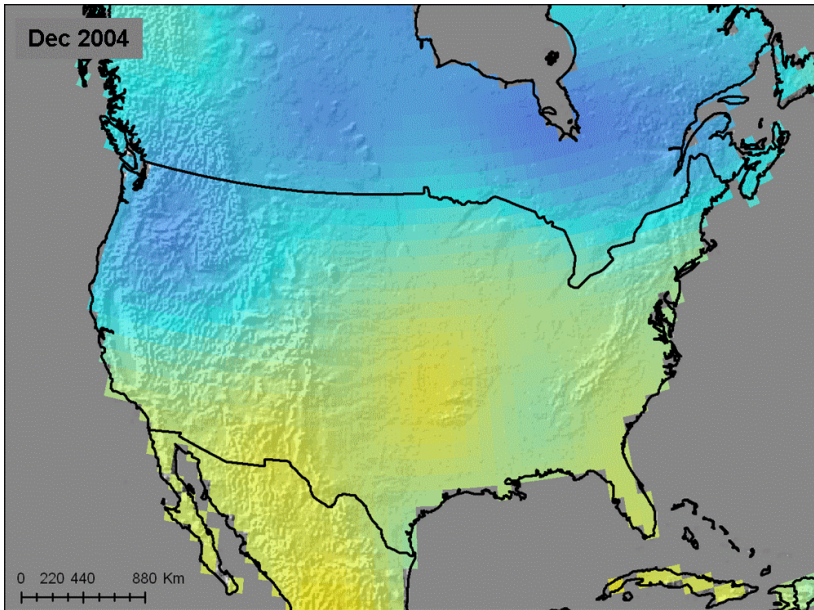


Highly accurate measurement of distance between twin satellites



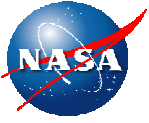
Gravity anomaly

“Fast” signal (weekly to monthly; after correction for atmospheric pressure)



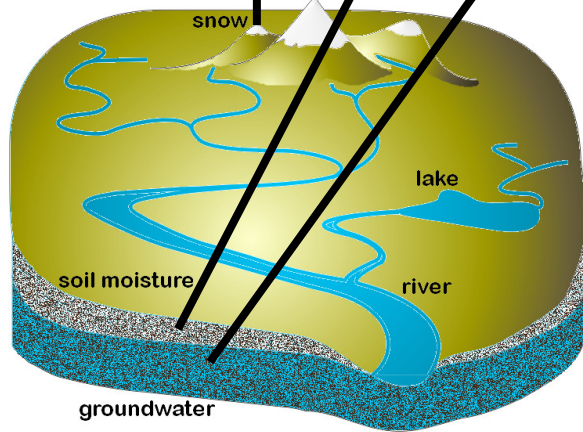
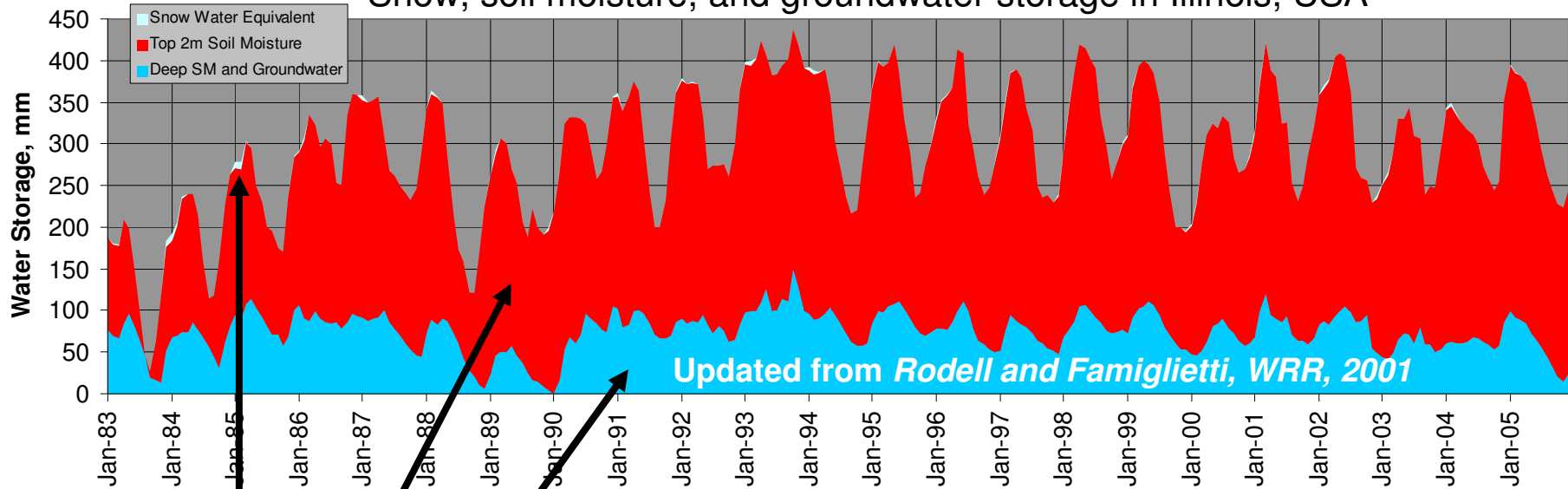
Terrestrial water storage (TWS) anomaly

-15.0 15.0
Water Storage Anomaly (cm)



Terrestrial water storage (TWS) variations

Snow, soil moisture, and groundwater storage in Illinois, USA



GRACE obs. of changes in terrestrial water storage (TWS):

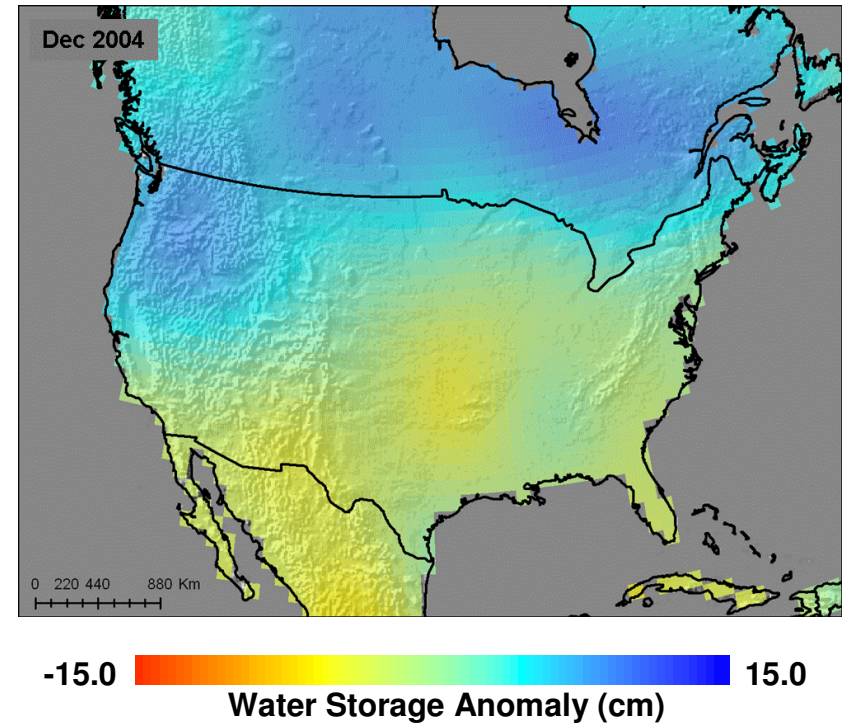
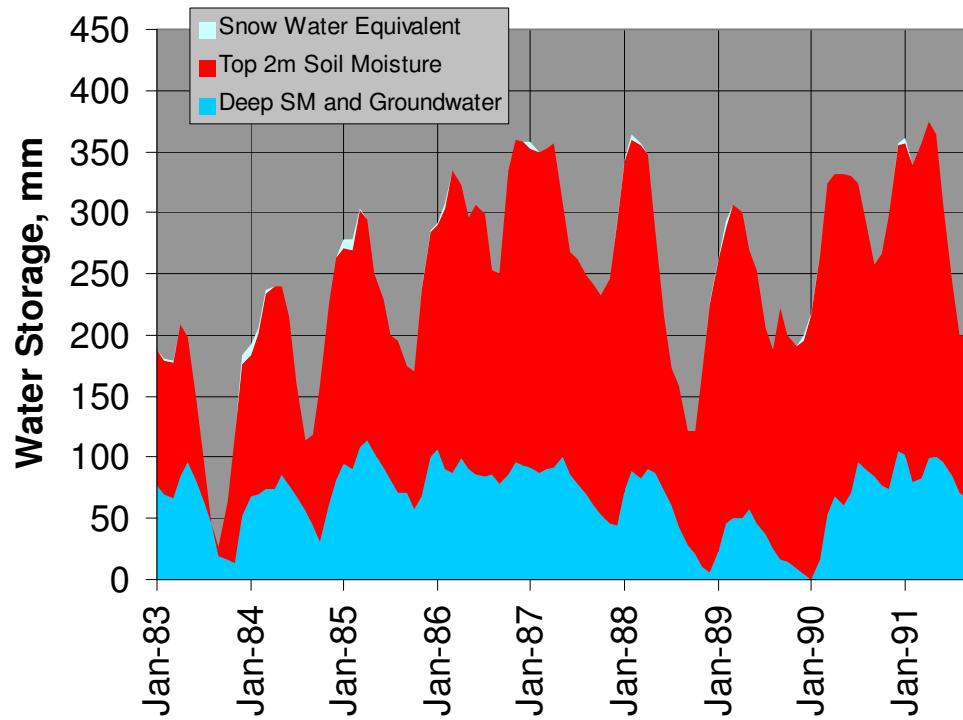
- groundwater + soil moisture + snow + surface water
- large spatial scales (>500km)
- monthly time scale

TWS variations are dominated by:

- soil moisture in temperate regions
- snow in polar and alpine regions
- surface water in wetlands



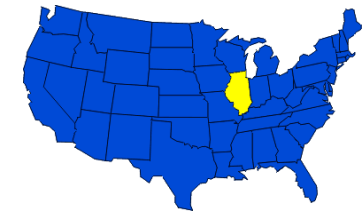
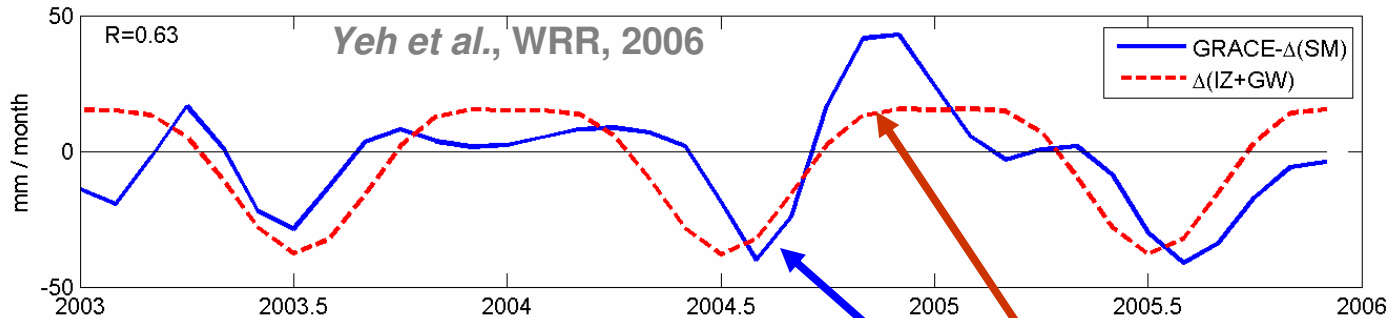
Water storage anomalies from GRACE



How can we derive water cycle components (groundwater, soil moisture,...) at higher spatial and temporal resolution?



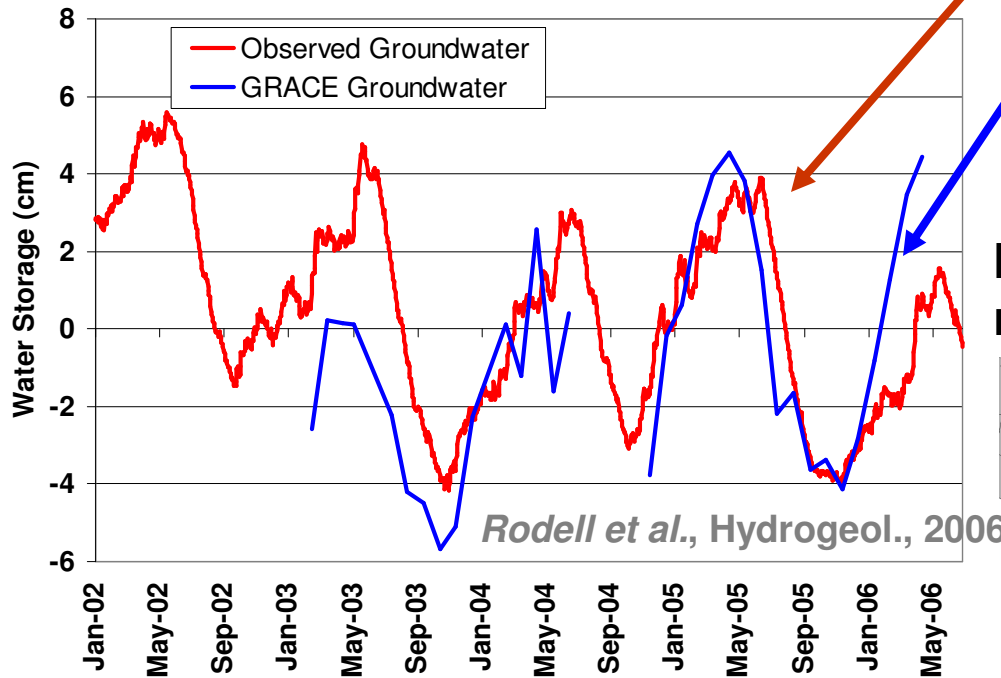
Estimating water cycle components from GRACE TWS



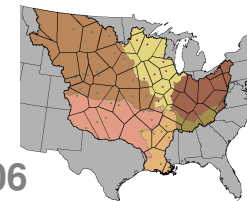
Illinois

Groundwater well obs.

GRACE groundwater estimate



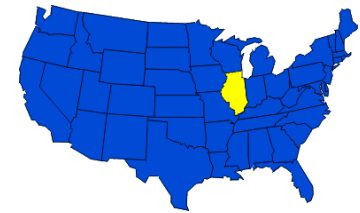
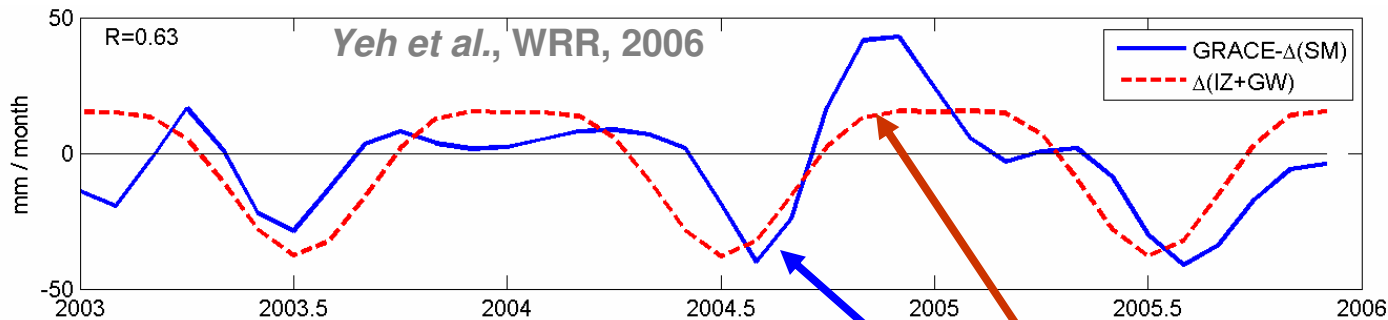
Mississippi river basin



Soil moisture from (top) in-situ obs. or (bottom) a land surface model can be used to isolate **groundwater** from GRACE-derived TWS variations.



Estimating water cycle components from GRACE TWS

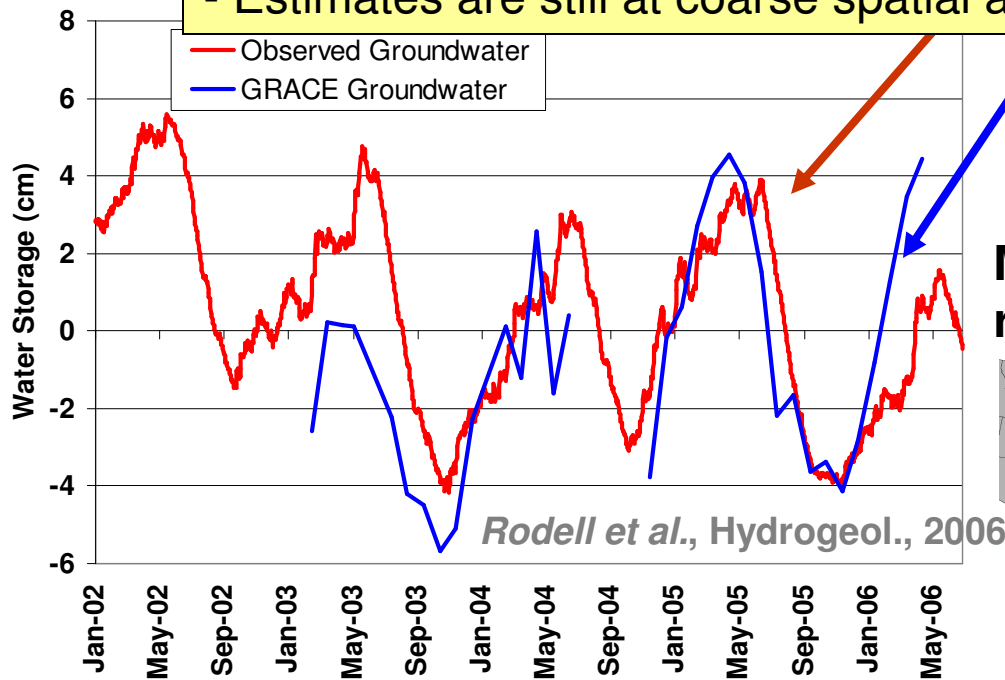


Illinois

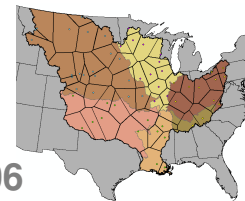
Limitations:

- Need “perfect” soil moisture to estimate groundwater.
- Estimates are still at coarse spatial and temporal scales.

estimate



Mississippi river basin

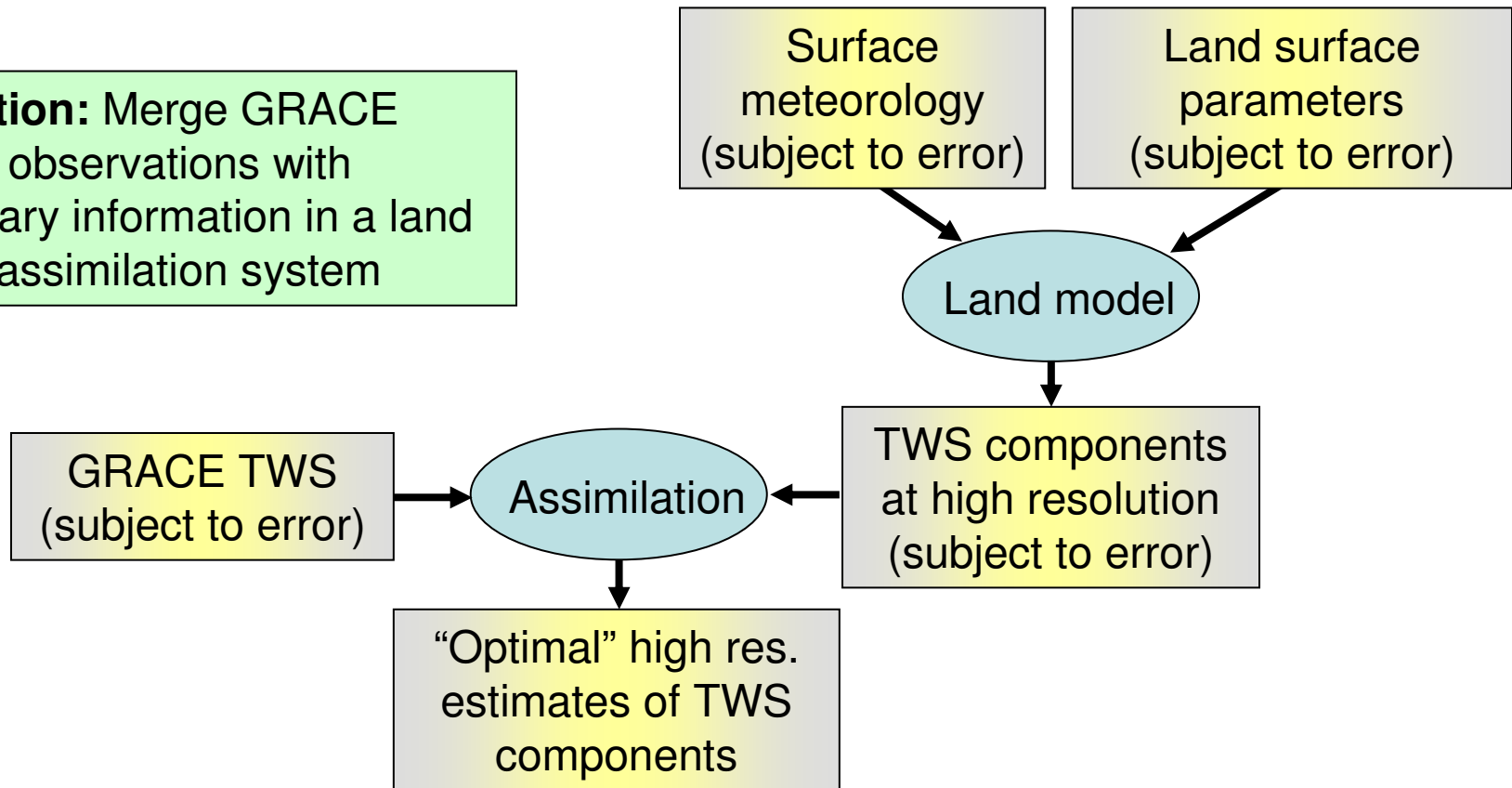


Soil moisture from (top) in-situ obs. or (bottom) a land surface model can be used to isolate **groundwater** from GRACE-derived TWS variations.



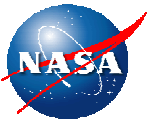
GRACE data assimilation

Solution: Merge GRACE TWS observations with ancillary information in a land data assimilation system

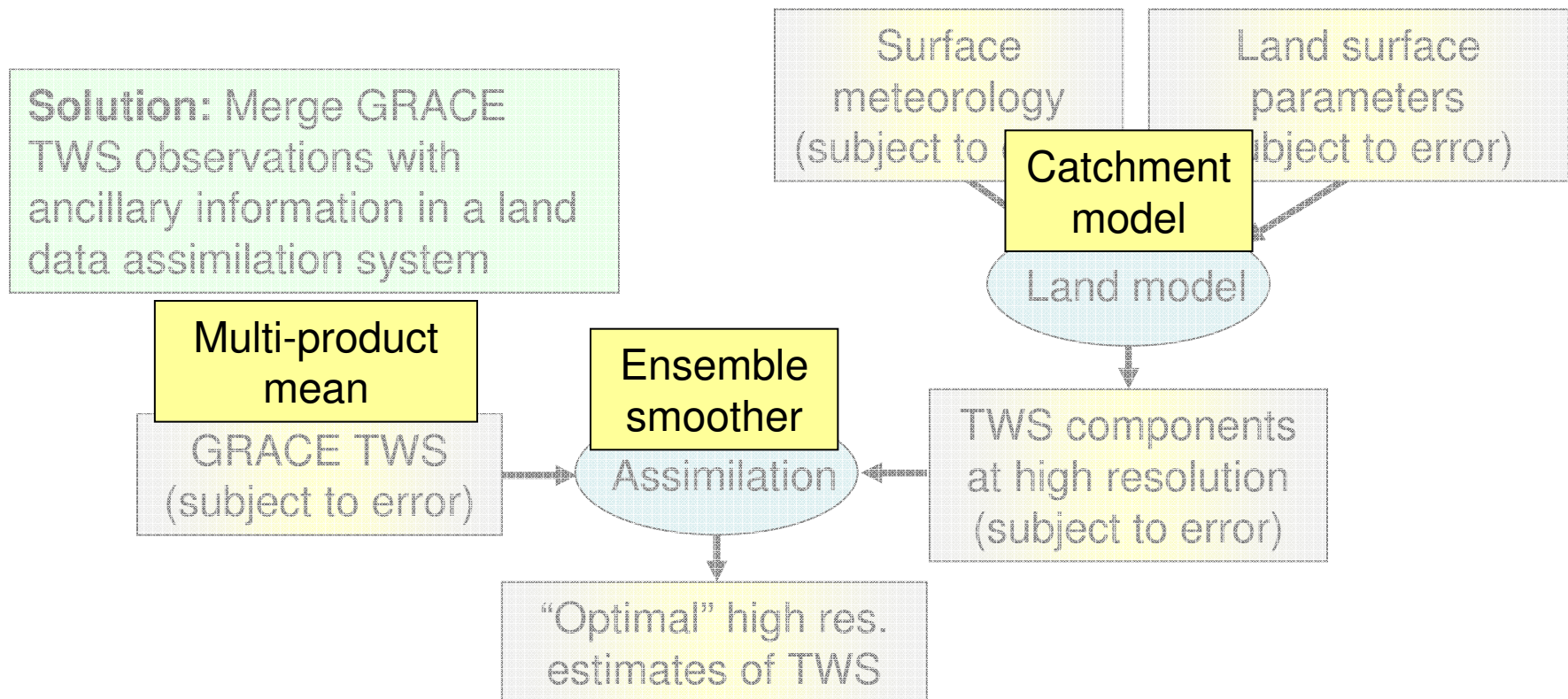


CHALLENGES: GRACE TWS observations

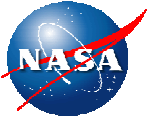
- are sum of groundwater, soil moisture, surface water, and snow,
- have coarse spatial resolution,
- are not instantaneous,
- measure anomalies (change detection).



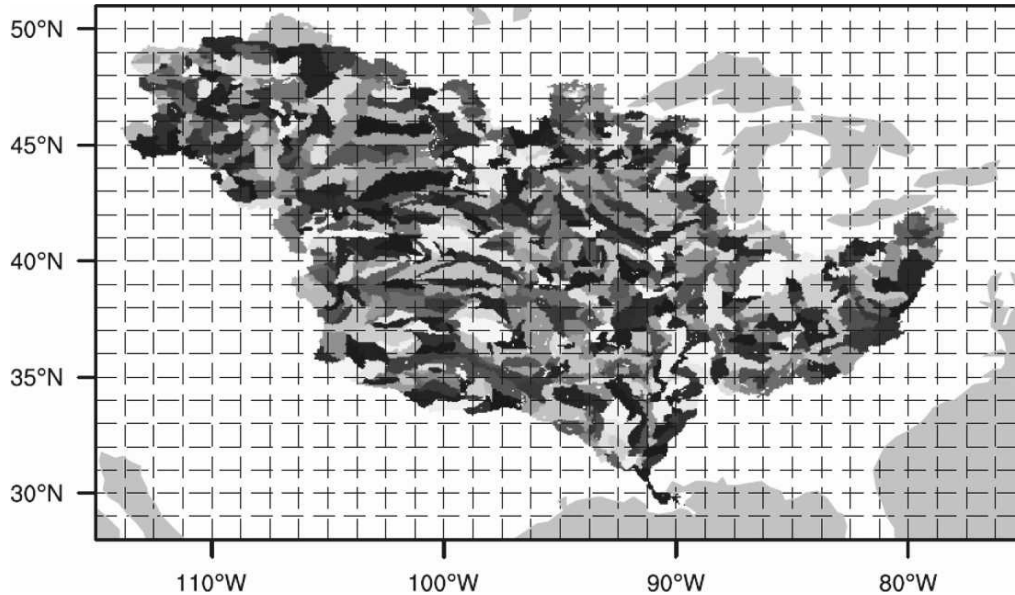
GRACE data assimilation



- Catchment model with GLDAS forcing (Jan 2003 - May 2006)
- 10-year spin-up with 2002 forcing
- Assimilate monthly GRACE anomalies (mean of CSR/GFZ/JPL)
- Ensemble Kalman smoother
- 20 ensemble members for open loop (no assim.) and assimilation integrations



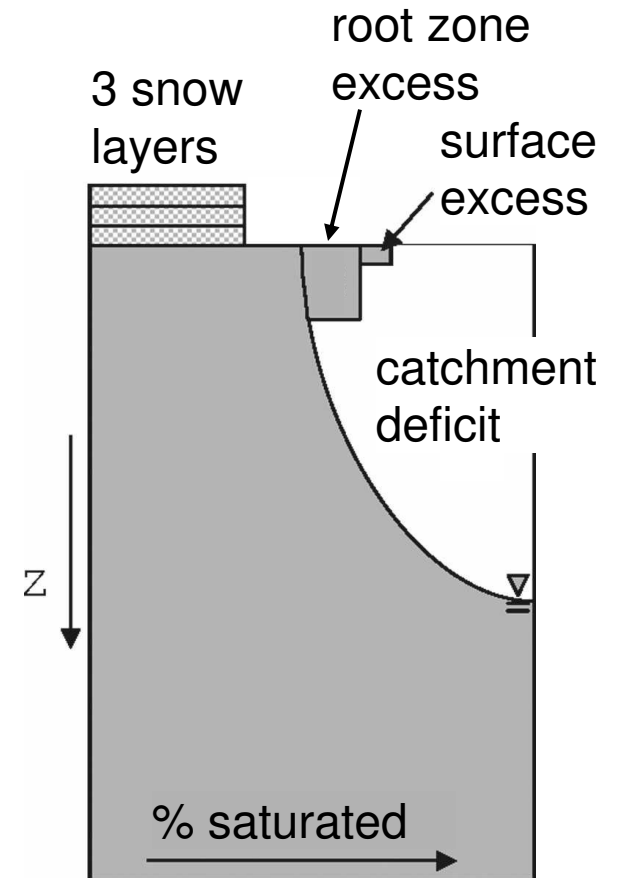
Catchment land surface model



Domain: Mississippi river basin

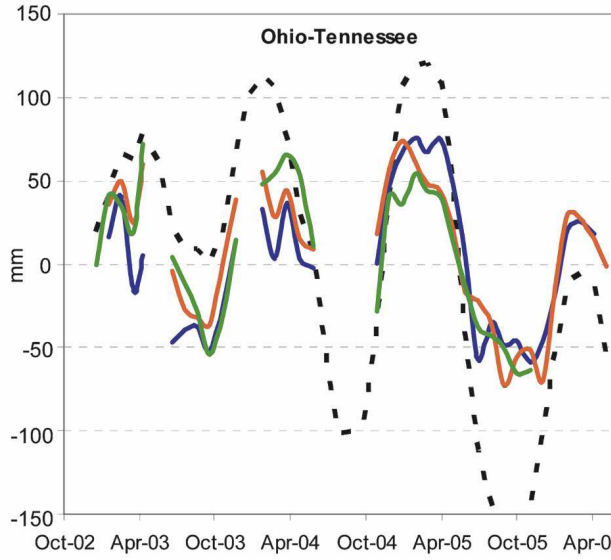
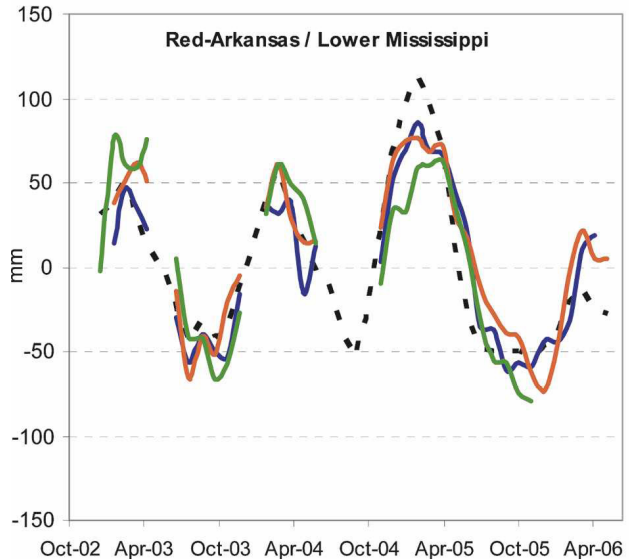
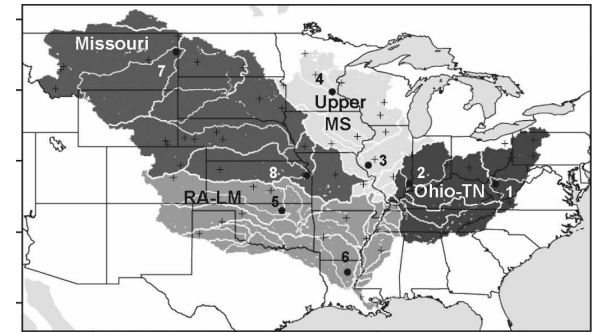
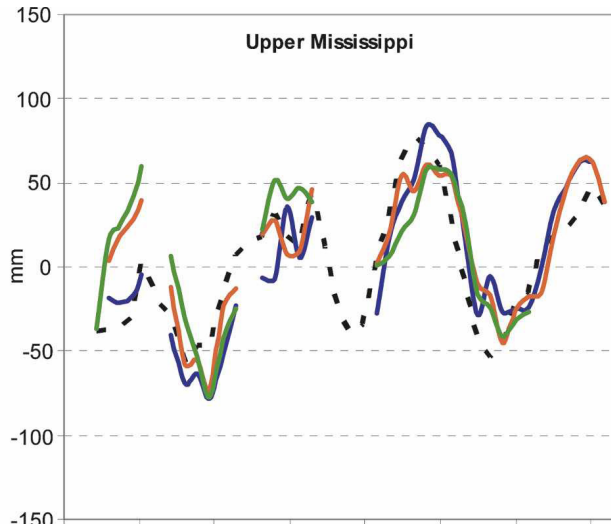
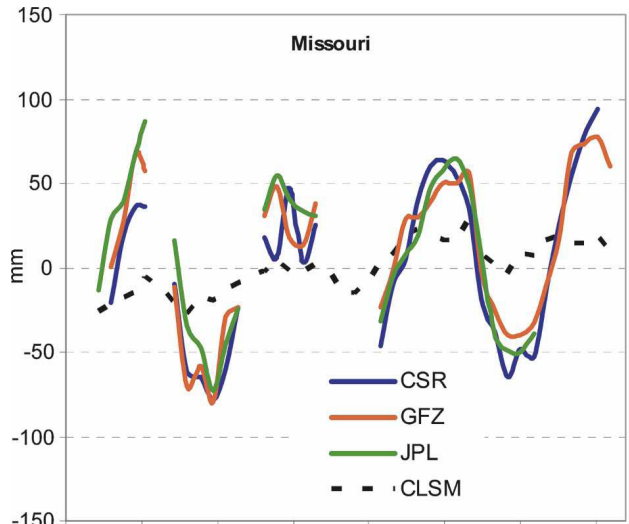
Computational elements (“tiles”):
Unique combinations of watersheds
and overlying regular lat./lon. grid
(linear scale approx. 35km)

Catchment model
includes groundwater,
soil moisture, and snow

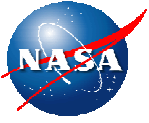




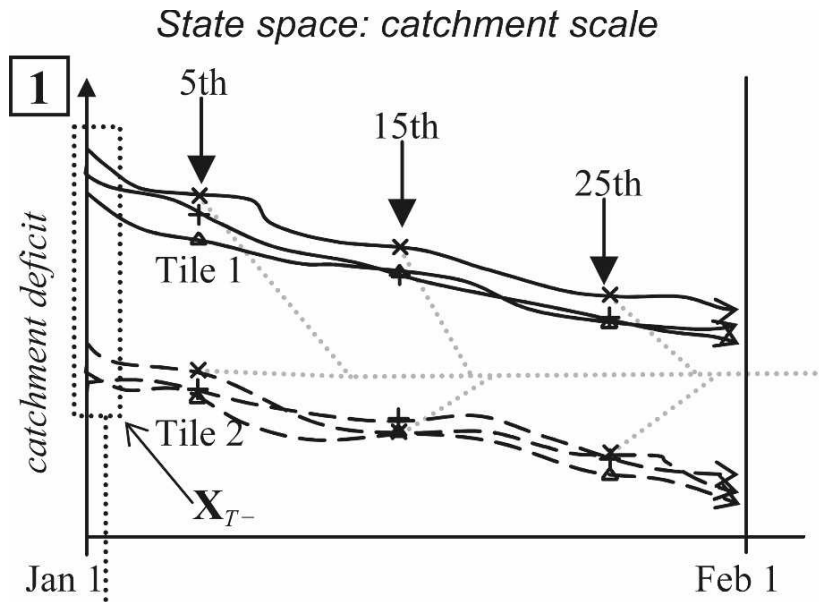
GRACE and Catchment model estimates of TWS



Available GRACE TWS products (solid lines) differ from each other, but not as much as from Catchment model estimates (dashed line).



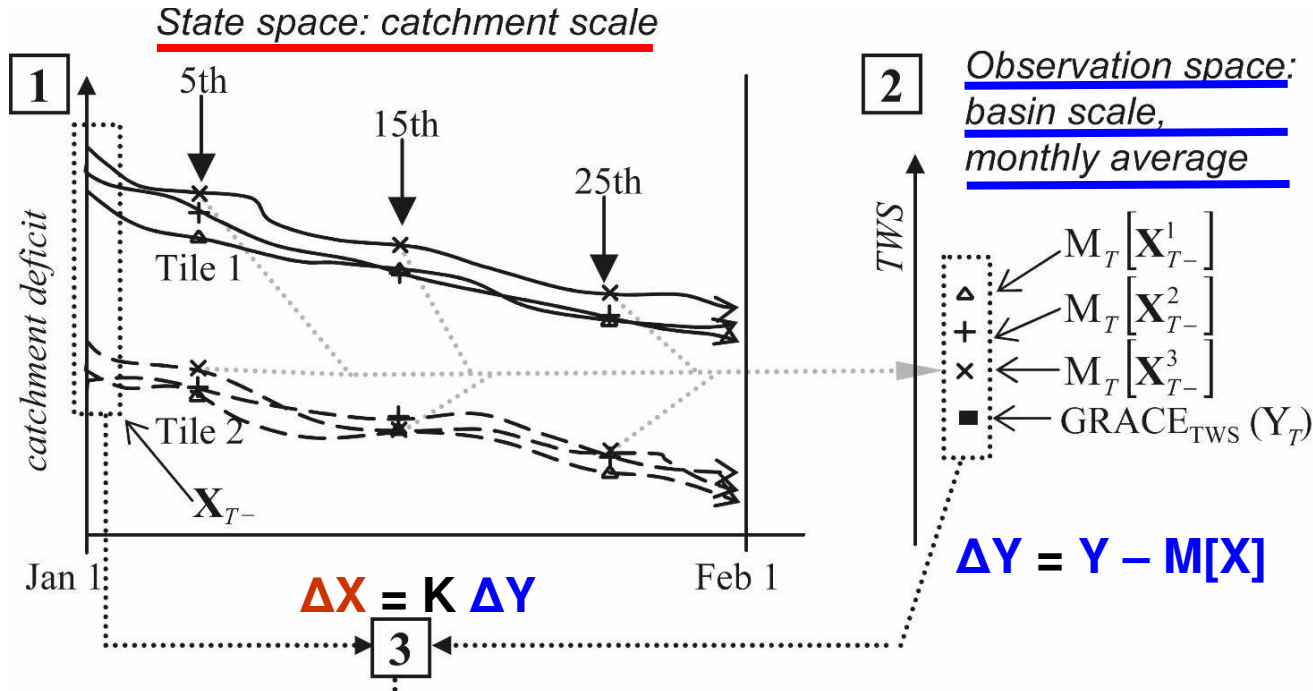
Ensemble Kalman smoother



1.) Run high-resolution land model forecast for one month



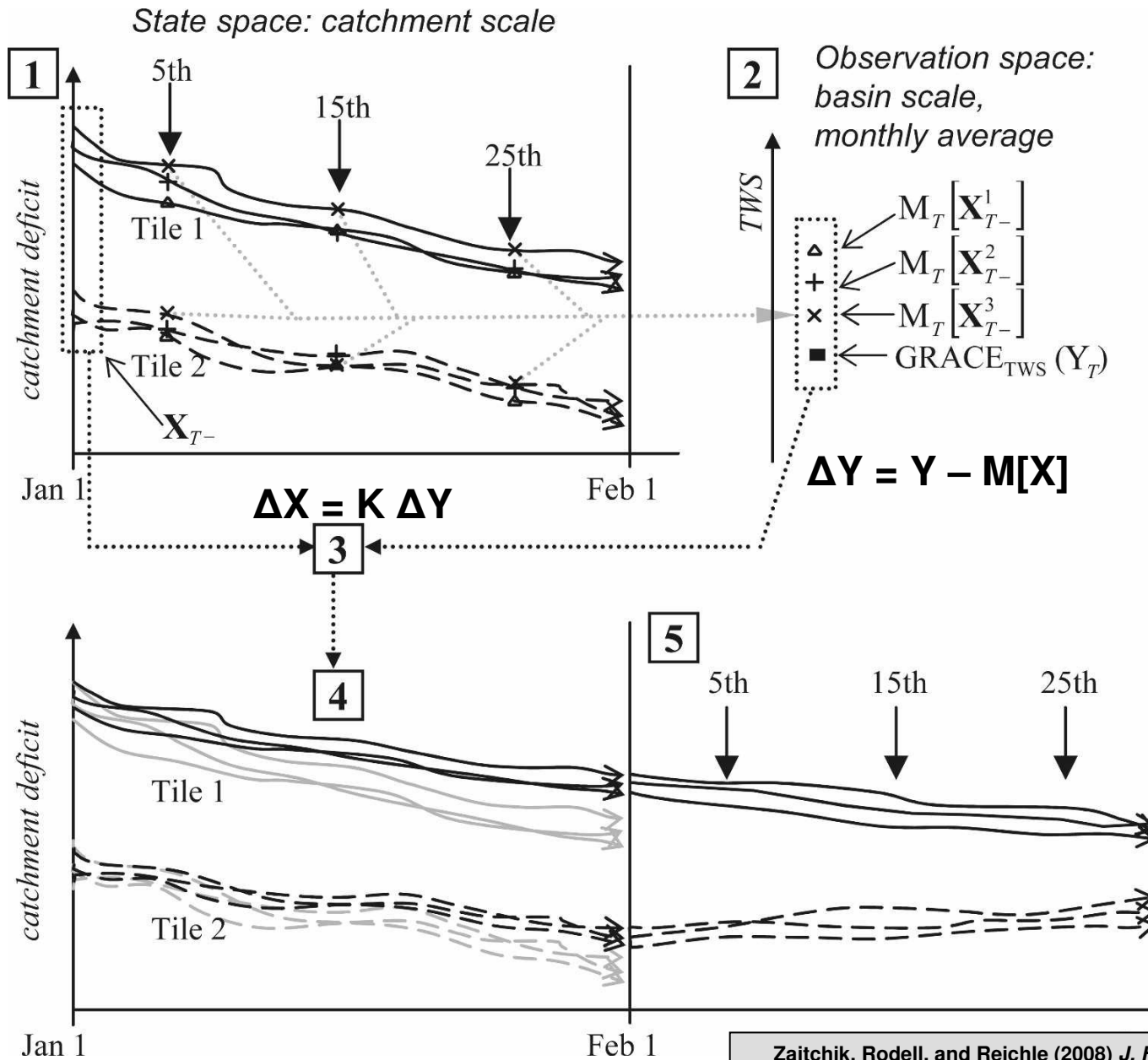
Ensemble Kalman smoother



- 1.) Run high-resolution land model forecast for one month
- 2.) Diagnose large-scale TWS on the 5th, 15th, and 25th, compute innovations (ΔY), Kalman gain (K)
- 3.) Compute increments (ΔX)



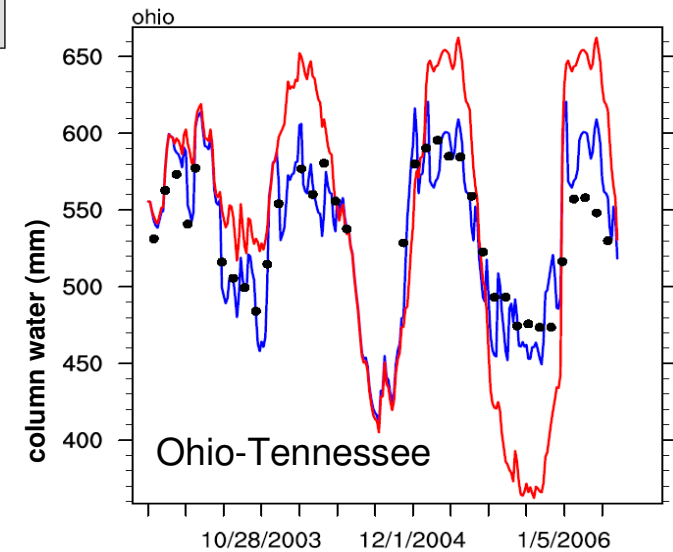
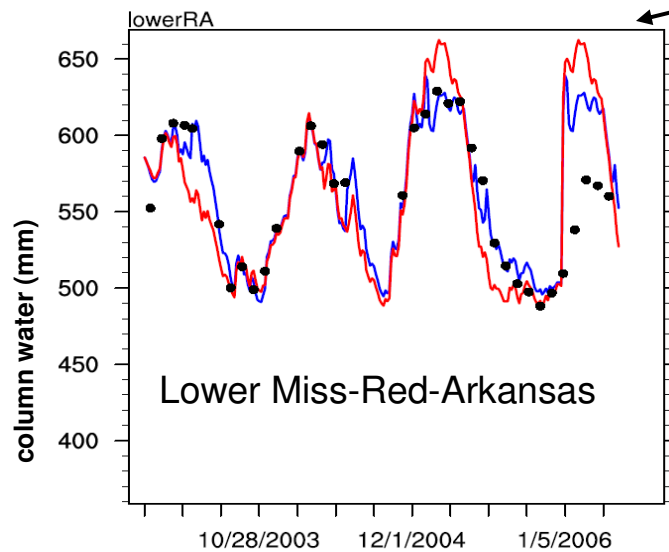
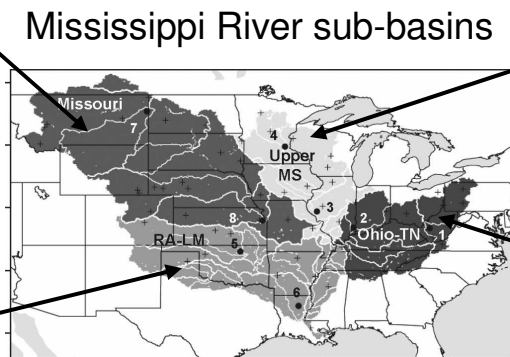
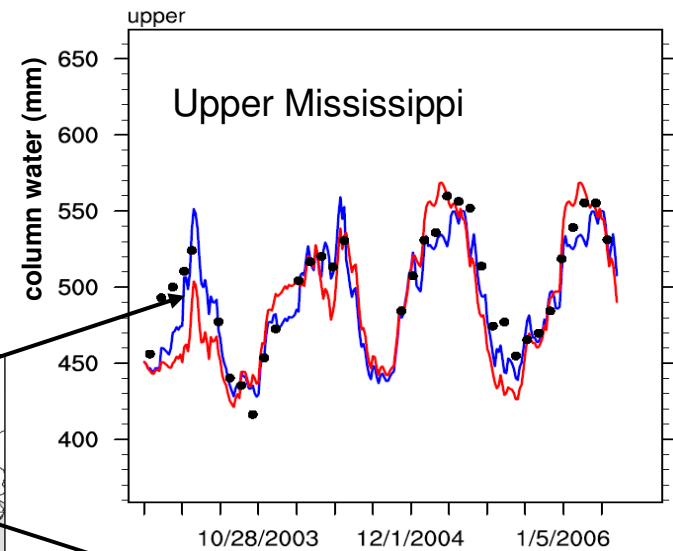
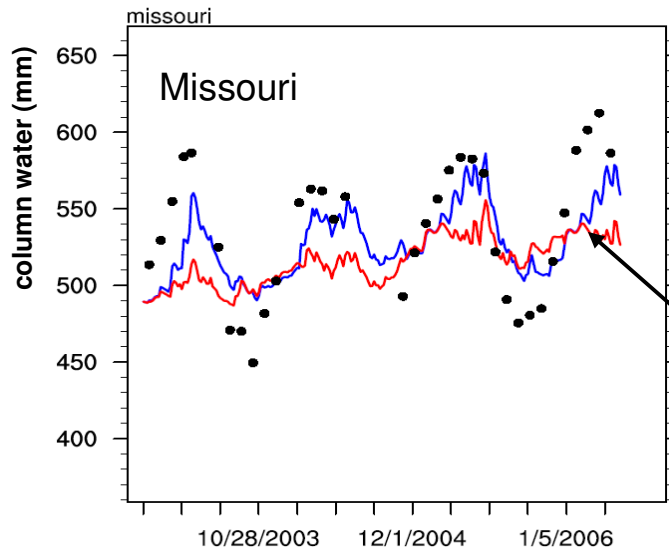
Ensemble Kalman smoother



- 1.) Run high-resolution land model forecast for one month
- 2.) Diagnose large-scale TWS on the 5th, 15th, and 25th, compute innovations (ΔY), Kalman gain (K)
- 3.) Compute increments (ΔX)
- 4.) Apply increments *during* second integration
- 5.) Repeat for next month...

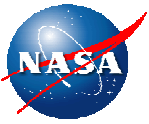


Assimilation of GRACE terrestrial water storage (TWS)

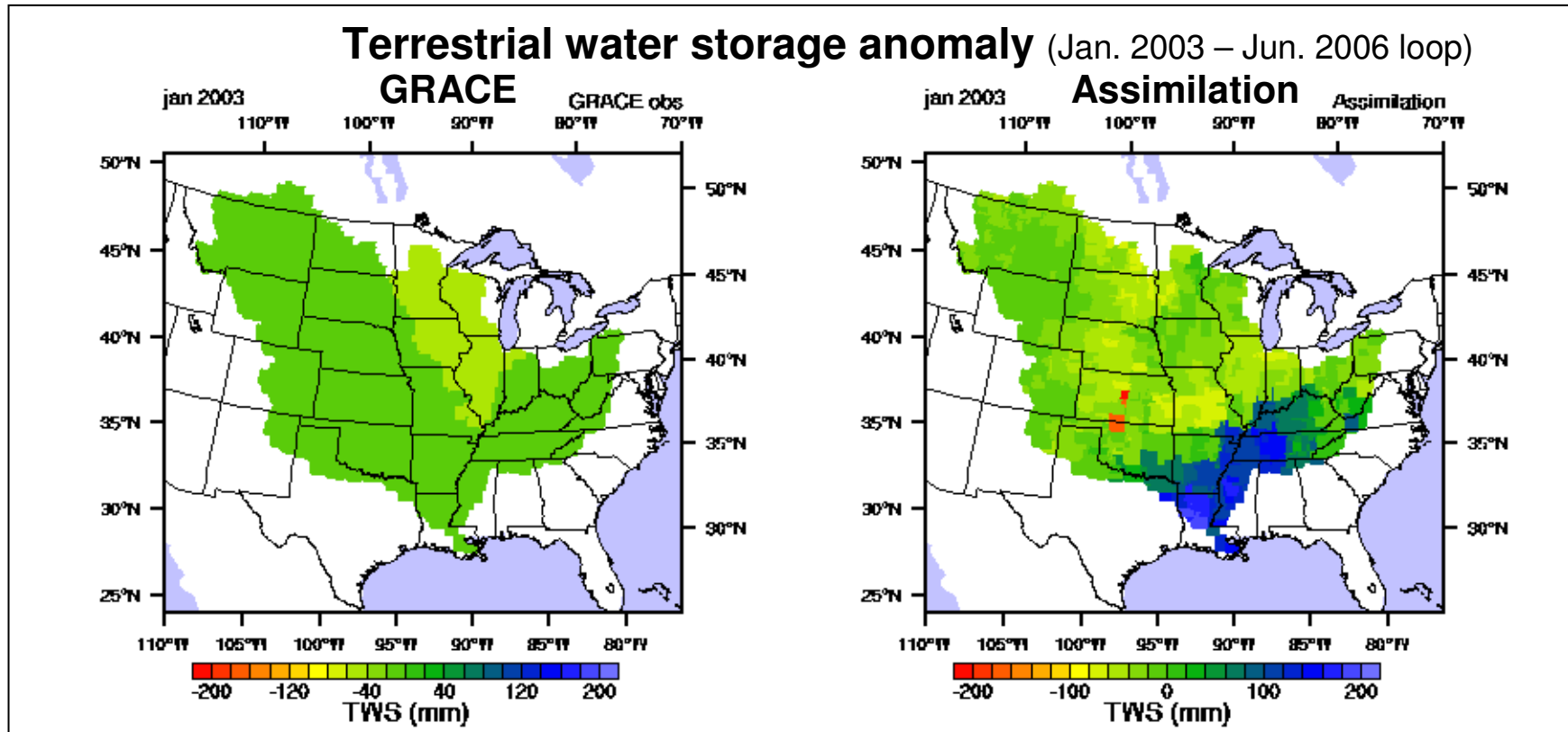


- GRACE TWS
- Modeled TWS
- Assimilation

Daily continuous estimates critical for applications.



Assimilation of GRACE terrestrial water storage (TWS)

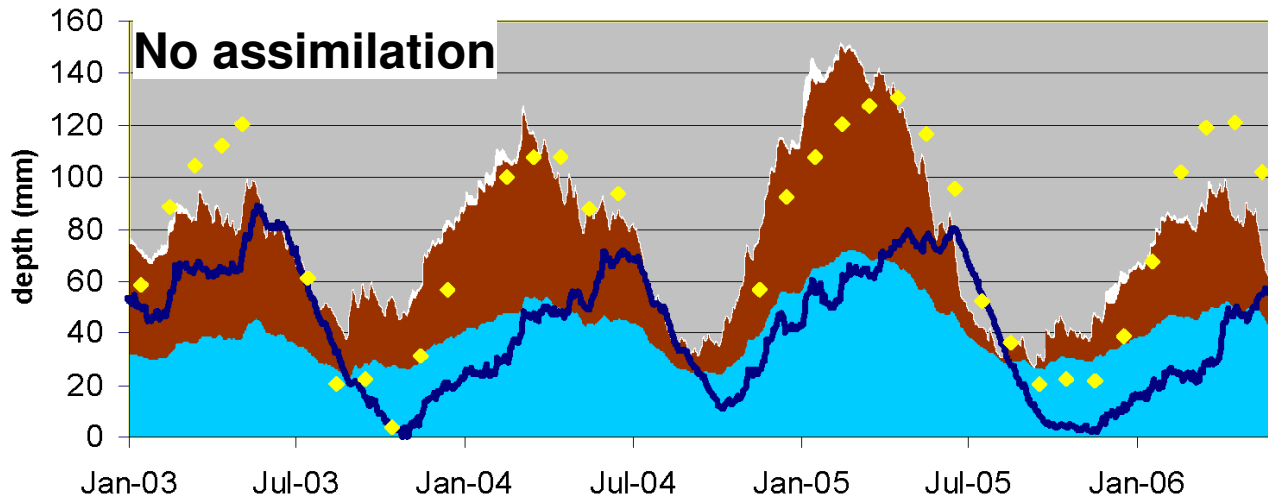


From scales useful for water cycle and climate studies...

... to scales needed for water resources and agricultural applications.

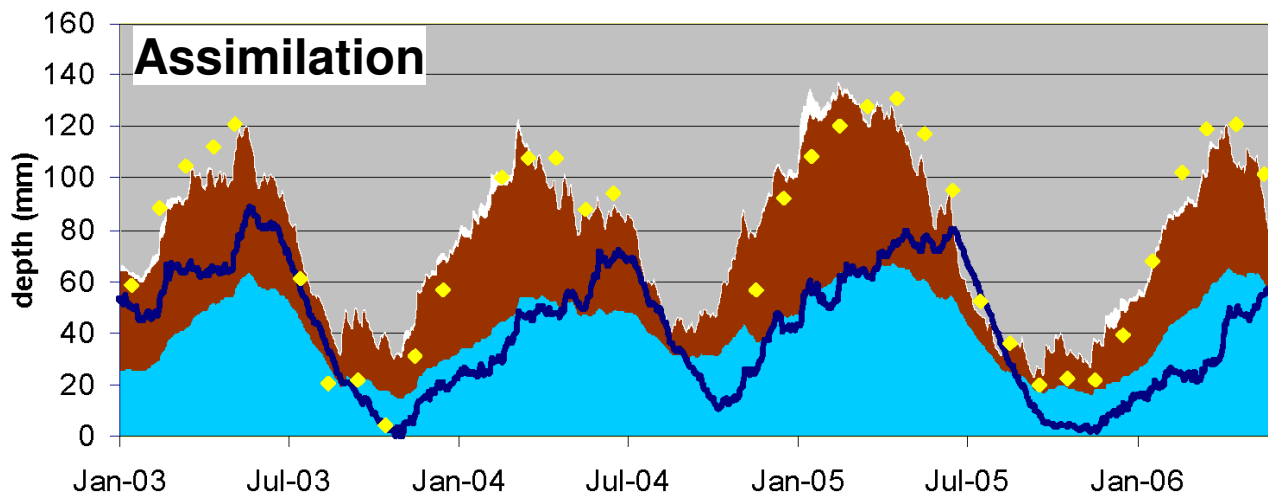


Assimilation of GRACE terrestrial water storage (TWS)

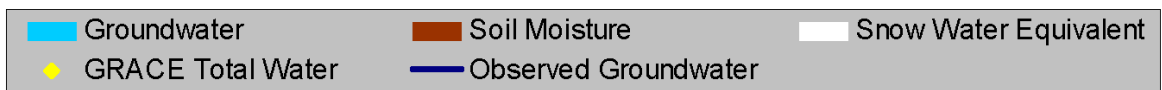


Validation against observed groundwater:

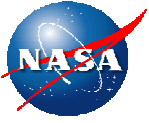
RMSE = 23.5 mm
 $R^2 = 0.35$



RMSE = 18.5 mm
 $R^2 = 0.49$



Assimilation disaggregates GRACE data into snow, soil moisture, and groundwater. Assimilation estimates of groundwater better than model estimates.



Validation against in situ groundwater obs.

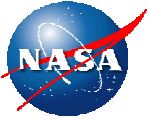
	Model		Assimilation		Δ -skill [%]
	r	RMSE [mm]	r	RMSE [mm]	
Mississippi	.59	23.5	.70	18.5	21
Ohio-TN	.78	62.8	.82	40.4	36
Upper Miss.	.29	42.6	.27	39.6	07
Red.-Ark./LM	.69	30.9	<i>.72</i>	26.4	15
Missouri	.41	24.5	.66	19.7	20

Assim. yields statistically significant improvement of groundwater estimates.

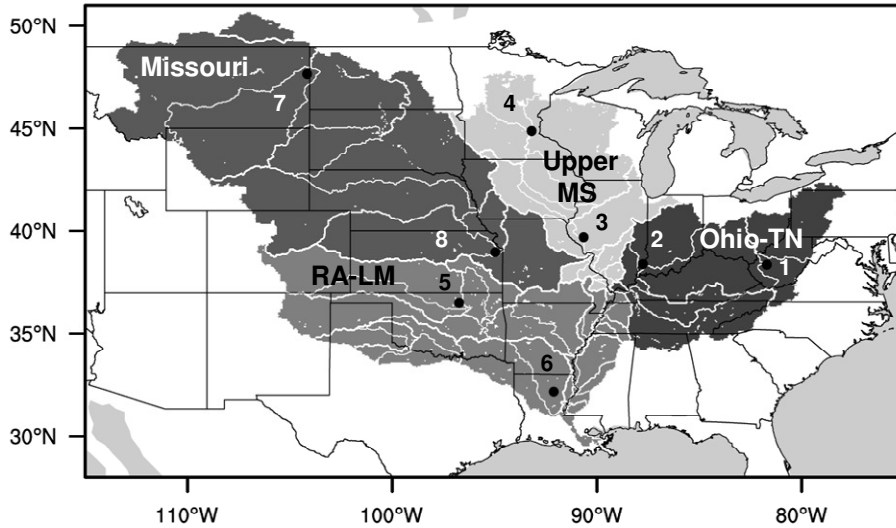
r = time series correlation coefficient

Δ -skill $\equiv 1 - \text{RMSE}_{\text{Assim}} / \text{RMSE}_{\text{OL}}$

significance level: bold=5%, italics=10%



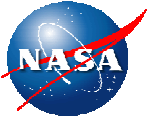
Validation against gauged discharge



Assim. yields some improvement at smaller (watershed) scales.

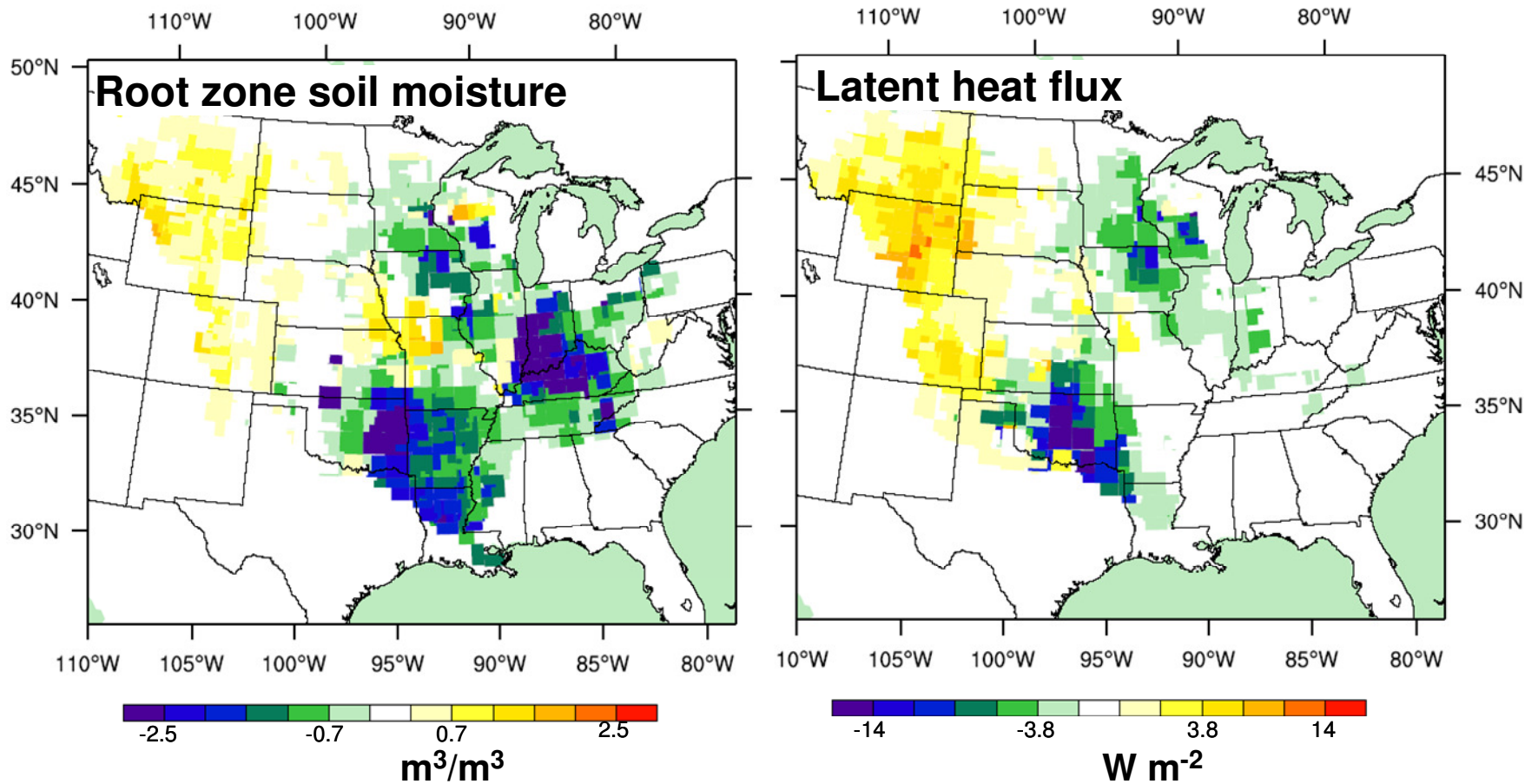
r = time series correlation coefficient
significance level: bold=5%, italics=10%

	River	m ³ /s Discharge	r _{TWS}			r _{runoff}	
			OL	GRACE	DA	OL	GRACE DA
1	Kanawha	537	0.41	0.42	0.52	0.52	
2	Wabash	1,001	0.55	0.62	0.18	0.18	
3	Illinois	527	0.68	0.72	0.30	0.29	
4	Minnesota	160	0.61	0.69	0.35	0.36	
5	Arkansas	240	0.19	0.29	0.20	0.22	
6	Ouachita	83	0.37	0.35	0.04	0.04	
7	Yellowstone	212	0.24	0.26	0.35	<i>0.42</i>	
8	Kansas	107	0.4	0.49	0.55	<i>0.59</i>	



Impact of GRACE assimilation on other variables

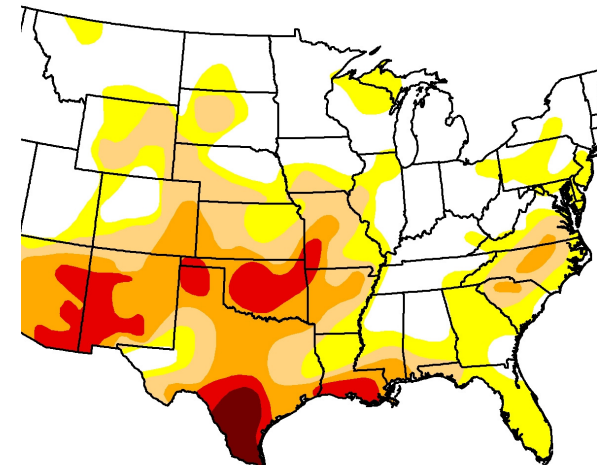
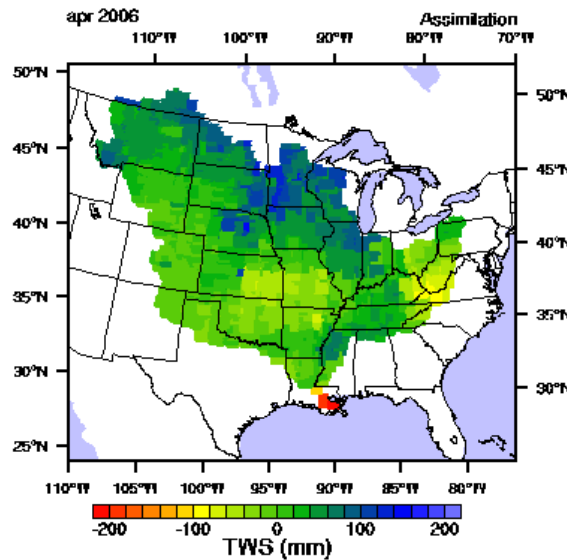
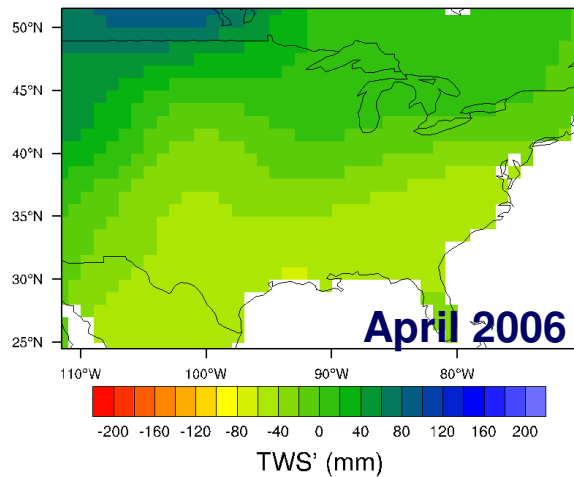
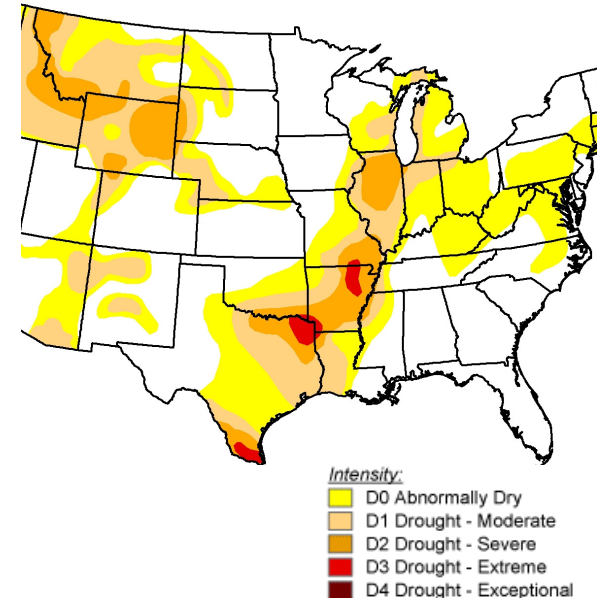
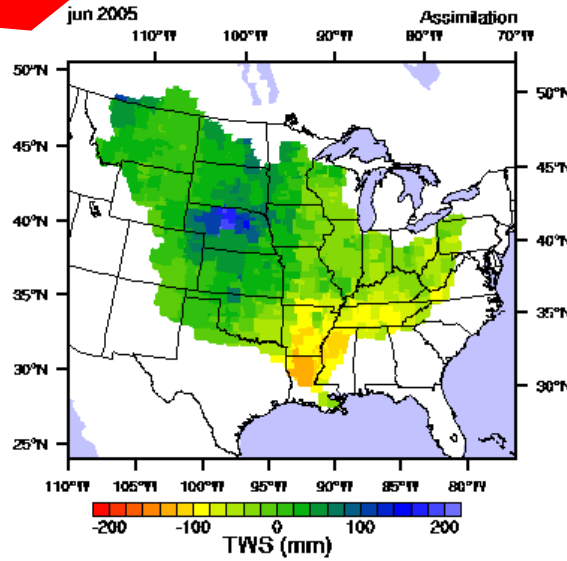
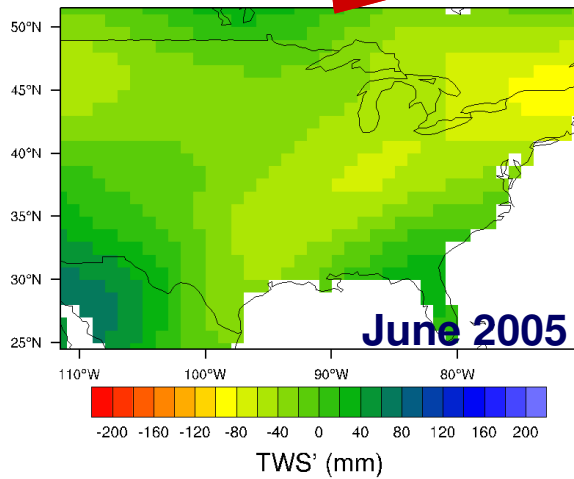
Assimilation minus open loop estimates (April 2005)



GRACE assimilation influences other model variables



Water resources applications



GRACE obs.

GRACE assimilation

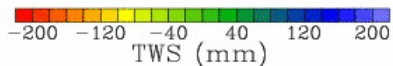
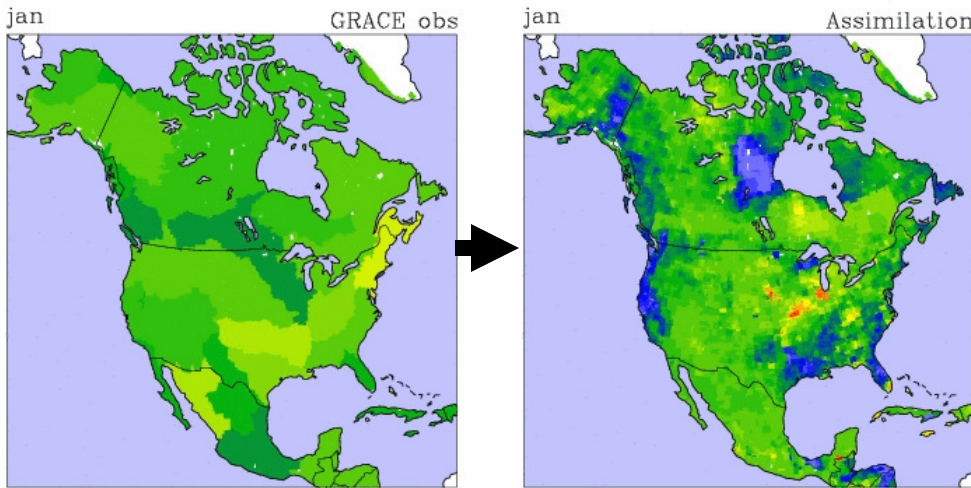
US Drought Monitor



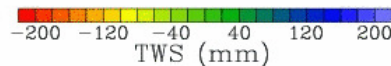
Recent progress and applications

Extension to other regions

Jan - Dec 2003 loop

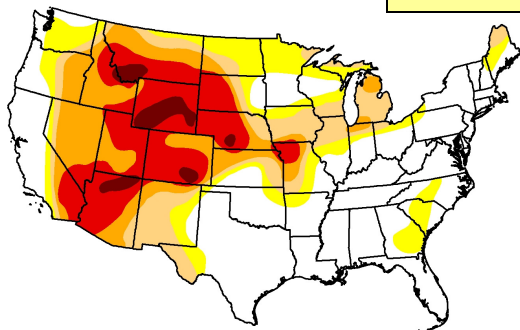


GRACE



Assimilation

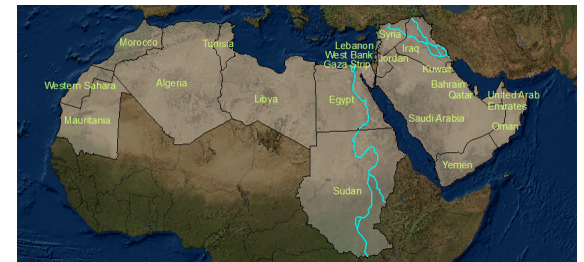
US and North American Drought Monitors



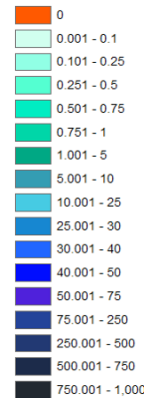
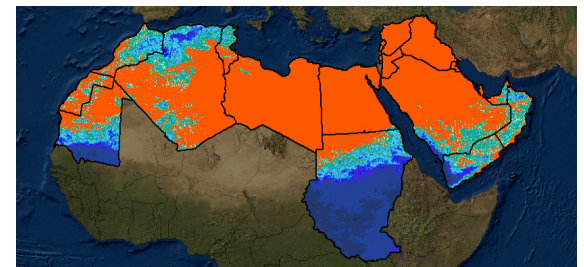
Intensity:

- D0 Abnormally Dry
- D1 Drought - Moderate
- D2 Drought - Severe
- D3 Drought - Extreme
- D4 Drought - Exceptional

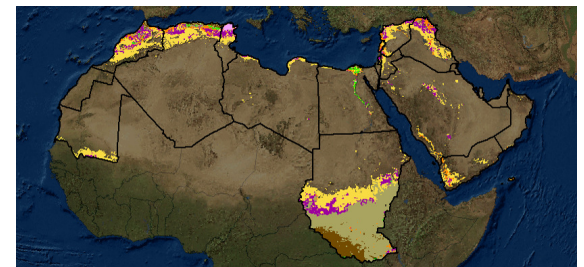
Arab Land Data Assimilation System



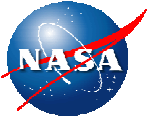
July 2007 Precipitation [mm]



Dominant Land Cover Type



- EVERGREEN NEEDLELEAF FOREST
- EVERGREEN BROADLEAF FOREST
- DECIDUOUS BROADLEAF FOREST
- WOODLAND
- WOODED GRASSLAND
- CLOSED SHRUBLAND
- OPEN SHRUBLAND
- GRASSLAND
- BARE GROUND
- URBAN AND BUILT-UP
- BARLEY
- MAIZE
- OTHER CROPS
- SORGHUM
- WHEAT



Summary

GRACE is unique in its ability to monitor water in all phases and at all depths.

Nevertheless, GRACE TWS observations are not perfect:

- Coarse spatial and temporal scales
- Incomplete coverage
- Vertically integrated measurements
- Measurement errors

Data assimilation merges the advantages of observations and land surface models and can enhance the value of GRACE TWS observations.

Specifically, data assimilation enables:

- Spatial and temporal downscaling
- Disaggregation of GRACE TWS obs. into water cycle components
- Data gap filling
- Quality control

Estimates from GRACE assimilation will be used for the US and North American Drought Monitors.