# Improving Soil Moisture Estimation through the Joint Assimilation of SMOS and GRACE Satellite Observations

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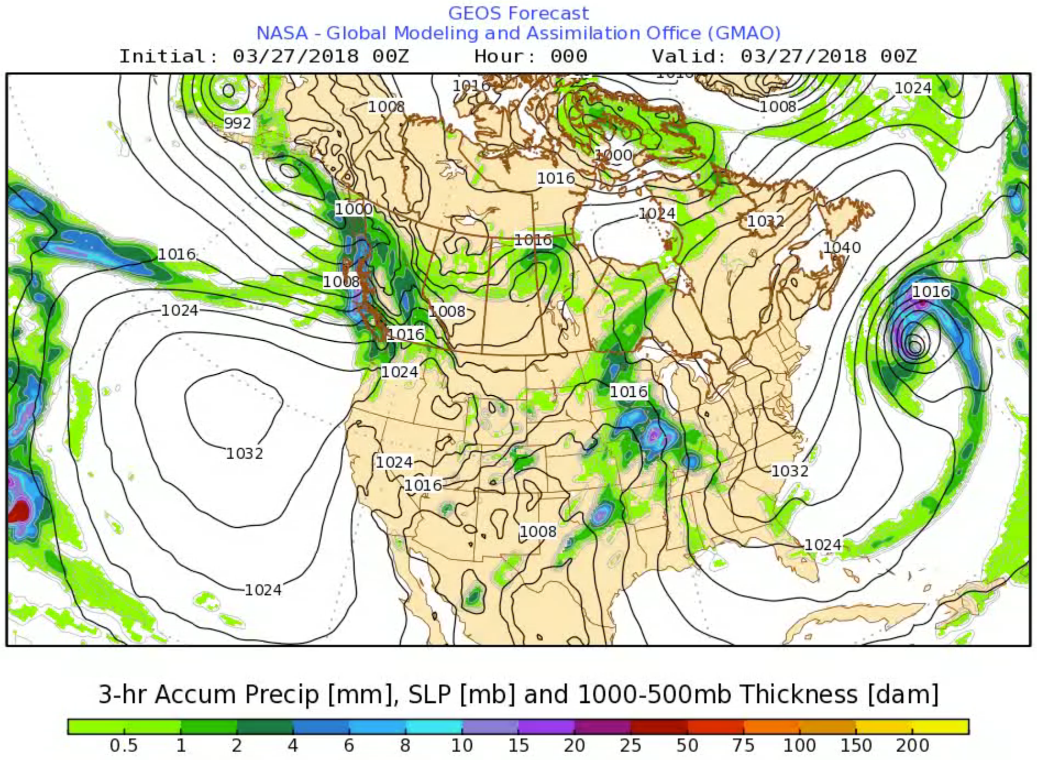
# Outline

- Introduction & Motivations
- GRACE-DA (Downscaling GRACE Observations)
- SMOS(SMAP)-DA
- Joint Assimilation of SMOS+GRACE
- Conclusions & Future Directions

# Importance of Soil Moisture and Groundwater

## Weather & Climate Forecasts

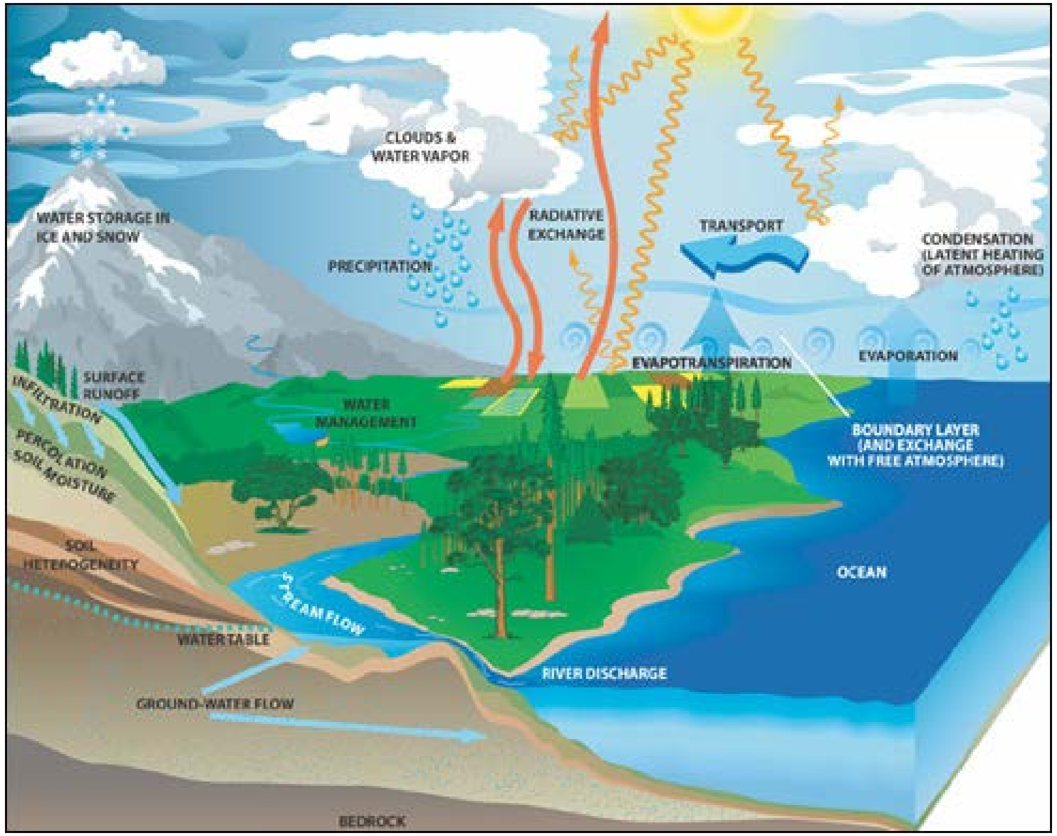



## Agricultural Productivity

- Enhance weather and climate forecast skills
- Improve agricultural practices
- Improve flood prediction and drought monitoring

- Economic impacts
- Link between water, energy, carbon at the land surface

# Importance of Soil Moisture and Groundwater




| RESERVOIR | VOLUME (KM³) | RESIDENCE TIME |
|---|---|---|
| Oceans | 1,322,000,000 | 2500 years |
| Ice caps & glaciers | 29,199,700 | - |
| Groundwater (near-surface) | 4,171,400 | 8 years |
| Lakes & Rivers | 130,700 | 88 days |
| Soil Moisture | 66,700 | 47 days |
| Atmosphere | 12,900 | 9 days |

Soil Moisture (SM) vs. Groundwater (GW):

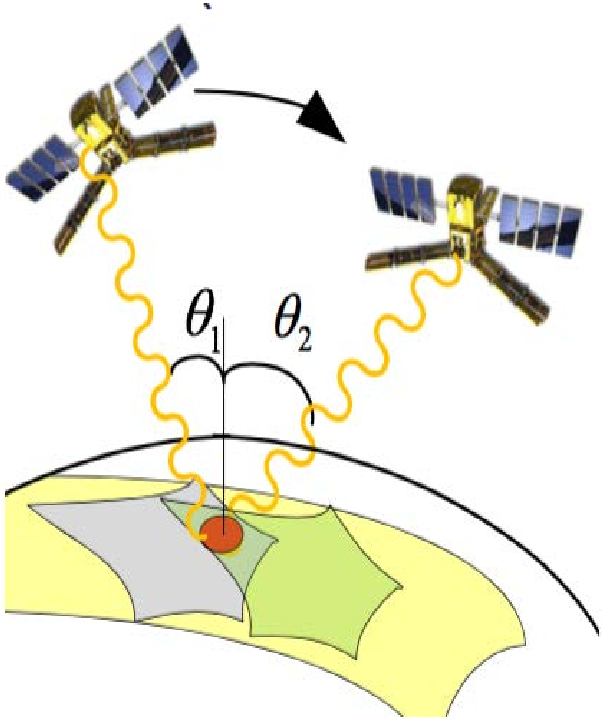
SM smaller volumes & more temporally dynamic than GW

**A look at these from Space?**

**Soil Moisture ← SMOS/SMAP**
**Groundwater ← GRACE [?]**

# Soil Moisture From Space

*Soil Moisture and Ocean Salinity (**SMOS**) Mission*




- L-band at multiple incidence angles
- Lauched: Nov. 2009
- ~40 km resolution

## Advantages:

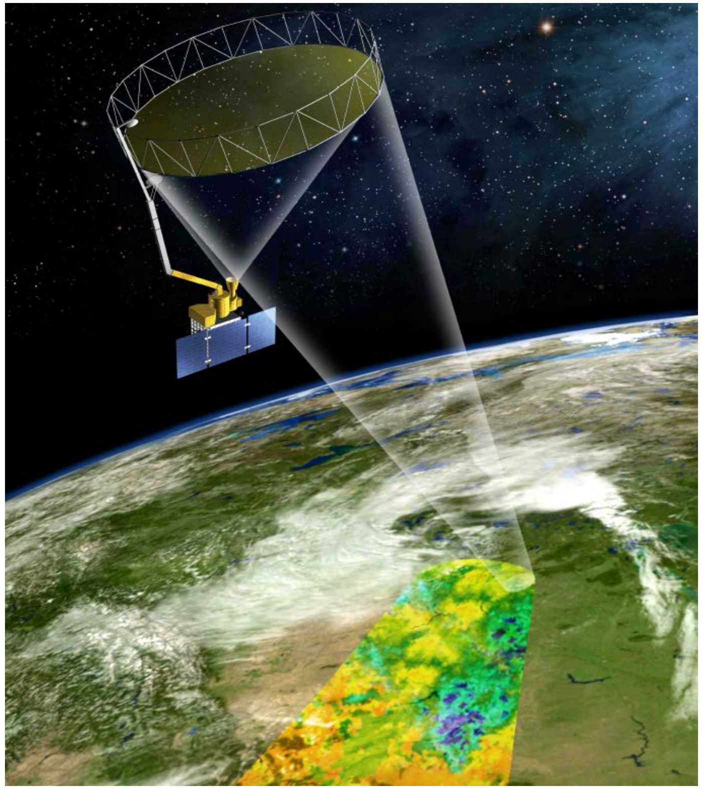
- Tb (L-band,1.4GHz) depends on soil moisture
- Frequent observations ( e.g., global coverage **every 2-3 days**)
- Good horizontal resolution (**40km**)

## Disadvantages:

- Only sensitive to soil moisture of **surface** layer (i.e., ~<5cm)

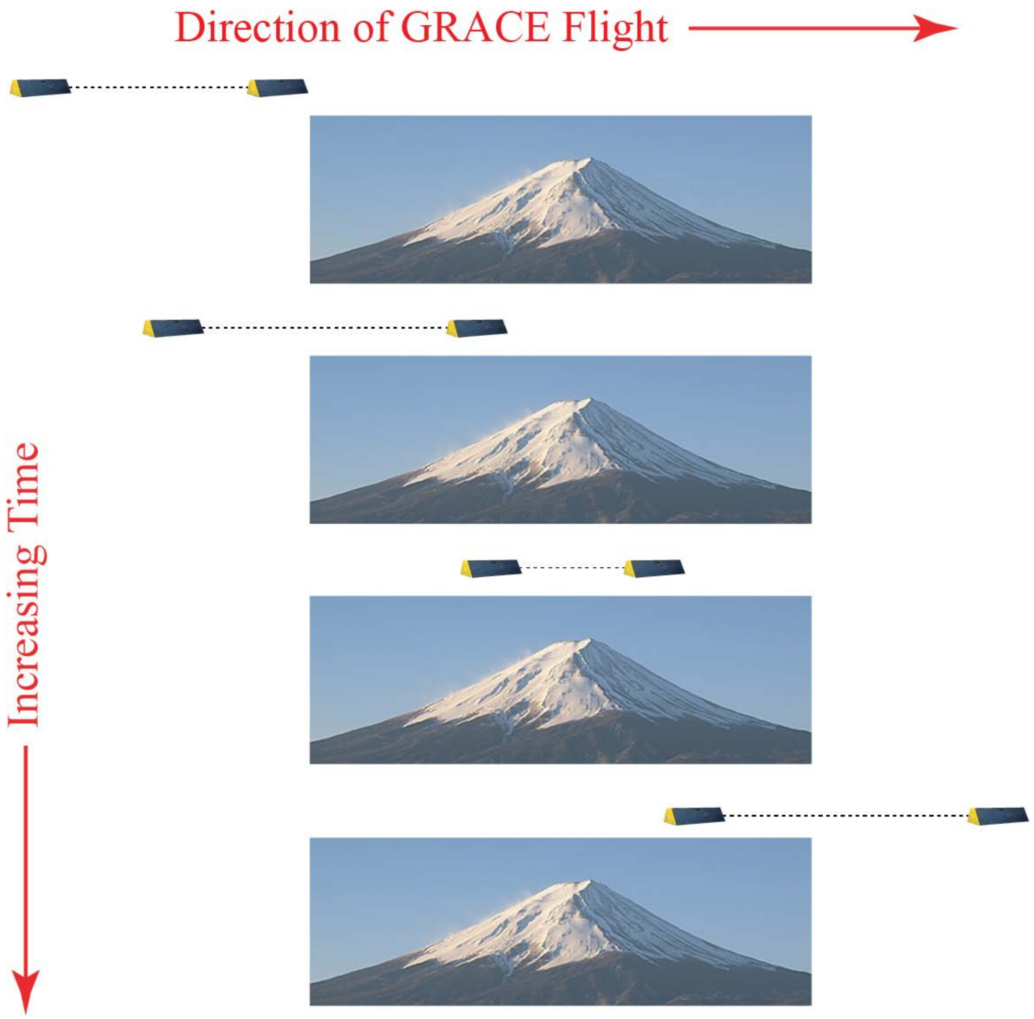
**What about rootzone and groundwater?**

*Soil Moisture Active Passive (**SMAP**)*

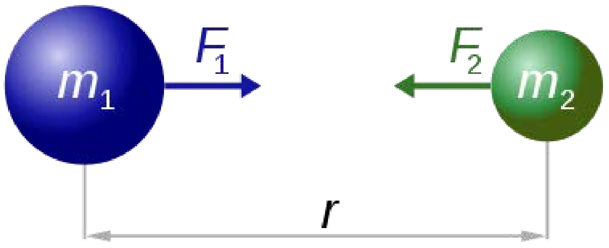


- L-band (active)/passive
- Launch: 31 Jan 2015
- (3)-40 km resolution

# Groundwater from Space: GRACE?



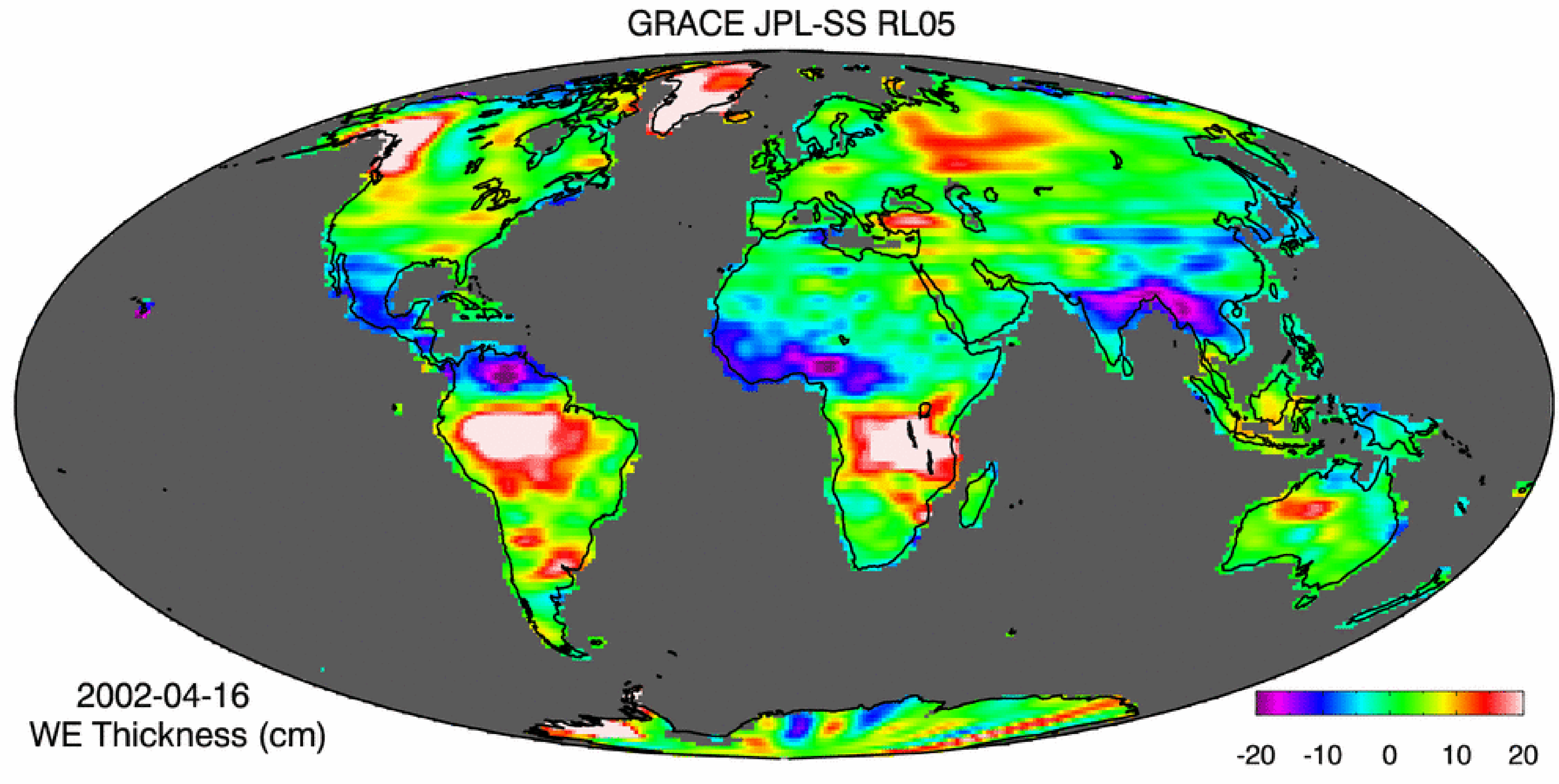

**GRACE** = Gravity Recovery and Climate Experiment




$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

- Gravity = *f*(mass)
- Gravity varies in **space** (e.g., mountains = more mass)
- Gravity can be measured with two satellite one running after the other [range-rate observations] → GRACE!

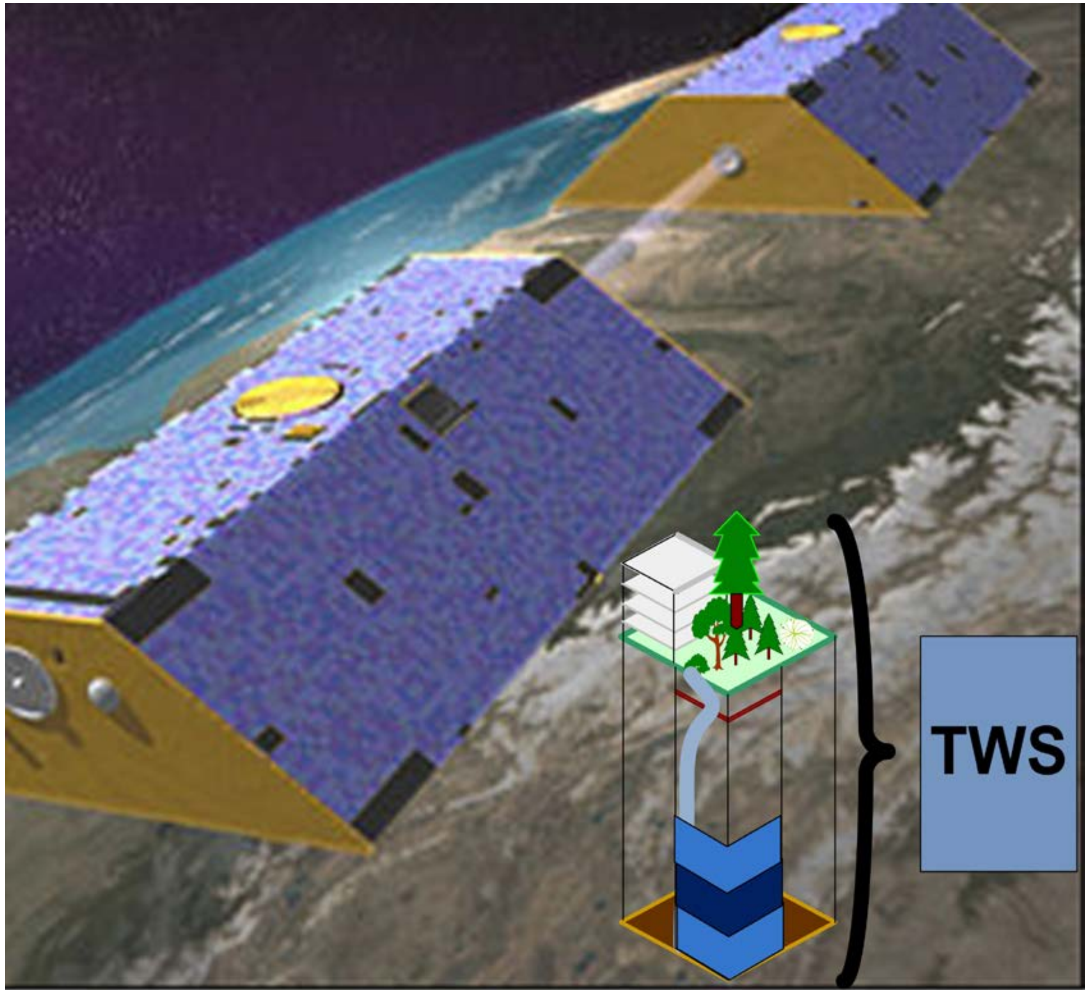
# Groundwater from Space: GRACE?




- Gravity varies in **time**
- Water changes the Earth's mass
- Mass changes the gravity field (in **space** and **time**)
- GRACE observations: monthly **TWS** anomalies

**Gravity (GRACE) can monitor where the water is now and how it is changing over time**

# Groundwater from Space: GRACE?




**TWS = Terrestrial Water Storage**

[sum of groundwater, unsaturated soil moisture profile, snow, vegetation storage]

**Advantages:**

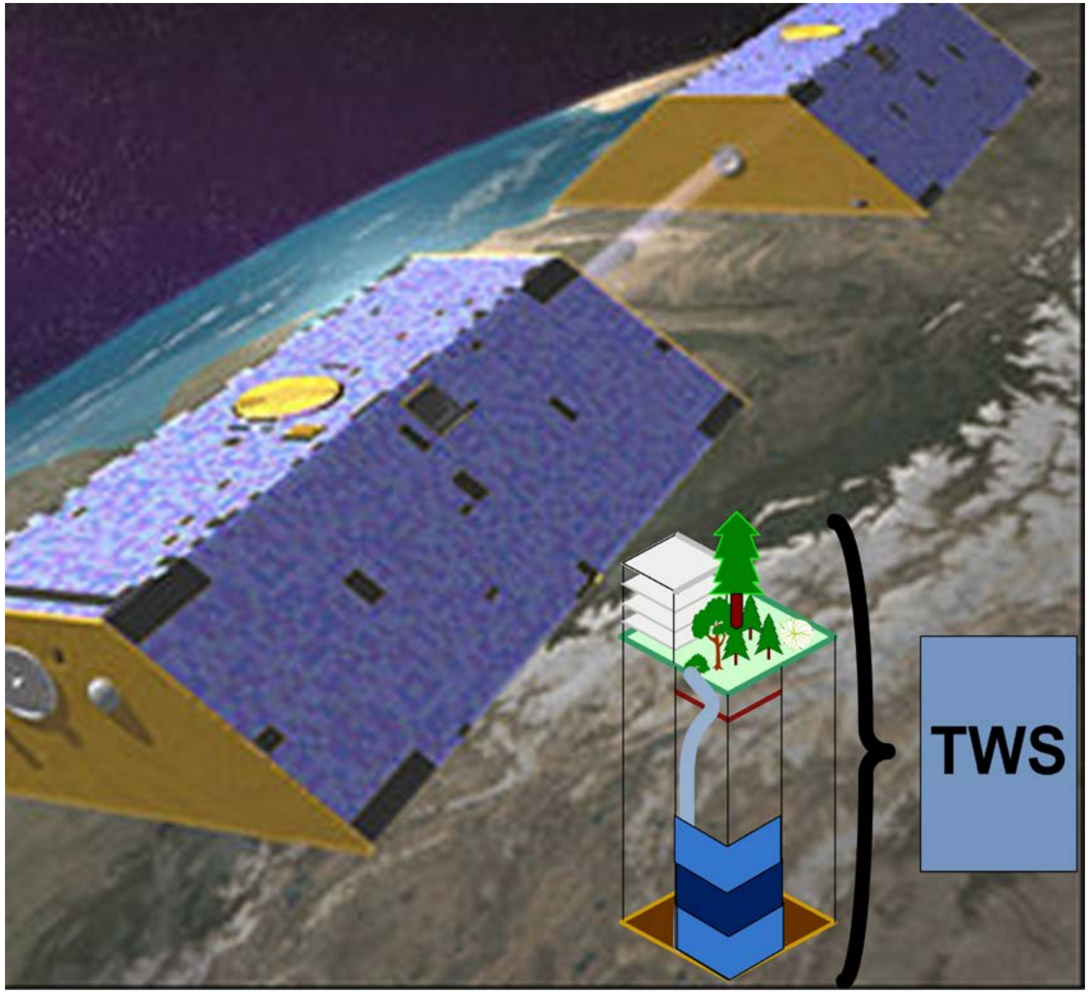
- Unique Mission: can see beyond the surface

**Applications:**

- Ice Melt Loss [e.g., Antarctica & Greenland]
- Droughts [e.g., Texas, California]
- Groundwater Depletion [e.g., India]
- Sea Level Rise

→ **Scales used for global mass balances**

# Groundwater from Space: GRACE?




## Disadvantages:

- Column integrated [**no partitioning into storages**]
- **Coarse horizontal resolution** [300-400 km]
- **Coarse temporal resolution** [monthly]
- Strong spatial error correlations

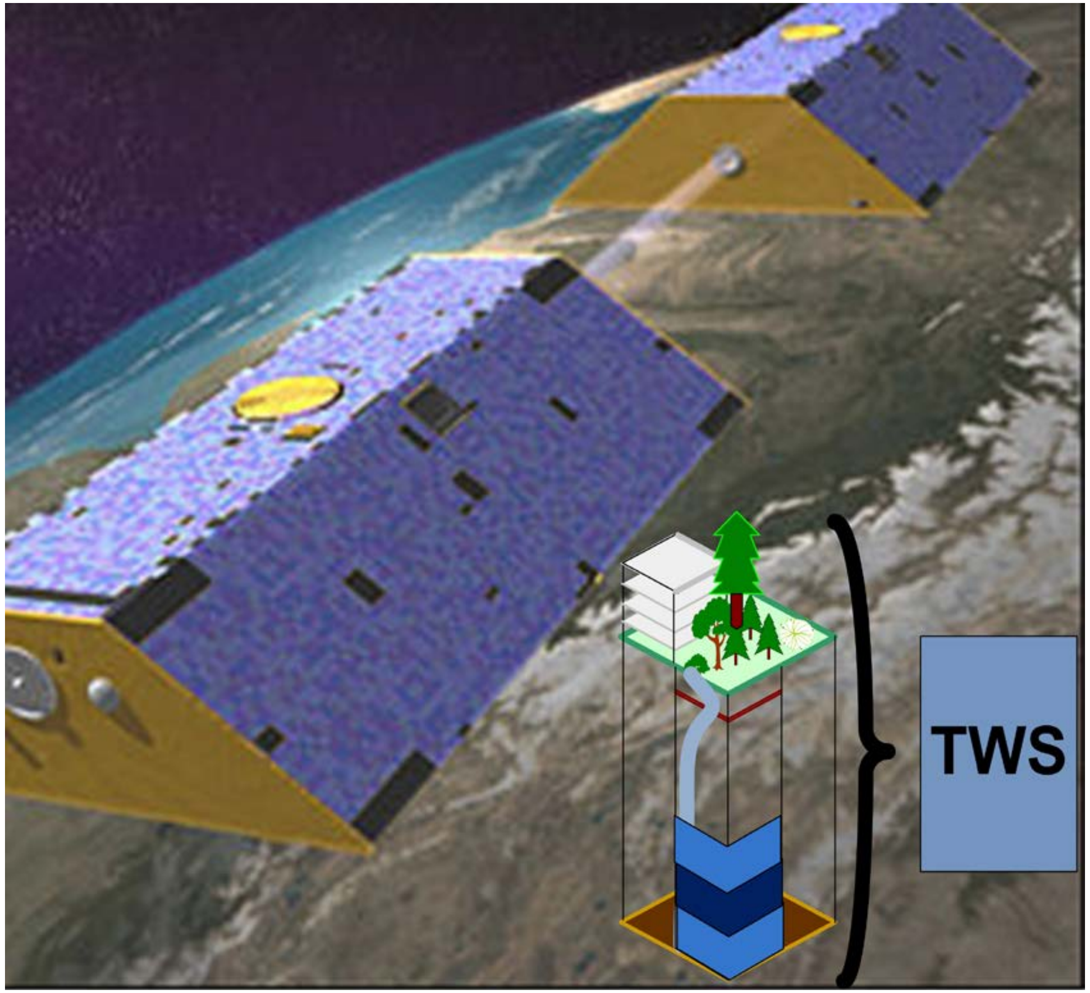
**Scales used for global mass balances**

**?**

*Downscaling*:
- **Horizontal**
- **Temporal**
- **Vertical**

**Scales that are more useful for hydrological applications**

# Groundwater from Space: GRACE?

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**Scales used for global mass balances**

**DATA ASSIMILATION**

*Downscaling*:
- **Horizontal**
- **Temporal**
- **Vertical**

**Scales that are more useful for hydrological applications**

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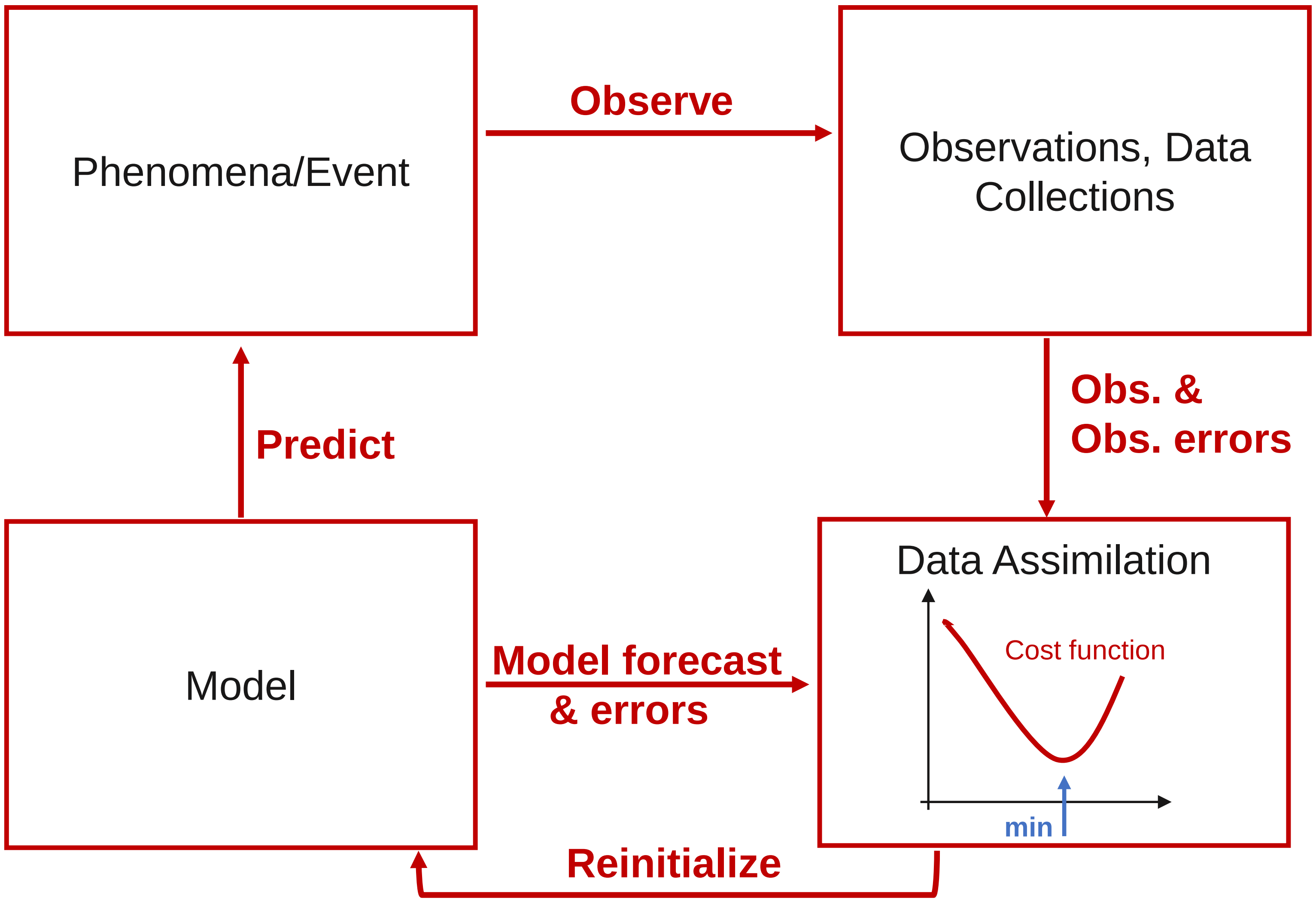
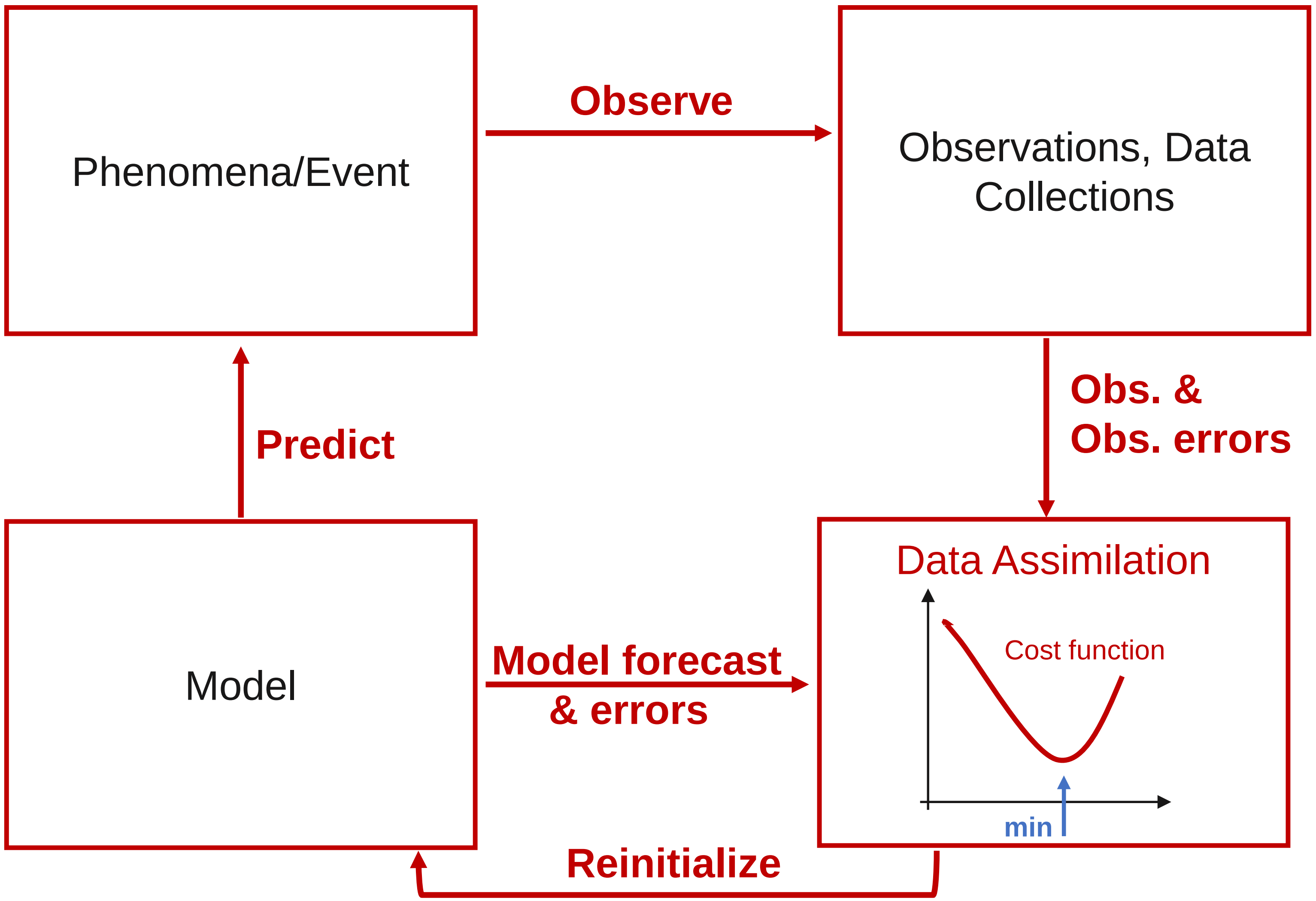
# Data assimilation (DA)




**The Key Idea of DA:**

- Estimates of a Specific Phenomena can be obtained form **Model** & **Observations**
- Neither are perfect
- Use them in combination to optimize the estimates

# Data assimilation (DA) for hydrology




Observations
- Satellite Remote Sensing
- Insitu Observations
- Airborne Observations

**The Key Idea of DA:**

- Estimates of a Specific Phenomena can be obtained form **Model** & **Observations**
- Neither are perfect
- Use them in combination to optimize the estimates

**Apply DA using SMOS and GRACE observations to estimate soil moisture profile**

# GRACE data assimilation (DA) as a downscaling approach

## <u>Catchment Land Surface Model</u> (CLSM)

- **"High" spatial and temporal resolutions**
  - 36 km (vs. 300-400 km)
  - Hourly/daily (vs. monthly)
- MERRA (&MERRA-2) forcings

- **Soil Moisture Profile:**

[1] catdef (**i.e., groundwater**)

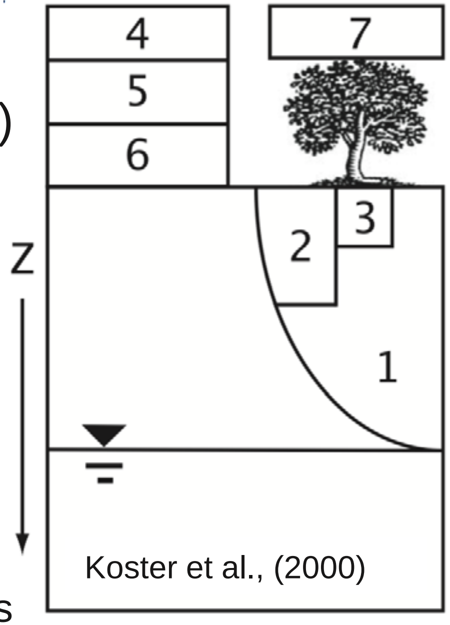
[2] rzexc

[3] srfexc

- Other water storages:

[4-6] snow [7] canopy

* Note: missing lakes and river storages




**Modeled (predicted) TWS** ← ***f*** **([1], [2], [3], [4-6], [7])**

**Observed (GRACE) TWS** (Coarse scales) **DA** → **[1], [2], [3], [4-6], [7]** (model, fine scales)

**Take advantage of the model structures to downscale GRACE observations**

# GRACE DA: Two-Steps Ensemble Kalman Filter

[1] Conduct 1 month forecast ensemble integration without assimilation

[2] Calculate model terrestrial water storage (TWS) observation prediction (space and temporal aggregation)

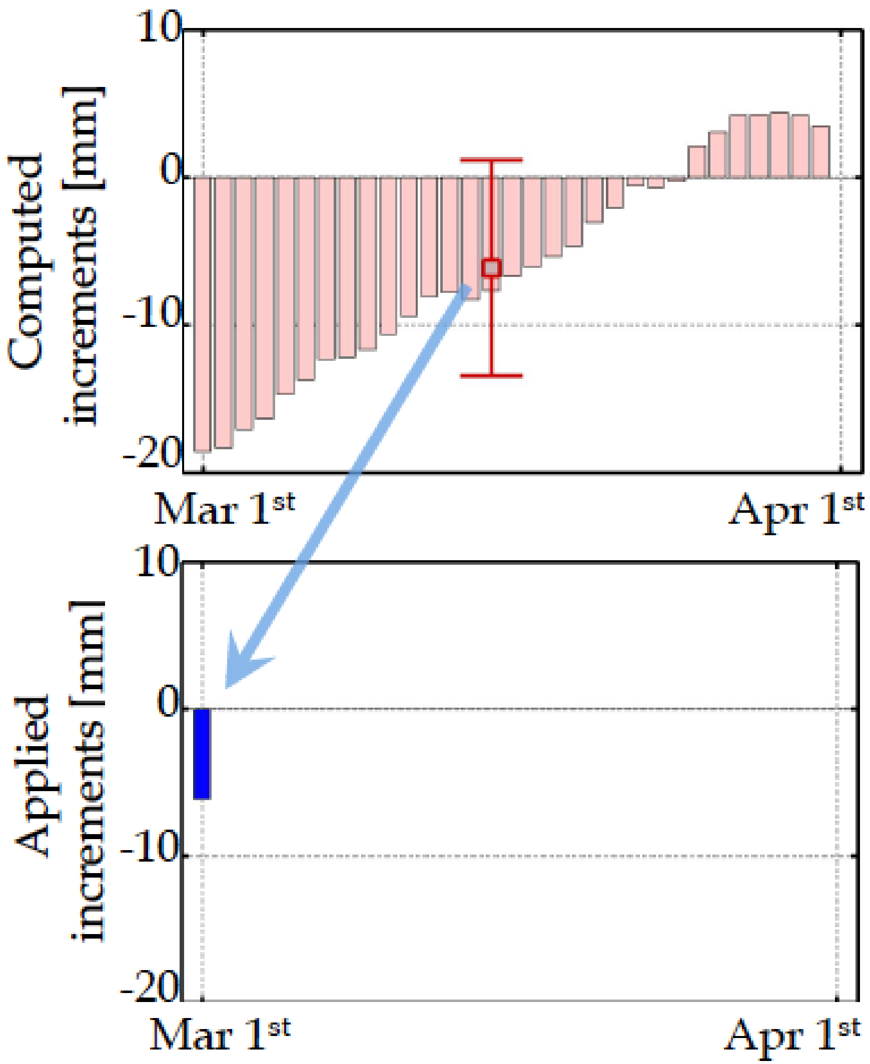
[3] Calculate the increments via ensemble Kalman filter analysis

[4] Rewind and apply increments repeat from [1] for the next month.

**How to compute analysis for a *monthly-averaged* observations?**

Girotto et al., (2016) WRR

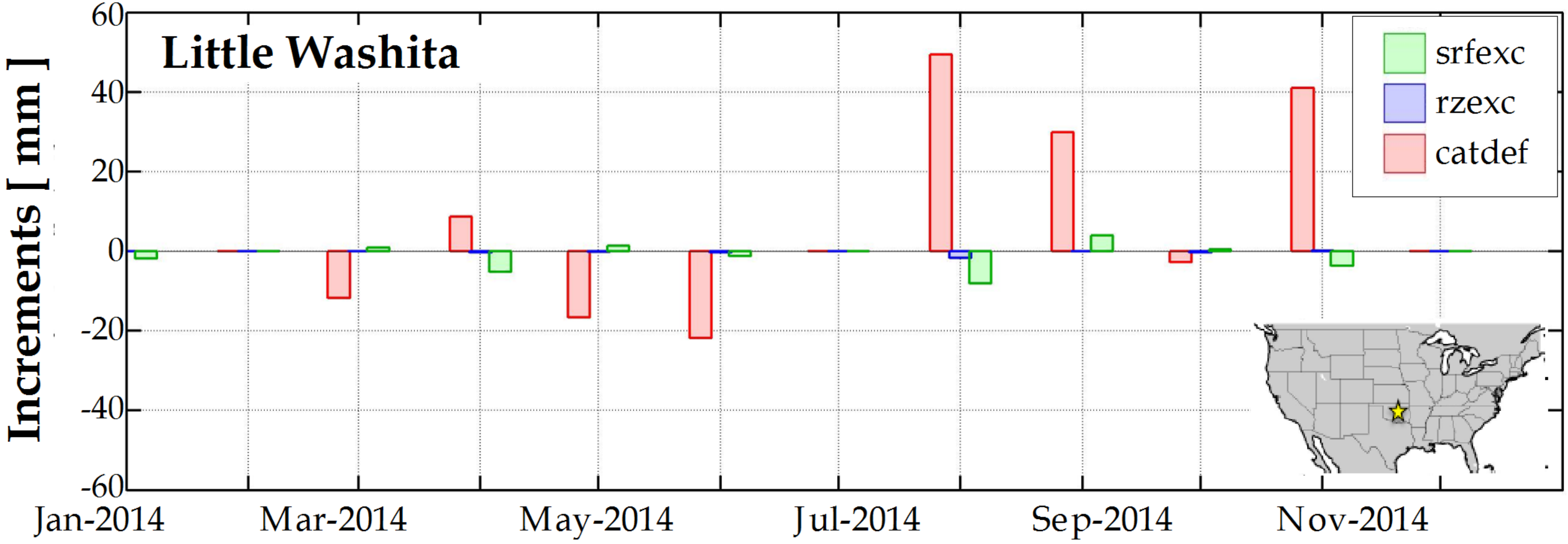
# GRACE DA: Temporal Aggregation and Downscaling




- Calculation of the increment as an average (i.e., "**monthly increment**")
- Application of the increment as an **initial condition** at the beginning of the month
- **Downscaling** the observed TWS from monthly to model **temporal** resolution (i.e., daily)
- Day-to-day **variability** [largest in surface soil moisture]

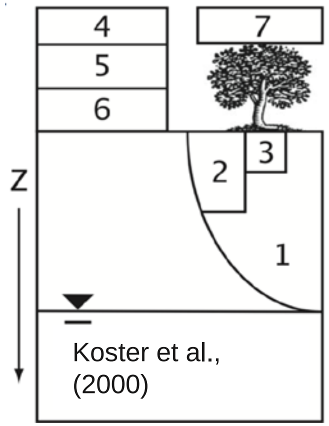
**DA should better represent the monthly signature of the assimilated GRACE-TWS observations**

# GRACE DA: Vertical Downscaling




**Soil Moisture Profile:**
[1] catdef
(**i.e., groundwater level**)
[2] rzexc
[3] srfexc

Other water storages:
[4-6] snow [7] canopy




- Catdef dominates profile increments

(i.e., largest GRACE-DA impact in **groundwater**)
Use GRACE-DA to update catdef (i.e., the groundwater only!)

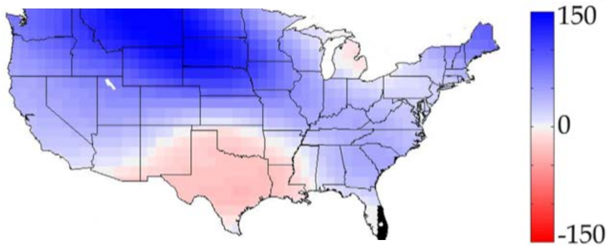
# GRACE DA: Vertical & Horizontal Downscaling

**Scales used for global mass balances (~300-400 km)**

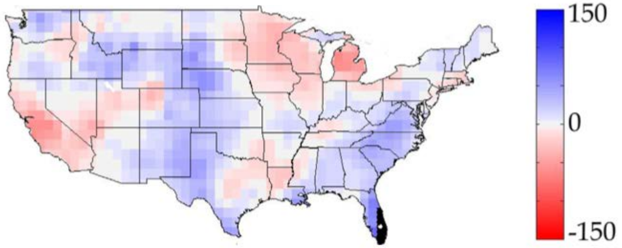
**Scales that are more useful for hydrological applications (36 km)**

TYPICAL MONTHLY ABSOLUTE INCREMENTS (2003-2015)

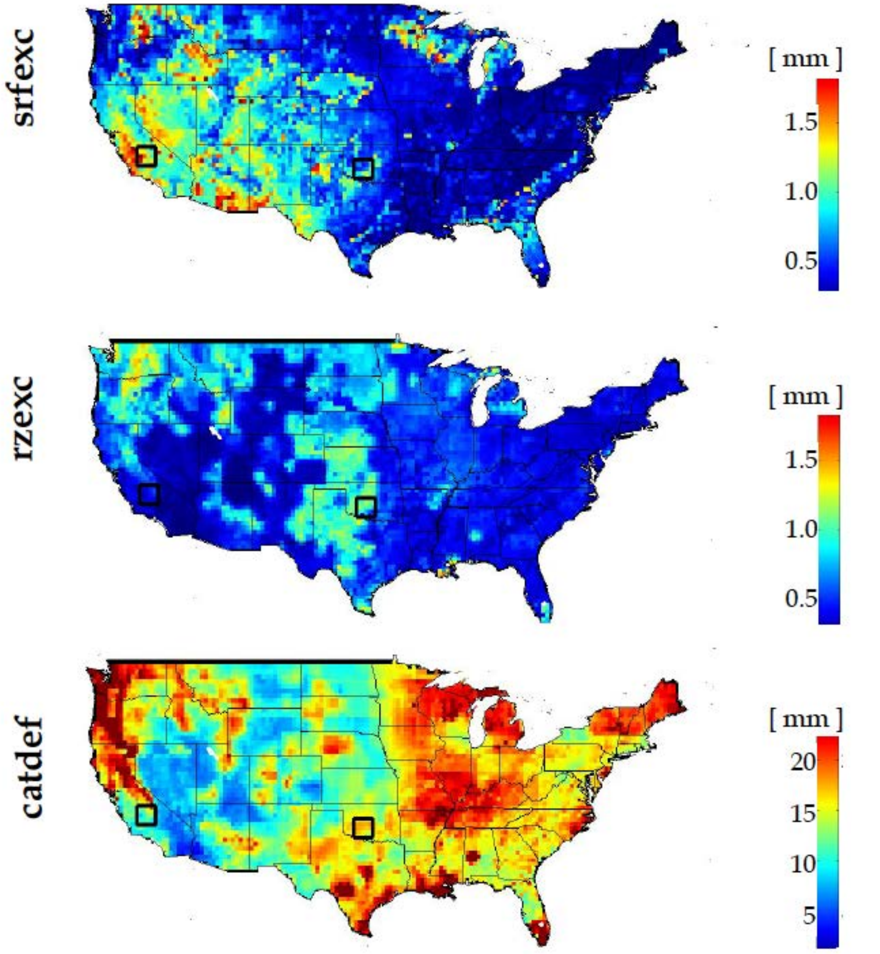
GRACE TWS observations




Obs – Forecasts TWS [z- M(x)]




**DATA ASSIMILATION**




- **Horizontally downscaled TWS**
- Typical monthly increments:
  srfexc = 0.63 mm
  rzexc = 0.54 mm
  catdef = 15.30 mm
- Largest impact in (catdef) groundwater (residence time?)

*Scaling the observations prior to DA: Unbiased observations to match model climatology (long-term mean and standard deviation)

Girotto et al., (2016) WRR

# GRACE Data Assimilation: Validation

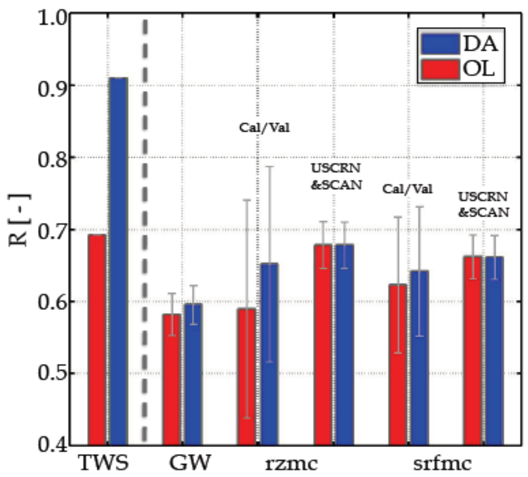
**Soil Moisture:**
- 157 SCAN (Soil and Climate Analysis Network)
- 95 USCRN (U.S. Climate Reference Network)
- 4 Cal/Val USDA sites

- Surface (0-5 cm)
- Rootzone (0-100 cm)

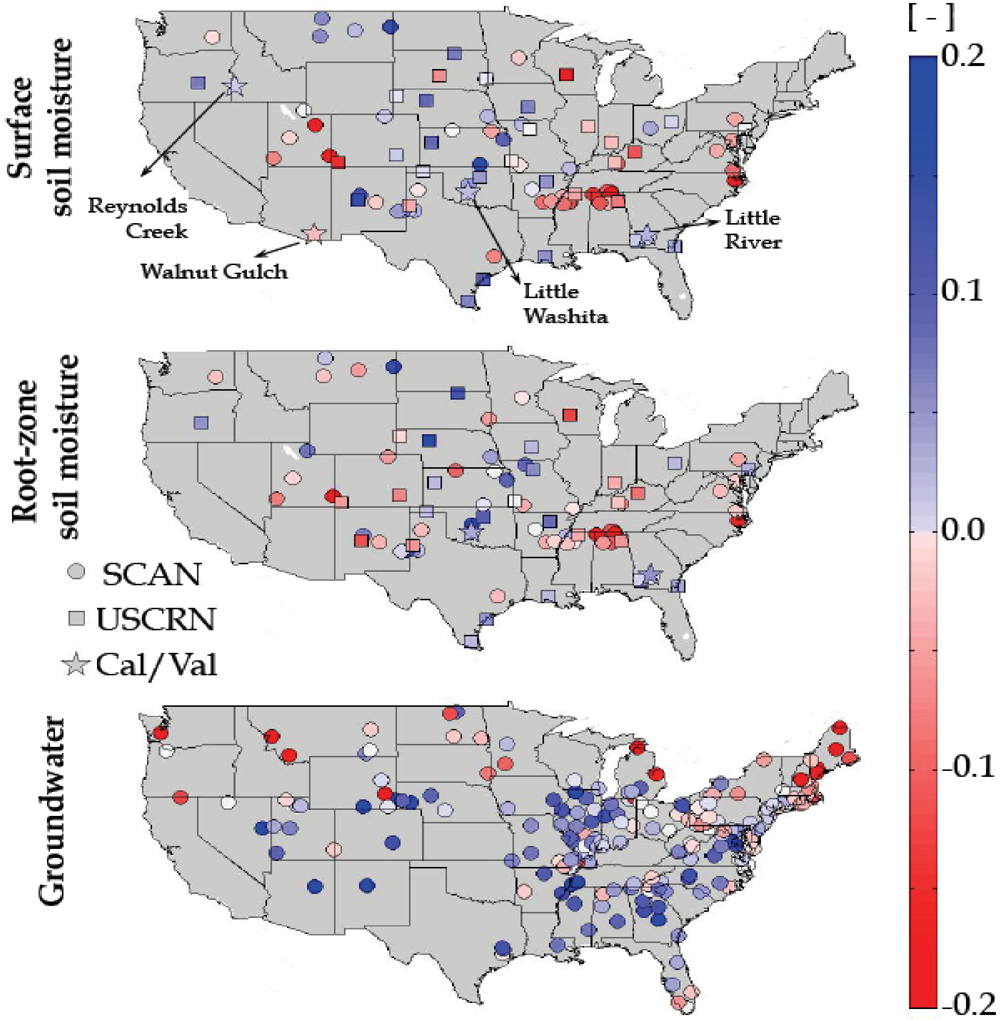
**Groundwater:**
- 136 USGS (Unconfined aquifer only)

**Statistical Methods:**
Skill: Anomalies Correlations
Monthly values Jan. 2003 - Dec. 2013

Bulk Statistics




$\Delta R = R_{DA} - R_{OL}$ [ BLUE = DA better than OL ]




## GRACE-DA
- Improves groundwater estimates
- Mixed results for root-zone and surface soil moisture (Short memory? Small increments?)

**→ Add soil moisture (SMOS/SMAP)?**

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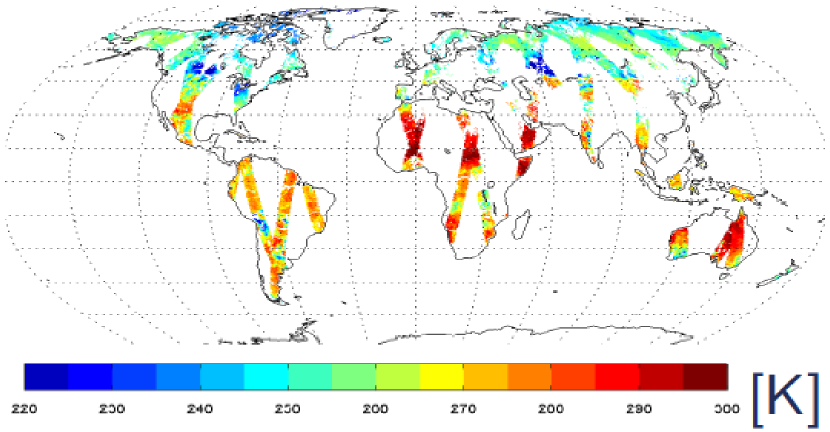
# SMOS(SMAP) to help with surface soil moisture?

**SMOS/SMAP Brightness Temperature (Tb)**




**Models**

- Catchment Land Surface Model
  - ➢ Estimate surface soil moisture, temperature
- Radiative Transfer Model (*De Lannoy et al., 2013*)
  - ➢ Estimate Tb [e.g., to compare with observed Tb]

**Data Assimilation**

For one location *k*, one time step *i*, one ensemble member *j*:

$$\hat{\mathbf{x}}_{k,i}^{j+} = \hat{\mathbf{x}}_{k,i}^{j-} + \mathbf{K}_{k,i}[\mathbf{y}_i^j - \hat{\mathbf{y}}_i^{j-}]$$

$\hat{\mathbf{x}}_{k,i}^{j}$ Soil moisture, temperature (signs -: forecasts, +analysis)

$\mathbf{K}_{k,i}$ Kalman gain

$\mathbf{y}_i^j$ Tb SMOS/SMAP observations

$\hat{\mathbf{y}}_i^{j-}$ Tb forecast in observation space

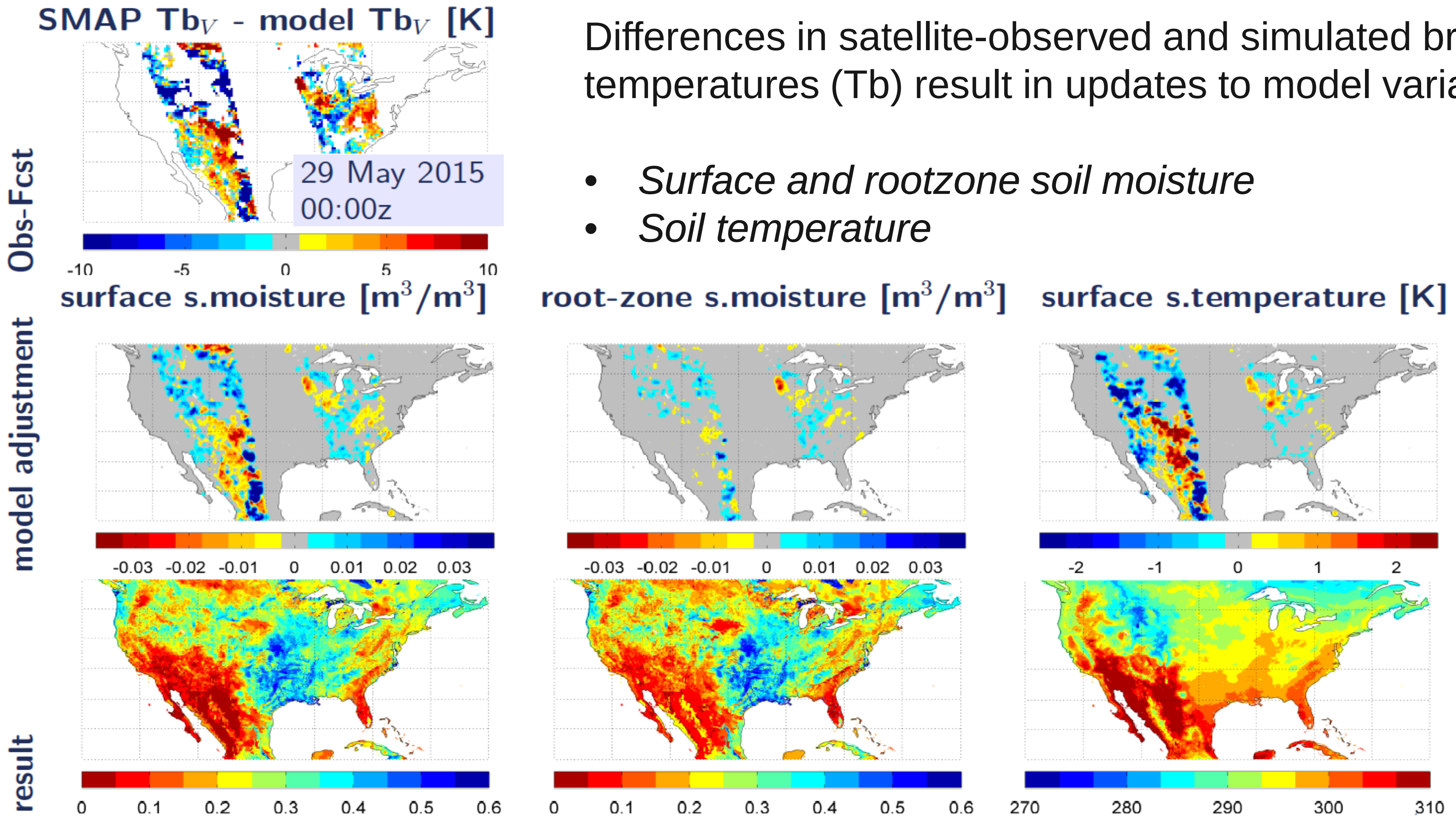
Continuous estimates of surface, rootzone, soil moisture (+ others)

Every 3-hrs, 9 km (SMAP_L4)
- 36 km (this presentation)

# SMOS(SMAP) to help with surface soil moisture?

Differences in satellite-observed and simulated brightness temperatures (Tb) result in updates to model variables:

- *Surface and rootzone soil moisture*
- *Soil temperature*






De Lannoy and Reichle 2016

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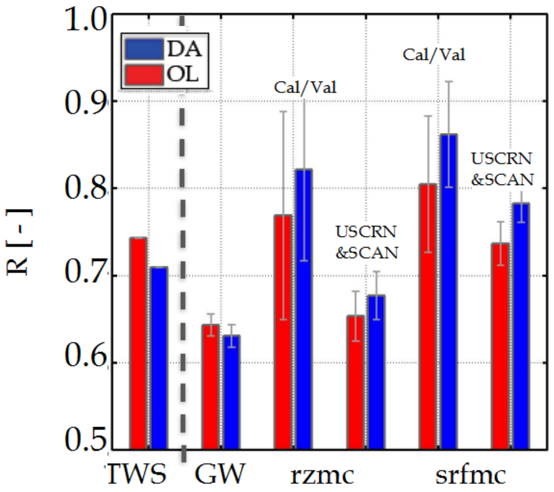


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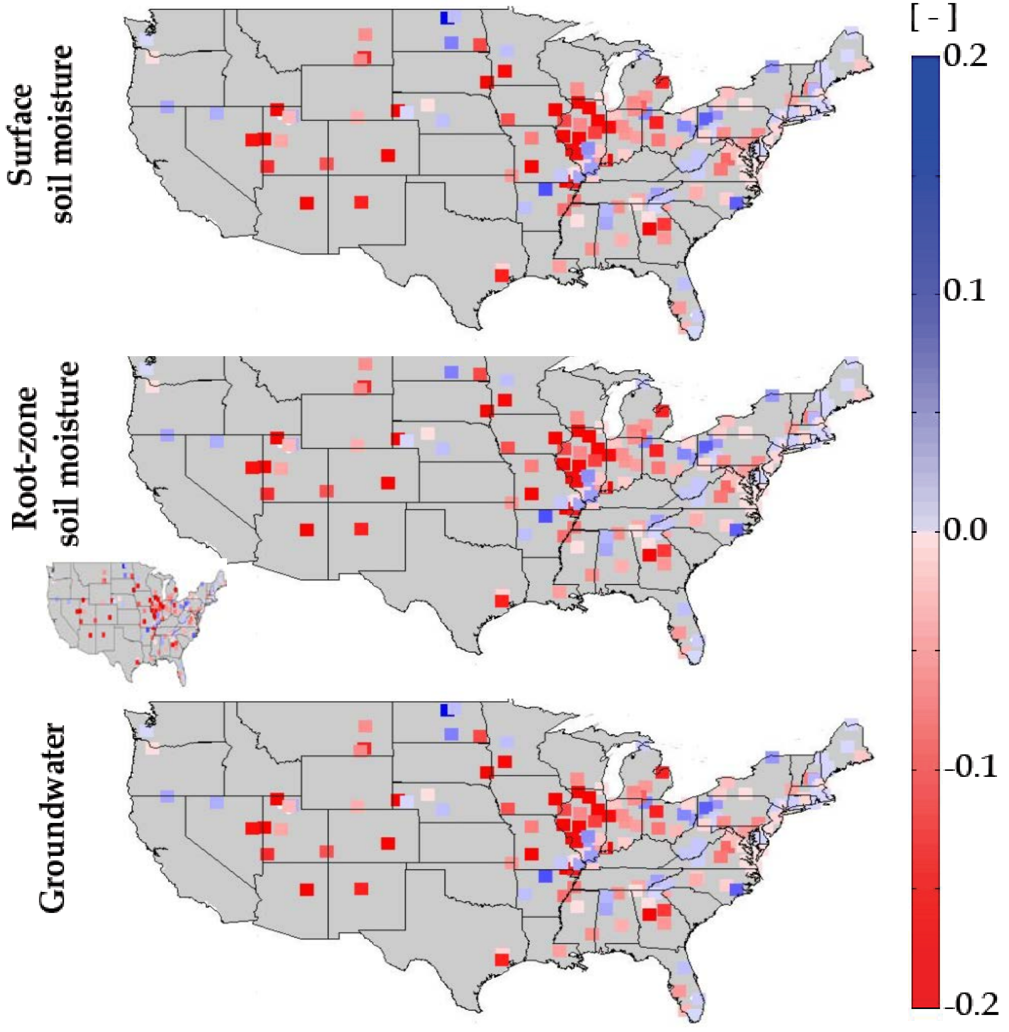


## SMOS-DA
- Beneficial for surface and root zone soil moisture
- But has degraded groundwater

**→ What if we incorporate both GRACE+SMOS observations together?**

# GRACE Data Assimilation: Validation

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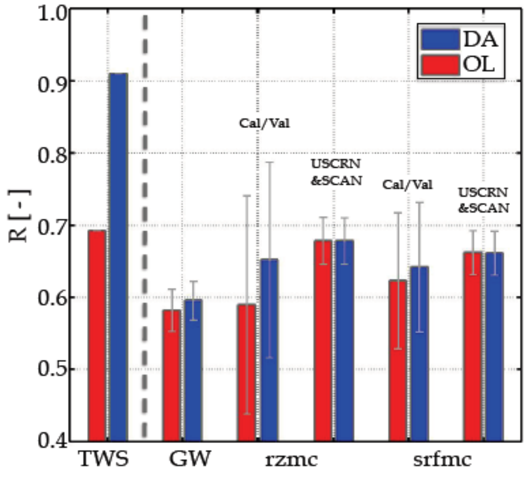


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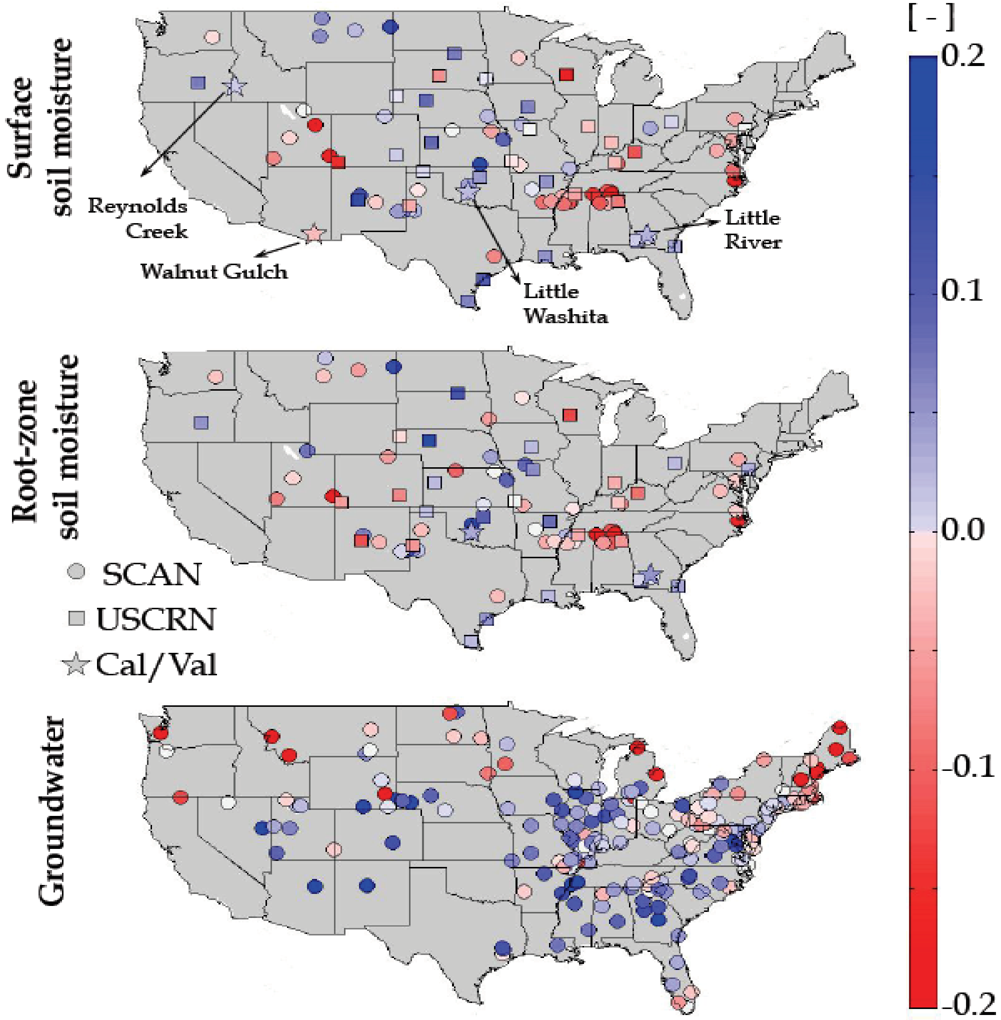


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- Mixed results for root-zone and surface soil moisture (Short memory? Small increments?)

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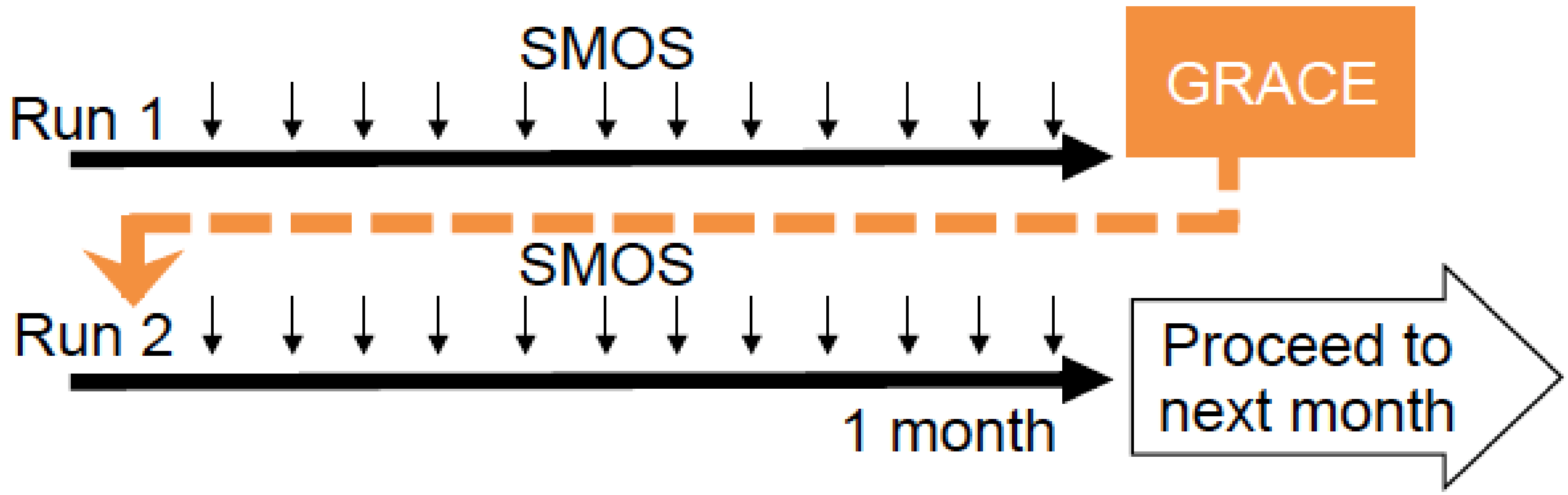
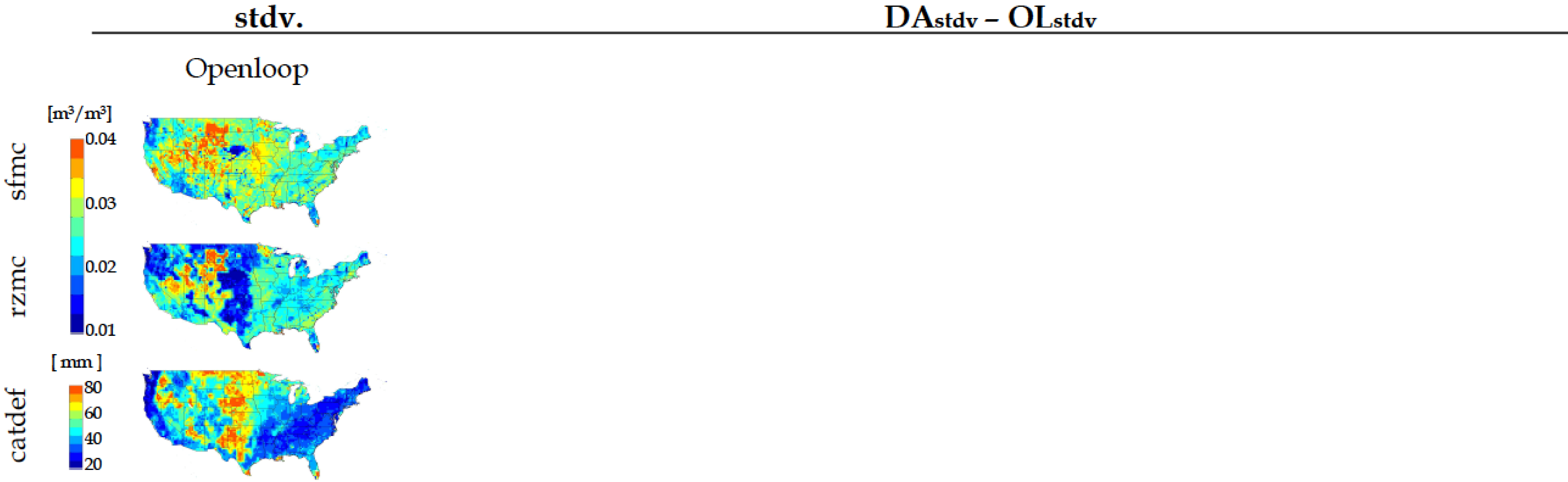
# GRACE+SMOS Data Assimilation: Method

**What if we incorporate both GRACE+SMOS observations together?**




Girotto et al., (in prep.)

# GRACE+SMOS Data Assimilation: Vertical Structure of the Updates

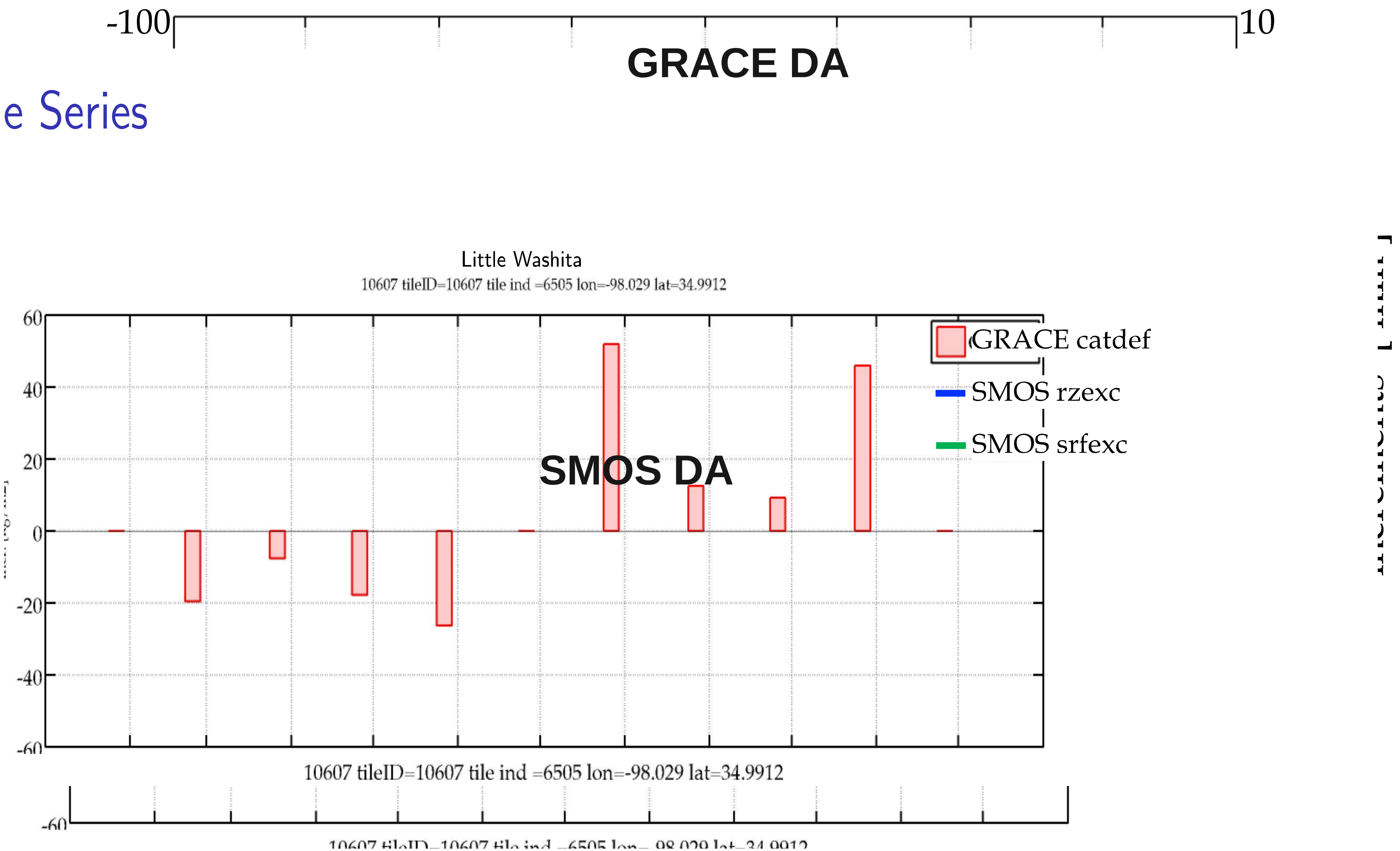



- The uncertainty of **top (surface)** water storages is mostly reduced because of the assimilation of SMOS
- The uncertainty of **bottom** water storages is mostly reduced because of the assimilation of GRACE
- The combination of the two observations keeps the uncertainty reduction on both **surface and deeper** storages.



Girotto et al., (in prep.)

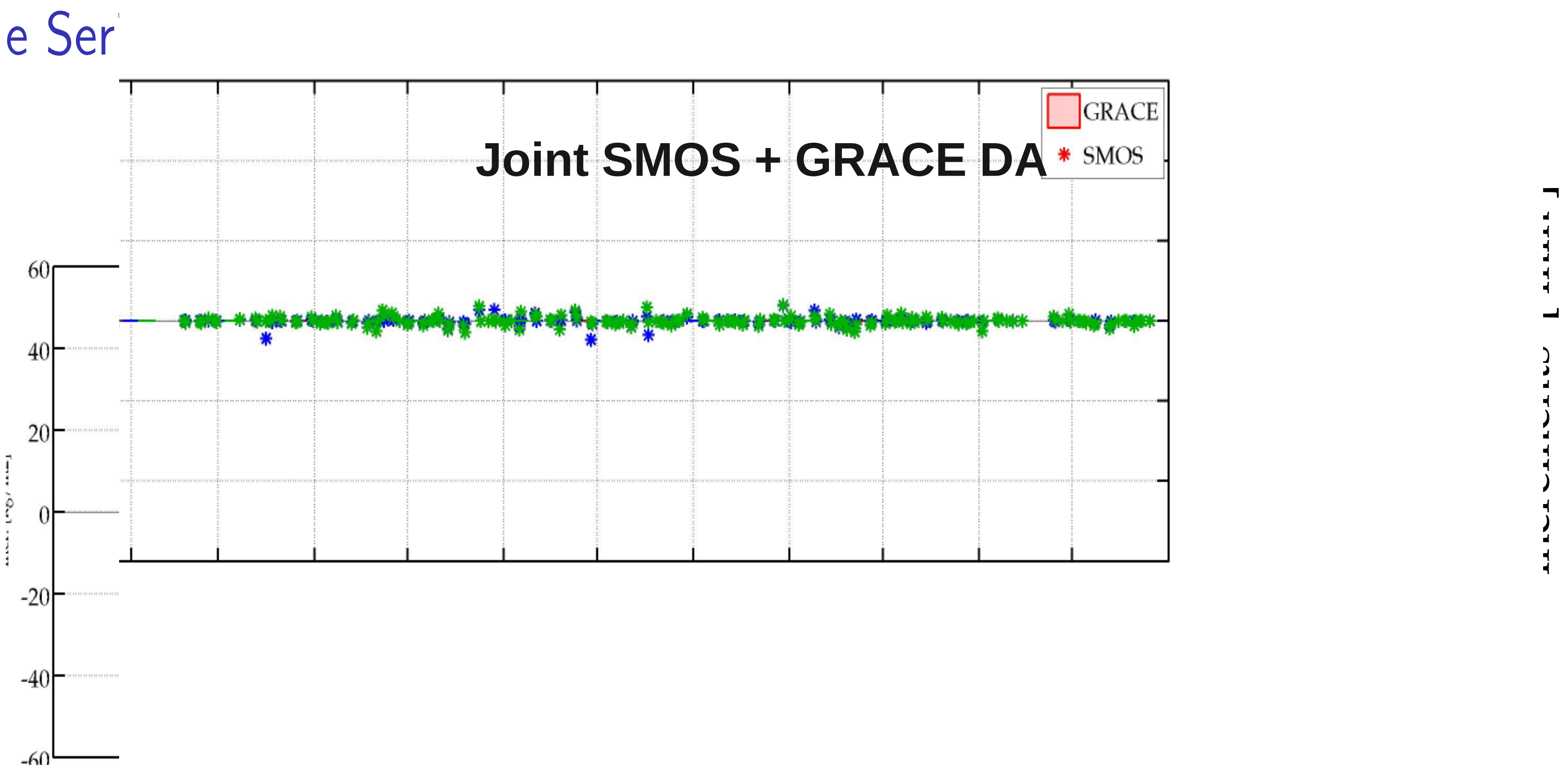
# GRACE+SMOS Data Assimilation: Method




- Example loc in Idaho
- GRACE DA only increments in catdef (i.e., groundwater)
- GRACE DA calculates year-round increments.
- SMOS DA increments only for warm months (i.e., no frozen soil)
- Srfexc & rzexc increments agree in terms of directions

Girotto et al., (in prep.)

# GRACE+SMOS Data Assimilation: Method




- catdef increments similar to GRACE DA
- srfexc & rzexc incr. similar to SMOS DA

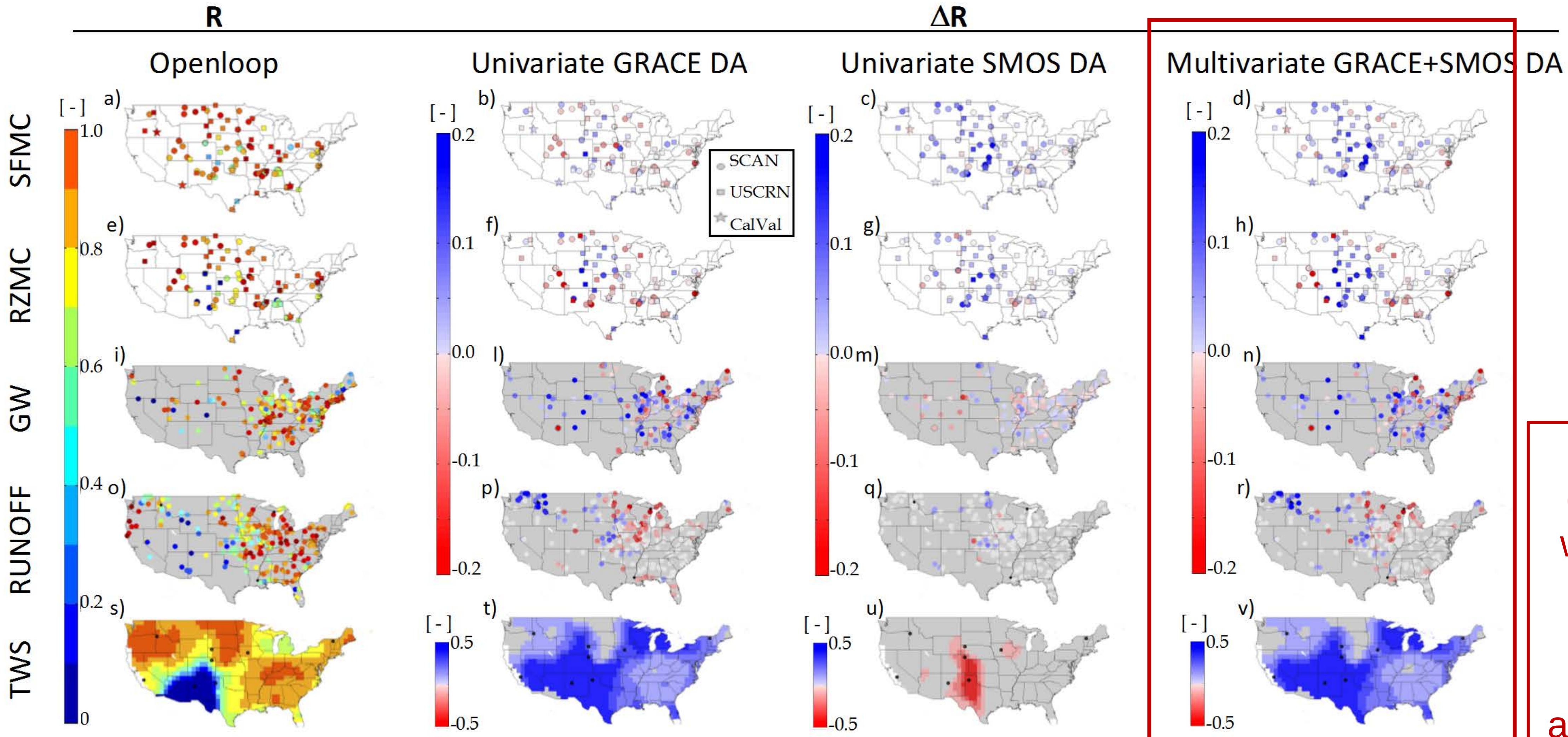
→ Characteristics of the univariate assimilations are maintained in the joint system

- Anti-correlation between increments brought about GRACE & SMOS

→ Fighting observations?

Girotto et al., (in prep.)

# GRACE+SMOS Data Assimilation: Validation

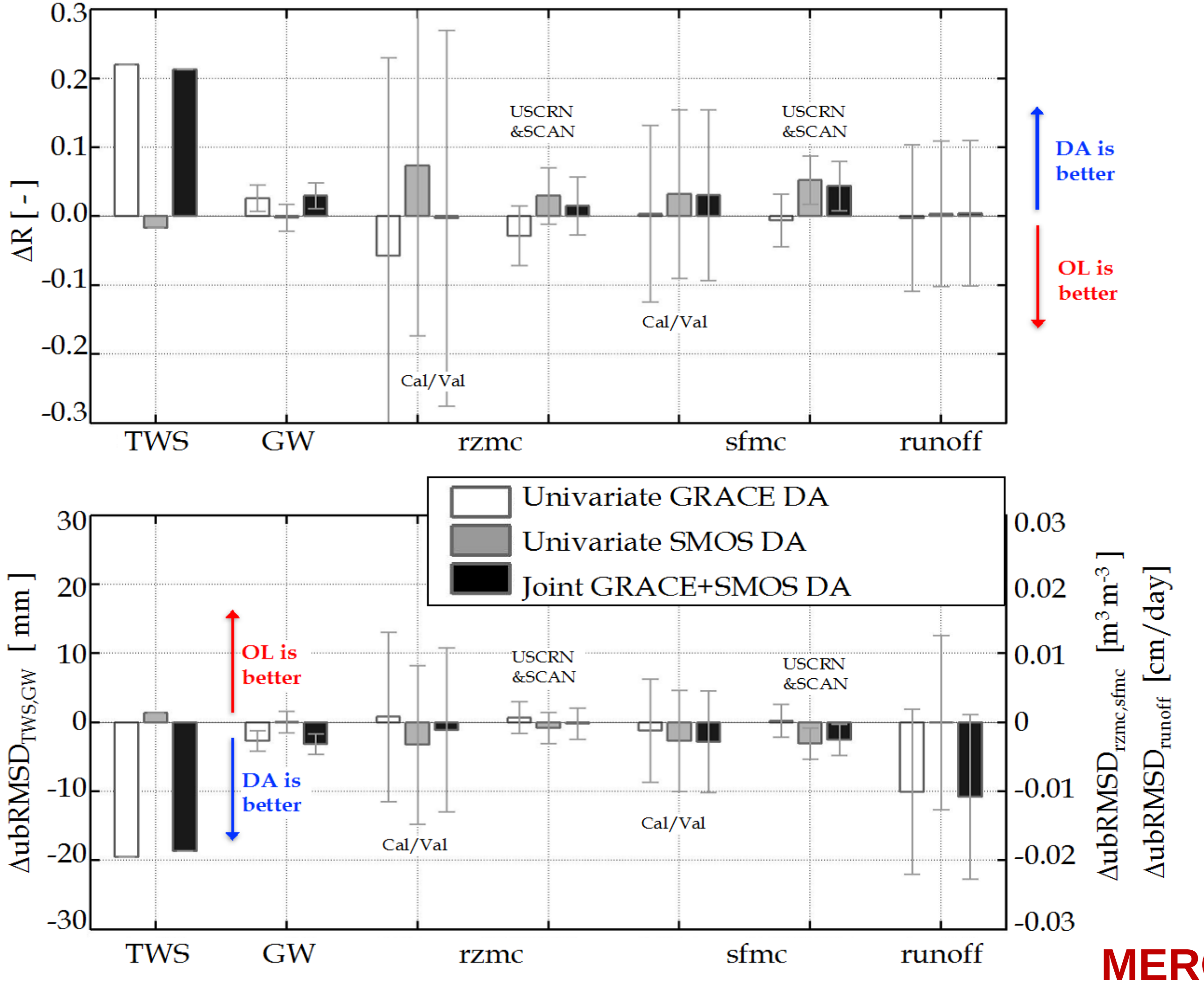



Best estimates when both SMOS & GRACE obs. are assimilated!



Girotto et al., (in prep.)

# GRACE+SMOS Data Assimilation: Validation




## GRACE DA

- Improves groundwater estimates
- Mixed results for root-zone and surface soil moisture

## SMOS DA

- Improves surface and root zone soil moisture
- It degrades groundwater

## SMOS+GRACE DA

- Improves surface and root zone soil moisture
- it maintains high skills vs. TWS
- It overcomes the degradation of groundwater

**MERGING SMOS+GRACE LEAD TO THE BEST RESULTS!**



Girotto et al., (in prep.)

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# Soil Moisture Profile Estimates

## GRACE DA

- GRACE DA primarily affects groundwater and has smaller impacts on soil moisture
- GRACE DA leads to <u>improve groundwater</u>

## SMOS DA

- SMOS DA is mostly beneficial to <u>improve surface soil moisture</u>
- SMOS DA marginally improves rootzone soil moisture
- SMOS DA leads to minimal changes in the groundwater

## Joint SMOS+GRACE DA

- The entire soil moisture profile is improved when both SMOS & GRACE observations are used jointly

## GRACE DA as a Downscaling Method

- Vertical: [from TWS to the various water storage compartments (e.g., groundwater, etc.)]
- Horizontal: [from 300-400 km to 36 km increments]
- Temporal: [from monthly to daily]

## Impacts onto the Vertical Profile

- GRACE, SMOS, and the joint assimilations decrease model uncertainties
- GRACE affects deepest moisture storages
- SMOS affects shallower moisture storages

- There is an anti-correlation between increments brought about the GRACE and SMOS

**The best hydrology can be achieved for when both observation types are assimilated jointly**

# Thanks for your attention!

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Manuela Girotto


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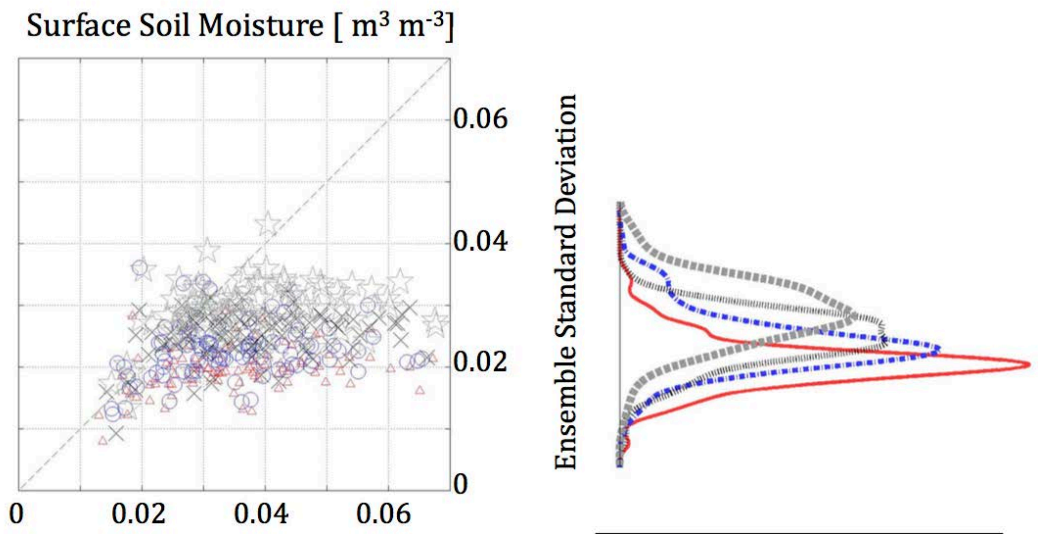
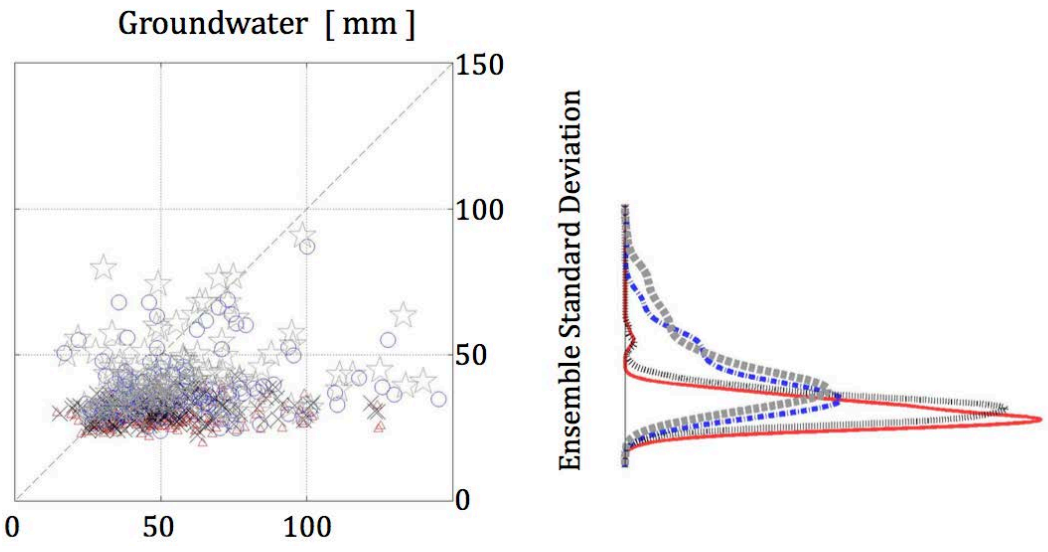
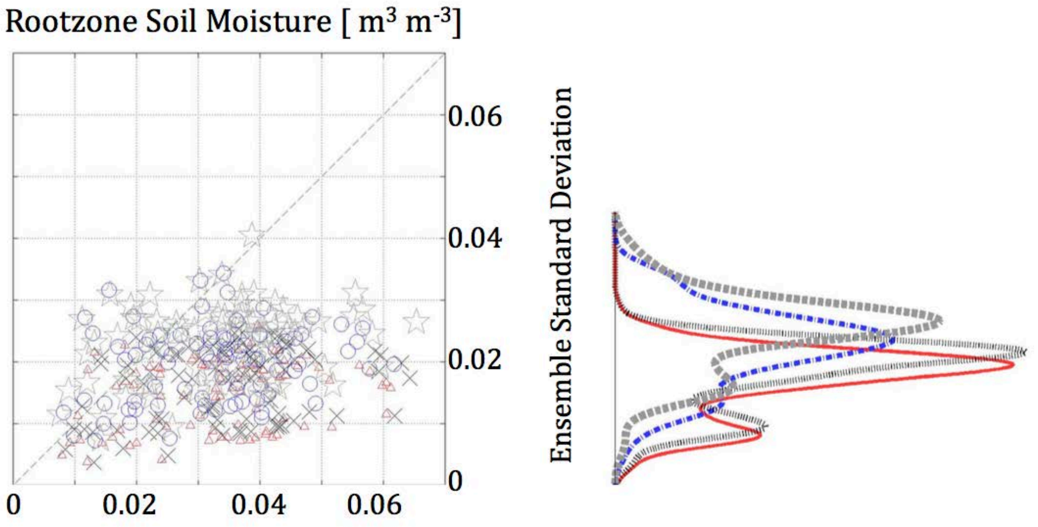
- GRACE-DA & Anthropogenic Hydrological Processes
- Conclusions & Future Directions

# GRACE+SMOS Data Assimilation: Vertical Structure of the Updates



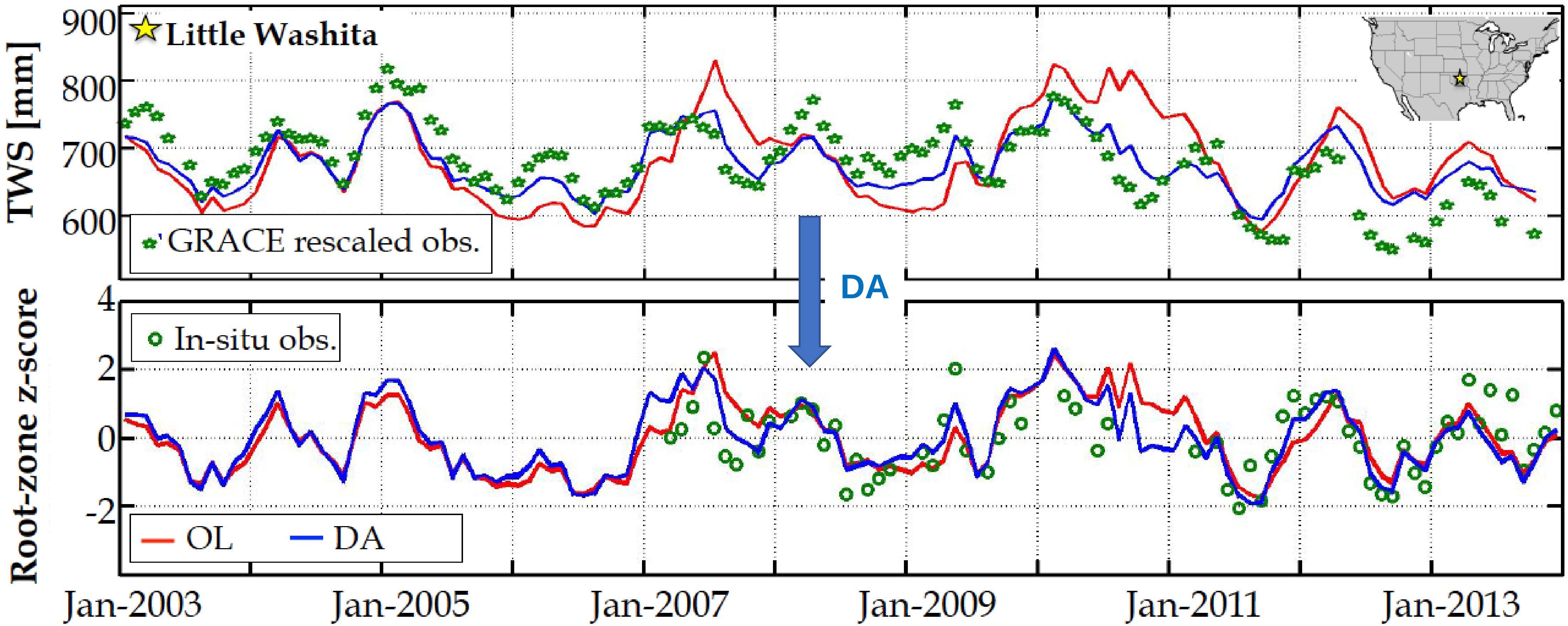

**Grab this from the science snapshot?**
**Key points**



Girotto et al., (in prep.)

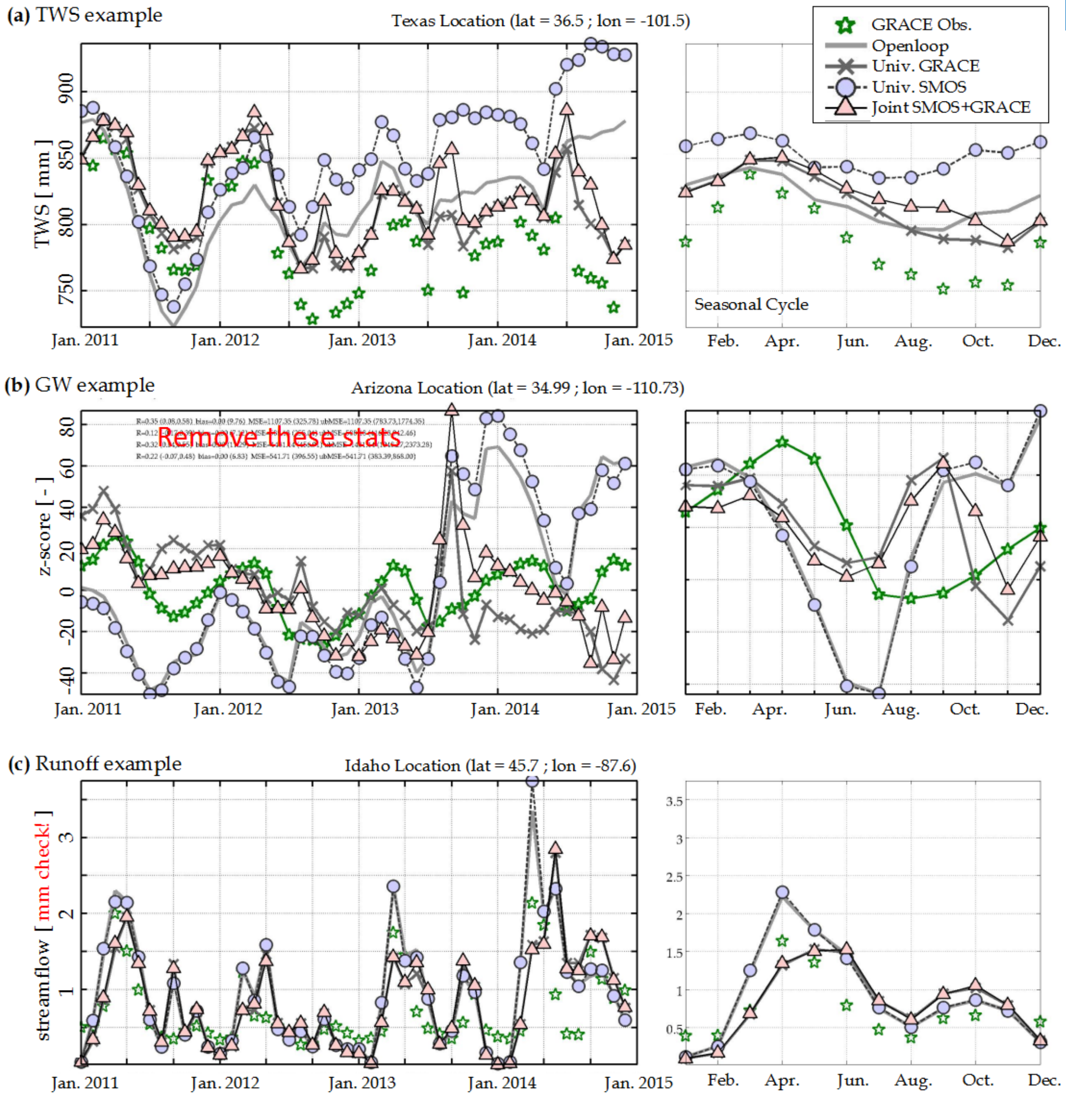
# GRACE DA: Vertical & Spatial downscaling

## Impact of TWS to the single storages (e.g., rootzone soil moisture)




- Data Assimilation is better than Open Loop (model only) at this location

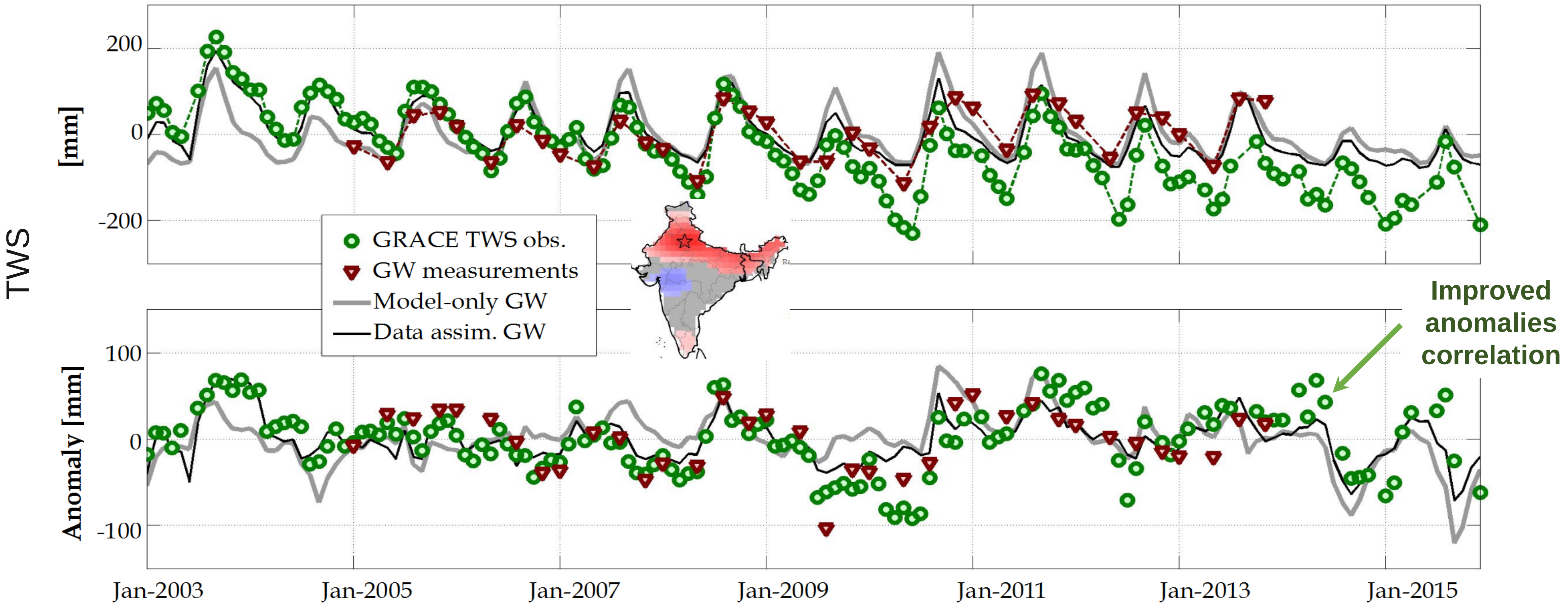
# GRACE+SMOS Data Assimilation: Validation






Girotto et al., (in prep.)

# GRACE Data Assimilation: Trends and Anomalies in TWS




- GRACE DA fails to adjust for dry conditions [2011-2016] → **known (model) depth to bedrock issue**!
- **Improved anomalies agreement between assimilation and observed TWS (and GW)**