Benefits and Pitfalls of GRACE Terrestrial Water Storage Data Assimilation

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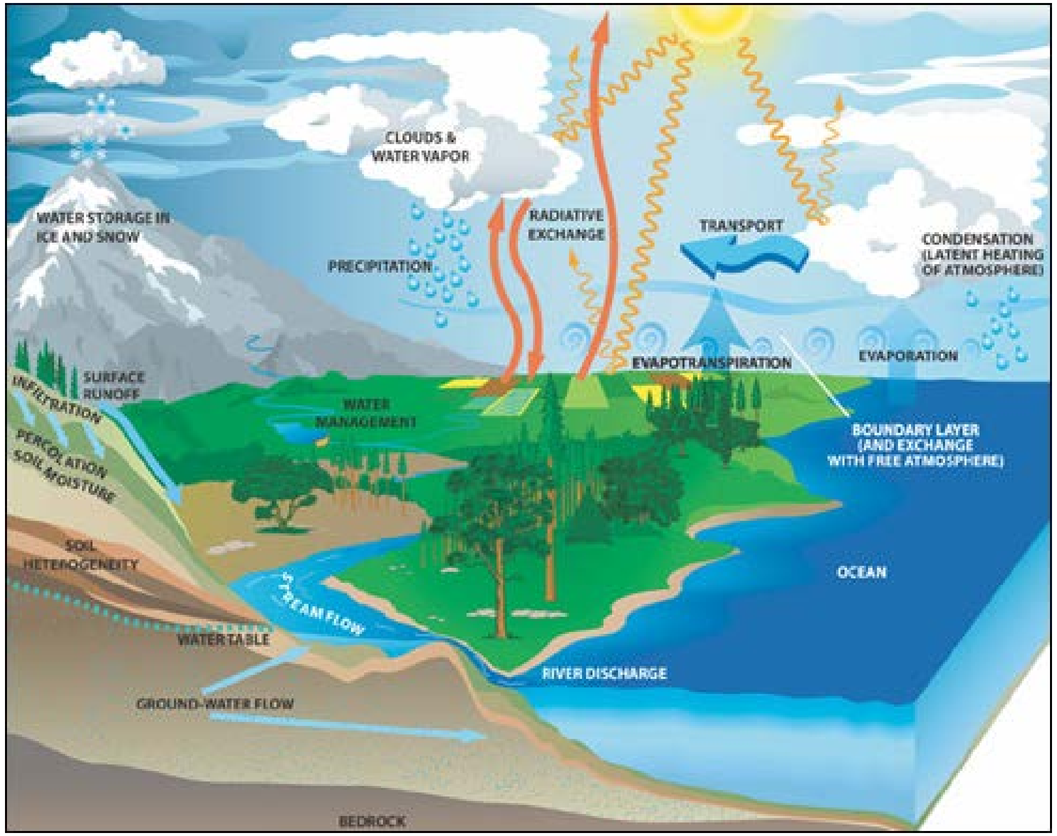
Outline

- Introduction & Motivations
- Downscaling GRACE Observations (GRACE-DA)
- GRACE-DA & Anthropogenic Hydrological Processes
- Conclusions & Future Directions

Importance of Soil Moisture and Groundwater



- Weather and climate dynamics
- Drought/Flood characterization
- Economic Impacts

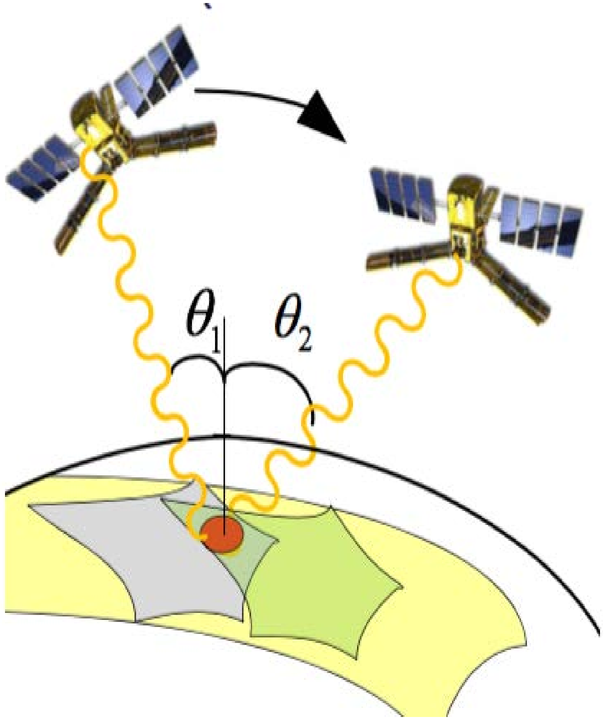
RESERVOIR	VOLUME (KM³)	RESIDENCE TIME
Oceans	1,322,000,000	2500 years
Ice caps & glaciers	29,199,700	-
Groundwater (near-surface)	4,171,400	8 years
Lakes & Rivers	130,700	88 days
Soil Moisture	66,700	47 days
Atmosphere	12,900	9 days

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 depends on soil moisture
- Frequent observations

(**1 observations every 2-3 days**)

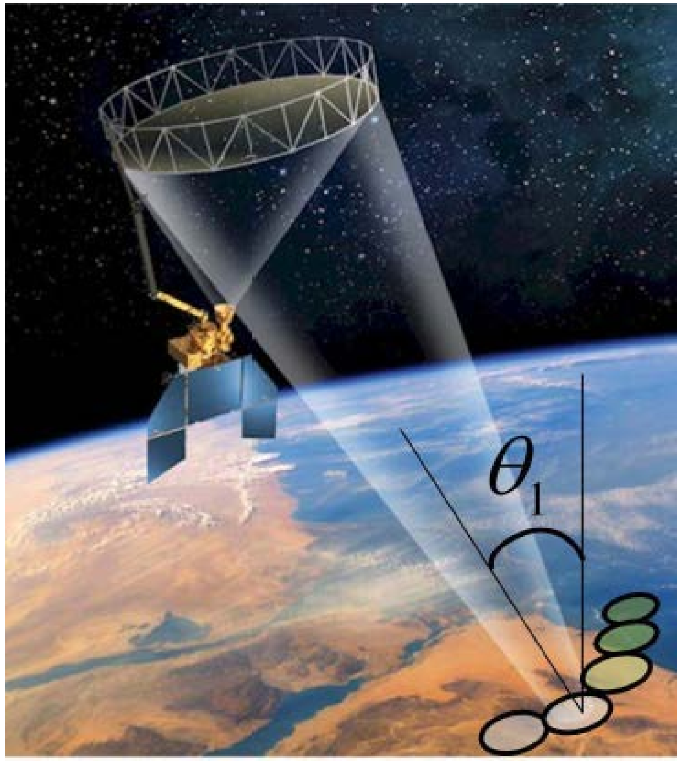
- Good horizontal resolution (**40km**)

Disadvantages:

- Only sensitive to soil moisture of **surface** layer

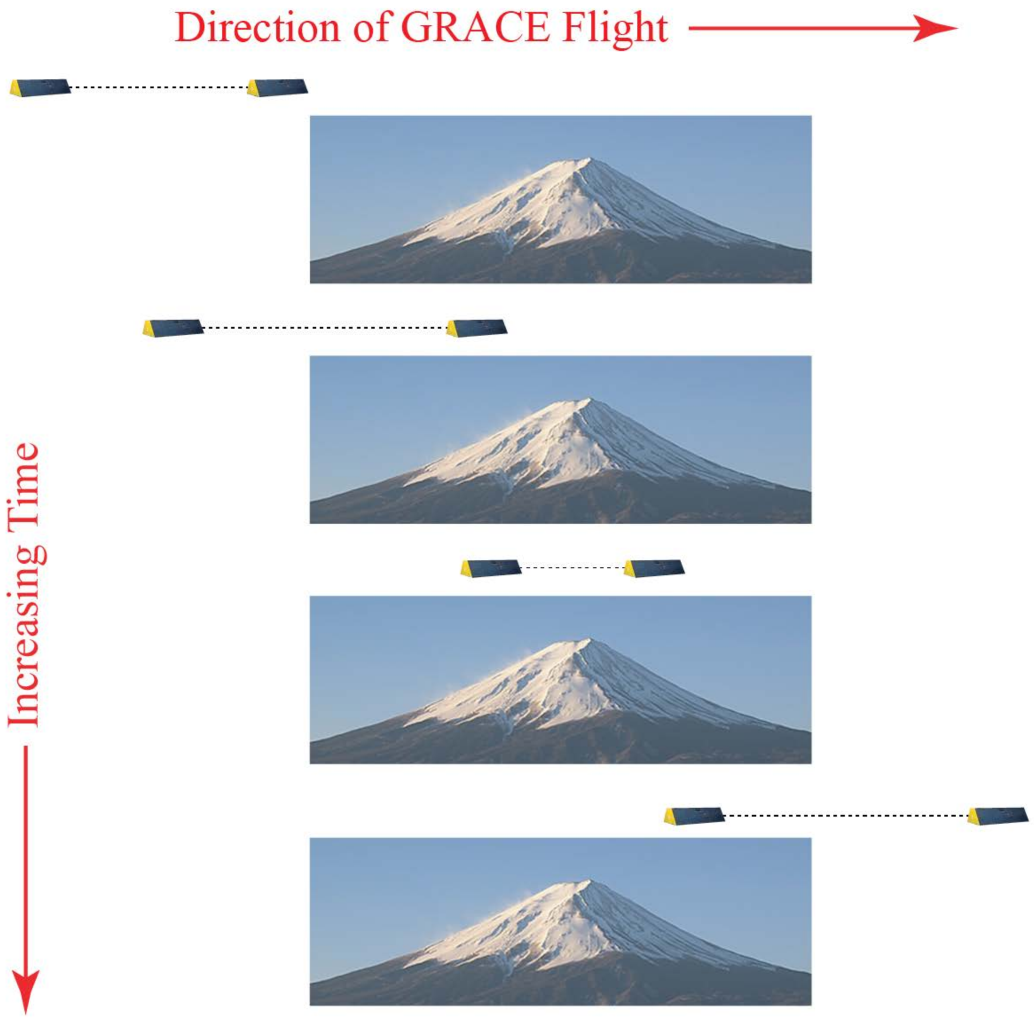
What about rootzone and groundwater?

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

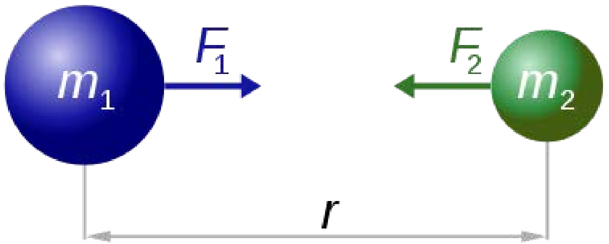


- ➢ L-band (active)/passive
- ➢ Launch: 31 Jan 2015
- ➢ (3)-40 km resolution

Groundwater from Space: GRACE?



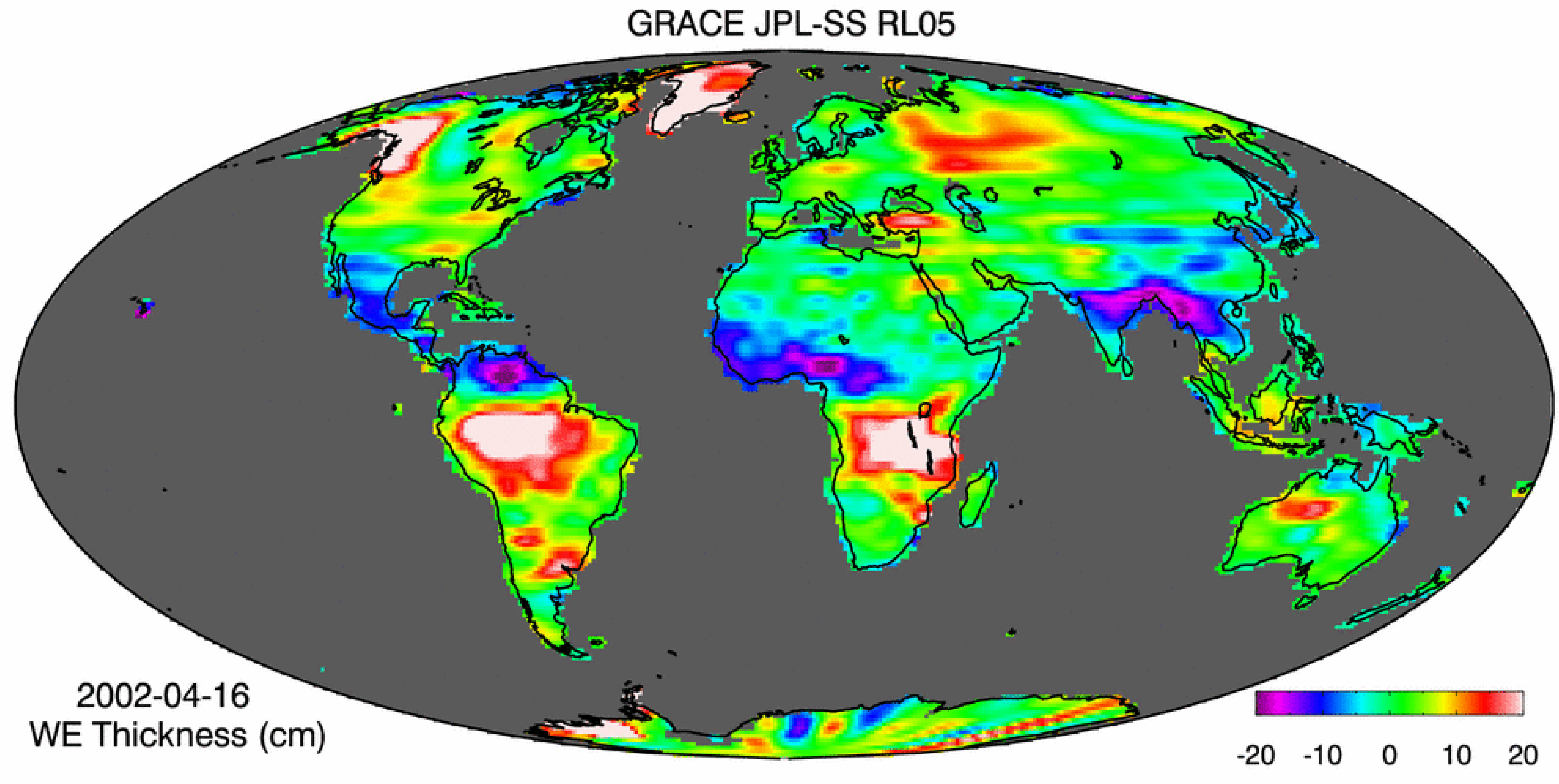
GRACE = Gravity Recovery and Climate Experiment



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

- 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!

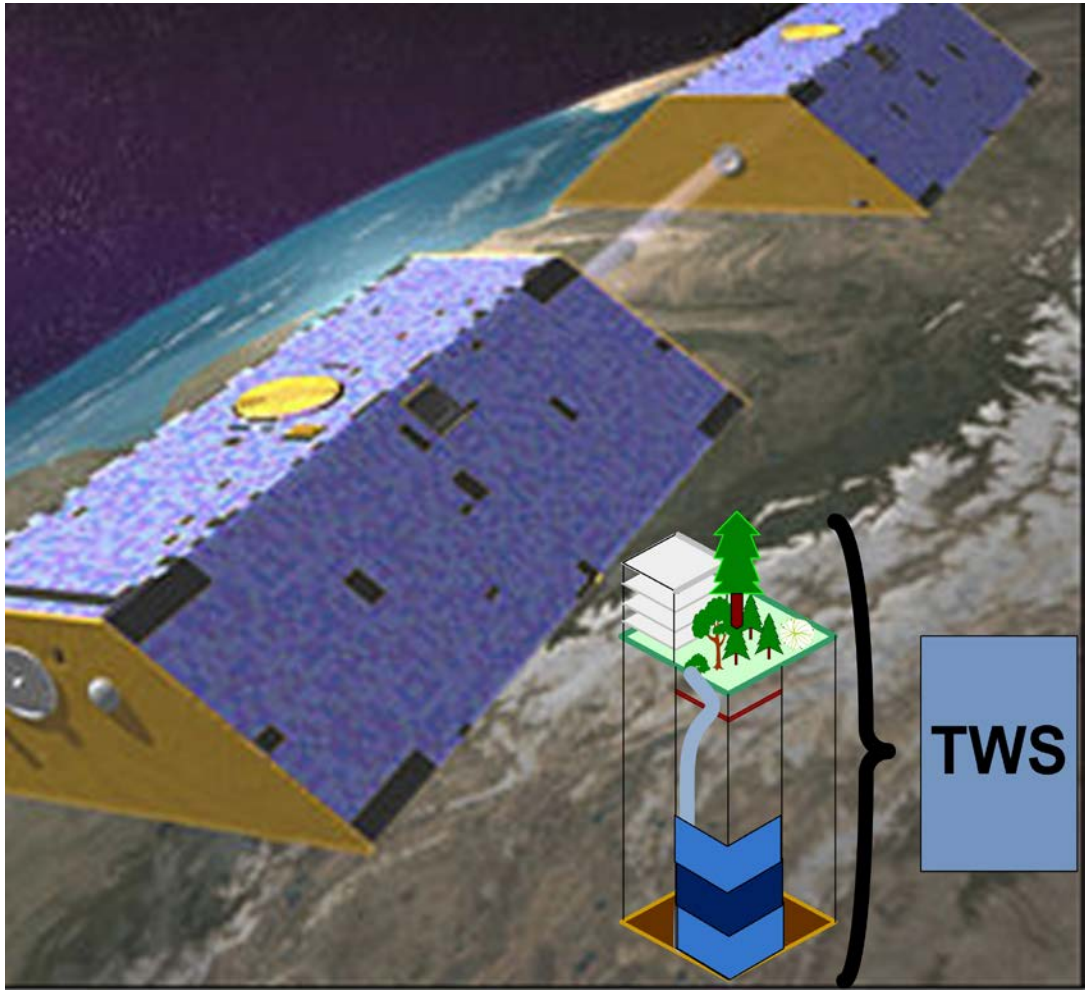
Groundwater from Space: GRACE?



- 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:

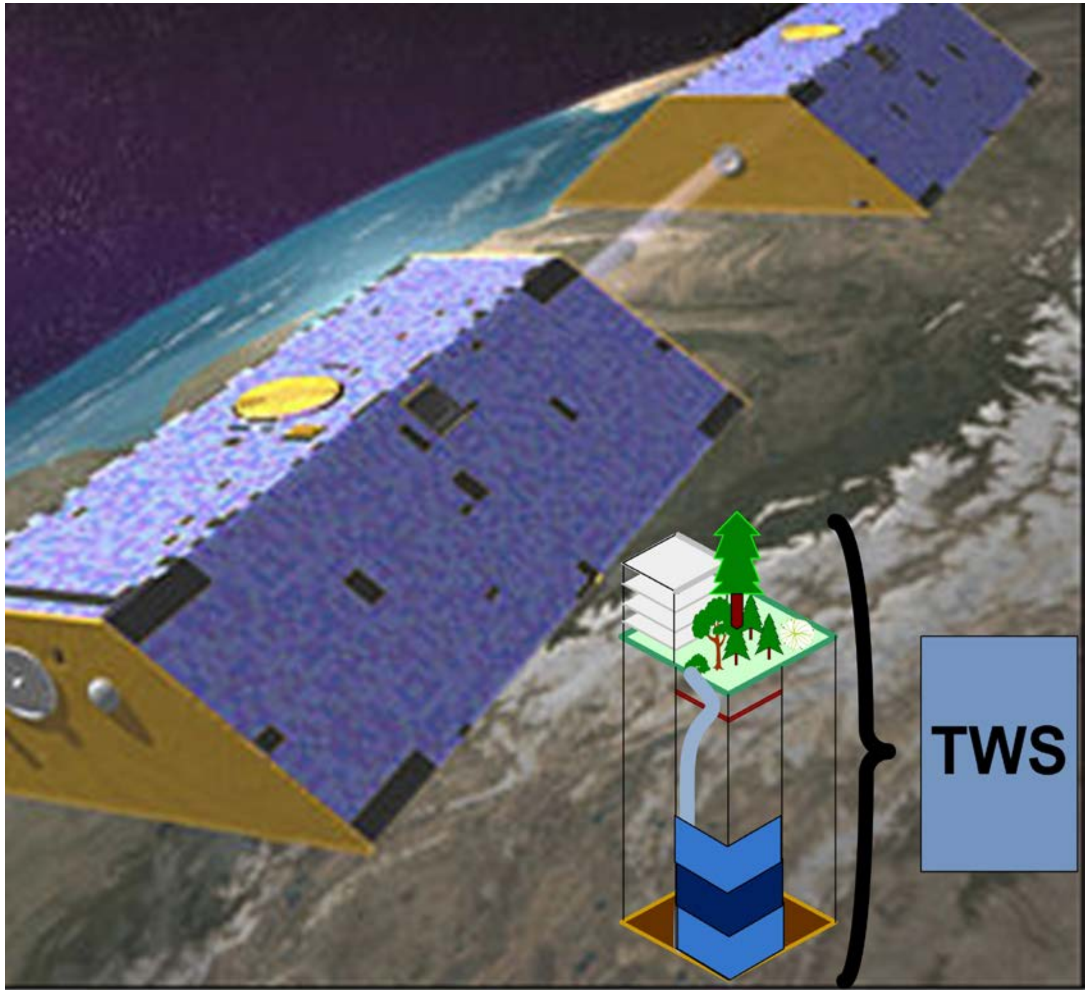
- Unique Mission: can see beyond the surface

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

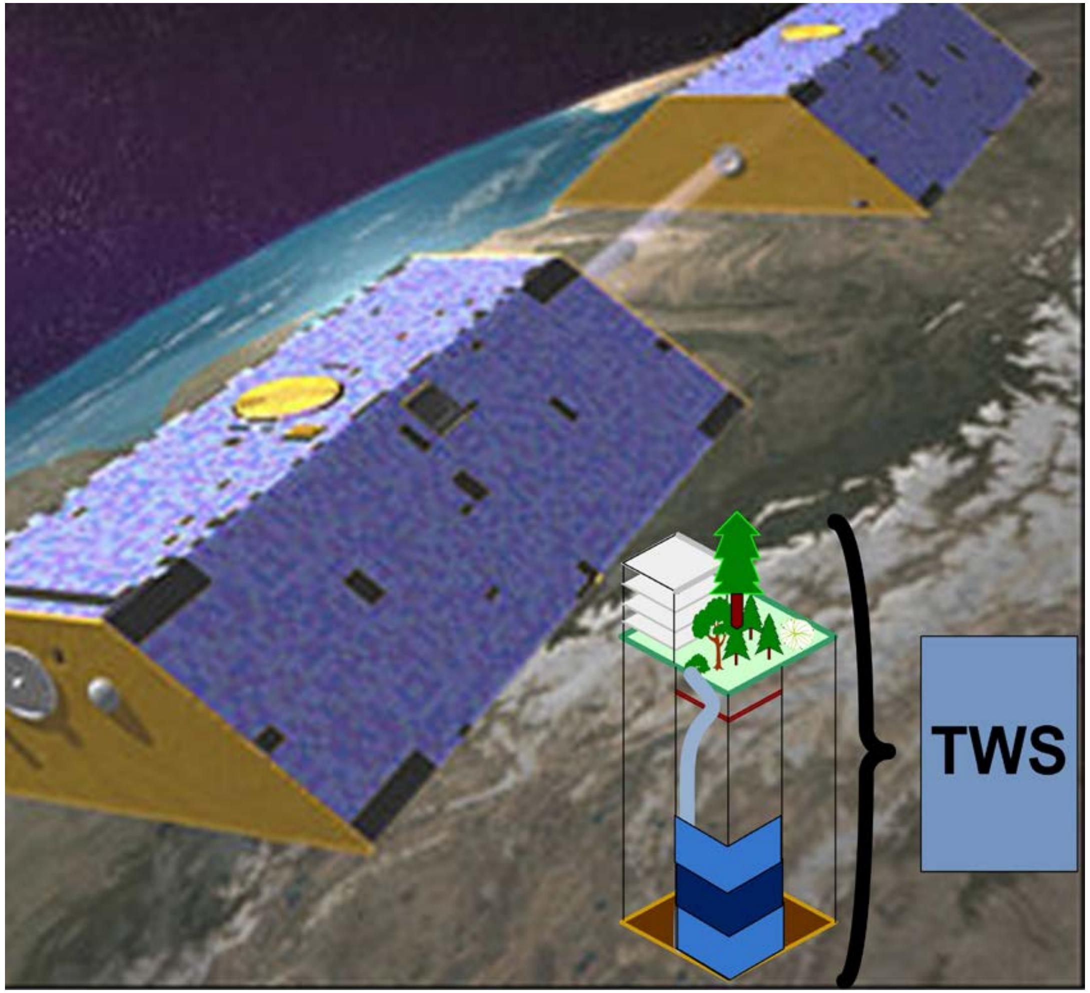
Scales used for global mass balances

?

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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GRACE data assimilation (DA) as a downscaling approach

Catchment Land Surface Model (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**)

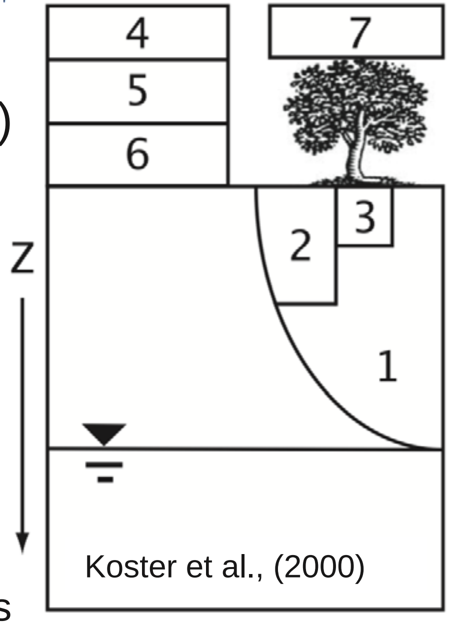
[2] rzexc

[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 —DA⟶ **[1], [2], [3], [4-6], [7]**

(Coarse scales) (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)

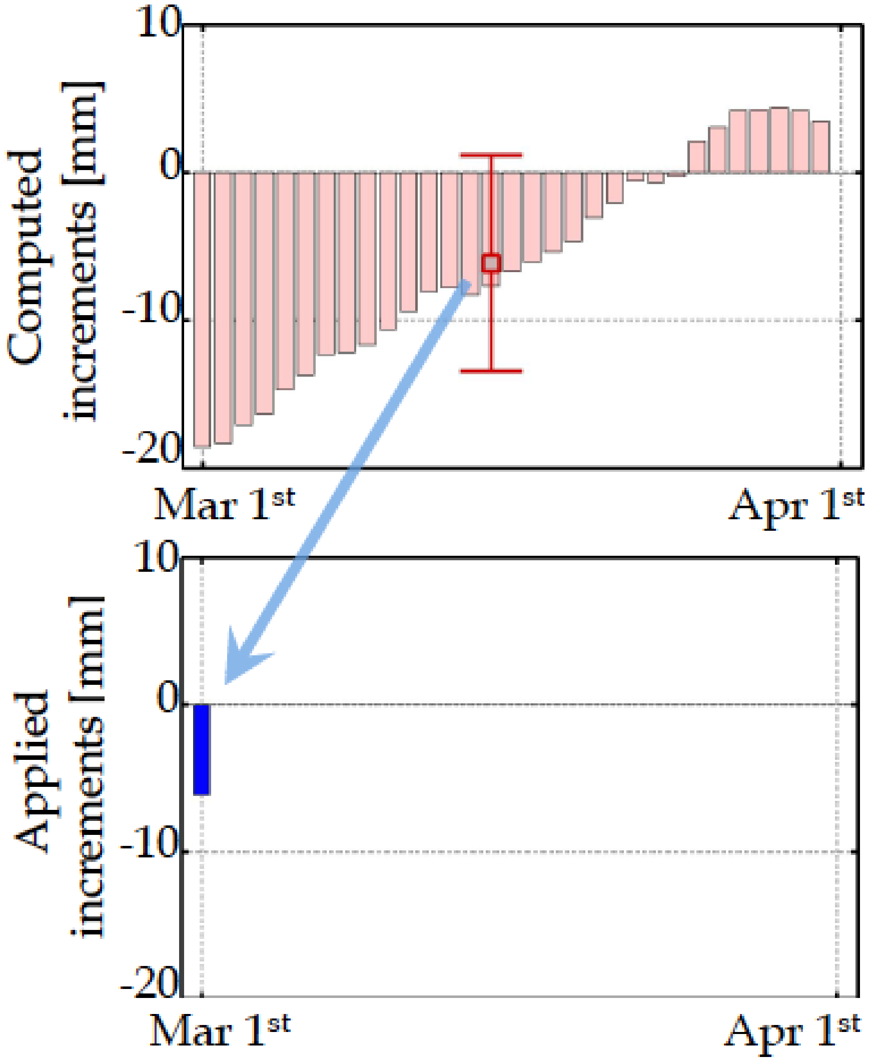
[3] Calculate the increments via ensemble Kalman filter analysis

[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

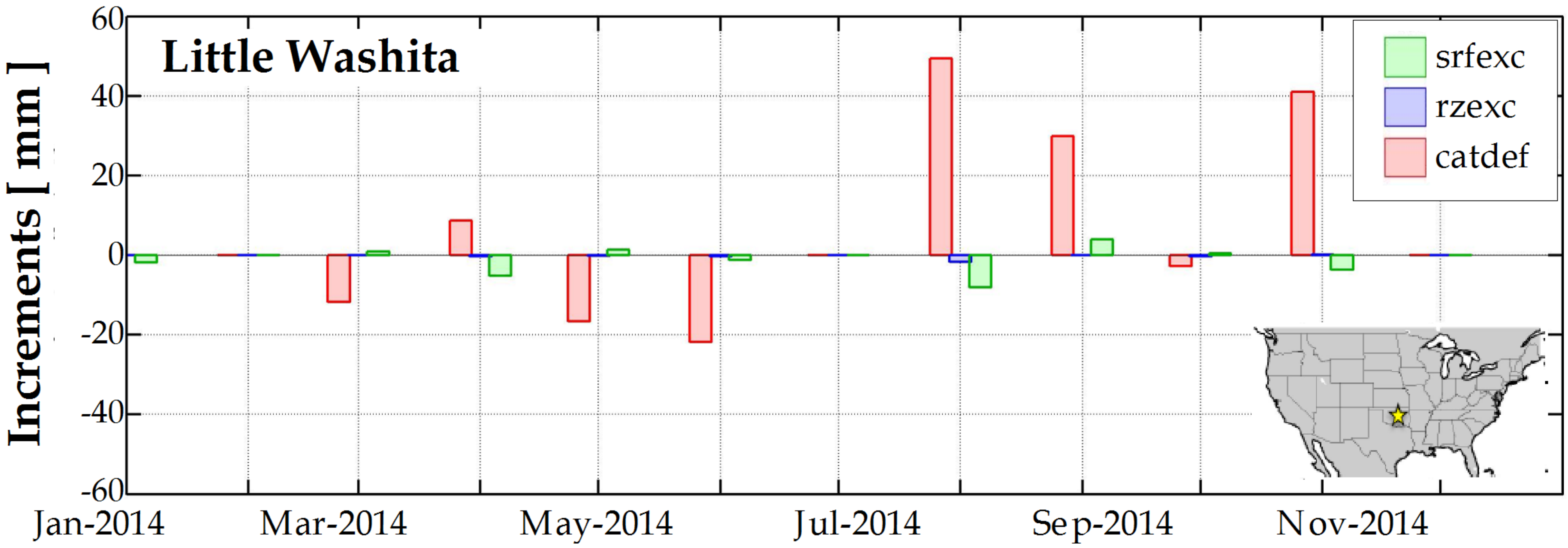
GRACE DA: Temporal Aggregation and Downscaling



- 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]

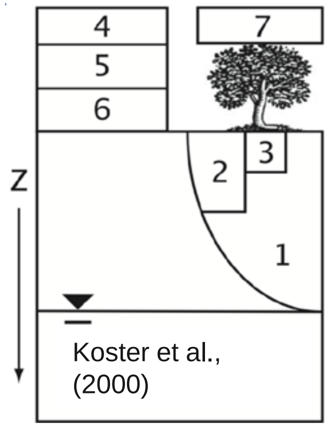
DA should better represent the monthly signature of the assimilated GRACE-TWS observations

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



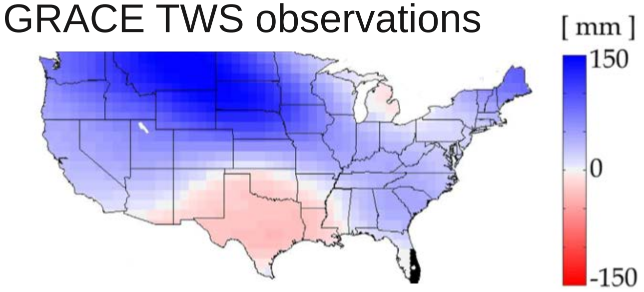
- Catdef dominates profile increments
(i.e., largest GRACE-DA impact in **groundwater**)

GRACE DA: Vertical & Horizontal Downscaling

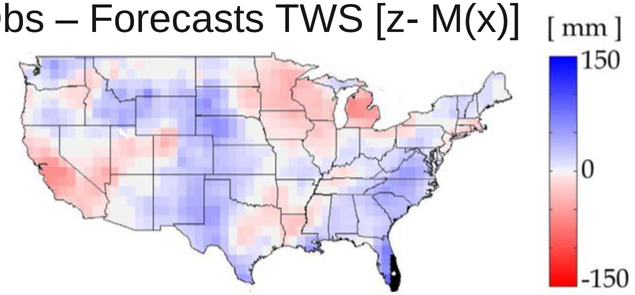
Scales used for global mass balances (~300-400 km)

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

GRACE TWS observations

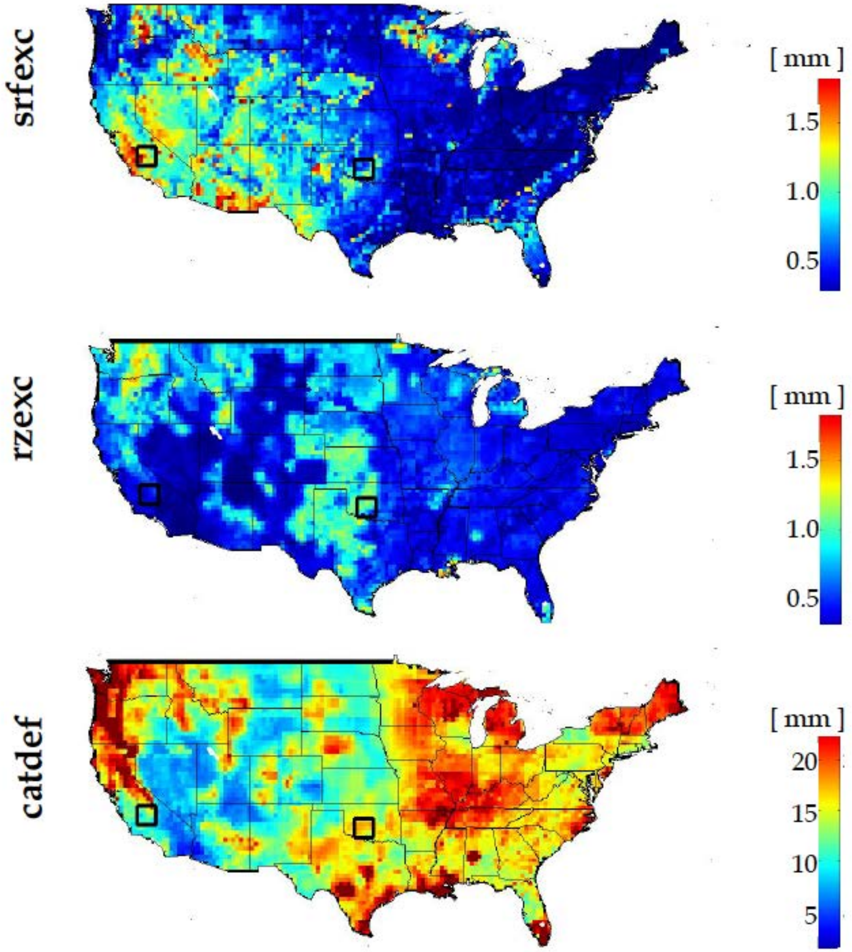


Obs – Forecasts TWS [z- M(x)]



DATA ASSIMILATION

TYPICAL MONTHLY ABSOLUTE INCREMENTS (2003-2015)



- **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

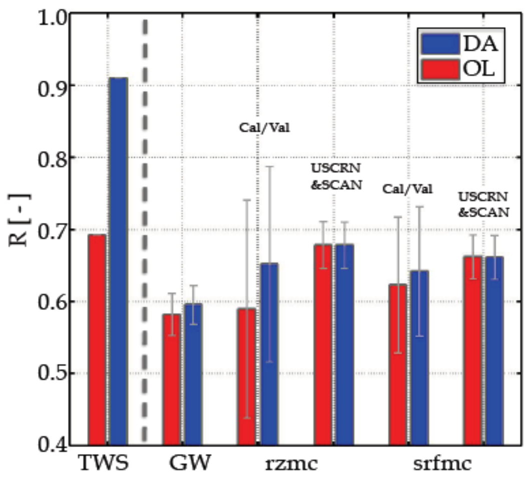
GRACE Data Assimilation: Validation

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

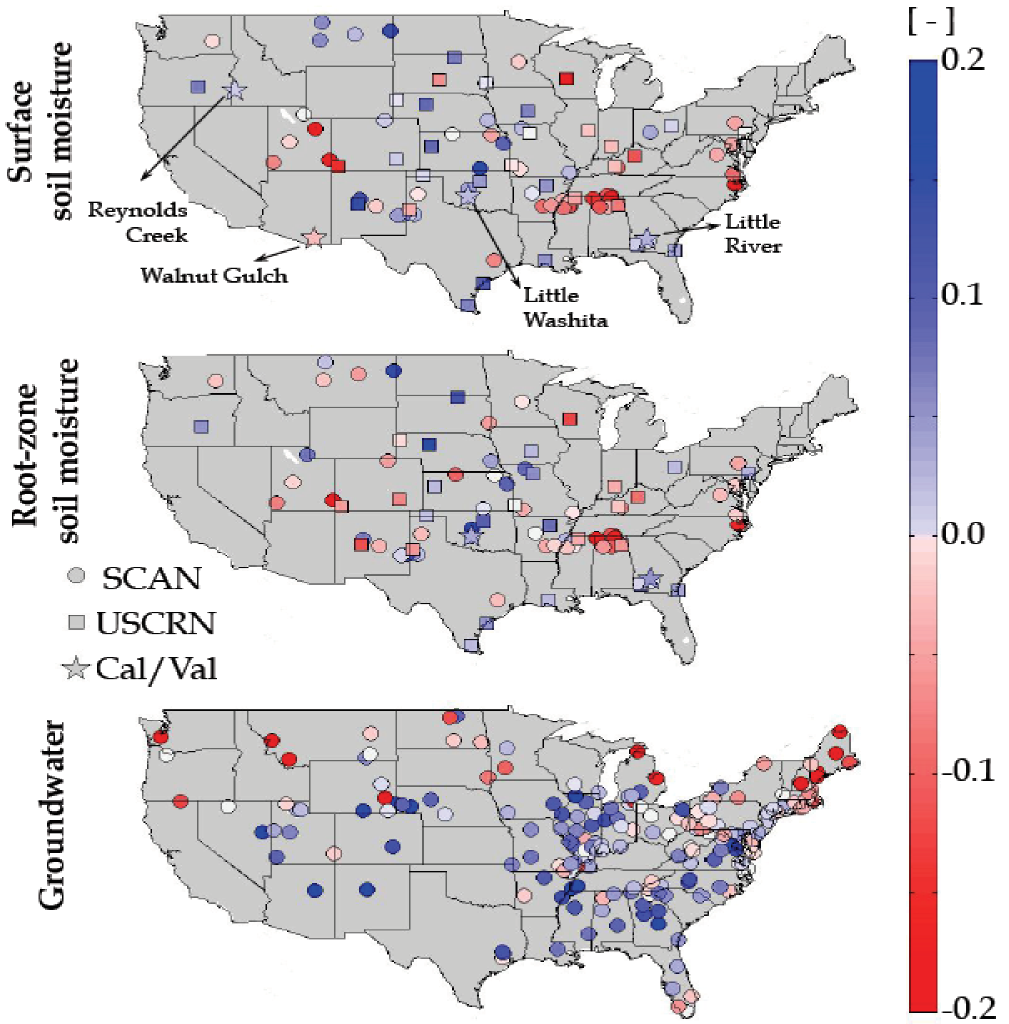
Groundwater:
- 136 USGS (Unconfined aquifer only)

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

Bulk Statistics



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



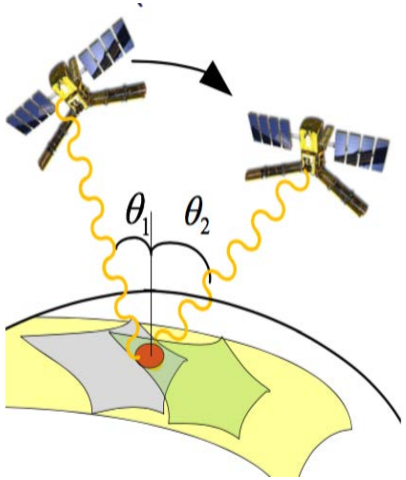
GRACE-DA

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

→ Add soil moisture (SMOS/SMAP)?

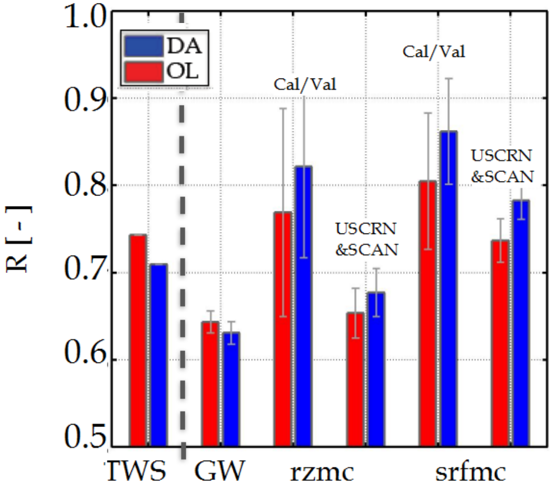
SMOS(SMAP) to help with surface soil moisture?

Soil Moisture and Ocean Salinity (SMOS) Mission DA



*Same algorithm as of SMAP L4_SM

Bulk Statistics



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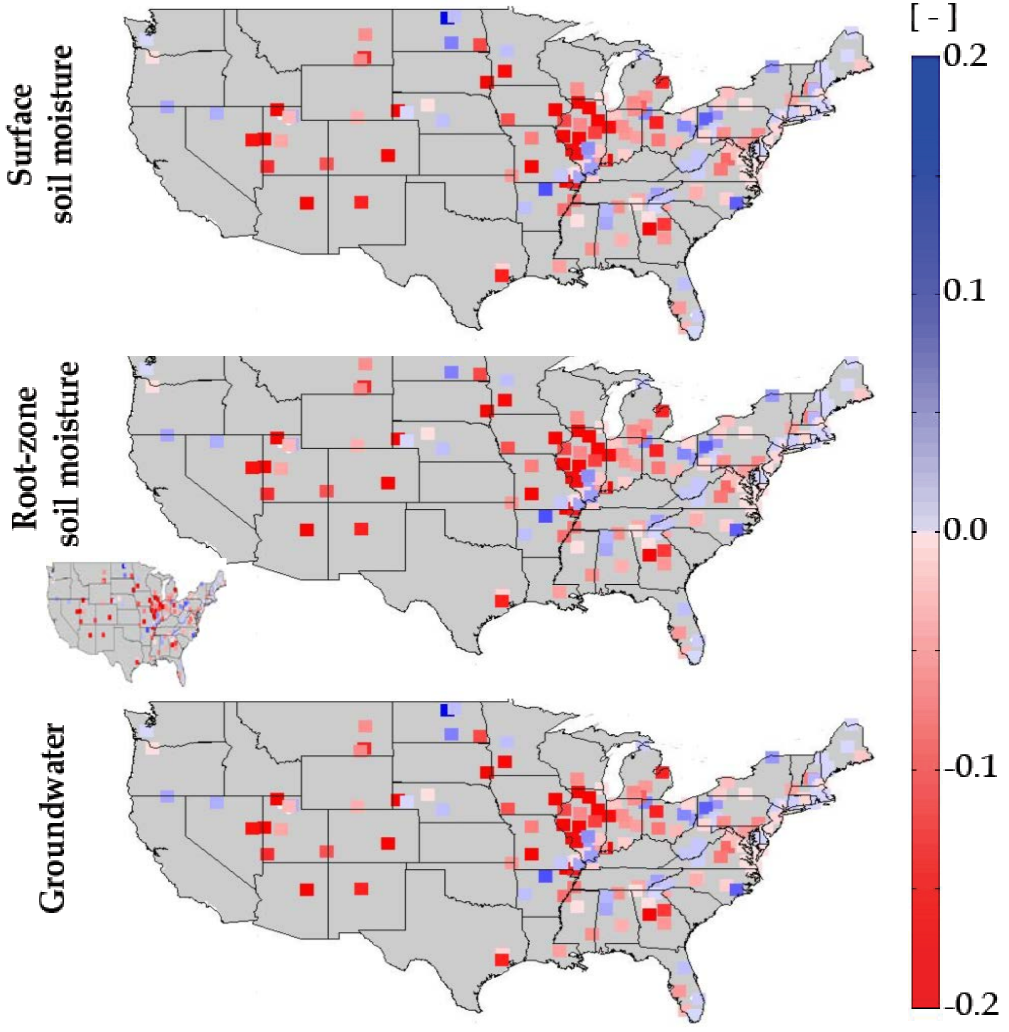


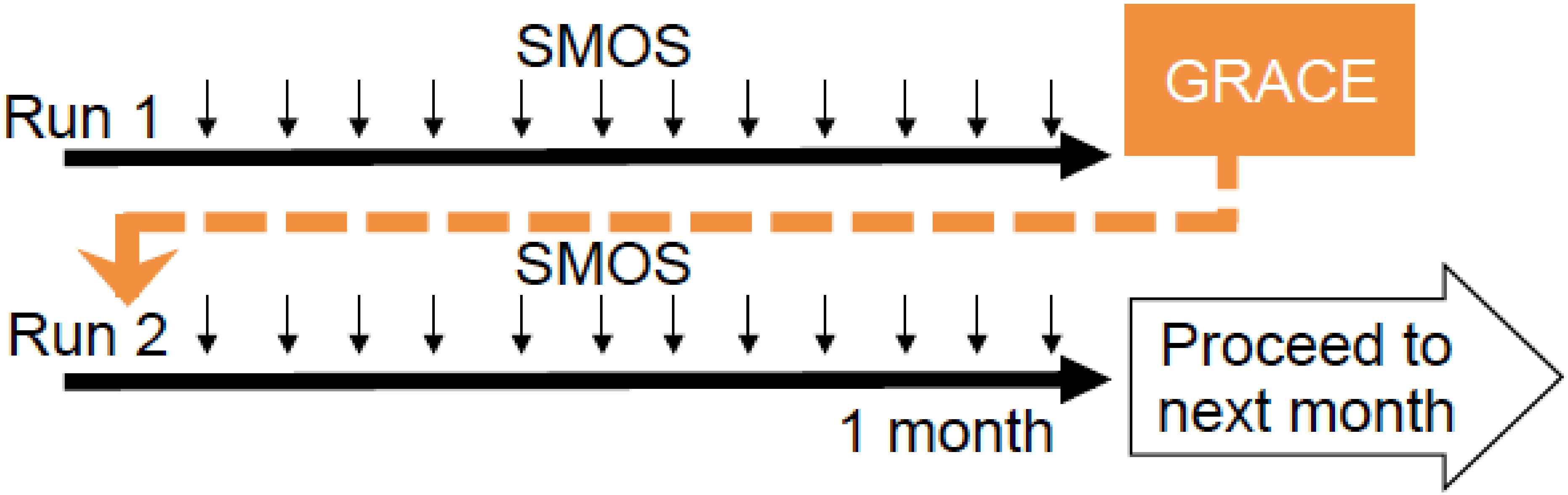
SMOS-DA

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

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

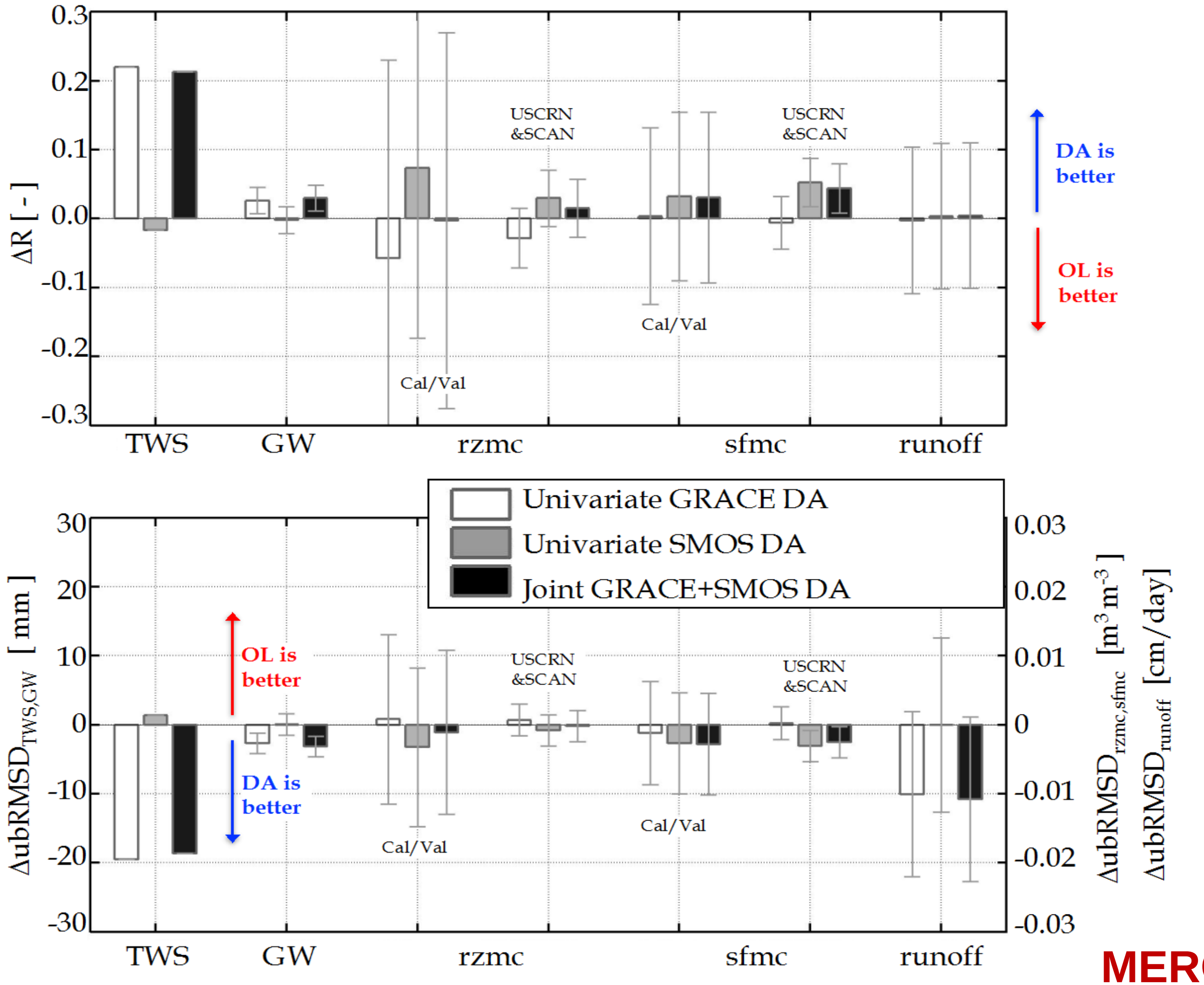
GRACE+SMOS Data Assimilation: Method

What if we incorporate both GRACE+SMOS observations together?



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.)

Downscaling: Benefits & Remaining Challenges

Scales used for global mass balances

DATA ASSIMILATION

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

Scales that are more useful for hydrological applications

- Challenge to run a joint assimilation with GRACE and SMOS(SMAP) observations because of their very different spatial/temporal resolution!

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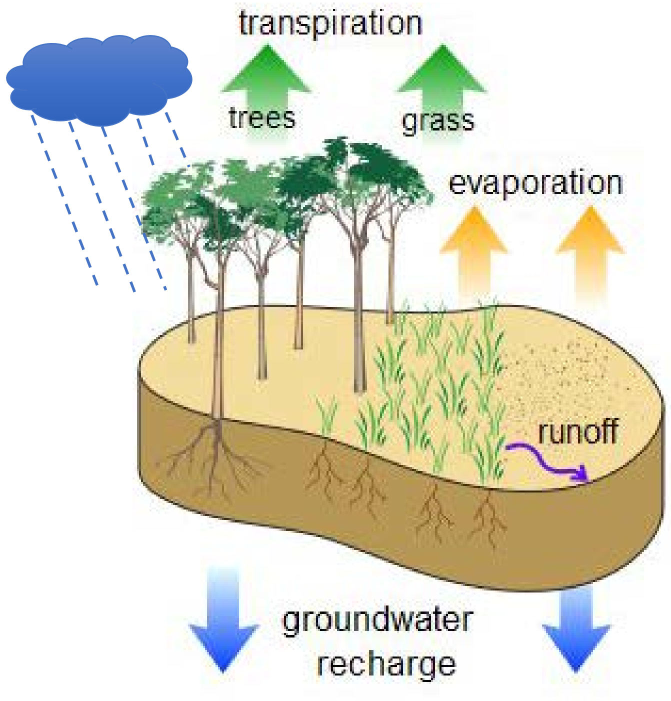
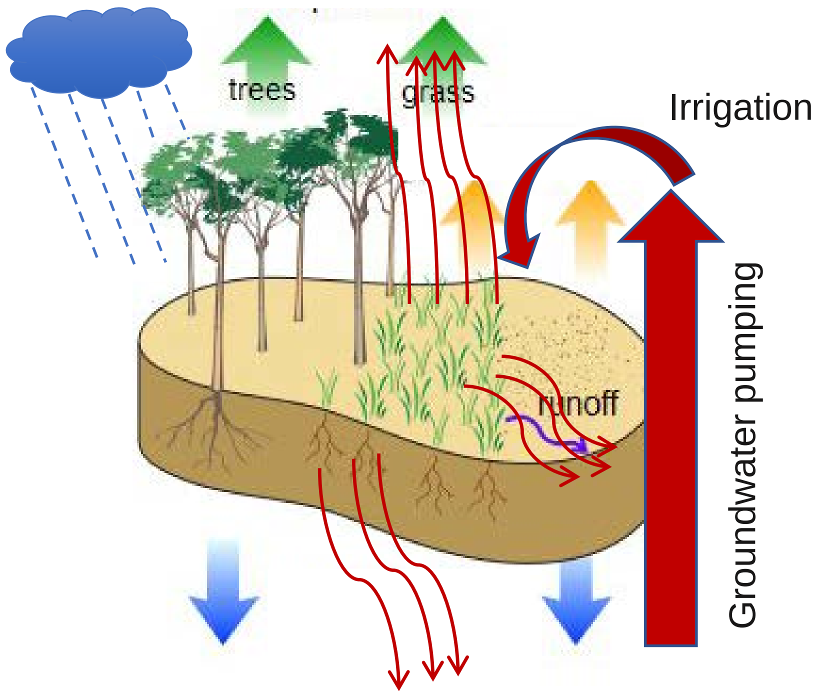
GRACE DA: The Role of Anthropogenic Processes

Natural Processes



Anthropogenic Processes



- Satellite observations monitor the hydrological cycle in its entirety

→ i.e., do not know if human or natural

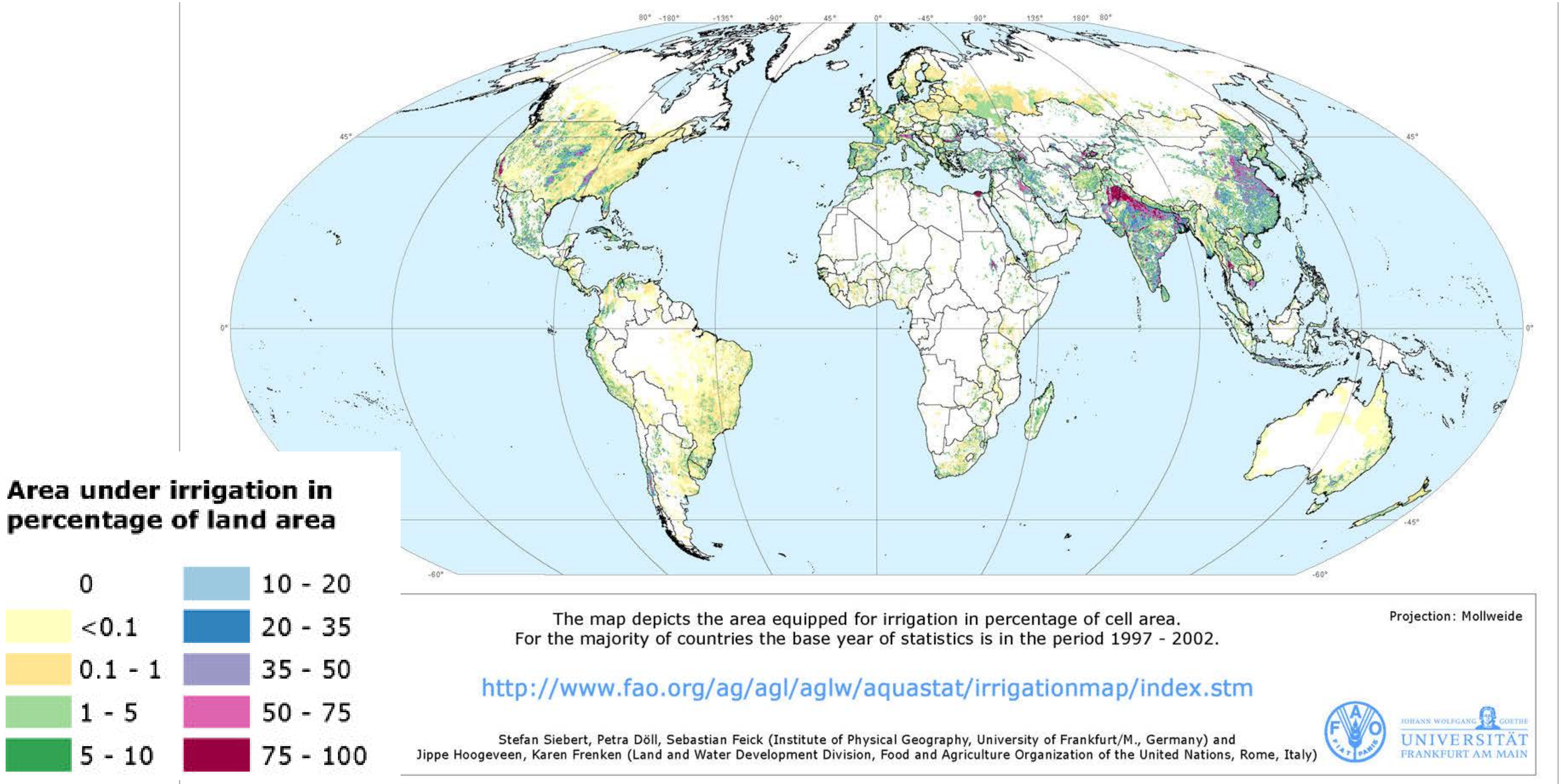
Can GRACE-DA improve models in the presence of human processes?

Included in most global land surface models

Excluded by most global land surface models

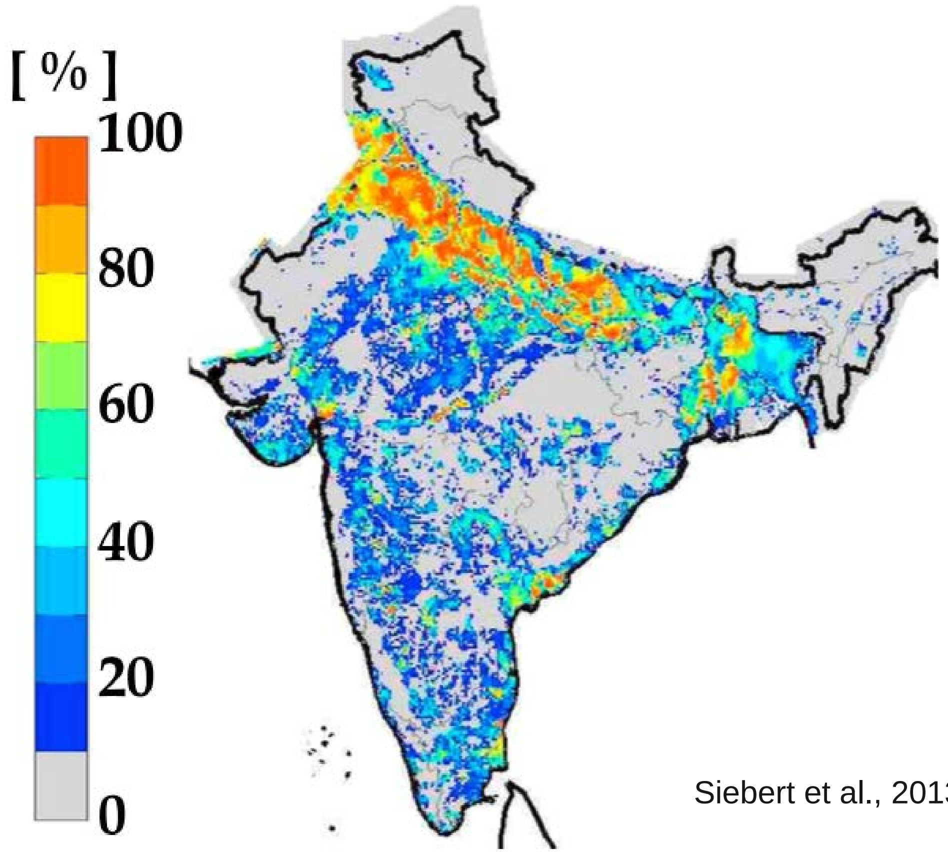
(They influence dynamics of hydrological processes)

Global Map of Irrigated Areas



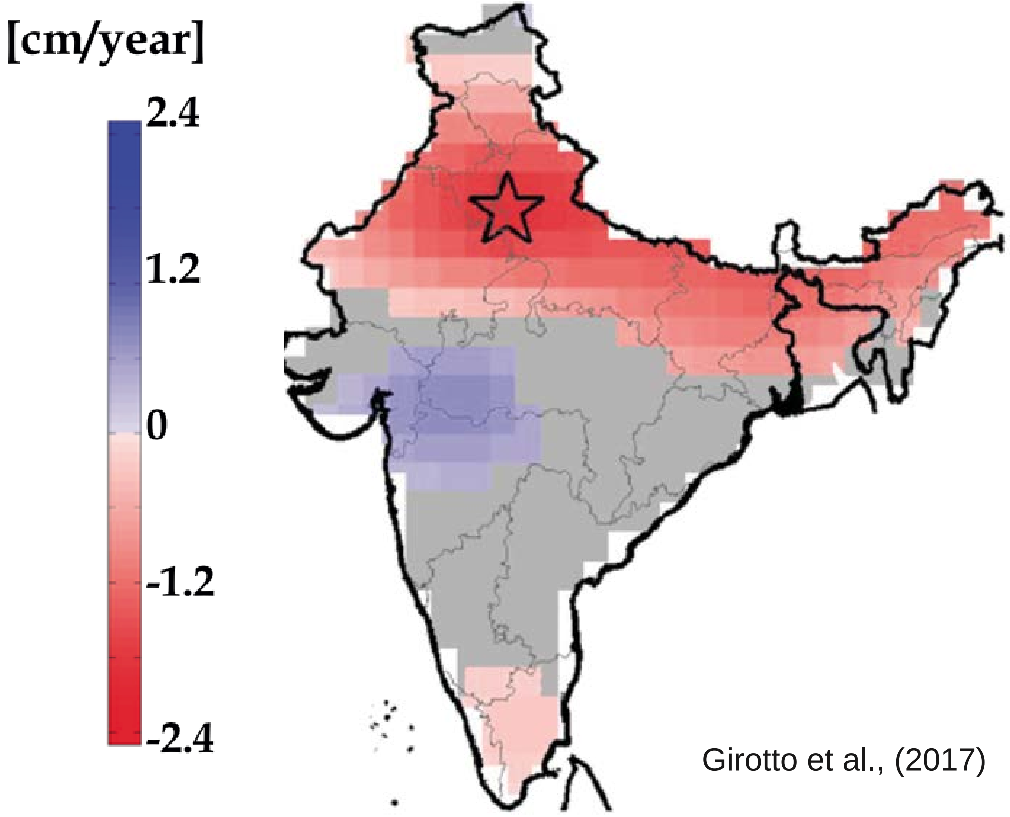
GRACE DA: Trends in the Assimilated Observations

Percentage of area equipped for irrigation



Siebert et al., 2013

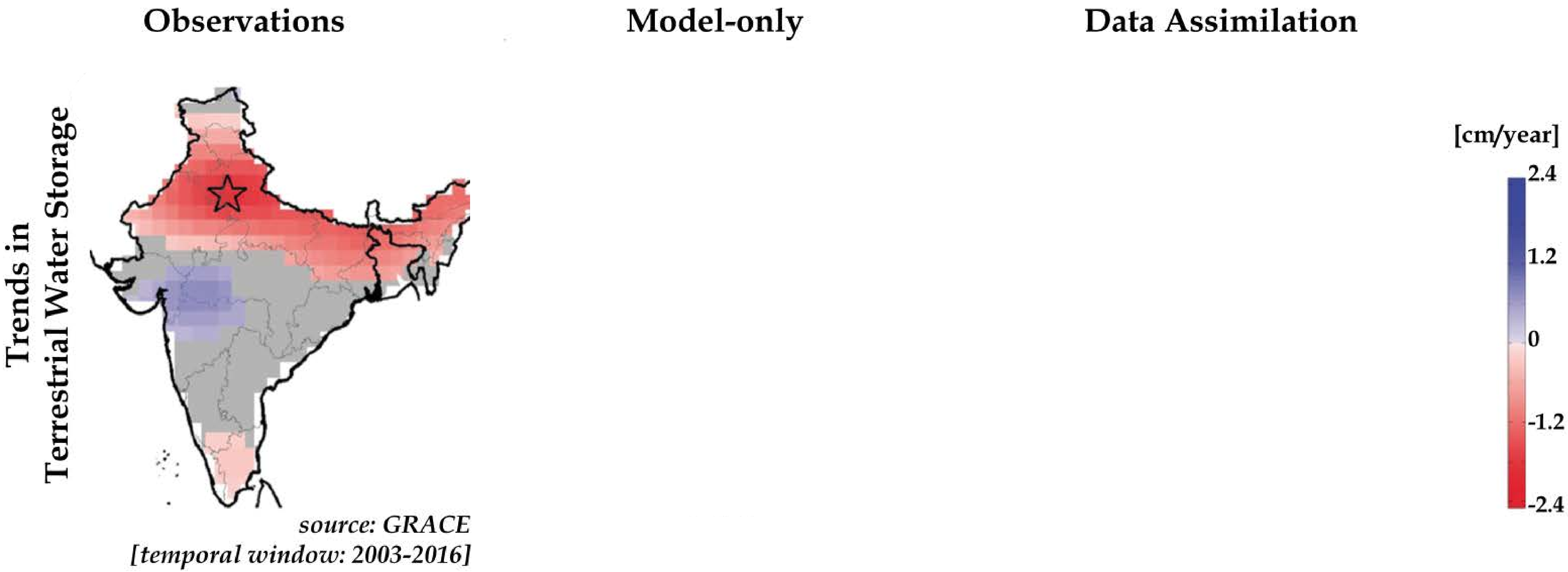
Trends in Terrestrial Water Storage (TWS) [2003-2016]



Girotto et al., (2017)

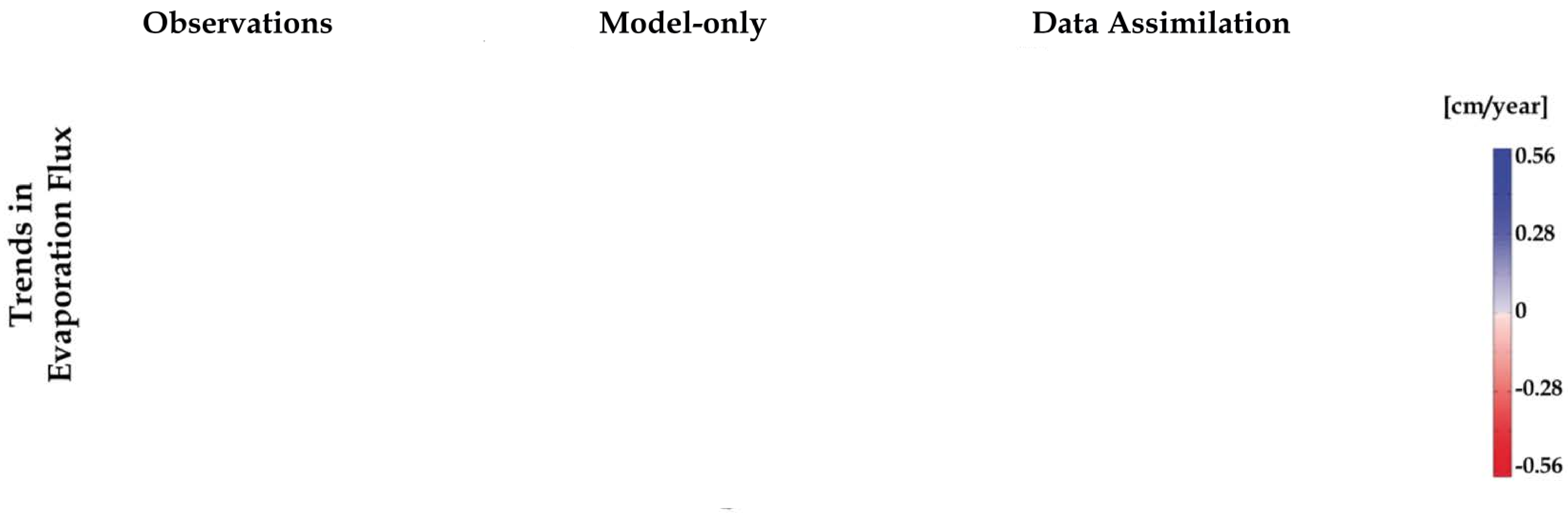
GRACE observations of TWS show trends likely associated with groundwater extraction

GRACE DA: Trends in TWS



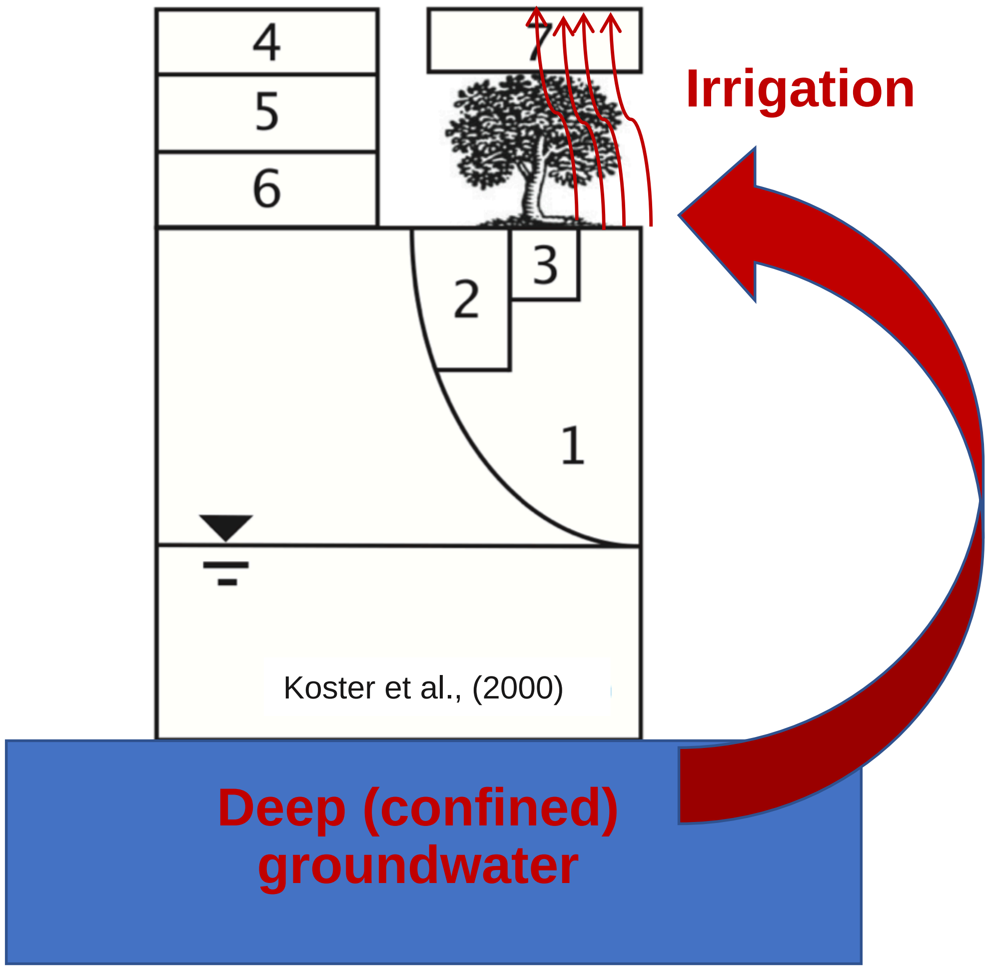
- Model only [no assimilation] does not reproduce TWS trends
- GRACE DA corrects TWS for the observed trends

GRACE DA: Trends in Evapotranspiration



- Model only & referenced ET no significant trends in evapotranspiration (ET)
- GRACE DA adds trends in evapotranspiration ← groundwater deficit induced by the assimilation
- **But, irrigation likely sustains root-zone moisture and should allow ET to continue steadily!**

GRACE Data Assimilation: Evapotranspiration



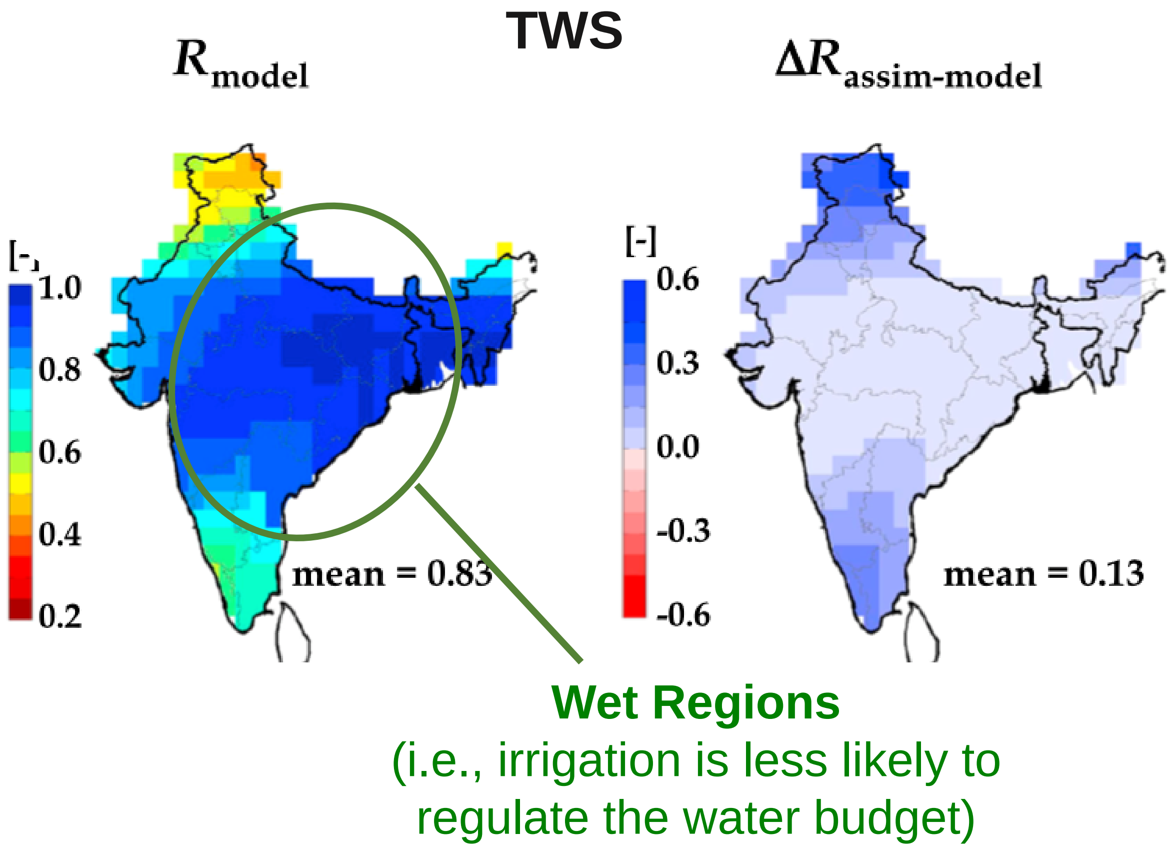
- GRACE DA vertical partitioning is based upon the physics of the model
- The model does not represent the right physics (i.e., does not include irrigation & pumping)
- GRACE DA causes degradation of some hydrological states and fluxes

Land surface model (& assimilation) communities should better represent human driven processes!

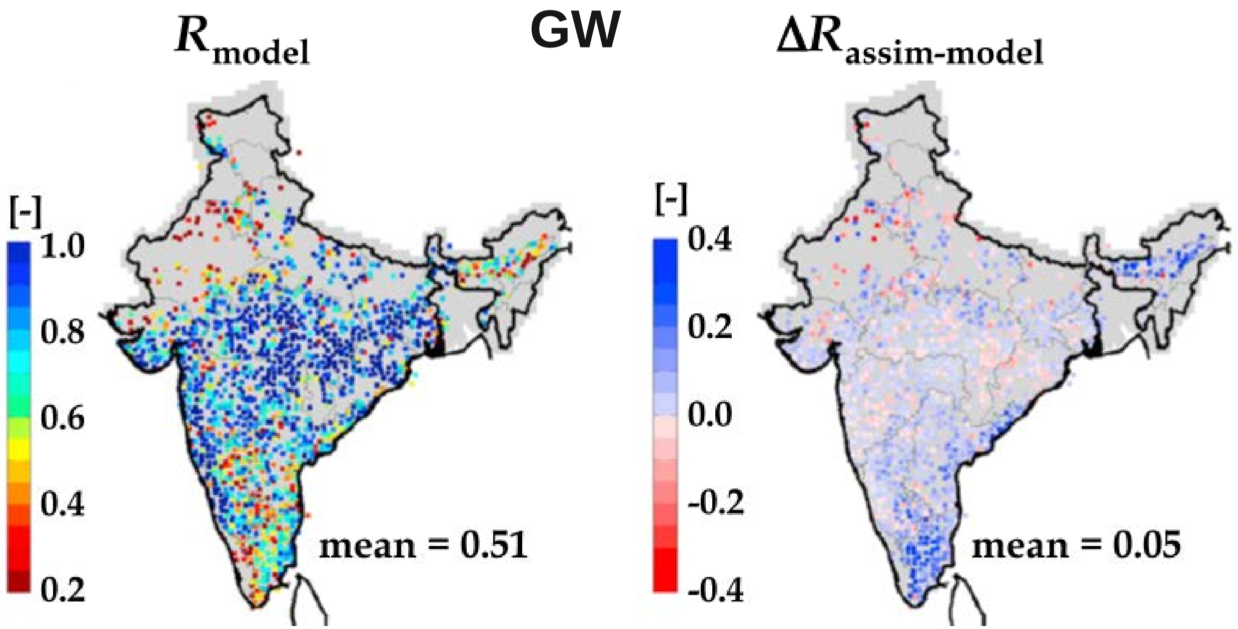
What about seasonal and interannual scale dynamics?

GRACE Data Assimilation: TWS & GW Verification

SKILLS INCLUDING SEASONAL AND INTERANNUAL VARIABILITY (trend included)



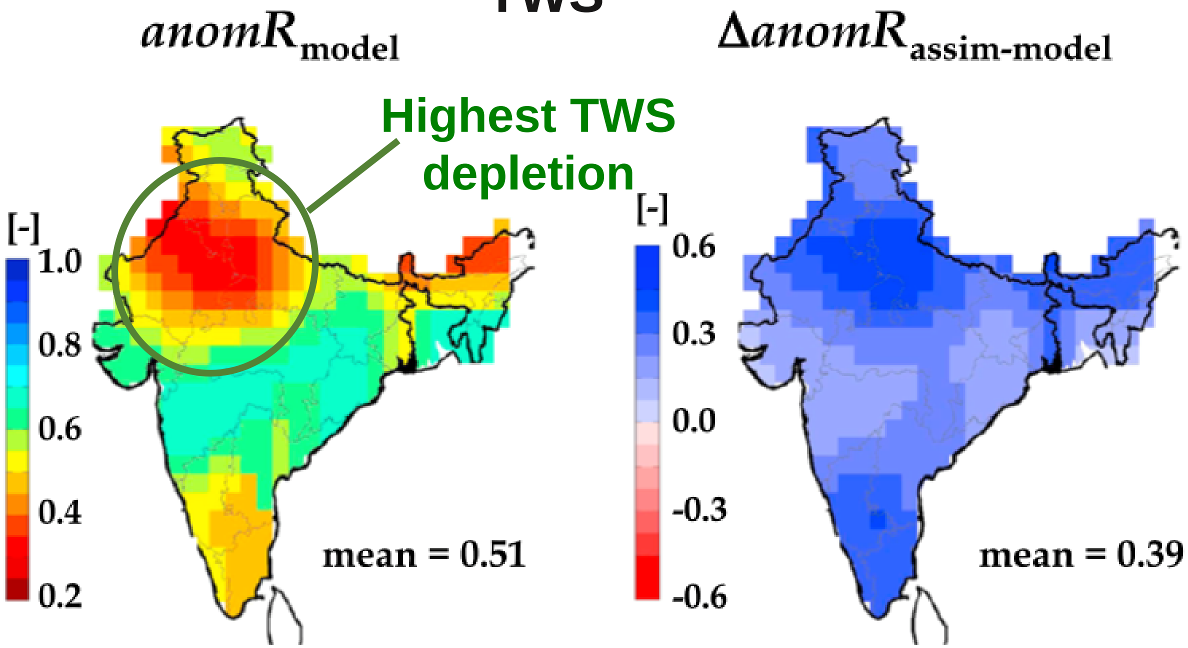
- Higher model skills in wet regions
- Overall DA improved skills
- Some locations have degraded R...



GRACE Data Assimilation: TWS Verification

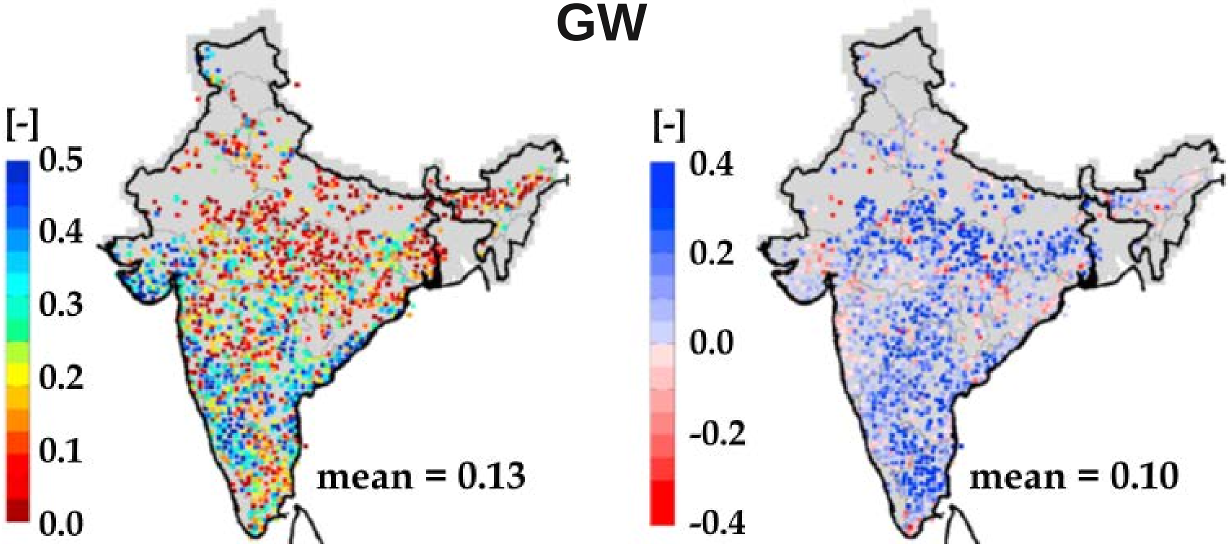
SKILLS INCLUDING INTERANNUAL VARIABILITY (trends and seasonal cycle removed)

TWS



- TWS: Lowest model anomR & larger DA improvements where human processes are intense
- GW: Poor model skills for groundwater interannual variability (lack of irrigation and return flow?)

GW



GRACE-DA can enhance interannual variability even in the presence of human processes

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GRACE Data Assimilation: Benefits and Pitfalls

BENEFITS:

Downscaling:

- 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]

Improvements Upon Model-only:

- GRACE-DA primarily affects groundwater and has smaller impacts on soil moisture.
- GRACE-DA leads to improved groundwater

Anthropogenic Processes:

- GRACE-DA can enhance the interannual variability in the presence of anthropogenic processes

PITFALLS:

Soil Moisture:

- The assimilation of GRACE-TWS leads to marginal/no improvements in soil moisture

→ **SMOS/SMAP missions to the rescue**

- Technical challenges associated with the different spatial/temporal scales of the two observation types

Anthropogenic Processes:

- GRACE-DA introduces unrealistic ET reduction, due to lack of groundwater-fed irrigation modelling

→ **Land surface model (and assimilation community) should better represent anthropogenic processes**

Thanks for your attention!

Benefits and Pitfalls of GRACE Terrestrial Water Storage Data Assimilation

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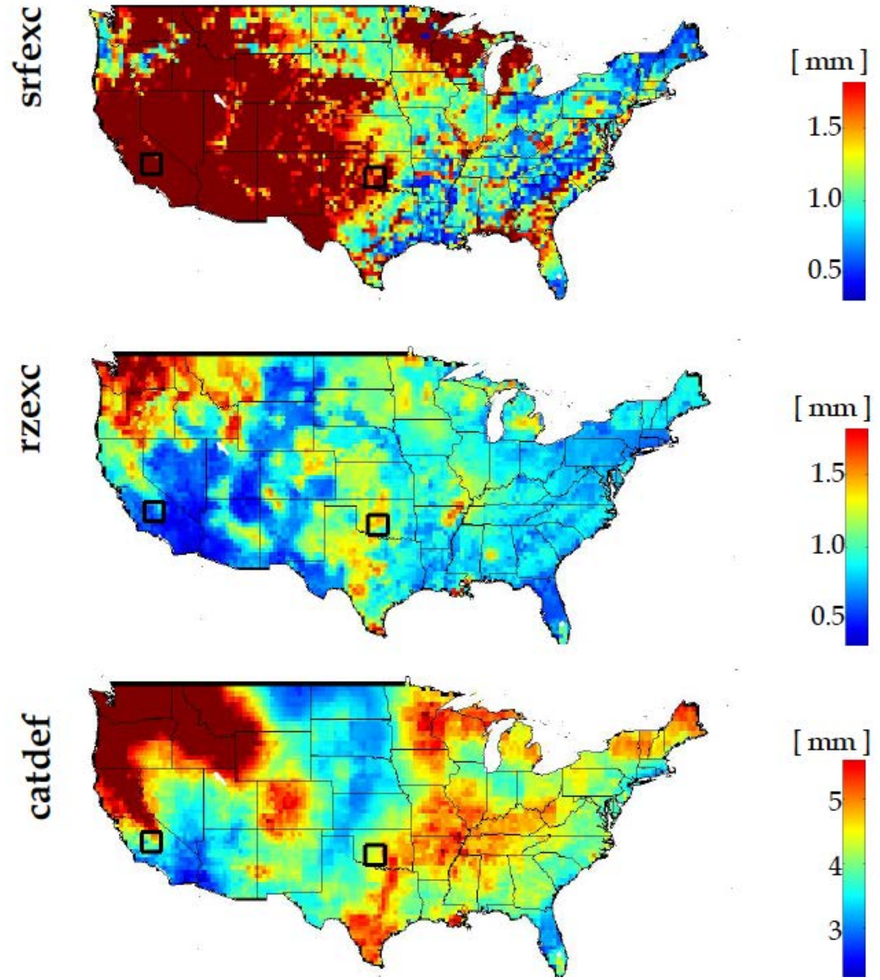
GRACE DA: Temporal Variability of the Increments

STANDARD DEVIATION OF THE DAILY INCREMENTS WITHIN THE MONTH (avg. 2003-2015)



- **High values = daily increments vary greatly within the month**

→ Choosing a single instant to compute increments will be suboptimal

- **Largest variability for srfexc/rzexc**

→ double the magnitude of the increments

- **Smaller variability for catdef**

→ Catdef (groundwater) is a more persistent quantity

GRACE-DA largest effect in the groundwater storage.
Less effective for surface (root-zone) soil moisture. Shorter memory?

Girotto et al., (2016) WRR

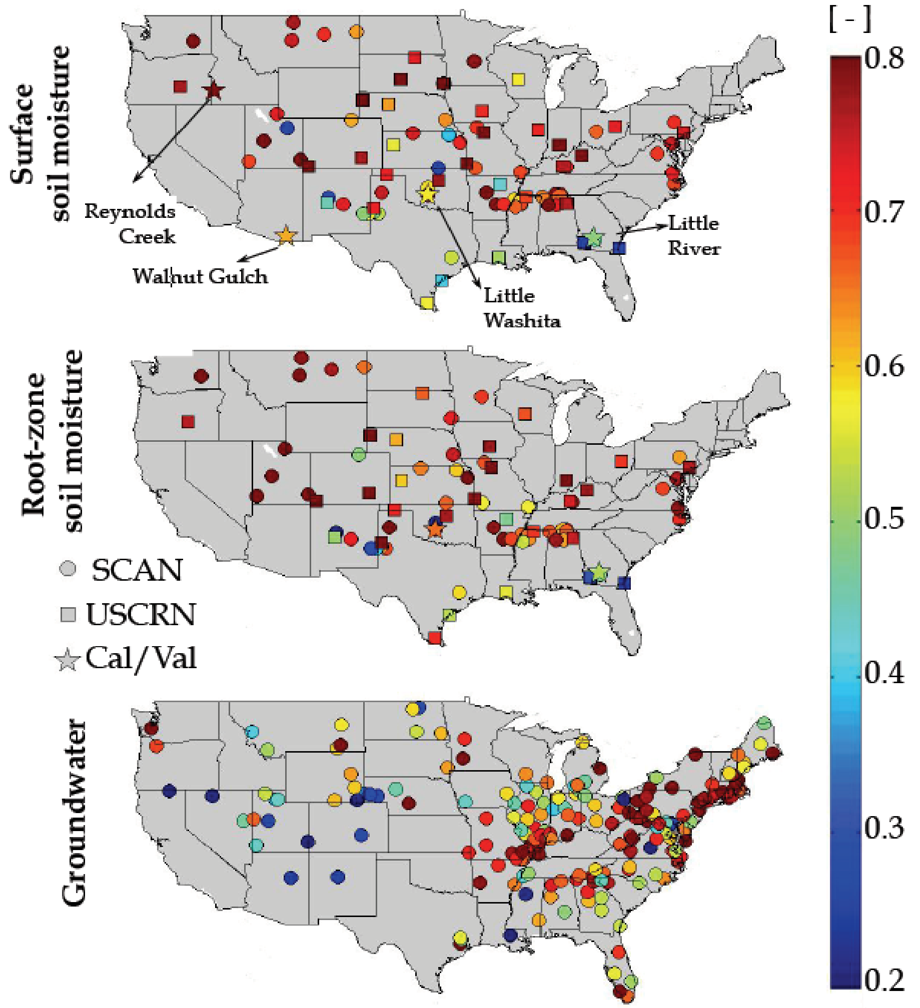
GRACE Data Assimilation: Validation

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

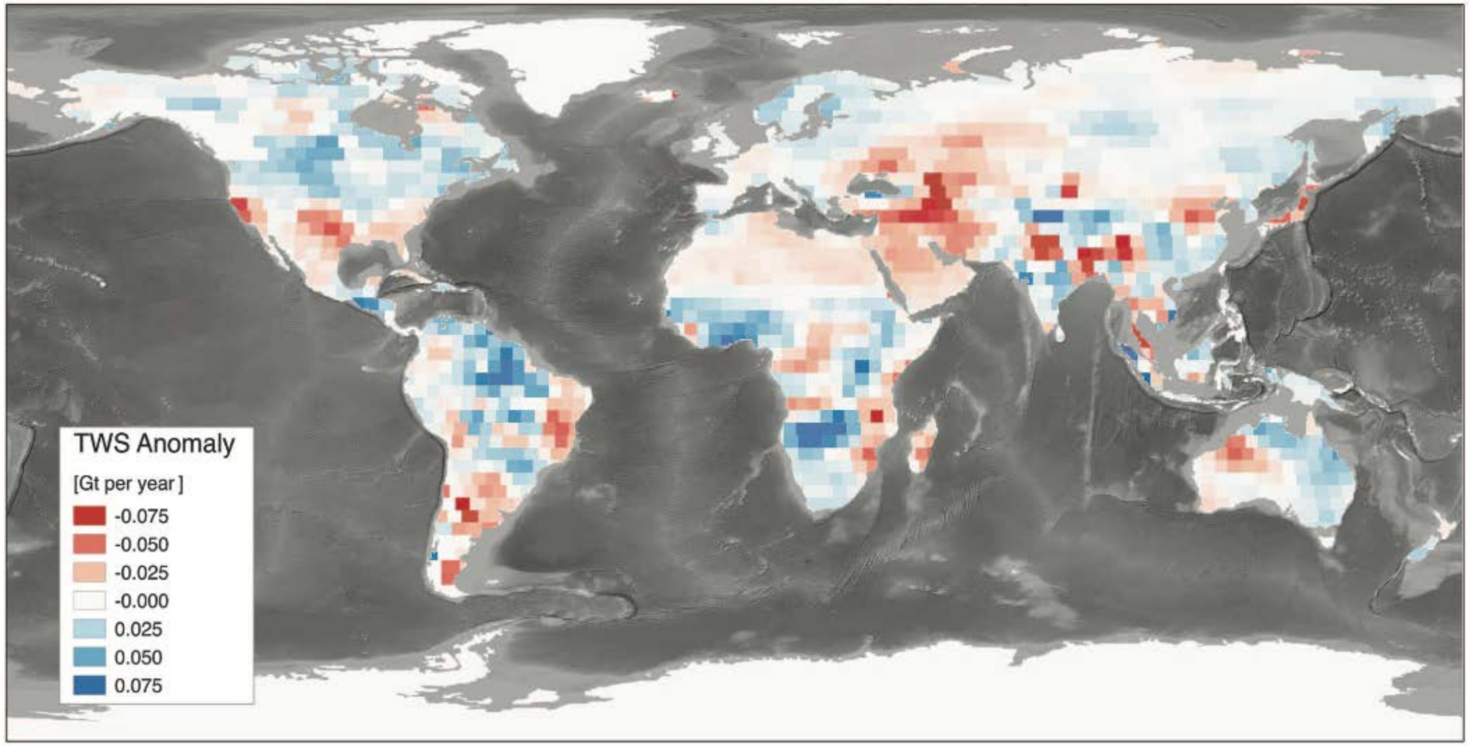
Groundwater:
- 136 USGS (Unconfined aquifer only)

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

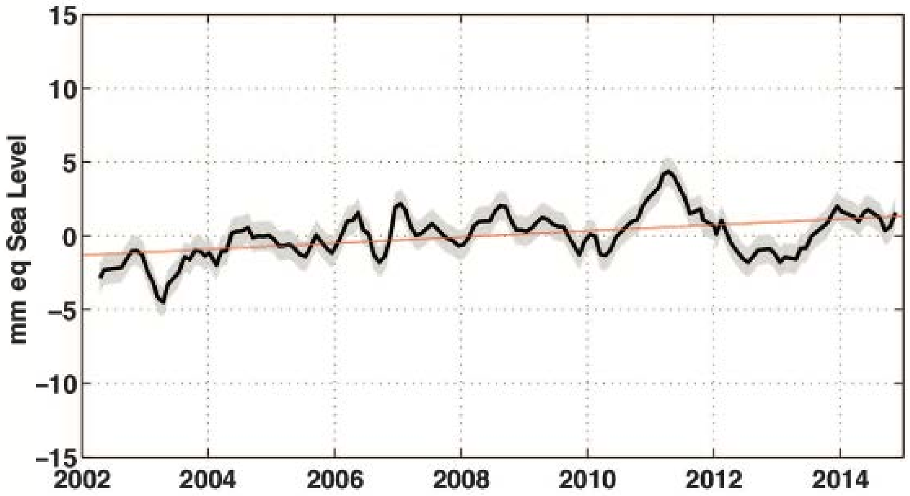
Correlation (Open-Loop, or model-only)



GRACE Applications: Land Contribution to Sea Level Rise



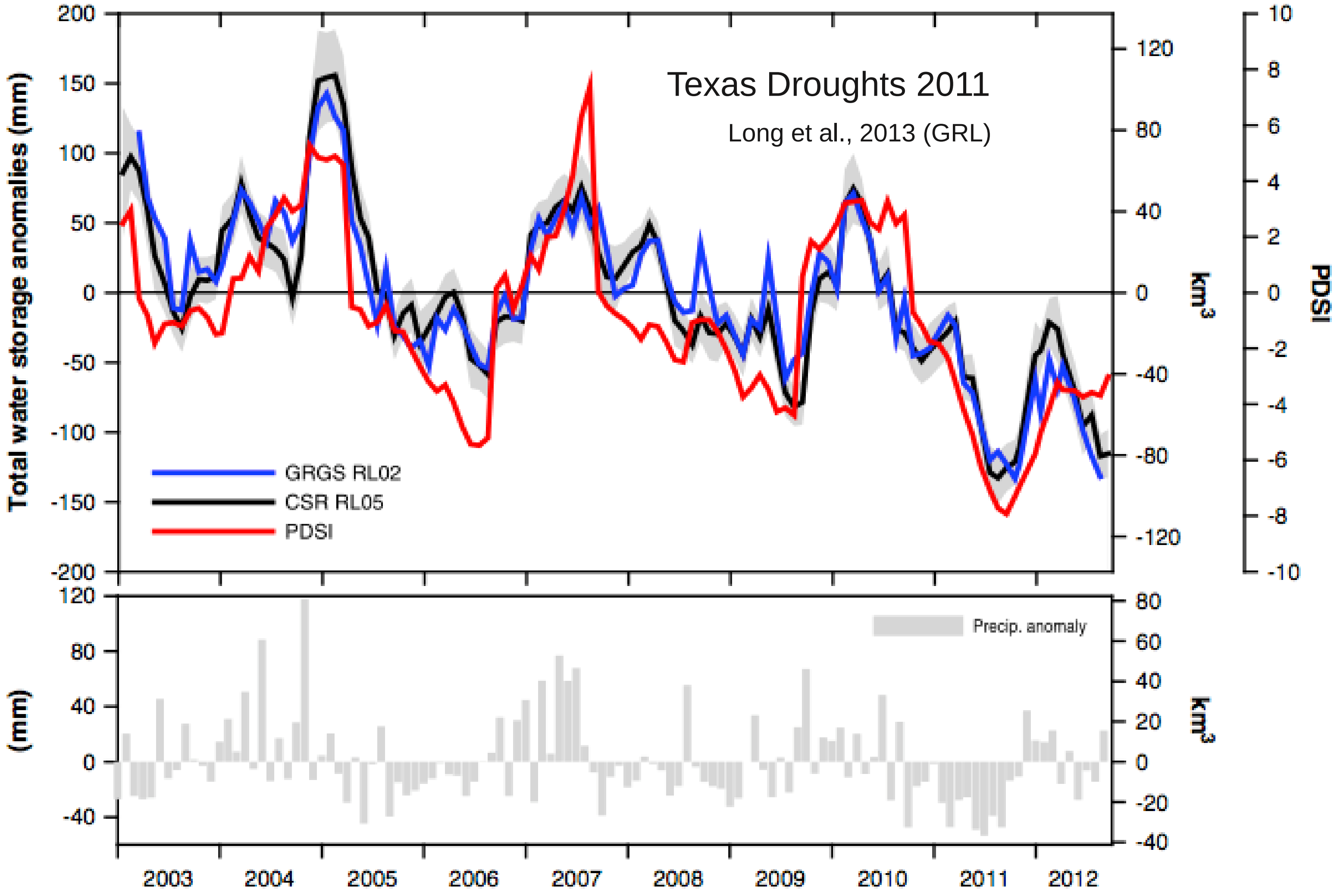
Trends in land water storage from GRACE observations



Land TWS partially offset water losses from ice sheets, glaciers, and groundwater pumping,

Slowing the rate of sea level rise by 0.71 ± 0.20 millimeters per year [Reager et al., 2016, Nature]

Example of GRACE Applications: Droughts

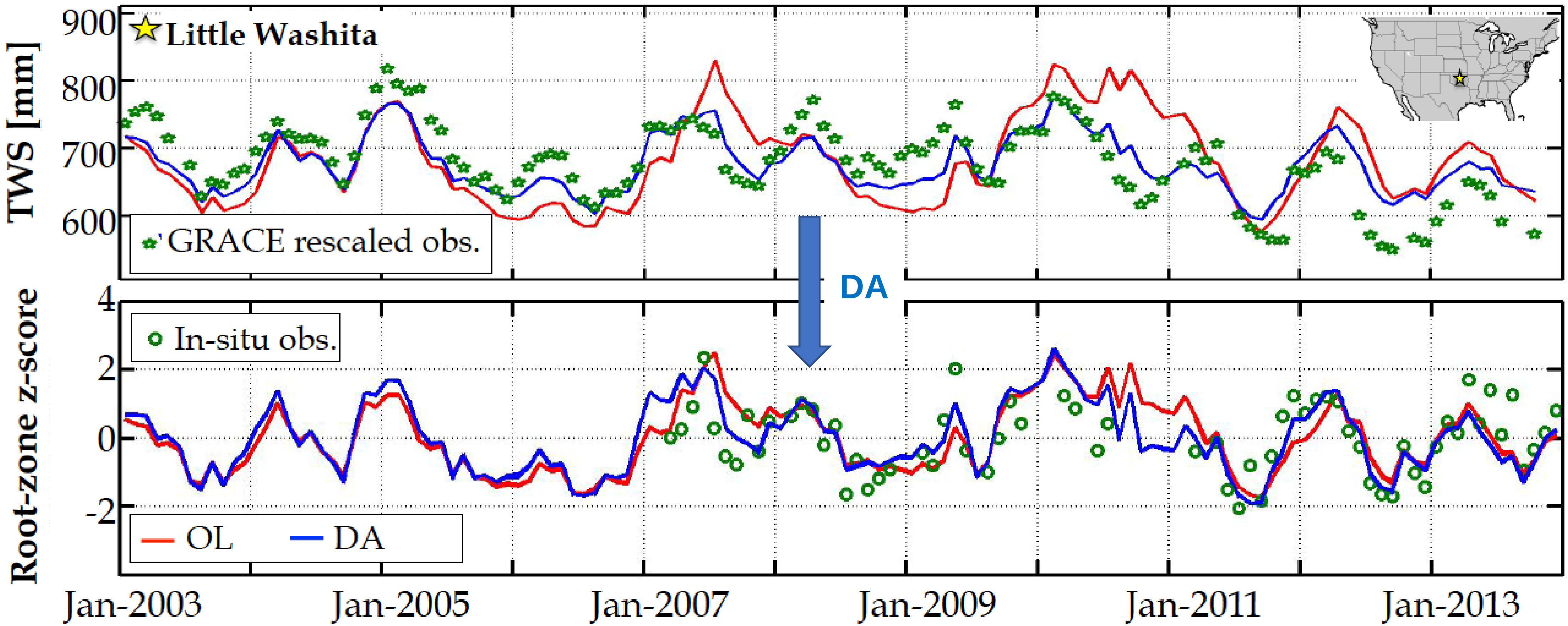


- GRACE is a 'scale in the sky'
- GRACE senses water storage depletion [e.g., drought monitoring]
- Strong correlation of TWS with drought monitoring indexes

GRACE: Unique Mission: can see beyond the surface, but..

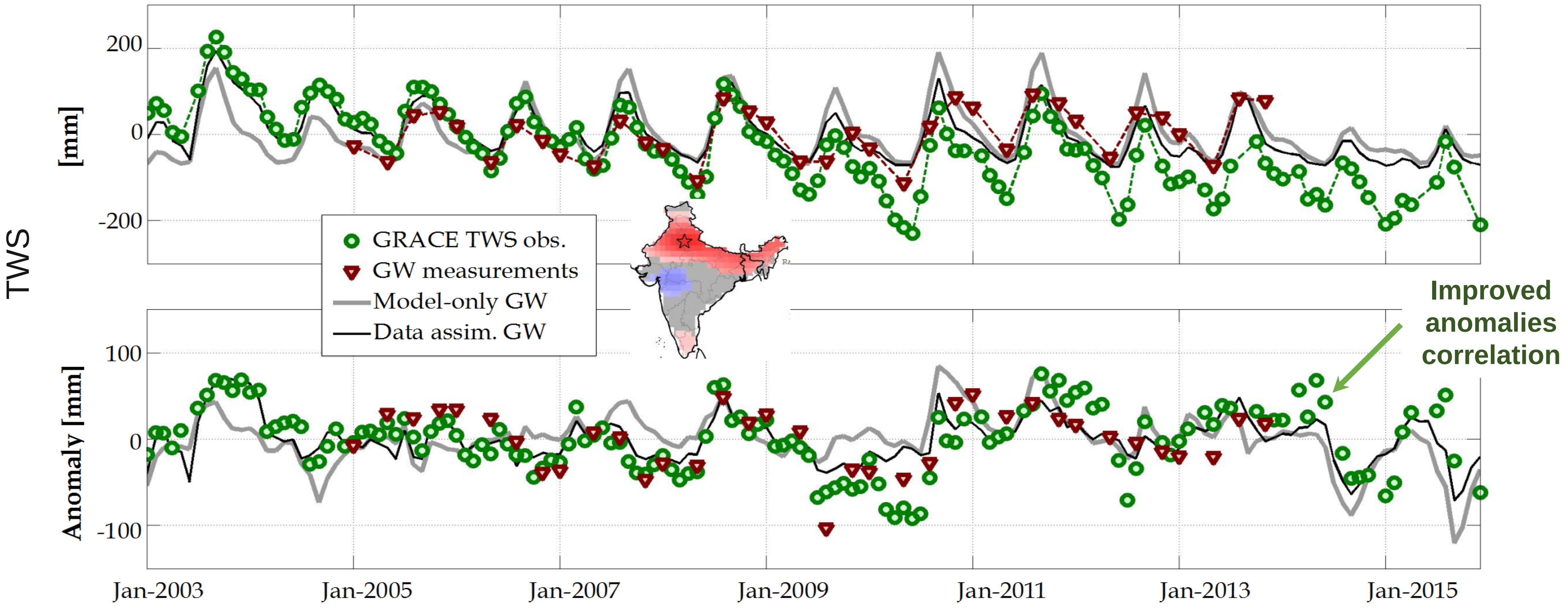
GRACE DA: Vertical & Spatial downscaling

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 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)**