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

Manuela Girotto

George Mason University, Department of Civil, Environmental, and Infrastructure Engineering
March 28th 2018
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

- 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

Soil Moisture (SM) vs. Groundwater (GW):
SM smaller volumes & more temporally dynamic than GW

<table>
<thead>
<tr>
<th>RESERVOIR</th>
<th>VOLUME (KM$^3$)</th>
<th>RESIDENCE TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>1,322,000,000</td>
<td>2500 years</td>
</tr>
<tr>
<td>Ice caps &amp; glaciers</td>
<td>29,199,700</td>
<td>-</td>
</tr>
<tr>
<td>Groundwater (near-surface)</td>
<td>4,171,400</td>
<td>8 years</td>
</tr>
<tr>
<td>Lakes &amp; Rivers</td>
<td>130,700</td>
<td>88 days</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>66,700</td>
<td>47 days</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>12,900</td>
<td>9 days</td>
</tr>
</tbody>
</table>

A look at these from Space?

Soil Moisture $\leftrightarrow$ SMOS/SMAP
Groundwater $\leftrightarrow$ GRACE [?]
Soil Moisture From Space

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 at multiple incidence angles
• Launched: Nov. 2009
• ~40 km resolution

L-band (active)/passive
• Launch: 31 Jan 2015
• (3)-40 km resolution
Groundwater from Space: GRACE?

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

- Gravity = \( f(\text{mass}) \)
- Gravity varies in space (e.g., mountains = more mass)
- Gravity can be measured with two satellite one running after the other [range-rate observations] \( \rightarrow \) GRACE!
Gravity (GRACE) can monitor where the water is now and how it is changing over time.

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

DATA ASSIMILATION

Downscaling:
- Horizontal
- Temporal
- Vertical

Scales that are more useful for hydrological applications
Outline

• Introduction & Motivations

• GRACE-DA (Downscaling GRACE Observations)

• SMOS(SMAP)-DA

• Joint Assimilation of SMOS+GRACE

• Conclusions & Future Directions
The Key Idea of DA:

- Estimates of a Specific Phenomena can be obtained from **Model** & **Observations**
- Neither are perfect
- Use them in combination to optimize the estimates
Data assimilation (DA) for hydrology

**The Key Idea of DA:**
- Estimates of a Specific Phenomena can be obtained from 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

**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**

[1], [2], [3], [4-6], [7] (Coarse scales)

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

Koster et al., (2000)
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


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
• 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)

GRACE TWS observations

Obs – Forecasts TWS [z - M(x)]

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

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

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?)

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

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

→ Add soil moisture (SMOS/SMAP)?
Outline

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

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

- $\hat{x}_{k,i}^{j}$: Soil moisture, temperature (signs -: forecasts, +: analysis)
- $K_{k,i}$: Kalman gain
- $y_i^j$: Tb SMOS/SMAP observations
- $\hat{y}_i^j$: 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
SMOS(SMAP) to help with surface soil moisture?

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

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

What if we incorporate both GRACE+SMOS observations together?

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

Bulk Statistics

- 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
**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

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

→ Add soil moisture (SMOS/SMAP)?
Outline

• Introduction & Motivations

• GRACE-DA (Downscaling GRACE Observations)

• SMOS(SMAP)-DA

• Joint Assimilation of SMOS+GRACE

• Conclusions & Future Directions
GRACE+SMOS Data Assimilation: Method

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

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>ΔR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Openloop</td>
<td><img src="image" alt="Map" /></td>
<td><img src="image" alt="Map" /></td>
</tr>
<tr>
<td>Univariate GRACE DA</td>
<td><img src="image" alt="Map" /></td>
<td><img src="image" alt="Map" /></td>
</tr>
<tr>
<td>Univariate SMOS DA</td>
<td><img src="image" alt="Map" /></td>
<td><img src="image" alt="Map" /></td>
</tr>
<tr>
<td>Multivariate GRACE+SMOS DA</td>
<td><img src="image" alt="Map" /></td>
<td><img src="image" alt="Map" /></td>
</tr>
</tbody>
</table>

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

• Introduction & Motivations

• GRACE-DA (Downscaling GRACE Observations)

• SMOS(SMAP)-DA

• Joint Assimilation of SMOS+GRACE

• Conclusions & Future Directions
## Soil Moisture Profile Estimates

### GRACE DA
- GRACE DA primarily affects groundwater and has smaller impacts on soil moisture
- GRACE DA leads to improve groundwater

### SMOS DA
- SMOS DA is mostly beneficial to improve surface soil moisture
- 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!

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

Manuela Girotto
Outline

• Introduction & Motivations

• Downscaling GRACE Observations (GRACE-DA)

• 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
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

(a) TWS example

(b) GW example

(c) Runoff example
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)