Benefits and Pitfalls of GRACE Terrestrial Water Storage Data Assimilation

Manuela Girotto

Manhattan College, Civil and Environmental Engineering Department
March 26th 2018
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

A look at these from Space?

Soil Moisture <-> SMOS/SMAP
Groundwater <-> GRACE [?]
Soil Moisture From Space

Soil Moisture and Ocean Salinity (SMOS) Mission

**Advantages:**
- Tb depends on soil moisture
- Frequent observations (1 observation 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 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?

GRACE = Gravity Recovery and Climate Experiment

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

- Gravity = \( f(\text{mass}) \)
- Gravity varies in \textit{space} (e.g., mountains = more mass)
- Gravity can be measured with two satellite one running after the other [range-rate observations] \rightarrow \text{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
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
- Horizontal
- Temporal
- Vertical

Scales that are more useful for hydrological applications
Outline

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

Observed (GRACE) TWS

DA

\[ f ([1], [2], [3], [4-6], [7]) \]

\[ [1], [2], [3], [4-6], [7] \]

(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)

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

Other water storages:

Koster et al., (2000)
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)

- 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)*

**DATA ASSIMILATION**

GRACE TWS observations

Obs – Forecasts TWS \[ z - M(x) \]

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

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?

**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!**
Downscaling: Benefits & Remaining Challenges

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

Scales used for global mass balances
- Horizontal
- Temporal
- Vertical

Scales that are more useful for hydrological applications

DATA ASSIMILATION

Downscaling:
Outline

• Introduction & Motivations

• Downscaling GRACE Observations (GRACE-DA)

• GRACE-DA & Anthropogenic Hydrological Processes

• Conclusions & Future Directions
GRACE DA: The Role of 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

The map depicts the area equipped for irrigation in percentage of cell area. For the majority of countries the base year of statistics is in the period 1997 - 2002.


Stefan Siebert, Petra Düll, Sebastian Feick (Institute of Physical Geography, University of Frankfurt/M., Germany) and Jippe Hoogeveen, Karen Franken (Land and Water Development Division, Food and Agriculture Organization of the United Nations, Rome, Italy)
GRACE DA: Trends in the Assimilated Observations

Percentage of area equipped for irrigation

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

GRACE observations of TWS show trends likely associated with groundwater extraction

Siebert et al., 2013

Girotto et al., (2017)
GRACE DA: Trends in TWS

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

(source: GRACE
(temporal window: 2003-2016)

[cm/year]

-2.4  -1.2  0  1.2  2.4
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

Deep (confined) groundwater

Irrigation

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...

**Wet Regions** (i.e., irrigation is less likely to regulate the water budget)
GRACE Data Assimilation: TWS Verification

SKILLS INCLUDING INTERANNUAL VARIABILITY (trends and seasonal cycle removed)

- 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?)

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

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

Manuela Girotto
GRACE DA: Temporal Variability of the Increments

- **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
Land TWS partially offset water losses from ice sheets, glaciers, and groundwater pumping, slowing the rate of sea level rise by $0.71 \pm 0.20$ 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)