Assimilation of GRACE terrestrial water storage estimates in the North American Land Data Assimilation System

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Motivation

A key focus of the new phase of NLDAS is to include the assimilation of remotely sensed satellite measurements, including soil moisture, snow, terrestrial water storage, land surface temperature, vegetation, altimetry.

LIS includes the capabilities for the concurrent, multivariate assimilation of these measurements.
Altimetry

Land surface temperature

Irrigation

TWS

Snow (snow depth, snow cover)

Soil Moisture

NLDAS relevant remote sensing measurements


SMMR

SSM/I

AMSR-E

ASCAT (SMOPS)

SMOS (ESA)

Aquarius

SMAP

WindSAT (SMOPS)

AMSR-2 (JAXA)

MODIS

GRACE

VIIRS

GOES (100-H)

Jason

GOES (100-H)
Terrestrial Water Storage (TWS)

\[
\text{TWS} = \text{Snow} + \text{Surface water} + \text{Soil Moisture} + \text{Groundwater}
\]

In CLSM, the simulated TWS is calculated by subtracting the catchment deficit from the maximum available pore space of the catchment and by adding the surface and root zone excess terms.

Ground water storage = TWS - root zone soil moisture - SWE - canopy water storage
GRACE - Gravity Recovery and Climate Experiment (launched in 2002) satellite provides measurements of Earth’s gravity field anomalies.

Measurements are NOT derived from electromagnetic waves: GRACE uses a microwave ranging system to measure changes in the speed and distance between two identical spacecrafts (“Tom” and “Jerry”) flying in a polar orbit about 220 km apart, 500 km above Earth.

The twin satellites sense minute variations in Earth’s gravitational pull. By combining the data of distance between the satellites and GPS measurements of the position of satellites, a detailed map of Gravity anomalies can be constructed.

Estimates of terrestrial water storage changes can be estimated from GRACE measurements after removing the influence of atmospheric and oceanic circulations and impacts of major geophysical events.
GRACE data

Standard GRACE products are at 1-degree spatial resolution at monthly time scales and provide estimates of TWS anomalies (Tellus RL05 spherical harmonics solution used in this study).

A number of filtering procedures are applied to reduce measurement errors and to convert data from the spectral domain to geographical coordinates using a Gaussian filter.

Gaussian smoothing means that the TWS estimates and errors are horizontally correlated.

Previous studies employed basin-scale assimilation, which simplifies the handling of spatially correlated errors, but creates artificial boundaries in the assimilation estimates.

This study employs gridded GRACE estimates in assimilation, without requiring preprocessing to subjectively defined basins.

The study also employs the spatially distributed, temporally static error estimates, instead of uniform error assumptions.
GRACE observations are time averaged TWS anomalies and reported at monthly intervals.

3-dimensional Ensemble Kalman Smoother (EnKS) temporally disaggregates the observations into a finer, daily scale.

Products are assimilated with a horizontal error correlation scale of ~ 300 km.
Results: TWS

GRACE DA leads to changes in the interannual variability of TWS estimates.

Influence of DA is more in the later years and over Northeast, Midwest, Great plains and Southwest.

Unique information in GRACE observations seems to inform the model even with high quality NLDAS precip.
Results: Groundwater

- Compared to quality controlled USGS groundwater well data

- Anomaly R differences (DA - OL); warm colors indicate improvements from DA, cool colors indicate degradations

- Systematic improvements in Upper Mississippi, parts of Northeast; Degradations in the Missouri basin stations.

<table>
<thead>
<tr>
<th></th>
<th>OL</th>
<th>DA</th>
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<tbody>
<tr>
<td>Anomaly R</td>
<td>0.64 +/- 0.02</td>
<td>0.69 +/- 0.02</td>
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Results: Soil Moisture

Compared to quality controlled SCAN and ARS measurements

Systematic, significant improvements in surface and root zone soil moisture skills

<table>
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<tr>
<th>Anomaly R</th>
<th>OL</th>
<th>DA</th>
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<tbody>
<tr>
<td>Surface soil moisture</td>
<td>0.44±± 0.02</td>
<td>0.58 ±± 0.02</td>
</tr>
<tr>
<td>Root zone soil moisture</td>
<td>0.48±± 0.02</td>
<td>0.54±± 0.02</td>
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Results: Streamflow

Compared to USGS daily streamflow data, over unregulated outlets

Impacts from DA shown as normalized indices (NIC) for RMSE, R and NSE

\[ NIC_R = \frac{(R_a - R_o)}{(1 - R_o)} \]

NIC > 0 implies DA improves; NIC < 0 implies DA degrades

Impact from GRACE DA on streamflow estimates are small
Results: Snowdepth

Compared to GHCN, CMC and SNODAS (RMSE(OL) - RMSE(DA))

Impact on snow depth estimates is very small (not statistically significant in most parts of the domain)

Over the Rocky mountains, Sierra Nevada and Cascades, GRACE-DA provides improvements (consistent in all three comparisons)
Results: Evapotranspiration

Compared to ALEXI, FLUXNET, UW, and MOD16 (RMSE(OL) - RMSE(DA))

Areas of decreased RMSE in the West, Great Plains, Southeast; increased RMSE over upper Mississippi (except in case of MOD16)
Influence of scaling factor and measurement errors

Filtering procedures are applied to reduce the level of noise to generate the gridded GRACE data, which also lead to loss of signal.

To reduce the differences between the signal amplitudes of the original and filtered data a multiplicative scale factor was developed:

- DA1 - distributed measurement error + scaling factors
- DA2 - uniform error + scaling factors
- DA3 - uniform error + no scaling

Scaling factor seems to have a large influence than the distributed measurement error.
Comparison of DA with gridded and basin averaged data

**DA1** - default configuration with gridded GRACE data, distributed measurement errors, use of scaling factors

**DA1b** - basin scale DA with distributed measurement errors and scaling factors

**DA1b** includes artifacts of basin boundaries

Basin averaged DA has marginally higher skills for root zone soil moisture; Groundwater skill comparison shows mixed results; Small differences in the streamflow fields

Jul 2006  **TWS(DA1b) - TWS(DA1)**  Jun 2008
2004; OL underestimates drought severity

2006; The underestimation of the D0-D2 categories are improved by DA

2011; Onset of the Texas drought is improved in DA

2012; OL overestimates drought severity over Minnesota, Iowa, Wyoming and underestimates over Kansas, Oklahoma
Comparison of drought area estimates

OL skills are high; Impact of DA is mixed


Drought area representation is marginally improved by GRACE DA in late 2012 drought.
GRACE DA assimilation provides significant improvements in soil moisture and groundwater estimates; marginal impacts on streamflow, snow and ET.

The skills from gridded and basin averaged DA were comparable.

The use of scaling factors was more impactful compared to the use of distributed measurement errors.

The impact of GRACE-DA on drought estimates were mixed; GRACE-DA improved the representation of moderate droughts in general.