Model assimilation of satellite soil moisture observations

Sujay V. Kumar¹, Christa D. Peters-Lidard¹, David Mocko¹, Rolf Reichle², Ken Harrison¹, Joe Santanello¹, Yuqiong Liu¹, Kristi Arsenault¹, Youlong Xia⁴, Michael B. Ek⁴, George Riggs⁵, Ben Livneh⁶, Michael Cosh⁷

¹ – Hydrological Sciences Laboratory, NASA/GSFC, Greenbelt, MD
² – NASA Global Modeling and Assimilation Office, Greenbelt, MD
³ – Johns Hopkins University, Baltimore, MD
⁴ – Environmental Modeling Center, NOAA, College Park, MD
⁵ – Cryospheric Sciences Branch, NASA/GSFC, Greenbelt, MD
⁶ – Cooperative Institute for Research in Environmental Sciences, Boulder, CO
⁷ – USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD
Outline

- Background (modeling and assimilation environment – NASA Land Information System (LIS); evaluation environment – NASA Land surface Verification Toolkit (LVT))
- Soil moisture data assimilation - methods
- Soil moisture data assimilation for drought applications in the NLDAS system
- Soil moisture OSSEs conducted in support of SMAP
A system to study land surface processes and land-atmosphere interactions

Integrates satellite- and ground-based observational data products with land surface modeling techniques

Capable of modeling at different spatial scales

A comprehensive, sequential data assimilation subsystem based on NASA (Global Modeling and Assimilation Office) GMAO infrastructure for improved state estimation using remote sensing observations

LVT is a framework developed to provide an automated, consolidated environment for systematic land surface model evaluation.

Includes support for a range of in-situ, remote-sensing and other model and reanalysis products.

LIS infrastructure

End-to-end platform for terrestrial hydrology that links raw observations, radiative transfer models, data assimilation, uncertainty estimation, physical models, end-use applications and evaluation and verification techniques within a single integrated framework.
Soil moisture retrievals are available from low-frequency (C, X, and L-band) active and passive microwave data (SMMR, TMI, AMSR-E, WindSat, SMOS, SMAP, ...)

Several studies in the past decade that has demonstrated utility from assimilating passive microwave retrievals of soil moisture (Drusch et al. (2005), Reichle et al. (2007), Liu et al. (2011), Draper et al. (2012), Peters-Lidar et al. (2012) to name a few).

**Essential Climate Variable (ECV) soil moisture product (Liu et al. 2012, Wagner et al. 2012) from ESA; uses C-band scatterometers (ERS-1/2 scatterometer, METOP advanced advanced scatterometer) and multi-frequency radiometers (SMMR, SSM/I, TMI, AMSR-E, Windsat) spans 1978 to 2011.**
Data assimilation of AMSR-E retrievals into Catchment LSM (Liu et al. 2011)

Commonly used Assimilation algorithm: Ensemble Kaman Filter (EnKF)

Update at $t_k$:

$$x_k^{i+} = x_k^{i-} + K_k(y_k - H_k x_k^{i-})$$

for each ensemble member $i=1...N$

$$K_k = \frac{P_k^{-}H_k^T}{H_k P_k^{-}H_k^T + R_k}$$

Data flagged for light and moderate vegetation, no precipitation, no snow cover, no frozen ground, no RFI are used in data assimilation.

The observations are scaled to the LSM’s climatology using CDF matching.
Soil moisture DA in the NLDAS system

**Model domain:** Continental United States (CONUS) at 1/8\(^{th}\) degree spatial resolution, including parts of Canada/Mexico (25-53° N; 125-67° W)

**Forcing data:** NLDAS-phase II (NLDAS2) meteorological forcing data. Hourly precipitation includes CPC’s daily PRISM Corrected gauge analysis, downward shortwave radiation bias-corrected using GOES SRB shortwave data, all other fields derived from the NCEP North American Regional Reanalysis (NARR) data.

**Land surface model:** Noah LSM version 3.3, includes a 15-year spin-up, followed by a 33

**Data assimilation method:** Ensemble Kalman Filter (EnKF)

**Time period:** Jan 1, 1979 to 1 Jan 2012.

Soil moisture:
- USDA Soil Climate Analysis Network (SCAN); 123 stations chosen after careful quality control (used for evaluations between 2000-2011)
- Four USDA ARS experimental watersheds (“CalVal” sites) (used for evaluations between 2001-2011)

Streamflow: Gauge measurements from unregulated USGS streamflow stations (1981-201)
Statistically significant improvements in surface soil moisture and root zone soil moisture as a result of soil moisture DA

Anomaly R increases, Anomaly RMSE reduces and unbiased RMSE reduces with soil moisture assimilation.
Soil moisture DA: Evaluation of streamflow

The improvements are expressed using an Normalized Information Contribution (NIC) metric that measures the skill improvement from DA as a fraction of the maximum possible skill improvement

\[
NIC_{RMSE} = \frac{(RMSE_o - RMSE_a)}{RMSE_o}
\]

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

\[
NIC_{NSE} = \frac{(NSE_a - NSE_o)}{(1 - NSE_o)}
\]

Overall improvements in all skill metrics (RMSE, R and NSE) are observed in streamflow estimates after data assimilation

Skill improvements from soil moisture assimilation are mostly over parts of the Mississippi, Missouri and Arkansas-Red basins and parts of Southeastern U.S.
July 18-25, 2006: DA improves estimates over Texas, Nebraska, Dakotas (D0 and D1)
June 17-24, 2008: DA indicates more intense drought over North Dakota and Montana, reduces severity over Nevada, increases spatial extent over Texas and New Mexico.
May 10-17, 2011: DA predicts increased severity of drought over Texas and Oklahoma.
Comparison of area under drought

South (Noah)

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>OL</th>
<th>DA-SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>0.91</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>0.91</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>0.89</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>0.78</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>0.73</td>
<td>0.73</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>RMS</th>
<th>OL</th>
<th>DA-SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>15.7</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>11.1</td>
<td>11.1</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>9.9</td>
<td>9.2</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>9.0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>6.7</td>
<td>6.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Bias</th>
<th>OL</th>
<th>DA-SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>11.2</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>4.7</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>3.8</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>0.5</td>
<td>-0.7</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>-0.4</td>
<td>-0.8</td>
<td></td>
</tr>
</tbody>
</table>
Soil moisture OSSE in support of SMAP

Simulation Domain: Continental U.S.,
35KM Spatial resolution

Nature Run

- Mosaic + NLDAS2 forcing
- LIS-RTM (CMEM)

LIS-RTM

V-pol

H-pol

Masking for dense vegetation
rain/snow events
1.3 K gaussian noise
1 observation per day

LVT

impact of having L-band
brightness temperature
observations for improving the
representation of drought/flood
events

System Simulation

Noah+ MERRA forcing (open loop)

LIS-DA
LIS-RTM

How much improvements in the drought/flood risk
assessments are obtained?
How do these improvements translate to associated
cost reductions?
Maps present Anomaly R (DA) – Anomaly R (OL) of surface and root zone soil moisture.

Blue (positive values) indicate improvements
Red (negative values) indicate degradations

Assimilation of L-band Tb provides improvements to both surface and root zone soil moisture fields.

Surface soil moisture

Root zone soil moisture
Comparison of percentile maps

Aug 1989 case: DA correctly intensifies the drought over the Midwest

July 2003 case: DA reduces the severity of drought over the Highplains (that was incorrectly specified in the open loop run)

May 2011: DA correctly intensifies the drought over Texas

Drought intensity is classified into 5 categories: D0 (percentile < 30%), D1 (percentile < 20%), D2 (percentile < 10%), D3 (percentile < 5%), D4 (percentile < 2%)

The assimilation of L-band Tb observations aid in improving the representation of drought estimates
Decision theory model for an economic assessment of the SMAP OSSE

Statistical decision theory has lots of say about making OSSEs relevant. E.g. : “Commercial decisions are often made, not on the basis of events which are likely to occur, but on the basis of events that are unlikely to occur, but which if they occur, would involve serious financial loss (Palmer, 2002)”

A simple approach:

C – cost of taking action to mitigate event (e.g. drought) regardless of whether event happens or not

L – loss if event happens and no-mitigation was taken. We assume C/L < 1

p – probability of the event as assessed by the ensemble

The total cost is computed by summing across the cost/loss incurred for each flood/drought event

The costs can be computed both from a “deterministic” approach that uses the ensemble mean values in the decision tree or a “probabilistic” approach that diagnoses the probability of the event from the ensemble.
Sequence of decision theory analysis in the SMAP OSSE

Open loop run (Noah)

Truth run (Mosaic)

DA run (Noah)

Drought/Flood risk assessments based on root zone soil moisture percentiles

Cost-Loss Model

Value of Information (VOI) = Cost_{OL}/Cost_{DA}

Cost_{OL}

Cost_{DA}
The contribution to the value of information metric for low C/L ratios are from the improving the probability of detection of drought events through DA and for high C/L ratios are from reducing the false alarm ratio of drought events in the open loop run.

The gain from DA compared to OL is at least about 10% of cost reduction – fully attributed to the L-band measurements.
The assimilation of remotely sensed soil moisture show promise for improving drought estimation at short time scales in the NLDAS system.

The NLDAS system produces high quality soil moisture products without data assimilation (due to the high quality forcing inputs). Therefore the added value provided by the remotely sensed soil moisture products is significant.

The L-band measurements from SMAP is expected to provide greater enhancements in model assimilated products.