Conceptual Problems (2): Land Surface Data Assimilation: where are we at?

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9 Feb 2012
Soil Moisture Data Assimilation
Snow Data Assimilation
Terrestrial Water Storage Assimilation
Modeling, Re-Analysis
Gaps in Our Understanding
Conclusions
Soil Moisture Data Assimilation

SM DA
SM RS
SM Val
AMSR-E DA
AMSR-E/ASCAT
SMOS/SMAP
SMOS SM DA
SMOS Tb DA
SMOS Tb/SM DA

Summary

Snow Data Assimilation

Terrestrial Water Storage Assimilation

Modeling, Re-Analysis

Gaps in Our Understanding

Conclusions
Assimilation of Surface Soil Moisture

**AMSR-E/SMOS/SMAP/ . . . surface obs**
- only 5 cm depth, coarse scale
- limited coverage in space and time
- measurement error

**Ancillary information**
- data assimilation parameters
- land surface model (LSM)
- radiative transfer model (RTM)
- surface meteorology
Assimilation of Surface Soil Moisture

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Data Assimilation

- Surface soil moisture (∼ top 5 cm)
- Root zone soil moisture (∼ top 1 m)
- Other geophysical fields
  ⇒ continuous, fine-scale, with error estimates

GMAO works on SMAP L4_SM
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**Validation**: in situ ground measurements
Remote Sensing of Soil Moisture

- active/passive microwave
  - actual measurements: brightness temperature or backscatter retrieval: soil moisture
  - ⇒ assimilate radiances or retrievals
- lower frequency → deeper penetration depth
  - better correlation between surface observations and root-zone soil moisture
  - correspondingly adjust model structure
- resolution: 3-40 km
  - downscaling, scale mismatch with model
In Situ Soil Moisture: Validation

USA:
- SCAN (×): point measurements
- USDA CalVal (□): watershed average

Cross-mask locations and times with qualitative satellite and in situ data

Australia (Murrumbidgee):
- point measurements
- satellite pixel average (dense point-scale obs)
Soil moisture (anomaly) skill increases with
- precipitation corrections, and
- assimilation of surface soil moisture retrievals

Improved root-zone soil moisture
Little River CalVal site
coarse-scale AMSR-E downscaling (3D-filter)
initialize with low, medium, high soil moisture

(Sahoo et al., AWR, 2012, in review)

Assimilation helps balancing the model and reduces spinup time
State updating with **passive** (AMSR-E) and **active** (ASCAT) microwave obs

- Skill: anomaly R [-] (+ confidence intervals)
- 2007-2010
- SCAN/SNOTEL (US) + Murrumbidgee (AUS)

Significant skill increase:
- AMSR-E and ASCAT assimilation
- surface and root-zone soil moisture
- mainly low vegetation

*(Draper et al., GRL, 2012, accepted)*
SMOS (ESA, Soil Moisture Ocean Salinity)

- launched November 2009
- L-band radiometer
- sensing depth = 5 cm
- 40 km resolution

→ Assimilate soil moisture retrievals and brightness temperatures (separately) from SMOS to prepare for SMAP

SMAP (NASA, Soil Moisture Active Passive)

- launch 2014
- L-band radiometer/radar
- sensing depth = 5 cm
- 3-40 km resolution
- **GEOS-5 Catchment LSM:**
  - 36 km, 1 Jan 2010 - 1 Nov 2011
  - Fortuna 2.3 version with 5 cm surface layer, MERRA forcings

- **Radiative Transfer Model (RTM):**
  - $\tau - \omega$ model: soil moisture/temperature, vegetation water/temperature $\rightarrow$ $T_b$

- **Confront Model with Observations:**
  - soil moisture: bias, LSM soil parameterization; anomaly DA
  - $T_b$: RTM parameter estimation; assimilation
Model SM is wetter & less variable (not shown) than SMOS SM

- bias $\rightarrow$ CDF-matching
- anomaly assimilation
Model SM is wetter & less variable (not shown) than SMOS SM

- bias → CDF-matching
- anomaly assimilation

Work on partial bias reduction:

- update global soil texture, include organic material
- update soil hydraulic parameters
- account for gravel corrections
SMOS retrieval assimilation improves soil moisture estimates for both the surface and root-zone.
Limit model bias before data assimilation

1 Jan 2011 - 1 Nov 2011

⇐ SMOS observed Tb, H-pol, 42.5°

↓ Model predictions Tb, H-pol, 42.5°

- with prescribed RTM parameters (SMAP, LSMEM literature, ECMWF)
- after RTM parameter estimation (1 Jan 2010 - 1 Jan 2011)

Split sample: Unbiased Tb predictions after multi-angular Tb calibration
**Method:** At each individual pixel, minimize difference in:

- climatological mean (6 angles)
- temporal variability (6 angles)
- calibrated parameter and best guess

*Little River CalVal Watershed*
1 January 2010 - 1 November 2011: multi-angle average of H-pol Tb observation-minus-forecasts [K]

Some limited seasonal bias remaining after climatology calibration
### SMOS Retrieval vs. Radiance Assimilation

<table>
<thead>
<tr>
<th>SCAN/SNOTEL</th>
<th>Surface</th>
<th>Root-zone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SM DA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R* [-]</td>
<td>0.52(0.37,0.65)</td>
<td>0.64(0.53,0.73)</td>
</tr>
<tr>
<td>ubRMSE** [m³/m³]</td>
<td>0.072</td>
<td>0.049</td>
</tr>
<tr>
<td><strong>Tb DA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
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* with 95% confidence intervals; ** target uncertainty for SMAP = 0.04 m³/m³

- ✓ increase in R, decrease in RSME
- not screened for complex topography; see next slide
- Tb DA still includes seasonal bias, non-optimal RTM (preliminary results!)
- number of analysis steps different for retrieval and radiance assimilation; see next slide
Assimilation Time Steps

% assimilation time steps with SM only

% assimilation time steps with both SM and Tb

Only half of the time steps have both valid SM retrievals and Tb observations available. Main reason: Tb is limited to alias-free zones only, while SM is not.

Most data in Great Plains
SMOS Retrieval vs. Radiance Assimilation

Surface soil moisture skill, incl. identical amount of time steps (analysis and forecast, during 1 Jan 2010 - 1 Jan 2011)

Retrieval DA skill $R$ [-]

$\Delta$ Skill=0.05
$\Delta$ Skill masked=0.11

Radiance DA skill $R$ [-]

$\Delta$ Skill=0.06
$\Delta$ Skill masked=0.09

SM retrievals may not be optimal in complex terrain

Complex terrain does not significantly affect Tb DA; work in progress

Retrieval and radiance assimilation may be more or less beneficial in particular conditions; work in progress
Soil Moisture Assimilation

- new missions → deeper soil penetration
- retrieval assimilation (AMSR-E, ASCAT, SMOS SM into CLSM): well documented improvements in surface and root-zone soil moisture
- radiance assimilation (SMOS Tb into CLSM+RTM): promising improvements in surface and root-zone soil moisture
- climatological observation-forecast bias:
  - CLSM soil parameters optimization
  - RTM parameter calibration
- scale discrepancies: downscaling, anomaly assimilation

Preparation for SMAP L4_SM product
Snow Data Assimilation
Remote Sensing of Snow

Soil Moisture Data Assimilation

Snow Data Assimilation

Snow RS
SWE DA
SCF DA
Setup
AMSR-E/MODIS snow
AMSR-E Tb
Terrestrial Water Storage Assimilation

Modeling, Re-Analysis

Gaps in Our Understanding

Conclusions

**AMSR-E**: passive microwave sensor (radiometer), snow: dominantly 18.7/36.5 GHz, 25 km resolution

**MODIS**: visible/near infrared, spatial resolution: 500 m

- **AMSR-E**:
  - Actual measurements = brightness temperature
  - Snow Water Equivalent = retrieval

- 25 km AMSR-E snow water equivalent (SWE) → downscaling

- 500 m MODIS snow cover fraction (SCF) → update SWE
snow water equivalent = coarse-scale estimate of water in the snowpack

- 3D filter, using multiple coarse obs for each fine-scale update
- spatially correlated forecast perturbations
- no boundary effects, horizontal propagation
- snow cover fraction = fine-scale indirect/incomplete measurement of snowpack
- observation operator converts SWE to SCF
- model divergence → rule-based update

\[
\hat{x}_i^- = \begin{pmatrix} swe_i^- \\ snd_i^- \end{pmatrix}_i \quad \text{if} \quad \text{Cov}[\hat{\mathbf{x}}_i, \hat{\mathbf{y}}_i] = 0
\]
\[
scf_i^- = \hat{y}_i^- \equiv h_i(\hat{x}_i^-)
\]
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\hat{x}_i^- = \begin{pmatrix} swe^- \\ snd^- \end{pmatrix}_i
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\[
scf^- = \hat{y}_i^- \equiv h_i(\hat{x}_i^-)
\]

If no predicted snow:
if $[scf^{obs} - scf^-] > 0.5$, then add snow
- snow cover fraction = fine-scale indirect/incomplete measurement of snowpack
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\[
\hat{x}_i^- = \begin{pmatrix} swe^- \\ snd^- \end{pmatrix}_i
\]

If no predicted snow:
if \[
|scf^{obs} - scf^-| > 0.5
\]
then add snow

If full cover snow (no spread):
if \[
|scf^{obs} - scf^-| < 0.5
\]
then remove snow

Forecasts perturbations
Study Area

- North Park, CO, $75 \times 100 \text{ km}^2$
- period 2002-2010
- validation: SNOTEL (○), COOP (△)
25 km **AMSR-E** snow water equivalent (SWE) downscaling:

Joint (multi-scale) SWE and SCF assimilation: improved results in shallow snow locations (only)

- AMSR-E SWE: lacks realistic interannual variability, mainly in deep snow
- MODIS SCF DA: improved timing of snow accumulation onset

(De Lannoy et al., WRR, 2012)
Prepare for the direct radiance assimilation of AMSR-E observations

- artificial neural network
- input: snow density, water equivalent, liquid water content
- output: $Tb_{H10}, Tb_{V10}, Tb_{H18}, Tb_{V18}, Tb_{H36}, Tb_{V36}$
- training & validation: split sample

ANN provides robust predictions of multi-channel/pol Tb (difficulty: ice layers)

(Forman et al., IEEE/TGARS, 2012, submitted)
Terrestrial Water Storage Assimilation
Total Water Storage = soil moisture + groundwater + vegetation + snow (SWE)

- monthly, $\sim$200 km resolution mass anomalies (with respect to a multi-year mean gravity field)
- partitioning into storage components
- ensemble Kalman smoother
Total Water Storage = soil moisture + groundwater + vegetation + snow (SWE)

- monthly, $\sim$200 km resolution mass anomalies (with respect to a multi-year mean gravity field)
- partitioning into storage components
- ensemble Kalman smoother
validation against runoff and SWE in the Mackenzie river basin (2002-2008)

GRGS product assimilated without post-glacial rebound correction

⇒ assimilation (■) of TWS improves individual storage components (SWE and runoff) over the open loop (□)

(Forman et al., WRR, 2012)
Modeling, Re-Analysis
MERRA and MERRA-Land

- **MERRA**: 1979-present (updated w/ ~1 month latency), global, Lat=0.5°, Lon=0.67°, 72 vertical levels

- **MERRA-Land**: Enhanced product for land surface hydrological applications (*Reichle et al., J. Clim., 2011*)

  ⇒ improved soil moisture, runoff, canopy interception and latent heat flux through precipitation corrections and an enhanced model parameterization
Remaining Gaps

Observations
- sensitivity to variable of interest (e.g. snow water equivalent, soil moisture penetration depth)
- time/space gaps, resolution

Models
- simplified processes
- structure
- parameters

Data Assimilation
- random/systematic error specification (e.g. optimal error magnitudes, Gaussian errors?, . . .)
- coupling of land surface updates with atmosphere/ocean
Use satellite data to improve land surface estimates

- **Retrieval** data assimilation
  - AMSR-E/ASCAT/SMOS SM: improved surface and root-zone SM
  - AMSR-E SWE: interannual variability?
  - MODIS SCF: improved snow onset
  - GRACE TWS: improved SWE, runoff

- **Radiance** data assimilation
  - RTM calibration for SMOS/SMAP
  - prepare observation operator for AMSR-E snow assimilation

- **Modeling, Re-analysis:**
  - MERRA/MERRA-Land

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