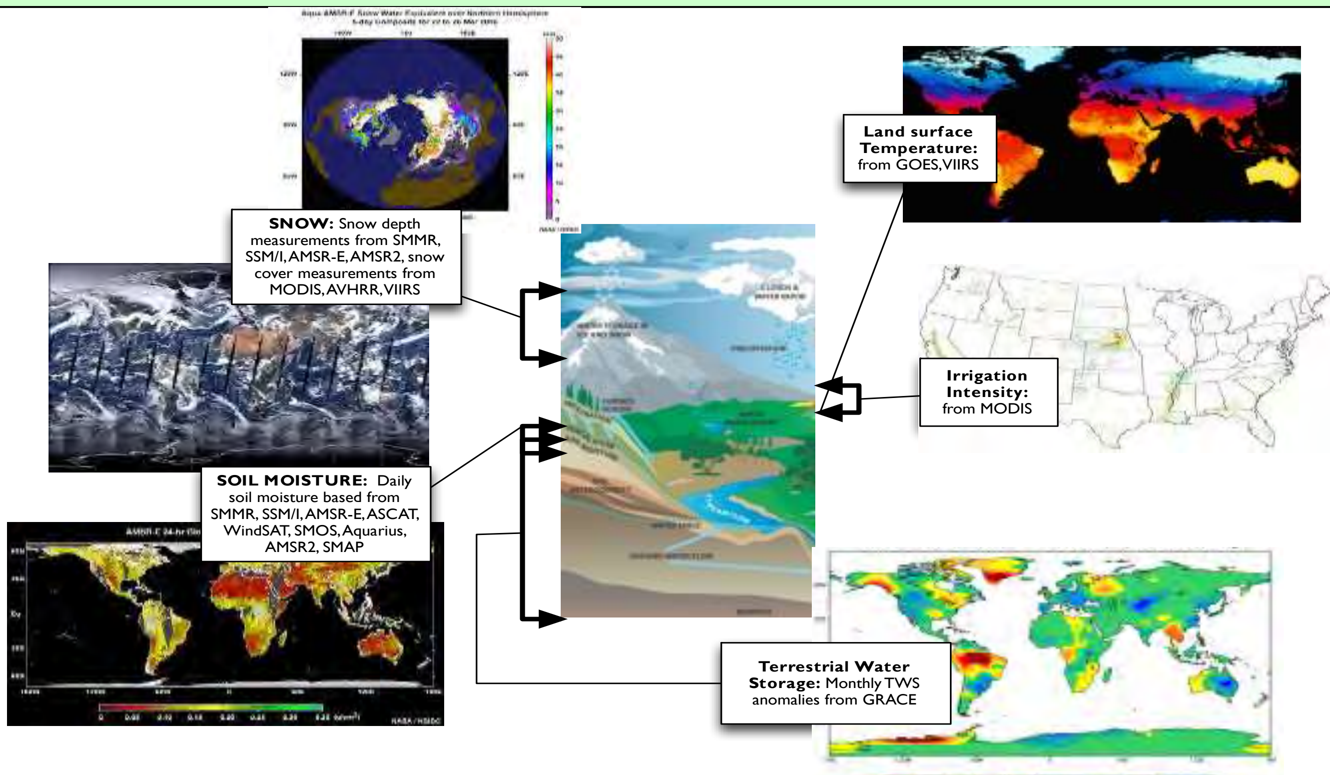
Multivariate assimilation of satellite-derived remote sensing datasets in the North American Land Data Assimilation System (NLDAS)

Sujay V. Kumar[1,2], Christa D. Peters-Lidard[1], David Mocko[1,2,3], Rolf H. Reichle[3], Benjamin Zaitchik[7], Augusto Getirana[4,2], Yuqiong Liu[4,2], Hiroko Kato[4,2], Matthew Rodell[1], Kristi Arsenault[1,2], Youlong Xia[6,5], Michael B. Ek[5]

1 – Hydrological Sciences Laboratory, NASA/GSFC, Greenbelt, MD
2 – SAIC at NASA/GSFC, Greenbelt, MD
3 – Global Modeling and Assimilation Office, NASA/GSFC, Greenbelt, MD
4 – Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD
5 – NOAA/NCEP/EMC, College Park, MD
6 – IMSG at NCEP/EMC, College Park, MD
7 –Johns Hopkins University, Baltimore, MD

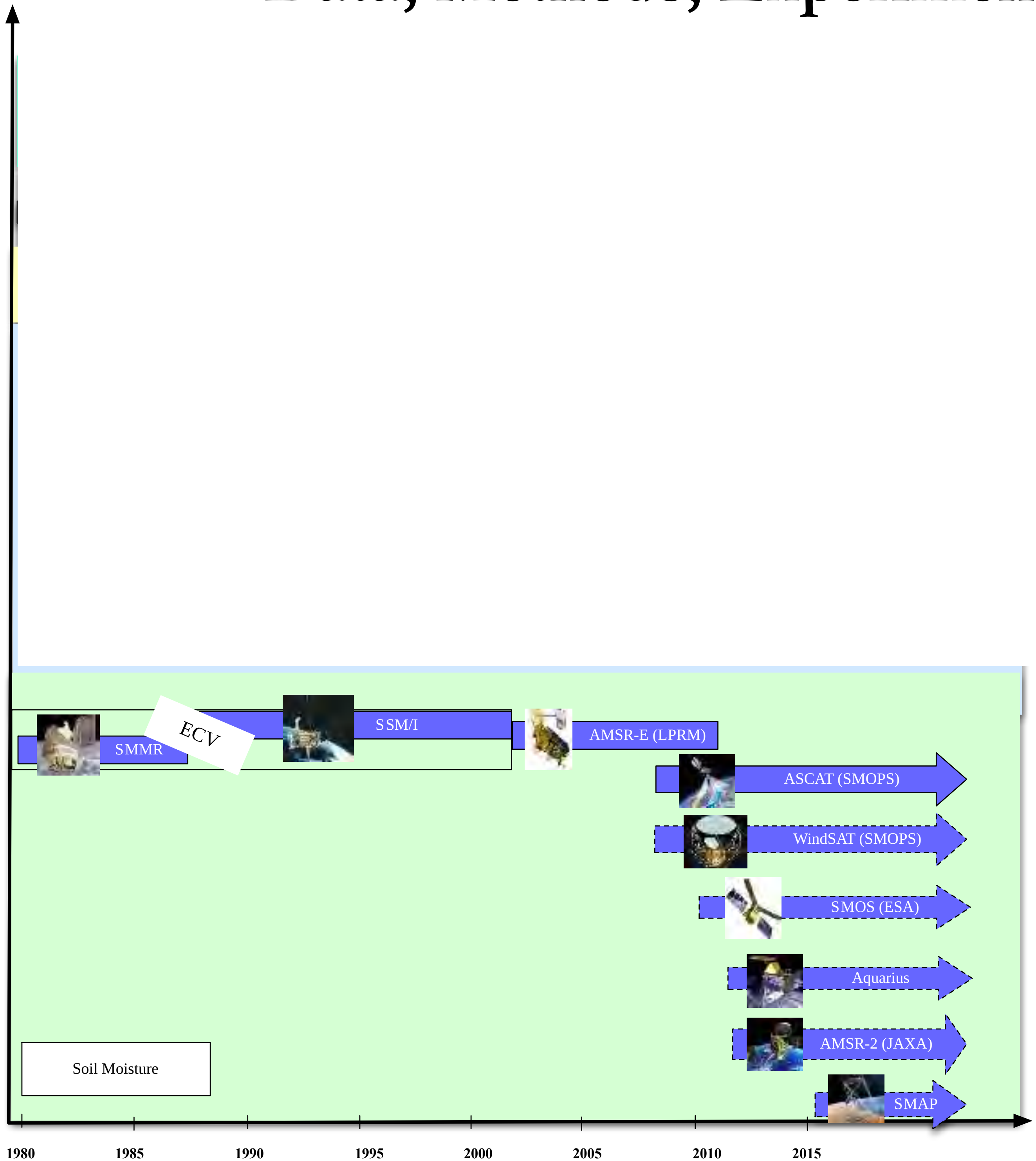
Introduction

- The North American Land Data Assimilation System (NLDAS) – a multi-institution effort
  - Domain over the continental U.S. at 1/8 degree spatial resolution
  - Over 34 years (Jan 1979 to present) of hourly land surface states, using 4 LSMs.
  - Best available observations and reanalysis to force LSMs (Precipitation forcing 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)
- NLDAS to-date, has not included the assimilation of remote sensing datasets. The focus of the new phase of NLDAS is to enable the "DA" in NLDAS.



As part of this new phase of NLDAS, we examine the assimilation of various terrestrial hydrological datasets, from 1979 onwards

Data, Methods, Experiment details



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

Forcing data: NLDAS-phase II (NLDAS2) meteorological forcing data.

Models: Noah LSM version 3.3, and CLSM Fortuna 2.5: a 60-year spin-up, followed by 34 years of simulation; streamflow simulations using HyMAP (Getirana et al. 2012)

Data assimilation method: 1-d Ensemble Kalman Filter (EnKF) and 3-d Ensemble Kalman Smoother (EnKS)

Time period: Jan 1, 1979 to 1 Jan 2013.

All simulations performed using the **NASA Land Information System (LIS; http://lis.gsfc.nasa.gov)**

Data, Methods, Experiment details

Soil moisture DA:

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

Snow DA:

Passive microwave snow depth retrievals are bias-corrected using the Cressman method using the in-situ observations from Global Historical Climate Network (GHCN).

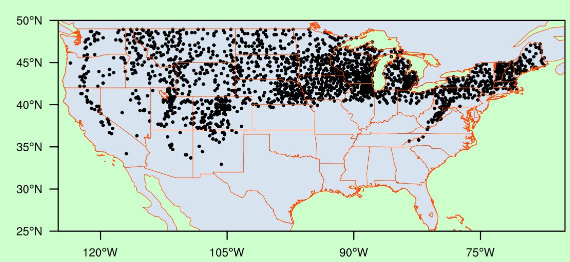
$$x^+ = x^- + \frac{\sum_{i=1}^{N} w_i (y_i - x_i^-)}{\sum_{i=1}^{N} w_i}$$

- y snow depth from obs
- x^- background field (from snow depth EDR)
- w_i weight function, which is a function of h horizontal (r) and vertical difference (h)

$$w = H(r)v(h)$$

$$H(r) = max(\frac{r_{max}^2 - r^2}{r_{max}^2 + r^2}, 0)$$

$$v(h) = \begin{cases} 1 & \text{if } 0 < h \\ \frac{h_{max}^2 - h^2}{h_{max}^2 + h^2} & \text{if } -h_{max} < h < 0 \\ 0 & \text{if } h < -h_{max} \end{cases}$$



Irrigation:

Employs a demand-driver ("sprinkler") irrigation scheme based on Ozdogan et al. JHM (2010).

Irrigation is triggered when the root zone soil moisture falls below a specified threshold (during the season, determined by green vegetation fraction/LAI)

Compute irrigation requirement as an equivalent height of water and add to the precipitation forcing

Evaluation of outputs

Soil moisture:

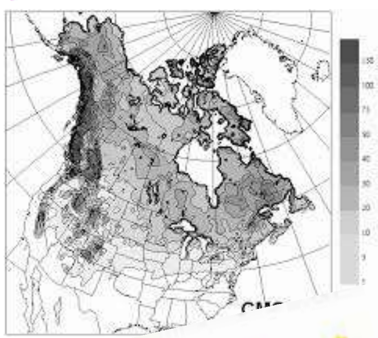
USDA Soil Climate Analysis Network (SCAN); 123 stations chosen after careful quality control (used for evaluations between 2000-2011)

Four USDA ARS experimental watersheds (“CalVal” sites) (used for evaluations between 2001-2011)

Snow depth:

Canadian Meteorological Center (CMC) daily snow depth analysis – used for evaluations between 1998-2012.

Snow Data Assimilation System (SNODAS) products from the National Operational Hydrologic Remote Sensing Center (NOHRSC) – used for evaluations between 2003/10 – 2012)

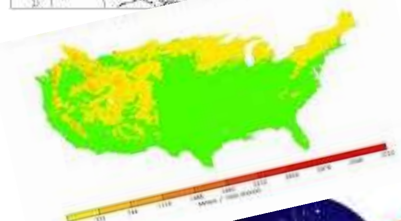


Streamflow:

Gauge measurements from unregulated USGS streamflow stations (1981-2011).

Groundwater: Gauge measurements from USGS ground water well stations (2000-2012).

Fluxes: Gridded FLUXNET (Jung et al. 2009), ALEXI (Anderson et al. 2007), UW (Tang et al. 2009) and MOD16(Mu et al. 2011)



All model verifications and analysis generated using the Land surface Verification Toolkit (LVT; Kumar et al. 2012)

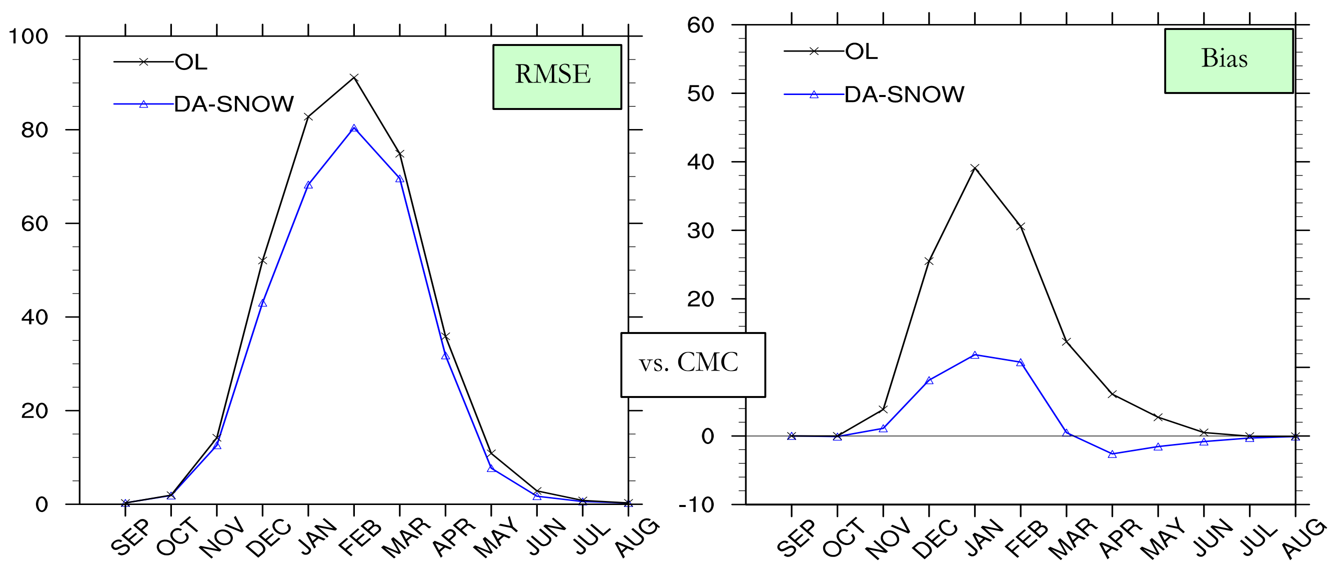
Soil moisture and snow depth assimilation

A recent study examined the **individual** assimilation of soil moisture (ECV, LPRM) and snow (SMMR, SSMI, AMSR-E) data sets, into the Noah LSM (Kumar et al., JHM 2014).

The open loop soil moisture skills are high and assimilation improvements in soil moisture were small and barely at the statistically significant levels.

The assimilation of snow depth datasets were found to generally improve the snow fields.

ARS CalVal (surface soil moisture)	**Open loop (no DA)**	**DA-SM**
Anomaly R	0.84 +/- 0.02	**0.86 +/- 0.02**
SCAN (surface soil moisture)	**Open loop (no DA)**	**DA-SM**
Anomaly R	0.67 +/- 0.02	0.67 +/- 0.02
SCAN (root zone soil moisture)	**Open loop (no DA)**	**DA-SM**
Anomaly R	0.60 +/- 0.02	0.59 +/- 0.02

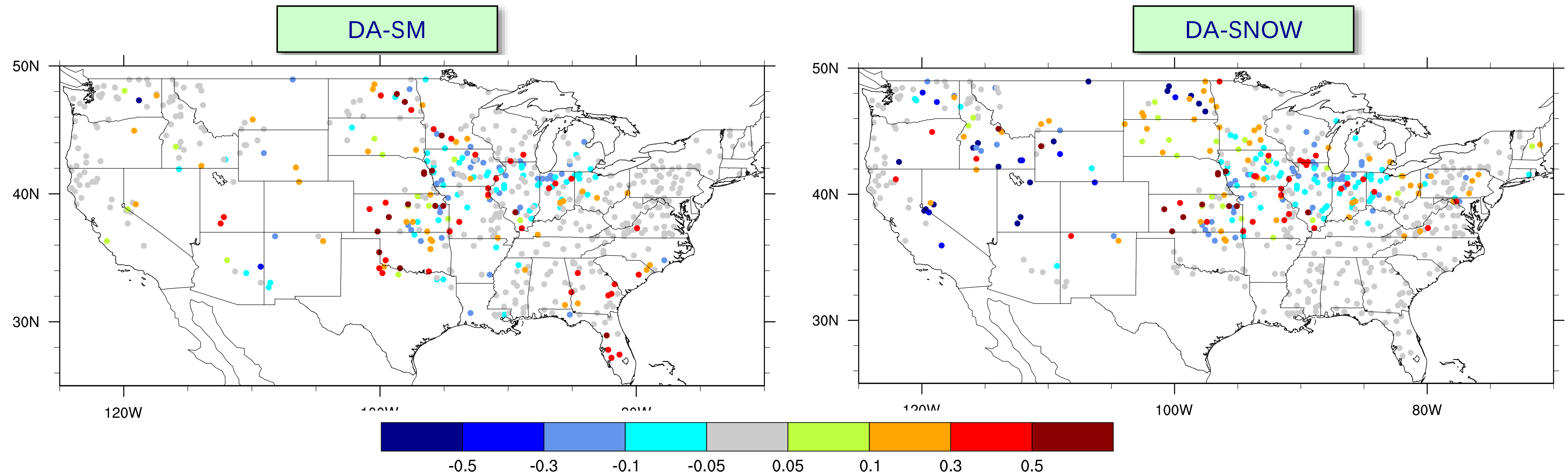


Kumar, S.V., C.D. Peters-Lidard, D. Mocko, R. Reichle, Y. Liu, K.A. Arsenault, Y. Xia, M. Ek, G. Riggs, B. Livneh, M. Cosh (2014), "Assimilation of remotely sensed soil moisture and snow depth retrievals for drought estimation" *Journal of Hydrometeorology,* in press.

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

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



Minor improvements are observed in streamflow estimates with soil moisture data assimilation. Snow DA indicates a slight overall degradation.

Skill improvements from soil moisture assimilation are mostly over parts of the Mississippi, Missouri and Arkansas-Red basins and parts of Southeastern U.S. Notable degradations due to snow DA are observed over Colorado headwater region and over Northwest U.S.

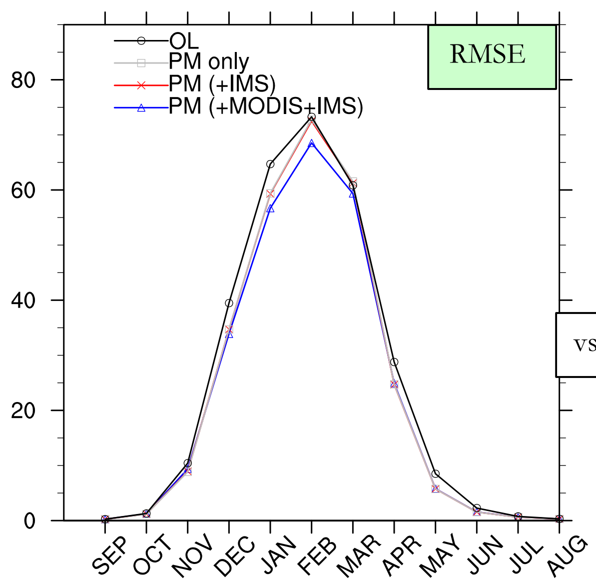
A refined approach for Snow DA

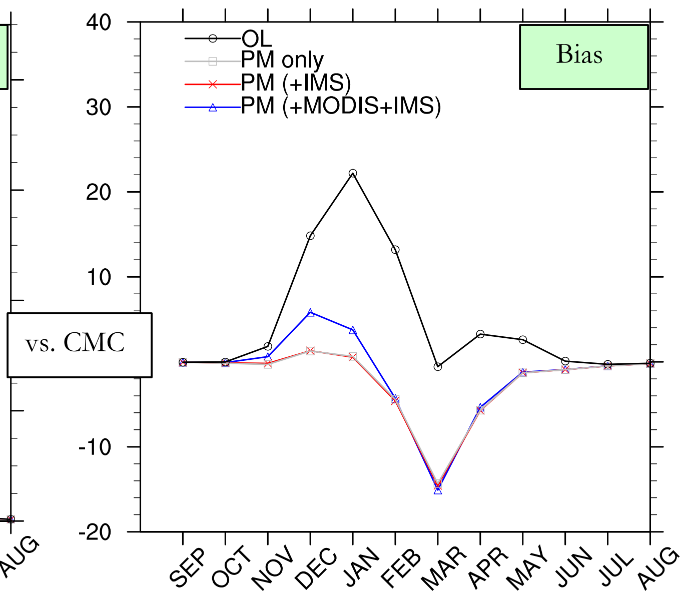
Snow DA approach was updated to use visible snow cover data (IMS/MODIS) as an added constraint.

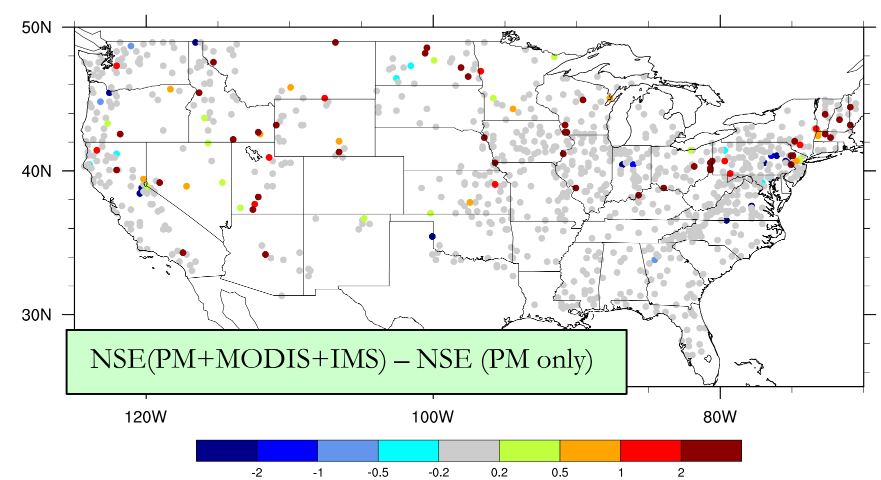
SCA observations are used as the default for identifying the presence or absence of snow.

If SCA indicates no-snow, zero snow depth is assimilated. If SCA indicates non-zero snow and passive microwave data indicates no-snow, then snow depth data is not assimilated.

Non-zero snow depth from passive microwave data is assimilated only if SCA data also indicates non-zero snow.





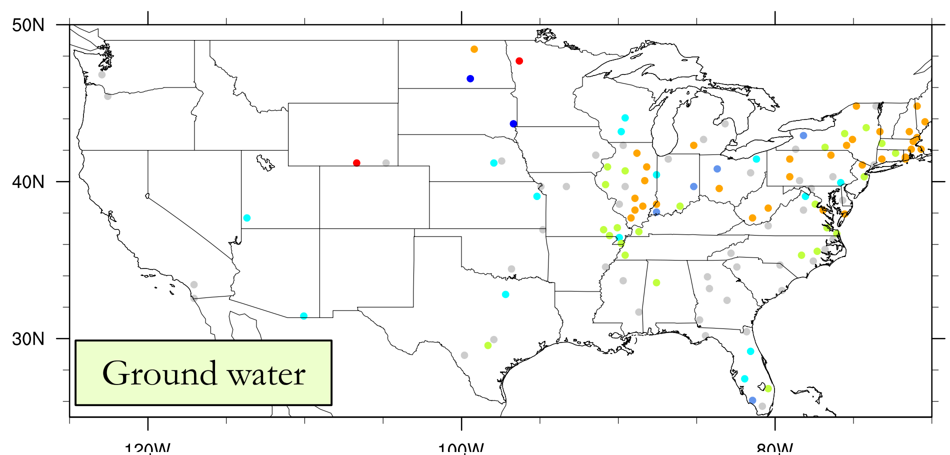


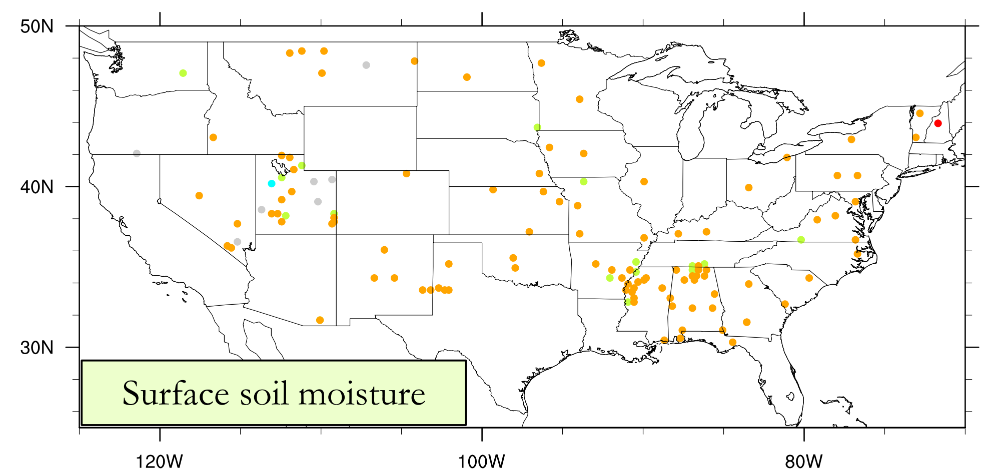
The use of SCA data is helpful in providing added improvements to the passive microwave snow data assimilation.

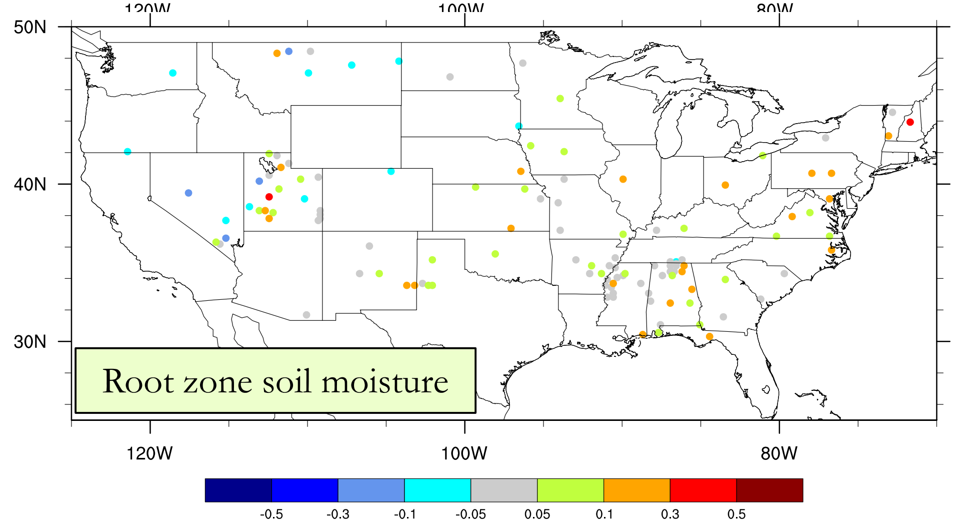
Kumar et al., (2014), Quantifying the added value of snow cover area observations in passive microwave snow depth data assimilation, Geophys. Res. Lett., in revisions.

Assimilation of GRACE data
(evaluation of ground water, soil moisture)

Maps show Anomaly R differences – Anomaly R(DA) – Anomaly R (OL); Warm colors indicate improvements and cool colors indicate degradations.



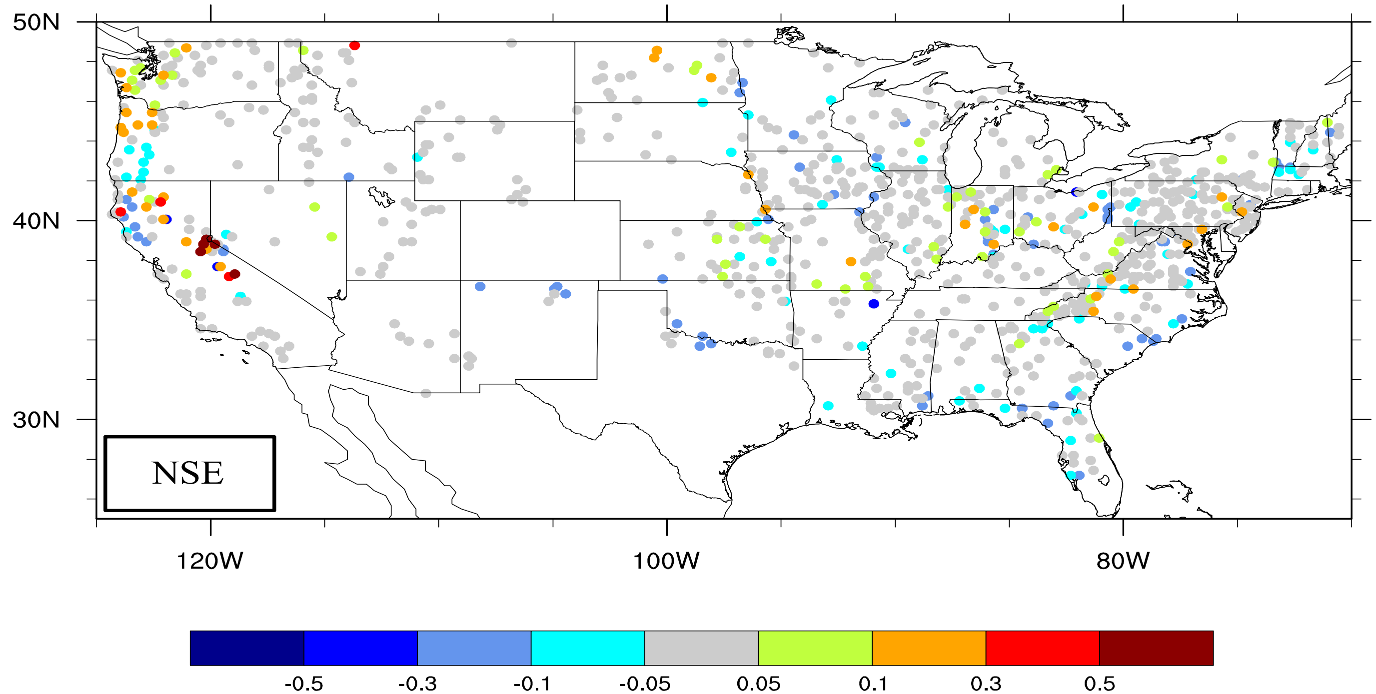




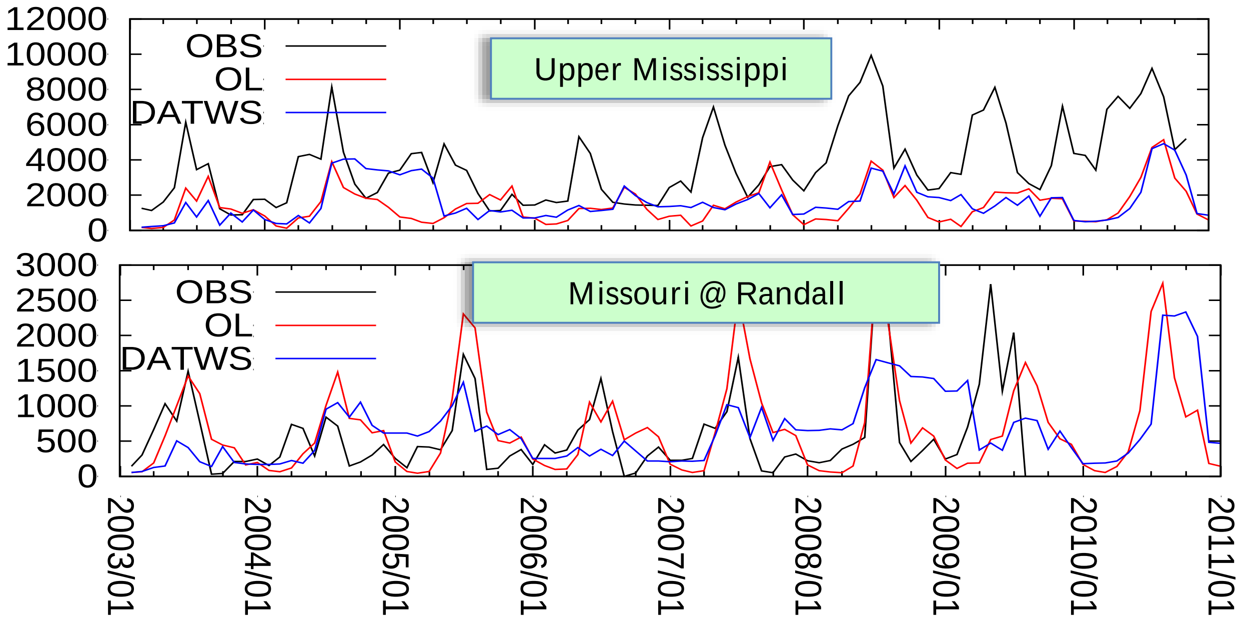
Anomaly R	OL	DA-TWS
Ground water	0.64 +/- 0.02	**0.69 +/- 0.02**
Surface soil moisture	0.44+/- 0.02	**0.59 +/- 0.02**
Root zone soil moisture	0.48 +/- 0.02	**0.53 +/- 0.02**

Statistically significant improvements in ground water and soil moisture fields from GRACE data assimilation

Assimilation of GRACE data (streamflow evaluation)



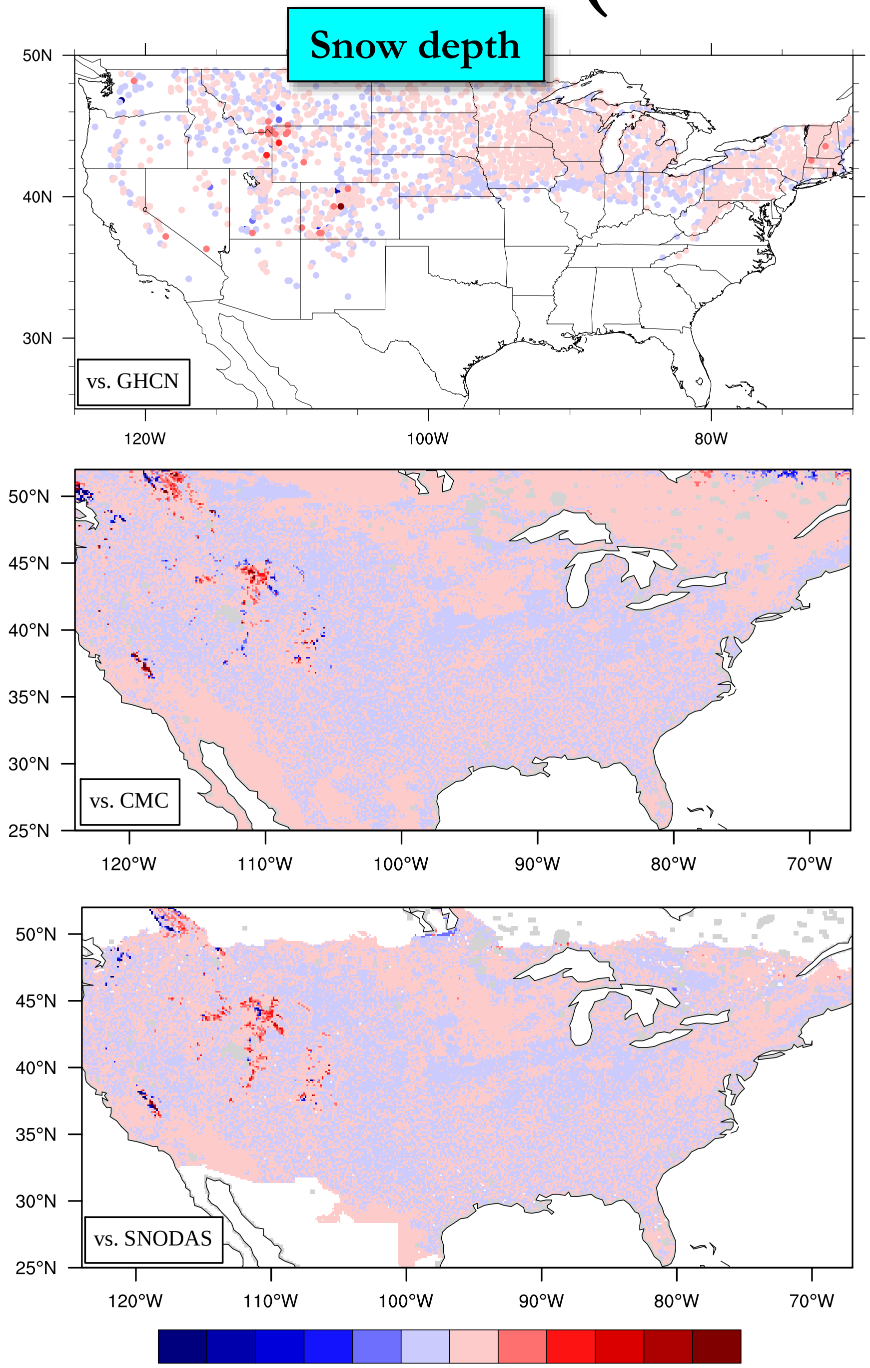
NIC maps of NSE; Warm colors indicate improvements and cool colors indicate degradations.

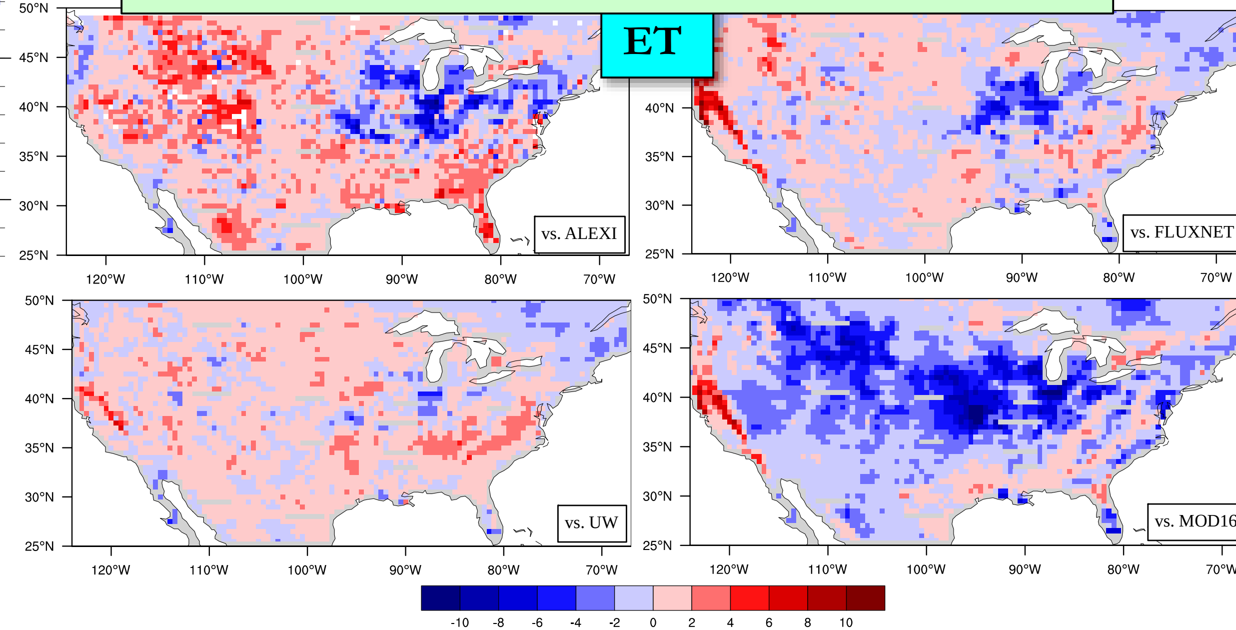


Streamflow improvements in West coast, Upper Mississippi, North east, degradations in South east, Lower Mississippi, Texas.

Assimilation of GRACE data (evaluation of snow, ET)

RMSE (OL) – RMSE (DA) ; Warm colors indicate improvements and cool colors indicate degradations.





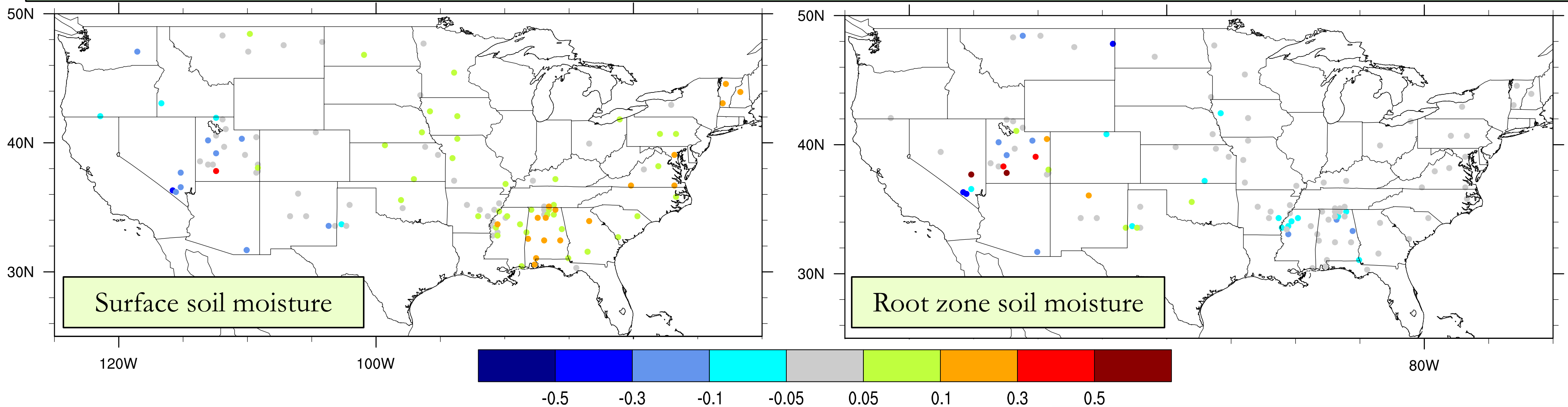
The impacts on snow and ET from GRACE-DA are small, but all evaluations show encouraging, positive and statistically significant trends.

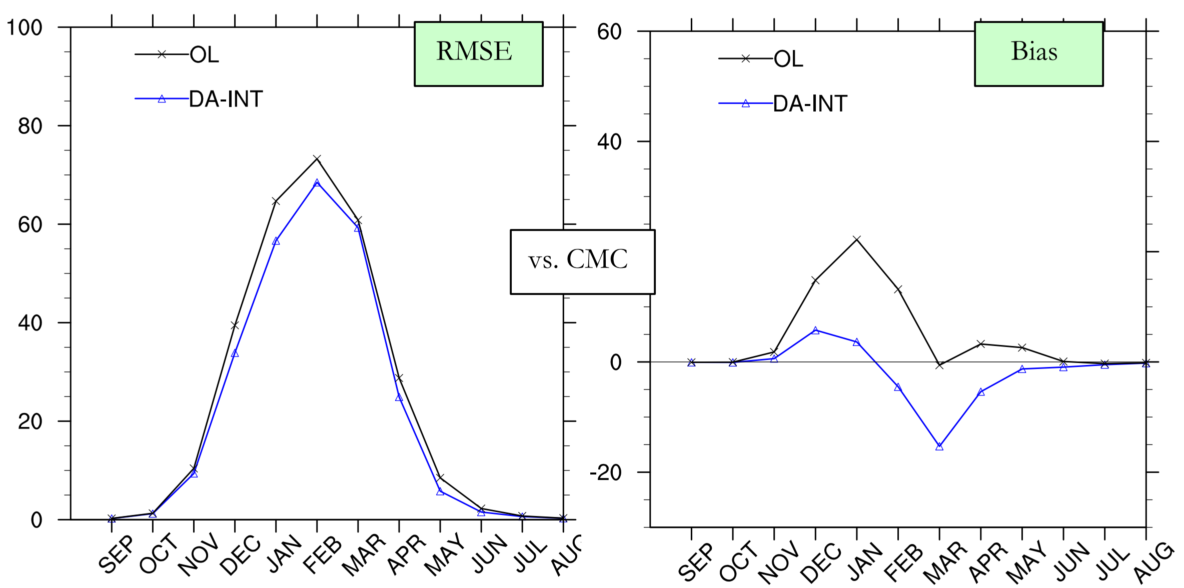
For snow, all three products show consistent patterns of improvement over parts of the Rockies, Sierra, and Cascade mountains.

For ET, comparisons against ALEXI, FLUXNET and UW show similar patterns of improvements and degradations.

Multi-variate assimilation with Noah LSM (soil moisture, snow depth, snow cover, irrigation)

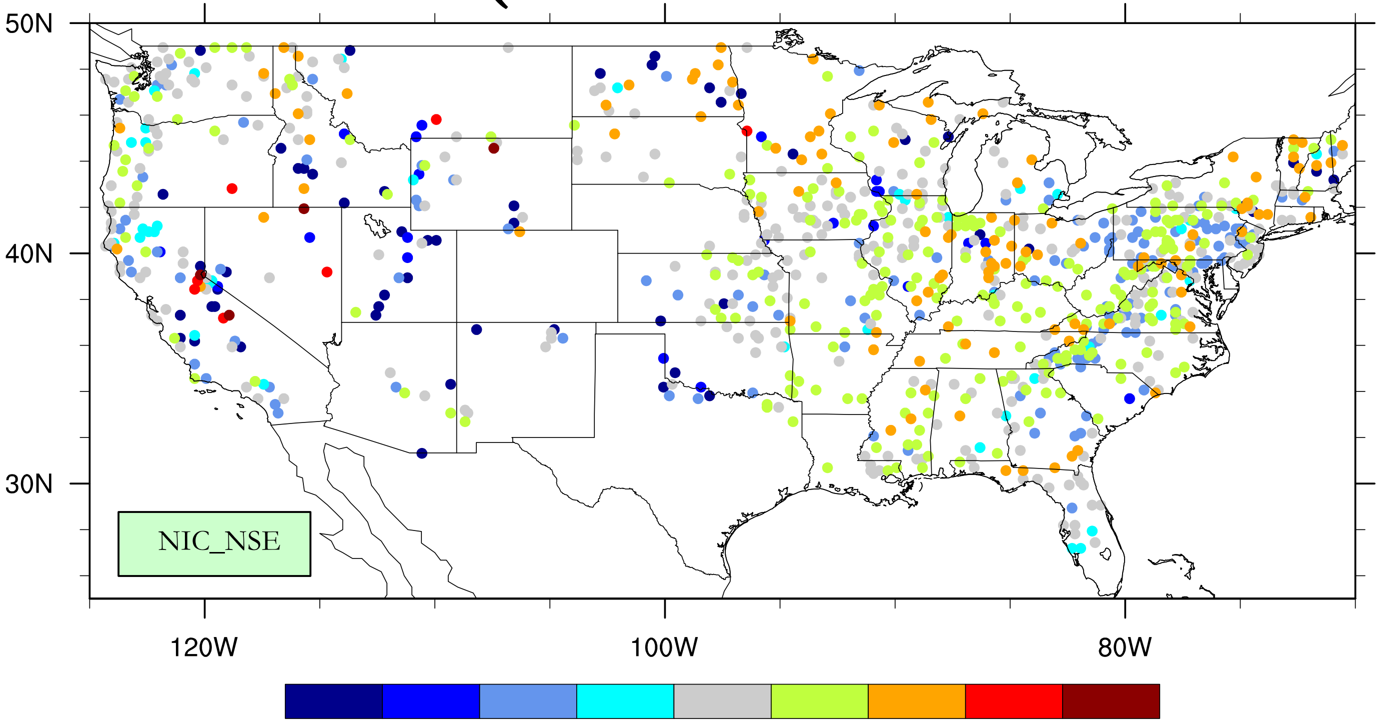
Maps show Anomaly R differences – Anomaly R(DA) – Anomaly R (OL); Warm colors indicate improvements and cool colors indicate degradations.

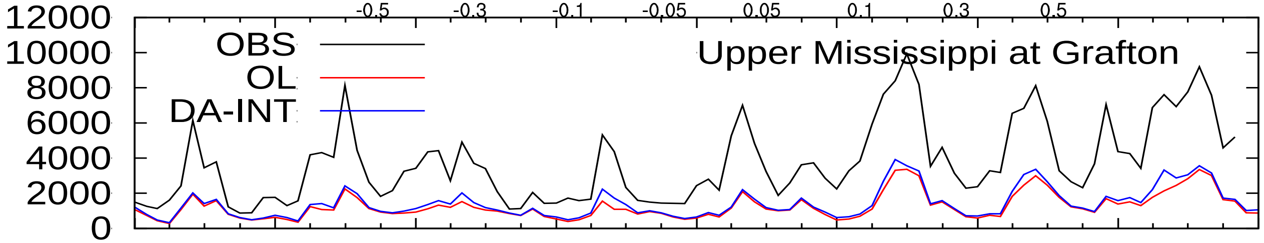


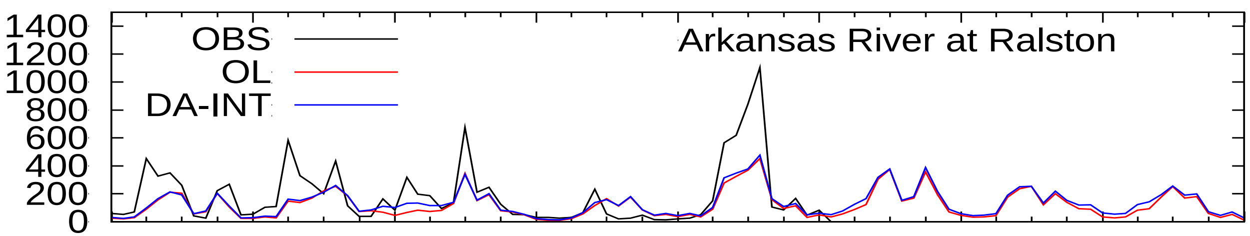


The improvements in soil moisture fields are small, some degradation in the western locations observed. Snow depth fields are generally improved, with more biases significantly reduced during the peak snow season. However, during the melt periods DA simulation shows an increased negative bias.

Concurrent assimilation with Noah LSM (evaluation of streamflow)



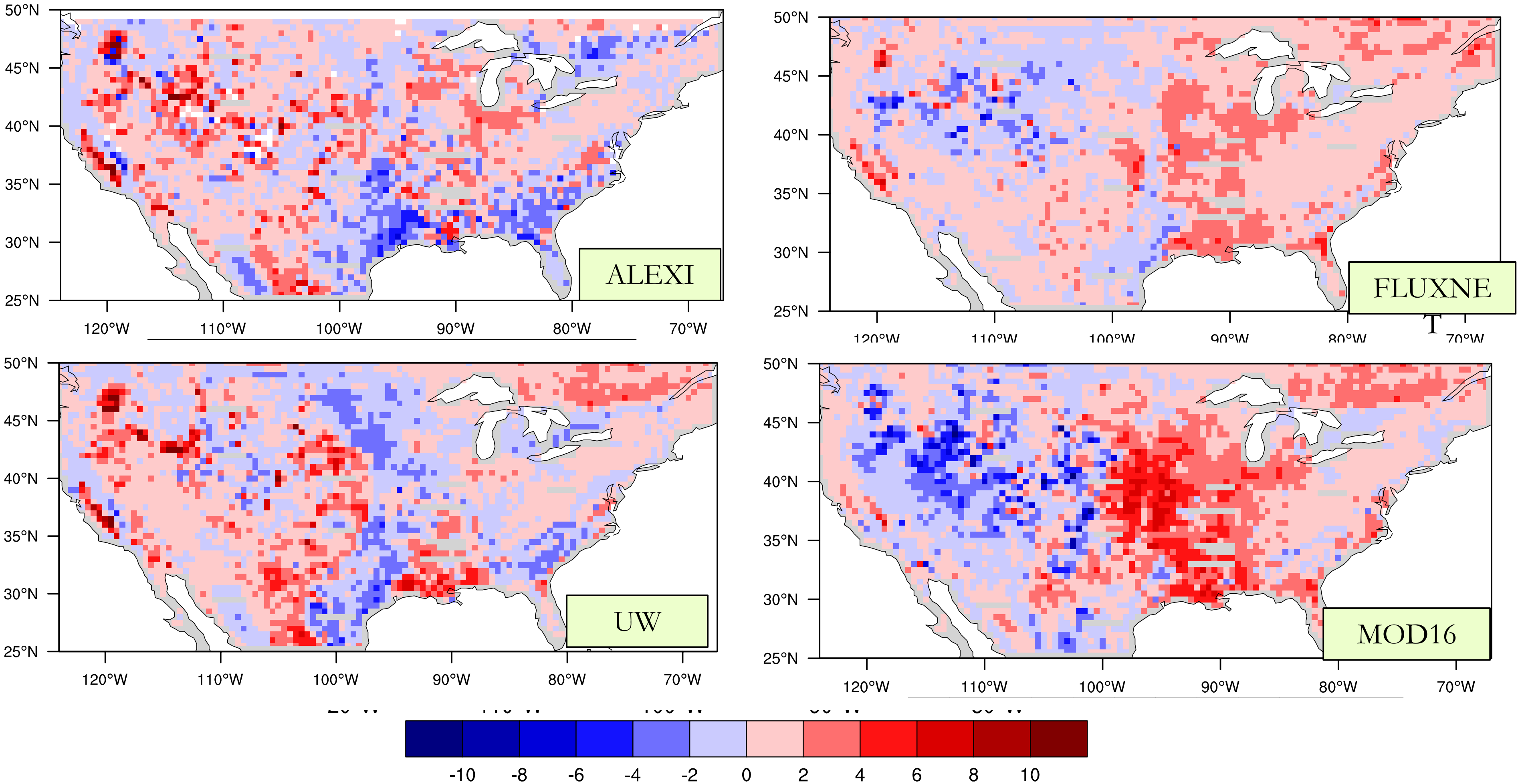




Generally improvements in streamflow simulation are observed in most parts of the domain. Notable degradations are in the Western U.S.

The streamflow improvements at major basin outlets are small (e.g. comparisons at Upper Mississippi and Arkansas river outlets show small improvements in streamflow magnitudes).

Multi-variate assimiliation with Noah LSM (evaluation of ET)



Similar patters in the ALEXI and UW comparisons (these datasets are expected to capture artifacts of irrigation) and FLUXNET and MOD16. Improvements in ET are obtained (in ALEXI, UW comparisons) over Nebraska, Sierra Nevada, Lower Mississippi - prominent regions with irrigation.

Summary

- The assimilation of remotely sensed, passive microwave-based soil moisture and snow datasets were employed into the NLDAS configuration
- The improvements in soil moisture fields were barely at the statistically significant levels, but these small improvements translated to small improvements in streamflow.
- Snow data assimilation was found to generally improve the snow fields, with some notable degradations observed in the Western U.S. Use of visible snow cover data was helpful for improving the use of passive microwave snow depth data for data assimilation.
- GRACE data assimilation was found to significant improvements in groundwater, soil moisture and smaller improvements in streamflow, snow and ET.
- Concurrent assimilation (soil moisture, snow, irrigation) with Noah shows promise; Generally small (but statistically significant) improvements are observed across various water budget components.
- Current work is focused on enabling concurrent data assimilation with other NLDAS land surface models (e.g. CLSM) and other datasets (e.g., GRACE, LST).