Land surface modeling and data assimilation with the NASA Land Information System (LIS)

http://lis.gsfc.nasa.gov

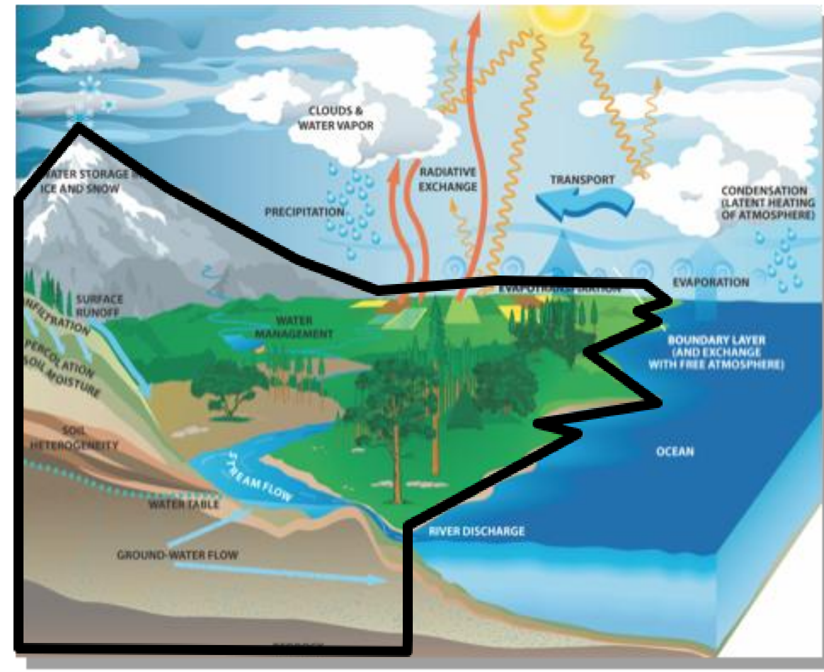
Sujay V. Kumar

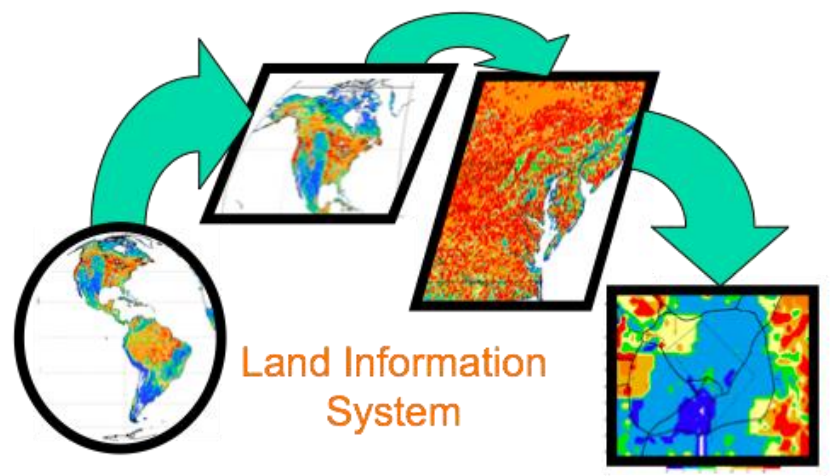
Science Applications International Corporation,

Hydrological Sciences Laboratory, Goddard Space Flight Center

NASA Land Information System (LIS)

- A system to study land surface processes and land-atmosphere interactions
  - “Use best available observations” to constrain and inform models.
- Runs a variety of land surface models
- Integrates satellite, ground and reanalysis data
- Includes high performance support for fine resolution modeling
- Built as a flexible framework that allows the interoperable use of data and models
- Coupled to other Earth system models
- Includes a number of computational subsystems for exploiting information from observations.

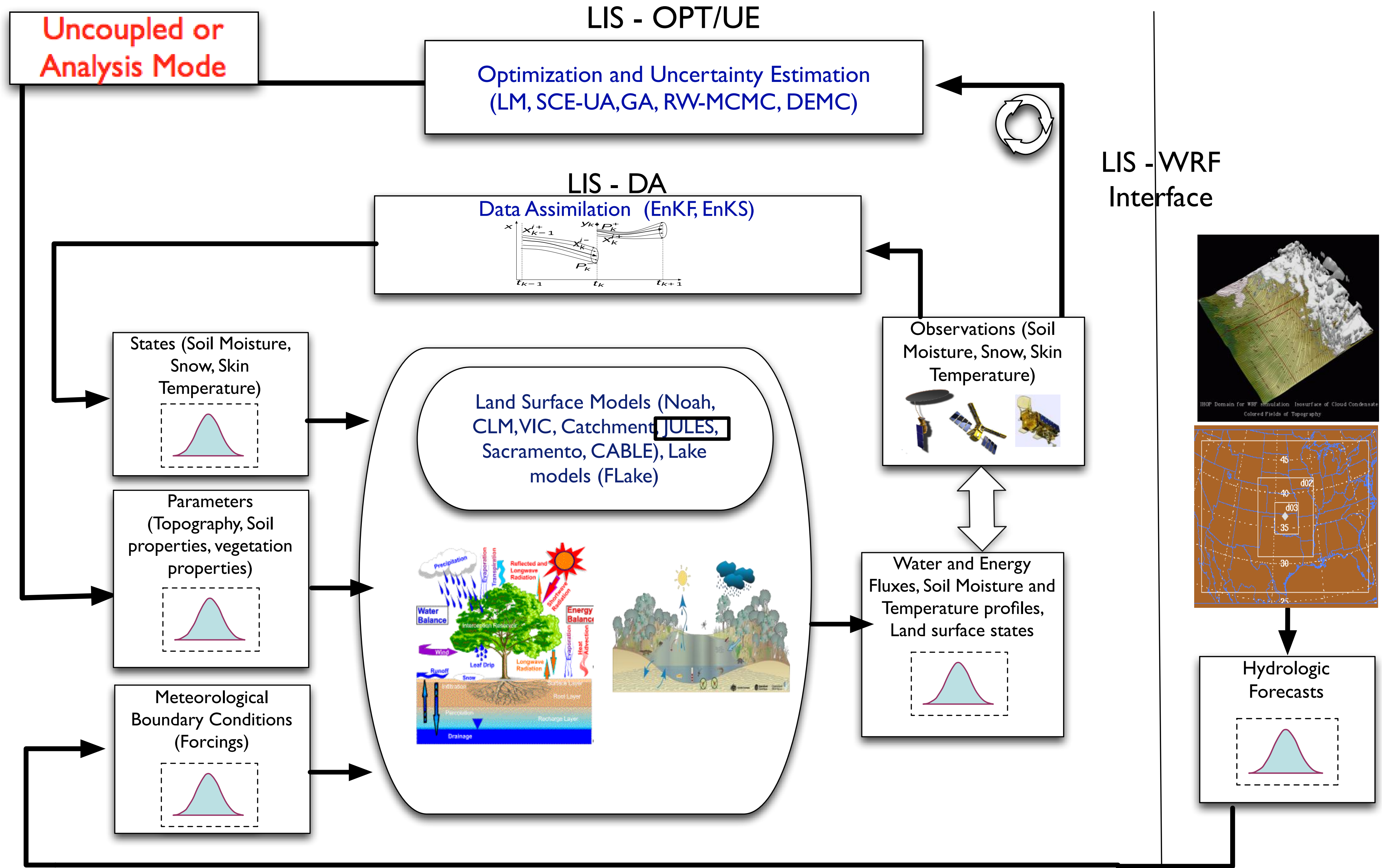




Kumar et al. (2006): Land Information System: An interoperable Framework for High Resolution Land Surface Modeling, Environmental Modeling and Software, Vol 21, pp 1402-1415.

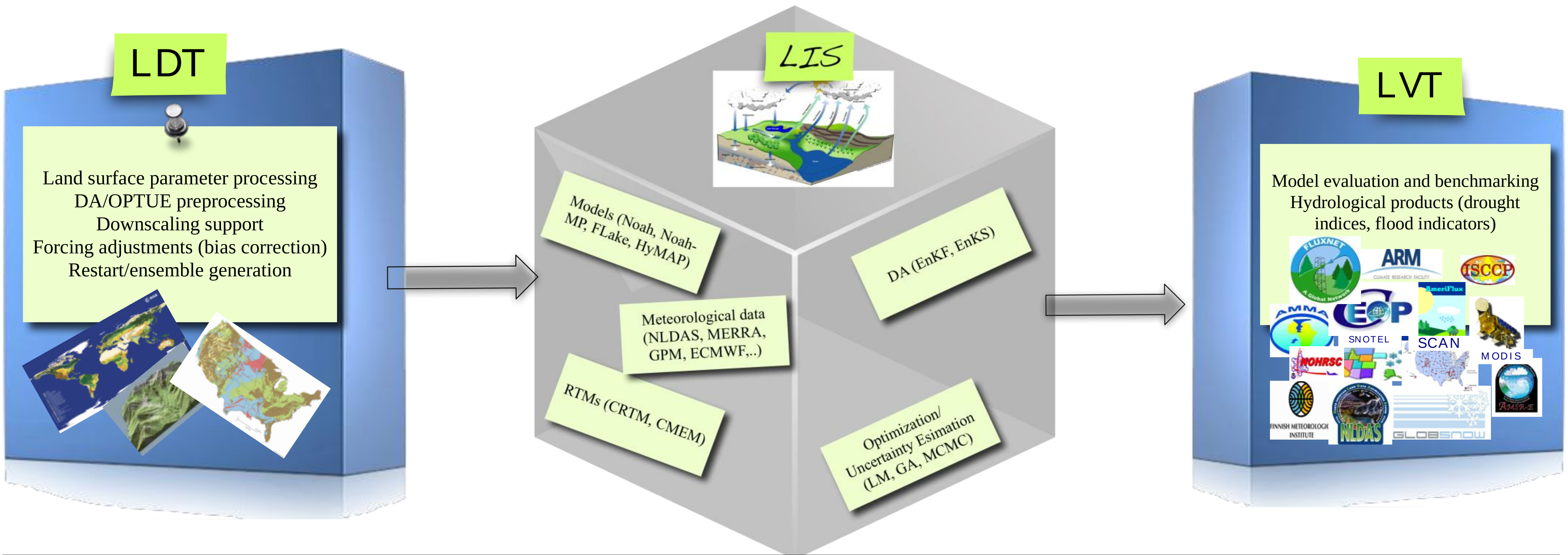
Peter-Lidard et al. (2007): High-performance earth system modeling with NASA/GSFC’s Land Information System, Innovations in Systems and Software Engineering, 3(3),157—165.

Computational subsystems and coupled models with LIS



Kumar, S.V., C.D. Peters-Lidard, J.L. Eastman, W.-K. Tao (2007), An integrated High Resolution Hydrometeorological Modeling Testbed using LIS and WRF, *Environmental Modeling and Software*, 23(2), 169-181.

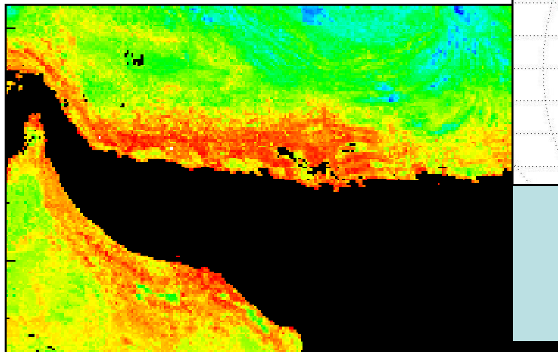
LIS subsystems and toolkits



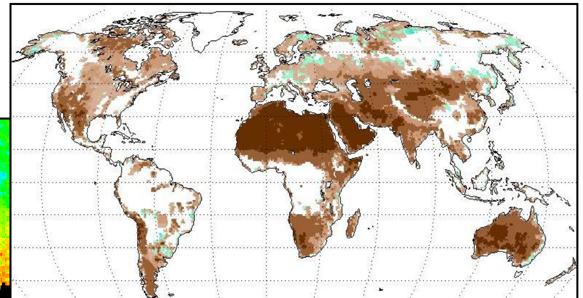
- LIS – modeling environment that encapsulates:
  - Land surface models, data assimilation support, radiative transfer models, meteorological data support.
- Land surface Data Toolkit (LDT) supports preprocessing needs of LIS:
  - Processing of land surface parameters from their native sources
  - Downscaling and bias correction of forcing data
  - Data fusion algorithms (ANNs, statistical learning)
- Land verification Toolkit (LVT) supports postprocessing, evaluation, benchmarking
  - Large suite of analysis metrics
  - Support for in-situ, reanalysis and remote sensing data.

Kumar et al. (2012), Land surface Verification Toolkit (LVT) – A generalized framework for land surface model evaluation, Geosci. Model. Dev.

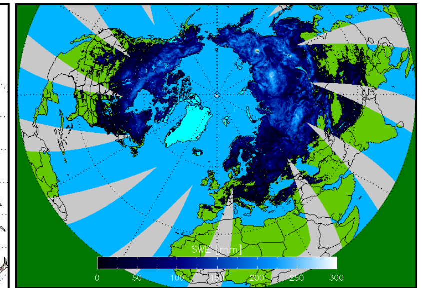
Remote sensing data for land data assimilation



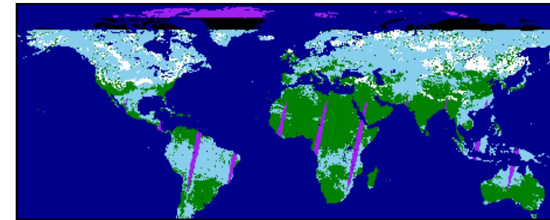
Land surface temperature
(MODIS, AVHRR,GOES,…)



Surface soil moisture
(SMMR, TRMM, AMSR-E, *SMOS, Aquarius, SMAP*)

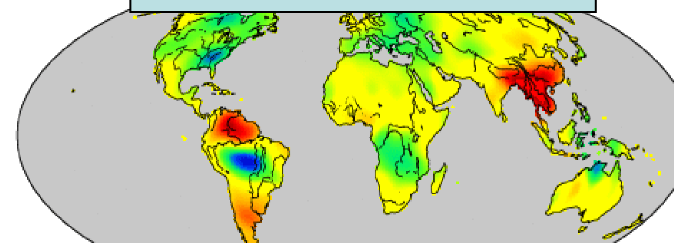


Snow water equivalent
(AMSR-E, SSM/I, *SCLP*)

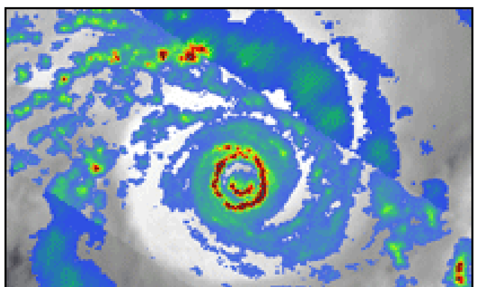


Snow cover fraction
(MODIS, *VIIRS*, *MIS*)

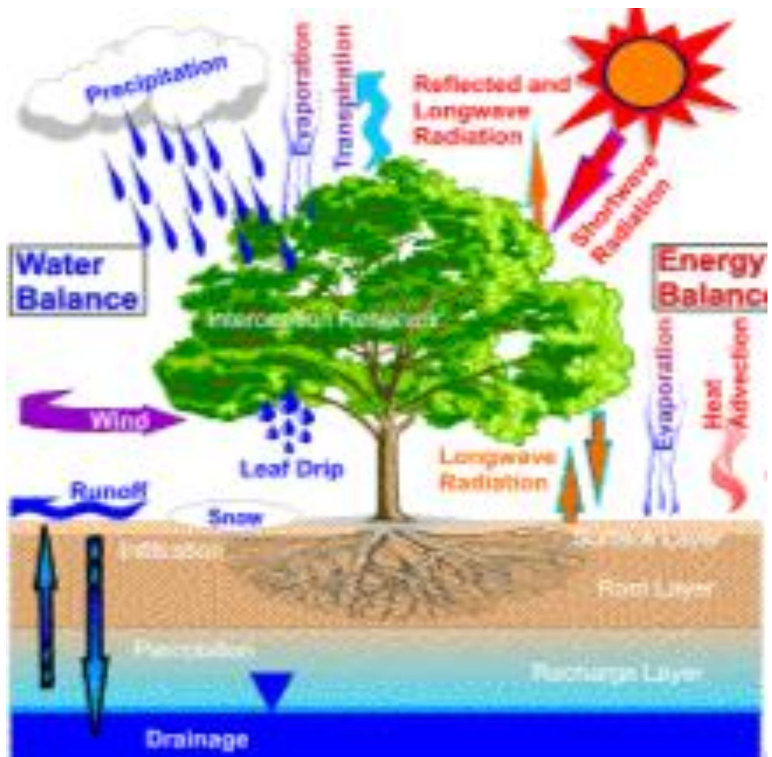
Water surface elevation
(*SWOT*)

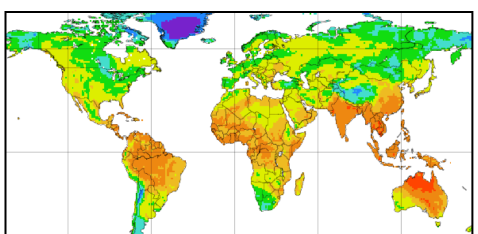


Terrestrial water storage (GRACE)



Precipitation
(TRMM, *GPM*)



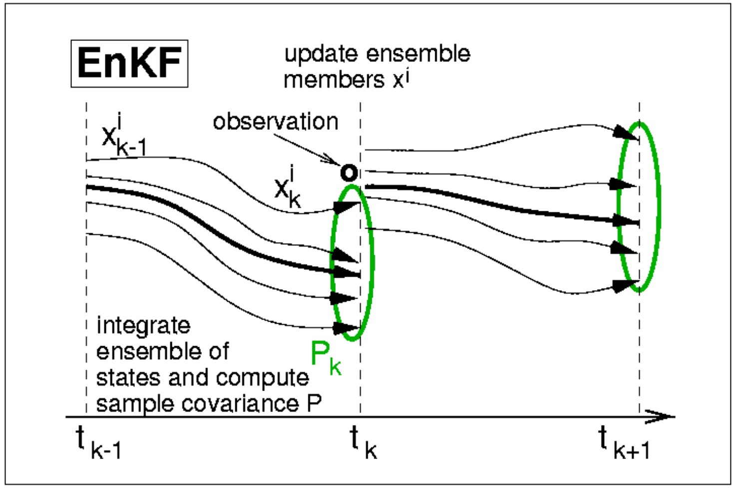


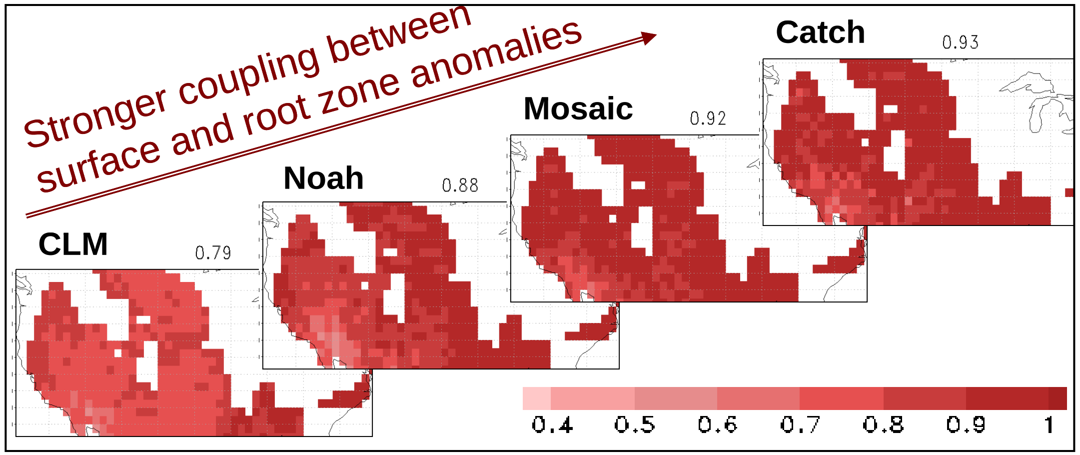
Radiation
(CERES, *CLARREO*)

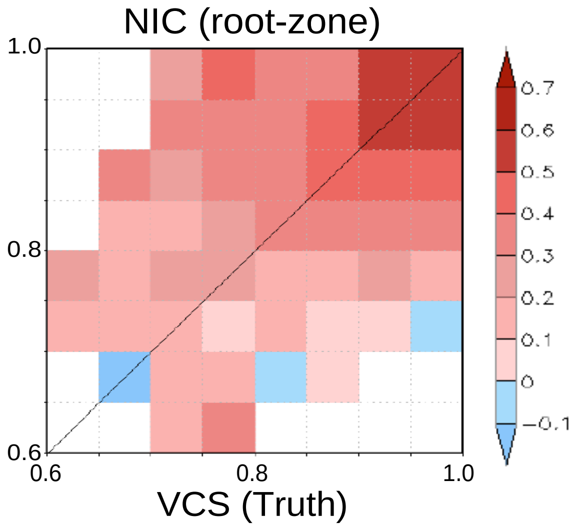
Vegetation/Carbon
(AVHRR, MODIS, *DESDynI, ICESat-II, HyspIRI, LIST, ASCENDS*)

Data Assimilation subsystem in LIS

- Primarily used for state estimation - Corrects model states based on observations
- Advanced algorithms such as the Ensemble Kalman Filter (EnKF), Ensemble Kalman Smoother (EnKS)
- Supports the interoperable use of multiple land surface models, multiple algorithms and multiple observational data sources
- Support for concurrent data assimilation, forward models, radiance assimilation, observation operators employing advanced data fusion methods (deep learning)







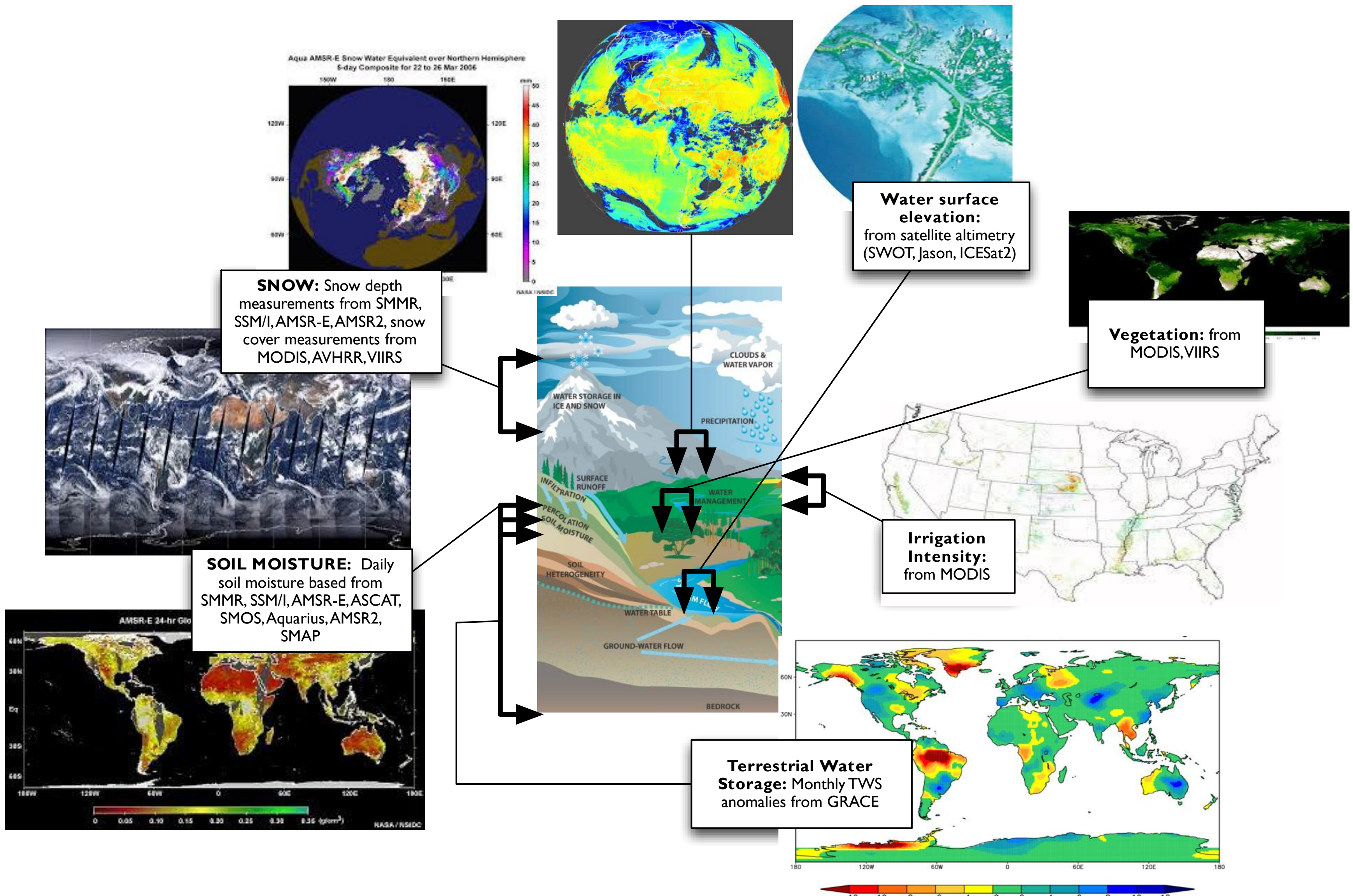
NIC = normalized information contribution

VCS = vertical coupling strength

Stronger coupling between surface and root zone provides more "efficient" assimilation of surface observations.

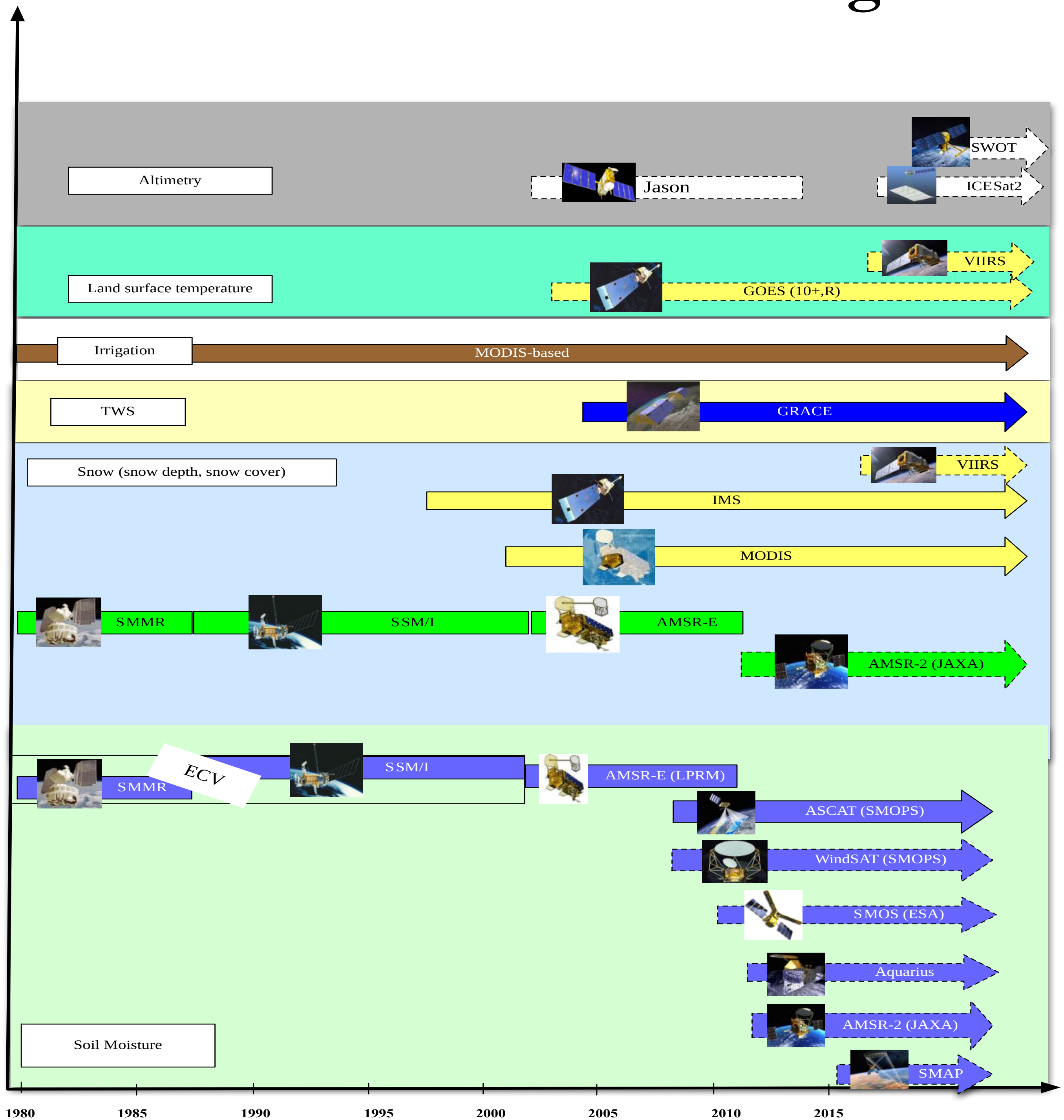
Kumar, S.V., R.H. Reichle, C.D. Peters-Lidard, R.D. Koster, X. Zhan, W.T. Crow, J.B. Eylander, P.R. Houser (2008), A Land Surface Data Assimilation Framework using the Land Information System: Description and Applications, *Adv. Wat. Res.*, 31, 1419-1432.

An Integrated Terrestrial Water Analysis System enabled by LIS



A unique analysis that concurrently employs a comprehensive set of remote sensing measurements to constrain terrestrial water budget terms in the NLDAS configuration, using LIS-DA capabilities.

NLDAS configuration



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.

Boxes with solid lines represent products that are currently assimilated, dashed boxes represent products in pipeline

Evaluation of NLDAS 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.

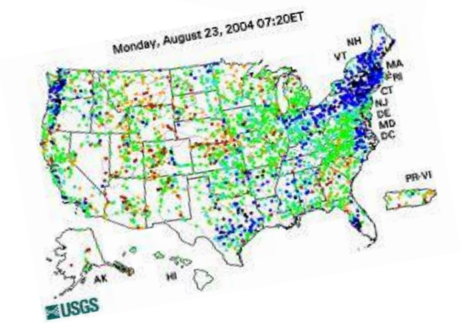
Snow Data Assimilation System (SNODAS) products from the National Operational Hydrologic Remote Sensing Center (NOHRSC) – used for evaluations between 2003/10 – 2012)

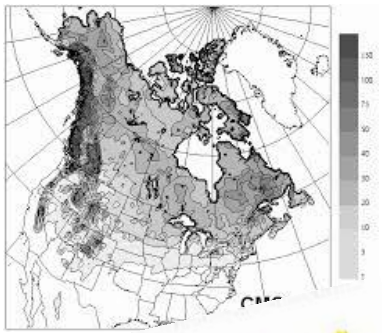
Streamflow:

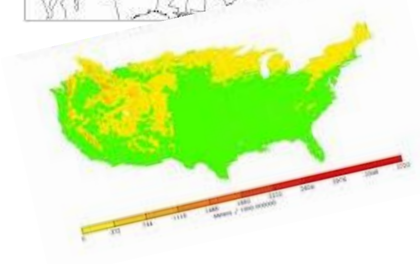
Gauge measurements from unregulated USGS streamflow stations (1981-2011).

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)







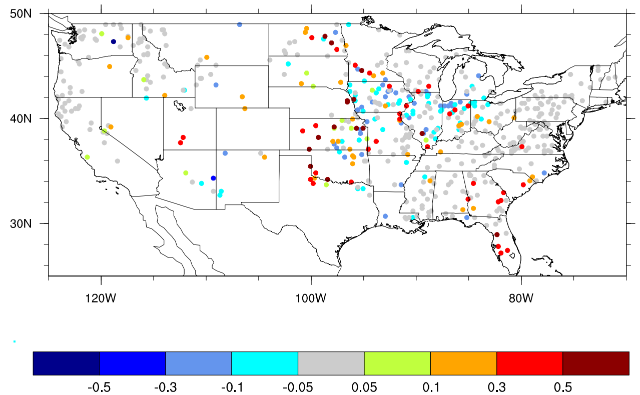
All model verifications and analysis generated using the Land surface Verification Toolkit (LVT; Kumar et al. 2012)

Assimilation of remotely sensed soil moisture measurements in NLDAS (Univariate assimilation)

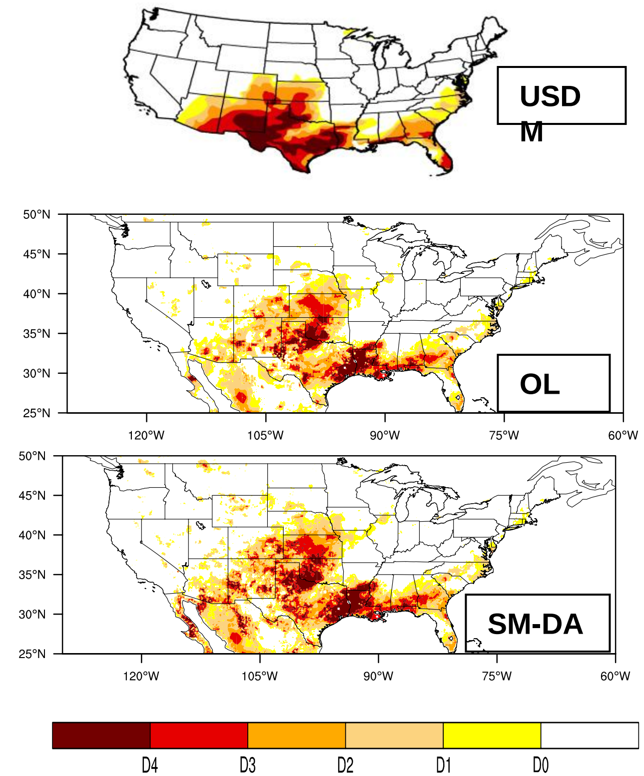
The impact of assimilating soil moisture retrievals from SMMR, SSMI, AMSR-E, ASCAT into the Noah LSM during a time period of 1979-2012.

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

Impact of soil moisture DA on soil moisture skills



Impact of soil moisture DA on streamflow skills (Warm colors indicate locations where DA provides improvement in streamflow NSE and cool colors indicate locations where DA leads to degradation in streamflow NSE)



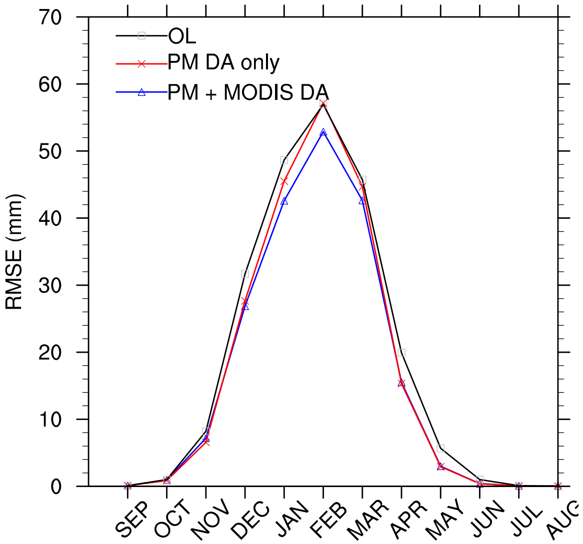
Impact of soil moisture DA on drought estimates (May 10-17, 2011).

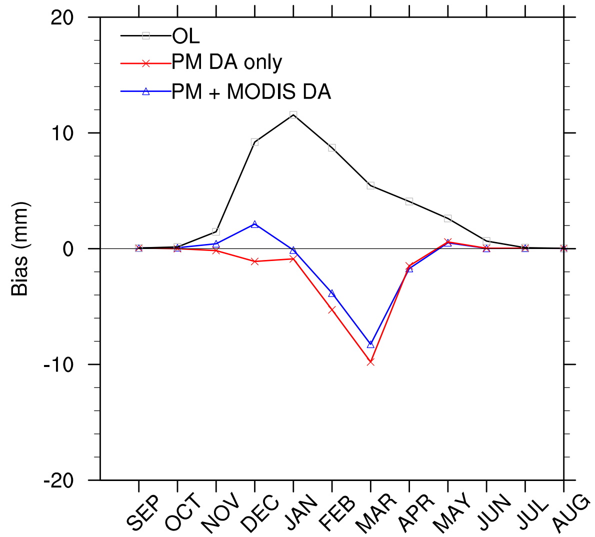
- Improvements in soil moisture fields are barely at the statistically significant levels
- Small improvements in streamflow
- Improvements in drought estimates at short time scales are seen from soil moisture DA

Kumar, S.V., C.D. Peters-Lidard, D. Mocko, R. Reichle, Y. Liu, K. 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*, 15, 2446-2469, doi: http://dx.doi.org/10.1175/JHM-D-13-0132.1

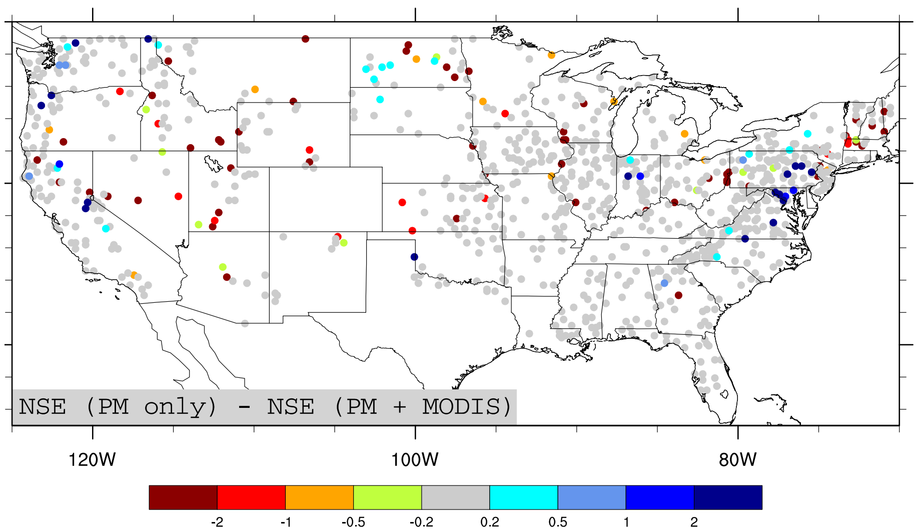
Assimilation of remotely sensed snow depth and snow cover measurements in the NLDAS (Univariate assimilation)

Quantify the added impact of using snow covered area (SCA) from MODIS during the assimilation of passive microwave snow depth observations.





Average seasonal cycle of RMSE and Bias for snow depth from the open loop (OL) and DA integrations



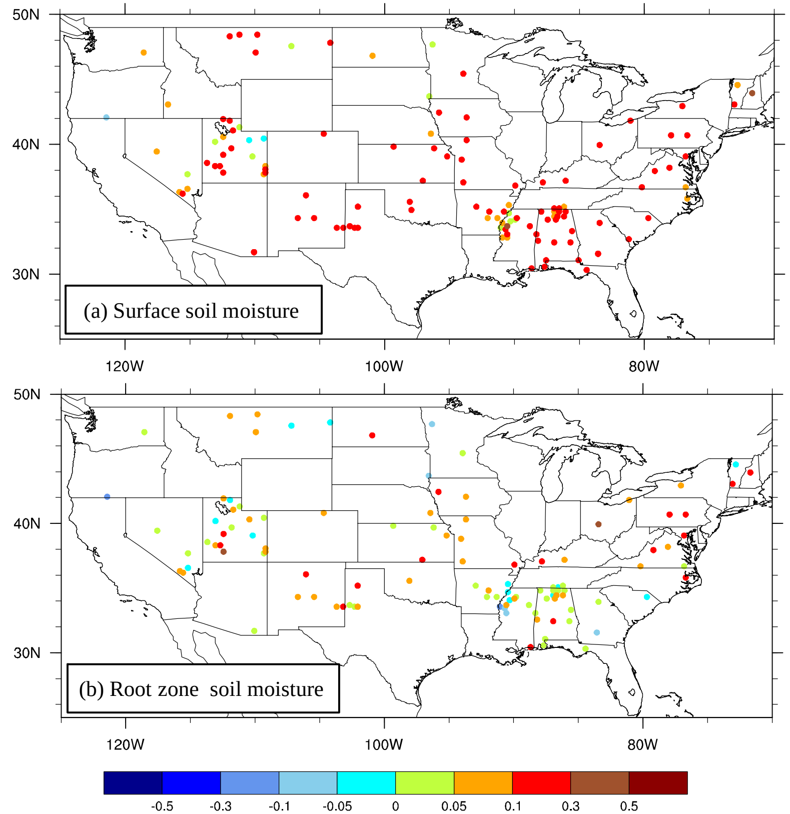
Differences in NSE of streamflow estimates from the use of MODIS SCA over passive microwave data alone

- The use of MODIS data provides systematic improvements in snow depth fields over the assimilation of passive microwave data alone.
- These improvements are translated to improvements in streamflow, especially in the western U.S.

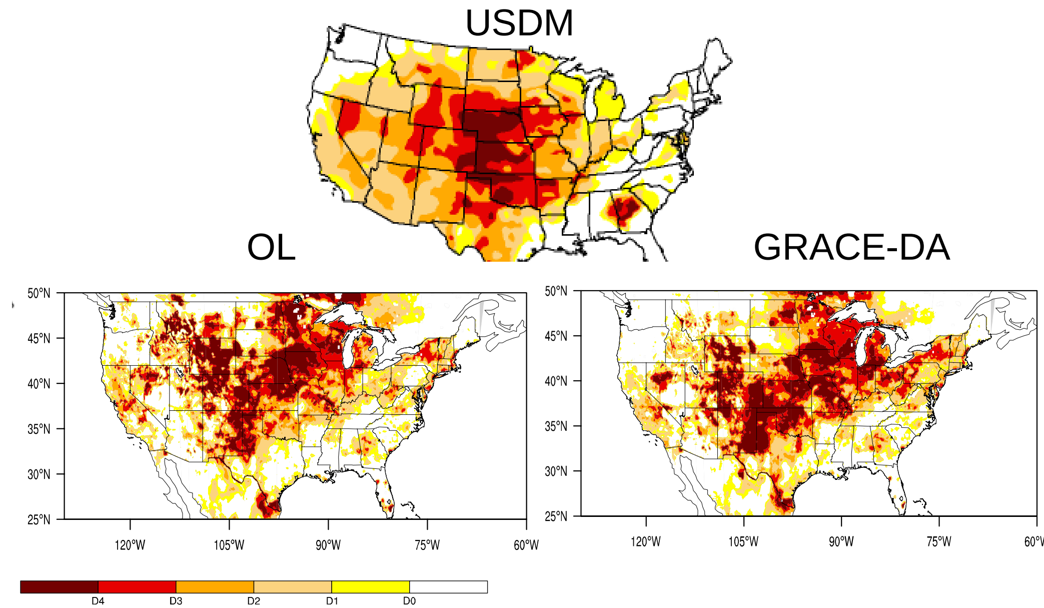
Kumar, S.V., C.D. Peters-Lidard, K.R. Arsenault, A. Getirana, D. Mocko, Y. Liu: 2015
Quantifying the added value of snow cover area observations in passive microwave snow depth data assimilation
Journal of Hyrometeorology, in press, doi:10.1175/JHM-D-15-0021.1

Assimilation of remotely sensed terrestrial water storage measurements in the NLDAS (Univariate assimilation)

This study examines an approach of assimilating terrestrial water storage (TWS) anomaly estimates from GRACE into the Catchment LSM using an Ensemble Kalman Smoother. The gridded GRACE TWS product is assimilated during a time period of 2003-2012.



Anomaly R differences of surface soil moisture (top panel) and root zone soil moisture (bottom panel) from GRACE-DA relative to the open loop integration.



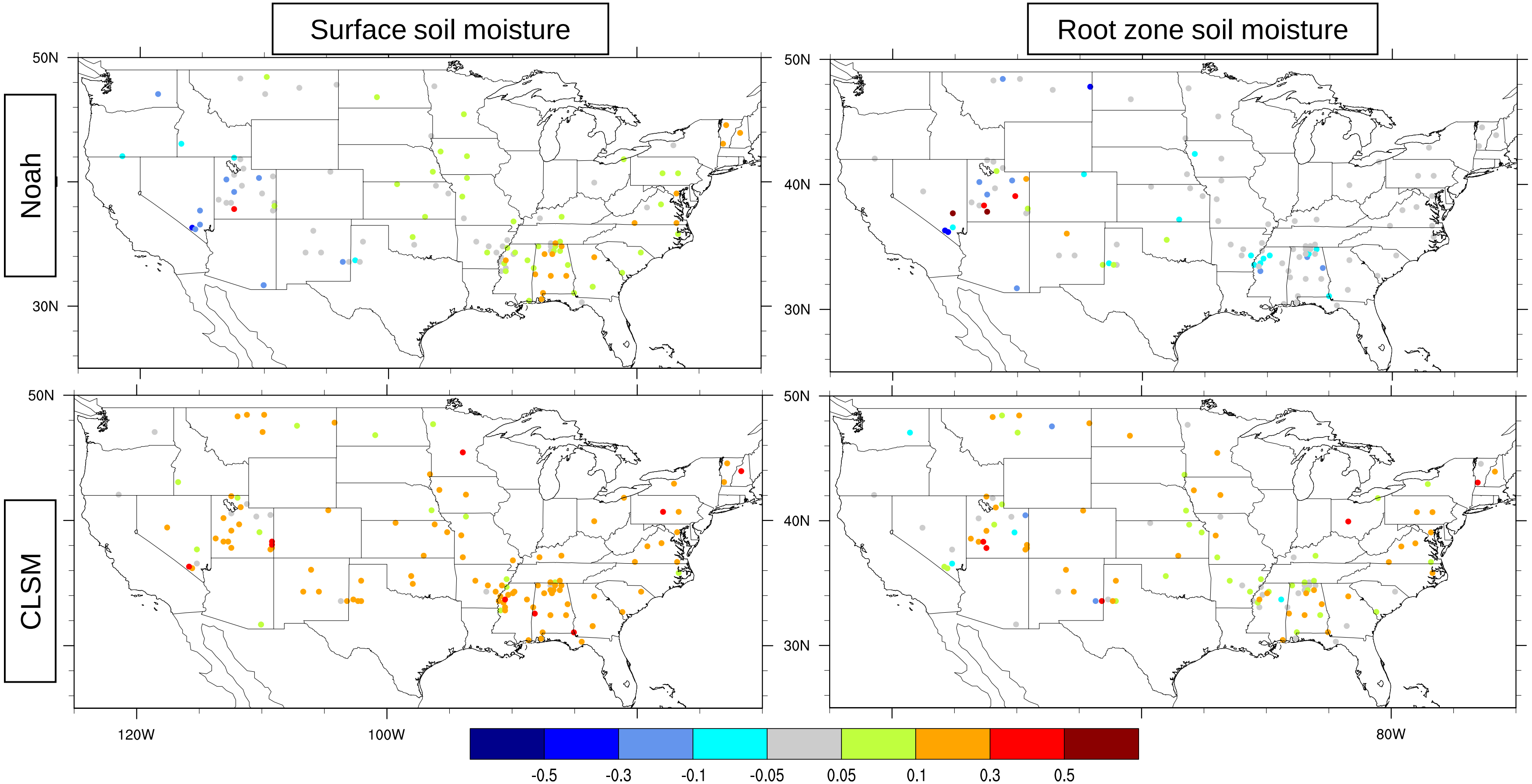
Comparison of the drought percentile maps from the open loop and GRACE-DA integrations against the corresponding USDM estimate for Sept 18-25, 2012. GRACE-DA helps to reduce the overestimation of drought severity in the OL over Minnesota, Iowa, Wyoming and increases the severity of drought over Kansas and Oklahoma, consistent with USDM.

- GRACE-DA has a positive impact on the simulation of unconfied groundwater variability and on the simulation of surface soil moisture.
- GRACE-DA also help to improve model derived drought estimates

Kumar, S.V., B. F. Zaitchik, C.D. Peters-Lidard, M. Rodell, R. Reichle, B. Li, M. Jasinski, D. Mocko, A. Getirana (2015), Assimilation of gridded GRACE terrestrial water storage estimates in the North American Land Data Assimilation System (NLDAS), *to be submitted to Journal of Hydrology.*

Multivariate assimilation in the NLDAS

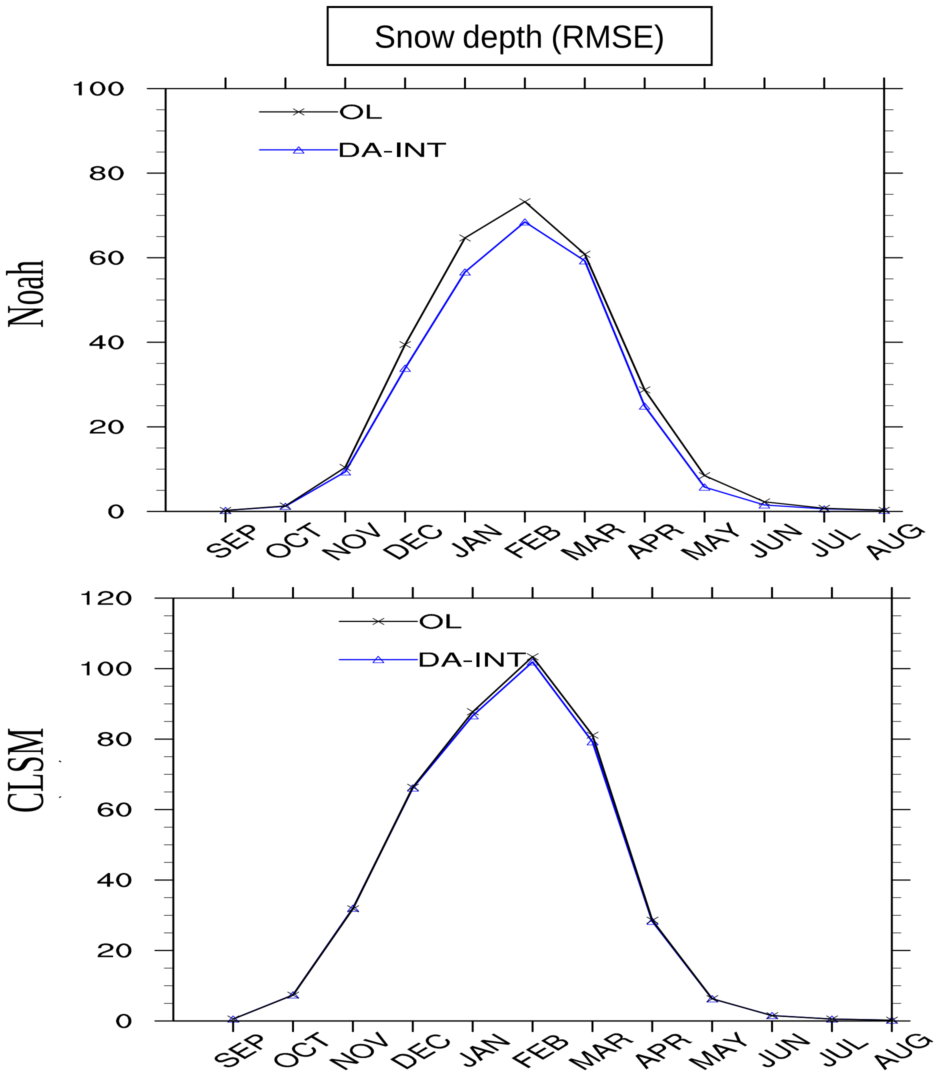
A unique ‘land reanalysis’ that concurrently assimilates soil moisture (SMMR, SSMI, AMSR-E, ASCAT), snow depth (SMMR, SSMI, AMSR-E), snow cover (IMS, MODIS), TWS (GRACE) and irrigation intensity (MODIS) into Noah and CLSM land surface models in the NLDAS configuration from 1979-2012.

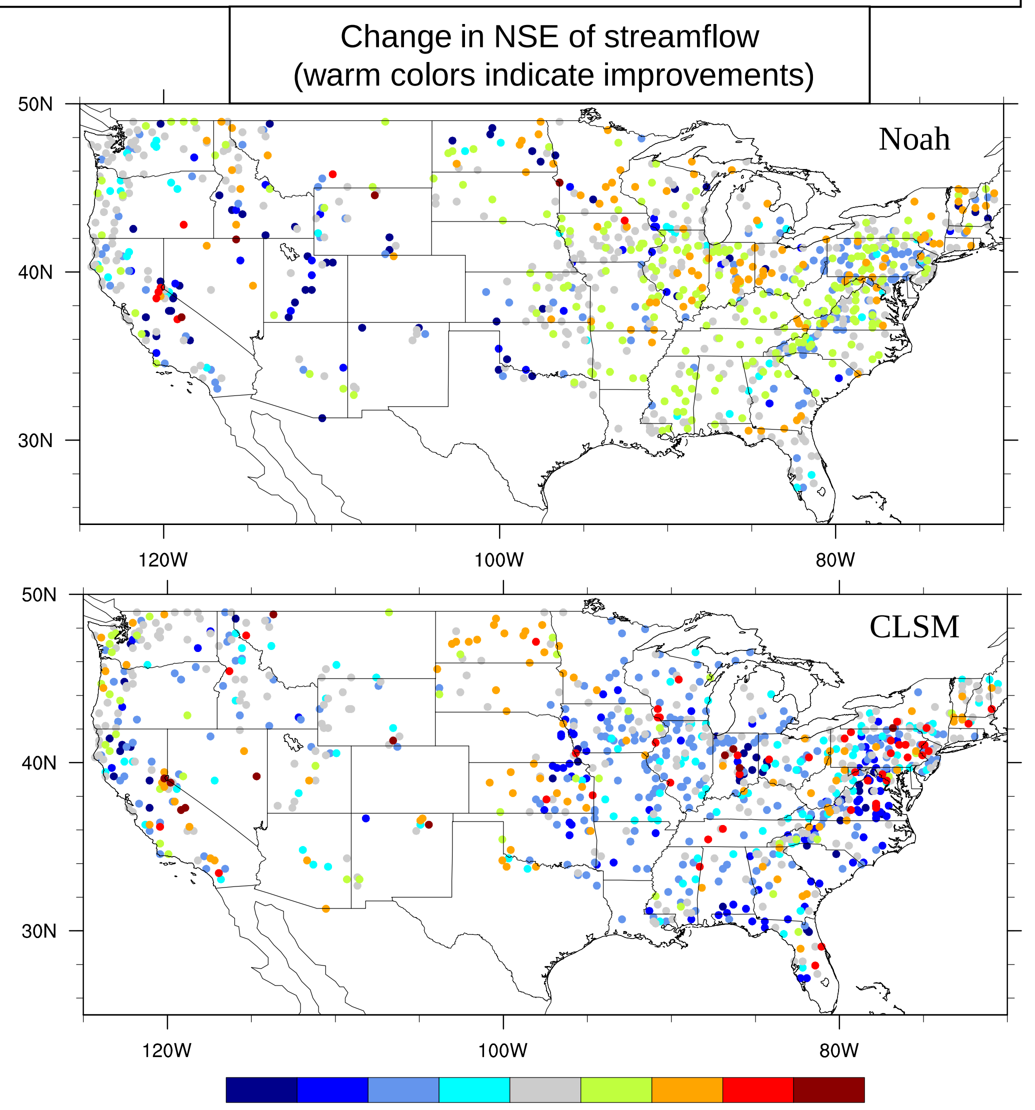


For Noah LSM, the improvements in soil moisture fields are small with degradations in the western U.S. In CLSM, more significant improvements in both surface and root zone fields are observed, possibly due to the influence of GRACE-DA.

Multivariate assimilation in the NLDAS

A unique 'land reanalysis' that concurrently assimilates soil moisture (SMMR, SSMI, AMSR-E, ASCAT), snow depth (SMMR, SSMI, AMSR-E), snow cover (IMS, MODIS), TWS (GRACE) and irrigation intensity (MODIS) into Noah and CLSM land surface models in the NLDAS configuration from 1979-2012.



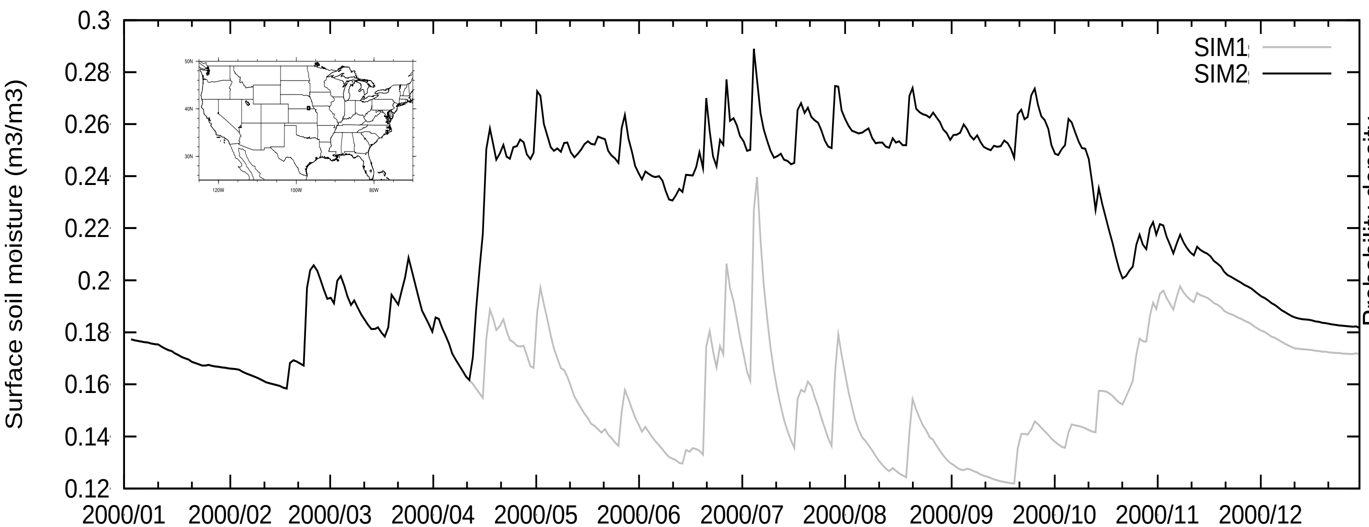


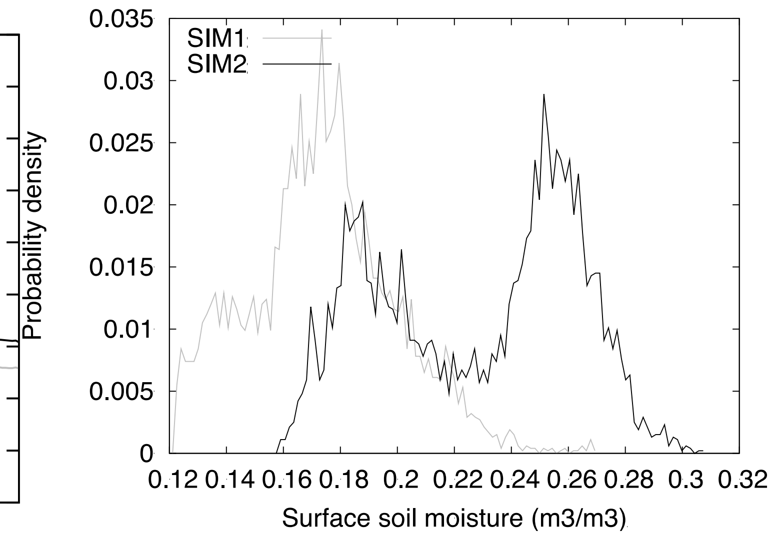
For Noah, Snow depth fields are generally improved, with biases significantly reduced during the peak snow season. For CLSM, the improvements in snow depth fields are minor. DA leads to marginal improvements in bias during the late winter and melt periods.

For Noah, generally improvements in streamflow simulation are observed in most parts of the domain. Notable degradations are in the Western U.S. For CLSM, degradations observed in the eastern parts of the domain with improvements over Missouri, Northwest, parts of Northeast.

Land Data Assimilation : Challenges

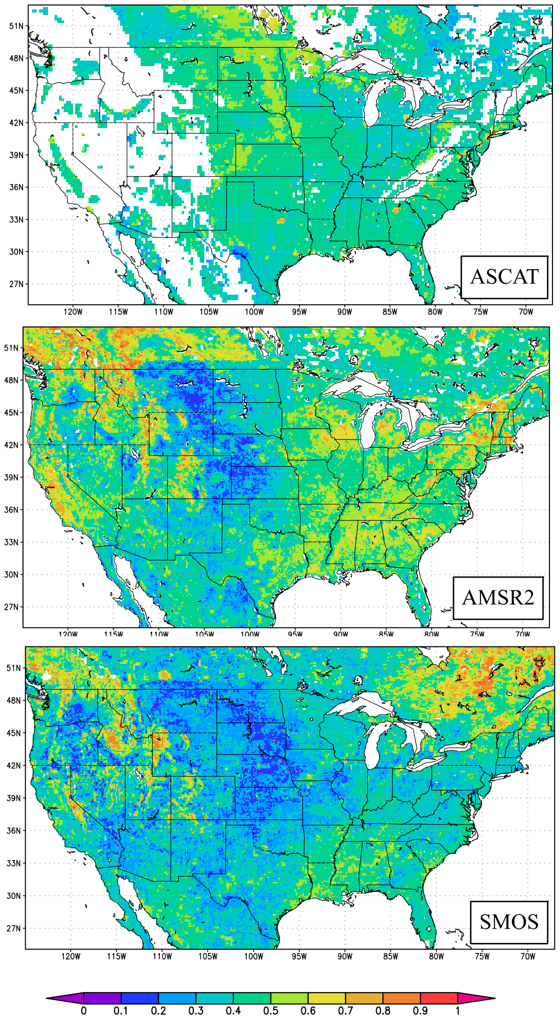
- Human impacts due to expansion of infrastructure and agriculture have significantly transformed (> 50%) the natural features of the land surface
- e.g. irrigated agriculture, urbanization, deforestation
- Current LSMs are limited in representing impacts of such engineered artifacts.
- Can modern soil moisture remote sensing data detect such unmodeled features?
- Are the DA methods effective in incorporating such signals?



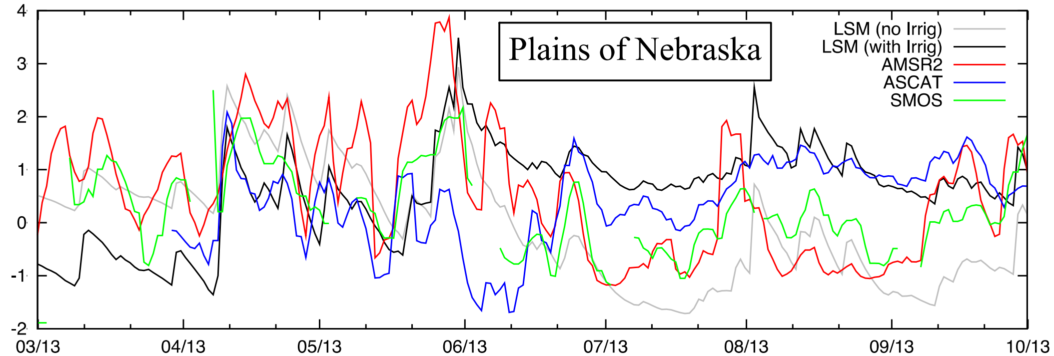


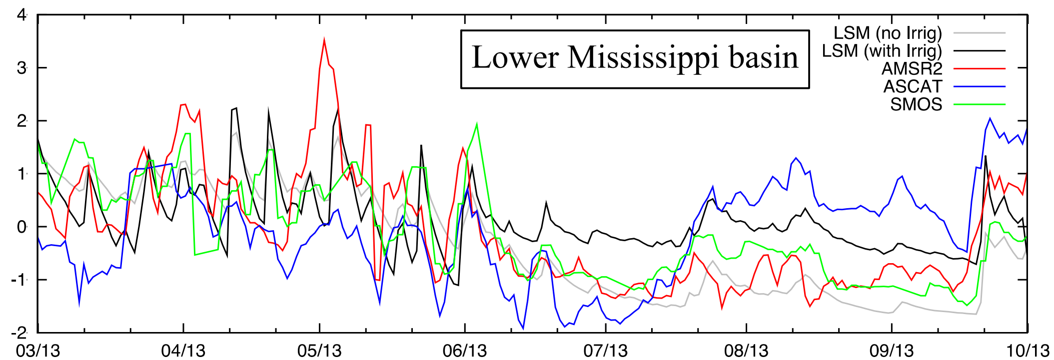
Kumar, S.V. et al. (2015), Evaluating the utility of modern soil moisture remote sensing retrievals over irrigated areas and the suitability of data assimilation methods to correct for unmodeled processes, *submitted to HESS*.

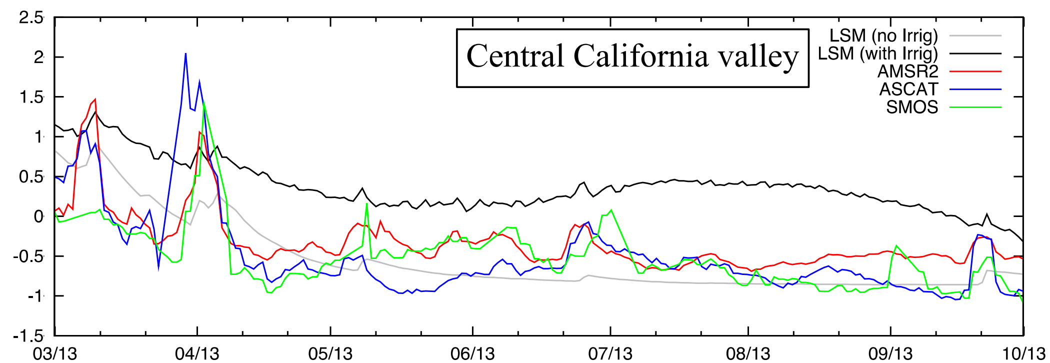
Comparing distributions from satellite soil moisture retrievals

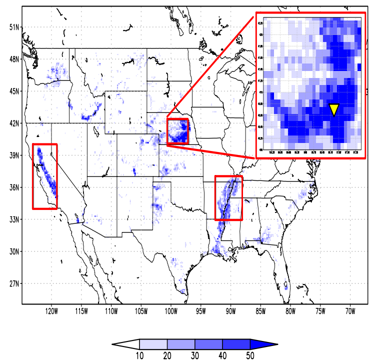


Kolmogorov Distance from the comparison of soil moisture distributions from the land model and satellite retrievals



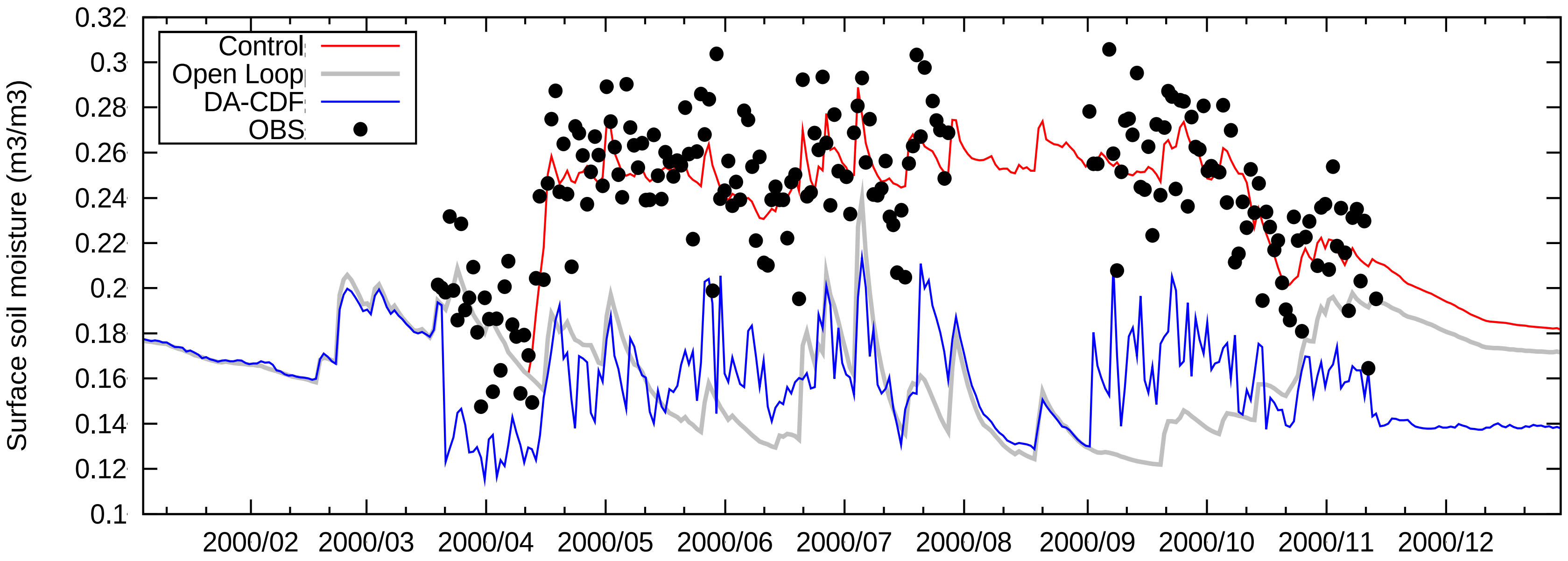






The skill of the satellite retrievals in representing irrigation artifacts is mixed, with ASCAT based products somewhat more skillful than SMOS and AMSR2.

Impact of a priori bias correction strategies in representing unmodeled processes



Standard bias correction practice in LDA is to rescale the observations to the model climatology. When unmodeled processes are involved, this approach leads to the loss of valuable signals.

Summary

- LIS – an environment for interoperable land surface modeling and data assimilation
- Significant advances has been made in LDA towards multivariate assimilation of remote sensing data
  - An interoperable environment (multiple observation types, multiple LSMs, multiple algorithms) for LDA
  - Suited for both sequential and reanalysis simulations
  - Supports a large suite of retrievals products and their concurrent assimilation
- Significant gaps and challenges
  - Land is more heterogeneous (compared to atmosphere and ocean) and the skill of the retrieval products must be improved
  - LDA methods must be improved to overcome the limitations in representing unmodeled features. Possible solutions include more data-driven approaches (deep learning).
  - The biases in the models must also be reduced. Development of LSMs must include more "observable" outputs.
  - Extend multivariate DA to exploit complementary information across sensors (temperature, soil moisture, vegetation)