Monitoring Soil Moisture and Drought Using a Thermal Two-Source Energy Balance Model

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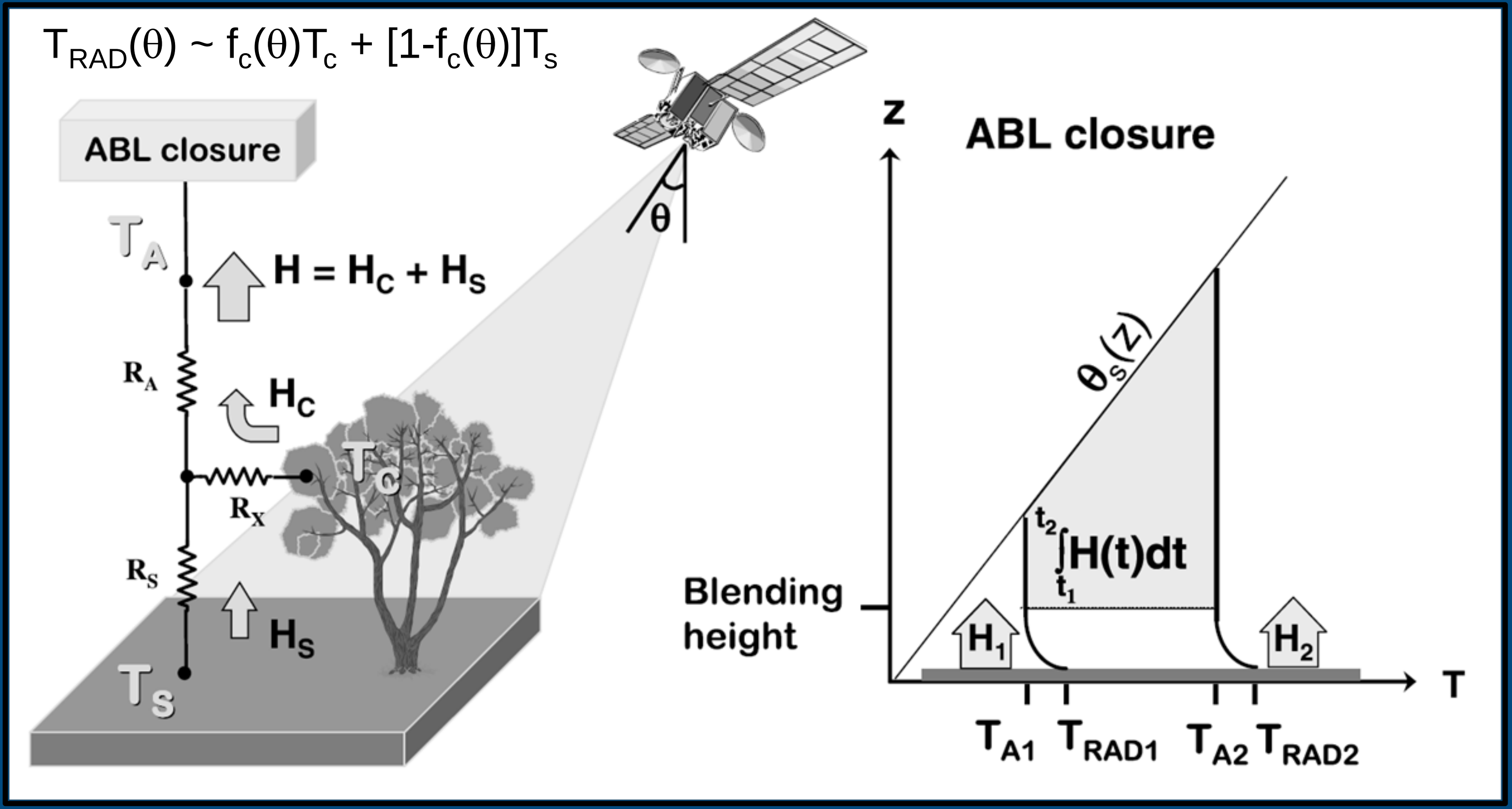
Atmosphere Land Exchange Inverse (ALEXI) Model

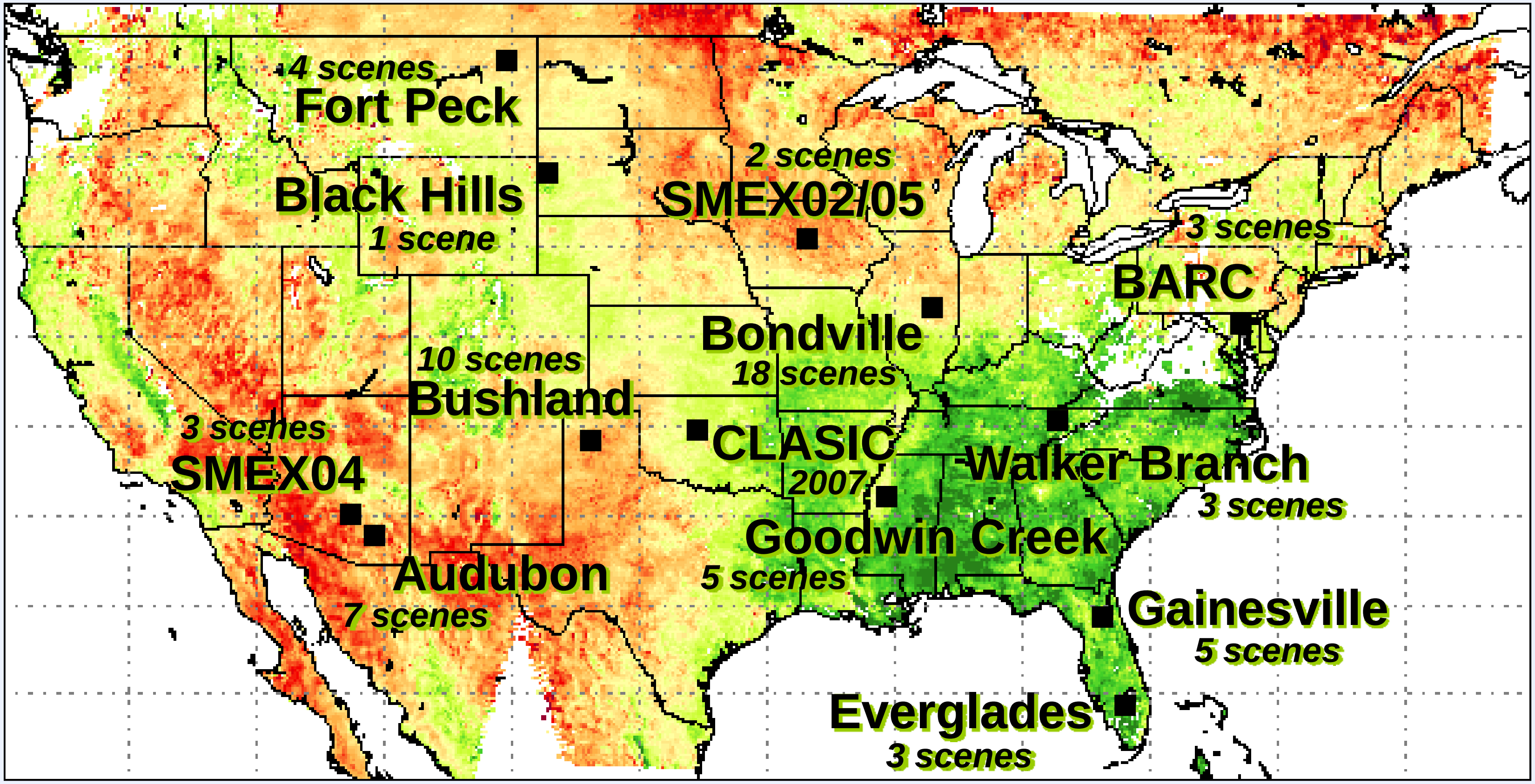


The main advantages of ALEXI include:

i) the minimization of ancillary meteorological inputs
ii) two-source approximation (Norman, Kustas et al. 1995)
iii) treats soil/canopy-atmosphere coupling differently
iv) accommodates off-nadir thermal sensor view angles
v) time-differential ABL closure
vi) provides information of soil/canopy fluxes and stress (i.e. soil moisture)

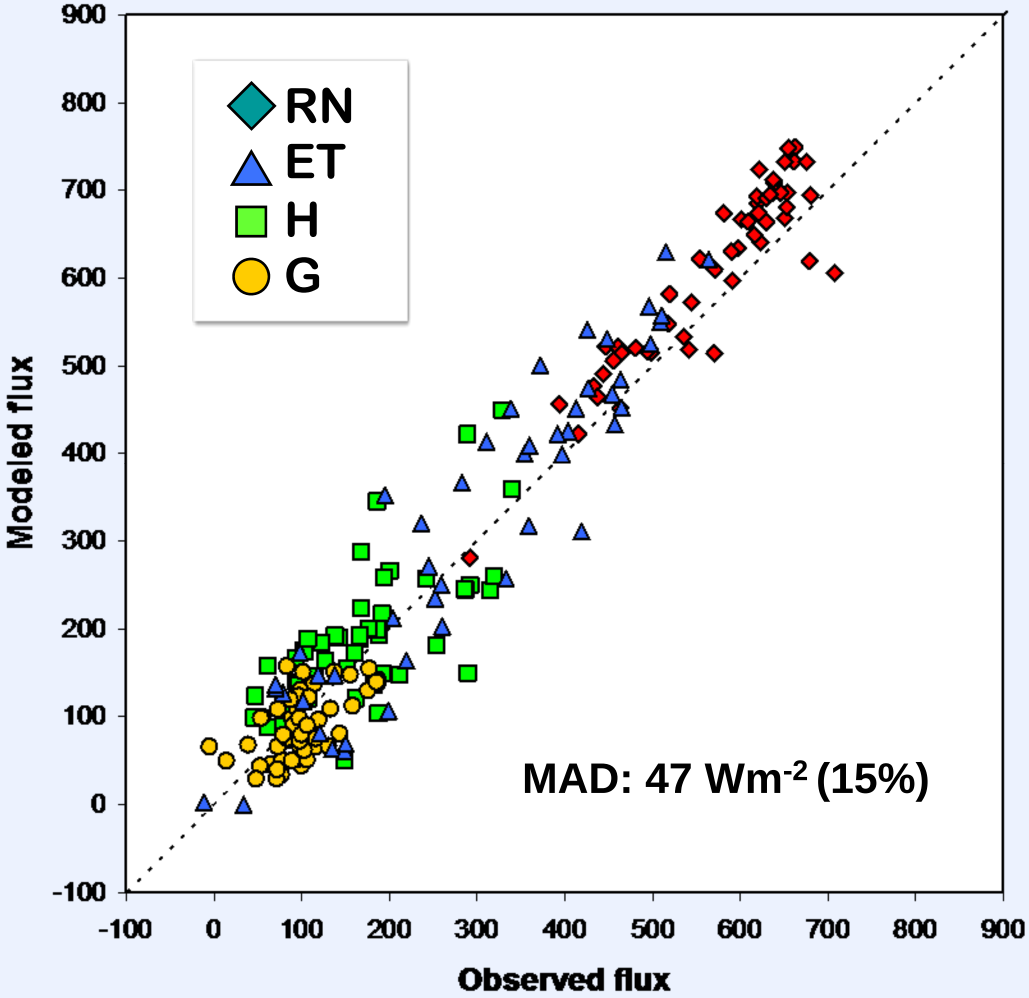
$$T_{RAD}(\theta) \sim f_c(\theta)T_c + [1-f_c(\theta)]T_s$$

ALEXI validation sites



(Provided by Martha Anderson)

Clear-sky fluxes using Landsat TIR (~100m)



(Provided by Martha Anderson)

ALEXI Soil Moisture Methodology

The rate of temperature increase of either a soil or canopy component is related to an increase or decrease in ET, which in turn is related to soil moisture. In general, dry soil or stressed vegetation heats up more rapidly than wet soil or unstressed vegetation.

This relationship can be exploited to retrieve current soil moisture conditions using thermal infrared observation from remote sensing platforms.

Anderson et al. (2007b) and Hain et al. (2009) describe a technique for simulating the effects of soil moisture on ET estimates from ALEXI using a soil moisture stress function:

$$\boxed{f_{PET} = \frac{LH}{PET}} \longrightarrow \boxed{f_{AW} = \frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}}}$$

In this study, we choose to focus on using a multi-year (2000-2009) climatology to compute ALEXI f_{PET} anomalies which will be related to soil moisture through the following weighting function based on a partitioning of surface and root-zone soil moisture with the fraction of green vegetation cover.

$$\boxed{f_{PET} = (1 - f_c)\theta_{sfc} + f_c\theta_{rz}}$$

Passive Microwave Surface Soil Moisture Retrievals

Algorithms that retrieve estimates of surface soil moisture from microwave brightness temperatures exploit the large differences in the dielectric constant of dry soil and wet soil and their effect on the natural microwave emission from the soil.

Microwave soil moisture retrievals suffer from substantial retrieval errors over moderate to dense vegetation (i.e. C-band sensitivity has been shown to cease at a vegetation water content of 1.5 kg m^{-2}).

Longer wavelengths (L-band; 1.4 GHz; SMOS; SMAP) have a greater potential for penetration through vegetation.

VUA/NASA AMSR-E Surface Soil Moisture Product (Owe et al. 2008)

- derived using the Land Surface Parameter Model (LPRM; Owe et al. 2001; 2007), which is a three parameter retrieval for T_b observations, using one dual polarized channel (either C-band or X-band) for the retrieval of soil moisture and vegetation water content, while effective soil temperature is derived from the vertically polarized 36.5 GHz channel
- vegetation optical depth is parameterized as a function of the Microwave Polarization Difference Index (MPDI; Meesters et al. 2005)
- Main advantages over the NSIDC is the use of a higher frequency band for retrieval of T_s and the parameterization of vegetation optical depth, leaving only soil moisture to be retrieved

Observation Overview

	ALEXI	**AMSR-E**
Observed Variable	f_{PET} / f_{AW} (%)	Volumetric Soil Moisture (m^3 m^{-3})
Spatial Resolution	10 km	~56 km (at 6.925 GHz) ~40 km (at 10.65 GHz)
Temporal Resolution	Daily (Clear sky constraint)	2x Daily
Domain Coverage	~ 5-10 days (function of cloud climatology)	~ 2 days
Sensing Depth	Variable as function of f_c	~ top 1 cm

Intercomparison Study Methodology

The main motivation of the multi-year (2003-2008) intercomparison is to attempt to quantify the relative skill of ALEXI soil moisture retrievals when compared to soil moisture retrievals/model estimates from AMSR-E and Noah across the CONUS.

As stated above, it is assumed that ALEXI f_{PET} is a composite view of surface and root-zone soil moisture partitioned by f_c. Thus, f_{PET} consistent values from AMSR-E and Noah must be computed for a direct comparison.

(1) f_{PET} formulation

$$AMSRE_{f_{PET}} = (1 - f_c)\theta_{AMSRE(sfc)} + f_c\theta_{AMSRE(rz)}$$

$$Noah_{f_{PET}} = (1 - f_c)\theta_{Noah(0-5\ cm)} + f_c\theta_{Noah(5-100\ cm)}$$

Additionally, findings from this type of analysis will likely prove to be useful with regards to any attempt at assimilating ALEXI soil moisture retrievals in the future.

It should be noted that the goal of the study is not to attempt to quantify the skill of AMSR-E soil moisture retrievals, yet the use of AMSR-E in the analysis provides an additional independent source of soil moisture information.

Land Information System

- The Land Information System (LIS) is a software framework that integrates the use of satellite and ground-based observations along with advanced land surface models (LSMs) and computing tools to accurately characterize land surface states and fluxes (Kumar et al. 2004).

- LIS also employs advanced data assimilation plug-ins which allow a user to implement satellite-based retrievals of land surface states using either direct insertion or an ensemble Kalman filter (EnKF).

LIS Version	v5.0
Study Domain	CONUS
Spatial Resolution	25 km
Atmospheric Forcing Dataset	NLDAS
Noah Version	v2.7
Fractional Vegetation Dataset	Climatological AVHRR
Soil Texture Dataset	FAO/Zobler

AMSR-E Root-zone Soil Moisture Product

- As stated above, it is assumed that ALEXI f_{PET} represents a composite observation of surface and root-zone soil moisture as a function of f_c, in an attempt to compare AMSR-E with ALEXI, an exponential filter is used to compute a root-zone soil moisture product from AMSR-E surface soil moisture.

- The use of an exponential filter exploits the strong relationship between surface and root-zone soil moisture and is based on a simple two-layer water balance approach:

$$AMSRE_{rz}(t_n) = \frac{\sum_i^n AMSRE_{sfc}(t_i)e^{\frac{t_n - t_i}{T}}}{\sum_i^n e^{\frac{t_n - t_i}{T}}}$$

- Wagner (1999) used a similar approach and found statistically significant relationships between values derived from ERS scatterometer retrievals and 0-100 cm ground-based soil moisture observations.

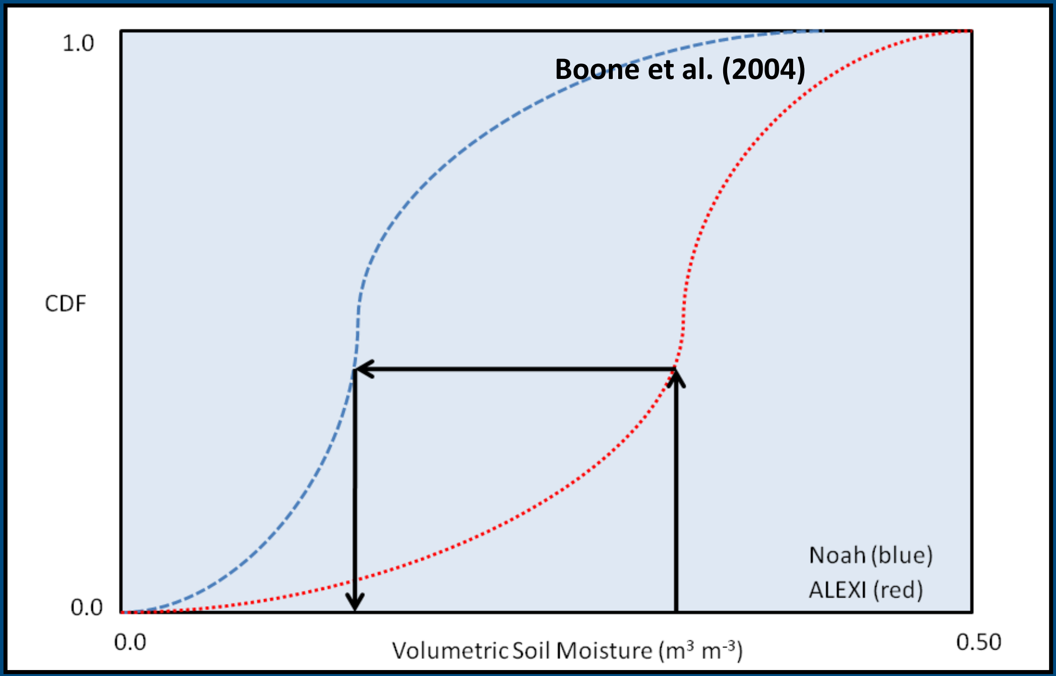
Re-scaling Observations with Model Climatology

- Soil moisture retrievals and observations from various sources (i.e. LSM predictions, satellite retrievals, ground measurements) have been shown to provide representative and useful information with regards to their seasonal cycle and anomaly signals.

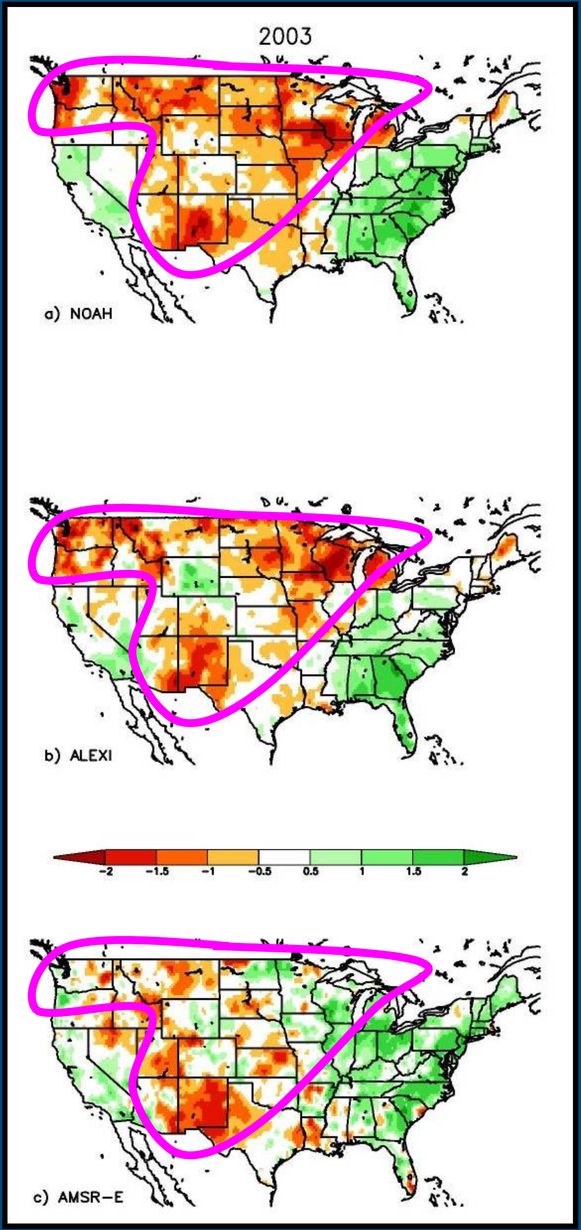
- Yet, many retrievals and observations typically exhibit very different statistical and dynamic ranges and these biases can severely limit the effectiveness of retrievals if they were to be directly assimilated.

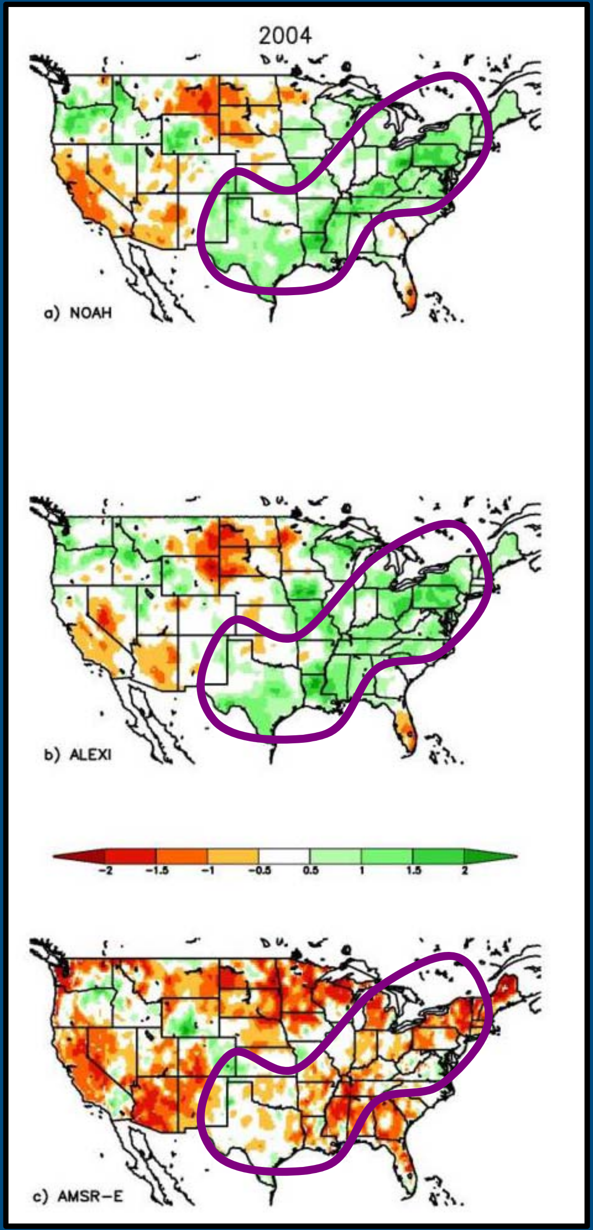
- In this study, retrievals from ALEXI and AMSR-E are re-scaled to be consistent with the LSM (Noah) climatology using a CDF matching technique (Reichle and Koster 2004).

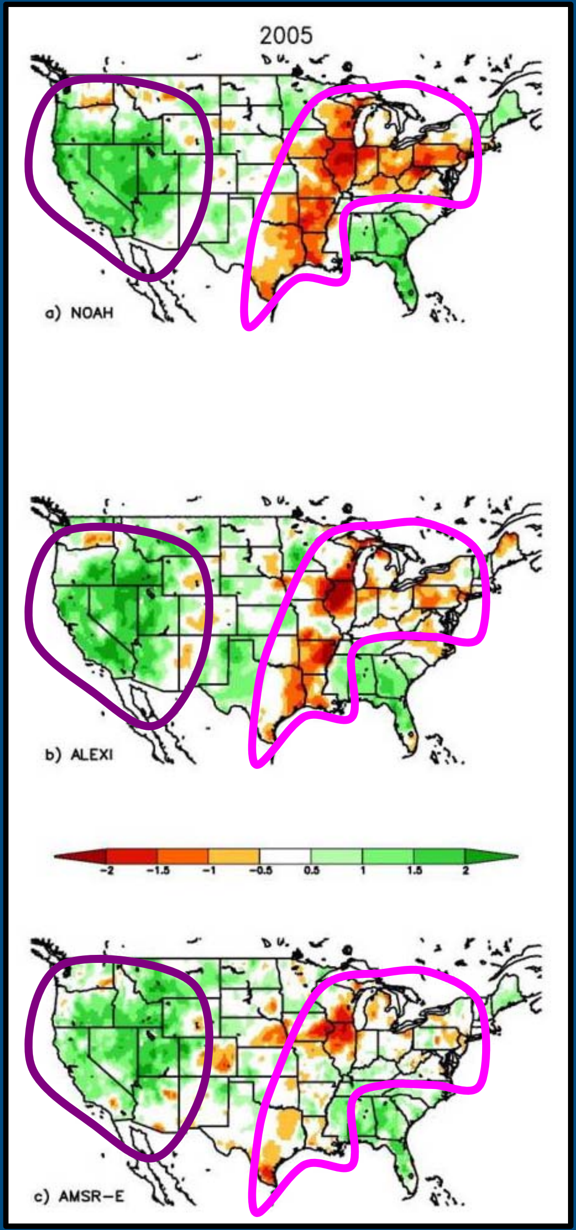
$$CDF_{Noah}(x') = CDF_{ALEXI}(x).$$


Boone et al. (2004)

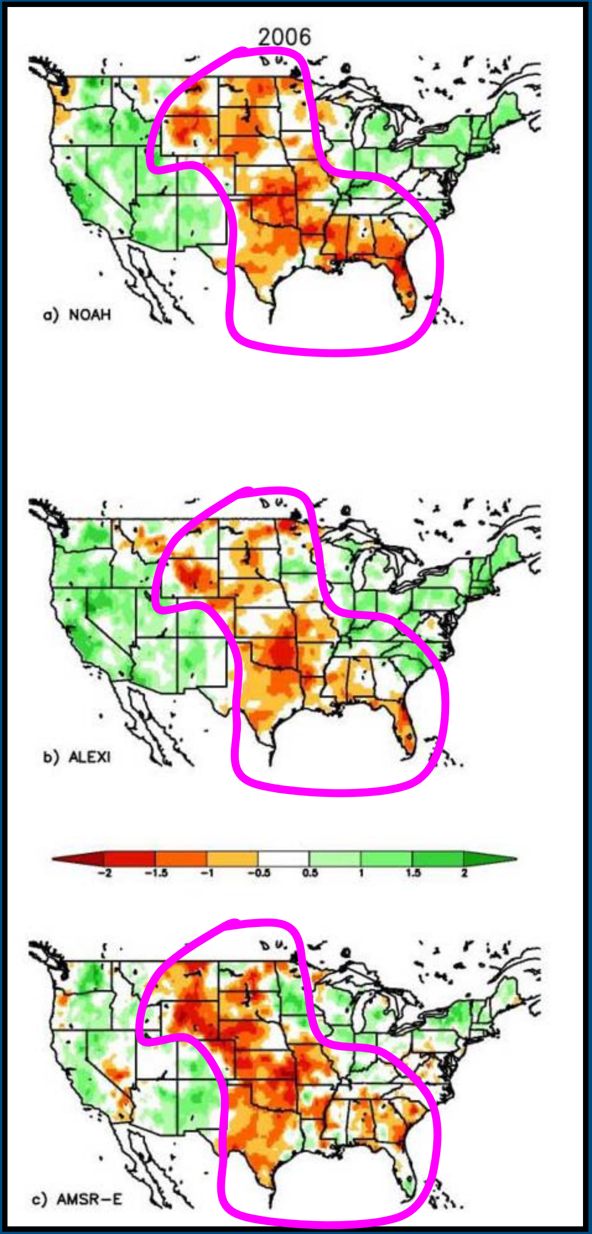
Seasonal Anomaly Composites (April-October; 2003-2008)

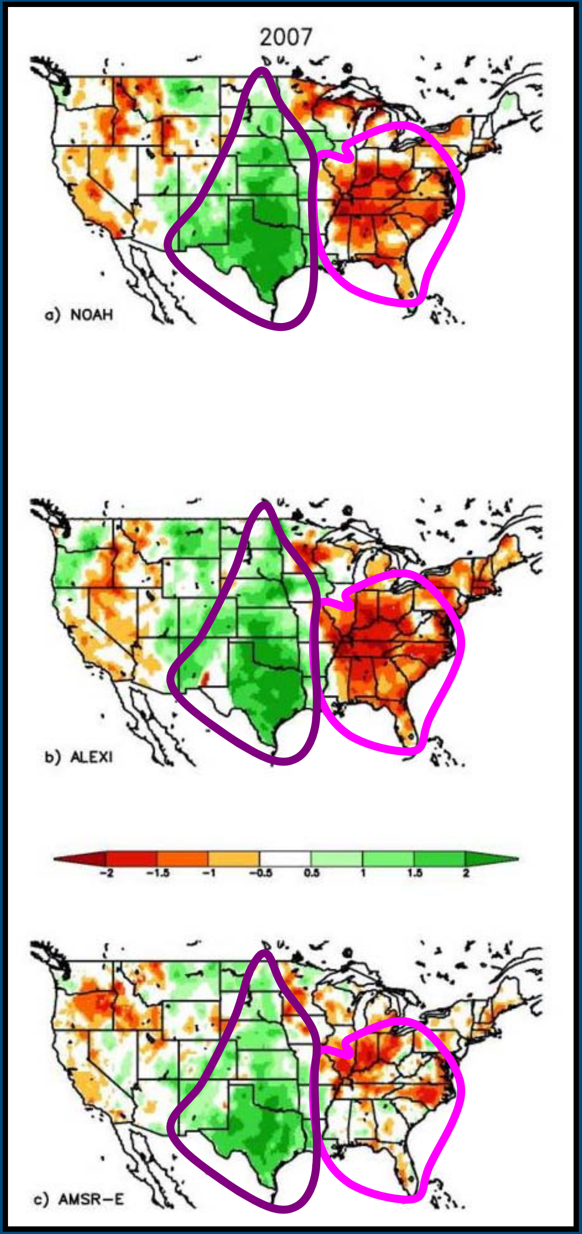






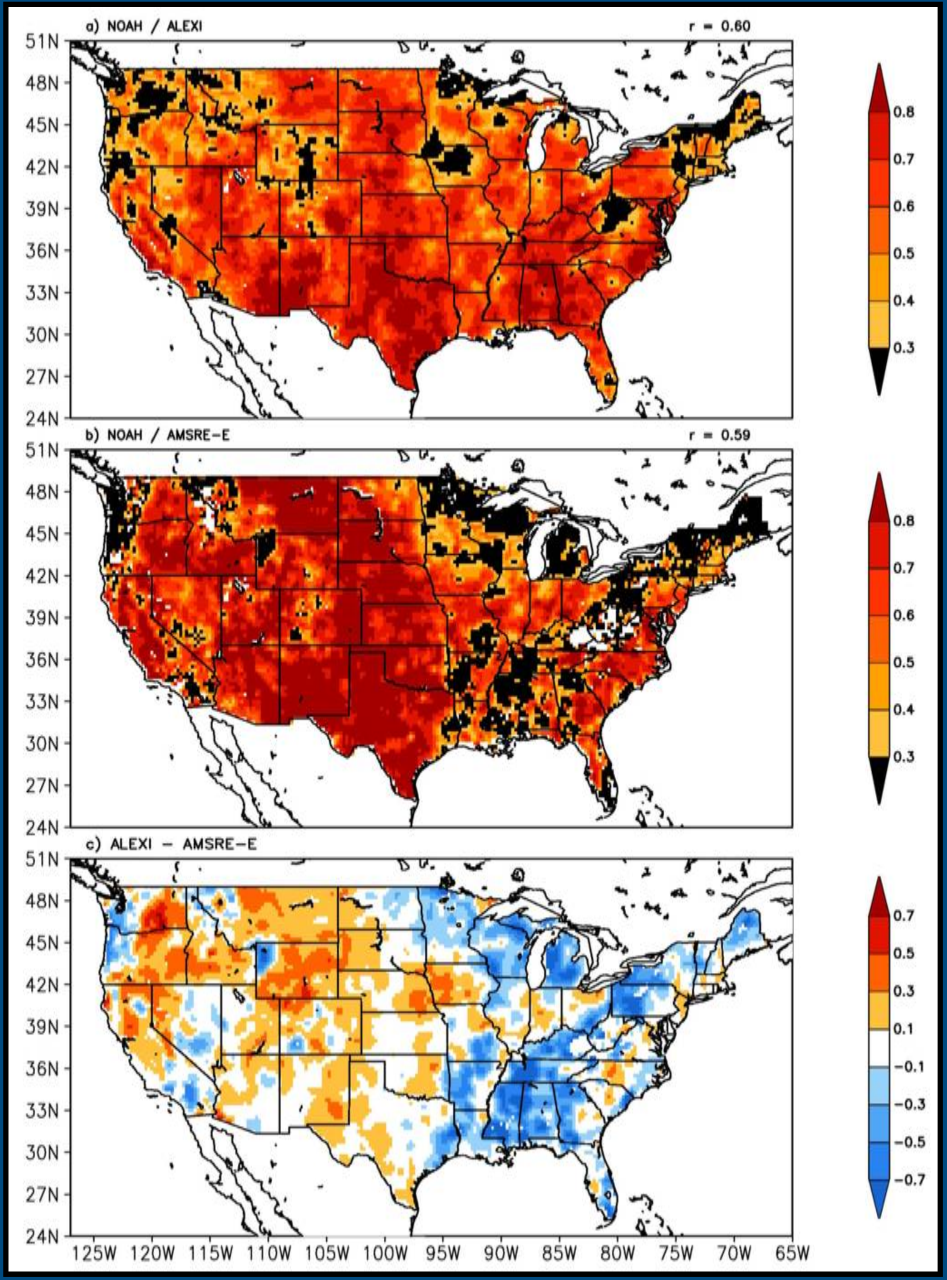
Seasonal Anomaly Composites (April-October; 2003-2008)





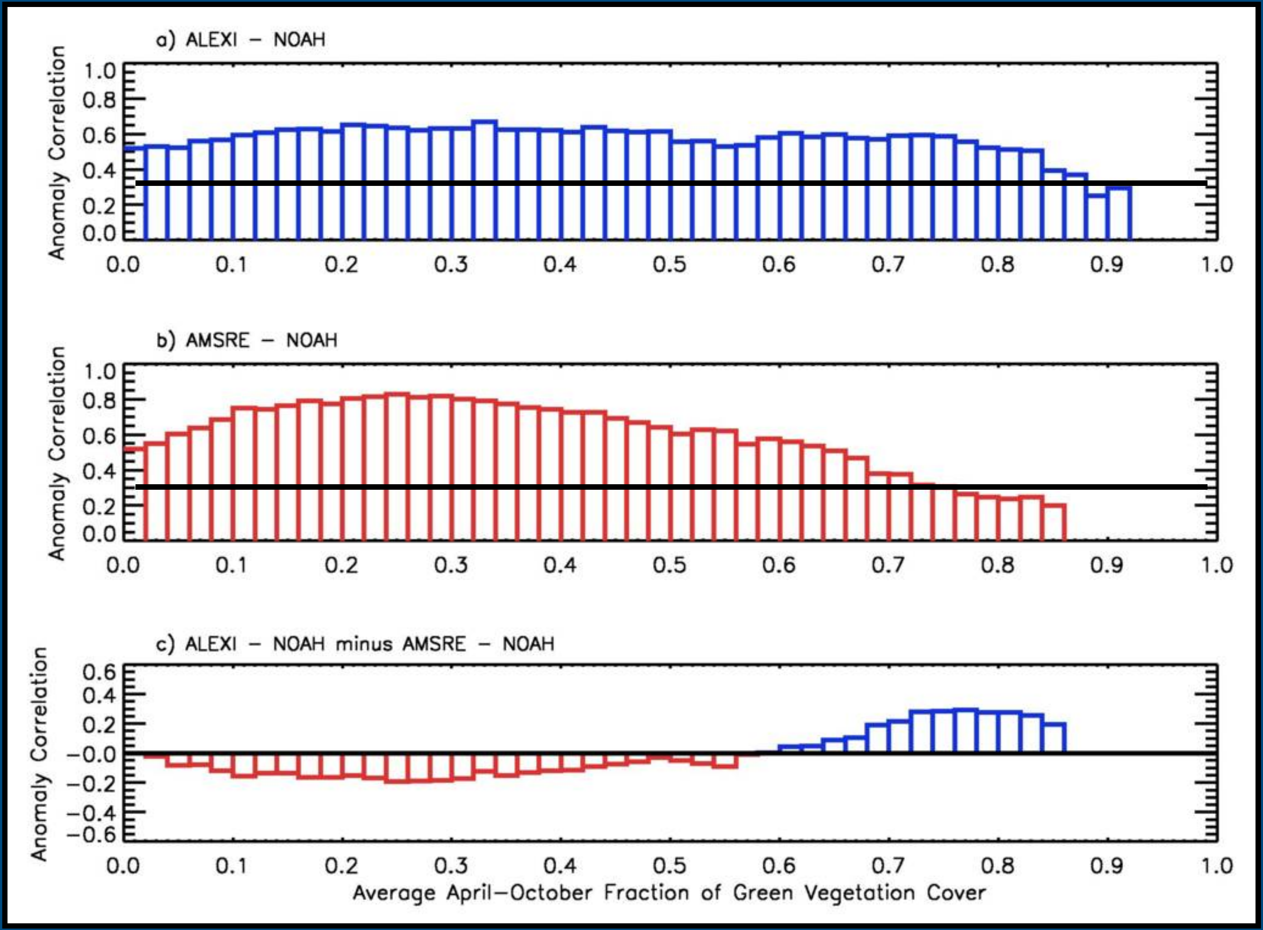
Spatial Anomaly Correlation	ALEXI/ Noah r	AMSR-E/ Noah r
2000	0.62	-
2001	0.54	-
2002	0.66	-
2003	0.69	0.40
2004	0.65	0.27
2005	0.74	0.56
2006	0.78	0.61
2007	0.81	0.67
2008	0.52	0.47
2000-2008 Average	0.67	-
2003-2008 Average	0.70	0.50

Time Series Anomaly Correlation Analysis (2003-2008)



- This analysis used time series at each pixel of 14-day composites of each soil moisture estimate. Anomalies were computed using a centered 29-day window to remove the seasonal cycle.
- In general, AMSR-E showed higher anomaly correlations over much of the central and western US, collocated with low green vegetation.
- However, ALEXI shows statistically significant skill over a large portion of the entire US, with the most significant upgrade in skill over densely vegetated sections of the eastern US.

Time Series Anomaly Correlation Analysis (2003-2008)



In general, AMSR-E performs better than ALEXI when f_c is less than 60%, although significant skill is still evident in ALEXI.

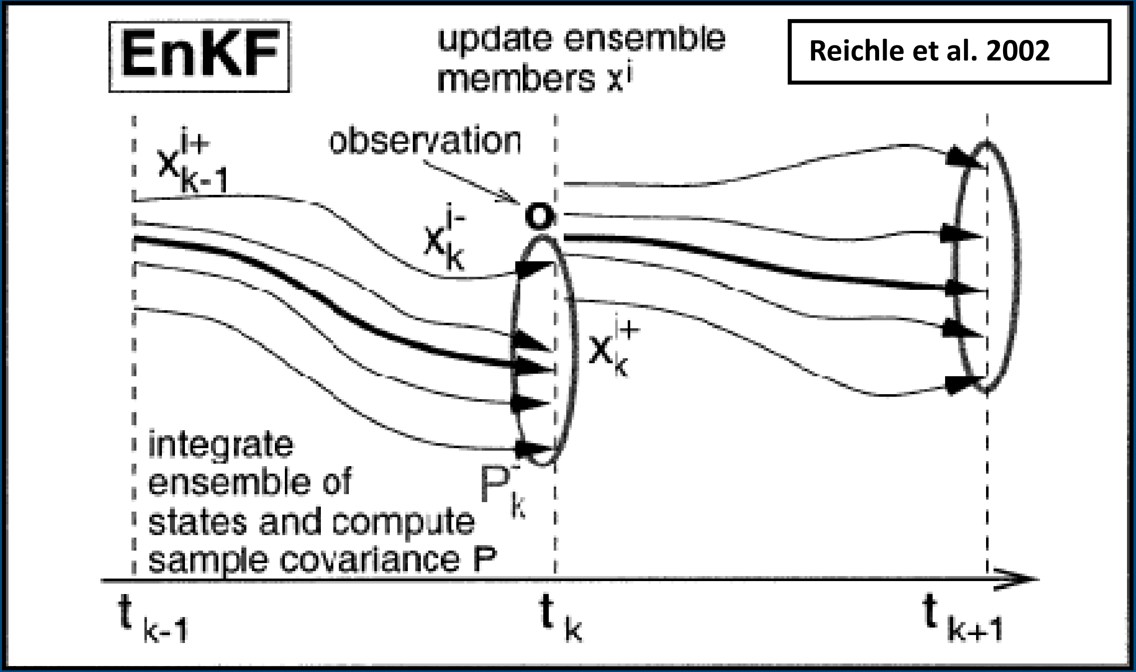
However, as f_c increases beyond 60%, AMSR-E skill rapidly drops off, while ALEXI maintains a statistically significant anomaly correlation over dense vegetation.

Ensemble Kalman Filter (EnKF)

- The Kalman filter is a sequential estimator that optimally updates model predictions with observations based on the relative magnitude of uncertainties present in the model and observations.

- In the ensemble form the of the KF, a Monte Carlo approach is used to create an ensemble of model vectors that are used to estimate the model error covariance.

- The representation of model and observation error covariance is crucial for the optimal performance of the filter.



Data Denial Assimilation Flowchart

Assimilation Methodology:

- SIM 1: Control (Benchmark)
  High-quality precipitation dataset (NLDAS; gauge-based); No DA

- SIM 2: Open Loop (Degraded); No DA
  2005 forced with 2008 precipitation
  2006 forced with 2007 precipitation
  2007 forced with 2006 precipitation
  2008 forced with 2005 precipitation

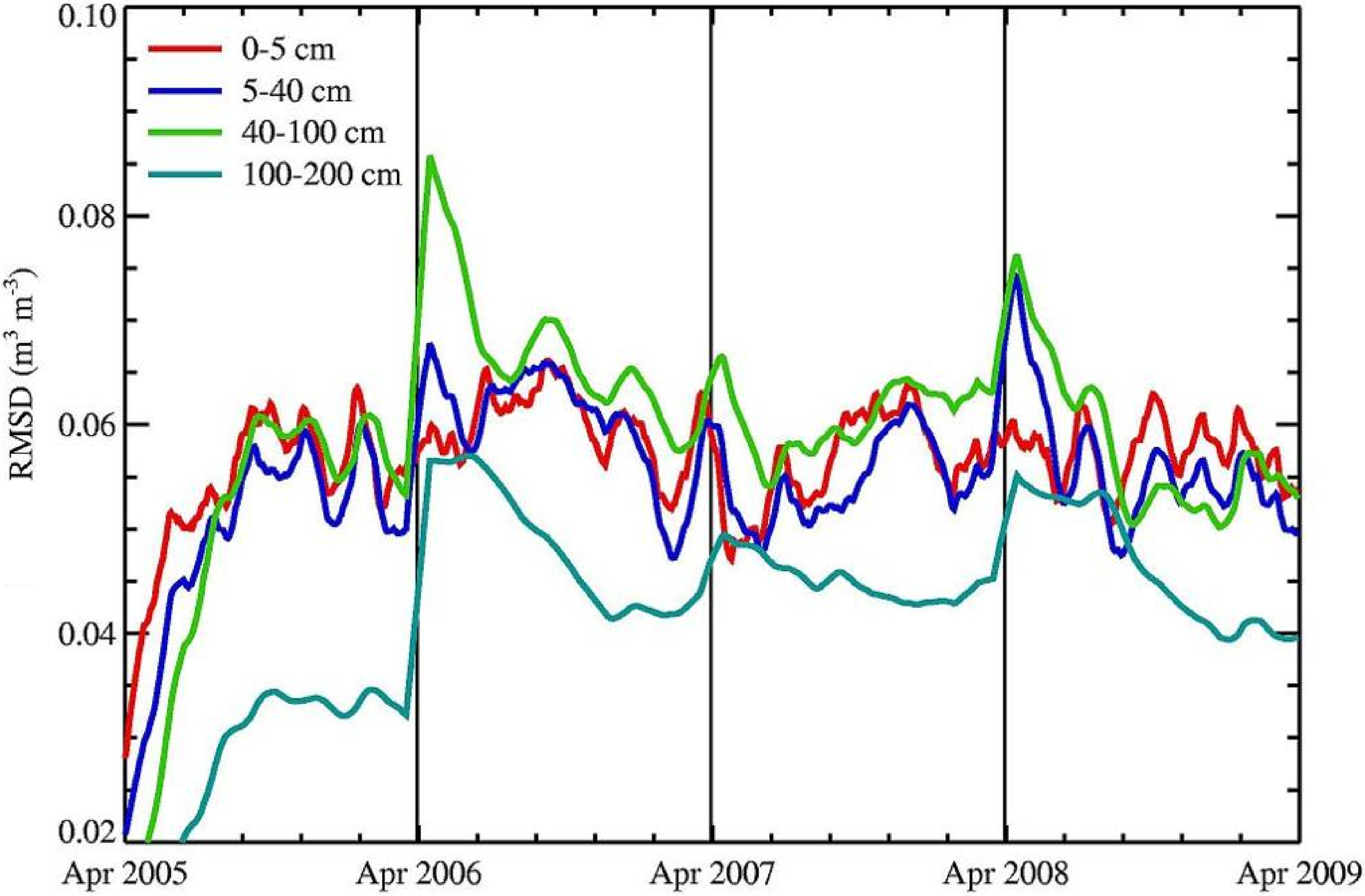
- SIM 3: ALEXI
  En-KF assimilation of ALEXI retrievals with SIM 2 precipitation

- SIM 4: AMSR-E
  En-KF Assimilation of AMSR-E retrievals with SIM 2 precipitation

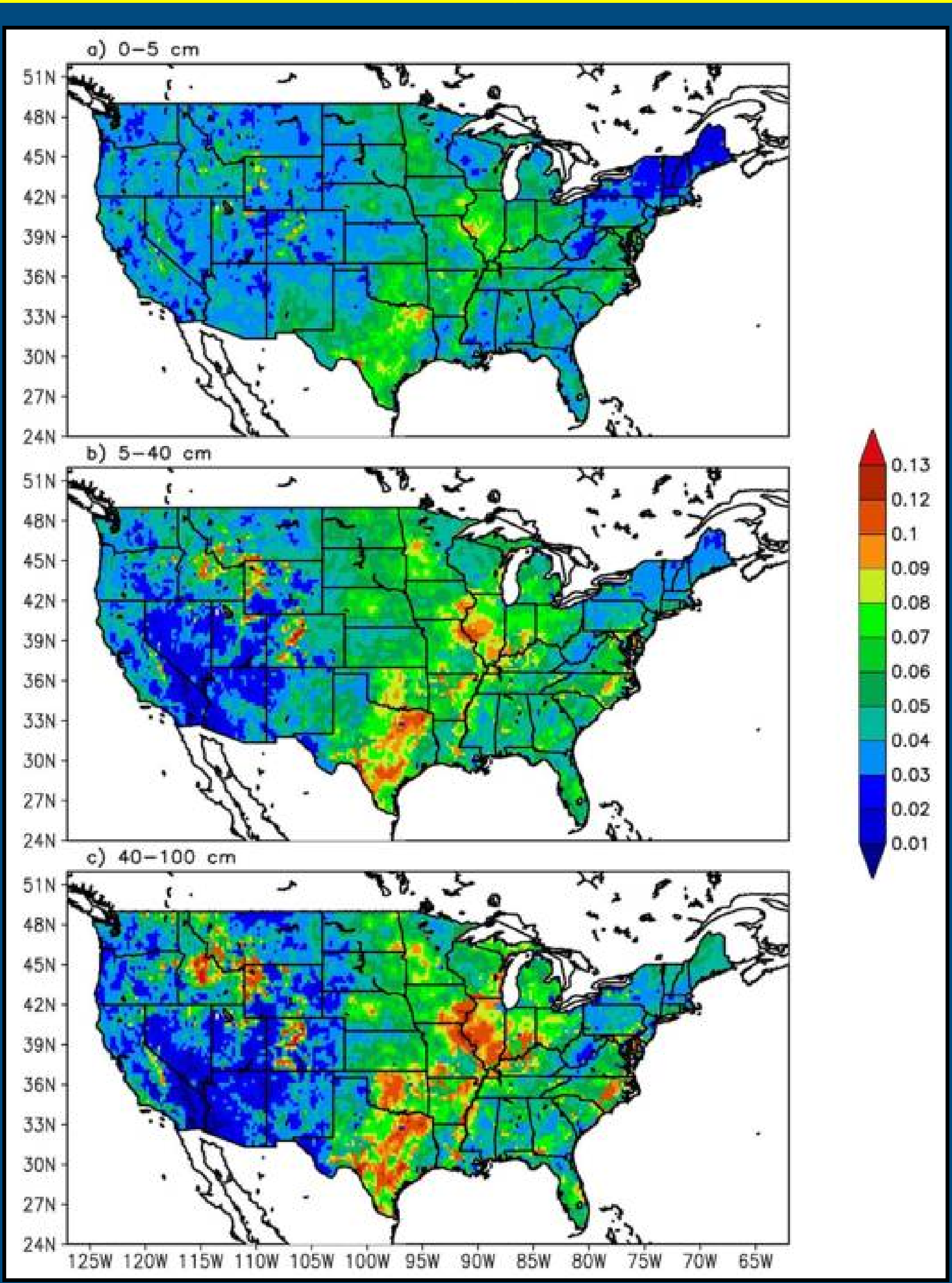
- SIM 5: DUAL
  En-KF assimilation of ALEXI and AMSR-E retrievals with SIM 2 precipitation

Number of Ensemble Members	40
Retrieval Error Covariance	0.03 $m^3\ m^{-3}$
Model Error Covariance	0.03 $m^3\ m^{-3}$ (scaled with respect to layer thickness)
Model Resolution	25 km
Study Period	1 April 2005 – 31 October 2008

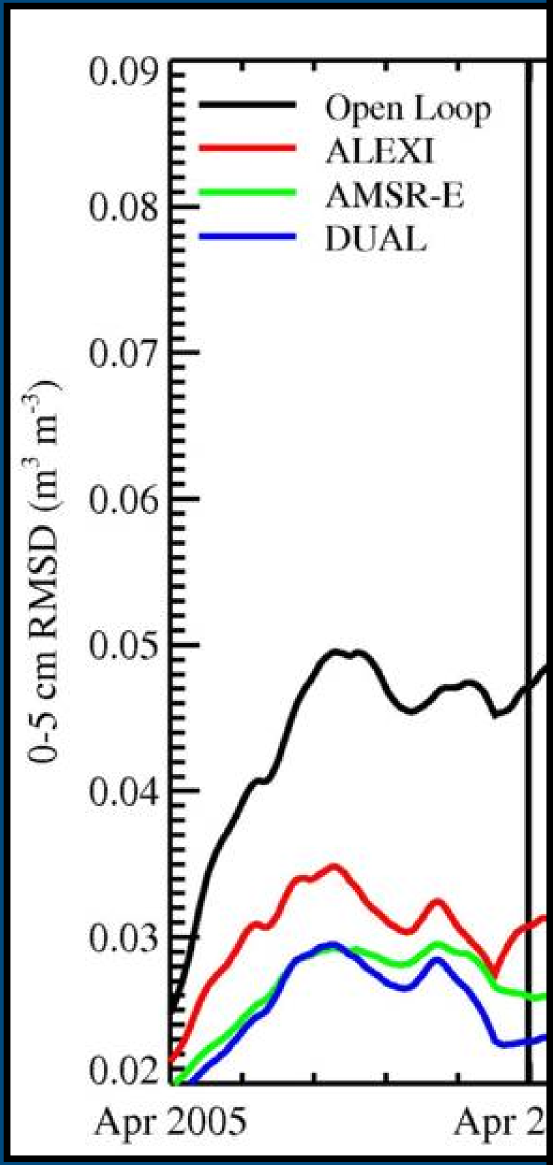
Domain Averaged Open Loop (Degraded Precipitation) RMSD

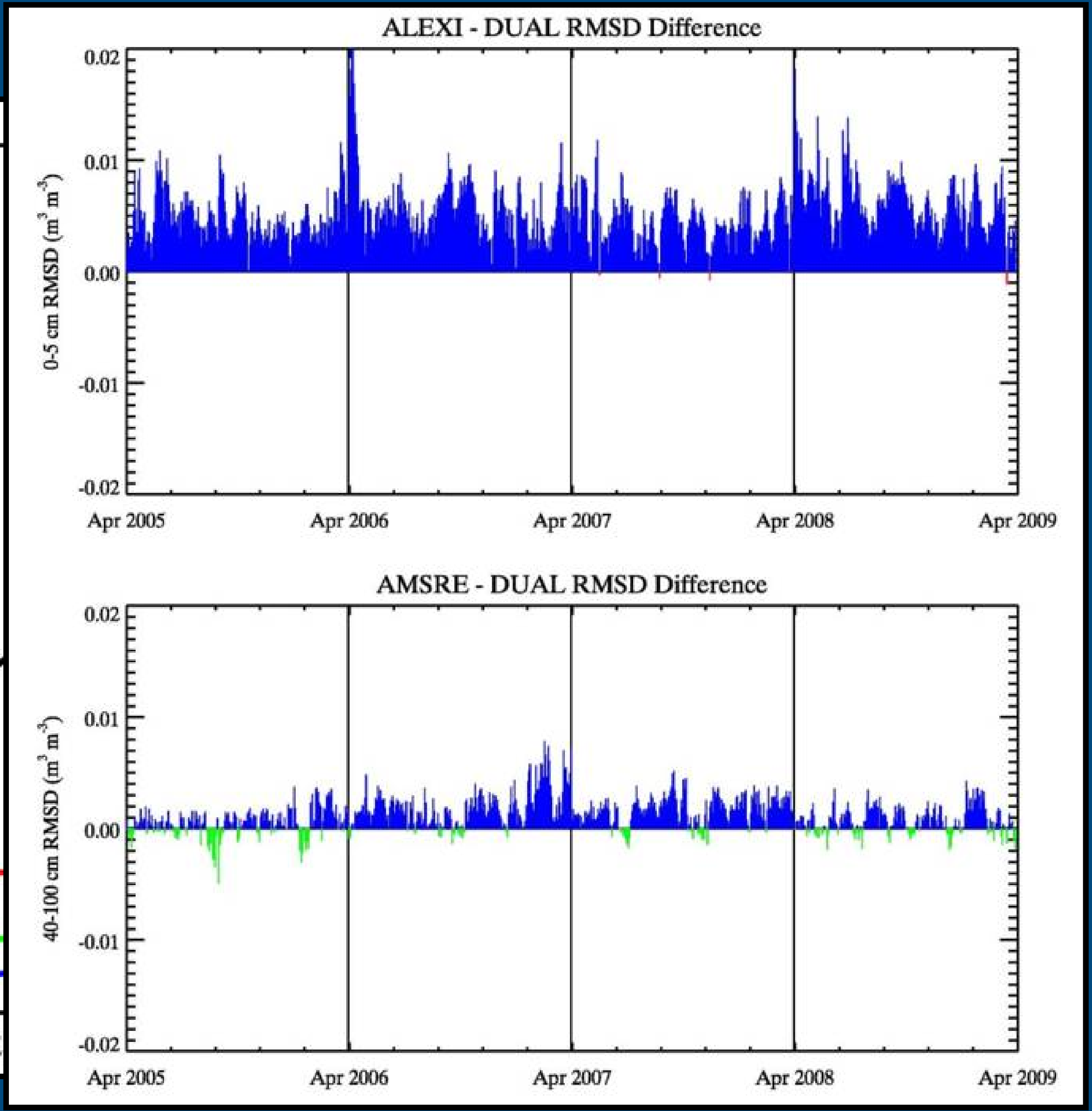


Open Loop Precipitation (Degraded Precipitation) RMSD

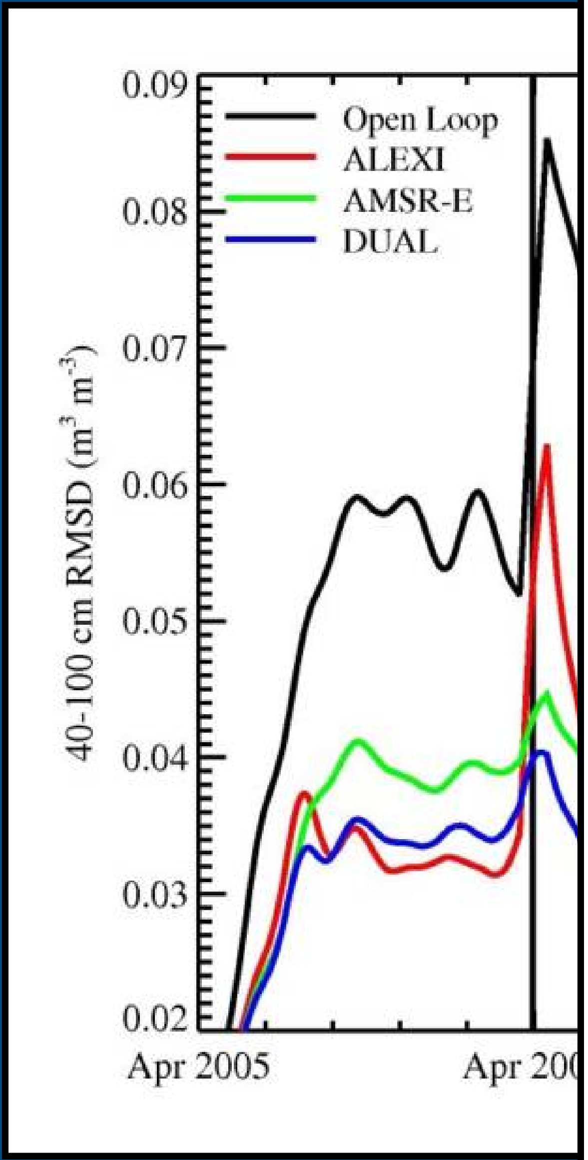


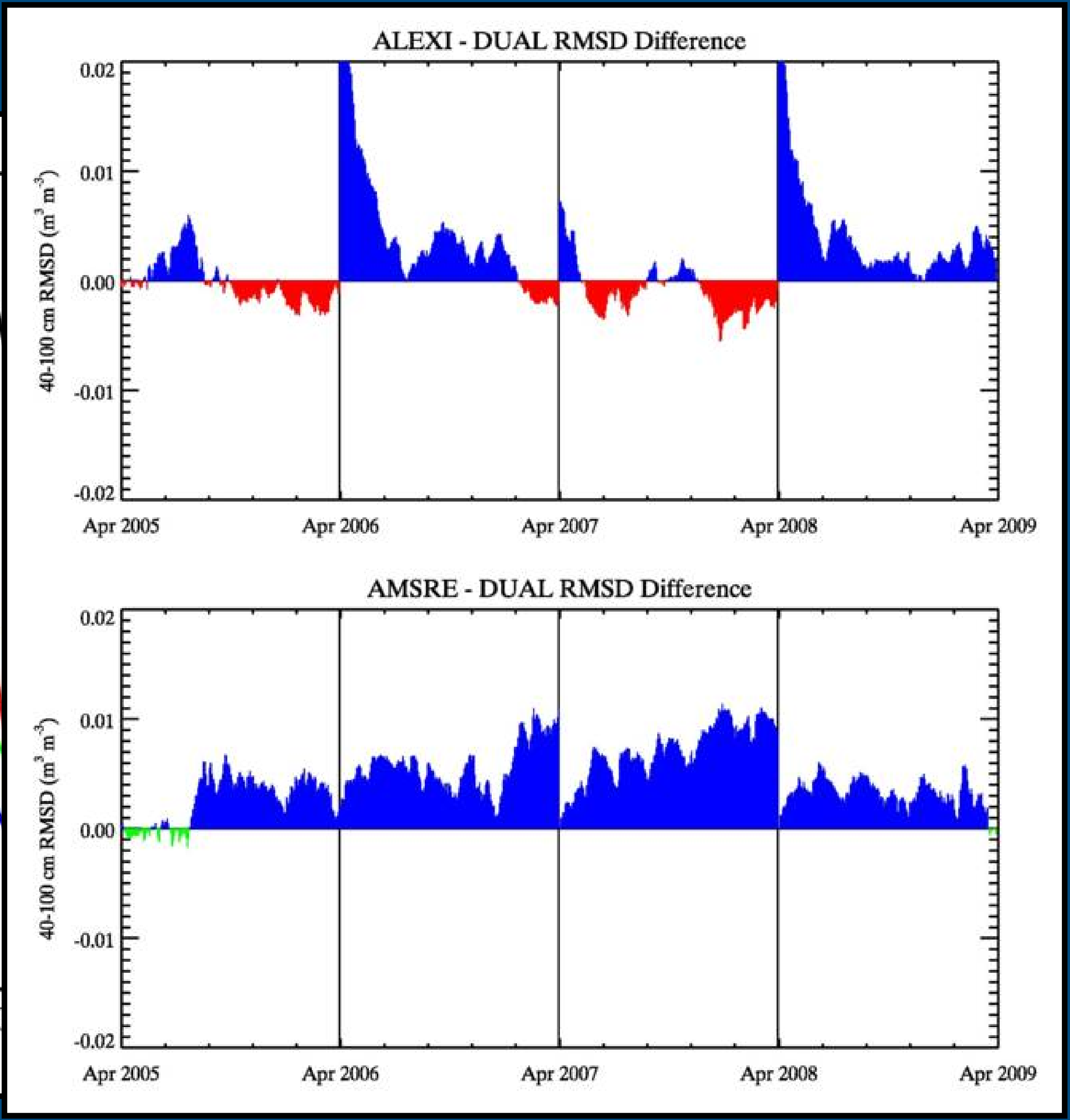
Constant Q=0.03 $m^3 m^{-3}$ / R=0.03 $m^3 m^{-3}$ Simulations





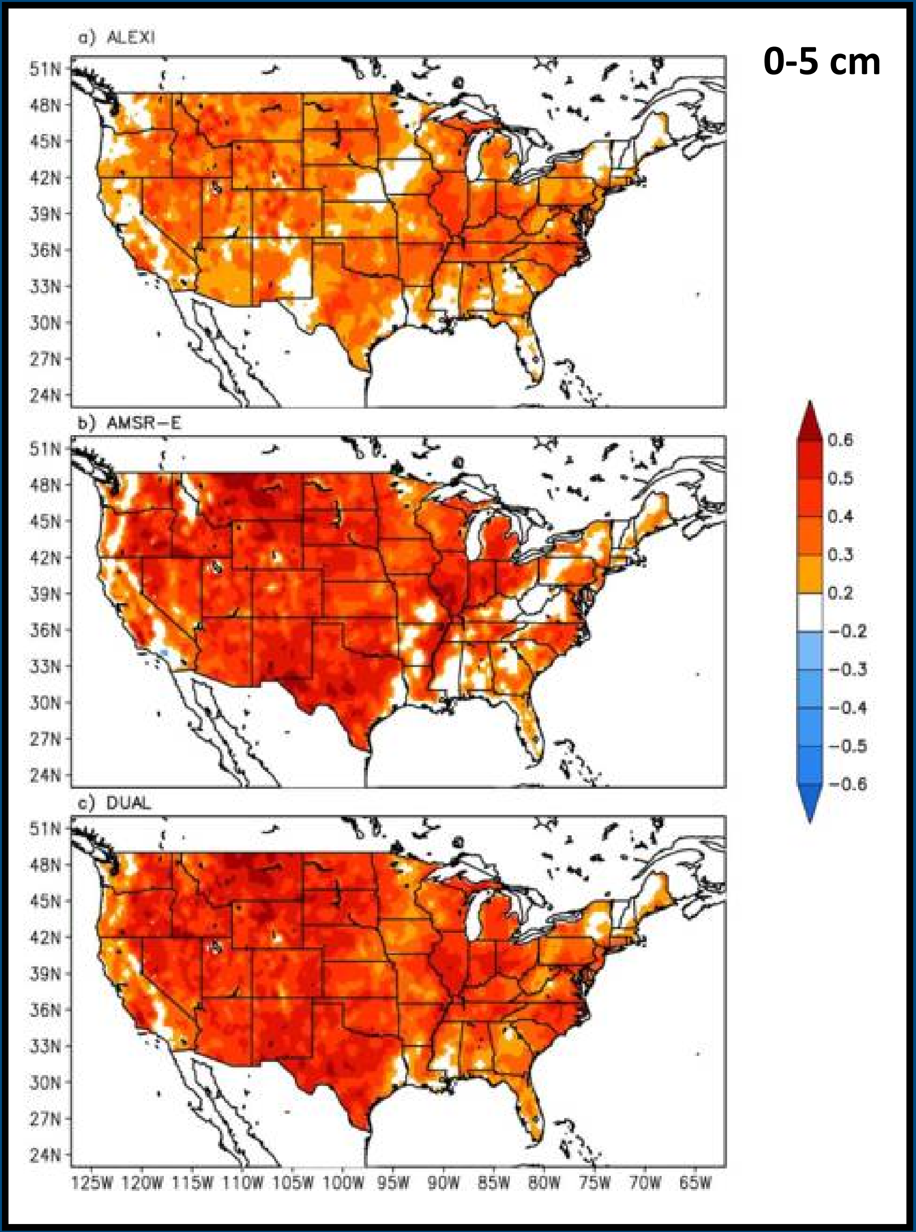
Constant Q=0.03 $m^3 m^{-3}$ / R=0.03 $m^3 m^{-3}$ Simulations

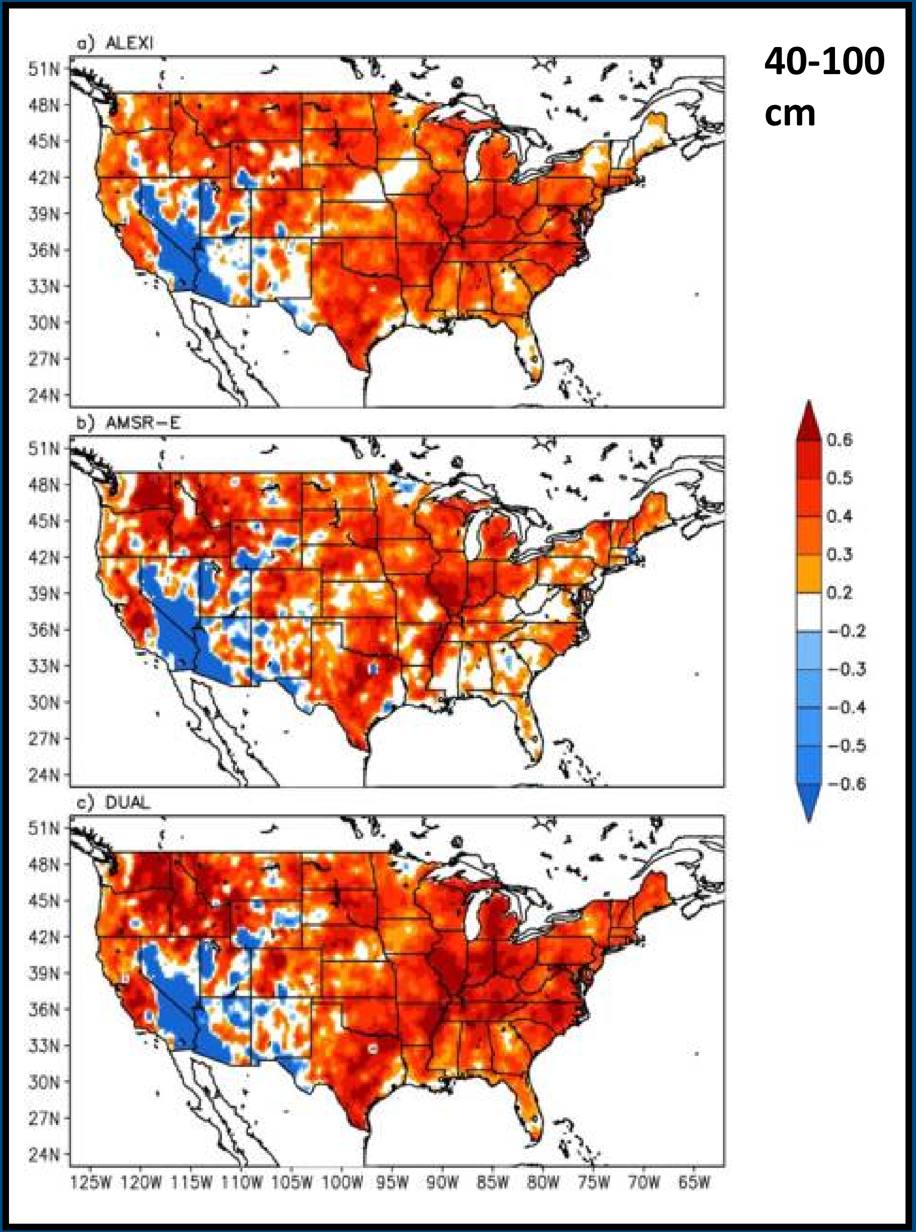




Constant Q=0.03 m^3 m^{-3} / R=0.03 m^3 m^{-3} Simulations

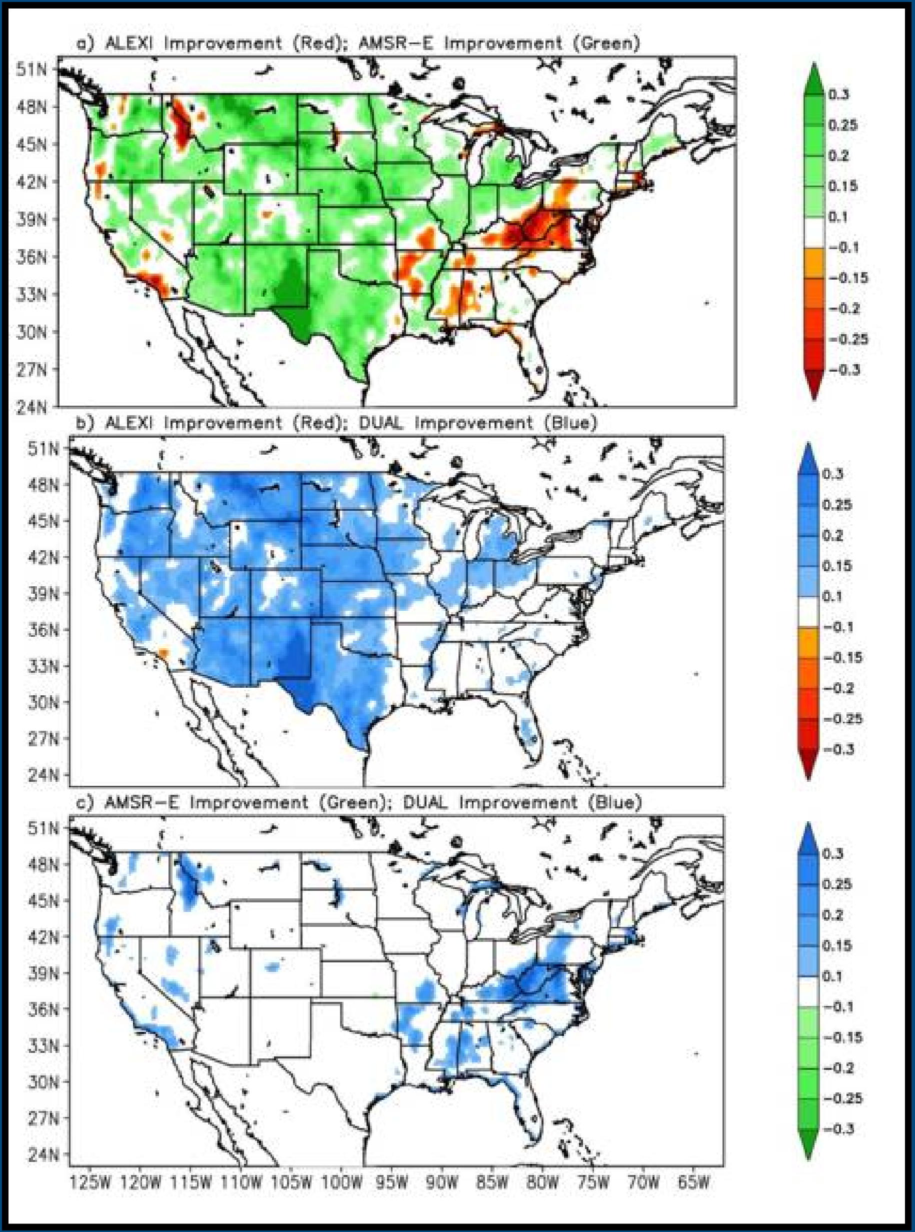
Assimilation Convergence Index : (RMSD$_{OpenLoop}$ – RMSD$_{ALEXI}$) / RMSD$_{OpenLoop}$


0-5 cm

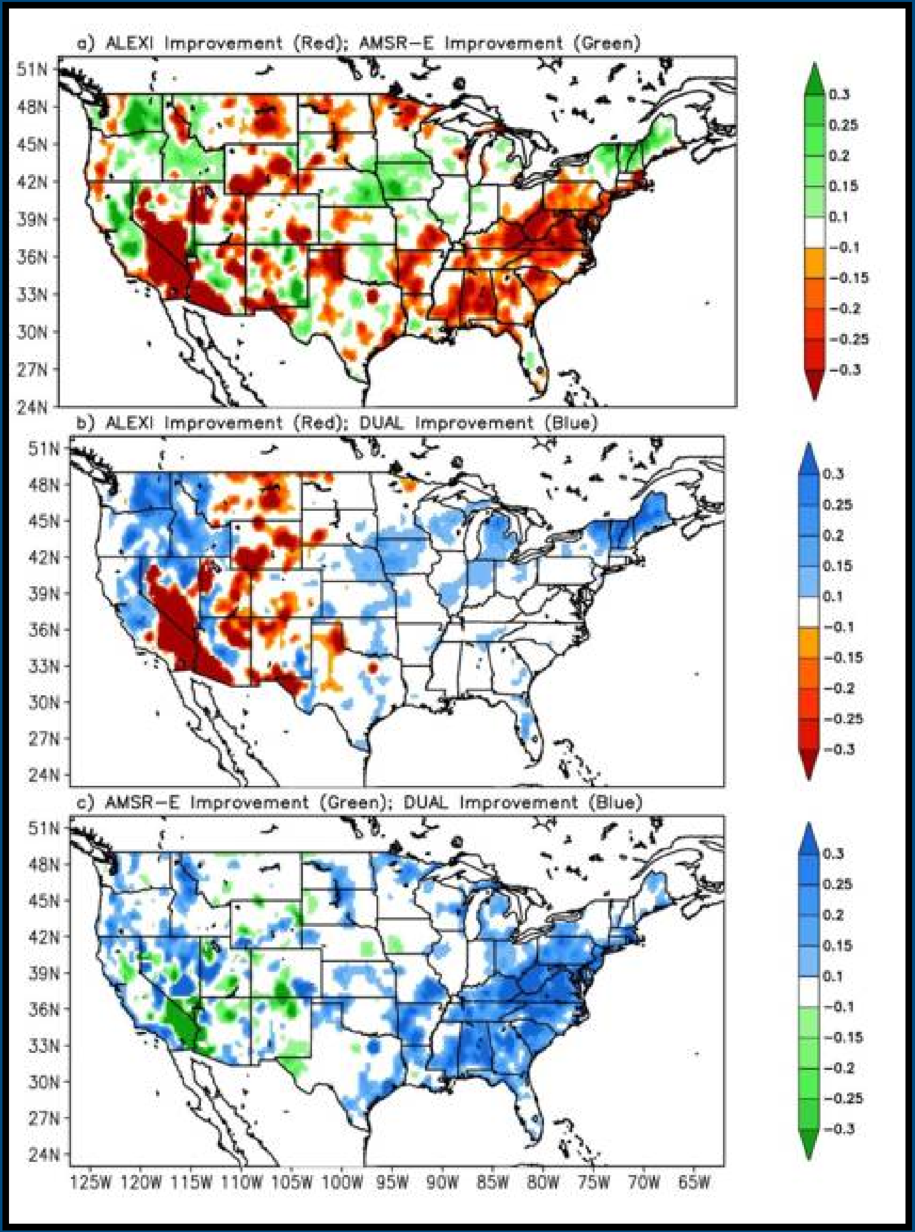

40-100 cm

Constant Q=0.03 $m^3\ m^{-3}$ / R=0.03 $m^3\ m^{-3}$ Simulations

0-5 cm



40-100 cm



Constant $Q=0.03\ m^3\ m^{-3}$ / $R=0.03\ m^3\ m^{-3}$ Simulations

Time Series RMSD	Open Loop	ALEXI	AMSR-E	DUAL
Layer 1 ($m^3\ m^{-3}$) 0-5 cm	0.045	0.031 (-31%)	0.027 (-40%)	0.025 (-44%)
Layer 2 ($m^3\ m^{-3}$) 5-40 cm	0.052	0.039 (-25%)	0.037 (-29%)	0.036 (-31%)
Layer 3 ($m^3\ m^{-3}$) 40-100 cm	0.053	0.034 (-36%)	0.036 (-32%)	0.031 (-41%)

Time Series Correlation	Open Loop	ALEXI	AMSR-E	DUAL
Layer 1 ($m^3\ m^{-3}$) 0-5 cm	0.67	0.83	0.85	0.87
Layer 2 ($m^3\ m^{-3}$) 5-40 cm	0.63	0.78	0.81	0.84
Layer 3 ($m^3\ m^{-3}$) 40-100 cm	0.59	0.80	0.75	0.84

Drought Index Intercomparison

INDEX SUITE

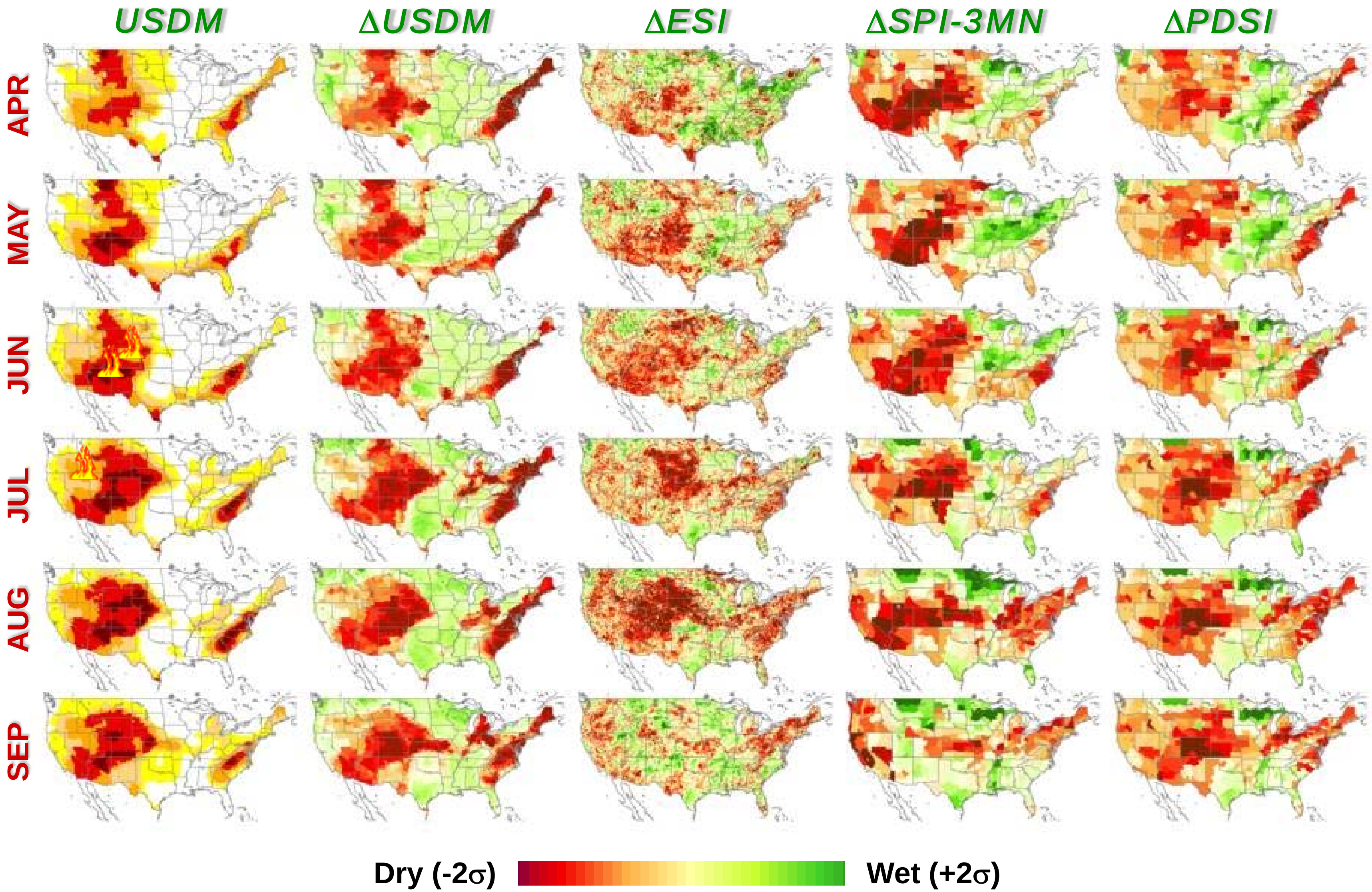
- U.S. Drought Monitor
- Evaporative Stress Index (ESI)
- Palmer Indices (1965)
    - Z-Index (monthly precip)
    - Palmer Drought Severity Index (PDSI)
    - Palmer Hydrologic Drought Index (PHDI)
- Standardized Precipitation Indices (SPI)
    - 1,2,3 and 6 month

Normalized anomalies

$$\Delta I = (I - \langle I \rangle)/\sigma_I$$

(Provided by Martha Anderson)

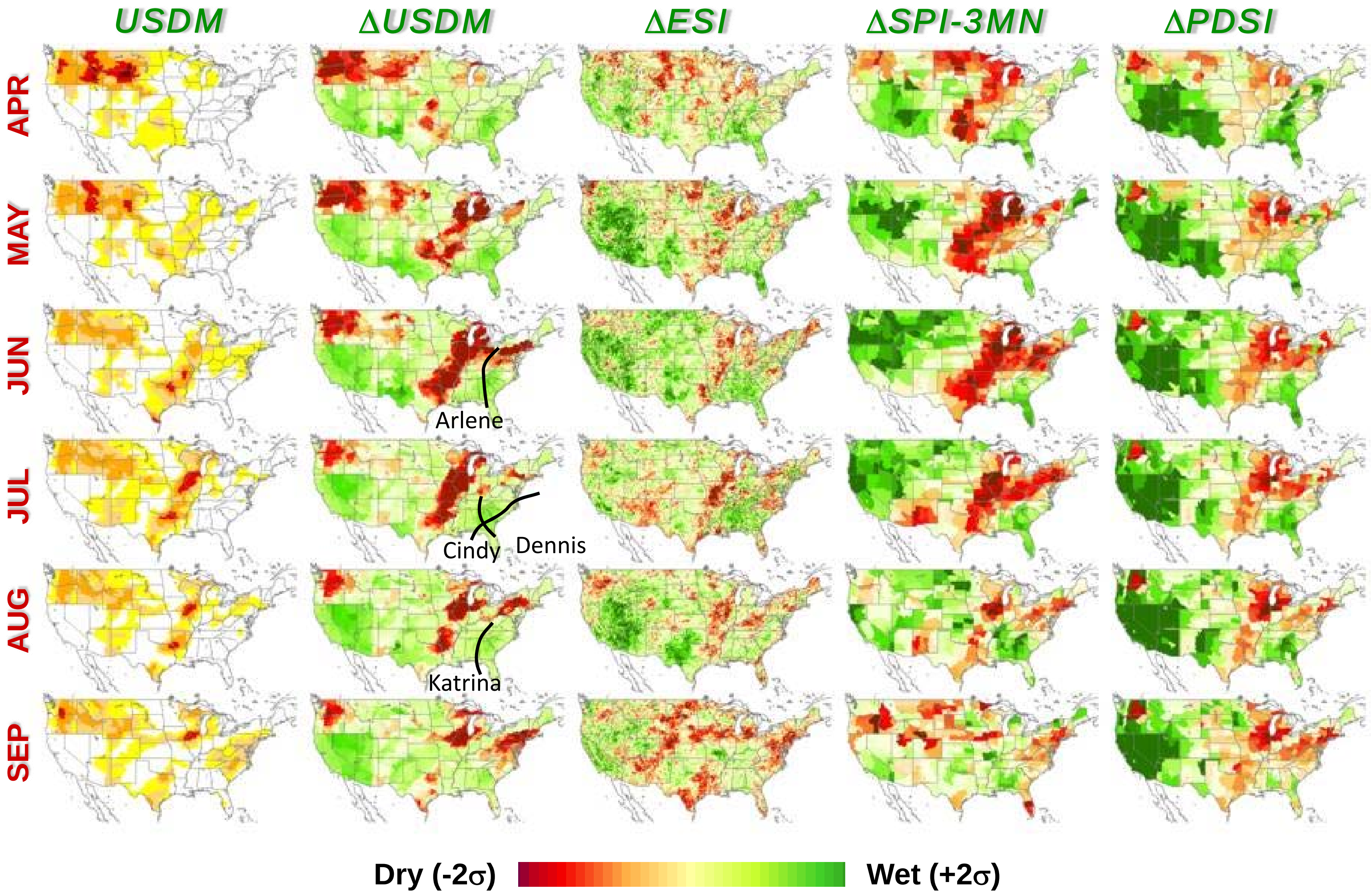
MONTHLY ANOMALIES



2002

(Provided by Martha Anderson)

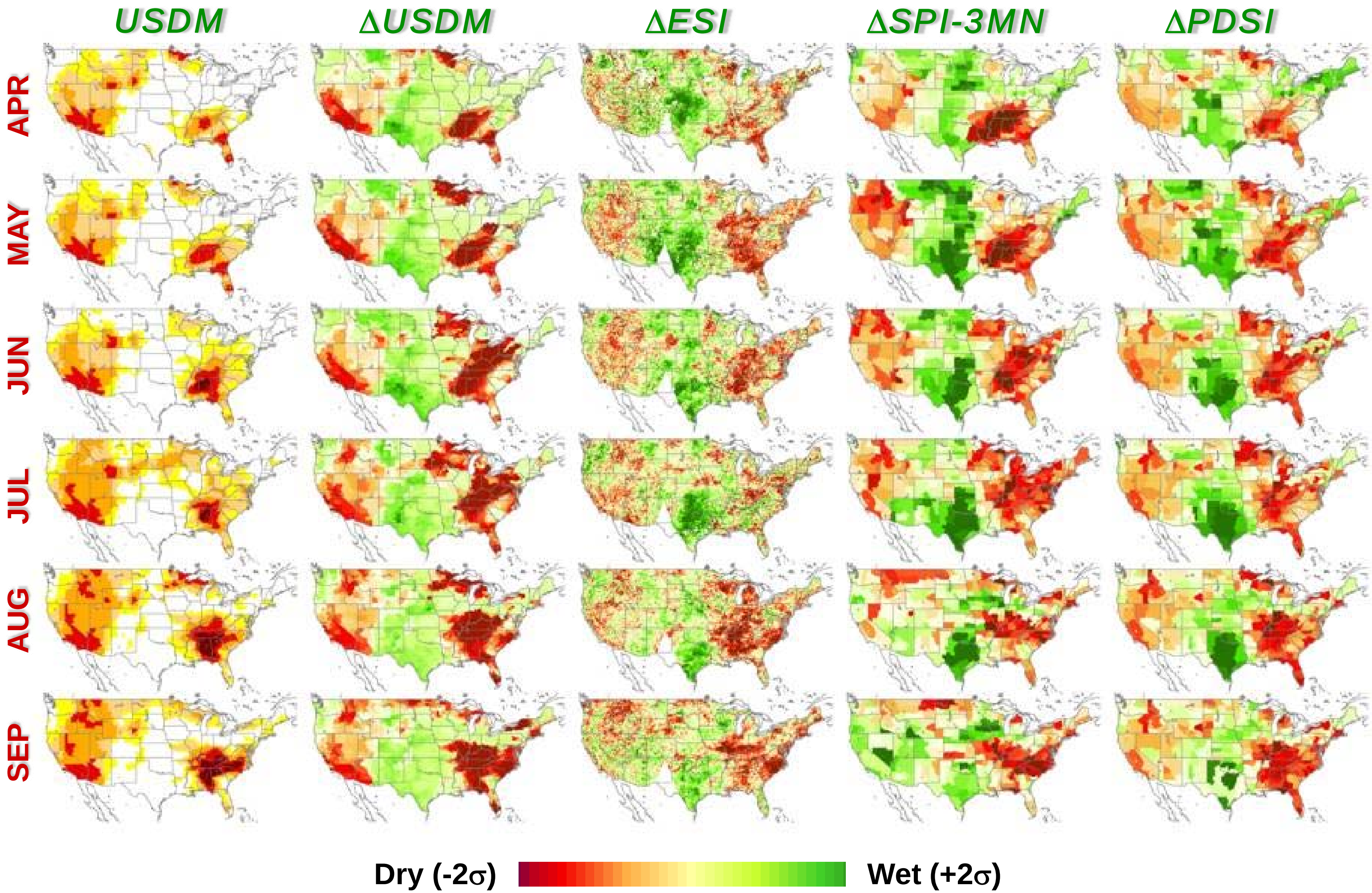
MONTHLY ANOMALIES



2005

(Provided by Martha Anderson)

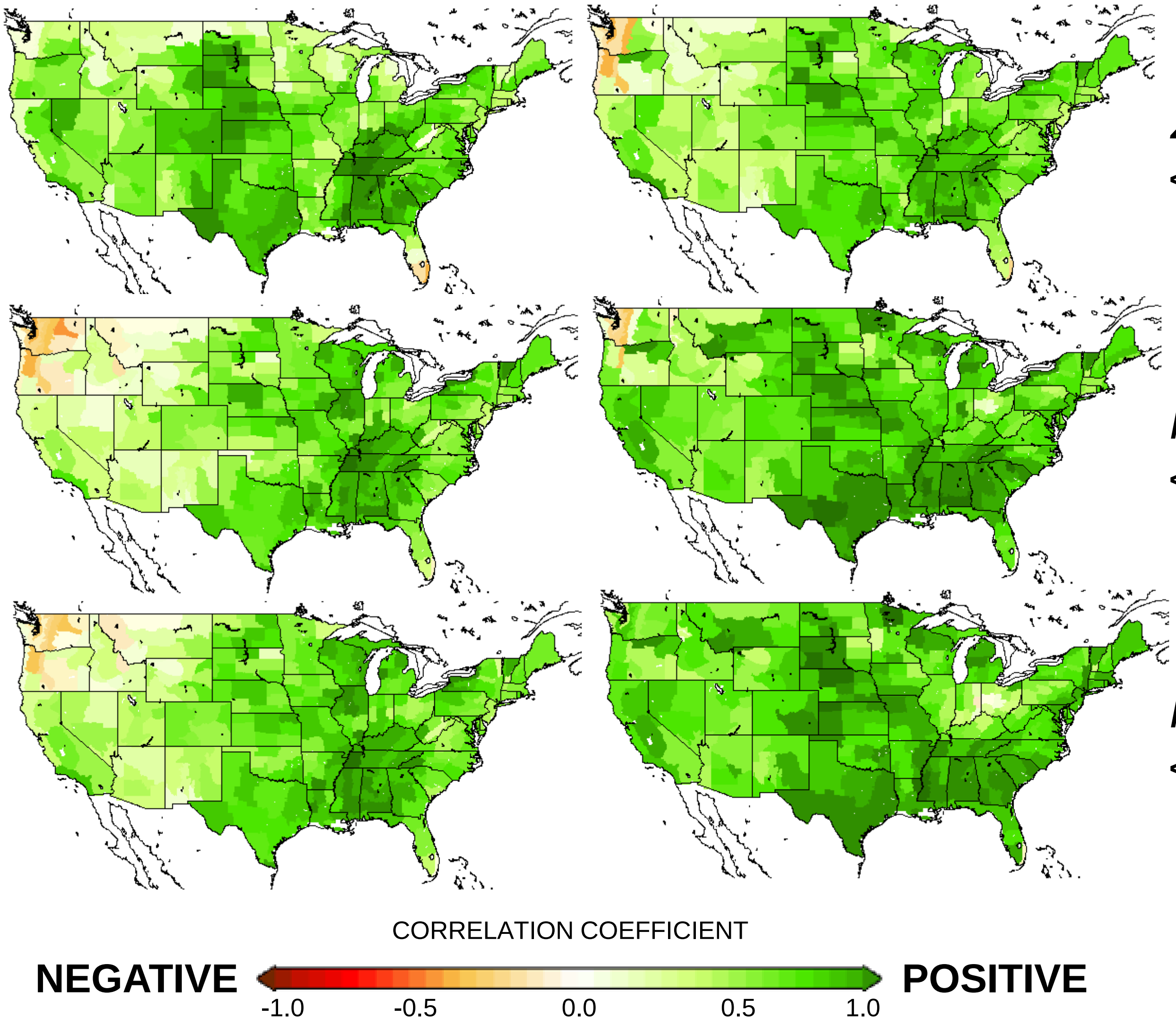
MONTHLY ANOMALIES



2007

(Provided by Martha Anderson)

Temporal correlation with USDM class



ALEXI ESI
<r>=0.62

Z-Index
<r>=0.58

SPI-2MN
<r>=0.51

PDSI
<r>=0.72

SPI-3MN
<r>=0.55

PHDI
<r>=0.75

(Provided by Martha Anderson)

Conclusions

a. ALEXI (thermal) can provide meaningful and representative estimates of soil moisture over a wide array of vegetation conditions as shown in a multi-year (2003-2008) intercomparison study.

b. ALEXI (thermal) soil moisture has the potential to complement PM retrievals of surface soil moisture, providing root-zone soil moisture information over densely vegetated pixels where PM retrievals are not possible.

c. Single assimilations of either ALEXI or AMSR-E soil moisture retrievals can provide increased skill over an open-loop simulation (degraded precipitation), yet there appears to be a potential avenue for additional benefit in a dual assimilation system.

d. Future work is needed in the area of ALEXI and AMSR-E data assimilation.

e. ALEXI ESI has been shown to be an effective tool for the monitoring of drought conditions across the continential United States.