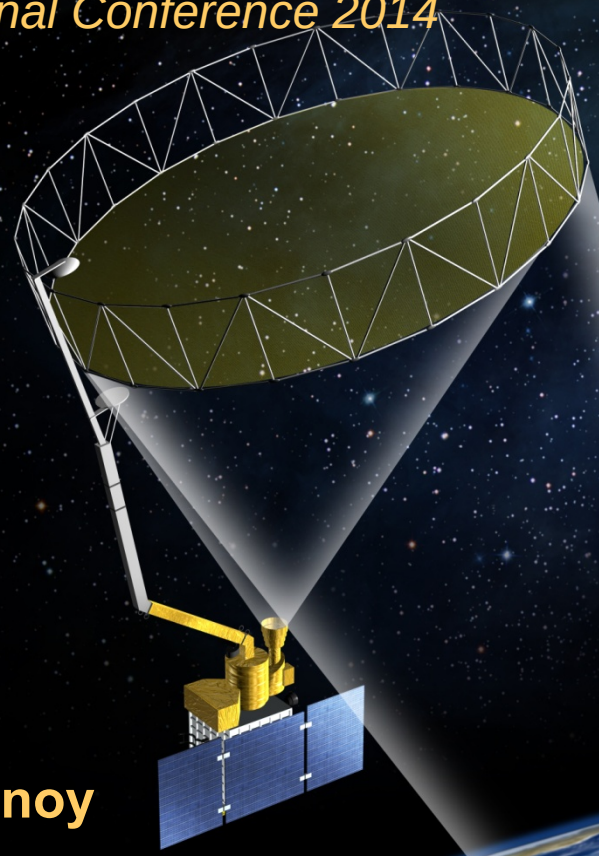
TERENO International Conference 2014
Oct 2, 2014
Bonn, Germany

National Aeronautics and Space Administration



Global Estimates of Surface & Root Zone Soil Moisture From the Assimilation of Satellite Microwave Observations Into a Land Surface Model

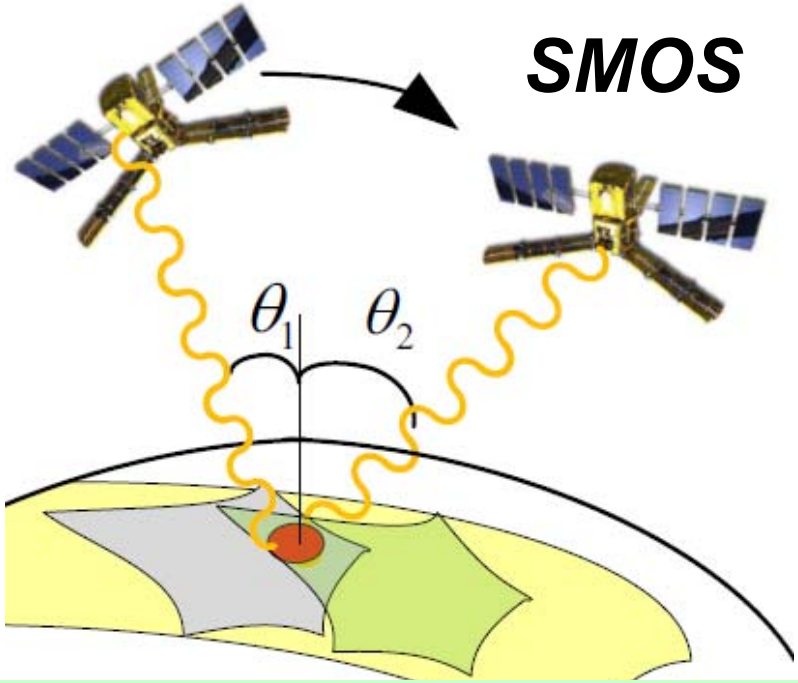
Rolf Reichle &
Gabrielle De Lannoy
NASA/GSFC
Greenbelt, MD
USA

Outline

1) Motivation and Objectives
2) SMAP L4_SM Product and Algorithm Overview
3) Validation
4) Algorithm Calibration

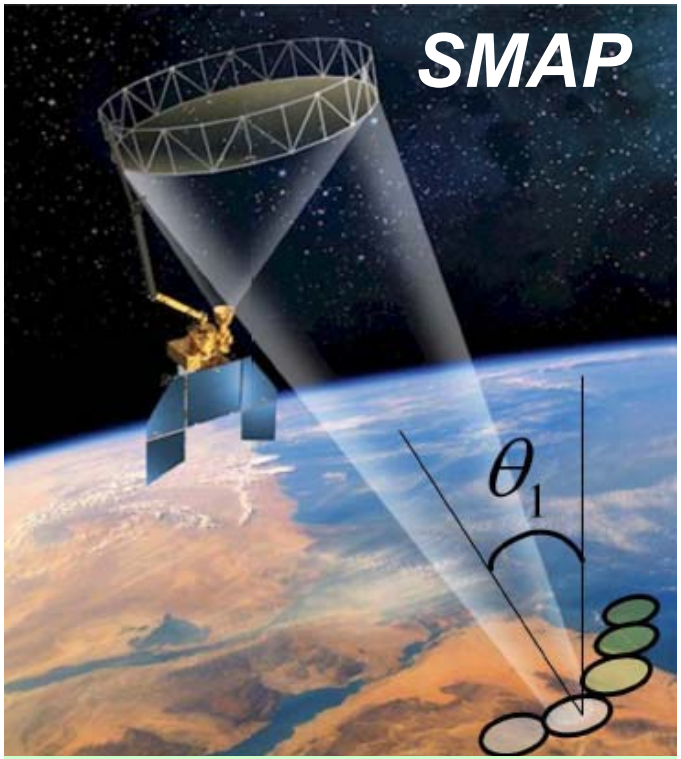
Satellite Soil Moisture Missions

SMOS



2009-present
L-band passive
40 km resolution
Interferometric & multi-angular

SMAP



Launch: Jan 2015 (?)
L-band active/passive
3-40 km resolution

Use SMOS data **to prepare for** the **SMAP** Level 4 Surface and Root Zone Soil Moisture (L4_SM) product.

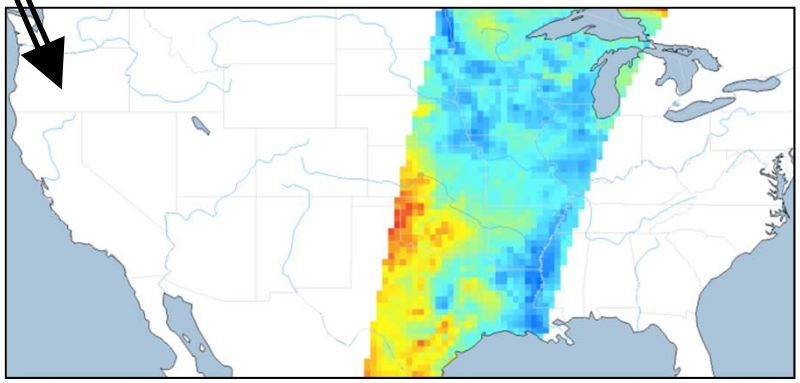
Key Limitations of Satellite Microwave Observations

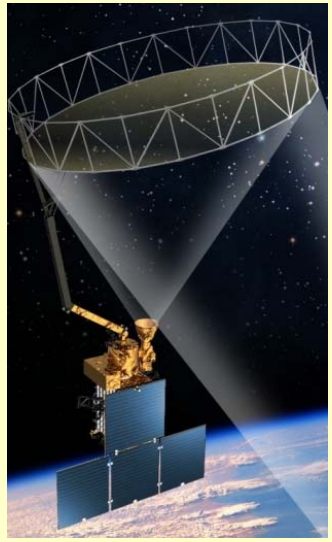
L-band microwave observations:

1) are sensitive to soil moisture and temperature ***only*** in a 5 cm surface layer (and only if less than 5 kg/m^2 vegetation),

2) have limited coverage in time and space, and

3) are subject to measurement errors.





Need *root-zone* soil moisture for many applications of interest.

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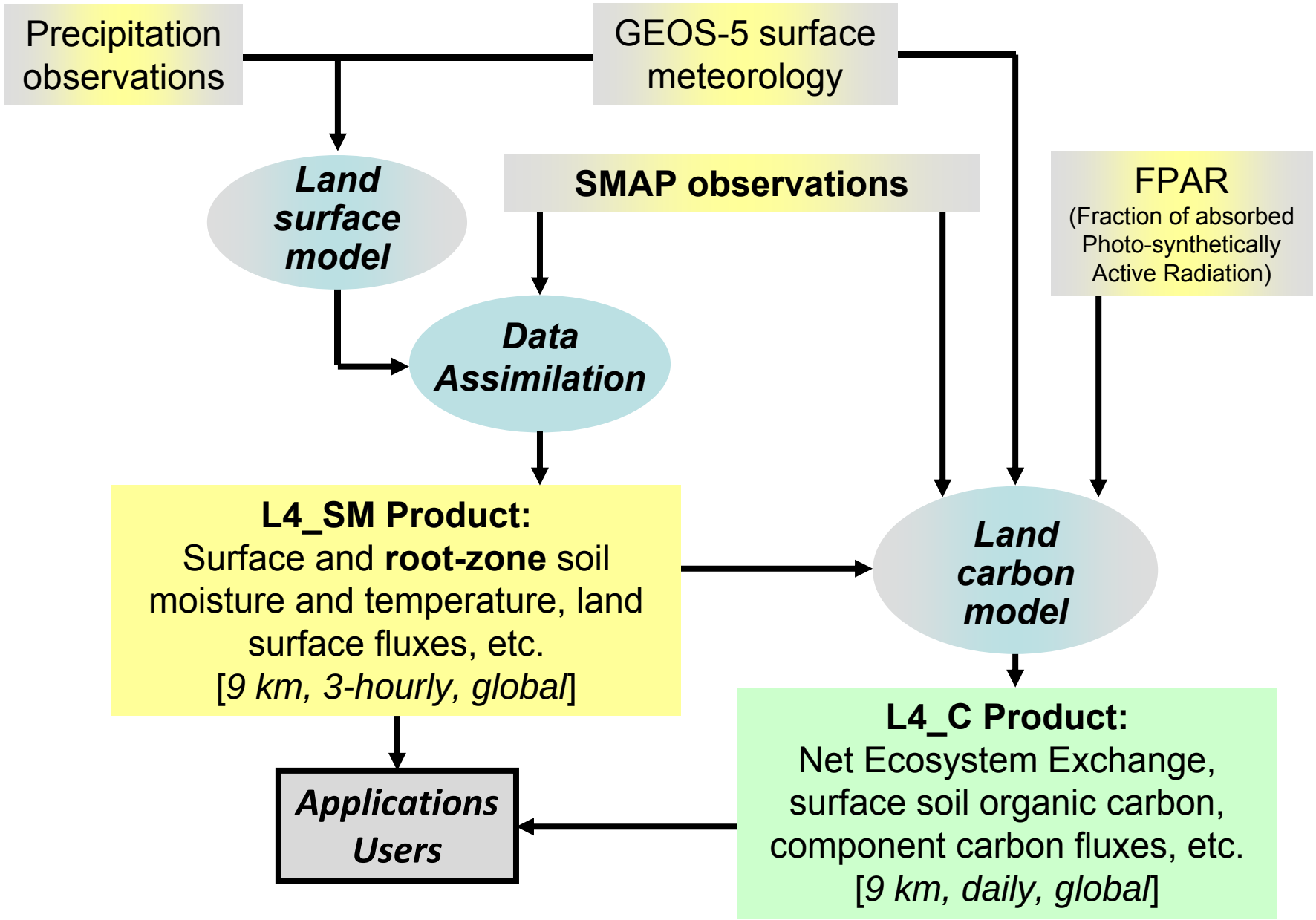
SMAP Level 4 Data Products

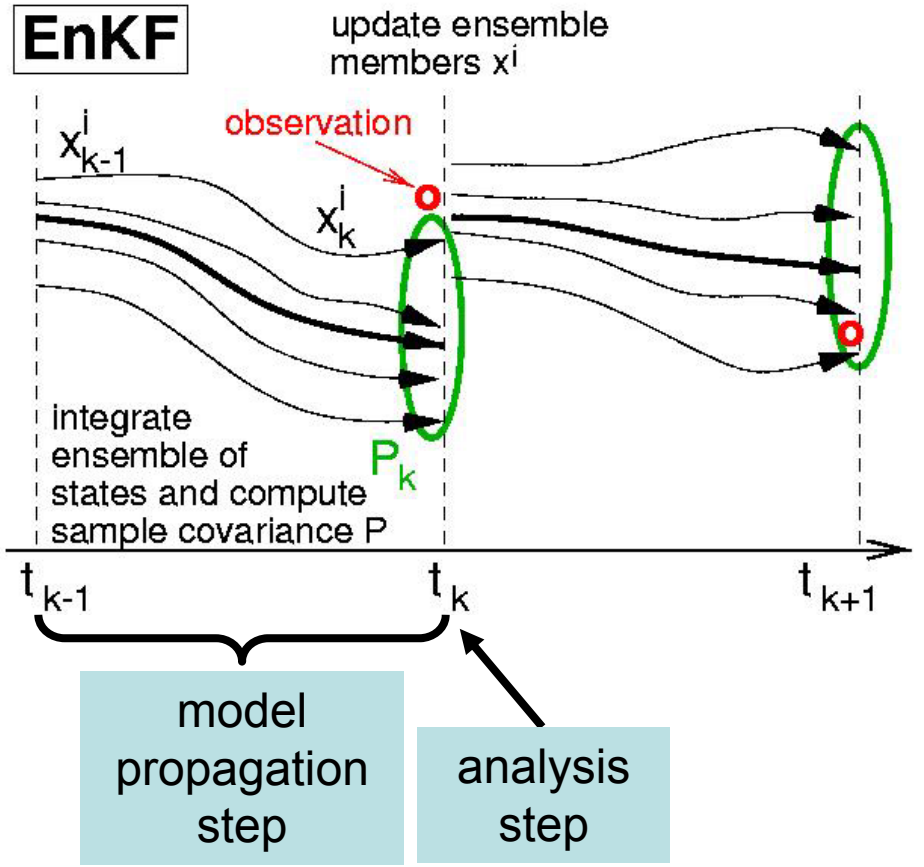


SMAP L4_SM Algorithm

Customized version of the NASA GEOS-5 Land Data Assimilation System

- 3d ensemble Kalman filter: *spatial extrapolation, interpolation, and disaggregation of assimilated observations*
- GEOS-5 Catchment land surface model
- Observations-based precipitation

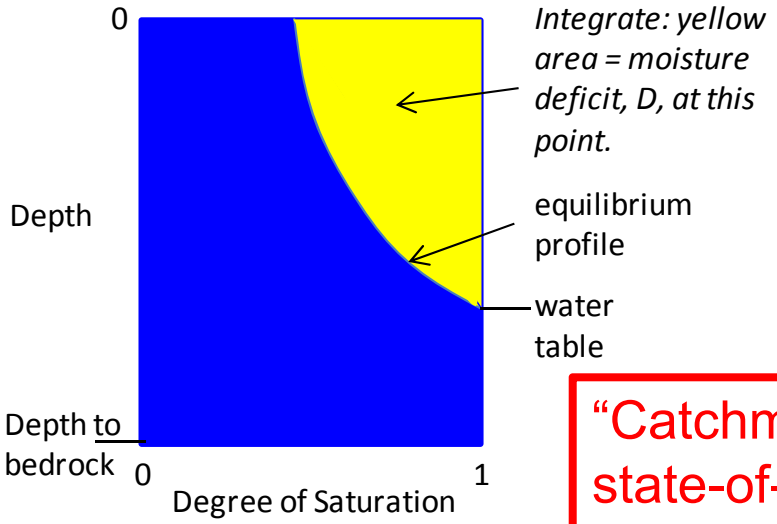
Uncertainty estimation is at the heart of the ensemble-based approach.



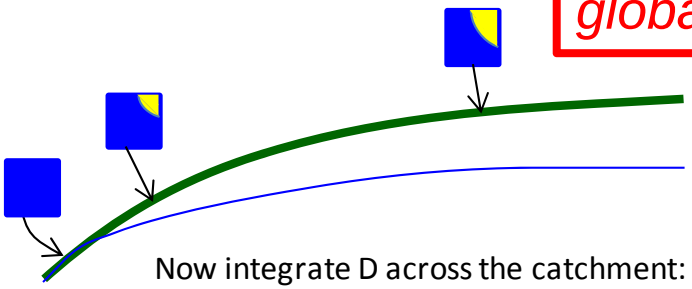
NASA GEOS-5 Catchment Land Surface Model

"Catchment Deficit" variable

Consider an arbitrary point in the catchment:



"Catchment" is a state-of-the-art hydrology model for *global* applications.

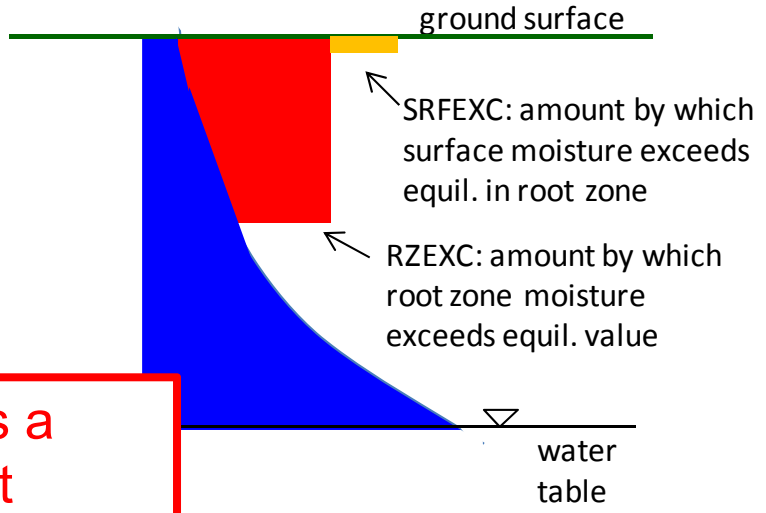


Now integrate D across the catchment:

CATDEF = $(1/A) \int_A D \, dA$

= the average amount of water, per m^2, that must be added to the catchment to bring it to complete saturation, assuming equilibrium profiles.

"Root Zone Excess" and "Surface Excess" variables: the view at a point



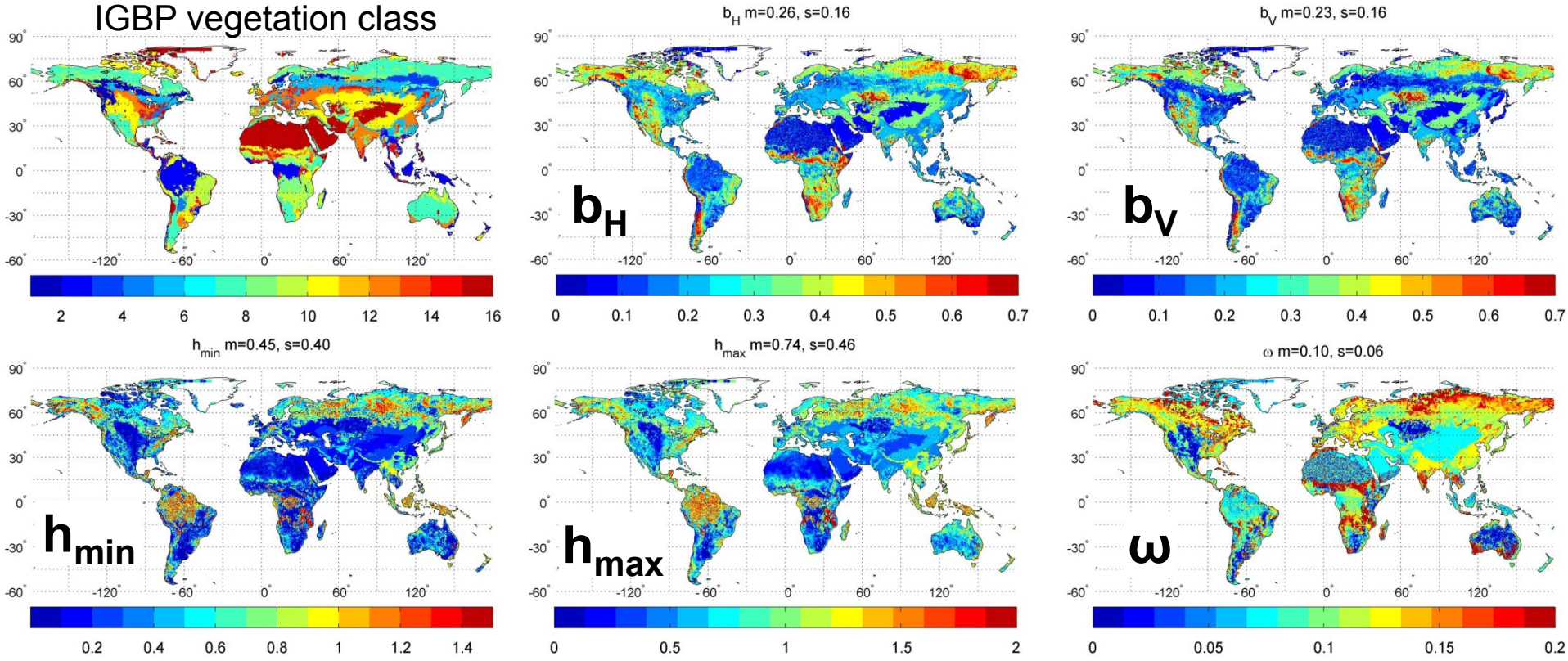
Diffusion calculation

Functions relating time scales of diffusion to the moisture variables are pre-computed from Richard's equation calculations at high vertical resolution. The time scales for diffusion between RZEXC and CATDEF reflect net diffusion over a spatially distributed set (across the catchment) of independent columns.

Koster et al. (2000)
Ducharne et al. (2000)

L4_SM Radiative Transfer Model

- **Radiance assim. requires unbiased L-band radiative transfer model.**
- **Locally** optimized parameters to minimize differences in long-term mean and std-dev between Tbs from **SMOS** and **GEOS-5**.
- Areas where SMOS data are not suitable for calibration (e.g., due to RFI) are filled with calibrated parameter values that are (spatially) averaged by vegetation class.



De Lannoy et al., *RSE*, 2014, doi:10.1016/j.rse.2014.03.030

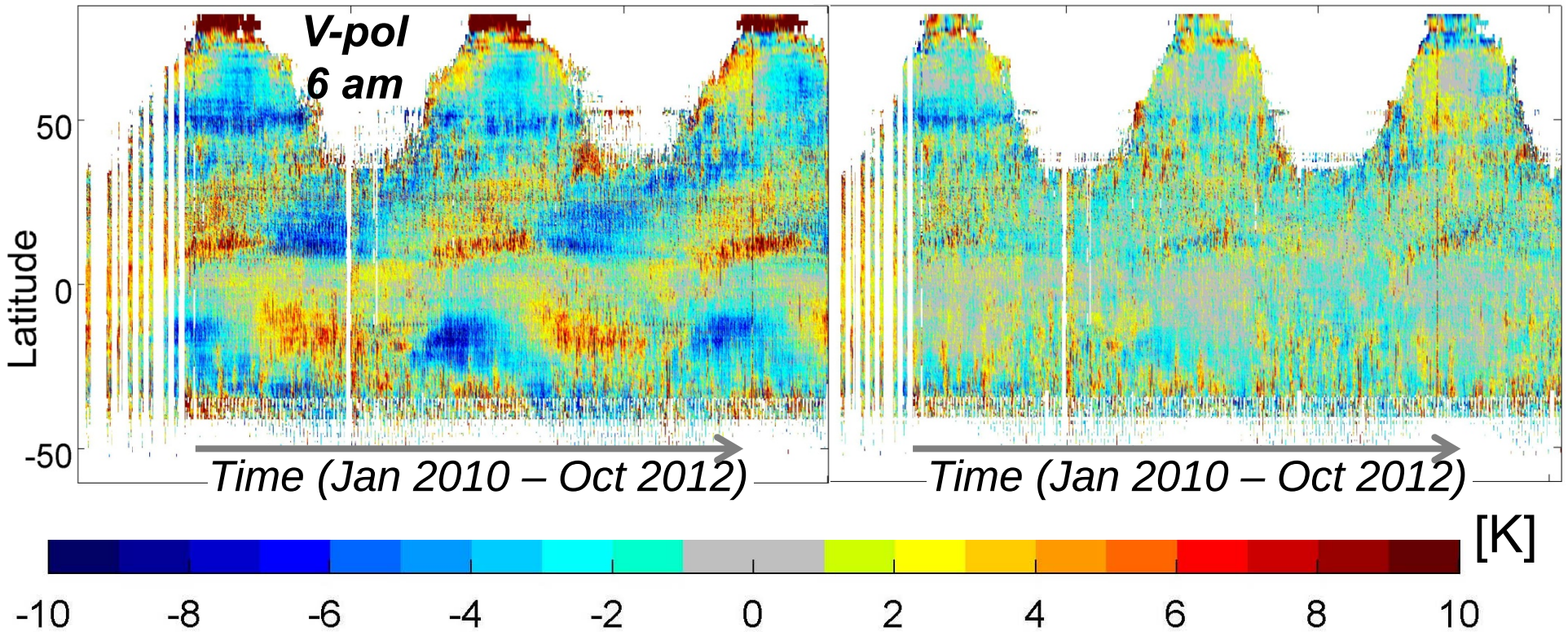
L-band Brightness Temperature: SMOS minus GEOS-5

Seasonally varying biases remain even after calibration of the microwave radiative transfer model (RTM) parameters.

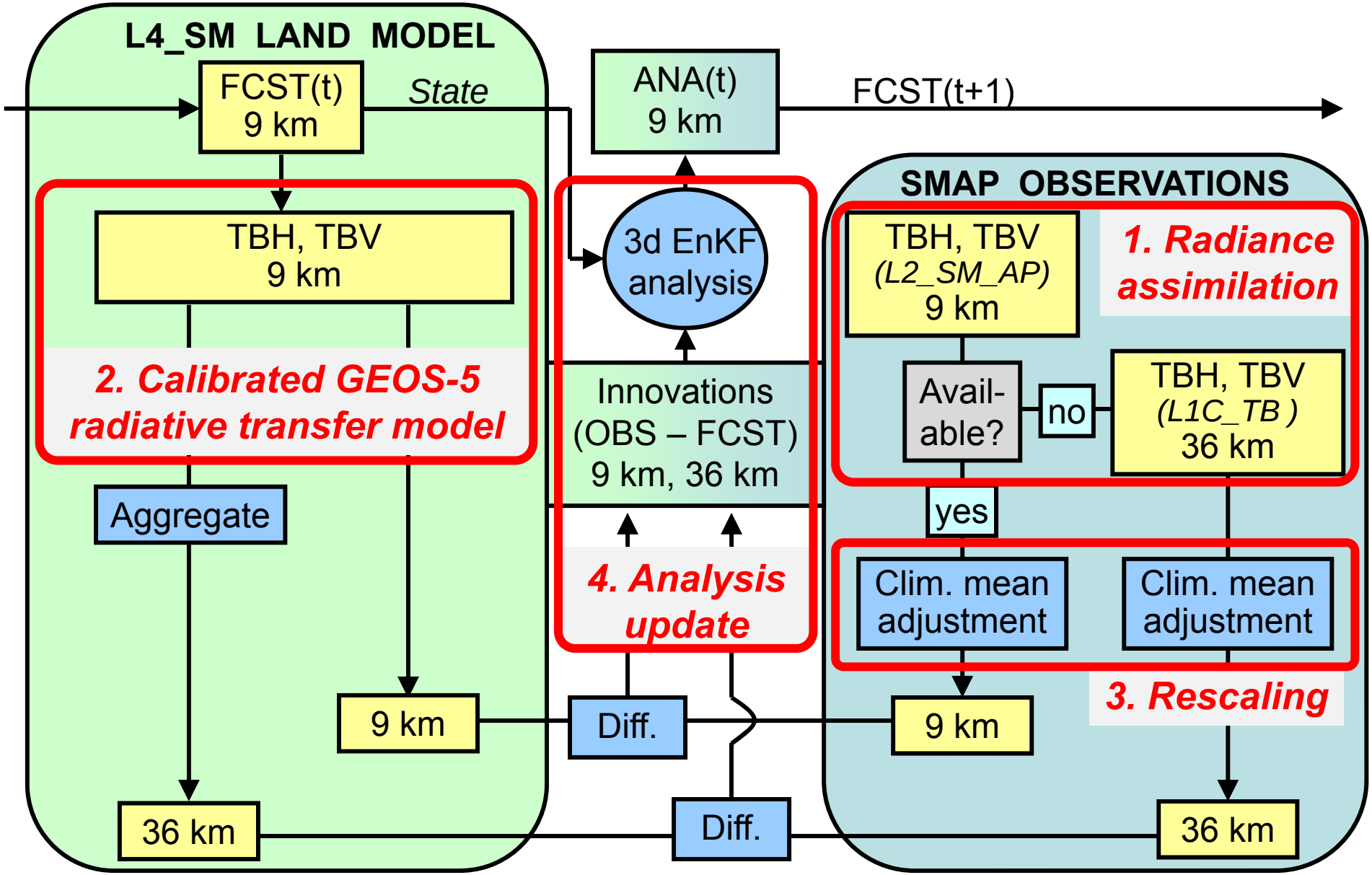
Derive climatological scaling parameters (based on 4 years of SMOS data).

After calibration of RTM parameters

After climatological Tb scaling



Summary of SMAP L4_SM Soil Moisture Analysis



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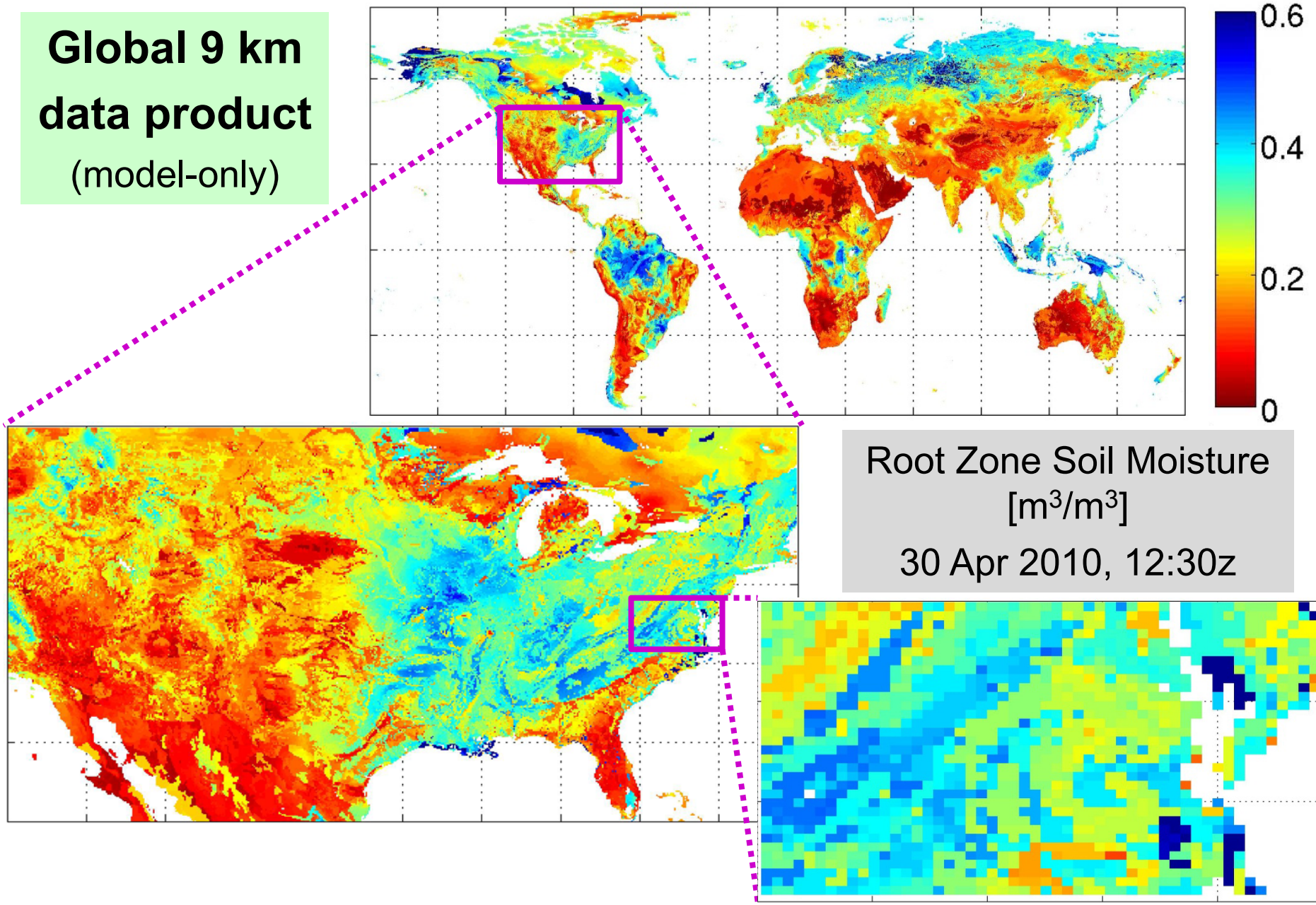
Sample Output from SMAP Nature Run v03

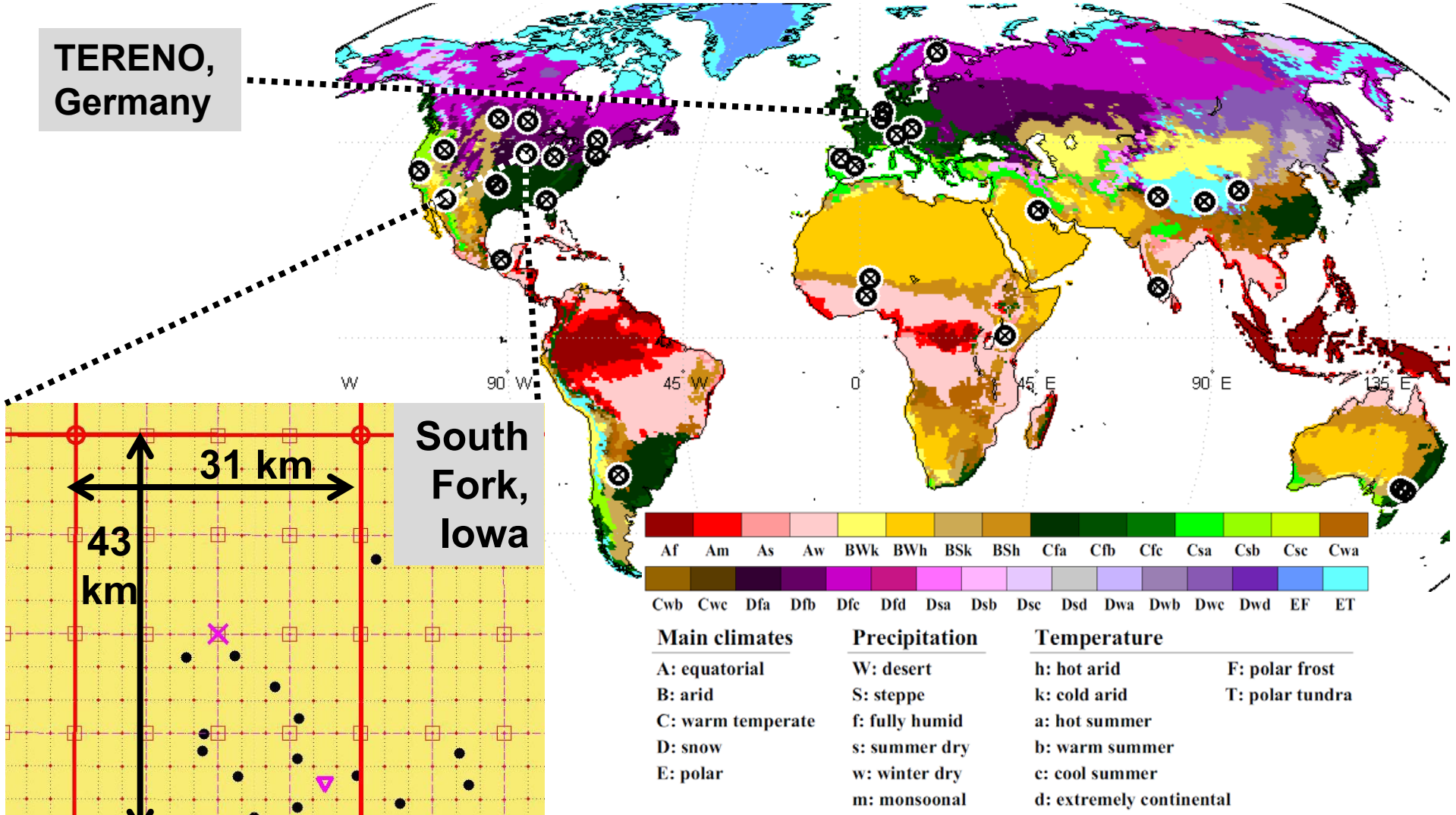
Global 9 km data product
(model-only)



Root Zone Soil Moisture
[m^3/m^3]
30 Apr 2010, 12:30z

SMAP Core Validation Sites (Candidates)

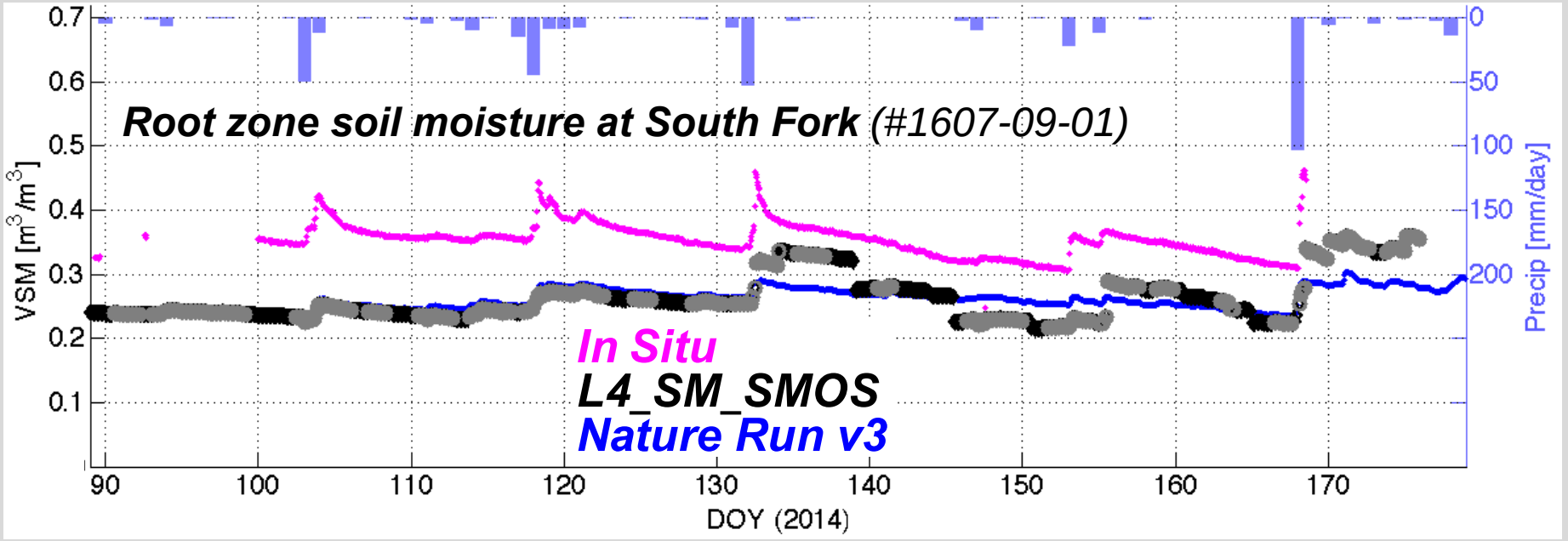
TERENO, Germany



South Fork, Iowa

SMAP **core validation sites** include dense in situ measurement networks within satellite footprint scales.

Validation at SMAP Core Validation Sites



L4_SM_SMOS: Assimilation of "40° fitted" SMOS Tbs
9 km resolution
With CPCU precipitation corrections

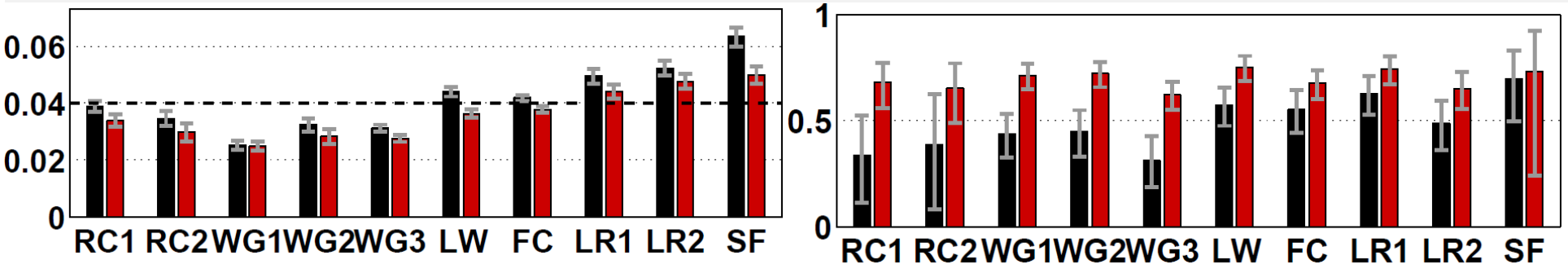
Courtesy of A. Colliander (JPL)

Validation at SMAP Core Validation Sites

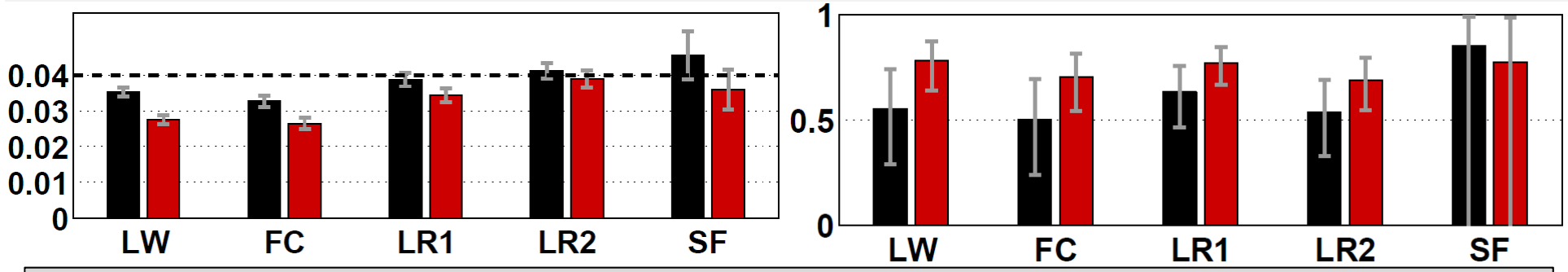
Generally better soil moisture skill with SMOS assimilation.

ubRMSE *[m³/m³]*	***Anomaly R*** *[-]*

Surface soil moisture [m³/m³]



Root zone soil moisture [m³/m³]

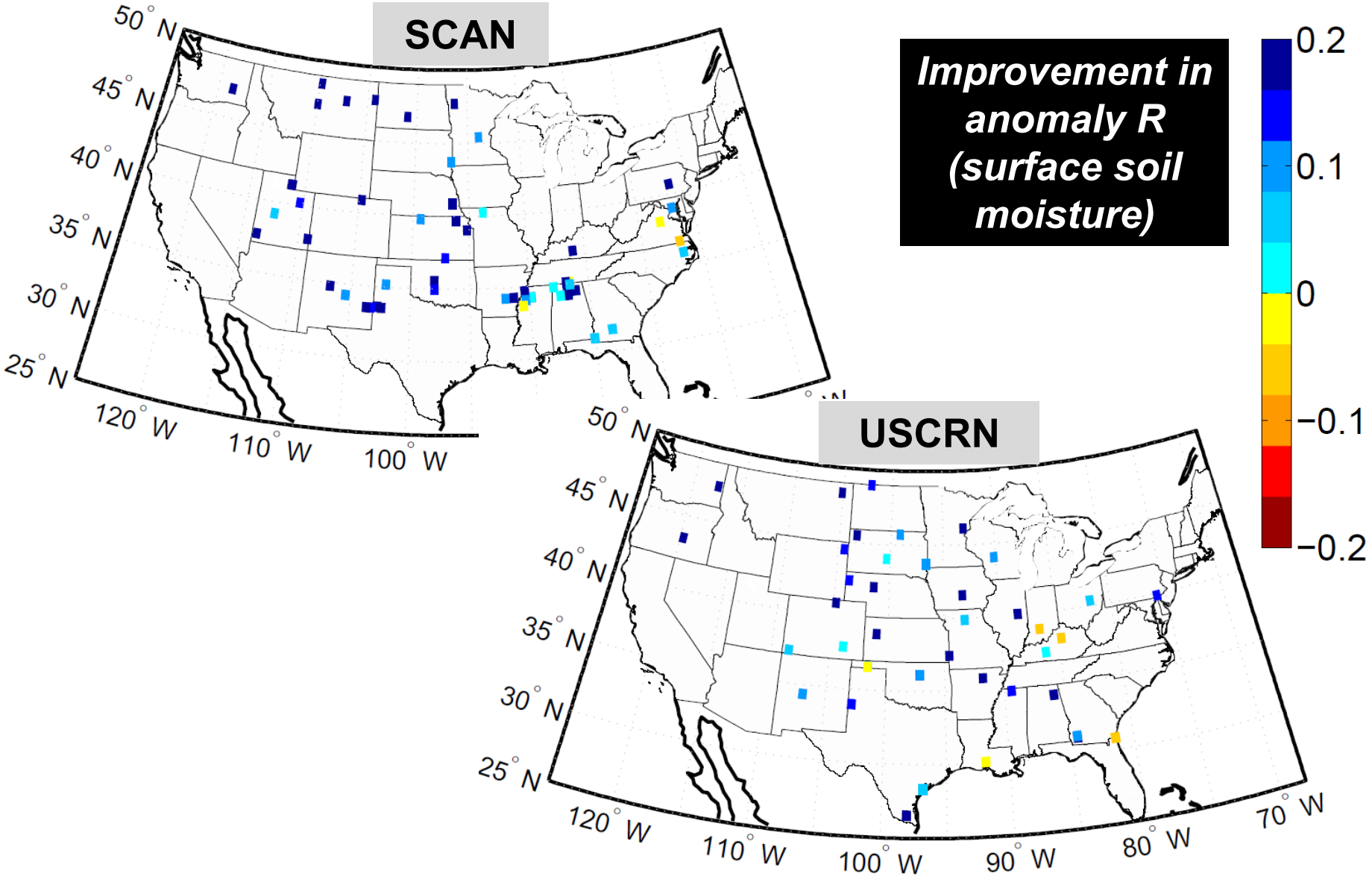


July 2010 – June 2014
36 km resolution.
Assimilation of "7-angle" SMOS Tbs.
<u>Without</u> CPCU precip. corrections (reflecting areas with few precip. gauges).

Black: Model-only
Red: With SMOS assimilation

Validation at Sparse Network Sites

Typically just one (profile) sensor within satellite footprint.

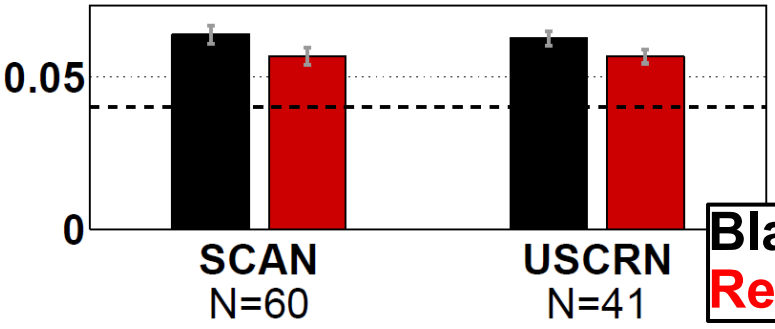


Validation at Sparse Network Sites

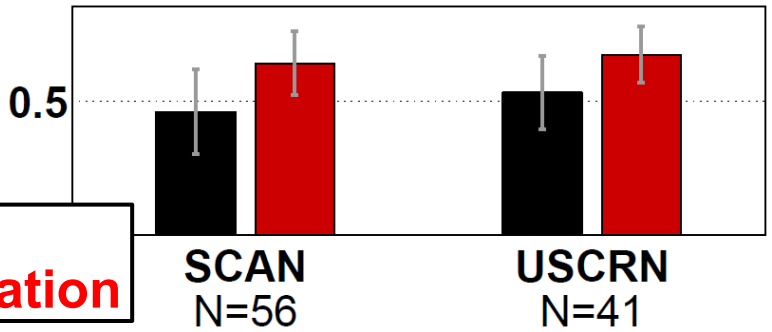
De Lannoy et al., 2014, in preparation.

ubRMSE | Jul 2010 – Jun 2014 | ***anomaly R***

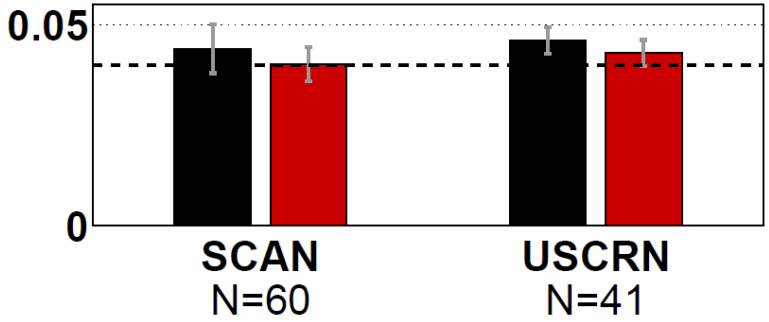
Surface soil moisture [m^3/m^3]

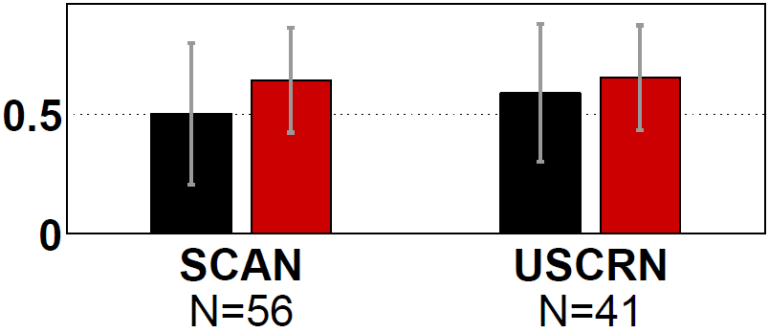


Black: Model
Red: Assimilation

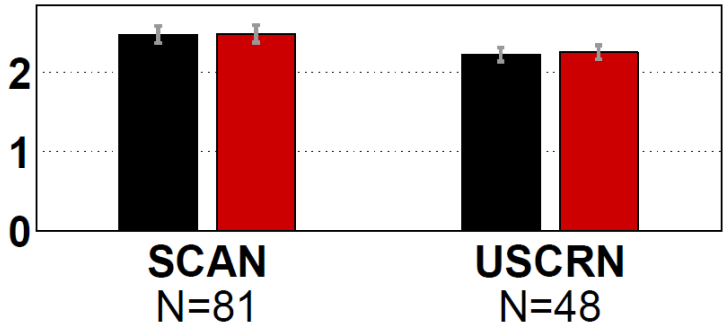


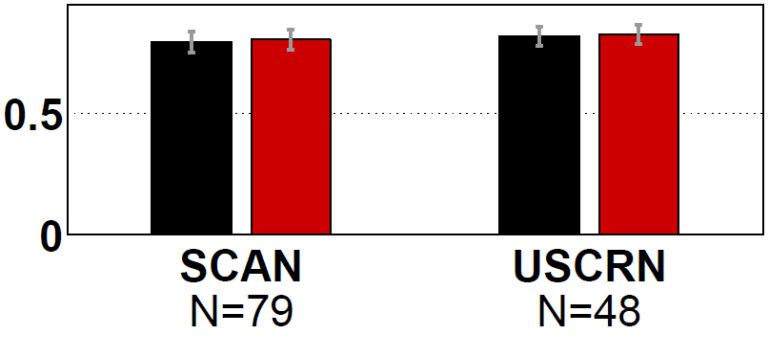
Root zone soil moisture [m^3/m^3]





Surface soil temperature [K]





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Calibration of the Data Assimilation System

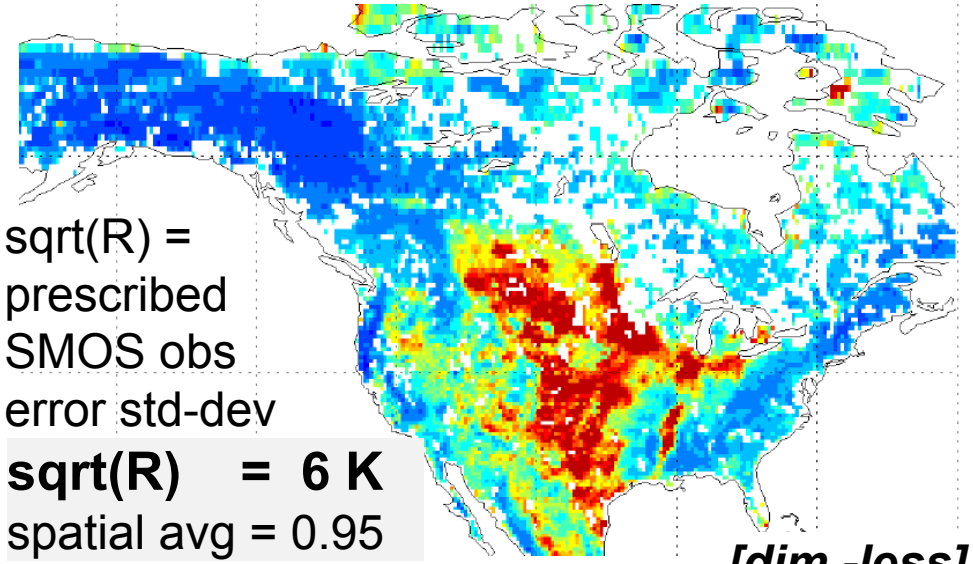
Perturbation	**Additive (A) or Multipli-cative (M)**	**Std-dev**	**AR(1) time series correlation scale**	**Spatial correlation scale**	**Cross-correlation with perturbations in**		
					P	SW	LW
Precipitation (P)	*M*	*0.5*	*24 h*	*50 km*	*n/a*	*-0.8*	*0.5*
Downward shortwave (SW)	*M*	*0.3*	*24 h*	*50 km*	*-0.8*	*n/a*	*-0.5*
Downward longwave (LW)	*A*	*20 W/m²*	*24 h*	*50 km*	*0.5*	*-0.5*	*n/a*
					catdef	srfexc	
Catchment deficit (catdef)	*A*	*0.03 kg/m²*	*3 h*	*50 km*	*n/a*	*0.0*	
Surface excess (srfexc)	*A*	*0.02 kg/m²*	*3 h*	*50 km*	*0.0*	*n/a*	

Perturbations applied at every 3 h forcing time step (or 7.5 min model time step).

Calibration of **model and observation error** parameters guided by validation vs. in situ measurements and by internal assimilation diagnostics.

Calibration of the Data Assimilation System

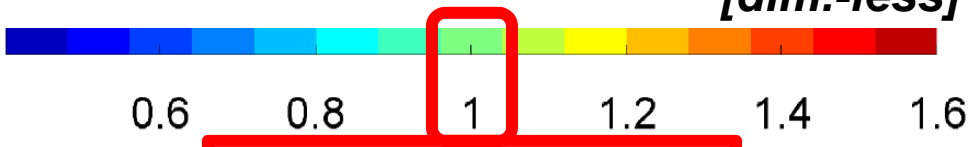
Std-dev of normalized observation-minus-forecast residuals



sqrt(R) = prescribed SMOS obs error std-dev

sqrt(R) = 6 K
spatial avg = 0.95

[dim.-less]

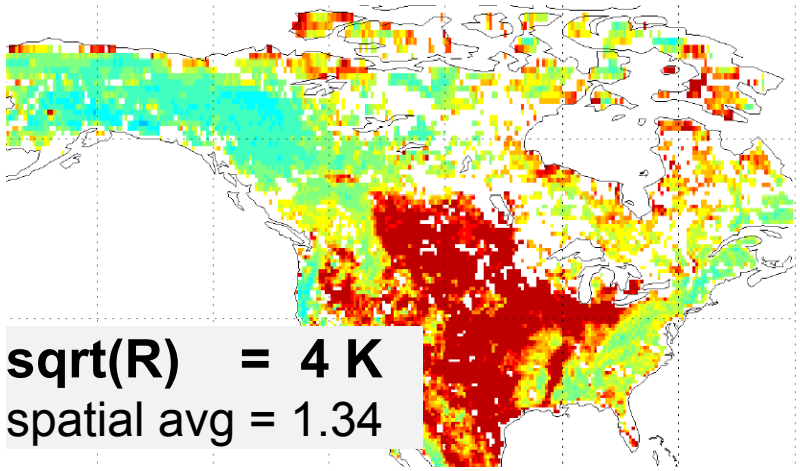


Target value = 1

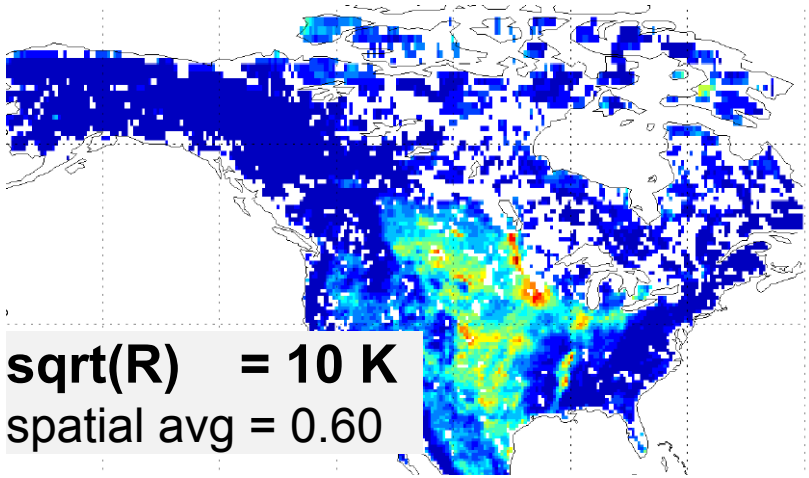
DA system

overestimates ← → **under**estimates

actual uncertainty



sqrt(R) = 4 K
spatial avg = 1.34



sqrt(R) = 10 K
spatial avg = 0.60

Further calibration underway using newly implemented infrastructure for **spatially distributed** perturbation std-devs and observations error std-devs.

De Lannoy et al., 2014, in preparation.

Conclusions

SMAP L4_SM data product

- Global, 9 km, 3-hourly output incl. root zone soil moisture and related fields
- Quasi-operational, 3-4 day latency
- Available next year

Validation

- Core validation sites and sparse network sites
- Assimilation of SMOS observations adds skill to model-only results

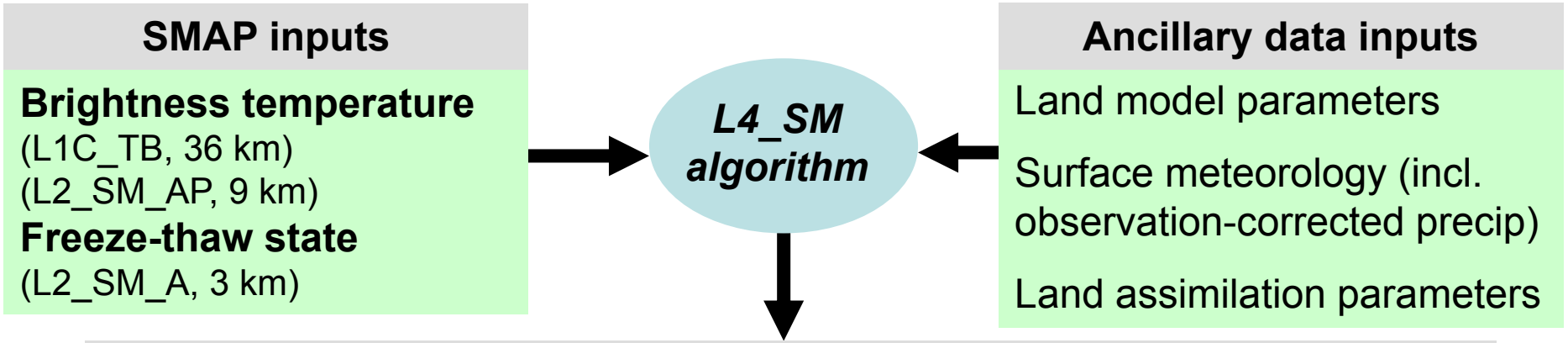
Calibration

- Refining model and observation error covariances (spatially distributed)
- Observation-minus-forecast residuals (internal data assimilation diagnostics)

Thanks for listening!

EXTRA SLIDES

SMAP L4_SM Data Product Overview



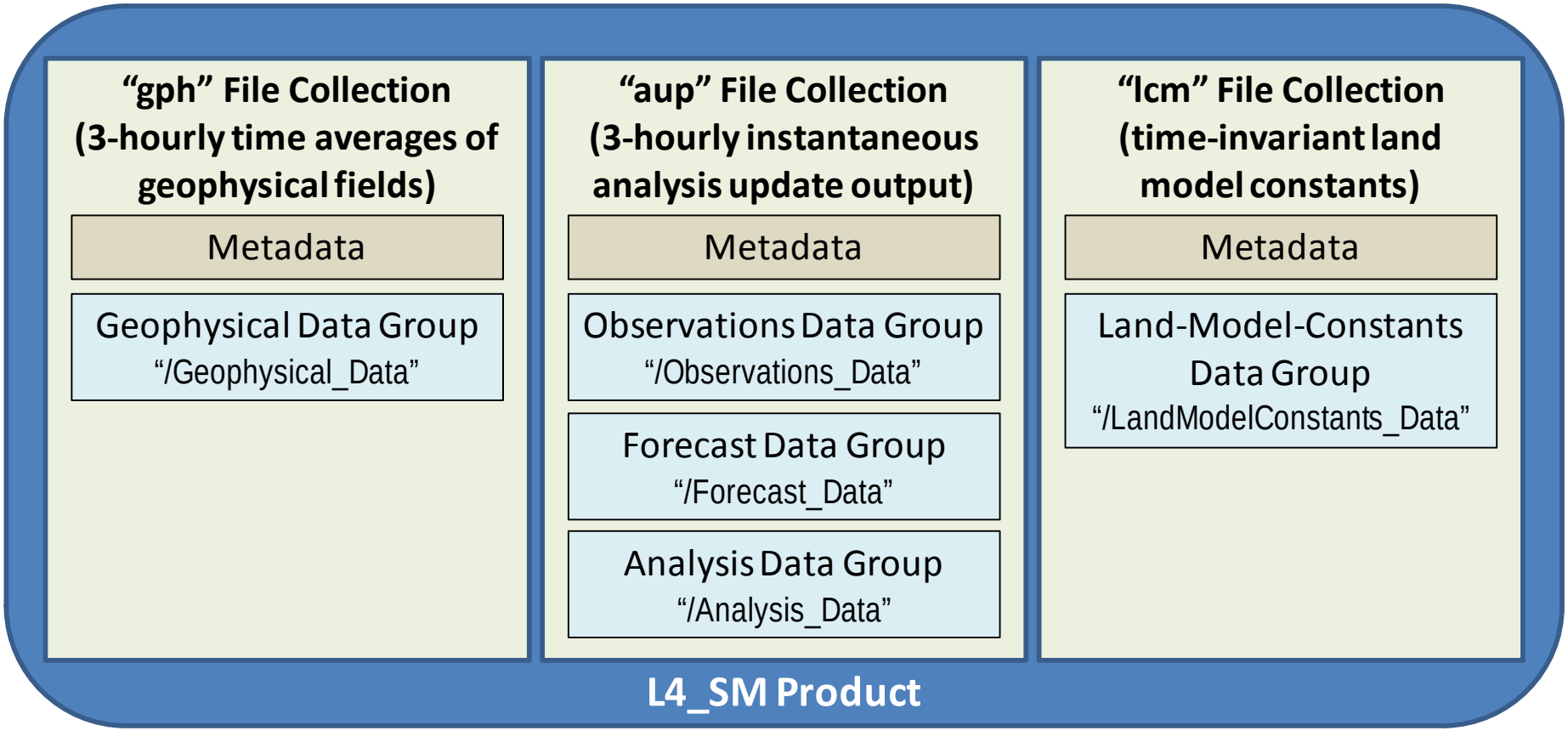
L4_SM product

9 km, 3-hourly global output with 3-4 day latency

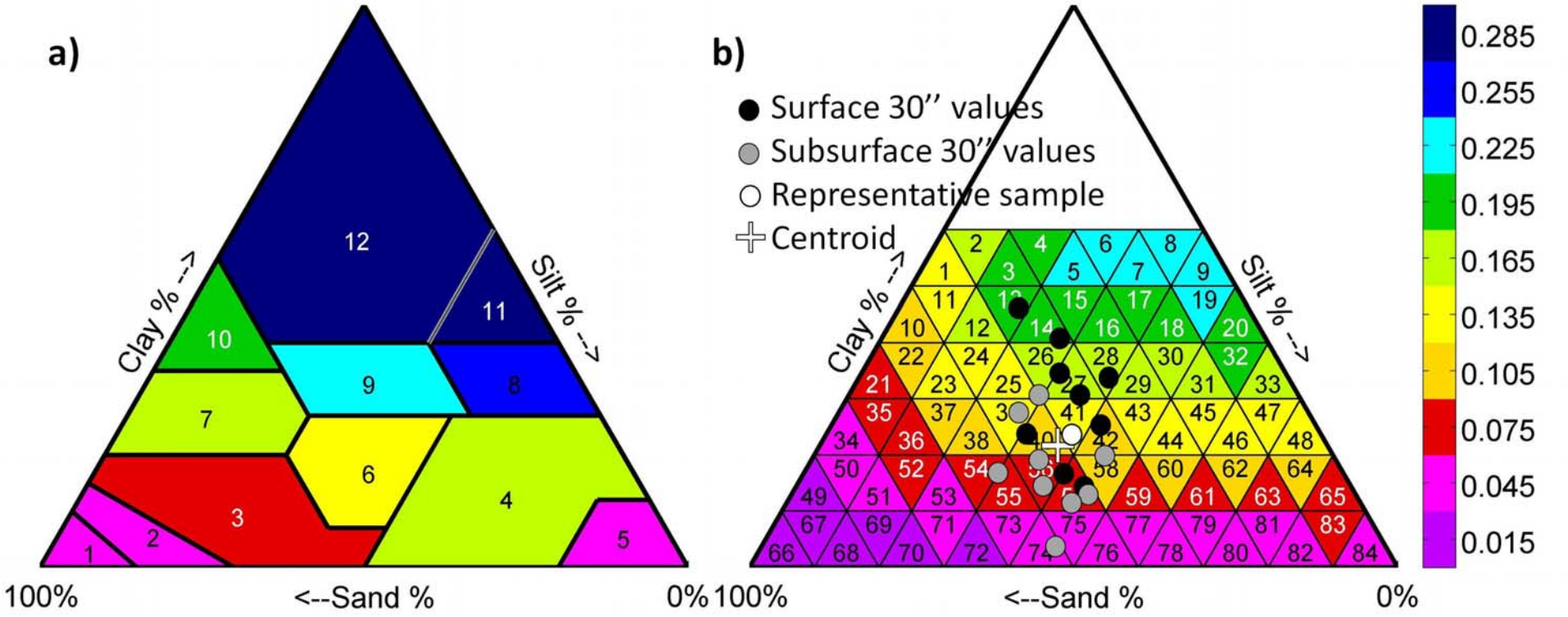
- **Surface soil moisture (≡ top 5 cm)**
- **Root zone soil moisture (≡ top 1 m)**
- **Research output**
  - surface and soil temperatures (**input to L4_C**)
  - sensible, latent, and ground heat flux
  - runoff, baseflow, snowmelt
  - surface meteorological forcings (air temperature, precipitation, …) [ancillary]
  - **error estimates** (generated by assimilation system)
  - assimilation diagnostics (observations-minus-forecast residuals, increments)

Jan 2015 – Launch
Apr 2015 – Start of science operations and Cal/Val phase
Oct 2015 – **Provisional L4_SM product (beta) release** (probably earlier)
Apr 2016 – **Validated L4_SM product release**

L4_SM Data Product Overview (2)



- L4_SM provides a global product → **no exclusion masks** (besides QC of assimilated observations).
- L4_SM provides quantitative information about snow, soil temperature, etc → **binary flags not needed** in most cases.
- "aup" Collection includes error estimates (ensemble spread) and assimilation diagnostics (observations-minus-forecast residuals, increments)


a)
Clay % -->
Silt % -->
<--Sand %
100%
0%
12
11
10
9
8
7
6
4
3
2
1
5
b)
Surface 30'' values
Subsurface 30'' values
Representative sample
Centroid
Clay % -->
Silt % -->
<--Sand %
100%
0%
0.285
0.255
0.225
0.195
0.165
0.135
0.105
0.075
0.045
0.015

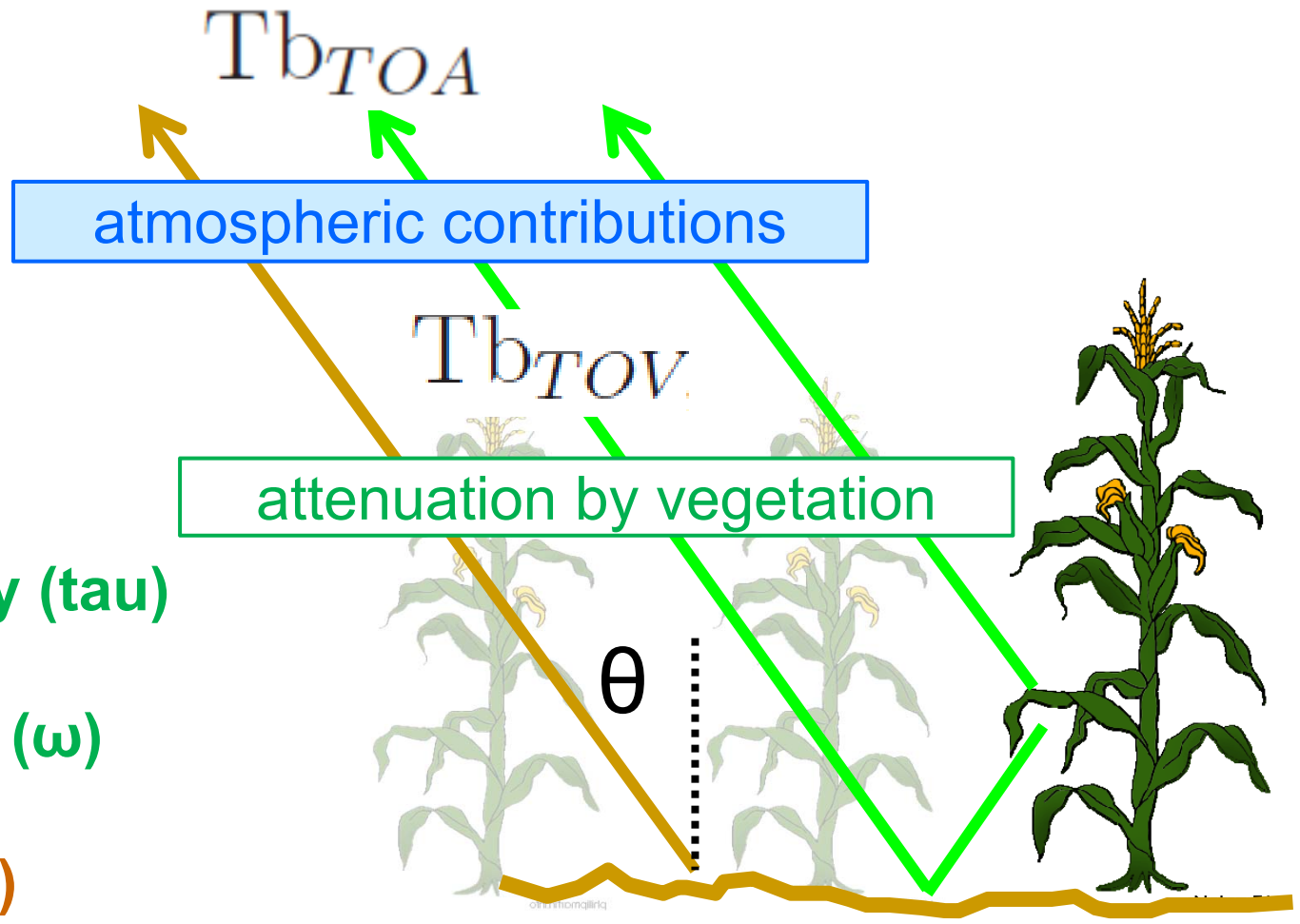
Zero-order (tau-ω) Microwave Radiative Transfer Model

Key microwave parameters:

Vegetation opacity (tau)

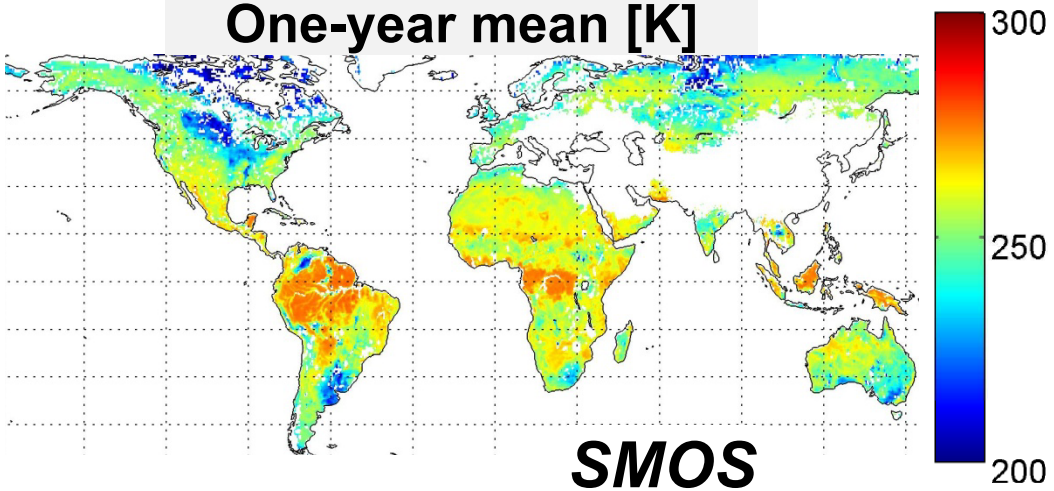
Scattering albedo (ω)

Soil roughness (h)



L-band Brightness Temperature: SMOS vs. GEOS-5

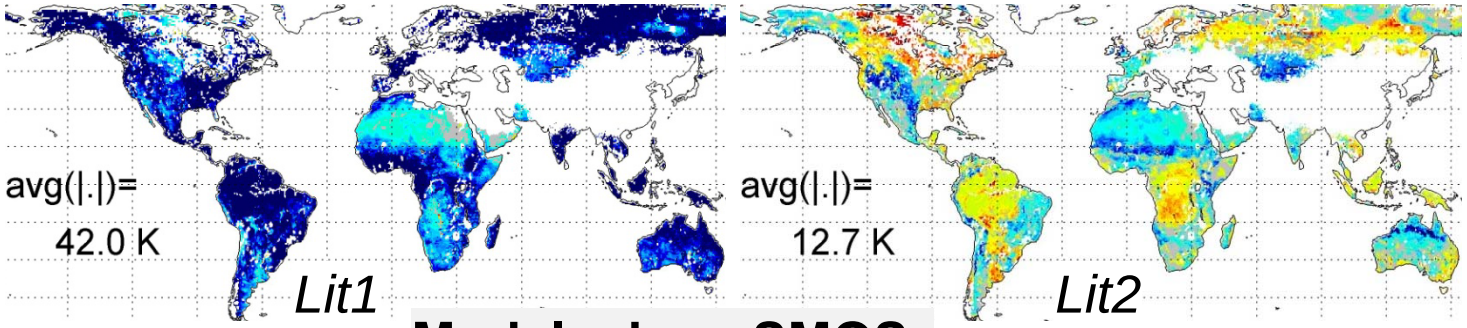
One-year mean [K]



SMOS

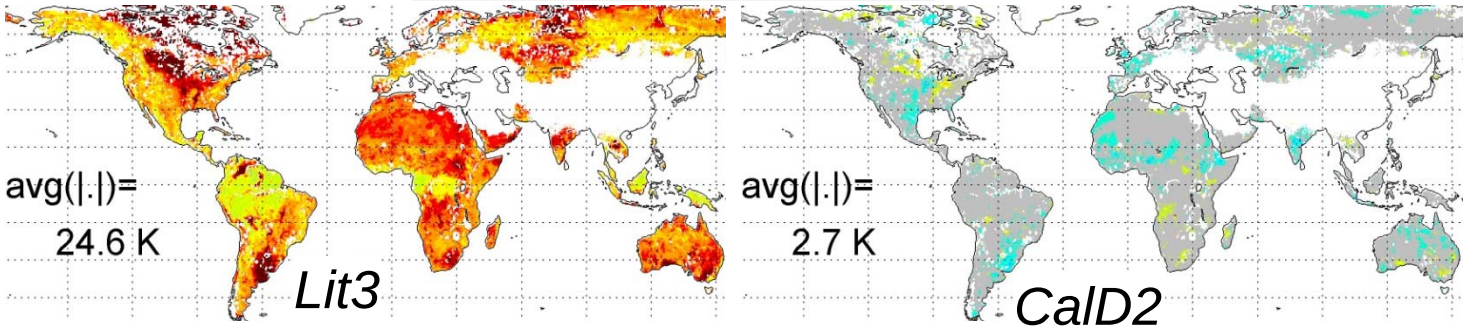
H-pol 42.5^0	Jul 2010 – Jun 2011 (validation period)

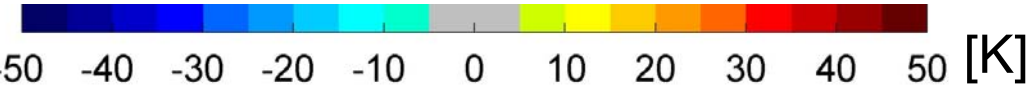
Calibration used multi-angular obs from Jul 2011 – Jun 2012.



Literature values for parameters yield strongly biased Tb.

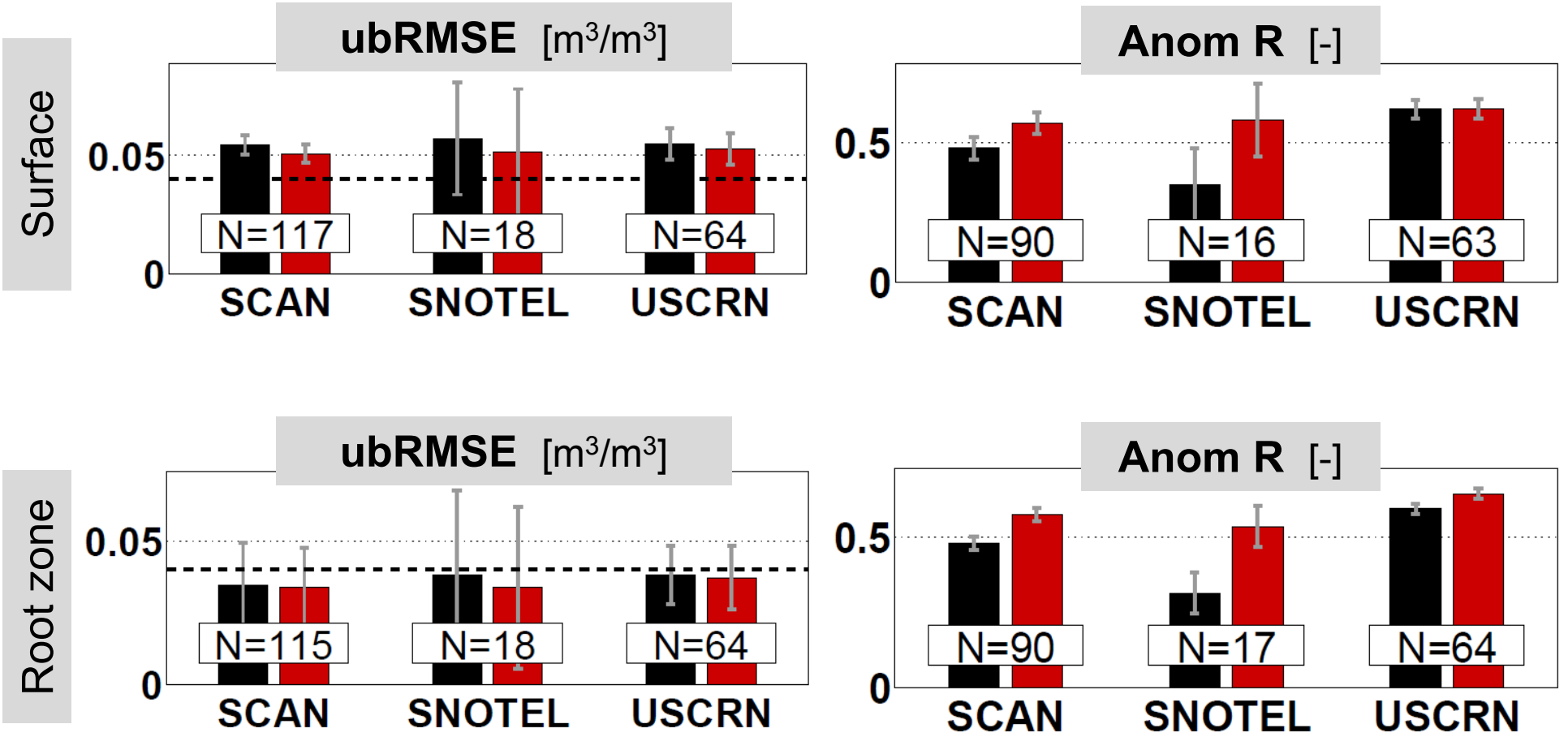
Model minus SMOS





Calibrated parameters yield mostly unbiased long-term mean Tb.

Soil Moisture Skill for Sparse Networks (Single-profile Sensors)



Improvements from Tb assimilations are somewhat greater without CPCU corrections.

ubRMSE still close to 0.04 m^3/m^3.

Black: Model only
Red: L4_SM_SMOS

Jun 2010 – Jan 2013

L4_SM_SMOS: Innovations and Increments

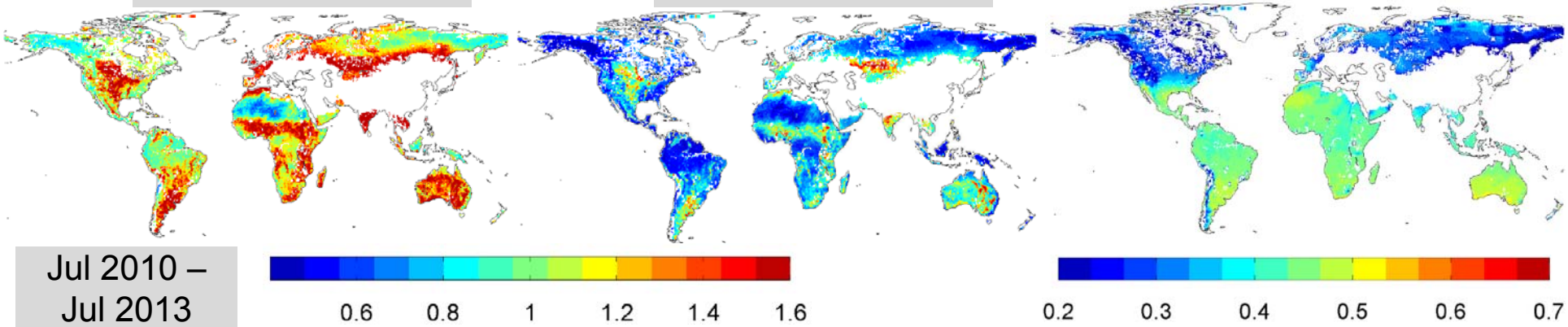
Observation-minus-forecast residuals ("innovations", 36 km obs space)

Stdv of *normalized* innovations

Obs error stdv=4 K

Obs error stdv=8 K

Number of assimilation times per day



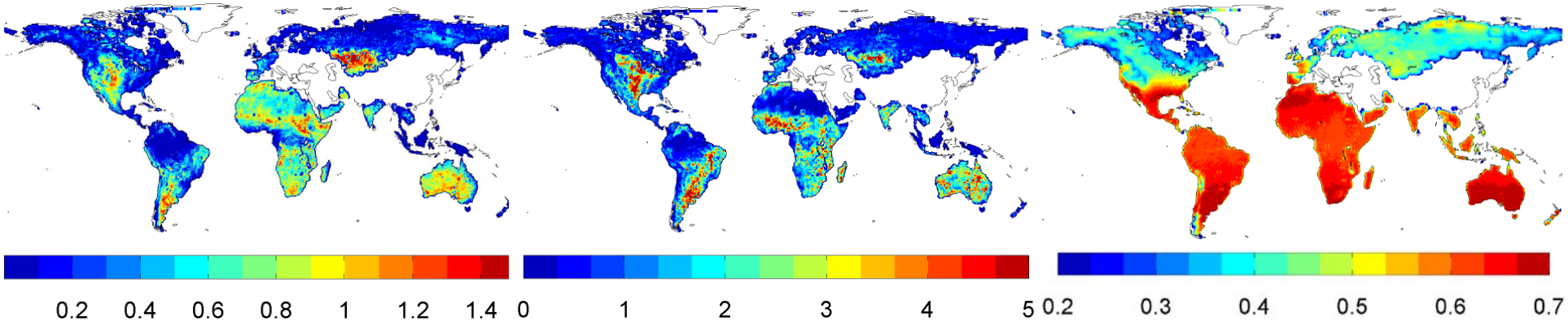
Jul 2010 – Jul 2013

Analysis-minus-forecast residuals ("increments", 9 km model space)

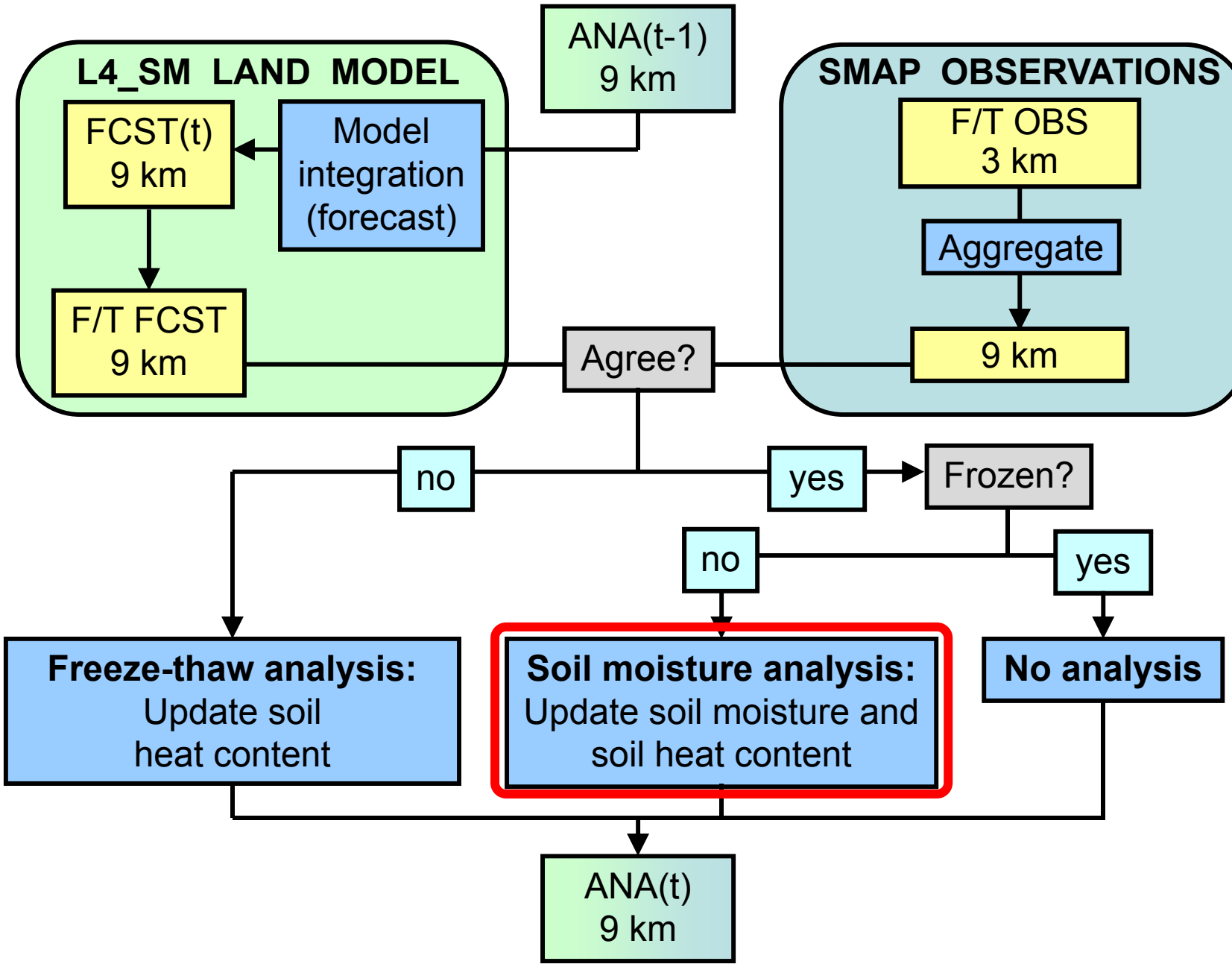
Stdv of **surface** excess incr.
avg=0.4 mm

Stdv of **root zone** excess incr.
avg=2.7 mm

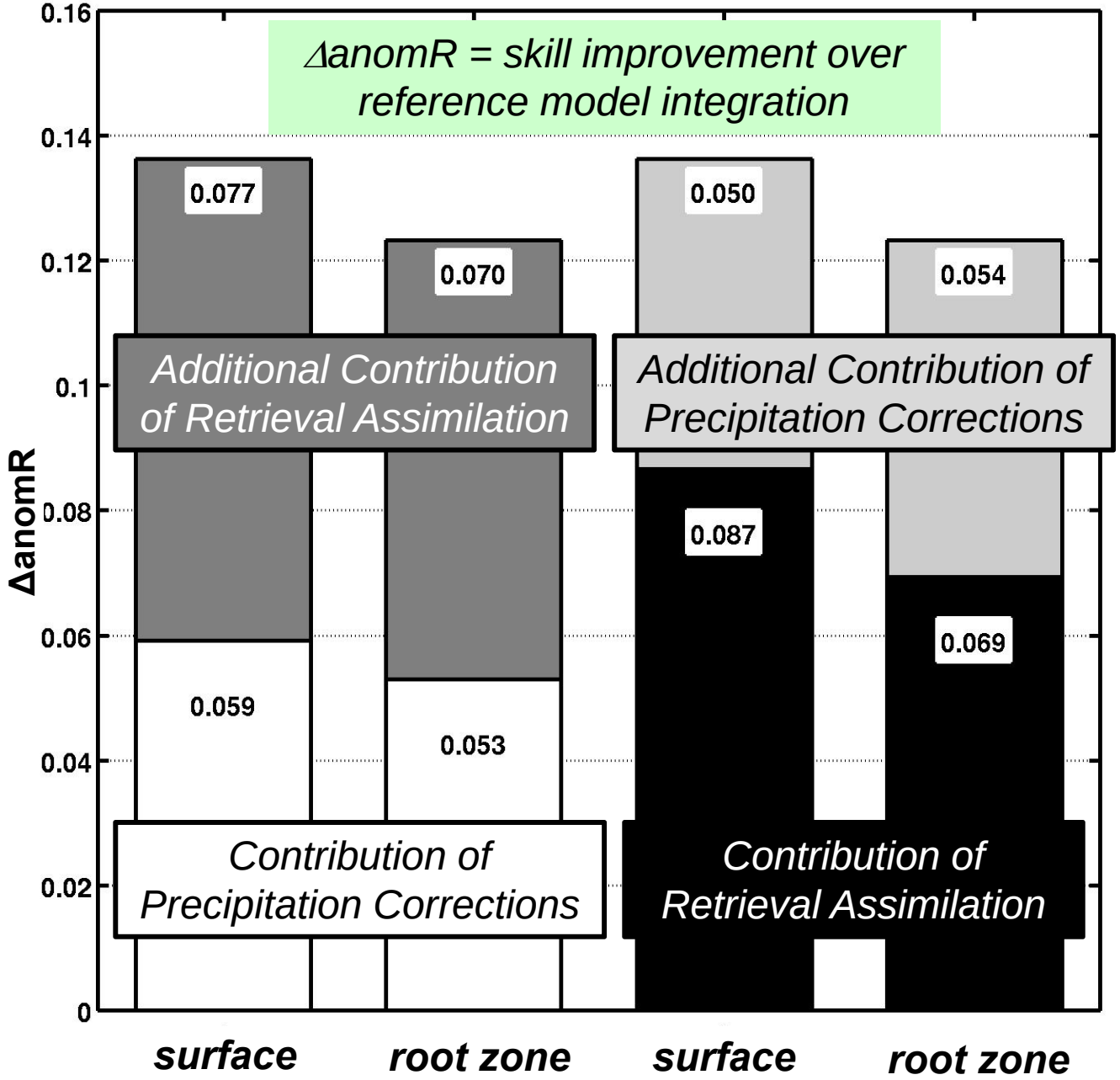
Number of increments per day



SMAP L4_SM Analysis Overview



Soil Moisture Assimilation and Precipitation Corrections



Precipitation corrections and retrieval assimilation contribute approximately:

- *evenly and*
- *independently*

to skill improvement.

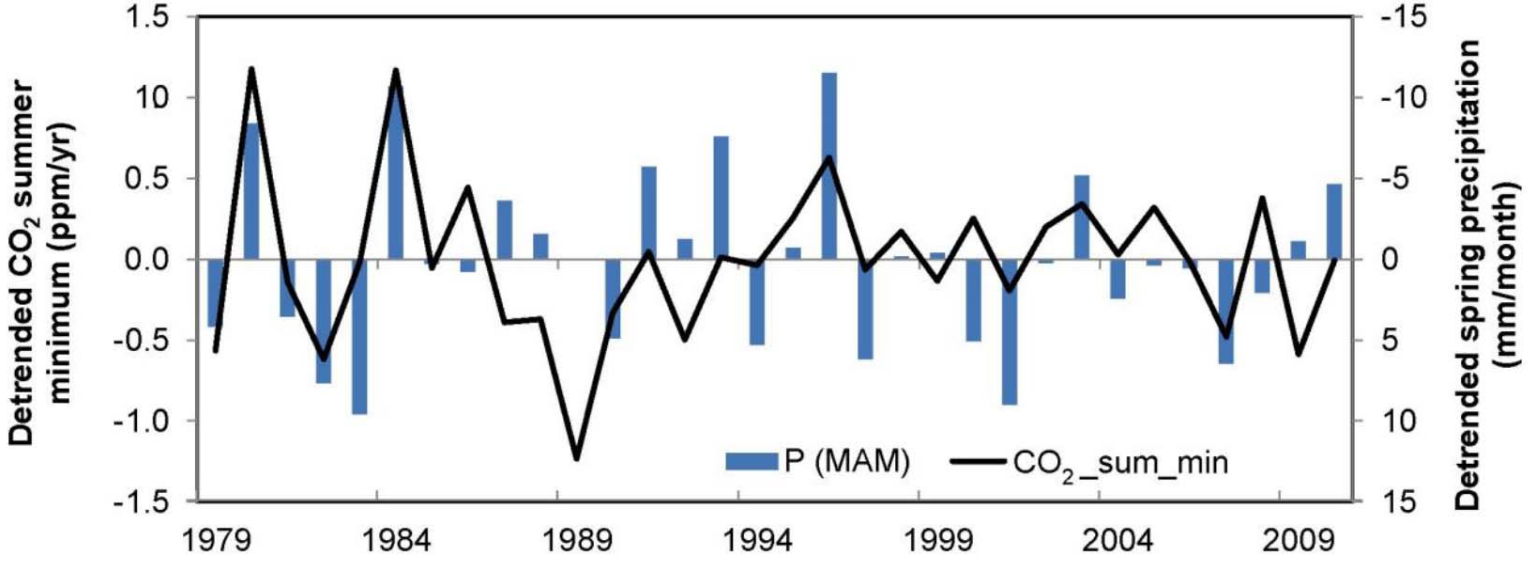
Results from single sensor per watershed (SCAN data) are consistent with those from distributed CalVal in situ sensors.

Liu et al. JHM (2011)
doi:10.1175/JHM-D-10-05000.

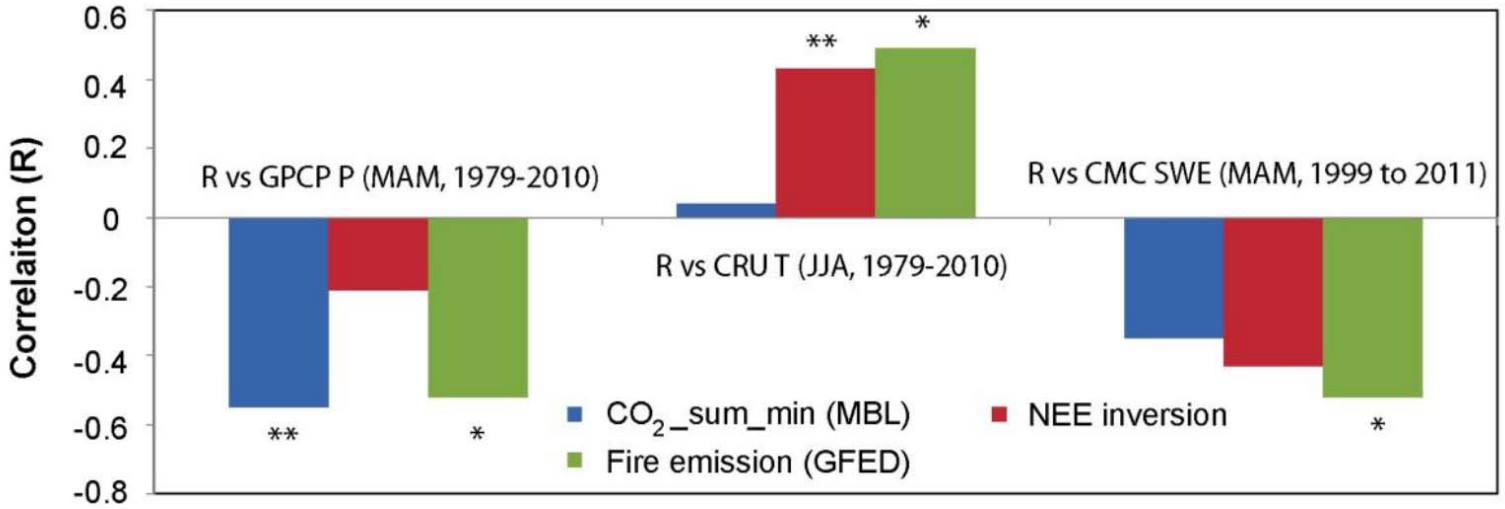
Outline

1) SMAP Level 4 Products Motivation and Objectives
2) SMAP L4_SM Product and Algorithm Overview
3) A Prototype SMAP L4_SM Product
4) Beyond SMAP Level 4 Products

Coupling of the water and carbon cycles



Higher spring precipitation is associated with larger net carbon uptake (>50ºN).



Higher fire emission is associated with low spring precipitation & snow water equivalent (SWE) and high summer temperature.

Yi et al. 2014, *ERL*, in press.

GEOS-5 Soil Parameter Revisions

SMAP data products are **global**.

Input parameter datasets strike a **compromise between accuracy and consistency** (across the globe).

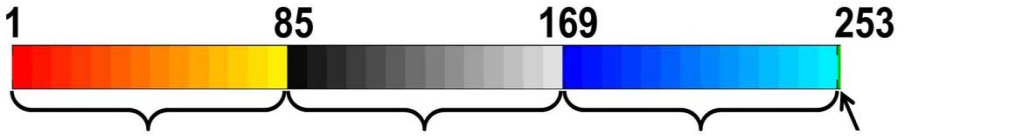
Surface soil texture (0-30cm)

class **source**

Root zone soil texture (0-100cm)

class **source**

HWSD1.21 STATSGO2 Filled



De Lannoy et al. (2014), JAMES, submitted.

Beyond the SMAP Level 4 Data Products

Objective

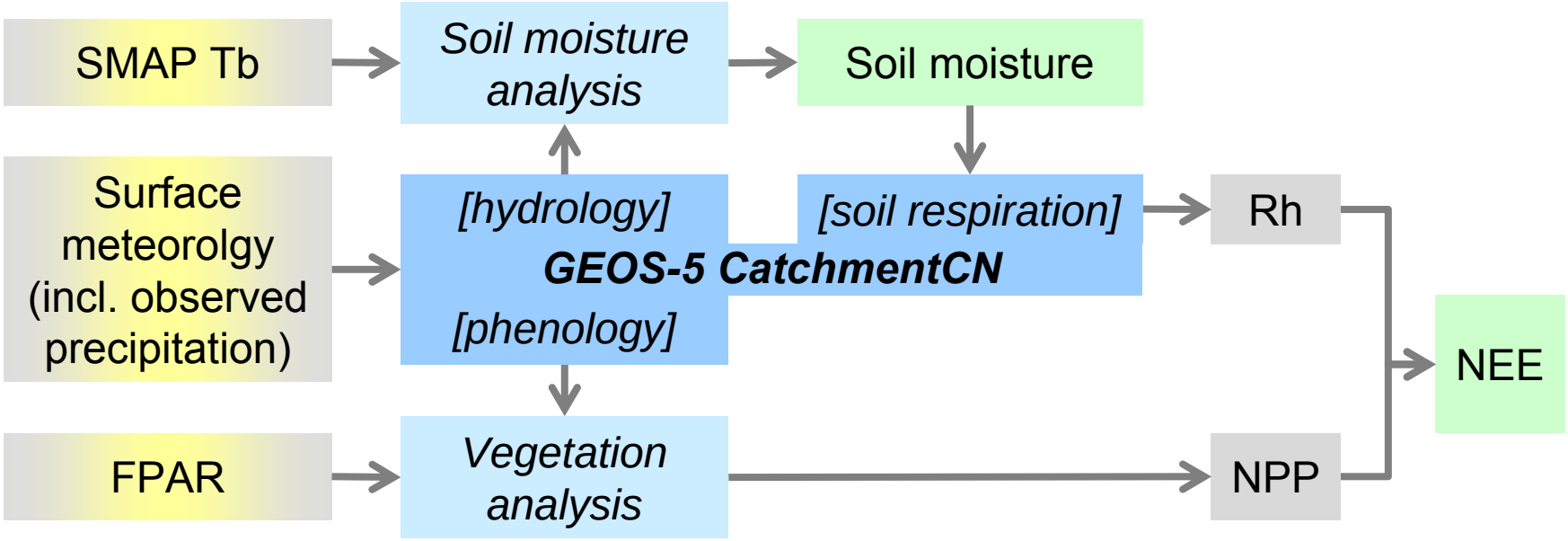
Estimate global root zone soil moisture and Net Ecosystem CO_2 Exchange (NEE).

Approach:

In addition to SMAP Tb, assimilate satellite observations of FPAR (or fluorescence) into the new GEOS-5 prognostic land surface hydrology and dynamic vegetation model (CatchmentCN).

Advantages:

Vegetation phenology model provides information in addition to satellite FPAR.
Consistent hydrology and vegetation data assimilation in a single system (rather than the baseline tiered approach of the SMAP Level 4 data products).



GEOS-5 Soil Parameter Revisions

Updated soil texture datasets

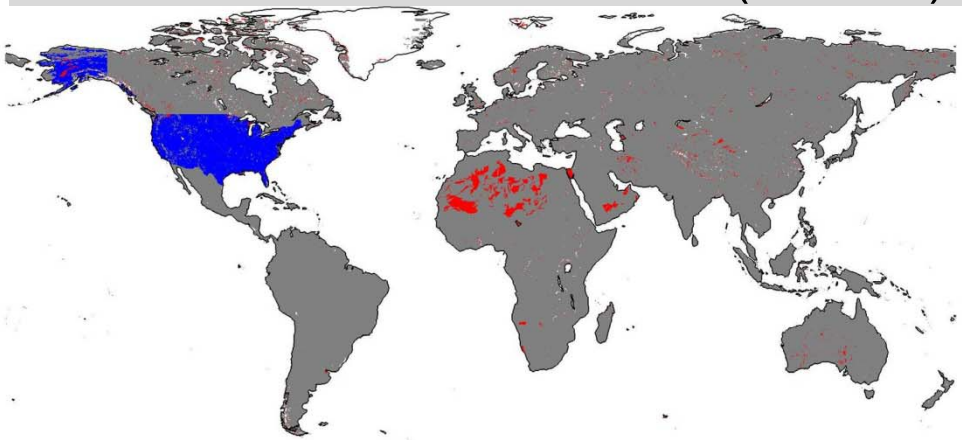
Old ("baseline")

- NGDC

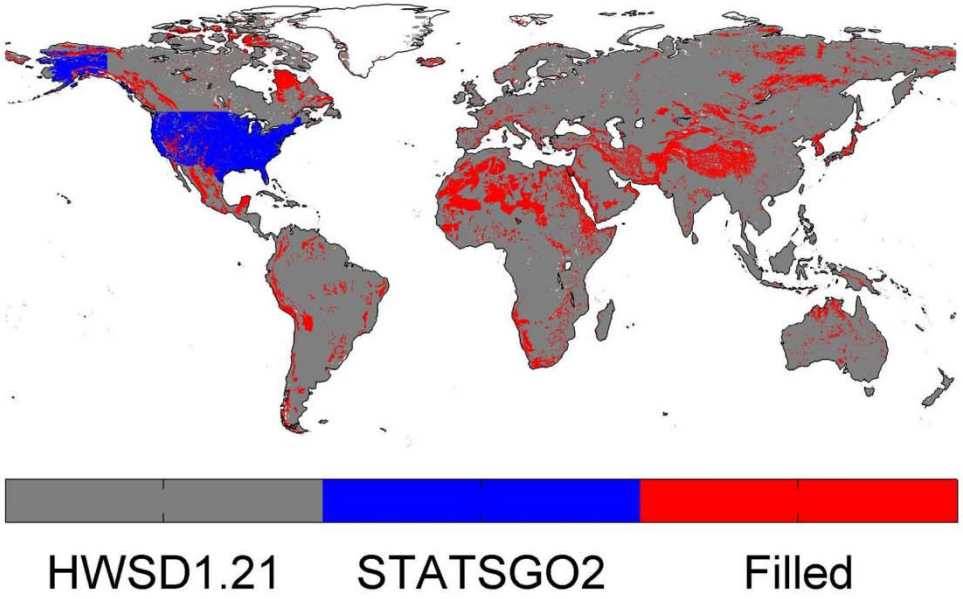
New ("revised")

- STATSGO-2
- HWSD-1.21

Surface soil texture **source** (0-30cm)



Root zone soil texture **source** (0-100cm)



De Lannoy et al. (2014), JAMES, submitted.

GEOS-5 Soil Parameter Revisions

Updated soil texture datasets

Old ("baseline")

- NGDC

New ("revised")

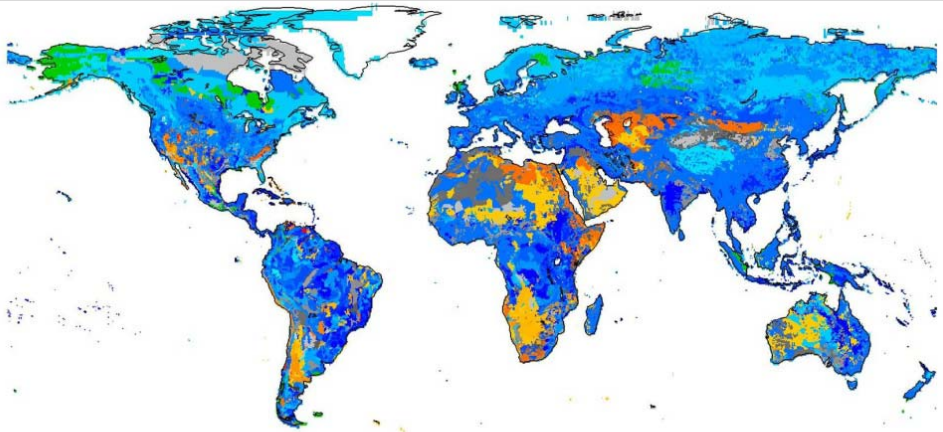
- STATSGO-2
- HWSD-1.21

Added organic carbon content.

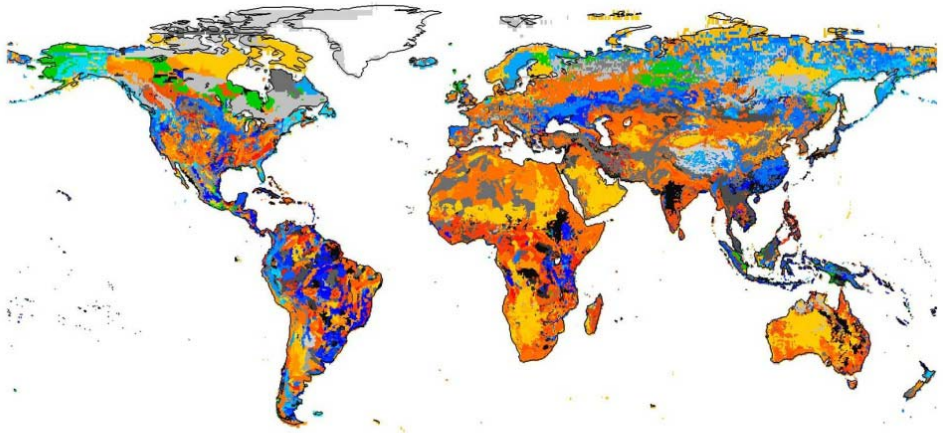
Updated pedo-transfer functions.

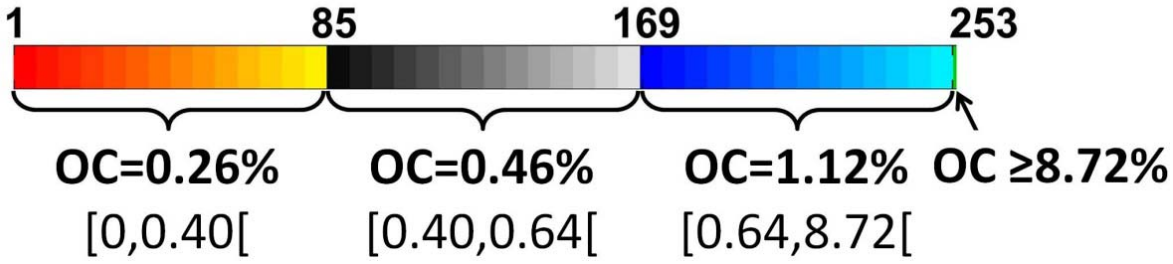
Soil classes:
Each of three organic classes contains 84 mineral classes. Special peat class (=253) shown in **green**.

Surface soil texture **class** (0-30cm)



Root zone soil texture **class** (0-100cm)





De Lannoy et al. (2014), JAMES, submitted.

Calibration of the Data Assimilation System

Calibration of the distributed ("3-dimensional") analysis requires **perturbation parameters** for surface meteorological forcing and soil moisture:

- *Std-dev*
- *Spatial correlation scales*
- *Temporal correlation scales*
- *Cross-correlations*

Assimilated Tb observations from SMOS are multi-angular, but for now observation error cross-correlations are neglected.

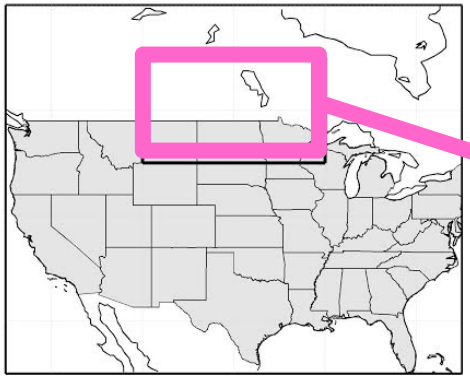
Freeze-thaw OSSE

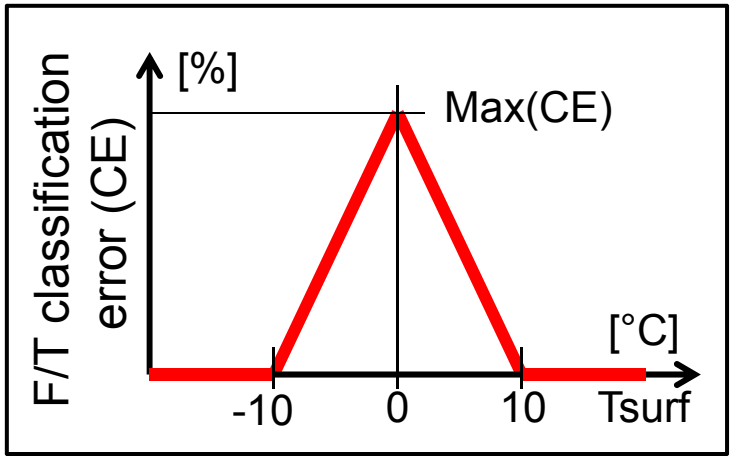
OL = Open loop (no assimilation)
DA = Assimilation of synthetic F/T obs.
ΔRMSE = RMSE(OL) – RMSE(FT)

Small improvements with realistic classification errors:

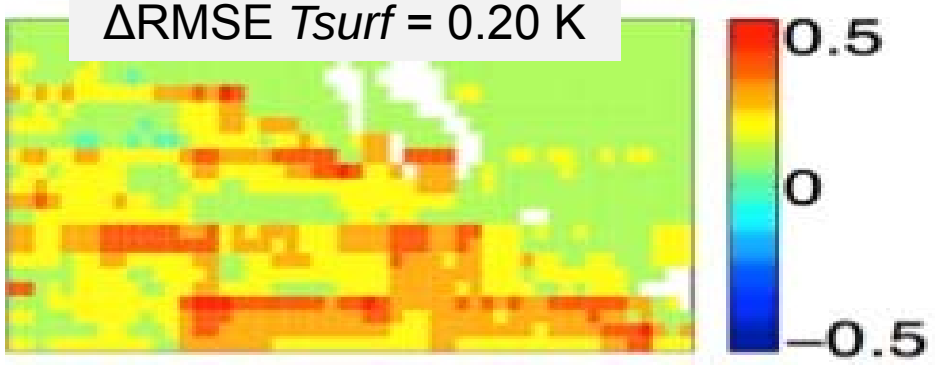
	OL RMSE* [K]	ΔRMSE* [K] Max. Classification Error			
		0%	5%	10%	20%
Tsurf	3.08	0.21	0.20	0.18	0.15
Tsoil	1.97	0.06	0.05	0.04	0.01

*Excl. times & locations with Tair>7°C or Tair<-7°C

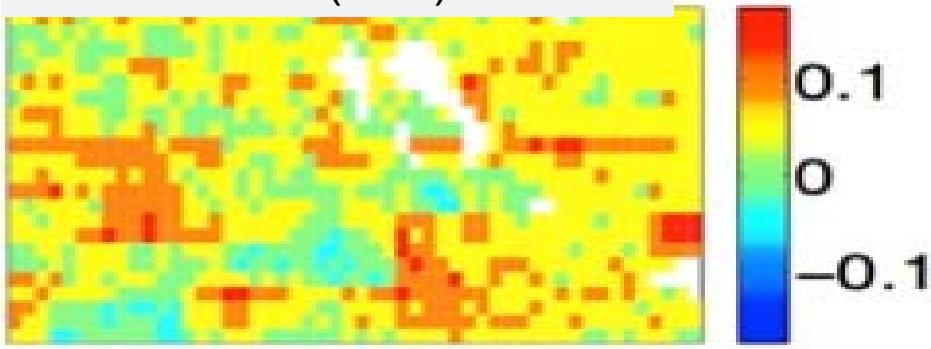




ΔRMSE *Tsurf* = 0.20 K



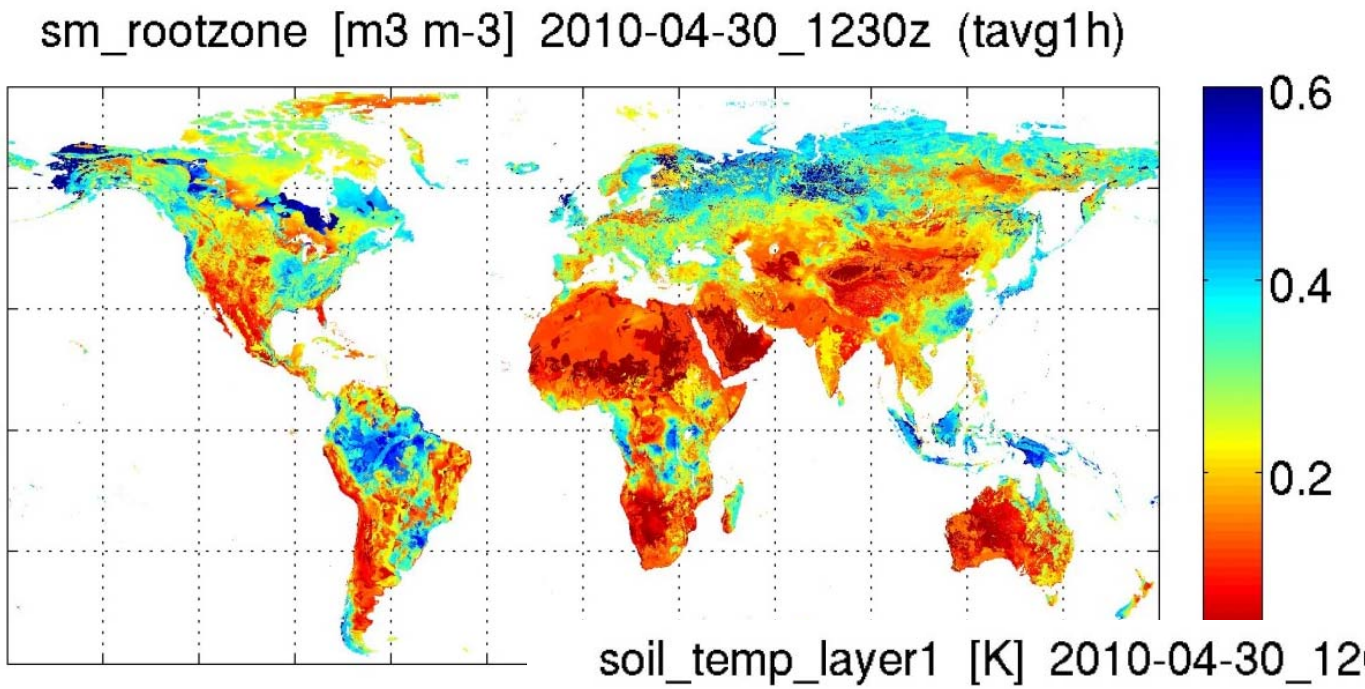
ΔRMSE *Tsoil* (5cm) = 0.05 K



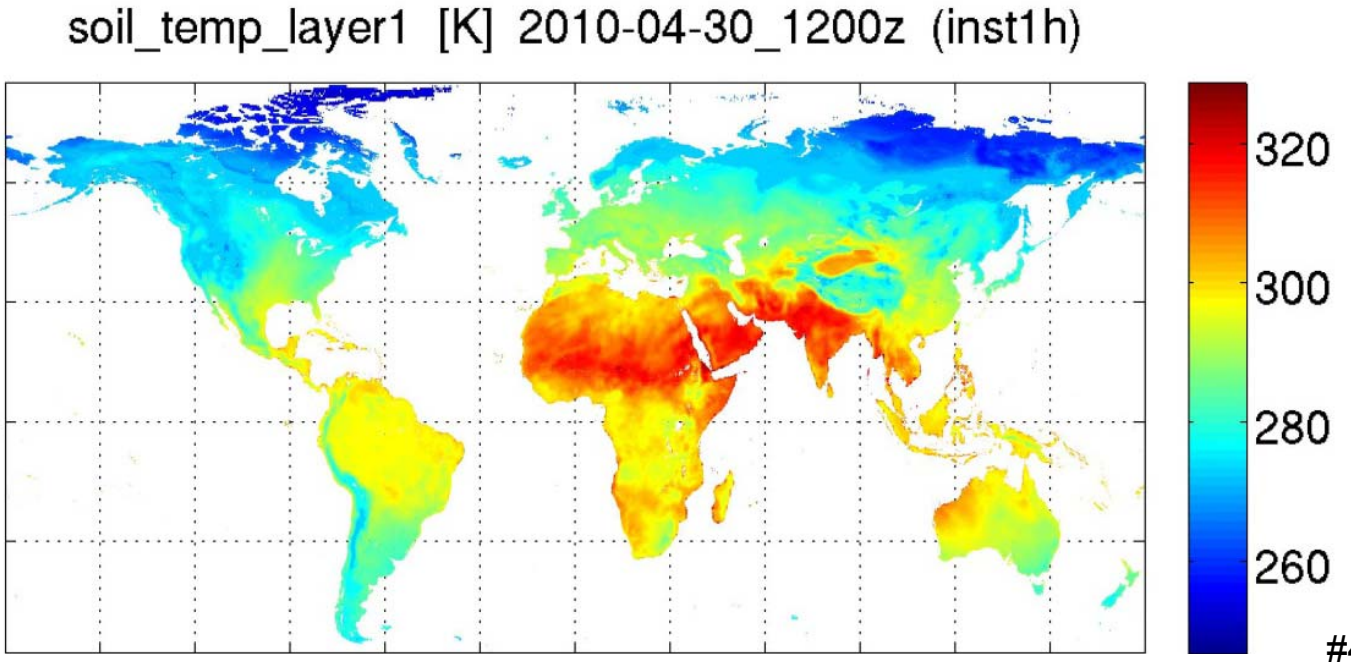
See talk by Leila Farhadi (Wed. am)

Farhadi et al., 2014, JHM, conditionally accepted.

Sample Output from SMAP Nature Run v03



Global 9 km data product (model-only)



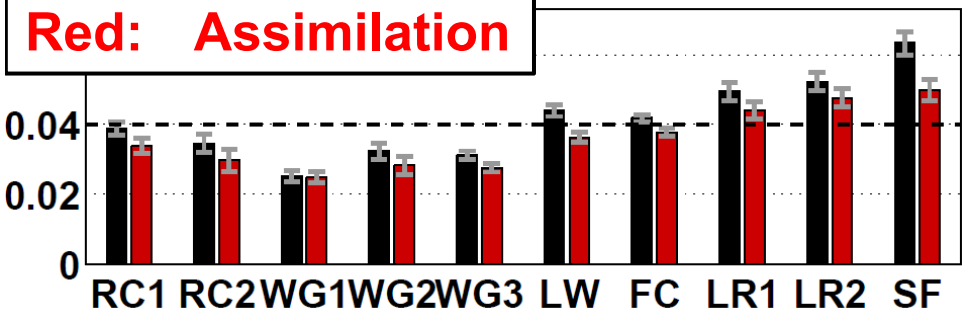
Validation at SMAP Core Validation Sites

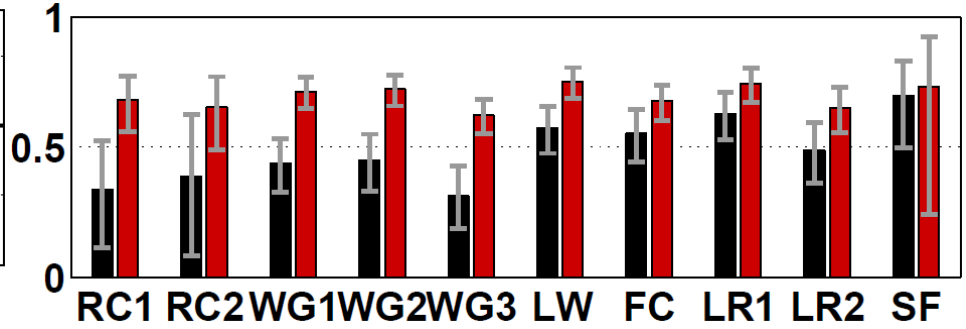
De Lannoy et al., 2014, in preparation.

ubRMSE | Jul 2010 – Jun 2014 | ***anomaly R***

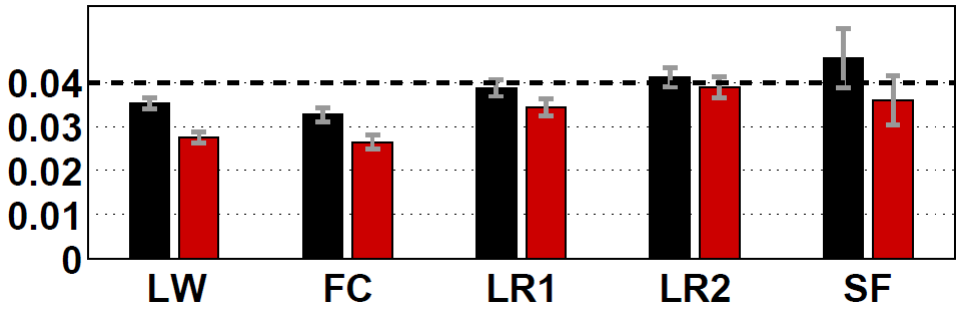
Black: Model
Red: Assimilation

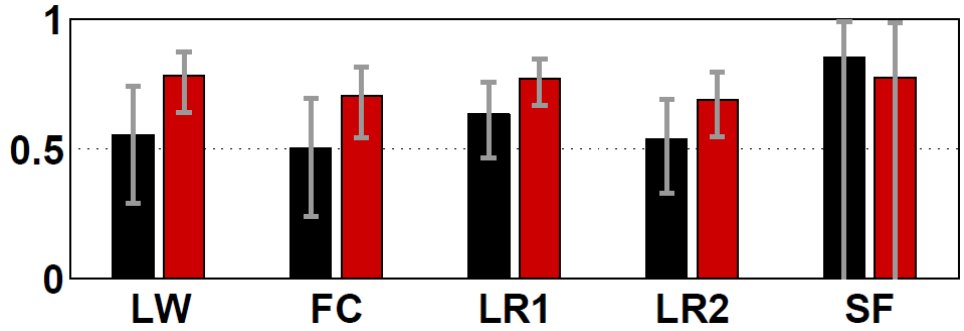
Surface soil moisture [m³/m³]





Root zone soil moisture [m³/m³]





Surface soil temperature [K]