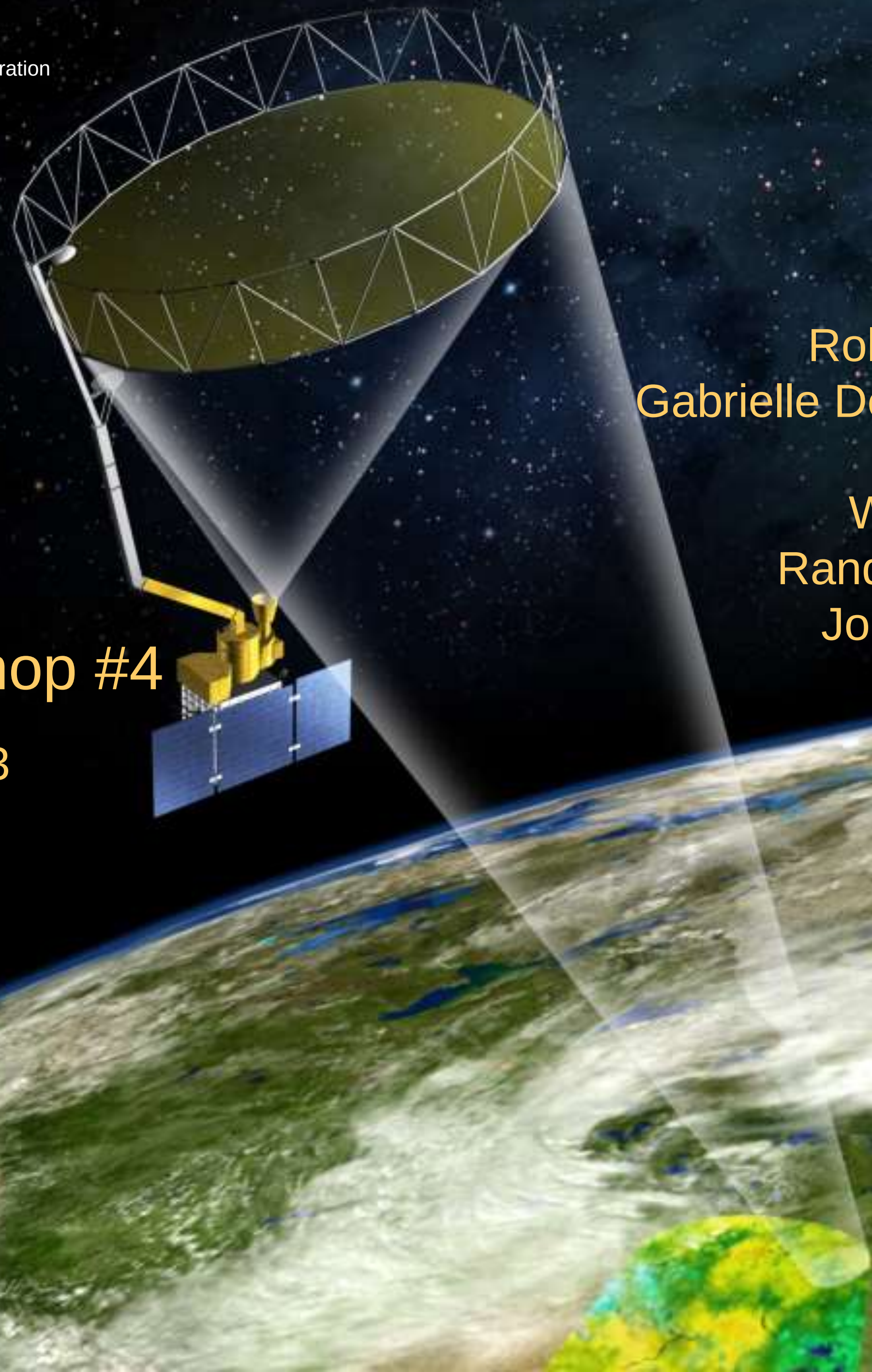
National Aeronautics and Space Administration



L4_SM

Rolf Reichle (NASA/GSFC)
Gabrielle De Lannoy (NASA/GSFC)
Qing Liu (NASA/GSFC)
Wade Crow (USDA/ARS)
Randy Koster (NASA/GSFC)
John Kimball (U. Montana)

Soil Moisture
Active Passive
Mission

SMAP

Cal/Val Workshop #4

November 5-7, 2013

Outline

1) Motivation and requirements
2) Calibration and validation approach and activities
3) Validation of prototype L4_SM products
   – Rehearsal Phase 1 – model-only prototype product
   – Prototype product based on SMOS assimilation

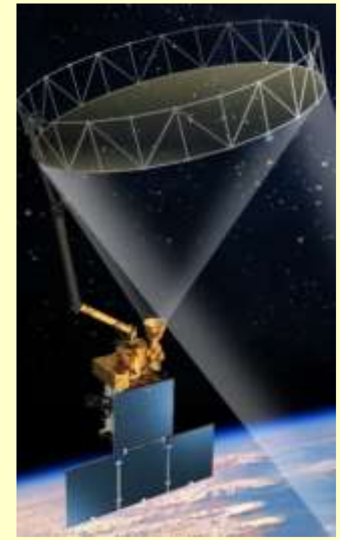
Key limitations of SMAP observations

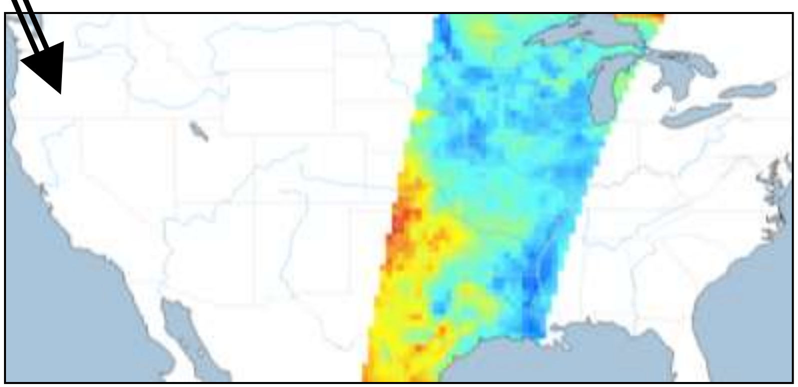
SMAP observations:

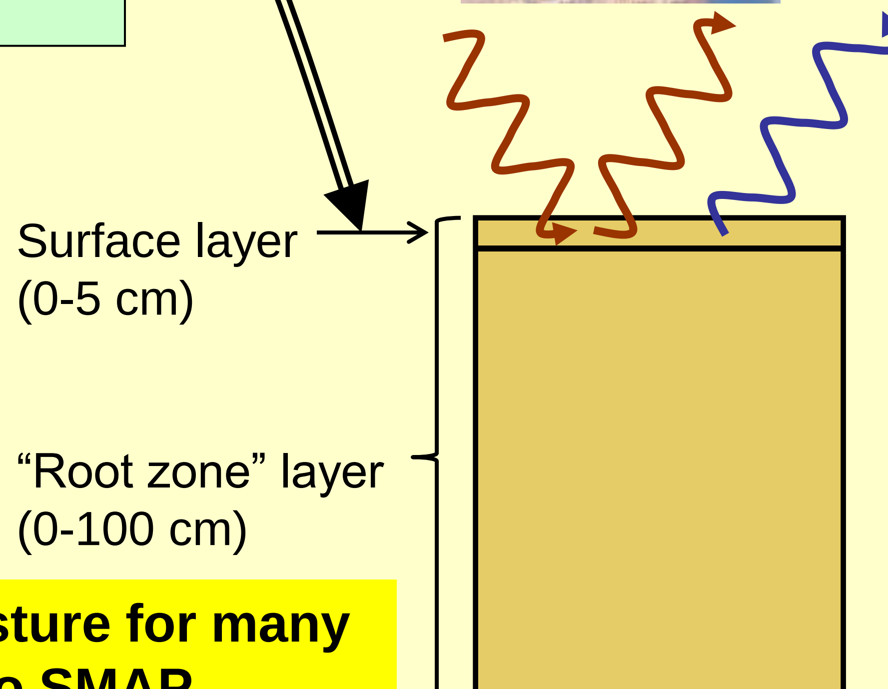
1) are sensitive to moisture and temperature ***only*** in a 5 cm surface layer (and only if less than 5 kg/m^2 vegetation),

2) have limited coverage in time and space, and

3) are subject to measurement errors.

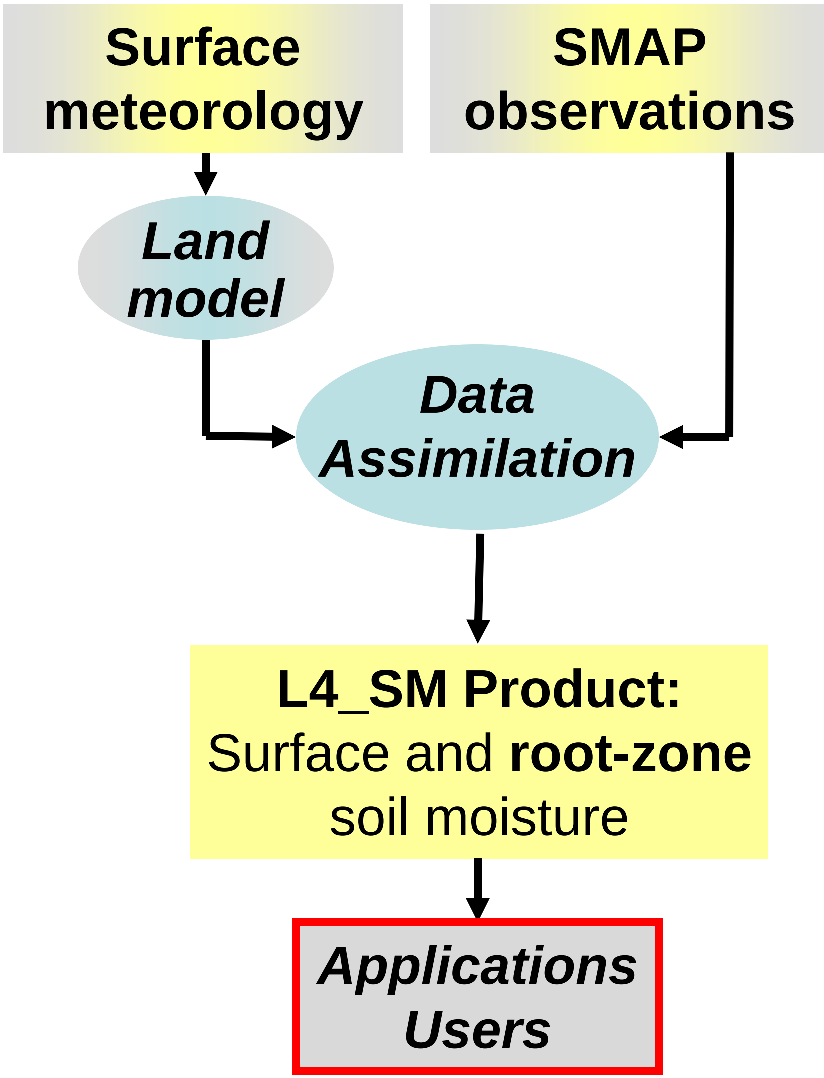






Need *root-zone* soil moisture for many applications of interest to SMAP.

SMAP Level 4 soil moisture product



L4_SM Product:

Assimilating SMAP data into a land model driven with observation-based forcings yields:

– a root-zone moisture product (reflecting SMAP data), and

– a complete and consistent estimate of soil moisture & related fields.

L4_SM output includes

- **global,**
- **3-hourly,**
- **9 km**

estimates of surface (0-5 cm) and root zone (0-100 cm) soil moisture.

L4_SM data product requirements

Motivated by the SMAP Level 1 Science Requirements, the

L4_SM surface (0-5 cm) and **root zone (0-100 cm) soil moisture** estimates will be validated to an **ubRMSE requirement of 0.04 m^3m^{-3}.**

[Identical to L2 soil moisture product validation and excluding regions of snow and ice, frozen ground, mountainous topography, open water, urban areas, and vegetation with water content greater than 5 kg m^{-2}.]

[ubRMSE = RMSE after removal of long-term mean bias.]

Research outputs (surface meteorological forcing fields, land surface fluxes, soil temperature and snow states, runoff, and ensemble-based error estimates) will be **evaluated on a best effort basis**.

Outline

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L4_SM validation approach

Will be used to verify "0.04 m^3m^{-3}" requirement

Methodology	Data	Importance	Metric
Core Sites	Observed grid cell average values (time-continuous)	**Primary**	**RMSE**, bias, correlation
Sparse Networks	Observed values (time-continuous)	Primary	**Correlation**, RMSE, bias
Satellite Products	Orbit-based match-ups (SMOS, ASCAT, …)	Secondary: Pending cont'd operation	**Correlation**, RMSE, bias
Model Products	Global modeling and assimilation systems (ECMWF, NCEP, …)	Primary	RMSE, bias, correlation, **assim. diagn.**
Field Experiments	Detailed estimates for a very limited set of conditions	Secondary	**RMSE**, bias, correlation

L4_SM pre-launch Cal/Val activities

Cal/Val activities to date:

- Calibrating modeling and assimilation system:
  - Soil parameters.
  - Microwave radiative transfer (tau-omega) model parameters.
  - Model and observation error parameters.
- Participated in Cal/Val Rehearsal Phase 1.
- Validating L4_SM system driven with **SMOS** Tb obs.

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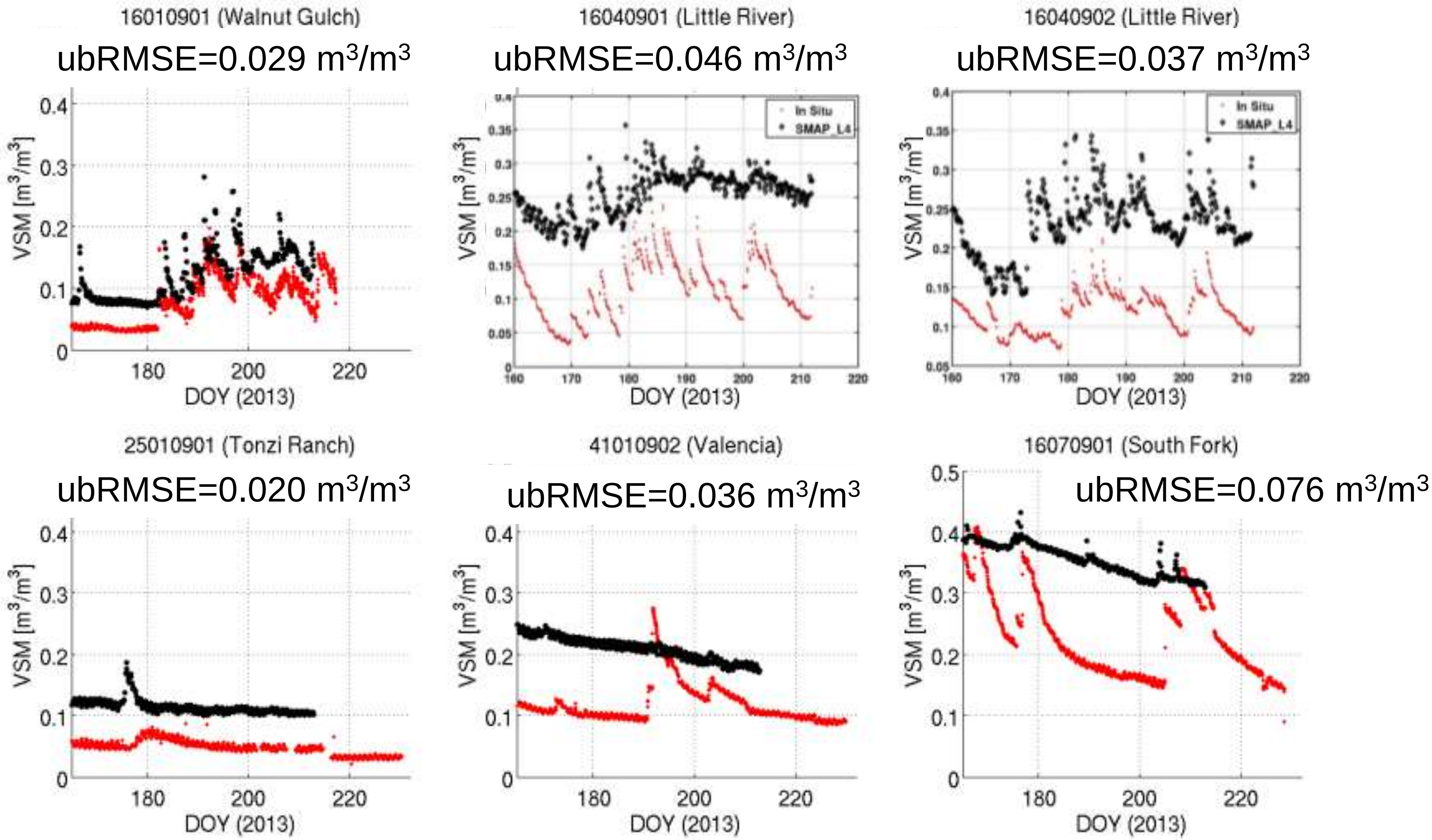
Validation at core-site reference pixels (surface)

Special thanks to A. Colliander & M. Cosh!

Average: ubRMSE=0.041 m³/m³



Red:	**Core-site in situ measurements**
Black:	**L4_SM (model-only prototype, no data assimilation)**

Validation at core-site reference pixels (surface)

Special thanks to A. Colliander & M. Cosh!

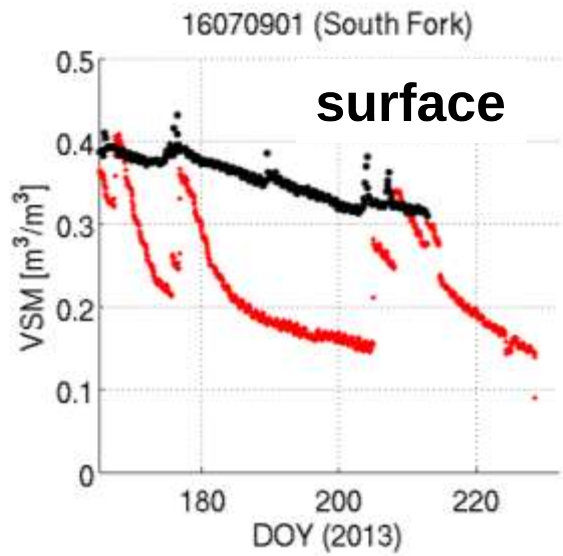
Additional metrics are also reported.

Site	RefPix	ubRMSE	Bias	RMSE	R	Site name
1601	0901	0.029	0.056	0.065	0.652	Walnut Gulch
1604	0901	0.046	~~0.023~~	~~0.041~~	~~0.456~~	Little River
1604	0902	0.037	~~-0.004~~	~~0.044~~	~~0.395~~	Little River
2501	0901	0.020	0.074	0.073	0.747	Tonzi Ranch
1607	0901	0.086	0.072	0.101	0.627	South Fork
4101	0902	0.036	0.098	0.096	0.659	Valencia
		0.044	***~~0.053~~***	***~~0.070~~***	***~~0.589~~***	***AVERAGE***

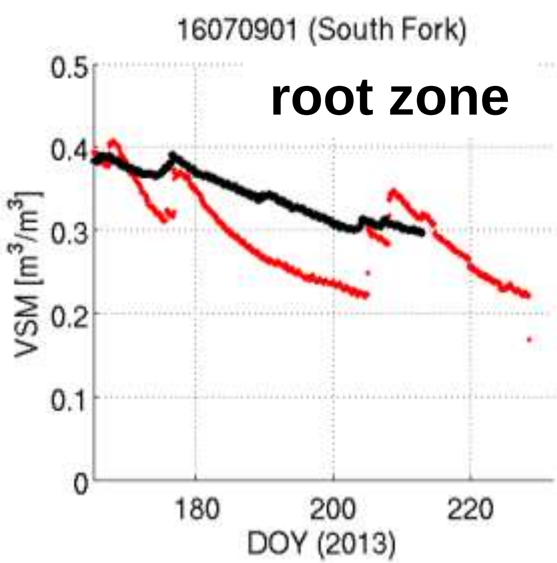
(L4_SM is model-only prototype, no data assimilation)

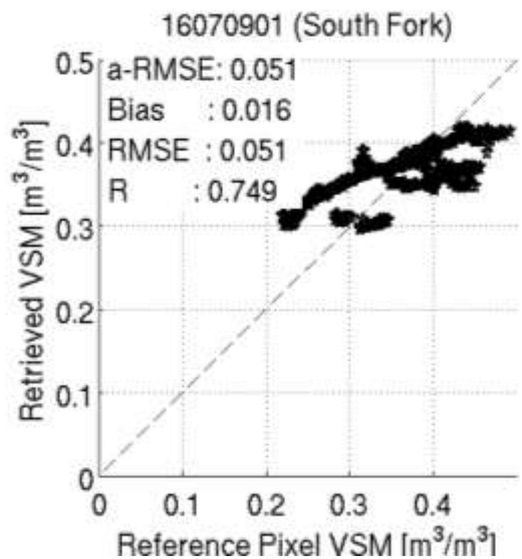
Validation at core-site reference pixels (root zone)

Special thanks to A. Colliander & M. Cosh!



Red: **Core-site in situ measurements**
[avg. of 5, 10, 20, and 50cm obs]
Black: **L4_SM (model-only prototype)**





Outline

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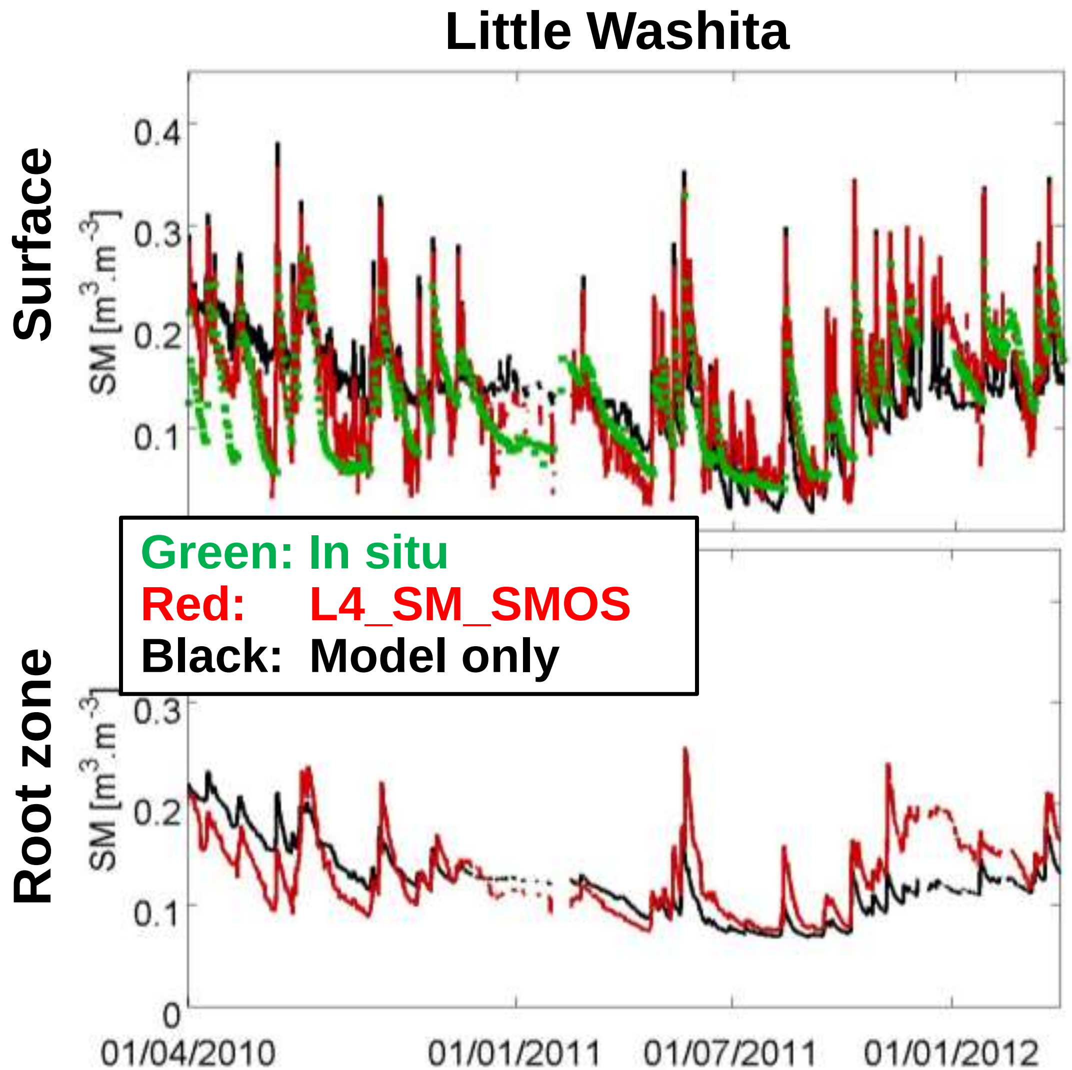
Prototype product based on SMOS (L4_SM_SMOS)

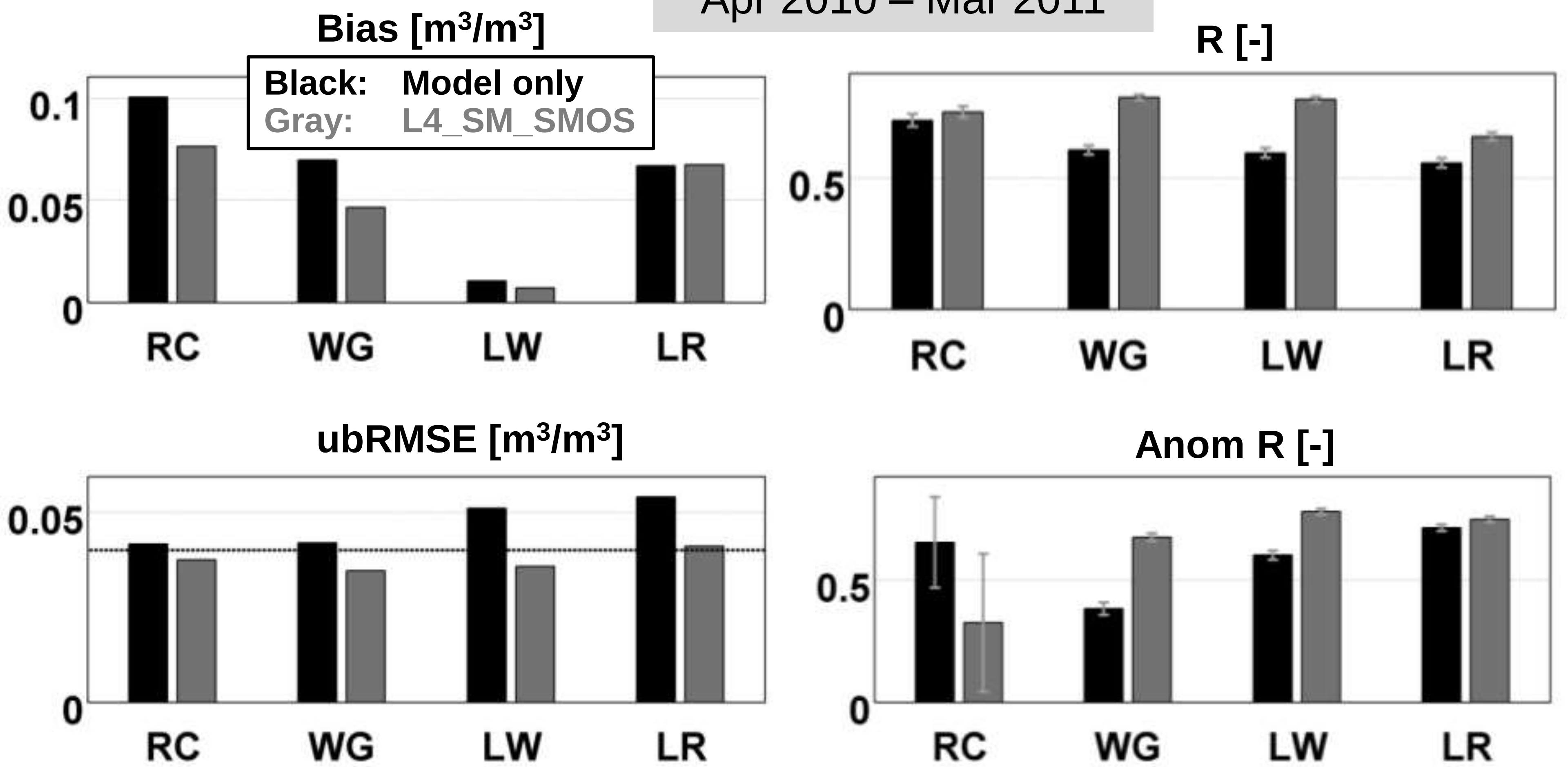
- **Assimilate SMOS Tb** (7 angles, 36 km, 6 am/pm, H- and V-pol)
- MERRA surface meteorology
- CPCU daily 0.5 deg precipitation corrections
- 9 km EASEv2 Catchment model resolution
- Calibrated microwave RTM parameters
- Mean-adjustment of SMOS observations prior to assimilation

L4_SM_SMOS: Cal/Val (core) sites



L4_SM_SMOS: Cal/Val (core) sites

Apr 2010 – Mar 2011



- **ubRMSE** reduced to less than 0.04 m^3/m^3.
- **(Anomaly) correlation** significantly increased (except RC).
- **Bias** reduced.

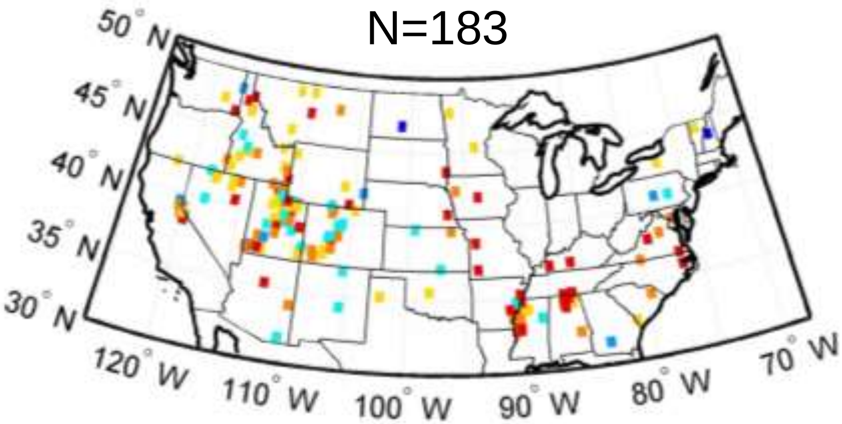
L4_SM_SMOS: Sparse networks

SCAN/SNOTEL	USCRN

Surface soil moisture

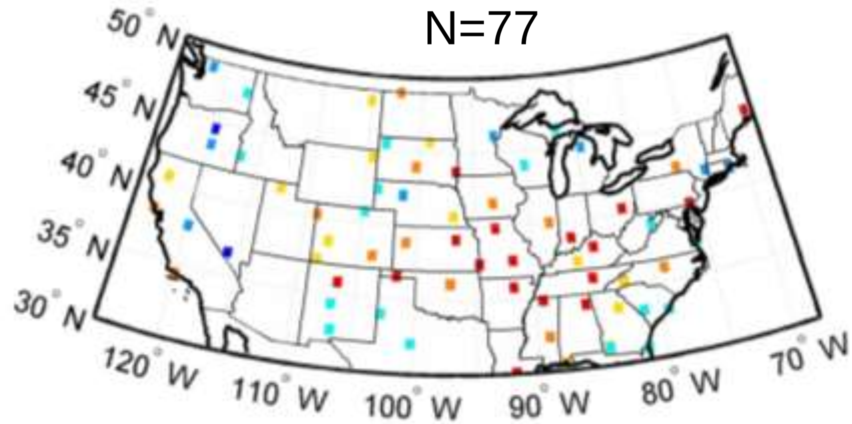
ubRMSE=0.056 m³/m³

N=183



ubRMSE=0.052 m³/m³

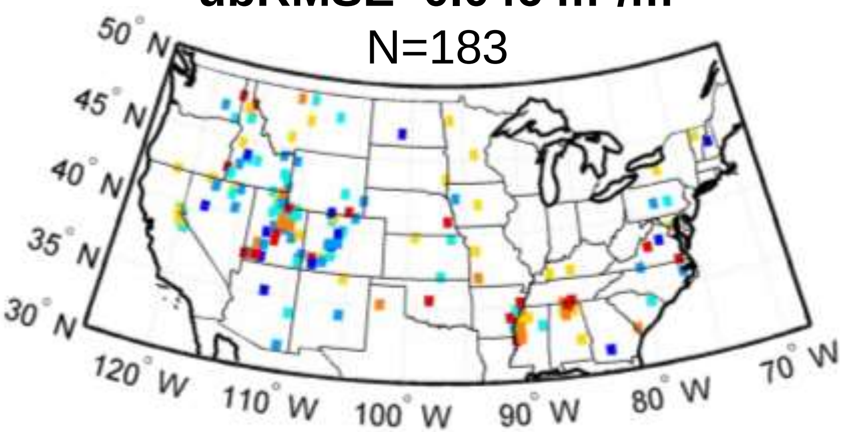
N=77



Root zone soil moisture

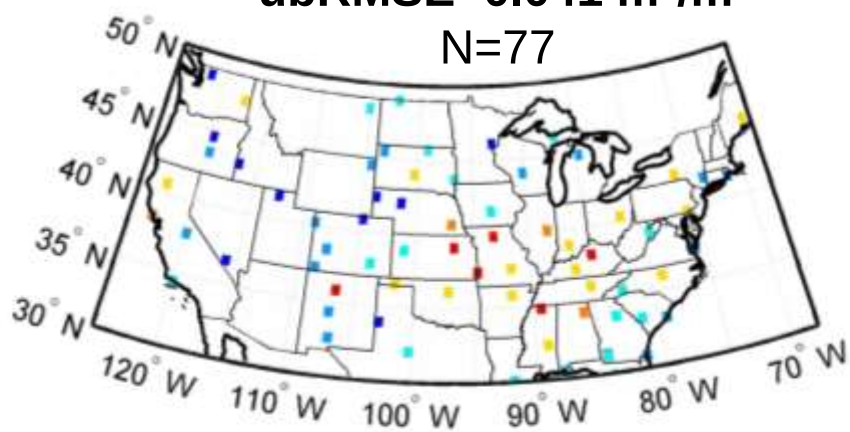
ubRMSE=0.046 m³/m³

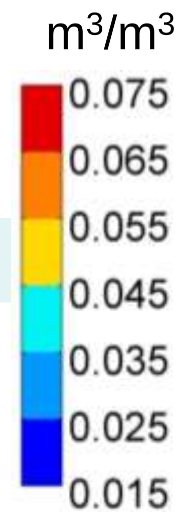
N=183



ubRMSE=0.041 m³/m³

N=77

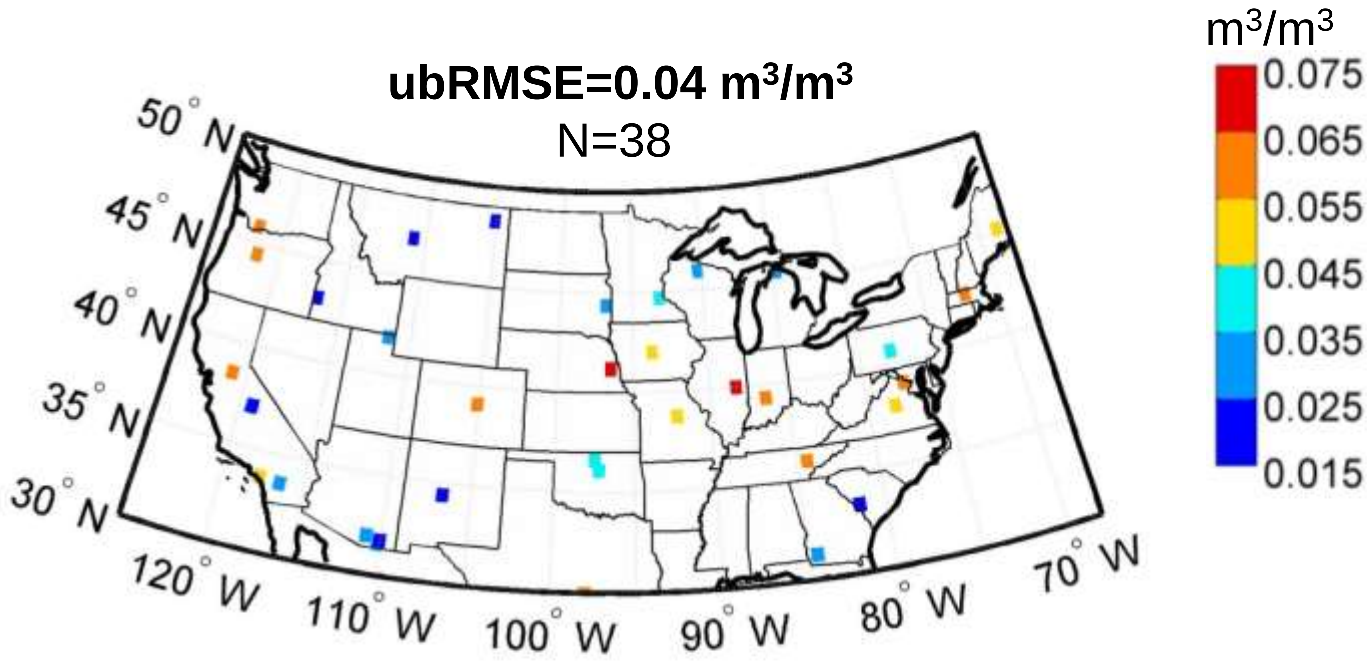




L4_SM_SMOS: Sparse networks

COSMOS

Root zone soil moisture



Thank you for your attention!

EXTRA SLIDES

Cal/Val extras

Diagnostics of filter performance

Filter update: $x^+ = x^- + K(y - x^-)$

$K = P\,(P + R)^{-1}$ = **Kalman gain**

Diagnostic: $E[(y - x^-)\,(y - x^-)^T] = P + R$

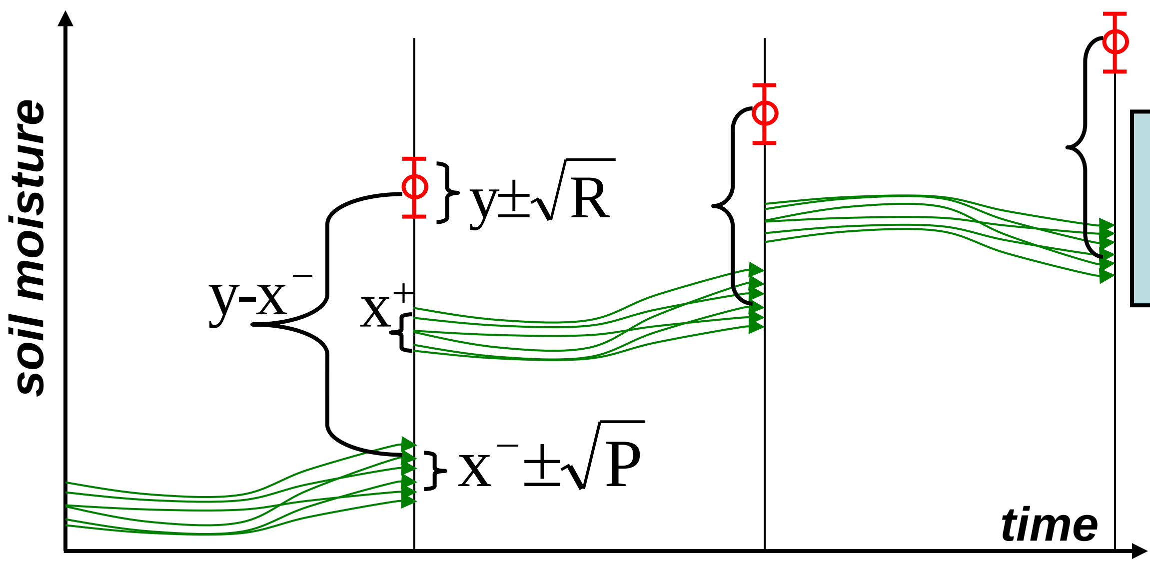
x^- = model forecast

x^+ = "analysis"

y = observation

innovations ≡ obs – model prediction (internal diagnostic)

state err cov + obs err cov (controlled by inputs)



Example:

1) Bias.

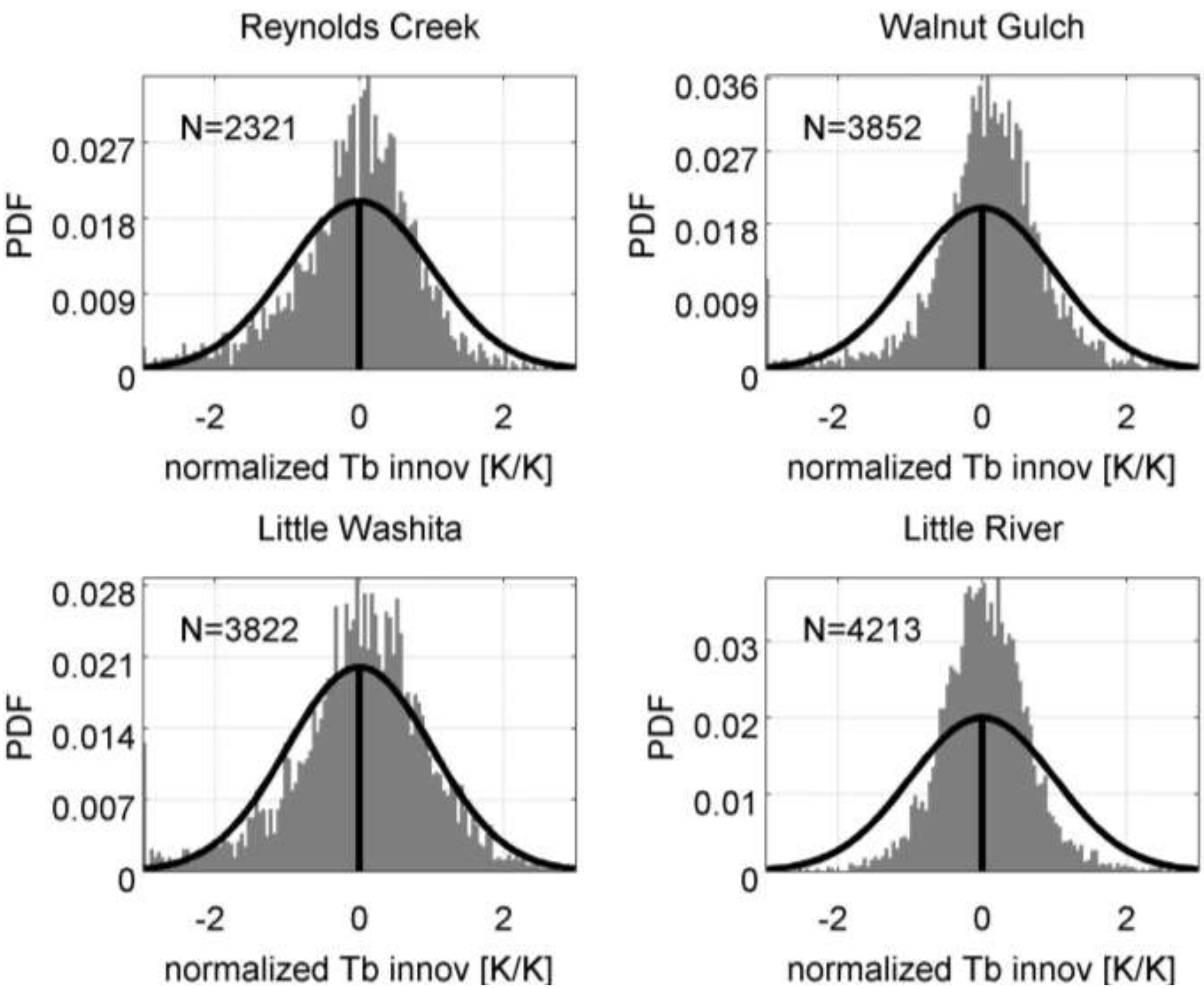
2) Input uncertainties too small.

Innovations diagnostics are ALWAYS available within assimilation system.

- Mean of innovations should equal zero. ***Otherwise have bias!***
- Normalize innovations with sqrt(P+R) → std-dev should equal one.

Otherwise (input) model and obs error parameters are inconsistent!

L4_SM_SMOS: Normalized Tb innovations



Apr 2010 – Mar 2012

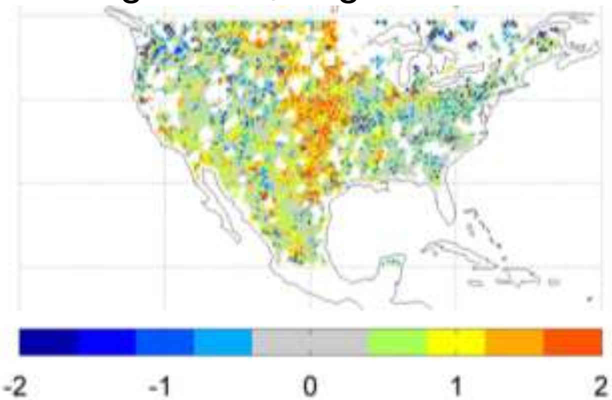
Normalized innovations histograms suggest some over-estimation of the input error variances (of model and/or observations).

L4_SM_SMOS: Innovations and increments

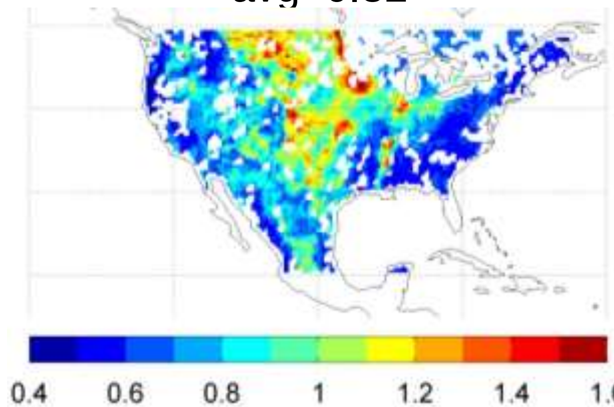
Apr 2010 – Mar 2013

Innovations (36 km observation space)

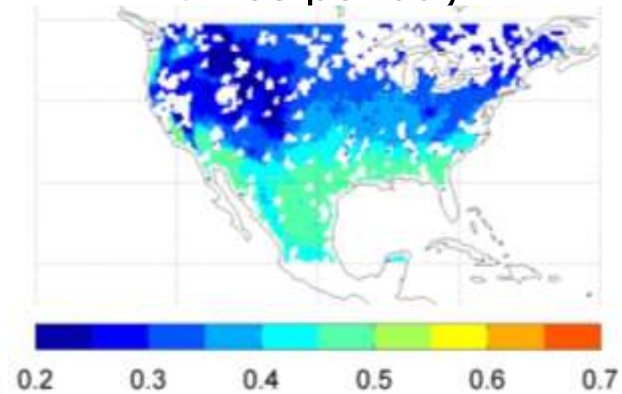
Mean of innovations
avg=0.4 K, avg abs=0.7 K



Stdv of *normalized* innovations
avg=0.82

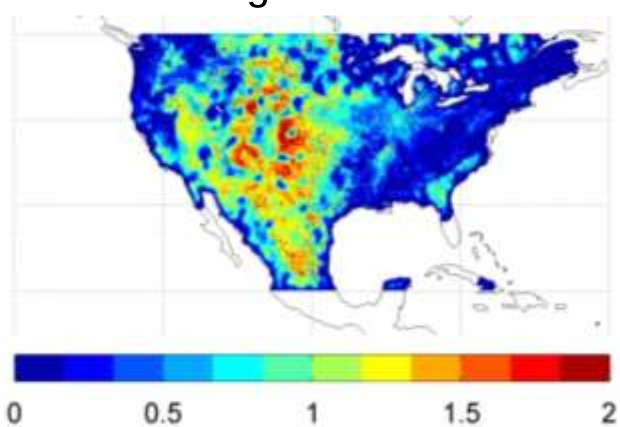


Number of assimilation times per day

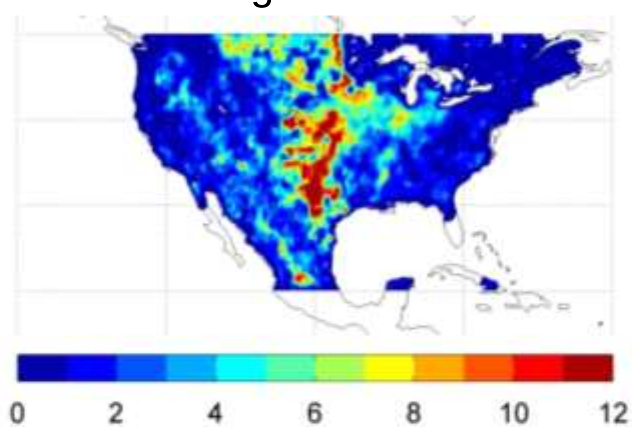


Increments (9 km model space)

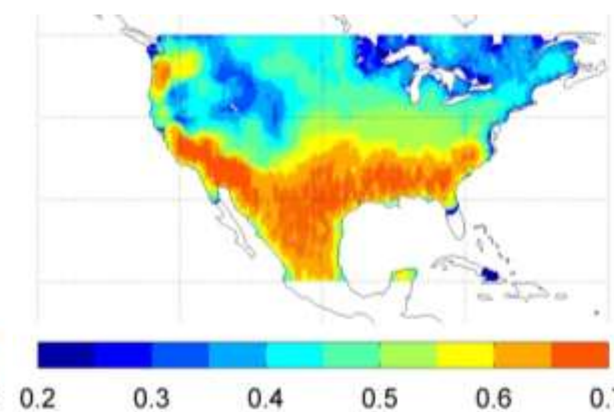
Stdv of **surface** excess incr.
avg=0.6 mm



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



Number of incr. per day
(avg: ~1 every other day)

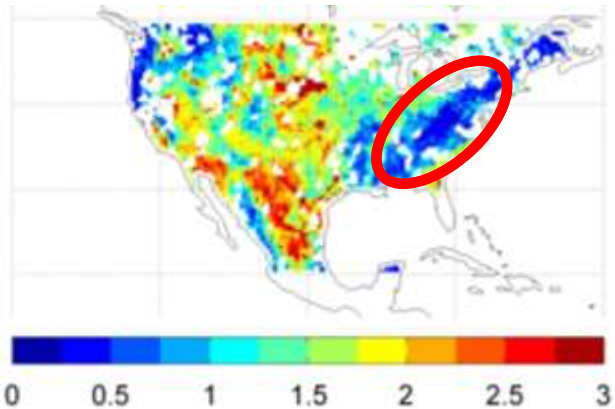


L4_SM_SMOS: Ensemble error estimates

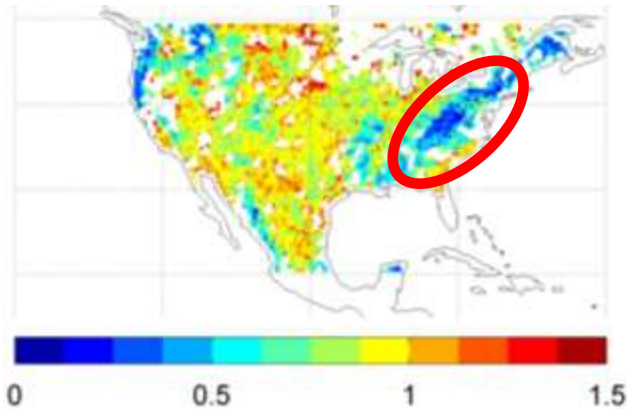
Apr 2010 – Mar 2013

Tb ensemble std-dev (36 km obs. space)

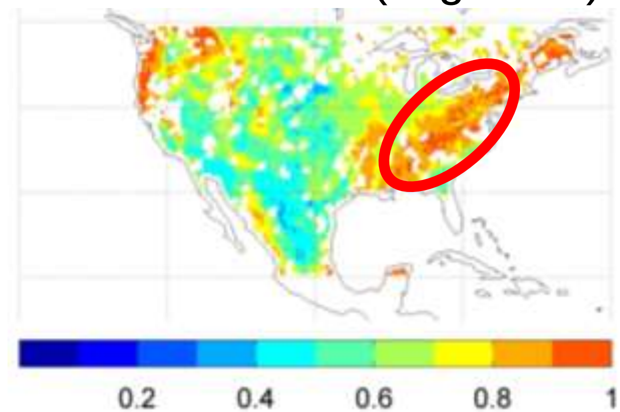
Mean **forecast** error std-dev
avg=1.5 K



Mean **analysis** error std-dev
avg=0.83 K

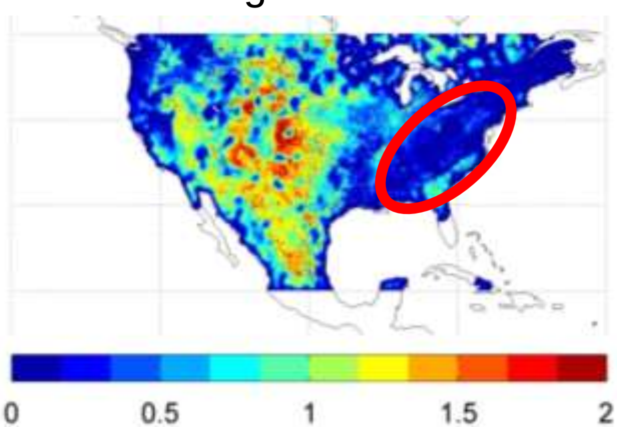


Mean analysis/forecast error std-dev (avg=0.67)

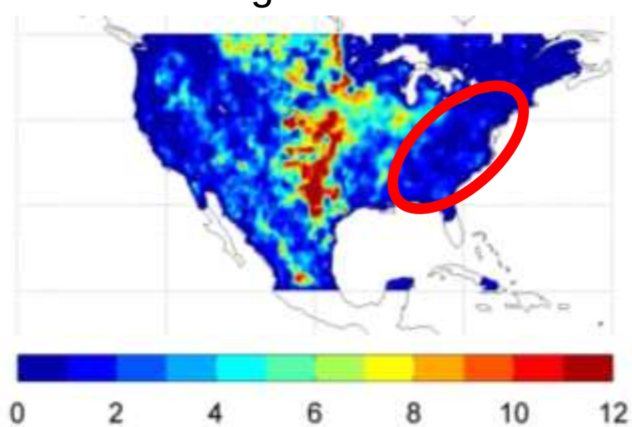


Increments (9 km model space)

Stdv of **surface** excess incr.
avg=0.6 mm



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



Tb forecast errors and soil moisture increments are small over densely vegetated regions.

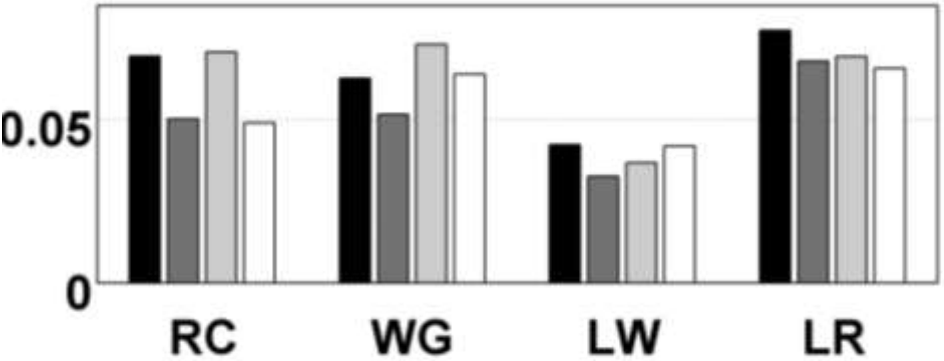
(Soil moisture ensemble spread was not written out and remains to be evaluated.)

Impact of CPCU on soil moisture skill: CalVal sites

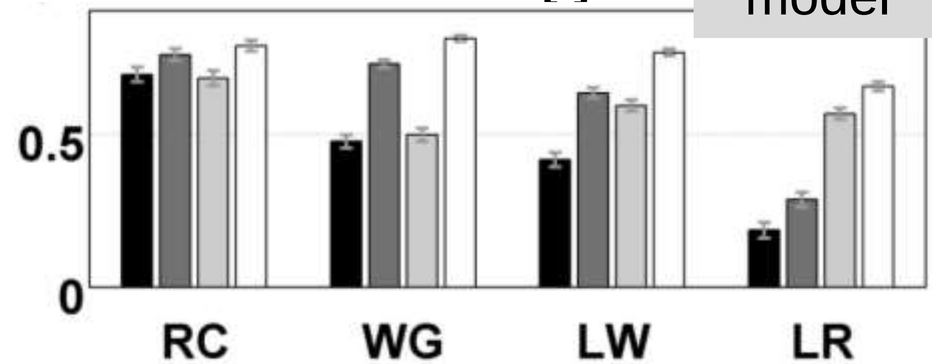
Apr 2010 – Mar 2011

36 km model

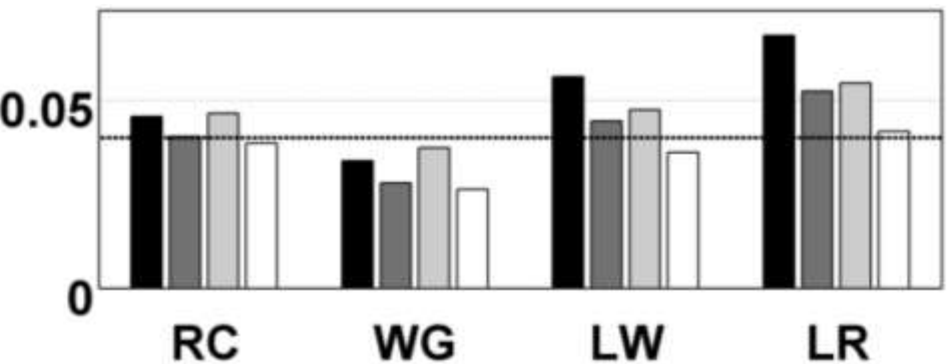
Bias [m³/m³]



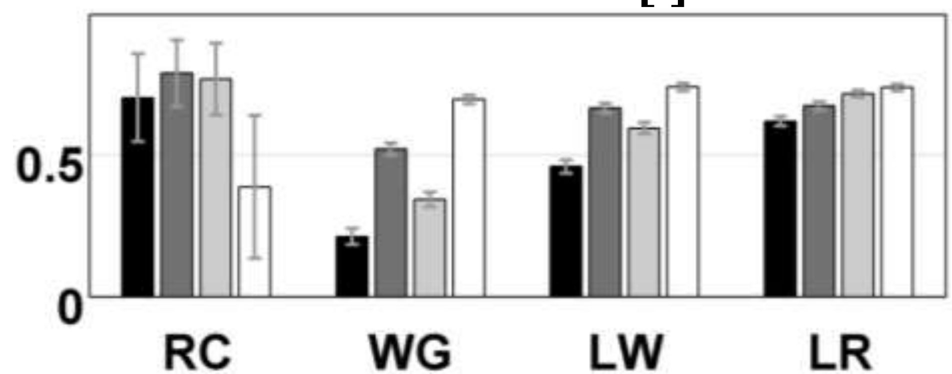
R [-]



ubRMSE [m³/m³]



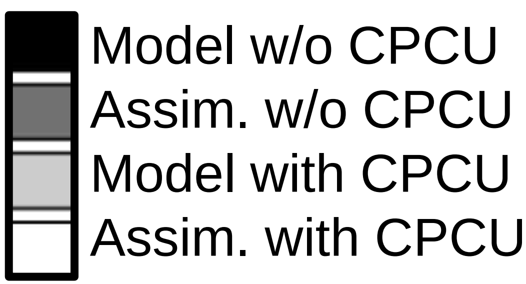
Anom R [-]



Withholding CPCU precipitation corrections simulates conditions in poorly observed regions.

Improvements from Tb assimilations are somewhat greater without CPCU corrections.

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



Impact of CPCU on soil moisture skill improvement: SCAN/Snotel

With CPCU precipitation | **Without** CPCU precipitation

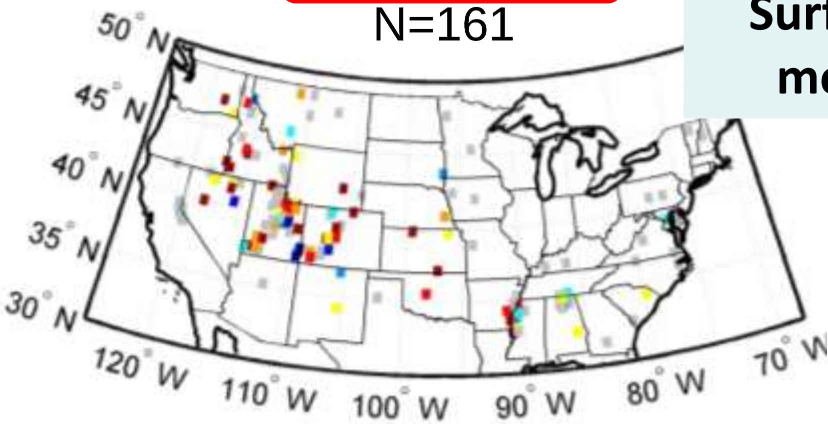
ΔanomR = anomR(assim) – anomR(model)

36 km model

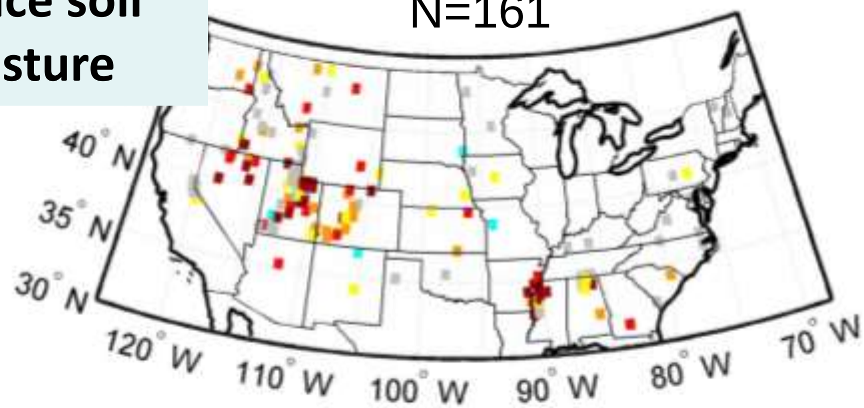
ΔanomR=0.08 → **ΔanomR=0.16**

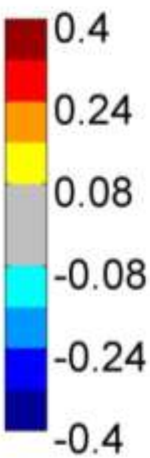
Surface soil moisture

N=161



N=161

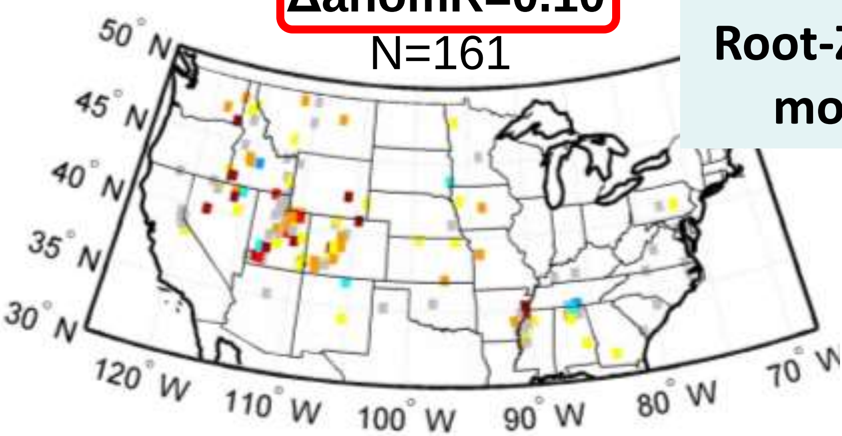




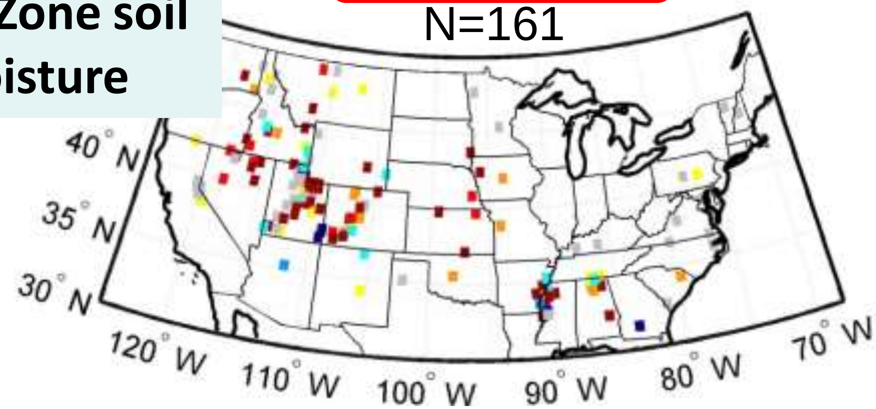
ΔanomR=0.10 → **ΔanomR=0.19**

Root-Zone soil moisture

N=161



N=161



Greater improvements in terms of anomaly R without CPCU corrections.

L4_SM post-launch Cal/Val activities

Post-launch, emphasis is on *validation* of the L4_SM *data product*.

Post-launch validation:

- See earlier slides on validation requirements, data resources, and approach.
- Can ingest IOC and Cal/Val phase L1 and L2 brightness temperature observations, but poor quality data likely eliminated during L4_SM internal QC.

Refine algorithm calibration as needed (SMOS → SMAP):

- Re-calibrate microwave radiative transfer model parameters to **SMAP** Tb.
- Re-derive scaling parameters for **SMAP-based** system.
- Adjust model and observation error standard deviations in response to **SMAP-based** observation-minus-forecast residuals.
- Re-calibrate F/T analysis using **SMAP F/T** observations.

Operational monitoring:

- QC/QA (e.g., checks against range thresholds)
- Assimilation diagnostics

L4_SM Cal/Val Schedule

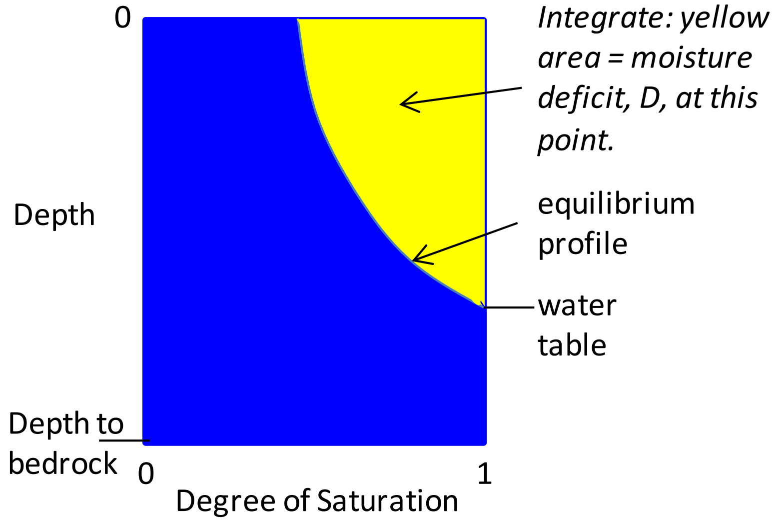
- SMOS-based **L4_SM calibration** (on-going).
- Science algorithm software **Delivery 5** (Feb 2014).
- SMAP **Cal/Val Rehearsal Phase 2** (May 2014).
- SMAP **launch** (Oct 2014) and IOC (Winter 2014/15); initiation of SMAP operations and L4_SM production.
- **Post-launch Cal/Val activities** (Feb 2015-Jan 2016).
- L4_SM **Beta Product release** to NSIDC (6 months after IOC; Aug 2015).
- L4_SM **Stage I Validated Product release** to NSIDC (12 months after IOC; Feb 2016).
- Release of post-launch **Cal/Val report** (Feb 2016).

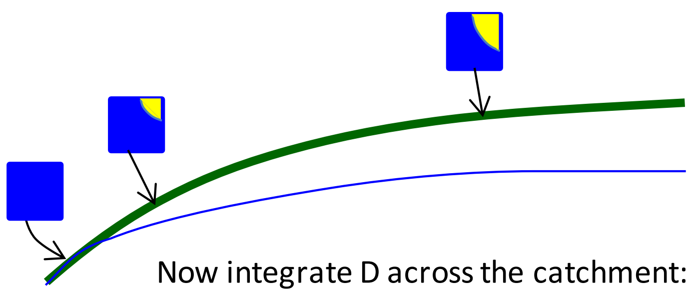
Algorithm development extras

NASA GEOS-5 Catchment land surface model

“Catchment Deficit” variable

Consider an arbitrary point in the catchment:



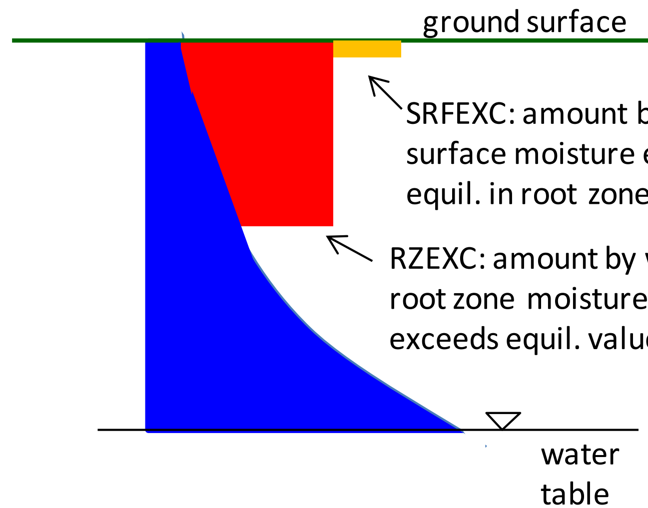


Now integrate D across the catchment:

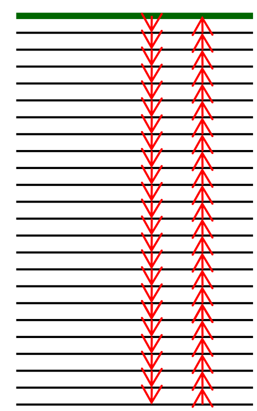
CATDEF = (1/A) $\int_A$ D dA

= 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 data product overview

SMAP inputs

Brightness temperature
(L1C_TB, 36 km)
(L2_SM_AP, 9 km)
Freeze-thaw state
(L2_SM_A, 3 km)

L4_SM algorithm

Ancillary data inputs

Land model parameters

Surface meteorology (incl. observation-corrected precip)

Land assimilation parameters

L4_SM product

9 km, 3-hourly global output with 7-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)

L4_SM data product overview (2)

L4_SM Product

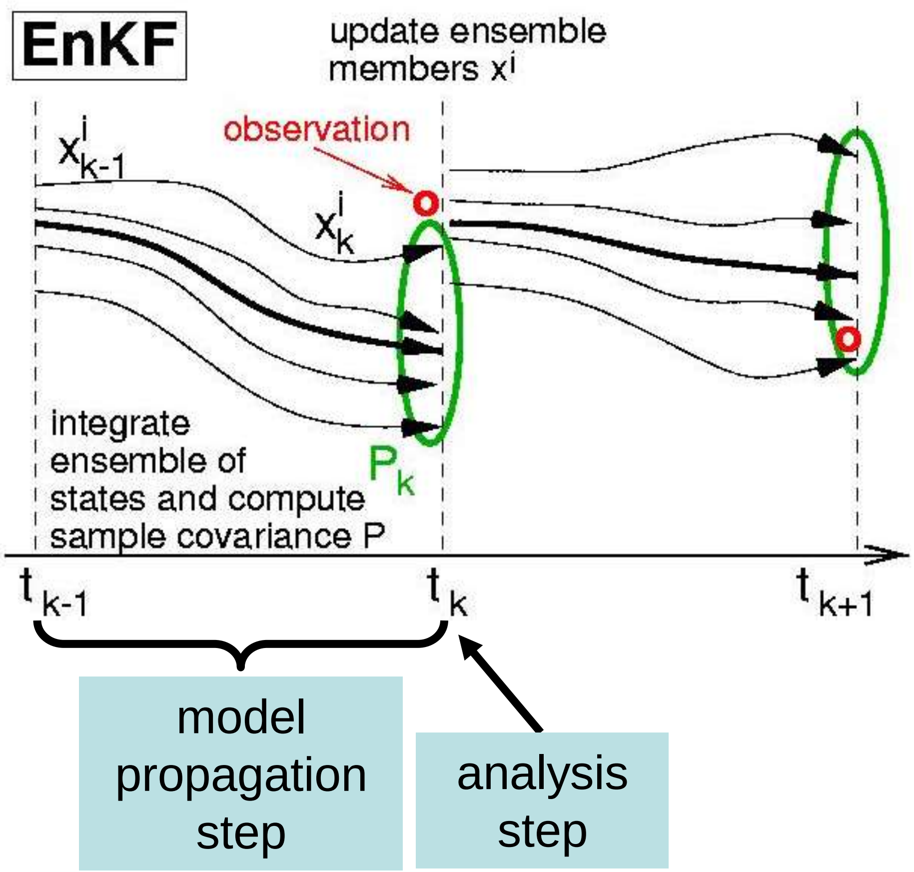
“gph” File Collection (3-hourly time averages of geophysical fields)	“aup” File Collection (3-hourly instantaneous analysis update output)	“lcm” File Collection (time-invariant land model constants)
Metadata	Metadata	Metadata
Geophysical Data Group “/Geophysical_Data”	Observations Data Group “/Observations_Data”	Land-Model-Constants Data Group “/LandModelConstants_Data”
	Forecast Data Group “/Forecast_Data”	
	Analysis Data Group “/Analysis_Data”	

- 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)

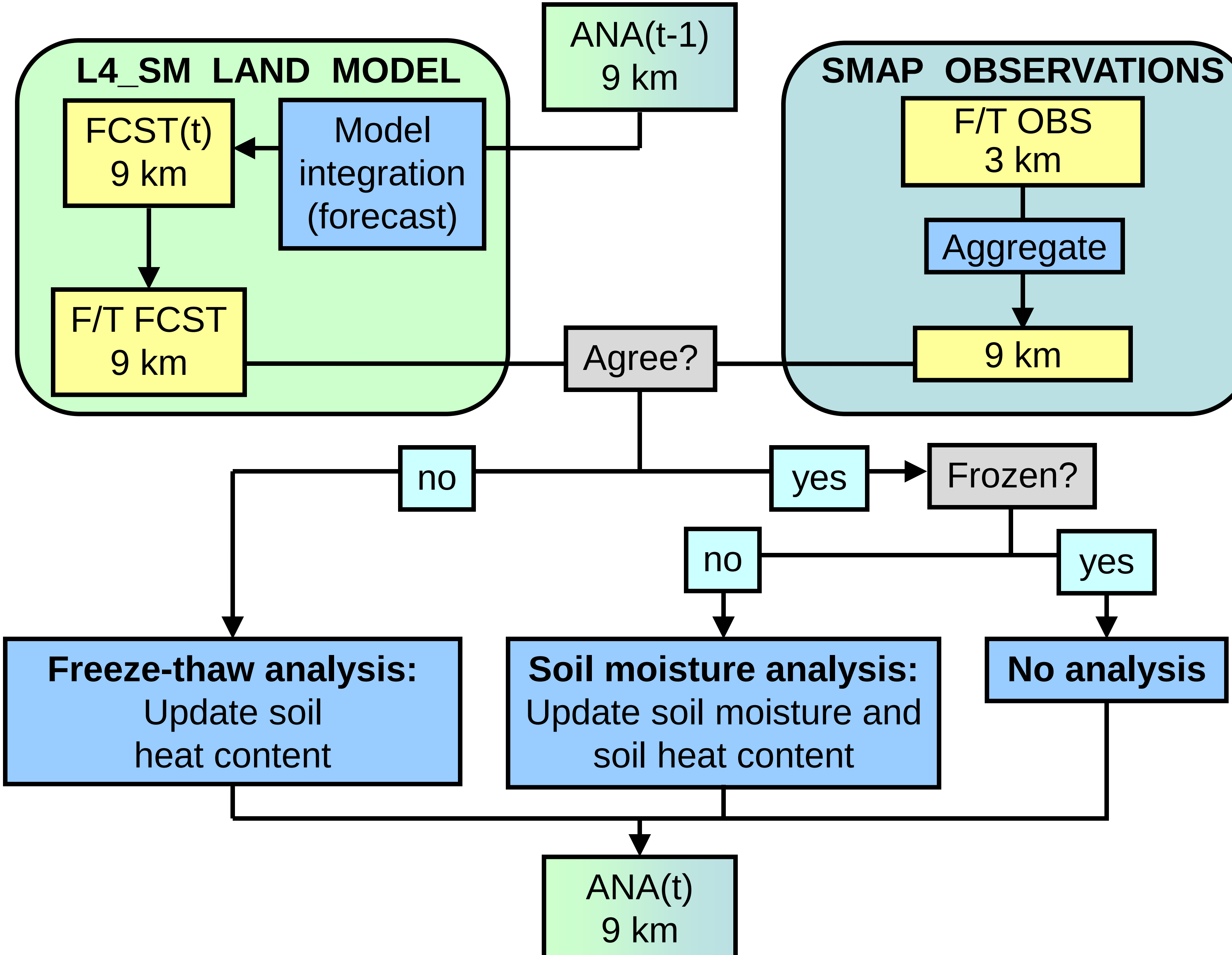
L4_SM baseline algorithm

Baseline algorithm:

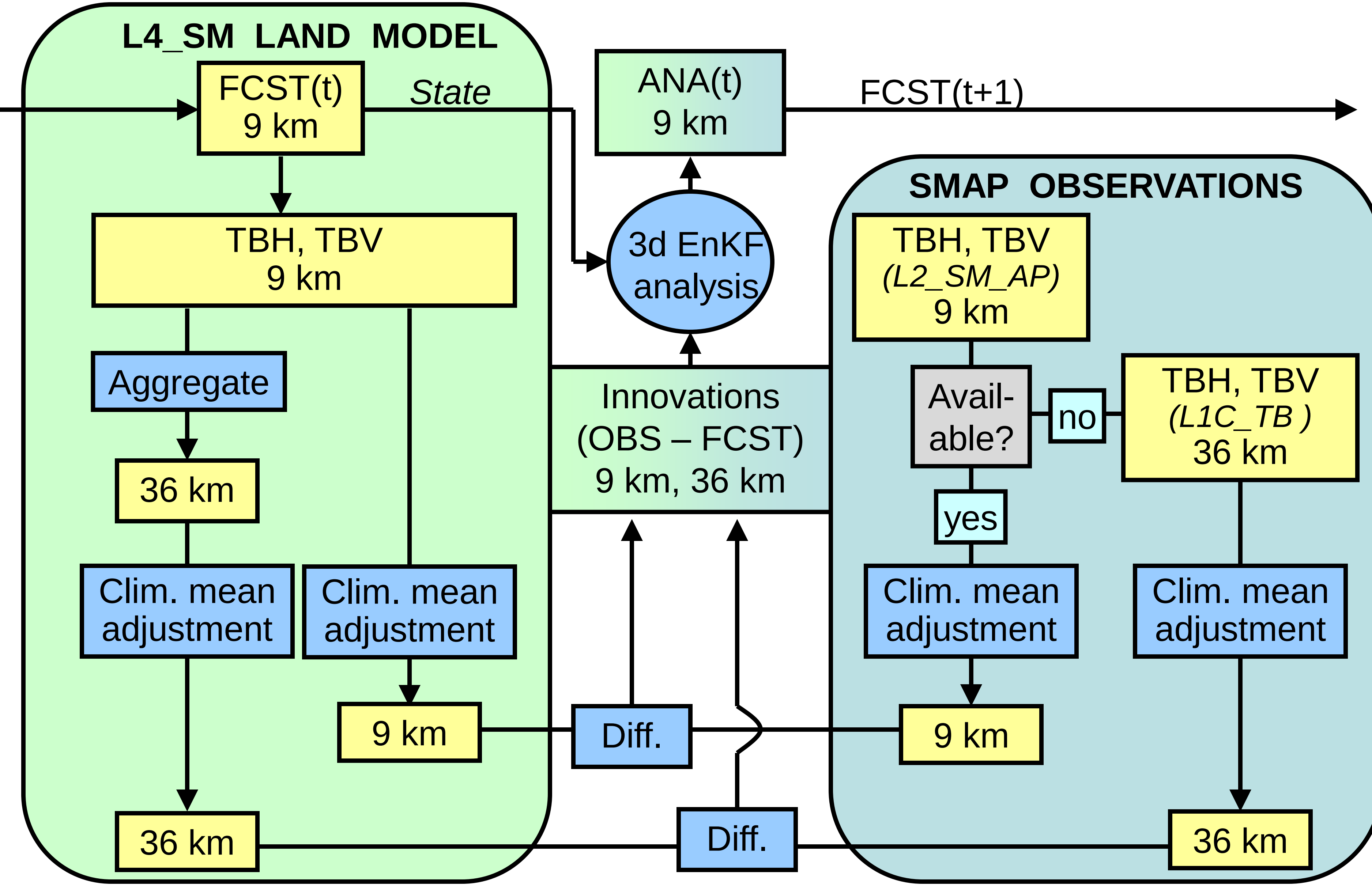
- Customized version of NASA GEOS-5 Land Data Assimilation System
  - 3d ensemble Kalman filter: *spatial extrapolation, interpolation, and disaggregation of assimilated observations*
  - Catchment land surface model with tau-omega microwave radiative transfer model
  - Observations-based precipitation
- No optional algorithms.



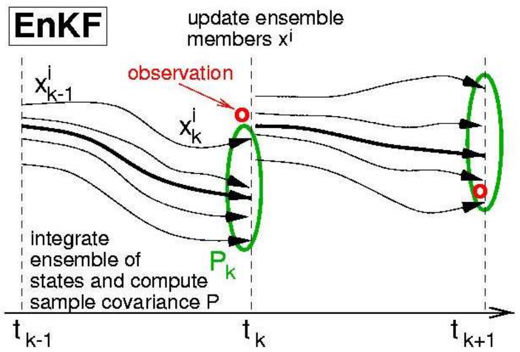
L4_SM analysis overview



L4_SM soil moisture analysis



L4_SM soil moisture analysis (2)



Analyzed model states:

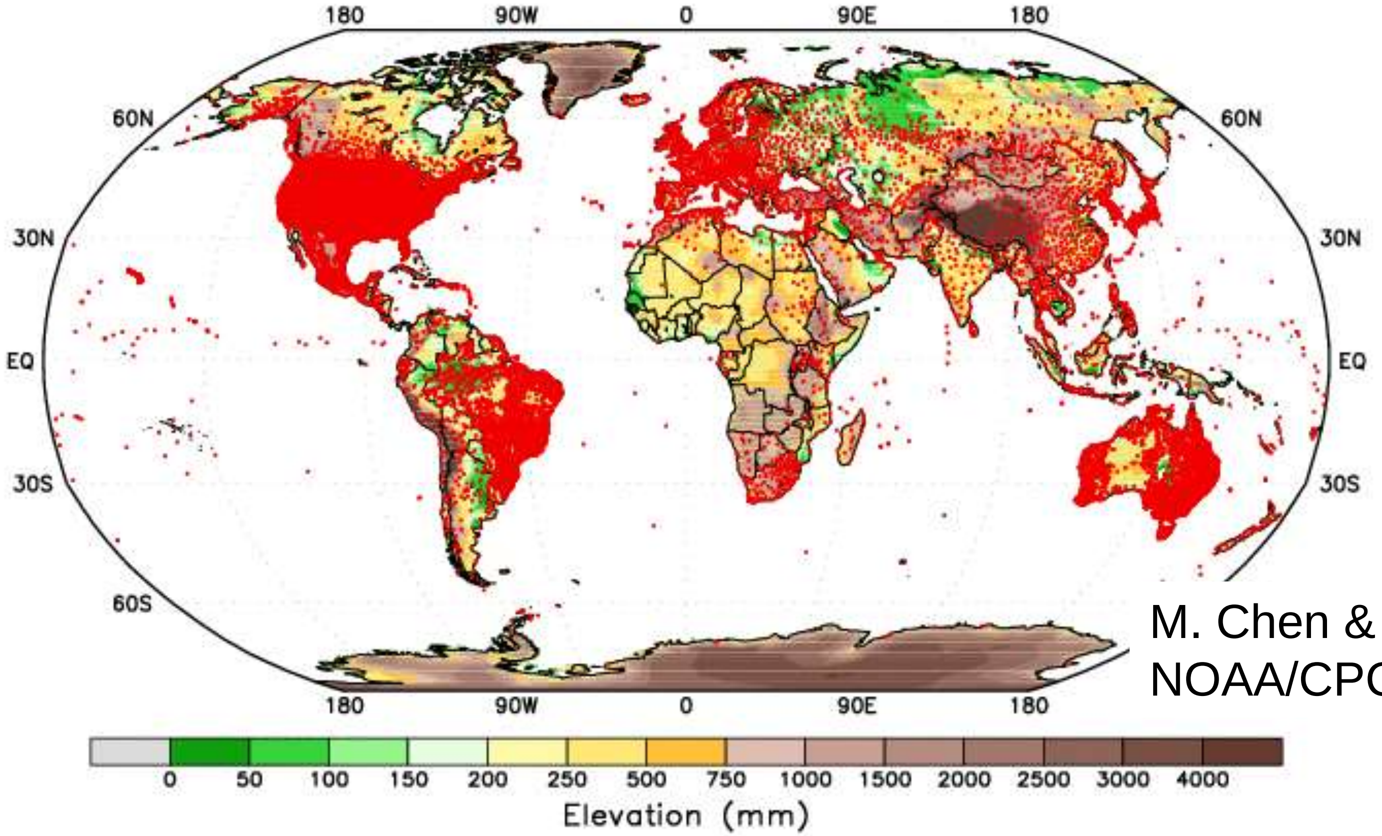
$$x^- = \begin{bmatrix} x_1^- \\ x_2^- \\ \cdots \\ x_{N9}^- \end{bmatrix} \quad \text{where} \quad x_j^- = \begin{bmatrix} \mathrm{SRFEXC\_FCST}_j \\ \mathrm{RZEXC\_FCST}_j \\ \mathrm{CATDEF\_FCST}_j \\ \mathrm{TC1\_FCST}_j \\ \mathrm{TC2\_FCST}_j \\ \mathrm{TC4\_FCST}_j \\ \mathrm{GHT1\_FCST}_j \end{bmatrix}$$

Soil moisture prognostic variables. (SRFEXC_FCST, RZEXC_FCST, CATDEF_FCST)

Surface temperature and top-layer soil temperature prognostic variables. (TC1_FCST, TC2_FCST, TC4_FCST, GHT1_FCST)

N9: # of 9 km grid cells incl. in soil moisture analysis.
j=1...N9
Subscripts for time and ensemble member omitted.

Precipitation corrections



M. Chen & P. Xie
NOAA/CPC

NOAA/CPC Unified Daily Gauge Data

- Provided on 0.5 deg grid with ~2-day latency
- Dense gauge networks from special CPC collections in US, Mexico, and S. America
- GTS gauge network elsewhere
- Daily reports available from ~17,000 stations

Precipitation corrections

GEOS-5 (NWP)
Hourly
0.25° x 0.3125°

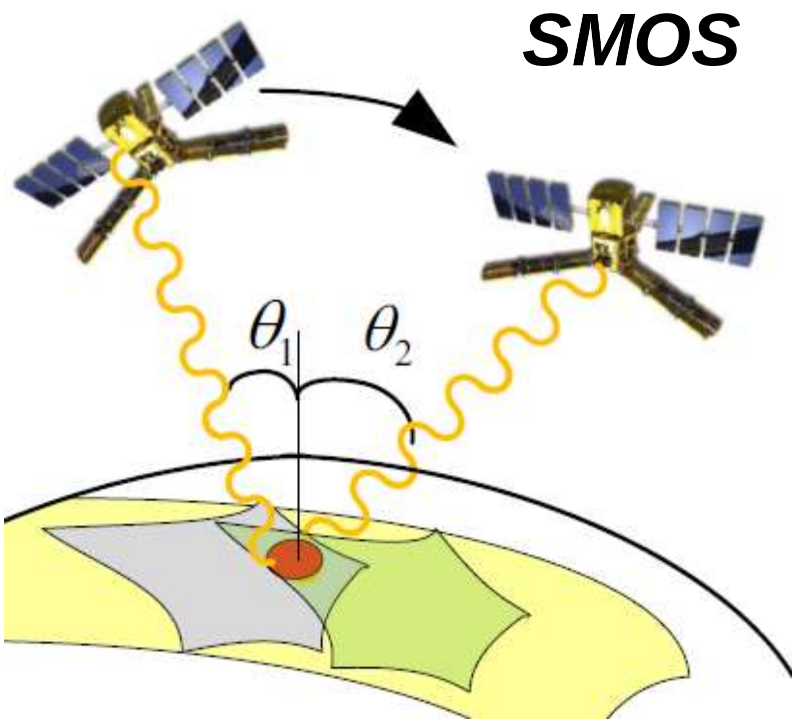
Rescale GEOS-5
separately for each day and 0.25° x 0.3125° grid cell

CPCU
Gauges
Daily
0.5° x 0.5°

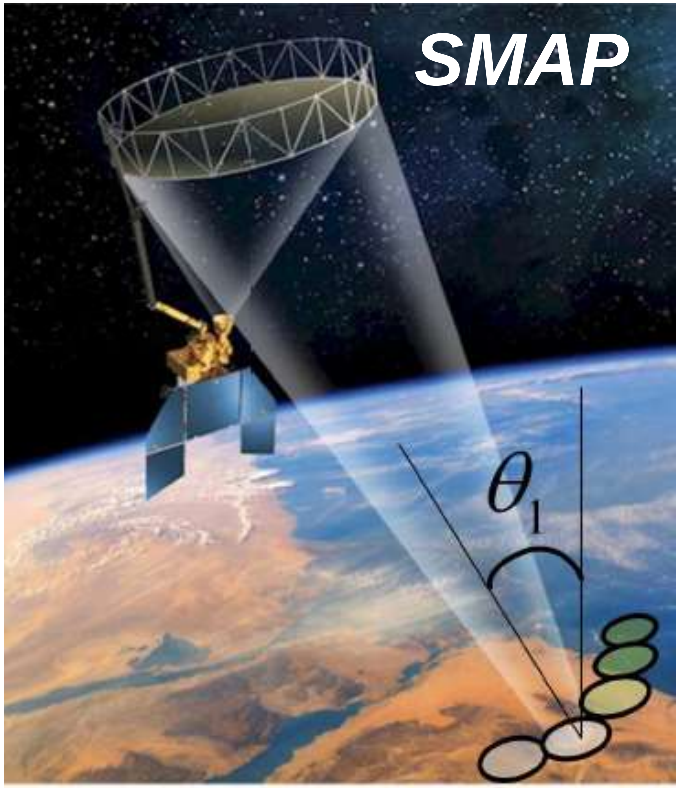
GEOS-5 + CPCU
(hourly, 0.25° x 0.3125°)

For each day and each 0.25° x 0.3125° grid cell, the corrected GEOS-5 precipitation (almost) matches CPCU observations.

Satellite remote sensing of (surface) soil moisture



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



Launch: 2014
L-band active/passive
3-40 km resolution

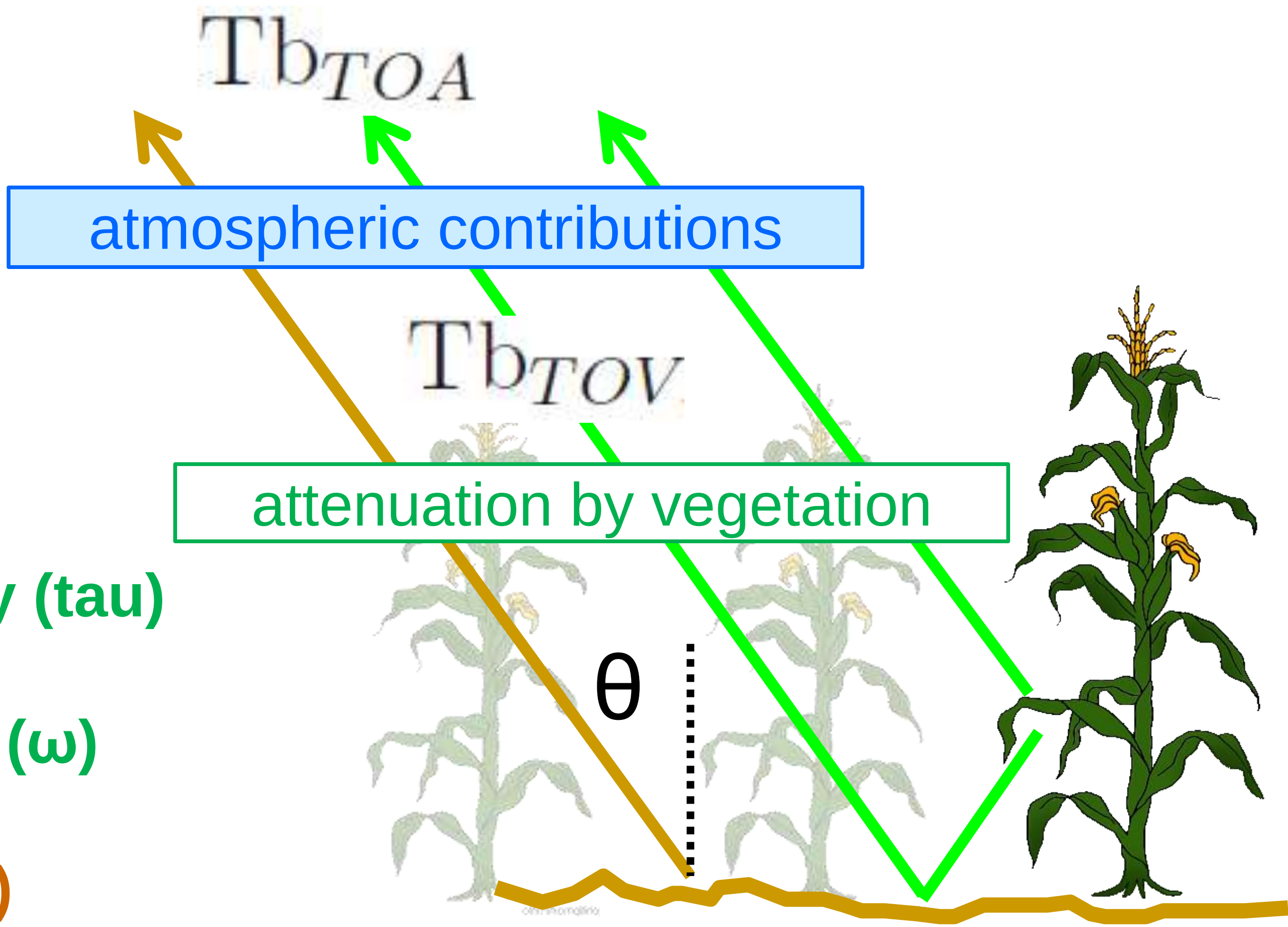
Zero-order (tau-ω) microwave radiative transfer model

Key microwave parameters:

Vegetation opacity (tau)

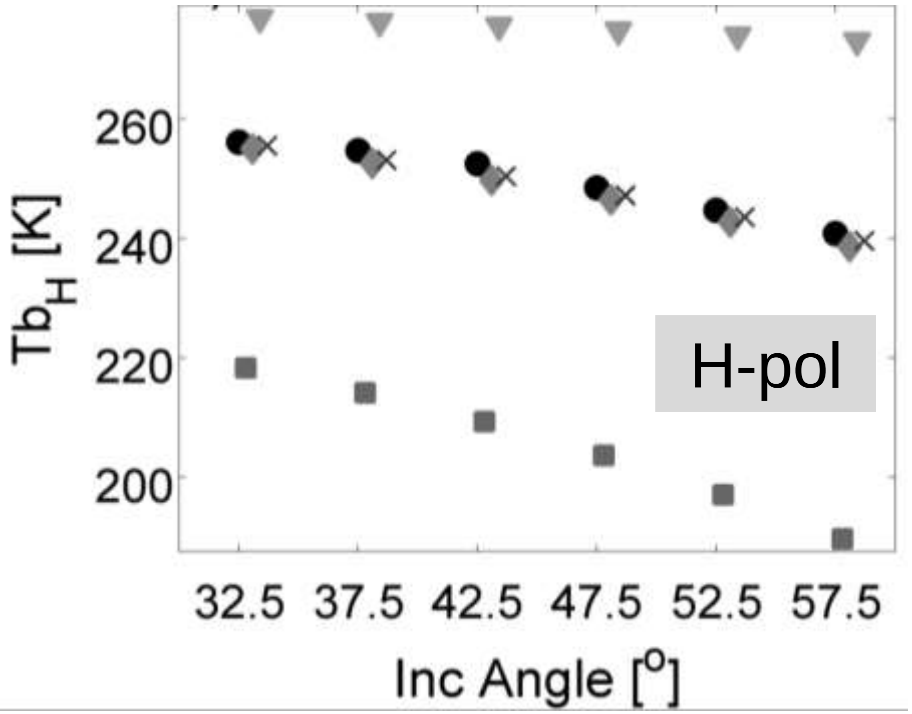
Scattering albedo (ω)

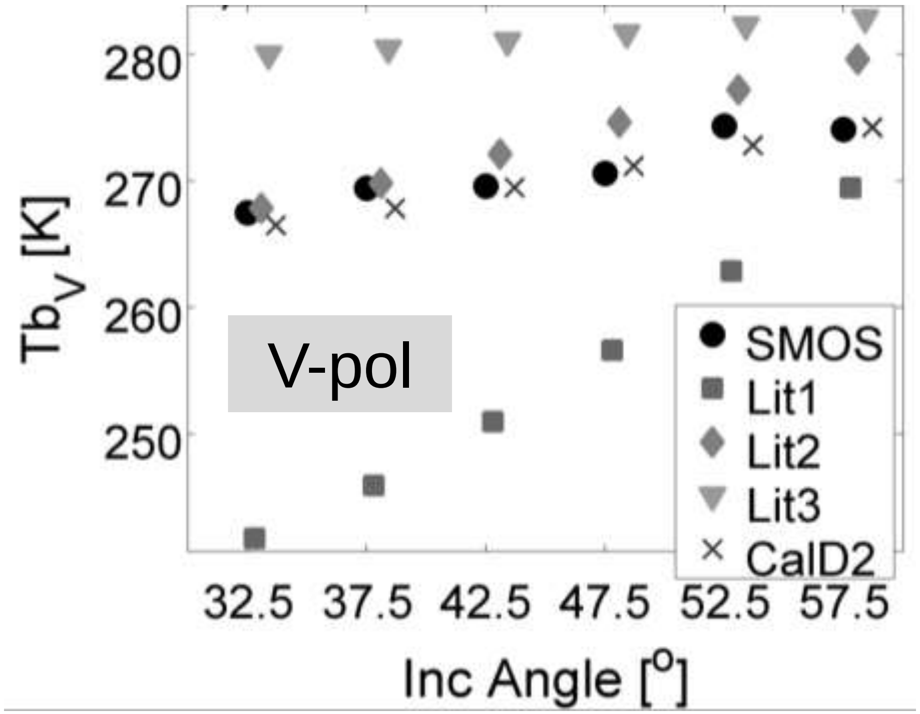
Soil roughness (h)



L-band brightness temp.: SMOS vs. GEOS-5

One-year global average Tb (Jul 2010 – Jun 2011)





For some RTM parameter sets, GEOS-5 (model) Tb is strongly biased vs. SMOS observations.

De Lannoy et al, 2013, doi: 10.1175/JHM-D-12-092.1

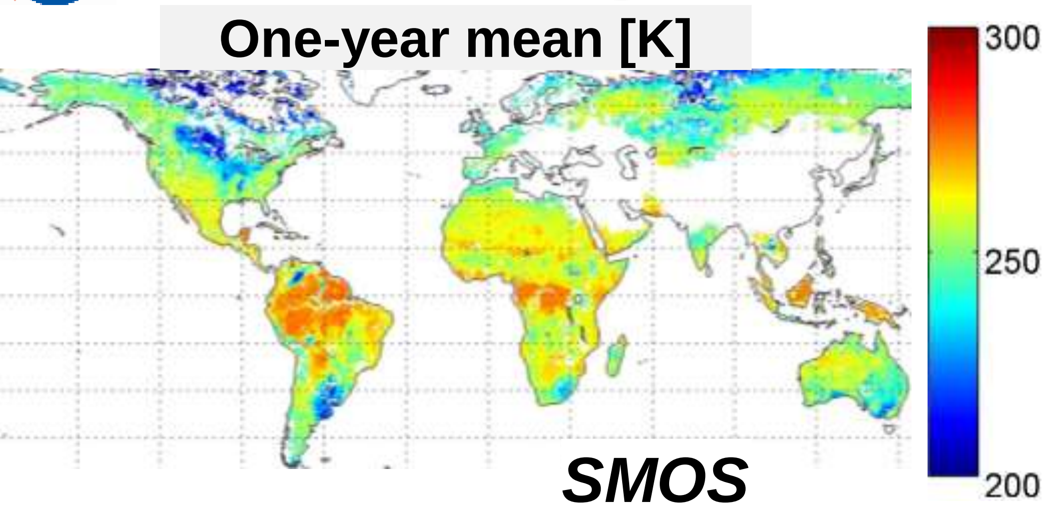
Prescribed RTM parameters:

Lit1: SMAP Level2 ATBD

Lit2: LMEB literature

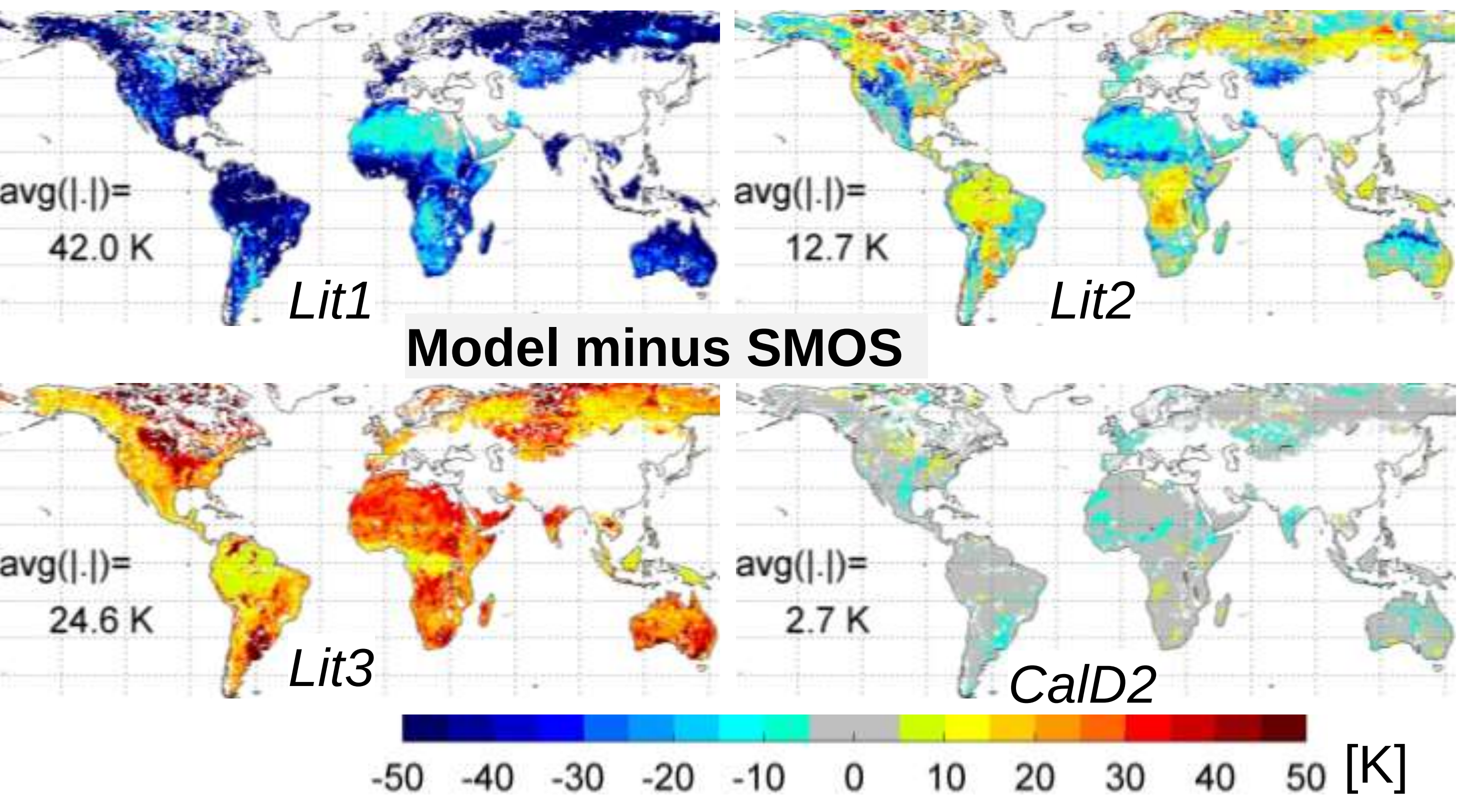
Lit3: ECMWF SMOS monitor

L-band brightness temp.: SMOS vs. GEOS-5



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

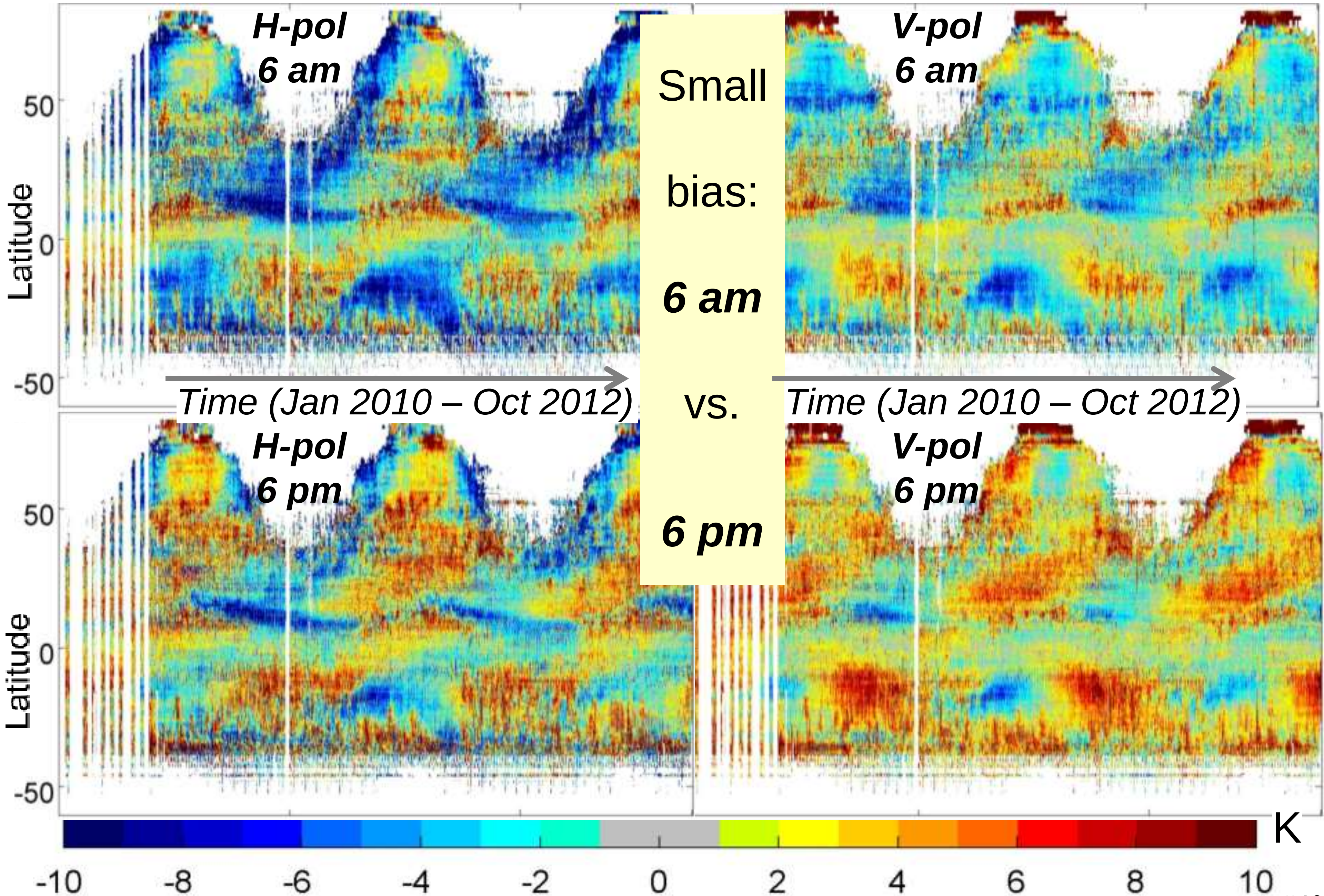
Calibration used multi-angular obs from Jul 2011 – Jun 2012.



Literature values for parameters yield strongly biased Tb.

Calibrated parameters yield mostly unbiased long-term mean Tb.

L-band brightness temp.: SMOS vs. GEOS-5



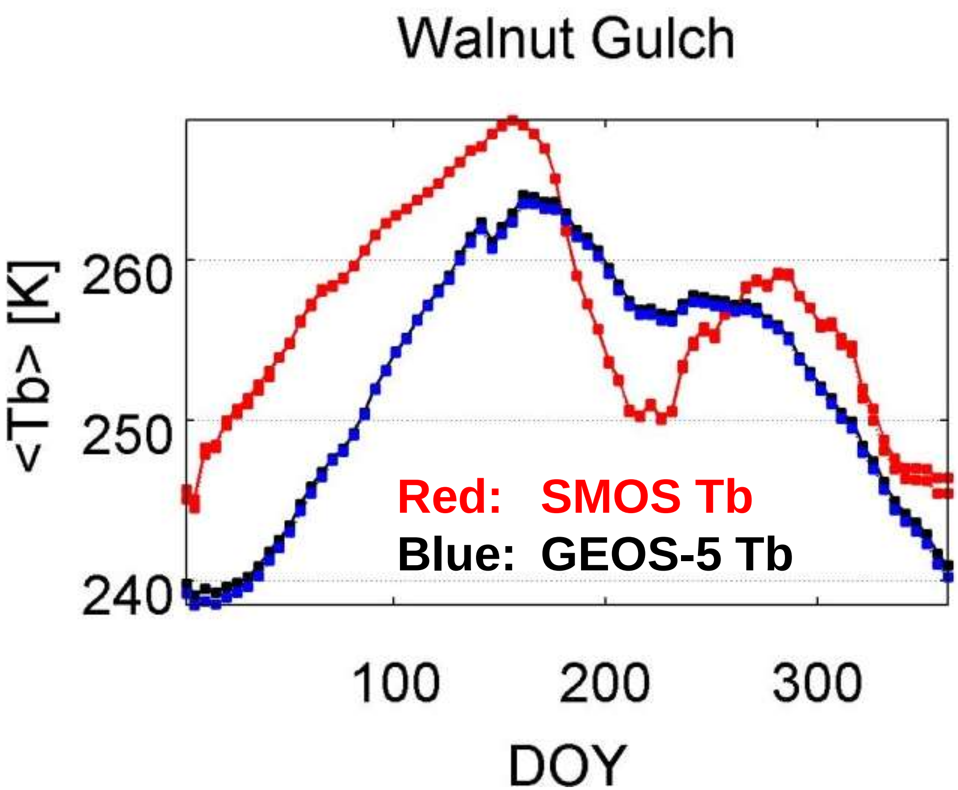
Scaling statistics

Some bias remains between observations and simulations.

(e.g., due to errors in seasonal cycle of vegetation inputs, seasonal and diurnal errors in soil temperature inputs, imperfect observations, and/or imperfect calibration).

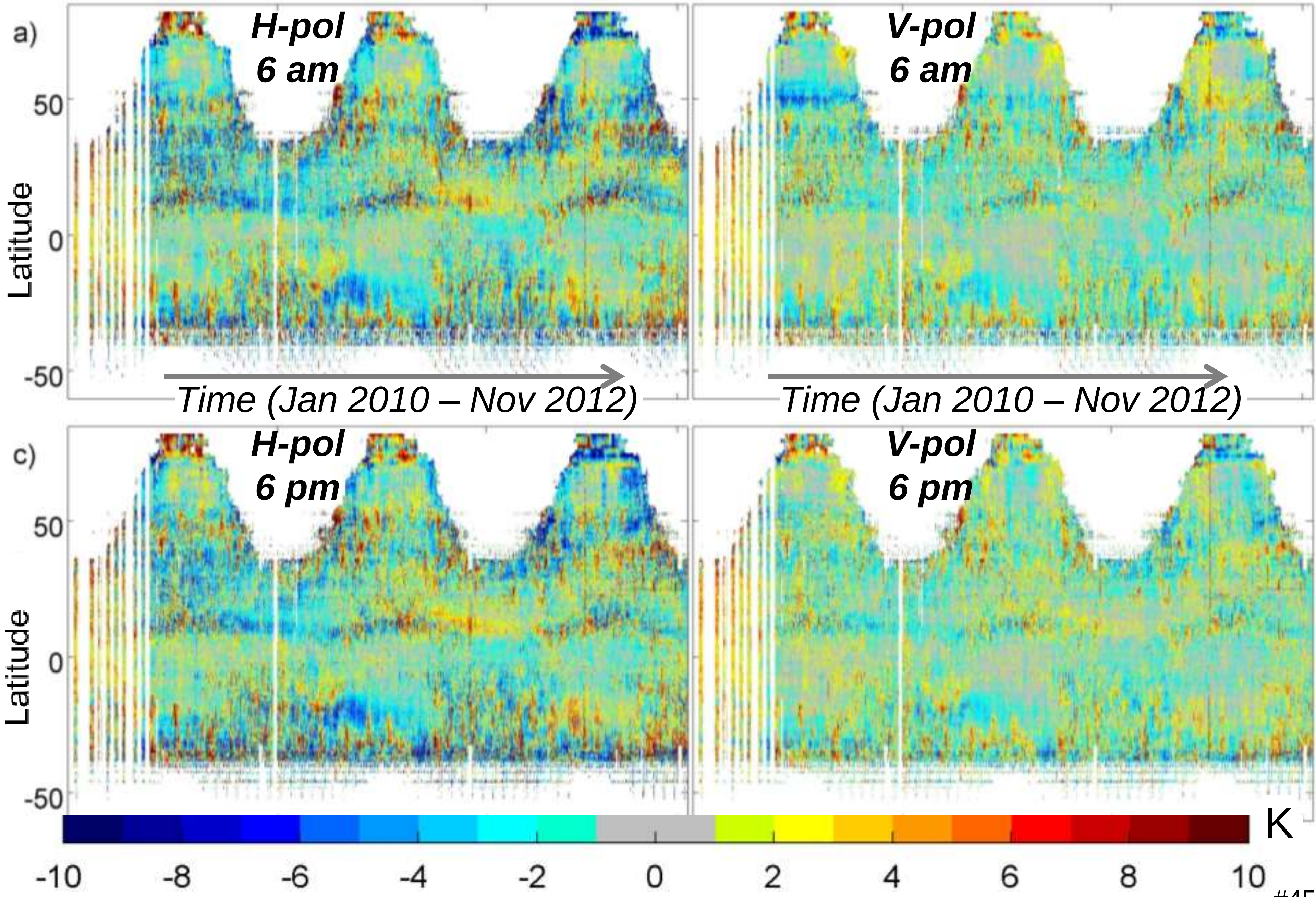
Adjust Tb observations such that their (3-year) mean value for each grid cell matches that of the simulated Tb.

(separately for each day-of-year, after smoothing)



Example of residual biases after calibration of microwave RTM parameters
(6 am, 40º inc angle, H-pol, June 2010 – May 2013)

L-band brightness temp.: SMOS (scaled) vs. GEOS-5



Observation and model error parameters

Input parameter settings evolved from soil moisture retrieval assimilation.
Algorithm calibration primarily adjusts these parameters, based on validation metrics (see below).

Observation error parameters (SMOS Tb)

Standard deviation: 8 K
(additive, uncorrelated in space and time)

Horizontal scale of distributed (3d) analysis: 1.25 deg (radius)

Model **forcing** error parameters

Perturbation	Additive (A) or Multiplicative (M)?	Standard deviation	AR(1) time series correlation scale	Spatial correlation scale	Cross-correlation with perturbations in		
					P	SW	LW
Precipitation (P)	M	0.5	1 day	0.5 deg	1.0	-0.8	0.5
Downward shortwave radiation (SW)	M	0.3	1 day	0.5 deg	-0.8	1.0	-0.5
Downward longwave radiation (LW)	A	20 W m^{-2}	1 day	0.5 deg	0.5	-0.5	1.0

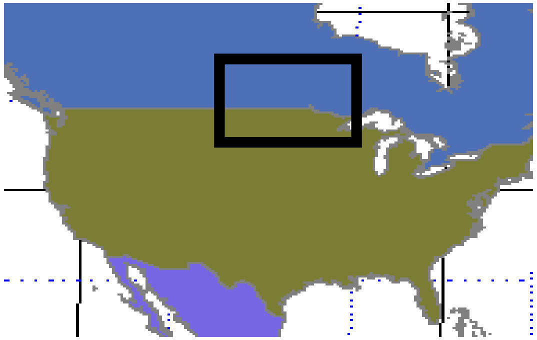
Observation and model error parameters

Model **prognostics** error parameters
(Prognostics perturbations account for errors in model structure and model parameters.)

Perturbation	Additive (A) or Multiplicative (M)?	Standard deviation	AR(1) time series correlation scale	Spatial correlation scale	Cross-correlation with perturbations in			
					Catdef	Srfexc	Tsurf	Ght1
Catchment deficit (Catdef)	A	0.07 mm	3 h	0.5 deg	1.0	0.0	0.5	0.3
Surface excess (Srfexc)	A	0.04 mm	3 h	0.5 deg	0.0	1.0	-0.3	-0.2
Surface temperature (Tsurf)	A	0.2 K	3 h	0.5 deg	0.5	-0.3	1.0	0.6
Top-layer soil heat content (Ght1)	A	500 J/m^{-2}	3 h	0.5 deg	0.3	-0.2	0.6	1.0

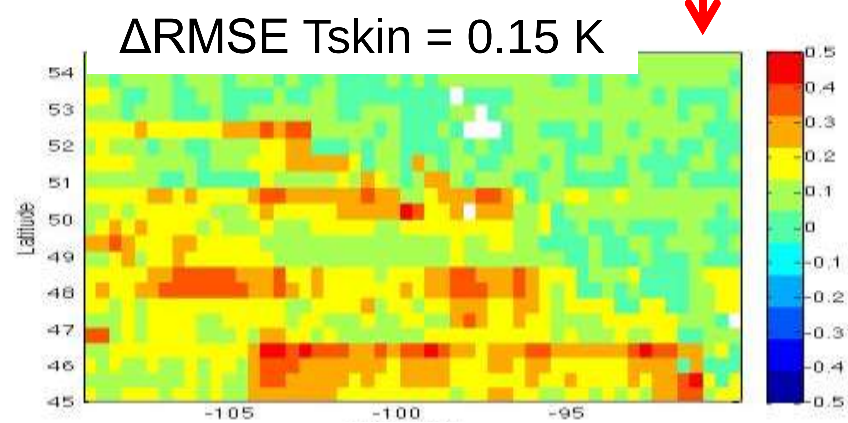
Freeze-thaw OSSE

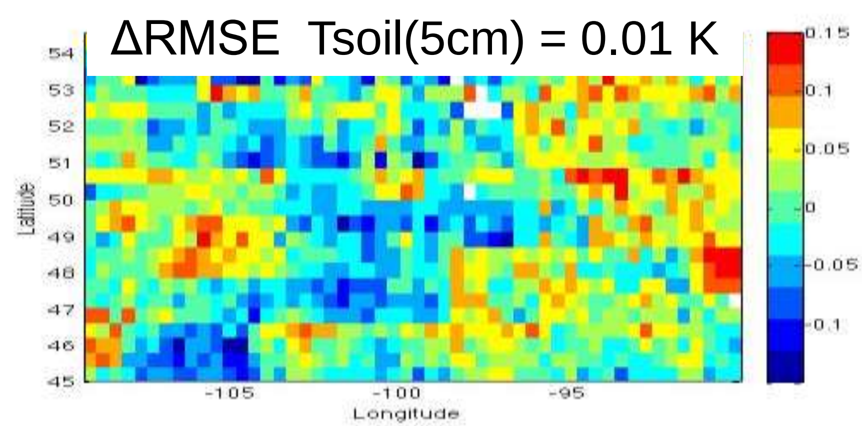
OL = Open loop (no assimilation)
DA = Assimilation of synthetic F/T obs.
ΔRMSE = RMSE(OL) – RMSE(FT)



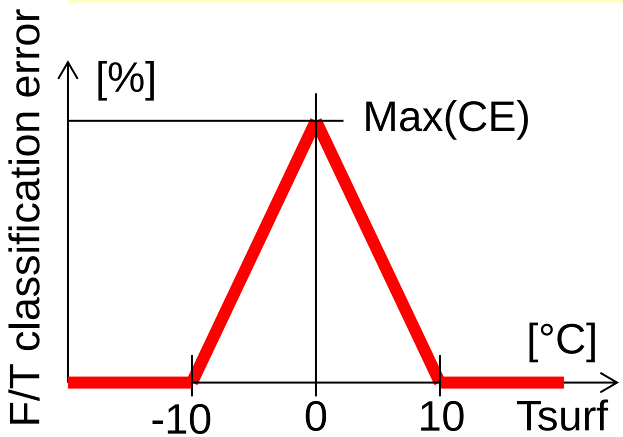
	OL RMSE* [K]	ΔRMSE* [K]				
		Max. classification error [%]				
		0	5	10	20	30
Tskin	3.08	0.21	0.19	0.18	0.15	0.12
Tsoil	1.97	0.06	0.05	0.04	0.01	-0.03

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





Minimal improvements with realistic classification errors.



Farhadi et al., 2013, in prep.