CAHMDA-VI, Austin, TX, USA
9 September 2014

Towards Multi-variate Land Data Assimilation in the NASA GEOS-5 System

Rolf Reichle

With contributions from:

C. Draper, L. Farhadi, B. Forman, G. De Lannoy, Q. Liu, and many others

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Outline

Introduction

• GEOS-5 land data assimilation system

• Multi-source observations and multi-variate analysis

Multi-source observations

• Geostationary skin temperature retrievals (*LST analysis*)

• Active and passive soil moisture retrievals (*soil moisture analysis*)

• Precipitation and soil moisture retrievals (*soil moisture analysis*)

• Snow water equivalent and snow cover fraction retrievals (*snow analysis*)

Multi-variate analysis

• Soil moisture and snow analysis

• Soil moisture and soil temperature analysis

Introduction – GEOS-5

The NASA Goddard Earth Observing System, Version 5 (GEOS-5) is a global Earth system modeling and data assimilation framework.

GEOS-5 is being developed to support NASA's Earth science research, including data analysis, observing system modeling and design, climate and weather prediction, and basic research.

GEOS-5 is used to generate the MERRA reanalysis.

GEOS-5 includes a land data assimilation system component, typically run in “off-line” (land-only) mode.

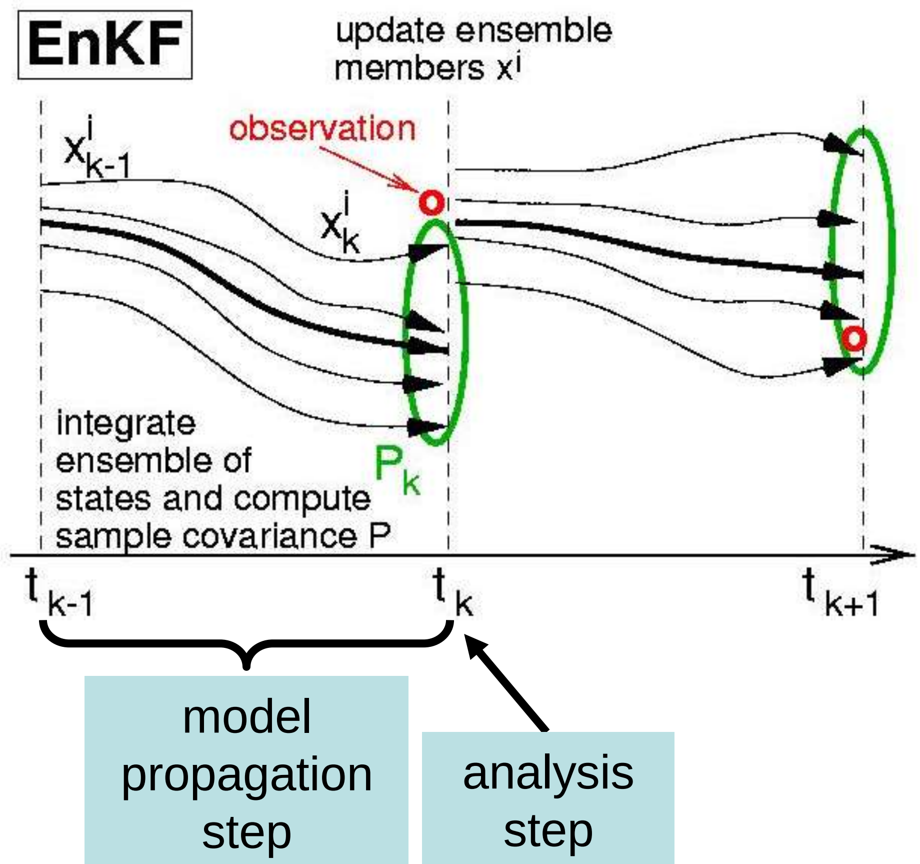
Introduction – GEOS-5 Land Data Assimilation System

Ensemble Kalman filter:

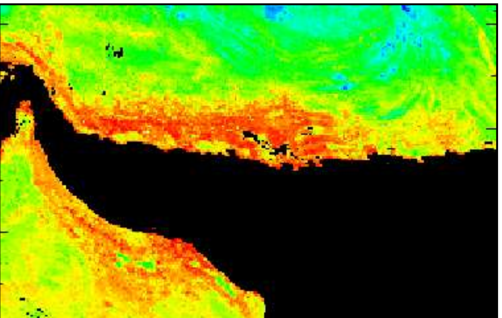
local *("1d") or* ***distributed*** *("3d"), where 3d includes spatial extrapolation, interpolation, and disaggregation of assimilated observations*

GEOS-5 Catchment land surface model

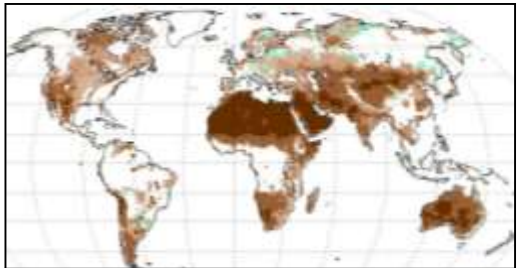
Uncertainty estimation is at the heart of the ensemble-based approach.



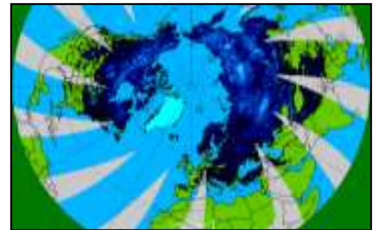
Introduction



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



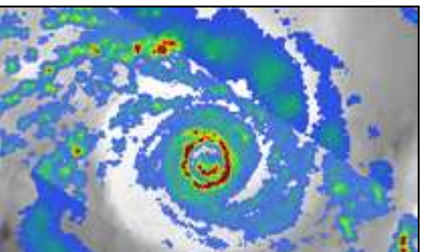
Surface soil moisture (SMMR, TRMM, AMSR-E, ASCAT, SMOS, SMAP)



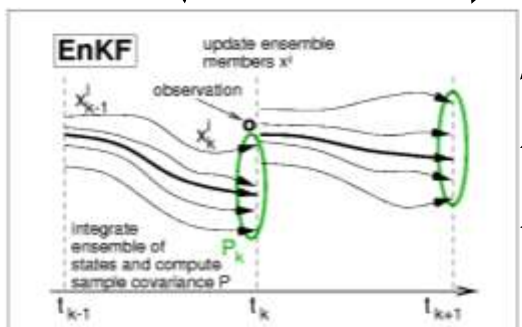
Snow water equivalent (AMSR-E, SSM/I, SCLP)

Snow cover fraction (MODIS, VIIRS)

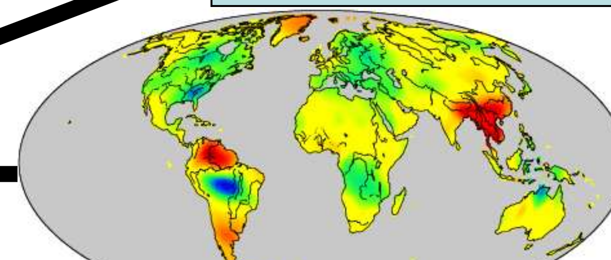
Water surface elevation (SWOT)



Precipitation (TRMM, GPM)

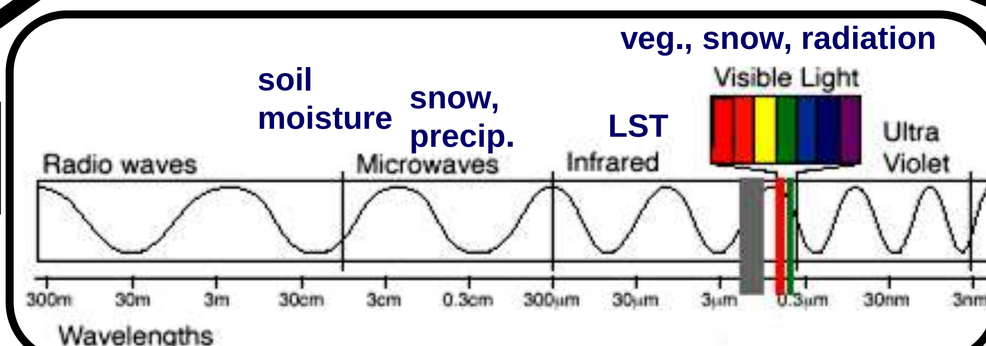


Land data assimilation system



Terrestrial water storage (GRACE)

Radiation (CERES, CLARREO)



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

Introduction

Session title: "*Utilization of **Multi-source** Observations*"

Sensors and assimilated observations:

Which types of observations are assimilated?

Where do they come from?

Presentation title: "*Towards **Multi-variate** Land Assimilation…*"

Geophysical (control) variables:

Which model variables are updated in the analysis?

Introduction

Update equation at the heart of the land assimilation system:

Analysis Increments = Gain * Innovations

or

$\Delta x = K * (y - h(x))$

"O-F residuals"

h = obs. operator

x = control variables

→ ***multi-variate***

y = observations

→ ***multi-source***

Introduction

Early land data assimilation projects typically used a **single observation type** in a **uni-variate** analysis, e.g.:

- AMSR-E soil moisture retrievals → soil moisture analysis
- AMSR-E snow water equivalent retrievals → snow analysis
- MODIS skin temperature retrievals → land surface temperature analysis

Towards **multi-source** observations in a **multi-variate** analysis:

1.a.) Same type of observations, but from different sensors

1.b.) Different types of observations

2.a.) Single type of observation, multi-variate analysis

2.b.) Different types of observations, multi-variate analysis

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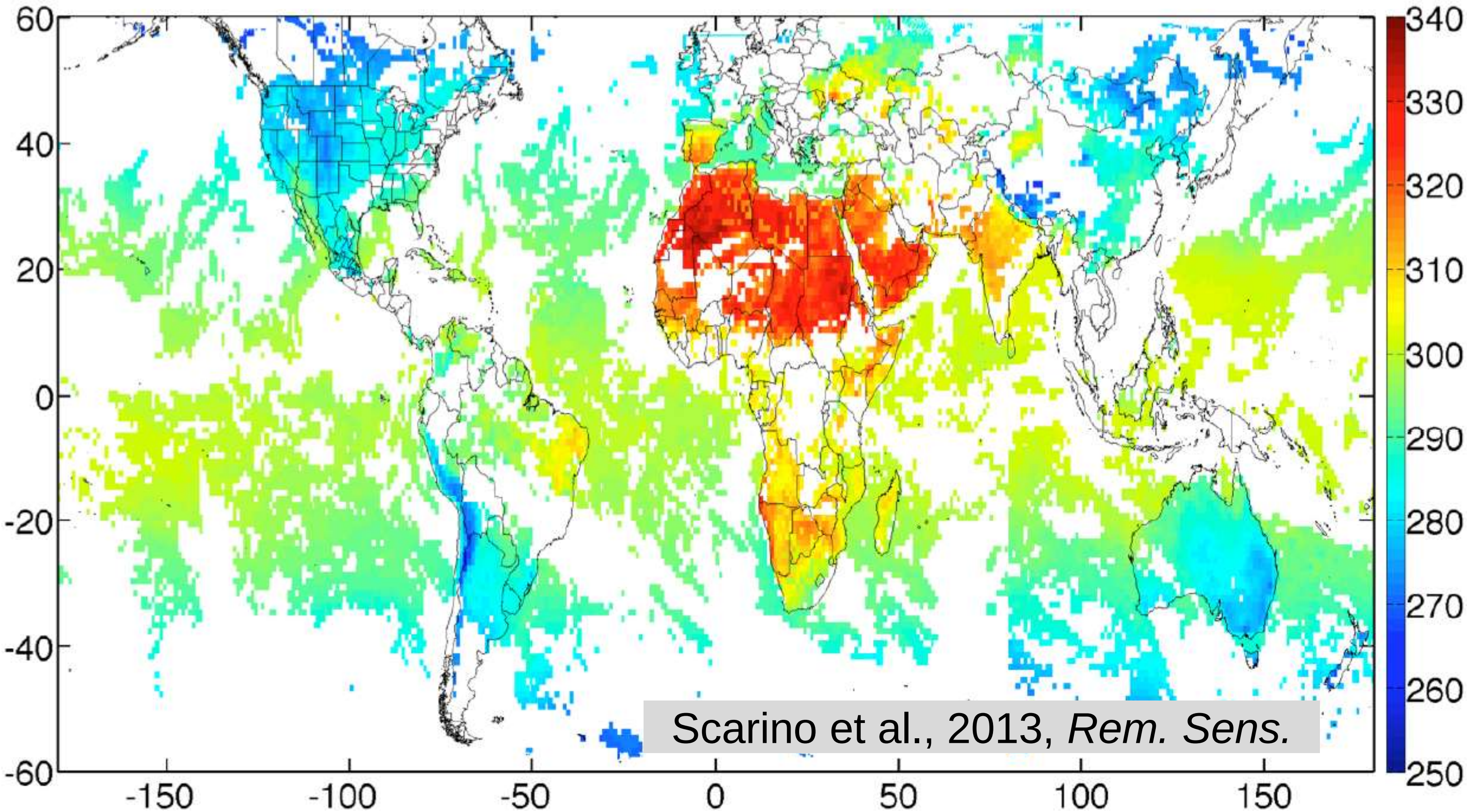
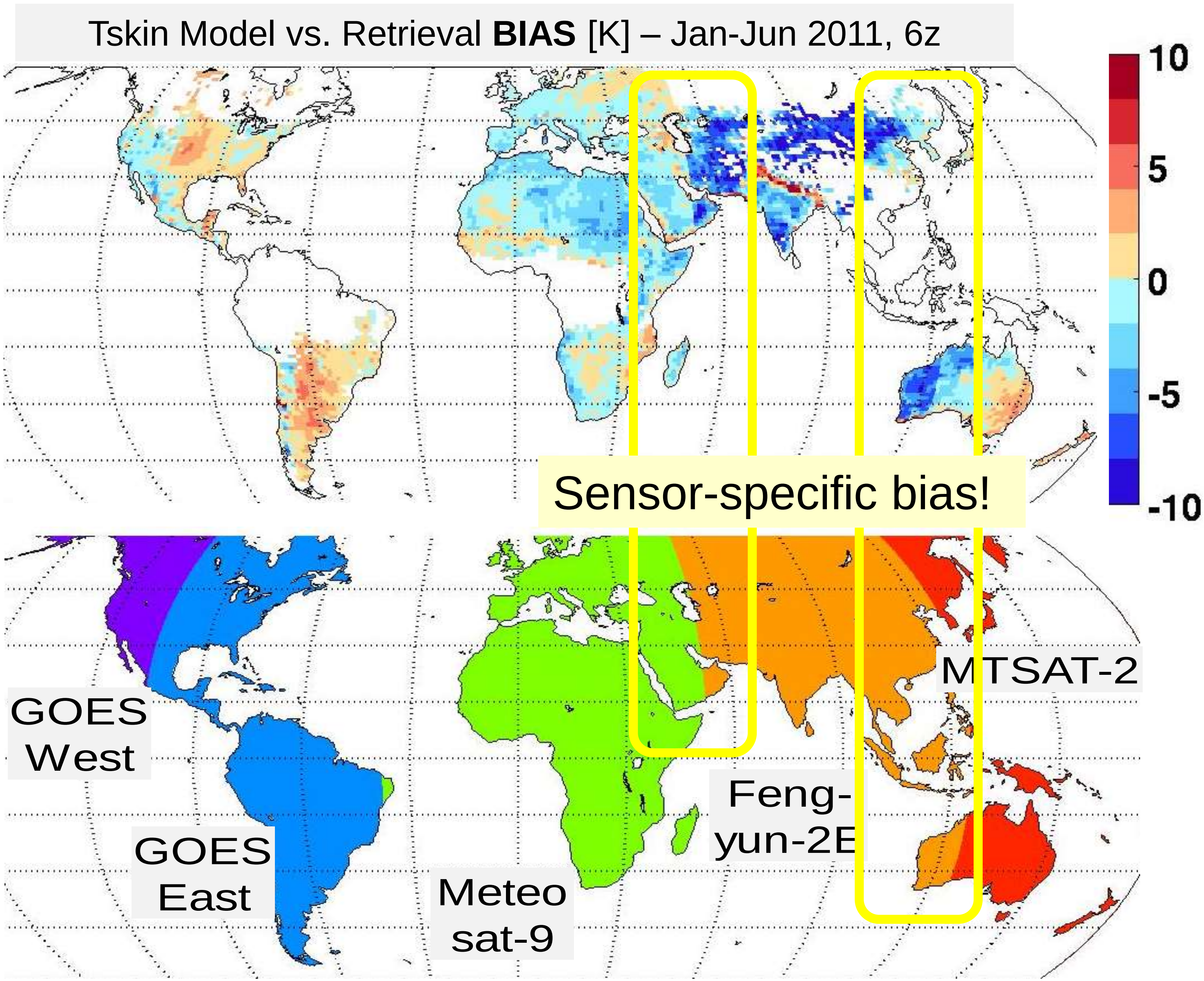
Geostationary Tskin observations

Clear-sky Surface Skin Temperature [K] – 15 May 2012, 12z



Near-real-time, 3-hourly composites of Tskin retrievals from 5 geostationary imagers.
Provided by NASA Langley Research Center (LaRC).

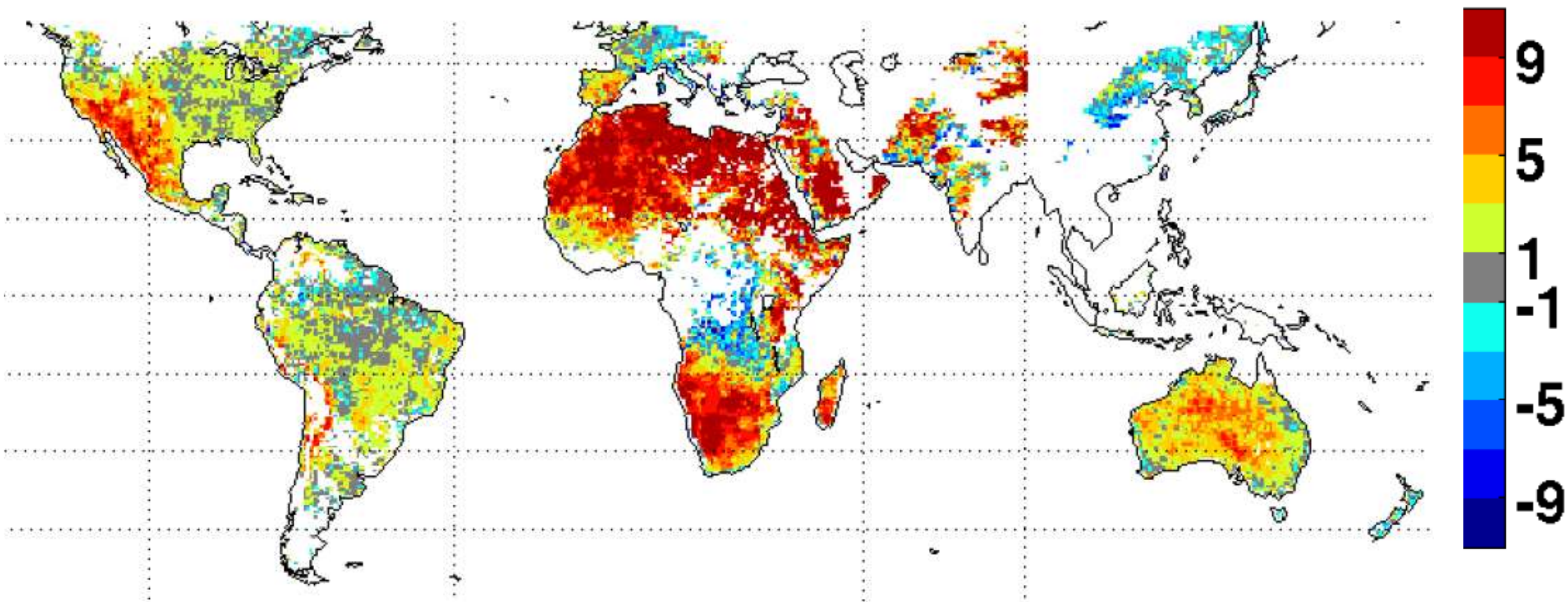
Geostationary Tskin observations



Geostationary Tskin Observations

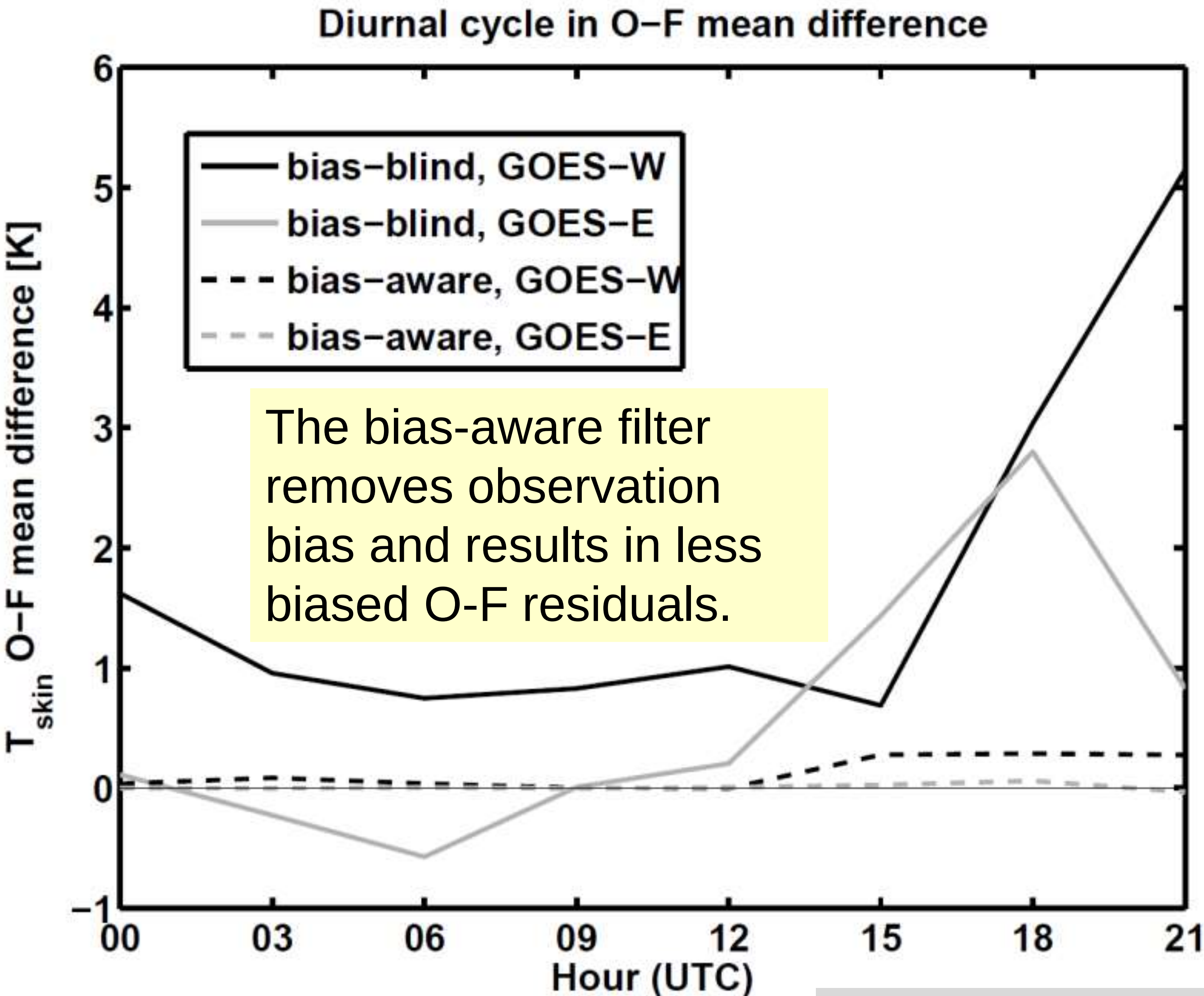
Draper et al. (2014) developed a dynamic *observation* bias estimate based on observations minus forecast (O-F) residuals.

Estimate of Tskin observation bias [K], 1 June 2012



Draper et al., 2014, *JHM*, accepted.

Geostationary Tskin Observations

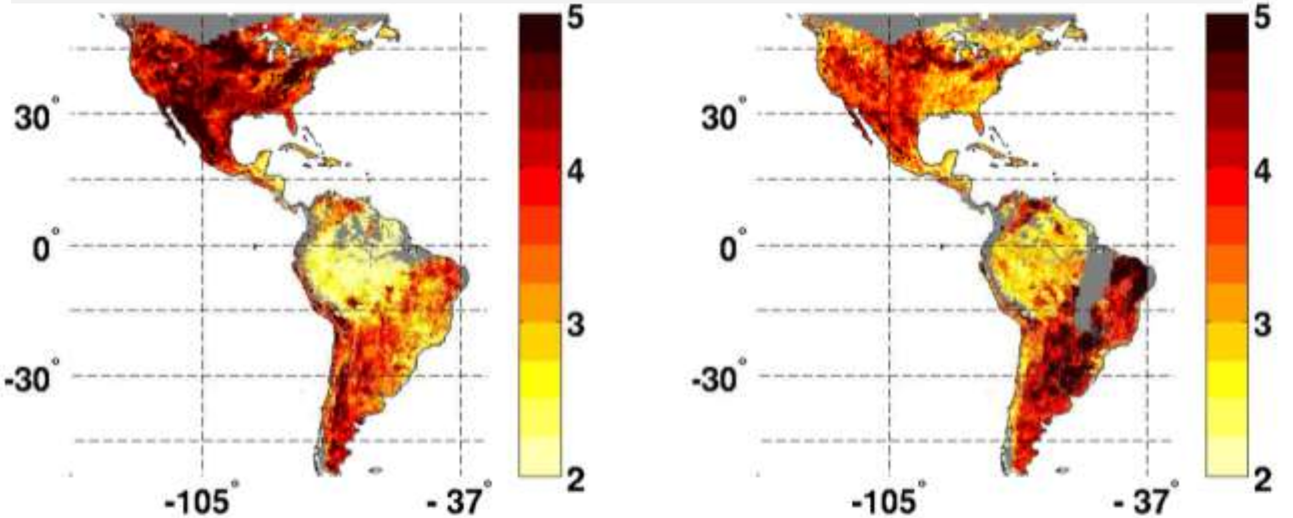


Draper et al., 2014, *JHM*, accepted.

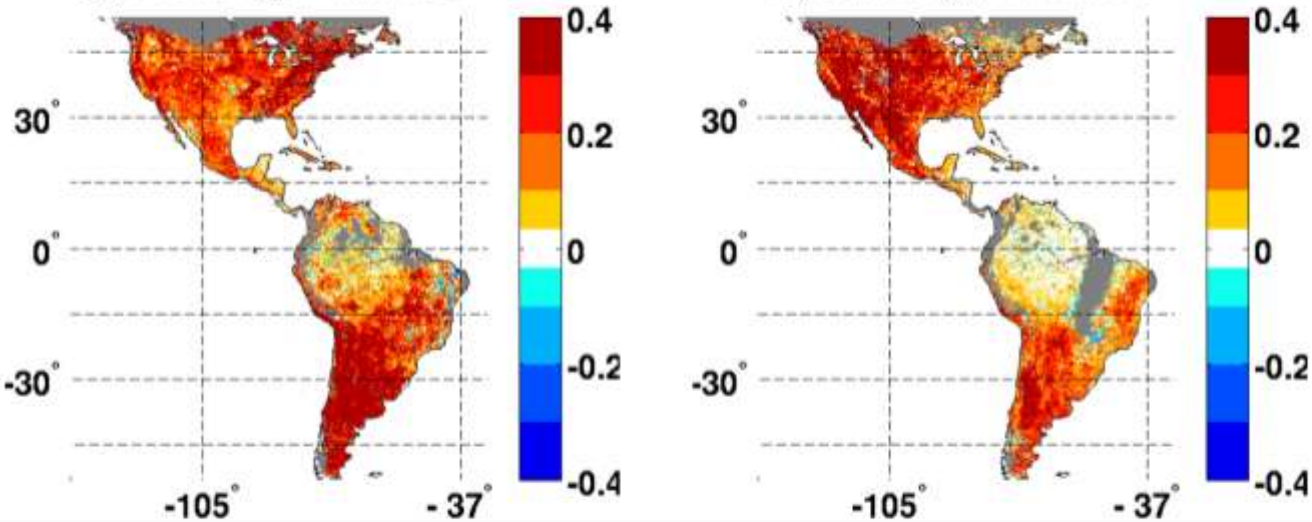
Geostationary Tskin Observations

10:30am LST **1:30pm LST**

ubRMSD without assimilation (open loop)



ubRMSD open loop minus ubRMSD with assimilation



The bias-aware filter yields improved assimilation estimates (when compared to the open loop skill).

Skill is vs. independent satellite observations (MODIS).

Similar results vs. in situ obs (SURFRAD).

Draper et al., 2014
JHM, accepted.

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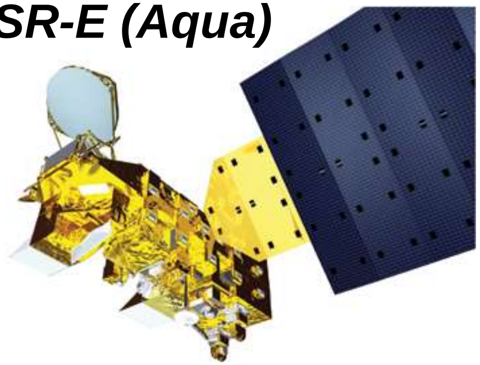
• Soil moisture and soil temperature analysis

Satellite Remote Sensing of (Surface) Soil Moisture

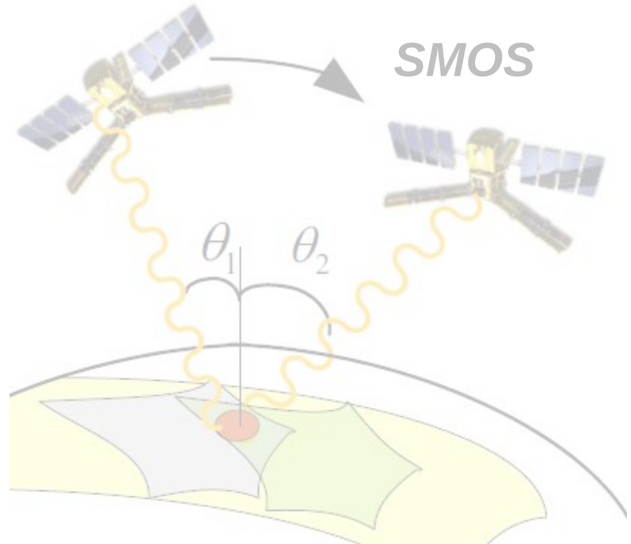
AMSR-E (Aqua)



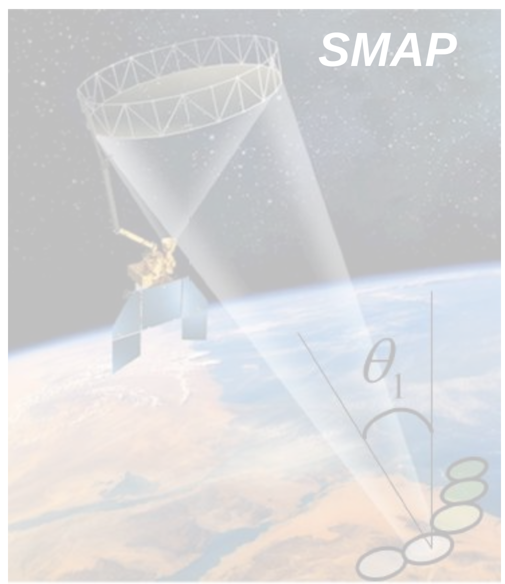
2002-2011
C/X-band passive
40 km resolution

ASCAT (Met-op)

2007-present
C-band active
40 km resolution



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



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

Frequency band	Sensing depth
C/X-band	1 cm
L-band	5 cm

Assimilation of Soil Moisture Retrievals

Skill increases significantly through data assimilation.

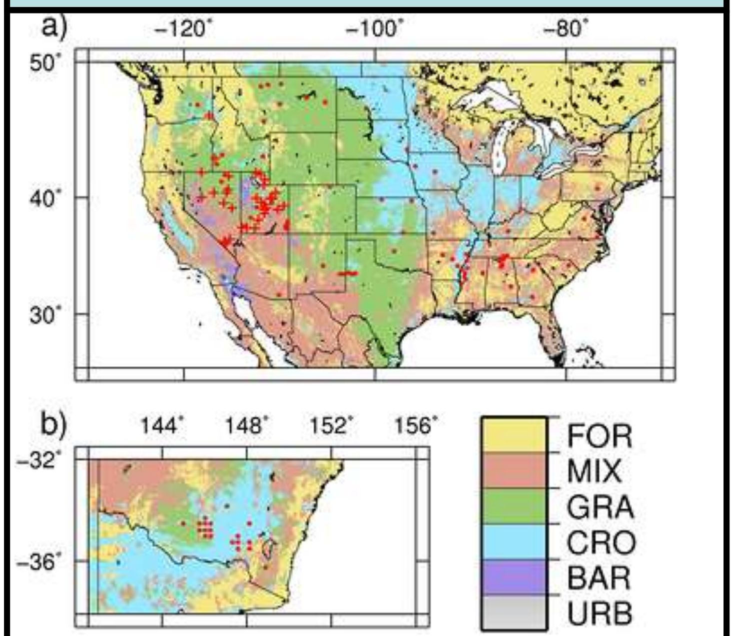
Similar improvements from AMSR-E and ASCAT.

Root-zone *not* observed by satellite. **Improvements** may be critical for applications.

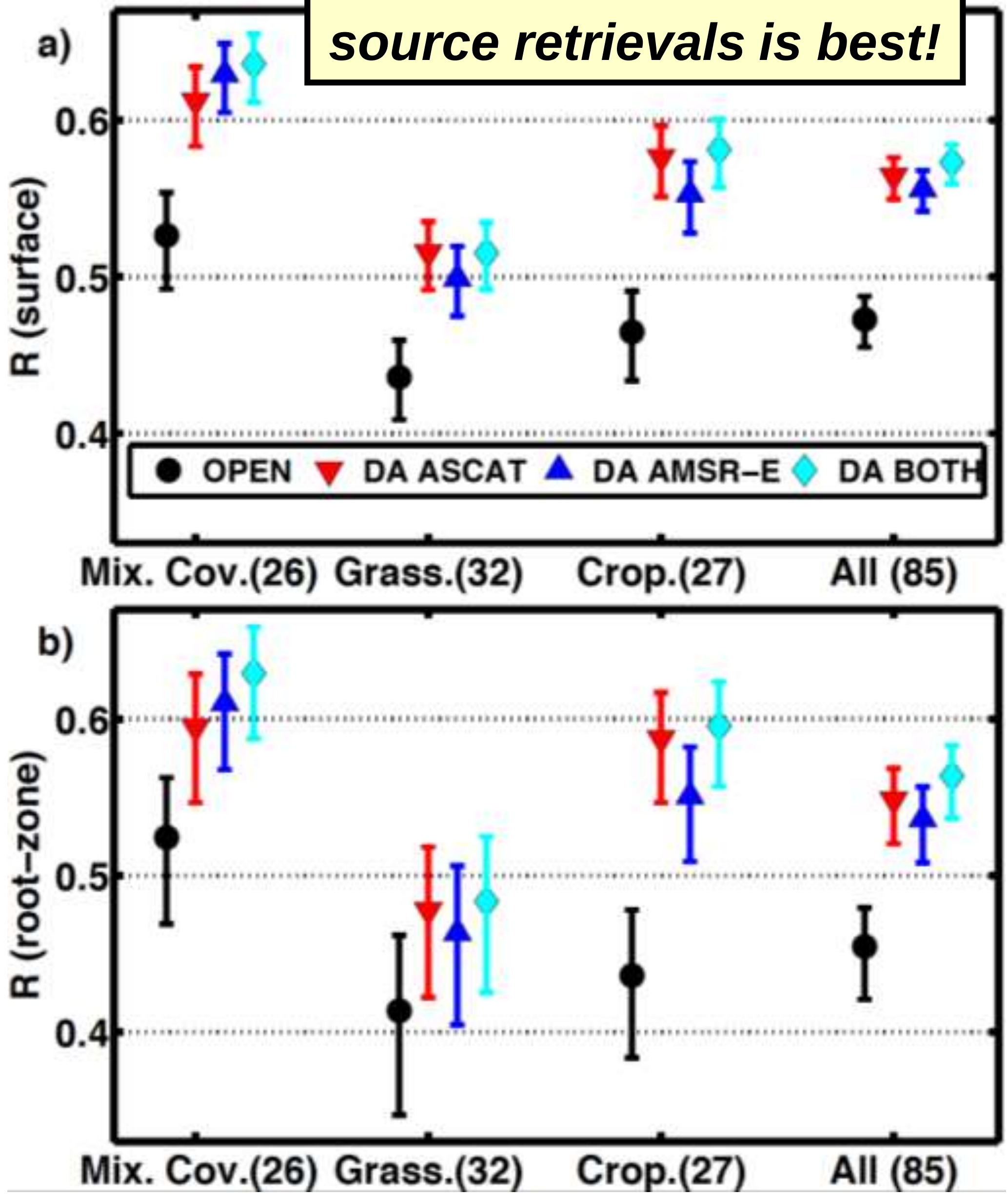
Metric:* *Anom. time series corr. coeff. (R)

Anomalies ≡ mean seasonal cycle removed

Validated with in situ data

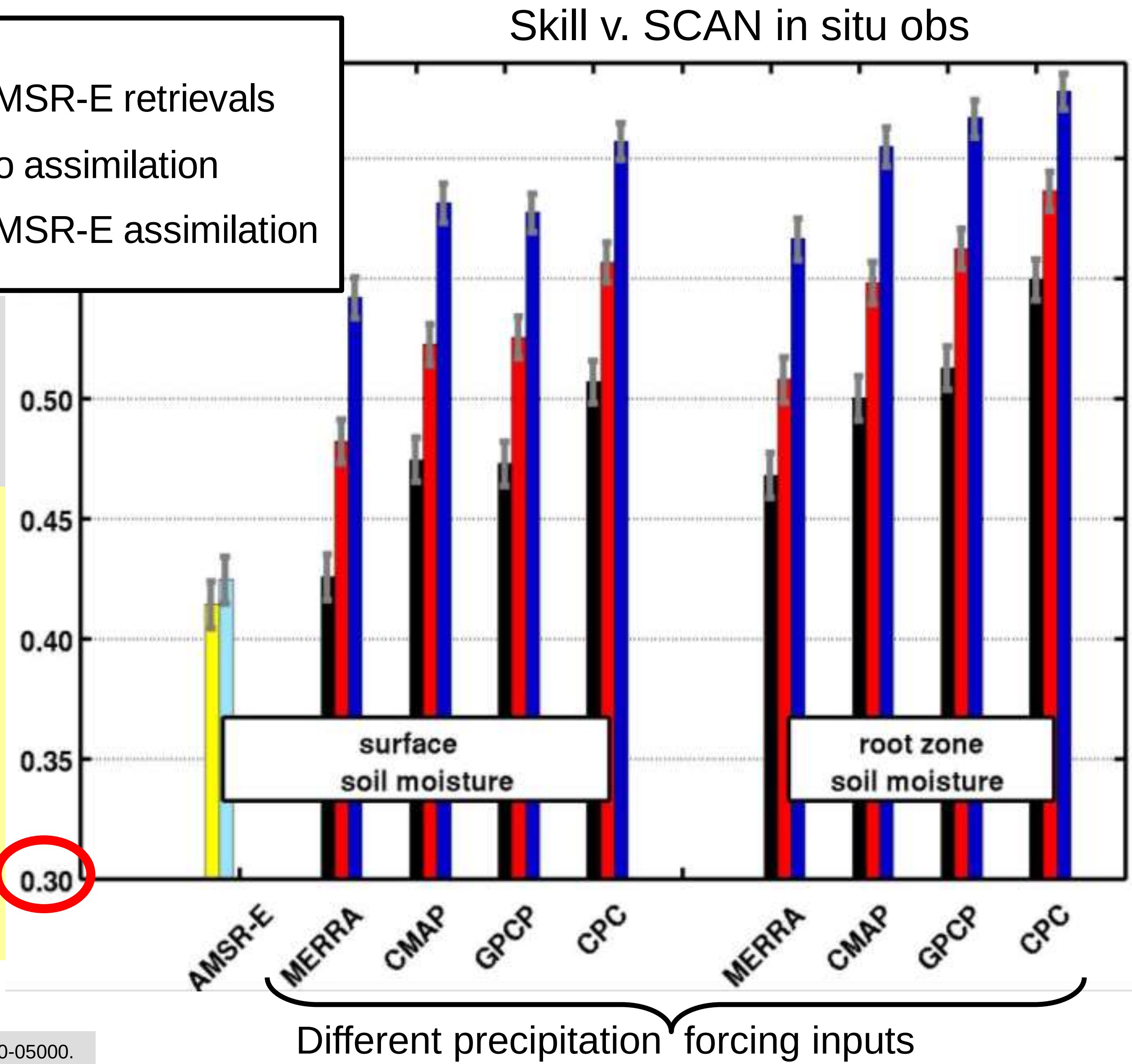


Assimilation of multi-source retrievals is best!



Draper et al. (2012), GRL, doi:10.1029/2011GL050655.

Soil Moisture Assimilation and Precipitation Corrections



Anomalies ≡ mean seasonal cycle removed

Skill metric: Anom. time series corr. coeff. R

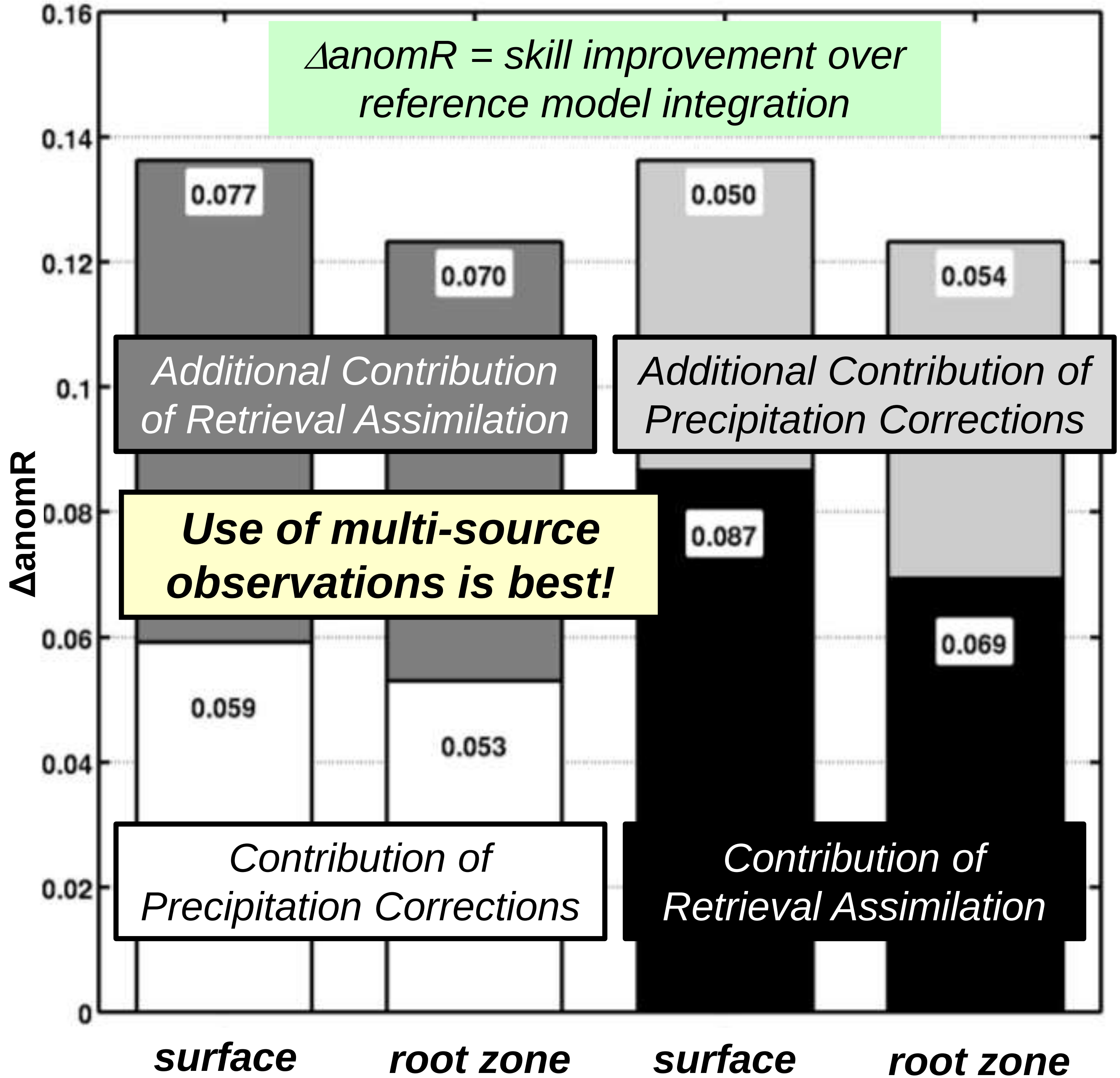
Soil moisture skill increases with

- **precipitation corrections and**
- **assimilation of surface soil moisture retrievals.**

Improved root zone soil moisture!

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

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.

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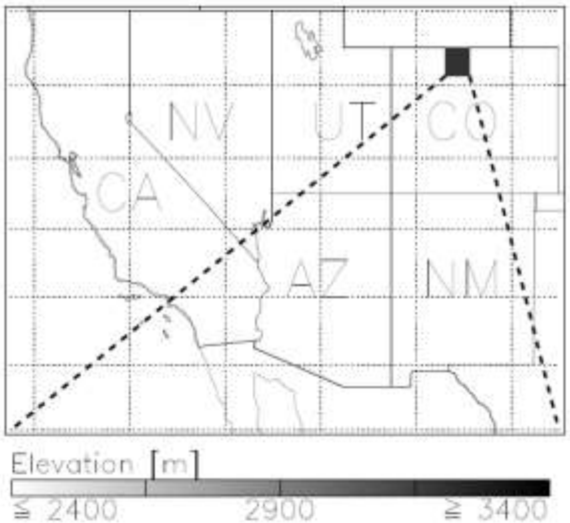
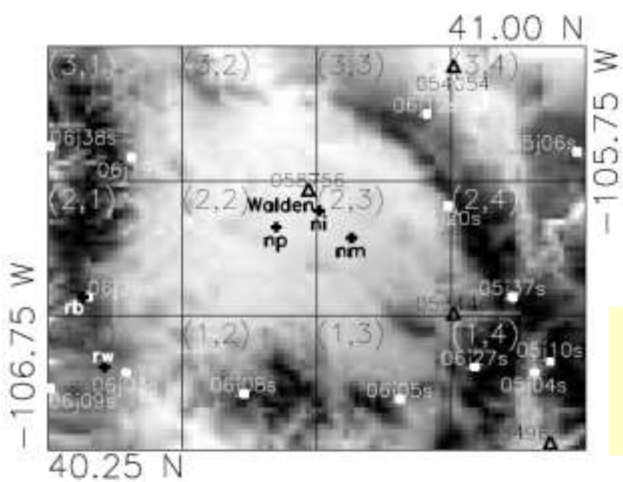
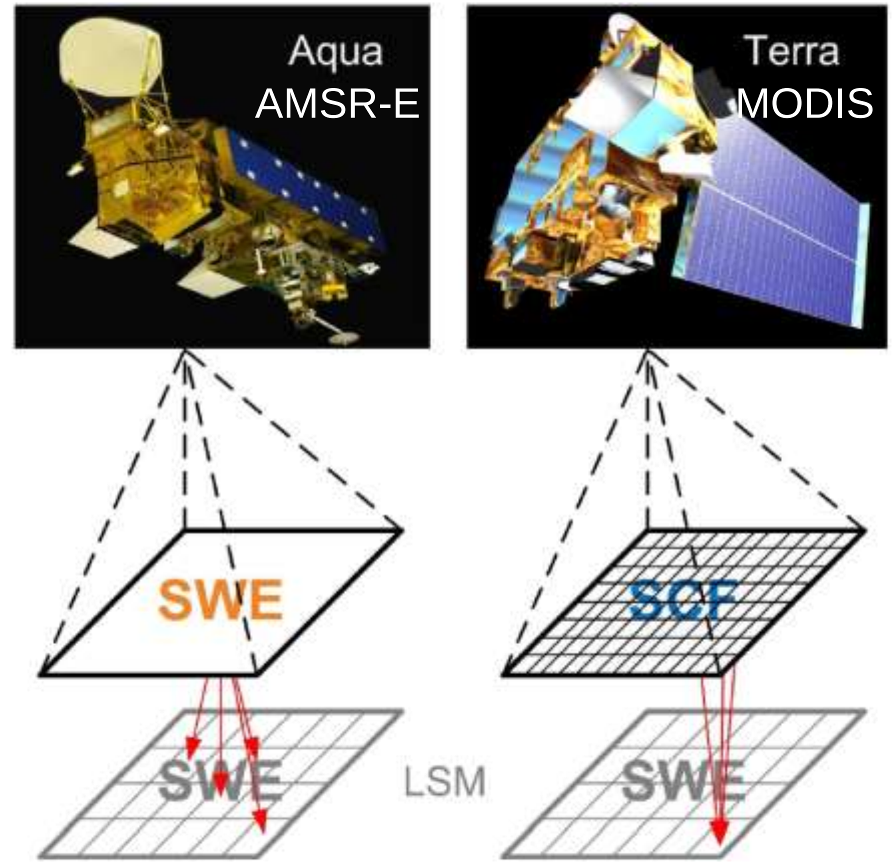
Assimilation of MODIS and AMSR-E Snow Observations

Noah land surface model
(1 km resolution)
100 km X 75 km domain
in northern Colorado



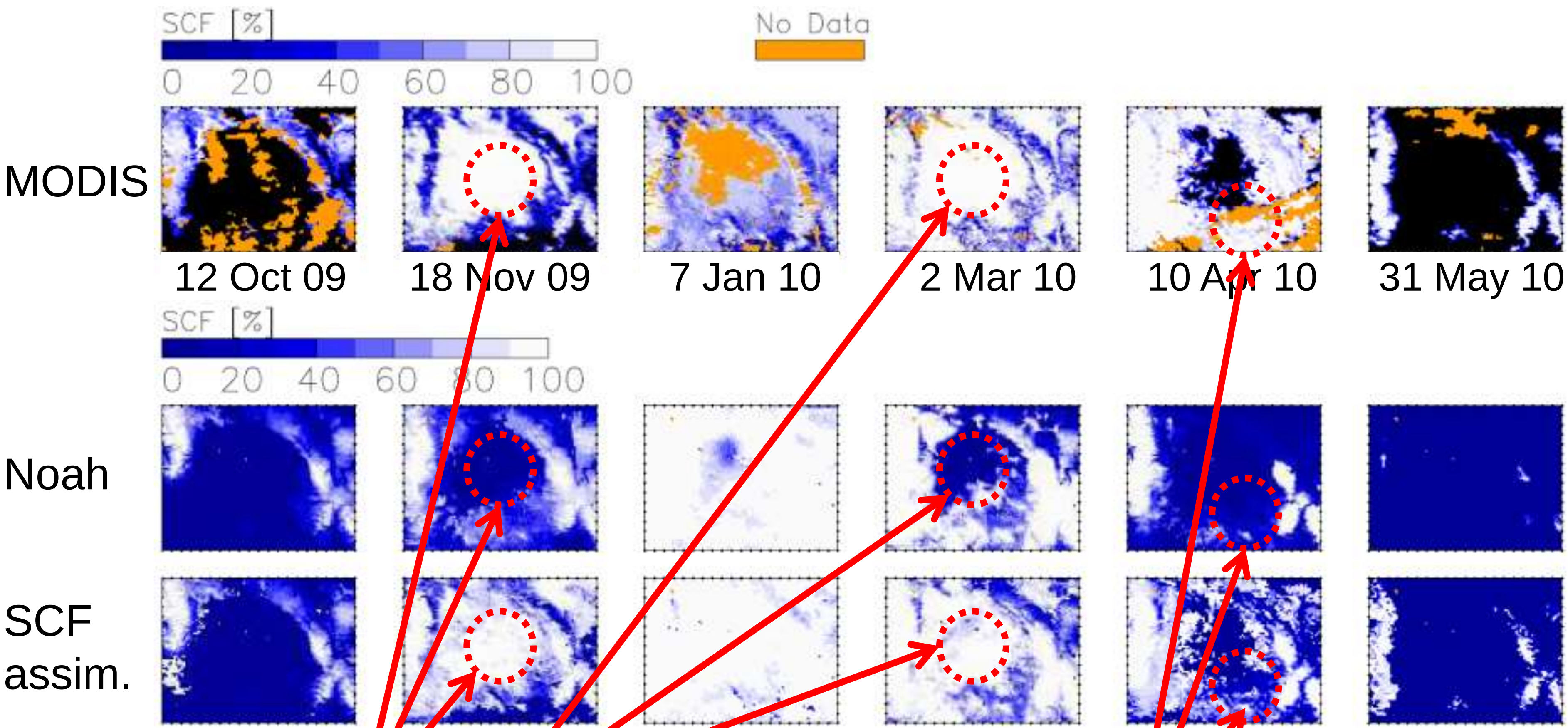




Multi-scale assimilation of
- AMSR-E snow water equivalent (SWE) and
- MODIS snow cover fraction (SCF).

Validation against in situ obs from COOP (Δ) and Snotel (▪) sites for 2002-2010.

Assimilation of MODIS Snow Cover Fraction (SCF)



MODIS SCF successfully adds missing snow,

… except sometimes during melt season.

MODIS SCF also improves timing of onset of snow season (not shown).

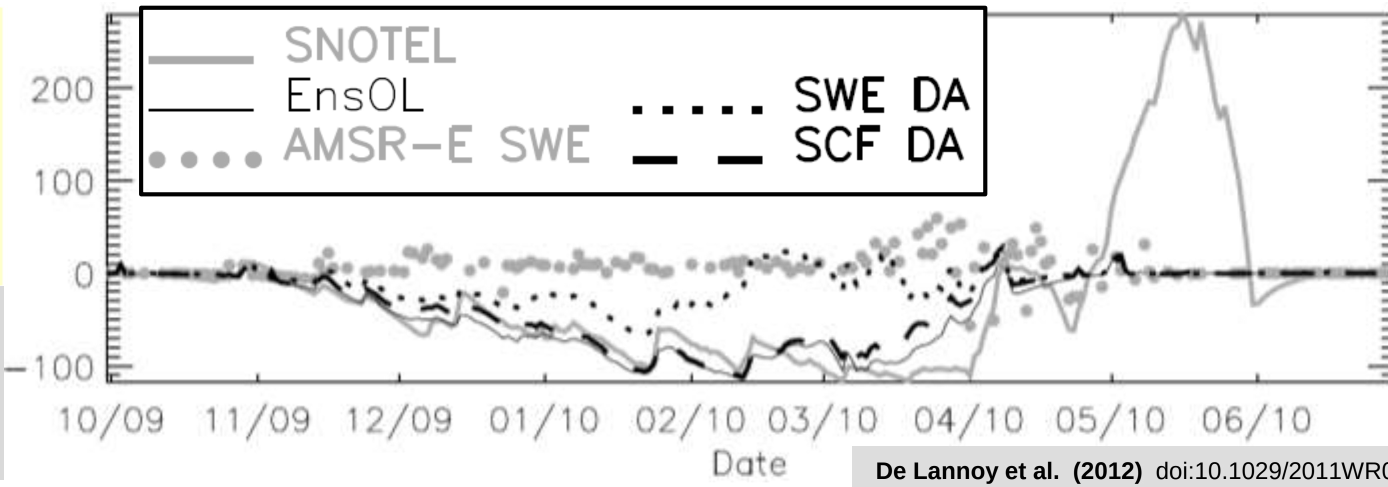
De Lannoy et al. (2012) doi:10.1029/2011WR010588.

Assimilation of AMSR-E Snow Water Equivalent (SWE)

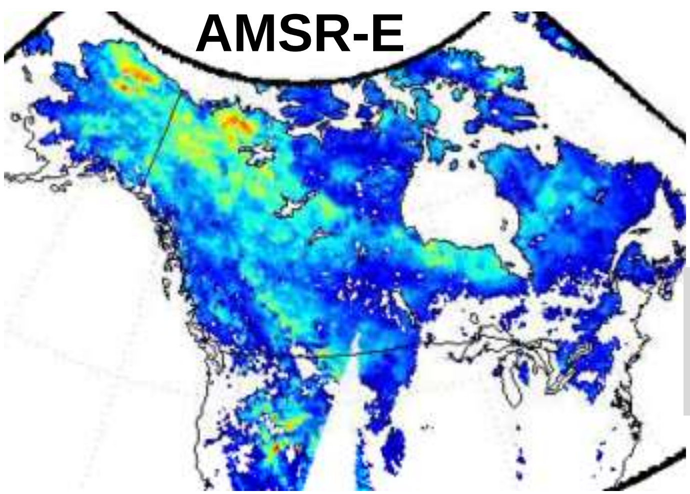
Assimilation of AMSR-E SWE *retrievals* did **not** help.

See presentation by Sujay Kumar (Wed am)

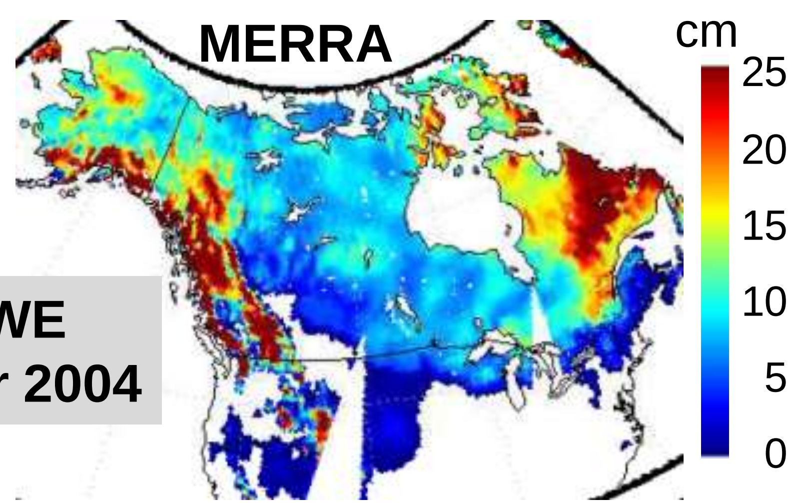
SWE anomalies (40.38N, 106.66W)



De Lannoy et al. (2012) doi:10.1029/2011WR010588.



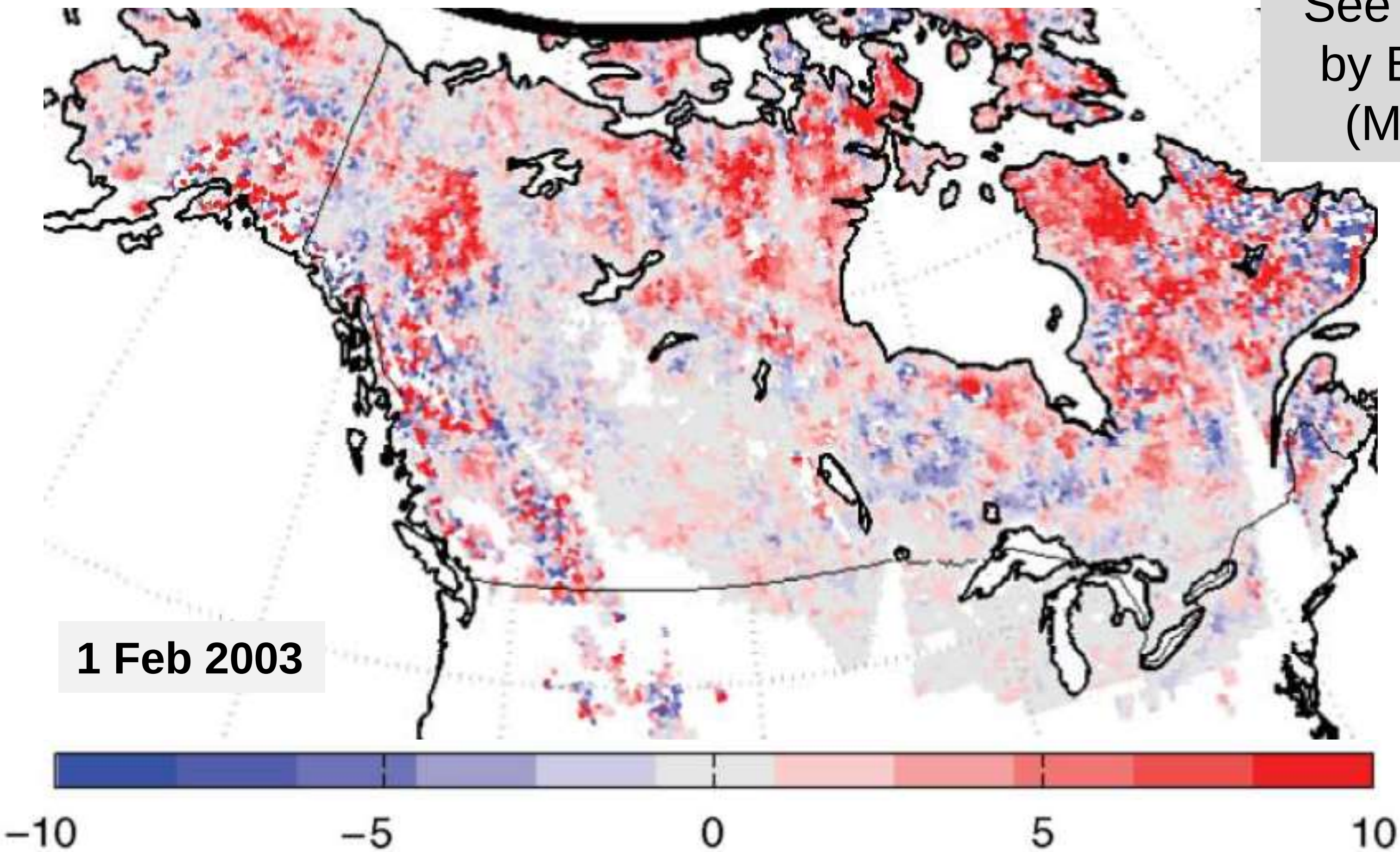
SWE
1 Mar 2004



- AMSR-E SWE retrievals and MERRA differ **a lot**.
- Working on observation operator based on machine learning.

Assimilation of AMSR-E Snow Water Equivalent (SWE)

See presentation by Bart Forman (Monday pm)



Kalman gain for SWE vs. ΔTb [mm/K]

where ΔTb ≡ TbV(18 GHz) – TbV(36 GHz)

Forman and Reichle (2014) doi:10.1109/JSTARS.2014.2325780.

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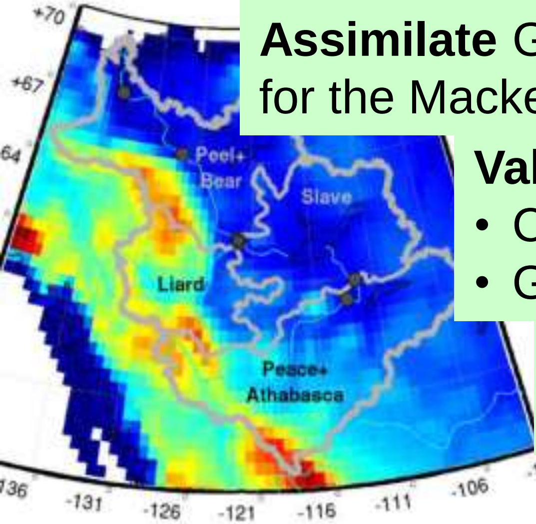
Assimilation of GRACE Terrestrial Water Storage (TWS)

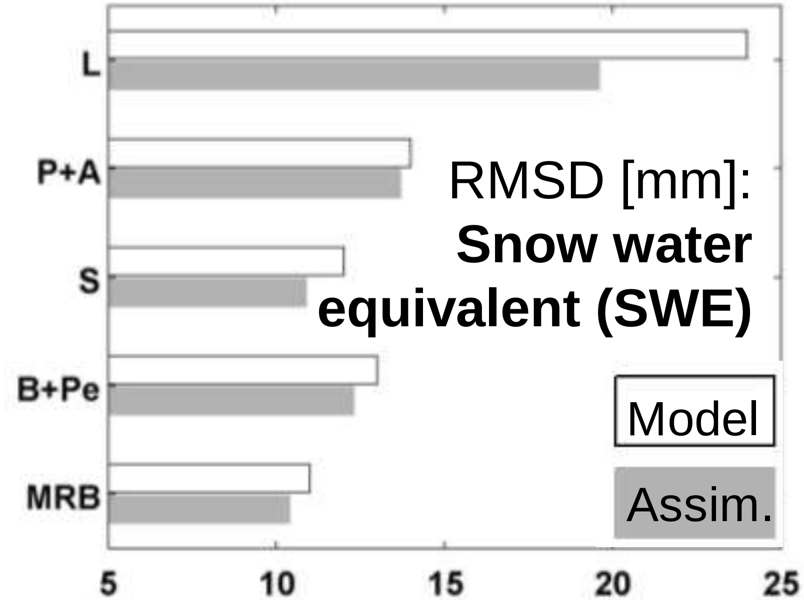


Assimilate GRACE TWS (2002-2009) for the Mackenzie river basin (MRB).

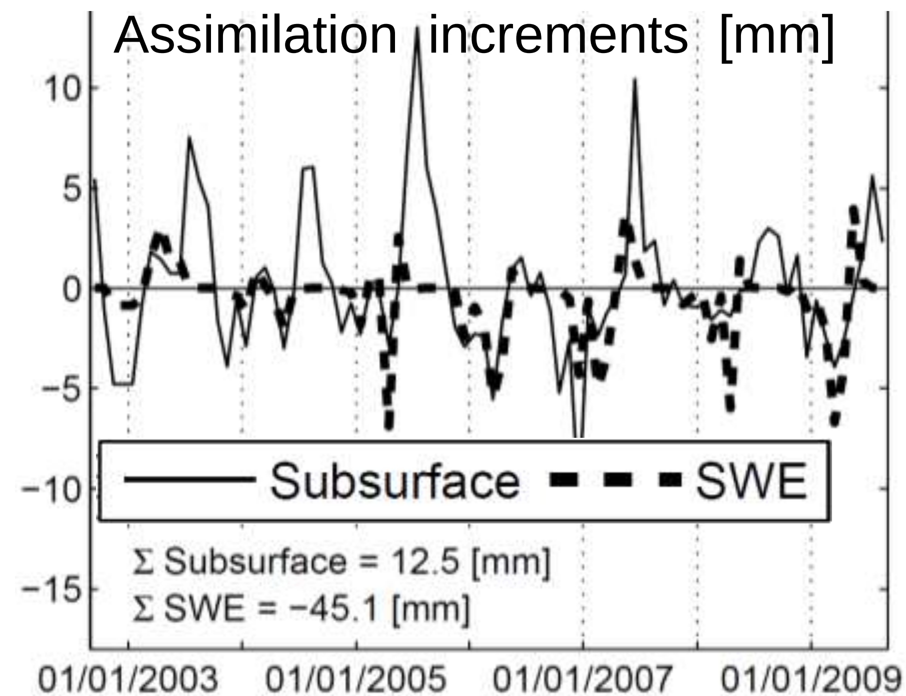
Validate vs.

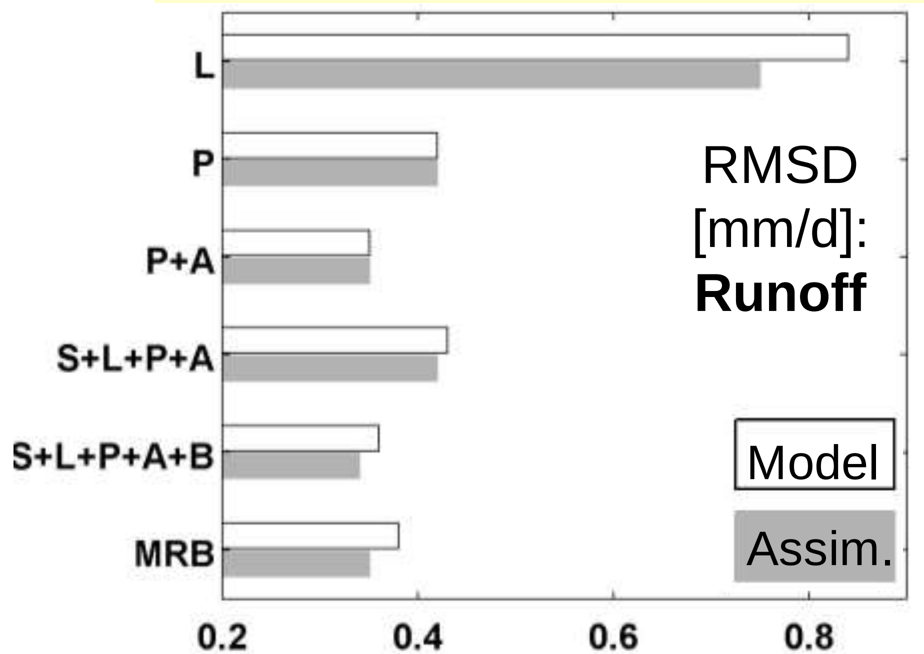
- CMC snow product
- GRDC runoff obs.

Not shown: Trend issues w/ post-glacial rebound.



Assimilation reduces RMSD





Forman et al. ***WRR*** **(2012)** doi:10.1029/2011WR011239.

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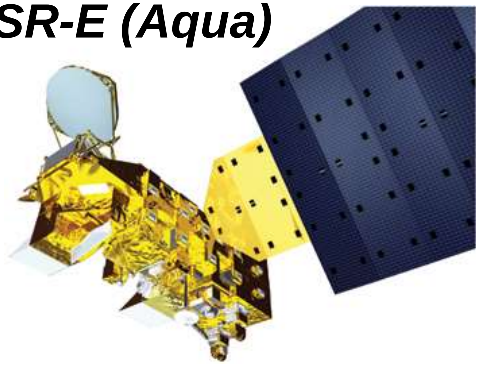
Satellite Remote Sensing of (Surface) Soil Moisture

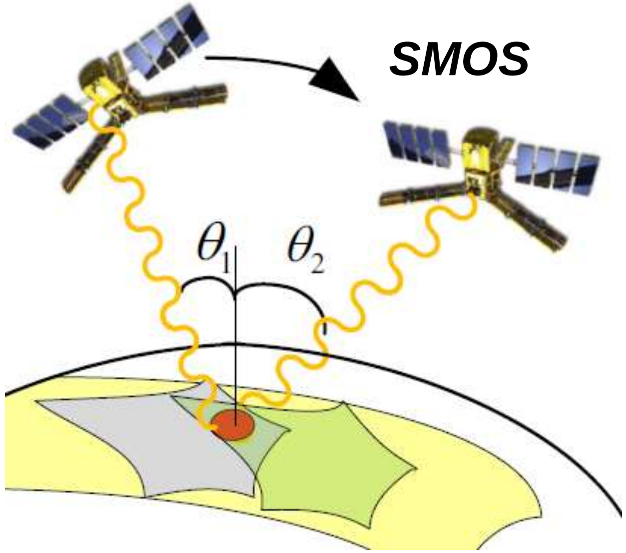
AMSR-E (Aqua)



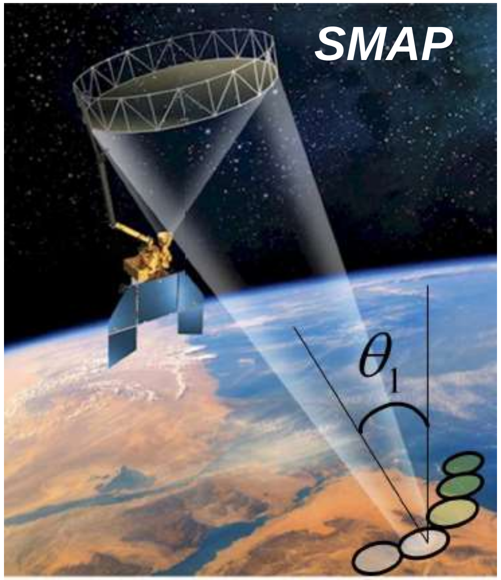
2002-2011
C/X-band passive
40 km resolution

ASCAT (Met-op)

2007-present
C-band active
40 km resolution



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



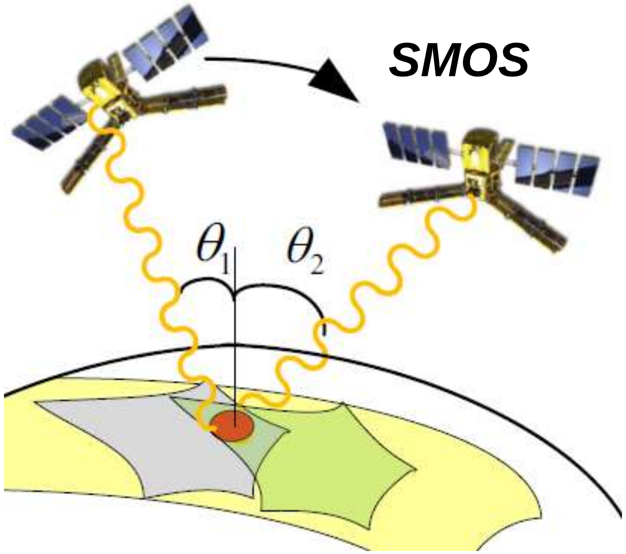
Launch: 2014 (?)
L-band active/passive
3-40 km resolution

Frequency band	Sensing depth
C/X-band	1 cm
L-band	5 cm

Satellite Remote Sensing of (Surface) Soil Moisture

Use SMOS data to prepare for the

SMAP Level 4 Surface and Root Zone Soil Moisture (L4_SM) product.



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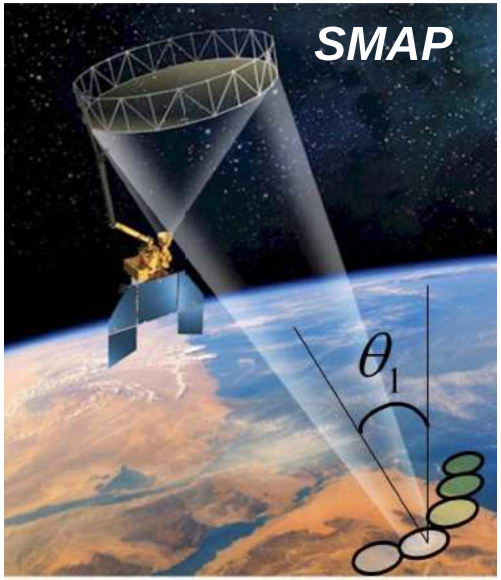

Launch: 2014 (?)
L-band active/passive
3-40 km resolution

Frequency band	Sensing depth
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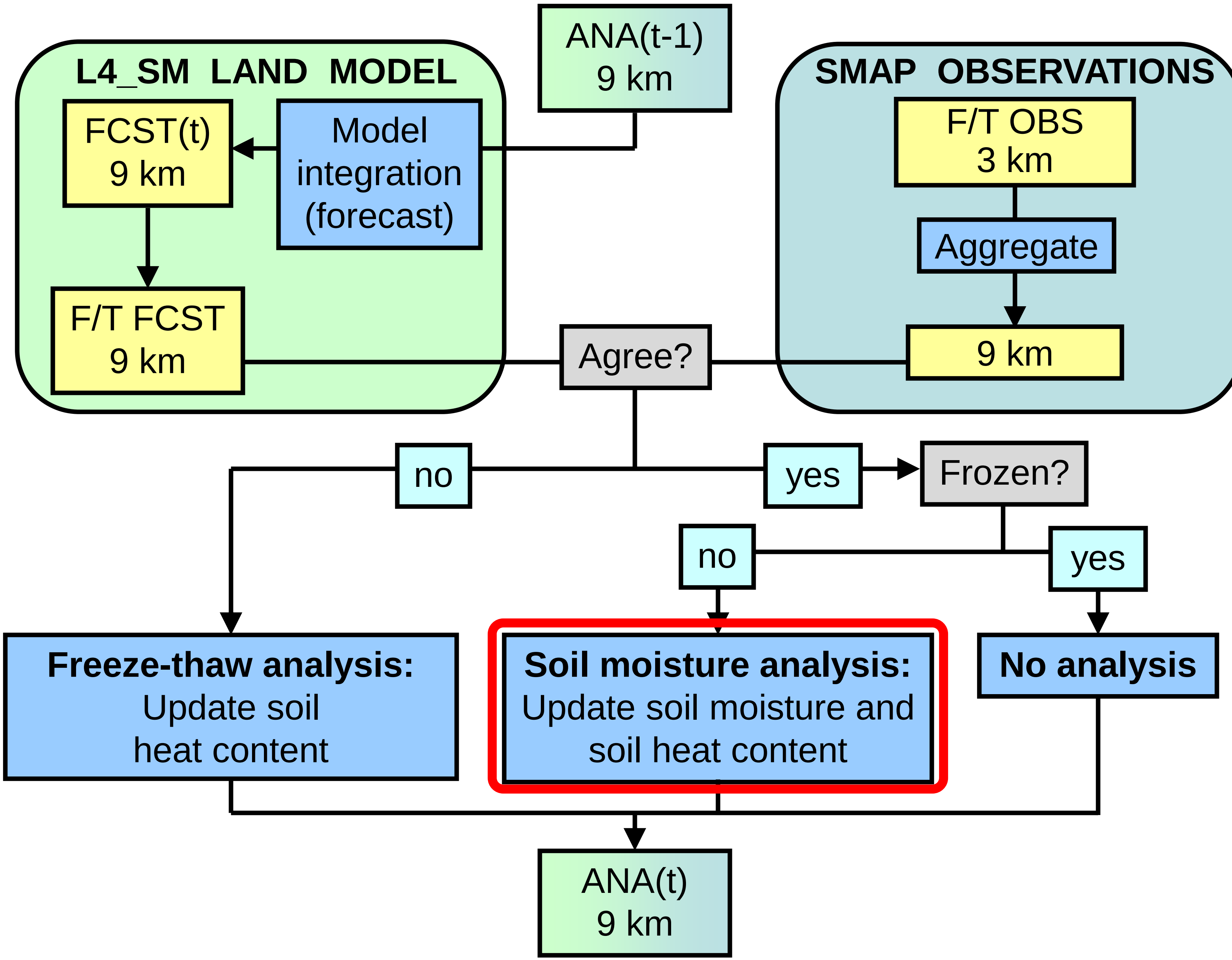
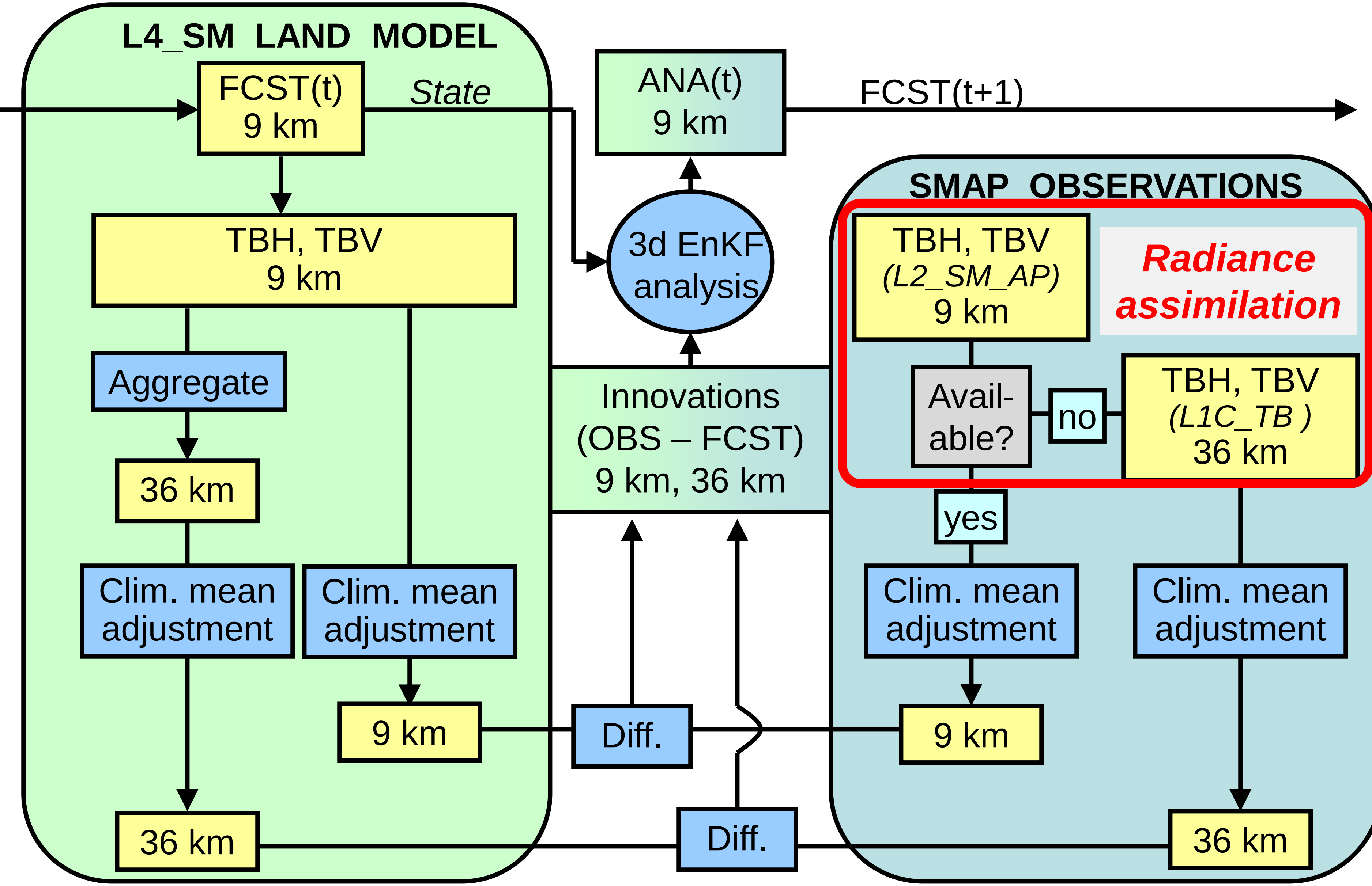
SMAP L4_SM Analysis Overview

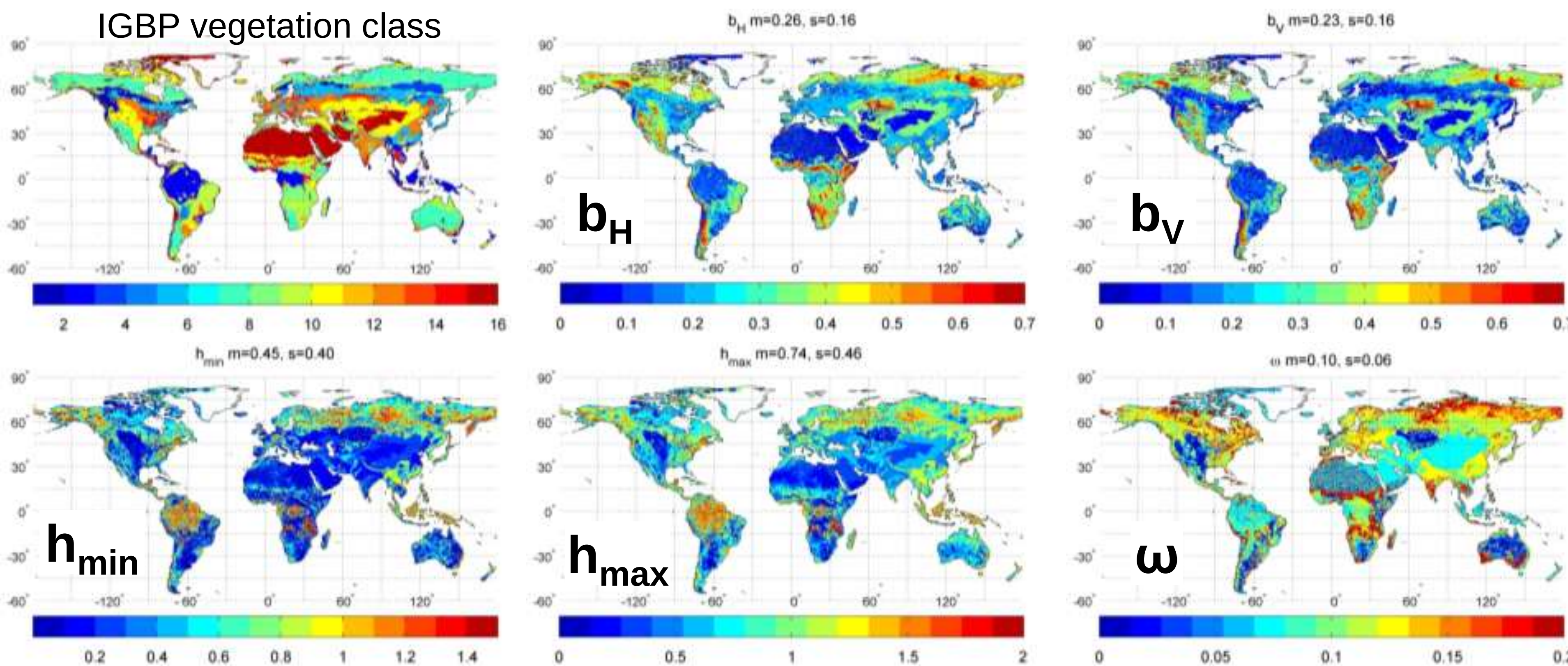


L4_SM Soil Moisture Analysis



L4_SM Radiative Transfer Model Parameters

- **Radiance assim. requires unbiased L-band radiative transfer model.**
- **Locally** optimized to minimize differences in long-term mean and std-dev between Tbs from **SMOS** and **GEOS-5** forward modeling
- 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.

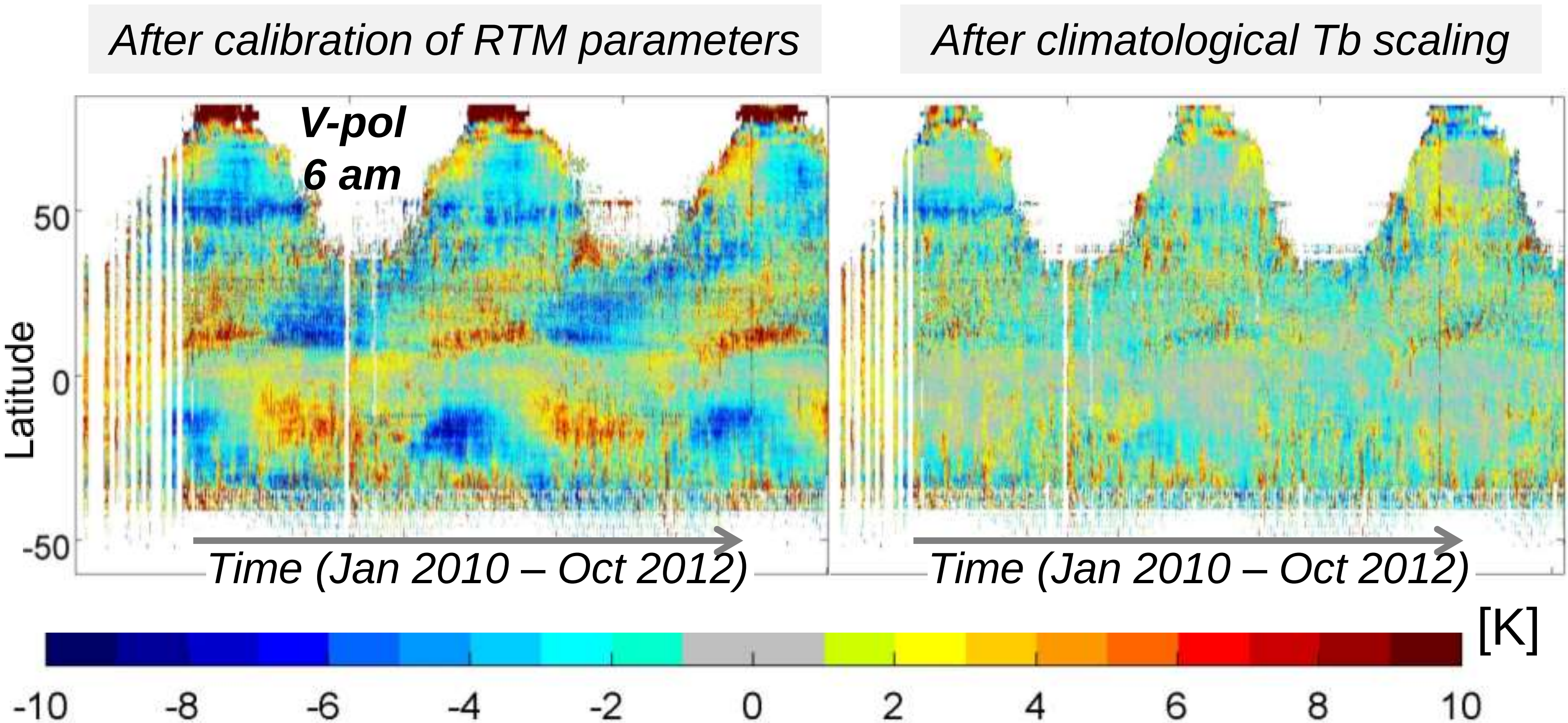


De Lannoy et al., *RSE*, 2014, doi:10.1016/j.rse.2014.03.030

L-band Brightness Temperature: SMOS vs. 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).



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.

Calibration of the Data Assimilation System

Perturbation	Additive (A) or Multiplicative (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/m^2*	*24 h*	*50 km*	*0.5*	*-0.5*	*n/a*
					catdef	srfexc	
Catchment deficit (catdef)	*A*	*0.03 kg/m^2*	*3 h*	*50 km*	*n/a*	*0.0*	
Surface excess (srfexc)	*A*	*0.02 kg/m^2*	*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.

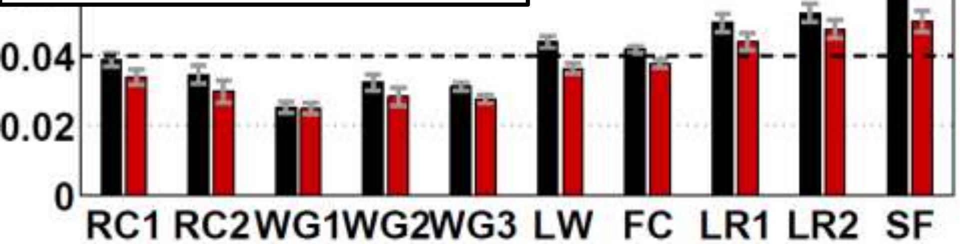
Validation at SMAP Core Validation Sites

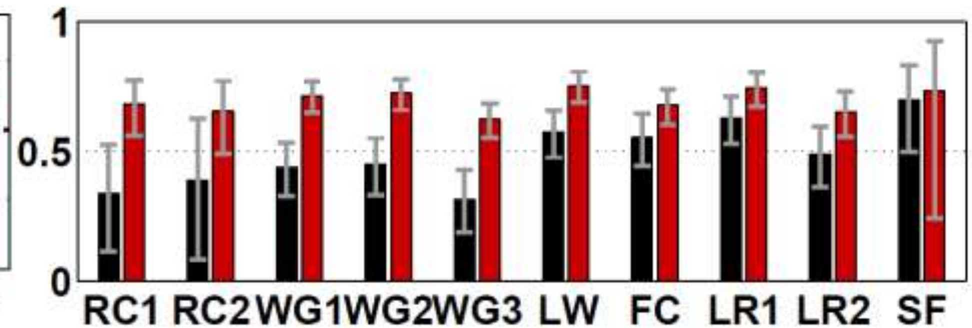
De Lannoy et al., 2014, in preparation.

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

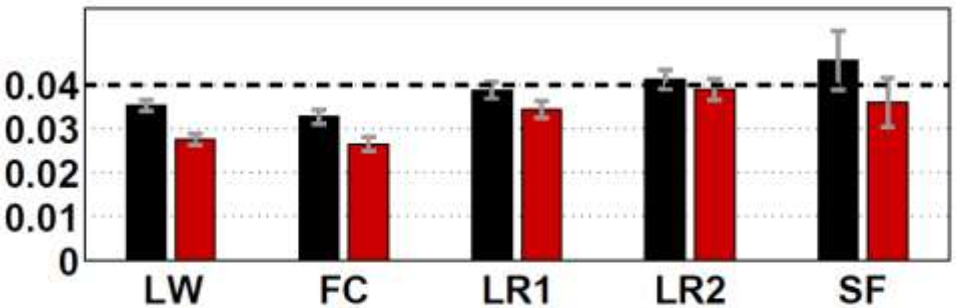
Black: Model
Red: Assimilation

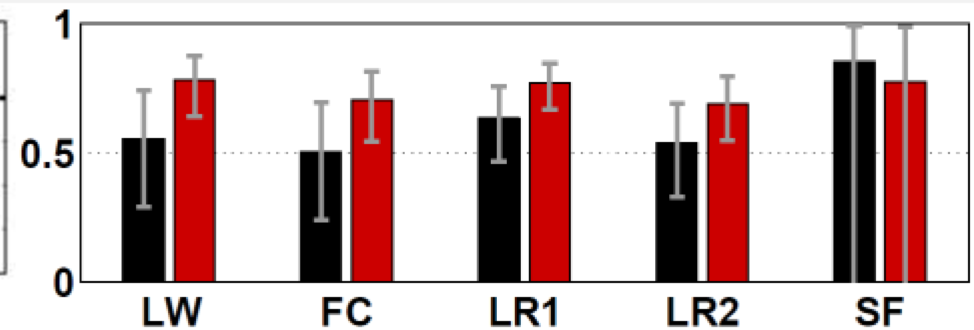
Surface soil moisture [m^3/m^3]



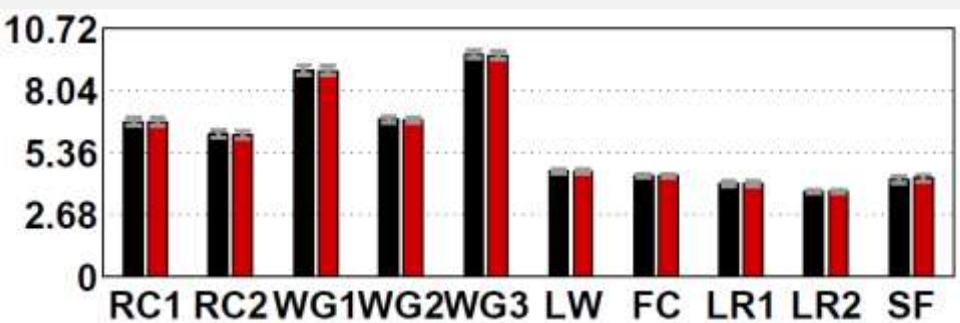


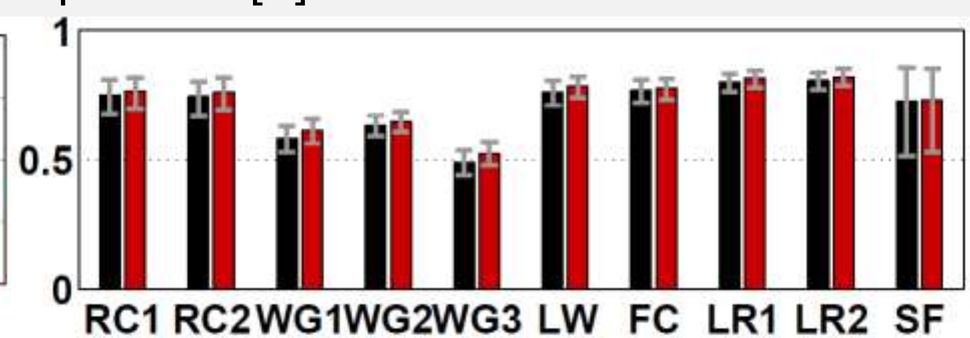
Root zone soil moisture [m^3/m^3]





Surface soil temperature [K]



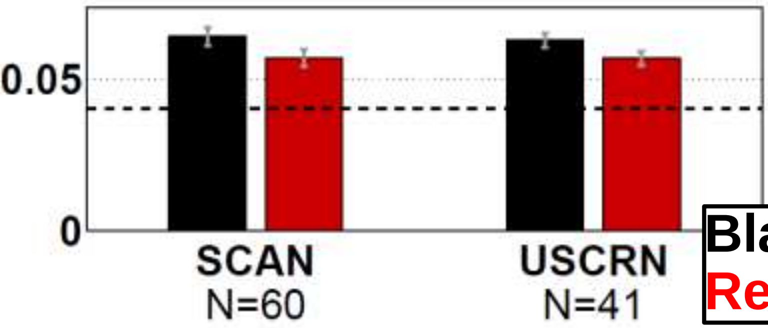


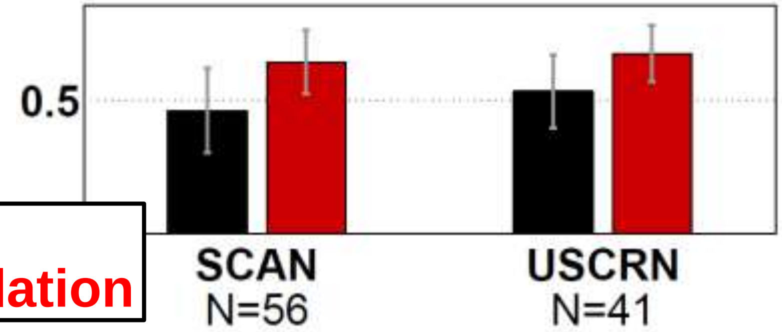
Validation at Sparse Network Sites

De Lannoy et al., 2014, in preparation.

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

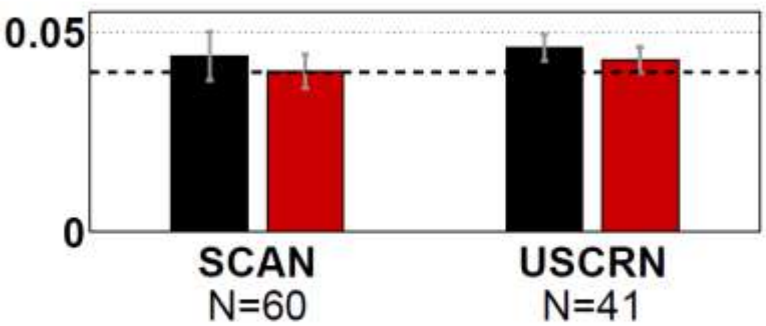
Surface soil moisture [m³/m³]

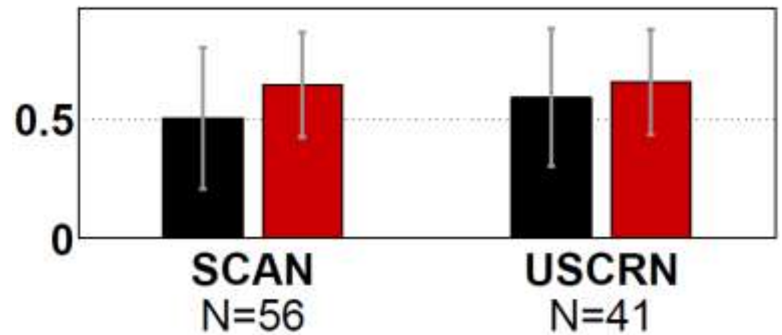




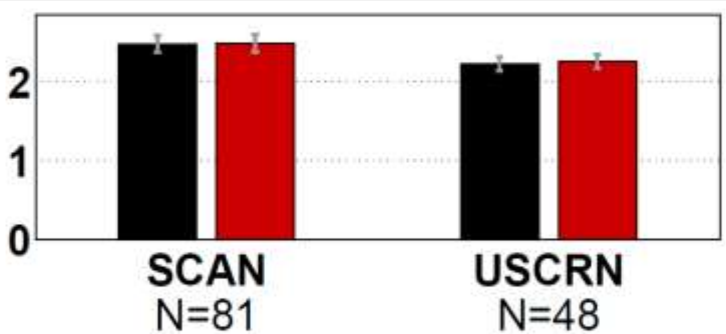
Black: Model
Red: Assimilation

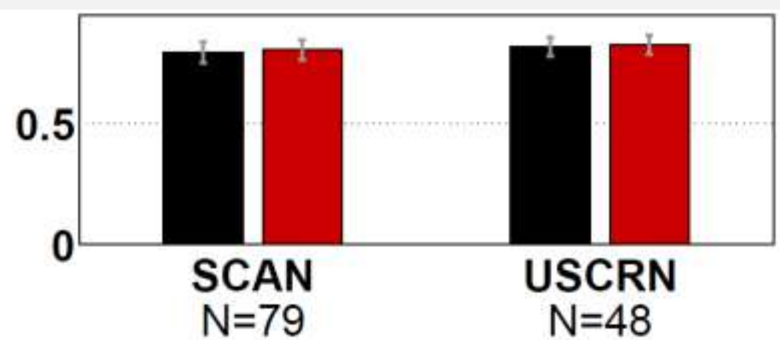
Root zone soil moisture [m³/m³]





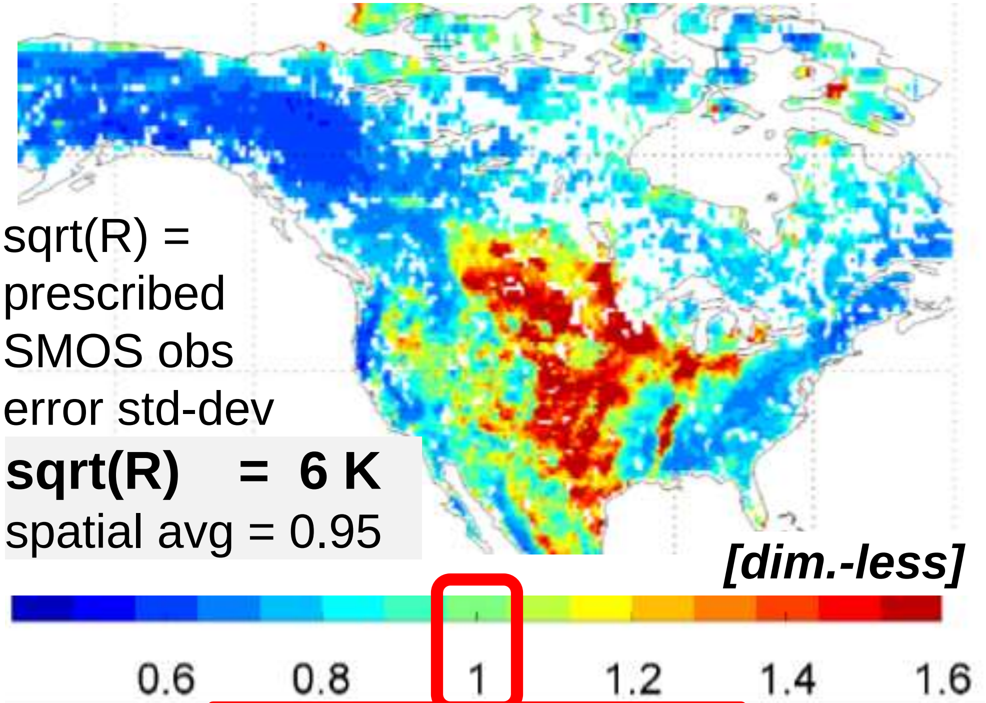
Surface soil temperature [K]





Calibration of the Data Assimilation System

Std-dev of normalized observation-minus-forecast residuals

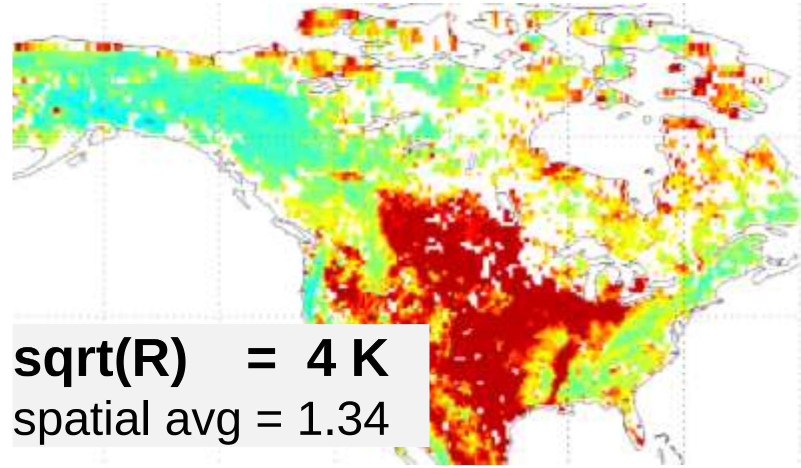


sqrt(R) = prescribed SMOS obs error std-dev

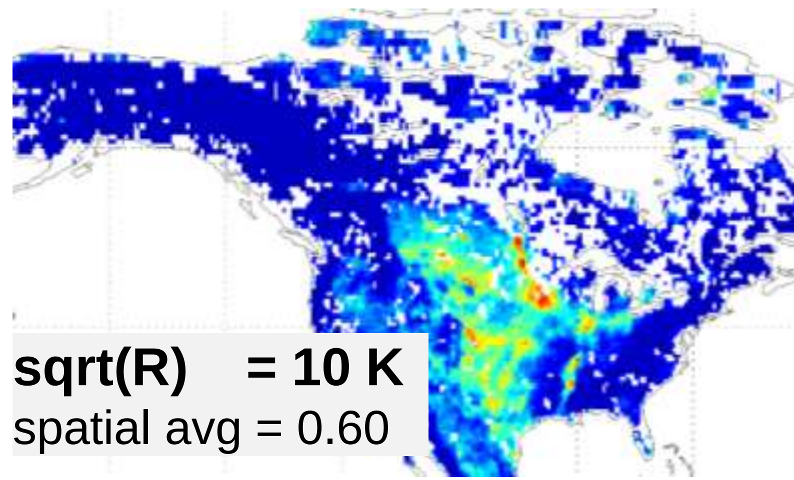
sqrt(R) = 6 K
spatial avg = 0.95

Target value = 1

DA system
← **over**estimates → **under**estimates
actual uncertainty



sqrt(R) = 4 K
spatial avg = 1.34

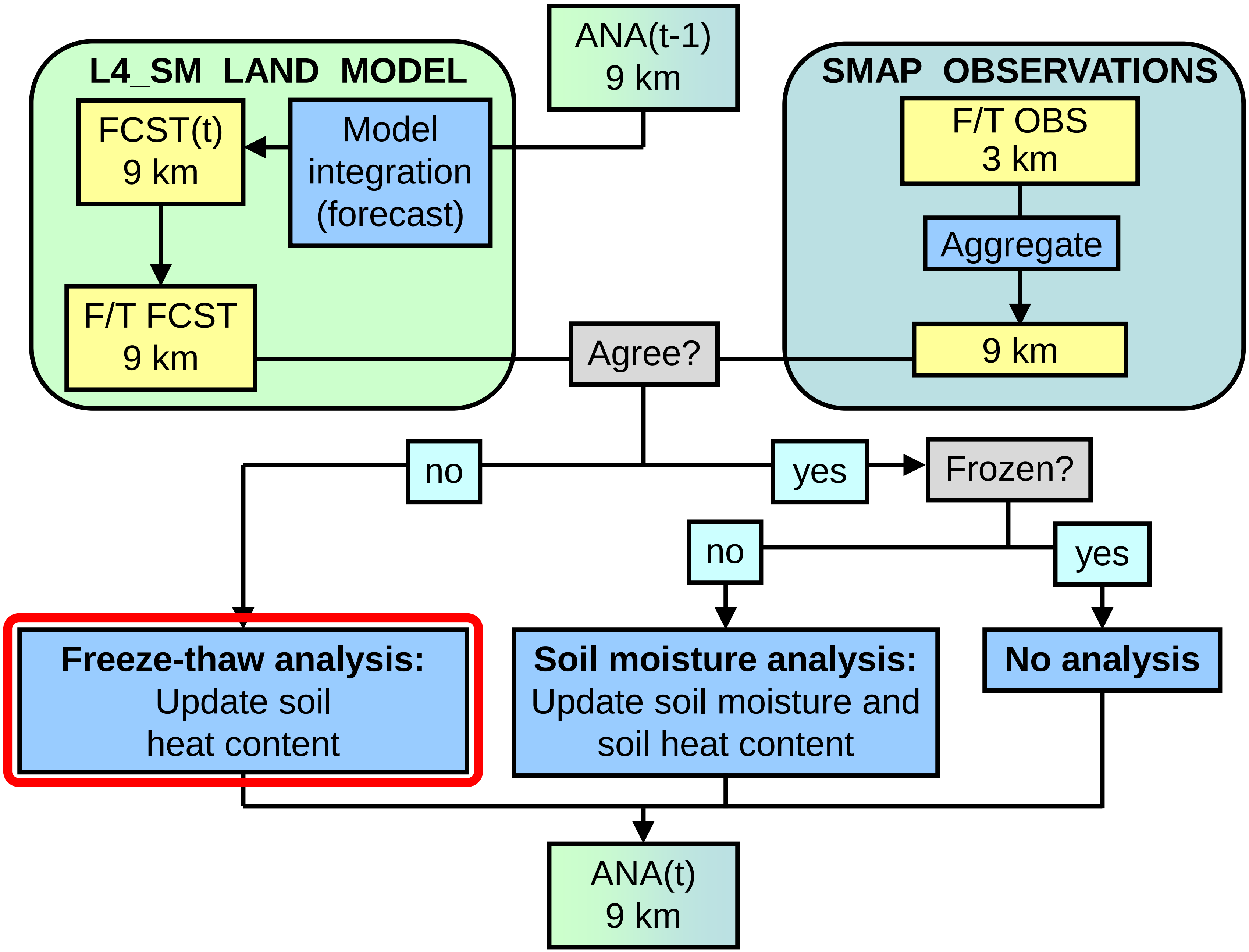


sqrt(R) = 10 K
spatial avg = 0.60

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.

SMAP L4_SM Analysis Overview



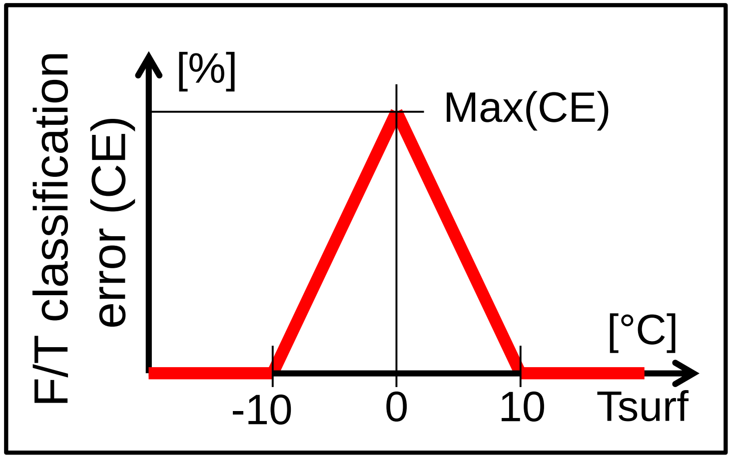
Freeze-thaw OSSE

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

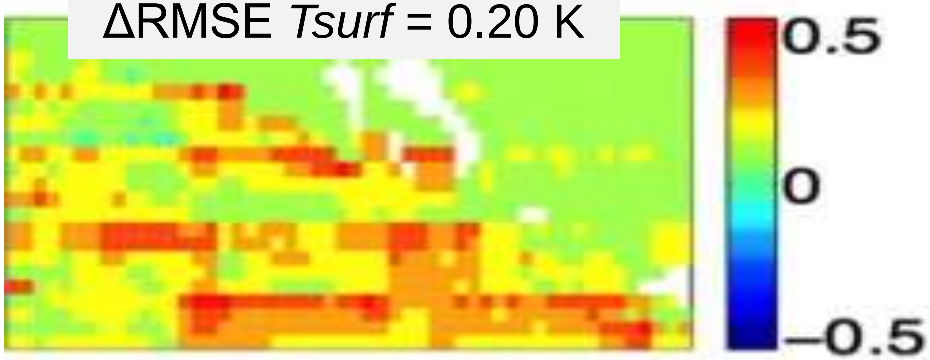
Small improvements with realistic classification errors:

	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

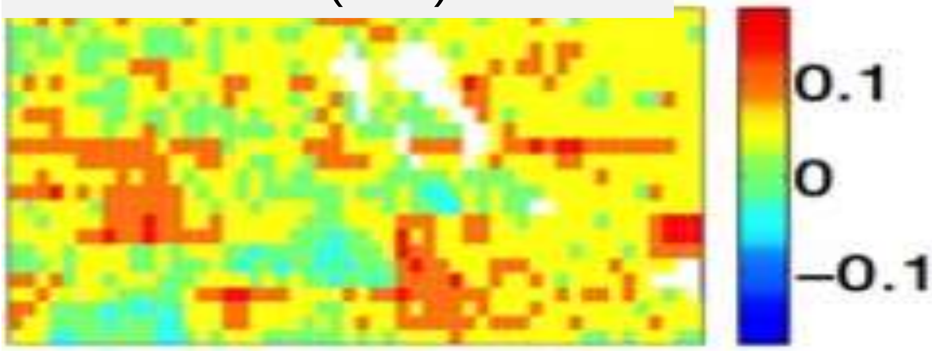
*Excl. times & locations with Tair>7°C or Tair<-7°C



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.

Conclusions

Multi-source observations:

- Address sensor-specific observation bias, e.g.,
  - geostationary Tskin.
- Improved skill with assimilation of data from multiple sources, e.g.,
  - active and passive surface soil moisture retrievals,
  - precipitation corrections and soil moisture assimilation,
- but this does not always work, e.g.,
  - MODIS SCF and AMSR-E SWE assimilation, b/c of poor-quality SWE retrievals.

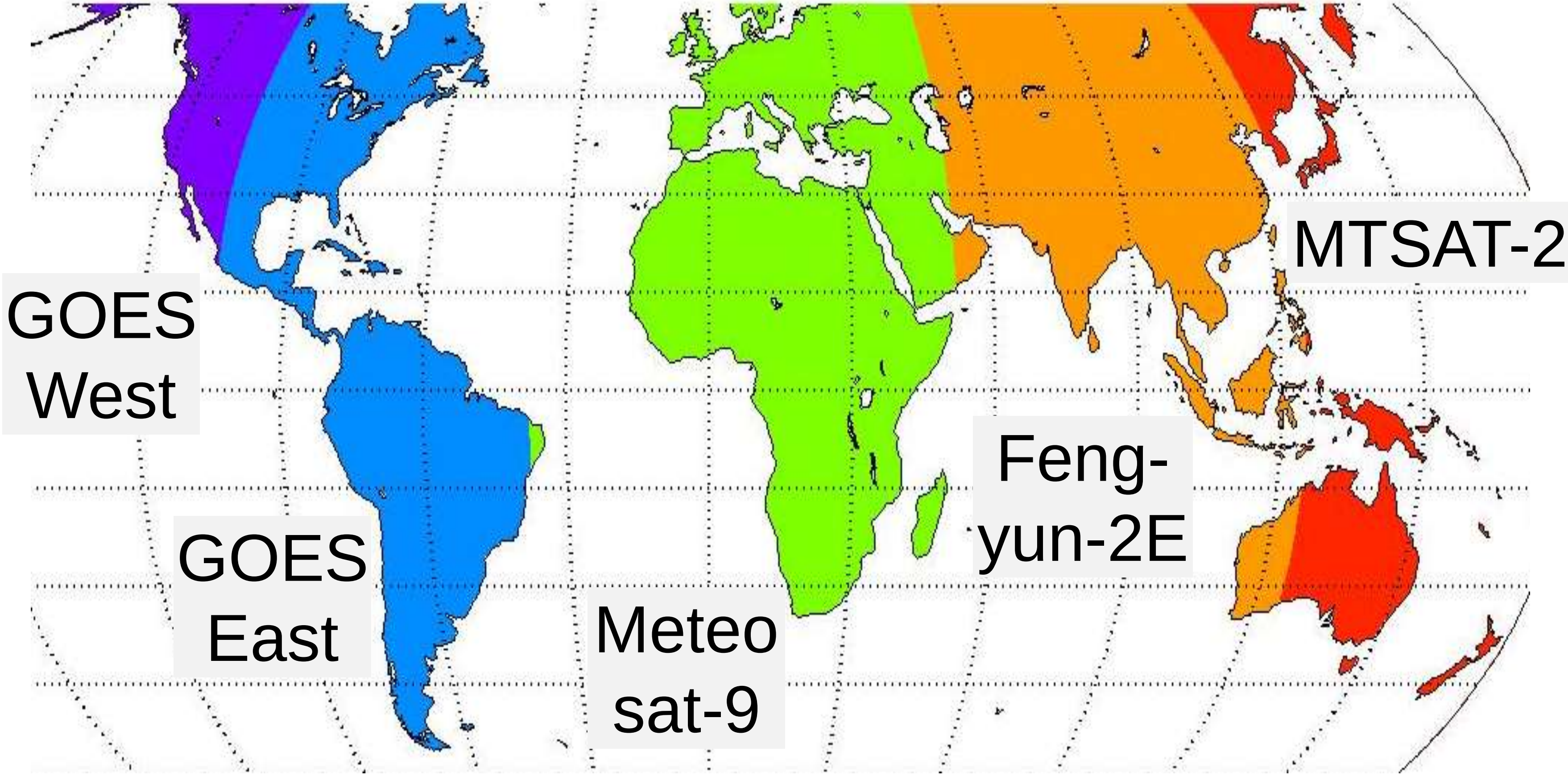
Multi-variate analysis:

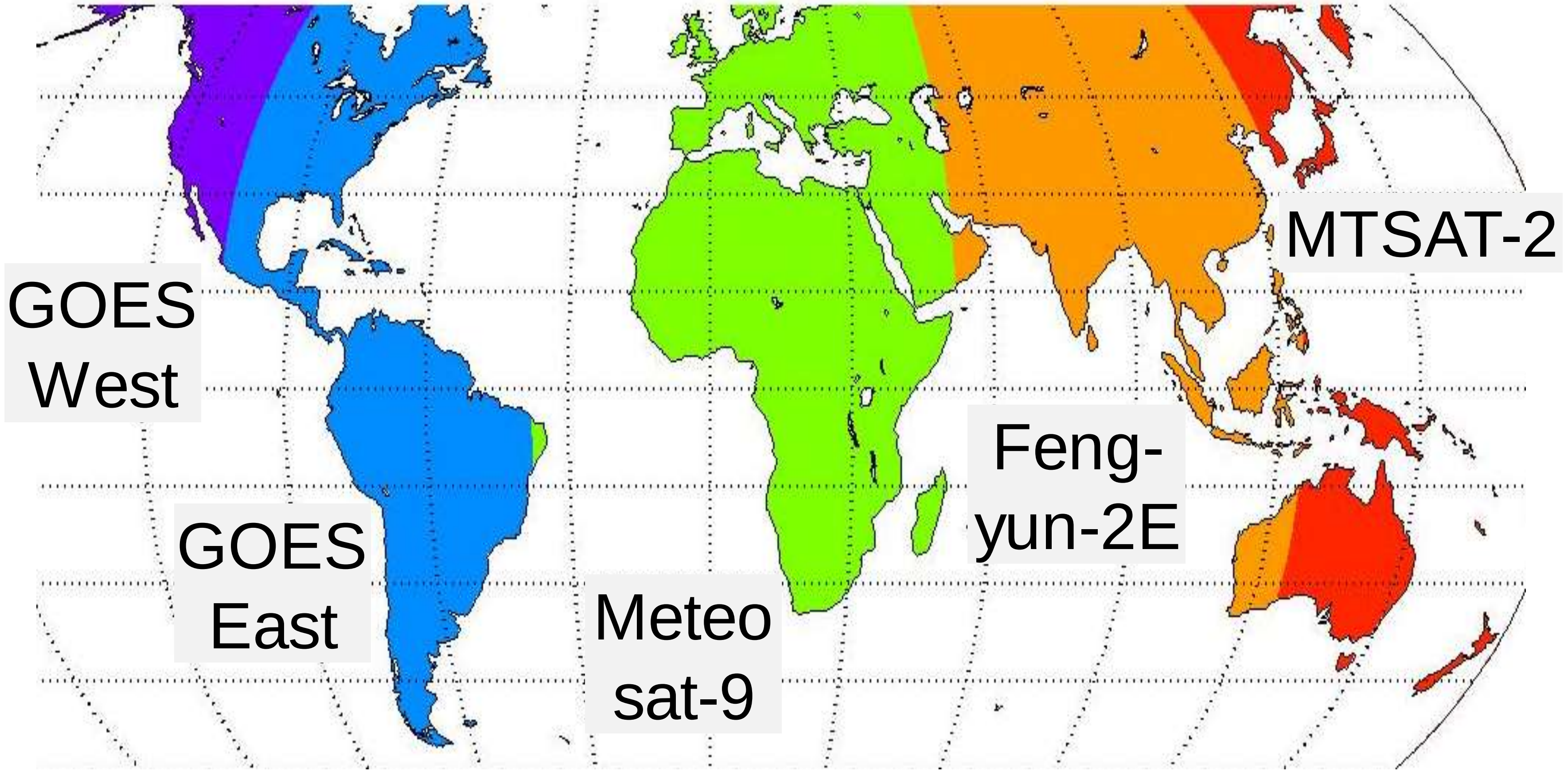
- Assimilation of GRACE TWS retrievals yields improvements in soil moisture and snow estimates.
- Assimilation of SMOS L-band brightness temperature yields improvements in soil moisture but not in soil temperature estimates.
- The SMAP Level 4 Surface and Root Zone Soil Moisture (L4_SM) product is **based on multi-source observations and a multi-variate analysis**.

In progress:

- Assim. of Tskin & L-band Tb; Assim. of GRACE TWS & L-band Tb.

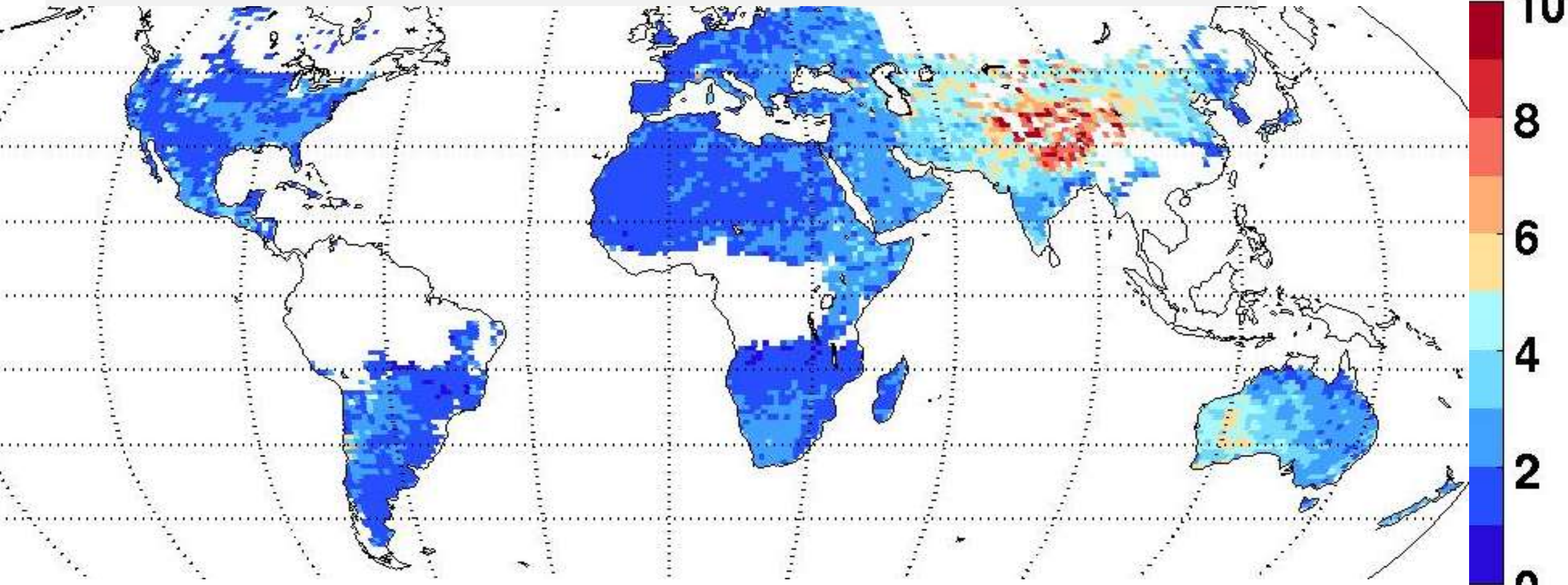
Thank you for your attention!

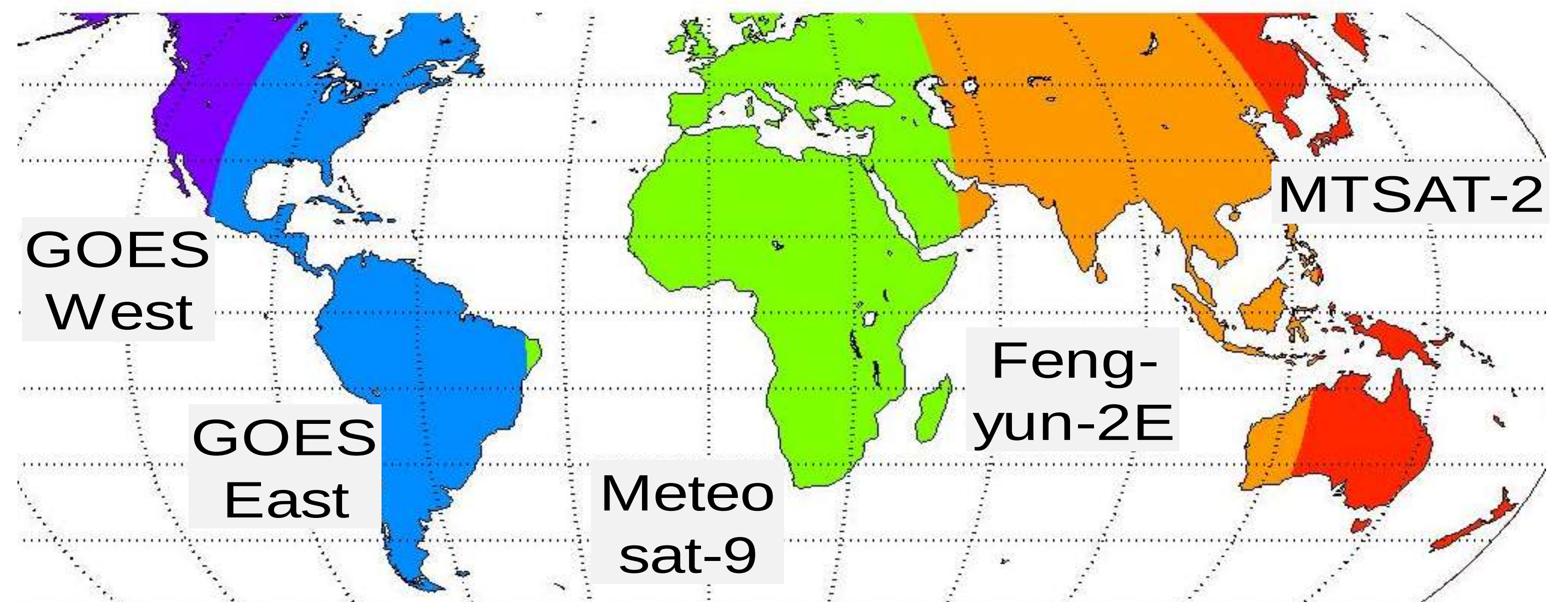

MTSAT-2
GOES West
GOES East
Meteo sat-9
Feng-yun-2E


MTSAT-2
GOES West
GOES East
Meteo sat-9
Feng- yun-2E

Geostationary Tskin observations

Tskin Model vs. Retrieval **ubRMSD** [K] – Jan-Jun 2011, 6z





Geostationary Tskin observations

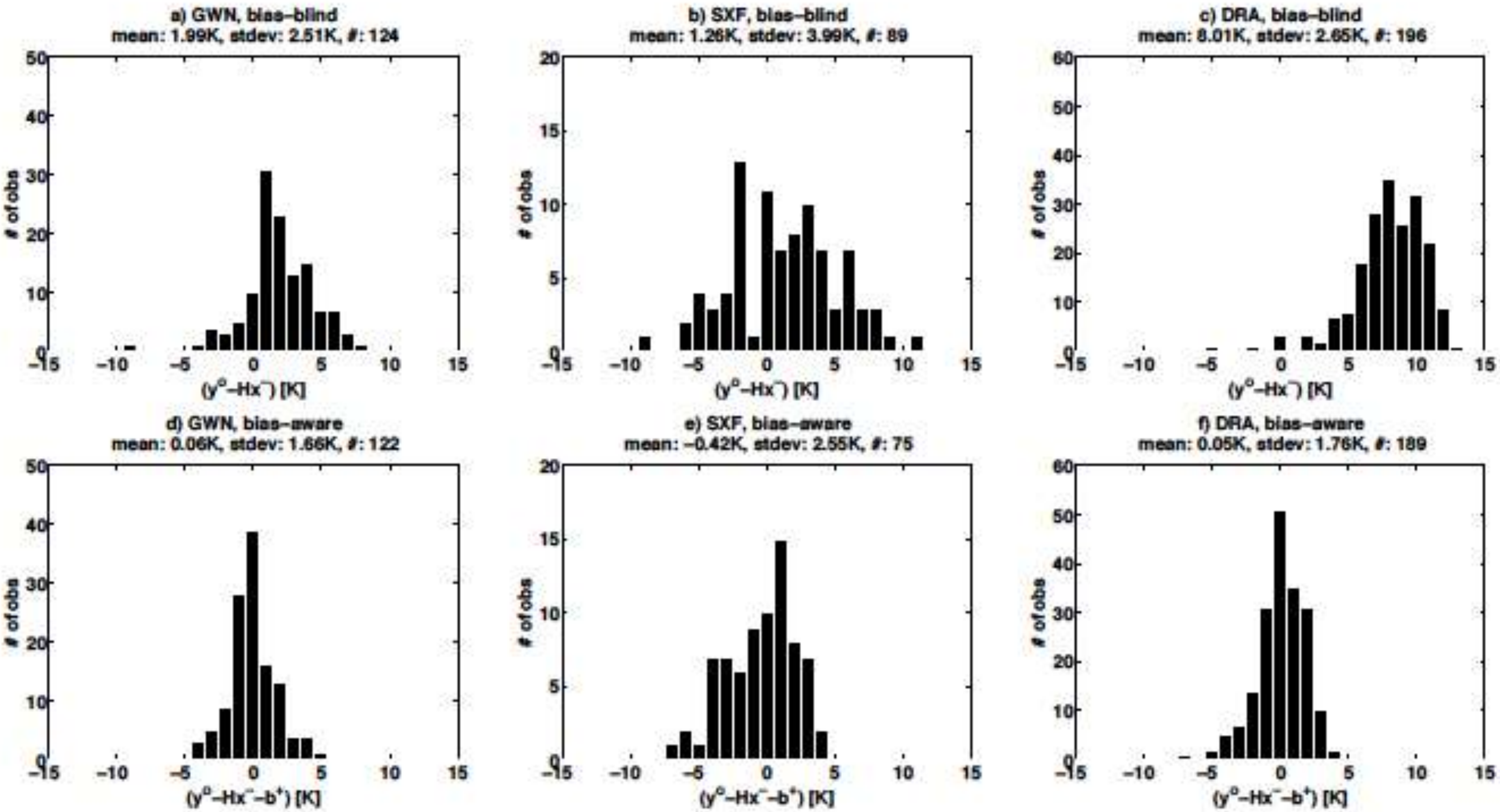
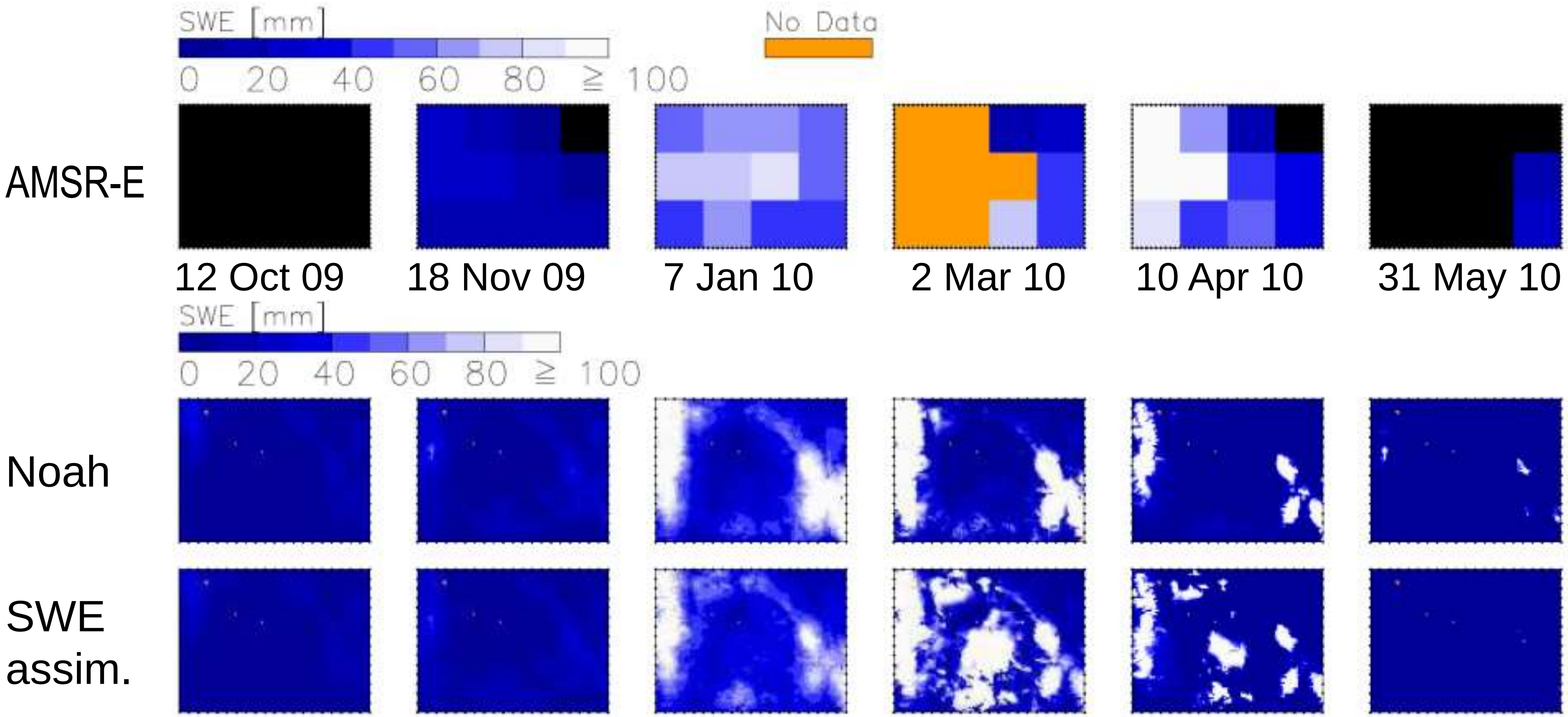


FIG. 4. Histograms of the state update innovations at 21:00 UTC, for the assimilation of geostationary T_{skin}, at the Goodwin Creek (GWN), Sioux Falls (SXF), and Desert Rock (DRA) SURFRAD sites, for a bias-blind assimilation (upper), and for the two-stage observation bias and state estimation bias-aware assimilation with τ=20 days (lower).

Assimilation of AMSR-E snow water equivalent (SWE)



AMSR-E does not observe thin snow packs

→ no improvement at start and end of snow season.

Some improvement at lower elevations with shallow snow pack (COOP sites).

Problematic in mountains with deep snow packs (SNOTEL sites).

De Lannoy et al. WRR (2011) submitted.