Land Data Assimilation in Atmospheric Systems

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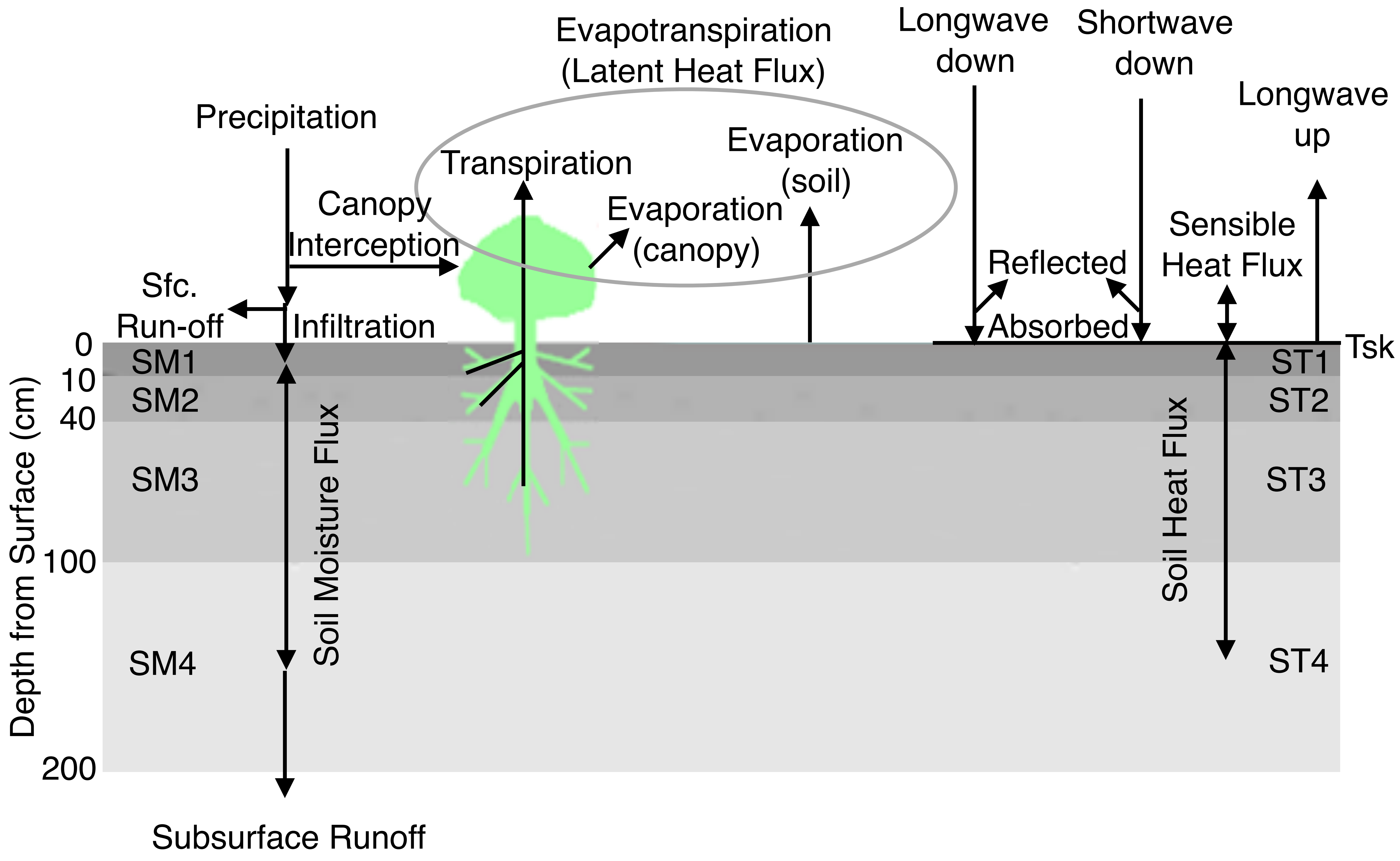
The Land Surface

The land surface stores energy and moisture, which are later released to atmosphere as latent and sensible heating:

- Soil moisture, soil temperature, and snow pack are forced by energy and water inputs from the atmosphere
- Soil and snow states then control the partition of incoming energy into latent, sensible, and ground heating, and also how much energy and moisture enters the surface (vs, reflected or run-off)
- Near surface layers respond rapidly to atmospheric forcing, while deeper layers have a filtered response

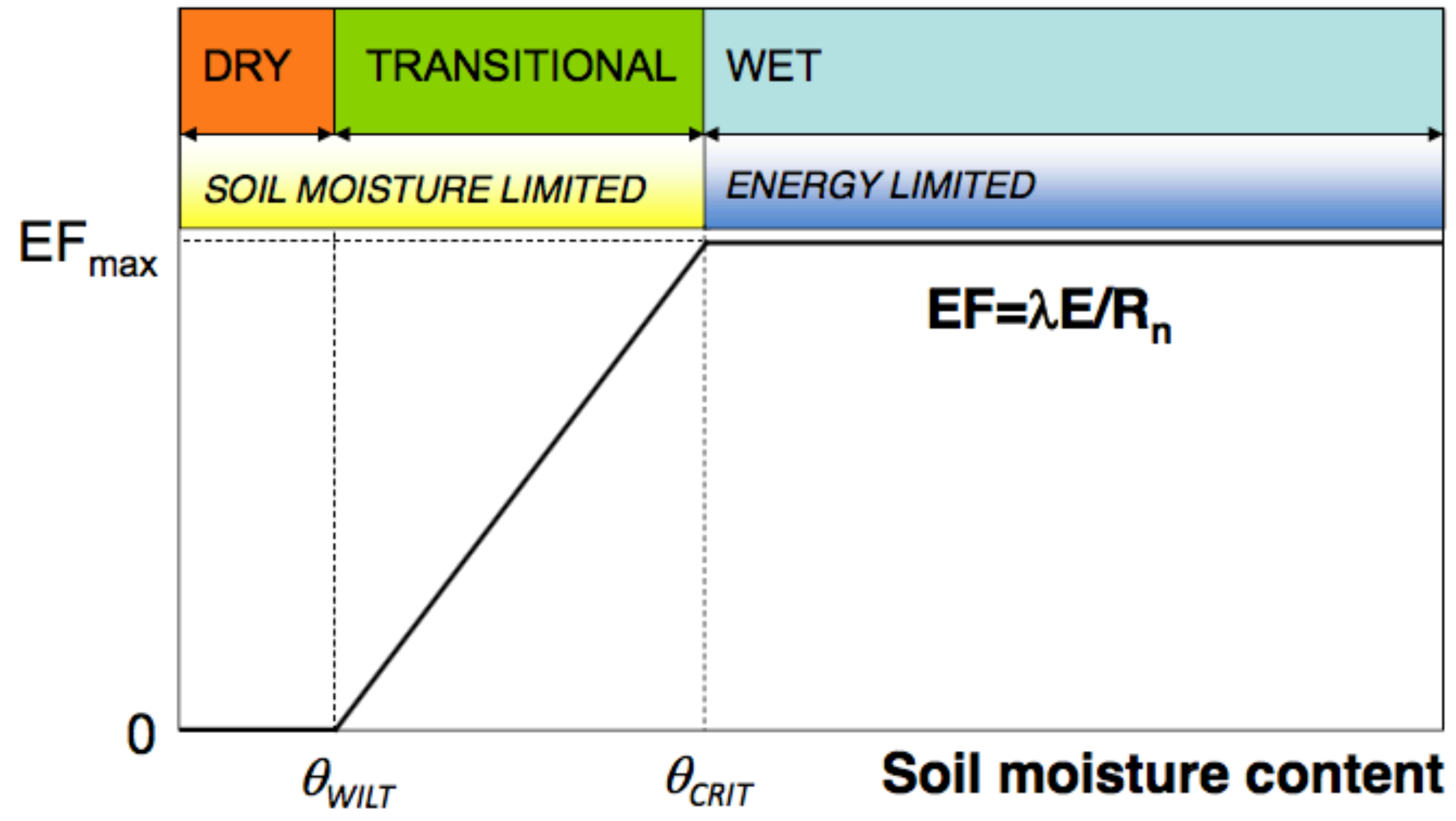


Soil Moisture

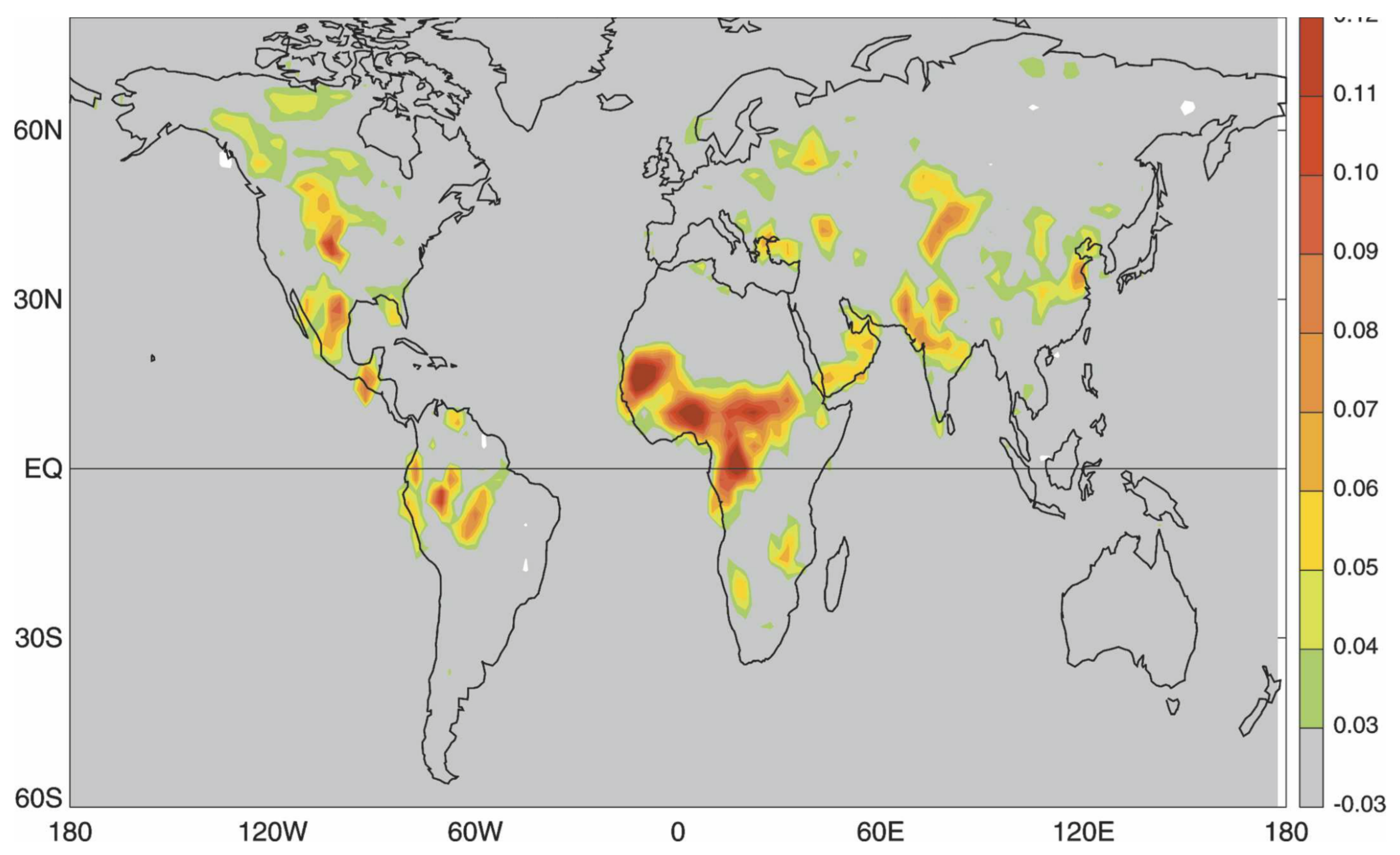
- Rootzone soil moisture (surface to 0.5 - 1.0m) controls the partition of incoming radiation into latent and sensible heating, by limiting the water available to plants for transpiration (latent heating)
  - Can have a profound impact on the boundary layer

- Soil moisture can provide predictability at least up to seasonal time scales
  - Rootzone soil moisture has a longer memory than the atmosphere (anomaly decay time: 1-3 months)
  - Soil moisture anomalies can be further enhanced by positive precipitation / soil moisture feedback

Soil Moisture Control on Evapotranspiration



JJA coupling strength, soil moisture/ precipitation



GLACE: Koster et al (2006)

Land DA

Land Data Assimilation

- The land can control the surface flux and moisture partition, exerting a strong influence on the boundary layer
  - Affects atmospheric forecasts, from short-range to (at least) seasonal
  - Most NWP centers constrain their model soil moisture, soil temperature, and snow pack

- Hydrology community (flood forecasting, drought monitoring, agricultural modeling,…) uses land DA to constrain wide range of states (soil moisture, soil temperature, snow, vegetation, terrestrial water storage, stream flow,…)

Unique Aspects of the Land

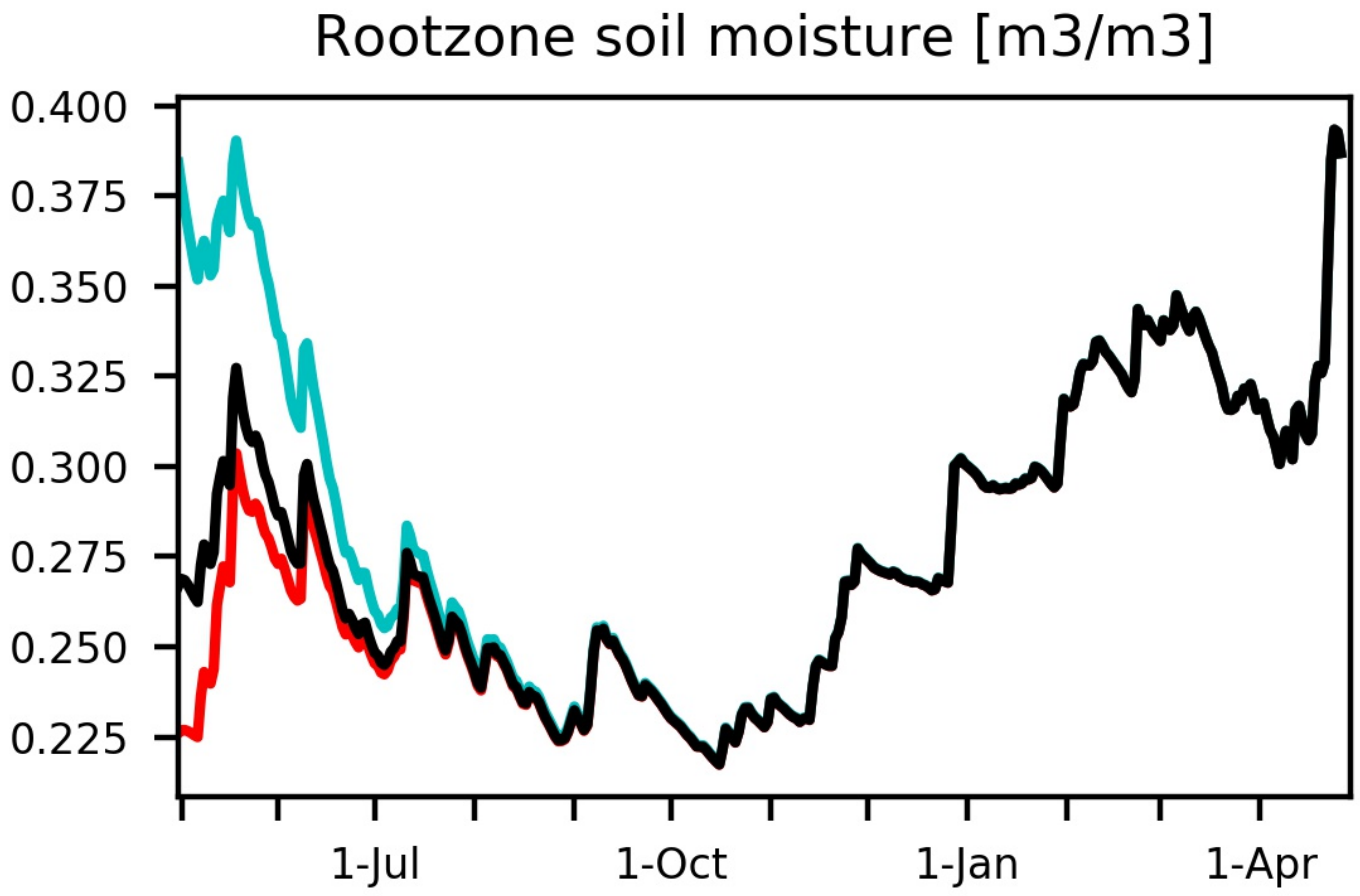
- The land is strongly forced
- The land surface is highly heterogenous, and there are associated large systematic differences between state estimates from different sources
- Land models are highly non-linear (inc. many switches), and have no adjoints
  - Land DA relies on ensemble (or 'simplified') methods
- NWP land models simulate each grid cell independently (no horizontal information exchange)
  - Land DA typically neglects horizontal error correlations

- Satellite sensors generally observe a thin near-surface layer, while the variables we most which to constrain are much deeper:
  - Must use models (directly, or through DA) to propagate surface information downwards
  - Time scale difference between (rapidly varying) observed variables and (slowly varying) model update states

The Land is Strongly Forced

- When de-coupled from the atmosphere, an offline land model will eventually converge to a state determined by the atmospheric forcing, and not the initial conditions (e.g, the land is not chaotic)

Offline Catchment model simulations with different soil moisture initial conditions at a location in Arkansas converge within 4-5 months



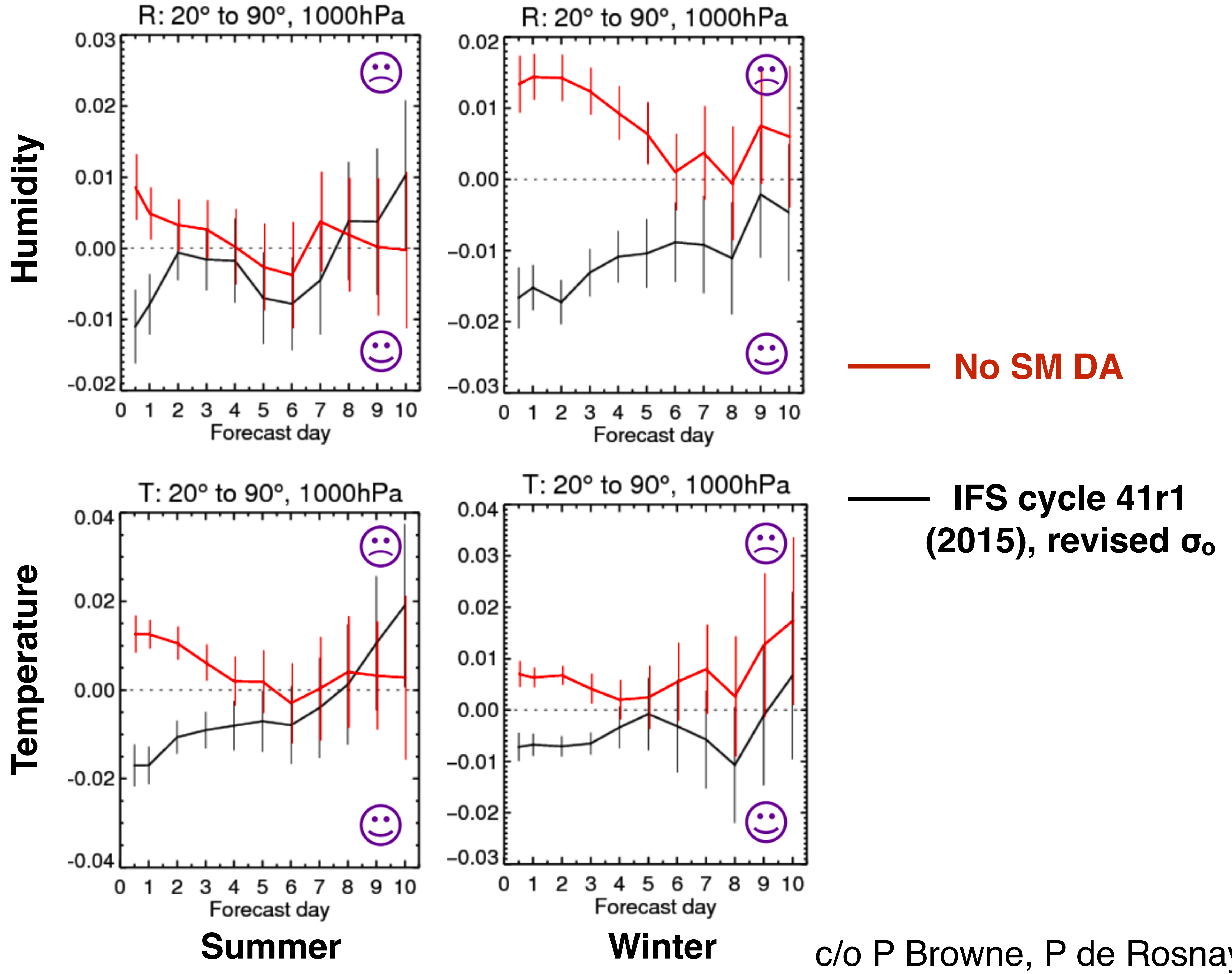
Soil Moisture DA in NWP

- Principal concern is atmospheric forecasts
- Most major NWP centers constrain model soil moisture and soil temperature with 2-m temperature and 2-m relative humidity observations
  - First introduced at ECMWF in the early ‘90s, to prevent a strong drift in the land surface
- DA performed with a weakly coupled Simplified EKF (ECMWF, Meteo-France, HIRLAM, UKMO), OI (EC, or EnKF in their regional system)
  - Made affordable by performing the DA independently at each model grid cell
  - Make use of an offline land surface model for the extra forecasts required by the DA (except ECMWF)

Assimilation of 2-m Observations

- If the land surface is too dry and warm, latent (sensible) heating will be underestimated (overestimated), resulting in a too warm/dry boundary layer
- These errors are corrected by adjusting the initial soil states accordingly
- Significantly improves NWP forecasts

Impact of soil moisture DA at ECMWF, compared to IFS cycle 40r1 (2013)



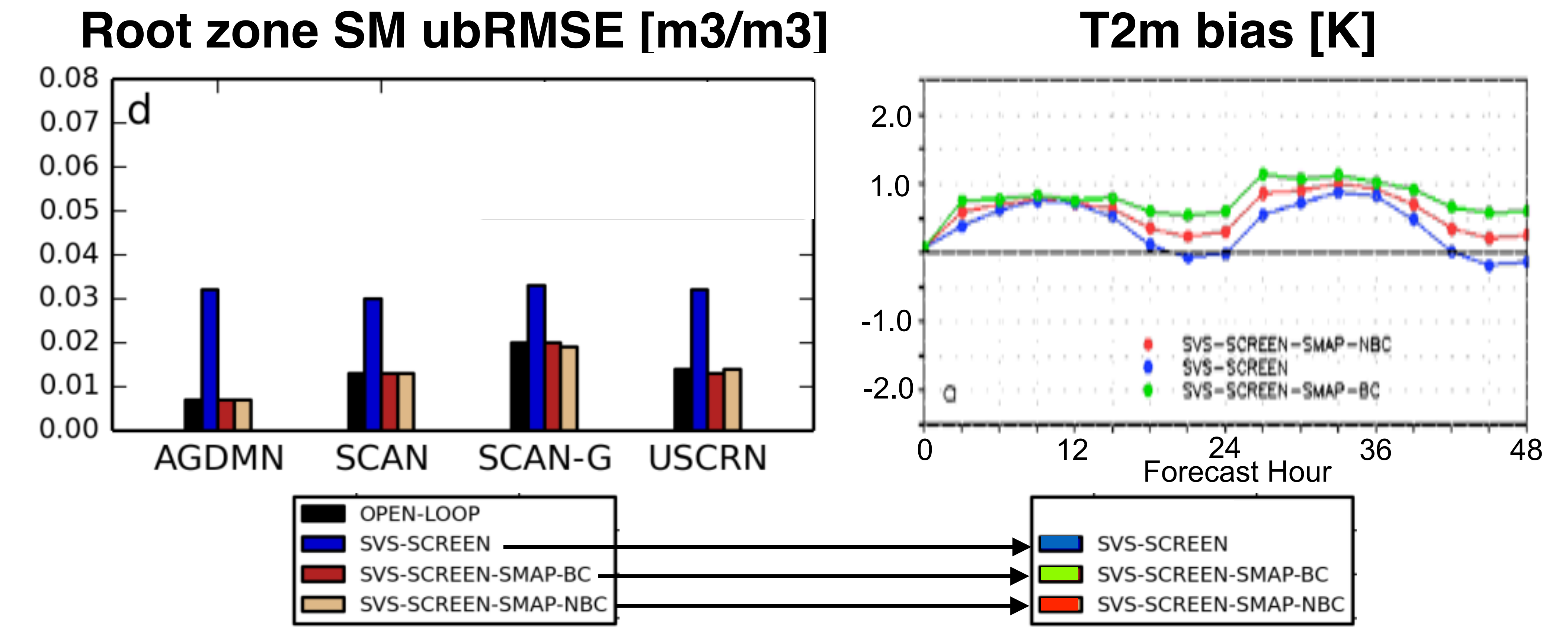
c/o P Browne, P de Rosnay

Assimilation of 2-m Observations

- Assimilating 2-m observations often degrades model soil moisture
  - Soil moisture is adjusted to account for errors elsewhere in the model
- Can be ameliorated by also assimilating satellite soil moisture observations
  - However, improved model soil moisture may degrade NWP forecasts

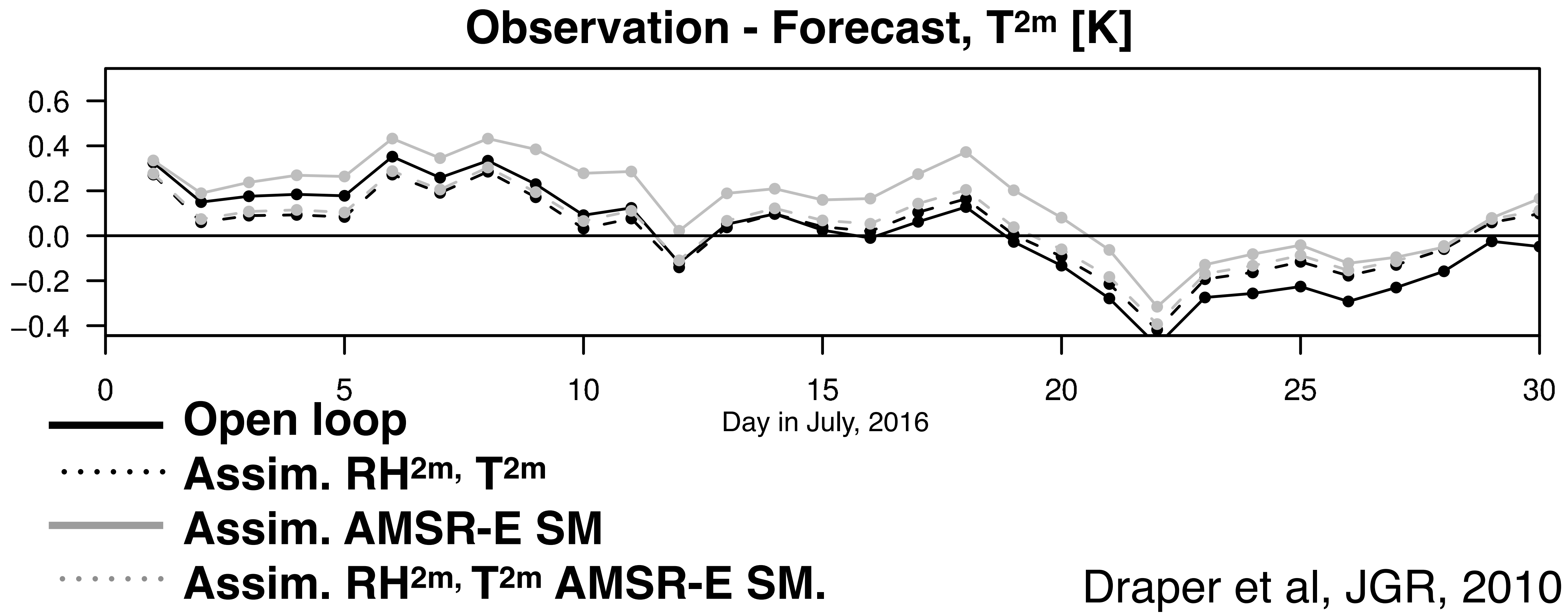
- Since early 2000’s, ECMWF and UKMO have been successfully assimilating ASCAT satellite soil moisture together with the 2-m observations

Environment Canada: 48-hr forecasts, June 2015, based on 3 mo. (offline) land assimilation spin-up



Carrera et al, JHydromet (sub)

Meteo-France: EKF assimilation, July 2006



Draper et al, JGR, 2010

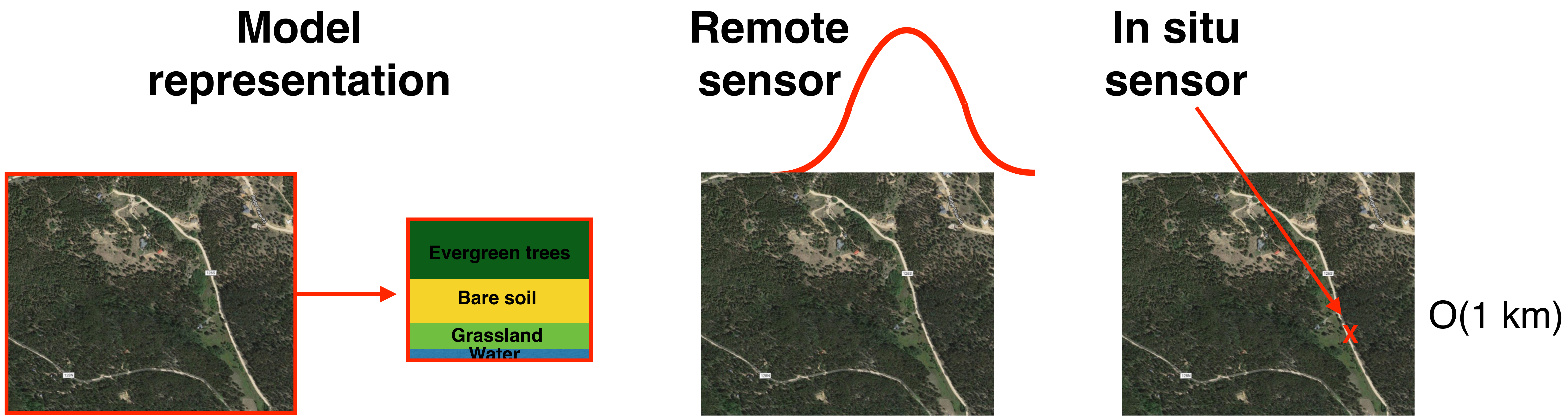
Soil Moisture DA in Hydrology

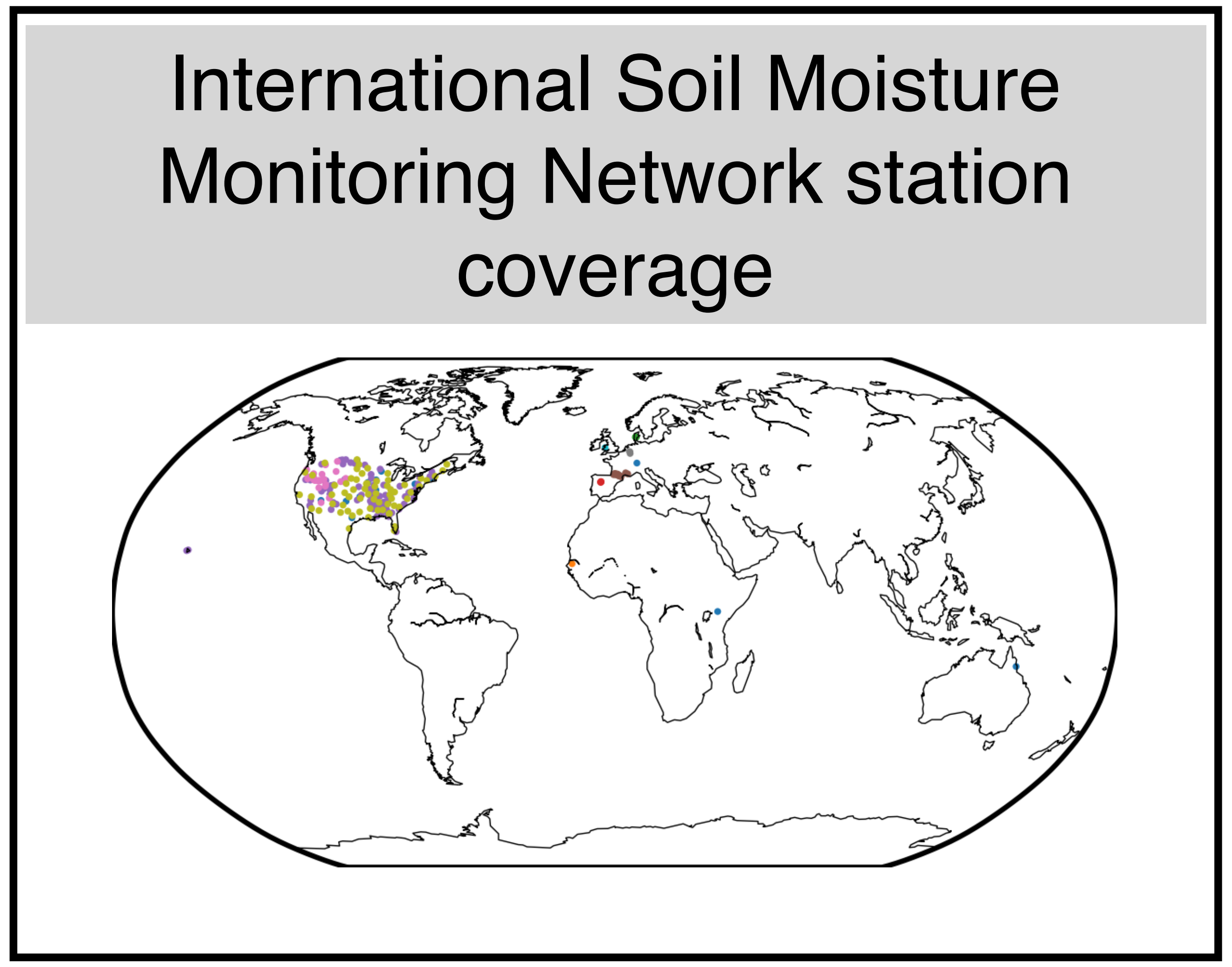
- Use offline (stand-alone) land surface models, and principal concern is land states/fluxes
- Assimilate satellite soil moisture (a more direct observation of root-zone soil moisture than the 2-m observations)
- Most often using an EnKF
  - Somewhat robust to model nonlinearities, flexible representation of model errors, can account for cross-correlated errors
    (comparisons of EnKF & EKF for soil moisture assimilation tend not to favor either)
  - Usually 20-30 ensemble members (much less than atmosphere: models are strongly forced, no horizontal flows)
  - Ensembles created using a single atmospheric realization, and applying randomly generated perturbations to a selection of the atmospheric forcing, land states, and parameters (not really 'errors of the day')

- Obs. are near-surface, yet most applications interested in root-zone soil moisture

Heterogeneity & Modeled/Observed Estimates

- The land surface is highly heterogenous
- Heterogeneity is treated differently by models, remote sensors, and in situ sensors
- Large upscaling errors when comparing grid-scale and in situ estimates



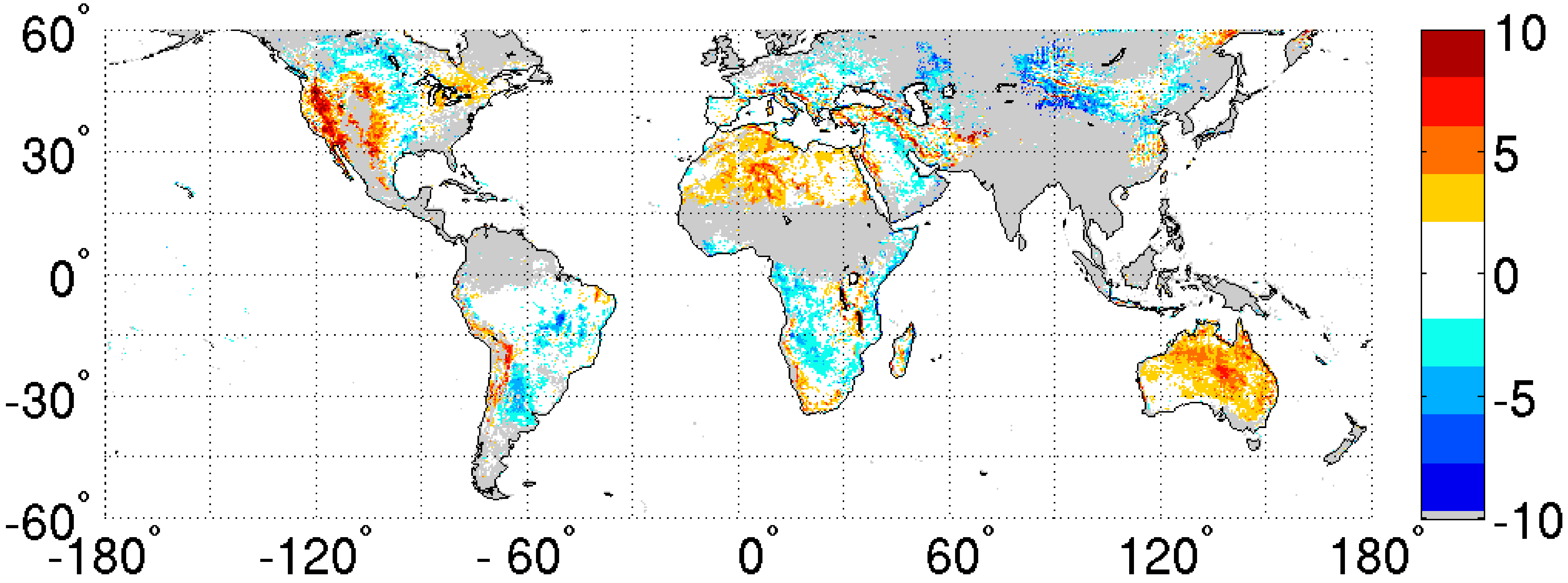


- In situ observations have very limited coverage
- Excepting a few intensely monitored sites, no agreed on global truth for most land states, including soil moisture and associated model soil parameters

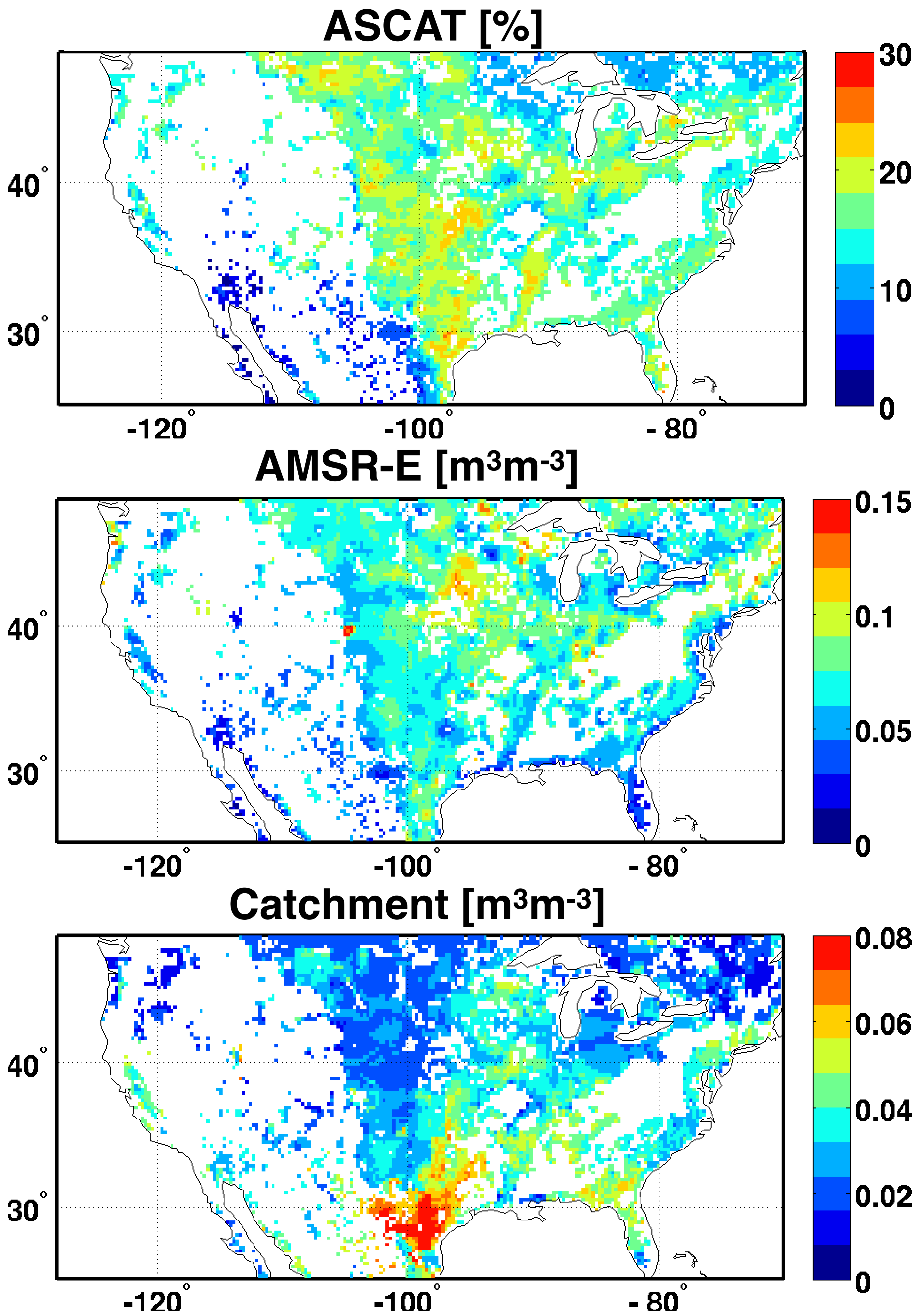
Comparing Observed and Modeled Estimates

- There are large systematic differences between different modeled and observed land surface estimates
- Without an anchor (recognized true mean) against which to estimate biases, cannot attribute model-observation mean differences to biases in each

Mean Geostationary - GEOS-5 Tskin [K], July 2012 at 0 UTC



σ of 3 soil moisture estimates



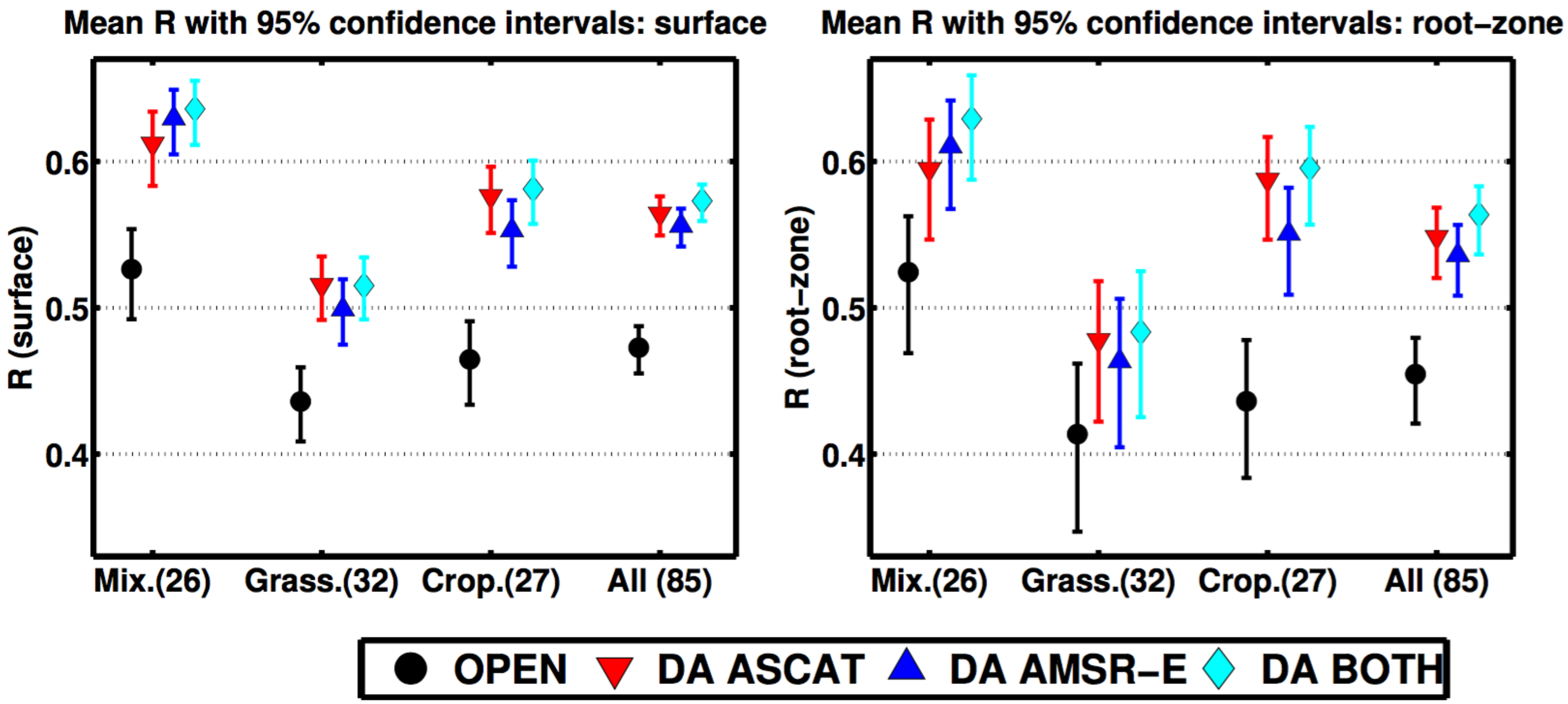
Soil Moisture Bias Correction

- DA assume observations and models are unbiased, yet for soil moisture both are almost certainly biased (by an unknown amount)
- Standard approach in soil moisture DA is to remove the biases *between* the model and the observations before assimilating the observations
  - Done by rescaling the observations to locally (at the grid-scale) match the mean and variance of the model soil moisture
  - Then the observed temporal anomalies are assimilated (but all spatial information is lost)

Soil Moisture Assimilation (offline)

- By assimilating rescaled satellite soil moisture observations, can correct model soil moisture temporal anomaly behavior

Correlation of daily anomalies from the seasonal cycle, at 85 sites



EnKF assimilation of 3.5 years of ASCAT and AMSR-E shows significant improvements in anomaly correlations with ground-based observations

Draper et al, GRL, 2012.

Summary: Land DA

- The land differs from the atmosphere in several important ways (models strongly forced and do not account for horizontal flow, timescale difference between observed and modeled variables, no anchor for estimating biases), DA approach must be appropriately tailored

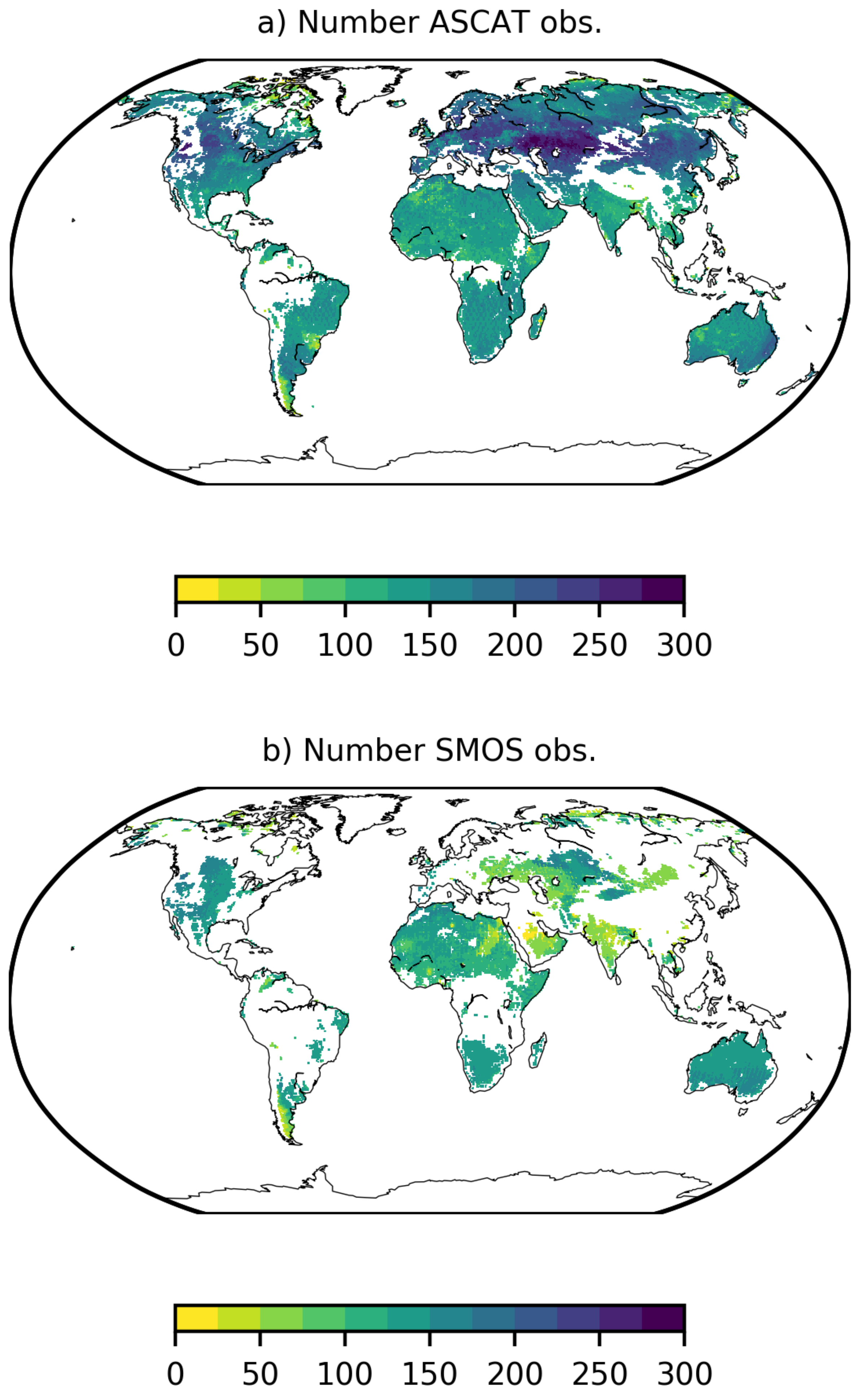
- If most interested in atmosphere (or land), best results often from assimilating atmospheric (or land) observations
  - Classic problem encountered in coupled DA, points to model errors
  - DA itself is an important tool to identifying and reducing model errors

Assimilating Satellite Soil Moisture into an Atmospheric (Earth System) Reanalysis

Coupled Land/Atmosphere DA experiments

- NASA's next reanalysis will be an integrated Earth system reanalysis, DA is targeted to improve both land and atmosphere

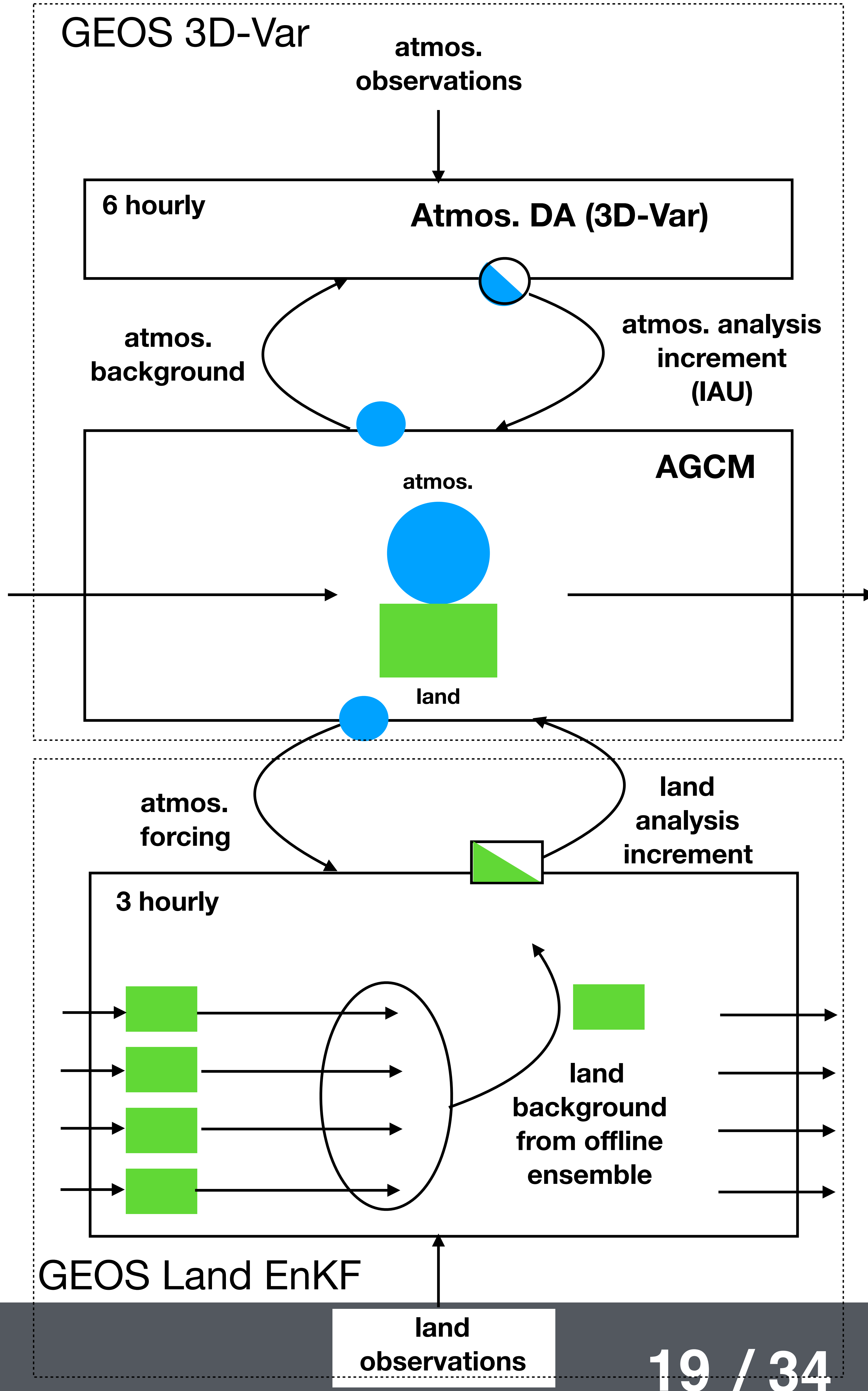
- Test impact of an EnKF assimilation of satellite soil moisture into a system similar to MERRA-2, from April - August, 2013:
  1. <u>AGCM-DAatmos:</u>
  Same AGCM, atmospheric DA system, and assimilated observations as MERRA-2
  2. <u>AGCM-DAland/atmos</u>:
  As above, plus assimilate ASCAT & SMOS soil moisture



Draper & Reichle, JClim (sub)

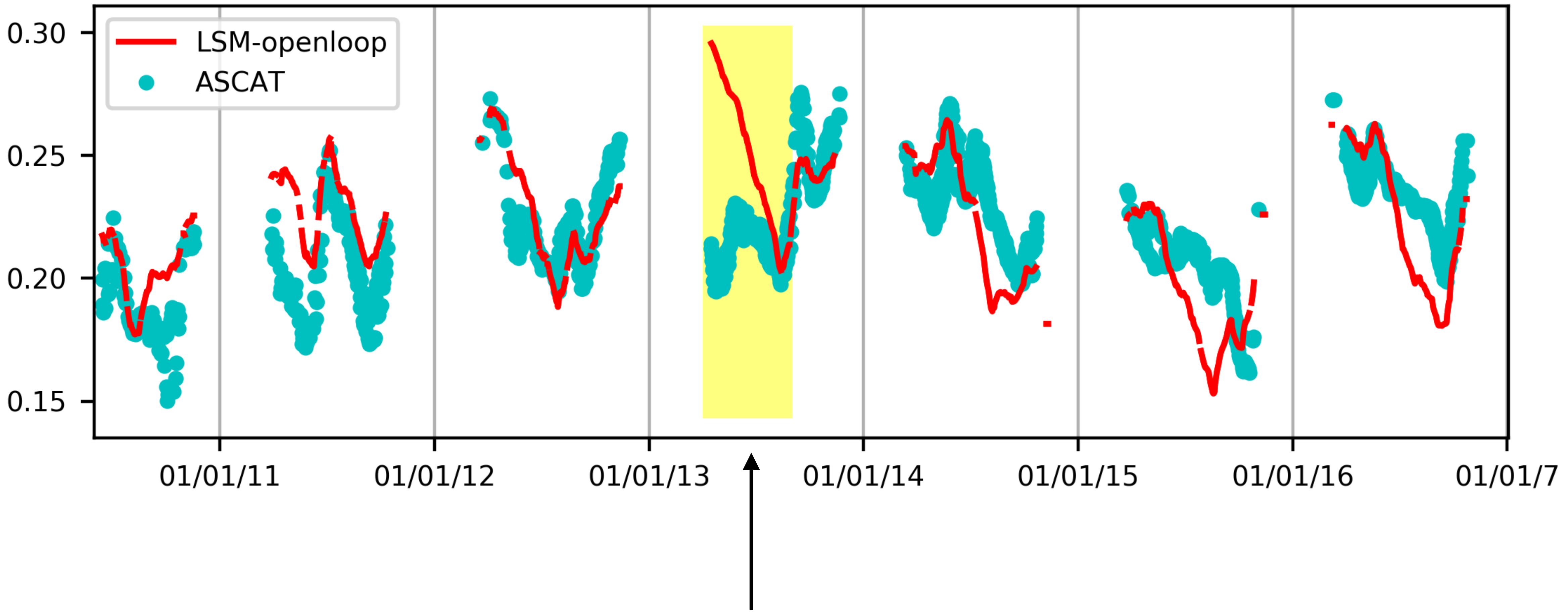
The GEOS Coupled Land/ Atmosphere DA

- Atmospheric DA is GEOS 3D-Var (as in MERRA-2)
- Land DA is GEOS EnKF (developed by Rolf Reichle)
    - Land ensemble is run offline, using atmospheric forcing updated at every assimilation cycle
- Weakly coupled: no observations or error covariances directly shared between land and atmosphere DA, but information is shared in subsequent forecast step



Bias Correction of the Satellite Soil Moisture

Surface SM [m3/m3] at Ukraine location:
Model climatology & rescaled observations

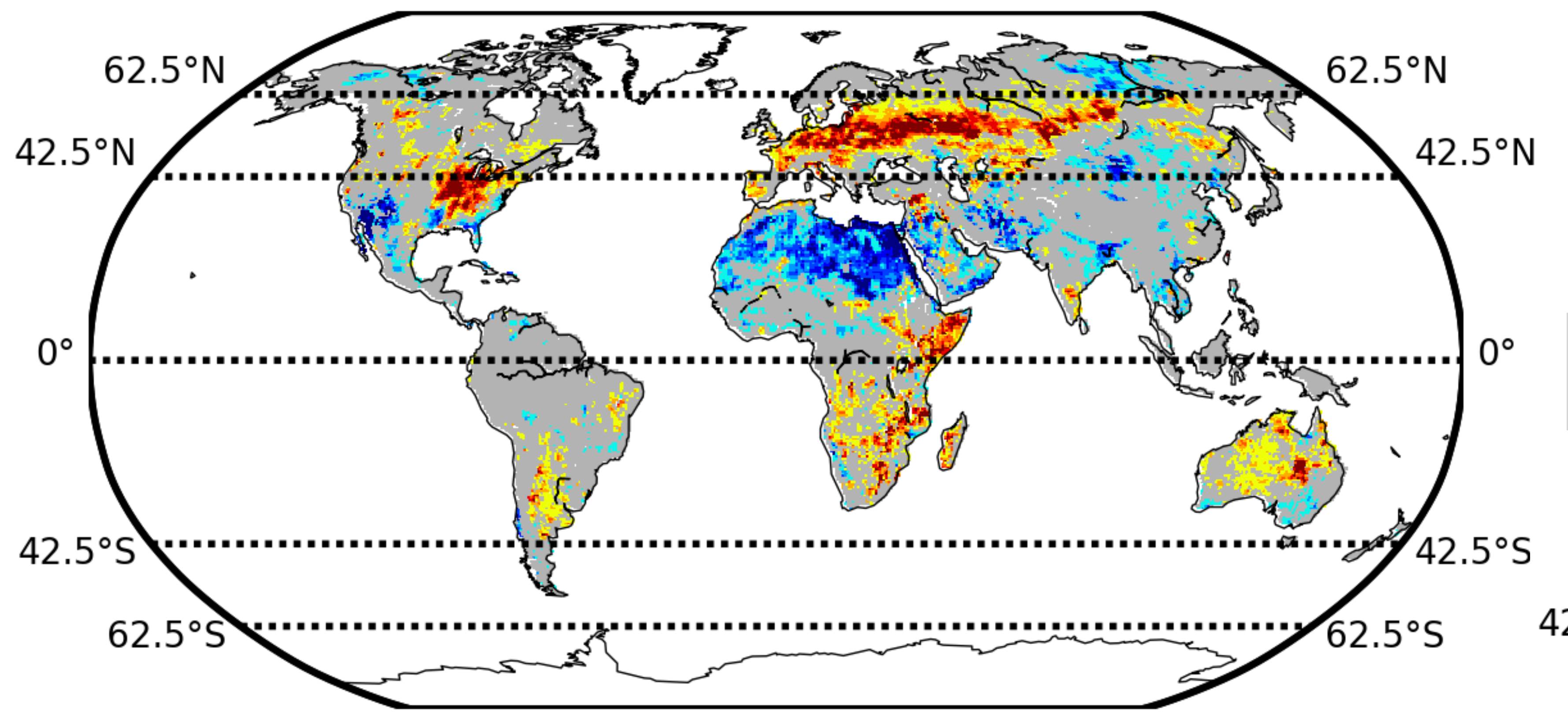


Period of AGCM experiment

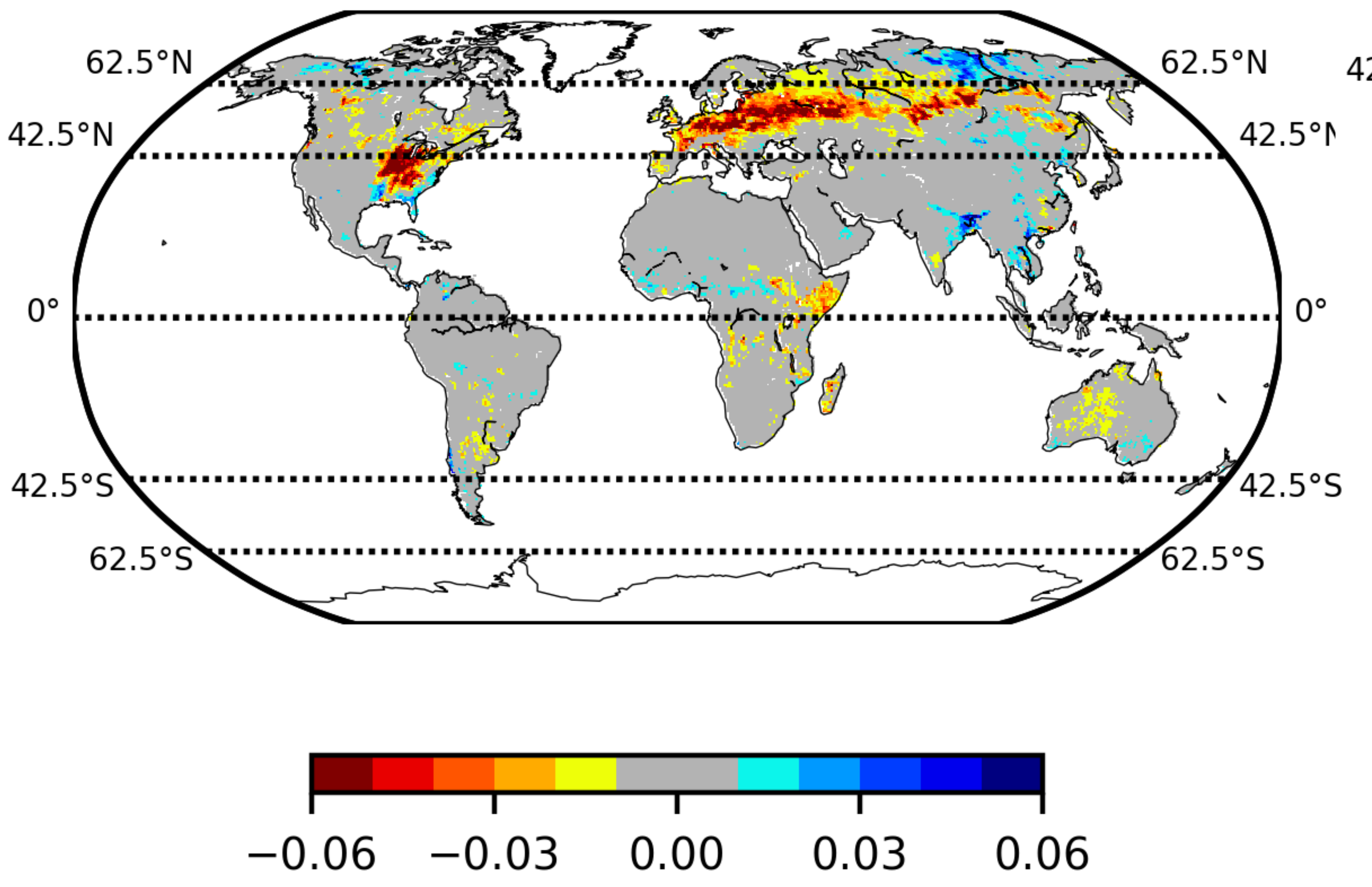
- The ASCAT/SMOS observations were 'bias-corrected' prior to assimilation, by rescaling them to match the climatology (mean, variance, …) of the model soil moisture *using the maximum available time period, of 6.5 years*
- Allows the assimilation to correct for model errors with inter-annual time scales

Impact on the model (mean differences in June)

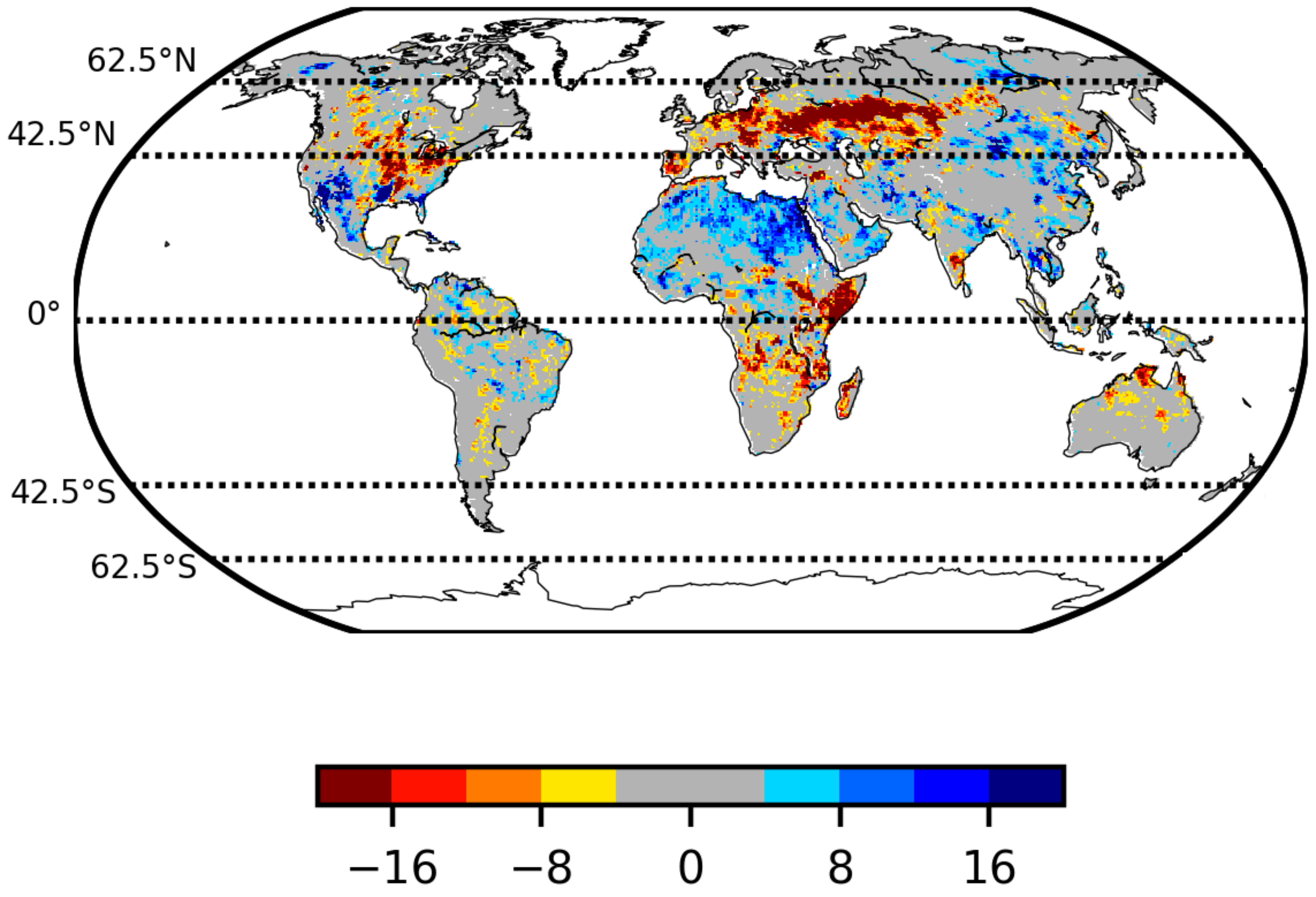
Surface Soil Moisture (0-5cm) [m3/m3]



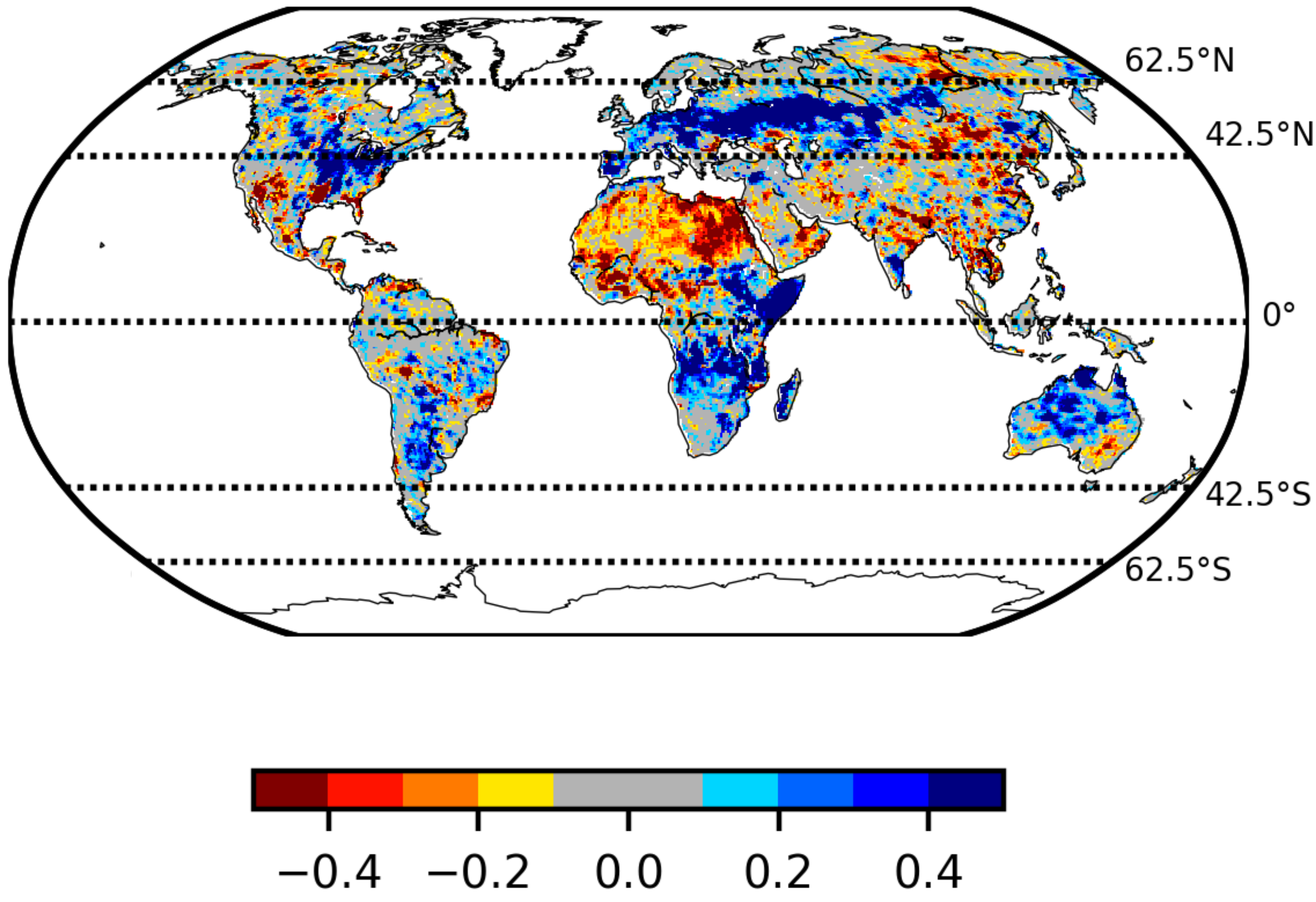
Root-zone Moisture (0-5cm) [m3/m3]



Latent heating [W/m2]



Daily Max T2m [K]



- Soil moisture DA induces relatively large changes in surface heat partition (hence, T2m, precipitation, boundary layer height)

Daily Max. T2m Skill (vs. GHCN obs) 14Apr-31Aug 2013

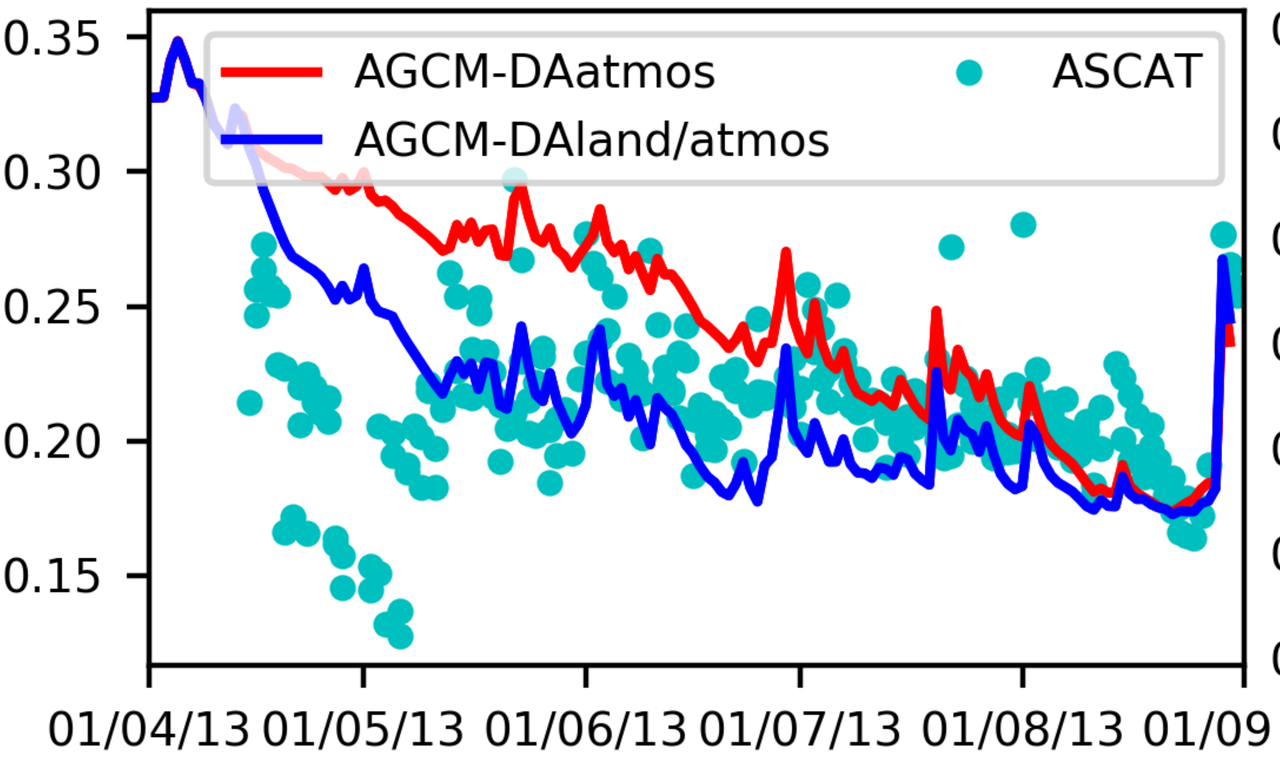
RMSE AGCM-DAatmos [K] | Bias AGCM-DAatmos [K] | ubRMSE AGCM-DAatmos [K]

Change from Soil Moisture Assim (AGCM-DAland/atmos - AGCM-DAatmos)

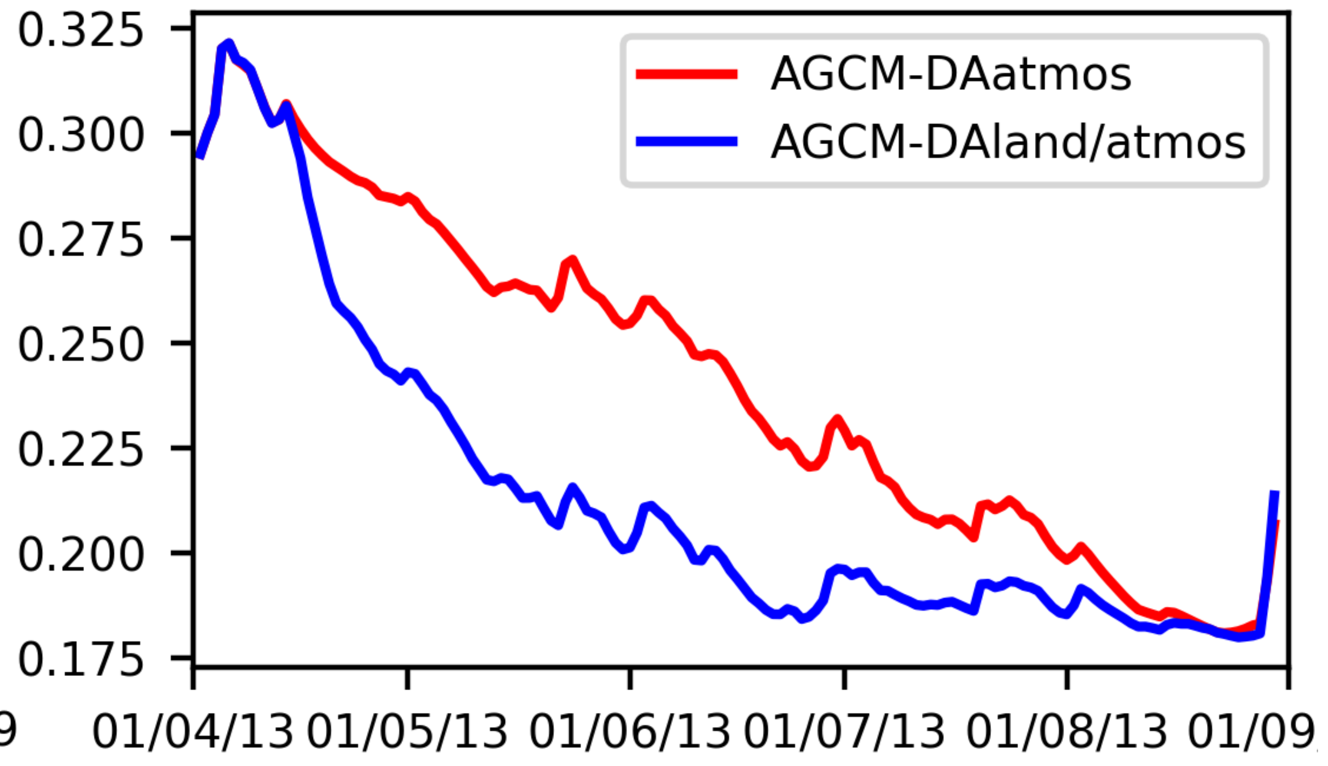
Change in abs(bias)

Example Timeseries: Ukraine

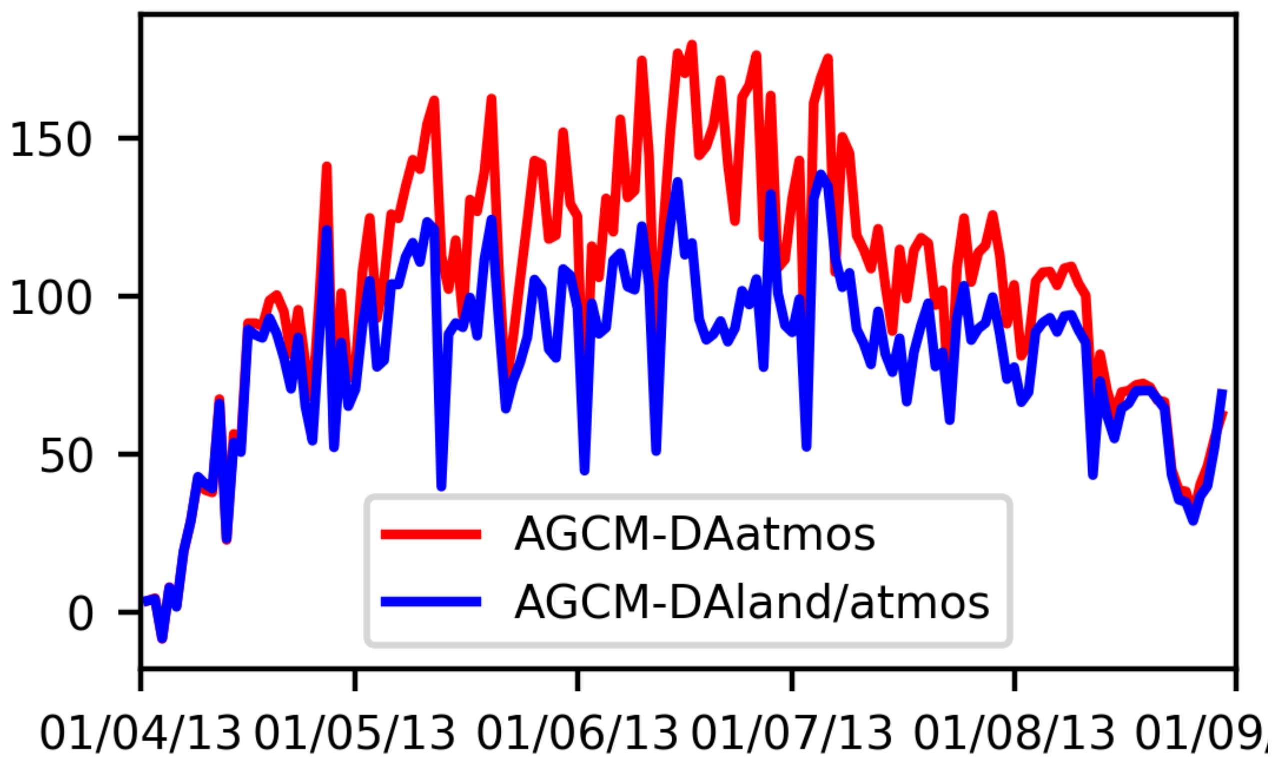
Surface SM [m3/m3]



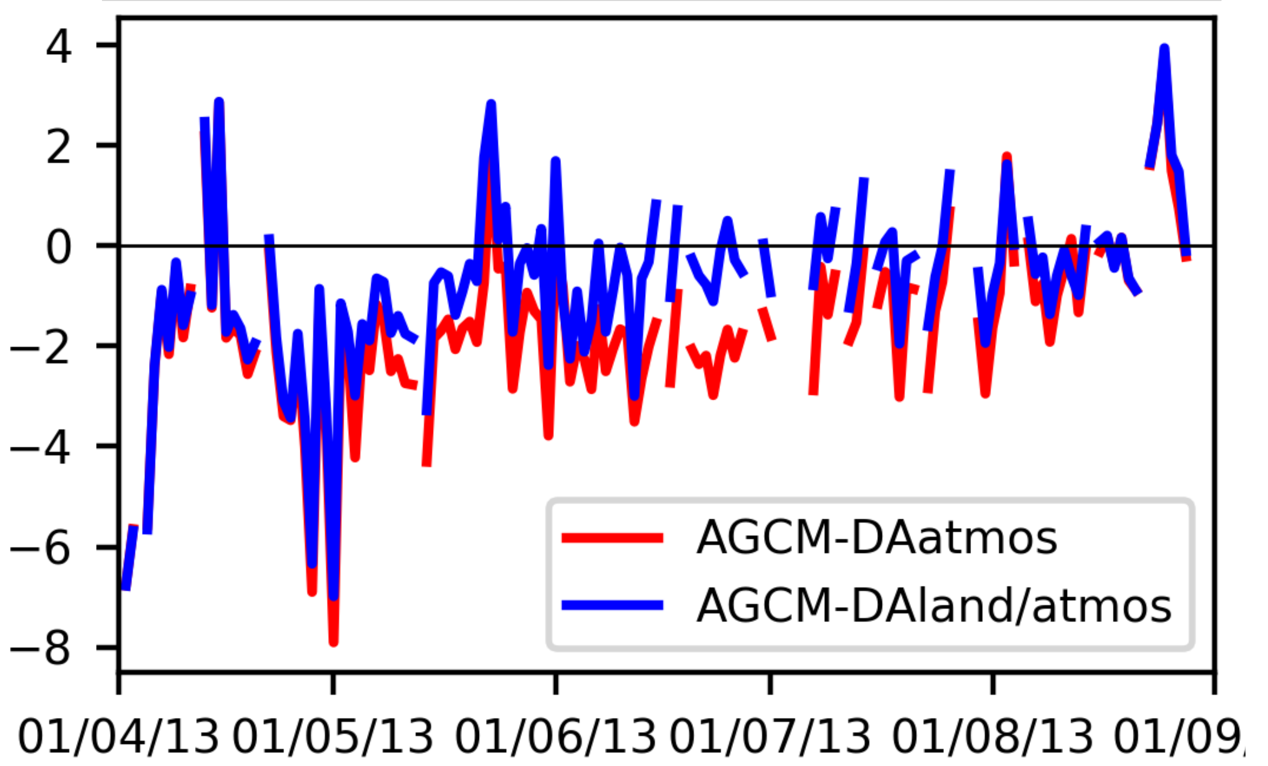
Root-zone SM [m3/m3]



Latent Heat [W/m2]



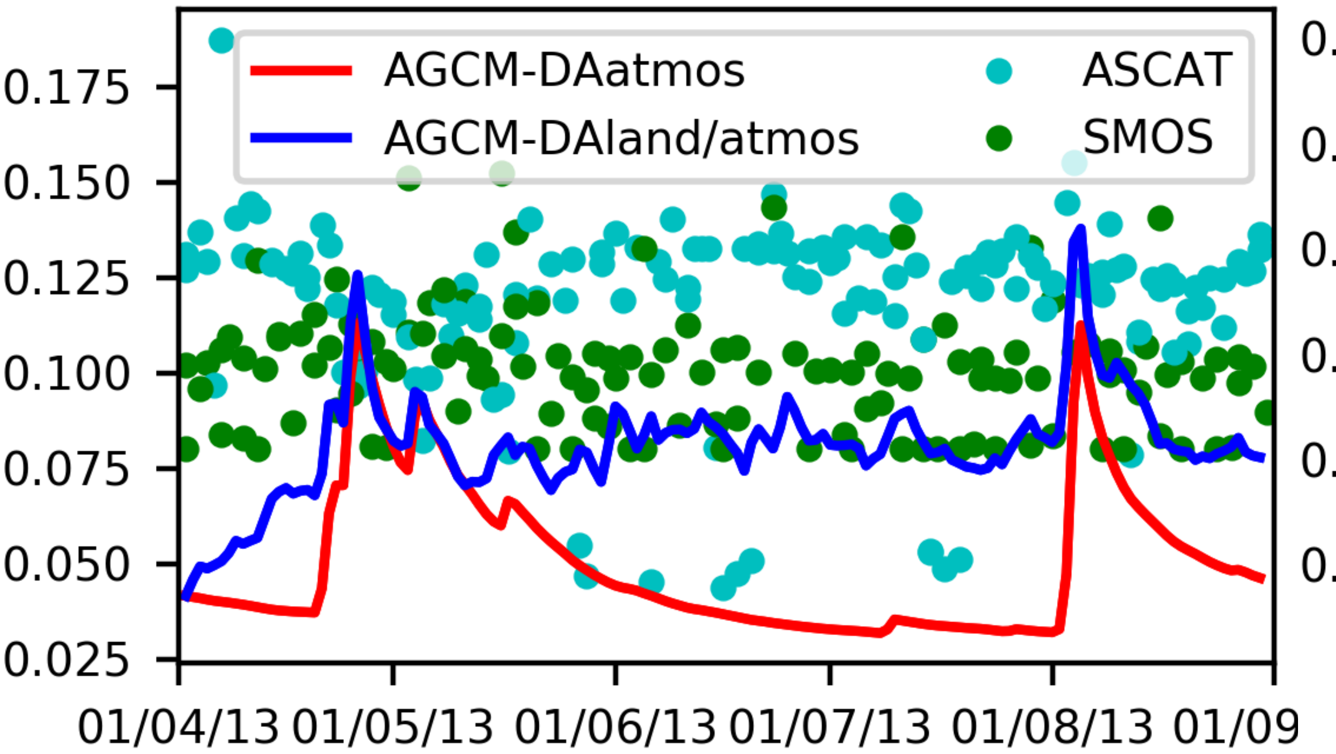
Daily Max T2m bias [K]



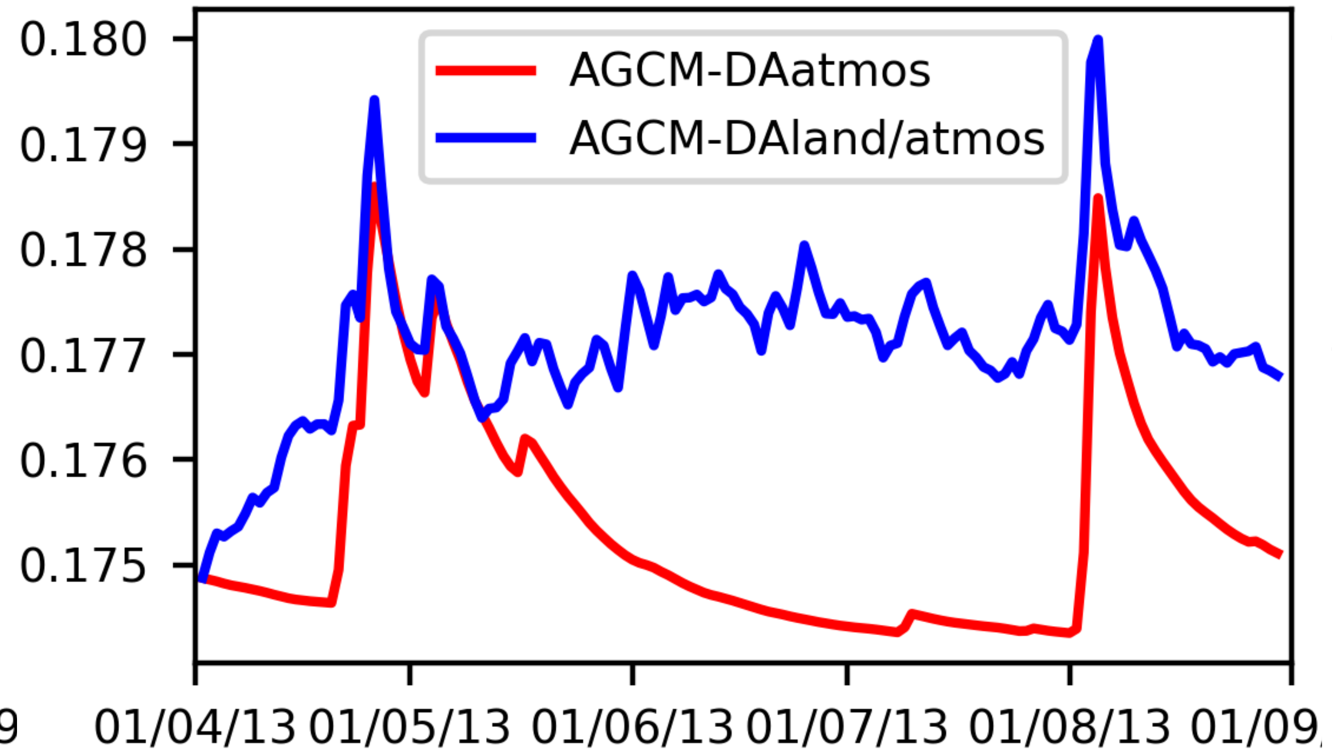
- Location representative of region spanning western Europe across southern Russia, with reduced T2m RMSE
- T2m RMSE reduced from 2.32 to 1.78 K
- The soil moisture assimilation dried the model soil moisture, decreasing latent heating (and increasing sensible heating), and reducing the cool bias

Example Timeseries: Algeria

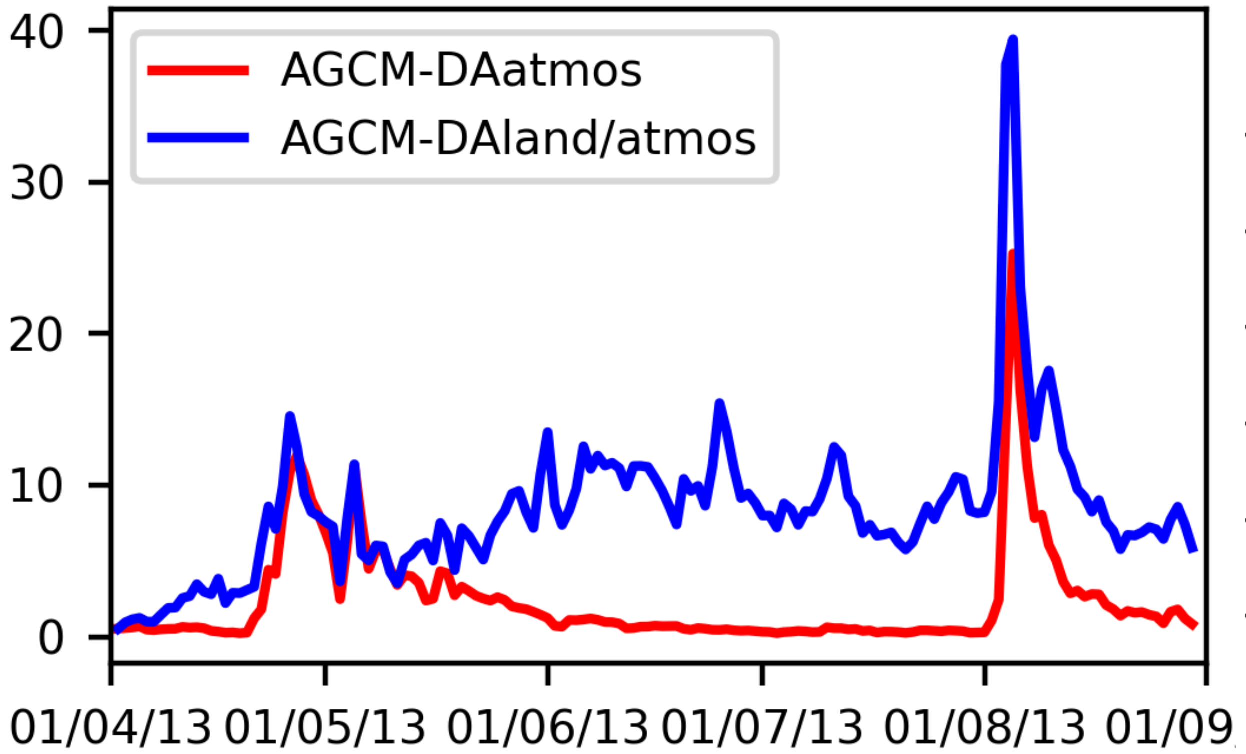
Surface SM [m3/m3]



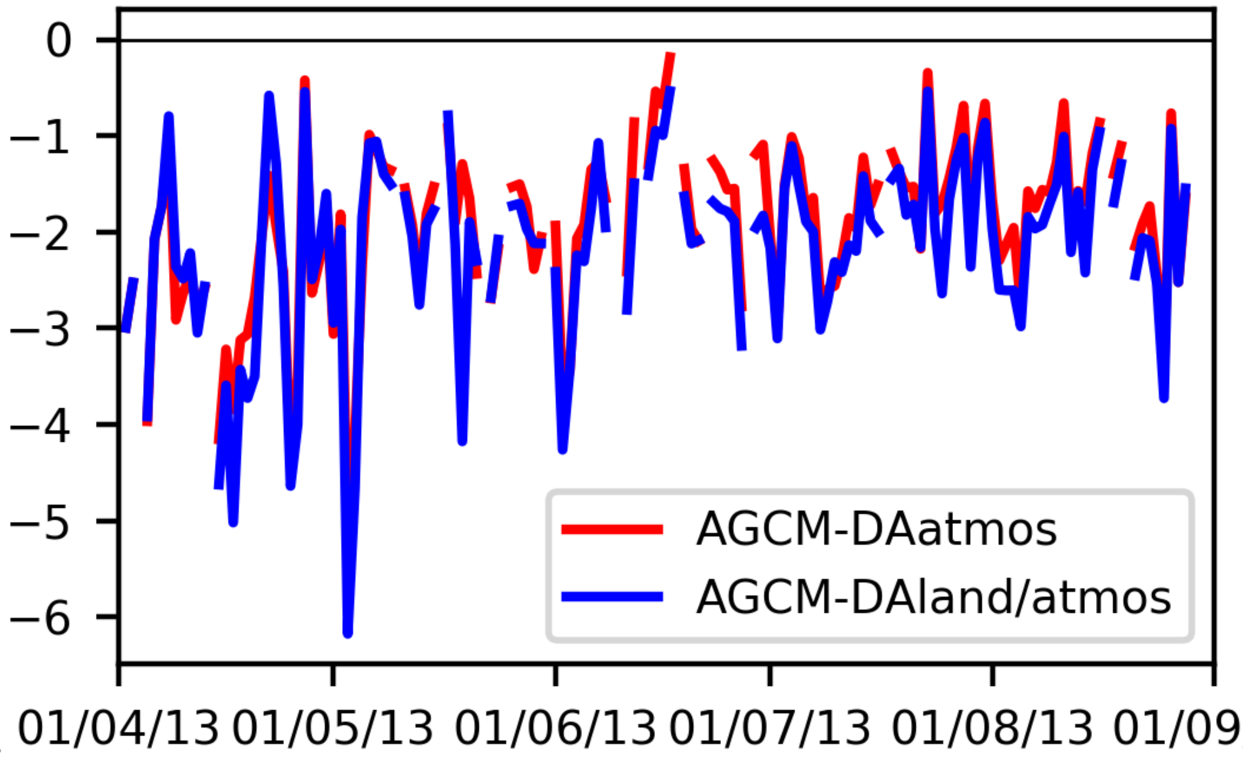
Root-zone SM [m3/m3]



Latent Heat [W/m2]



Daily Max T2m bias [K]



- Location representative of region across Sahara, where the assimilation wetted the model near-surface soil moisture, and increased latent heating by 5-15 W/m2
- T2m RMSE increased from 2.05 to 2.31 K
- Near surface soil moisture does not converge to obs.: instead assimilation persistently added small increments to the near-surface soil moisture, which are then evaporated
- Over time, a problematic volume of moisture is added to the system (enough to affect global circulation?)
  - Highlights importance of checking for serially correlated assimilation increments

Summary: Soil Moisture Assimilation into a Reanalyses

- Assimilating the satellite soil moisture into the AGCM improved the fit between the model soil moisture and ground-based observations, by a small amount
- Global average daily max T2m RMSE was decreased from 2.82 to 2.79K, with much larger reductions (~0.5 K) regionally
  - Do not expect uniform improvement, since T2m only sensitive to soil moisture where latent heating is moisture limited
  - Improvement in T2m due to improvement in biases at monthly-plus scales, rather than day-to-day variability

Next Steps: Better Integration of Land and Atmosphere DA

AGCM and Off-line Land Ensembles

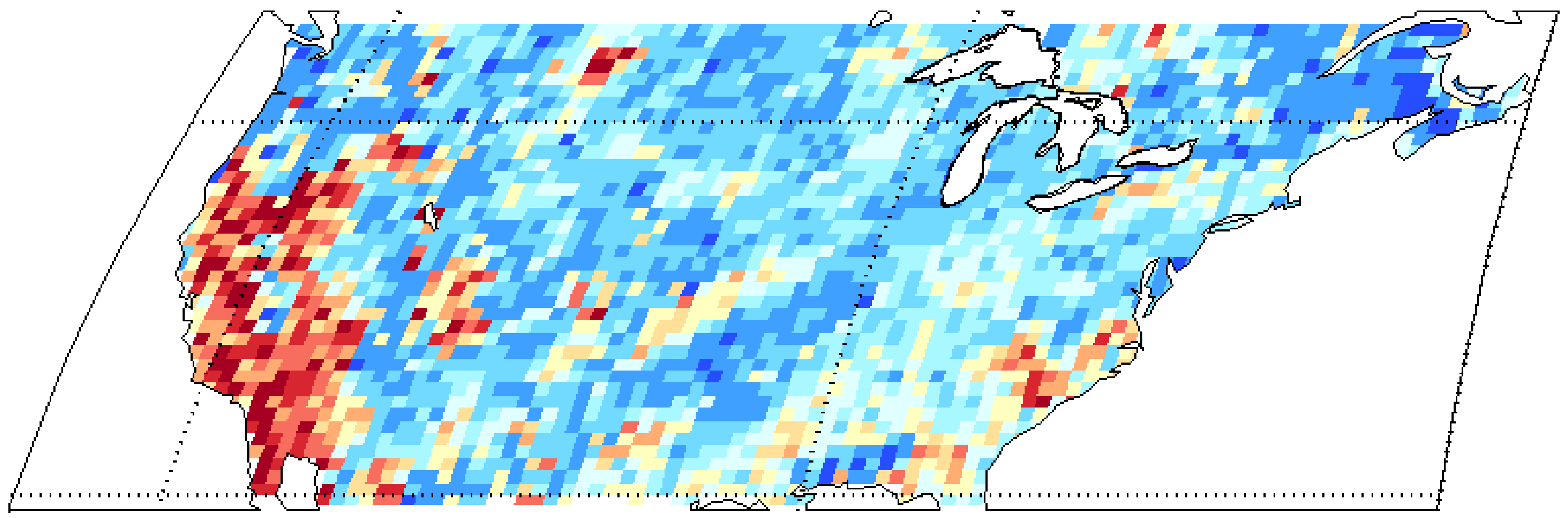
- Offline land ensembles are generated by perturbing a selection of the atmos. forcing, land states, & parameters
- Ensemble members are perturbed with climatological (usually globally defined) uncertainties, which do not represent 'errors of the day'

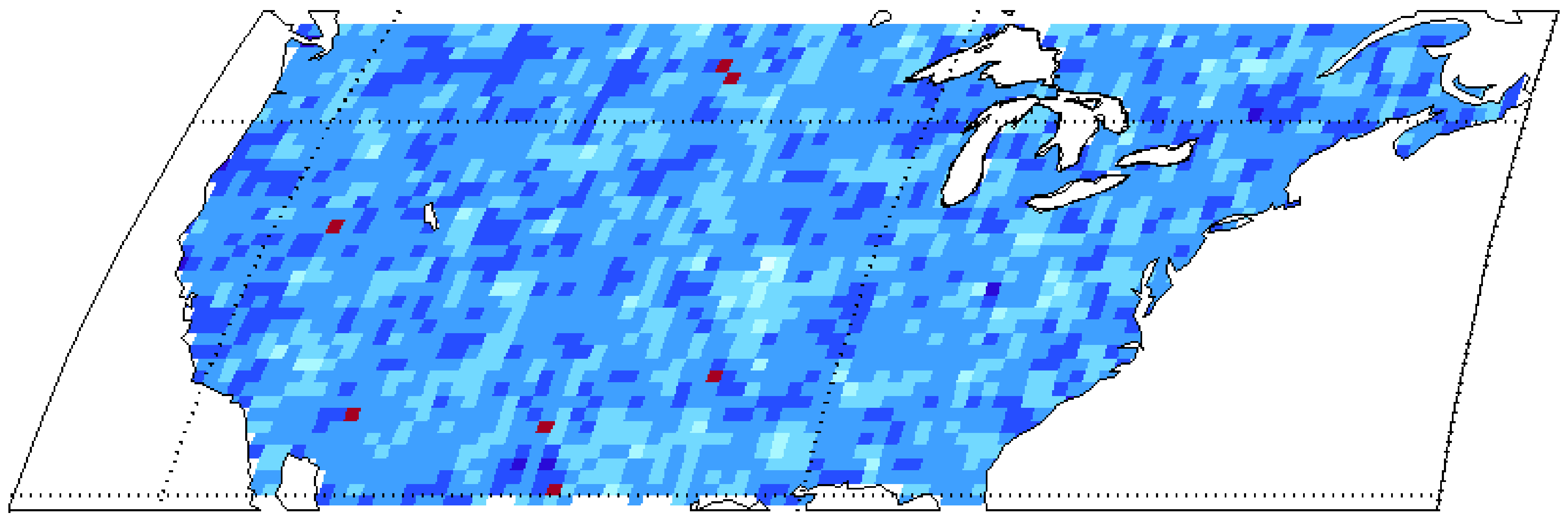
AGCM and Off-line Land Ensembles

Surface SM ens. stdev [m3/m3]

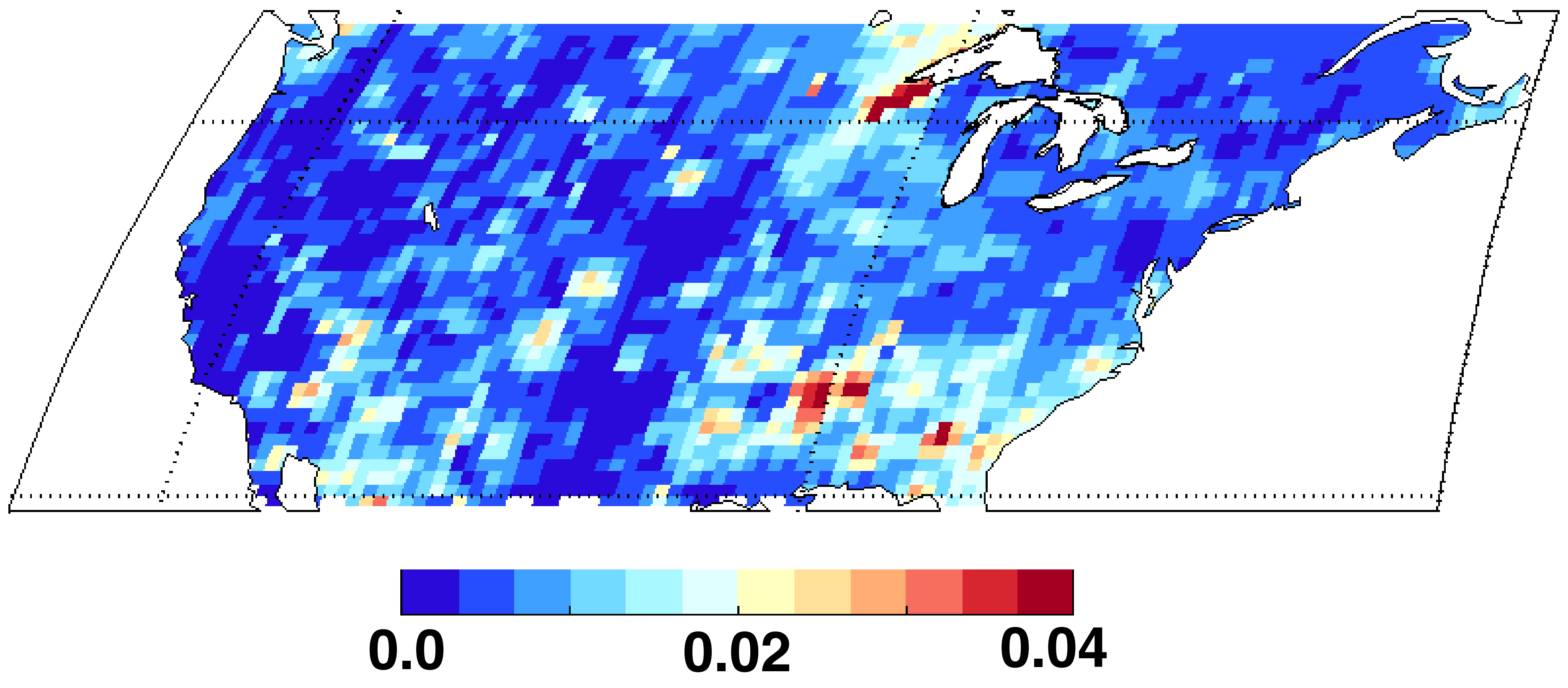
Surface SM ens. perturbation e-folding scale [°]

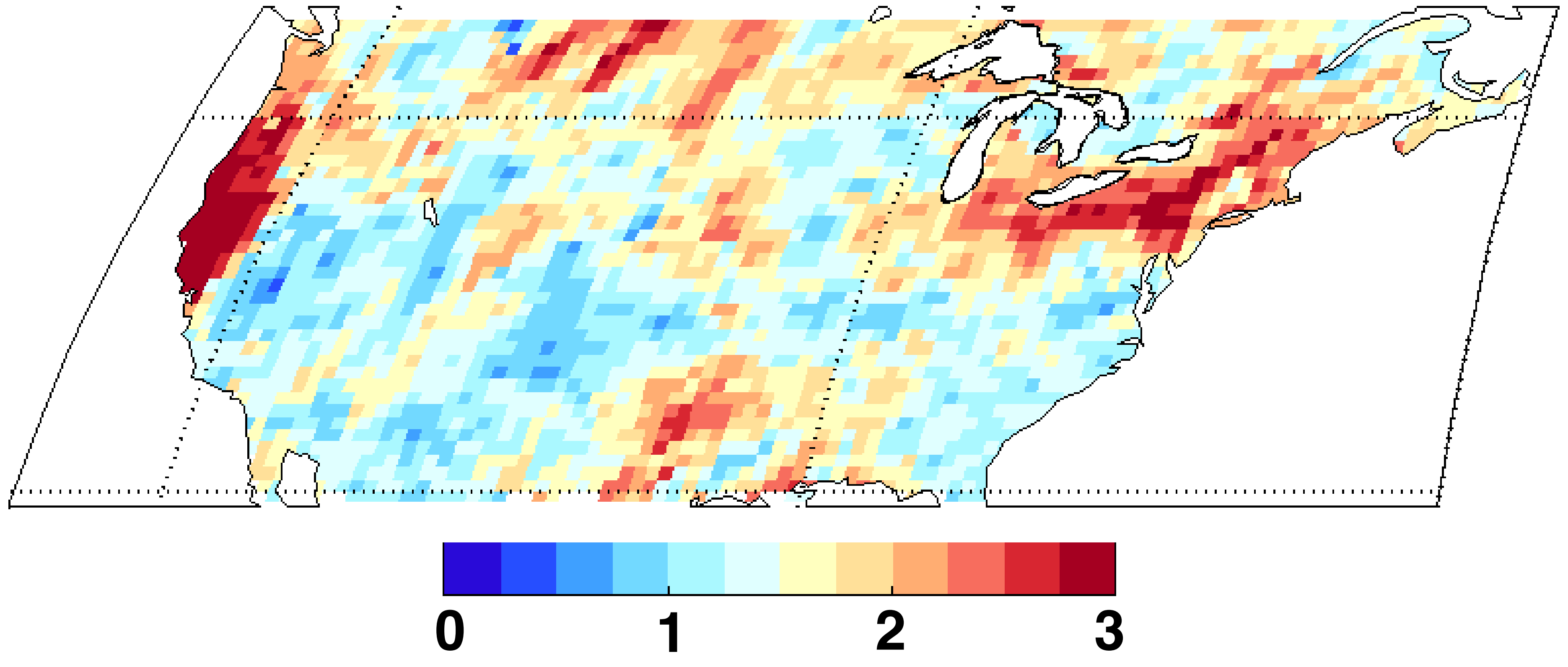
Offline from the GEOS Land EnKF





Ensemble from GEOS-5 3DVar Hydrid





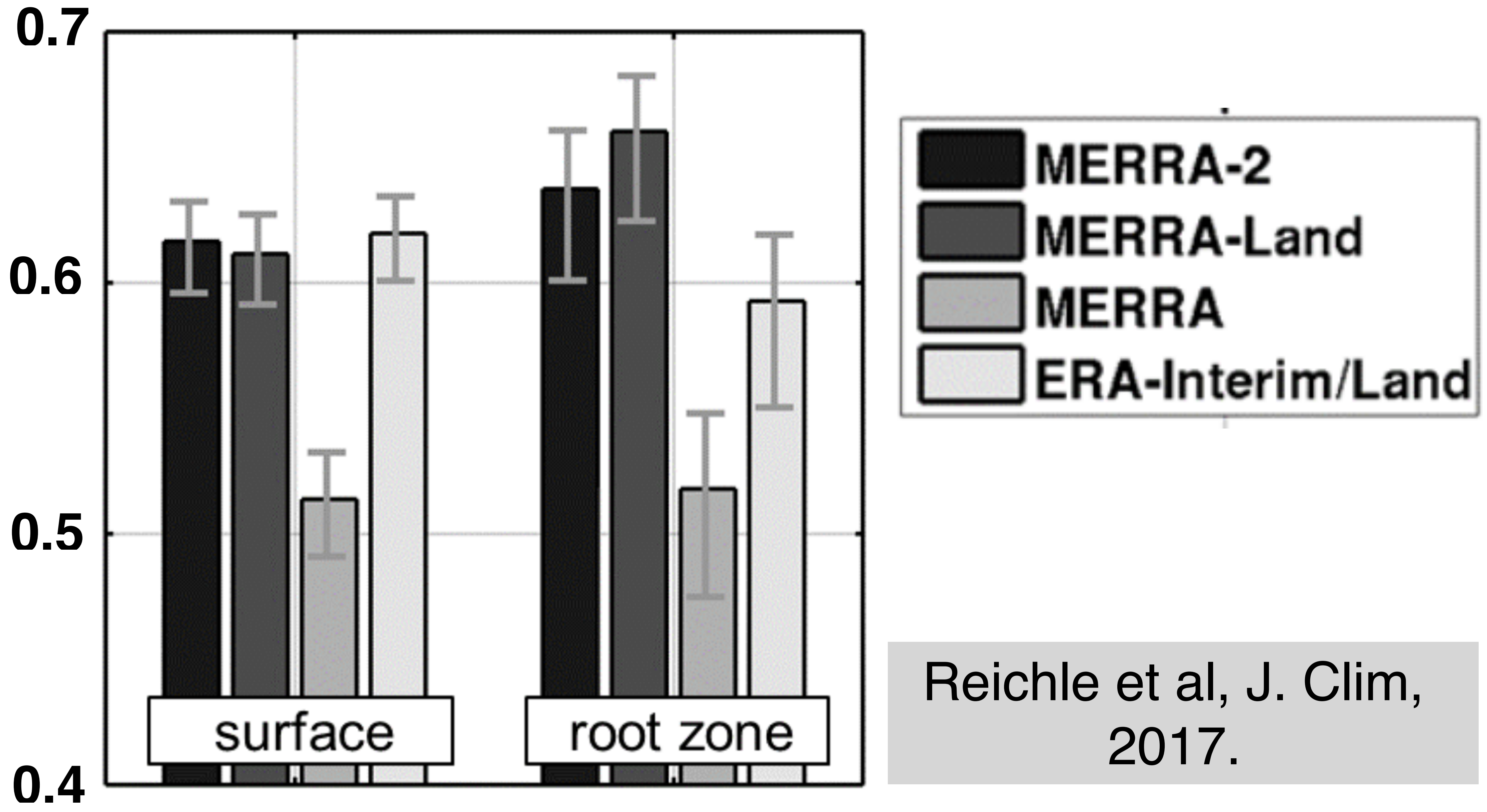
- Ensembles used in atmospheric DA do not explicitly perturb the land surface, and have insufficient spread near the surface

Complementary Approaches: Improved Land Surface Forcing

Observation-Corrected Precipitation

- Over a sufficiently long period, correct land forcing (precipitation, radiation) is more important than land initial conditions
- MERRA-2 (also CFSR, ERA-Interim Land) correct precipitation with observations as it enters the land surface
  - Significantly improves model soil moisture

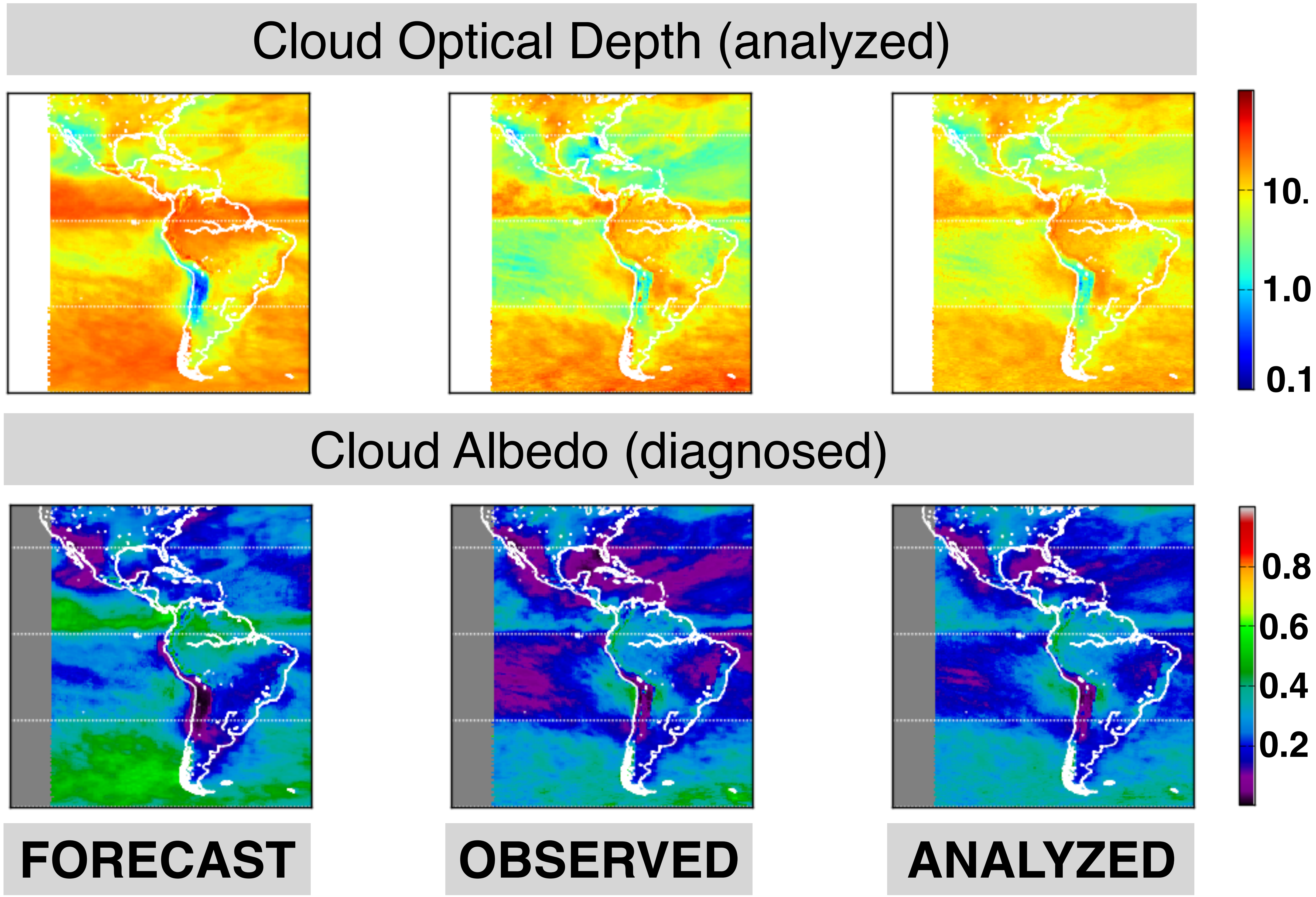
Soil moisture R_{anom}, v. in situ obs. (>200 sites)



Reichle et al, J. Clim, 2017.

Correcting Clouds/Radiation

- Assimilate cloud properties from hourly high resolution Geostationary TIR/Vis. observations, then derive corrected surface radiation



With Peter Norris, Arlindo da Silva

Summary

- Land differs from the atmosphere, land DA must be designed accordingly
- DA by design optimizes the assimilated variable, other variables are not necessarily improved
  (in coupled DA, cross-component model error particularly problematic)
- Atmosphere can be improved by assimilation of land and/or boundary layer observations
- In MERRA-2 experiments, added skill from soil moisture assimilation occurs at around monthly time scales (~time scale of root-zone soil moisture)

- Aside: focussed here in soil moisture DA, but many examples of assimilating other variables (snow DA improves NWP forecasts, vegetation DA is rapidly developing)

Outstanding Challenges

- Land DA currently targets only temporal anomalies in model states
  - How can we target the (large) model biases instead?
  - Can we improve the model by using DA methods to update model parameters?
  - How can we incorporate the spatial information in the observations?

- What are the consequences of the different time scales between (rapidly varying) observed states and the (slowly varying) model update states, and can we design a DA to address these differences?
- Can we improve land EnKF performance by using ensembles of atmospheric states?
- What is the best (design/strength) for land/atmosphere DA coupling?

Thanks for Listening

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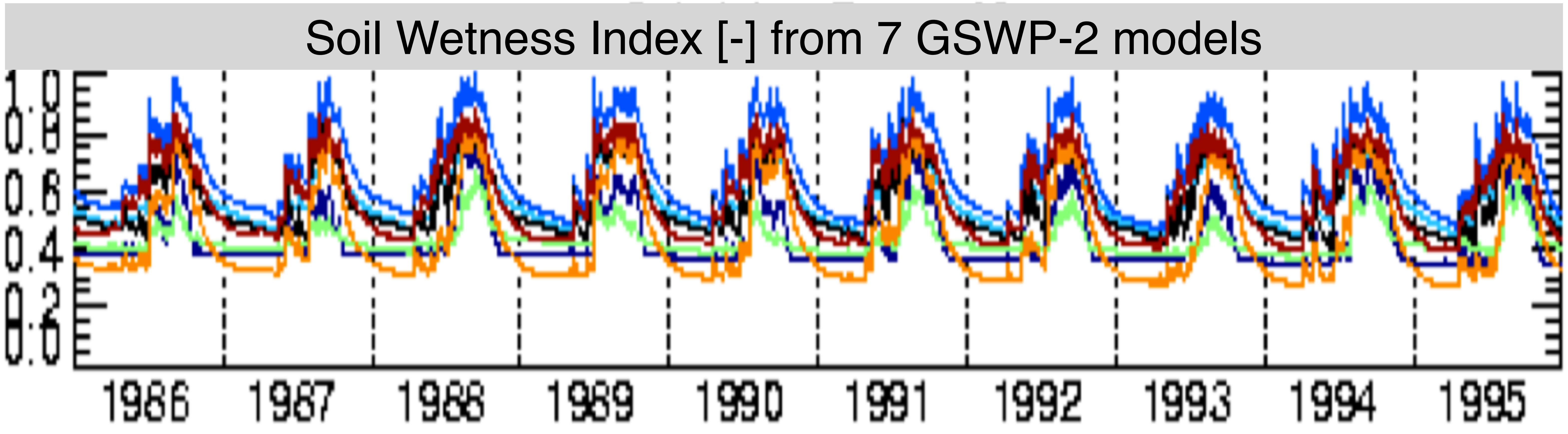
Ambiguous Definition of Model Soil Moisture

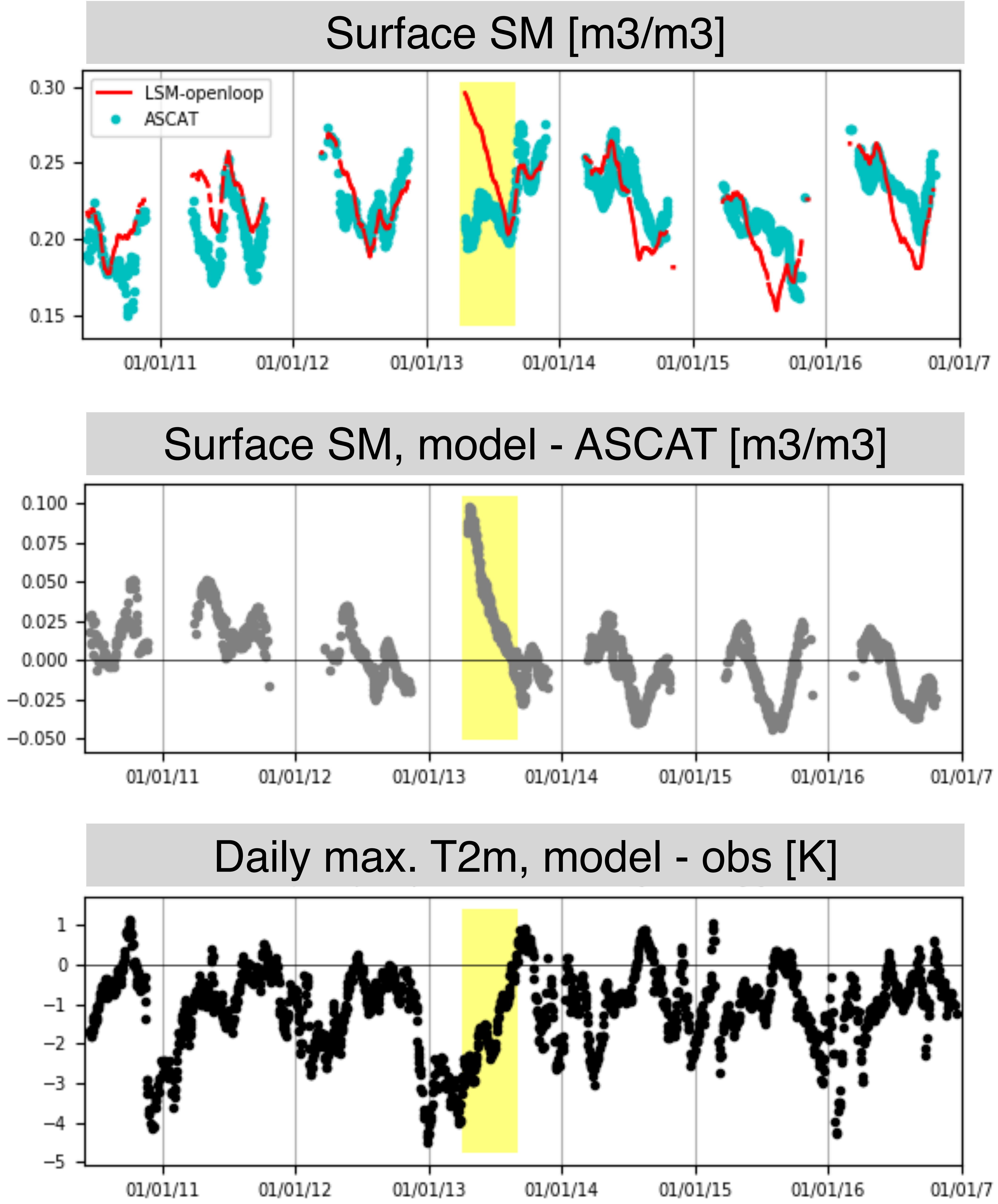
- The definition of soil moisture is model specific
- For soil moisture, the mean and variance differs between models, however temporal agreement is often good



Koster et al, J Clim, 2009

- Directly inserting soil moisture from one model (or remote sensor) into another model can cause inconsistencies and degrade forecasts

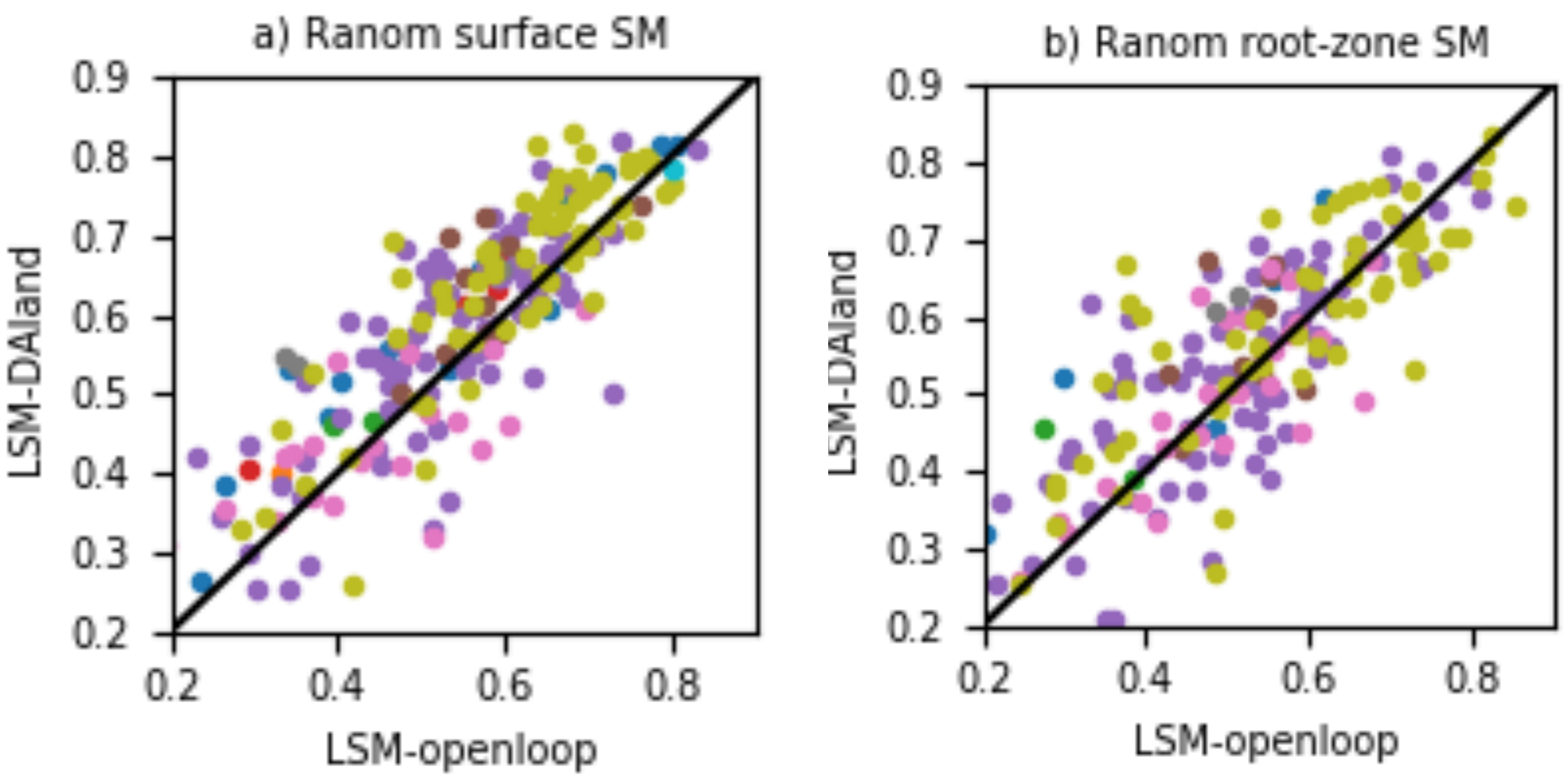
Example Timeseries: Ukraine



- The model was unusually wet during the AGCM experiment period
- Coincided with unusual cool bias in T2m
- ASCAT assimilation correctly detected this wet bias, to reduce the T2m bias

Impact on Soil Moisture Skill

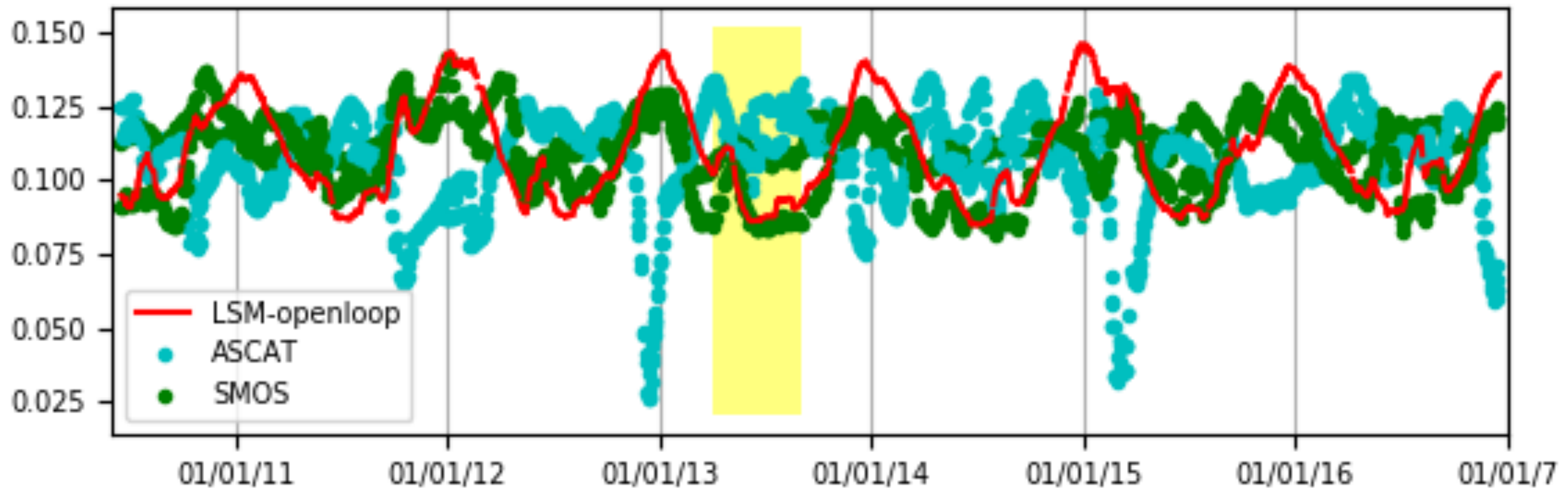
Correlation of daily anomalies from the seasonal cycle, at 215 sites



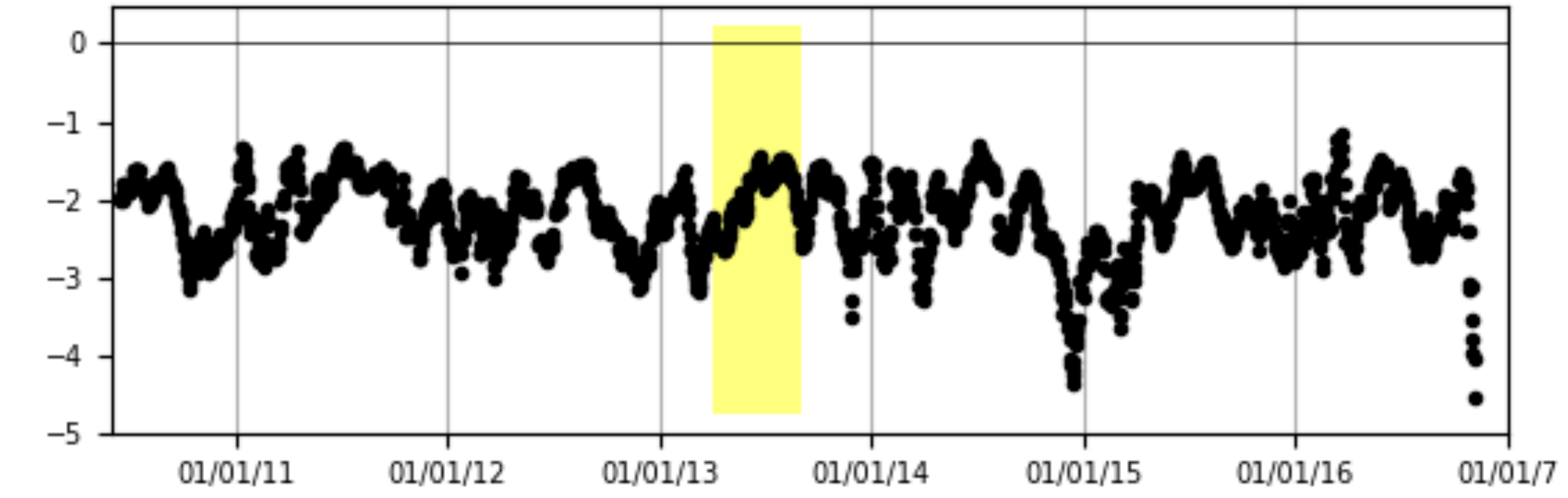
- Preliminary experiment using offline LSM to test impact on soil moisture skill of assimilating the ASCAT and SMOS soil moisture
- The fit with ground-based in situ observations by a small (but statistically significant amount)

Example Timeseries: Algeria

Surface SM [m3/m3]



Daily Max. T2m bias [K]



- Extremely arid regions are unlikely to benefit from assimilating soil moisture
- Satellite soil moisture does not look realistic
- Given very low temporal variability, observation signal-to-error ratio will be very low
- In future, screen out arid (low variability) regions

- Also, for land DA into AGCMs, check for serially correlated assimilation increments