

Soil Moisture & Brightness Temperature Assimilation for GEOS Reanalysis

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Introduction

- If atmospheric forecasts and reanalyses incorporate our **best estimates** of soil moisture (SM), the skill of these atmospheric products should **improve**
- A **weakly coupled data assimilation** system for land analysis was recently implemented in NASA GEOS, to use in future GEOS reanalyses (Reichle et al., 2023)
- Best estimate of SM from assimilating SM observations from **multiple sensors simultaneously**
    1. Have different spatial and temporal support
    2. Based on complementary measurement principles
- Adding capability to **assimilate ASCAT SM** to the established GEOS LDAS that assimilates SMAP Tbs

Important caveat:

- Satellites do not directly measure SM, relying on complex retrieval algorithms, causing large uncertainties in estimates and **inconsistency between sensors** (Gruber et al., 2020)

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Reichle et al., 2023. doi: 10.1002/qj.4486
Gruber et al., 2020. doi: 10.1016/j.rse.2020.111806

System Setup

SMAP Level-4 Soil Moisture (L4SM) system (Reichle et al., 2019)

Observations

- ASCAT Soil Moisture
  - Relative wetness, or **surface degree of saturation (SFDS)**, in 0-2 cm soil layer
- SMAP Brightness Temperatures

GEOS Land Data Assimilation System

- ASCAT SFDS Assimilation
- SMAP Tb Assimilation
- Multi-sensor Assimilation

Evaluation

- 18 SMAP core sites in-situ SM measurements
- Instrumental Variable Approach
- Data Assimilation Diagnostics

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Reichle et al., 2019. doi: 10.1029/2019ms001729

System Updates

Additions to the SMAP Level-4 Soil Moisture (L4SM) system (Reichle et al., 2019)

ASCAT SFDS assimilation

- Quality control flags are used to remove “bad” observations or if the Catchment model indicates frozen or snow-covered ground.
- Z-score based scaling factors correct for differences in (6-year) climatologies of the SFDS obs and modeled surface SM
  - Vary spatially (discretized on a 0.25° latitude/longitude grid) and temporally (5 day)
  - Implicitly includes change of units from observation space (wetness %) to model space (m^3/m^3)
- Assumed observation error of 9 % globally

Multi-sensor assimilation

- Jointly assimilate SMAP Tbs and ASCAT SM by identifying SMAP and ASCAT observations within a given assimilation window
- Combining both observation types (and the corresponding model-predicted values) into a single observation matrix

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Experiments

Experiment Name	Observations assimilated	Precipitation Forcing
CTRL_FP	None	Modeled FP precipitation
ASC_FP	ASCAT SM	
CTRL_IM	None	Observed IMERG precipitation
ASC_IM	ASCAT SM	
SMP_IM	SMAP Tb	
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- Simulation period: April 2015 – March 2021 (6 years)
- Model setup: Catchment land surface model run on 36 km resolution EASEv2 grid
- Forcing data: GEOS FP weather analysis at 0.25° x 0.3125° (latitude x longitude) resolution
- DA configuration: 24 member Ensemble Kalman Filter with perturbations, analysis every 3 hrs

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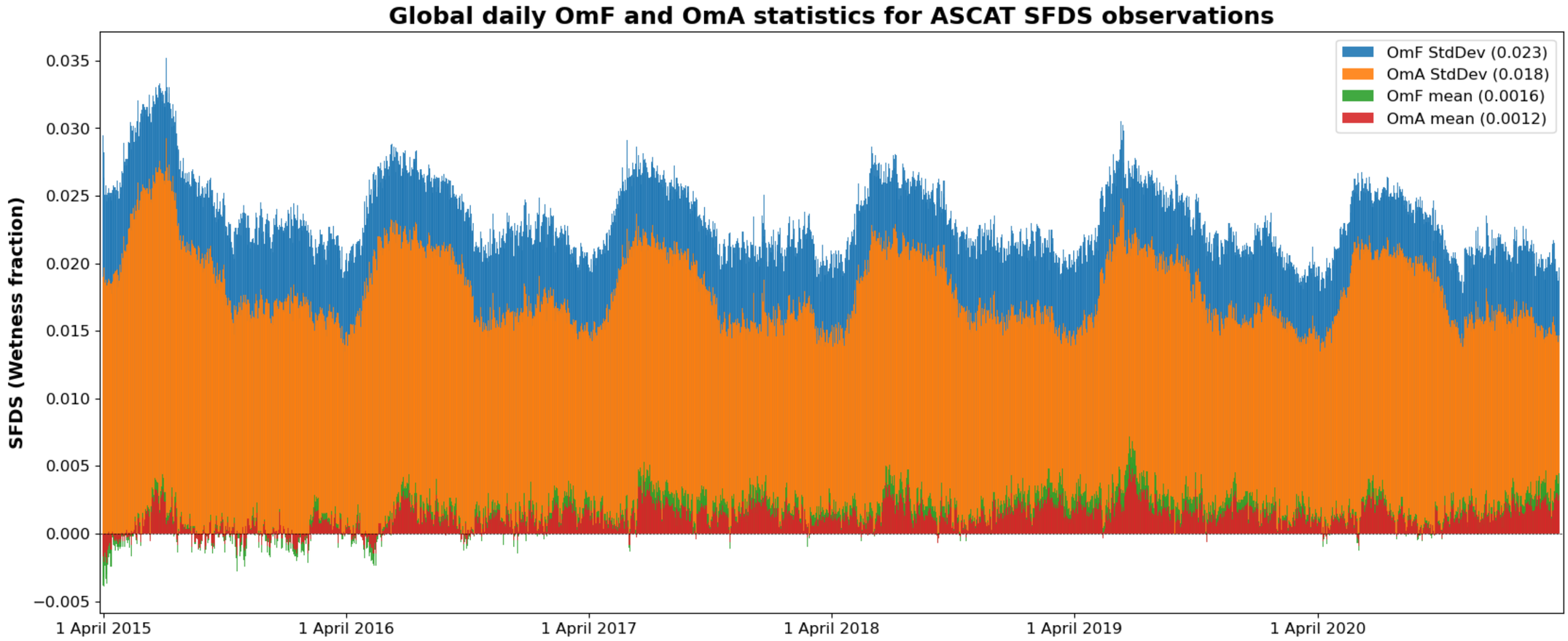
TODAY'S FOCUS

- Simulation period: April 2015 – March 2021 (6 years)
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Does the new ASCAT SM assimilation capability work, and what is its impact?

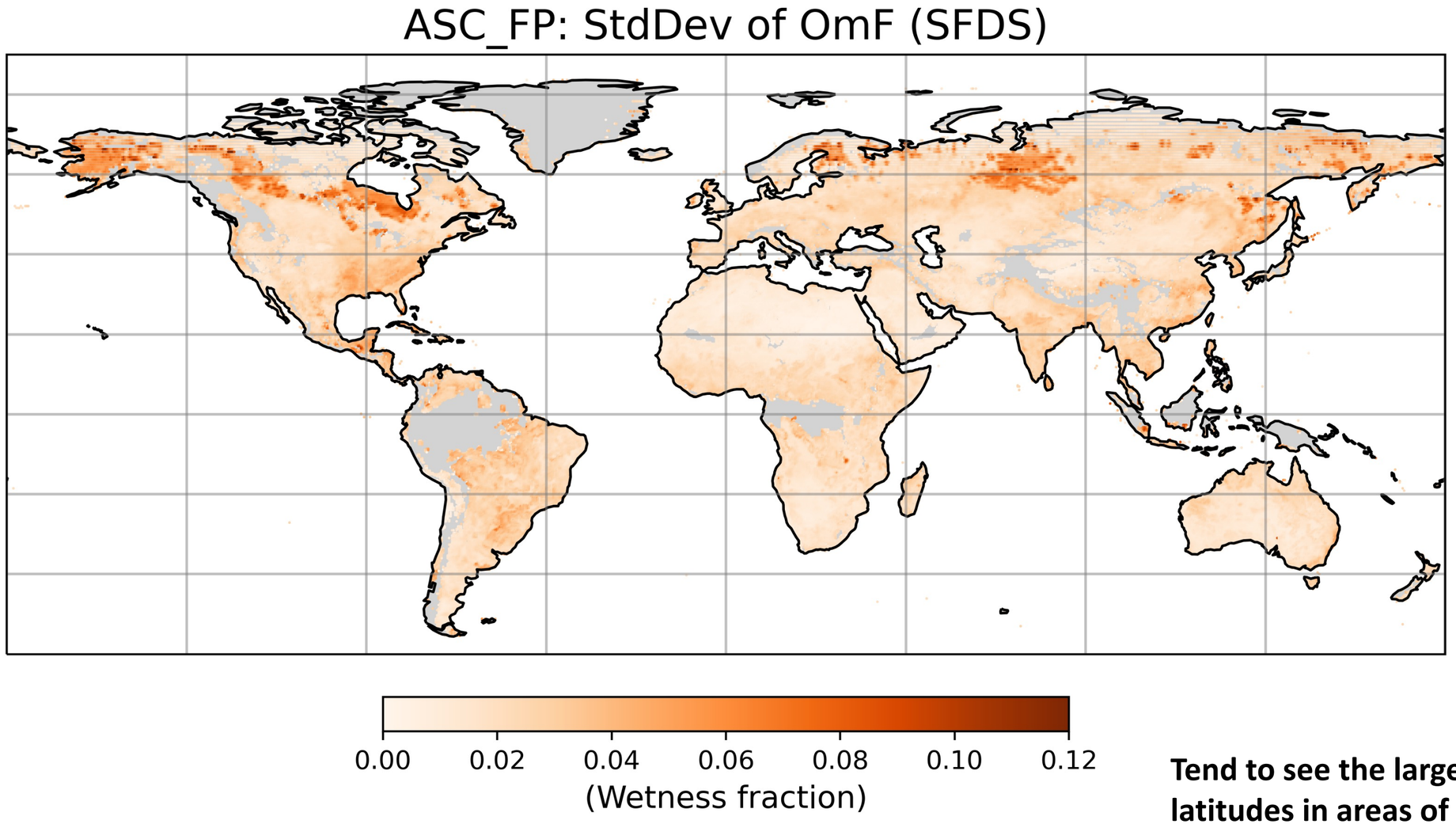
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Data Assimilation Diagnostics for ASC_FP



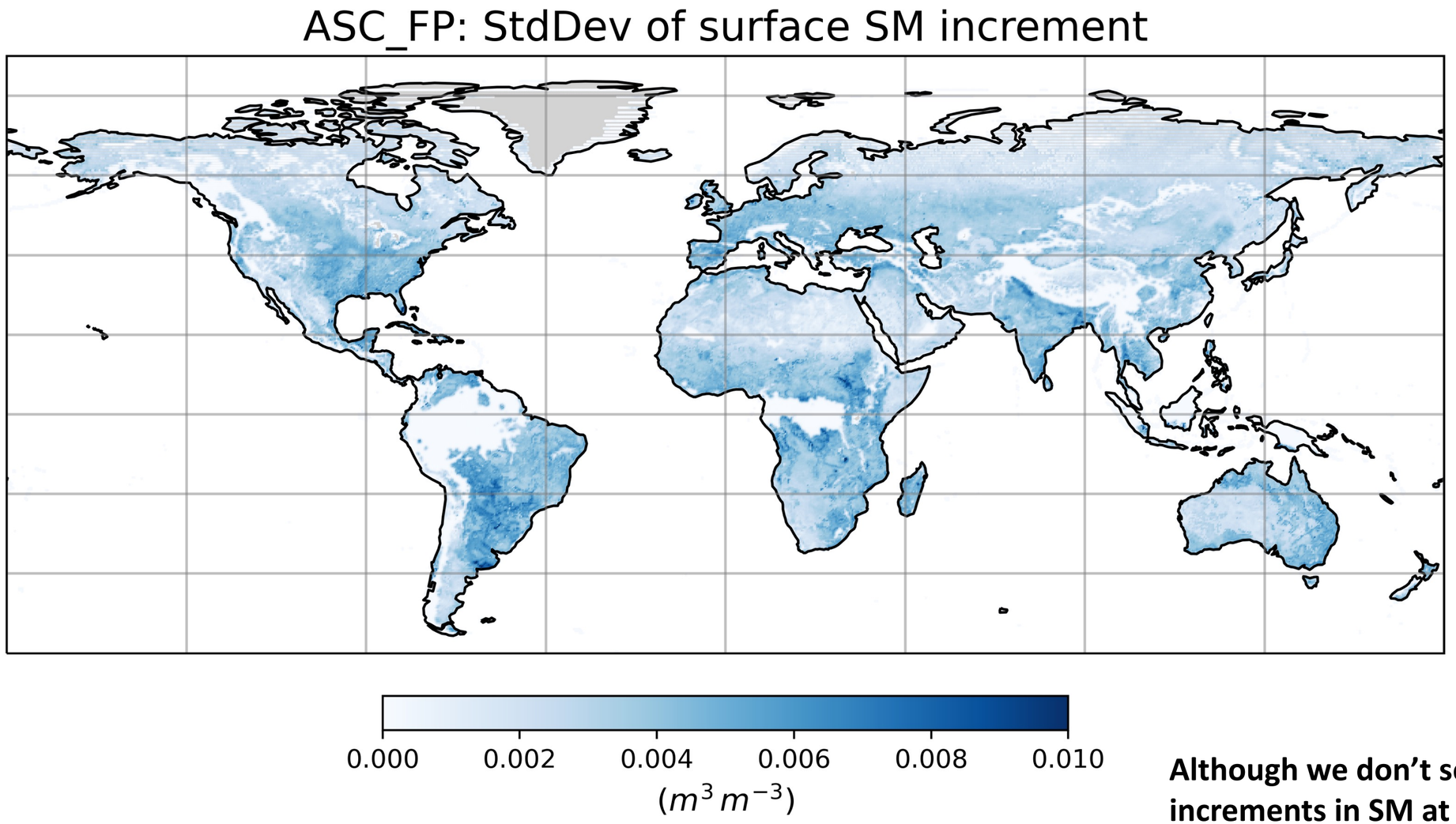
Initial DA diagnostics indicate system is performing correctly, with OmA consistently lower than OmF, and mean OmF tending towards zero

Time series StdDev of OmF residuals for ASC_FP



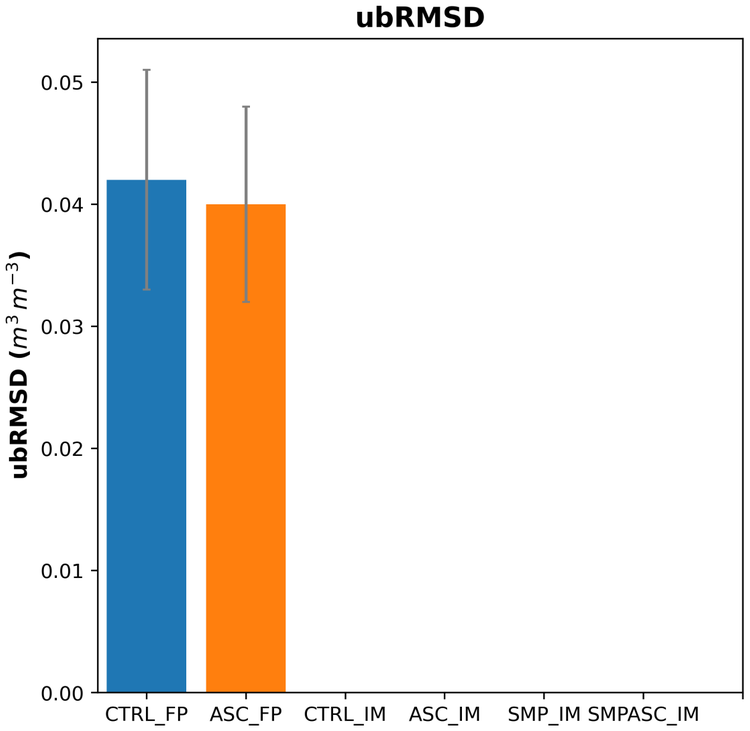
Tend to see the largest OmFs are high latitudes in areas of peatland, perhaps scaling not working as expected

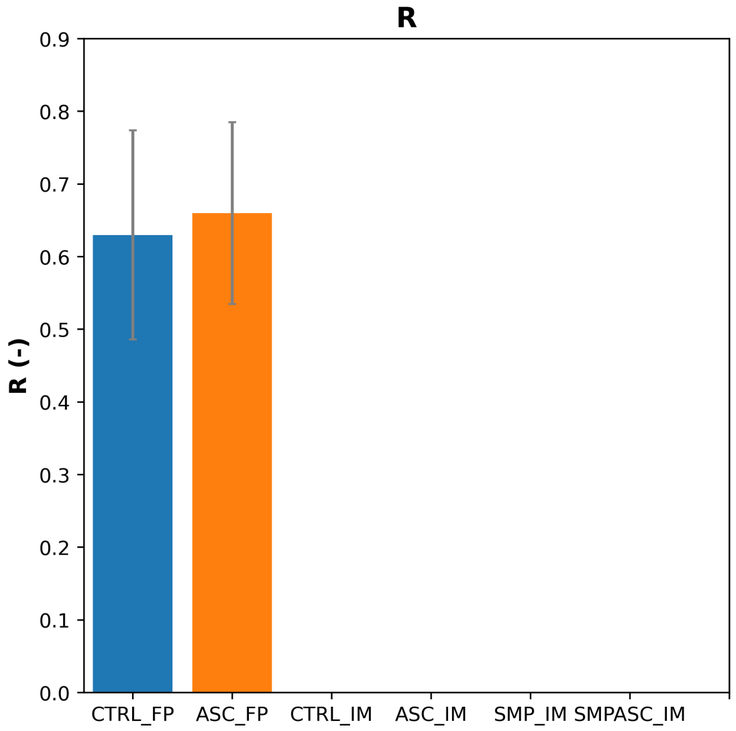
Time series StdDev of surface SM increments for ASC_FP

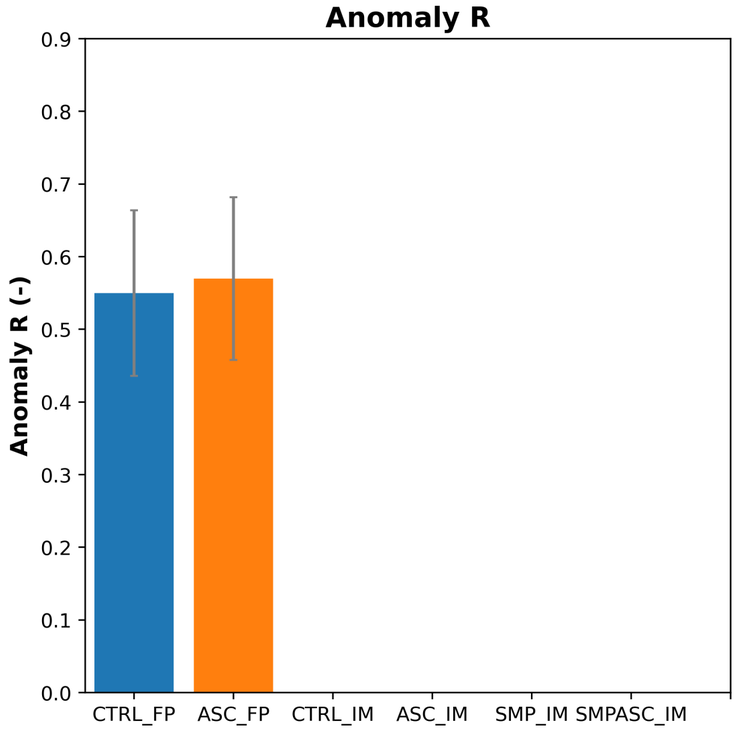


Although we don't see the largest increments in SM at these locations

Skill Metrics at Core Validation Sites for CNTL_FP & ASC_FP

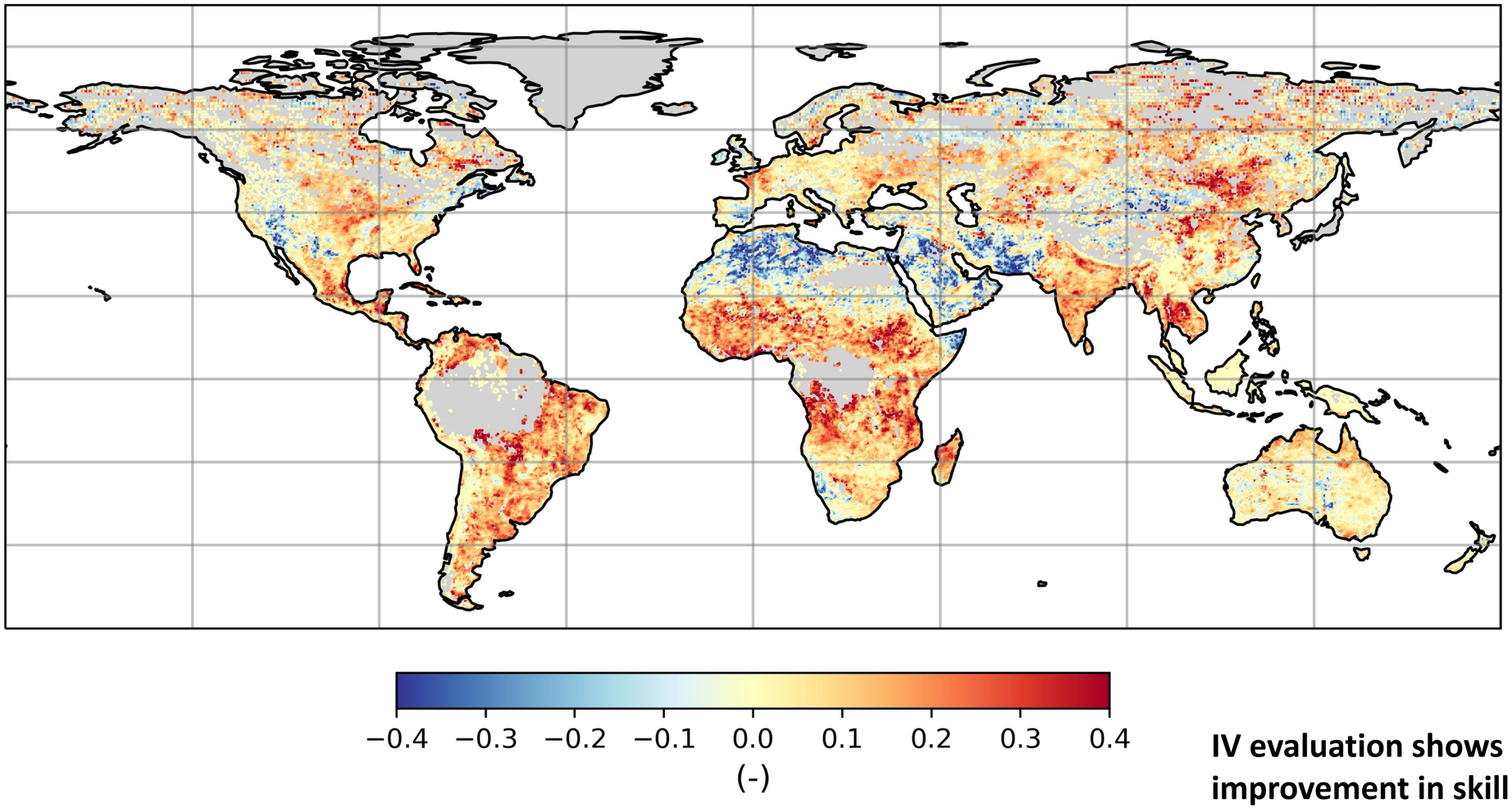






Overall improvement following the assimilation of ASCAT SM across the validation in-situ core sites

IV evaluation of ASC_FP minus CTRL_FP



IV evaluation shows a lot of improvement in skill after assimilation, but degradation over desert regions

How big is the impact of using observed precipitation?

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- GEOS reanalysis efforts will use “observed” precipitation, such as IMERGv7
- Skill of CTRL_IM comparable to ASC_FP
- Impact of ASCAT assimilation is much more limited when using observed precipitation
- SMP_IM has (much) more skill than ASC_IM at core sites, especially for correlation

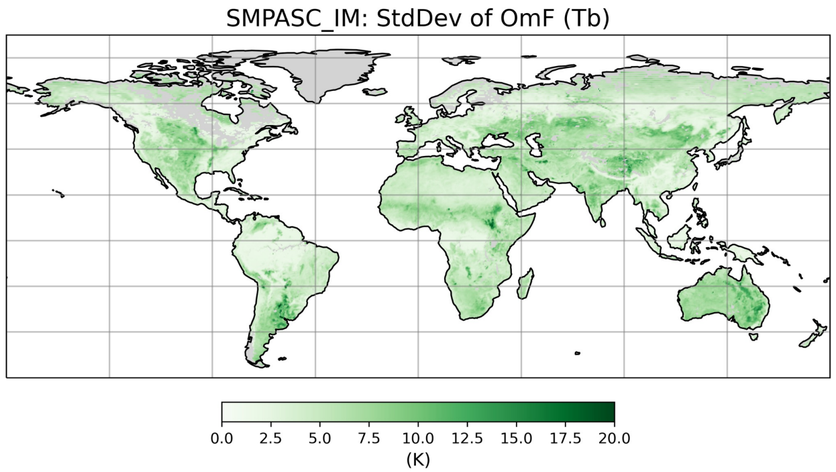
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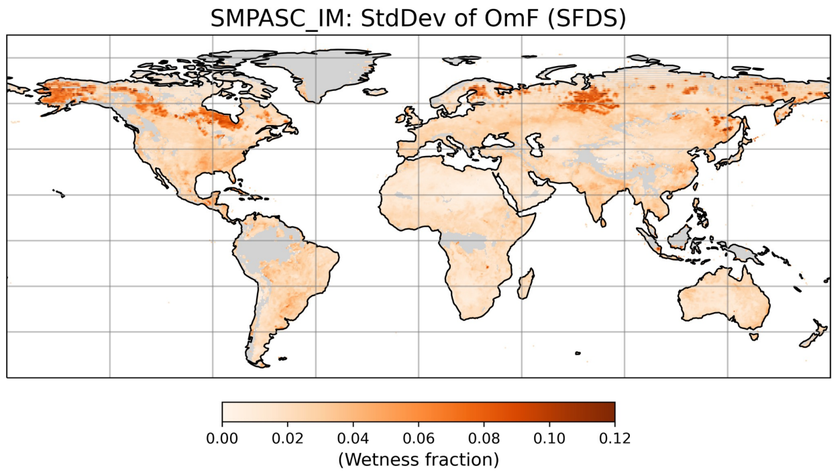
Reichle et al., 2023. doi: 10.1175/JHM-D-23-0063.1

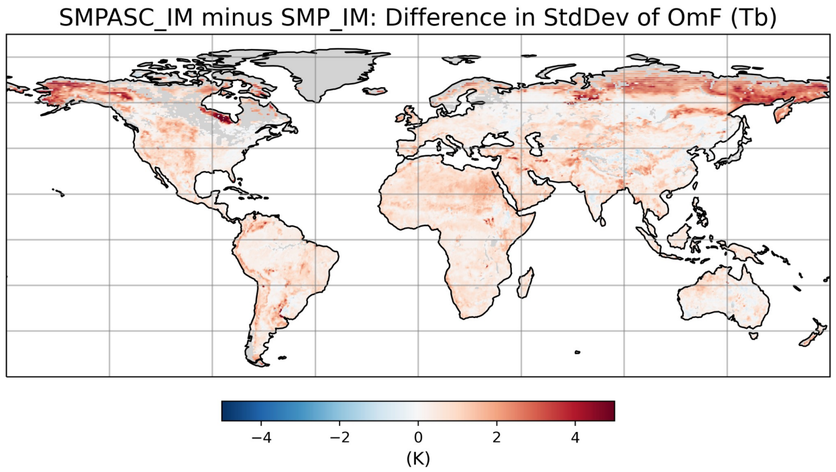
What is the impact of assimilating both SMAP Tbs and ASCAT SM simultaneously?

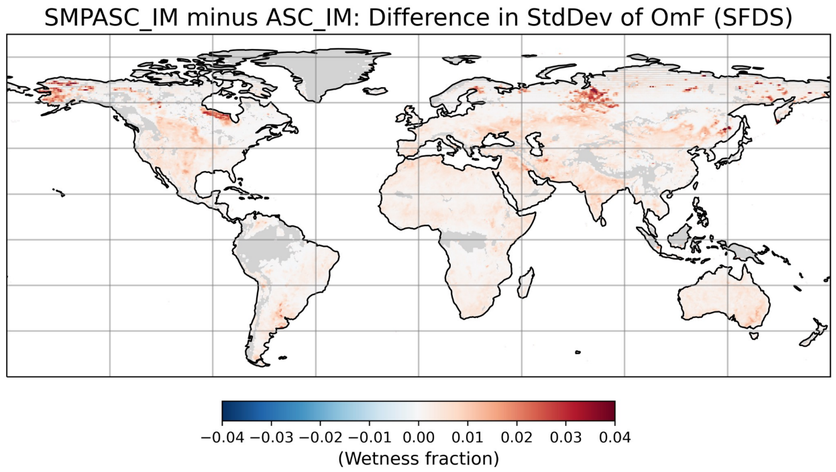
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Time series StdDev of OmFs for Tb and SFDS observations for SMPASC_IM



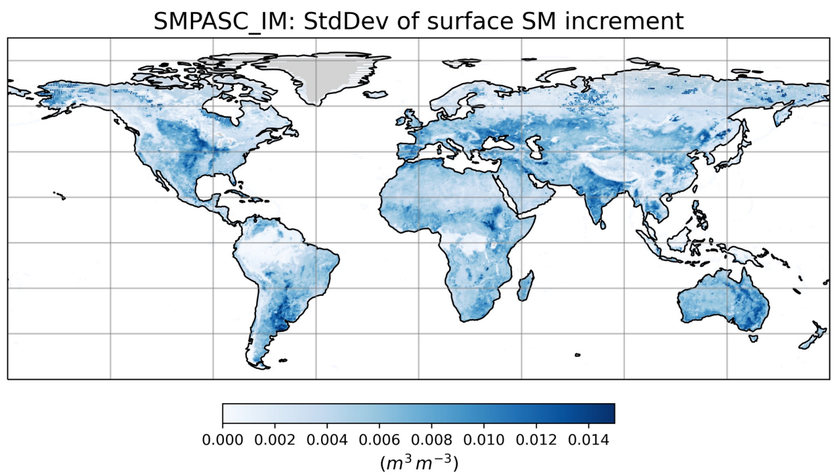


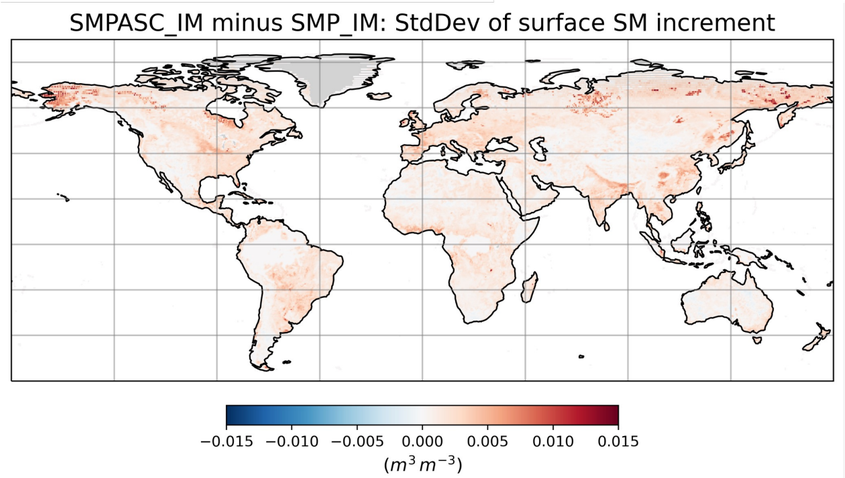


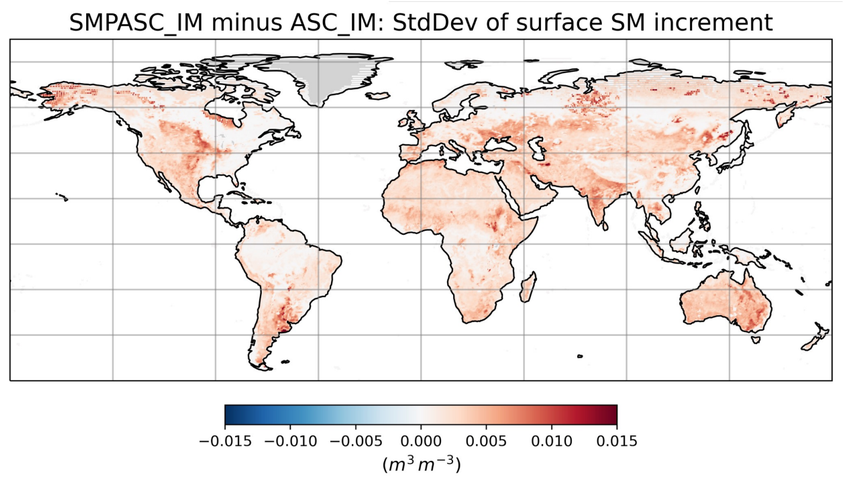


OmFs are larger for both types of observations, indicating they are providing inconsistent information

Time series StdDev of surface SM increments for SMPASC_IM

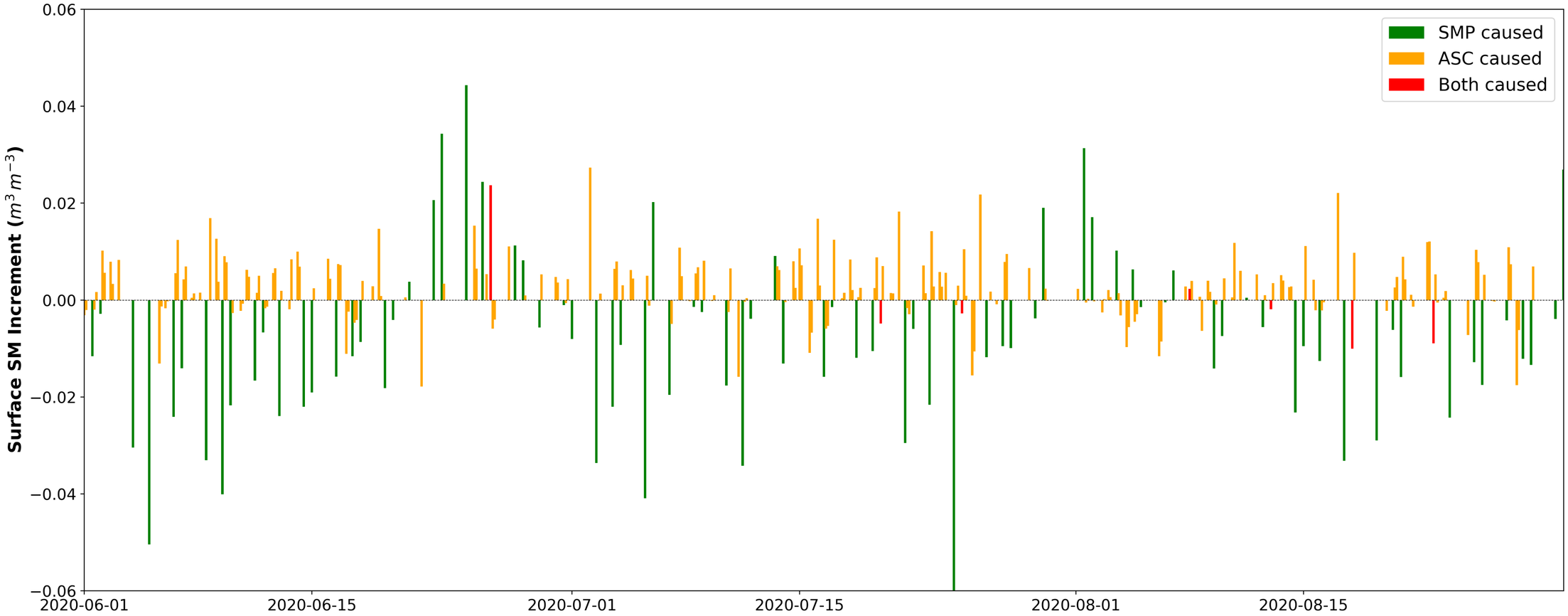






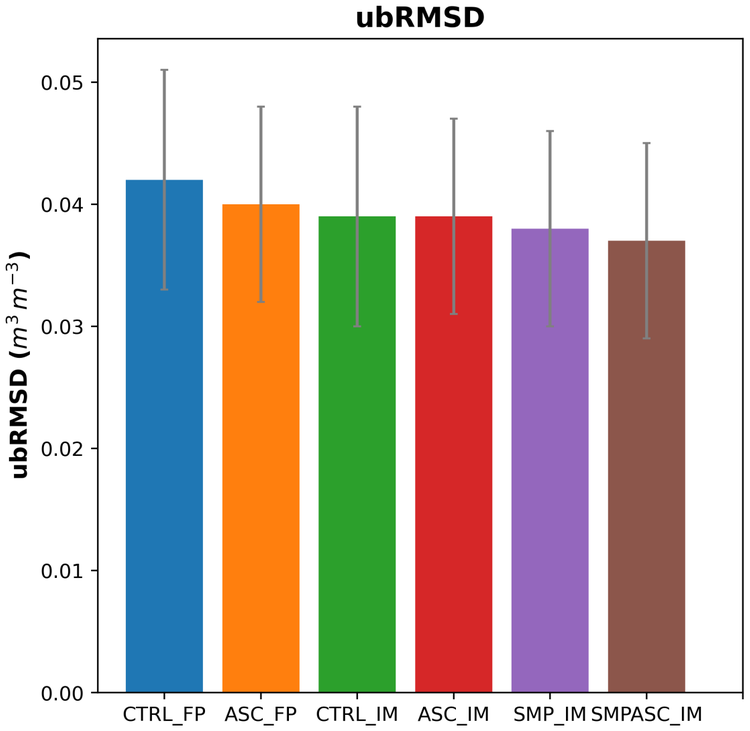
SM increments are larger than for the assimilation of each type alone, especially where SFDS OmFs are large

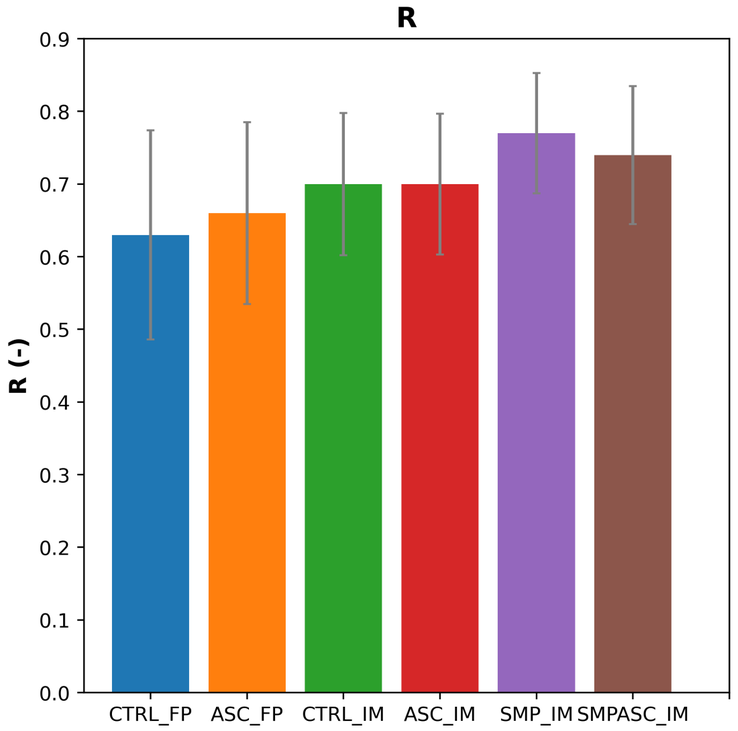
SM increments at Little Washita, OK core site, JJA 2020

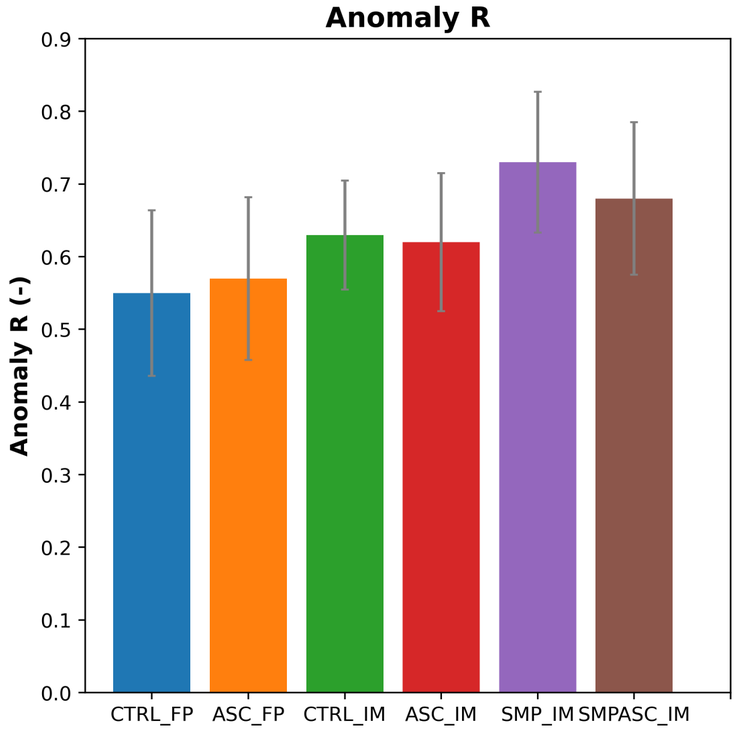


Often during this time period, SMAP assimilation is causing drying, whilst ASCAT is causing wetting, pulling the soil moisture in opposite directions

Skill Metrics at Core Validation Sites for SMPASC_IM







Assimilating both observation types does lead to small decrease in ubRMSD, but degradation in correlation

Summary and Next Steps

Summary

- Added capability to assimilate ASCAT SM and SMAP Tbs simultaneously to GEOS LDAS
- Neutral (at best) impact, but marked degradation over deserts

Next steps

- System improvements to address “desert” issue
- Assess impact of ASCAT SM DA in pre-SMAP time period
- Experiment in weakly coupled DA system
- Integrate into the reanalysis system

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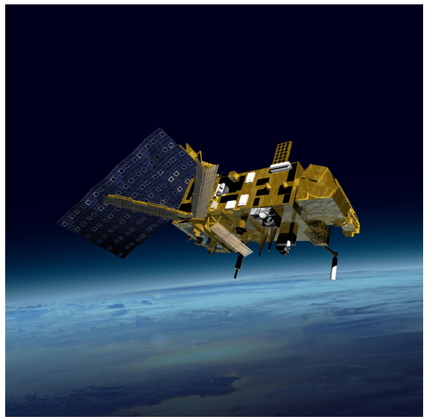
andrew.fox@nasa.gov

Extra Slides

Observations

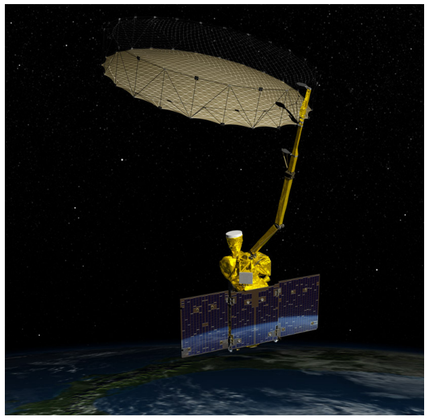
ASCAT Soil Moisture

- Soil wetness retrievals from C-Band (5.3 GHz) backscatter measurements from ASCAT sensor onboard the Metop series of satellites
- 25 km swath grid, BUFR format, near-real time
- Relative wetness, or **surface degree of saturation (SFDS)**, in 0-2 cm soil layer is retrieved by a change detection algorithm to a backscatter time series.
- SFDS observations range between 0% and 100%, representing the driest and wettest observations at each location



SMAP Brightness Temperatures

- SMAP has an L-band (1.4 GHz) radiometer highly sensitive to water in the surface (0-5 cm) soil layer
- Horizontal (H) and vertical (V) polarization brightness temperatures (Tb)
- Provided on the 36-km resolution Equal-Area Scalable Earth version 2 (EASEv2) grid



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GEOS Land Data Assimilation System

Forms the basis of the SMAP Level-4 Soil Moisture (L4SM) algorithm (Reichle et al., 2019)

ASCAT SFDS assimilation

- Quality control flags are used to remove “bad” observations or if the Catchment model indicates frozen or snow-covered ground.
- Z-score based scaling factors correct for differences in (6-year) climatologies of the SFDS obs and modeled surface SM
  - Vary spatially (discretized on a 0.25° latitude/longitude grid) and temporally (5 day
  - Implicitly includes change of units from observation space (wetness %) to model space (m^3/m^3)
- Assumed observation error of 9 % globally
- EnKF state vector includes model prognostic moisture variables, “surface excess”, “root-zone excess” and “catchment deficit”
- Soil moisture (m^3/m^3) is diagnosed for the “surface” (0-5 cm), “root-zone” (0-100 cm), and “profile” (0 cm to bedrock) layers

SMAP Tb assimilation

- SMAP Tb observations are scaled to match the climatology of the simulated Tbs
- Model forecast Tbs are estimated using a “tau-omega” L-band radiative transfer model
- Observation error of 4 K globally

Multi-sensor assimilation

- Jointly assimilate SMAP Tbs and ASCAT SM by identifying SMAP and ASCAT observations within a given assimilation window
- Combining both observation types (and the corresponding model-predicted values) into a single observation matrix

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Reichle et al., 2019. doi: 10.1029/2019ms001729

Evaluation

In-situ soil moisture measurements

- 18 different SMAP core validation sites (Colliander et al., 2017)
- Calculate unbiased root-mean-square difference (ubRSMD, or standard deviation of the error), time series correlation (*R*) and anomaly *R* metrics

Instrumental variable approach

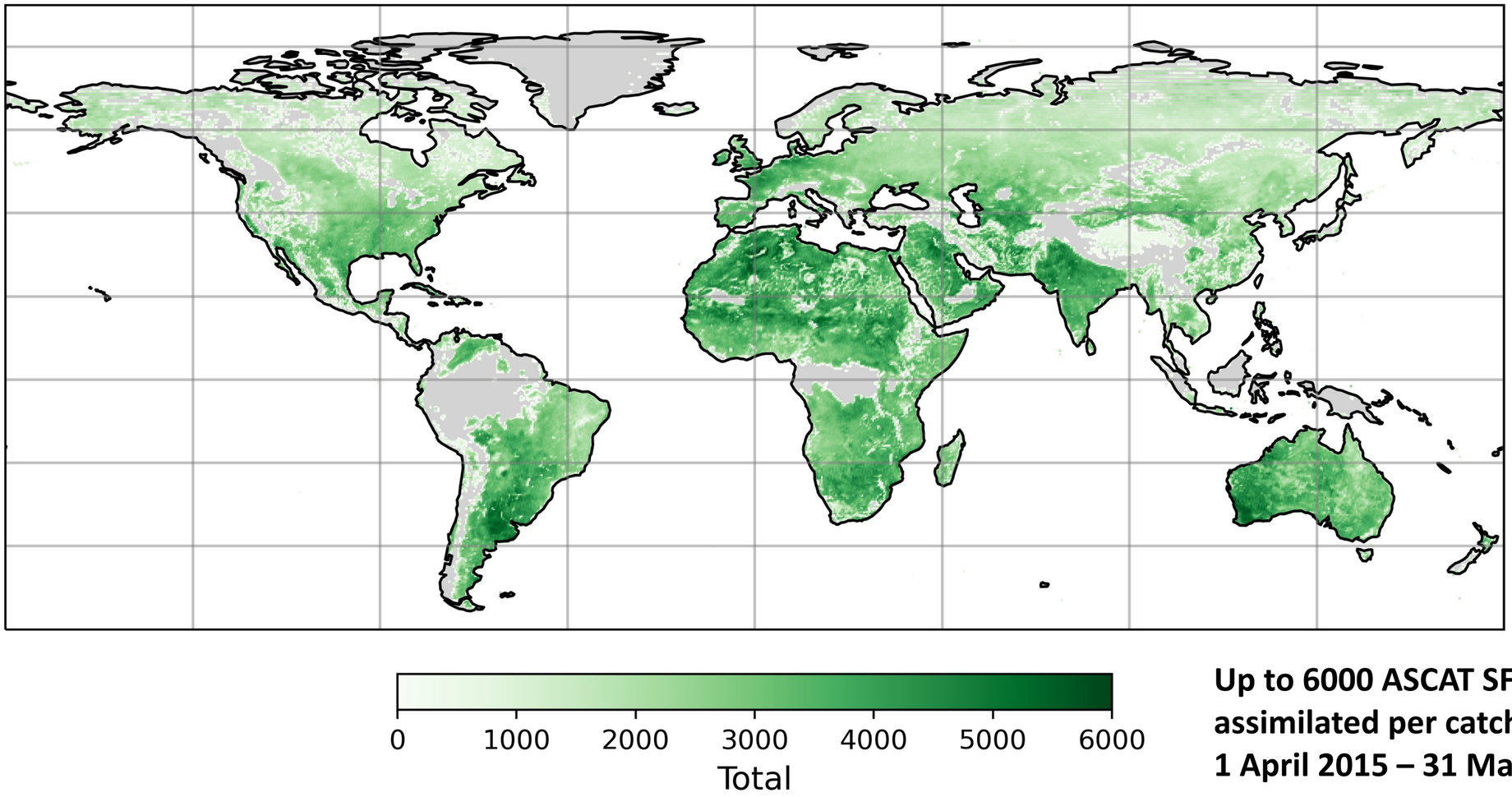
- Differences in soil moisture skill between the experiments quantified using SMAP daily SM product is used as an Instrumental Variable (IV) to assess ASCAT-only experiments (Su et al., 2014)
- IV method obtains the difference in skill between different surface SM estimates versus an unknown true SM through their sample correlation versus the independent satellite observations

Data assimilation diagnostics

- Statistics describing observation-minus-forecast (OmF) residuals, observation-minus-analysis (OmA) residuals and SM analysis increments are typically the most informative metrics
- Time series StdDev of the OmF provides an estimate of the typical misfit between the model forecast and the (scaled) observations

Colliander et al., 2017. doi: 10.1016/j.rse.2017.01.021
Su et al., 2014. doi: 10.1002/2013JD021043

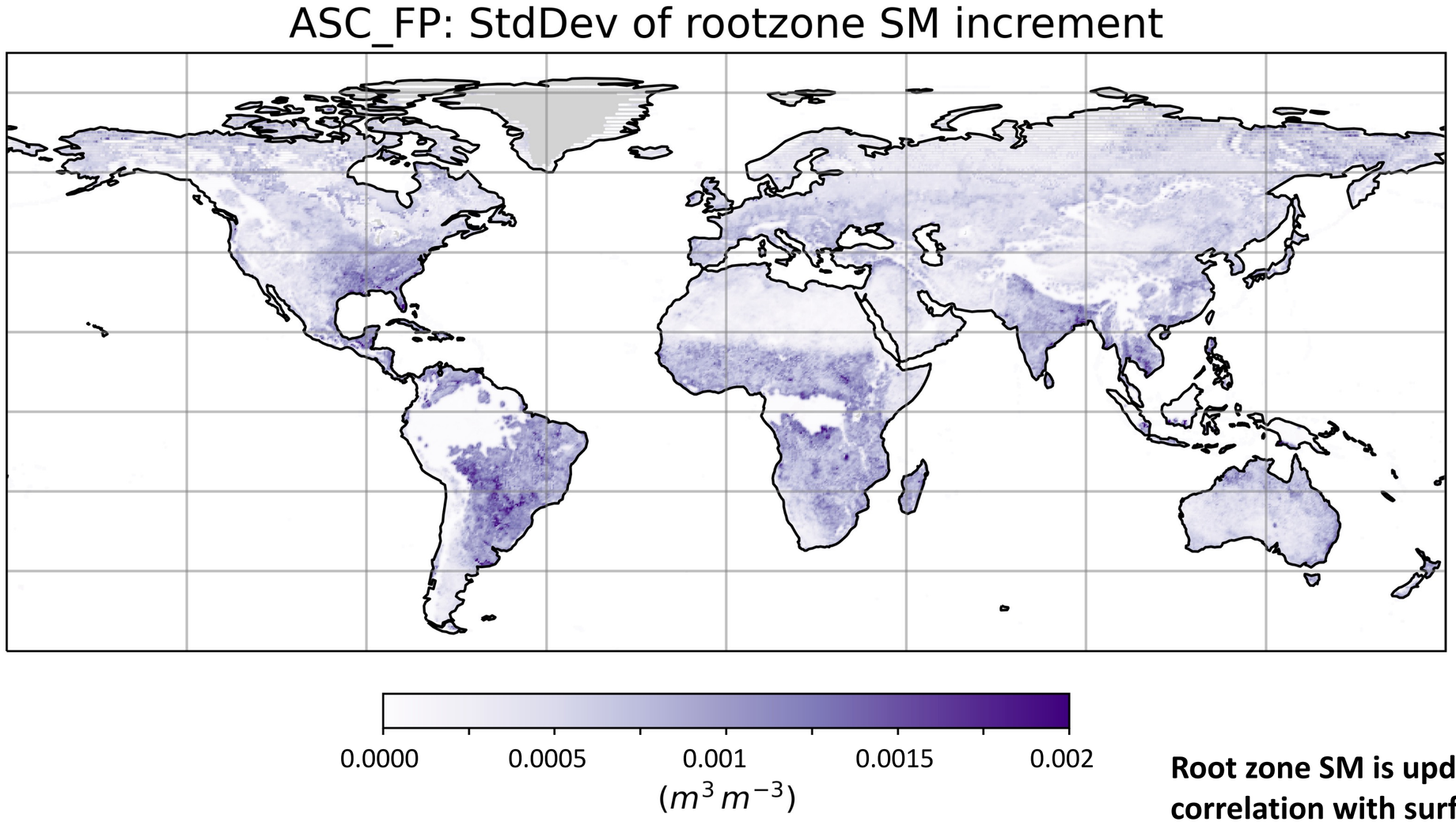
Observation counts for ASC_FP



Up to 6000 ASCAT SFDS observations assimilated per catchment
1 April 2015 – 31 March 2021

All observations from Metop-A, -B and -C, ascending and descending orbits are treated in the same way

Time series StdDev of root zone SM increments for ASC_FP



Root zone SM is updated through its correlation with surface SM, and shows very similar patterns

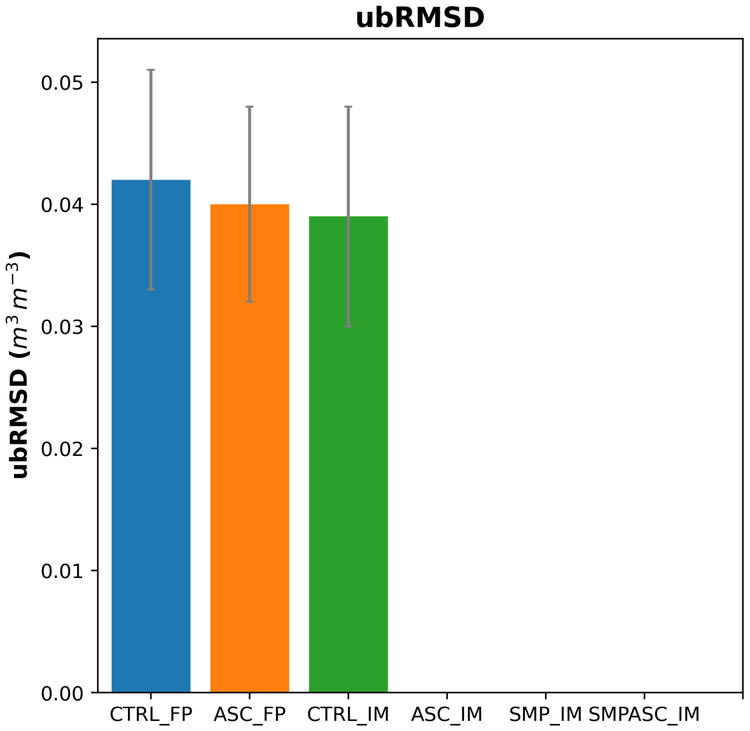
How big is the impact of using observed precipitation?

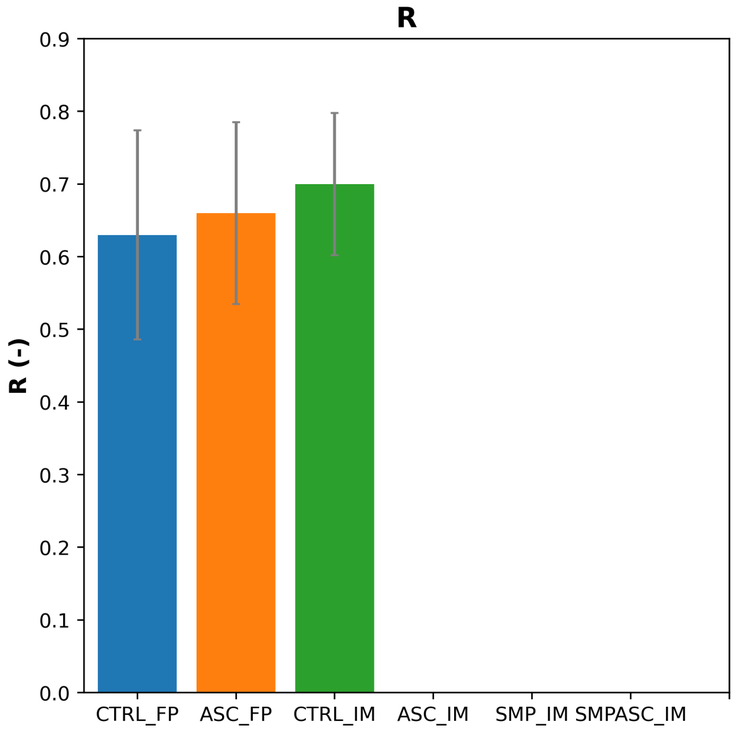
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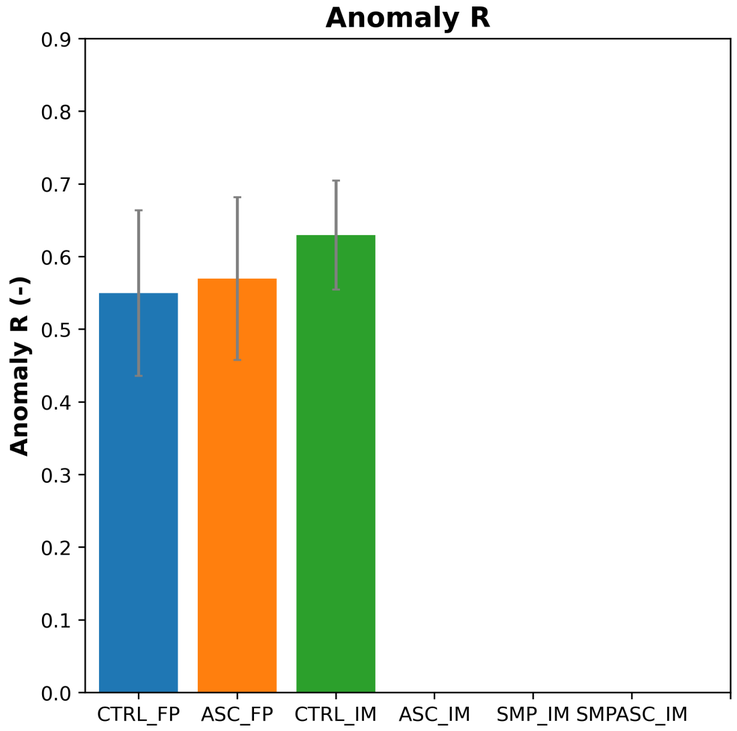
- GEOS reanalysis efforts will use “observed” precipitation, such as IMERGv7
- This has been shown to greatly improve modeled SM skill (Reichle et al., 2023)

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Skill Metrics at Core Validation Sites for CNTL_IM

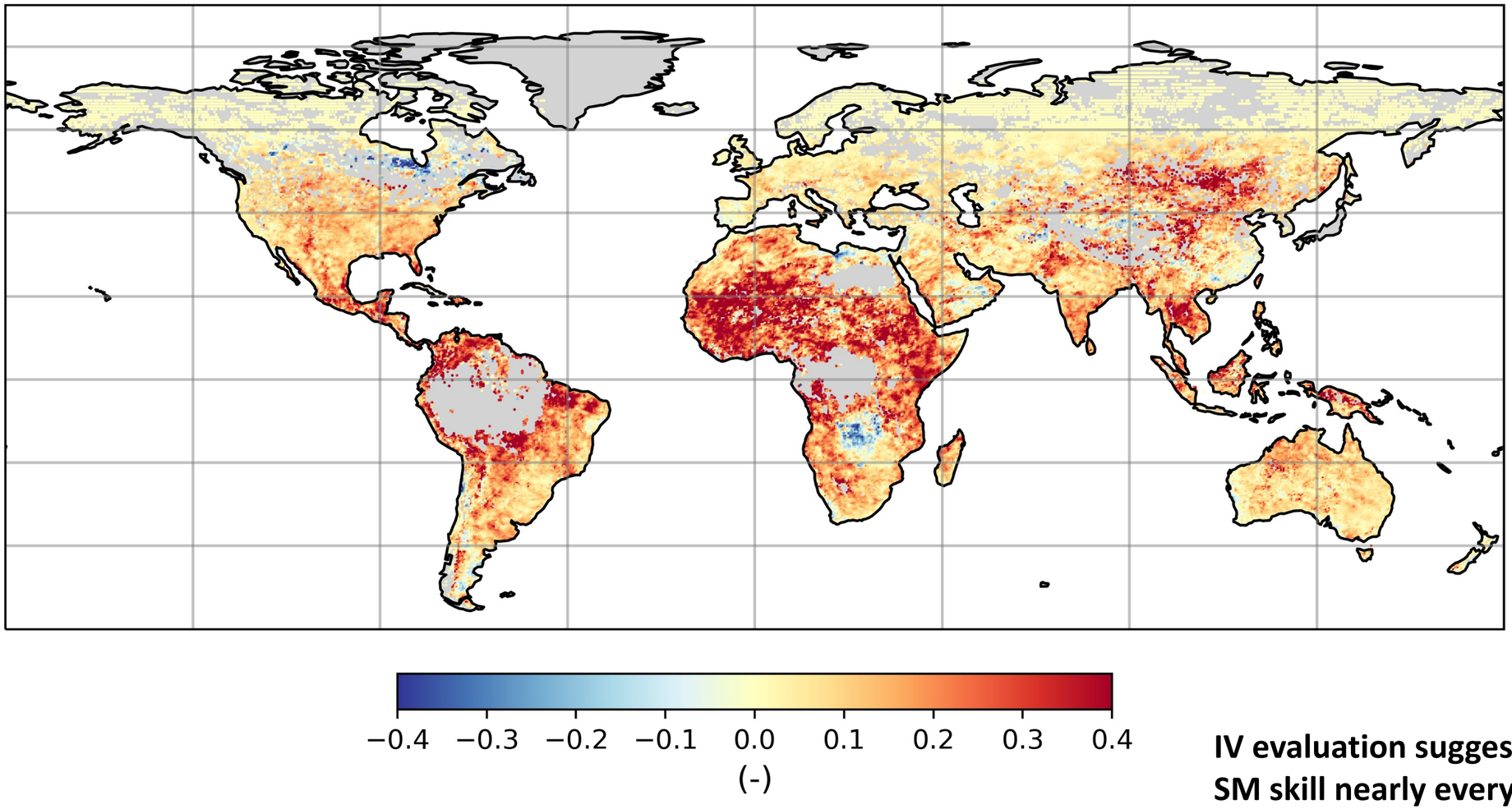






Switching control to IMERG precipitation results in a large skill increase, greater than for the ASC_FP DA experiment

IV evaluation of CNTL_IM minus CTRL_FP

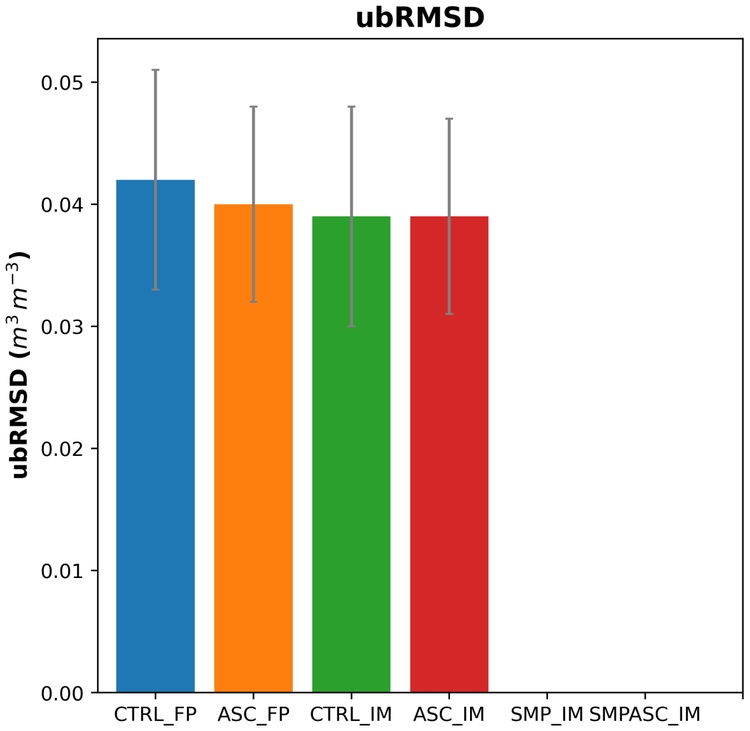


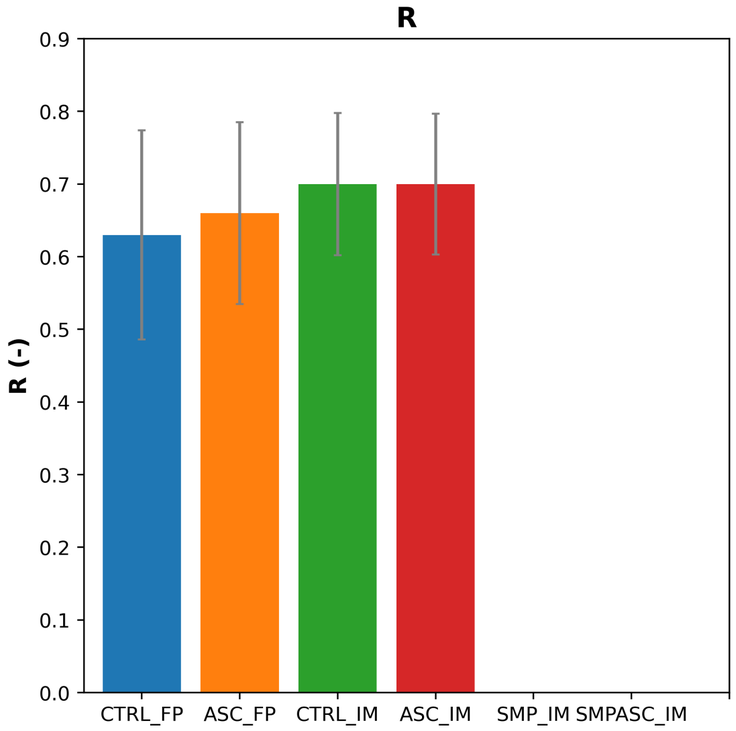
IV evaluation suggests improvements in SM skill nearly everywhere with this change in precipitation

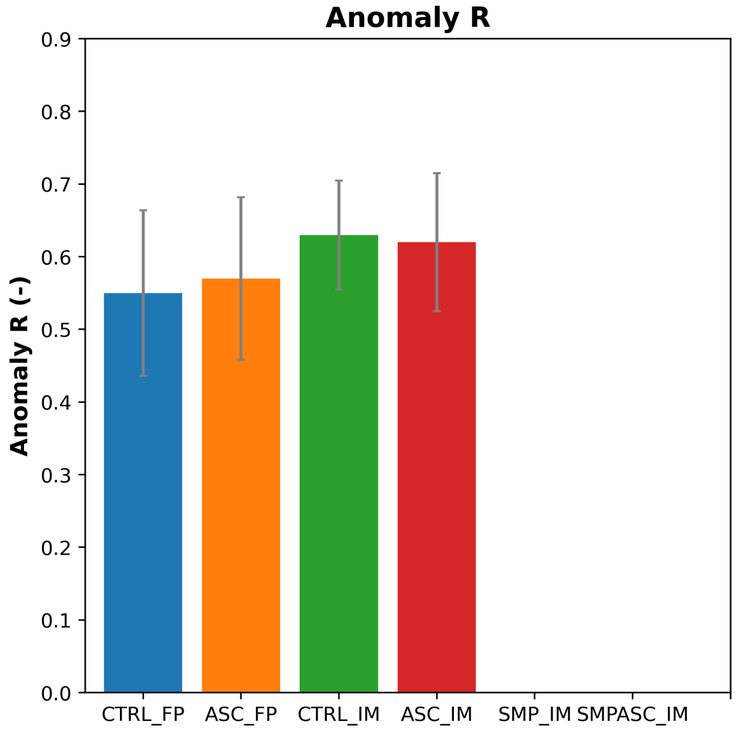
What is the impact of assimilating ASCAT SM if we also use observed precipitation?

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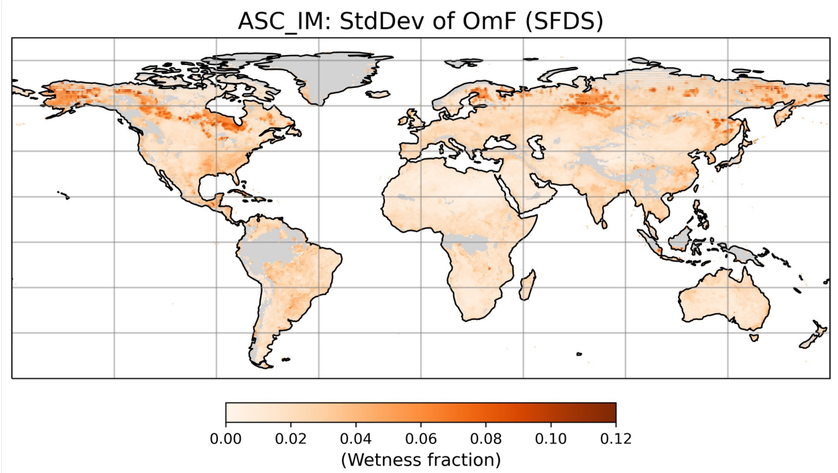


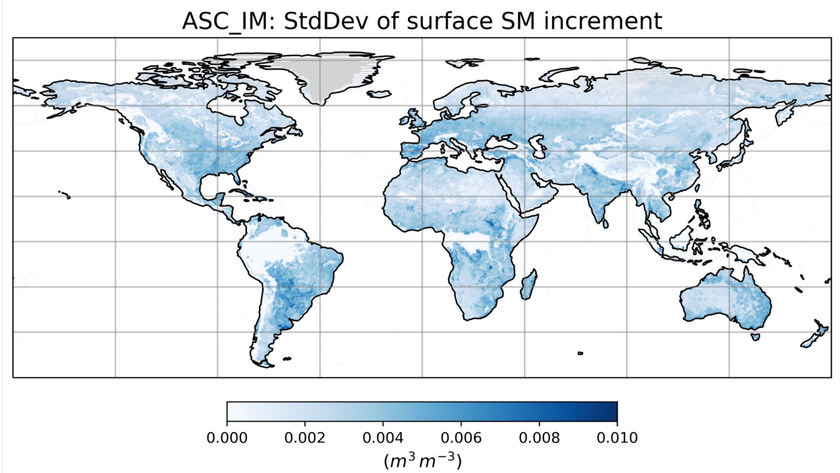


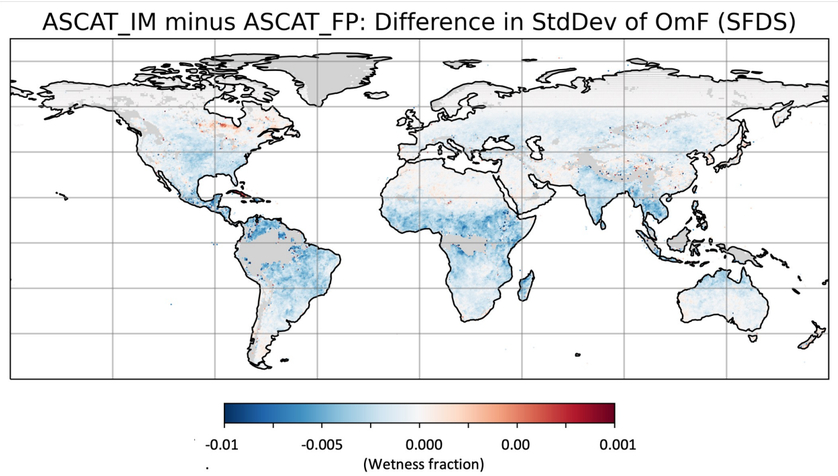


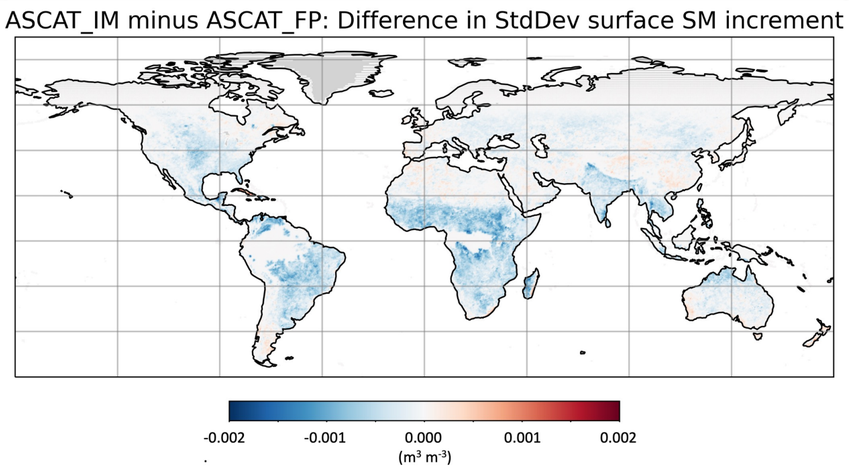
Little difference in skill at core sites following ASCAT assimilation with IMERG precipitation

Time series StdDev of OmFs and SM Increments for ASC_IM minus CTRL_IM





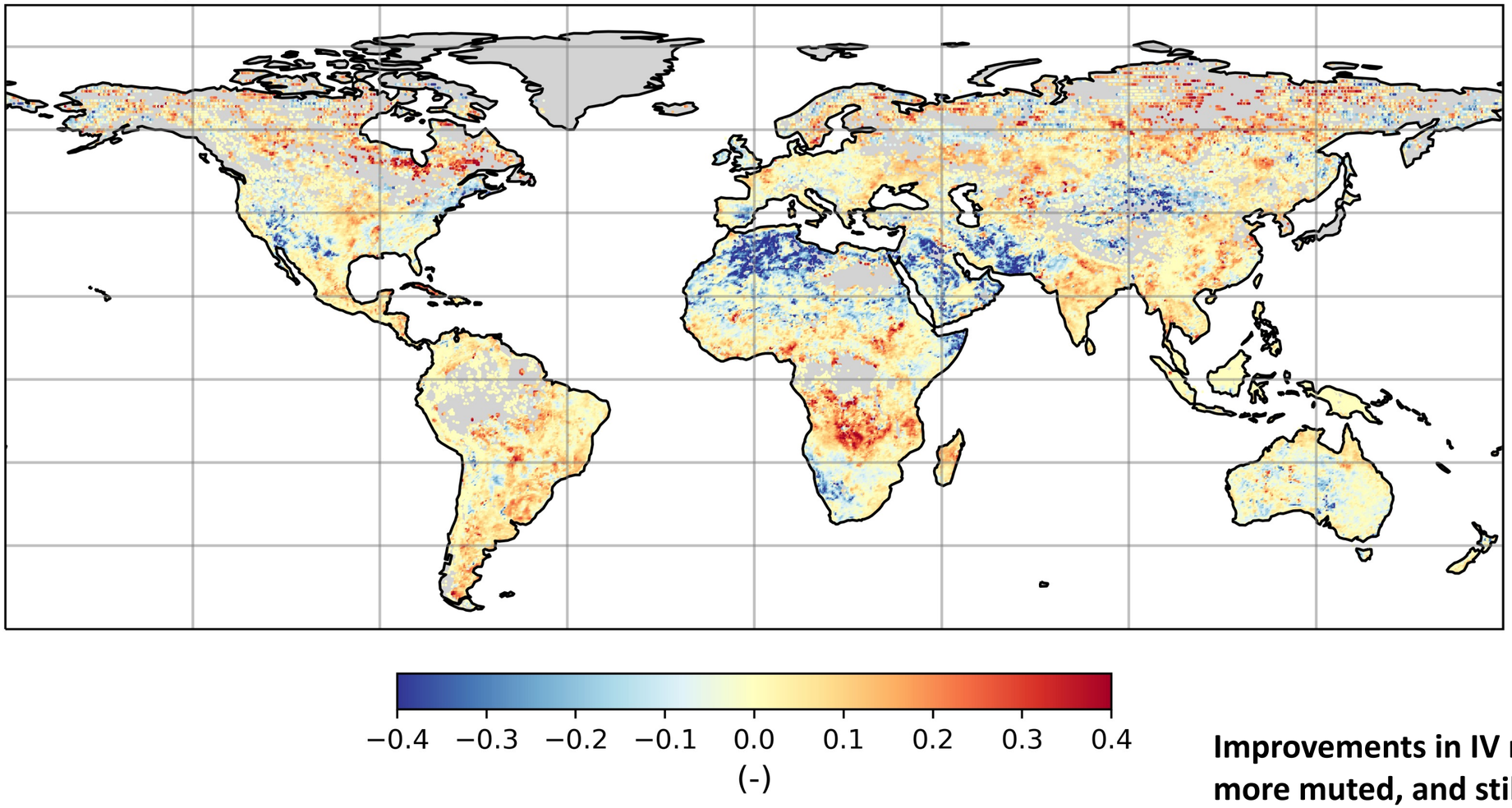




OmFs and resultant increments are correspondingly smaller with IMERG precipitation

IV evaluation of ASC_IM minus CTRL_IM

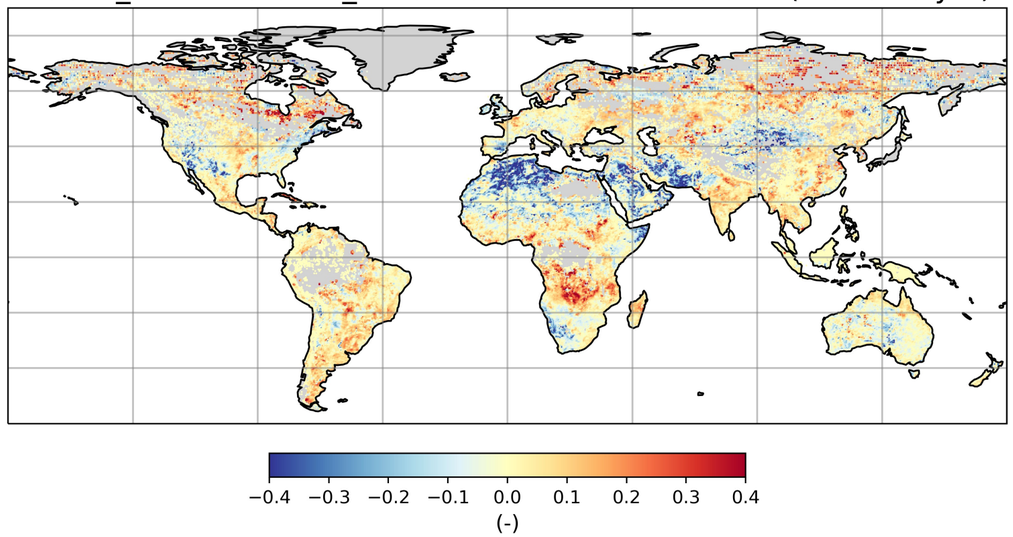
ASCAT_IM minus CTRL_IM: Surface Soil Moisture Skill (Δ anomaly R)



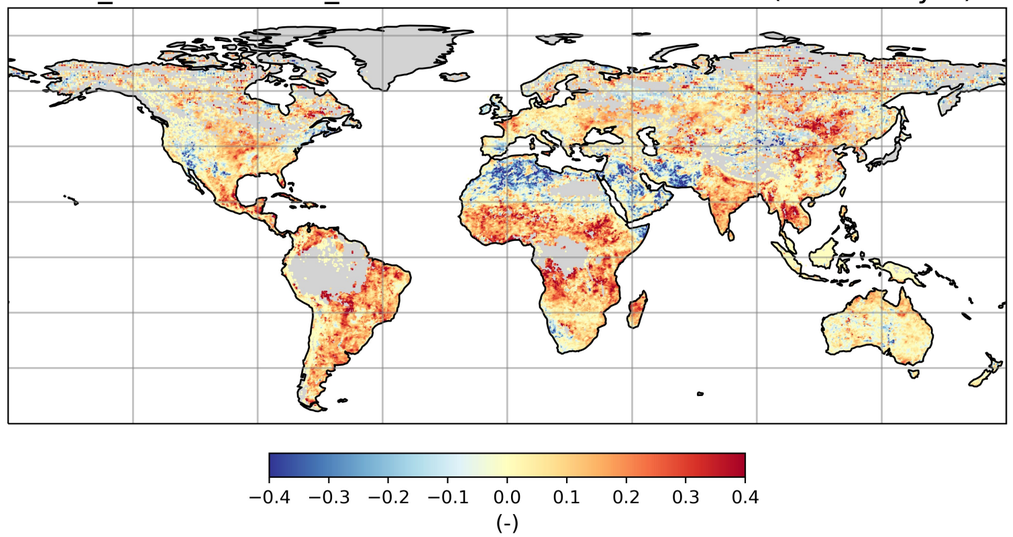
Improvements in IV metrics are much more muted, and still degradation over desert areas

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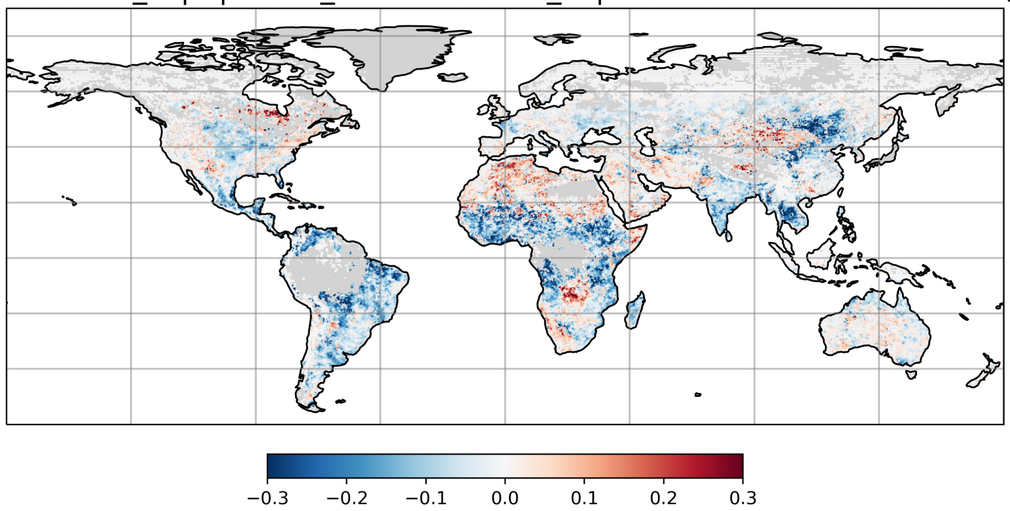
ASCAT_IM minus CTRL_IM: Surface Soil Moisture Skill (Δ anomaly R)



ASC_FP minus CTRL_FP: Surface Soil Moisture Skill (Δ anomaly R)



|ASCAT_IM minus CTRL_IM| - |ASCAT_FP minus CTRL_FP|: Surface Soil Moisture Skill (Δ anomaly R)

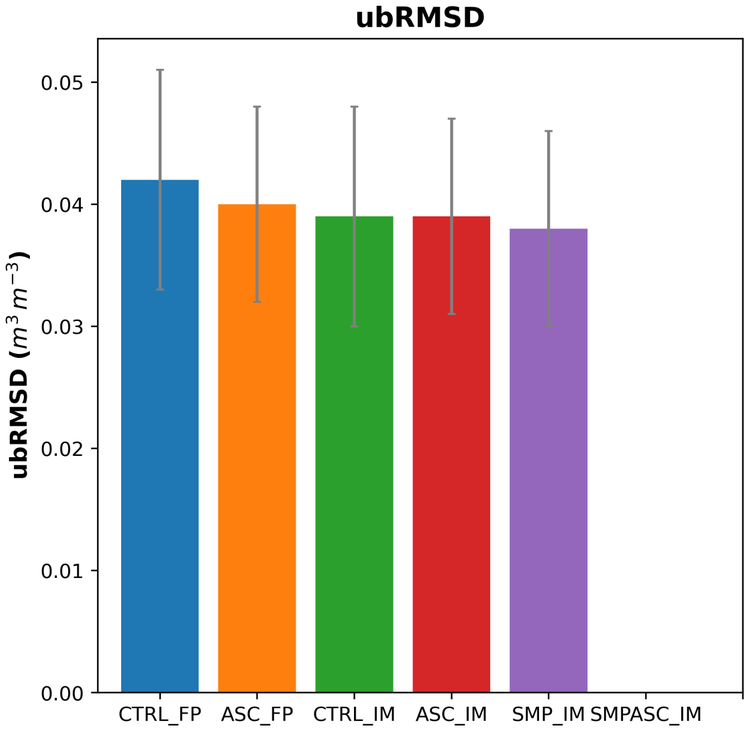


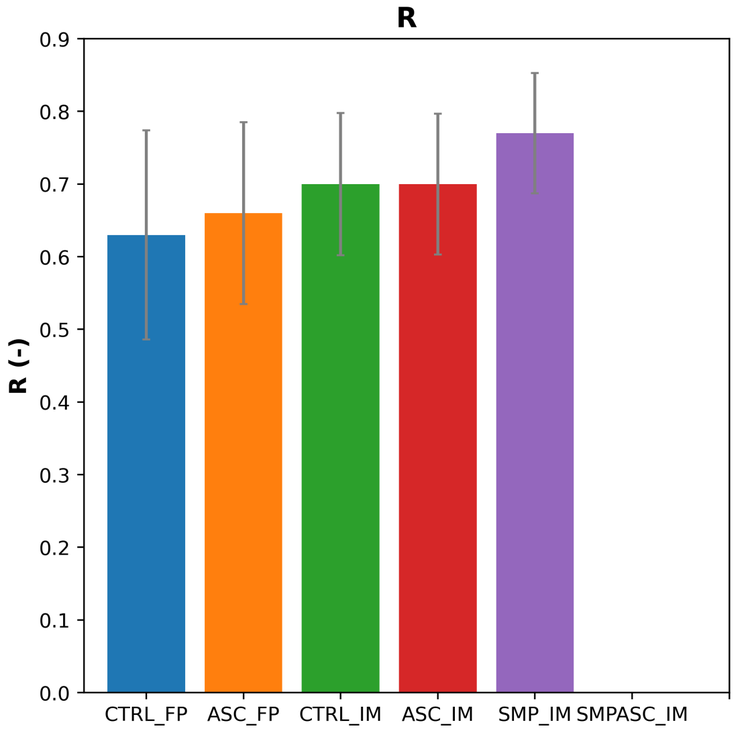
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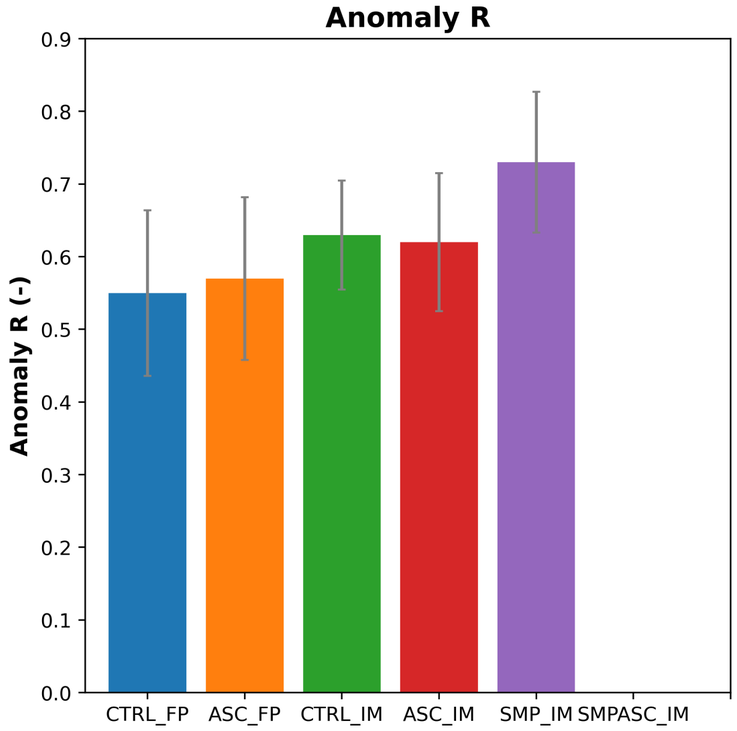
How do these results with ASCAT SM compare to assimilating SMAP Tbs?

Experiment Name	Observations assimilated	Precipitation Forcing
CTRL_FP	None	Modeled FP precipitation
ASC_FP	ASCAT SM	
CTRL_IM	None	Observed IMERG precipitation
ASC_IM	ASCAT SM	
SMP_IM	SMAP Tb	
SMPASC_IM	SMAP Tb & ASCAT SM	

Skill Metrics at Core Validation Sites for SMP_IM







Assimilation of SMAP Tbs show larger improvements at core sites, particularly in correlation skill