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Effects of Climate Forcing Uncertainty And Persistence On Soil Moisture Memory Process

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What is Soil Moisture Memory (SMM)?

Soil moisture memory (SMM) indicates how long a soil moisture anomaly (either too wet or too dry) persists or dissipates over time.

If an anomalous state (wet or dry) has developed, then SMM measures how quickly it returns to normal (dissipation) or how long the anomaly lasts (persistence)

SMM from the first principle

Water balance equation:

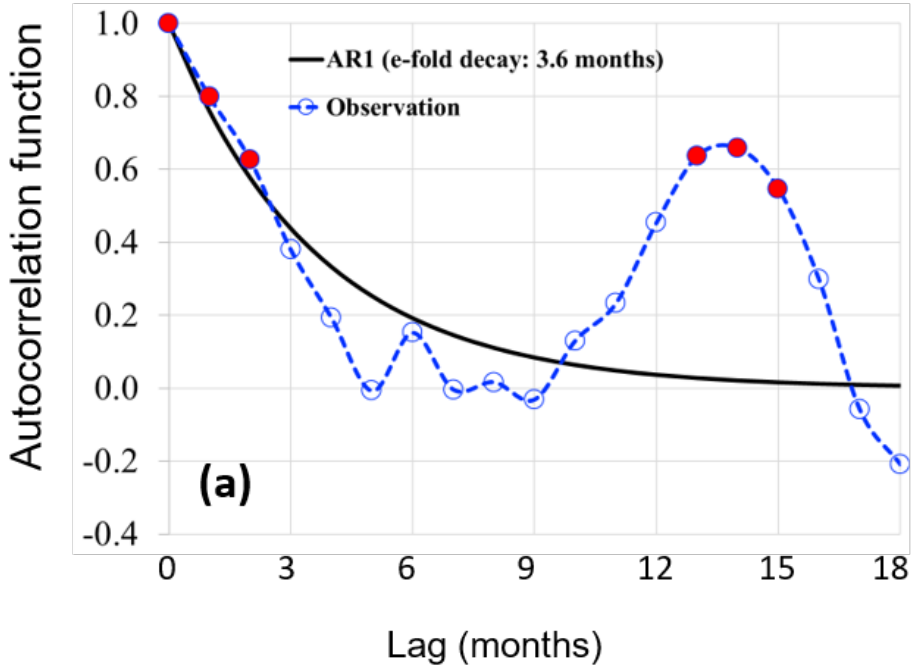
$$\frac{ds}{dt} = P - E - R \qquad (1)$$

Here, S is the root zone soil moisture (mm), p is precipitation rate (mm/month), ET is evapotranspiration (mm/month), and R is runoff (mm/month)

E and R can be taken as a function of soil moisture [ET = f(s), and R = g(s)], and precipitation can be taken as white noise (ε), so the water balance equation reduces to the **first-order Markov process** as shown below

$$\frac{ds}{dt} = -\lambda\, s + \varepsilon \qquad (2)$$

In this view, **SMM is a land surface characteristic** that can vary spatially depending on soil, vegetation, and topography.



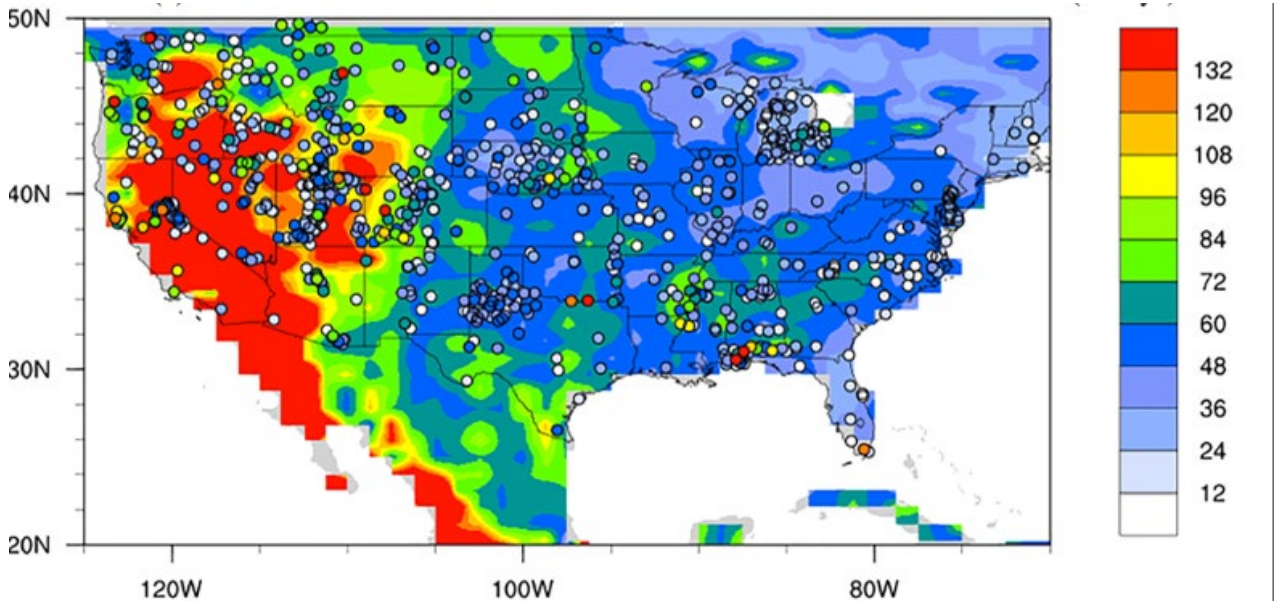
SMM time scale in Illinois observations (Kumar et al., 2019)

Key unknowns for SMM process

- Uncertainty in climate models' SMM estimates
- Model parametrization uncertainty – key hydraulic parameters

- Atmospheric forcing driver uncertainty
- Soil moisture to precipitation feedback uncertainty

Rahmati et al., 2024; Koster et al., 2004



Soil moisture residence time in CLM5 and its comparison with in-situ measurements (unit: in days) (Lawrence et al., 2019)

Research Questions, and Method

Q1: Given a land surface model (CLM5), to what extent is SMM affected by the persistence in the atmospheric forcing drivers?

➔ Randomized atmospheric forcing driver experiments.

Q2: A related question – how does uncertainty in atmospheric forcing driver impact SMM, and why?

➔ Climate Forecast System Reanalysis (CFSRv2), 1980-2022

➔ Global Soil Wetness Project Phase 3 (GSWP3), 1971-2014

Q3: Performance of the coupled climate model (CESM2-LE)

Randomized Runs

Ens # 1

Simulation year	Forcing data
Jan 1980	Jan 2018
Feb 1980	Feb 2009
Mar. 1980	Mar. 1997
.	.
.	.
Dec. 2022	Dec. 1987

.....

Ens # 10

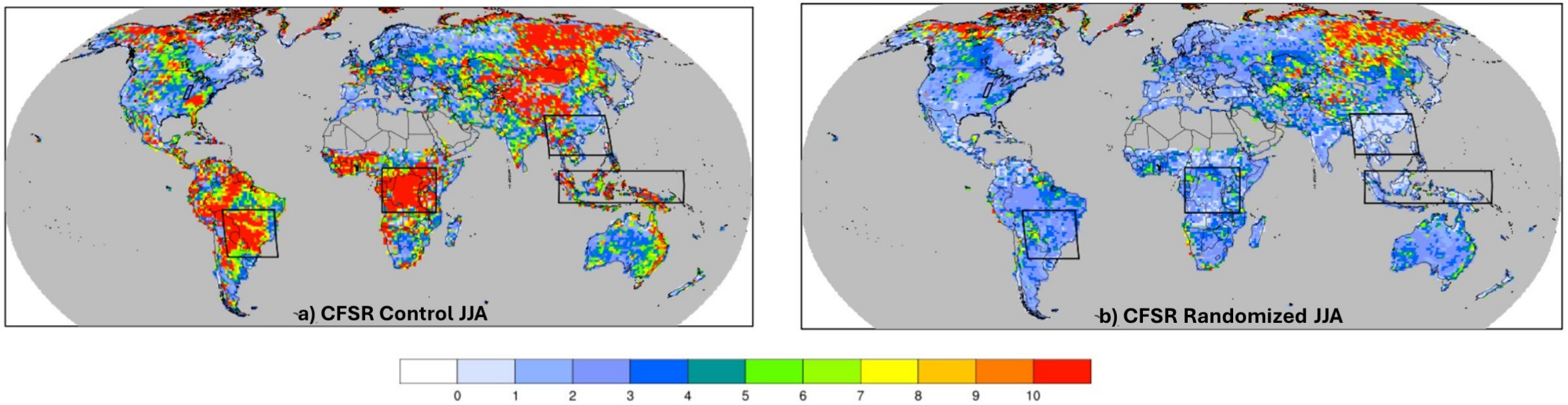
Simulation year	Forcing data
Jan 1980	Jan 1998
Feb 1980	Feb 1987
Mar. 1980	Mar. 2007
.	.
.	.
Dec. 2022	Dec. 1981

We developed one control run and 10 ensemble runs using randomized forcing from GSWP3 and CFSRv2 atmospheric forcing

Result 1.1: Randomized atmospheric forcing decreases SMM considerably in CFSR forced run

CFSR Control

CFSR Randomized

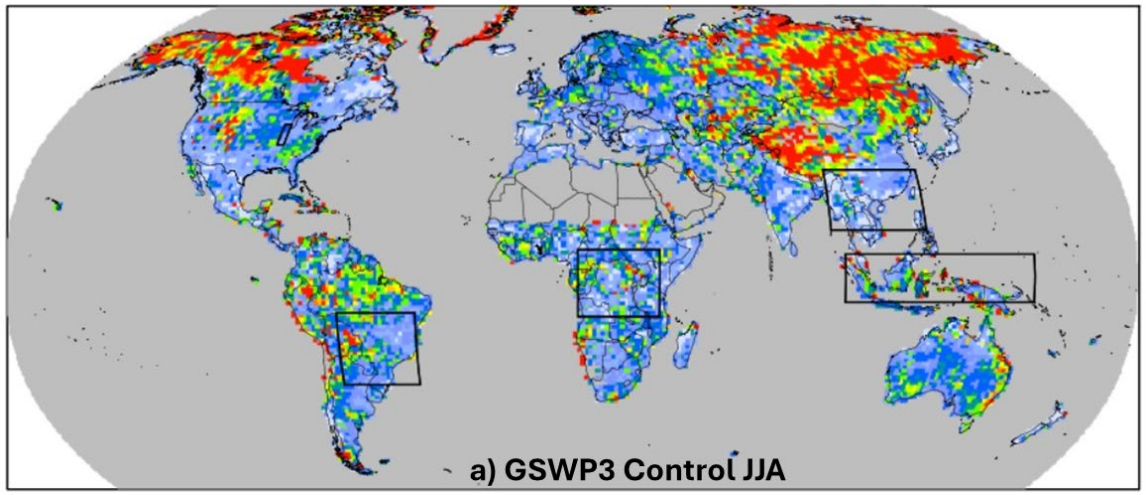


SMM during JJA in the control run (default CFSR forced) and randomized run (randomized CFSR forced) (SMM unit – in months)

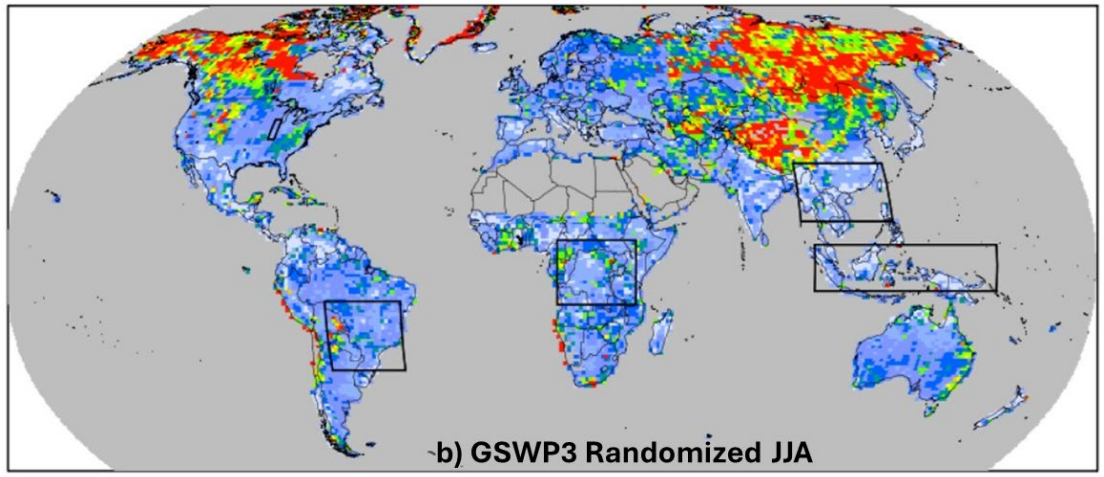
SMM is reduced by 67% & 74% in La Plata & Congo Basin, respectively.

Result 1.2: The decrease in SMM is less substantial in GSWP3 forced run

GSWP3 Control



GSWP3 Randomized

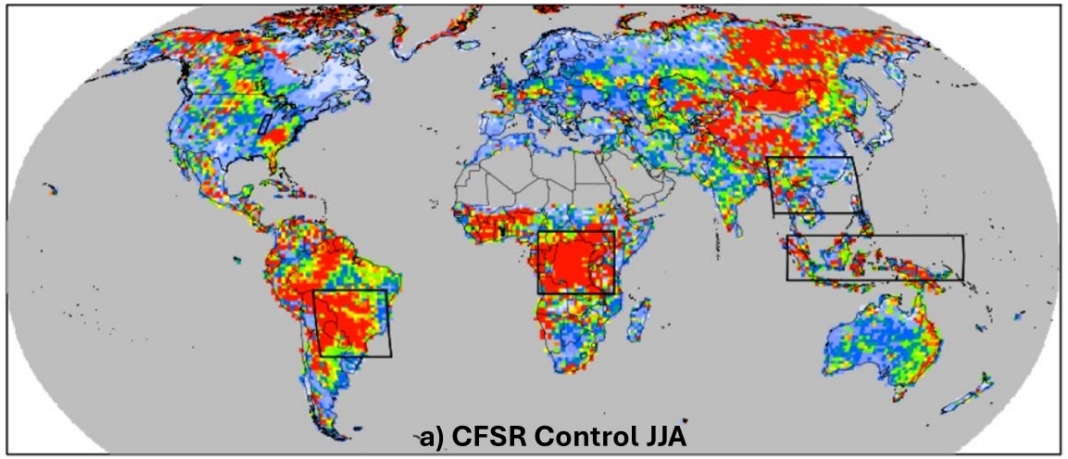


SMM during JJA in the control run (default GSWP3 forced) and randomized run (randomized GSWP3 forced) (SMM unit – in months)

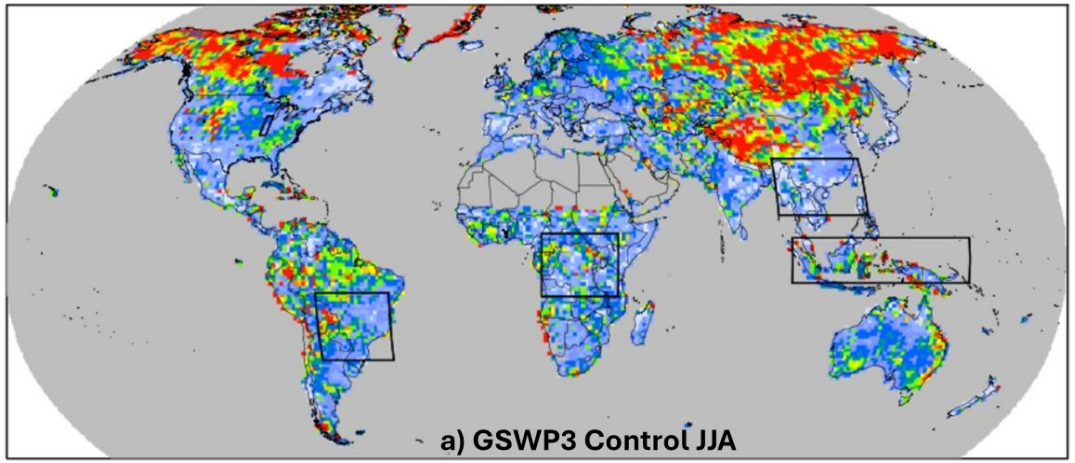
SMM is reduced by 21% & 11% in La Plata & Congo Basin, respectively.

Result 2.1: Forcing uncertainty significantly impacts SMM estimates: A higher SMM in CFSR than GSWP3 forced run

CFSR Control



GSWP3 Control



SMM during JJA in control runs (SMM unit – in months)

CFSR Forced: 11 & 14 months in La Plata & Congo Basin, respectively.

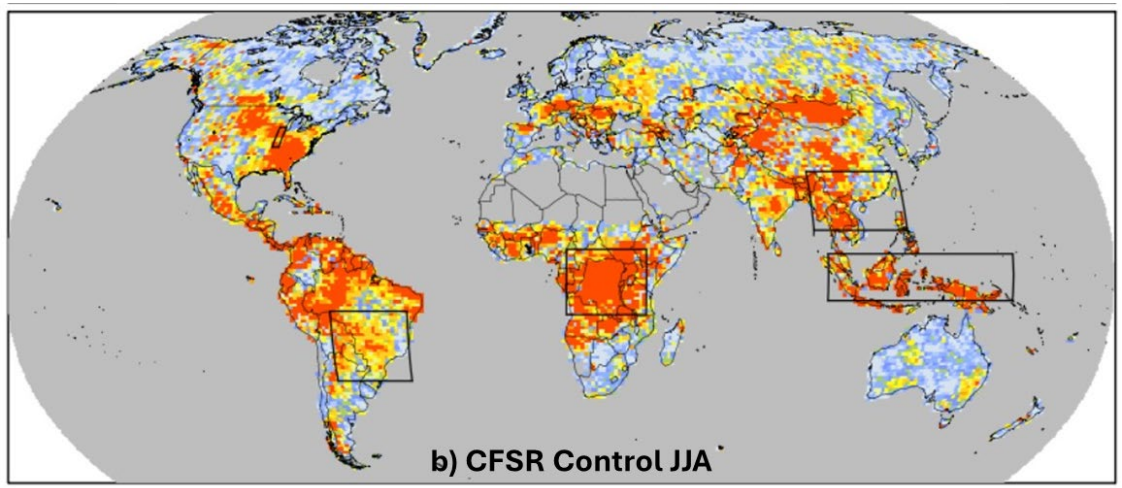
GSWP3 Forced: 4 & 3 months in La Plata & Congo Basin, respectively.

A Land-Atmosphere Interaction Pathway for SMM

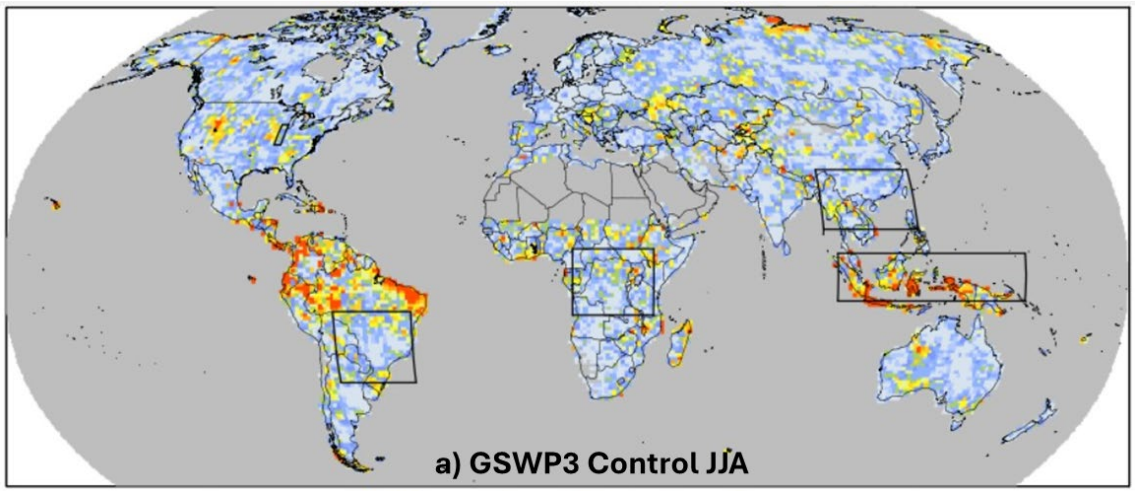
Stronger soil moisture to precipitation feedback can lead to a higher SMM in CFSR than GSWP3 runs

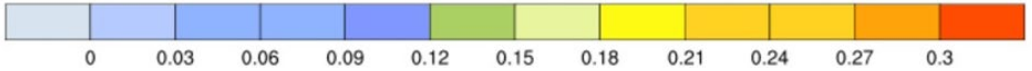
Result 2.2: Soil moisture to precipitation feedback is considerably stronger in CFSR forcing than GSWP3

CFSR Control



GSWP3 Control



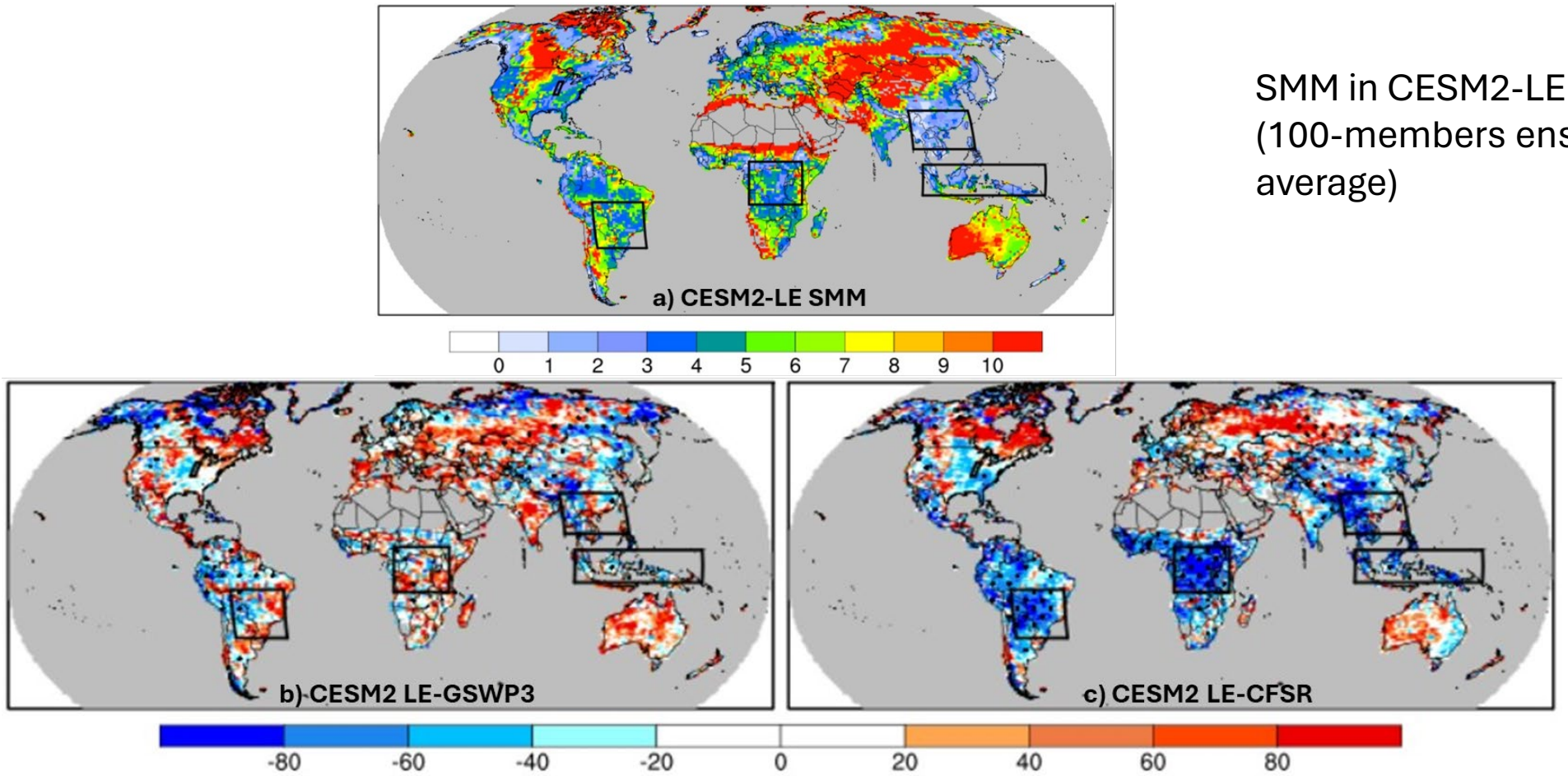


One month lead-lag correlation between precipitation (lead) & soil moisture (lag) anomalies – seasonal cycle removed, and considering all months

GSWP3 Forced: 0.06 & 0.05 in La Plata & Congo Basin.

CFSR Forced: 0.21 & 0.44 in La Plata & Congo Basin

Result 3: SMM estimates in CESM2-LE is generally closer to GSWP3 than CFSR



SMM in CESM2-LE for JJA (100-members ensemble average)

Difference in soil moisture memory (%) between CESM2-LE and reference data (Left -GSWP3, and Right – CFSR); Stippling shows the SMM in the reference data is outside the 95% range across 100 ensembles in CESM2-LE.

GSWP3 Forced: 14% & 33% higher; CFSR Forced: 57% & 58% lower for La-Plata, and Congo basin respectively

Conclusions

A new knowledge developed- **SMM is a coupled climate system metric**.

The SMM estimates significantly depend on the atmospheric driver uncertainty.

There is up to 70% reduction in SMM due to randomization of the atmospheric forcing in the CFSR run, compared to 10-20% reduction in the GSWP3 run.

A higher memory in the CFSR run is attributable to the stronger soil moisture and precipitation feedback mechanism.