Quantification of human contribution to soil moisture-based terrestrial aridity

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Background

Increasing terrestrial aridity under climate change is widely reported

Anthropogenic forcings are found responsible for the change by detection and attribution (D&A) studies

D&A studies have mostly focused on meteorological drought indices/PDSI and annual/summer changes

High uncertainty remains in soil moisture aridity due to inaccurate historical data and w.r.t. seasonal and vertical patterns

Overview of study

Question: What are the impacts of anthropogenic forcings on soil moisture-based terrestrial aridity in different seasons and soil layers?

Components

- Development of merged soil moisture data sets
- Historical D&A of standardized soil moisture index
- Future anthropogenic signals and changes in standardized soil moisture index corrected by emergent constraint

Development of merged soil moisture data sets

Objective

Take as many existing data sets as possible, which cover varying time periods and soil layers, and combine them to form a consistent global multi-layer data set over 1971–2016 at monthly 0.5^{o} resolution

Source datasets

- 1 satellite dataset (ESA CCI)
- 5 reanalysis datasets (GLEAM, CERA20C, ERA20C, ERA-Interim, ERA5),
- 13 offline land surface models (GLDAS Noah, ERA-Land, MsTMIP, TRENDY)
- CMIP5 and CMIP6 models

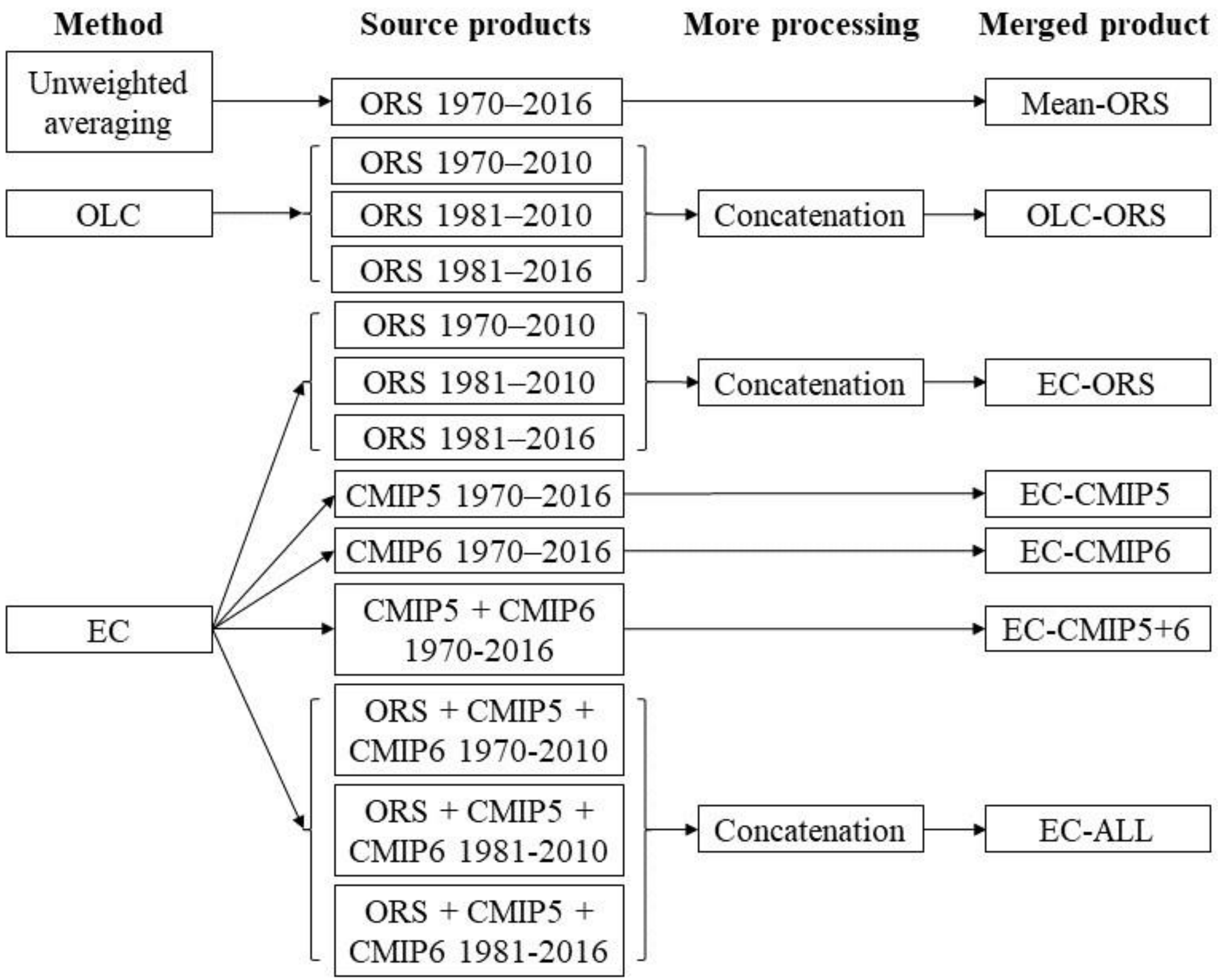
Methods

- Unweighted averaging
- Optimal least squares (OLC)
- Constraint using precipitation and temperature

Concatenation

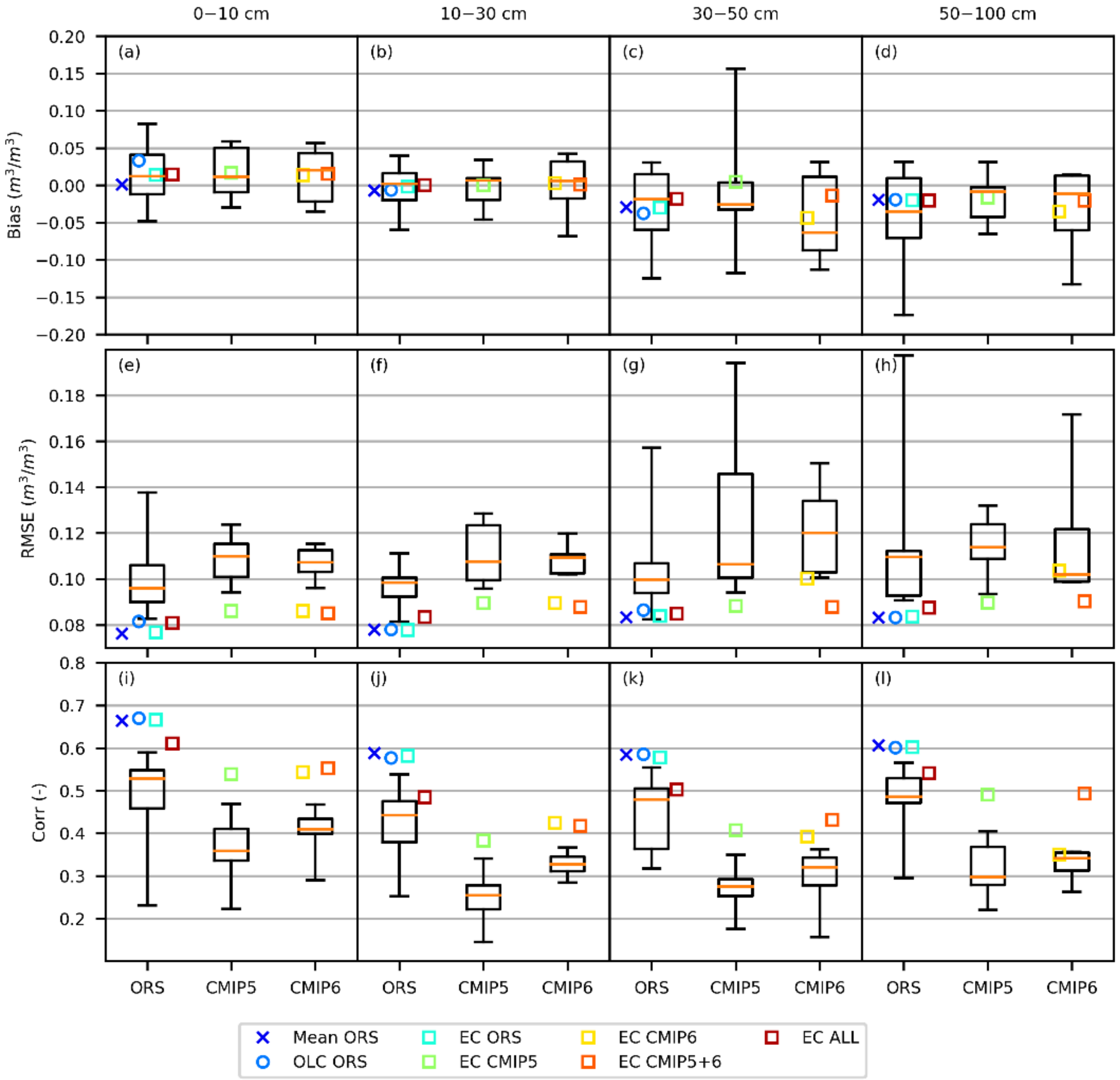
- Linear interpolation to 0–10cm, 10–30cm, 30–50cm, 50–100cm
- Cumulative distribution function mapping for temporal consistency

Procedure


Method
Source products
More processing
Merged product
Unweighted averaging
ORS 1970–2016
Mean-ORS
OLC
ORS 1970–2010
ORS 1981–2010
ORS 1981–2016
Concatenation
OLC-ORS
ORS 1970–2010
ORS 1981–2010
ORS 1981–2016
Concatenation
EC-ORS
CMIP5 1970–2016
EC-CMIP5
CMIP6 1970–2016
EC-CMIP6
EC
CMIP5 + CMIP6 1970-2016
EC-CMIP5+6
ORS + CMIP5 + CMIP6 1970-2010
ORS + CMIP5 + CMIP6 1981-2010
ORS + CMIP5 + CMIP6 1981-2016
Concatenation
EC-ALL

Performance evaluation

Test set: 40% of the ISMN observations



Performance evaluation

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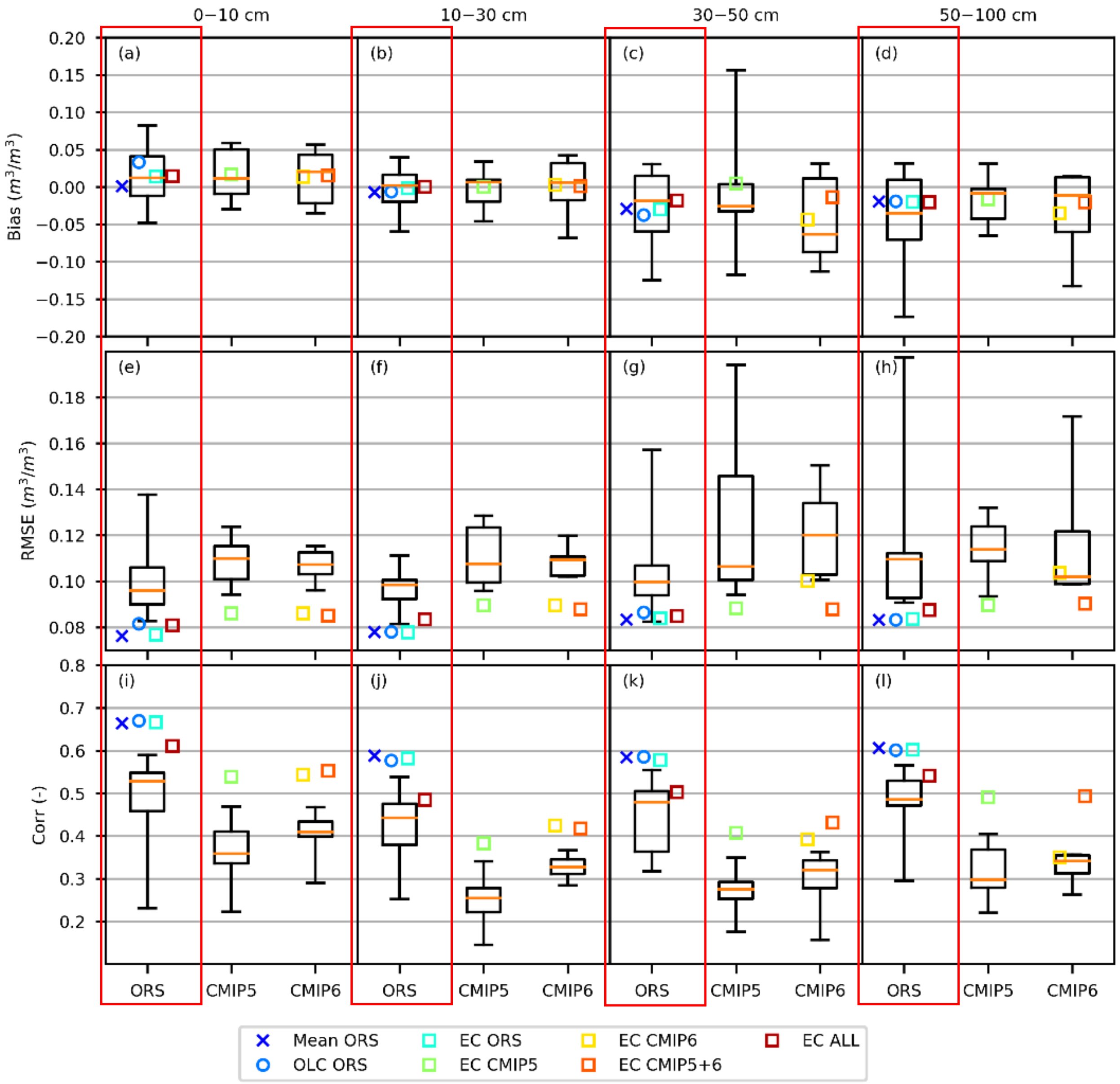


Additional sanity checks

Comparison against un-merged regional or short global data sets

- OLS √ CMIP5 √ CMIP6 √

Homogeneity around the major break points in source data coverage: 1970-1980, 1981-2010, 2011-2016

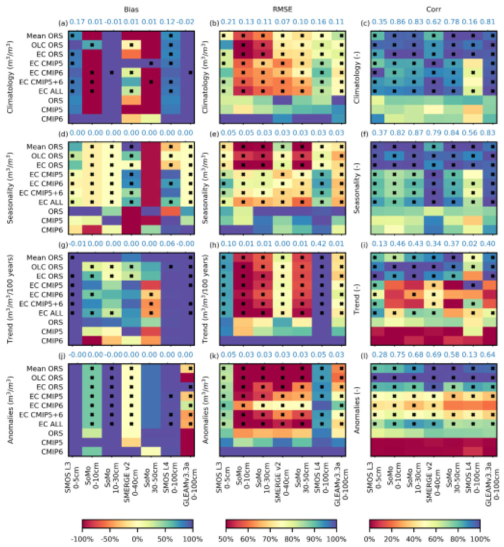
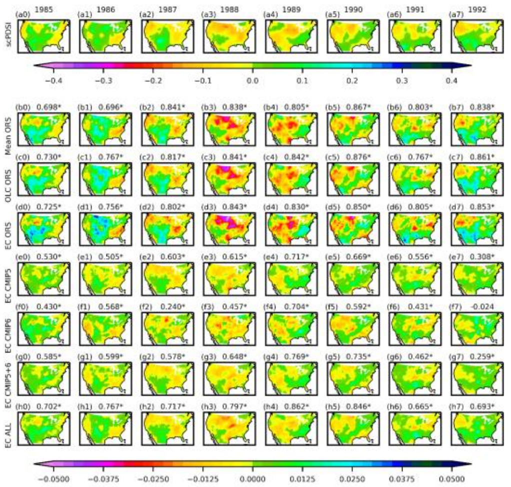
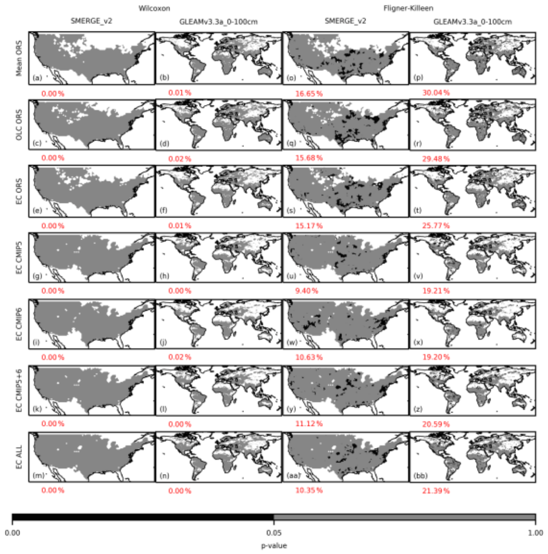
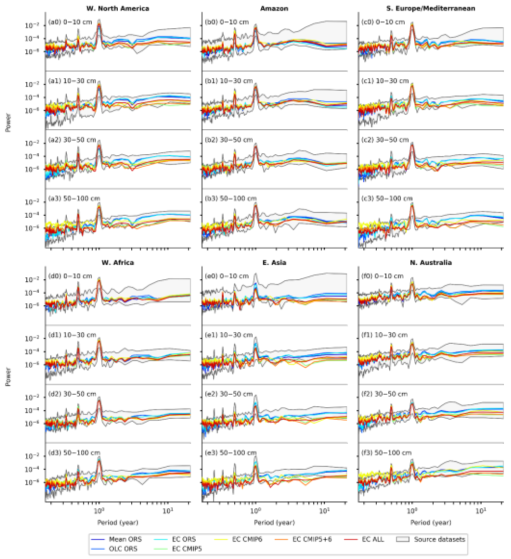
- Mean: OLS 0% CMIP5 0% CMIP6 0%
- Std: OLS 20% CMIP5 15% CMIP6 15%

Ability to capture major drought events

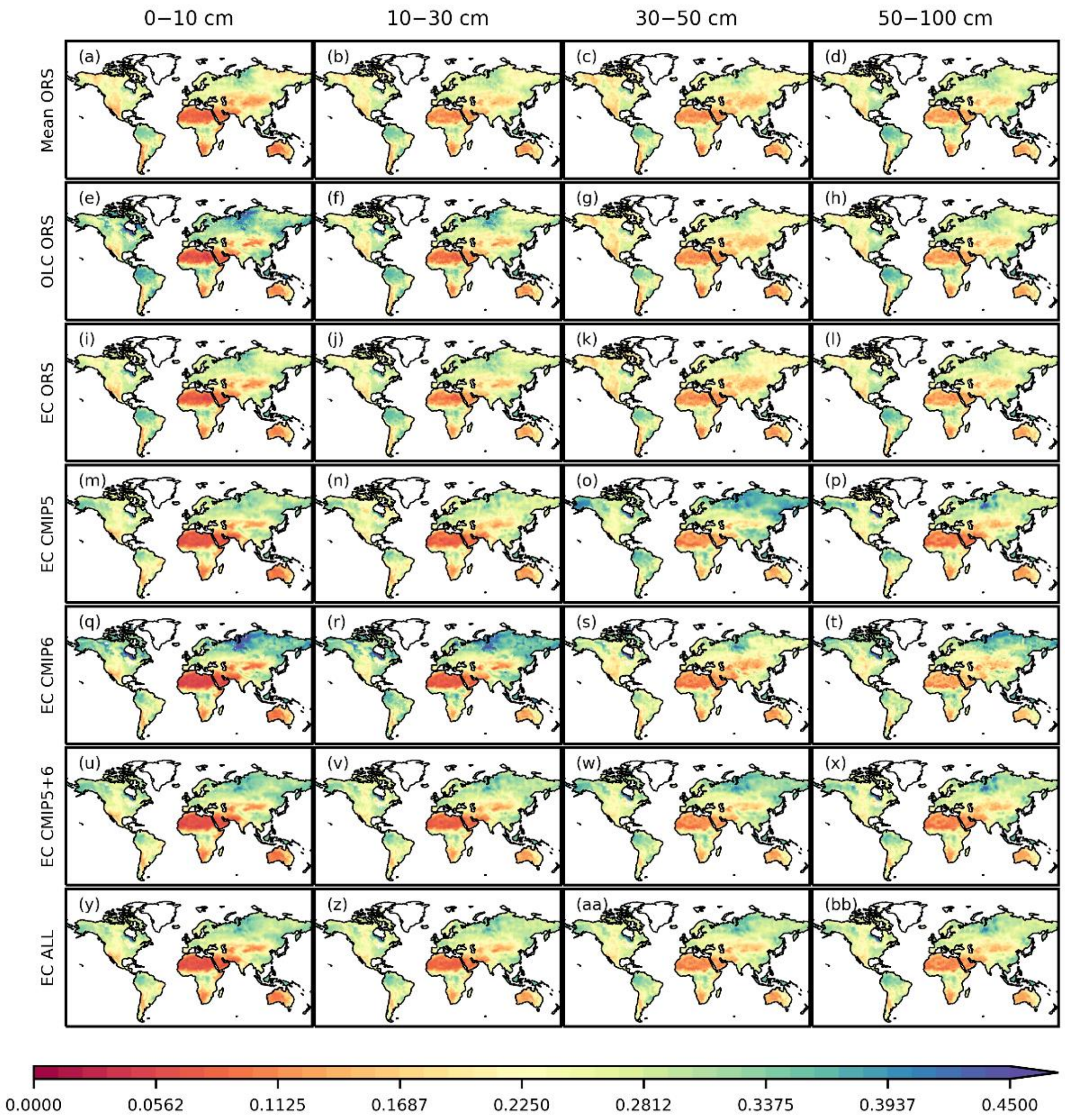
- OLS √ CMIP5 X CMIP6 X

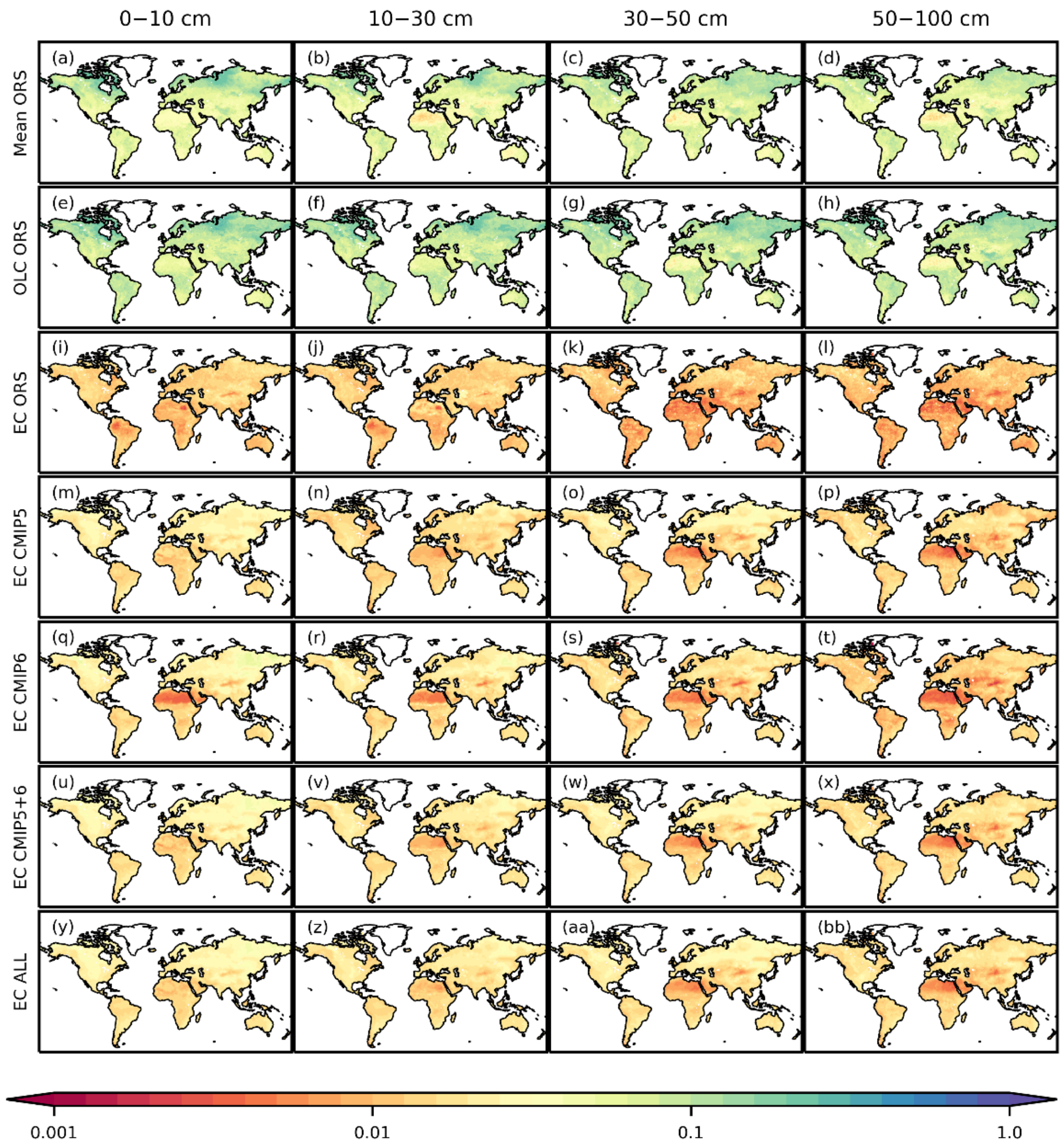
No shrink in variance due to averaging

- OLS √ CMIP5 √ CMIP6 √

Climatology and uncertainty of the merged data





Summary

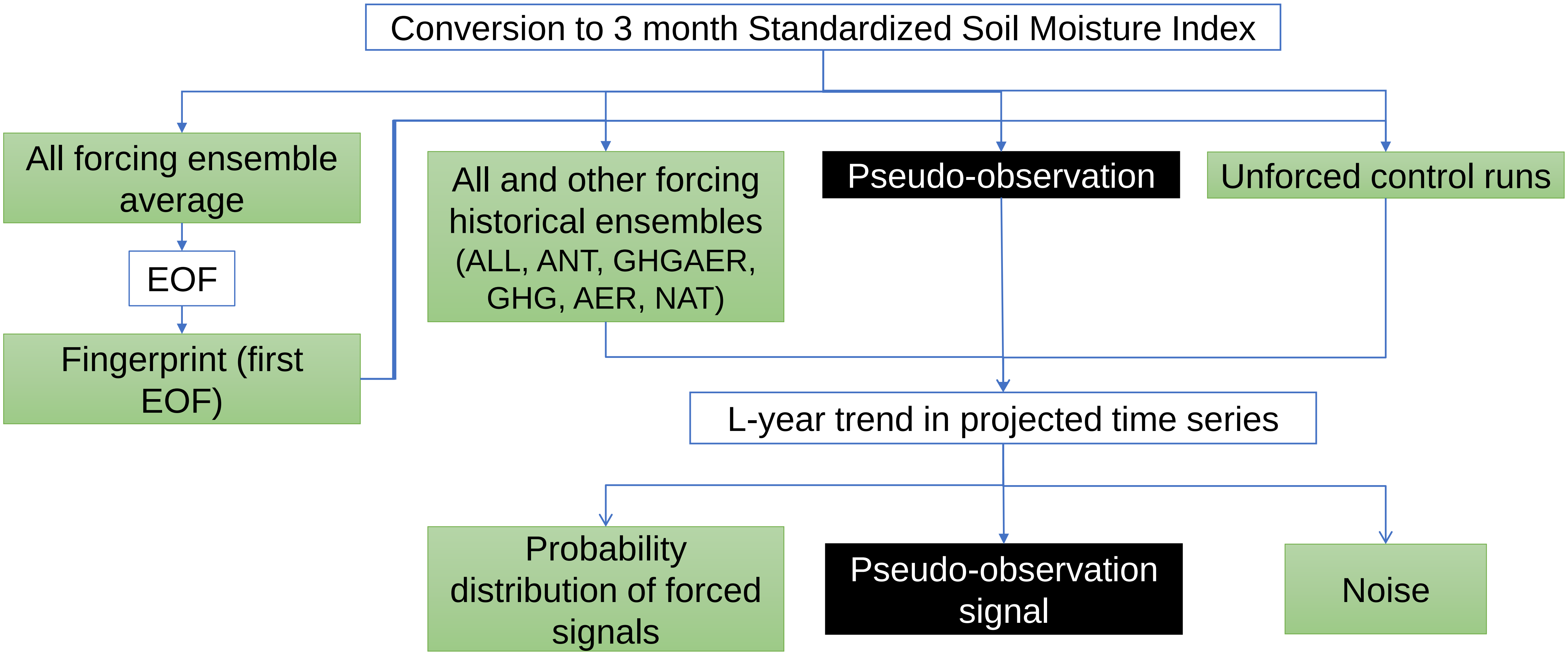
The merged products are of higher quality than the original sources and have reasonable statistical properties and continuity

The realism of the original sources matter. Merged observations and observation-drive reanalysis/offline simulations are better than coupled simulations

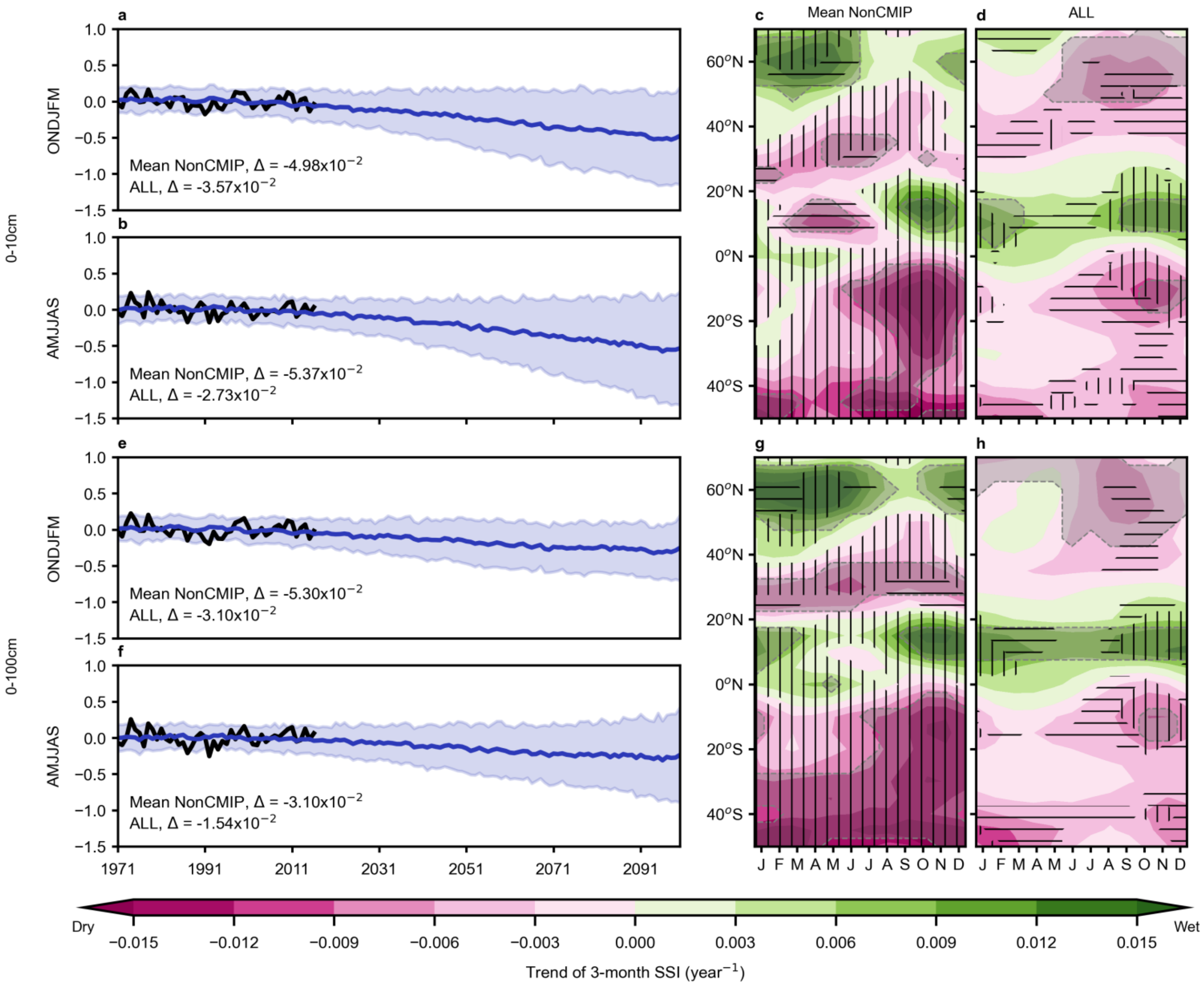
Uncertainty estimation still needs improvement

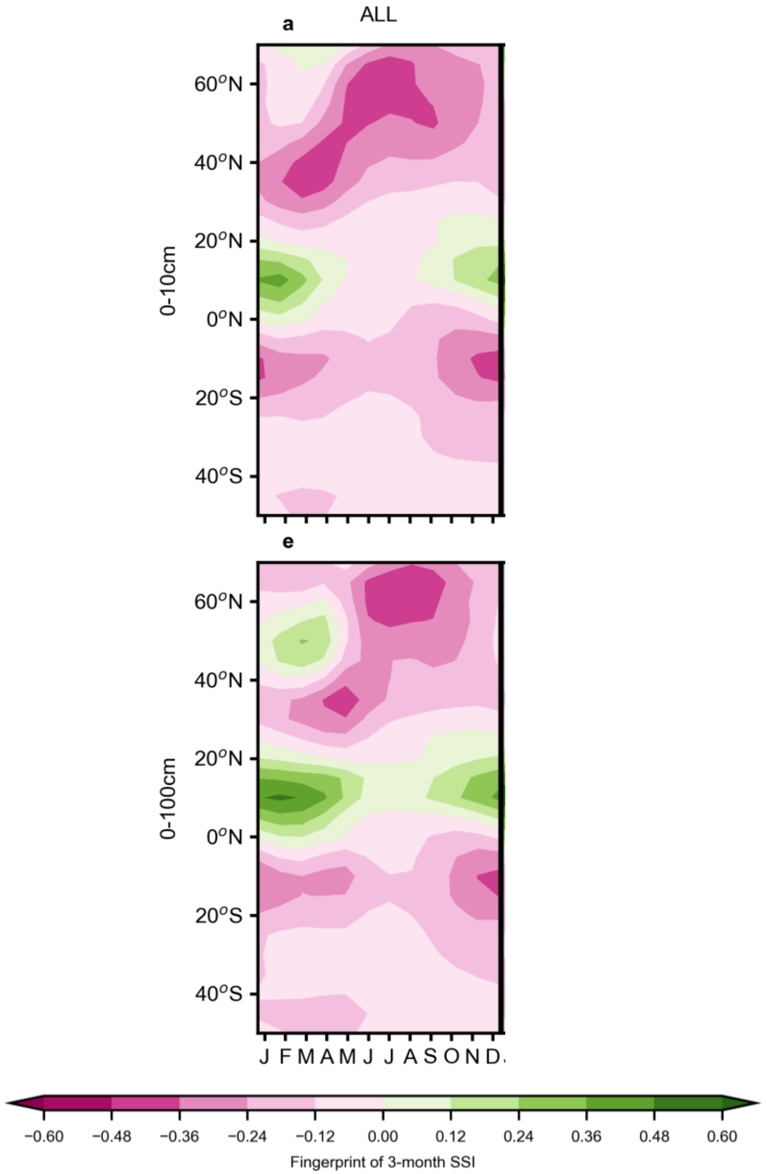
Historical D&A

Data sources: CMIP6 simulations; pseudo-observation (average of the ORS products)
Input format: 5^{o} latitudinal averages, monthly, 0-10cm and 0-100cm



Overall trends and the fingerprint





Judgement criteria

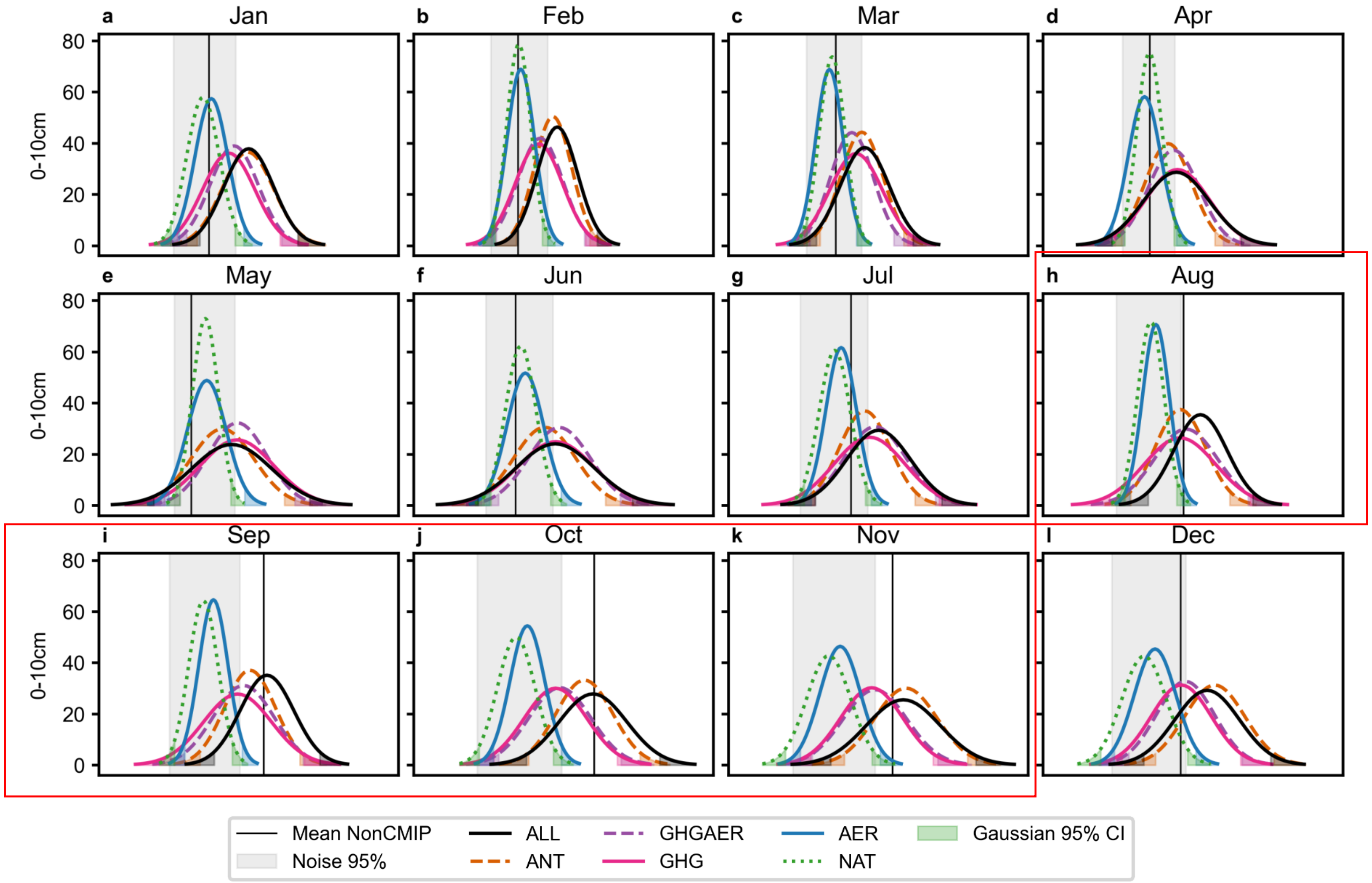
Detection

- Signal of the pseudo-observation > upper bound of the 95% confidence interval of the noise (signal-to-noise ratio > 1.96 by Gaussian assumption)

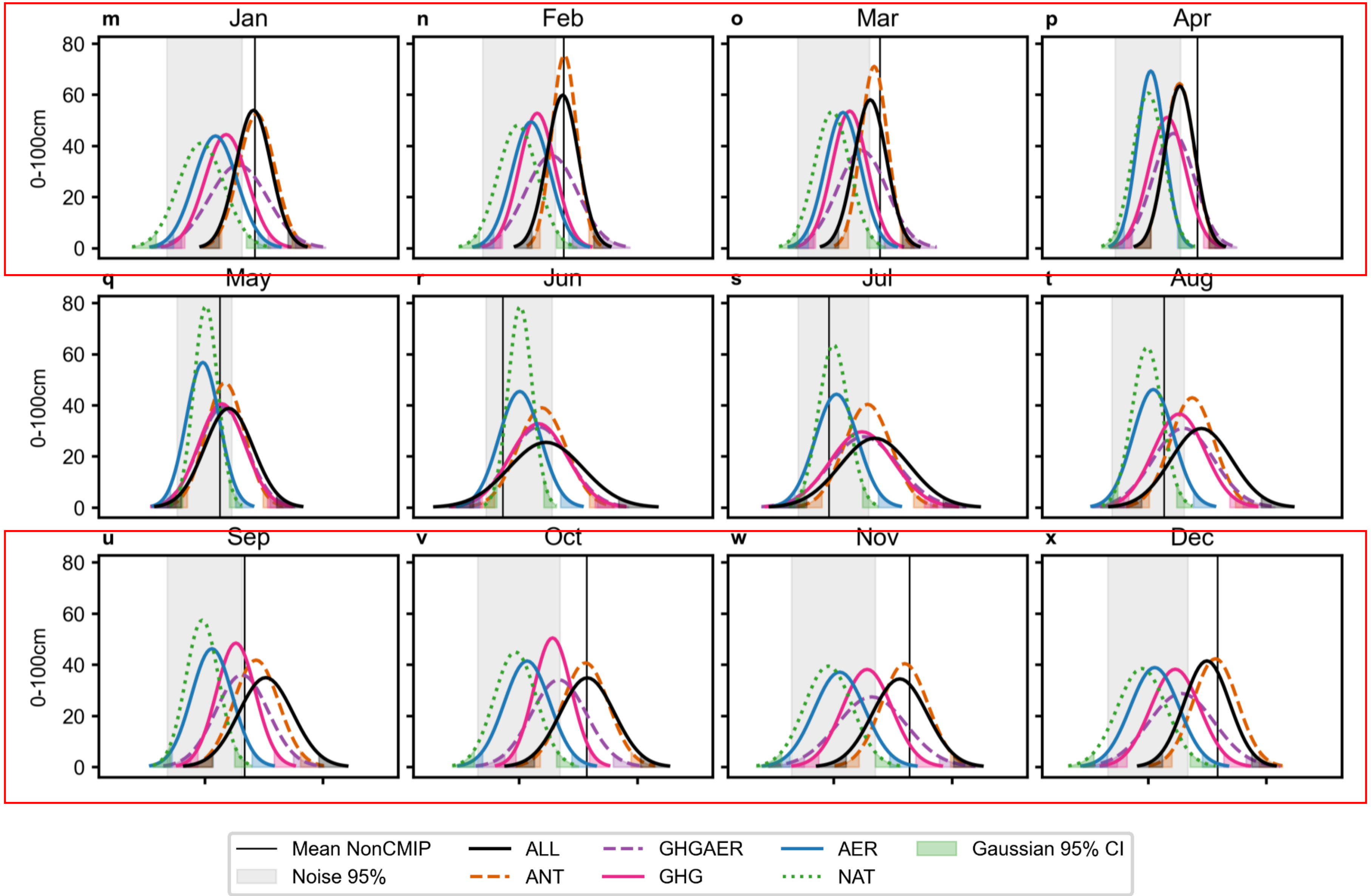
Attribution to a forcing

- Signal of the pseudo-observation within 95% confidence interval of the forced signals

D&A results for 1971–2016, 0-10cm



D&A results for 1971–2016, 0-100cm



Detection time

Fixed the first year at 1971

Increase the window length L from 10 to 46 until the pseudo-observation was first detectable and attributable to the ALL forcing

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0–10 cm	—	—	—	—	—	—	—	2015	2002	1995	2005	—
0–100 cm	2013	2014	2013	2009	—	—	—	—	2012	1997	2000	1994

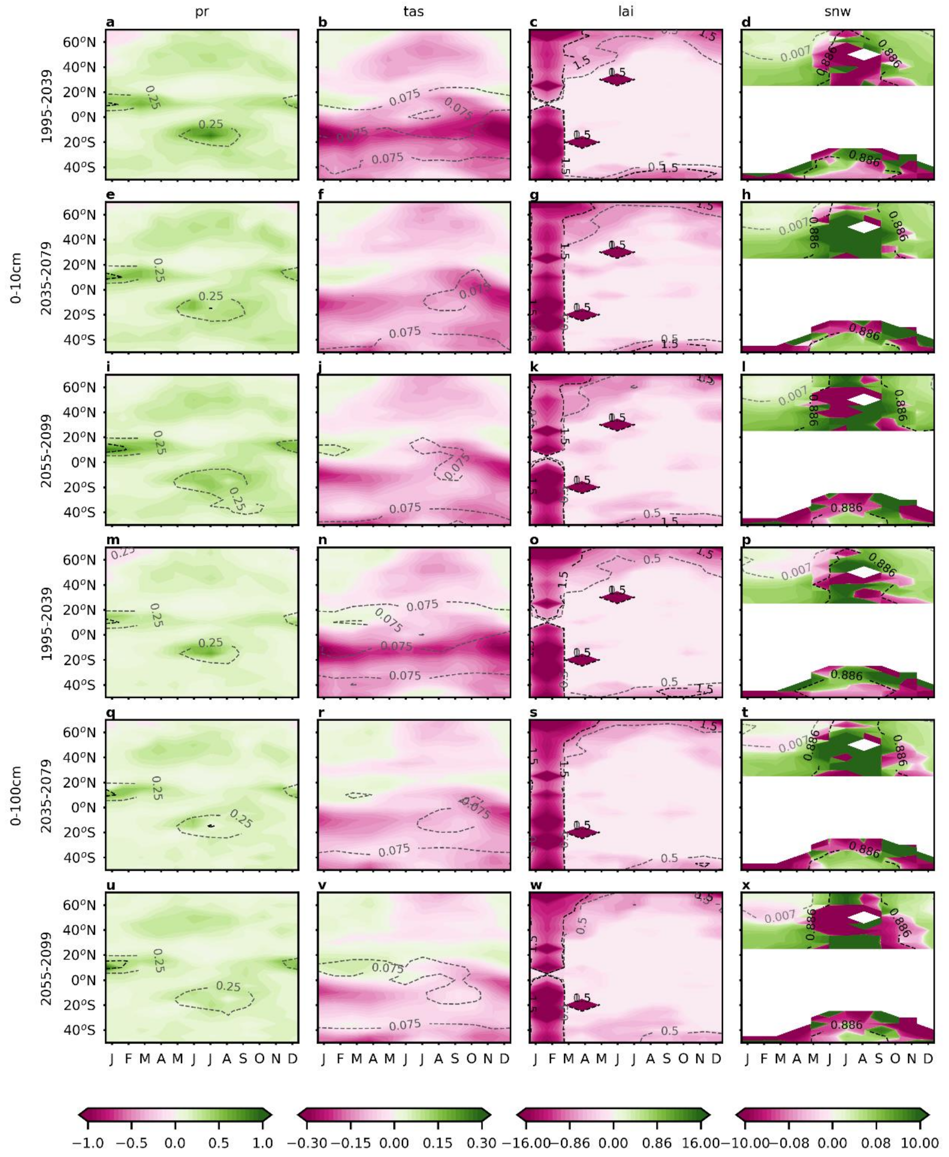
Emergent constraint of future signal-to-noise ratios

Justification of need

- Future simulated signal-to-noise ratios are inflated, because the models have common biases in the historical and future periods

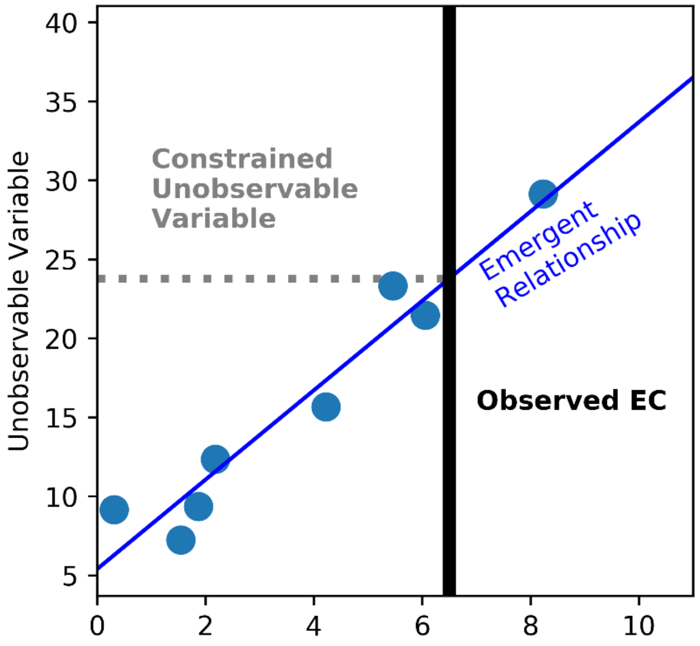
Physical basis

- Drivers of soil moisture (warming rates, leaf area, gross primary productivity) display emergent constraints (Tokarska et al. 2020; Winkler et al. 2019)
- Correlations between soil moisture and various drivers have consistent pattern over time



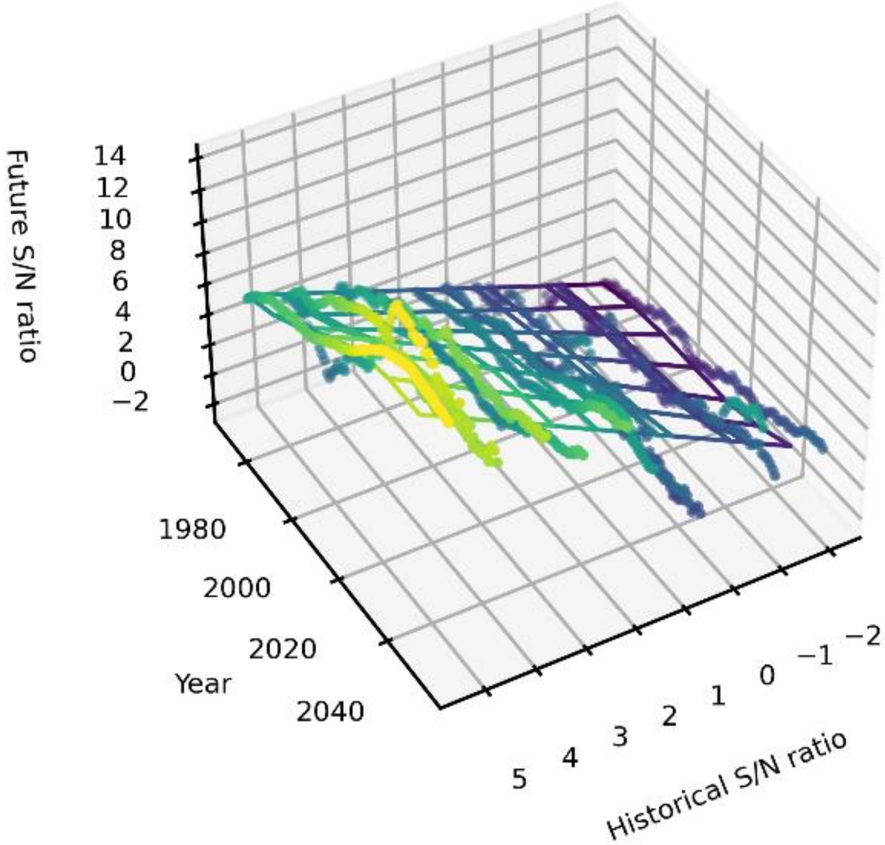
Emergent constraint of future signal-to-noise ratios

Conventional linear regression emergent constraint

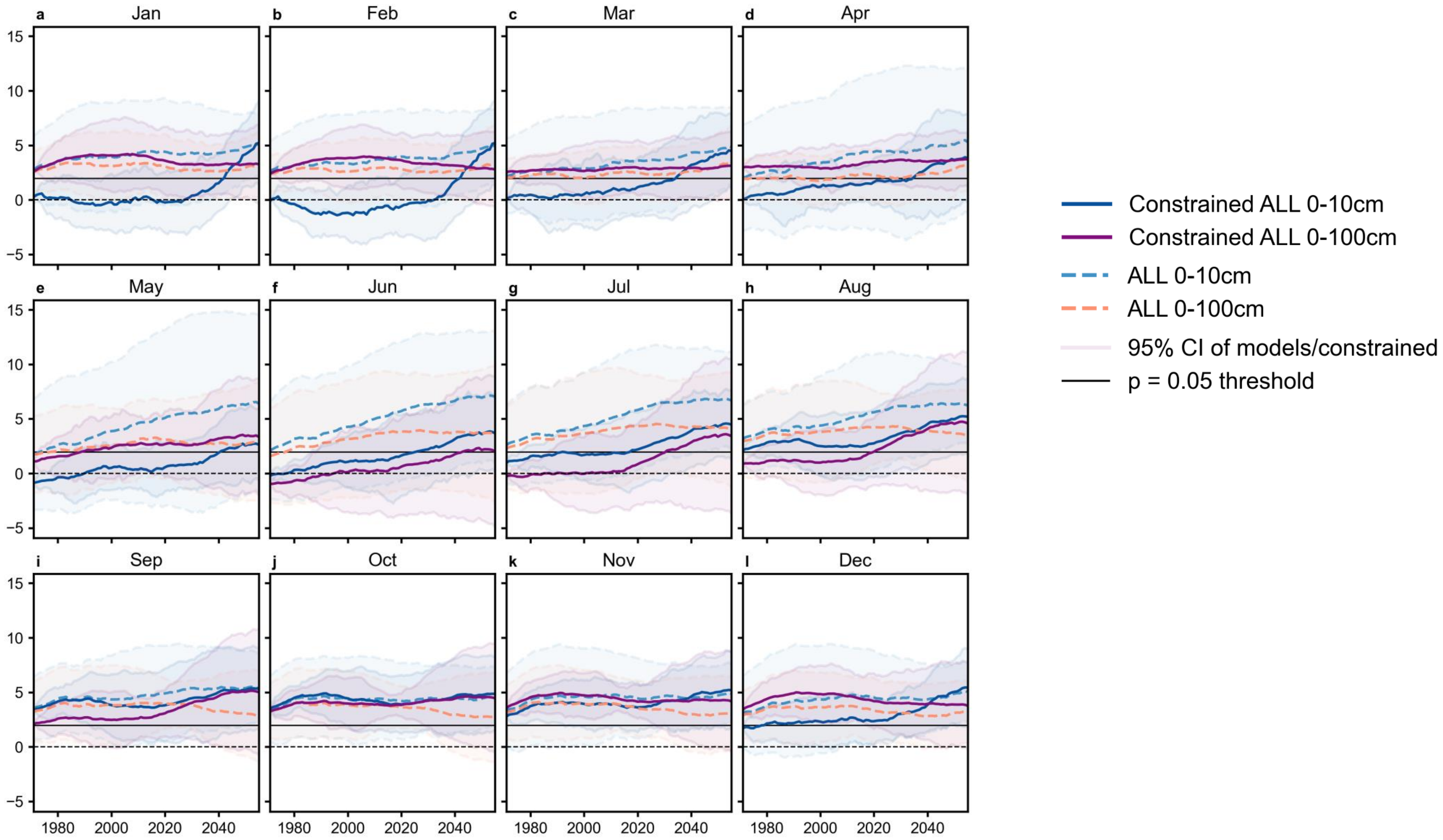


Generalized additive model

Significant at $p \leq 0.05$ for all months and soil layers



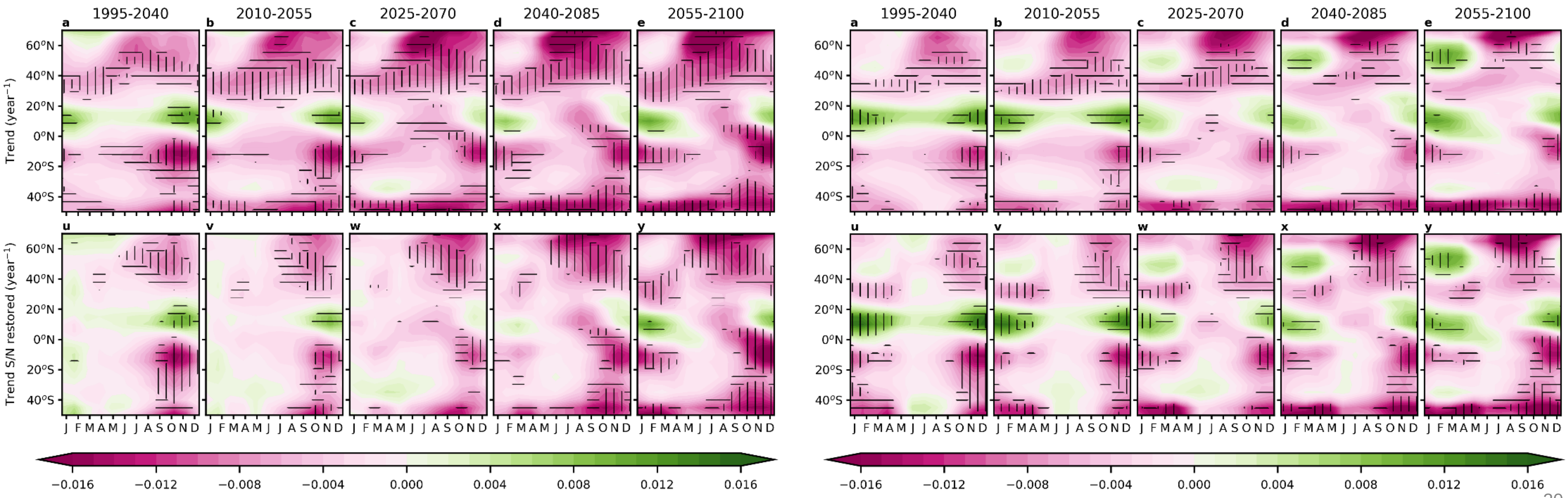
Future signal-to-noise ratio before & after constraint



Translation of the constraint on signal-to-noise ratios to trends

Trend(standardized soil moisture index) = S/N ratio x noise x fingerprint x weights + f(remaining EOFs)

0–10cm | **0–100cm**



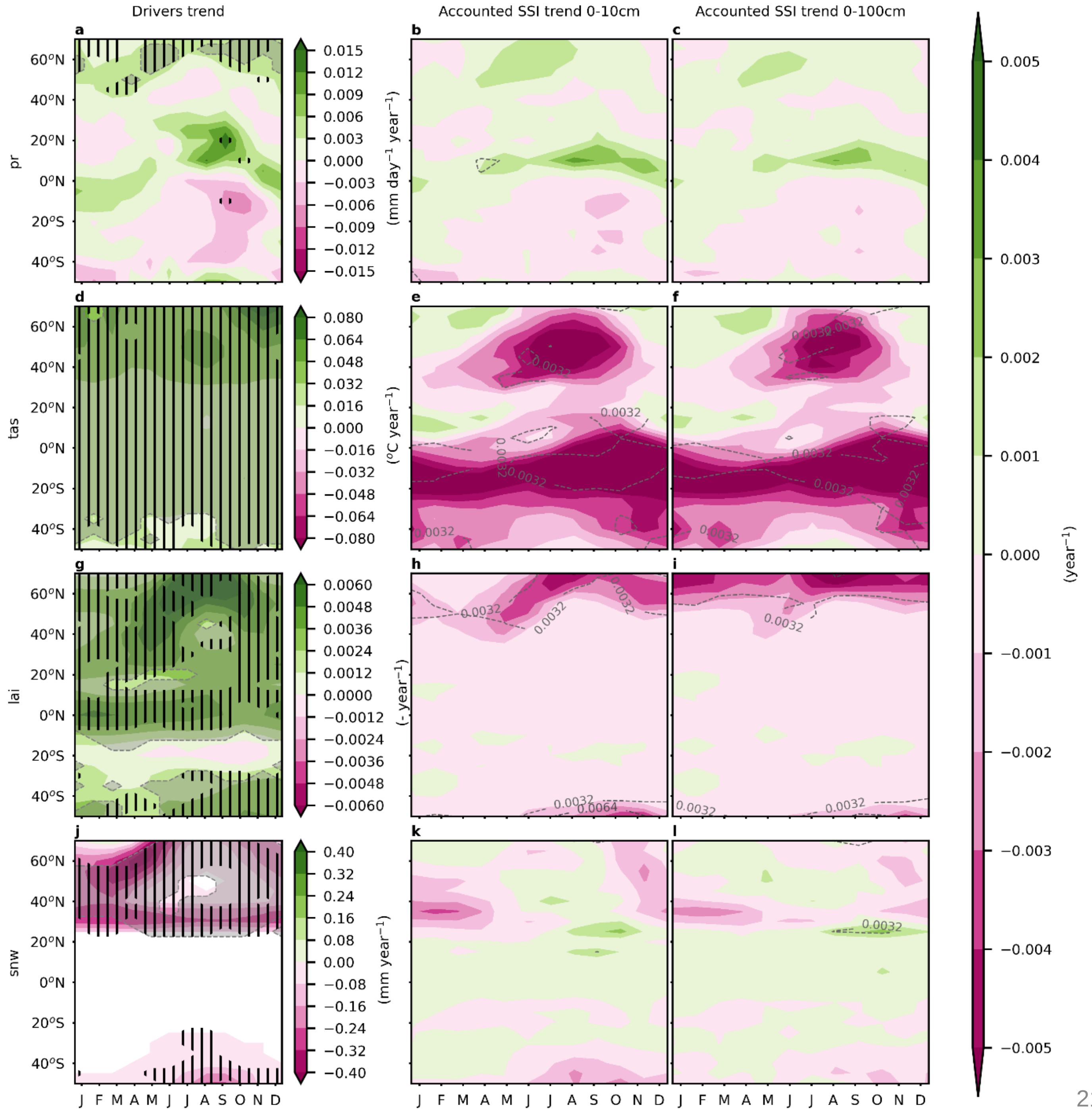
Future trends accounted for by individual drivers

pr – precipitation

tas – air temperature

lai – leaf area index

snw – snow water equivalent



Summary

Historical changes in standardized soil moisture index attributable to anthropogenic forcings, especially greenhouse gases

Clear latitudinal, seasonal and vertical patterns

- Prevalent mid-latitude drying, northern tropics (0–20°N) and root-zone spring high-latitude (~50°N) wetting
  - Drying mainly due to temperature, leaf area, and snowmelt
  - Wetting due to temperature and precipitation
- Detectable 0–10cm changes late summer to autumn (Aug–Nov)
- Detectable 0–100cm changes autumn to spring (Sep–Dec, Jan–Apr)
- Future drying accelerates faster in 0–10 cm than 0–100cm

Acknowledgements and More Info

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Dataset manuscript: Wang et al. 2021 https://essd.copernicus.org/articles/13/4385/2021/

D&A manuscript: Wang et al. 2022 https://doi.org/10.1038/s41467-022-34071-5