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Robust Impacts of Land Use Land Cover (LULC) Change on Regional Precipitation

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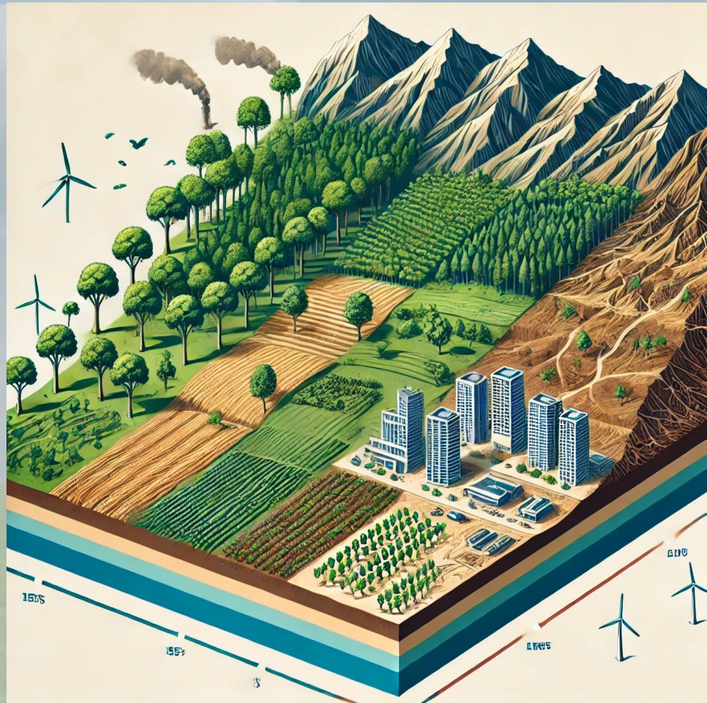


Motivation

- **LULC is a major driver of global environmental change**, influencing climate, ecosystem services, and society**.**
- **LULC alters regional climate** through changes in surface albedo and energy fluxes, affecting temperature and moisture balance.
- **The impact of LULC on precipitation remains uncertain**, requiring further investigation to improve climate predictions (Pitman et al., 2011; Boysen et al., 2020).
- **Determining whether LULC impacts fall within natural climate variability** is crucial for distinguishing human-induced changes from internal climate fluctuations.

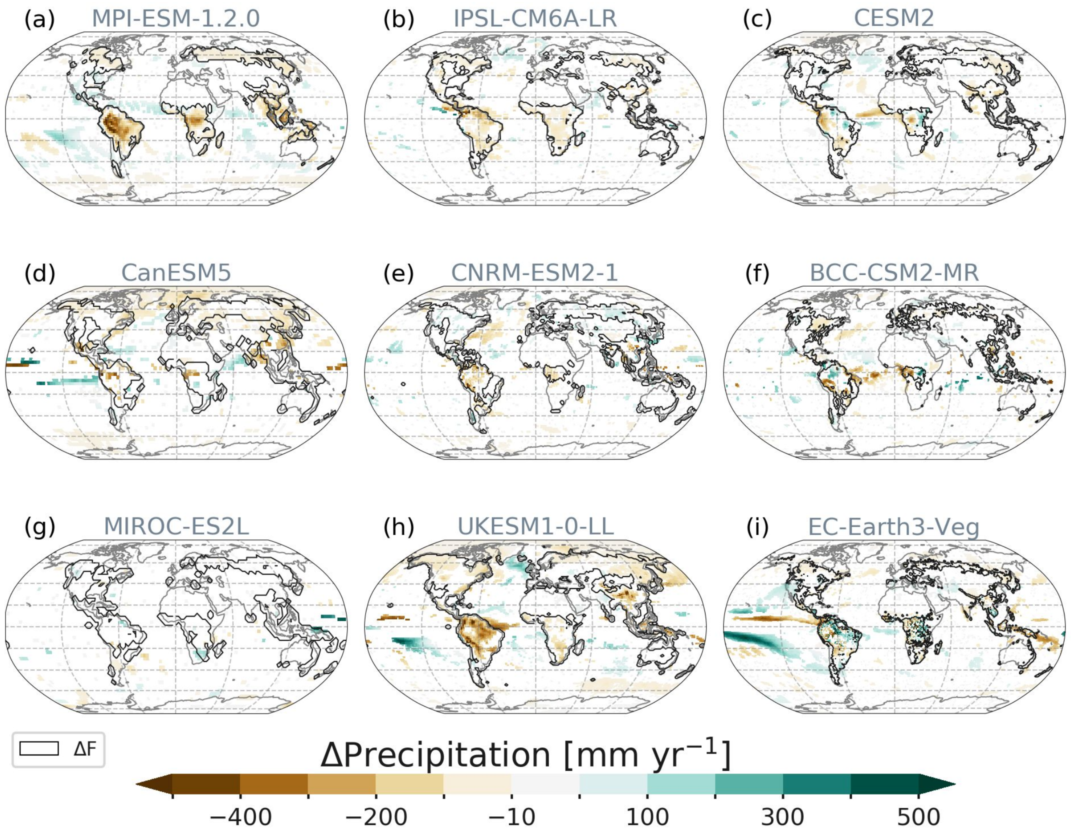
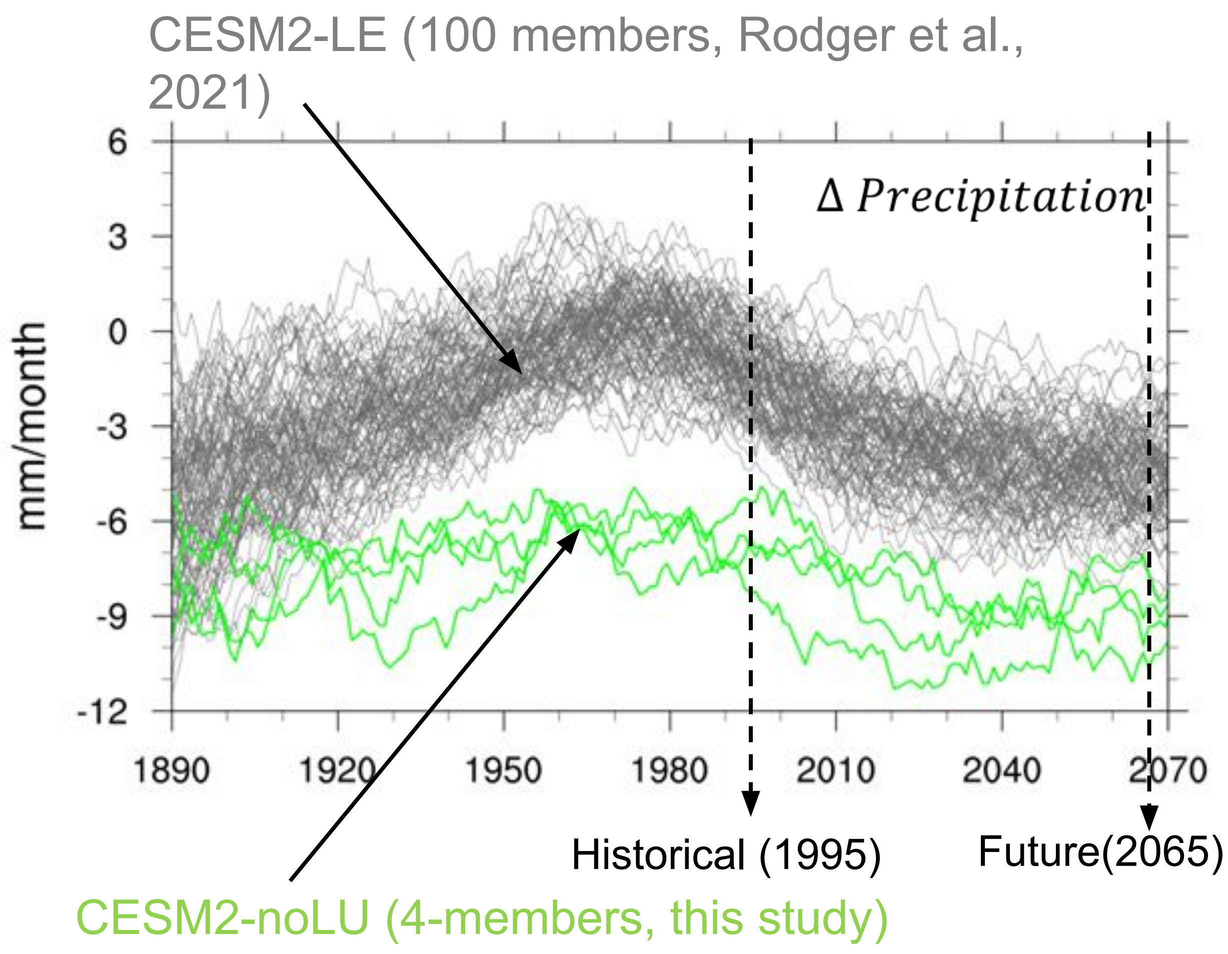


Figure 1: CMIP6 multi-model analysis of the idealized impact of deforestation on regional precipitation (Boysen et al., 2020). Results indicate no significant changes in precipitation patterns across mid-latitudes.

Research Objectives

- **Improve understanding of LULC impacts on regional climate** to enhance predictions and decision-making.
- **Use Large Ensemble (LE) climate data and limited sensitivity experiments** to assess LULC effects more effectively.
- **Evaluate how LULC impacts will evolve in a changing climate** to anticipate future risks and trends.

Are the 4-member CESM2-noLU experiments significantly different from the 100-member CESM2-LE? If so, in what ways, where, and why?



Data and Method

Experiment	Description	Reference
CESM2-LE	100 members: Fully coupled experiment (Land + Atmosphere + Ocean interactive), from 1850 to 2100 with SSP3.70 future scenario. Includes LU change; serves as a control run.	Rodger et al., 2021
CESM2-noLU	4 members: Same as CESM2-LE configuration but keeps land use at preindustrial conditions.	This study*
CESM2-LU	1 member: Validation run to reproduce CESM2-LE at NCAR machines.	

* Extension of CESM2-noLU [Singh, Kumar et al., 2024] to four members

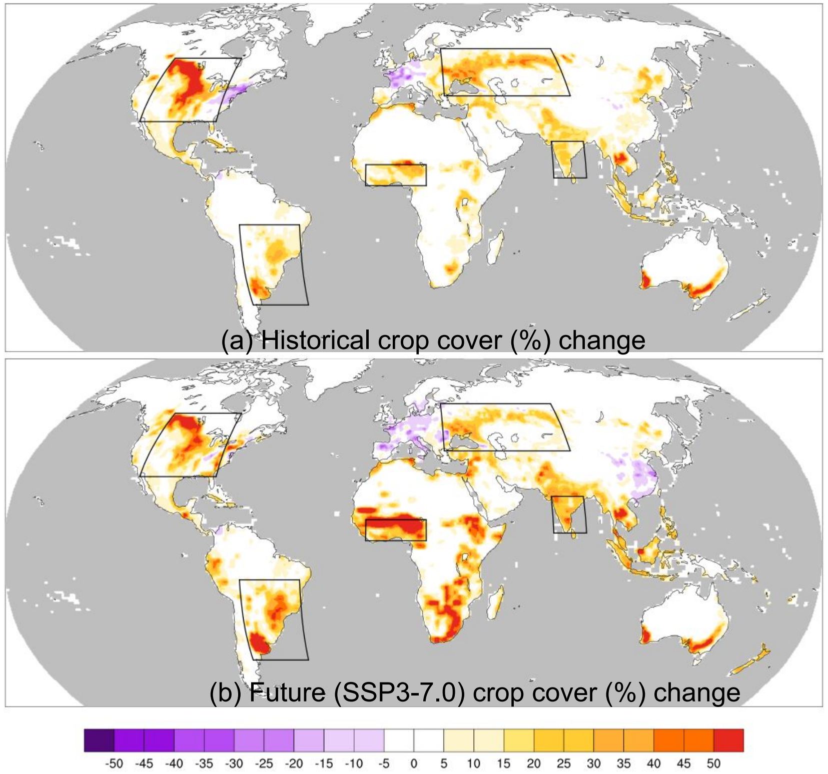
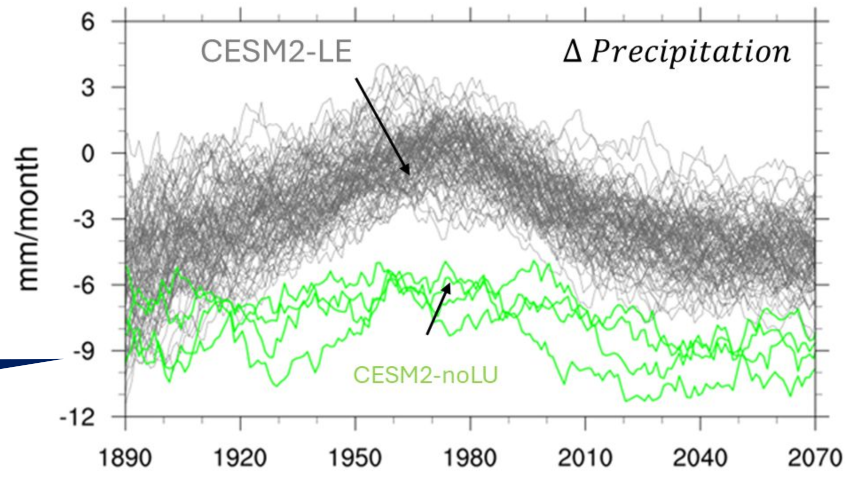
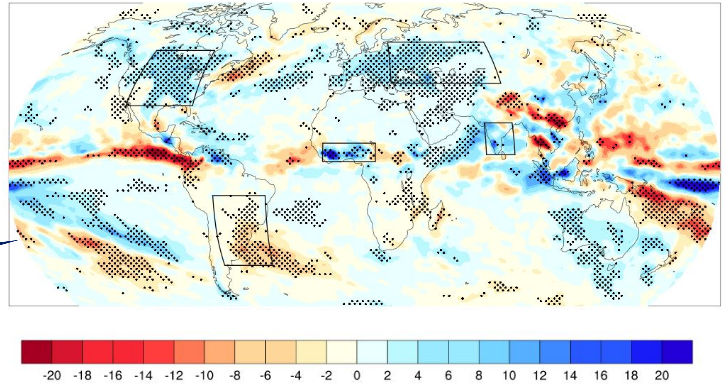


Figure 3: Changes in crop cover in historical and future climates relative to pre-industrial conditions.

Data Analysis and Statistical Method

1. **Grand Mean Calculation:** Compute gridded monthly reference climate from CESM2-LE (100 members, 1951–1980).
2. **Anomaly Calculation:** Subtract grand mean from CESM2-LE and CESM2-noLU ensembles.
3. **Seasonal Averaging:** Compute JJA seasonal mean anomaly time series.
4. **Temporal Smoothing:** Apply 30-year running mean to the JJA seasonal anomalies.
5. **Statistical Significance Assessment:**
   - Select 4 random CESM2-LE ensemble members and compute their mean.
   - Compute the mean of a 4-member CESM2-noLU subset.
   - Compute the difference between the two means.
   - Repeat the process 100 times to form a distribution.
   - Get the mean difference from the 100 samples (CESM2-LE minus CESM2-noLU).
   - The difference is significant if it falls outside the 95% range of the CESM2-LE distribution (CESM2-LE 4 members minus CESM2-LE mean; repeat it 100 times).





Stipplings – statistically significant differences at 95% CI

Model Validation

One member, CESM2-LU, successfully reproduced CESM2-LE.

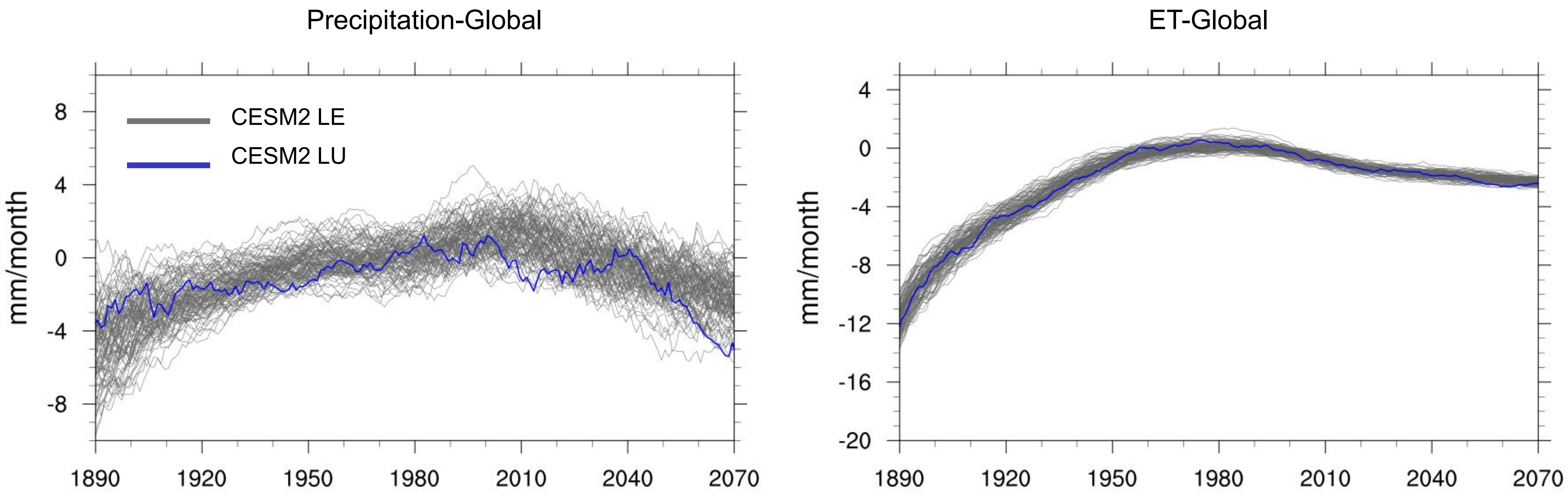
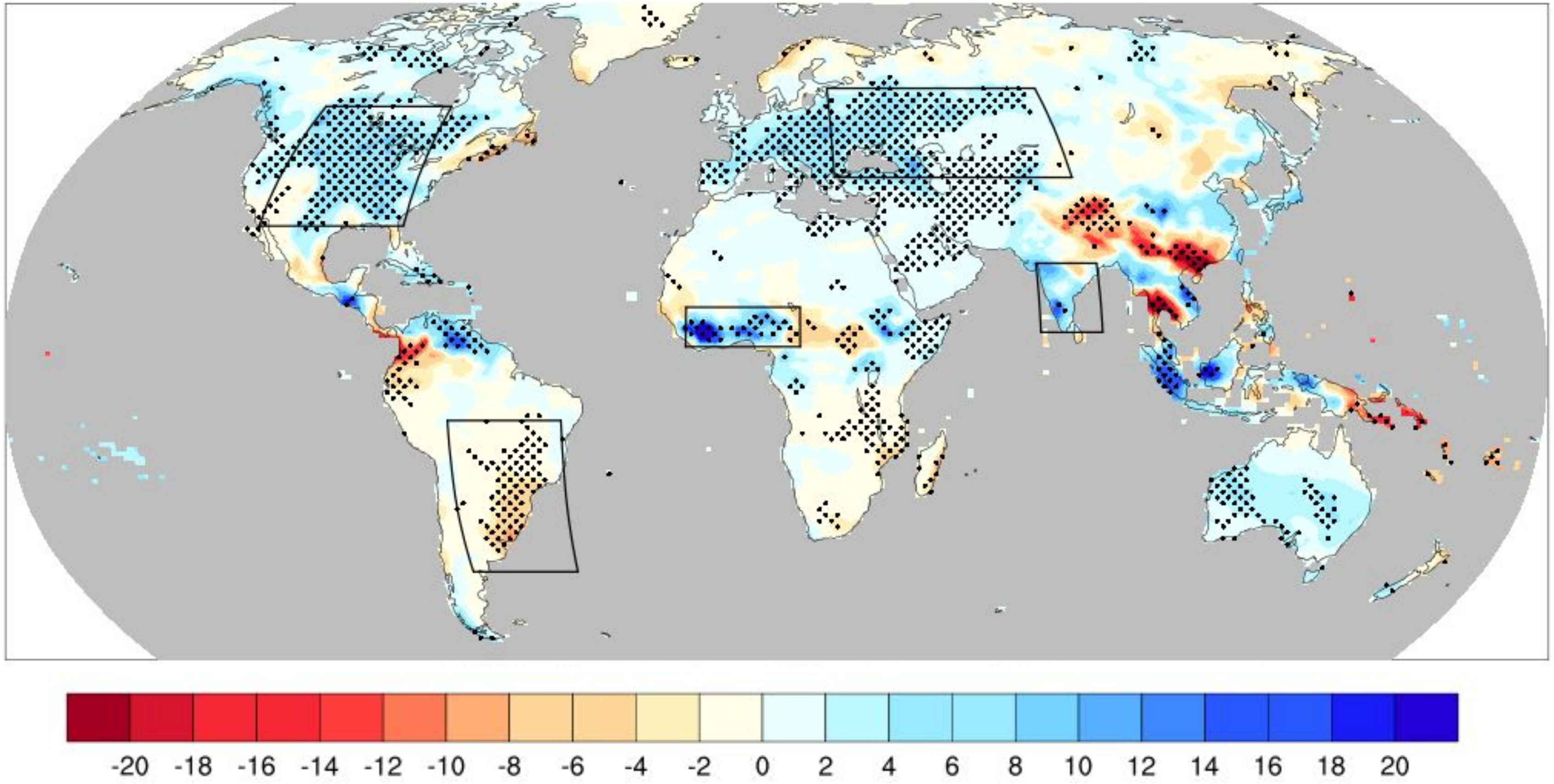


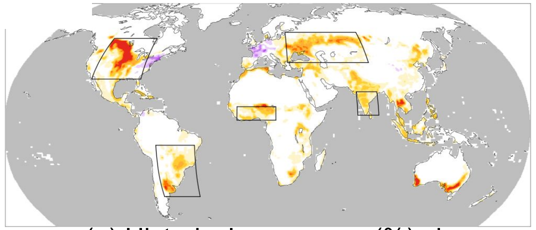
Figure 4: (a) Precipitation and (b) evapotranspiration anomalies relative to the CESM2-LE grand mean in regions with significant land-use change (Δ crop cover > 15%) globally.

LU change significantly increases precipitation in the mid-latitude



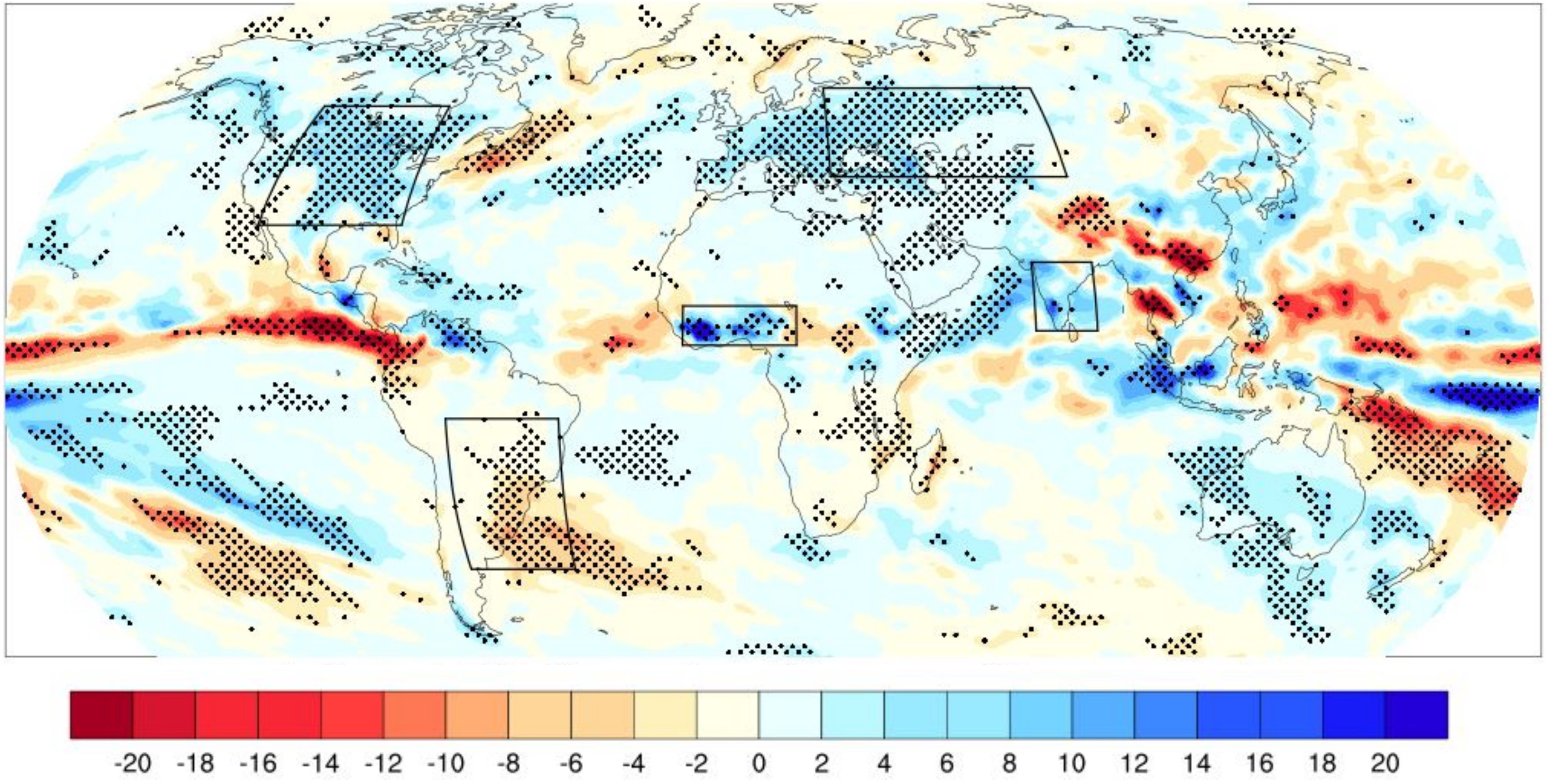
Historical Climate
(1981 to 2010)

CESM2-LE minus CESM2-noLU (mm/month, JJA)



(a) Historical crop cover (%) change

LU change impact precipitation globally including oceans

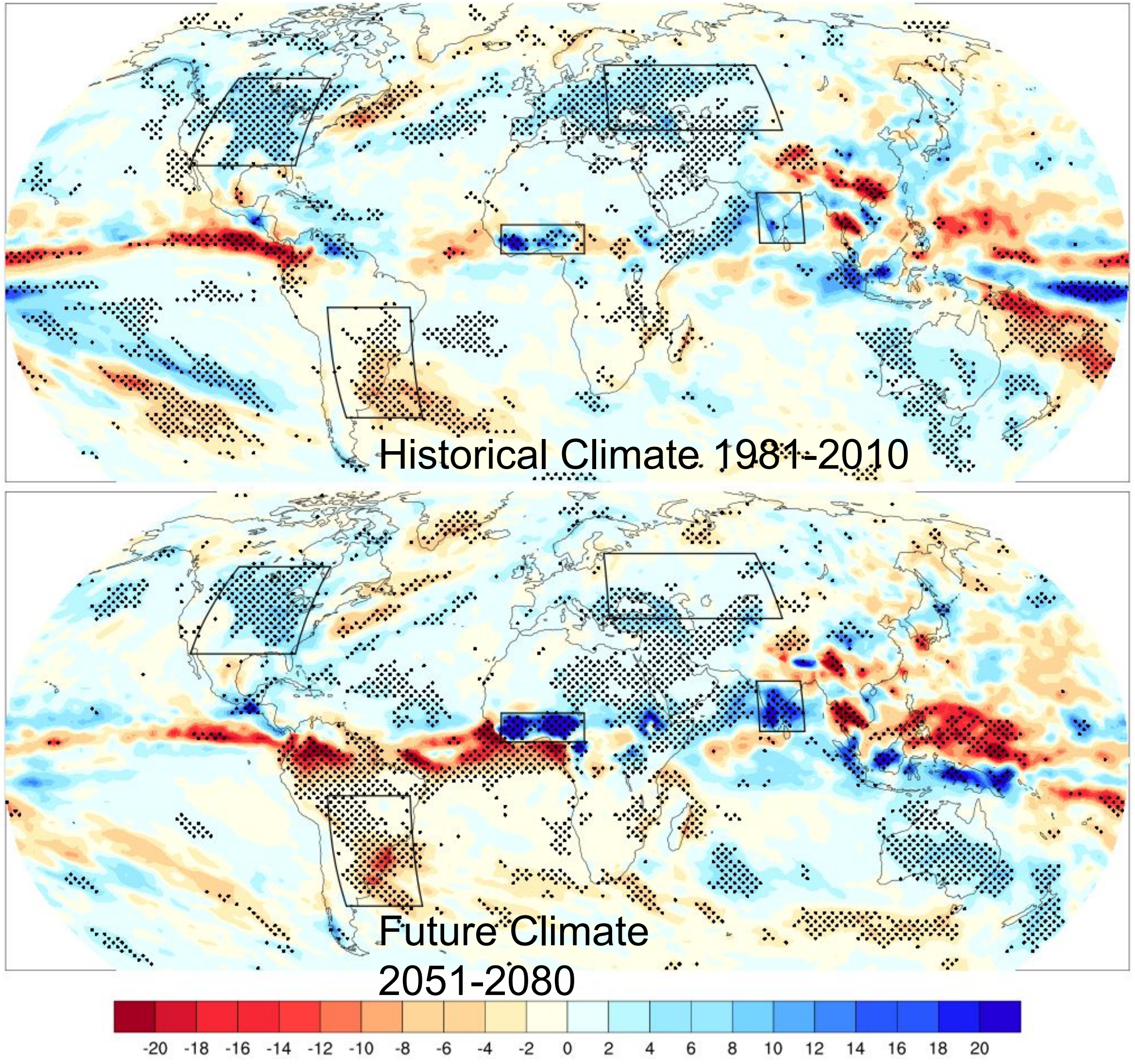


Historical Climate
(1981 to 2010)

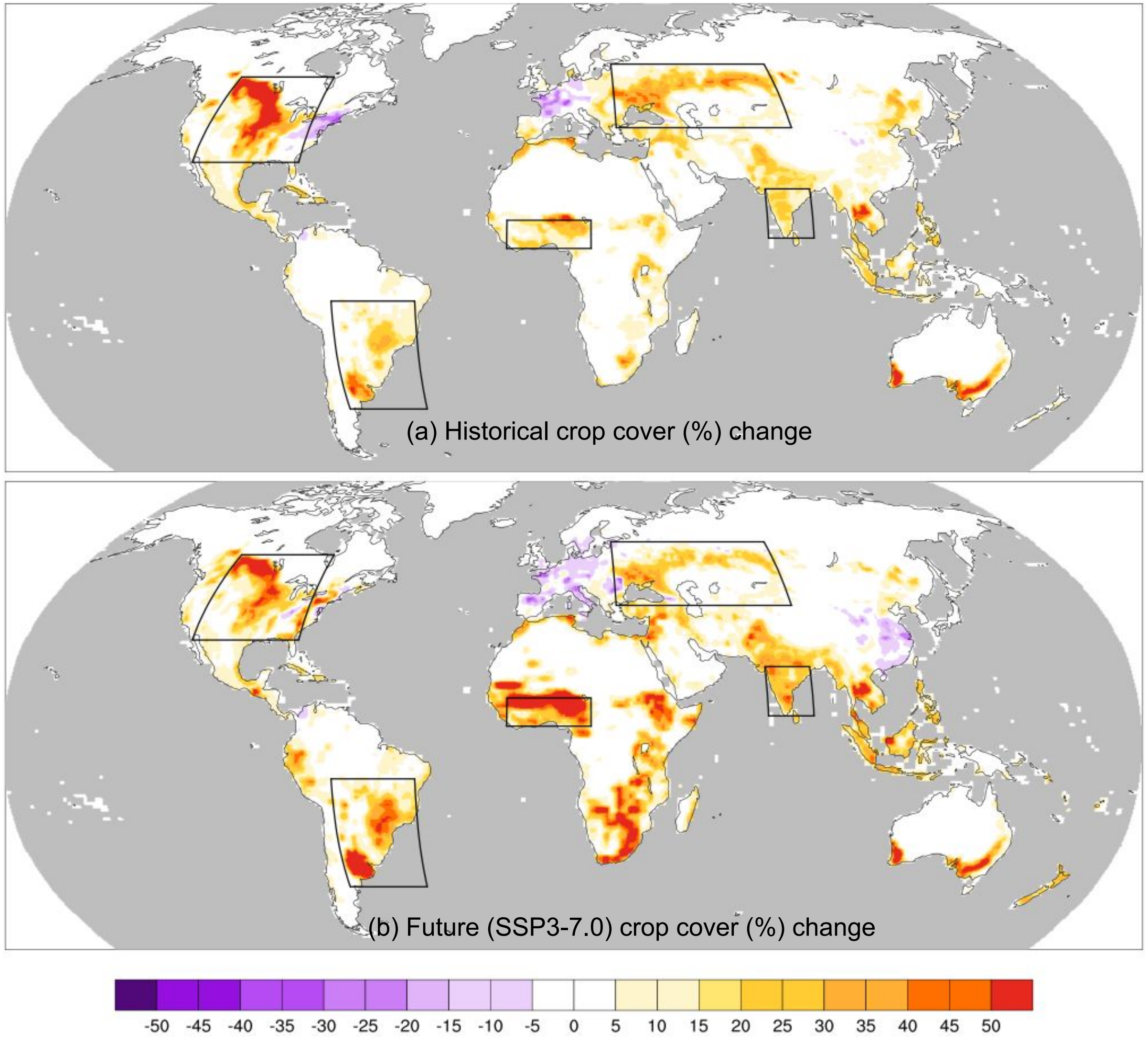
CESM2-LE minus CESM2-noLU (Precipitation, mm/month, JJA)

Future Climate – New hot sport in South America with decreased precipitation

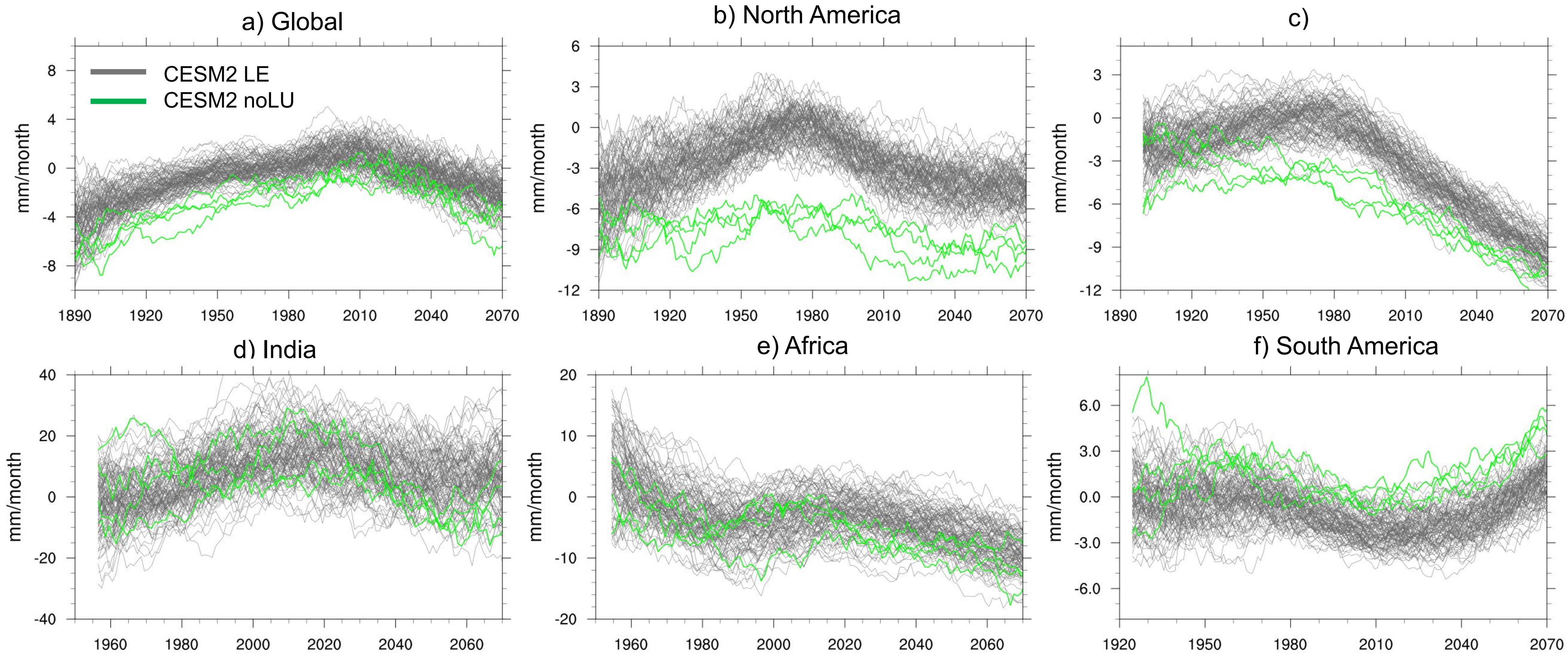
Δ *Precipitation (JJA, mm/month)*



Δ *Crop cover (% coverage)*

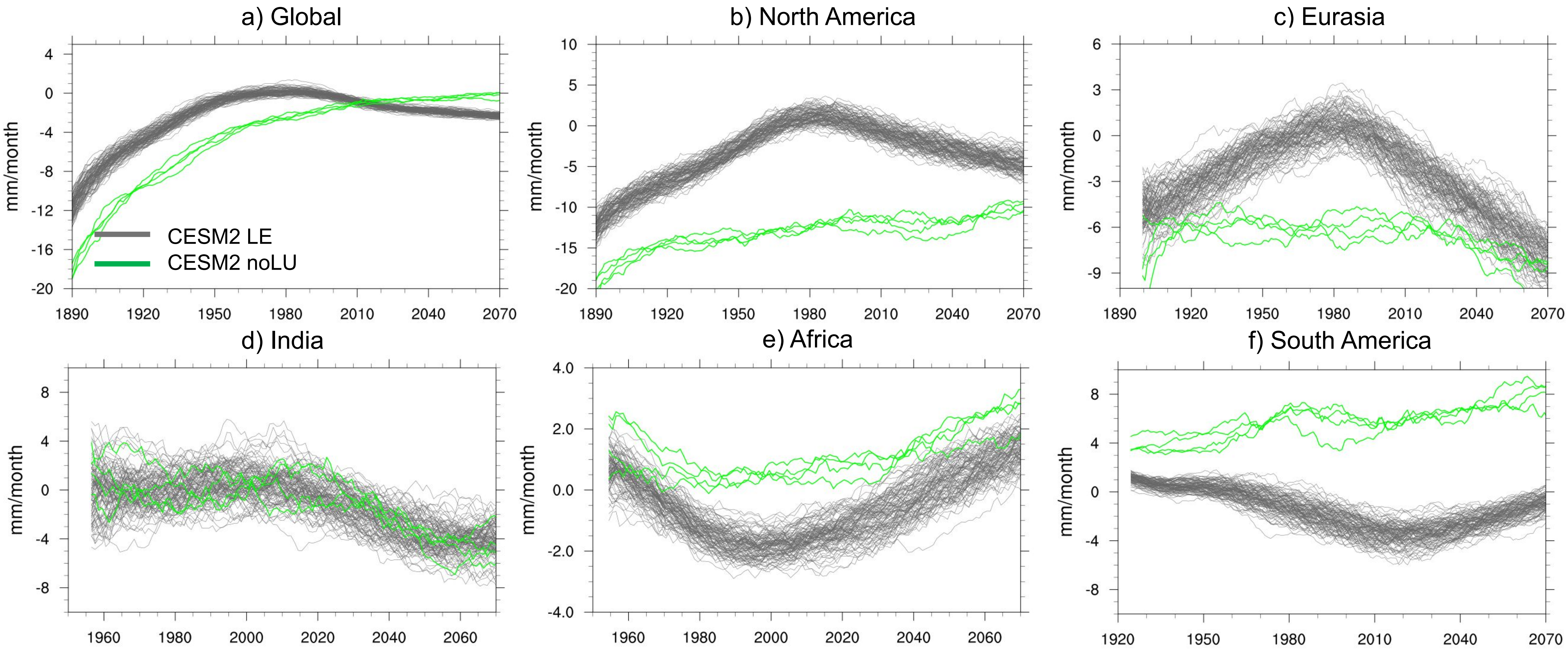


LULCC Impact on Historical and Future Precipitation



LULCC influence precipitation significantly in North America, Eurasia and South America

LULCC Impact on Historical and Future ET



LULCC influences ET significantly globally and in North America, Eurasia, Africa, and South America

Mechanistic Understanding of LU induced precipitation changes

- **LULC modifications influence precipitation patterns differently across latitudes**, increasing precipitation in mid-latitude regions (e.g., North America and Eurasia) while reducing it in tropical areas (e.g., South America).
- **LULC-driven changes in evapotranspiration (ET) likely drive precipitation changes**, with ET increasing in mid-latitudes but decreasing in the tropics.
- **Irrigation amplified increased ET** in areas like Central Valley, California and Ogalla Aquifer and Mississippi Valley.
- **ET changes contribute to precipitation variability both locally and globally** by affecting atmospheric moisture transport and circulation patterns. LULC-induced cooling may also have a role (ongoing investigation).
- **In mid-latitudes, the increase in ET exceeds the increase in precipitation**, leading to overall soil moisture depletion documented in our previous study (Singh, Kumar et al., 2024).

CESM2-LE minus CESM2-noLU (ET, mm/month, JJA)

Conclusions

To our knowledge, this is the first time we have identified the statistically significant impacts of LULC change on global and regional precipitation patterns.

LULC change increases precipitation in mid-latitude regions, particularly in North America and Eurasia, while decreases in South America.

Changes in LULC indued ET coupled with atmospheric circulation can impact precipitation locally and globally in CESM2.

Reference

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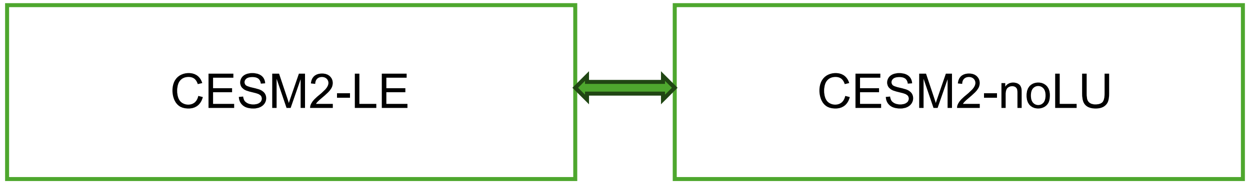
Developing CESM2-noLU

- After successful validation we developed CESM2-noLU model.
- We used preindustrial land use scenario in CESM2-noLU model.
- Developed 4 CESM2-noLU with the following set of initial condition:
    I. 1011.001
    II. 1251.011
    III. 1281.011
    IV. 1301.011
- Spatial resolution and time period is same as CESM2-LU run.
- We have compared our CESM2-noLU run with CESM2-LE (100 ensemble memerbes).



Developing CESM2 and Validation

- We have conducted fully coupled global climate model simulations using CESM2.
- Fully coupled CESM2 incorporates land, atmosphere, ocean and ice.
- First we developed fully coupled CESM2 with land use scenario (Control run).
- Fully spun up initial condition from the member b.e21.BHISTsmbb.f09_g17.LE2-1011.001 and was used.
- For future scenario we used initial condition from b.e21.BSSP370smbb.f09_g17.LE2-1011.001_noLU.
- Compared with CESM2-LE (100 ensemble members) to validate our model.

Historical scenario: 1850-2014; Future scenario: 2015-2100

Resolution: 192×288