Assessing the Role of Soil Moisture and Land Memory in Northern European Extremes Using a Coupled Large-Ensemble Prediction System

Akhilesh Nair, François Counillon, Noel Keenlyside

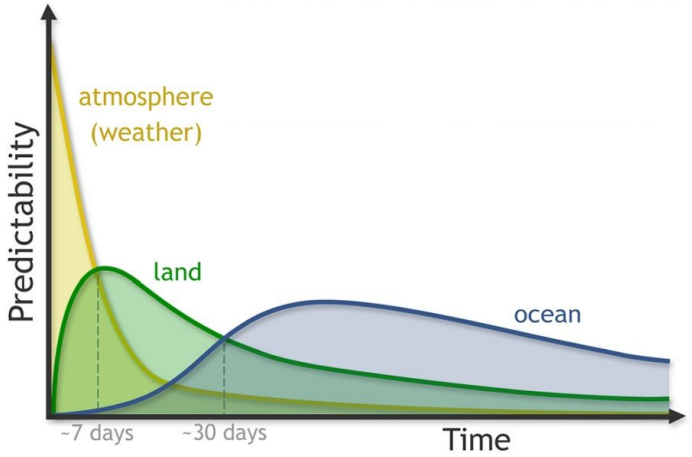
NERSC
STIFTELSEN NANSEN SENTER FOR MILJØ OG FJERNMÅLING
NANSENSENTERET · BERGEN · NORGE

Joint CP-TT/DA-TT Workshop 2026, 29th October

Land initialisation in S2S prediction

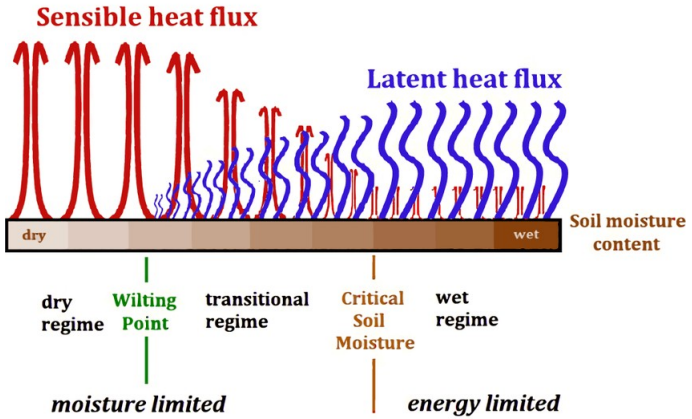
Why land initialisation in important

Relevance for S2S : From 2-4 weeks lead time, the land surface is a major source of predictability

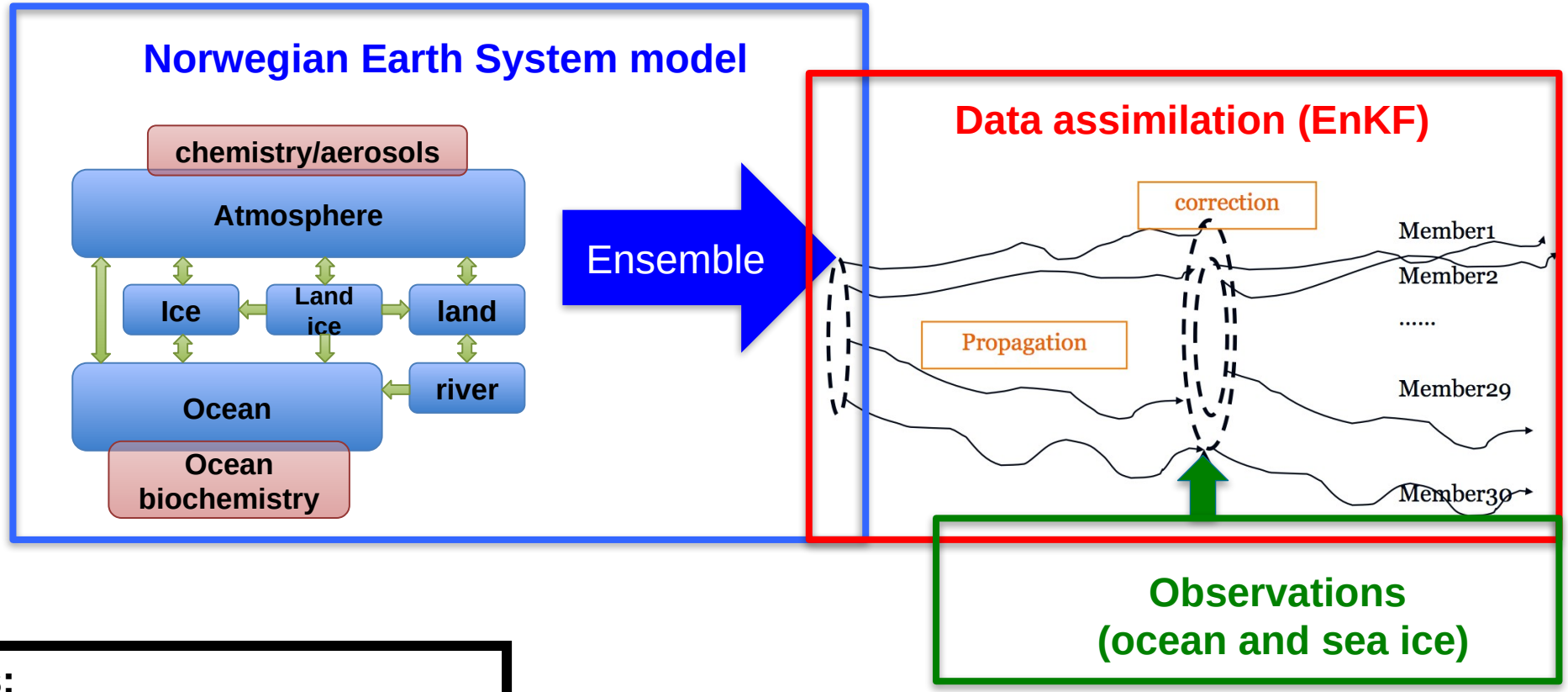


Source : Mariotti et al., 2018

Drives Land-Atmosphere Feedbacks : Soil moisture influences the balance between sensible and latent heat fluxes at the surface.



Norwegian Climate Prediction Model (NorCPM1)



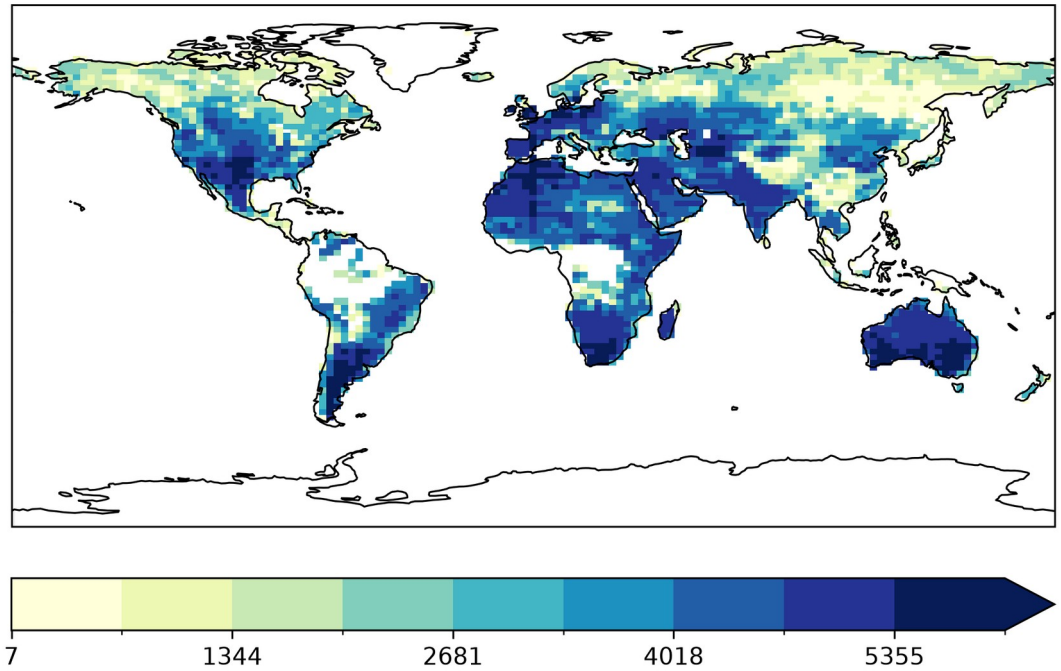
Objectives:

- **Long climate reanalysis**
- **Skillful and reliable climate prediction**

(Counillon et al. 2016)
(Bethke et al. 2021)

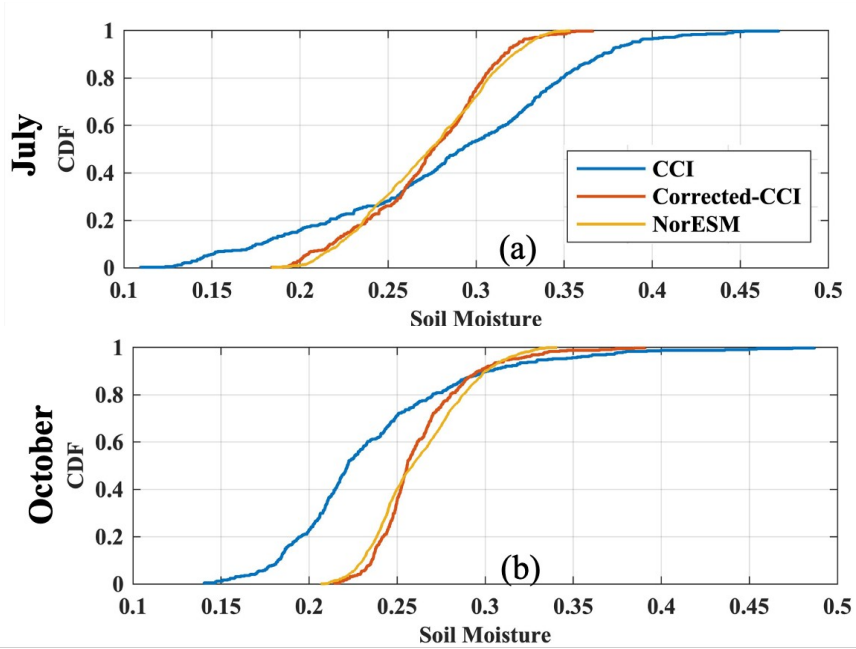
Soil moisture assimilation in NorCPM

CCI merged (passive satellite) product



Number of valid (Snowfree, Quality Flag) merged daily satellite observations between 2000-2019

Soil moisture and satellite observations strongly differ
We use CDF matching !



Nair et al., 2024

Testing the impact from Soil moisture

Free: 30 member with historical forcing

Reanalysis 2000-2024:

- **NorCPM1:** 30 mem EnKF assimilating (SST, T-S, SIC) monthly
- **NorCPM1-Land offline** (Nair et al. 2024): Assimilate ESA CCI soil moisture offline from FREE with an EnKF and quantile mapping anomaly assimilation
- **NorCPM1+Land online:** Assimilate monthly ocean and sea ice and subcycle assimilation of daily ESA C3S passive (operational with 10-day latency) soil moisture using pause-resume functionality and quantile mapping anomaly assimilation

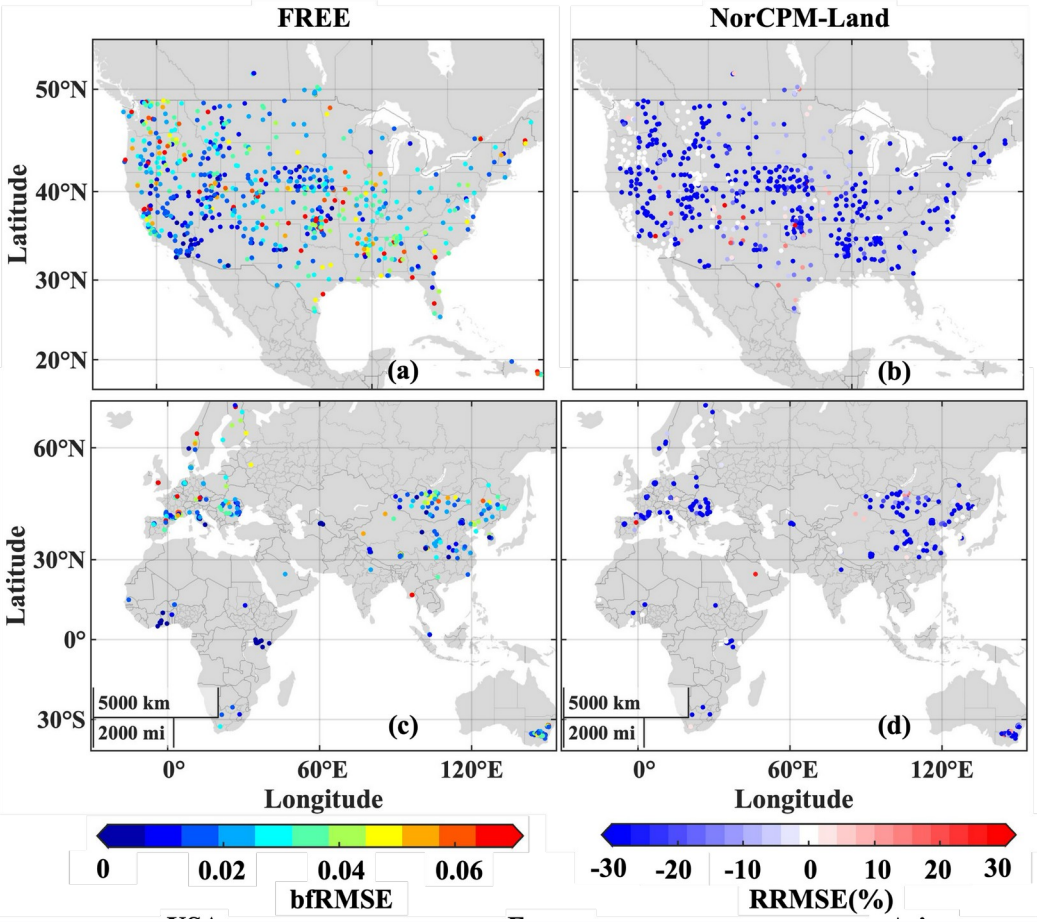
Hindcast 2000-2024 (monthly start, 10-60 members 2 months lead time):

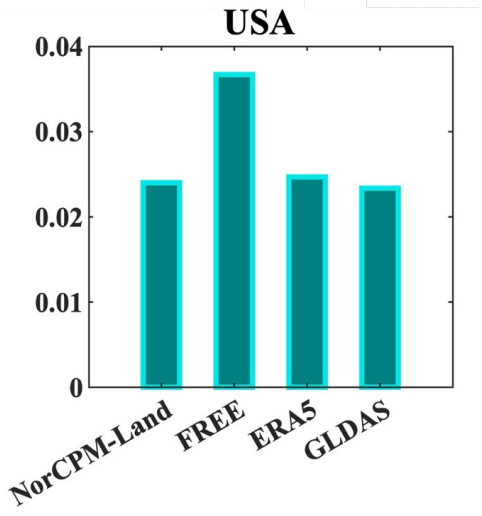
- **NorCPM1**: benchmark
- **Offline Land_init (30 members)**: Use the land initialisation from **Reana NorCPM-Land and other components from NorCPM1**
- **Online Land_init (60 members)**: Use all components from **NorCPM1+L**

Nair et al. (in prep.)

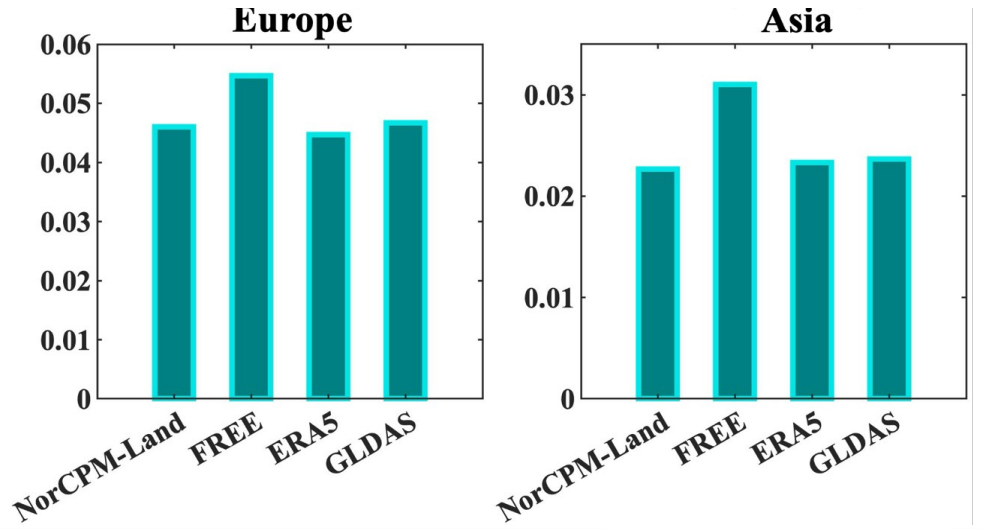
NorCPM-Land: Offline soil moisture assimilation

Verification vs independent in-situ measurements 1980-2019 from ISMN





SM DA produces realistic soil moisture estimate that comply with model dynamics

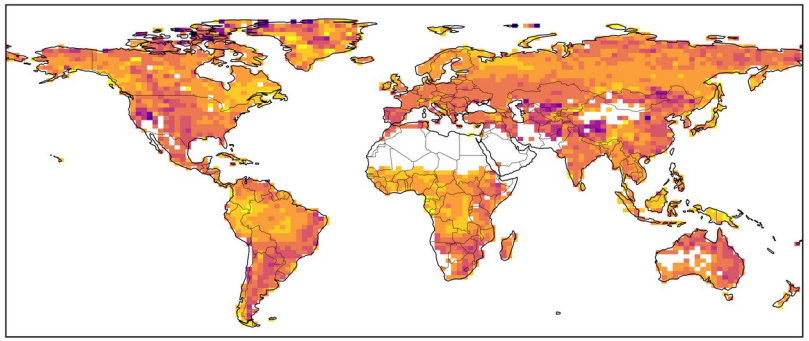


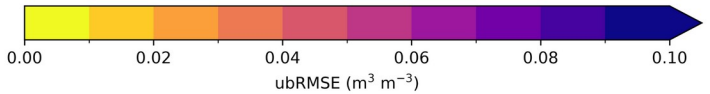
Nair et al., 2024

Added value of *Soil Moisture* assimilation in the reanalysis

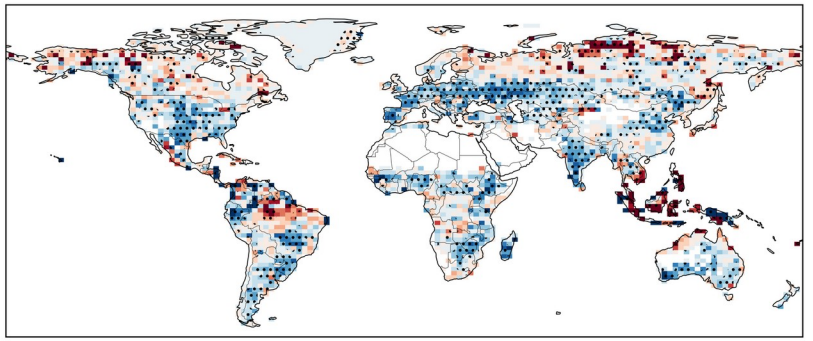
Offline vs Online

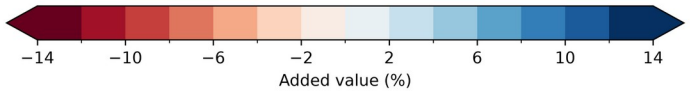
NorCPM1 reana



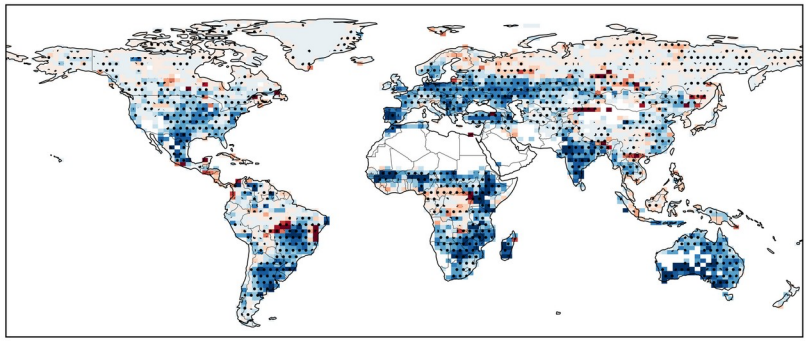


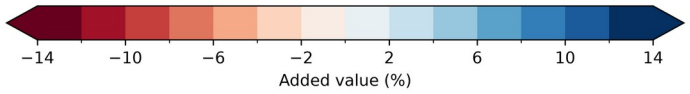
Offline-NorCPM1





Online-NorCPM1





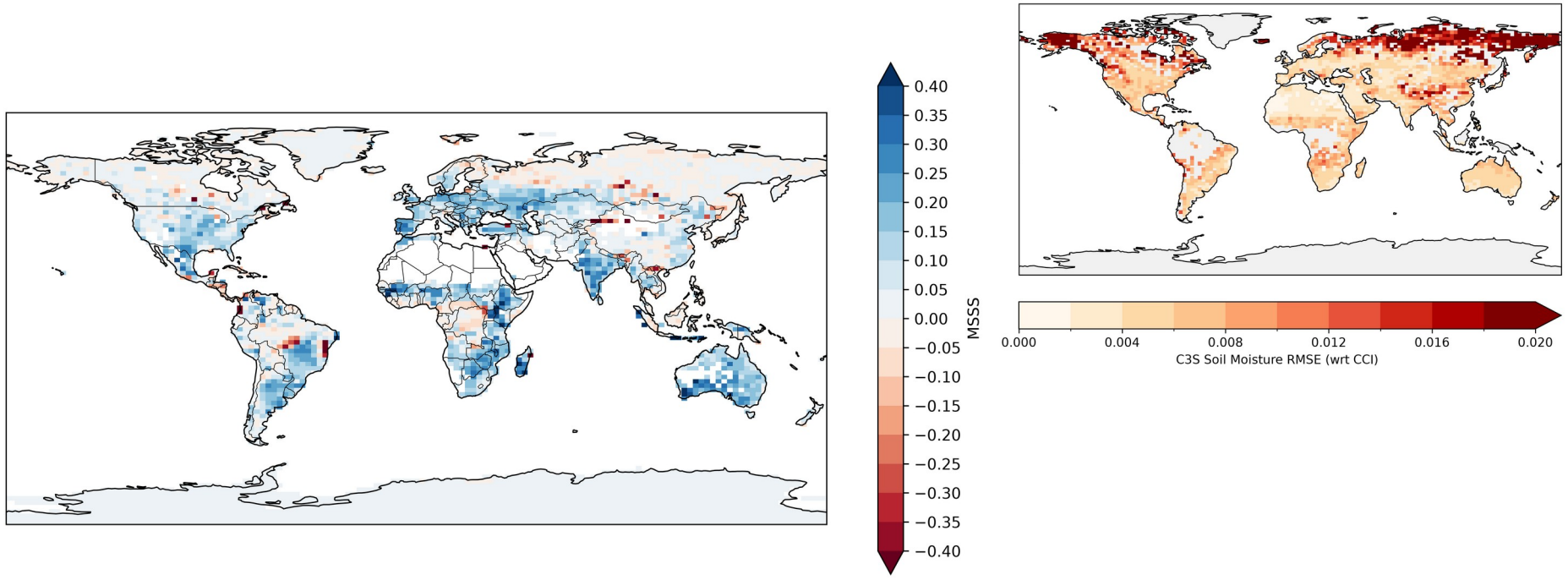
Added value =

Both online and offline assimilation systems improve soil moisture states

Online assimilation has a greater improvement because of land-atmosphere feedback and persistency of the updates

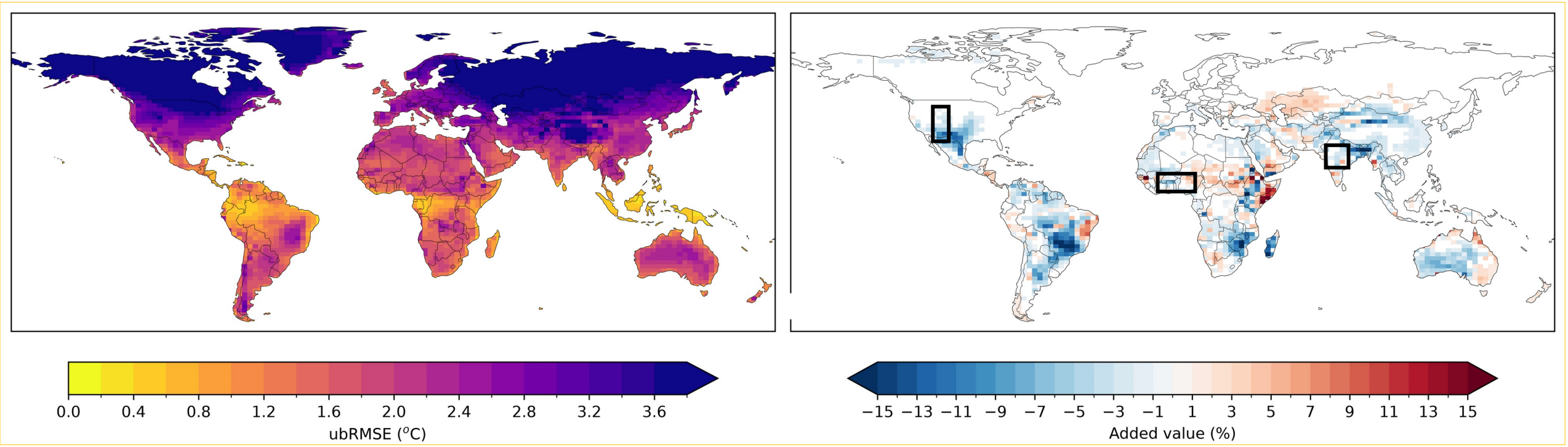
MSSS (NorCPM1-Land Offline) – (NorCPM1-Land Online)

MSSS = 1 -



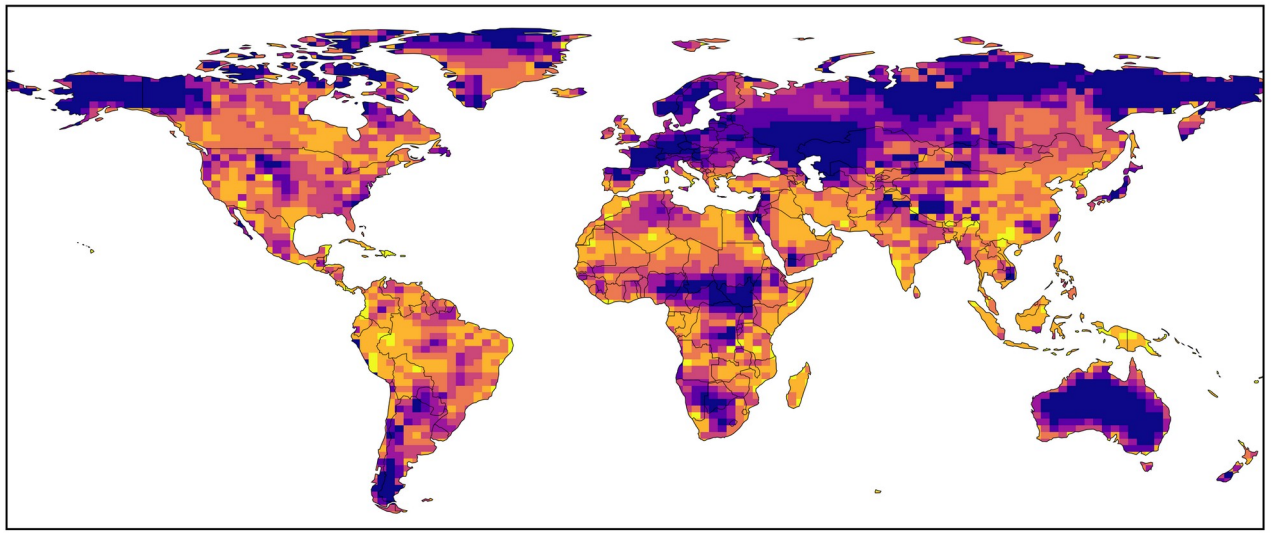
Online assimilation improved SM representation (dynamical consistency and persistence of the update)
Degradation correlates with mismatch between C3S and CCI product ?

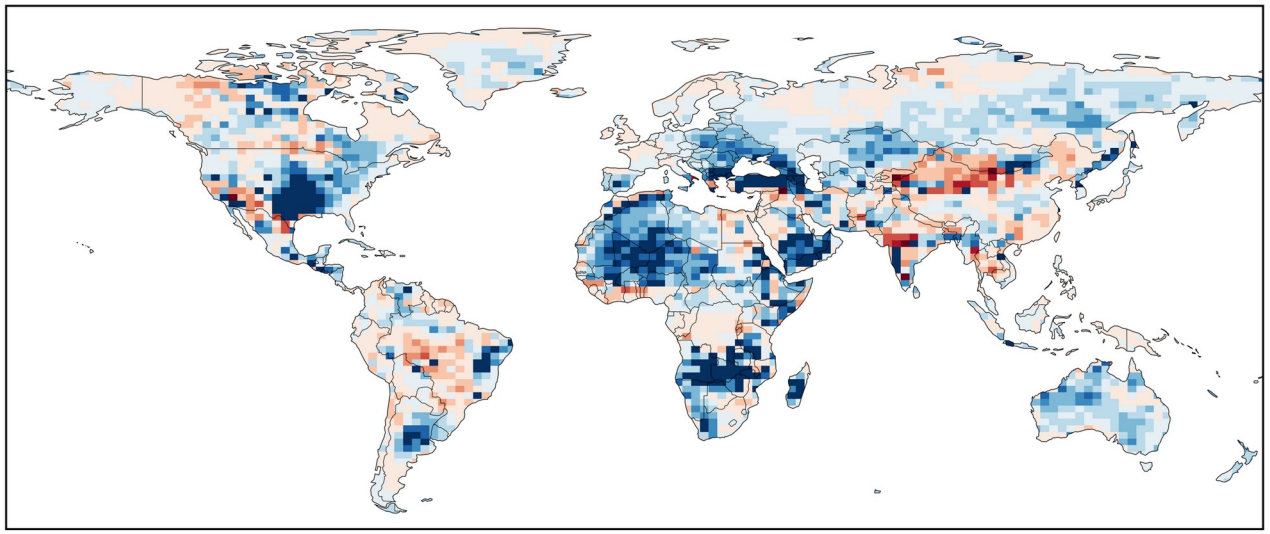
Impact on other variables
Temperature at 2 meters (ubRMSE)

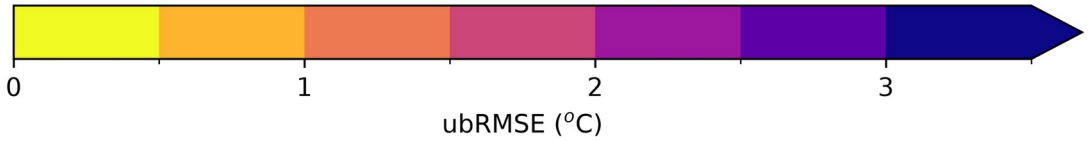


- Soil moisture assimilation reduces T2M error (blue) by up to in major coupling hotspots
- Northern high-latitude regions show near-zero added value despite higher initial error
- Some degradation inherent to model bias and C3S observation error ?

Impact on other variables
T2M 95th percentile





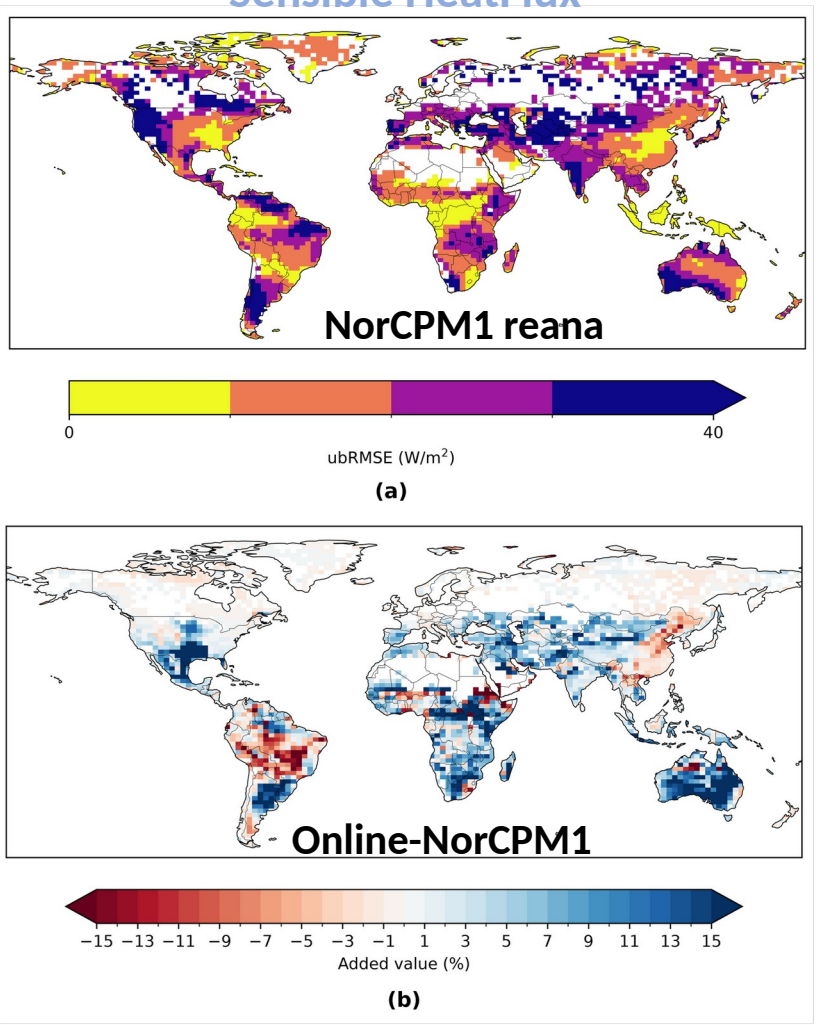




Soil moisture assimilation improves the representation of temperature extremes (also in the North)

Impact on other variables
Turbulent *Fluxes*:

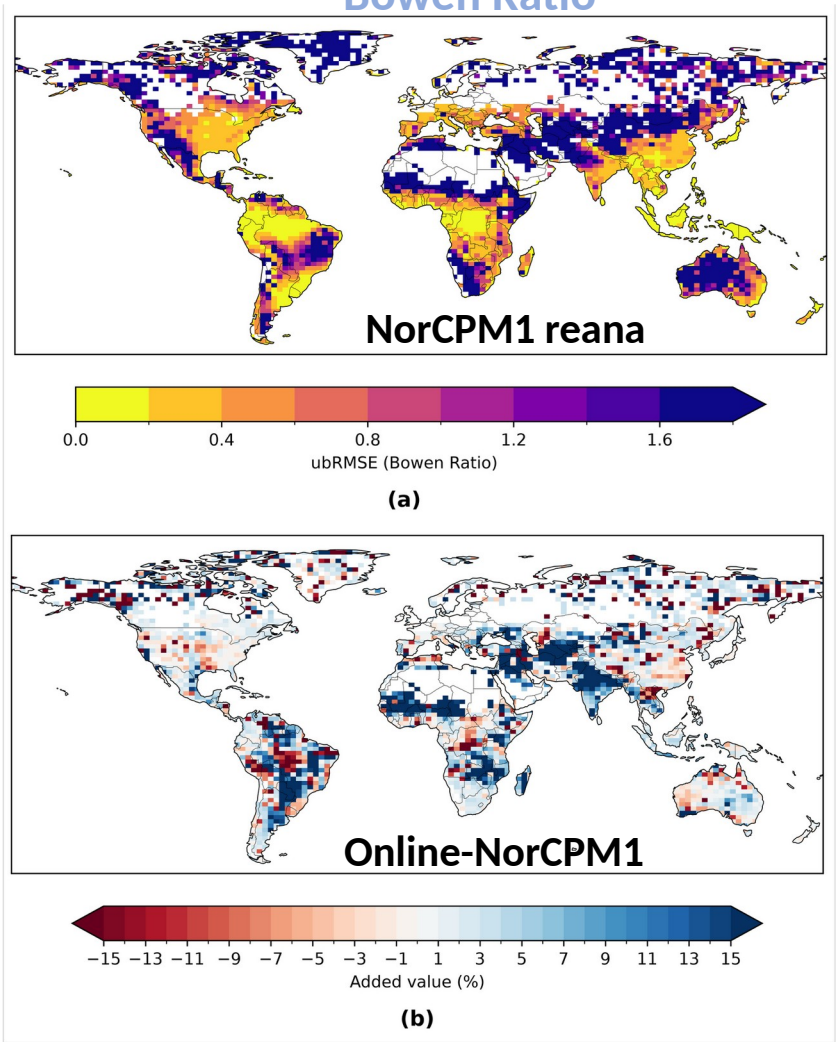
Sensible HeatFlux



Soil moisture assimilation improves the representation of Turbulent Fluxes

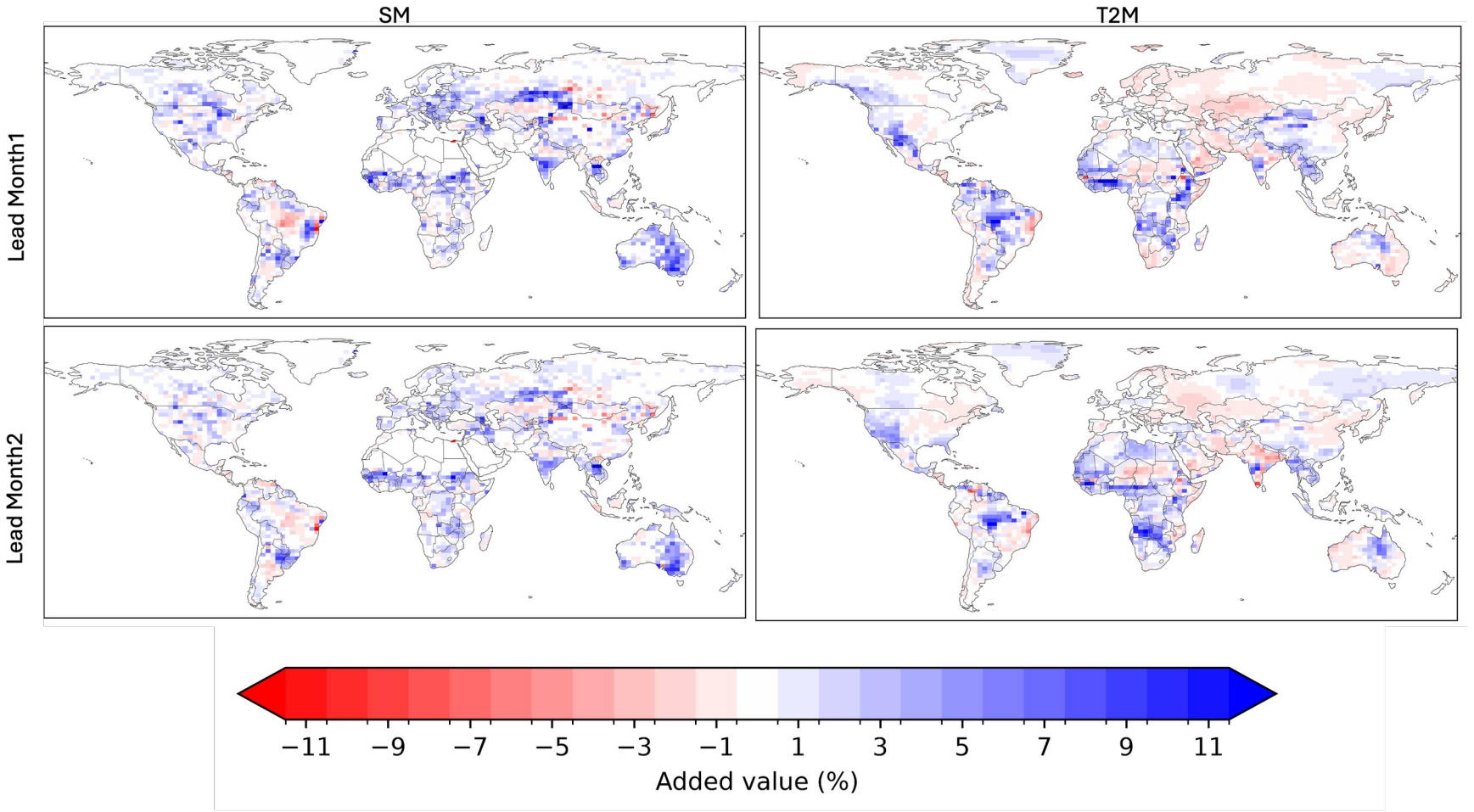
Bowen Ratio=

Bowen Ratio



Error are computed wrt to ERA5

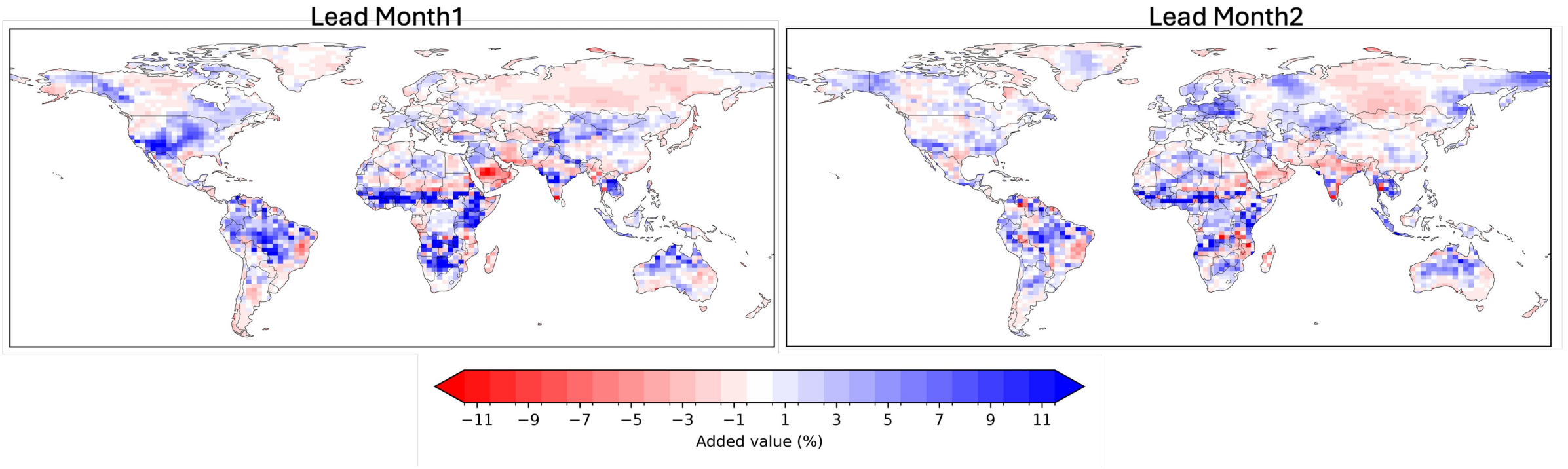
Soil moisture assim is also improving Soil moisture predictions



Added value =

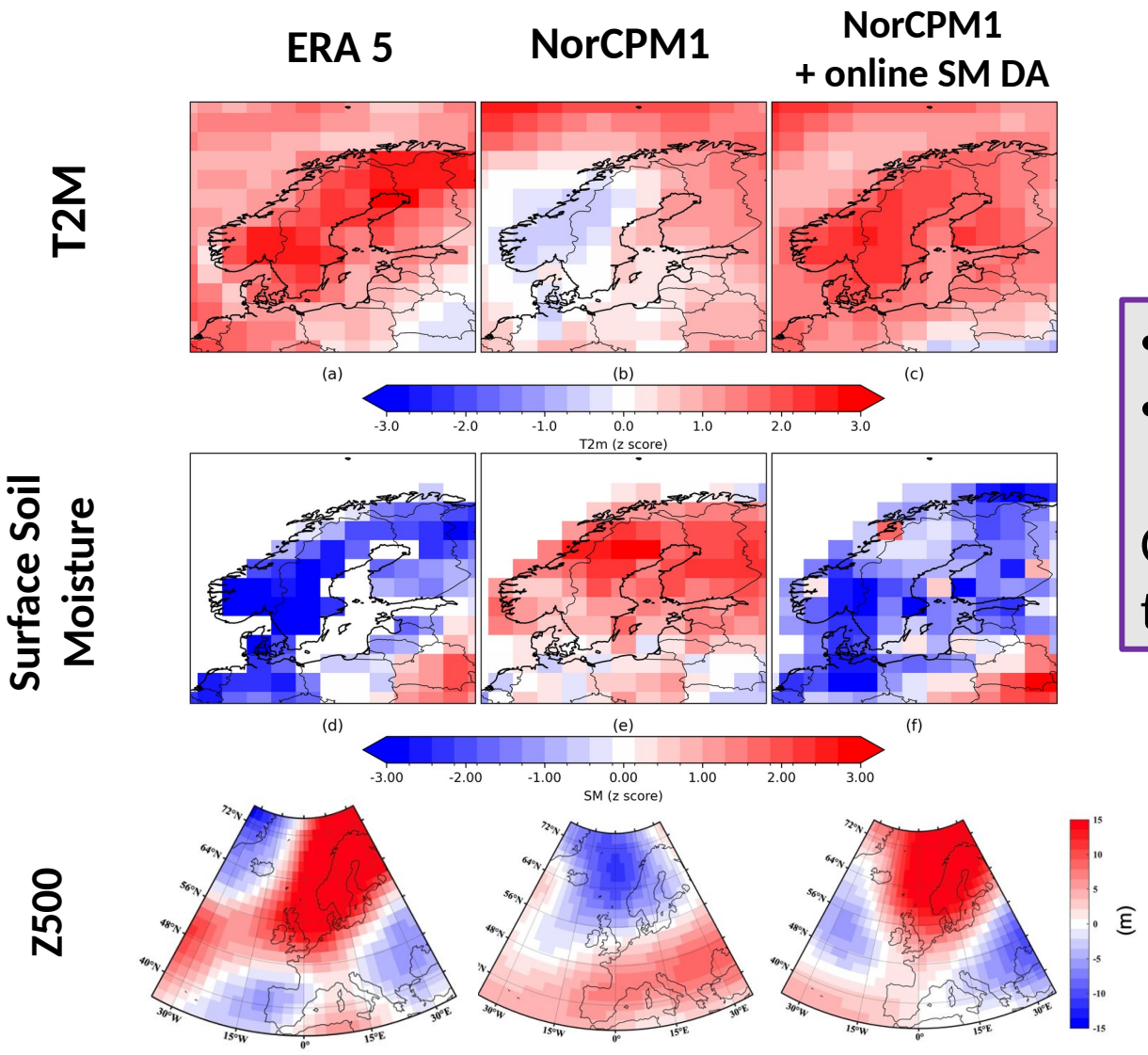
Error Reduction: Online SM assimilation overall reduces soil moisture error (ubRMSE) across both lead times and target months compared to standard NorCPM.

Soil moisture DA is also improving extreme temperature predictions



Improvements in extreme T2M (75th percentile), prominent in hostpot regions weaker in high latitudes.
Land-atmosphere coupling : differs for regions depending on seasons and soil moisture levels

2018 Scandinavian Heatwave
Does Soil moisture matter?



- Correct the soil moisture in the North
- Reproduce the heat waves and blocking

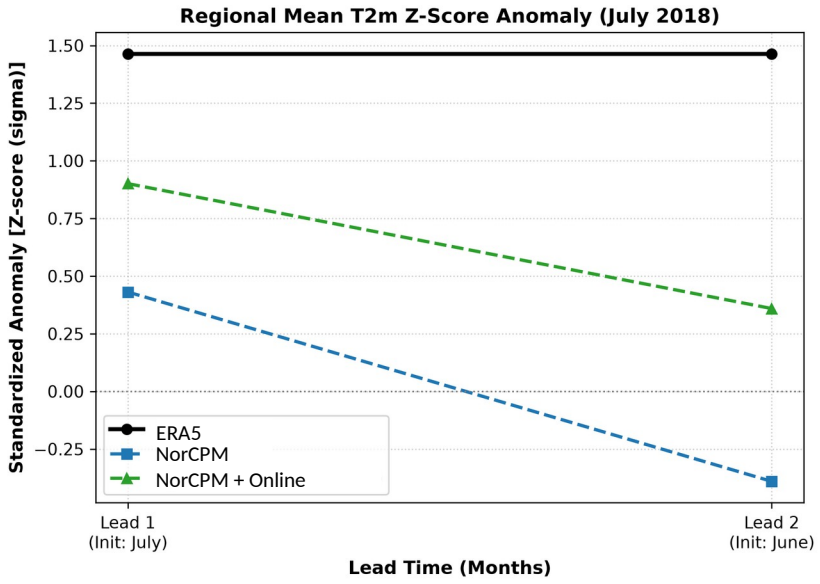
Can the change in turbulent heat flux influences the circulation ?

2018 Scandinavian Heatwave

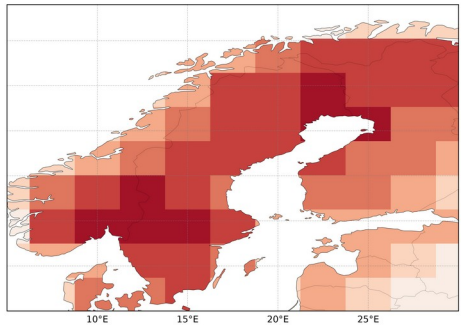
Can SM assimilation improve prediction?

Online Soil moisture assimilation enhance the signal of heat waves wrt the standard system

System 2 reduces absolute Z-score at 1–2 lead months



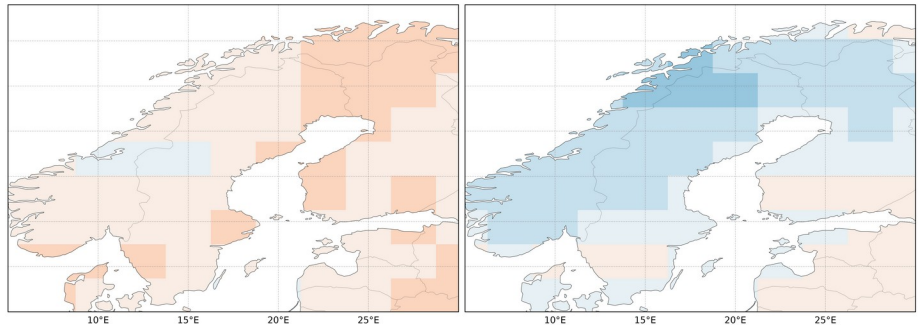
ERA5



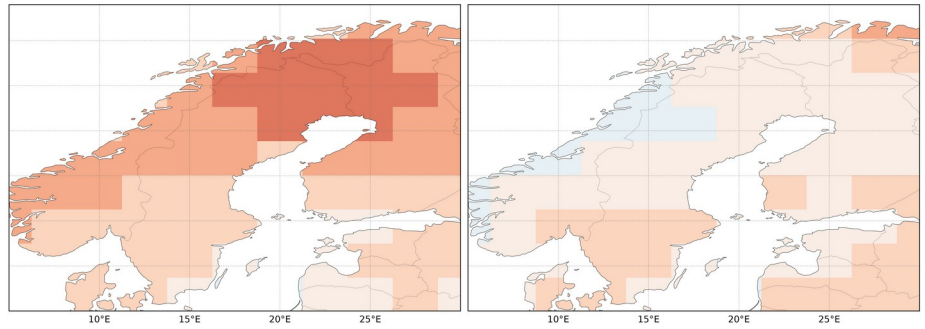
Lead month 1

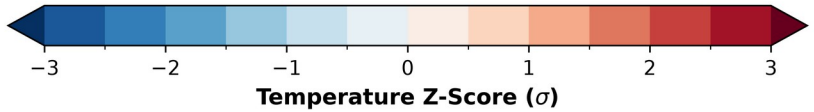
Lead month 2

NorCPM1



NorCPM1+online





Summary

Soil moisture assimilation reduces error in soil moisture and temperature. Most prominent in tropics and sub-tropics

Temperature extreme: Improves the representation of temperature extreme (th percentile) and land-drying feedbacks where standard NorCPM fails.

Online assimilation of SM is beneficial compared to offline assimilation

Multi-Month Forecast Skill: Maintains error reductions up to 2-month lead times, predicting regional heatwave magnitudes such as the 2018 Scandinavian heat waves

Next Steps...

1. Coupled multi-variate land data assimilation system (soil moisture with snow assimilation)
2. Upgrading core NorESM1 to NorESM2 (The current analysis are using older version of CLM and CAM)
3. Add an atmospheric constrain (spectral nudging of winds toward existing reanalysis / Atmo DA)