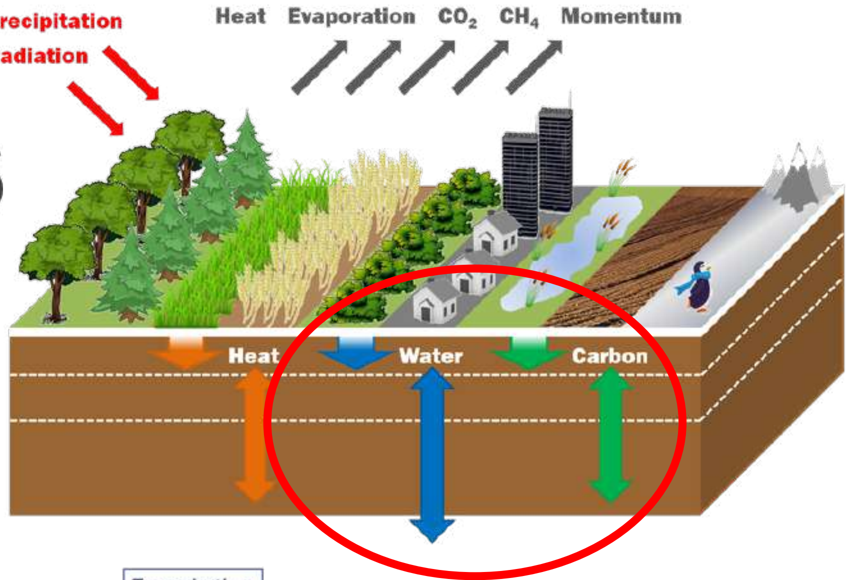
Using Satellite Observations to Improve Hydrological and Carbon Flux predictions of the JULES Land Surface Model

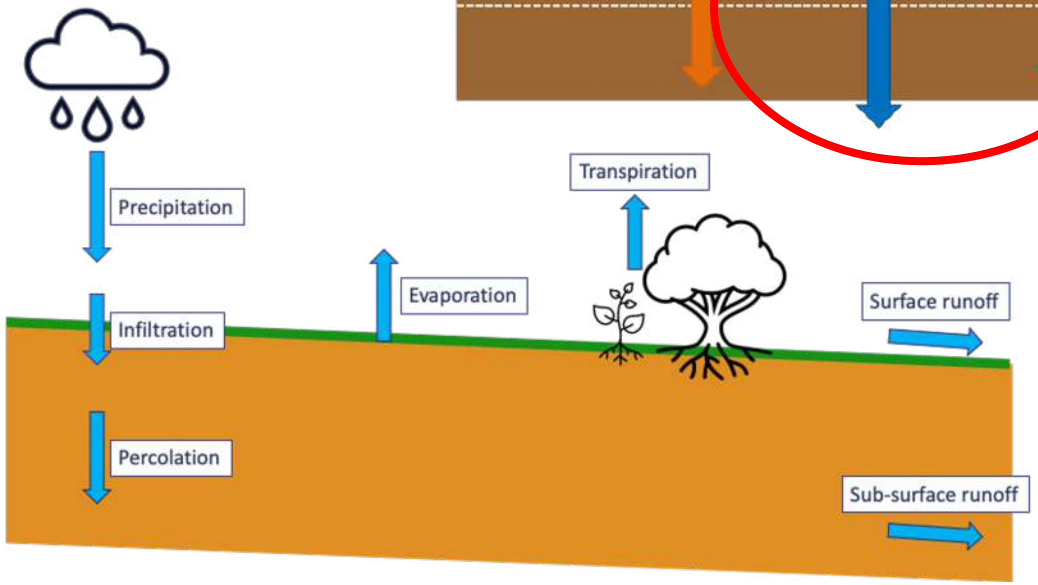
Ewan Pinnington and Tristan Quaife

Improving land surface model estimates

- Optimising Land Surface Model estimates using satellite data.
- Using Data Assimilation methods to update the parameters of the model.
- Combining model and observations to improve land surface and hydrological predictions.

JULES
Joint UK Land Environment Simulator





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Variational Data Assimilation

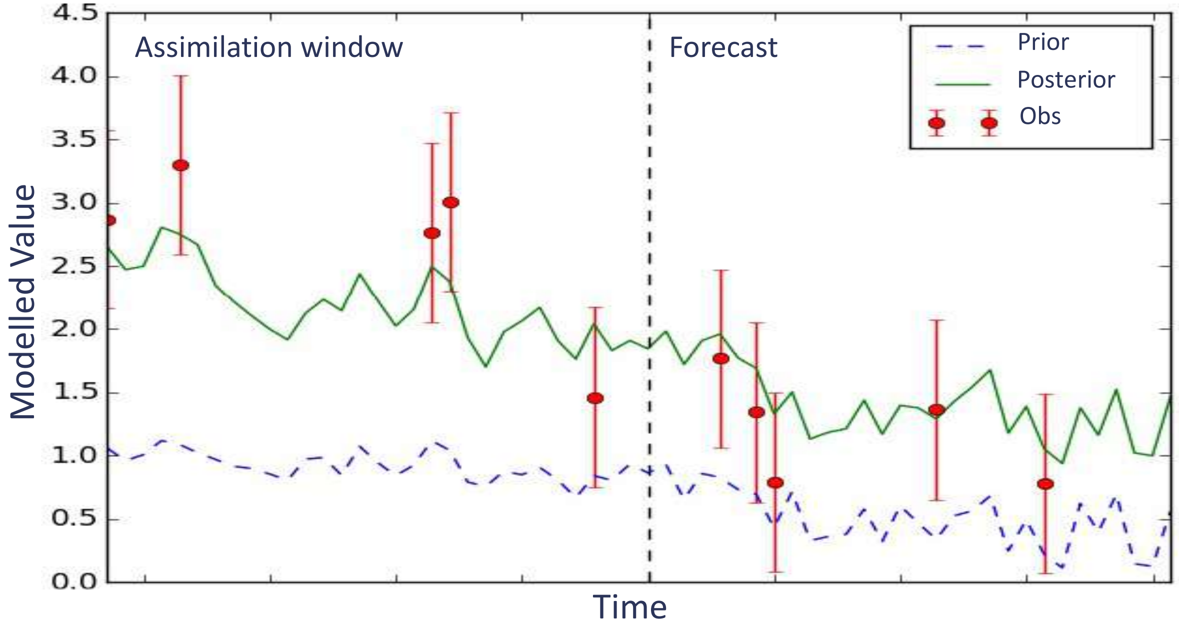
- Combine all sources of information over a time window to find best estimate to the state or parameters of a system.
- Do this by minimising a cost function.
- Typically requires the derivative and adjoint of the model.

<u>4DVar cost function:</u>

$$J(\boldsymbol{x}_0) = \underbrace{\frac{1}{2}(\boldsymbol{x}_0 - \boldsymbol{x}^b)^T \boldsymbol{B}^{-1}(\boldsymbol{x}_0 - \boldsymbol{x}^b)}_{\textbf{Prior}} + \underbrace{\sum_{i=0}^{N} \left(h_i\left(m_{0,i}(\boldsymbol{x}_0)\right) - \boldsymbol{y}_i\right)^T \boldsymbol{R}_i^{-1}\left(h_i\left(m_{0,i}(\boldsymbol{x}_0)\right) - \boldsymbol{y}_i\right)}_{\textbf{Observations}}$$

<u>Gradient of cost function:</u>

$$\nabla J(\boldsymbol{x}_0) = \boldsymbol{B}^{-1}(\boldsymbol{x}_0 - \boldsymbol{x}^b) + \sum_{i=0}^{N} \boldsymbol{M}_{i,0}^T \boldsymbol{H}_i^T \boldsymbol{R}_i^{-1}\left(h_i\left(m_{0,i}(\boldsymbol{x}_0)\right) - \boldsymbol{y}_i\right)$$



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LAVENDAR

- The Land Ensemble Variational Data Assimilation fRamework (LAVENDAR) implements Hybrid DA technique similar to Iterative Ensemble Kalman Smoother (IEnKS) for land surface models.
  - https://github.com/pyearthsci/lavendar
  - The Land Variational Ensemble Data Assimilation Framework: LAVENDAR v1.0.0, *Geosci. Model Dev.*, https://doi.org/10.5194/gmd-13-55-2020, **2020**.
  - Improving soil moisture prediction of a high-resolution land surface model by parameterising pedotransfer functions through assimilation of SMAP satellite data, *Hydrology & Earth System Sciences*, https://doi.org/10.5194/hess-25-1617-2021, **2021**.
- Allows us to find improved parameters/state for models, informed by observations.
- Approximate model adjoint and derivative with ensemble of model trajectories.

LAVENDAR

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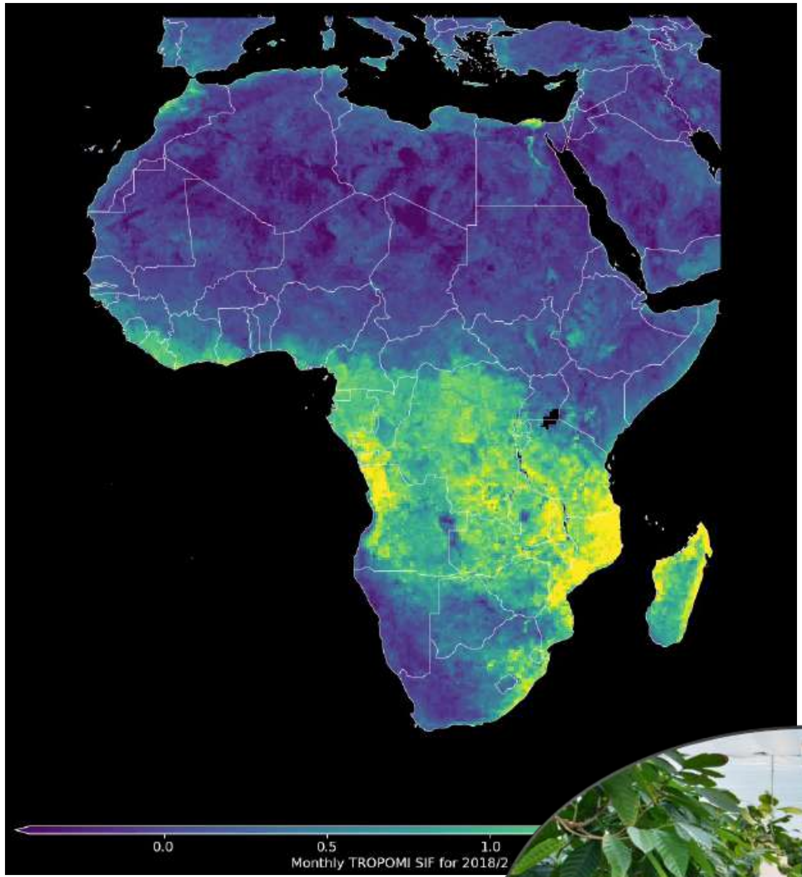
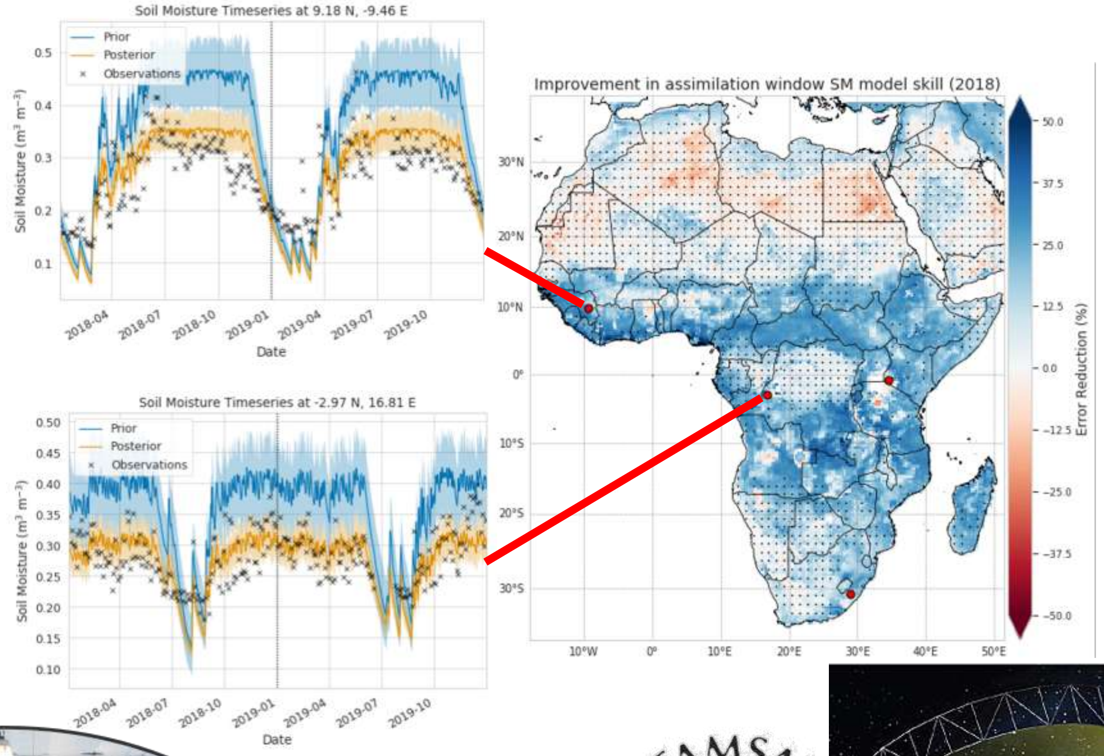
Improving land surface model estimates





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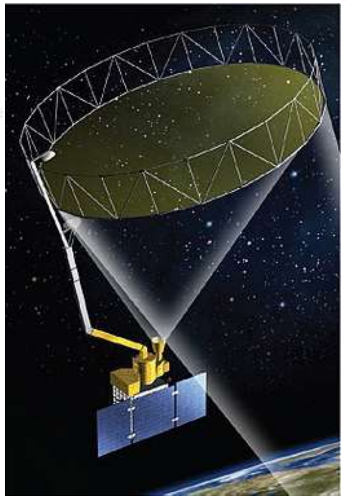
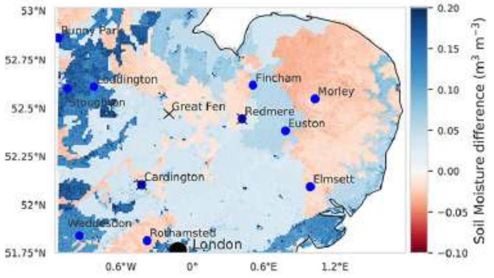
TAMSAT



Hydro-JULES



esa
European Space Agency

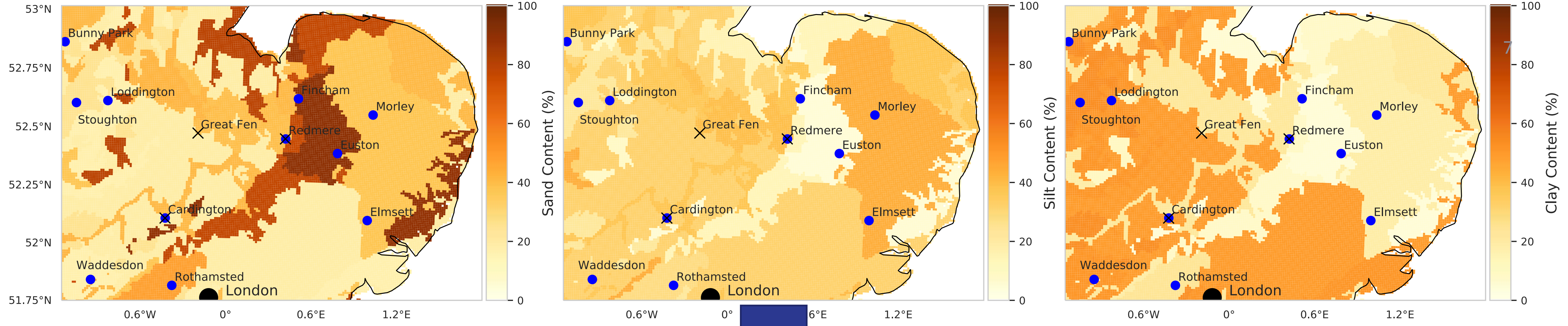
CLIMATE IMPACT EXPLORER
DIGITAL TWIN EARTH PRECURSOR

Mars

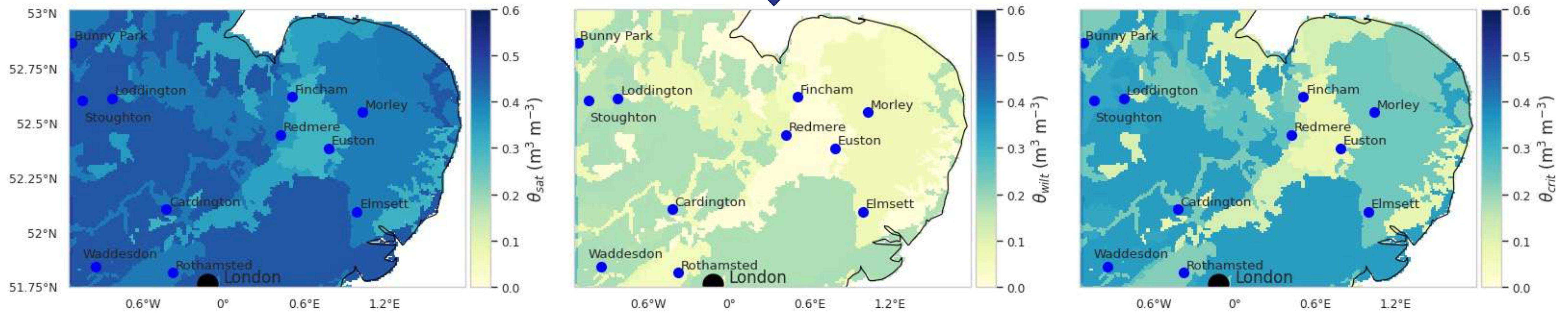
UK Soil Moisture Data Assimilation

- Developing Data Assimilation (DA) techniques for soil model parameter estimation.
- Running JULES at 1 km resolution over the UK using CHESS data.
- Assimilating satellite observations from the NASA SMAP mission.
- Validate results using the cosmic-ray soil moisture monitoring network (COSMOS-UK) established by UKCEH.

Hydro-JULES

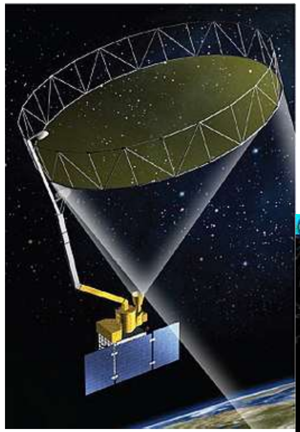


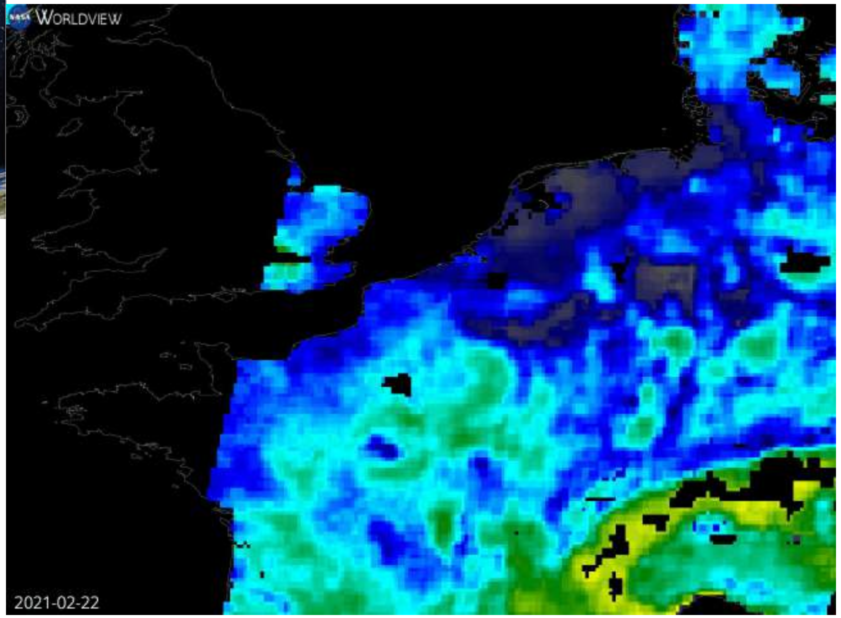
$$\textit{Pedotransfer Function}(\text{SOIL PROPERTIES}, \phi_1, \phi_2, \ldots, \phi_{15})$$



Satellite Soil Moisture Observations

- Estimates from JULES model are uncertain.
- Retrievals of soil moisture from satellites have gaps from over pass times, dense vegetation, urban areas, etc.
- Using Data Assimilation methods to combine satellite observations JULES soil moisture estimates.
- Using observations from the NASA SMAP satellite mission (see right)





SMAP soil moisture observations (22 Feb. – 4 Mar. 2021)

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Assimilating SMAP over East Anglia

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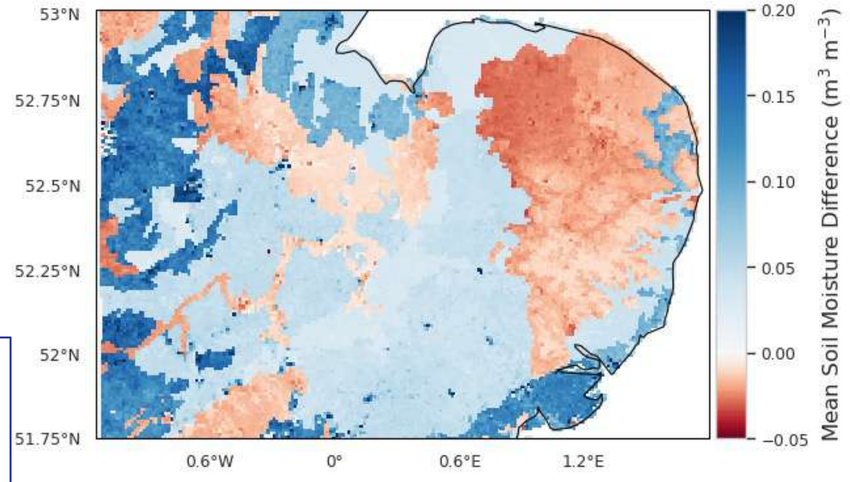
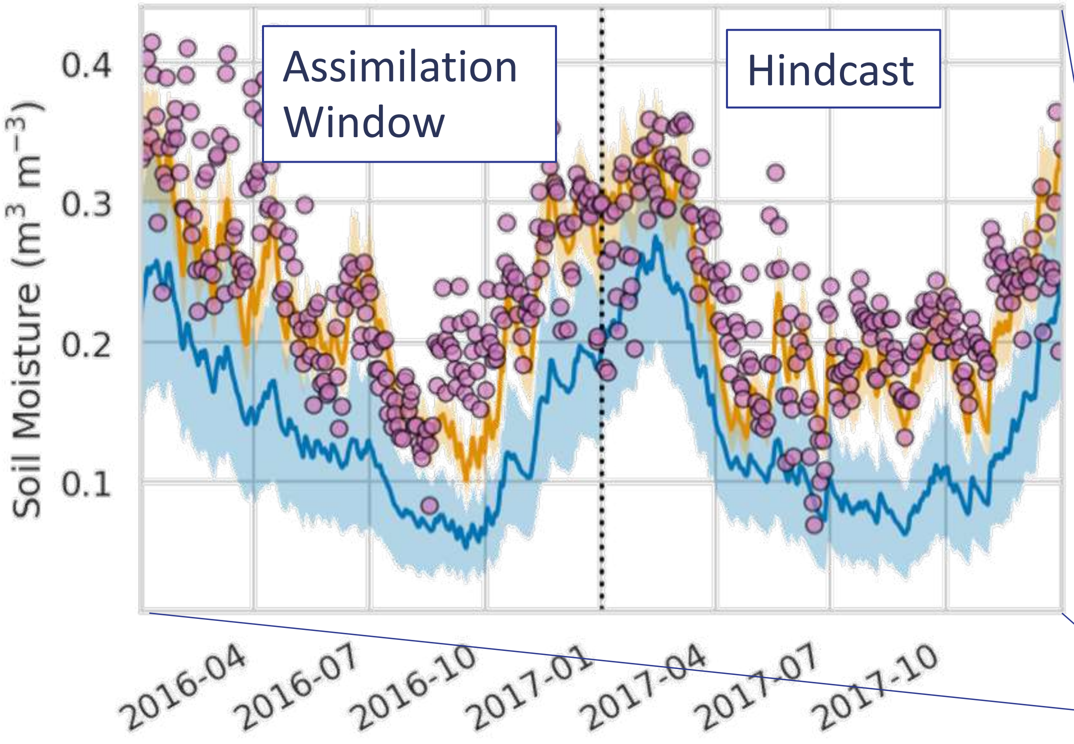
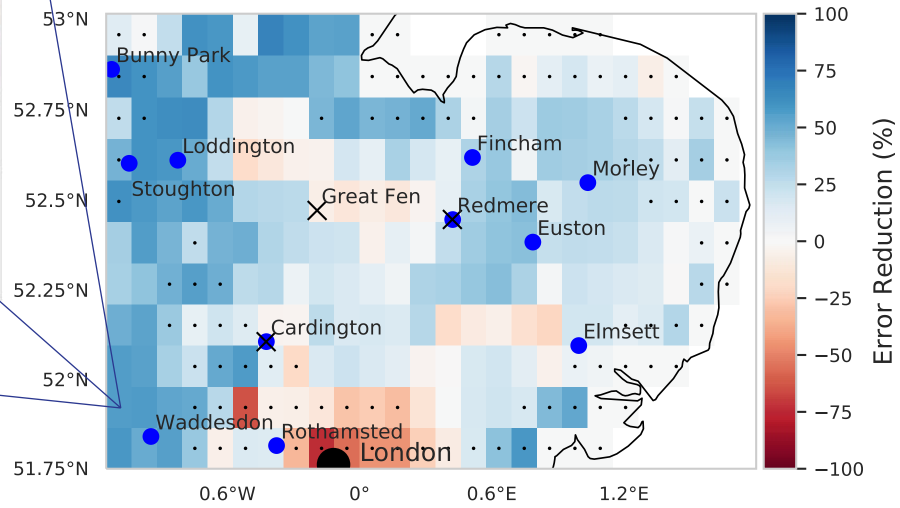
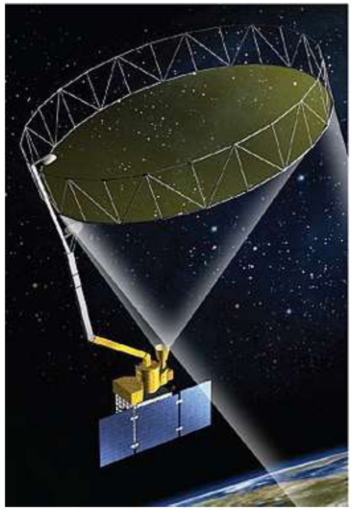




Pink: SMAP observations
Blue: JULES prior (before DA)
Orange: JULES posterior (after DA)





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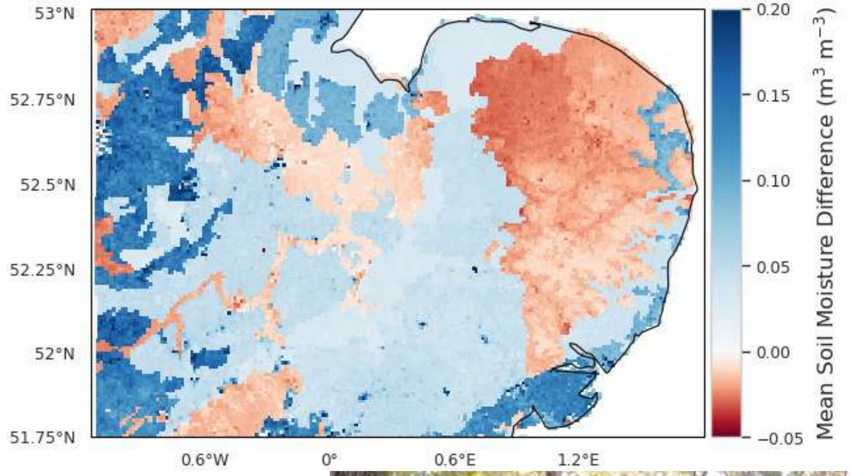
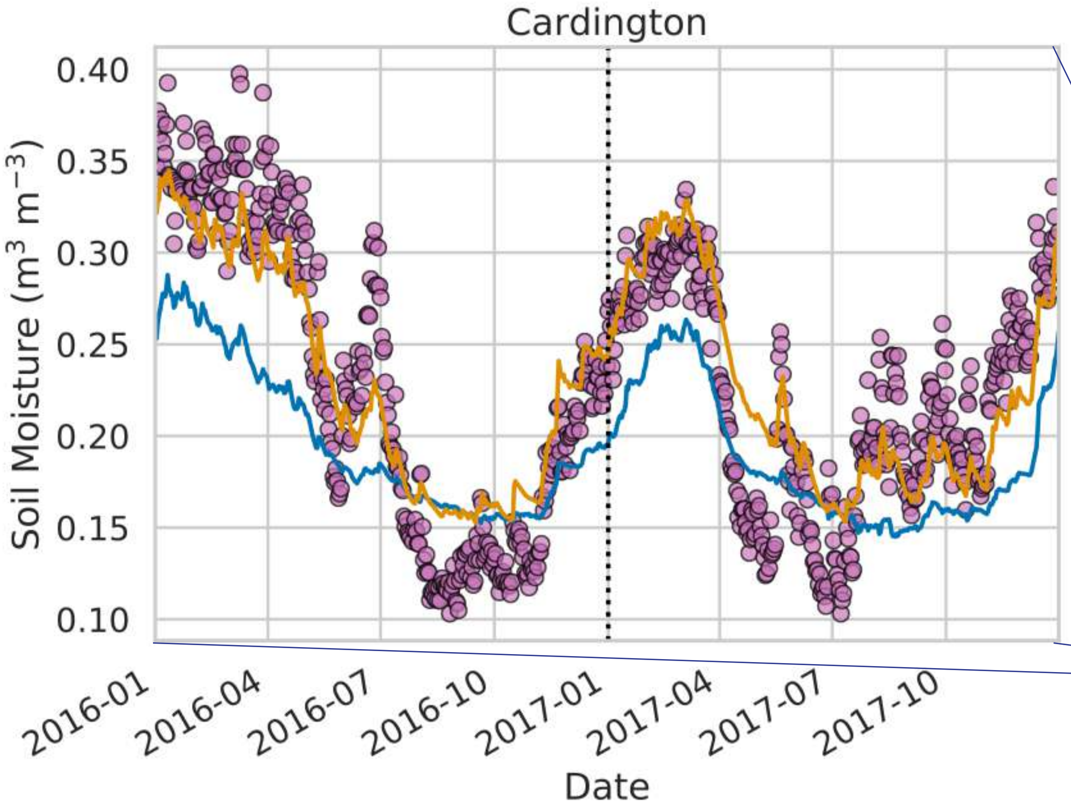
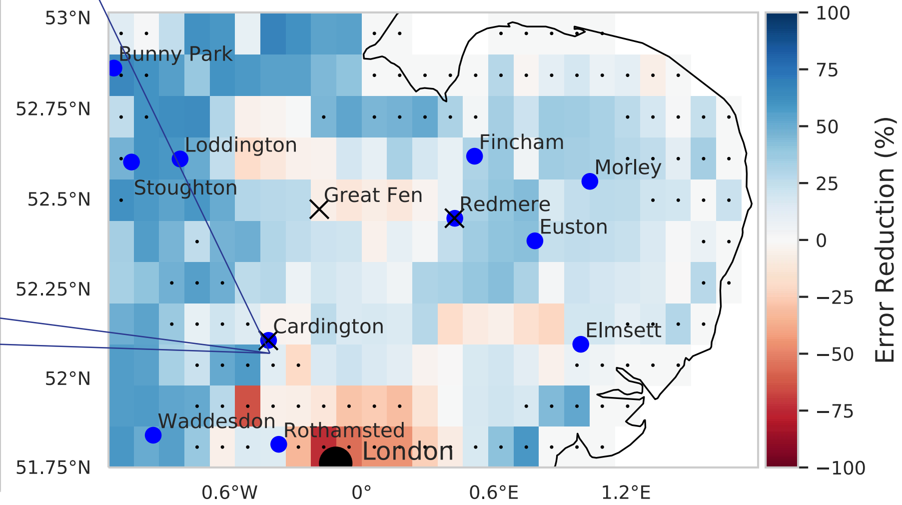




Pink: COSMOS observations
Blue: JULES prior (before DA)
Orange: JULES posterior (after DA)



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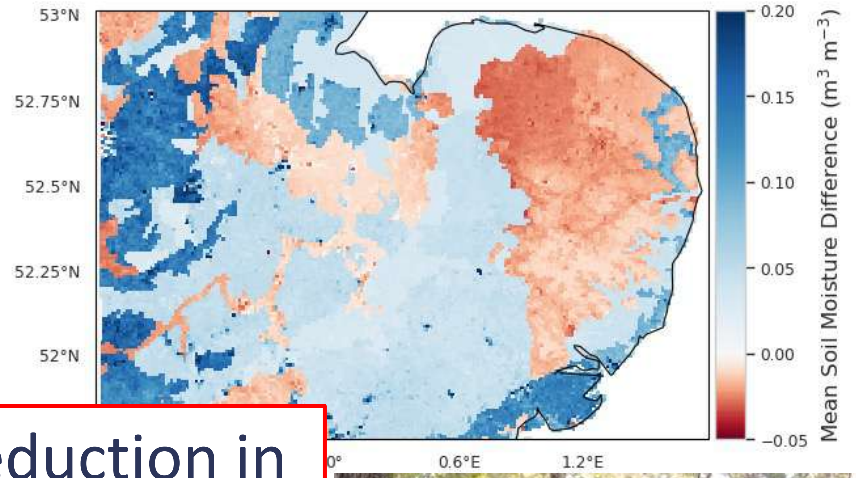
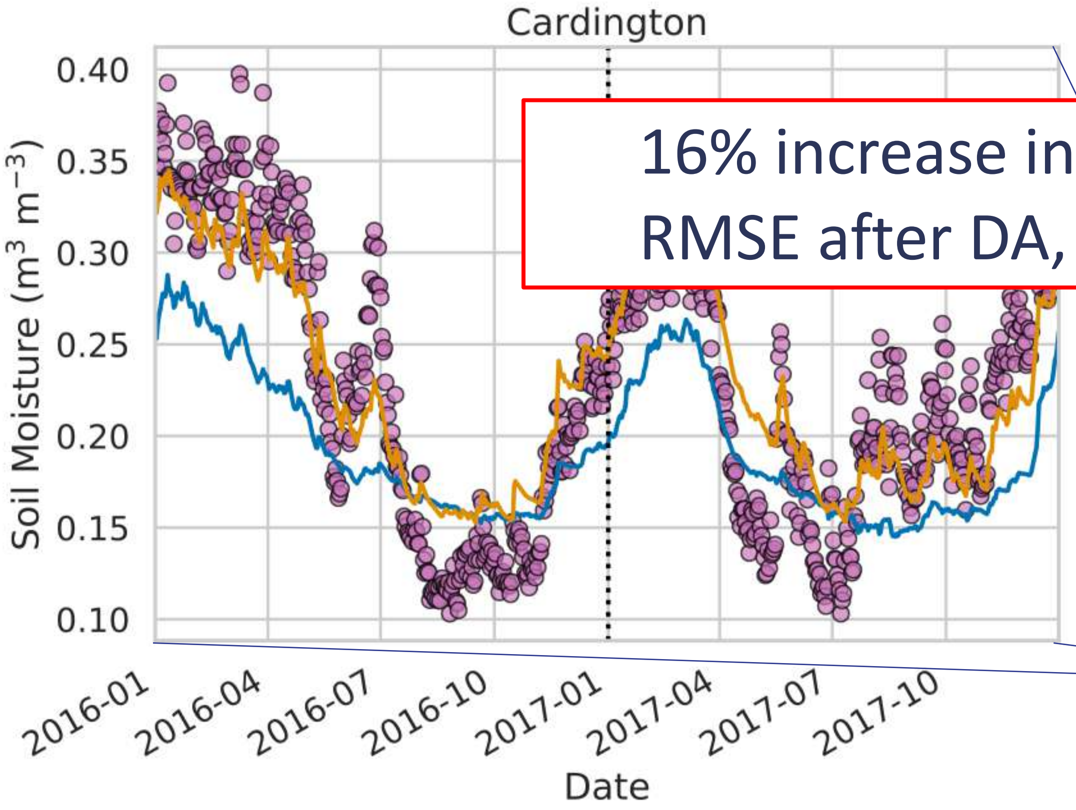
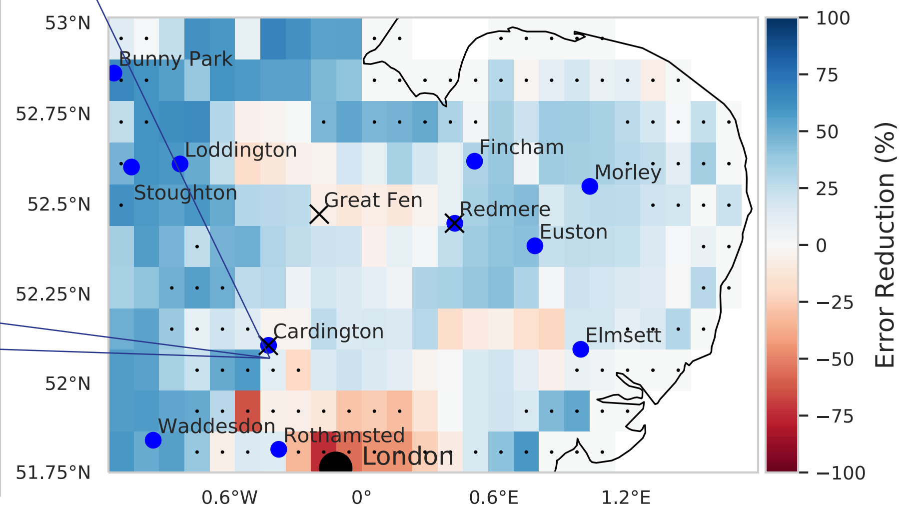
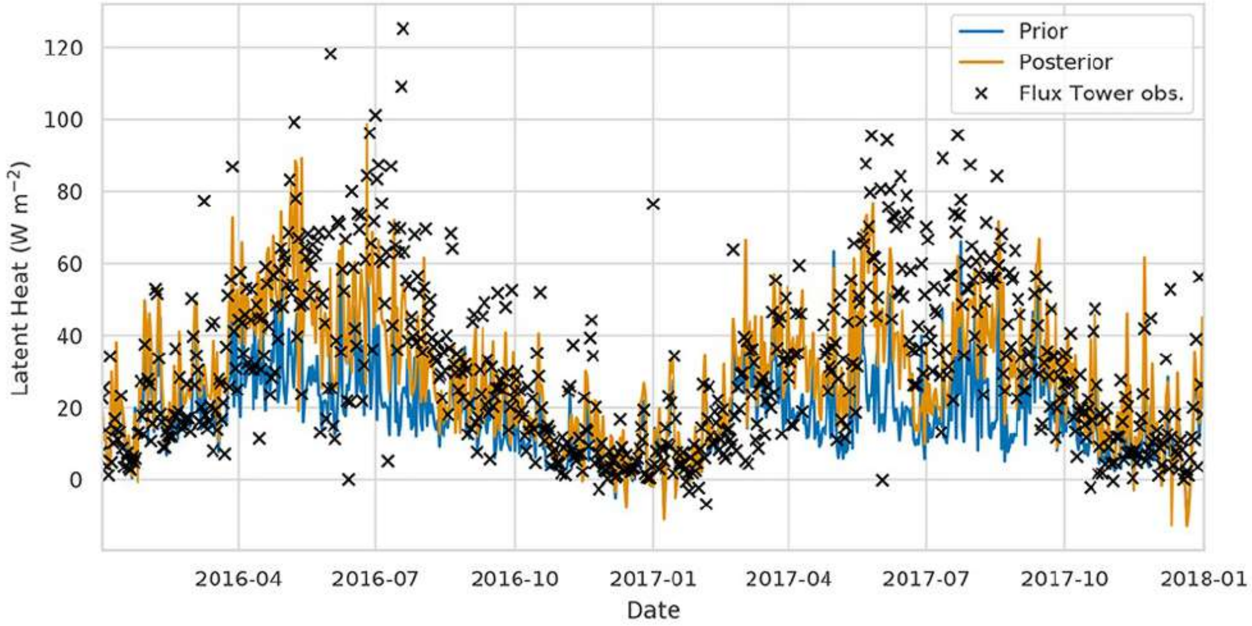


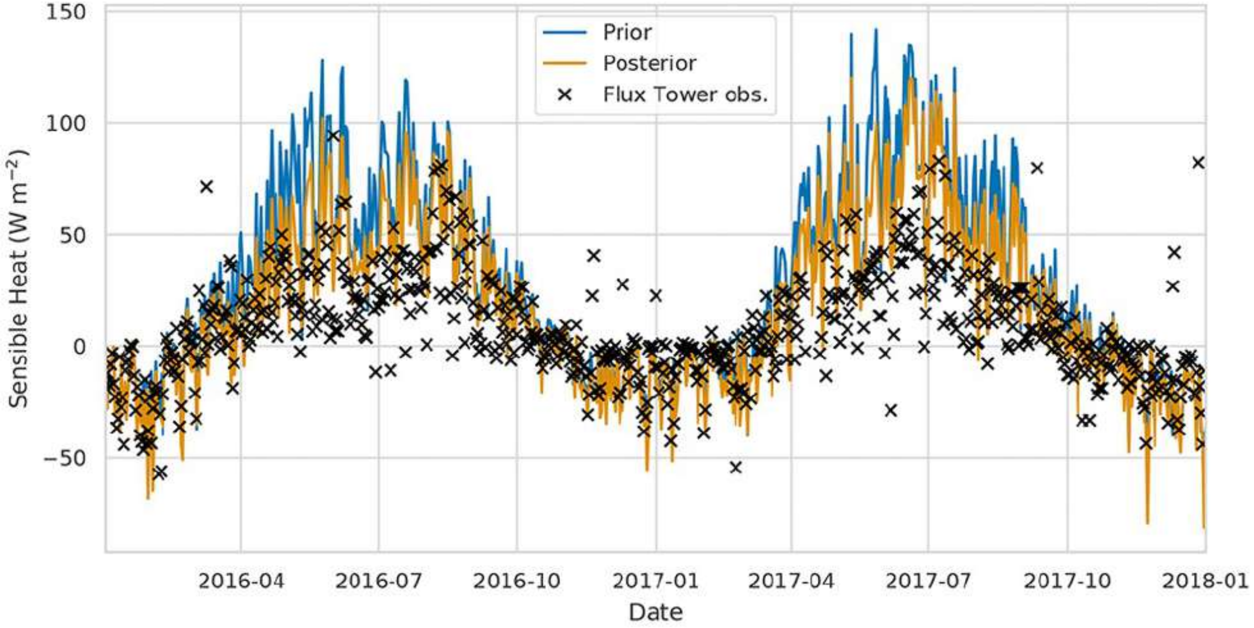


Pink: COSMOS observations

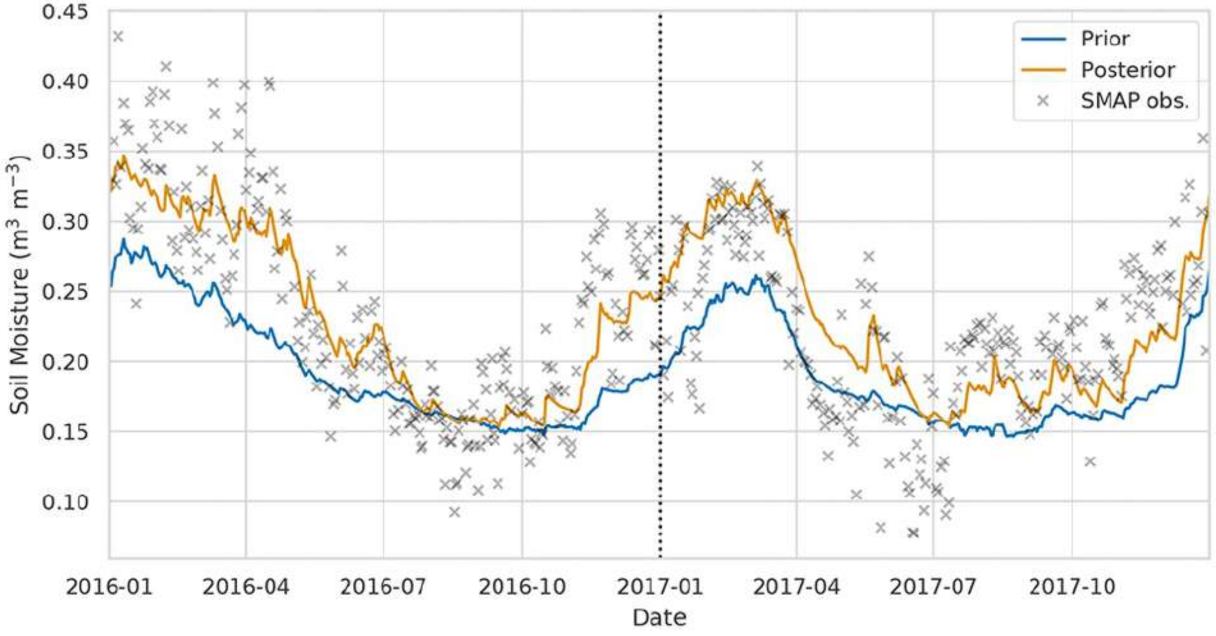
16% increase in correlation & 22% reduction in RMSE after DA, averaged over all sites.







Cardington Flux Tower Comparison



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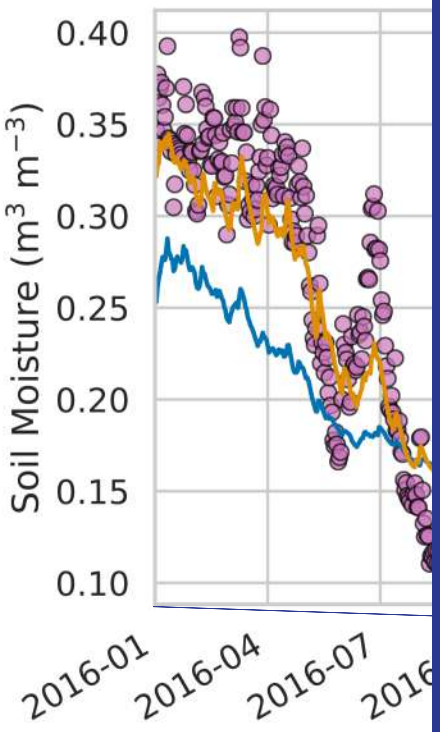

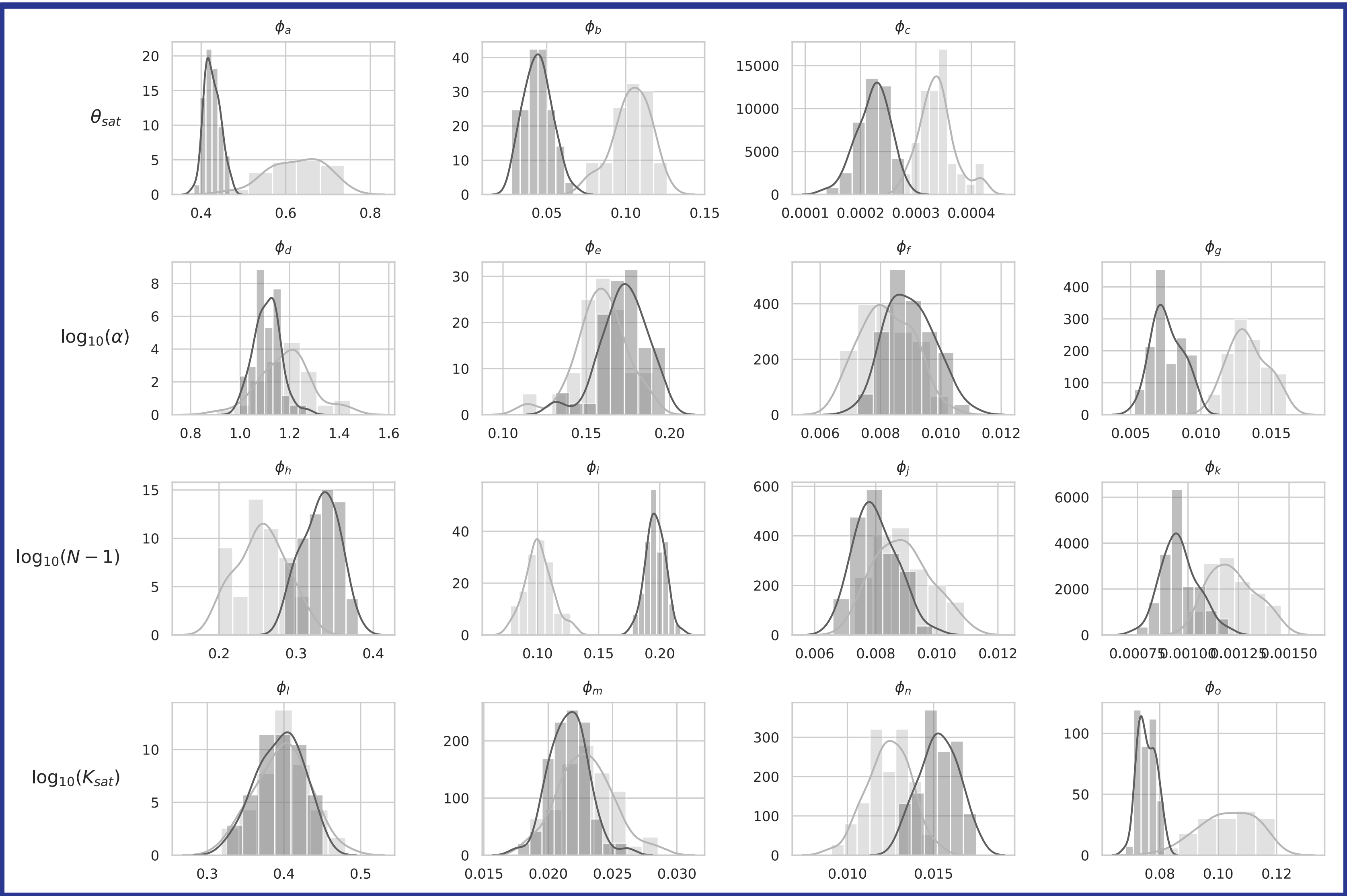

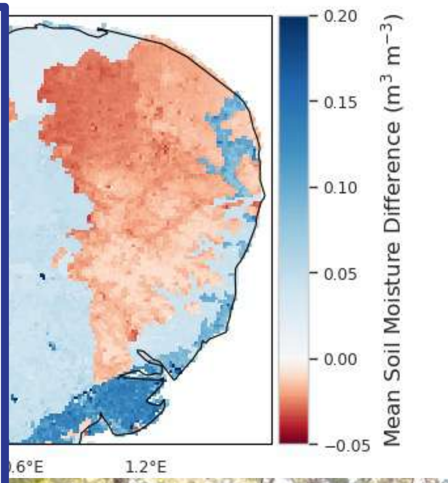

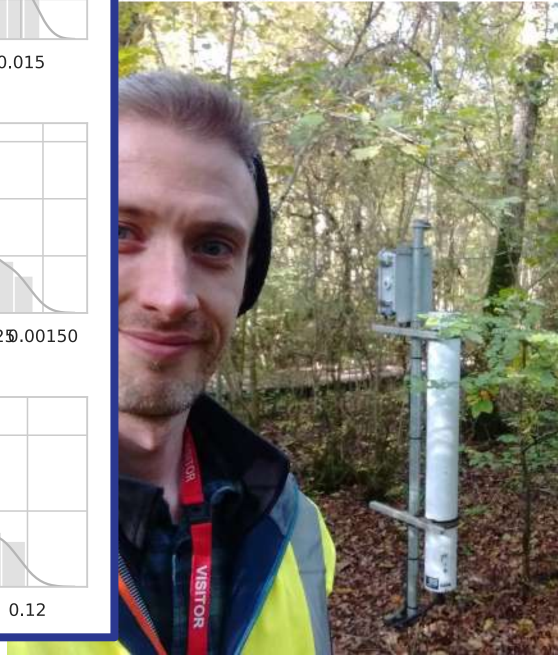

0.6°W 0° 0.6°E 1.2°E

Assimilating SMAP over East Anglia

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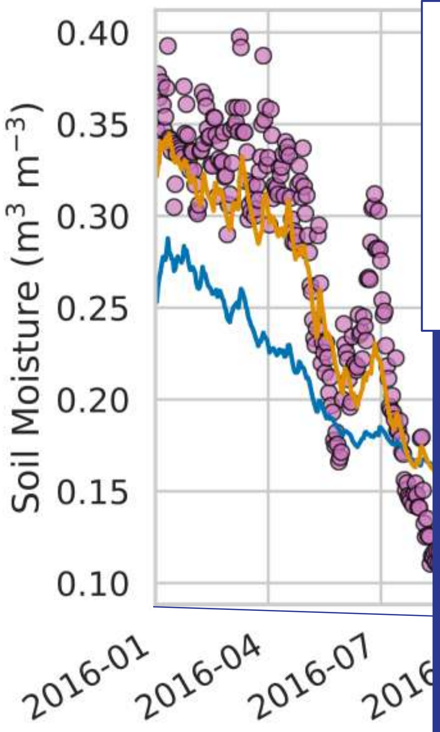
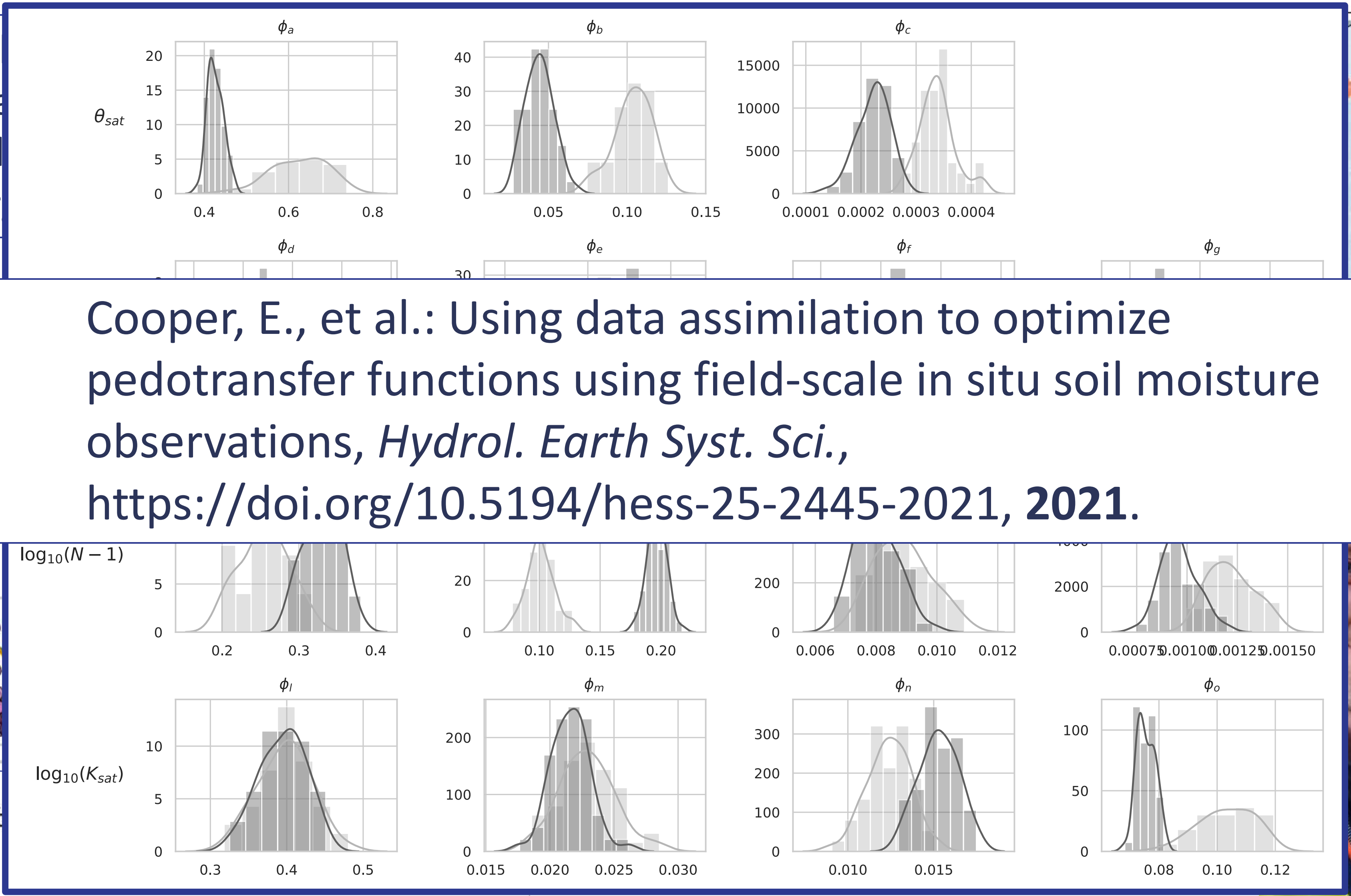
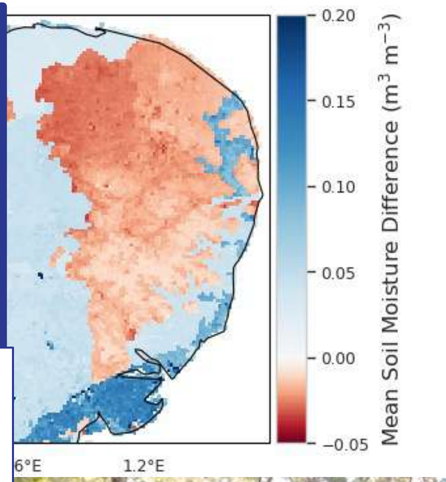




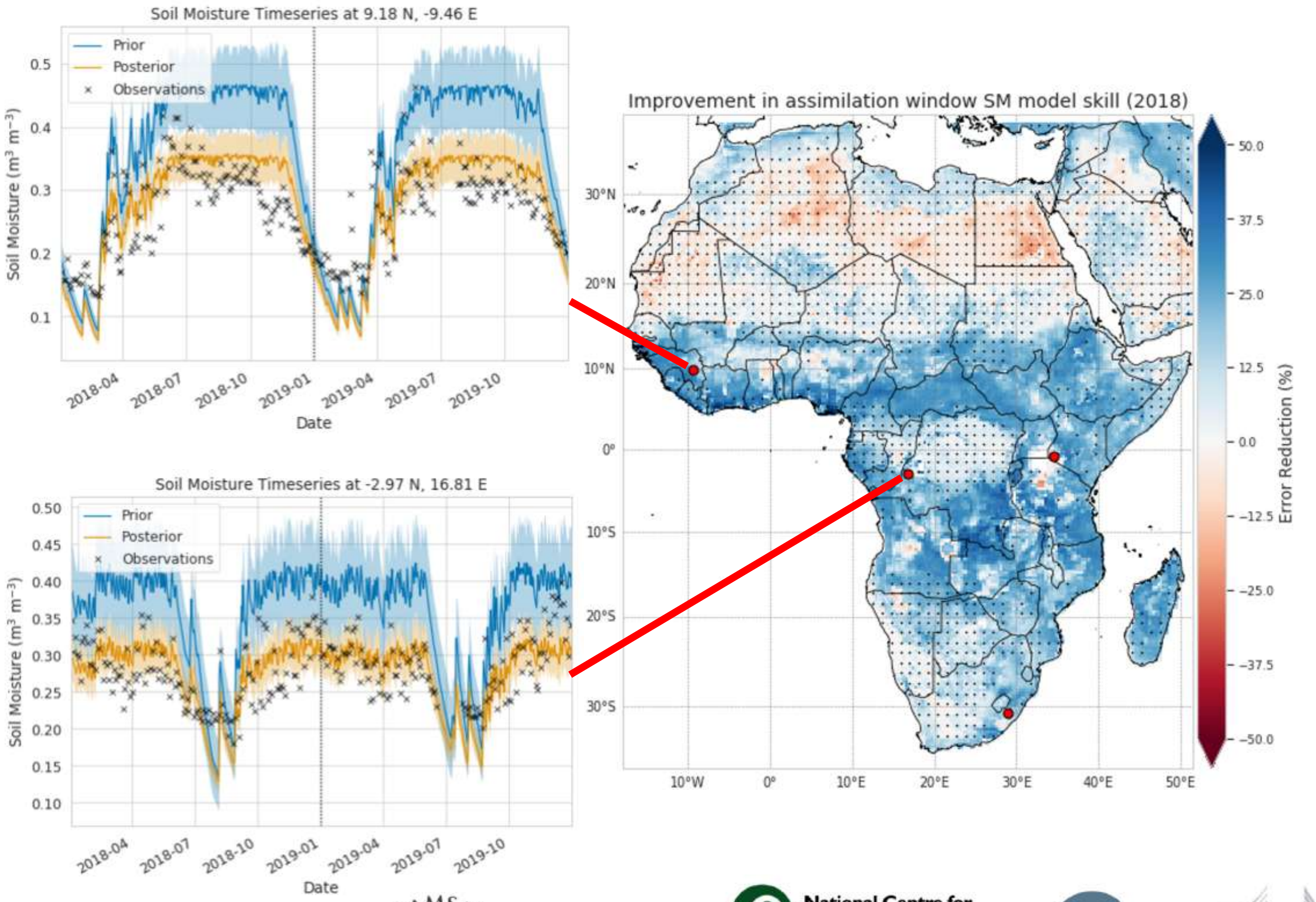
Cooper, E., et al.: Using data assimilation to optimize pedotransfer functions using field-scale in situ soil moisture observations, *Hydrol. Earth Syst. Sci.*, https://doi.org/10.5194/hess-25-2445-2021, **2021**.



0.6°W 0° 0.6°E 1.2°E

Extending SMAP DA to Africa

- Parameters optimised over all ~60,000 model grid cells and a years time window (~1.5 million observations) in an **instantaneous assimilation step** to find parameters valid in both space and time.
- Combining NASA SMAP satellite observations with JULES and TAMSAT rainfall to produce soil moisture dataset over Africa.
- Utilised in TAMSAT-ALERT agricultural drought early warning system.



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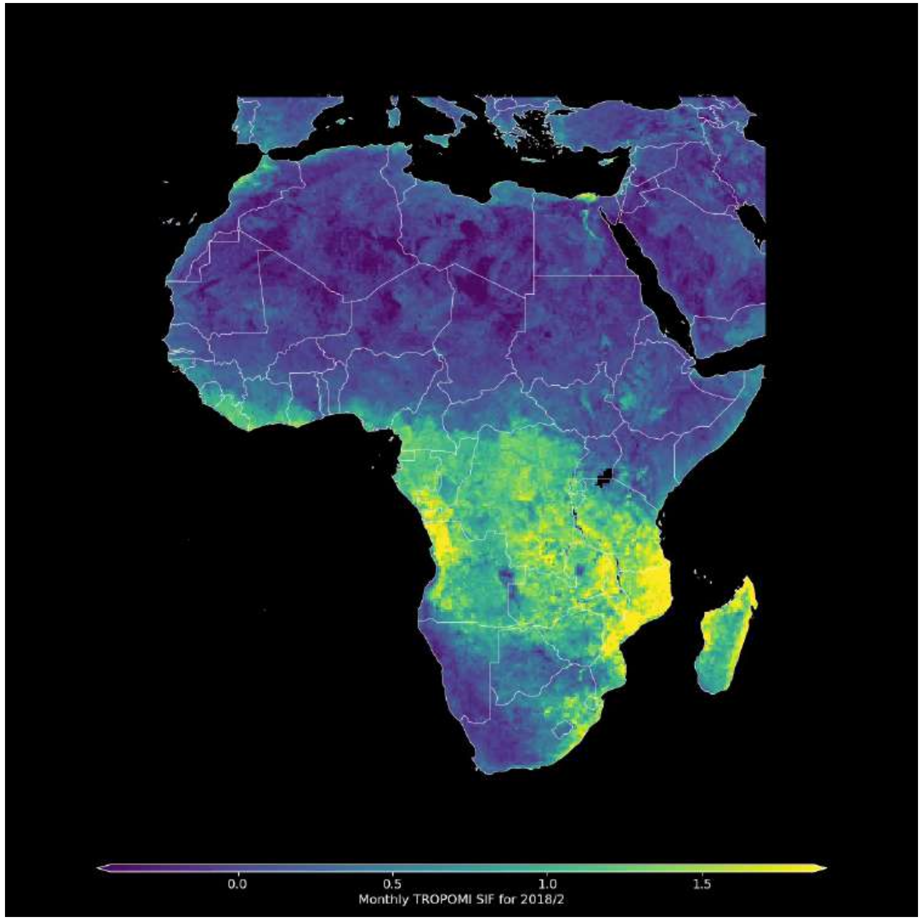
TROPOMI Solar Induced Fluorescence

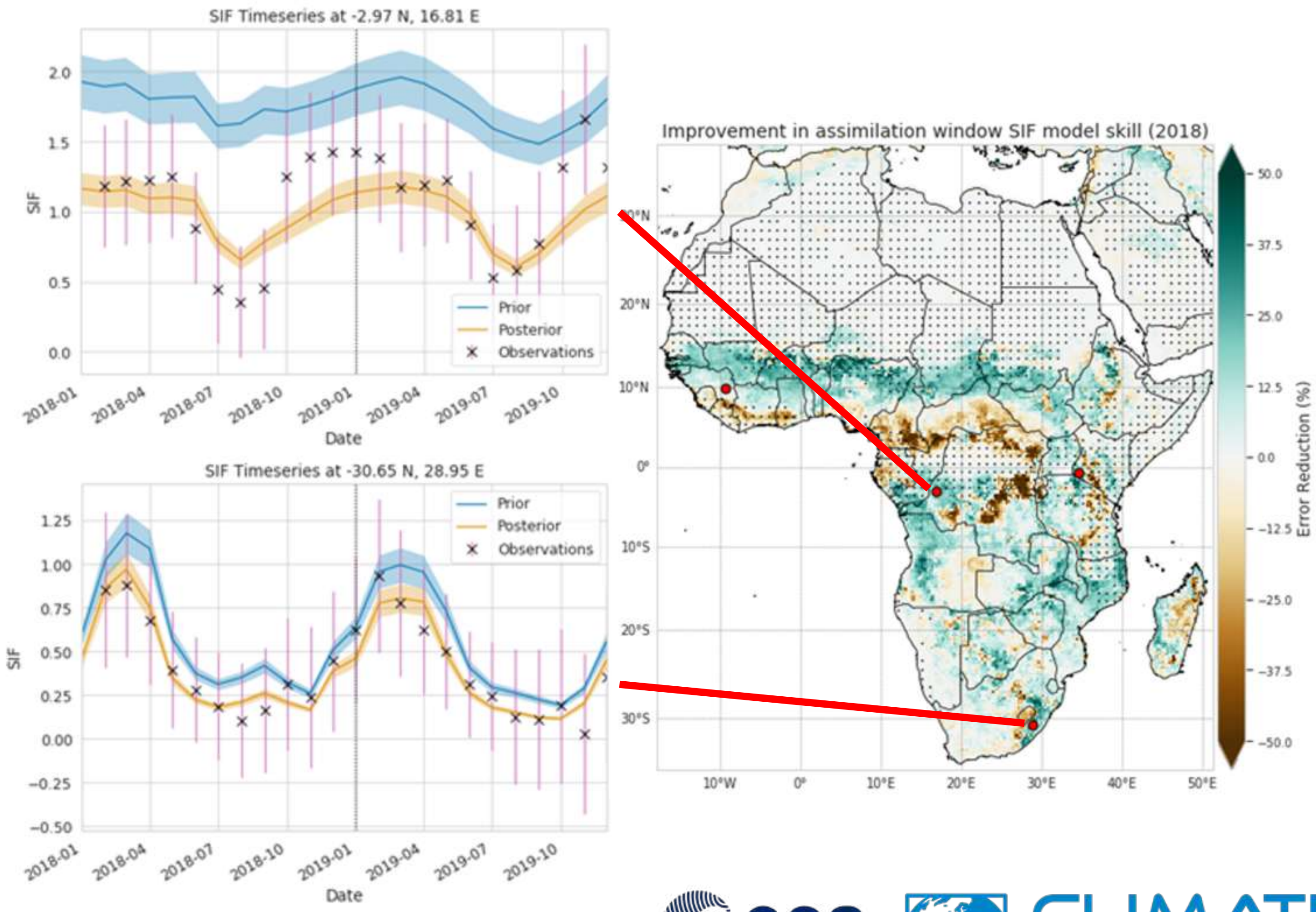
- Solar Induced Fluorescence observations from TROPOMI instrument on ESA Sentinel-5P satellite.
- **First direct observations of plant productivity from space!** Radiation signal emitted by plants during the process of photosynthesis observable at far-red wavelengths. $SIF \approx \eta \times Gross\ Primary\ Productivity$
- Photosynthesis from models usually very hard to validate! Large uncertainty in global carbon cycle and for climate projections more broadly.
- Chlorophyll fluorescence shown to be a more sensitive indicator of water stress compared to greenness indices due to the direct link to the underlying physical processes.



TROPOMI SIF Sentinel-5P observations

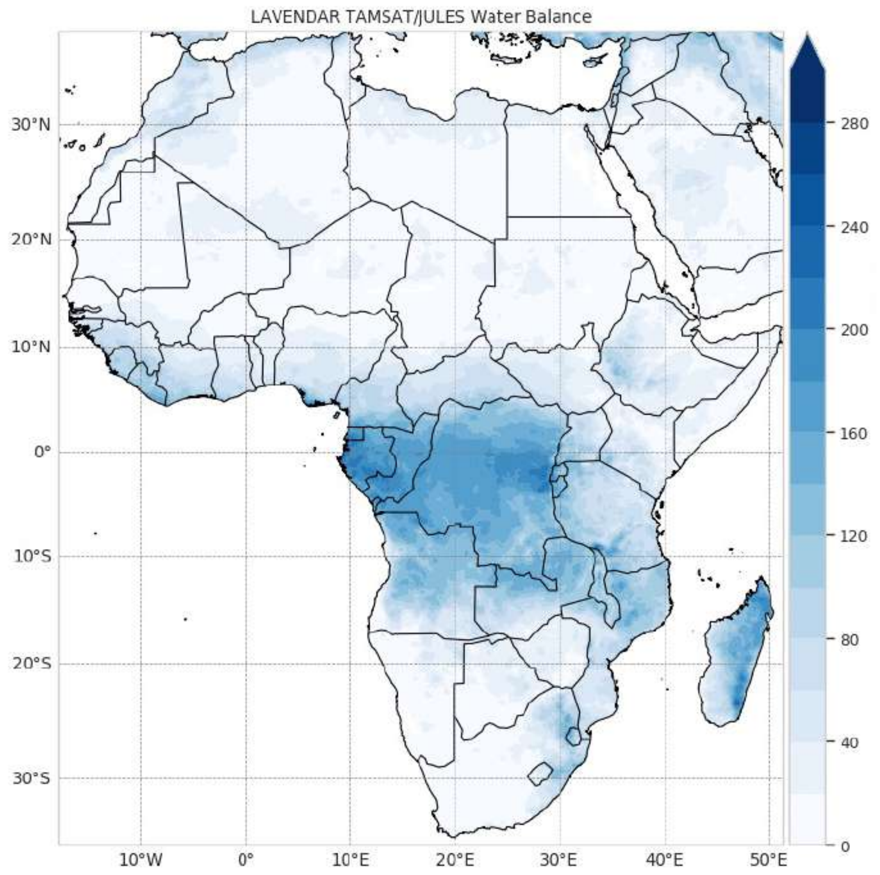
SIF Assimilation Results

- Promising results from TROPOMI SIF assimilation.
- Joint assimilation with NASA SMAP allows us to capture periods of low productivity due to water limitation much more accurately.
- Dominant factors affecting plant productivity across Africa?



TAMSAT Soil Moisture

- TAMSAT Soil Moisture dataset now available from:
  - gws-access.jasmin.ac.uk/public/odanceo/soil_moisture/
  - Button on tamsat.org.uk website TAMSAT-derived soil moisture
- Other variables also available: evapotranspiration, runoff, etc. Although these require more validation.
- Feeds TAMSAT-ALERT early warning drought forecasting system.



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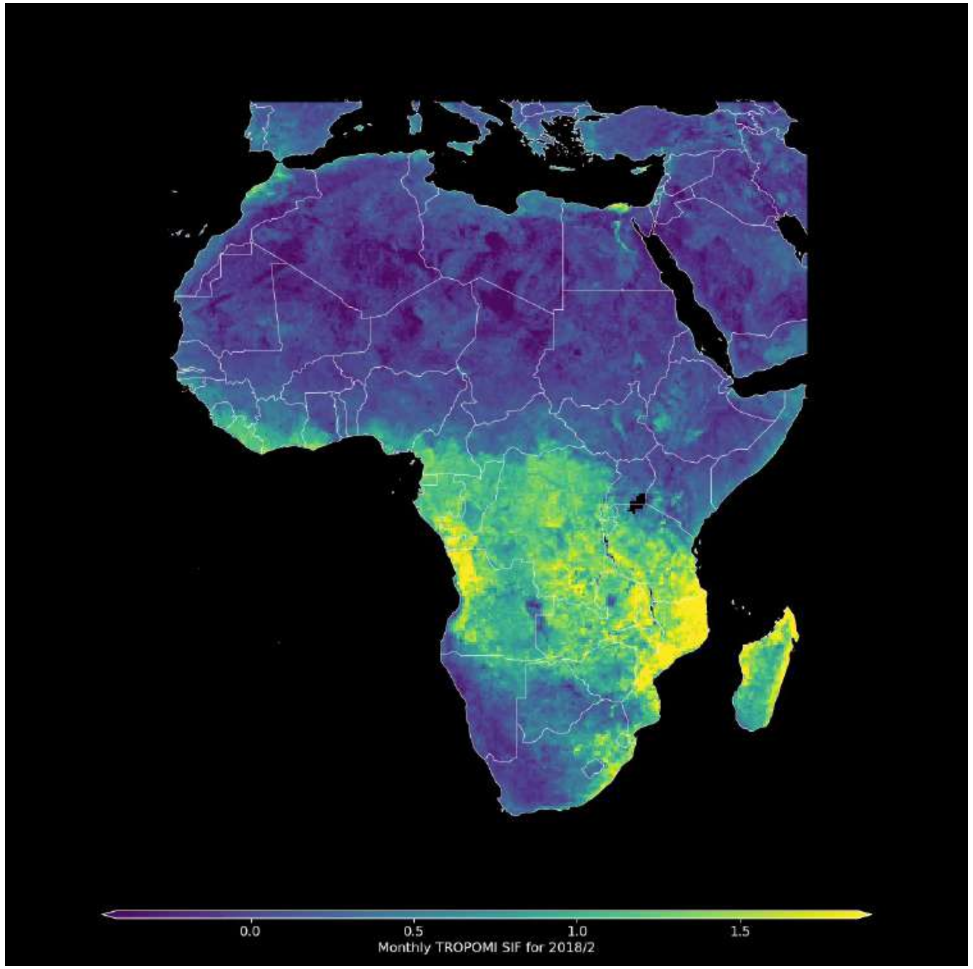
EUMETSAT
European Commission

Summary

- Using LAVENDAR DA for parameter estimation to improve land surface model physics. Considering both satellite and in-situ observations.
- Using NASA SMAP observations allows us to improve hydrological predictions from JULES validated by in-situ COSMOS observations.
- Improved JULES soil physics now being used by UK Met Office in high resolution climate model runs and in production of TAMSAT soil moisture dataset.
- SIF assimilation allows for novel constraint on vegetation productivity and water balance of JULES.



TROPOMI SIF Sentinel-5P observations

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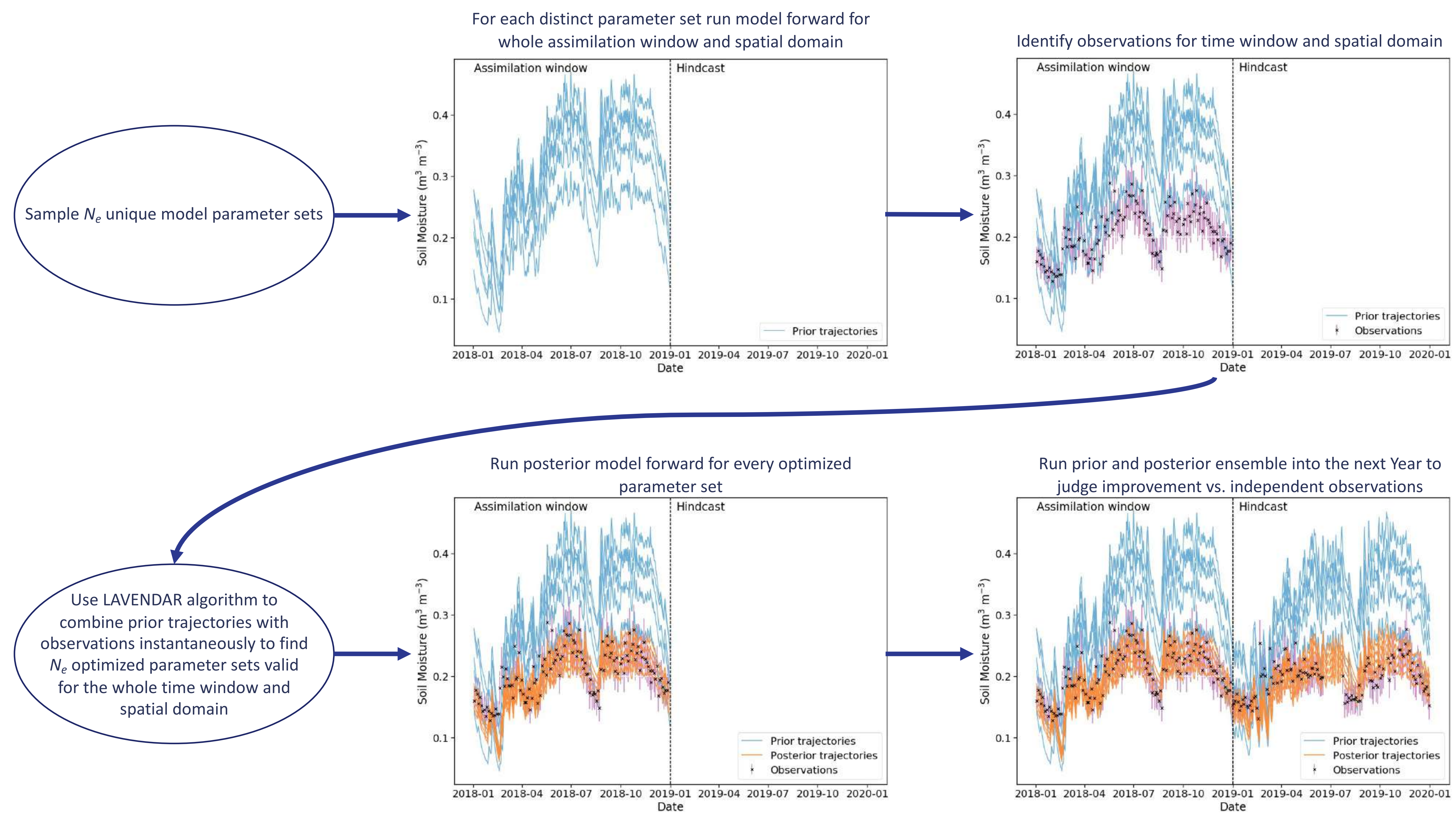
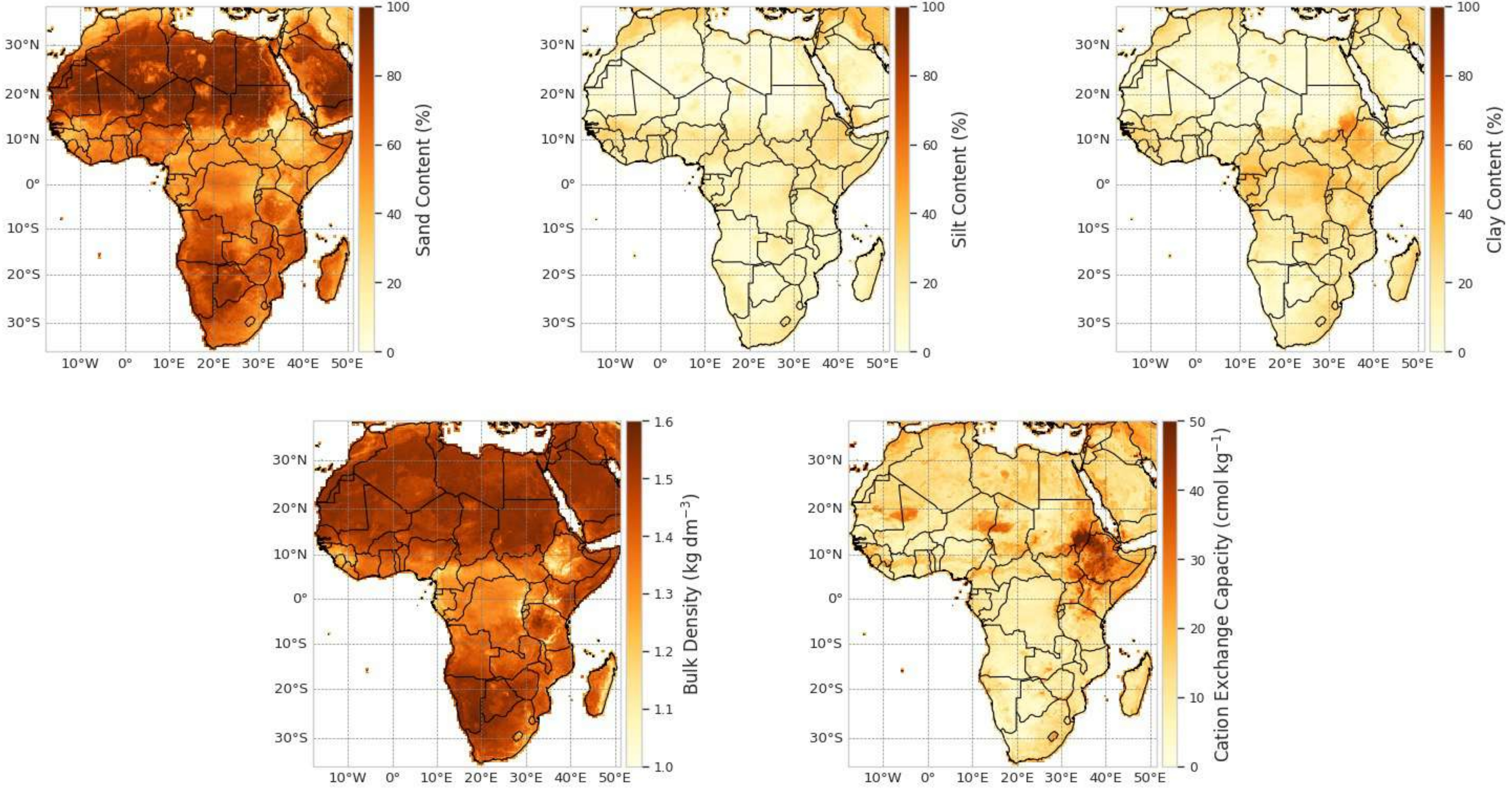


Sample N_e unique model parameter sets
For each distinct parameter set run model forward for whole assimilation window and spatial domain
Identify observations for time window and spatial domain
Use LAVENDAR algorithm to combine prior trajectories with observations instantaneously to find N_e optimized parameter sets valid for the whole time window and spatial domain
Run posterior model forward for every optimized parameter set
Run prior and posterior ensemble into the next Year to judge improvement vs. independent observations
Assimilation window
Hindcast
Soil Moisture (m^3 m^{-3})
0.1
0.2
0.3
0.4
Date
2018-01
2018-04
2018-07
2018-10
2019-01
2019-04
2019-07
2019-10
2020-01
Prior trajectories
Posterior trajectories
Observations



Sand Content (%)
Silt Content (%)
Clay Content (%)
Bulk Density (kg dm^{-3})
Cation Exchange Capacity (cmol kg^{-1})
0
20
40
60
80
100
1.0
1.1
1.2
1.3
1.4
1.5
1.6
10
30
50
30°N
20°N
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0°
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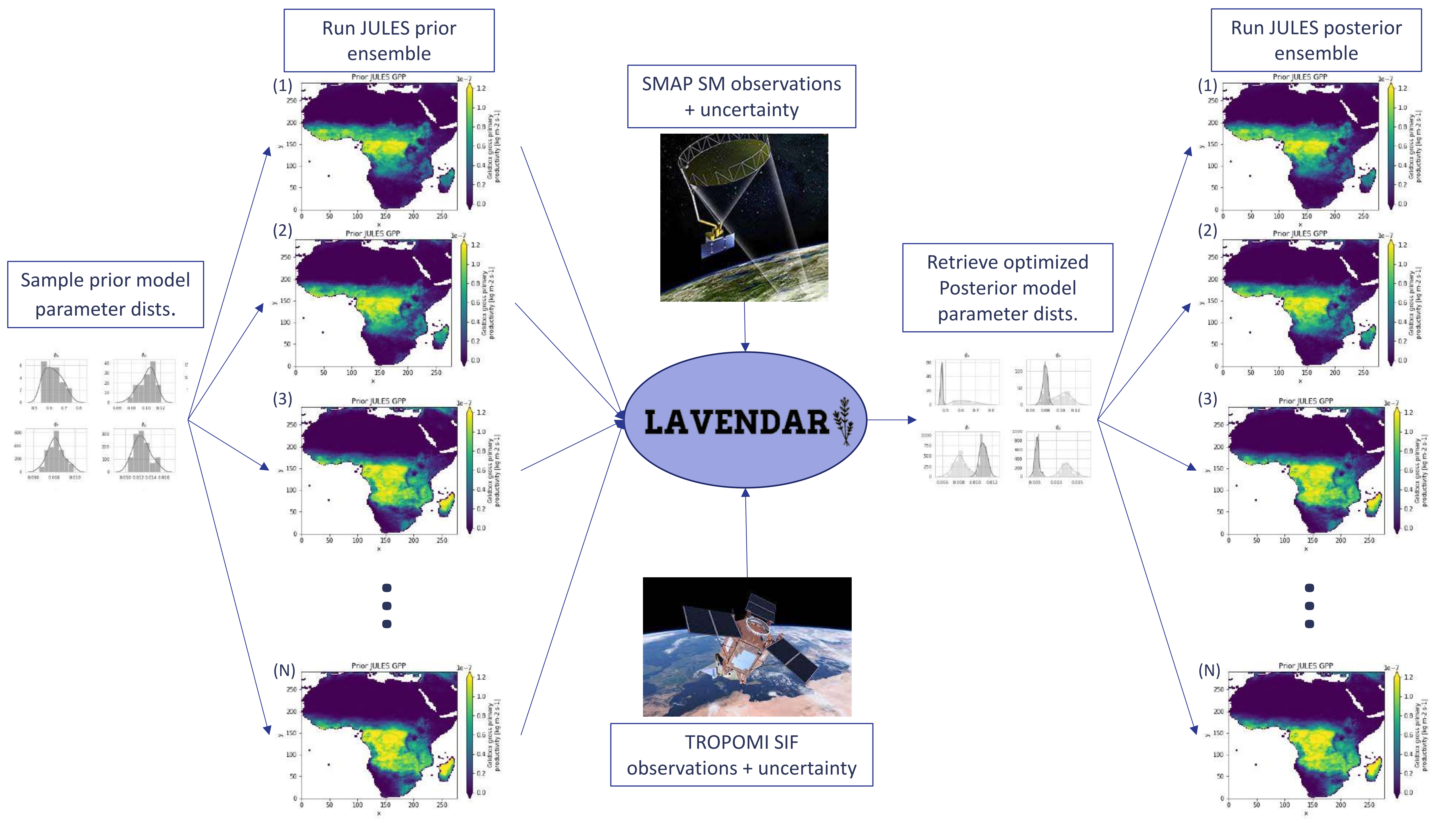
10°W
10°E
20°E
30°E
40°E
50°E


Run JULES prior ensemble
SMAP SM observations + uncertainty
Run JULES posterior ensemble
Sample prior model parameter dists.
Retrieve optimized Posterior model parameter dists.
LAVENDAR
TROPOMI SIF observations + uncertainty
(1)
(2)
(3)
(N)
Prior JULES GPP