Data Assimilation with the JULES Land Surface Model

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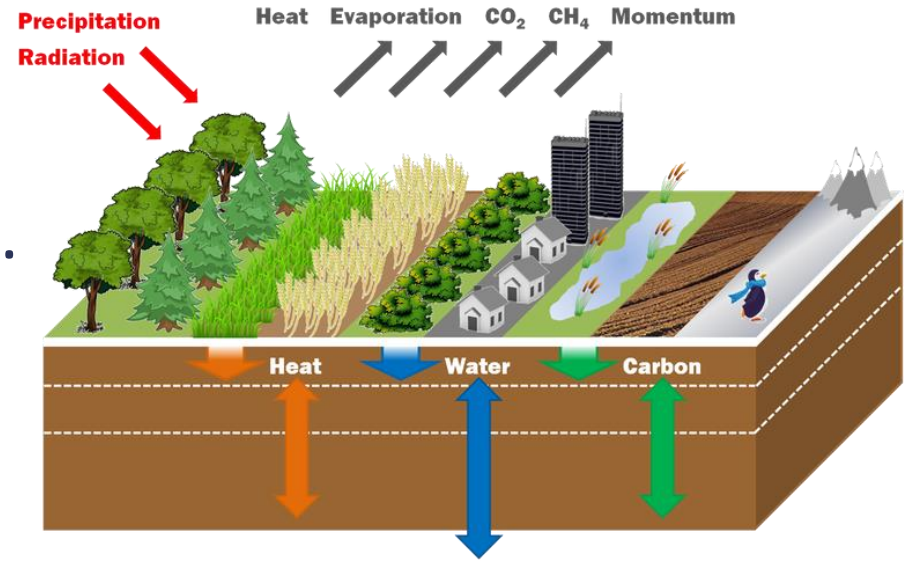
JULES land surface model

- The Joint UK Land Environment Simulator (JULES) community land model is used by UK Met Office in production of forecasts and in the UK Earth System Model (UKESM).
- Different tiles and soil layers, now including crops.
- Difficult to implement with variational Data Assimilation (DA) techniques which require derivative of the model due to high model complexity and many new releases.



JULES model schematic

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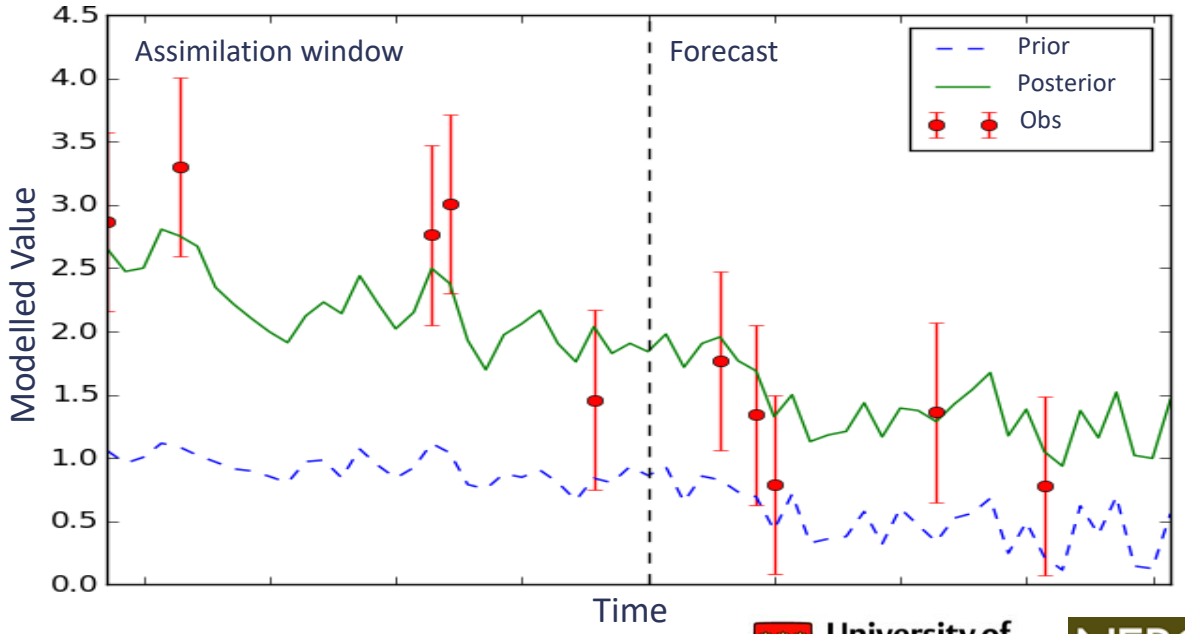
Four-Dimensional Variational (4DVar) DA

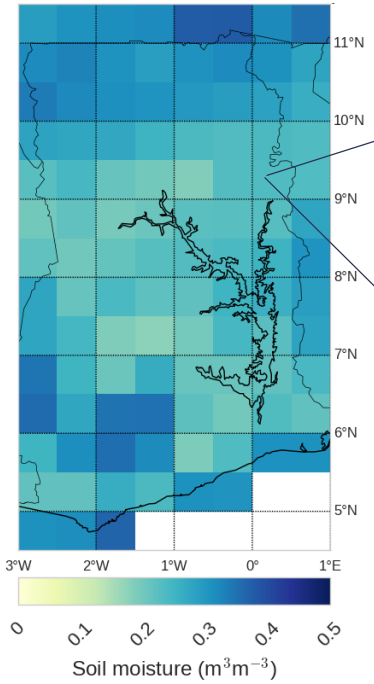
- Combine all sources of information to find best estimate to the state of a system.
- Do this by minimising a cost function.
- Typically requires the derivative of the model. This is an issue for JULES!

4DVar cost function:

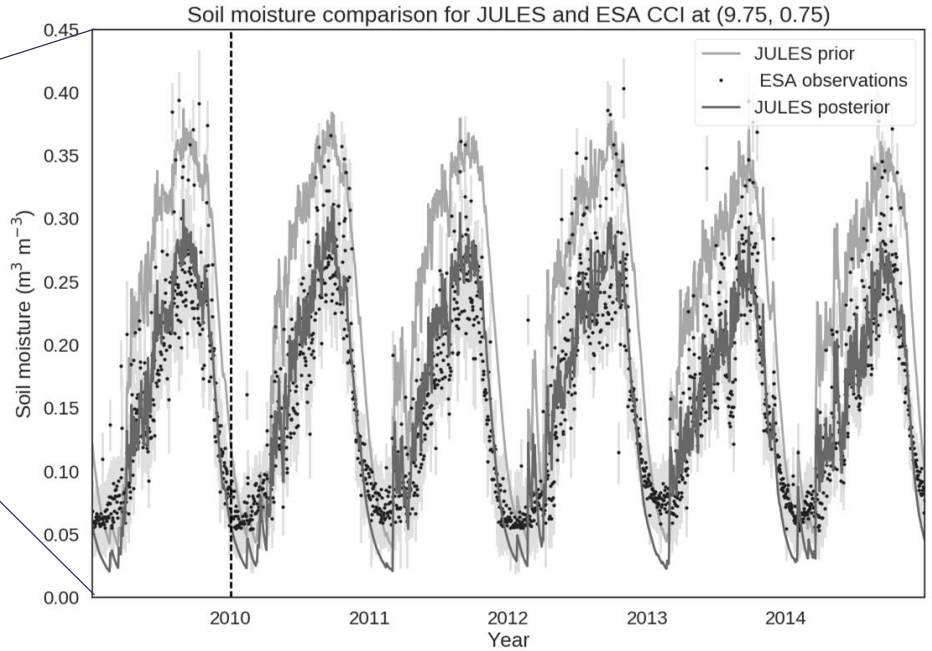
$$J(\mathbf{x}_0) = \underbrace{\frac{1}{2}(\mathbf{x}_0 - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}^b)}_{\textbf{Prior}} + \underbrace{\frac{1}{2}(\hat{\mathbf{h}}(\mathbf{x}_0) - \hat{\mathbf{y}})^T \hat{\mathbf{R}}^{-1}(\hat{\mathbf{h}}(\mathbf{x}_0) - \hat{\mathbf{y}})}_{\textbf{Observations}}$$



Improving soil moisture estimates for Ghana



JULES modelled soil moisture over Ghana



Pinnington, E., Quaife, T., and Black, E.: Impact of remotely sensed soil moisture and precipitation on soil moisture prediction in a data assimilation system with the JULES land surface model, Hydrol. Earth Syst. Sci., 22, 2575-2588, https://doi.org/10.5194/hess-22-2575-2018, 2018.

- Assimilated ESA CCI satellite observations of soil moisture to optimise soil parameters of JULES.
- Found a 20% reduction in unbiased-RMSE for 5-year hindcast.
- DA method was slow!
- In order to consider larger scales different approach to DA is required.

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Four-Dimensional Ensemble Variational (4DEnVar) DA

- Approximates 4D-Var Using an ensemble of model trajectories.
- Does not require the derivative of the model.
- Much faster than technique used in soil moisture work.
- Requires no code modification.
- Easily parallelisable.

$$\mathbf{X}_b' = \frac{1}{\sqrt{N-1}}(\mathbf{x}^{b,1} - \overline{\mathbf{x}}^b, \mathbf{x}^{b,2} - \overline{\mathbf{x}}^b, \ldots, \mathbf{x}^{b,N} - \overline{\mathbf{x}}^b), \quad (1)$$

$$\mathbf{B} \approx \mathbf{X}_b' \mathbf{X}_b'^T \quad (2)$$

$$\mathbf{x}_0 = \mathbf{x}_b + \mathbf{X}_b' \mathbf{w}, \quad (3)$$

$$J(\mathbf{w}) = \frac{1}{2}\mathbf{w}^T\mathbf{w} + \frac{1}{2}(\hat{\mathbf{H}}\mathbf{X}_b'\mathbf{w} + \hat{\mathbf{h}}(\mathbf{x}^b) - \hat{\mathbf{y}})^T \hat{\mathbf{R}}^{-1}(\hat{\mathbf{H}}\mathbf{X}_b'\mathbf{w} + \hat{\mathbf{h}}(\mathbf{x}^b) - \hat{\mathbf{y}}) \quad (4)$$

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LaVEnDAR

- The Land Ensemble Variational Data Assimilation fRamework (LaVEnDAR) implements 4DEnVar for land surface models.
  - https://github.com/pyearthsci/lavendar
  - Pinnington, E., Quaife, T., Lawless, A., Williams, K., Arkebauer, T., and Scoby, D.: The Land Variational Ensemble Data Assimilation fRamework: LaVEnDAR, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2019-60, in review, 2019.
- Written Python wrappers for JULES controlling functionality and running model.
- Wrappers allow us to easily run ensemble of models with different parameters in parallel and perform DA.

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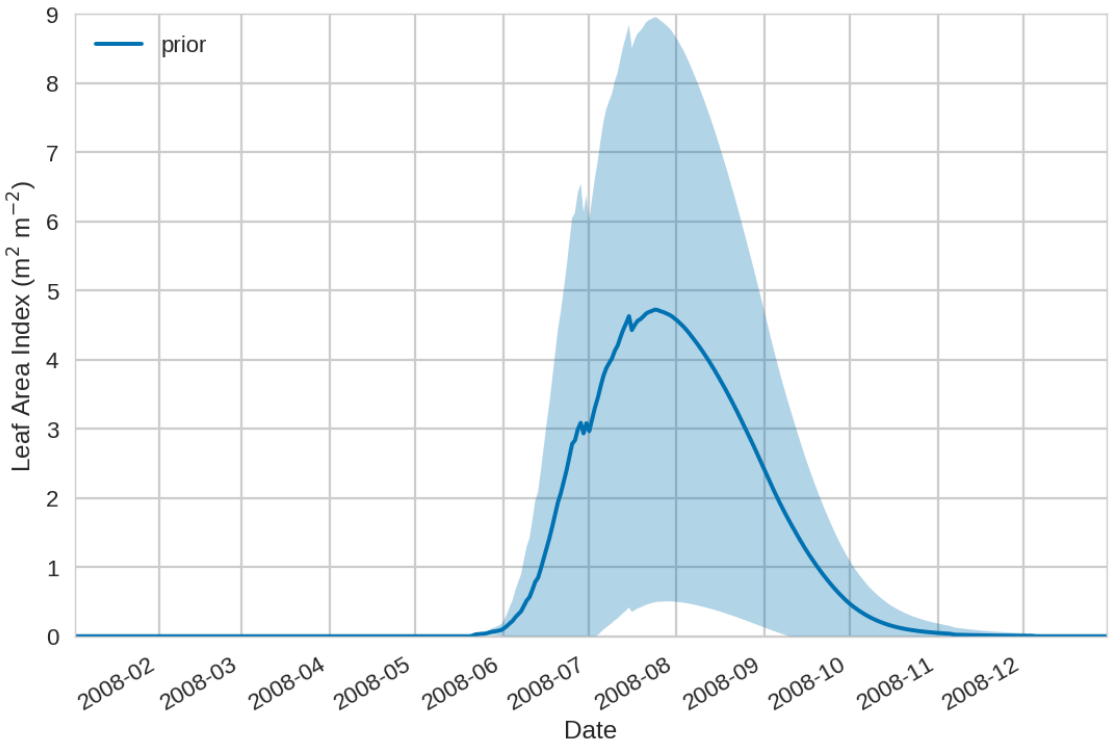
LaVEnDAR

- Tested technique for JULES at maize crop in Nebraska, USA. Assimilating leaf area index, canopy height and flux tower observations.
  - Pinnington, E., Quaife, T., Lawless, A., Williams, K., Arkebauer, T., and Scoby, D.: The Land Variational Ensemble Data Assimilation fRamework: LaVEnDAR, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2019-60, in review, 2019.
- Optimised 7 model parameters controlling crop behaviour.
- Improved model estimate of crop yield by 74% compared to independent observations.



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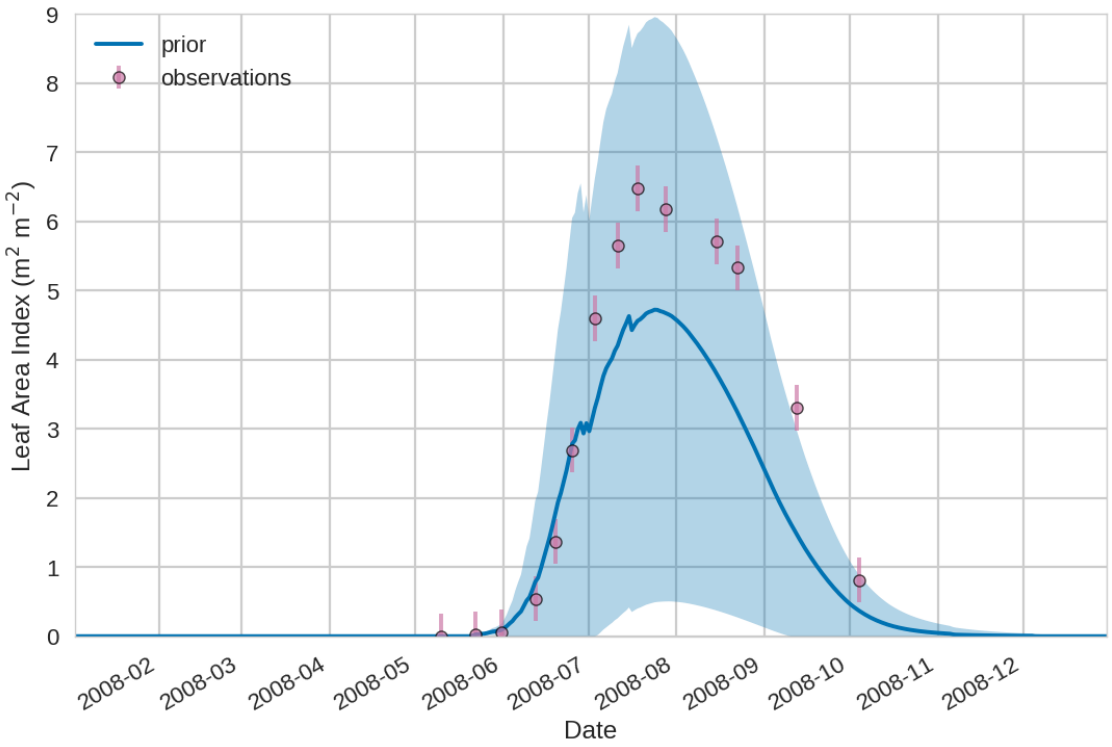

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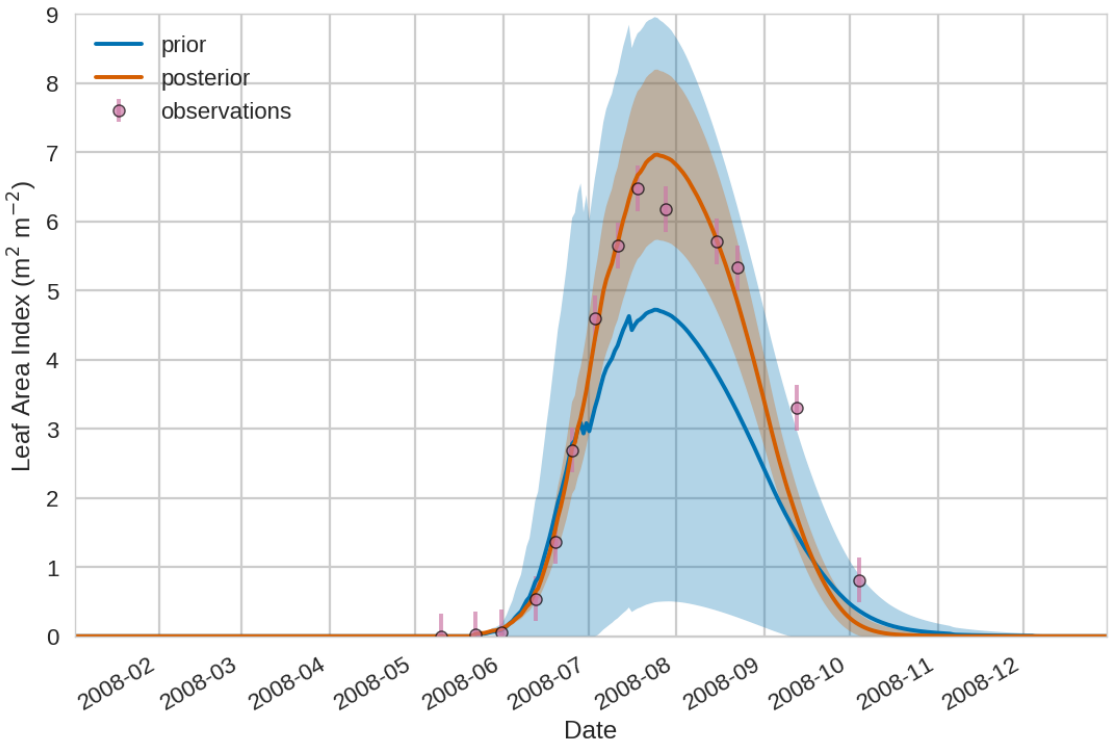

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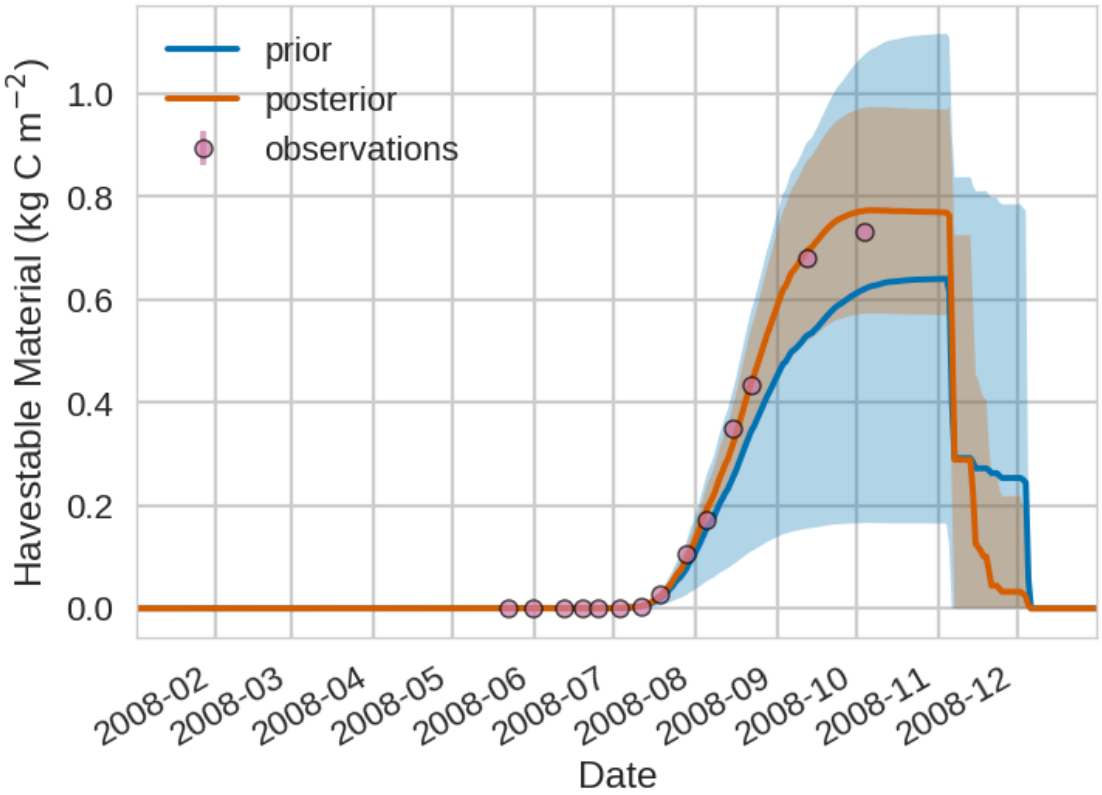

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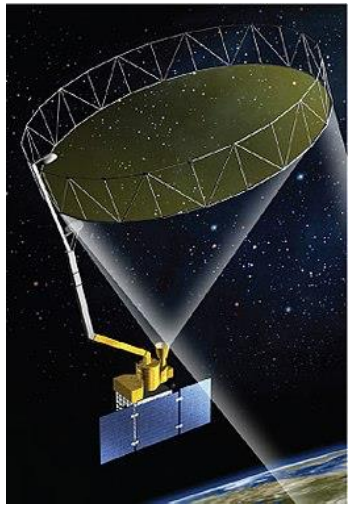
Continuing soil moisture work

- Further developing technique for soil moisture work over the UK on Hydro-JULES project.
- Running JULES at 1 km resolution over the UK.
- Assimilating satellite observations from the NASA SMAP mission.
- Validate results using the cosmic-ray soil moisture monitoring network (COSMOS-UK) established by CEH.

Hydro-JULES



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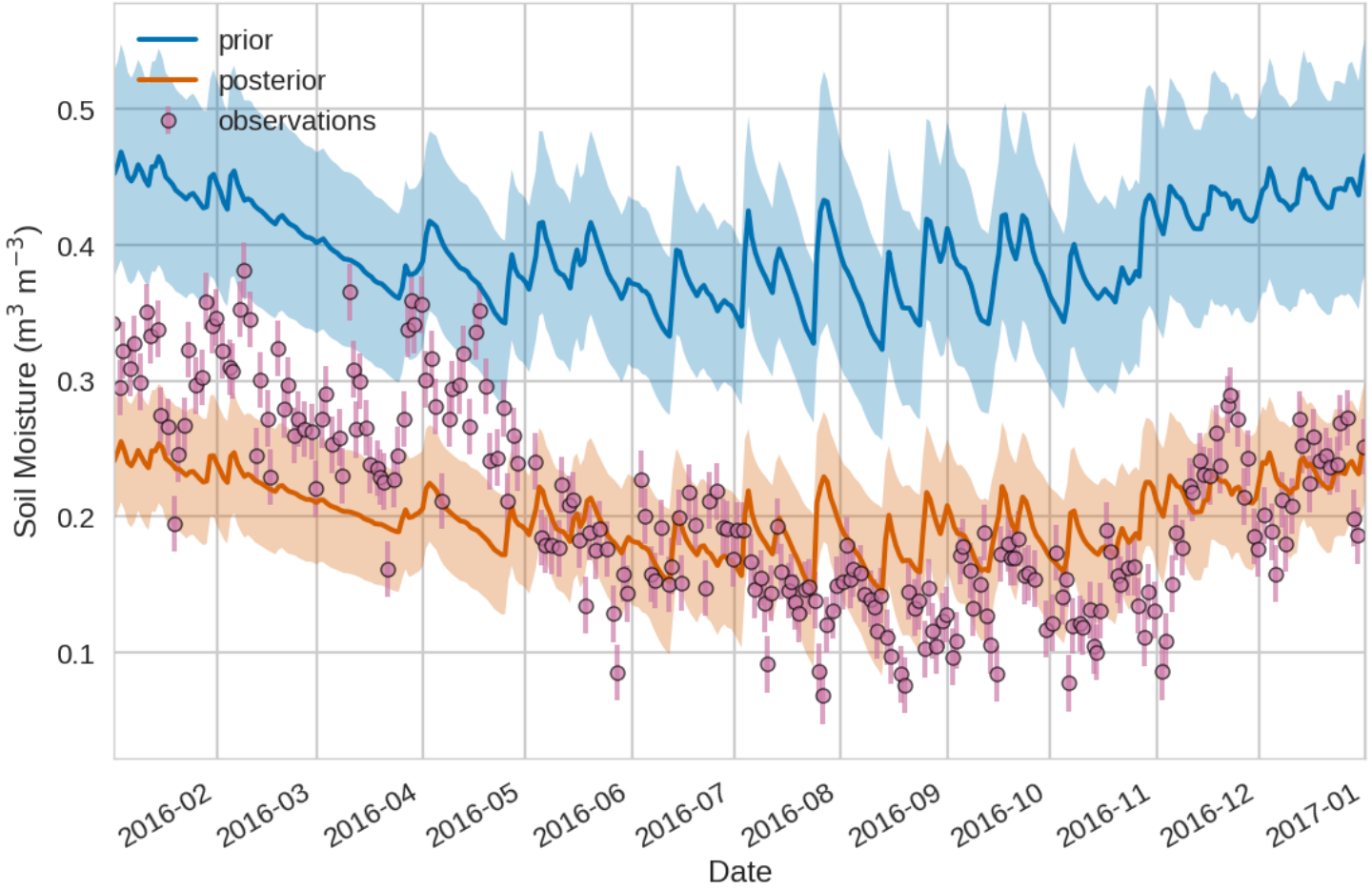
Assimilating SMAP at COSMOS site

- Optimising 8 soil parameters for JULES.
- Running 50 JULES ensemble members with varied parameter values.
- Showing mean and spread (+/- 1 σ) for prior and posterior (after DA) JULES ensemble.



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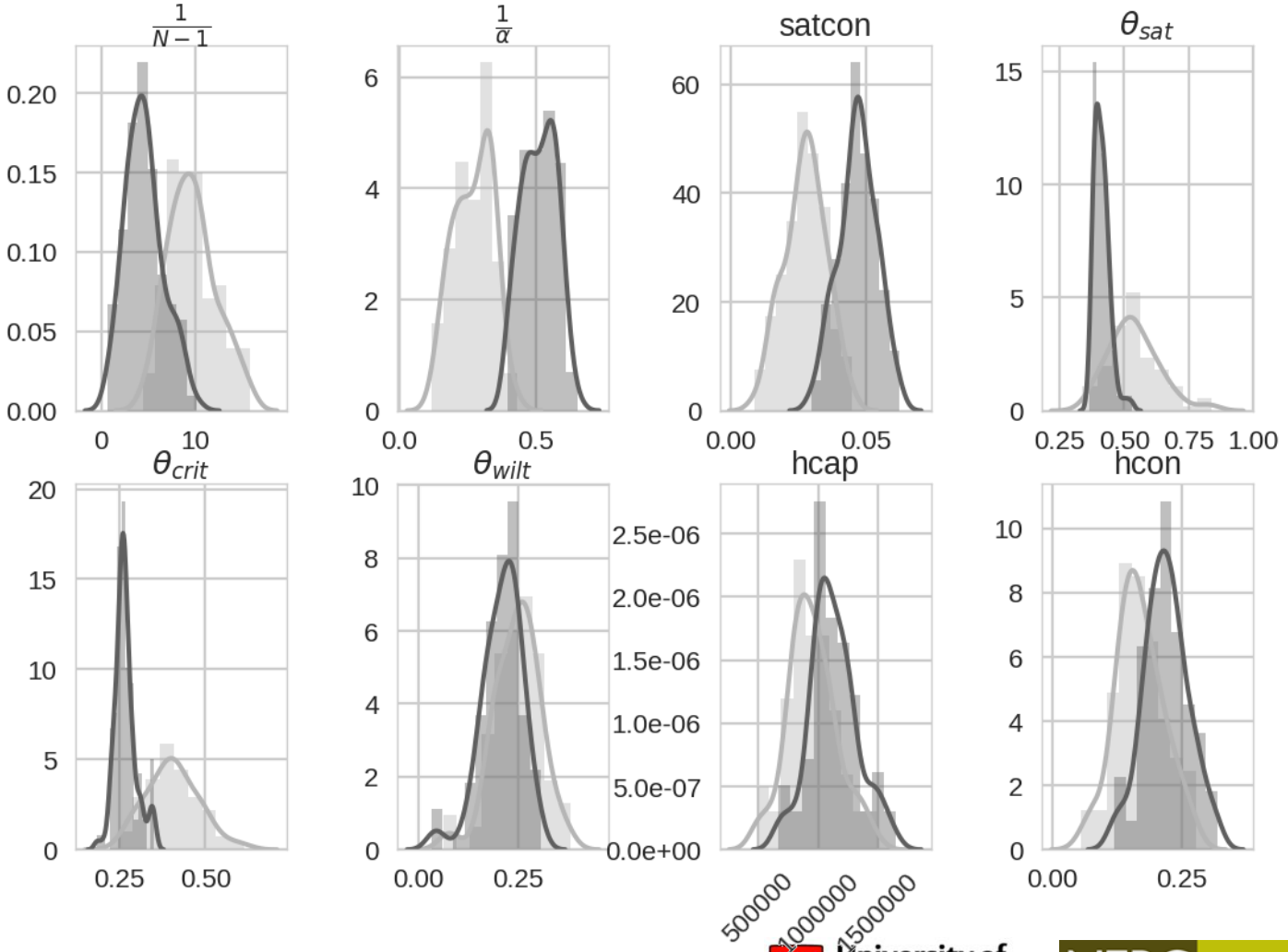

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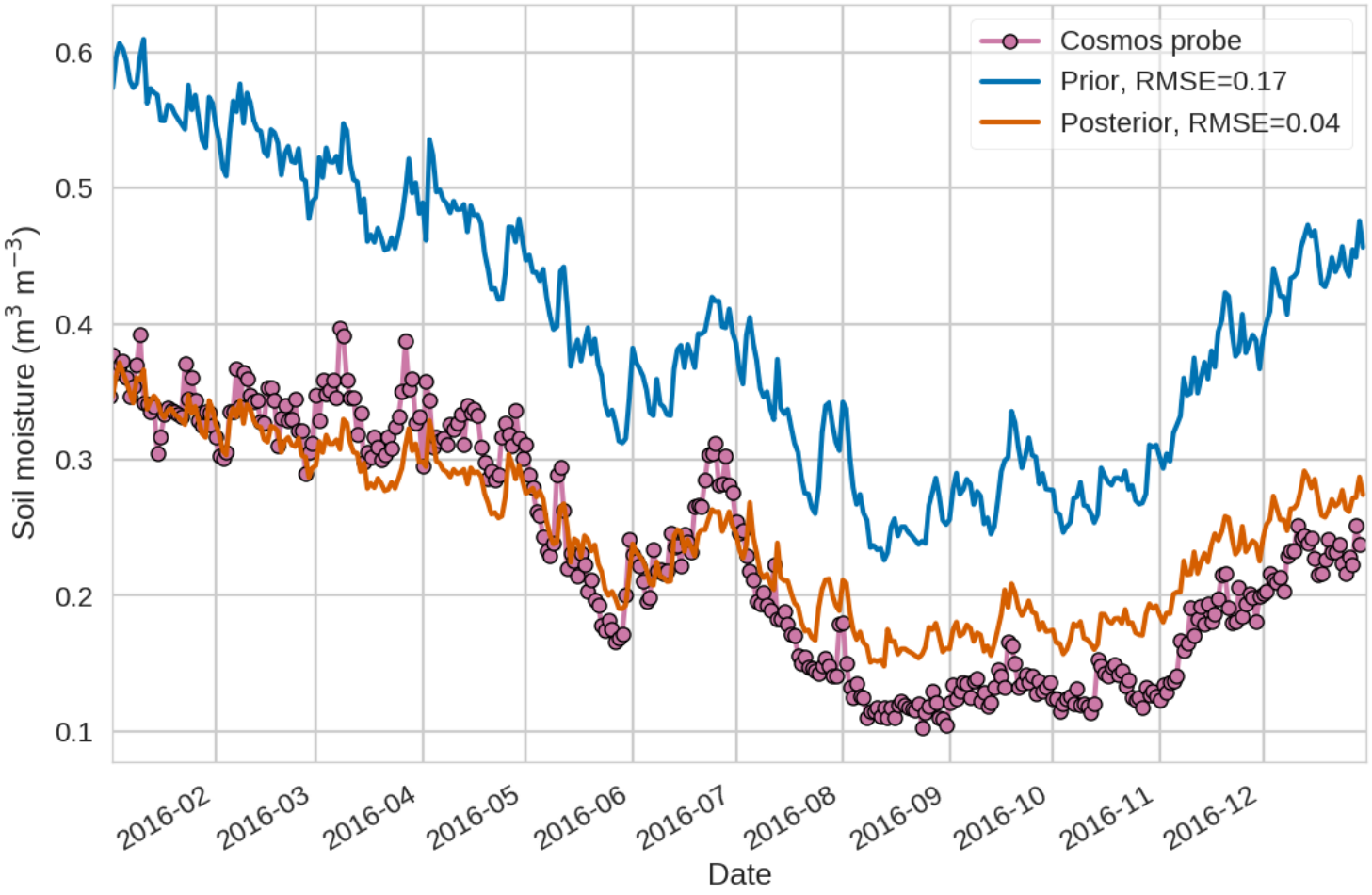
Assimilating SMAP at COSMOS site

- Compare JULES to in-situ COSMOS probe soil moisture.
- Select most likely ensemble member from posterior ensemble.



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Next steps

- Apply developments in soil moisture DA techniques to work in Africa.
- Feed into work with GSSTI and UCL looking at crop yields in Northern Ghana using Sentinel 2 retrievals.
- Working with TAMSAT group, contribute to system predicting meteorological risk to agriculture.
  - Asfaw, D., Black, E., Brown, M., Nicklin, K. J., Otu-Larbi, F., Pinnington, E., Challinor, A., Maidment, R., and Quaife, T.: TAMSAT-ALERT v1: a new framework for agricultural decision support, Geosci. Model Dev., 11, 2353–2371, https://doi.org/10.5194/gmd-11-2353-2018, 2018.

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TAMSAT-ALERT

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Conclusions

- 4DEnVar DA appears to be a good option for parameter and state estimation for land surface models.
- Shown examples of the LaVEnDAR system improving estimates for JULES.
- The increased efficiency of the technique will allow us to conduct data assimilation experiments at larger scales over Africa and at high resolution over the UK.

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Extra Slides

Assimilating SMAP at COSMOS site

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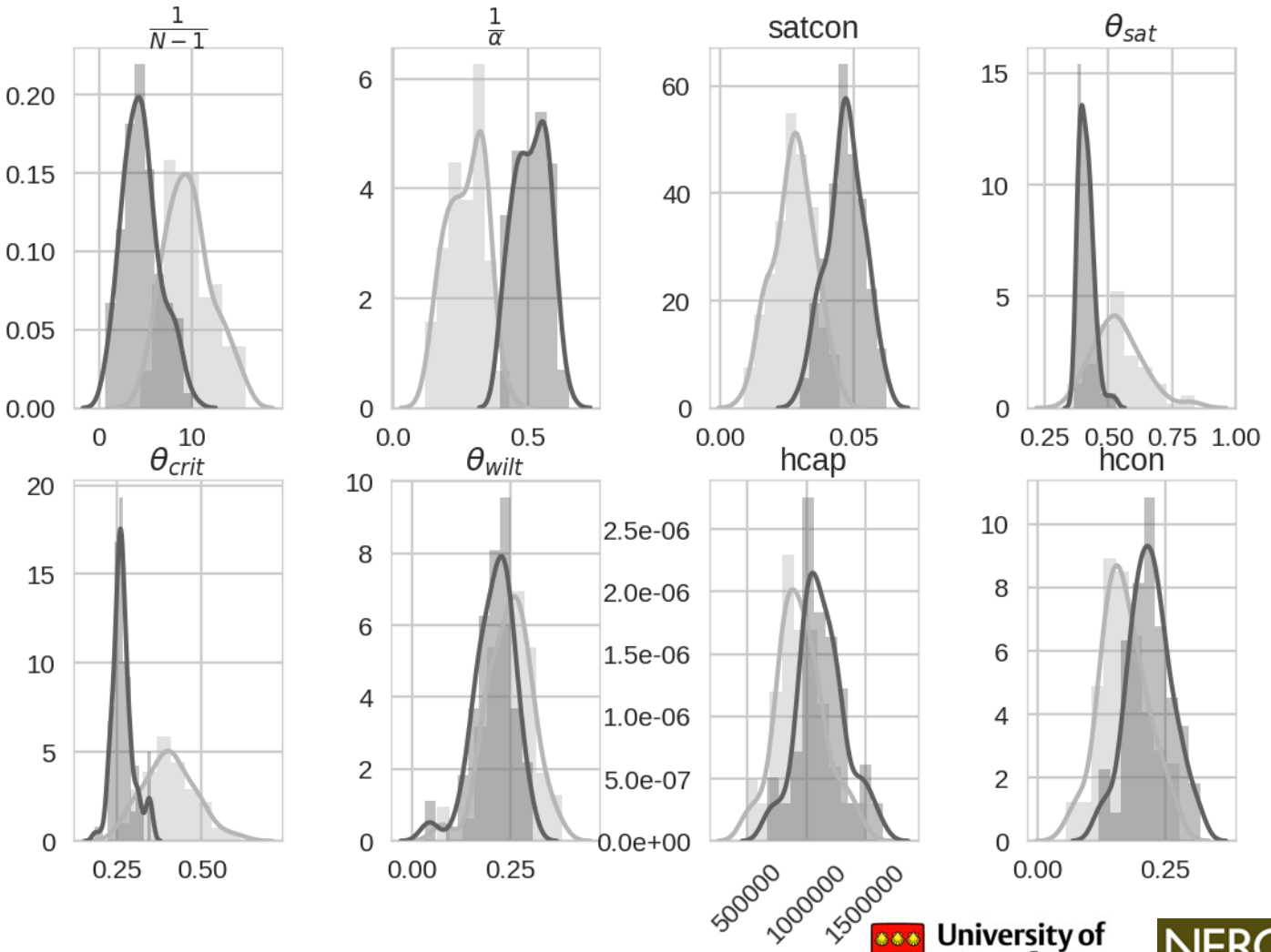

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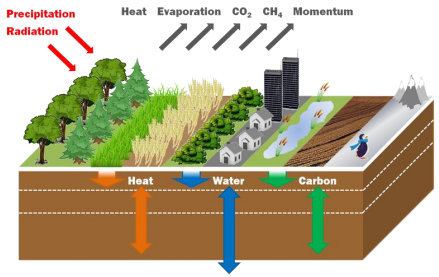
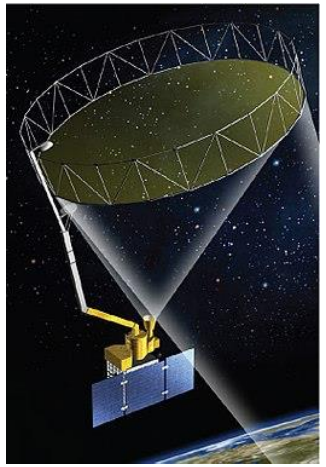
Feeding into other projects & future directions

MARS

Hydro-JULES





Official Development Assistance

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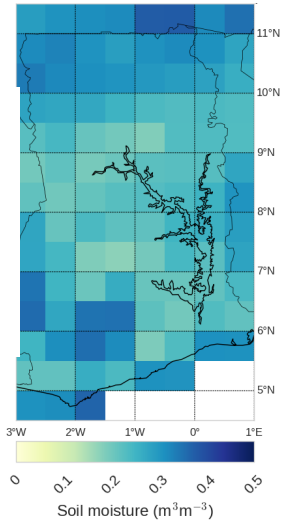

Improving soil moisture estimates for Ghana

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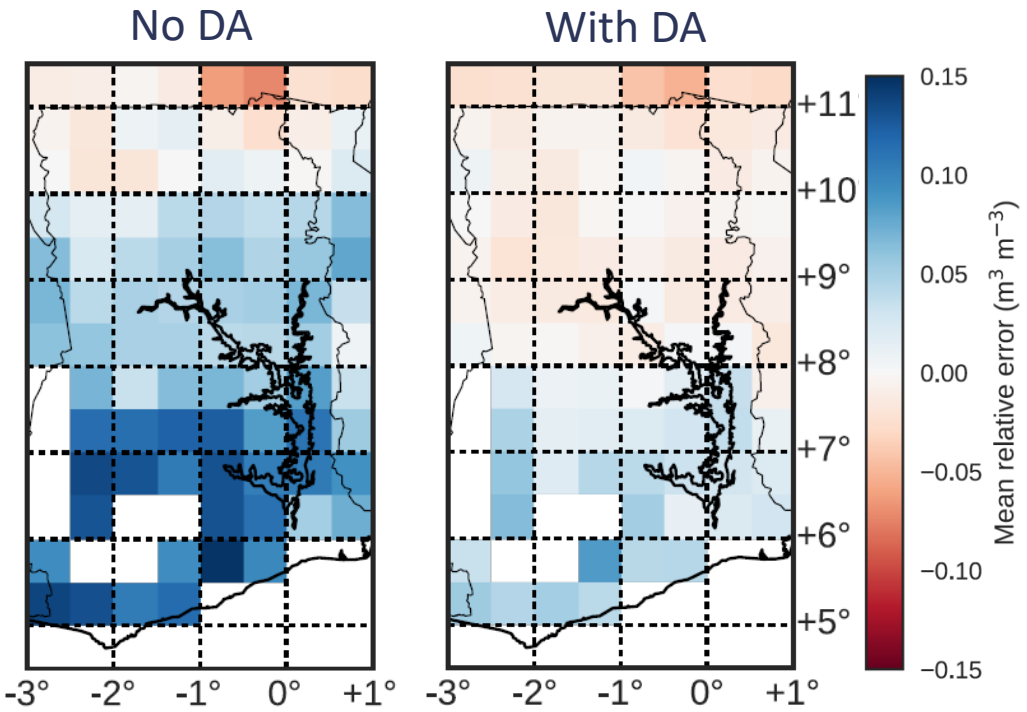

Mean relative error in volumetric soil moisture predicted by JULES in a hindcast experiment for 5 years for Ghana. Without Data Assimilation (left panel) and assimilating ESA CCI data (right panel)

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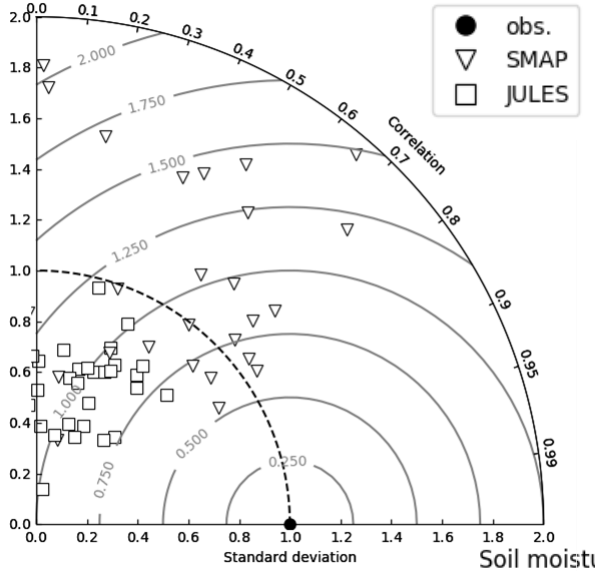
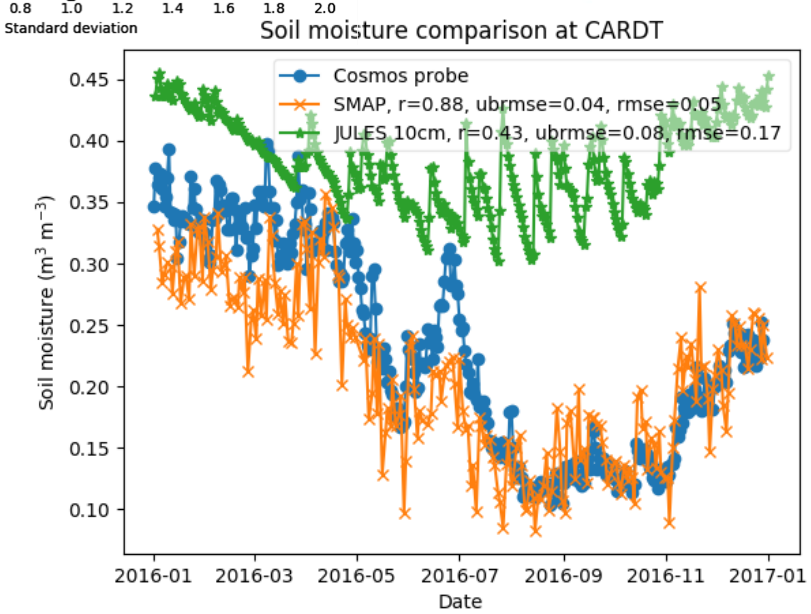
Hydro-JULES

- The Hydro-JULES project aims to develop models to improve hydrological predictions both over the UK and globally.
- As part of this project we will be assimilating SMAP satellite observations to improve JULES soil moisture predictions over the UK.
- JULES is driven with the 1 km CHESS meteorological data.
- To validate our results we use the cosmic-ray soil moisture monitoring network (COSMOS-UK)





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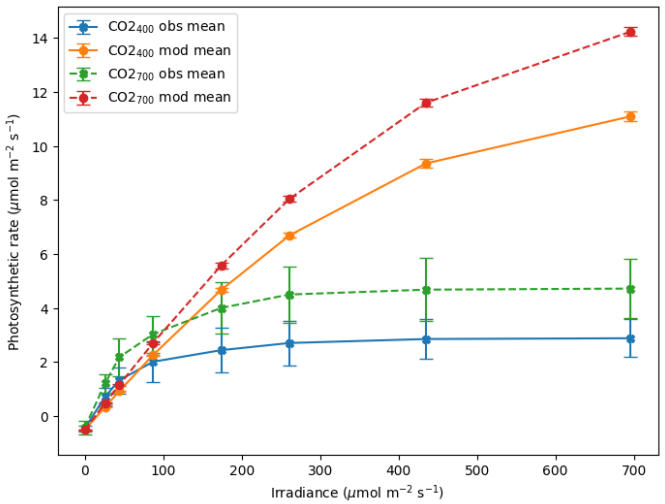
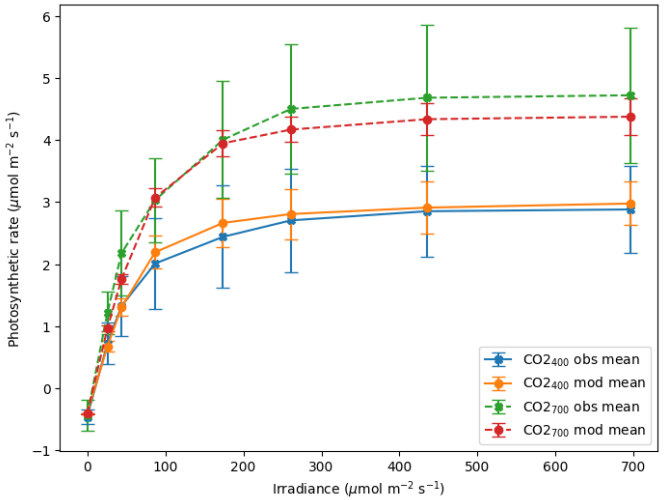
Climate change impact on cocoa productivity

- Work with Mars Incorporated and Cocoa group at Reading University.
- International center for tropical agriculture (CIAT) paper suggests production from cocoa could decrease in West Africa in the future as a result of climate change (Schroth et al. 2016).
- Using observations of leaf-level photosynthesis from greenhouses in Reading.
- Parameterise JULES to simulate cocoa with developed DA techniques.

Before DA

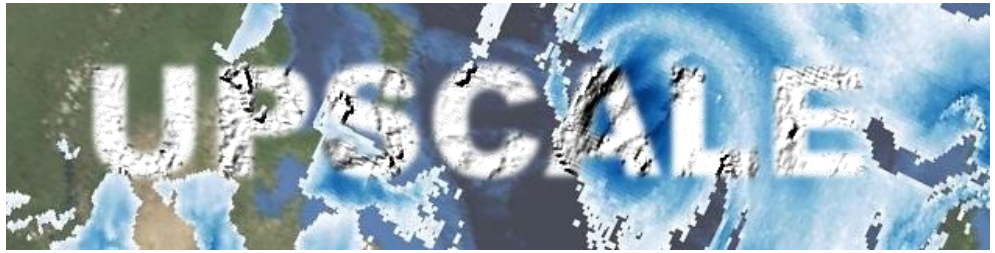


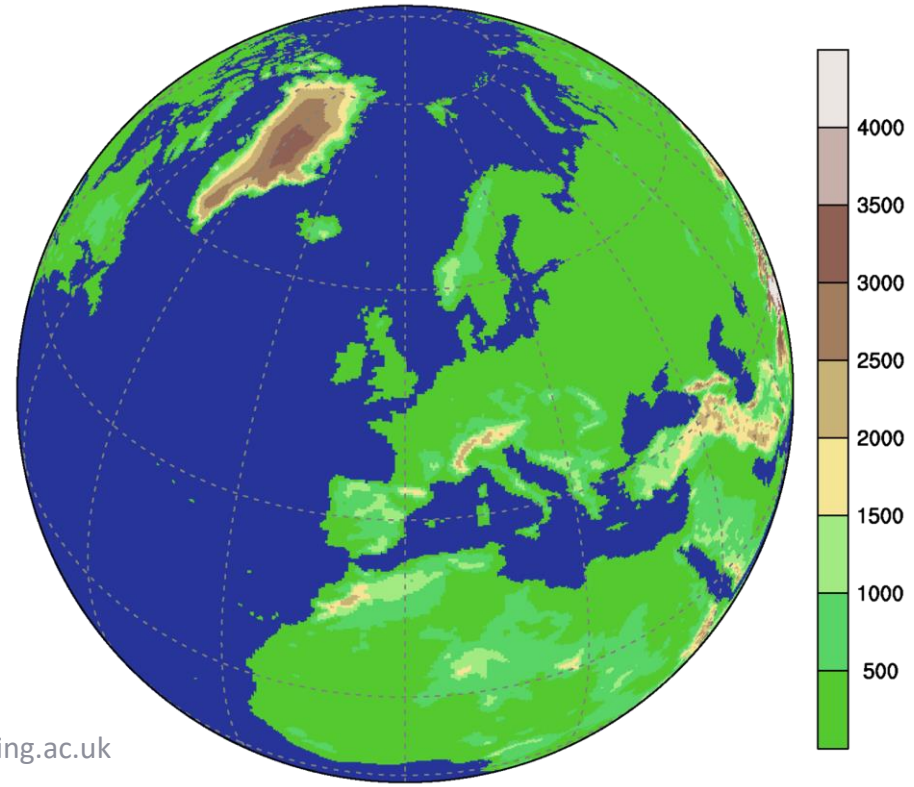
After DA



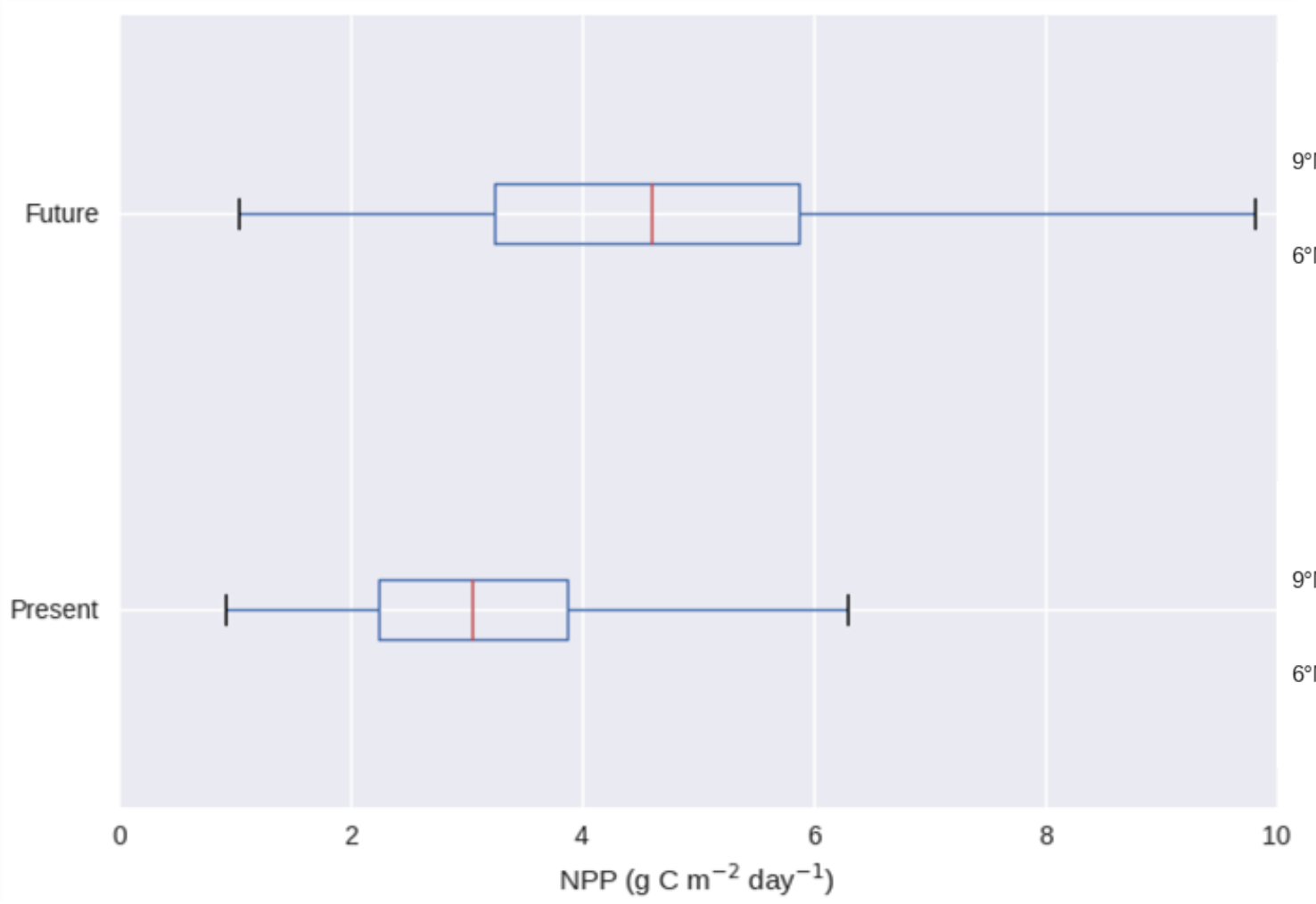
UPSCALE climate forcing data

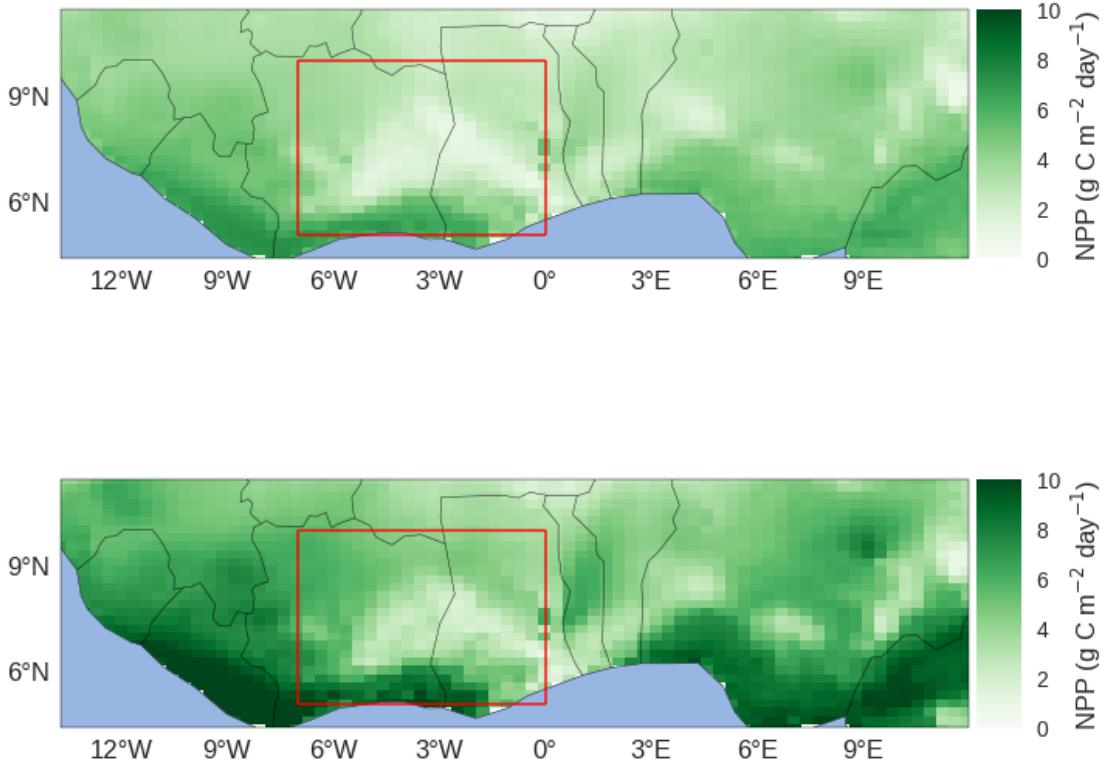
- Climate model runs by the UK Met Office Hadley Centre.
- 27 years of data for present climate conditions and potential future climate conditions (RCP 8.5).
- High model resolution (25 km) giving improved representations.
- Initially we run JULES with new cocoa vegetation type for UPSCALE present/future climate forcing.





Running for UPSCALE present and future





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