Data Assimilation with the JULES Land Surface Model

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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.
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:

\[ J(x_0) = \frac{1}{2}(x_0 - x^b)^T B^{-1} (x_0 - x^b) + \frac{1}{2}(\hat{h}(x_0) - \hat{y})^T R^{-1} (\hat{h}(x_0) - \hat{y}) \]
Improving soil moisture estimates for Ghana

JULES modelled soil moisture over Ghana

- 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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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.

\[
\begin{align*}
X'_b &= \frac{1}{\sqrt{N-1}} (x^{b,1} - \overline{x}^b, x^{b,2} - \overline{x}^b, \ldots, x^{b,N} - \overline{x}^b), \\
\mathbf{B} &\approx X'_b X'_b^T \\
x_0 &= x_b + X'_b \mathbf{w}, \\
J(w) &= \frac{1}{2} w^T w + \frac{1}{2} (\hat{H}X'_b w + \hat{h}(x_b) - \hat{y})^T \hat{R}^{-1} (\hat{H}X'_b w + \hat{h}(x_b) - \hat{y})
\end{align*}
\]
LaVEnDAR

- The Land Ensemble Variational Data Assimilation Framework (LaVEnDAR) implements 4DEnVar for land surface models.
  - [https://github.com/pyearthsci/lavendar](https://github.com/pyearthsci/lavendar)

- 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.
LaVEnDAR

• Tested technique for JULES at maize crop in Nebraska, USA. Assimilating leaf area index, canopy height and flux tower observations.

• Optimised 7 model parameters controlling crop behaviour.

• Improved model estimate of crop yield by 74% compared to independent observations.
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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.
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 \( \sigma \)) for prior and posterior (after DA) JULES ensemble.
• 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.
• Compare JULES to in-situ COSMOS probe soil moisture.
• Select most likely ensemble member from posterior ensemble.
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.
• 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.
Assimilating SMAP at COSMOS site

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- Running 50 JULES ensemble members with varied parameter values.
- Showing mean and spread (+/- 1 σ) for prior and posterior (after DA) JULES ensemble.
Feeding into other projects & future directions

MARS

Hydro-JULES

Official Development Assistance

TAMSAT-ALERT

University of Reading
Improving soil moisture estimates for Ghana

• Find a 20% reduction in unbiased-RMSE for 5-year JULES hindcast after assimilation of ESA CCI observations of soil moisture.

• Working with TAMSAT group at Reading. Ultimately build work into system predicting meteorological risk to agriculture.

• In order to consider larger scales different approach to DA is required.

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)
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)
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.
• 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