Developing Machine-Learning Based Emulators for the JULES Land Surface Model

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What is a Digital Twin?

- A digital representation of a physical system…
- With some predictive capability (i.e. a model)…
- That is data-driven (e.g. Earth Observation, in-situ, citizen data, etc)…
- Capable of providing decision support to stakeholders

- Lots of different components and considerations that span a whole host of scientific, logistical, technical and IT areas
- Potentially hugely complex and ambitious
- Can extend beyond *just* environmental science (e.g. economics, social sciences, public health, etc)

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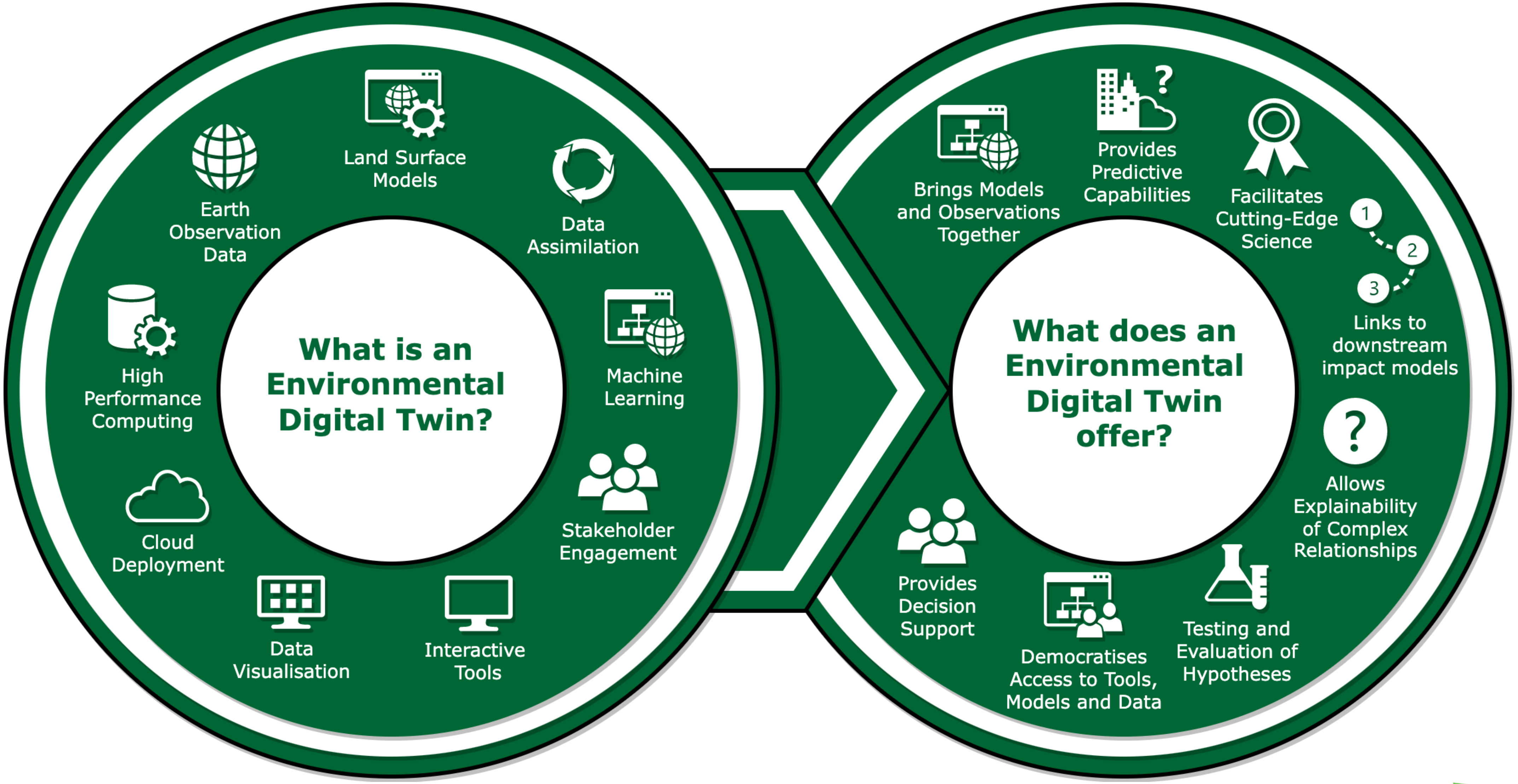
What is a Digital Twin and what does it offer?



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Benefits of emulating the JULES land surface model

Emulator can accurately reproduce JULES simulations but also:

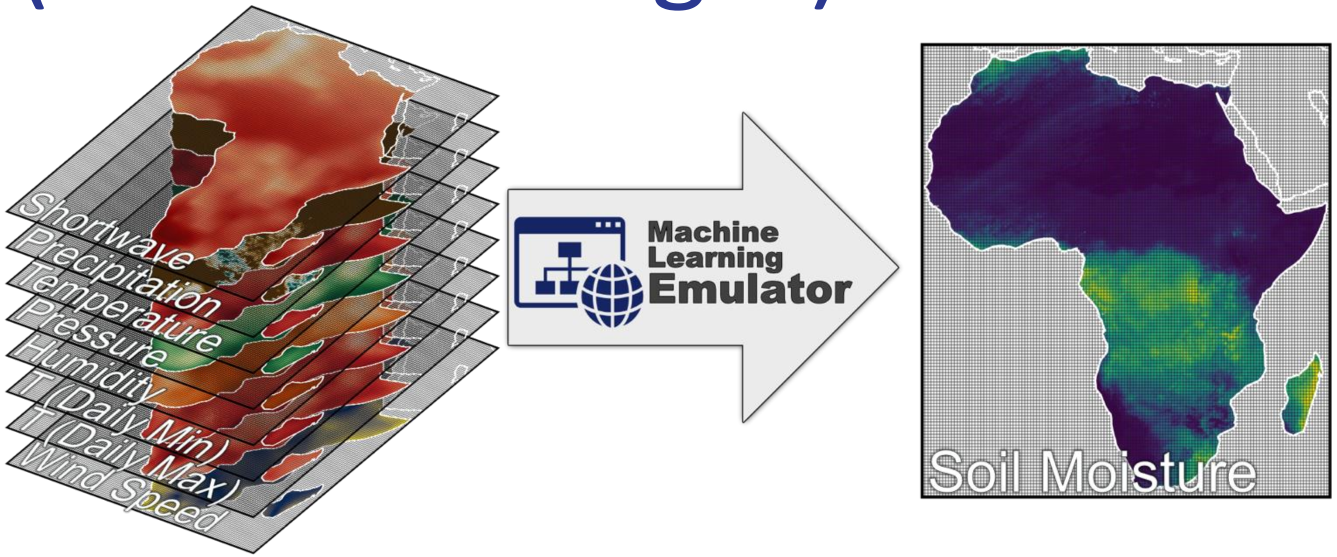
- is extremely fast (years per millisecond)
  - can run huge ensembles, sample uncertainties, etc
- is extremely simple/lightweight (deployed in cloud/notebook/etc)
  - makes JULES far more accessible to non-expert users
  - can be embedded into climate services
- allows explainability of model (Explainable AI methods)
- can be driven by other data (e.g. EO data)
  - constrained by the "physics" within JULES
  - but means we can potentially out-perform JULES by combining JULES and EO data
  - can run at whatever resolution we have available input data for

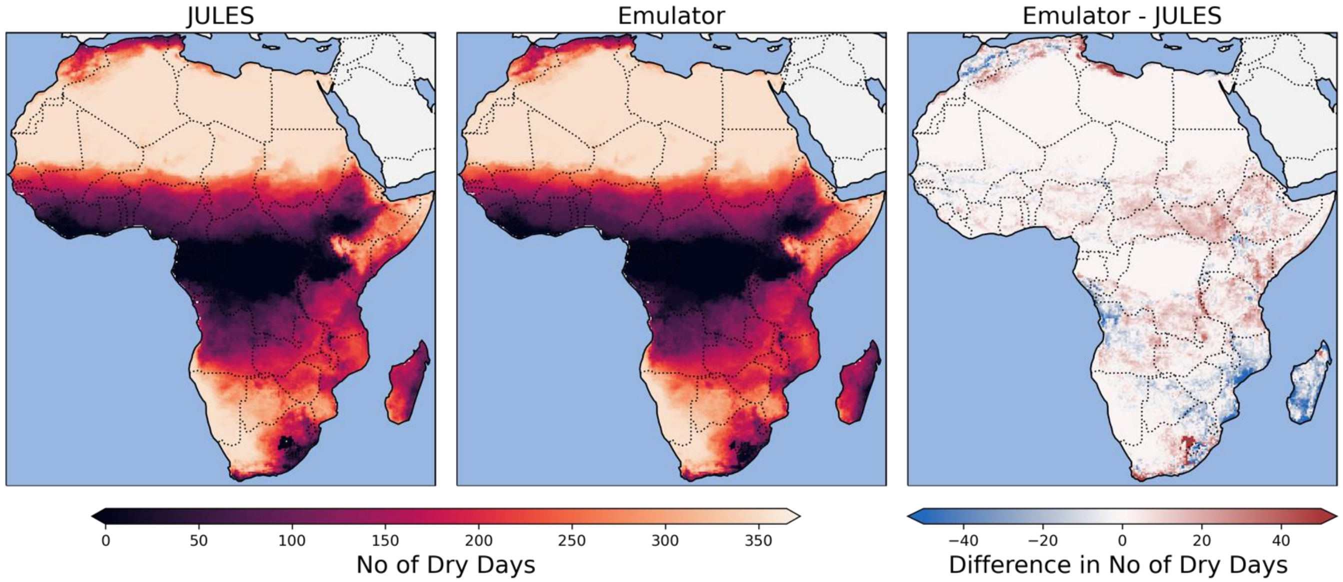
Two NCEO projects related to this work:

- ESA Digital Twin Earth - Drought - Soil moisture over Africa
- ESA IMITATE - Carbon Cycle - GPP over Europe

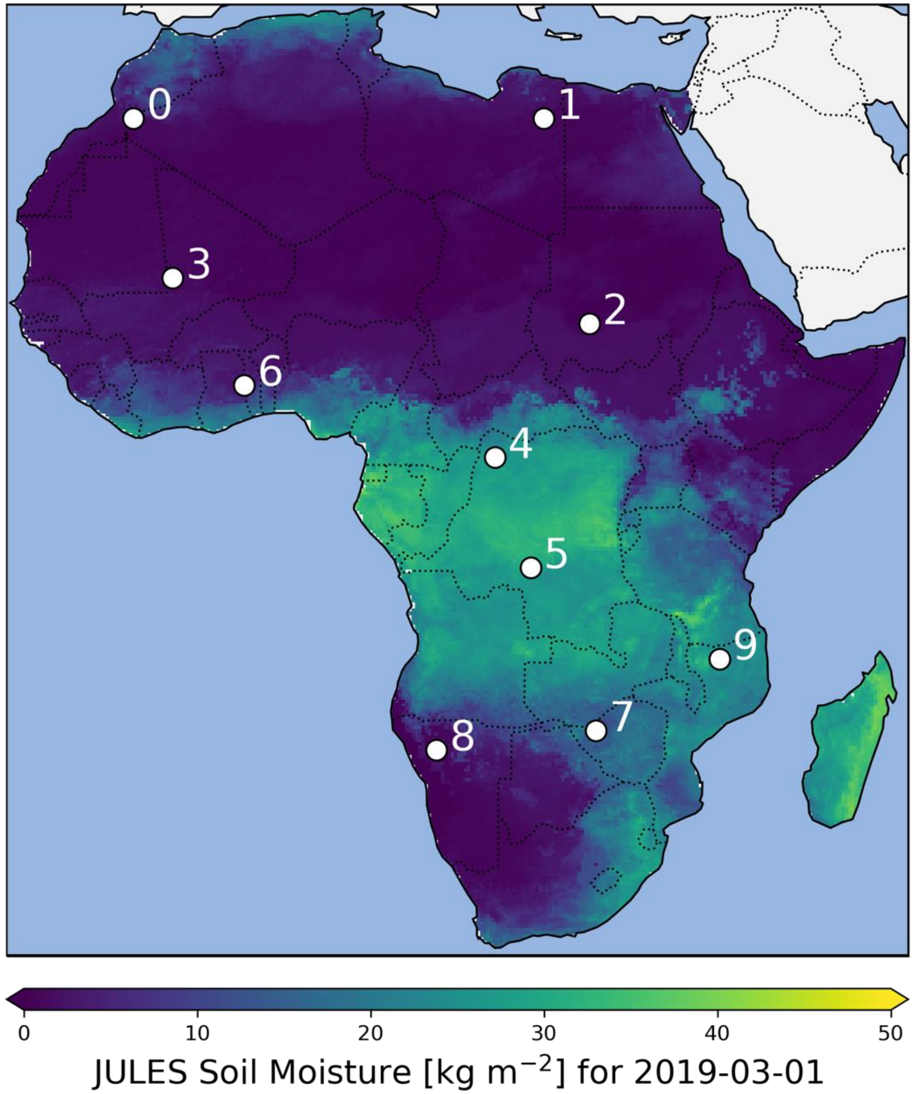
ESA Digital Twin Earth (African Drought)

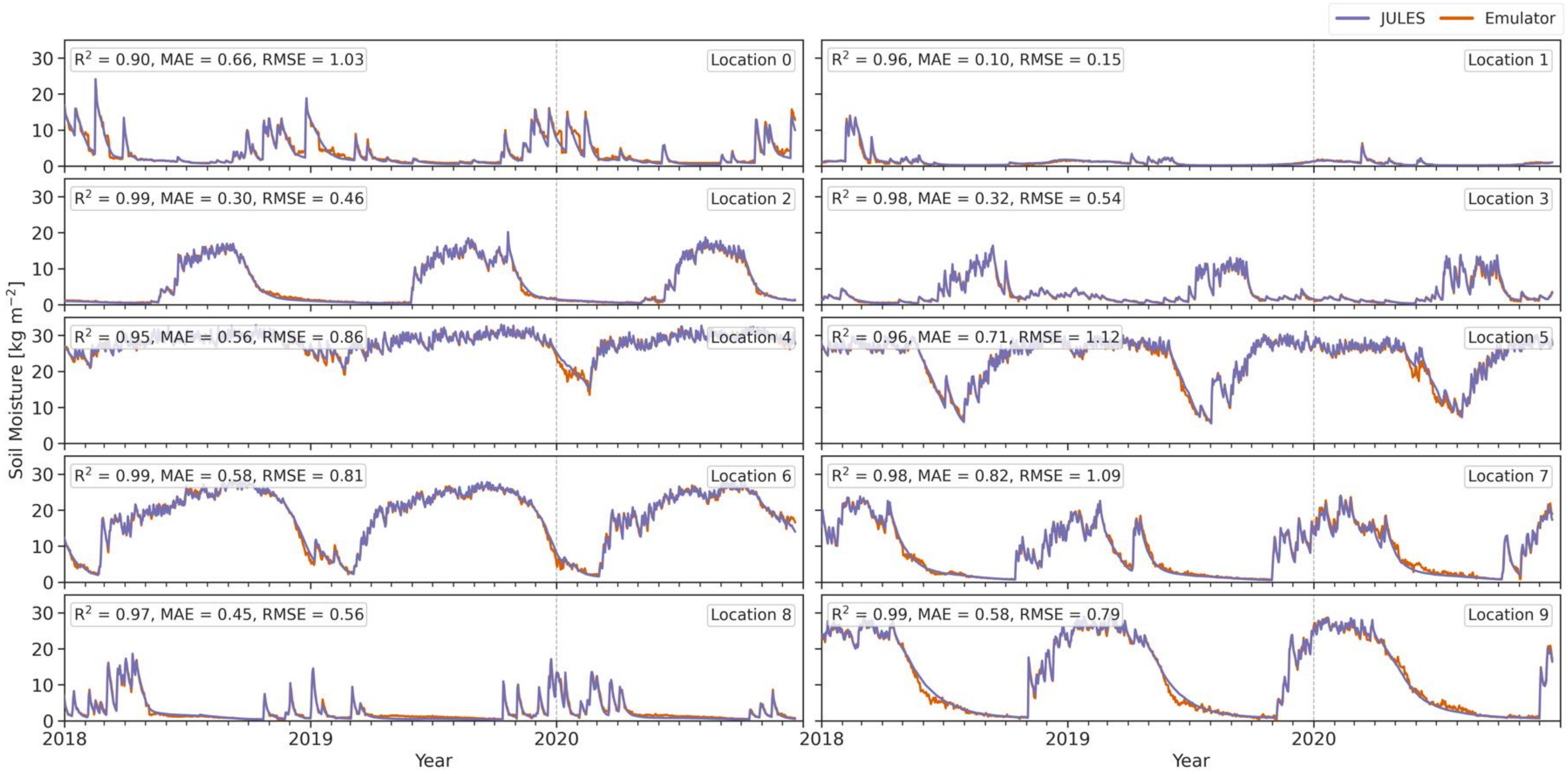
- We've used machine learning to emulate the complex, computationally expensive models in a very fast and light-weight way
- Produce drought metrics - currently **wet season length**, **start date of wet season** and **number of dry days**
- Widgets for these are deployed within our **Interactive Data Portal**
- Emulator is **extremely fast** and **runs in the web-browser**, allowing users to ask their own questions based around soil-moisture response to climate





Evaluation of Emulator





- ❑ Emulator performs exceptionally well and reproduces results of JULES model

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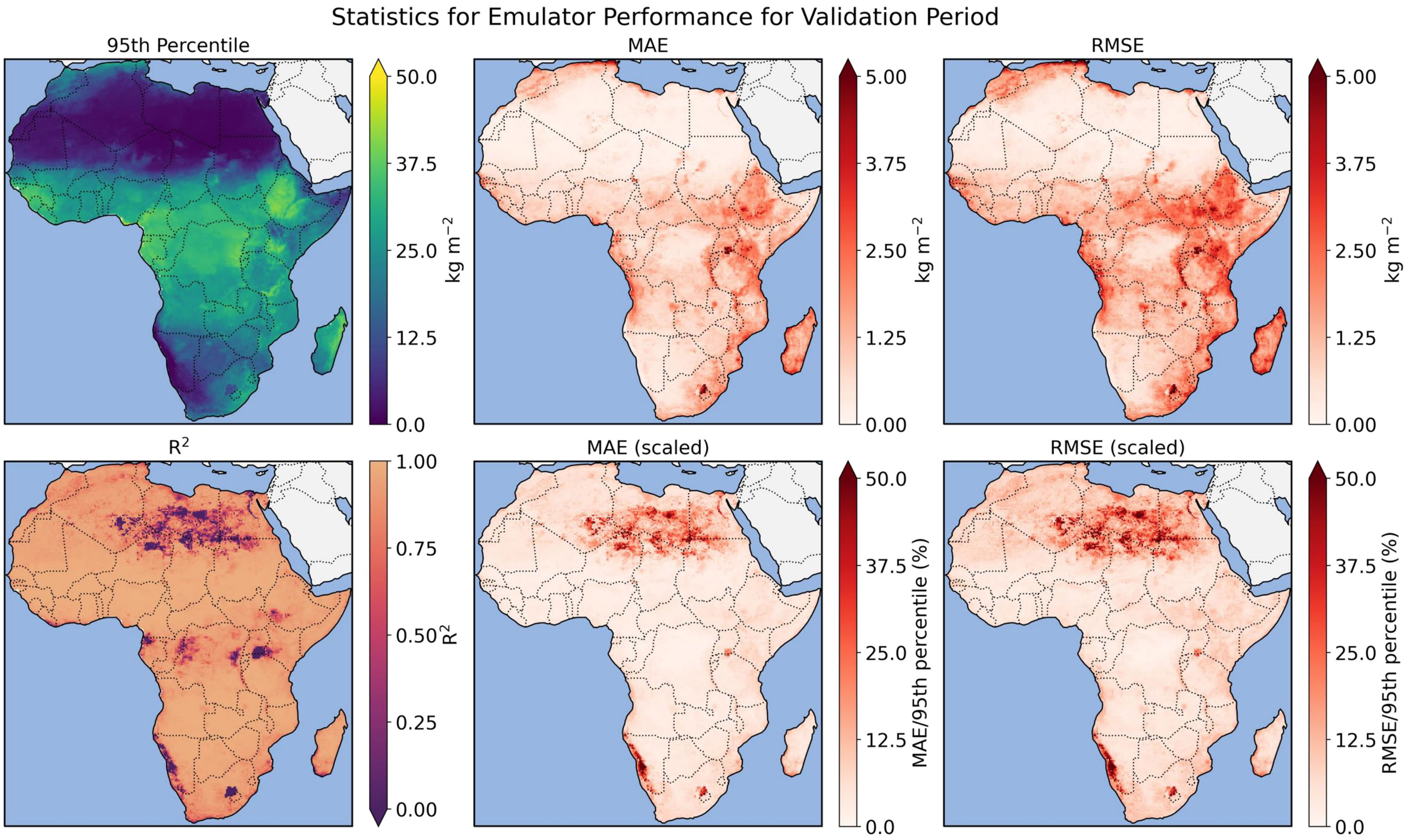
Statistics for Emulator Performance for Validation Period
95th Percentile
50.0
37.5
25.0
12.5
0.0
kg m⁻²
MAE
5.00
3.75
2.50
1.25
0.00
kg m⁻²
RMSE
5.00
3.75
2.50
1.25
0.00
kg m⁻²
R2
1.00
0.75
0.50
0.25
0.00
R2
MAE (scaled)
50.0
37.5
25.0
12.5
0.0
MAE/95th percentile (%)
RMSE (scaled)
50.0
37.5
25.0
12.5
0.0
RMSE/95th percentile (%)

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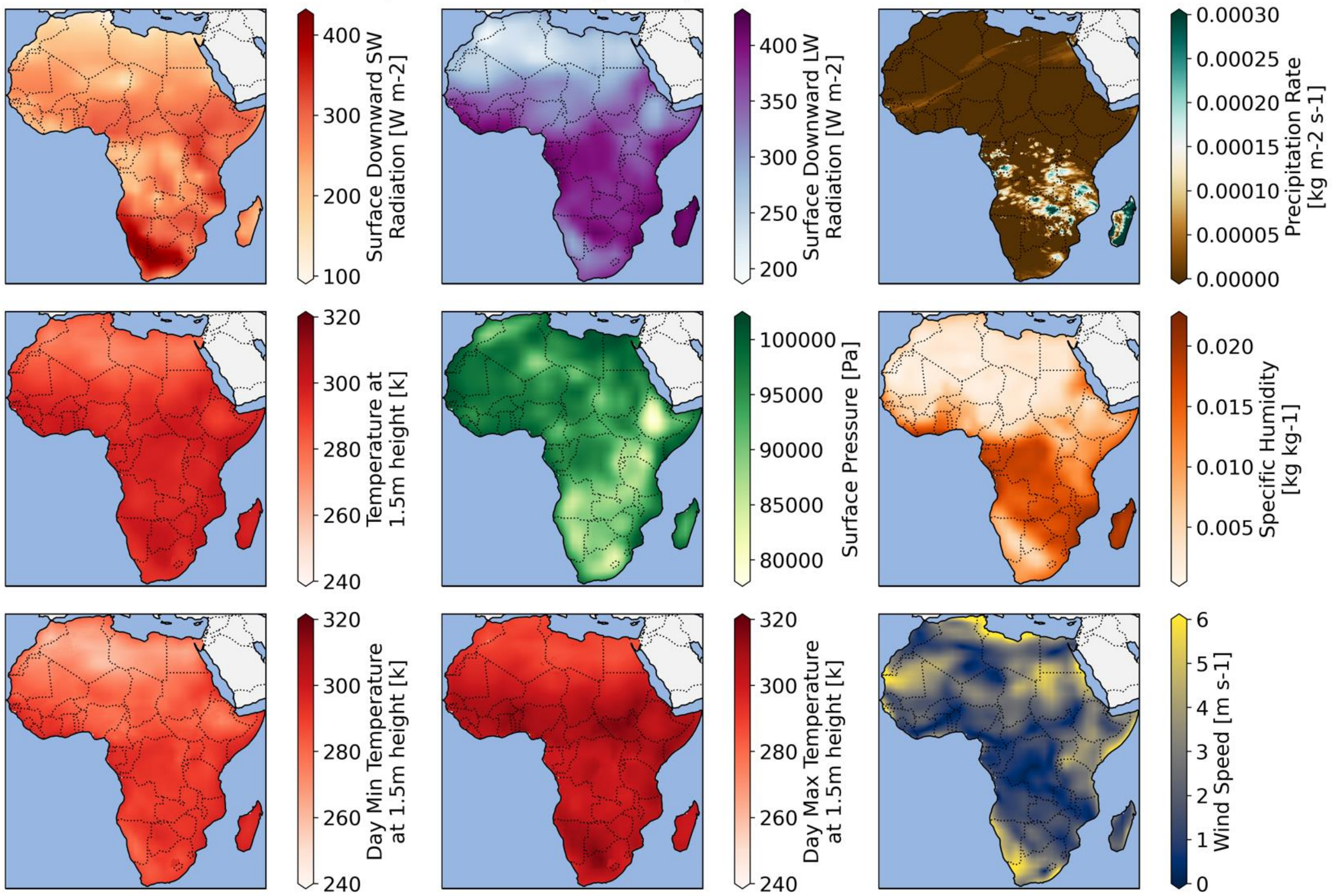
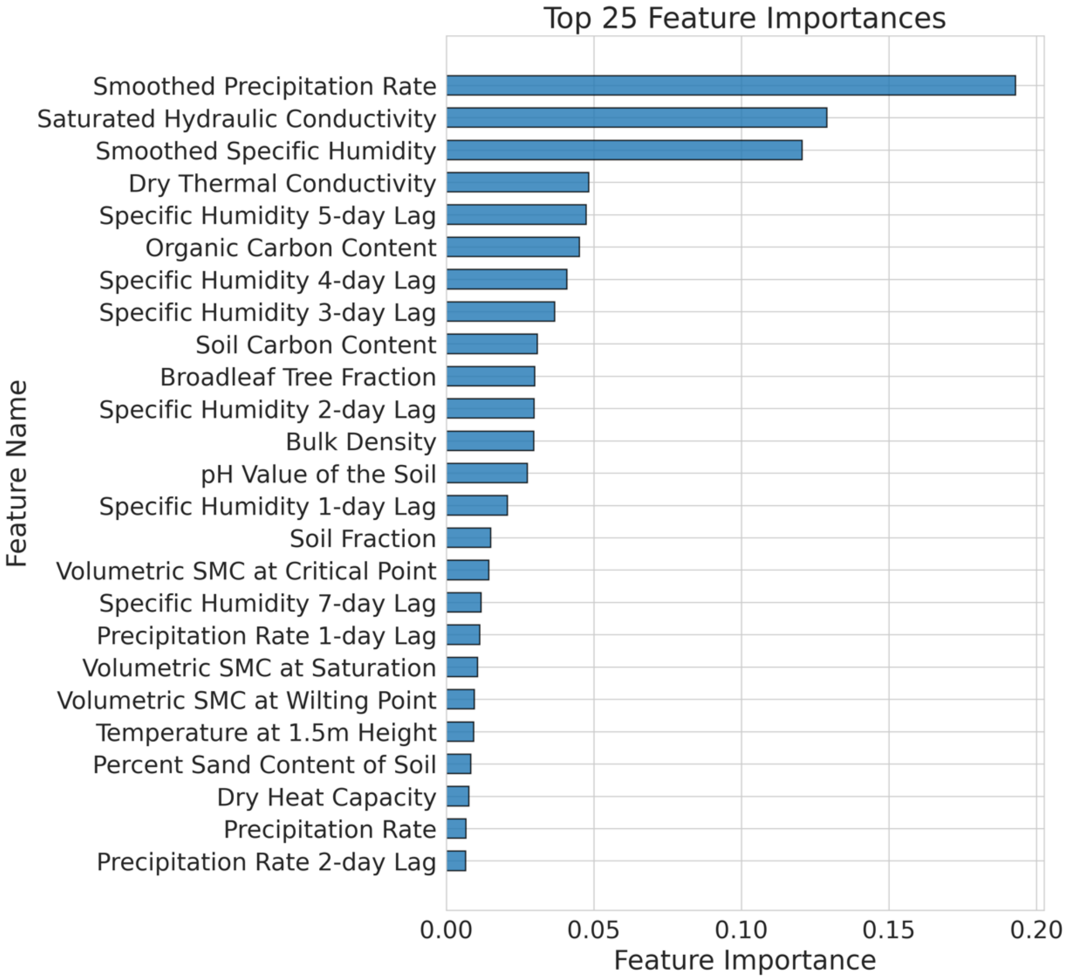
Explainability and Feature Importance





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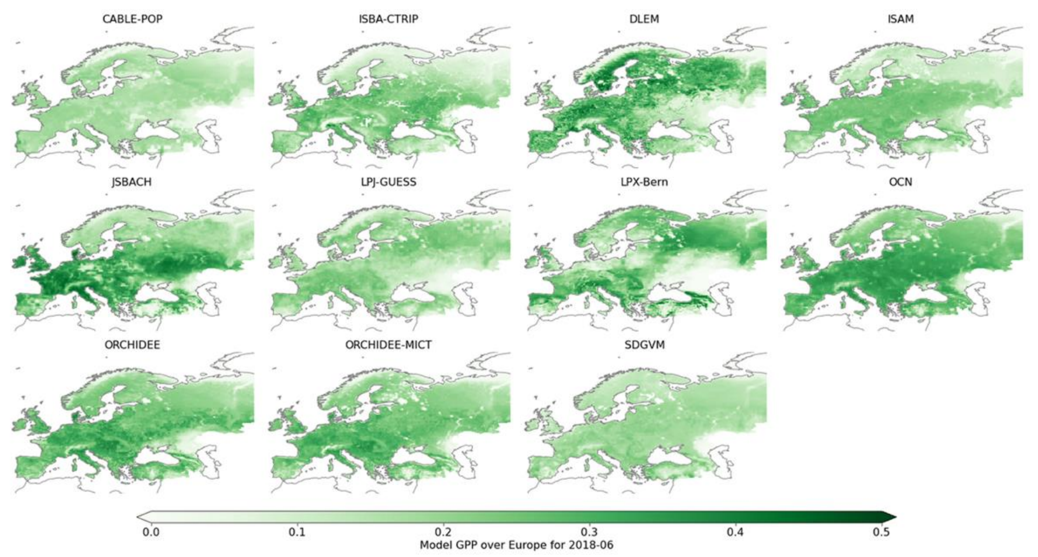
ESA IMITATE (Carbon Cycle)

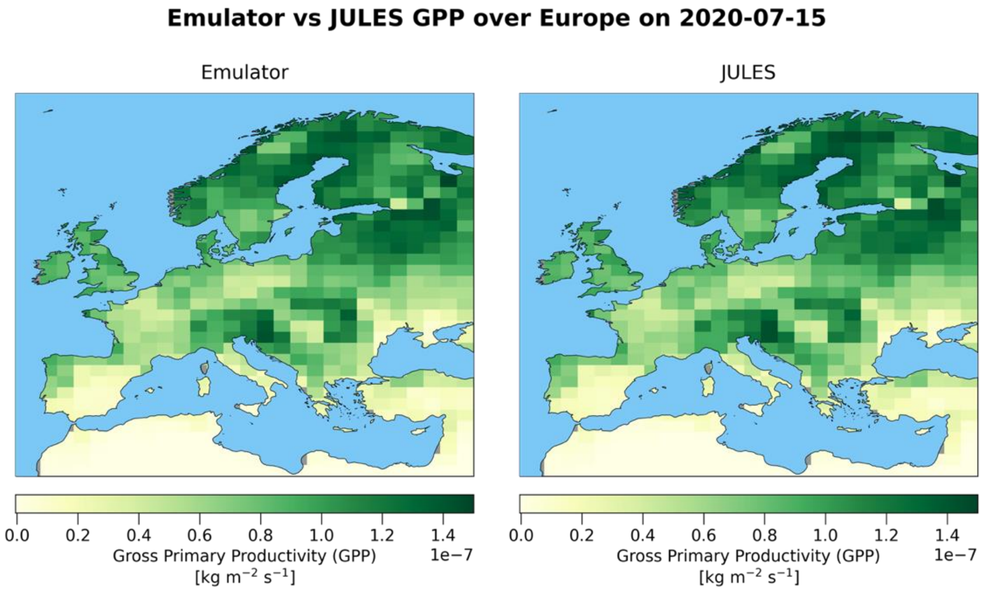
The carbon cycle over Europe is still **highly** uncertain and neither observations nor models alone are capable of addressing these issues.



We are developing machine-learning model **emulators** to replicate simulations from complex land surface model.

Emulators allow greater **understanding** of the model behaviour and let us explore the different relationships between the drivers and carbon fluxes.

We can then use emulator **with** Earth Observation data to derive **new** datasets that are explicitly tied to observations and can make use of their uncertainties.



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JULES Data

All GPP-related inputs

- Gridbox emulator
- Per-PFT emulator

Features used in emulator training:

- Minimum Temperature
- Maximum Temperature
- Soil moisture (**all layers**)
- Soil Moisture Availability Factor
- FAPAR
- SW Downwelling Radiation

1) Can we emulate JULES GPP using all available (relevant) JULES variables?

Observable inputs

- Per-PFT emulator

Features used in emulator training:

- Minimum Temperature
- Maximum Temperature
- Soil moisture (**top layer**)
- Diffuse VIS albedo
- Diffuse NIR albedo

2) Can we emulate JULES GPP using only JULES variables that have an EO equivalent?

EO Data

EO inputs

- Per-PFT emulator

Features used in emulator training:

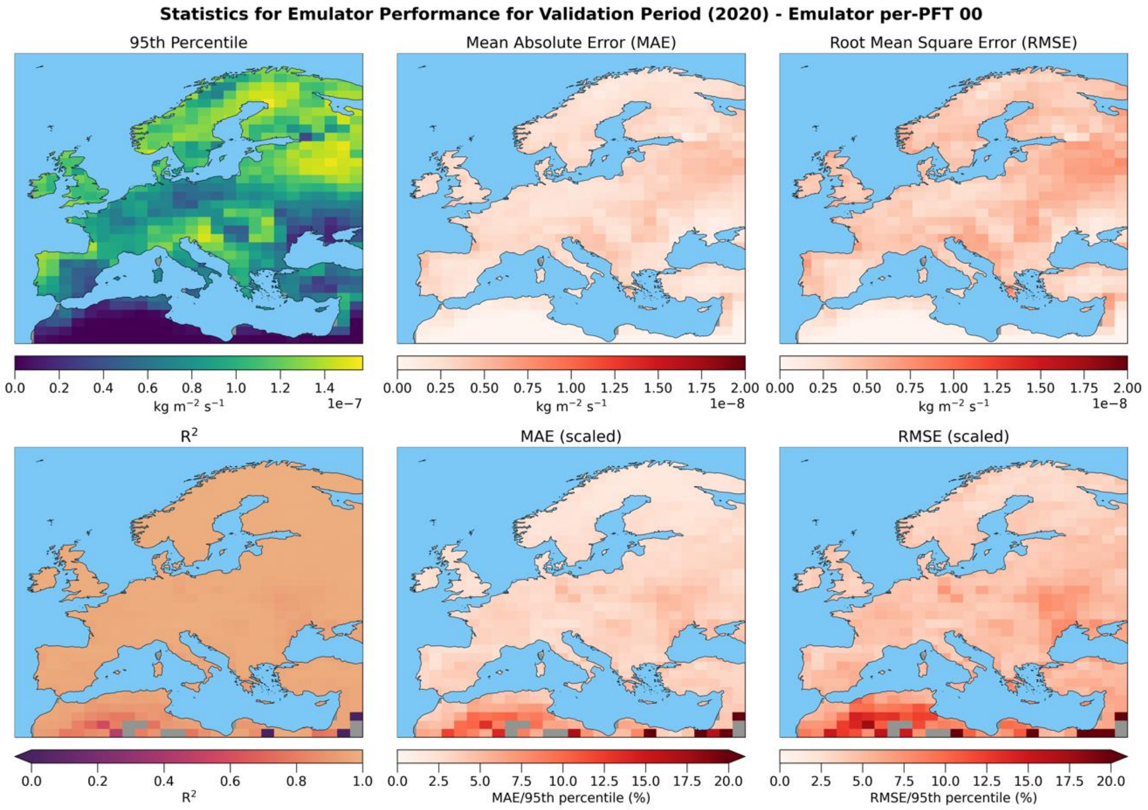
- Minimum LST
- Maximum LST
- Soil moisture (surface)
- White-sky VIS albedo
- White-sky NIR albedo

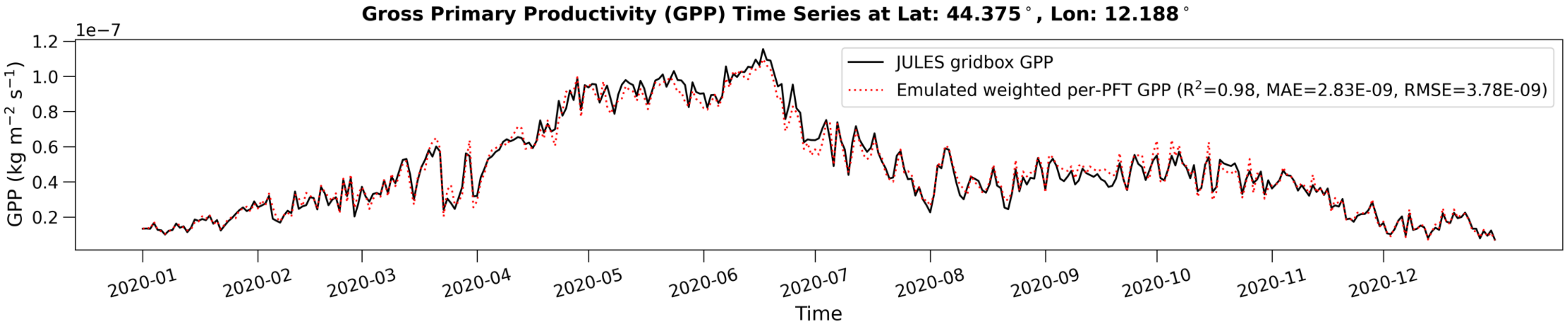
3) Can we use the EO data directly to produce an EO-based GPP data product constrained by JULES process representation?

1) Can we emulate JULES GPP using all available (relevant) JULES variables?

Features

- Minimum Temperature
- Maximum Temperature
- Soil moisture (**all layers**)
- Soil Moisture Availability Factor
- FAPAR
- SW Downwelling Radiation





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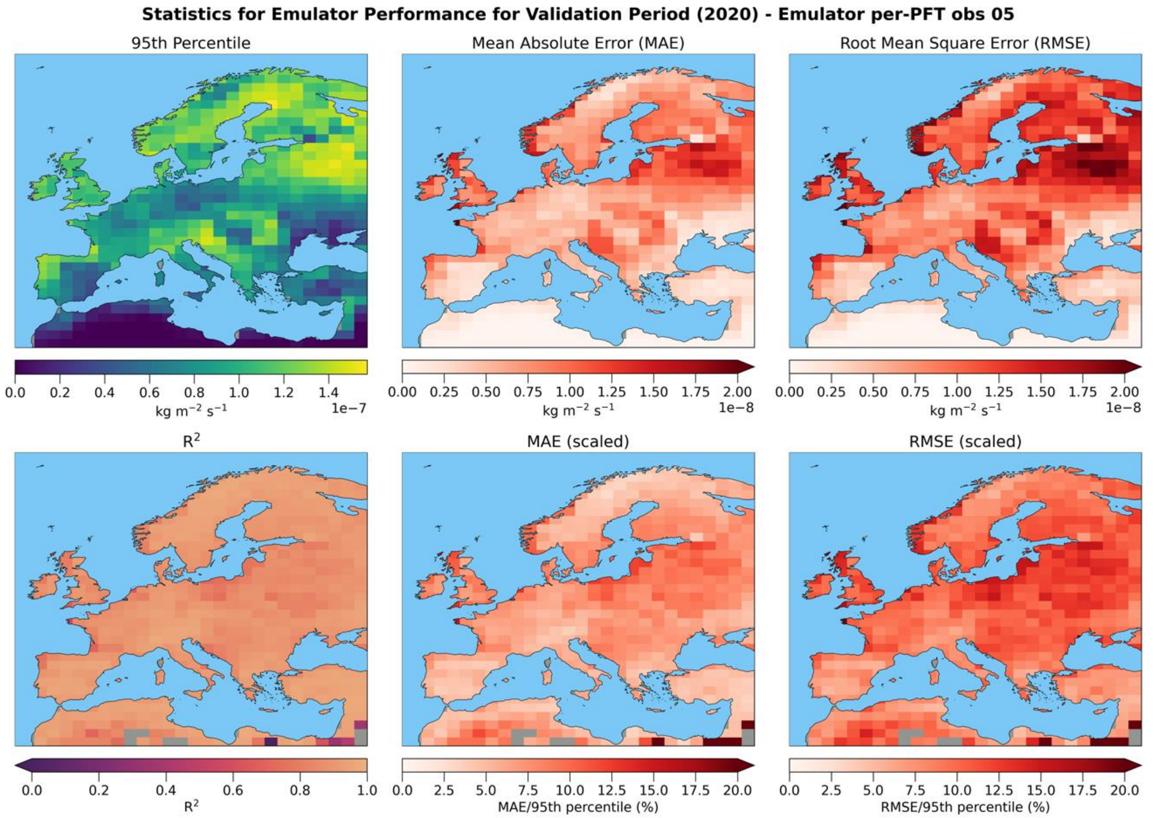
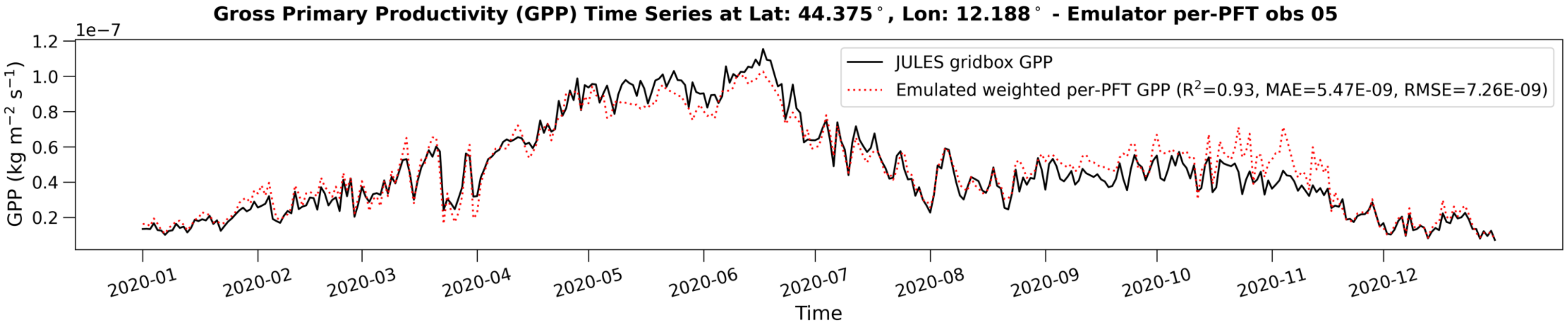
work in progress

2) Can we emulate JULES GPP using only JULES variables that have an EO equivalent?

Features

- Minimum Temperature
- Maximum Temperature
- Soil moisture (**top layer**)
- Diffuse VIS albedo
- Diffuse NIR albedo
- Soil Moisture Availability Factor





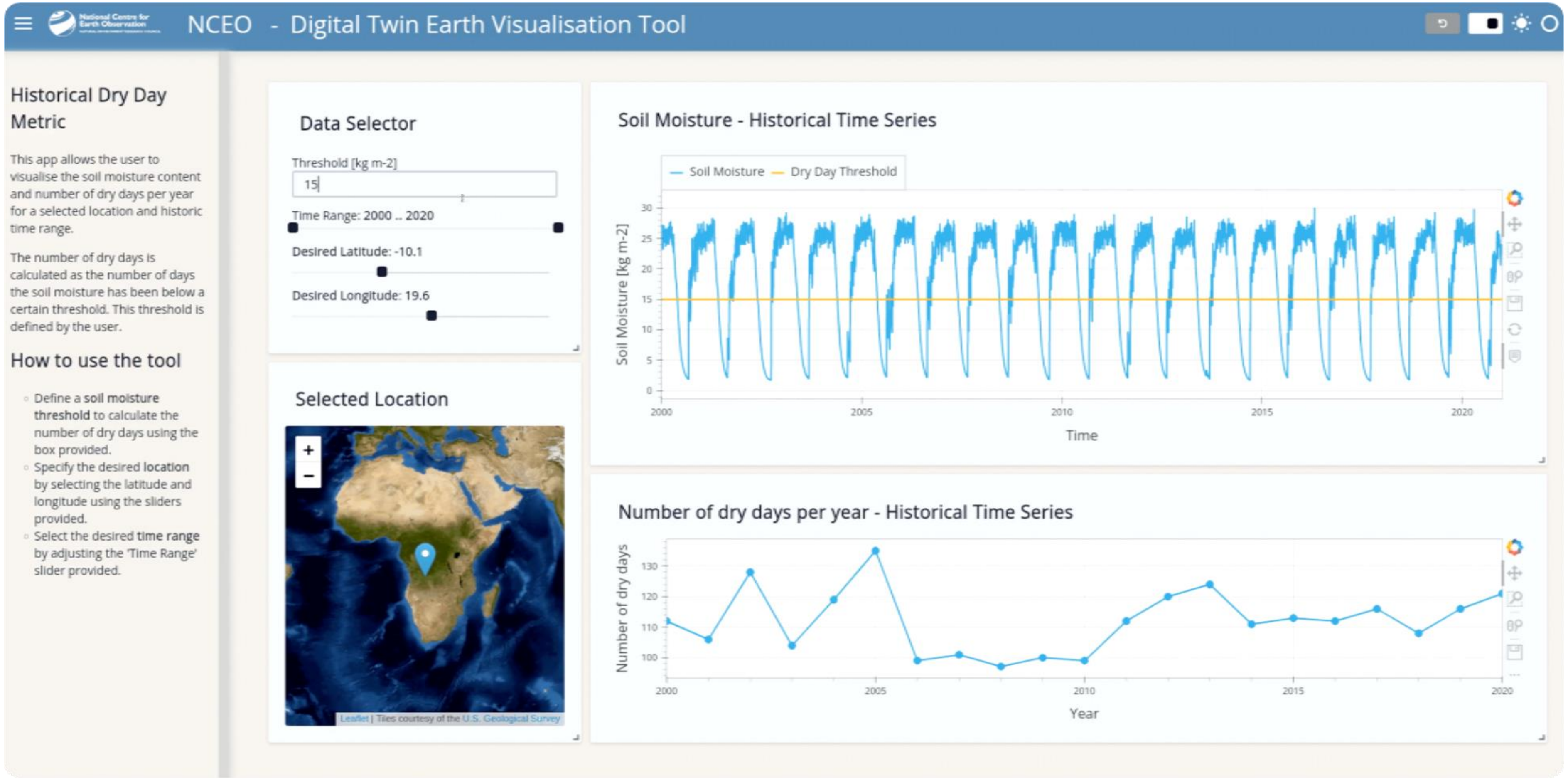
Summary and Conclusions

- We've successfully developed machine-learning based emulators for several different JULES applications (drought and GPP)
- These emulators are (very!) fast, easy to use, etc and open up a range of applications and potentially interesting science
- We're very interested in emulating other bits of JULES
  - Working with UKCEH/MO about a proof-of-concept for JULES-Inferno fires
  - Working with UKCEH/MO on methane emissions and wetland inundation
- If there are JULES simulations where we can easily map the inputs to the output, we can probably build an emulator for it
  - Much more work to do: deploying applications, Explainable AI, model-data fusion by driving with EO data, uncertainty propagation, extending beyond JULES to other land surface models, etc

Extra Slides

NERC Digital Twin Case Study

- In the ESA DTEP project we developed a ML-based emulator for JULES soil moisture over Africa
- This project builds on that and further develops interactive tools for stakeholder engagement
- NCEO (Leicester, Reading, CEDA) with Met Office and STFC-RAL as project partners



next steps

3) Can we use the EO data directly to produce an EO-based GPP data product constrained by JULES process representation?

	Soil Moisture	Land Surface Temperature	Albedo	Land Cover
Product	ESA CCI soil moisture v6.1 COMBINED	ESA CCI LST 3-hourly	MODIS MCD43C3 CMG Albedo	ESA CCI Global Land Cover Maps v2.0.7
JASMIN path	`/neodc/esacci/soil_moisture/data/daily_files/COMBINED/v06.1`	`/neodc/esacci/land_surface_temperature/data/MULTISENSOR_IRMGP/L3S/0.05/v1.00/daily`	N/A https://ladsweb.modaps.eosdis.nasa.gov/archive/allData/61/MCD43C3/	`/neodc/esacci/land_cover/data/land_cover_maps/v2.0.7`
Units	[m^3 m^{-3}]	[K]	[-]	[-]
Time range	1978-11-01 to 2020-12-31	2009-2020	2000-2022	1992 - 2015
Spatial resolution	0.25 degrees	0.05 degrees	0.05 degrees	300 metres