CopERnIcus climate change Service Evolution

D6.2 Report providing feedback on the impact of time varying vegetation in reanalysis on seasonal forecasts

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1 Executive Summary

This deliverable assesses the impact of interannually varying vegetation on summer seasonal forecasts in the ECMWF and MetO systems. The results show that while vegetation anomalies produce physically consistent and regionally coherent signals in temperature and soil moisture, their influence on forecast skill is modest and not statistically significant in either system. MetO displays stronger hydrological and thermodynamic sensitivity to vegetation perturbations than ECMWF, but these responses do not translate into robust improvements in predictive performance. Experiments with the ECMWF system in which the initial LAI anomaly is persisted into the forecasts, show more coherent and locally significant changes in long-term mean surface temperature biases, but still do not yield meaningful gains in predictive performance. Overall, time-varying vegetation information influences regional climatology but does not yet provide operationally significant improvements, underscoring the need for more accurate land-surface coupling and improved vegetation representation in future C3S seasonal prediction systems.

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2 Introduction

Advancing the representation of time-varying vegetation in both land reanalyses and coupled forecast systems is central to improving subseasonal-to-seasonal prediction skill. Building directly on the harmonised LAI and LULC datasets generated in CONFESS, the CERISE project has extended this foundation by incorporating temporally evolving vegetation information into the new ECMWF Offline Land Data Assimilation System (LDAS) and evaluating its influence on subsequent seasonal forecasts. Current operational systems typically rely on static or climatological vegetation fields, which limits their ability to capture vegetation-driven land - atmosphere feedback that affect soil moisture, surface fluxes and near-surface meteorology. In this deliverable, we assess this gap through a coordinated set of offline LDAS experiments and seasonal reforecasts, designed to isolate the effects of realistic, time-varying vegetation in the reanalysis and its propagation into the forecast system. This final phase of CERISE has enabled a systematic evaluation of the resulting changes in land-surface states, biases and skill, providing a robust evidence base for the potential implementation of time-varying vegetation in future generations of C3S seasonal prediction systems.

2.1 Background

The scope of CERISE is to enhance the quality of the C3S reanalysis and seasonal forecast portfolio, with a focus on land-atmosphere coupling.

It will support the evolution of C3S, over the project's 4-year timescale and beyond, by improving the C3S climate reanalysis and the seasonal prediction systems and products towards enhanced integrity and coherence of the C3S Earth system Essential Climate Variables.

CERISE will develop new and innovative ensemble-based coupled land-atmosphere data assimilation approaches and land surface initialisation techniques to pave the way for the next generations of the C3S reanalysis and seasonal prediction systems.

These developments will be combined with innovative work on observation operator developments integrating Artificial Intelligence (AI) to ensure optimal data fusion fully integrated in coupled assimilation systems. They will drastically enhance the exploitation of past, current, and future Earth system observations over land surfaces, including from the Copernicus Sentinels and from the European Space Agency (ESA) Earth Explorer missions, moving towards an all-sky and all-surface approach. For example, land observations can simultaneously improve the representation and prediction of land and atmosphere and provide additional benefits through the coupling feedback mechanisms. Using an ensemble-based approach will improve uncertainty estimates over land and lowest atmospheric levels.

By improving coupled land-atmosphere assimilation methods, land surface evolution, and satellite data exploitation, R&I inputs from CERISE will improve the representation of long-term trends and regional extremes in the C3S reanalysis and seasonal prediction systems.

In addition, CERISE will provide the proof of concept to demonstrate the feasibility of the integration of the developed approaches in the core C3S (operational Service), with the delivery of reanalysis prototype datasets (demonstrated in pre-operational environment), and seasonal prediction demonstrator datasets (demonstrated in relevant environment).

CERISE will improve the quality and consistency of the C3S reanalysis systems and of the components of the seasonal prediction multi-system, directly addressing the evolving user needs for improved and more consistent C3S Earth system products.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

This deliverable describes an assessment of the impact of time-varying vegetation in land data assimilation on summer temperature, soil moisture, and predictive skill in ECMWF and MetO seasonal reforecasts, providing a direct comparison of each system's sensitivity to vegetation-driven land-surface anomalies.

2.2.2 Work performed in this deliverable

In this deliverable the work outlined in The Description of Action (WP6 T6.2)

2.2.3 Deviations and counter measures

No deviations have been encountered.

2.2.4 Reference Documents

[1] Project 101082139- CERISE-HORIZON-CL4-2021-SPACE-01 Grant Agreement

2.2.5 CERISE Project Partners:

ECMWF	European Centre for Medium-Range Weather Forecasts
Met Norway	Norwegian Meteorological Institute
SMHI	Swedish Meteorological and Hydrological Institute
MF	Météo-France
DWD	Deutscher Wetterdienst
CMCC	Euro-Mediterranean Center on Climate Change
BSC	Barcelona Supercomputing Centre
DMI	Danish Meteorological Institute
Estellus	Estellus
IPMA	Portuguese Institute for Sea and Atmosphere
NILU	Norwegian Institute for Air Research
MetO	Met Office

3 Land surface initialisation and vegetation forcing

The land surface is initialised using the ECMWF Offline Land Data Assimilation System (LDAS). In its new offline configuration, the ecLand land-surface model is forced by meteorological fields from ERA5 (Hersbach et al, 2020), while observations are assimilated exclusively into land variables. This setup enables a consistent and cost-effective production of land reanalyses for targeted scientific experiments. Further details on recent developments to the ECMWF LDAS are provided in CERISE Deliverable D1.2 and D4.1.

Two dedicated LDAS experiments were used for initialization, both employing the harmonized Leaf Area Index (LAI) and Land Use/Land Cover (LULC) datasets developed in the H2020 CONFESS project (Bousetta and Balsamo, 2021) as boundary conditions. In LDAS_CTL, a 10-year (2010-2019) seasonally varying climatology of LAI is used. LULC is prescribed as a static field which provides spatial distribution of vegetation types, bare soil, crops, urban surfaces, lakes, and other land categories. In contrast, LDAS_VAR used seasonally and interannually varying LAI together with interannually varying LULC.

4 Seasonal reforecast configuration and methodology

4.1 ECMWF

The numerical experiments described in this deliverable consist of a set of 4-month long atmosphere-only seasonal reforecasts for the period 2000-2019, initialised on the 1st of May with an ensemble size of 25 members. The experiments were run with CY49R2b of the Integrated Forecasting System which is currently being finalised for use in ECMWFs next generation seasonal forecasting system SEAS6.
Three sets of reforecasts were performed:

- **CONTROL**: LAI and LULC in the initial condition and for the duration of the forecast are prescribed using the same CONFESS-based forcing as used in LDAS_CTL.
- **LAI_IC**: Same as CONTROL, but with LAI and LULC in the initial condition prescribed using the same CONFESS-based time varying LAI/LULC forcing as used in LDAS_VAR.
- **PERST_LAI**: Same as CONTROL, but with the LAI in the initial condition as in LAI_IC. The LAI anomaly is then persisted into the forecast using a space-time dependent lag-1 autocorrelation decay. LULC varies interannually as in LDAS_VAR.

4.2 MetO

Similar to ECMWF, the MetO numerical experiments consist of a set of 4-month long seasonal reforecasts for the period 2000-2019, initialised on the 1st of May, but with an ensemble size of 20 members. The experiments were run with GloSea6-GC3.2, the same seasonal forecast system as currently used for Met Office seasonal forecasts differing only in the land surface initial conditions.

Two sets of reforecasts were performed:

- **CONTROL**: Initialised from LDAS_CTL
- **LAI_IC**: Initialised from LDAS_VAR

In both sets, LAI is allowed to vary during runtime using the standard GloSea6 LAI monthly climatological dataset. Unlike in the ECMWF experiments, there is no attempt to modify this climatology to be consistent with the climatology of the analysis. Nevertheless, differences between LAI_IC and CONTROL are purely a result of the differences in the analysis supplying the initial conditions in each case. This ensures that the ECMWF and MetO experiments are comparable.

5 Results

5.1 Impact of time-varying vegetation initialization in ECMWF and MetO reforecasts

Here we present a comparative assessment of the ECMWF and MetO reforecasts to examine the influence of time-varying vegetation initialisation (LAI_IC) on summer near-surface temperature prediction skill, as well as long-term mean and trend biases in near-surface temperature and soil moisture.

5.1.1 Prediction skill

Figure 1 shows the anomaly correlation coefficient (ACC) differences for June-to-August 2-metre temperature between experiments initialised with time-varying land surface conditions (LDAS_VAR) and those using climatological vegetation (LDAS_CTL), for both ECMWF (Figure 1a) and MetO (Figure 1b) reforecasts. Positive values indicate regions where the inclusion of interannual variability in LAI and LULC improves ACC relative to the control. Both systems exhibit coherent regional responses, with improvements over key land–atmosphere coupling hotspots - such as the central United States, northern Africa, eastern Australia, and parts of northern Eurasia. The two systems exhibit some similar continental-scale patterns, but some notable differences, including over western North America and southern South America. However, these ACC differences are not widely statistically significant, and therefore the spatial patterns should be interpreted as indicative sensitivities rather than robust skill changes. This difficulty in identifying statistically robust changes in ACC skill relates to the more stringent requirements for data (ensemble size and length) for identifying changes in ACC compared to other metrics.

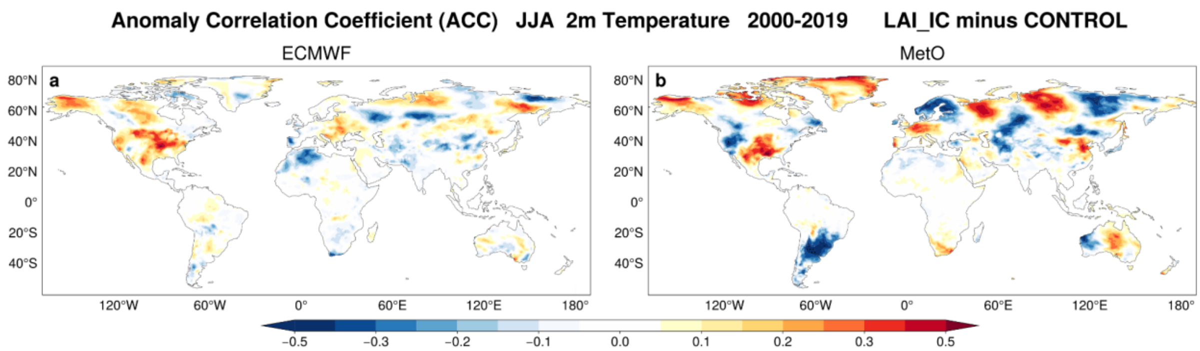

Figure 1: Anomaly Correlation Coefficient (ACC) for June-to-August seasonal mean 2-metre temperature, evaluated against ERA5 in (a) ECMWF and (b) MetO seasonal reforecasts, plotted as difference between LAI_IC and CONTROL. Hashed regions are statistically significant at 95%.

5.1.2 Mean state biases

Figure 2 shows the June-to-August long-term mean 2-metre temperature bias differences between the LAI_IC and CONTROL experiments and the corresponding relative bias changes for ECMWF and MetO over 2000-2019, evaluated against ERA5.

In the ECMWF reforecasts, the bias differences show identifiable warming tendencies over some parts of North America, Scandinavia, Central Asia, eastern Eurasia and southern Africa and cooling tendencies over parts of southern Europe, North America, and Australia. Although these signals are not statistically significant, the model does appear to respond coherently with soil moisture changes (see below). Since the source of these soil moisture changes is linked to changes in initial soil moisture resulting from the inclusion of vegetation in the analysis, it can be said that there is a sensitivity of temperatures to vegetation. The relative bias changes, which locally approach ±20%, indicate that vegetation initialisation can exert a sizeable and physically consistent influence on the temperature mean state in regions where land-atmosphere coupling is strong.

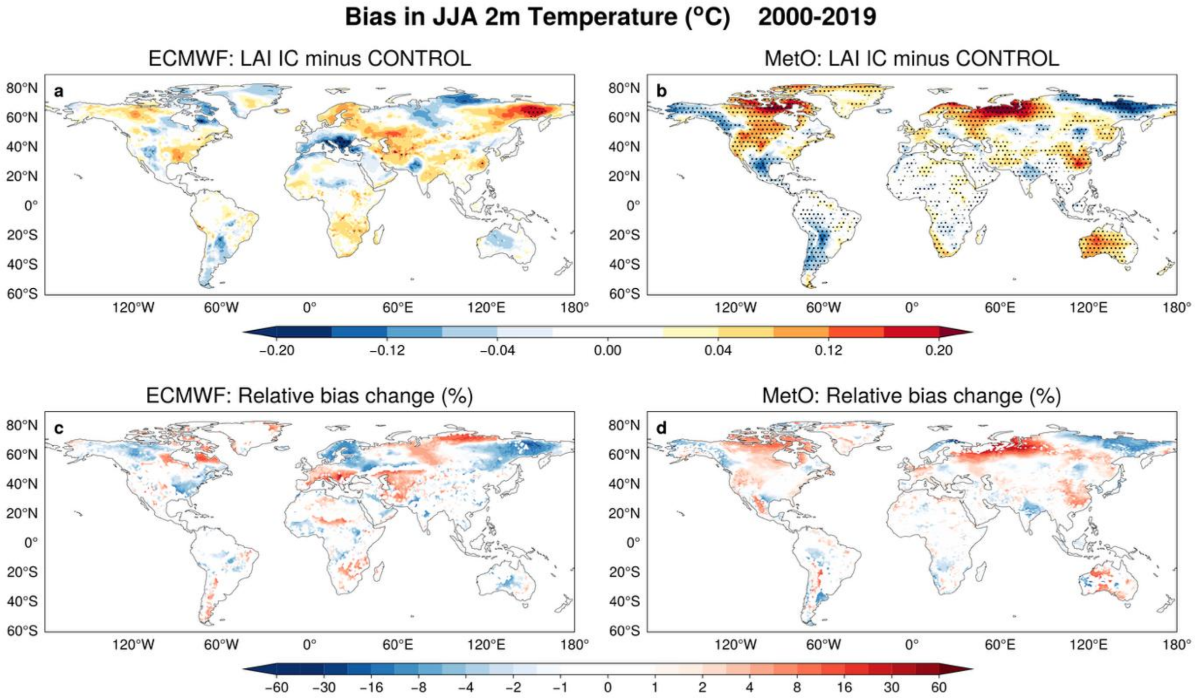

Figure 2: June-to-August seasonal mean 2-metre temperature long-term mean bias (°C) relative to ERA5 in (a) ECMWF and (b) MetO seasonal reforecasts, plotted as difference between LAI_IC and CONTROL. Also plotted in (c) and (d) are the corresponding relative change in bias (%). Hashed regions in (a) and (b) are statistically significant at 95%.

In MetO, vegetation initialisation leads to significant warming differences in LAI_IC relative to CONTROL across large parts of North America, high-latitude Eurasia, Australia and China and southern Africa. Cooling responses are present over the Alaskan region, central America, parts of South America and eastern high-latitude Eurasia - but are generally somewhat smaller in spatial extent. This implies an asymmetry opposite to that described previously: LAI_IC tends to amplify existing warm biases more robustly than it reduces them, indicating a strong but not uniformly beneficial sensitivity of the MetO system to LAI variability. The relative bias changes (up to ±30-60% locally) confirm substantial increases in warm bias over high-latitude land regions, while pockets of bias reduction are more localised. Compared with ECMWF, these patterns still point to a stronger overall sensitivity to vegetation initialisation in MetO, but one that often degrades rather than improves the JJA temperature climatology.

Figure 3 shows the June-to-August long-term mean bias in top 1 metre soil moisture (kg m^{-2}) for ECMWF and MetO, expressed as the difference between the LAI_IC and CONTROL, together with the corresponding relative bias change, evaluated against the GLEAM v3.8a dataset (Martens et al, 2017). Both systems display spatially coherent responses to vegetation initialisation, with greater correspondence between the systems than for temperature biases, but with distinct differences in amplitude and statistical robustness.

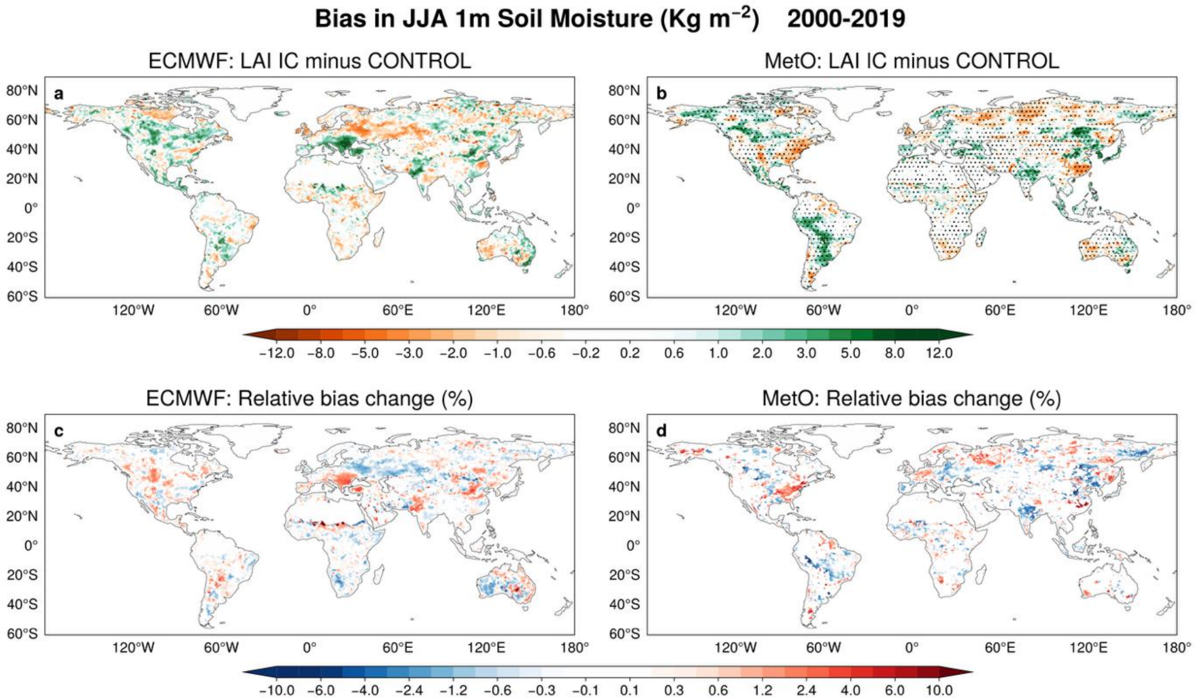

Figure 3: Same as Figure 2, but for top 1m Soil Moisture relative to GLEAM.

ECMWF exhibits weak but geographically organised wetting and drying signals—for example wetting over the central US, parts of South America, southeastern Europe and central Sahel, and drying across parts of central eastern Europe and central Asia. However, the magnitude of these changes is small (typically ±2-4 kg m^{-2}), relative bias changes remain below ±5-10%, and very few areas reach statistical significance. There is reduction in bias over central eastern Europe and central Asia, but degradation over southeastern Europe. The overall response is therefore physically consistent but not robust, in line with the weak and non-significant temperature-bias and ACC impacts seen in ECMWF reforecasts.

In MetO, the soil-moisture response to LAI_IC is more statistically significant than in ECMWF but typically of similar magnitude. MetO exhibits wetting anomalies, particularly across parts of North and South America, northeastern Eurasia, China and parts of India, many of which are statistically significant. Drying is seen in eastern North America, southern China and Siberia. In terms of bias changes, regions with drying tend to further degrade in the MetO system, whereas those with wetting show a relative improvement. Thus, the relative bias fields confirm that vegetation initialisation modulates soil moisture in MetO. There is, however, greater effect of these changes on temperature in regions of drying, with larger increases in biases.

5.1.3 Long-term trends

The difference in long-term trends in JJA 2-metre temperature between LAI_IC and CONTROL is shown in Figure 4. In ECMWF, the responses are generally moderate in amplitude but spatially coherent and statistically significant. These include a pronounced warming–cooling dipole over North America, significant cooling-trend differences over parts of South America and warming-trend differences in eastern Eurasia. The relative trend-bias changes (Figure 4c) are largely indicative of reduced trend biases, demonstrating that vegetation initialisation can meaningfully perturb regional trend characteristics in ECMWF, even if the impacts do not translate into statistically significant improvements in ACC or mean-state temperature bias.

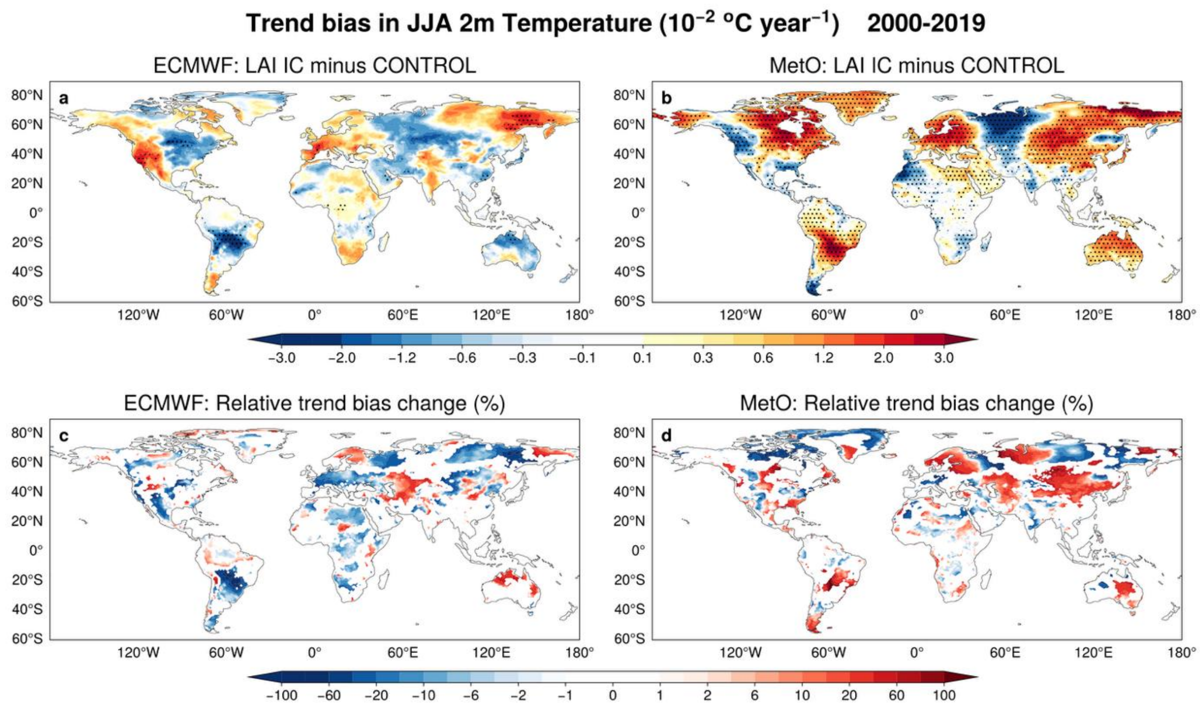

Figure 4: June-to-August seasonal mean 2-metre temperature trend bias (10^{-2} °C $year^{-1}$) relative to ERA5 in (a) ECMWF and (b) MetO seasonal reforecasts, plotted as difference between LAI_IC and CONTROL. Also plotted in (c) and (d) are the corresponding relative change in trend bias (%). Hashed regions in (a) and (b) are statistically significant at 95%.

In MetO, the trend-bias differences appear stronger, more extensive, and more robust, with clear warming-trend increases across parts of North and South America, northern Europe, eastern Eurasia and Australia, and cooling-trend over western North America, central Siberia and parts of Africa. It is notable that similar regions of coherent differences appear in the results of each system, albeit often with the opposite sign of change. Most of these differences are significant. Despite these stronger responses, the change in temperature trend bias is not as positive in the MetO system (Figure 4d) as in the ECMWF system.

The difference in JJA top 1m soil-moisture long-term trends between LAI_IC and CONTROL is shown in Figure 5. The responses are moderate but spatially coherent in ECMWF, with regions of wetting- and drying-trend differences including parts of North America and central South America as well as a band across Asia. Relative changes remain small - typically within ±5% but more negative (improvement) overall. The presence of statistically significant regional structures indicates that interannual vegetation initialisation can influence the long-term soil-moisture trajectory in ECMWF.

In MetO, vegetation initialisation produces stronger trend-bias adjustments, with wetting-trend differences across northwestern North America and parts of northern Eurasia, and drying-trend differences across eastern Eurasia, China and parts of Scandinavia. Again, the drying- and wetting-trend signals are generally significant. Nevertheless, despite their larger size, the fractional change in trend is very small in the MetO simulations, suggesting the existence of larger pre-existing trend errors than in ECMWF.

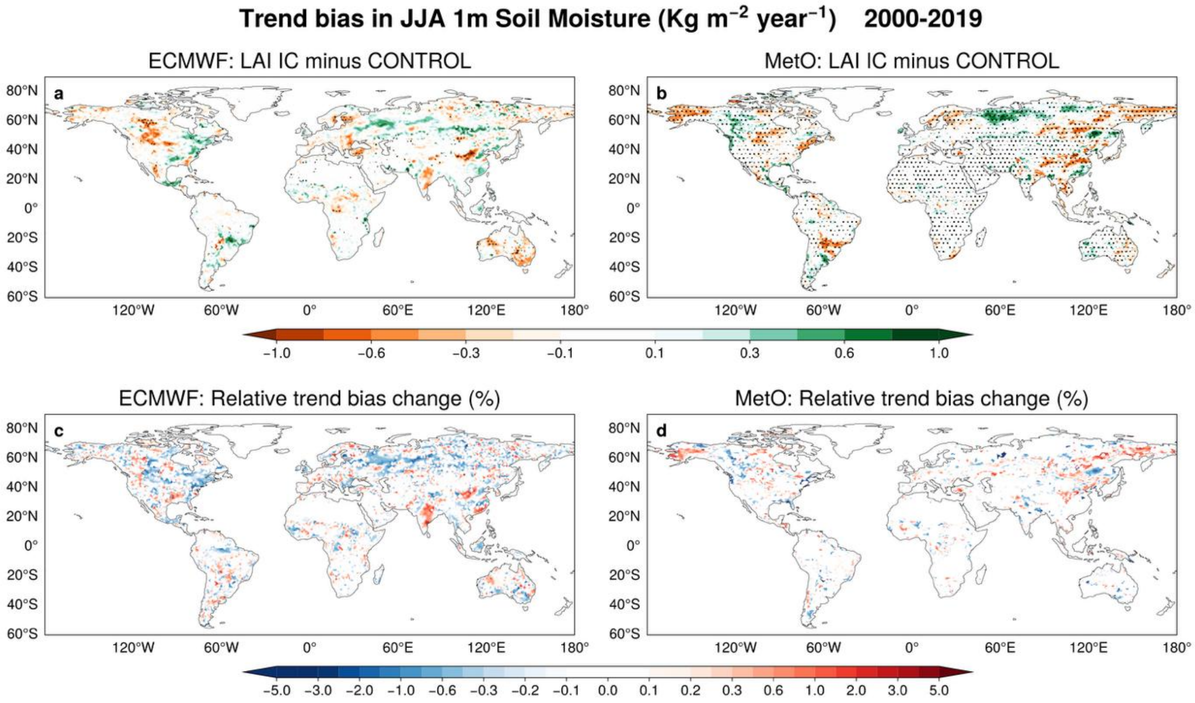

Figure 5: Same as Figure 4, but for top 1m Soil Moisture relative to GLEAM.

5.2 Impact of persistence of LAI initial condition in ECMWF reforecasts

Persisting the LAI anomaly is valuable in an operational forecast context because vegetation anomalies influence surface fluxes and soil-moisture evolution over several weeks - timescales that are not captured when LAI simply follows a seasonally varying climatology, as in CONTROL, or when the anomaly is applied only at initialisation, as in LAI_IC. Carrying the anomaly forward in time preserves realistic vegetation information during the early forecast period, when land-atmosphere coupling is strongest. This provides a more physically consistent representation of vegetation conditions and avoids the rapid loss of anomaly information inherent in single-step initialisation approaches.

5.2.1 Prediction skill

Unlike LAI_IC, which applies the LAI anomaly only at initialisation, the PERST_LAI experiments persist the anomaly forward in time using a space-time dependent lag-1 autocorrelation decay, allowing vegetation anomalies to influence the land surface during the early forecast period. The resulting ACC difference patterns are similar to those from LAI_IC (Figures 1a and 6a) in some locations (although different in others), but show slightly larger and more spatially coherent responses, with modest skill improvements over western North America, central Asia, and high-latitude Eurasia, and degradation over the southern parts of North America and south-central Europe. These enhancements reflect the extended influence of LAI anomalies on land-atmosphere coupling relative to the perturbation in LAI_IC transmitted through the other land surface variables. However, none of the PERST_LAI differences are statistically significant, reinforcing the conclusion that time-varying vegetation exerts only a subtle influence on summer temperature predictability in the ECMWF system.

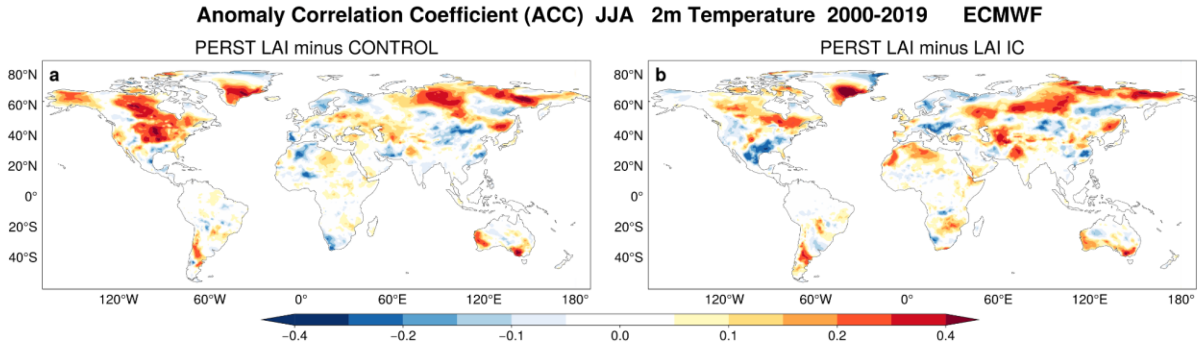

Figure 6: Anomaly Correlation Coefficient (ACC) for June-to-August seasonal mean 2-metre temperature in ECMWF seasonal reforecasts initialised from LDAS_VAR with persistence of LAI (PERST_LAI see 2.1) plotted as difference against (a) CONTROL and (b) LAI IC.

5.2.2 Mean state biases

The long-term mean JJA temperature biases indicate that persisting LAI anomalies produces more coherent and spatially extensive and significant bias responses than LAI_IC (Figures 7a and 2a). PERST_LAI reduces the excessive cold bias across the mid-to-high latitudes including Alaska, Scandinavia, parts of northern Eurasia and Canada (Figure 7c). Relative to LAI_IC (Figure 7b), the spatial patterns are amplified and more internally consistent, indicating that extending the influence of LAI anomalies into the early forecast period strengthens the vegetation signal and its impact on surface temperature and demonstrates that LAI anomaly persistence can produce detectable and regionally meaningful changes in ECMWF's climatological temperature biases.

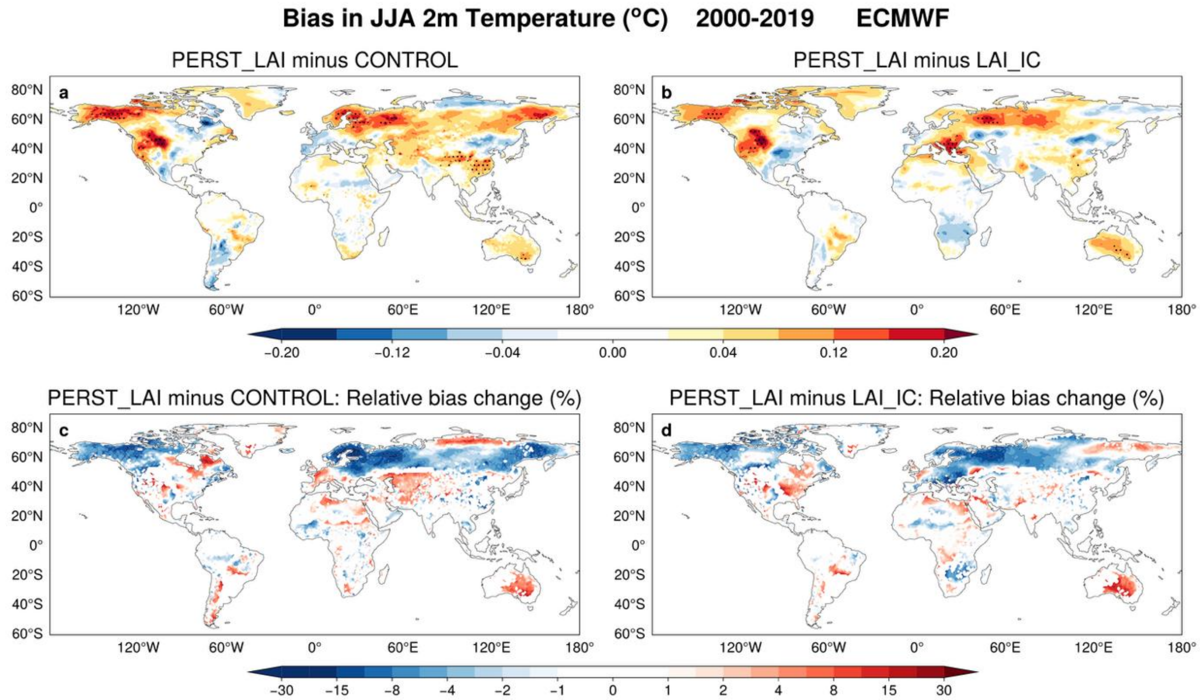

Figure 7: June-to-August seasonal mean 2-metre temperature long-term mean bias (°C) in ECMWF seasonal reforecasts plotted as difference between (a) PERST_LAI and CONTROL and (b) PERST_LAI and LAI_IC. Also plotted in (c) and (d) are the corresponding relative change in bias (%). Hashed regions in (a) and (b) are statistically significant at 95%.

5.2.3 Long-term trends

The impact of persisting the LAI anomaly on the long-term trend is shown in Figure 8. Relative to CONTROL, PERST_LAI reduces cooling-trend biases across central and eastern Europe, parts of northern Eurasia, parts of North America, central South America and the African continent; several of these responses are statistically significant, indicating a detectable influence of vegetation anomalies on regional trend characteristics. Comparison with LAI_IC reveals that persisting the LAI anomaly yields more consistent and spatially organised trend corrections, although the absolute magnitude of these adjustments remains small due to large pre-existing trend errors.

Overall, vegetation anomaly persistence affects regional trend biases in a physically consistent manner, and the presence of statistically significant regional signals suggests that it can have a detectable, if localised, effect on long-term temperature trends in the ECMWF reforecasts. Although these significant regions are geographically limited, they show that a persisting LAI anomaly can influence not only seasonal means but also multi-decadal trend characteristics.

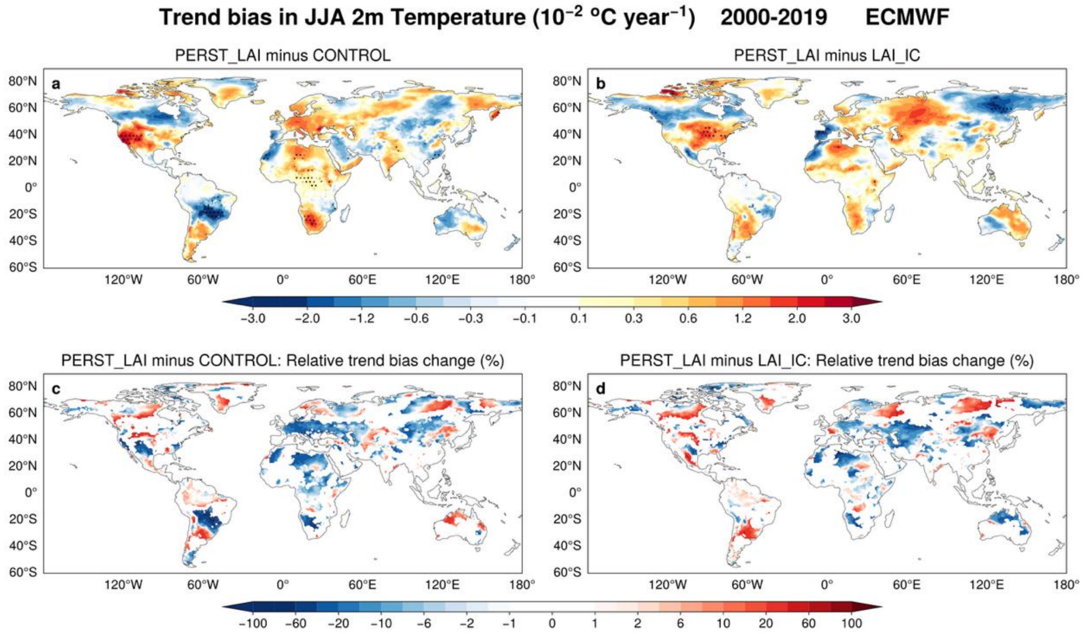

Figure 8: June-to-August seasonal mean 2-metre temperature trend bias (10^{-2} °C year^{-1}) in ECMWF seasonal reforecasts plotted as difference between (a) PERST_LAI and CONTROL and (b) PERST_LAI and LAI_IC. Also plotted in (c) and (d) are the corresponding relative change in bias (%). Hashed regions in (a) and (b) are statistically significant at 95%.

6 Conclusions

The analyses in this deliverable show that interannually varying vegetation introduces physically coherent and regionally meaningful signals in both ECMWF and MetO systems, particularly in regions of strong land–atmosphere coupling. Although these vegetation-driven adjustments generally represent a modest fraction of the errors in the systems, they nonetheless demonstrate that both systems respond in a thermodynamically consistent manner to realistic LAI variability. MetO displays higher hydrological sensitivity, while ECMWF shows more subdued effects, highlighting system-dependent responses likely related to underlying biases. Overall, the ACC diagnostics indicate that the predictive impact of vegetation anomalies is hard to detect, as it requires large changes in ACC to be significant with the ensembles used.

The long-term mean and trend bias analyses reinforce these findings by showing that vegetation-induced soil-moisture adjustments lead to temperature responses - wetting with cooling, drying with warming - that are physically interpretable and spatially coherent, even if their magnitude and statistical robustness vary between systems. Often, significant changes are localised in specific regions rather than being widespread at the continental scale. Nevertheless, there is tendency for significant features to contribute to amelioration of mean biases and trend errors.

Persisting the LAI anomalies during the forecast in ECMWF produces more coherent and, in some regions, statistically significant improvements in long-term mean temperature and trend biases. While these effects remain moderate and do not yet translate into significant ACC gains, they demonstrate that maintaining vegetation information into the forecast enhances the physical realism of the land surface evolution. It is also important to recognise that the ensemble sizes used in these experiments may limit the ability to detect weaker signals, meaning that some vegetation-related improvements could remain below the threshold of statistical significance.

Altogether, these results suggest that interannual vegetation information does influence regional climatology and can produce detectable improvements in mean-state behaviour, particularly when anomalies persisted beyond the initial state. Although current impacts on seasonal forecast skill remain limited, the analyses clearly identify regions and processes where vegetation carries predictive value. Nevertheless, biases in the model state and in processes remain large and could potentially affect the responses to the perturbations imposed in the experiments. This underscores the need for continued development of simulated vegetation-soil-moisture coupling and associated process understanding, improved land-surface coupling, prognostic vegetation, enhanced land initialisation, and larger ensemble sizes for unlocking the additional predictive value in future C3S seasonal prediction systems.

7 References

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Document History

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Internal Review History

Internal Reviewers	Date	Comments
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