REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation: United Kingdom

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Project Title: Forecast-based attribution of land-atmosphere coupling in weather extremes

To make changes to an existing project please submit an amended version of the original form

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2027	
Would you accept support for 1 year only, if necessary?	YES ×	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	215,895M	215,895M	
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]			
Accumulated data storage (total archive volume)[2]	[GB]	317,432	634,864	

[1] The Principal Investigator will act as contact person for this EMI R&D Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.
[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.
[3]The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

EWC resources required for project year:		**2027**	**2028**	**2029**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]			

Continue overleaf.

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Extended abstract

All EMI R&D Project requests should provide an abstract/project description including a scientific plan, a justification of the computer resources requested and the technical characteristics of the code to be used. The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

Following submission by the relevant Member State the EMI R&D Project requests will be published on the ECMWF website and evaluated by ECMWF and its Scientific Advisory Committee. The requests are evaluated based on their scientific and technical quality, and the justification of the resources requested. Previous EMI R&D Project reports and the use of ECMWF software and data infrastructure will also be considered in the evaluation process.

Requests exceeding 5,000,000 SBU should be more detailed (3-5 pages).

Abstract

Anthropogenic climate change has substantially increased the frequency and intensity of many extreme events. However, the extent to which land-surface forcing contributes to the occurrence and amplification of these extremes remains poorly quantified. Climate warming increases atmospheric vapor pressure deficit, particularly over water-limited regions, enhancing evaporative demand and accelerating moisture loss from soils and vegetation. These processes promote soil desiccation and vegetation stress, reducing evapotranspiration and triggering positive land–atmosphere feedbacks that further intensify drought conditions and other climate extremes. Despite growing evidence for the importance of these feedbacks, their contribution to different categories of extreme events has not been systematically isolated from the overall anthropogenic influence. This project aims to quantify the role of land-surface forcing in shaping extreme precipitation, heatwaves, floods, and droughts under past, present, and future climate conditions. We will employ initialized medium-range climate simulations to disentangle the contribution of land-surface processes from total anthropogenic forcing during the development of extreme events. **Building upon our previous work that successfully applied initialized high-resolution forecasts for the attribution of heatwaves, windstorms and tropical cyclones, we will develop an event-based attribution framework capable of explicitly tracking the influence of land-surface forcing on extreme event evolution.** The project will provide a more complete process-based understanding of how land–atmosphere interactions modulate anthropogenic influences on extreme events under climate change.

Project description

<u>Background</u>

Anthropogenic climate change has made it increasingly possible to attribute individual extreme weather events to human influence. Major progress has been achieved over the past decade in quantifying the role of greenhouse gases (Leach et al., 2021, 2023; Gu et al., 2023; Ermis et al., 2024; Weisheimer et al., 2025), aerosols (Cox et al., 2008; Ntelekos et al., 2009; Kuo et al., 2025), and large-scale circulation changes in shaping the frequency and intensity of extreme events. Yet one important source of uncertainty remains: the contribution of land-surface forcing and land-atmosphere coupling to different categories of extreme events is still poorly constrained. Recent work has shown that dry soils can intensify heat extremes through local and upwind land-atmosphere feedbacks, including the transport of advected sensible heat (Schumacher et al., 2019).

This issue is not confined to heatwaves. Schumacher et al. (2022) demonstrated that droughts can self-propagate through land-atmosphere feedbacks, with dryland events being particularly prone to downstream precipitation deficits; in drylands, precipitation reductions exceeded 15% for some events and reached 30% in individual months. More recently, Koppa et al. (2024) showed that land-atmosphere feedbacks can also drive the long-term expansion of drylands: as upwind drylands dry out, they contribute less moisture and more heat to downwind regions, promoting humid-to-dry transitions even where the dominant moisture source is not local evaporation. Together, these studies indicate that land-surface conditions can exert a remote and non-negligible influence on the evolution of hydroclimatic extreme events.

However, the broader implications of land-atmosphere coupling across different extreme-event types remain unresolved. Most attribution studies still emphasize thermodynamic and dynamic components of anthropogenic forcing (Gu et al., 2026): Thermodynamically, increasing atmospheric moisture content is expected to intensify precipitation extremes under climate warming (Pfahl et al., 2017); Dynamic contributions including anomalous atmospheric circulations influence moisture and heat advection, alter the conversion of water vapor into precipitation, and ultimately govern extreme events. However, the role of land-surface forcing is often treated indirectly or ignored altogether. In particular, it remains unclear whether the downstream impact of upwind land drying is always manifested as moisture deficits and precipitation shortages, or whether it can also alter floods and compound events through distinct pathways. This question is especially important in transitional and water-limited regions, where land-atmosphere feedbacks are strong and where small perturbations in surface moisture can produce disproportionate impacts on atmospheric water demand and event persistence.

Against this backdrop, there is an urgent need for a framework that can isolate land-surface forcing from total anthropogenic influence in a physically consistent way. We therefore propose to use state-of-the-art initialized forecast experiments to quantify the contribution of land-atmosphere coupling to the initiation, amplification, and propagation of extreme precipitation, heatwaves, floods, and droughts under past, present, and future climate conditions. This approach will build on our previous work on event attribution and will provide a bridge between climate science and downstream impact assessment. In the context of a Wellcome Trust Funding project (Bridging Research on Environmental Attribution and Health Equity, BREATHE), these experiments will also provide a critical input for our epidemiological models, enabling robust health attribution analyses under a warming climate.

Present Challenges

A central methodological challenge in initialized event attribution is how to consistently represent anthropogenic influences on the atmosphere-land system while preserving the observed synoptic evolution of the event. In existing forecast-based attribution frameworks, counterfactual simulations are typically initialized from the same atmospheric state as operational forecasts, while perturbations are applied to greenhouse gas concentrations, ocean states, or other boundary conditions. As a result, the atmosphere gradually adjusts toward the counterfactual climate during model integration, implying that the simulated response may only capture part of the full anthropogenic signal. In our previous attribution projects of heatwave and storms, this issue was addressed by scaling the event response according to the mean surface warming achieved during the simulation. Such an approach is physically justifiable when we choose to look at the thermodynamic effects and short-term dynamic adjustments using this setup. However, extending this framework to land-surface forcing is considerably more challenging. Unlike greenhouse gas forcing, land-surface anomalies are coupled to the atmosphere through two-way exchanges of water and energy. Consequently, the response to land-surface perturbations may not be assumed to scale linearly with global mean warming, making conventional scaling approaches less applicable.

A second challenge lies in identifying robust anthropogenic fingerprints in land-surface conditions. Unlike atmospheric temperature, long-term observations of soil moisture remain sparse and fragmented in both space and time (Dorigo et al., 2021). Different observational, remote-sensing, and reanalysis products often exhibit substantial discrepancies in the magnitude and even the direction of soil-moisture trends. Recent assessments have shown that uncertainties in soil moisture trend representation directly affect drought detection and attribution (Hirschi et al., 2025), highlighting the need for a robust characterization of land-surface change. To address these challenges, we will develop a multi-source land-surface attribution framework that integrates satellite observations, remote-sensing products, and reanalyses to identify robust anthropogenic fingerprints in soil moisture and related land-surface variables. We will evaluate the sensitivity of perturbations for different fields of land-surface, including surface and root-zone soil moisture, surface and root-zone soil temperature, and land-surface temperature. Chose the most appropriate variable of land-surface, combined with existing modifications of greenhouse gases, aerosols, and ocean conditions within initialized forecast experiments. Please refer to detailed research plans as follows.

Scientific Plan

We aim to address three key research questions over the duration of this project.

1. How does land-surface forcing (e.g., root-zone soil moisture, surface temperature) influence the hydrological cycle, in particularly extreme events such as heatwaves and extreme precipitation?
2. How does land-surface forcing influence the climate signal when combined with CO2 forcing, non-CO2 forcings (e.g., aerosols), and ocean-state perturbations?
3. How does perturbed land-atmosphere-ocean coupling regulate extreme events, particularly heatwaves, extreme precipitation, droughts, floods, and compound events?

The first question represents the primary technical challenge that we want to address. In our current experimental design, we perturb the ocean and sea-ice state and modify atmospheric CO2 concentrations. We also conduct experiments in which aerosol concentrations are perturbed in the model initial state to quantify their influence on extreme events. However, land-surface change represents another important source of external forcing that can alter the partitioning between sensible heating and latent heating, thereby influencing the initiation, intensification and recovery of extreme events. We have not yet considered how land-surface forcing affects extreme events. To date, we have not explicitly quantified how land-surface forcing affects extreme events through modifications to the surface energy budget and hydrological cycle. To address this gap, we will perturb land-surface forcings in the model initial state. Given the availability of long-term observational records, soil moisture and surface temperature will be considered as the primary candidate variables. Following our existing experimental framework, we will:

1) Estimate anthropogenic influence on the land-surface variables since the pre-industrial period using optimal fingerprint analysis. We first calculate the Anthropogenic Warming Index (AWI) using climate model output and observations (Hasselmann, 1997; Morice et al., 2021); We then regress the observed soil moisture and surface temperatures at grid-scale onto the AWI; Next, we scale the computed regression coefficients for each grid by changes in AWI between the pre-industrial period of 1850 – 1900 and target year to produce our final estimated perturbations.
2) Subtract (for the pre-industrial counterfactual world) or add (for the future counterfactual world) a perturbation of the estimated anthropogenic influence on the land-surface since the pre-industrial period from the initial conditions of the forecasts.
3) Check the land-surface fields for unphysical values. In particular, double-check perturbations in land-surface fields are within reasonable range.
4) Explore the sensitivity of different fields to perturbation. There are different land-surface variables, surface temperatures, surface soil moisture, root-zone soil moisture, surface soil temperature, root-zone soil temperature. Choose the best one that can represent land-surface perturbations and couple with other atmospheric and oceanic forcings.

Land-atmosphere coupling and feedbacks have been investigated in recent decades (Seneviratne et al., 2006, 2010, 2021; Schumacher et al., 2022; Koppa et al., 2024). The second research question enables us to thoroughly quantify the contribution of total external forcings to extreme events while explicitly isolating the role of land-surface forcing. However, there is one challenge that needs to be specially consider – physical consistency. Applying initial adjustment by perturbing atmospheric, oceanic, and surface-land fields may produce imbalanced initial states. Therefore, we propose an experiment design that relies on estimating perturbations from successive forecasts:

1) Begin by initialising a counterfactual (perturbed initial condition) forecast exactly as we have done previously.
2) Choose a time *t* (on the order of a few days) at which the next counterfactual forecast is to be initialised.
3) Use the counterfactual and operational forecasts to determine difference in the land-surface, atmospheric, and oceanic fields at time *t*.
4) For the counterfactual forecast at time *t*, perturb the land-surface, atmospheric, and oceanic state based on the factual-counterfactual difference at that time estimated from the previous forecast.
5) Apply this to successive forecasts in exactly the same way.

The first few iterations will not be fully balanced because the atmosphere continues to adjust to the imposed perturbations. However, after several forecast cycles, the diagnosed differences between factual and counterfactual simulations are expected to converge toward a stable solution. At this stage, the counterfactual forecasts will be initialized from an approximately balanced climate state. This approach effectively uses the model physics to estimate the physically consistent difference between factual and counterfactual initial conditions and is conceptually similar to perturbed data-assimilation approaches for generating balanced counterfactual states.

We plan to run this with medium-range simulations to the winter season 2022/2023 and summer season 2023. This season saw a diverse range of extreme events, including storm Otto, cyclone Freddy, cyclone Gabrielle, Afghanistan cold snap, North America storm complex, Philippines flooding etc. More importantly, analyzing entire seasons allows us to investigate how attribution signals evolve within a season and how responses differ between warm and cold seasons.

To answer the final question, we plan to use the setup of experiments to a broader collection of extreme events over recent decades. Using disaster databases such as EM-DAT, we will select representative events from four major categories: extreme precipitation, heatwaves, droughts and floods. For each category, we will run our factual-counterfactual experiments and systematically quantify the contributions of different external forcing sources. This approach will provide a comprehensive understanding of how different classes of extreme events respond to external forcings across different climatic regions of the world.

Furthermore, this forecast-based attribution framework developed in this project has the potential to form the basis of an operational attribution and projection service, enabling rapid and physically consistent assessments of anthropogenic influences on extreme weather and climate events.

In summary, we are planning to conduct the following simulations as part of the EMI R&D Project.

Phase	Year	Steps
Land-surface adjustment	2027	Estimate fingerprints of land-surface variables and produce land-surface perturbations for target year forecast simulations.
		Subtract or add perturbation of the estimated anthropogenic influence on the land-surface from the initial conditions of the forecasts.
		Check the reasonability of factual-counterfactual simulations and explore the sensitivity of different land -surface fields to perturbation.
Land-surface, atmospheric, oceanic adjustment	2028	Adjust land-surface, atmosphere, and ocean states to produce factual-counterfactual simulations across warm and cold seasons.
		Adjust land-surface, atmosphere, and ocean states to produce factual-counterfactual forecasts for a range of extreme events across the world.

Required resources

Our team has already established the technical capability to conduct forecast-based attribution experiments with the IFS, supported by rich experience running the model and close collaboration with ECMWF (e.g., Dr. Antje Weisheimer). The proposed project builds on these successful pilot experiments, requiring substantial resources. Specifically, we will generate successive two-week counterfactual forecasts for two seasons and a range of individual events. The costing of these experiments, based on the experiments we have already performed, is as follows:

Cost (SBU) for Year 1:
1500 SBU per ensemble member per day x
15 simulation days per initialization x
51 members per initialization x
3 types of run (one pre-industrial climate, one present-day and one future for testing the linearity of the response) x
54 initialisation dates (two dates per week for 6 months)
= 185,895,000 SBU
+ 30,000,000 SBU for exploratory experiments testing the sensitivity to different perturbations (soil vs surface temperature)

= 215,895,000 SBU

Cost (SBU) for Year 2:
1500 SBU per ensemble member per day x
15 simulation days per initialization x
51 members per initialization x
3 types of run (one pre-industrial climate, one present-day and one future for testing the linearity of the response) x
54 initialisation dates (two dates per week for 6 months)
= 185,895,000 SBU
+ 30,000,000 SBU for exploratory experiments testing the sensitivity to different perturbations (soil vs surface temperature)
= 215,895,000 SBU

Overall cost (SBU)
215,895,000x2 = 431,790, 000 SBU

Cost (Storage in GB):
2.4 GB per ensemble member per day x
123930 factors listed above x
2 (two years)
= 594,864
+ 40,000 for exploratory experiments
= 634,864 GB

If resources turn out to be very limited, we might be able to still run our proposed experiments with a reduced number of ensemble member.

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