REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: UNITED KINGDOM

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Project Title:

TOWARDS AN OPERATIONAL SERVICE FOR EXTREME WEATHER ATTRIBUTION AND PROJECTION

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** GBLEAC____________	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2023	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2023-2025: (To make changes to an existing project please submit an amended version of the original form.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	110,000,000		
Accumulated data storage (total archive volume)[2]	(GB)	220,000		

Continue overleaf

[1] The Principal Investigator will act as contact person for this Special 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.

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Extended abstract

Introduction and previous work

In our original special project in 2020, “The influence of CO_2 on an individual extreme event - the high February temperatures in the UK 2019”, we used a novel forecast-based approach to extreme event attribution to carry out an analysis of the direct influence of increased CO_2 over pre-industrial levels (through diabatic radiative heating) on an isolated extreme event: the February 2019 heatwave in Europe. For more information, see the full study that we published in PNAS late last year (Leach et al., 2021):

Leach, N. J., Weisheimer, A., Allen, M. R., & Palmer, T. (2021). **Forecast-based attribution of a winter heatwave within the limit of predictability**. Proceedings of the National Academy of Sciences, 118(49). https://doi.org/10.1073/pnas.2112087118

We then aimed to extend the forecast-based approach to provide a more complete estimate of the total anthropogenic contribution to an isolated extreme event in our special project for 2021. Our aim was to do this by modifying the initial 3D ocean state in the operational forecast such that it was representative of a pre-industrial climate (ie. cooler), and reducing the CO_2 concentrations correspondingly, just as we had done before. The combination of cooler ocean temperatures & reduced CO_2 concentrations should be more balanced than either one in isolation, and also provide a more complete estimate of the total anthropogenic contribution to an extreme. This is analogous to previous approaches (Pall et al., 2011), but in a coupled model.

With guidance from Chris Roberts (ECMWF), we have produced a methodology for generating the ocean state perturbations & then applying them to the operational restarts. This has allowed us to run “counterfactual” (representative of pre-industrial) forecasts of another extreme event of considerable scientific interest: the Pacific Northwest heatwave. These experiments have demonstrated that these perturbations do have a clear impact on the heatwave itself of 1-2°C, but do not seemingly have an impact on its predictability. This is vital for providing a robust attribution statement – and also an interesting finding in its own right.

The analysis of these counterfactual forecasts is ongoing, but we have written the results up into a study that we aim to submit in the next week or so. This study could have significant impact, as it represents the first time that such an attribution experiment has been performed in a state-of-the-art operational coupled forecast model. However, there are a number of outstanding questions that we aim to answer in order to demonstrate the utility of our approach as the attribution community advances towards an operational service (Wehner & Reed, 2022).

Project description

We aim to address 3 questions in the coming year:

1. Is our approach applicable to other types of extreme, given thus far we have focussed on heatwaves.
2. Can we address the rapid atmospheric adjustment to the perturbed initial conditions through successive factual and counterfactual forecast runs.
3. How would our approach work in practice as an operational extreme weather attribution and projection service?

The first of these is relatively straightforward. So far, we have studied two cases – both of which are extreme heat events. There were a number of reasons for this: the clear thermodynamic connection between climate change and heatwaves has made them an "easy" (relatively speaking) extreme event class for attribution science; the significant body of work already devoted to heatwave attribution; and limiting the scope of my own PhD thesis. However, heatwaves are by no means the only extreme weather event of interest to the scientific community and public. Therefore, we would like to apply our forecast-based approach to other classes of extreme, in particular heavy precipitation and extreme cold events. We have begun exploring whether the experiments we have already performed can be used for this purpose (ie. using precipitation events that just so happened to occur at the same time as the Pacific Northwest Heatwave), but also aim to examine a specific precipitation case study in this coming year.

The second point is the main technical question that we want to examine. In our current experiment design, we perturb the initial ocean and sea ice state and alter atmospheric CO2 concentrations. This produces a state consistent with a world without human influence on the climate. However, once the forecast is initialised, the atmosphere and land-surface rapidly adjust to this new climate state. Even though this adjustment is quite rapid (on a timescale of order days) it means that the forecasts produced on short- to medium-range leads do not measure the full anthropogenic influence on the extreme weather event of interest, but some fraction of it. In the study we have just carried out, we were able to mitigate this issue by exploiting the linearity of the local response to the global temperature response (ie. we measured the fraction of the local response using the level of global warming observed in the forecast, and then adjusted the measured local response using the present-day level of global warming). However, analysing and interpreting our counterfactual forecasts would be considerably simplified if we were able to remove this rapid adjustment.

A number of attribution studies have already accounted for this initial adjustment by perturbing thermodynamic atmospheric fields, for example so called "pseudo-global warming" approaches (Pall et al., 2017; Patricola & Wehner, 2018; Schär et al., 1996), or the forecast-based approach (albeit in a considerably lower resolution model) of BOM (Wang et al., 2021). However, applying these approaches could lead to physical inconsistencies given the specific state of the climate at the time the forecast is initialised. One way in which to produce a more balanced initial state would be to perturb the model prior to the data assimilation cycle (Hannart et al., 2016). While we believe that this would ultimately likely be the "best" approach, especially for one-off case studies, such perturbed data assimilation would be extremely technically complex, and would require significant input from someone with expertise in the specific data assimilation system used. Hence, we have come up with a simpler experiment design that relies on estimating perturbations from successive forecasts. The need for successive forecasts does mean that it could not be used for isolated attribution studies, but in the case of an operational attribution system (Wehner & Reed, 2022), this is no longer an issue.

Our proposed approach is as follows:

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 the (ensemble mean) difference in the land-surface and thermodynamic atmospheric fields at time *t*.
4. For the counterfactual forecast at time *t*, in addition to the ocean state perturbation (and CO2 concentration change), also perturb the atmospheric and land-surface 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 forecasts this routine is applied to still won't be in a balanced initial state, since the atmosphere will still be adjusting at time *t*. However, after this is applied to a few forecasts in a row, the measured factual-counterfactual differences between successive forecasts should stabilise. Once this stabilisation is achieved, the counterfactual forecasts should be being initialised from an approximately balanced state. In this way we would be using the physics of the model to determine what the difference between the factual initial state, and the counterfactual initial state should be at the start date of the forecast. This is conceptually quite similar to the perturbed data assimilation approach to estimated a balanced counterfactual initial state.

There are some scientific questions that we will need to answer along the way. Firstly, what fields will need to be perturbed? Previous work has tended to perturb atmospheric temperature and humidity fields and soil moisture (Wang et al., 2021), but we will explore the sensitivity to each perturbation separately. Secondly, what time *t* should be used? This time should be sufficiently small that forecast skill is very good and model errors are small; to ensure that the factual-counterfactual difference is genuinely representative of the initial climate state at the next forecast initialisation rather than having a significant component from dynamical variability (ie. the factual forecast should be sufficiently close to the data assimilated initial condition of the next forecast), and to ensure that model errors do not cause the perturbation estimated by the factual-counterfactual difference to grow indefinitely. We suggest that *t* should be on the order of a few days – perhaps a bi-weekly initialisation, but this is something we shall explore.

Our final point is highly related to this previous one – could this forecast-based approach be employed to provide an operational attribution service? The attribution community has targeted such a service for some time since it would address a number of issues with how extreme event attribution is carried out at the present: the speed at which results can be produced; the creation of a "standard" methodology; the bias towards extremes in the global North (ie. where the majority of attribution scientists reside). There has been some progress towards such as service, particularly in terms of the standardisation of methodologies (Philip et al., 2020).

We argue that using the same models used by operational forecast centres has a huge potential for advancing this goal. For a start, forecast models are already run on a regular basis, unlike the (often bespoke) climate model simulations used in attribution studies at the present. The reliability of forecast models is well studied and established, unlike the majority of climate models, which is vital for providing trustworthy attribution results (Bellprat et al., 2019; Palmer & Weisheimer, 2018). Forecast models are significantly higher resolution than the climate models currently used, and are coupled, which is vital for extremes where ocean-atmosphere interaction plays a role. Understanding if a forecast model is even able to simulate the event of interest is far easier than in a climate model – all you need to know is whether the model successfully predicted the event or not. A final practical advantage of using forecast models is that they are already used by hazard warning systems and users within this space. Using models that these users are already familiar with would maximize the utility of an operational system, not only in terms of communicating the impacts of climate change on extreme weather to relevant parties, but also in terms of linking the physical impacts to the socio-economic impacts. For example, forecast models are already used in flood forecasting systems to assess the potential risks and damages from an extreme precipitation event. Using these same models would make assessing the additional risks arising from climate change easier and more robust than having to design a bespoke methodology (eg. by coupling a climate model to a hydrodynamic model for a single study).

With this special project, we aim to demonstrate how a forecast-based approach could be used to provide an operational attribution (and projection) service in practice. At the same time, we will perform the experiments we have described here to address the major remaining issues with the approach we have used thus far.

Resources required

We will require enough resources to produce successive 15-day counterfactual forecasts for an extended period of time: we propose doing this for a single season. The costings of these experiments, based on the experiments we have already performed, is as follows:

Cost (SBU) :
1100 SBU per ensemble member per day x
1.5 scaling factor between current and ATOS computer systems (estimated using ATOS experiment hp5f) x
15 simulation days per initialisation x
51 members per initialisation x
3 types of run (one pre-industrial climate, one present-day and one “future” for testing the linearity of the response) x
27 initialisation dates (two dates per week for 3 months)
= 100,000,000 SBU
+ 10,000,000 SBU for exploratory experiments testing the sensitivity to different perturbations (land-surface vs atmospheric)

= 110,000,000 SBU

Cost (Storage in GB):
3.2 GB per ensemble member per day x
41,000 factors listed above
= 200,000
+ 20,000 for exploratory experiments

= 220,000 GB

Technical Characteristics

We will use the operational version of the ensemble prediction system. In our previous project, this was CY47r2. It is possible that we may have to make new changes to the code due to the move to the ATOS system. However, at this point we have some experience with making the required changes to the model code and scripts in order to run perturbed initial condition forecasts.

We will likely continue to run the forecasts at TCo639 resolution during this project, even if the operational forecast system increases its resolution to TCo1279 as planned. This is due to the additional cost associated with running the system at this increased resolution, and thus the compensation we would have to make in terms of number of forecast experiments run.

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All Special 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 Special 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 Special 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).