REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: United Kingdom……………………………..…

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Tim Palmer…………………………………………..……

Project Title:

Numerical weather prediction based event attribution

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.)	2021
Would you accept support for 1 year only, if necessary?	YES ☒ / NO ☐

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	10,000,000		
Accumulated data storage (total archive volume)[2]	(GB)	23,000		

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

In a 2020 special project, "The influence of CO2 on an individual extreme event - the high February temperatures in the UK 2019", we studied the late February 2019 heatwave that was experienced over the UK. This "event" was predicted by the ECMWF ensemble forecast system at a lead time of 10 days. Our research aimed to exploit this predictive skill to carry out an attribution experiment in which we compare the operational forecast ensemble to an ensemble in which the only change to the model is a reduction in CO2 concentrations from the current levels of 414 ppm to pre-industrial levels of 285 ppm (henceforth 'reduced' CO2). A comparison of the likelihood of the heatwave, defined in terms of the maximum temperatures observed, in each ensemble would allow us to quantify the influence of diabatic CO2 heating on the event.

We performed the experiment described above, initialising the forecast 9 days before the peak of the heatwave. At the same time, we ran an experiment in which the CO2 concentration was increased to 600 ppm (henceforth 'increased' CO2). This represents an equal and opposite change in radiative forcing when compared to the pre-industrial experiment; and therefore should approximately represent an equal and opposite change to the CO2 diabatic heating component of surface temperatures. This increased CO2 experiment allows us to confirm that any changes in event likelihood between the pre-industrial and operational ensembles are due directly to the change in CO2 concentration, rather than differences in the ensemble dynamics arising from the perturbation made to the chaotic weather system.

We performed an attribution analysis of the February heatwave using these experiments, and wrote up the results in a paper submitted to the BAMS Special Report: Explaining Extreme Events from a Climate Perspective. The manuscript is currently undergoing peer review. In brief, we found that removing the influence of diabatic CO2 heating just over the days immediately prior to the event reduces mean and maximum surface temperatures by up to 0.5 K (see fig 1) and the number of records broken over Europe during the heatwave by a best-estimate of 10 %. Alternatively, framing the direct influence of CO2 concentrations in terms of the widely-used "fraction of attributable risk" (Stone & Allen, 2005), calculated for different regions within Europe, we find that the fraction of risk attributable to the CO2 concentration change is 0.3 for the British Isles region, which experienced a particularly extreme heatwave.

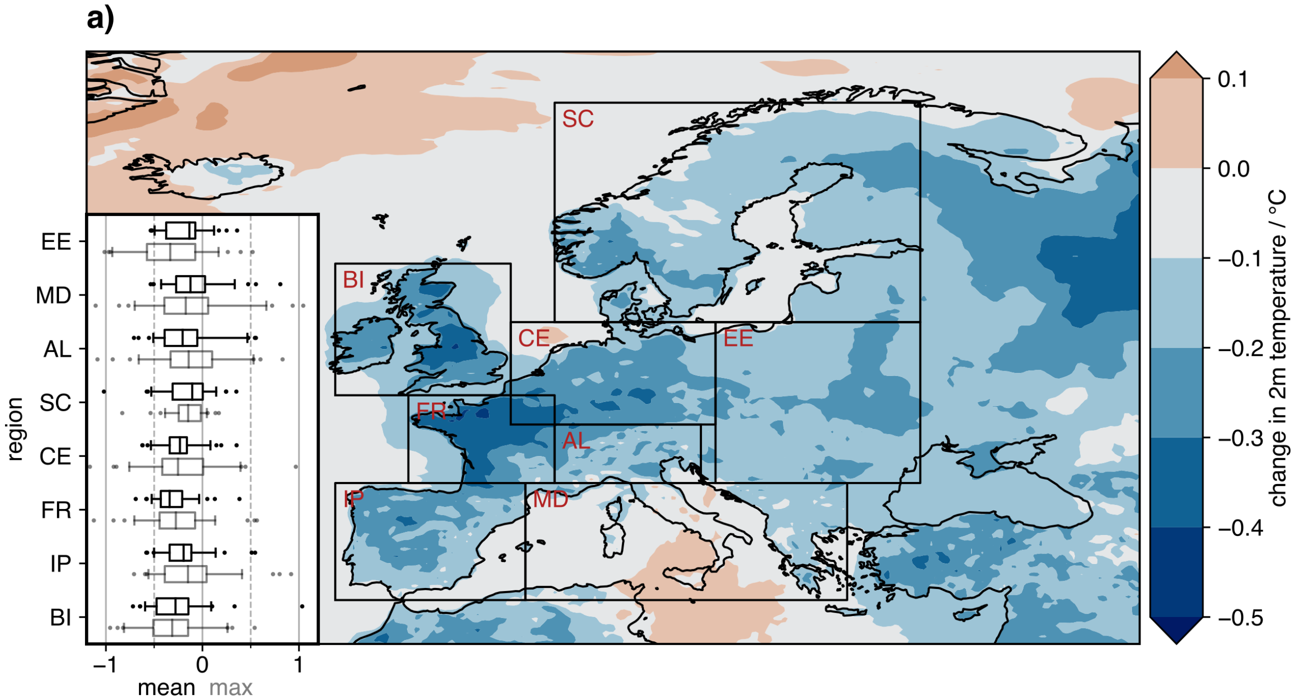

Figure 1: CO2 signal in mean 2m temperature over 25-27 February 2019. Inset shows the CO2 signal in both mean and maximum temperatures over the same period averaged over regional areas; boxplots indicate median, inter-quartile and 5-95% range.

Proposed research questions

Within this study we focussed on the European domain, and the attribution side of the analysis. However, several key questions relating to the use of NWP models in attribution science arose during the study:

- How the forecast lead time impacts upon attribution results, and on a related note, how the predictability of the event within the forecast ensemble impacts upon attribution results?
- How does the impact of perturbing CO2 change over time?
- Can we quantify the dynamical component of the February heatwave; and does this component change upon perturbing CO2 concentrations? This will answer the question as to whether we can be certain that the changes in event likelihood upon perturbing CO2 concentrations are entirely attributable to the CO2 and don't have some random dynamic component.
- Could we "naturalise" SST and SIC levels in the ensemble initial conditions such that we might perform a complete attribution to anthropogenic influence, rather than to just the direct effect of increased CO2 concentrations?
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Many contemporary attribution studies use large ensembles of prescribed-SST climate model simulations to determine the change in likelihood of an extreme event between the real "factual" world, and the "counterfactual" world, in which anthropogenic influences on atmospheric composition and SST/SICs have been removed. These simulations are generally initialised well in advance of the event they are used to analyse (Ciavarella et al., 2018; Massey et al., 2015). As such, they are relatively unconditioned (the only conditioning is introduced by the prescribed SST/SICs), and therefore - provided sufficient ensemble members - the ensemble will likely sample a significant fraction of the underlying climate distribution. The forecast model based attribution we have demonstrated for the February 2019 heatwave is different in this regard. Here the model used is initialized at a sufficiently short lead that it is able to predict the event, and therefore the forecast ensemble for the event is highly conditioned, sampling only a very small fraction of all possible underlying climate states. This level of conditioning is determined principally by the forecast lead time, though will also be somewhat dependent on the specific event itself.

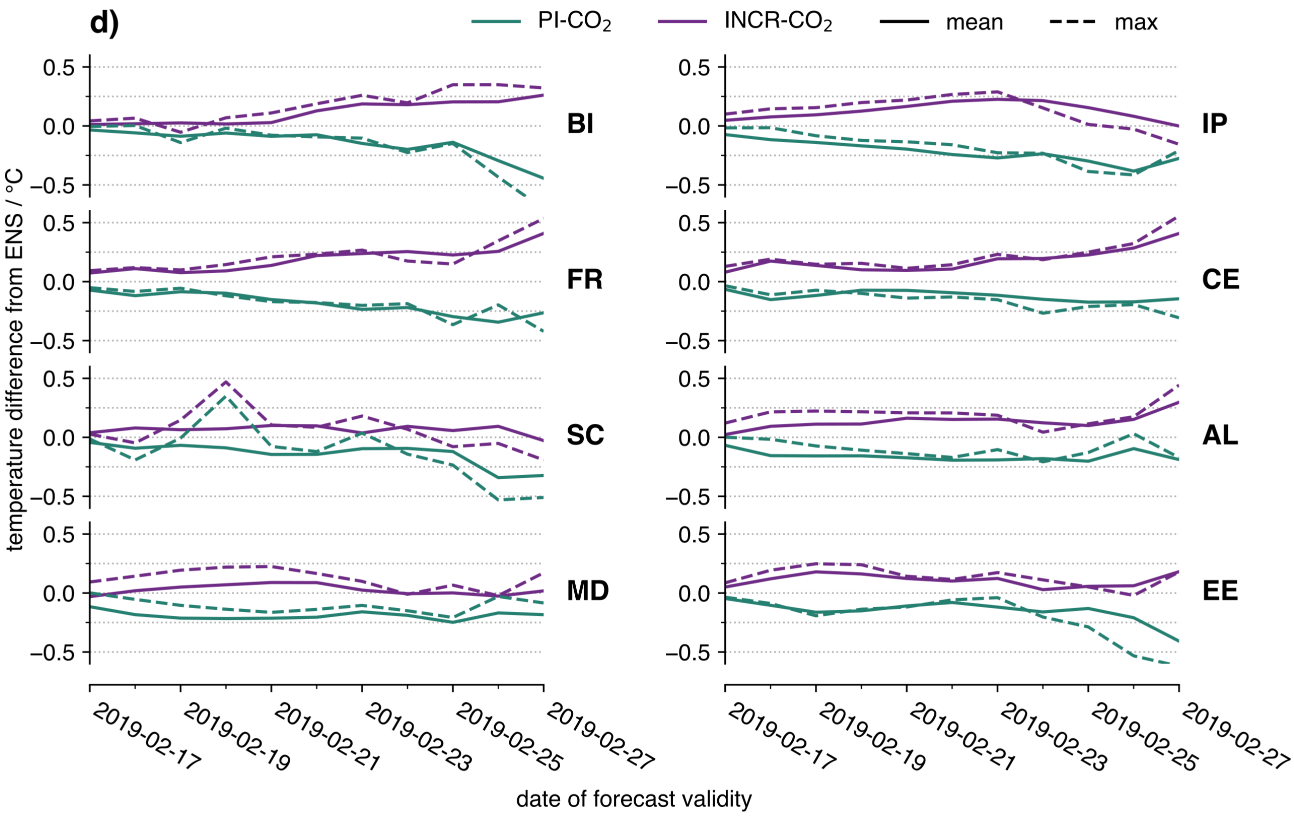

Figure 2: Ensemble mean differences from ENS for regional mean of daily mean and daily maximum temperatures in perturbed CO2 experiments.

For the here proposed project we intend to run perturbed-CO2 forecast ensembles of the February heatwave at a number of different start-dates and determine the quantified influence of perturbed CO2 concentrations on the heatwave for each date. This should allow us to explore how attribution results depend on the level of conditioning imposed for a specific event, and how a potential future operational attribution system would go about selecting a lead date for forecast re-initialisations.

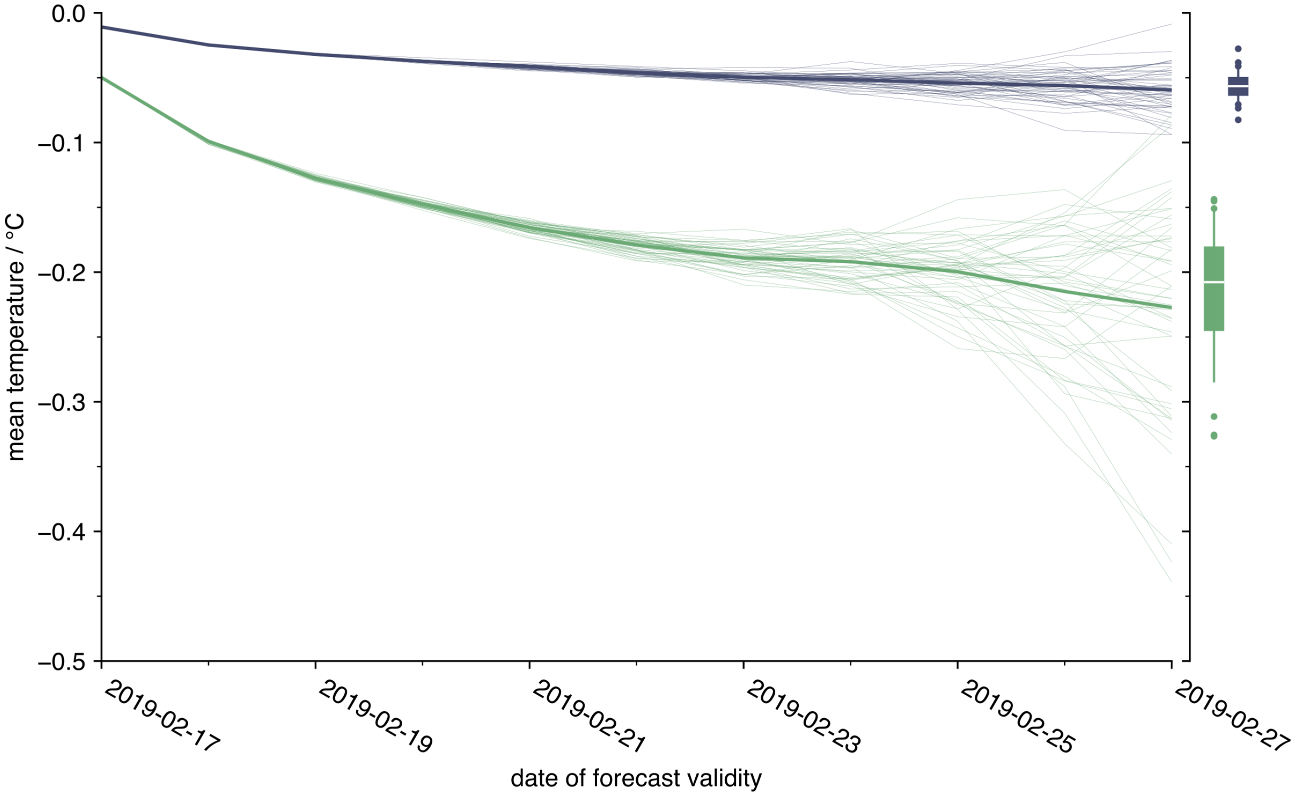

Figure 3: CO2 signal in globally averaged 2m land (green) and ocean (blue) temperatures. Thick lines show ensemble mean; thin lines show individual ensemble members. Boxplots show ensemble median, interquartile range, and 5-95% over the final three days of the integration.

A related question is how the perturbed CO2 impact on surface temperatures changes with integration time. On small spatial scales, such as the PRUDENCE European regions (Christensen & Christensen, 2007), the impact on surface temperatures materialises very rapidly, and remains fairly constant over the 11-day integration period; though possibly with a slight tendency to increase as the time since initialisation increases (fig 2). However, if we move to much larger spatial scales, such as all land / ocean gridpoints, the CO2 fingerprint in surface temperatures exhibits a much more regular behaviour (fig 3). The CO2 component of land surface temperatures, shown in green, appears to decay approximately exponentially towards a constant ensemble mean value, which would represent the mean contribution of diabatic CO2 heating above pre-industrial levels on land temperatures. It is important to understand the timescales involved in the diabatic CO2 heating component of surface temperatures such that we ensure that we are performing an attribution of the 'full' direct CO2 effect and not just a part of it. These timescales clearly depend on the spatial scales studied, and likely depend on the synoptic weather also. We will explore these timescales with the same variable lead time perturbed CO2 forecasts described above.

Decomposing an extreme event into individual drivers (eg. dynamic + residual) will allow us to properly explore how much of an impact the perturbations made to CO2 have had on the dynamic contribution to the event. This is important because it is crucial we are confident that we are not altering the likelihood of the event simply by making a change to the system (independent of what that change is). In the BAMS attribution analysis, we have mitigated against this possibility by perturbing CO2 in both directions, but quantifying whether the perturbations made to CO2 have had any impact on the dynamical component of an event is a key question that must be answered to ensure robust attribution statements can be made. Our initial plan is to attempt to adapt the dynamical decomposition method used in O'Reilly, Woollings, & Zanna, (2017) and Deser, Terray, & Phillips, (2016) to determine the dynamical and residual components of the February heatwave.

While being able to attribute the influence of increase diabatic CO2 heating over pre-industrial levels using an NWP model is certainly interesting, and a good initial demonstration of what forecast-based attribution may be able to do, it is not an alternative to attribution studies that attempt to determine the full anthropogenic contribution to an event. It was established some time ago (Gates, Cood, & Schlesinger, 1981; Mitchell, 1983) that the direct influence on surface temperatures of increased CO2 concentrations is a fraction of the size of the influence of increased sea surface temperatures. Therefore, a key step in performing a complete attribution to human influence, is estimating the anthropogenic footprint on ocean surface and subsurface temperatures, and sea ice concentrations. In contemporary prescribed-SST climate model based attribution studies, this is often done by subtracting a delta SST pattern from the prescribed observed SSTs. This delta SST pattern tends to be calculated using some derivative of the SST difference between CMIP historical and historicalNat experiments. Our ultimate aim is to adapt this technique for the case of an initialised forecast model as opposed to a prescribed SST climate model. This is likely to be a significant undertaking, as we will have to ensure that the model is not destabilised by the changes to ocean temperatures.

However, rather than aim to fully remove the anthropogenic fingerprint on ocean temperatures (estimated by eg. CMIP models) straight away, we believe that using the earlier data of ERA5 or ECMWF's centennial reanalyses as initial conditions in some form may provide an easier route to performing the counterfactual forecasts required to perform a full anthropogenic attribution (or an attribution to anthropogenic influence since 1950 or 1900 respectively for the cases of ERA5 and CERA-20C/ERA-20C initial conditions). It is possible we may have to attempt to match the phases of oceanic oscillations as closely as possible to avoid destabilising the model significantly. A method of producing such counterfactual re-initialisations could allow for attribution of specific events to be carried out operationally by NWP and climate forecasting groups, using state-of-the-art, high-resolution, comprehensively evaluated models that are unquestionably able to predict the extremes in question. This methodology of event attribution would resolve several outstanding issues with current techniques, increasing the confidence we have in them; and this special project would represent a crucial starting point. .

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Experimental Details

In our current special project for 2020, we have so far run several experiments with reduced ensemble sizes to test the changes made to the source code that alter the CO2 concentration. We have also run full ensembles for: 10 day integrations from 2019-02-17 with both reduced and increased CO2; and a 5 day integration from 2019-02-22 with reduced CO2. We plan to shortly run an equivalent experiment with increased CO2 levels.

To investigate the impact of forecast lead time on attribution analysis, we aim to run the pre-industrial CO2 and 600 ppm CO2 forecast simulations from a variety of different lead dates, ranging from just a couple of days before the event, out to the extended range of a month or more. Specifically, we plan on running perturbed CO2 forecasts initialised from: 2019-02-25, 2019-02-24, 2019-02-23, 2019-02-22, 2019-02-21, 2019-02-19, 2019-02-17, 2019-02-15, 2019-02-11, 2019-02-05. This spread of lead dates, ranging from a very high level of event predictability to a very low level, should allow us to fully explore the impact of changing the level of conditioning in the event definition through the lead time on attribution results. This totals 196 days of ensemble forecasts. However, we have already performed some of these experiments and still have some SBU remaining in our current Special Project referenced above, meaning we will only require around 120 days of ensemble forecast simulation to complete these runs.

Investigating how a full attribution to anthropogenic influence could be carried out with a NWP model is a broader question, and the specific experimental details are therefore less clear. However, we currently plan to run experiments of the same extreme event (the February heatwave) as for the lead time analysis to avoid having to re-run experiments for comparison. We will run reduced-member experiments with initial SST/SIC states from the early parts of reanalysis simulations and observe the impact on the forecast model.

Technical Requirements

We will use 51-member IFS CY45R1 ensembles at Tco639L91 coupled to the 0.25 degree NEMO 3.4 ocean model. Based on experiments we have performed already, a single member costs approximately 1150 BU and takes up 2.64 GB per day integration. To properly investigate the effect of changing forecast lead time on attribution, we will require around 60 x 2 (two CO2 concentrations) full-ensemble days of simulation. On top of that, we would like an additional 50 full-ensemble days to explore the possibility of altering the ocean initial conditions to perform a complete attribution to human influence. This totals 170 x 51 x 1150 = 10,000,000 BU and 170 x 51 x 2.64 = 23,000 GB of storage.

The completed form should be submitted/uploaded at https://www.ecmwf.int/en/research/special-projects/special-project-application/special-project-request-submission.

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.

Following submission by the relevant Member State the Special Project requests will be published on the ECMWF website and evaluated by ECMWF as well as the Scientific Advisory Committee. The evaluation of the requests is based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, disciplinary relevance, and 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 asking for 1,000,000 SBUs or more should be more detailed (3-5 pages). Large requests asking for 10,000,000 SBUs or more might receive a detailed review by members of the Scientific Advisory Committee.