

LATE REQUEST FOR A SPECIAL PROJECT 2022–2024

MEMBER STATE: UNITED KINGDOM.....

Principal Investigator¹: NICHOLAS J. LEACH.....

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Other researchers: ANTJE WEISHEIMER.....

MYLES ALLEN.....

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.)	2022	
Would you accept support for 1 year only, if necessary?	YES <input checked="" type="checkbox"/>	NO <input type="checkbox"/>

Computer resources required for the years: (To make changes to an existing project please submit an amended version of the original form.)	2022	2023	2024
High Performance Computing Facility (SBU)	12,500,000		
Accumulated data storage (total archive volume) ² (GB)	32,000 (55,000 if previous project included)		

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 an annual progress report of the project's activities, etc.

² 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.

Principal Investigator:

NICHOLAS J. LEACH.....

Project Title:NUMERICAL WEATHER PREDICTION BASED EVENT
ATTRIBUTION

Abstract

Using our special project for 2021, we have performed perturbed initial condition forecasts of the 2021 Pacific Northwest heatwave using the operational ensemble IFS setup. The perturbed forecasts are representative of pre-industrial and future climates, and together with the original operational (present-day) forecast they can be used to determine the changes in intensity and probability of the heatwave under these different climates. These experiments have demonstrated that the impact of human influence on the heatwave is robust over a wide range of lead times. They have also demonstrated that the predictability of the heatwave is also surprisingly insensitive to the perturbations we have applied. However, the most interesting lead date, initialised 11 days before the heatwave, which lies just on the edge of predictability, would demonstrably benefit from a significantly larger ensemble to robustly quantify the extreme tail of the forecast ensembles, where the event lies. Hence in this late application, we are requesting computer resources to allow us to expand the ensemble size for this specific lead date.

Extended abstract

In our original special project in 2020, “The influence of CO₂ 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 CO₂ 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, 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 (I have appended that request to this document). 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 CO₂ concentrations correspondingly, just as we had done before. The combination of cooler ocean temperatures & reduced CO₂ 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.

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.

We are currently preparing a manuscript for submission in a high-impact journal using the experimental data that we have already produced. However, a potentially key result lies out of the range of the statistical power of the ensemble sizes we have used (the operational ensemble size of 50+1 members). To explain this, I refer to Figures and 2, below.

Any statement of attribution based on a weather forecast, whether framed in terms of changes to the intensity or changes to the probability of an extreme event, is conditional on the component of that event that was predictable at the time the forecast was initialised. In general, this means that weather forecasts initialised closer to the event provide more heavily conditioned & “confident” statements. However, in our experimental setup, this is convolved with the fact that the model is continually adjusting to the perturbations from the initialisation time – hence forecasts initialised closer also tend to make weaker statements as they have had less time to adjust, even if those statements are more confident.

Figure 1 shows a forecast ensembles initialised about a week before the Pacific Northwest heatwave. They illustrate these as distributions on a “return-period” diagram: the y-axis shows “exceedance temperature”, and the x-axis shows the probability (conditional, based on the forecast ensemble) that that temperature is exceeded. Equivalently, the x-axis represents the estimated probability that a single new forecast realisation would exceed the corresponding temperature on the y-axis. We can see that the probability of a single member from the operational (“current climate”) forecast exceeding the observed event is around 1-in-10. This reduces to around 1-in-50 for the pre-industrial climate forecast. Based on this set of forecasts, we can make relatively confident statements about the changes in intensity and risk, conditioned on the predictable component of the event 7-days before it occurred.

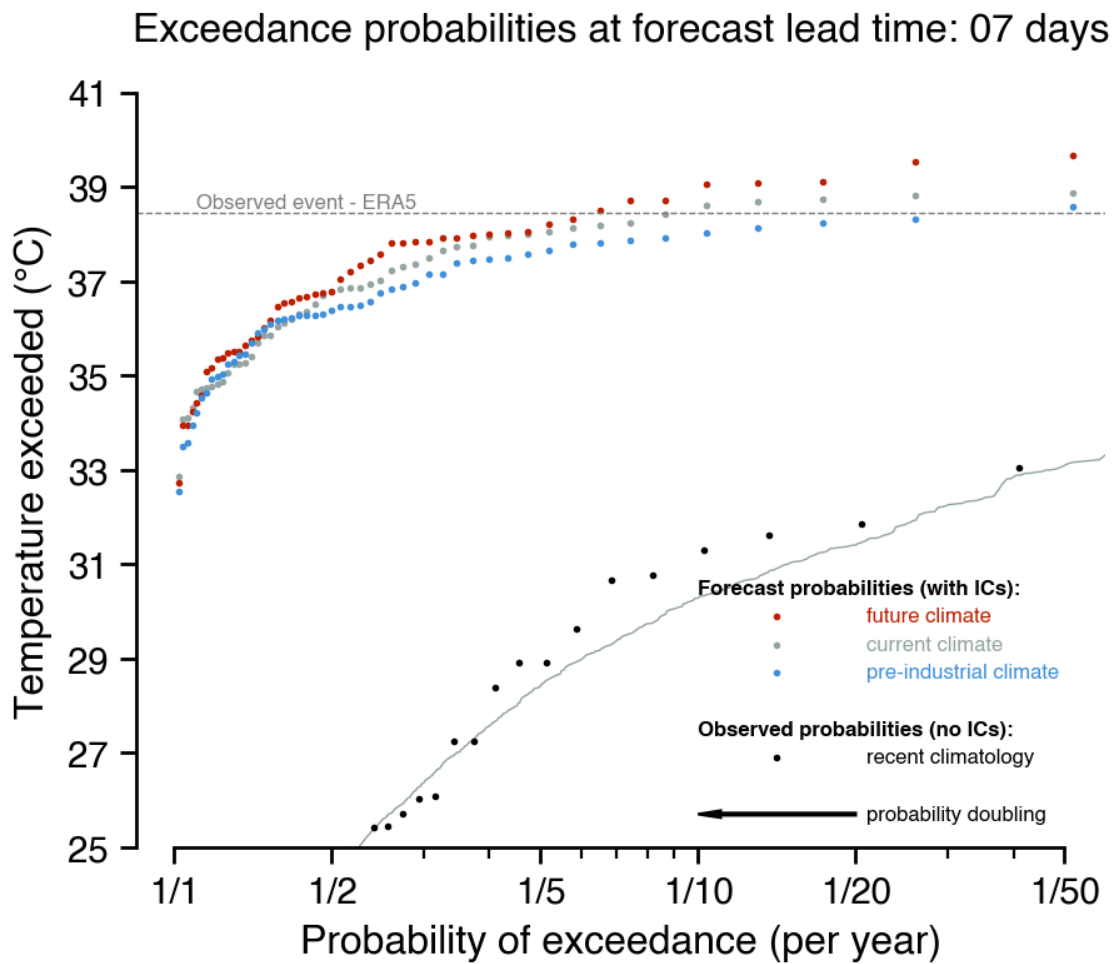


Figure 1: Return period diagram of operational and counterfactual forecast ensembles initialised on 2021-06-18.

The forecast initialised on 2021-06-22 (7-days out) was an exceptionally good forecast, given the unprecedented nature of the heatwave. There were a number of key proximal drivers of the heatwave (Overland, 2022; Lin et al., 2022) that would need to be well-represented by the model for the forecast to be accurate: a split in the polar vortex on 2021-06-17; an atmospheric river causing a large moisture intrusion in the locality of the heatwave around 2021-06-25; a tropospheric blocking ridge; high subsidence; soil-moisture feedbacks; and high insolation at the surface. These features were all well captured in the 2021-06-22 forecast. Mo et al. (2022) suggest that this lies around the limit of where a forecast could be expected to capture the extreme fully as forecasts initialised before 2021-06-21 do not capture the penetration of the atmospheric river sufficiently (ie. this feature is not “baked in” to the initial conditions before this date).

Figure 2 shows an analogous plot to Figure 1 for a forecast initialised 11 days before the event, on 2021-06-18. Here, we can see that far fewer members are able to capture the magnitude of the heatwave as observed. However, whereas both the “future climate” and operational (“current climate”) ensembles reach temperatures near the event, the pre-industrial climate forecast appears to tail off, with a hottest member around 2.5 degrees below the observed event. It is possible that this is simply chance – and that with a larger ensemble there would be members that approach the event magnitude, just as in the future and present climate forecasts. However, it is also possible that there is something more fundamental in the pre-industrial climate forecast that prevents these temperatures

from being obtained. This distinction is key for our study: in the first case we find that the probability of such an event has increased significantly, but was still possible in a pre-industrial climate (in contrast to the findings of Philip et al., 2021); but in the second we would conclude that this event may have been near-impossible in a pre-industrial climate.

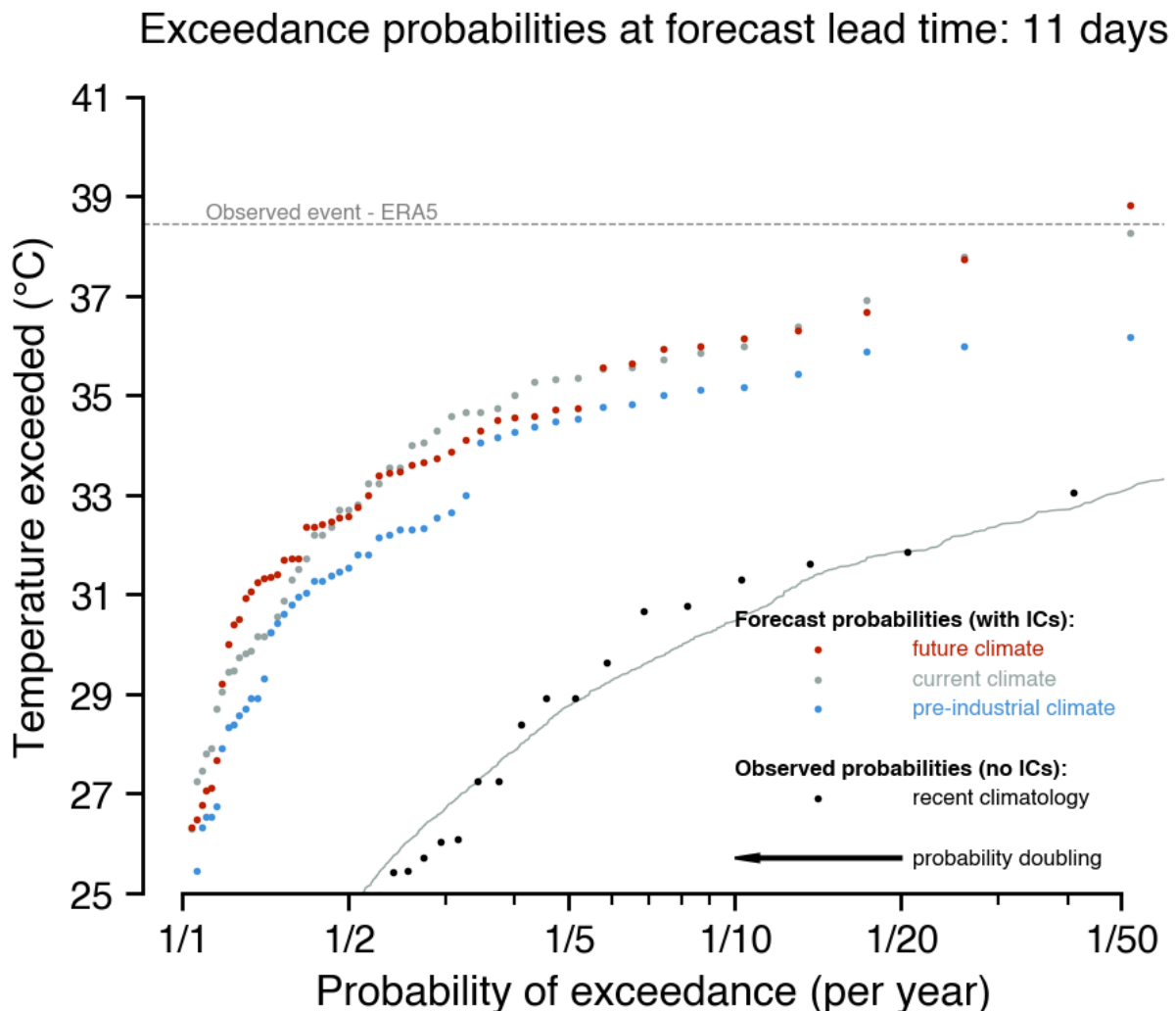


Figure 2: Return period diagram of operational and counterfactual forecast ensembles initialised on 2021-06-18.

Although the current state of our study is hopefully sufficient to warrant interest & impact (given the novelty and robustness of the approach as discussed in Leach et al., 2021), this particular result & conclusion would be highly impactful both within and beyond the attribution community. In order to produce this result, we need more statistical power than the operational ensemble size (as used currently) provides. Hence, we are proposing to run three additional experiments (pre-industrial, present / operational, and future climate forecasts) with increased ensemble sizes of 255 perturbed members (the maximum size without changes to the code and scripts used in prepIFS). We are entirely set up to run these experiments, and have consulted ECMWF support to ensure that we don't need to make any other changes to the model setup, so all we would require are the additional units and we would be able to run these very quickly.

There is some urgency to this request, as once ECMWF decommissions the current Cray supercomputer, we will no longer be able to run these experiments "as is", and since my PhD finishes in September, I won't be able to spend the time familiarising myself with the

new system (if indeed the new system is still able to predict this heatwave as well as the current one, which is not guaranteed).

Based on my previous experiments, 1 ensemble member costs 1100 SBU per day simulation. For a 14-day integration (from 2021-06-18 to 2021-07-02), and 255+1 members, over the three experiments, the total cost would be $1100 * 14 * 256 * 3 = 12$ million SBU. The data generated by these experiments would be around 32 GB.

References

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>

Overland, J. E. (2021). **Causes of the Record-Breaking Pacific Northwest Heatwave, Late June 2021**. Atmosphere, 12(11), 1434. <https://doi.org/10.3390/atmos12111434>

Lin, H., Mo, R., & Vitart, F. (2022). **The 2021 Western North American Heatwave and Its Subseasonal Predictions**. Geophysical Research Letters, 49(6), e2021GL097036. <https://doi.org/10.1029/2021GL097036>

Mo, R., Lin, H., & Vitart, F. (2022). **An anomalous atmospheric river linked to the late June 2021 western North America heatwave**. <https://doi.org/10.21203/rs.3.rs-1125330/v1>

Philip, S. Y., Kew, S. F., van Oldenborgh, G. J., Anslow, F. S., Seneviratne, S. I., Vautard, R., Coumou, D., Ebi, K. L., Arrighi, J., Singh, R., van Aalst, M., Pereira Marghidan, C., Wehner, M., Yang, W., Li, S., Schumacher, D. L., Hauser, M., Bonnet, R., Luu, L. N., ... Otto, F. E. L. (2021). **Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021**. Earth System Dynamics Discussions, 1–34. <https://doi.org/10.5194/esd-2021-90>

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.

Requests asking for 3,000,000 SBUs or more should be more detailed (3-5 pages).

Following submission by the relevant Member State the Special Project requests the evaluation will be based on the following criteria: Relevance to ECMWF's objectives, scientific and technical quality, 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.

All accepted project requests will be published on the ECMWF website.

REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: United Kingdom.....

Principal Investigator¹: Nicholas James Leach.....

Affiliation: University of Oxford.....

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OX1 3LZ.....

Other researchers: Antje Weisheimer.....
Myles Allen.....
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 <input checked="" type="checkbox"/>	NO <input type="checkbox"/>

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.

Principal Investigator: Nicholas James Leach.....

Project Title: Numerical weather prediction based event attribution

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.

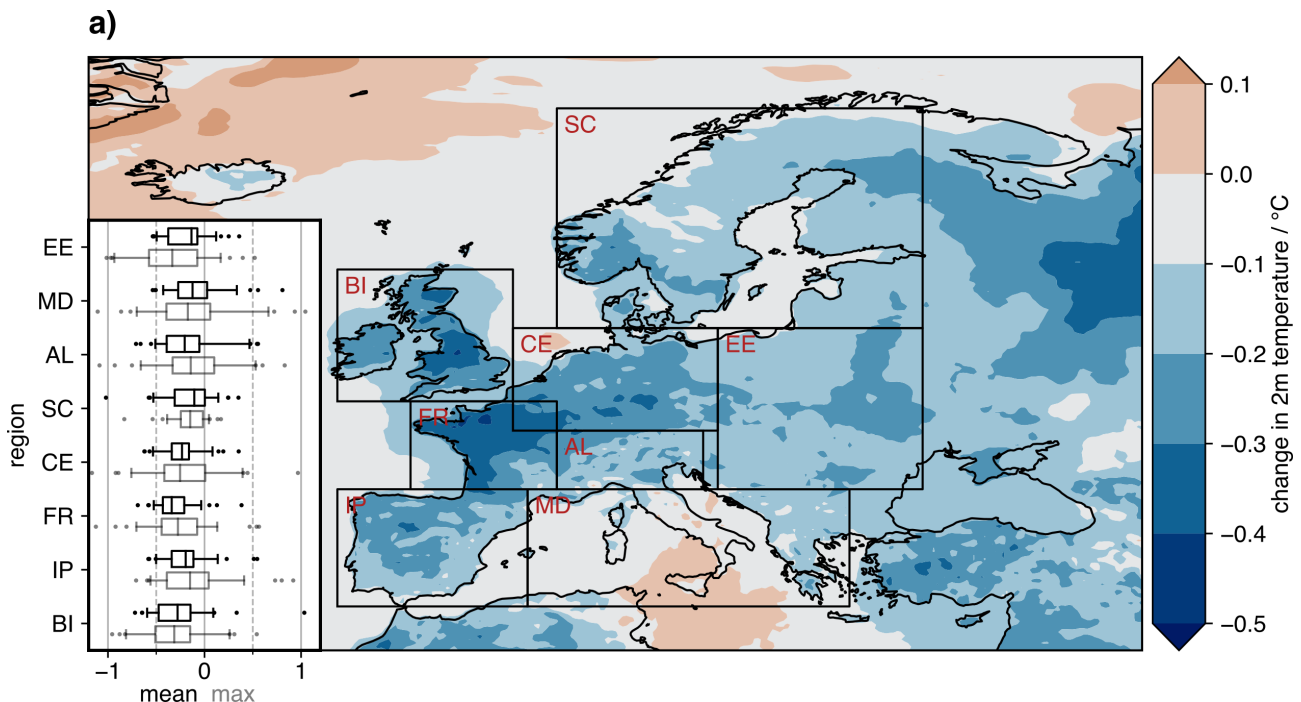


Figure 1: CO₂ signal in mean 2m temperature over 25-27 February 2019. Inset shows the CO₂ signal in both mean and maximum temperatures over the same period averaged over regional areas; boxplots indicate median, inter-quartile and 5-95% range.

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?
-

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.

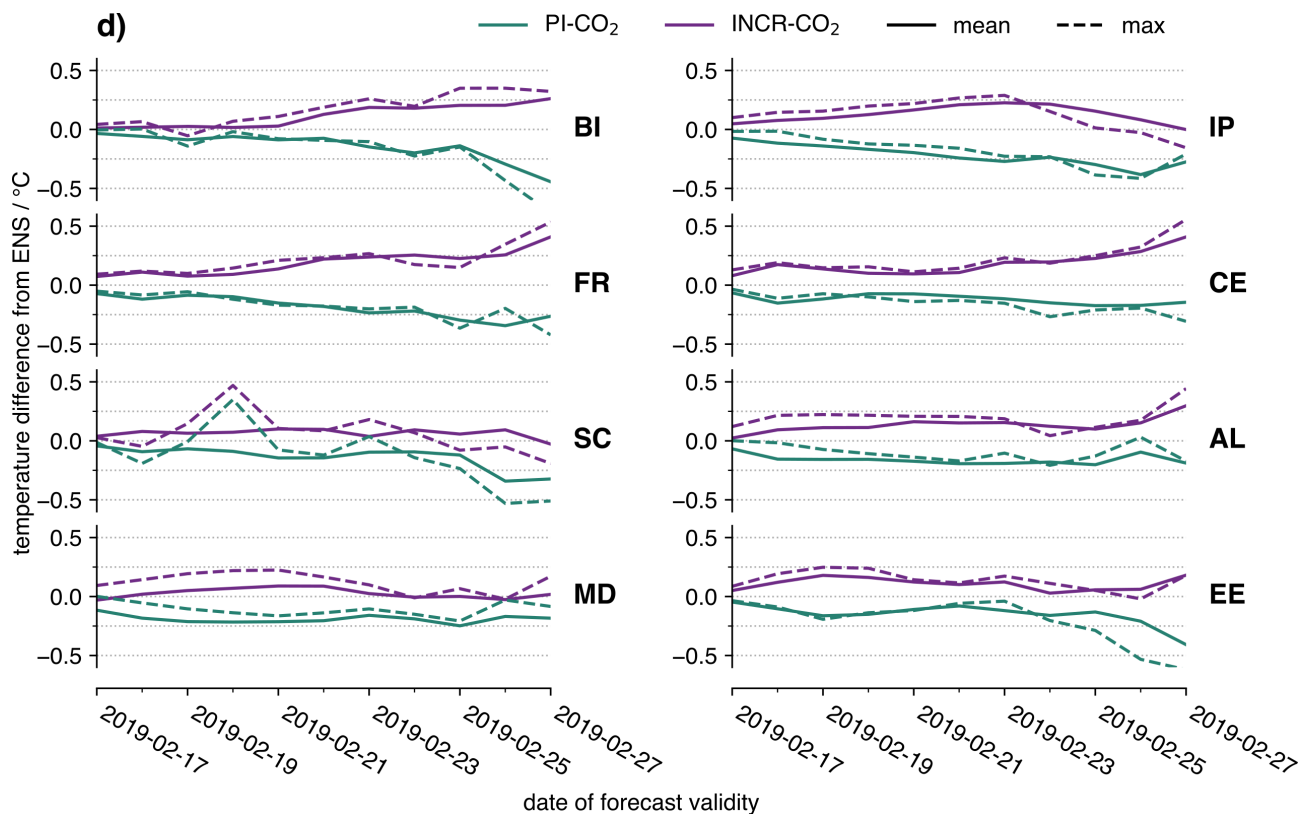


Figure 2: Ensemble mean differences from ENS for regional mean of daily mean and daily maximum temperatures in perturbed CO₂ experiments.

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.

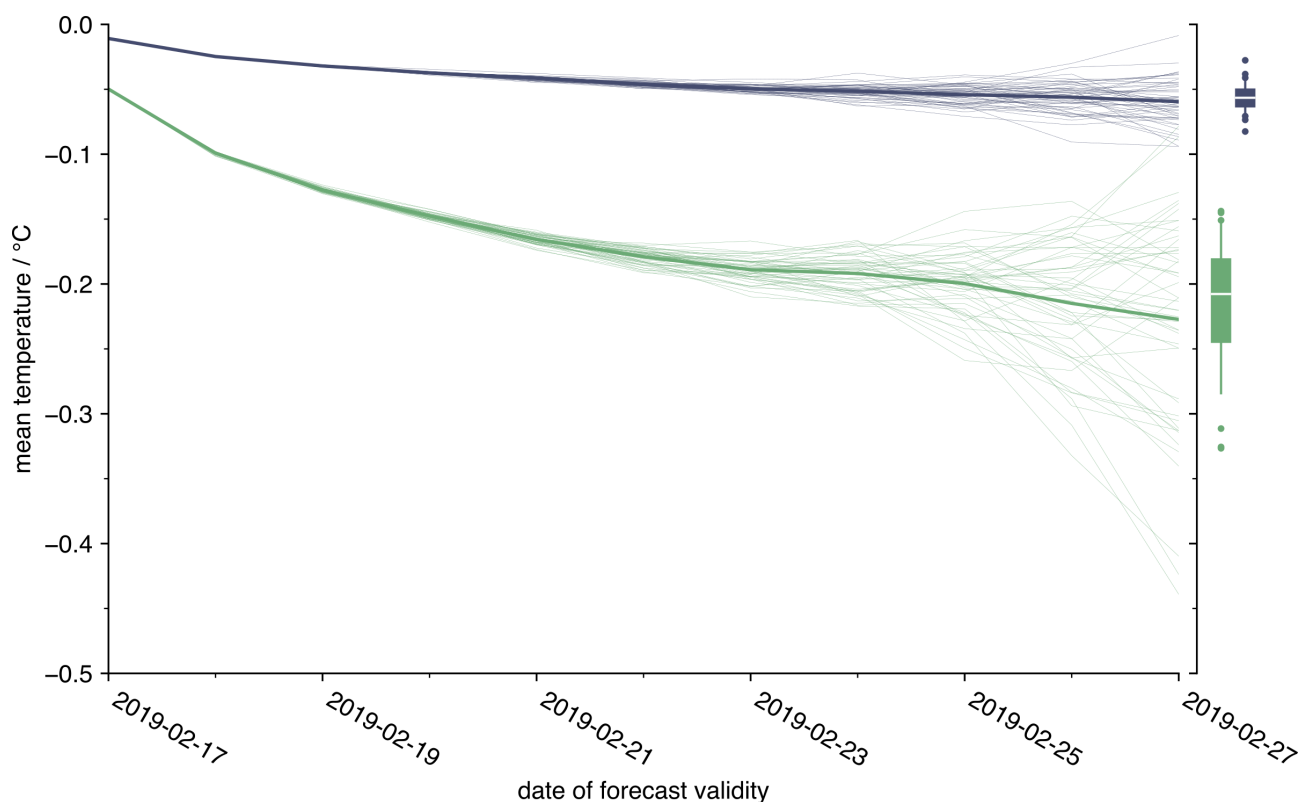


Figure 3: CO₂ signal in globally averaged 2m land (green) and ocean (blue) temperatures. Thick lines show ensemble mean; thin lines show individual ensemble members. Boxplots show ensemble median, interquartile range, and 5-95% over the final three days of the integration.

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 $170 \times 51 \times 1150 = 10,000,000$ BU and $170 \times 51 \times 2.64 = 23,000$ 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.