

REQUEST FOR A SPECIAL PROJECT 2020–2022

MEMBER STATE: United Kingdom.....

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Project Title: LARGe ensemble fOrecast and attribution of events (LARGO)
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If this is a continuation of an existing project, please state the computer project account assigned previously.	SP _____
Starting year: <small>(A project can have a duration of up to 3 years, agreed at the beginning of the project.)</small>	2020
Would you accept support for 1 year only, if necessary?	YES <input checked="" type="checkbox"/> NO <input type="checkbox"/>

Computer resources required for 2020-2022: <small>(To make changes to an existing project please submit an amended version of the original form.)</small>	2020	2021	2022
High Performance Computing Facility (SBU)	27 200 000	27 200 000	
Accumulated data storage (total archive volume) ² (GB)	40 000	60 000	

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

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.

This special project will compare the impacts of the SPPT and SPP perturbed-physics schemes on the ensemble spread, forecast skill, and attribution of events in large ensembles produced with the IFS using numerical single precision. From the perspective of extreme event attribution, we are firstly interested in heat waves, droughts, and heavy precipitation events, so we put the focus on the boreal summer of 2018 and 1976 (the hottest and the 2nd hottest summer in England), as well as the current summer and/or potentially some other extreme season(s), but our experimental setup will allow us to examine a wide spectrum of events. We put forward a template for the generation of counterfactual ensembles based on ERA5 and CERA-20C that could benefit a potential quasi-operational attribution system.

Introduction

Extreme weather and climate events, such as heat waves, cold spells, droughts, and floods, are intrinsic aspects of the time evolution of Earth system, and they can have substantial human, environmental, and economic impacts^{2,3}. Every event is the result of a combination of external drivers, natural (solar forcing and volcanos) and anthropogenic (carbon dioxide emissions, aerosol emissions, land use, etc.), and internal variability. Event attribution is an emerging field that aims to answer what is the role of anthropogenic drivers in an extreme event. More specifically, the risk-based or probabilistic event attribution assesses to what extent anthropogenic forcing modify the probability and/or magnitude (intensity, duration, and spatial extent), and hence the risk of an extreme event or a class of events to occur^{4,5,6}.

Skilful probabilistic prediction and attribution of events based on ensemble forecasts benefit us along numerous socio-economic dimensions (e.g., contributing to water management, food production, and planning of adaptation strategies). An ensemble forecast enables us to represent uncertainties in the forecasting system that arise from errors in the initial conditions (IC) and in the forecast model (due to approximations in governing equations and numerical methods)⁷. Ensemble forecasts involving only IC uncertainties tend to be under-dispersive (thus over-confident), so a further increase of an ensemble spread due to the inclusion of a representation of model uncertainties typically leads to improved forecast skill⁸

² Ciais P. et al., 2005, Europe-wide reduction in primary productivity caused by the heat and drought 2003, *Nature* 437(7058): 529–533.

³ Barriopedro D., et al., 2011, The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science* 332, 220–224.

⁴ Allen M.R., 2003, Liability for climate change. *Nature* 421(6926):891–92.

⁵ Stott P., et al., 2016, Attribution of extreme weather and climate-related events. *WIREs Clim. Change* 7:23–41.

⁶ Otto F.E.L., 2017, Attribution of Weather and Climate Events, *Annu. Rev. Environ. Resour.* 42:627–46.

⁷ Leutbecher and Palmer, 2008, Ensemble Forecasting, *J. Comput. Phys.* 227:3515-39.

⁸ Buizza, R., et al., 1999, Stochastic representation of model uncertainties in the ECMWF ensemble prediction system, *Q.J.R.Met.Soc.*, 134:2051-66.

and a potentially better sampling of extreme states (i.e. tails of distributions). The crucial objective is to enhance ensemble spread through a physically consistent representation of model uncertainty. The operational ECMWF ensemble prediction system uses the Stochastically Perturbed Parameterization Tendencies (SPPT) scheme that applies multiplicative noise to the net of physics parameterization tendencies (radiation, convection, and cloud physics, turbulent diffusion and gravity wave drag) leading to improved forecast skill⁹, but due to practical limitations the SPPT scheme does not perturb the tendencies over the entire atmospheric column and ensemble members no longer necessary conserve energy. The novel Stochastically Perturbed Parameterization (SPP) scheme has a targeted process-level approach by applying perturbations with specific prescribed means and standard deviations to loosely constrained parameters and variables inside of specific parameterization schemes. In this project, we will use the SPP scheme involving 20 key parameters and variables in the ECMWF Integrated Forecasting System (IFS) parameterizations of turbulent diffusion and sub-grid orography, convection, cloud physics, and radiation¹⁰, and compare it with the SPPT scheme and only IC perturbations for the generation of large ensemble forecasts and attribution of a spectrum of events.

The drive to increase resolution, complexity, and ensemble size in operational forecast systems can no longer rely on Moore's law¹¹ nor on expanding parallelisation, due to technological obstacles at nanoscales and increasing HPC power demands. A reduced numerical precision offers the possibility of a practical trade off allowing further advancement, higher resolution, and more extensive use of Earth system models with already available computing resources.

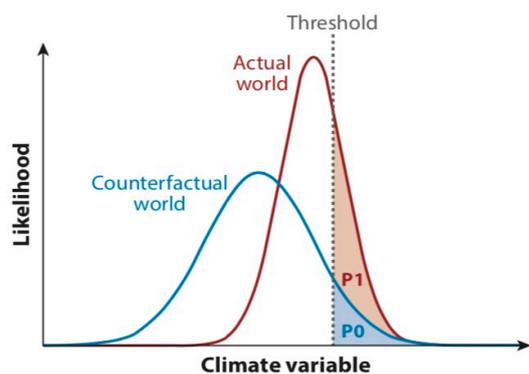


Figure 1: Schematic of the probability distribution functions of a variable under historical/actual climate (red) and in a counterfactual climate that might have been (blue)⁷. The extreme event is defined by a simple threshold (vertical dashed line), and the different probabilities of such an event occurring are marked P1 and P0 (areas under the red and blue curves). Risk ratio (RR) is $P1/P0$, and the fraction of attributable risk (FAR) is $1 - P0/P1$.

Hence, we will utilize a tested single precision option in IFS¹² to generate large ensembles. They are important for robust event attribution because at the foundation of a probabilistic event attribution is the comparison of the historical or actual probability distribution of a variable or a set of variables with the counterfactual (a hypothetical world without anthropogenic climate change) probability distribution¹³. To properly capture these two probability distributions, we need large model ensembles to reliably estimate characteristics of tails and risk indicators (e.g. RR, FAR, etc.) that are of interest to the research and operational communities as well as various stakeholders (Figure 1).

Scientific plan

Step 1: Generation of large actual (using observed forcings) ensemble forecasts with the atmosphere-land configuration of IFS during the periods enveloping the events of interest.

⁹ Palmer, T., et al. 2009, Stochastic Parameterization and Model Uncertainty, Tech. Memorandum 598, ECMWF, Reading, UK

¹⁰ Ollinaho, et al., 2017, Towards process-level representation of model uncertainties: stochastically perturbed parameterization in the ECMWF ensemble, *Q.J.R.Met.Soc.*, 143:408-422

¹¹ Mollick, E., 2006, Establishing Moore's law. *IEEE Ann. Hist. Comput.* 28:62-75

¹² Vána, F., et al., 2017, Single Precision in Weather Forecasting Models: An Evaluation with the IFS. *Mon. Wea. Rev.*, 145:495-502

¹³ NAS, 2016, *Attribution of Extreme Weather Events in the Context of Climate Change*. Washington, DC, doi: 10.17226/21852.

We will use a combination of singular vectors¹⁴ and ensemble data assimilation¹⁵ to represent IC uncertainties from the ERA5 atmosphere-land reanalysis¹⁶ to generate 100 perturbed IC at each start date of interest, so we will produce the following 10-day ensemble forecasts (initialized every 8 days in these periods) using various perturbed-physics options:

- i) 101 members initialized from the best estimate IC (control member) and additional 100 perturbed IC using unperturbed model (i.e. without SPPT or SPP schemes)
- ii) 100 members initialized from 100 perturbed IC plus using SPPT scheme⁹
- iii) 100 members initialized from 100 perturbed IC plus using SPP scheme¹⁰

Step 2: Analysis of ensemble spread and skill of actual forecasts of a wide spectrum of events: What is the impact of the applied SPP scheme versus the default SPPT scheme?

The SPPT and SPP schemes represent different aspects of model uncertainty hence it is important to assess differences in their medium-range forecast skills in not only very extreme events (such as intense heat waves, droughts, and floods), but also in a wider spectrum of events (to better sample the whole distribution) in both hemispheres to avoid preconditioning our verification sample (i.e., to avoid “the forecaster’s dilemma”¹⁷). Furthermore, the forecasted events will be closely examined from the point of how skilfully the associated circulation is realized. We will use ERA5 and available observations as the references.

Step 3: Generation of associated large counterfactual ensemble forecasts (here, more precisely, scaling back the anthropogenic forcing factors to the beginning of the 20th century) during the periods encompassing the events of interest. This is a critical step for the attribution part of the project LARGO that could be of benefit to a potential quasi-operational event attribution system build on the IFS.

We are going to perform the attribution of the selected actual events with respect to the climate of the first decade of the 20th century as captured by the CERA-20C coupled climate reanalysis (covering the 1901-2010 period)¹⁸. To construct counterfactual IC as close as possible to actual IC, but under the climate conditions at the beginning of the 20th century, for each start date of interest and from each actual IC we will remove the 2010-2019 mean IC averaged over the 10 ERA5 ensemble members and then put this actual IC residual (anomaly) on the top of the 1901-1910 mean IC averaged over the 10 CERA-20C ensemble members. Furthermore, in a similar manner we will take the residuals of ERA5 SST and SIC with respect to the 2010-2019 climate and add them to the CERA-20C 1901-1910 climate to force counterfactual forecasts at the ocean and sea-ice boundary. Of course, possible grid-cell unphysical values of counterfactual SIC in polar regions must be thermodynamically corrected with counterfactual SST before the launch. Also, we will force the counterfactual forecasts with the 1901-1910 mean greenhouse gas concentrations and aerosol loadings used in CERA-20C. We will perform large counterfactual 15-day ensemble forecasts (initialized every 8 days over the periods of interest) using different perturbed-physics options in the same ways as specified in the Step 1.

The first decade of the 20th century in CERA-20C does not exactly represent pre-industrial climate conditions, but it is acceptably close for the purpose of this project and it allows us to examine the influence of the bulk of anthropogenic historical forcings through the translation of the underlying climate conditions from the current decade to the first decade of the 20th century. We hope that the successor of CERA-20C will extend such coupled climate reanalysis further back in time (perhaps to the mid-19th century or even earlier) so

¹⁴Leutbecher, M, and Lang, S.T.K, 2014, On the reliability of ensemble variance in subspace defined by singular vectors, Q.J.R. Met. Soci. 1453-66

¹⁵Buizza, R., et al., 2008, Potential use of an ensemble of analyses in the ECMWF ensemble prediction system, Q.J.R. Met. Soci., 134:2051-66

¹⁶Hersbach, H., et al., 2018, Operational global reanalysis: progress, future directions and synergies with NWP, ERA Report Series 27, ECMWF, Reading, UK

¹⁷Lerch, S., et al., 2017, Forecaster’s dilemma: Extreme events and forecast evaluation. Statistical Science, 32:106-127.

¹⁸Laloyaux, P., et al., 2016, A coupled data assimilation system for climate reanalysis, Q. J. Royal Meteorol. Soc, 142:65-78.

that in the future this counterfactual approach could be utilized with the respect to the climate conditions experiencing even less anthropogenic influence.

Step 4: The event attribution of the selected extreme events using generated large actual and counterfactual ensemble forecasts.

We plan to use large actual and counterfactual forecast ensembles to perform robust non-parametric event attribution^{5,13} (e.g. estimating RR, FAR, and other risk indicators). We are not in position to directly assess the skill of counterfactual forecasts, of course, but we can use available observations and CERA-20C (and soon the NOAA-CIRES-DOE 20th Century reanalysis v3¹⁹) to perform parametric event attribution^{5,13} of the classes of our extreme events of interest, and thus indirectly get an assessment of the counterfactual skill through the comparison of risk indicators in these two approaches. Our suite of large ensembles will allow us to examine the influence of different perturb-physics schemes on the attribution results. Furthermore, our event attribution analysis will be conditioned on the atmospheric circulation^{20,21}, therefore we will be able to disentangle the dynamic and thermodynamic components of the anthropogenic contribution, and to assess the model biases relevant for the selected individual and compound extreme events (i.e., to assess if the relevant circulation patterns and their statistics are adequately represented in our IFS forecasts).

Events of interest

In the boreal summer of 2018 persistent soaring temperatures and droughts from Greece to Sweden led to health warnings, serious harm to crops and numerous wildfires. On 4 August 60% of Portugal endured temperatures above 40°C. It was the hottest summer on record in England just barely beating the summer of 1976. Other continents experienced exceptional extremes as well: In Japan, unprecedented heavy rain on 6-7 July led to more than 200 deaths and an evacuation order encompassing 1.9 million people, while the following heat wave lasted more than three weeks during which on 23 July the temperature reached 41.1°C in Kumagaya - the country's highest value ever recorded. Furthermore, this summer of 2019 has already started with the national maximum temperature records for June being toppled in Germany, Poland, and the Czech Republic, while the temperature in southern France (Gallargues-le-Montueux) reached 45.9C on 28 June which is now the new highest value on the country's record (breaking the previous record from the summer of 2003).

We are going to focus the special project LARGO on the following periods:

- 1) 2018 boreal summer: from mid-June to late August (70 days of forecast resources). The last summer Europe-wide heat wave and drought was a part of the larger northern hemisphere heat wave (e.g. encompassing also the northeast Asia).
- 2) 1976 boreal summer: from mid-June to late August (70 days of forecast resources). It was then the hottest summer for more than 350 years in the Central England Temperature record, and it was accompanied by a severe drought.
- 3) 2019 boreal summer (and possibly some other period of interest): we reserve 60 days of forecast resources to examine the currently unfolding heat wave (late June) and other events later this summer or in some other years or seasons (e.g. 2003 or ...).

Model and computer resources

We propose to use the IFS Cycle 45r1 in the atmosphere-land mode with single precision, but of course at the beginning of the LARGO project we could adapt some other cycle and/or release that could be potentially more suitable or efficient for the generation of our

¹⁹Slivinski, L.C., et al., Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system, submitted to Q. J. Royal Meteorol. Soc.

²⁰Vautard R., et al., 2016, Attribution of human-induced dynamical and thermodynamical contributions in extreme weather events, *Envir. Res. Lett.*, 11.

²¹Harrington, L.J., et al., 2019, Circulation analogues and uncertainty in the time-evolution of extreme event probabilities: evidence from the 1947 Central European heatwave, *Clim Dyn.*

large ensembles. ECMWF user support has kindly provided us with the estimate of computing costs in terms of SBUs with Tco399 (~50 km) L137 resolution:

288 SBU per ensemble member per forecast day with single precision (30 min time step). (The typical prepIFS settings run an ensemble member on 6 nodes (216 physical CPUs) with a total of 72 MPI tasks and 6 OpenMP threads per task and using 2 hyperthreads per CPU. Memory requested is 10236 MB per MPI task.)

Hence, a 10-day forecast of 301 actual ensemble members costs about 0.867 M SBU, while the associated 15-day forecast of 301 counterfactual ensemble members costs about 1.300 M SBU (combined 2.167 M SBU).

In the case of an actual 10-day forecast, if we have a longer lasting event under our scope we will use the 2 last days for matching with the following forecast segment yielding in effect an 8-day run. In the case of a counterfactual 15-day forecast the first 5 days will likely experience an initialization shock, so we will focus on the last 10 days and again, if necessary for a longer event, use the last 2 days for matching with the following forecast segment and thus we will be in effect dealing with an 8-day run.

Therefore, the planned 200 forecast days encompassing the selected spectrum of events in three or more years at the maximum require 25 units of 8-day forecasts that in total (301 actual and 301 counterfactual ensemble members) cost 54.175 M SBU, hence we are asking for two years of computing time at ECMWF of 27.2 M SBU each year.

The requested data storage volume in the first (second) year is 40 TB (60 TB).