REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Italy

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Project Title: Downscaled subsampled seasonal predictions of summer temperature in the Greater Alpine region

If this is a continuation of an existing project, please state the computer project account assigned previously.		
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☒	☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	45 000 000	50 000 000	25 000 000
Accumulated data storage (total archive volume)[2]	[GB]	40 000	60 000	70 000

EWC resources required for project year:		**2025**	**2026**	**2027**
Number of vCPUs	[#]			
Total memory	[GB]			
Storage	[GB]			
Number of vGPUs[3]	[#]	0	0	0

[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.
[3] The number of vGPU is referred to the equivalent number of virtualized vGPUs with 8GB memory.

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Extended abstract

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 10,000,000 SBU should be more detailed (3-5 pages).

1. Motivation

The frequency, intensity and duration of heat extremes have been increasing since the middle of the twentieth century on the global scale and these are expected to further increase in the future because of anthropogenic global warming (Seneviratne et al. 2021). Predicting heat extremes several months ahead is becoming increasingly important, especially for their impacts on socio-economic and environmental systems and human health (e.g., Ebi et al. 2021). Seasonal climate predictions are widely recognised as an important tool to support decision-making in the heath sector (see e.g., Shumake-Guillemot, J., et al., 2016) and their application in this area is documented worldwide (WMO, 2023). In this context, the Horizon Europe project TRIGGER (coordinated by University of Bologna and that sees ECMWF as a partner; https://project-trigger.eu/) aims to identify, monitor and quantify the impact of extreme heat and other climate-induced environmental hazards on human health through the direct collection of health, weather-climate, environmental and socio-economic data with user-friendly tools. The project addresses this objective also by developing usable seasonal predictions of innovative climate-health impact indicators and by testing their application in 5 demonstration labs across different climatic and socio-economic contexts in Europe.

A key knowledge gap in this scenario is the poor or limited skill in predicting extreme heat in many regions of Europe and their uptake by local communities is still hampered by high uncertainty in the predictions and lack of information at a spatial scale that is relevant for decision-making. Another fundamental limitation of SPSs is their coarse resolution (about 100 km at mid-latitudes), which prevents them from capturing the complex fine-scale heterogeneity of seasonal variability.

Both dynamical and statistical downscaling can be applied to downscale SPSs (Xue et al, 2014, Feddersen and Andersen, 2004). However, most of the attempts conducted until now used quite coarse resolutions (e.g., Freire et al, 2022, Sangelatoni et al, 2019), sometimes without finding an added value of the downscaling with respect to the coarse global model (Manzanas et al, 2018). Consequently, the resolution reached in dynamical downscaling exercises documented so far in the scientific literature was often not sufficient to fill the gap between data needs by stakeholders (e.g., Fig. 1 of Smid and Costa, 2018).

The low prediction skills of SPSs for European heat extremes is partly attributable to the underestimation of predictable components of climate variability in the model ensemble (Dunstone et al., 2023). In this context, it has been recently shown that the predictive skills of state-of-the-art SPSs can be enhanced by refining ensemble dynamical forecasts using the subsampling technique (e.g., Neddermann et al., 2019). This approach involves retaining only those ensemble members that meet specific statistical criteria related to atmospheric circulation, allowing to better capture the phase of observed atmospheric variability. This, in turn, amplifies the amplitude of predictable components of climate variability compared to the ensemble mean and increase the SPS prediction skills. By increasing the skill while reducing the ensemble size, subsampling methodology may reveal an unprecedented opportunity to produces low-cost, high-resolution and skilful seasonal predictions in Europe.

Here we combine a novel subsampling methodology (Famooss Paolini et al., 2024), broadly consistent with the approach of Dobrynin et al., 2022, and a high-resolution dynamical downscaling technique to produce a set of downscaled seasonal predictions in the Greater Alpine Region. The chosen domain includes 3 of the 5 labs of the TRIGGER project (namely the cities of Bologna, Geneva and Augsburg), enabling a readily uptake by local community and test applications in real-life environment. In terms of forecast skill this is a transitional region that includes very skilful and poorly performing seasonal predictions and where skill comes both from a long-term trend and from interannual variability (see Prodhomme et al., 2021)

Finally, this area is characterized by a complex orography, with the steep Alpine mountain ridge in the centre of the selected domain. Even though the Added Value (AV) of dynamical downscaling of climate simulations is a debate point, in this peculiar area there is agreement that RCMs nested in global simulations can significantly enhance the simulation skills (Torma et al, 2015, Ban et al, 2014, Prein et al., 2013). Complex orography is a local forcing that significantly modifies the climate signal at small scales. Consequently, in this area the dynamical downscaling can improve the GCM skill, simulating physical phenomena do not present in the global model (e.g., breeze and convective cells) and reproducing more accurately the spatial distribution of surface variables such as temperature (Giorgi et al, 2015). The proposed activities outline an innovative approach that can renew the interest of the community in dynamical downscaling of climate predictions and bridge the gap between the forecast products and the decision-making context.

2. Scientific plan

Planned activities can be summarised in the following three tasks:

1) Subsampling of ensemble members from seasonal forecast systems provided by the Copernicus Climate Change Service

2) Dynamical downscaling of the sub-selected ensemble members

3) Assessment of the forecast skill and the added value of the downscaled predictions

The three streams of activities are detailed in the three sections reported hereafter.

2.1 Seasonal forecast systems and subsampling methodology

The project will use seasonal forecast data provided by the Copernicus Climate Change Service (https://confluence.ecmwf.int/display/CKB/Description+of+the+C3S+seasonal+multi-system), including the ECMWF system. A teleconnection-based subsampling methodology will be adopted, following the approach suggested by Dobrynin et al. (2022). This approach relies on subsampling the SPS ensemble by retaining only a fraction of the ensemble members that better capture the link between the summer North Atlantic Oscillation (NAO) and its predictors in the preceding season (spring). This means selecting the members that predict the summer NAO as closely as possible to its statistical predictions based on spring predictors. The summer NAO is selected as weather regime of interest because it accounts for the largest percentage of the summer low-frequency atmospheric variability over the North Atlantic sector (about 35%). Therefore, downscaling only those ECMWF members that better represent the summer NAO variability is expected to provide more reliable predictions of the variables of interest on the small spatial scale compared to using the full multi-member ensemble. Other modes of variability, such as the Eastern Atlantic, that are associated with heat extremes in parts of the target regions, will be considered, although Famooss Paolini et al. (2024) suggest that model biases prevent their applicability. We adopt as predictors of the summer NAO the April state of the North Atlantic Sea surface temperature (SST), the Arctic sea-ice concentration (SIC), the North Hemisphere snow cover and the zonally-averaged zonal wind in the lower stratosphere. Indeed, the state of these climatic components has been previously shown to play an important role for the summer NAO variability (e.g. Baker et al. 2019; Wang and Ting 2022). The NAO statistical predictions from the ERA5 dataset are obtained from the detrended area-weighted anomalies over regions of statistically significant correlations between NAO and each April predictor. Specifically, these areas are detected correlating the summer NAO and each of the predictors until the year before the forecasted year. This means for instance to use data in the 1950—1992 period to forecast year 1993, data during 1950—1993 for the forecast year 1994. Similarly to the approach followed by Hurrell et al. (2003), the NAO index is defined as the leading principal component of the summer Z500 over the North Atlantic, both for the ERA5 dataset and the ECMWF SPS.

2.2 Dynamical downscaling

Downscaling involves the extraction of more detailed spatial climate data from the coarser-resolution outputs generated by Global Climate Models (GCMs), and on a refined temporal resolution. Two major approaches have been commonly adopted, namely dynamical and statistical downscaling. Dynamical downscaling employs high-resolution Regional Climate Models (RCMs) to generate realistic climate information. However, the accuracy of RCM output depends on the quality of GCMs (or SPSs), and it can still contain errors, often necessitating bias correction. Conversely, statistical downscaling establishes empirical relationships between historical large-scale atmospheric data and local climate variables (Fowler et al., 2007). Once validated, these relationships are used to predict future local climate variables based on projected atmospheric conditions from GCMs (or SPSs). This method can provide site-specific climate projections, offering higher resolution than RCMs. However, it relies on the assumption that current large-scale to local climate relationships remain consistent in future climate. Nevertheless, this assumption may not universally hold true (Slonosky et al., 2001), and consequently statistical downscaling methods tend to underestimate variability and may poorly represent extreme events (Jang and Kavvas, 2015). A dynamical downscaling approach is planned for this study because our aim is to investigate seasonal predictability of extreme weather events in a complex orographic area, hopefully obtaining an AV with respect to SPSs and statistical downscaling, according to other studies that dynamically downscaled GCMs (Fosser et al, 2015, Ban et al., 2014, Prein et al., 2013, Kanada et al., 2013). As discussed in section 2.3, the quality of dynamically downscaled predictions will be compared with statistically downscaled forecasts and the global SPSs used to initialize the RCM for the three case studies of the TRIGGER project.

The RCM used for the dynamical downscaling in this study is the Weather Forecasting and Research (WRF) model (Skamarock et al, 2019), that has already been used several times to downscale climate data (Lo et al, 2008, Caldwell et al, 2009). WRF simulations will be initialized with the subsampled ECWMF seasonal forecasts selected before. Those data are characterized by 13 pressure levels and have a grid-spacing of 1°x1°, hence about 100 kmx100 km at the mid-latitudes. An additional WRF simulation will be performed downscaling ERA5 with the same model configuration: this simulation will be the benchmark against which will be assessed the skill of the downscaled sub-sampled ensemble. The downscaling will be done with three one-ways nested domains (Table 1), with a spatial resolution of 27 km (d01), 9 km (d02) and 3 km (d03). ERA5, that has a resolution of about 25 km at the mid-latitudes, will be downscaled with only the two innermost nested domains (d02 and d03). These three nested domains have been selected after some tests, where the skill and the computational costs of different choices were evaluated. Tests carried out downscaling ERA5 using a single domain from 25 km to 3 km was less skilful in reproducing 2m temperature and 2m relative humidity in the urban area of Bologna than the three nested domains described before, without an improvement in the computational time. Another test performed adding a fourth d04 domain with 1 km of grid-spacing showed that this simulation was as skilful as the one with 3 km of grid-spacing, suggesting that the d04 domain is not necessary for our purposes.

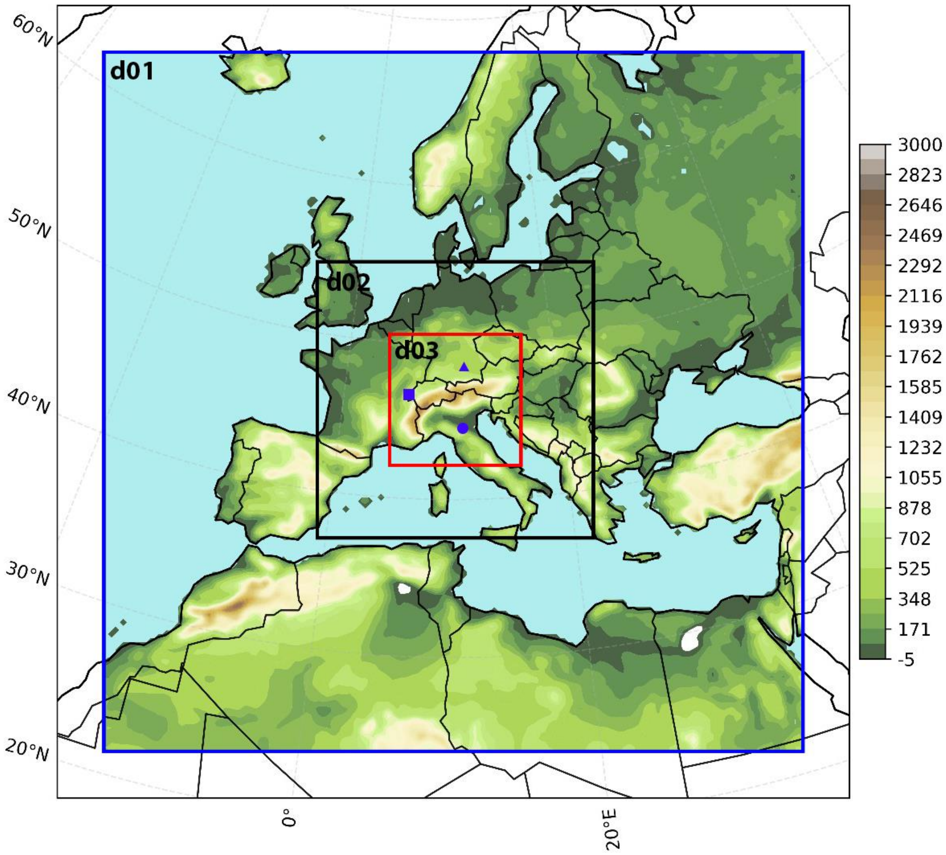

Fig. 1: Orography (m, colour shading) in the outermost d01 WRF domain with 27 km of grid-spacing (blue contour). The two inner domains d02 and d03 are highlighted with, respectively, black and red contours. The CHC labs of Bologna (Italy), Augsburg (Germany) and Geneva (Switzerland) are highlighted with respectively a blue circle, triangle and square.

The domain is designed to include three TRIGGER Climate-Health Connection (CHC) labs of Bologna (Italy), Augsburg (Germany) and Geneva (Switzerland) in the innermost d03 domain, enough far away from its boundaries (e.g., as in Fig.

1). The resulting d03 domain covers the Greater Alpine Region, where dynamical downscaling of GCMs showed some of its best performance (Giorgi et al, 2015). The results of these simulations might be used for additional studies on seasonal predictions in this area in the future, beyond those related to the TRIGGER project. Simulations will be performed with 45 vertical levels: tests with less levels showed worse results, while tests with more levels increased the computational costs without improving the results.

Domain	Horizontal grid-spacing	Number of grid-points	Vertical levels
d01	27 km	181x181	45
d02	9 km	214x214	45
d03	3 km	304x304	45

Table 1: characteristics of the three-nested domains

For each year, we will downscale 9 sub-sampled members of the seasonal prediction ensemble and the ERA5 reanalysis data using the downscaling method previously described. The simulations will be initialized the 1st of June (with the seasonal forecasts initialized in May) and they will be run until the 31st of August. This procedure will be replicated each year from 1993 to 2016 (a 25-year period).

2.3 Assessment of the forecast skill and the added value of downscaling

The results of the simulations will be assessed comparing surface observations of weather stations located in the proximity of the TRIGGER HPC labs of Bologna, Augsburg and Geneva, to the nearest grid-points of the downscaled simulations. 2 m temperature, 2 m relative humidity and 10 m wind speed and direction will be assessed and used to compute biases and percentile-based indices (e.g., tx90p, Sulikowska et al, 2020). This assessment will be designed to facilitate the uptake and exploitation by the communities involved in the three labs of the TRIGGER project. Health-related indices such as the Universal Thermal Climate Index (UTCI, Błażejczyk et al, 2013) will be computed as a secondary output of the model at post-processing state. This evaluation will be performed for the global ECMWF SPS, the downscaled sub-sampled seasonal predictions, and the downscaled ERA5 reanalysis. Comparison with other high-resolution reanalysis such as CERRA (Schimanke et al, 2021) and SPHERA (Giordani et al., 2022) is planned as well. The results of statistical downscaling from the same SPSs for the three TRIGGER labs will be compared with those obtained through dynamical downscaling. This comparison aims to evaluate the AV of our new method.

3. Justification of Computational Resources

The estimate of the computational resources is based on the preliminary tests that we did in the Open Physics Hub (OPH) cluster managed by the Department of Physics and Astronomy of the University of Bologna (https://apps.difa.unibo.it/wiki/oph:cluster:resources). . Specifically, we performed a model run parallelized with 112 cores, simulating the weather of one week (from 1st June 2023 to 7th June 2023) and with the model configuration desired for the final experiments. Such a run took about 20 hours. Consequently, considering that we have to downscale 10 simulations (9 sub-sampled members plus ERA5) for 3 summer months for 25 years, an estimate of 114 670 080 SBU is obtained (Table 2). These preliminary simulations are used as a reference for the estimation of the computational resources needed by the project.

Number of years that we want to simulate	Number of ensemble members	Estimate time (hours) of one simulation (tests on OPH cluster)	Cores used in the OPH cluster	Testing and post-processing	Total SBU
25	10	240	112	5 329 920 SBU	120 000 000 SBU

Table 2: estimated SBU necessary to run the downscaling of the sub-sampled ensemble.

An addition of 5 329 920 SBU is added to short experimental runs and post-processing of model outputs, for a total of 120 000 000 SBU. The computational resources are distributed mostly in the first two years (45 000 000 SBU and 50 00 000 SBU), when we expect to perform most of the simulations, while a smaller amount is reserved for the last year of the project.

Regarding data storage, we are planning to store both WRF outputs in NetCDF files and time series lists (tslist). NetCDF outputs are useful for performing spatial analysis of relevant fields, while time series lists are useful for detailed comparisons between simulations and observations in the studied areas. NetCDF files saved every 6 hours for all the integration domains result in approximately 223 GB for one simulation (one season). Tslist files for 12 points (4 weather stations for each CHC lab) archived for the same period result in a weight of 48 GB. Consequently, considering the 10 ensemble members over 25 years, the total estimated data storage required is 67 750 GB. This estimate does not include initial and boundary conditions, which occupy 37 GB per single member per year. We are not planning to archive these data after the simulation is performed. Considering the space devoted to archive static geographic data and some initial and boundary conditions needed to perform the simulations, a demand of an additional 2.25 TB is estimated. Thus, the total amount of data storage that we expect to use is 70 000 GB (Table 3).

Number of years that we want to simulate	Number of ensemble members	Estimate weight of netcdf output files for 1 simulation (tests on OPH cluster)	Estimated weight of tslist output files for 1 simulation (tests on OPH cluster)	Extra space for initial and boundary conditions, static data and buffer	Total data storage
25	10	223 GB	48 GB	2 250 GB	70 000 GB

Table 3: estimated total data storage.

4. Technical characteristics of the code to be used

For this project version 4.5 of the Weather Research and Forecasting model (WRF) will be used. WRF is a non-hydrostatic fully compressible model widely used for atmospheric research. To be compiled WRF needs gfortran, gcc and cpp compilers, as well as netCDF libraries and MPICH or Open MPI libraries to be run in parallel. The WRF Preprocessing System (WPS) is necessary to initialize the simulation. Additionally, the NCL (NCAR Command Language) will be installed and used to display results from simulations. CDO and ECCODES libraries will be likely necessary as well to manage netcdf and grib files in the pre-processing and post-processing of data.

5. Reference

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