REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: The Netherlands…………………………………………………………

Principal Investigator[1]**:** Geert Lenderink………………………………………………………

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Project Title: Future Weather: weather predictions of rainfall extremes in past, present and future climate conditions……………………………………………

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To make changes to an existing project please submit an amended version of the original form.)

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ………….	
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 X☐	NO ☐

Computer resources required for project year:		**2025**	**2026**	**2027**
High Performance Computing Facility	[SBU]	60,000,000	60,000,000	60,000,000
Accumulated data storage (total archive volume)[2]	[GB]	3,000	6,000	10,000

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

Continue overleaf.

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[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).

Summary

With a large number of convective rainfall extremes happening in recent years, the question of whether and how they are influenced by climate change is of paramount importance. While it is commonly understood that rainfall extremes will increase due to increases in humidity following from the so-called Clausius-Clapeyron relation, the rate at which increases occur is uncertain (Fowler et al. 2021b, a). In particular small-scale dynamical processes happening in the cloud (changing updraft strengths) and below the cloud (cold pool dynamics) could well cause deviations from the expected increase due to the humidity increases (Lenderink and van Meijgaard 2008; Lenderink et al. 2017; Fowler et al. 2021b; Lochbihler et al. 2021). These processes start to be resolved in convection permitting climate models (CPMs) and global storm resolving earth systems models, which run at resolutions higher than 5 km. Yet, these extremes are also rare in terms of local return times, typically only occurring once every 100 years at the specific location of the extreme events. The combination of both – the necessity of high resolution and the local rarity of the event – is an enormous scientific challenge. From typical "free" climate simulations – using global climate models, either running at storm resolving scales, or embedding a CPMs into a global climate model – it is very challenging to look at the dynamical changes occurring for events similar in type and as rare as the observed one, and extensive statistical processing (for example, regional pooling of data) needs to be applied to get the information needed. This implies that the information obtained from common free climate simulations may not be sufficiently representative for the extremity of the event, or suffers from misrepresentation of regional specific effects (such as for example, the interaction with the topography). Here, we use the approach of pseudo global warming (PGW) in a semi-operational forecasting setting to improve on this situation. Starting from ECMWF analysis, forecasts are made with a combination of a 12 km climate model (RACMO) and embedded a convection permitting models HCLIM (2.5 km). Forecasts are repeated for colder (-1.5 degrees) and warmer (1.5 and 3 degrees global warming) climates based on PGW perturbations derived from global climate modelling (CMIP6). For 1.5 degrees it uses a perturbation based on the mean CMIP6 response, whereas for 3 degrees the response is separated into a relative wet and dry large-scale response, giving in total 5 large-scale settings (1 past, 1 present, and 3 future) in which the extreme can be simulated. The system runs in ensemble mode using RACMO (4 runs per large-scale setting) and embedded are HCLIM simulations (one per large-scale setting), but this can be extended to the full ensemble when an extreme event occurs. Testing the system on extreme events from the past year shows that it has good performance in terms of representing the observed event, and in many cases shows a well-defined response to warming (and cooling). Moreover, the system allows to look at dynamic changes at the scales of the cloud and the meso-scale. Our focus is on rainfall extremes, but the system also provides information on other convective phenomena, such as wind gusts, that appear to be rather strongly influenced by climate change (Prein 2023). Besides this, we can also look at heatwaves and drought in a climate change setting. In this special project we request the computational resources to run the system for the period 2025-2027. Besides, we also will run extended runs for extreme events happening to answer the question concerning the attribution of the event to climate change.

Background

Summer 2023 and begin summer 2024 were characterized by an unprecedented number of vigorous extremes from organized convective systems, leading to widespread flooding (2023: e.g. Italy: May 1-15; Slovenia: August 3-5; Norway: August, 6-9; several events Mediterranean Sea: September 1-14. 2024: 30 May – 3 June, Bavaria, Germany). More localized showers also caused **massive hail events** in Germany and Italy. Whereas the direction of present and future changes of these extremes is anticipated and mostly understood, **we currently lack a thorough**

understanding of the present rate of change, the severity of future events, and their associated climate risks. Important challenges in this respect are:

1. **Insufficient resolution**: Typical predicted changes in rainfall amounts are following the increases in moisture content — the so-called Clausius-Clapeyron prediction (typically 7% per °C). The IPCC report quotes that changes to the dynamics of convective systems could be important as well and that these could lead to larger increases, but that these changes are still uncertain. One of the reasons is that most of this information is still based on climate models that have a too coarse resolution to resolve the dynamical processes in convective rain systems, and these models rely on uncertain *statistical* descriptions of the involved processes (called "parameterizations"). The lack of sufficient resolution in climate models is therefore considered to be a major obstacle in achieving reliable information on the changes of these type of extremes. **In fact, leading scientist consider higher resolution modeling an essential prerequisite in providing reliable information on climate change impacts (e.g. in nextGEMS).** Therefore, in the last decade a new generation of high-resolution climate models in which the dynamics of convection is (partly) resolved instead of parameterized – globally called Storm Resolving Earth System Models and regionally Convection Permitting Models (CPMs) – has been developed.
2. **Poor signal-to-noise**: However, increases in model resolution also pose a challenge related to signal-to-noise. Since these new high-resolution models have very high computational demands, climate runs are still relatively short with typical simulation lengths of 10-30 years on regional domains (and even shorter for global domains). This implies that they have low signal-to-noise ratios, limiting the use of these models to study how climate change affects rare rainfall extremes. **Thus, high resolution modeling is not a straightforward solution on its own, and needs to be accompanied by effective methods to run and analyze these modeling systems.**
3. **Understanding climate risk in relation to changes in rainfall characteristics:** Climate change will affect the spatial and temporal characteristics of rainfall events, typically leading to more intense rain. Under certain conditions rainfall systems will mainly be more concentrated in time and space with little change to total rainfall amounts, whereas in other conditions rainfall systems could become larger in scale and last longer, also causing large changes to total rainfall amounts. While these effects are uncertain, they do strongly determine the impact of rainfall events. For instance, rapid surface runoff causing a flashflood is determined by rainfall intensities exceeding the capacity of the soil to absorb water and is a highly nonlinear function of rainfall intensity. The deadly flooding of the river Ahr in July 2021 occurred in a few hours only, whereas the attribution study on this event focusses on rainfall amounts over 48 hours and a much larger area (mainly because data on smaller scales is merely lacking). **Thus, the actual impact of a rainfall extreme could well exceed the expectations from the accumulated precipitation change at larger scales.**
4. **Understanding the consequences of climate change by the general public.** Communication on climate change is complex as changes are often expressed in abstract statistics, without context. **Thus, climate change information is not well connected to how people experience the climate, which is through the daily weather.**

Science plan

In the past year we have developed a system based on RACMO in which we can repeat present-day weather for colder ("past climate") and warmer ("future climate") conditions. RACMO is a hydrostatic climate model, run at the moment at 12 km resolution with parameterized convection. The system is based on the so-called Pseudo Global Warming (PGW) approach using an ensemble of simulations with our regional climate model RACMO (12 km resolution). This system shows promising results in reproducing rainfall extremes. An example of the output of the systems is shown in Figure 1, where we show the 2-day accumulated rainfall produced by storm "Hans" over southern Scandinavia in August 2023. A good reproduction of the observed case is shown, as well as a clearly defined response from cooler to warmer climate conditions. The response to warming is in this case quite large, and if we trust RACMO storm "Hans" could have caused a major climate disaster in the future climate, with damages far exceeding the present-day ones. The response in this case is also very robust; and confirmed by the other ensemble members of RACMO.

Yet, analysis of rainfall extremes in RACMO shows that it has biases in the response to warming. As such, RACMO tends to underestimate the sensitivity of rainfall extremes to humidity for moderate humidity values (dew points up to 14 degrees), but start to strongly overestimate the sensitivity when the atmosphere is very unstable (high CAPE) and very humid (Lenderink et al. 2024). This behavior is also strongly visible in the response of summertime rainfall extremes. The convection permitting model HCLIM shows a much more reliable sensitivity to absolute and relative humidity, more consistent with observed relations (Lenderink et al. 2024). Therefore, we will run embedded in the RACMO simulations, HCLIM simulations at convection permitting scales.

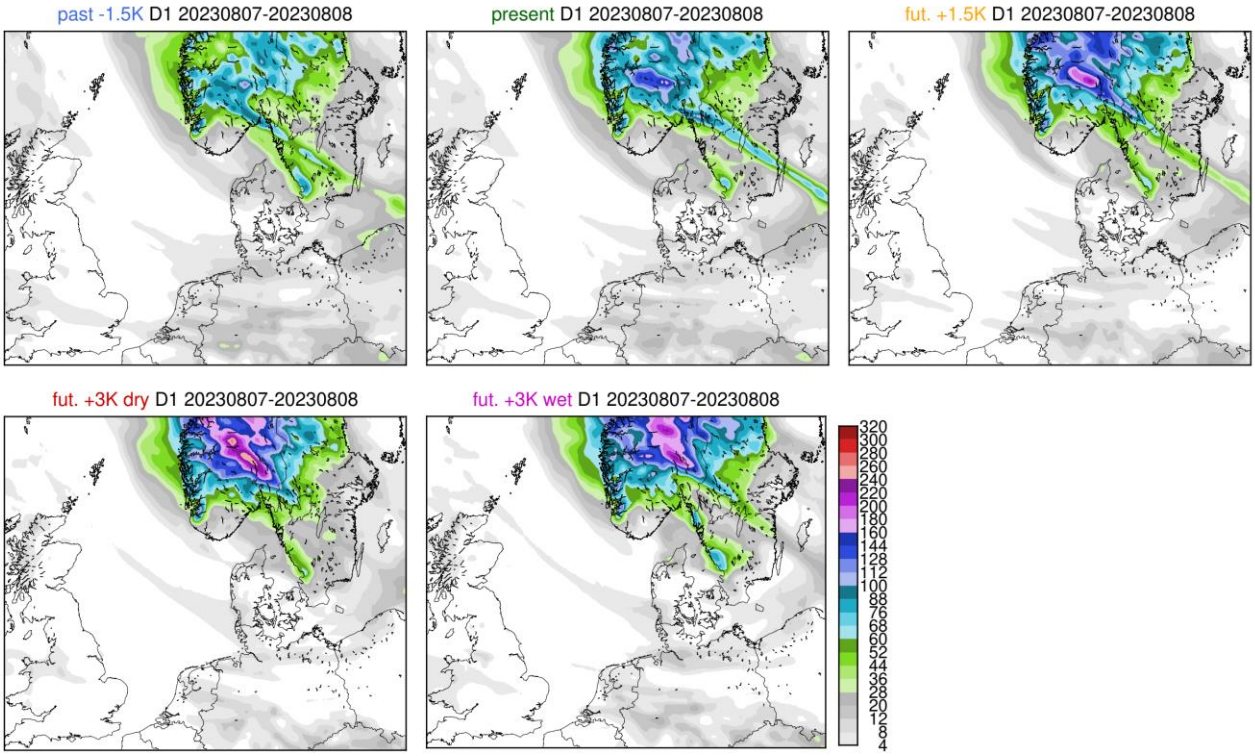

Figure 1. Simulation of rainfall Storm "Hans" for colder past, present, and warmer futures. It is shown that accumulated rainfall increases sharply with warming, approximately at a rate of 10-20% per degree global warming. In a 3 °C warmer world storm "Hans" would have caused a major climate disaster. This result is obtained with the prototype 12 km version of the system using RACMO output. In this case, the control simulation for present conditions is generally close to the observed amounts.

Embedded HCLIM into the system is now being tested for several testcases, covering a range of high impact weather. An example of the control simulation for the spring floods in Italy May 2023 is shown in Figure 2. In this project we will further perform runs for a number of extreme rainfall events. The main target, however, is to run the system (semi) continuously throughout the year, so that information on how a rainfall event is influenced by climate change can be obtained in a few days to a week after the event occurs.

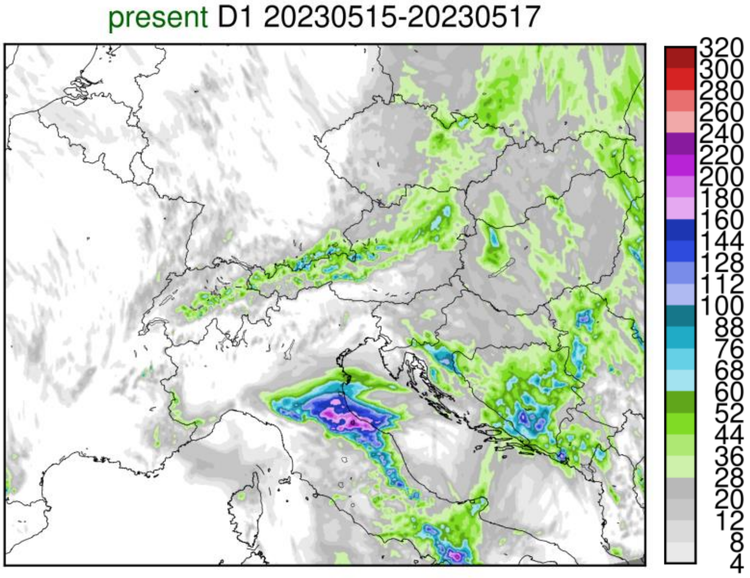

Figure 2. 3-day rainfall accumulation for the most intense rainfall within the spring floods in Italy 2023 with HCLIM, embedded into RACMO, for present-day climate conditions. Observed rainfall amounts in that period are up to 240 mm, and the model faithfully captures those (https://www.cimafoundation.org/en/news/the-italian-floods-of-may-2023-a-scientific-analysis/). The response to warming is currently being investigated, but early results already showed to the potential of a remarked climate change influence. A science paper on this event and a number of other extreme events, and explaining the system in detail is planned to be submitted in fall.

Computation resources

We use the regional climate model HCLIM for the runs. The model uses nonhydrostatic dynamics and an adapted version of the AROME physics, with changes to cloud and turbulence (Belušić et al. 2020). It runs on a domain covering western Europe, roughly 1000x1000 grid points at 2.5 km resolution. Depending on the case, the domain may be adapted. The systems run 72h “forecasts”, starting each day and 5 warming levels, implying that one year of simulations encompasses 15 years of simulations with the model. Besides, we envisage runs with the full ensemble (4 runs starting per warming level for a limited number of cases and a number of test runs to calibrate the model. In total we expect to run 20 years of simulations with HCLIM per project year. Costs per simulation year are 3 MSBU (3,000,000 SBU), so we request a total of 60 MSBU. Data is mainly transferred to our KNMI storage systems (locally and at surfsara.nl).

References

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