

EMI R&D PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year 2026.....

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

Computer Project Account: spnllend

Principal Investigator(s): Geert Lenderink, Christiaan van Dalum, Hylke de Vries, Bert van Ulf and Erik van Meijgaard

Affiliation: KNMI.....

Name of ECMWF scientist(s) collaborating to the project (if applicable)

Start date of the project: 1-1-2025.....

Expected end date: 31-12-2027.....

Computer resources allocated/used for the current year and the previous one (if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	60,000,000	31,689,774	40,000,000	8,600,000
Data storage capacity	(Gbytes)	10 Tb	10 Tb	10 Tb	20 Tb

Summary of project objectives (10 lines max)

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In this project we run continuous forecasts to past, present and future climate conditions. The aim is to establish the influence of climate change on our weather. This can be used in attribution studies, to construct counterfactual climate, and to study processes in a changing climate, for instance related to cloud dynamical changes in rain events. The aim of this special project is running a convection permitting model (HCLIM) embed in coarser resolution (12km) modelling results using RACMO.

Summary of problems encountered (10 lines max)

A scripting system to run the convection permitting model HCLIM within RACMO has been completed and fully tested. However, we still have problems with finetuning HCLIM to perform longer continuous forecasting cycles. During longer simulations with HCLIM it turned out that surface scheme related problems (too much evaporation leading to too dry soil in summer and too high temperatures) prevented us to do the continuous cycles. This year, a number of test runs has been performed with HCLIM to investigate the sensitivity of the simulation to soil parameters. This has led to substantial improvements of the behaviour, yet some model deficiencies still remain. Since September 2025 a continuous forecasting cycle is running in test phase. The reason of underspending of the computing resources is also related to the fact that a continuous forecasting is still in test phase.

Summary of plans for the continuation of the project (10 lines max)

During summer we will replace the test setup with an update of the soil scheme, and do some reruns to establish its performance in the Future Weather system. We will also test the system on an number of recent flood cases. Starting October 2026 we (finally) will have a targeted person working on the system as part of the EXTREME-FUTURES project (UK Royal Society Faraday Grant awarded to Hayley Fowler, Newcastle University). We will be also part of Diode Phase 3, comparing this PGW based forecasting system with the storyline simulation of the DT, which is an exciting opportunity to evaluate the performance of these systems. These developments will raise the computational demands substantially from fall this year onwards.

List of publications/reports from the project with complete references

Summary of results

As indicated above computing resources have been used to improve the model quality, in particular related to deficiencies in the soil water budget. In order not to wait for a *perfect* model, we already started a continuous run in fall 2025, awaiting the model improvements. These two developments are discussed in two sections below.

a. Improvements of the soil scheme

Some HPC resources have been allocated to experiments designed to improve the representation of soil processes in HCLIM. Previous work revealed temperature biases in multi-year HCLIM experiments for most of western Europe during spring and early summer during dry years, limiting further usage of HCLIM for longer simulations. In addition, the scheme showed very rapid transitions from energy limited evaporation to soil moisture limited evaporation, associated with a transition from a too cold bias to a too warm bias. Such transition is not visible in the coarser resolution RACMO simulations that use HTESSEL as a surface scheme (similar to the ECMWF model).

Changing and tuning of surface and soil moisture related parameterizations shows a considerable reduction of summer temperature biases. Figure 1 shows the summer average temperature during a dry summer (2018) with respect to the gridded observational data set of EOBS for an experiment with default HCLIM settings (a) and where surface and soil related changes have been applied incrementally (b-f). With each step, biases are reduced on average.

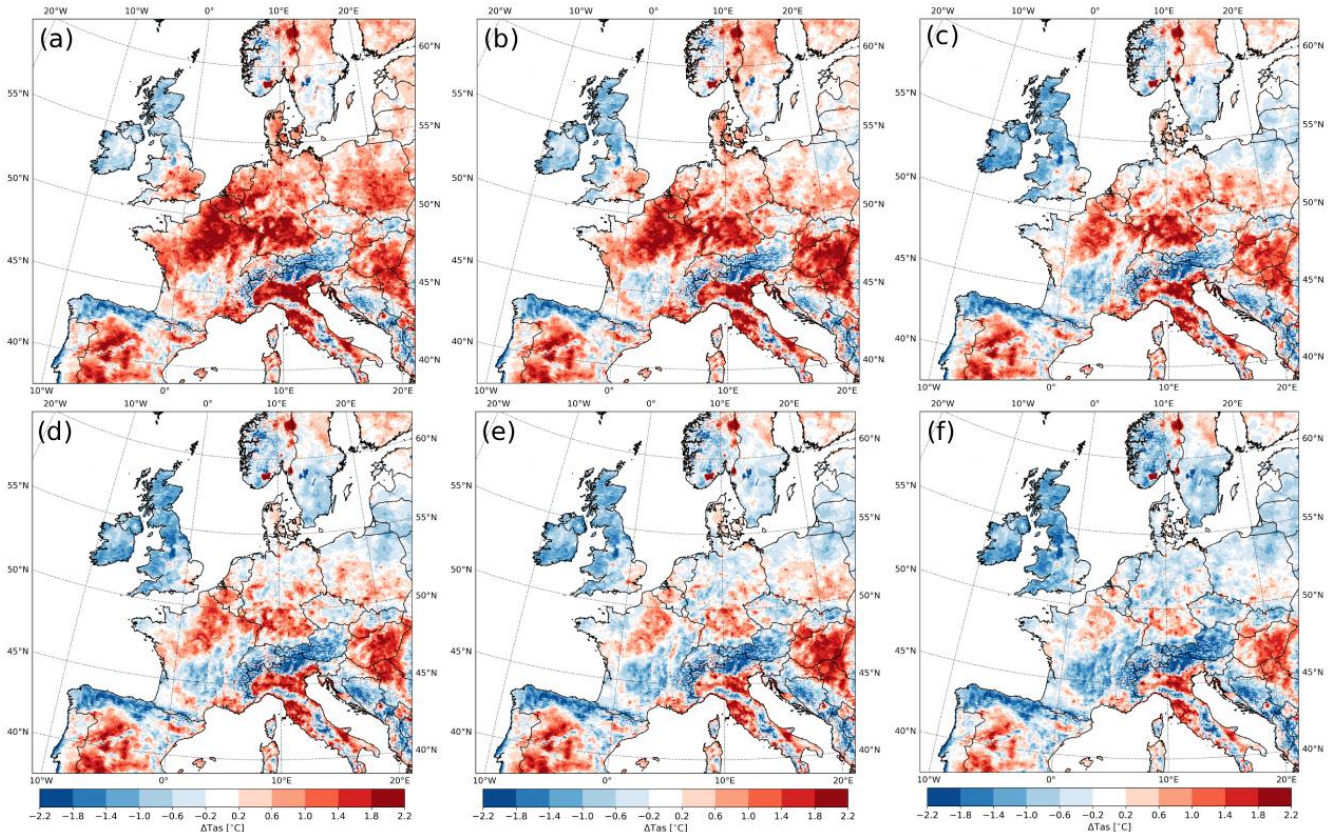


Figure 1: Average summer temperature difference in 2018 of HCLIM experiments with respect to the gridded observational data set EOBS, with (a) HCLIM with default settings and (b-f) with incrementally changing aspects in HCLIM related to surface and soil moisture. With updates in the following parameterizations: (b) root distribution, (c) saturated hydraulic conductivity, (d) soil percolation, (e) field capacity and wilting point and (f) surface albedo.

Several experiments are planned or ongoing, where other aspects of the model are changed. After completion, the final product will be examined and evaluated if HCLIM is then suitable to make reliable multi-year simulations.

b. Results from the test runs of the Future Weather system

The storyline forecasting system has been running in a quasi-operational mode since 1 September 2025. It uses pseudo global warming (PGW) to adjust initial conditions and boundary conditions of the forecast. Each day, a 72-hour forecast is produced for five different climate configurations. By suitably concatenating these forecasts, a continuous time series can be constructed. In this example, the approach is applied to calculate the total precipitation sum for January 2026 using a concatenation of the Day-1 (24–48 h) forecasts. This effectively allows for a 24-hour spin-up period, enabling the PGW simulations to adjust to the altered climate conditions. We here show the added value of the system with two recent examples.

Example 1: Precipitation responses for January 2026

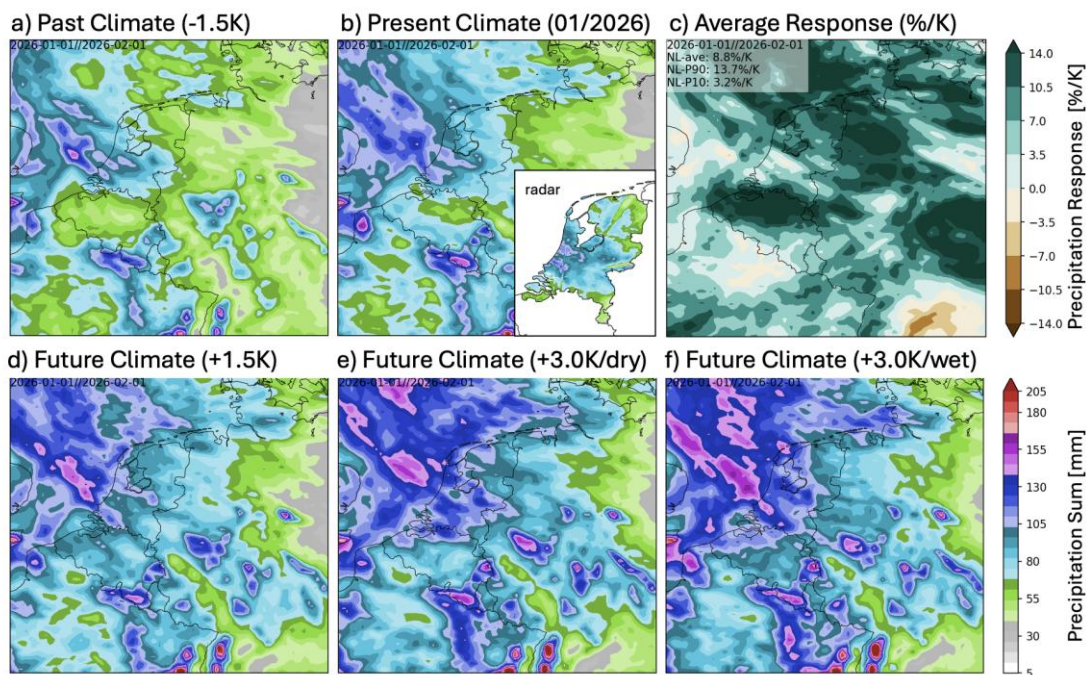


Figure 2: total precipitation sums (mm) in January 2026, as simulated by HCLIM46 using the PGW Future Weather framework. Panels a-b and d-f show the different climate realizations. Panel c shows the ensemble mean precipitation response per degree global warming. Inset in panel b shows accumulated radar data.

January 2026 was a relatively cold month, with substantial snowfall reported particularly during the first decade of the month (see also below). Most precipitation occurred near the coast and in regions with significant elevation. In both the spatial pattern and the total precipitation amounts, the control simulation representing the current climate agrees well with precipitation estimates derived from accumulated radar observations (see inset in panel b), although the radar data contain some spurious line artefacts).

Figure 2c displays the precipitation scaling, expressed as percentage increase per degree of global warming and computed as the ensemble average of the four climate responses after normalisation by their respective warming levels. In line with findings from the broader literature, precipitation increases with increasing levels of warming. Averaged over the Netherlands, the scaling is approximately $8.8\% \text{ K}^{-1}$, somewhat exceeding the Clausius–Clapeyron relation. We note that in typical climate simulations, often the response is sub-CC, in the order of 3–5 % per degree global

warming (see KNMI climate scenarios issued in 2024). So the finding that in this case the response is substantially larger is interesting. Considerable spatial variability is also present in the local scaling values, which is likely affected by internal variability. At coarser resolution (12 km) we also run the system in ensemble mode, using 5 different initial conditions. Downscaling those could help assessing whether some of these patterns are robust and can be physically explained.

This example demonstrates that, despite the PGW system being fundamentally based on relatively short 72-hour forecasts, it is capable of accurately reproducing winter precipitation on monthly timescales.

Example 2: the snowy start of January 2026

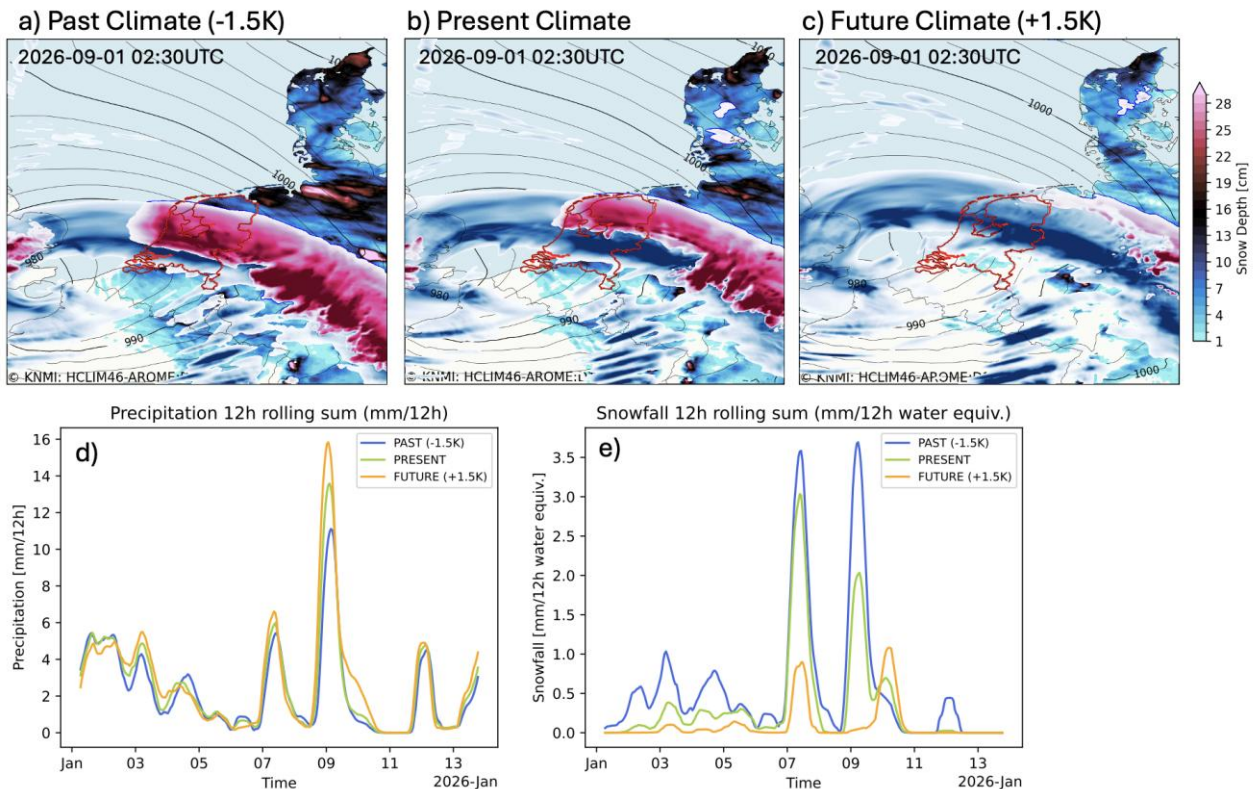


Figure 3: (a-c) Hourly snapshot of HCLIM46 for January 9, 02:30UTC, in three different climates. Blue colours show precipitation intensity, pink colours snowfall intensity (both qualitatively). Thin lines indicate mean sea level pressure. Base layer shading displays the snow deck in cm. Panels d-e show the time evolution of total precipitation and snowfall averaged over the Netherlands.

In the second example, we examine the cold and snowy episode that affected Western Europe, and particularly the Netherlands, during the first two weeks of January 2026. Temperatures were already below average at the start of the year and gradually decreased further until 11 January. This cooling was enhanced by the formation of a snow cover resulting from repeated snow showers. After 11 January, temperatures increased again in the south-western parts of the Netherlands, while the north-east remained somewhat colder, largely due to the persistence of an extensive snow cover over Germany.

From a climate-change perspective, this cold episode is particularly interesting because, although winter precipitation is generally expected to increase with warming (see also Figure 2), the response of snowfall can differ substantially. In regions where snowfall is temperature-limited, warming is expected to reduce snowfall amounts, whereas in regions that remain sufficiently cold even under warmer conditions, snowfall may increase. In practice, such increases are mainly found in regional climate model simulations at very high elevations and in parts of Scandinavia.

The top row of Figure 3 presents a snapshot of the hourly precipitation associated with the low-pressure system that arrived during the night of 9 January. Rainfall is shown in blue shades and snowfall in pink shades, while the background shading represents the existing snow cover. In the southern and western parts of the Netherlands, precipitation mainly fell as rain, whereas snowfall dominated in the northern half of the country. Temperatures were close to 0°C, or locally slightly above, resulting in intense snowfall. In the +1.5 K warmer climate simulation, this precipitation fell predominantly as rain, while in the –1.5 K colder climate simulation snowfall started earlier and extended further south. The figure also reveals small shifts in the timing and exact location of the precipitation front. Such differences may partly result from subtle dynamical changes, but they are also generally expected in a PGW framework in which, besides temperature and humidity perturbations, a small circulation perturbation is applied at the model boundaries.

The time series shown in the lower panels further confirm that mean precipitation intensities generally increase with increasing levels of warming, whereas snowfall intensities decrease, except for a brief period around 10 January. This indicates that, under present-day Dutch winter conditions, snowfall is primarily temperature limited.

An illustration of the opposite response — namely enhanced snowfall under warming — was found during a snowfall episode in Northern Italy in the final week of December 2025, associated with storm “Hans”. In that case, the highest-elevation regions in the warmer-climate PGW simulations received massive amounts of more snowfall than in the present-day climate simulations (Figure 4), with more than a doubling a snowfall at altitudes above 2500m, and almost no snow below 2000 m in the warmest simulations.

Accumulated snowfall related to storm Hans (December 2025)

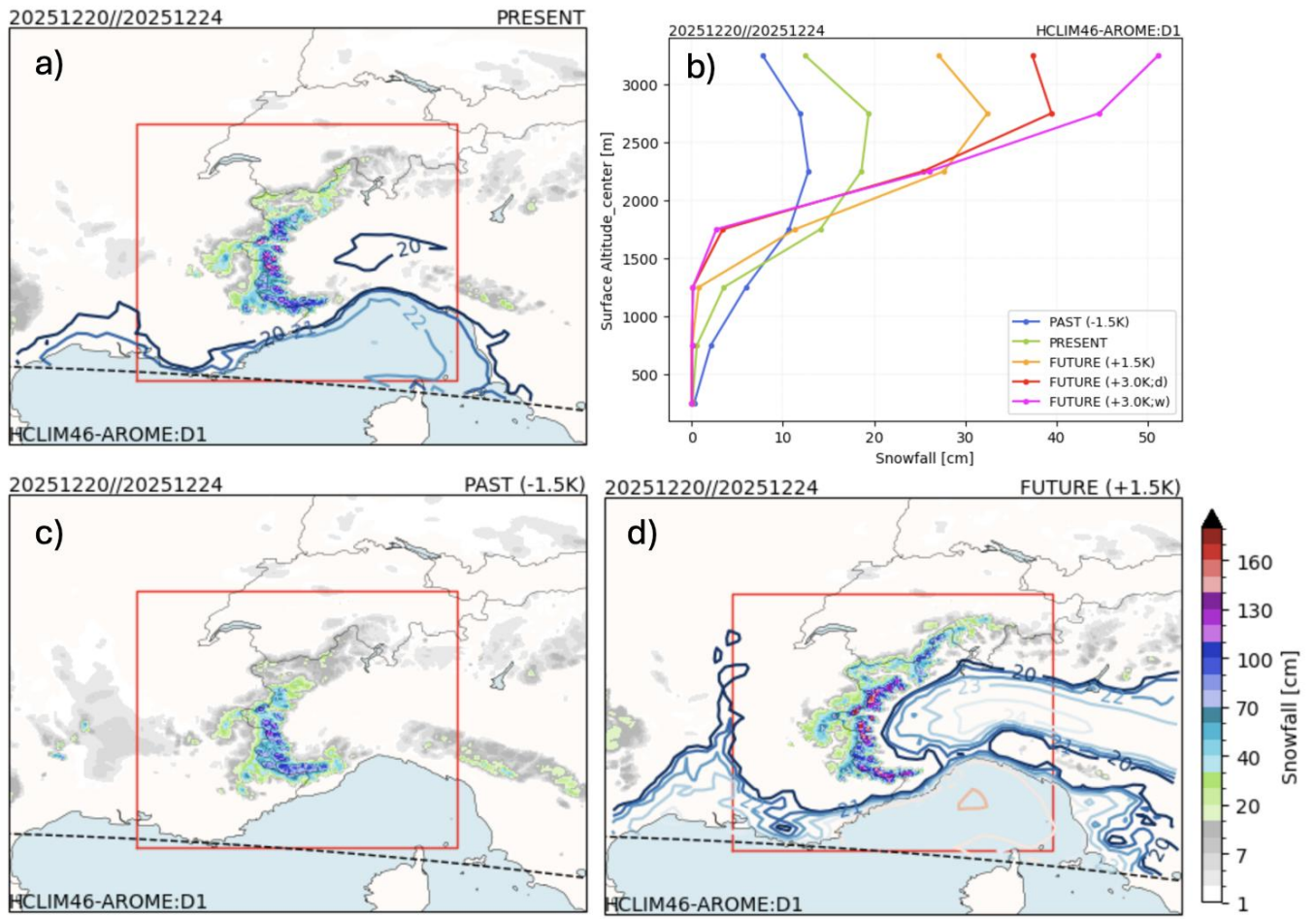


Figure 4: Accumulated snowfall associated with storm Hans, in the third week of December 2025. Shading in panels a, c and d show total snowfall amounts (in mm water equivalent \sim cm snowfall) over the shown period, in HCLIM46 in three different climates. Contours show total precipitable water (prw) above 20 kg/m² (interval 1kg/m²). The dashed line indicates the southern boundary of HCLIM46 simulation domain. Panel b shows snowfall amounts aggregated by elevation within the red box.