REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation: Netherlands/KNMI

Principal Investigator[1]**:** Dr. Eveline van der Linden

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Project Title: High-resolution RACMO simulations of Antarctic atmospheric rivers and surface mass balance under present and future climate conditions

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.)	2027	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for project year:		**2027**	**2028**	**2029**
High Performance Computing Facility	[SBU]	75,000,000	142,000,000	80,000,000
Graphics Processing Unit Cluster-A	[GBU]	0	0	0
Graphics Processing Unit Cluster-B	[GBU]	0	0	0
Accumulated data storage (total archive volume)[2]	[GB]	300,000	858,000	1,215,000

EWC resources required for project year:		**2027**	**2028**	**2029**
Number of vCPUs	[#]	-	-	-
Total memory	[GB]	-	-	-
Storage	[GB]	-	-	-
Number of vGPUs[3]	[#]	-	-	-

Continue overleaf.

[1] The Principal Investigator will act as contact person for this EMI R&D 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

Scientific objectives

Atmospheric rivers (ARs) are major contributors to Antarctic precipitation and surface melt and play an increasingly important role in the variability of the Antarctic Ice Sheet surface mass balance. Recent studies have demonstrated that a large fraction of Antarctic snowfall occurs during short-lived AR events, while extreme ARs can simultaneously induce widespread surface melt, firn saturation, runoff and hydrofracturing. The frequency, intensity and persistence of ARs are projected to increase under climate warming, yet their future impact on Antarctic surface mass balance remains poorly constrained.

This project supports Task T1 ("Atmospheric change and variability over the Southern Ocean-Antarctica region") of a proposed NWO-ENW XL research programme currently under evaluation by the Dutch Research Council (NWO) investigating interactions between the atmosphere, ocean, sea ice and Antarctic Ice Sheet. The objective is to quantify how atmospheric rivers influence Antarctic precipitation, melt and surface mass balance under present-day and future climate conditions, and how these processes are modulated by changes in sea ice and Southern Ocean conditions.

The simulations will provide atmospheric forcing and surface mass balance diagnostics required by downstream work packages addressing firn evolution, hydrofracturing and ice-sheet dynamics. Together, these tasks will improve process-based projections of Antarctic ice-sheet evolution and its contribution to future global sea-level rise.

Scientific plan

The project consists of a suite of high-resolution Antarctic regional climate simulations with RACMO2.4p1 at approximately 11 km resolution. The simulations will be used to investigate the role of atmospheric rivers (ARs) in Antarctic climate variability, surface mass balance and ice-shelf vulnerability under present-day and future climate conditions. An example of the RACMO2.4p1 Antarctic configuration used in this project is shown in Fig. 1.

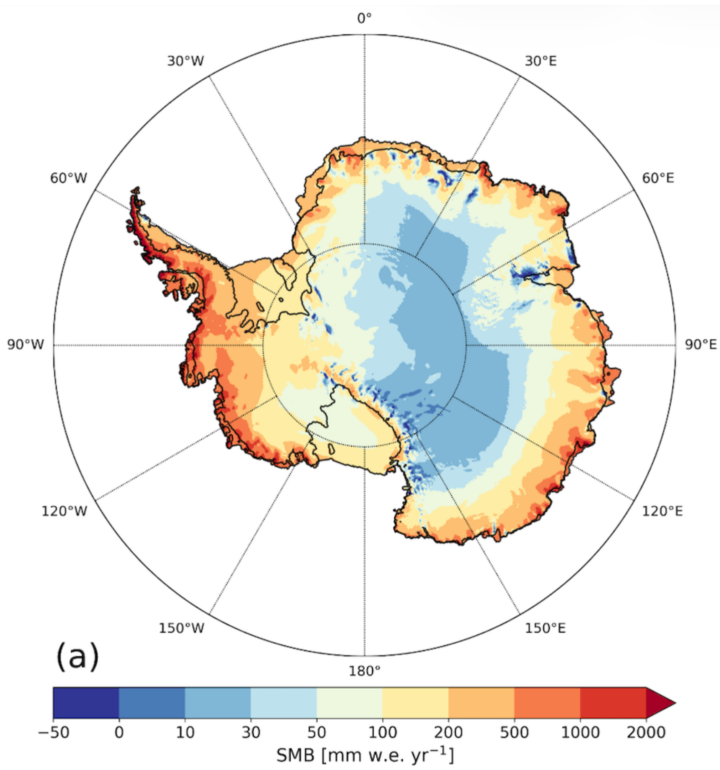

Figure 1. Annual mean surface mass balance (SMB; mm w.e. yr^{-1}) of the Antarctic Ice Sheet simulated with RACMO2.4p1 at ~11 km horizontal resolution over the model domain used in this project, forced by ERA5 reanalysis. The figure illustrates the model's ability to resolve the spatial variability of Antarctic SMB and demonstrates the modelling configuration on which the proposed simulations are based (adapted from van Dalum et al., 2025).

First, historical and future simulations will be driven by selected global climate model projections representative of different climate warming pathways. These will be used to quantify the contribution of atmospheric rivers to Antarctic precipitation, snowfall, surface melt and mass balance changes. Attention will be given to regional differences between East Antarctica, West Antarctica and the Antarctic Peninsula, as well as to seasonal and interannual variability associated with large-scale modes of climate variability.

Second, the simulations will be used to analyse the interaction between atmospheric rivers, Southern Ocean conditions and Antarctic sea ice. By combining atmospheric-river diagnostics with information on moisture sources, transport pathways and sea-ice conditions, we will assess how changes in the ocean-sea ice system influence the frequency, intensity, landfall location and inland penetration of atmospheric rivers.

Third, a set of selected high-impact atmospheric-river events will be simulated at ca. 5 km resolution using pseudo-global warming (PGW) experiments Each event will be simulated under three thermodynamic warming scenarios representing approximately −1 °C, +2 °C and +3 °C changes relative to present-day conditions, allowing the sensitivity of atmospheric-river characteristics and Antarctic surface processes to different climate states to be quantified. These simulations will isolate the thermodynamic effects of climate warming on extreme atmospheric-river events by perturbing the large-scale atmospheric state according to projected future climate changes. The experiments will quantify changes in moisture transport, precipitation phase, snowfall, melt, runoff and firn conditions under warmer climates, while explicitly resolving mesoscale processes that are not adequately captured at coarser resolution. Additional sensitivity experiments will be performed to assess the influence of sea-ice conditions on atmospheric-river evolution and impacts.

Finally, the future-climate simulations (2025-2300) will be analysed to quantify long-term changes in atmospheric-river characteristics under different warming scenarios. The simulations will be used to assess future changes in atmospheric-river frequency, duration, moisture transport, precipitation efficiency and associated impacts on Antarctic surface mass balance. Emphasis will be placed on understanding the balance between increased snowfall and increased melt, and on identifying regions where atmospheric-river impacts may contribute to future ice-shelf vulnerability through enhanced firn saturation, runoff and hydrofracturing.

Model output will be combined with state-of-the-art atmospheric-river detection algorithms and diagnostics of integrated vapour transport, moisture source regions, precipitation phase, snowfall, melt, runoff and surface mass balance. The model output will provide atmospheric forcing and surface mass balance diagnostics for several downstream tasks within the proposed NWO-XL programme, including studies of firn evolution, ice-shelf vulnerability and ice-sheet dynamics.

Model description and technical characteristics
The simulations will be performed with the Regional Atmospheric Climate Model RACMO2.4p1, which is described in detail by van Dalum et al. (2025). RACMO combines the hydrostatic dynamical core of HIRLAM with the physics parameterisations of the ECMWF Integrated Forecasting System (IFS, cycle Cy47r1). The model has been further developed with a comprehensive representation of atmosphere-surface interactions over snow- and ice-covered surfaces and has been specifically tuned and extensively evaluated for polar environments. The Antarctic configuration has already been successfully applied for transient climate simulations extending to 2100 under future climate scenarios and has formed the basis of several recent studies (e.g. Gilbert et al., 2026; Hofsteenge et al., 2026), demonstrating that the proposed modelling framework is mature and well validated for Antarctic climate projection studies.

The computational requirements of these simulations, which include multi-century integrations, multiple future climate scenarios and high-resolution pseudo-global warming experiments, exceed the capacity of local computing facilities and require access to ECMWF's high-performance computing infrastructure.

For this project, RACMO will be applied over Antarctica at approximately 11 km horizontal resolution. The model includes a detailed treatment of surface energy balance, snow and firn processes, meltwater production and refreezing, making it particularly suitable for investigating the impacts of atmospheric rivers on Antarctic surface mass balance, melt and runoff.

RACMO is fully parallelised using MPI and is routinely deployed on large-scale high-performance computing systems. The Antarctic configuration scales efficiently across a large number of processor cores, enabling long transient integrations and high-resolution sensitivity experiments. The simulations will generate substantial data volumes because atmospheric river diagnostics require high-temporal-frequency output of meteorological variables, moisture transport fields, precipitation, surface energy balance components and surface mass balance diagnostics.

Justification of requested computing resources
The requested resources are based on previous RACMO Antarctic integrations performed at 11 km resolution. In addition to the 11 km continental-scale simulations, the project includes a limited number of targeted pseudo-global warming experiments at approximately 5 km horizontal resolution. The requested resources should be regarded as provisional. The project is currently under evaluation for external funding, and the exact number and duration of RACMO simulations may be adjusted following the funding decision and project start. The estimates provided here are based on the currently proposed work plan and are intended to ensure sufficient computational capacity is available should the full modelling programme be approved.

Year	Experiment	Period	Number of simulations	HPC resources (MSBU)	Storage (TB)
2027	Historical simulation	1850–2024	1	75	300
2028	Future scenario simulations	2025–2100	2	60 (30 each)	250
2028	Future scenario simulations	2100–2200	2	80 (40 each)	330
2028	Pseudo-global warming simulations (5 km)	10 events, 3 scenarios, each event one month	30	2	5
2029	Future scenario simulations	2200–2300	2	80 (40 each)	330
Total storage required					1215

The requested storage volume reflects the need to archive high-frequency atmospheric and surface mass balance fields required for atmospheric river diagnostics and for coupling with downstream analyses of firn processes and ice-sheet evolution. The archived output includes meteorological forcing variables, moisture transport diagnostics, precipitation and snowfall, melt and runoff fields, surface mass balance components, and snow and firn characteristics required by subsequent project work packages.

It should be noted that this EMI R&D Project request is complementary to the concurrent ECMWF computing request submitted by Dr. Willem Jan van de Berg (IMAU, Utrecht University). While both requests support RACMO-based Antarctic climate research, the present request is dedicated to the additional simulations and analyses associated with the proposed NWO-XL programme, including multi-century transient simulations, pseudo-global warming experiments, and high-frequency atmospheric river diagnostics, and therefore does not duplicate the resources requested under the IMAU allocation.

Expected outcomes
The project will produce a unique set of high-resolution RACMO simulations covering historical, present-day and future climate conditions over Antarctica. These simulations will provide physically consistent datasets of atmospheric forcing, atmospheric-river characteristics, precipitation, snowfall, rainfall, surface melt, runoff and surface mass balance at spatial and temporal scales relevant for Antarctic ice-sheet processes.

The simulations will enable a comprehensive assessment of how atmospheric rivers contribute to Antarctic accumulation and melt, how their characteristics vary across regions and seasons, and how they respond to changes in sea-ice extent and Southern Ocean conditions. The resulting analyses will improve understanding of the mechanisms linking large-scale climate variability and warming to Antarctic surface mass balance.

In addition, the project will generate dedicated datasets for selected extreme atmospheric-river events and pseudo-global warming experiments, providing process-level insight into the response of Antarctic snowfall, melt and runoff to future warming. These simulations will help identify conditions under which atmospheric rivers shift from accumulation-dominated events to melt-dominated events, with implications for firn saturation, surface ponding and hydrofracturing.

The model output will serve as a key input for downstream studies of firn evolution, ice-shelf vulnerability and ice-sheet dynamics. In particular, the simulations will provide atmospheric forcing and surface mass balance diagnostics for assessments of firn storage capacity, meltwater production, runoff and hydrofracturing potential, thereby supporting improved projections of Antarctic ice-sheet stability and future sea-level rise.

A further outcome will be a unique set of high-resolution (ca. 5 km) pseudo-global warming simulations of extreme Antarctic atmospheric-river events. These experiments will provide process-level understanding of how future warming modifies atmospheric-river intensity, inland penetration, precipitation efficiency and melt potential. The resulting datasets will offer unprecedented detail on the mechanisms linking extreme moisture transport events to snowfall, surface melt, runoff and hydrofracturing risk, providing valuable constraints for firn, ice-shelf and ice-sheet modelling studies.

More broadly, the project will contribute to reducing uncertainties in Antarctic climate and mass-balance projections by providing a process-based understanding of the role of atmospheric rivers within the coupled Southern Ocean-Antarctica system. By linking Southern Ocean variability, atmospheric rivers and Antarctic ice-sheet processes across multiple spatial and temporal scales, the project forms a key component of the proposed NWO-XL programme, ultimately contributing to more robust projections of Antarctic contributions to future global sea-level rise.

References

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