REQUEST FOR AN EMI R&D PROJECT 2027–2029

Country/Organisation:	Switzerland, WSL Institute for Snow and Avalanche Research, SLF Davos
Principal Investigator[1]:	Dr. Sergi González-Herrero; Dr. Dylan Reynolds; Prof. Michael Lehning
Affiliation:	WSL Institute for the Snow and Avalanche Research (SLF)
Address:	Flüelastrasse, 11 7260 Davos Dorf
Other researchers:	Rainette Engbers; Lorena Accossato; Jaquemine Delfieu; Samuele Viaro
Project Title:	Understanding current and future snow climate regimes in Polar and High Mountain regions using CRYOWRF and SCHNAPS

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]	30,000,000	30,000,000	30,000,000
Graphics Processing Unit Cluster-A	[GBU]			
Graphics Processing Unit Cluster-B	[GBU]	5,000,000	5,000,000	5,000,000
Accumulated data storage (total archive volume)[2]	[GB]	100,000	200,000	300,000

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

[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.

Continue overleaf.

Principal Investigator:	Dr. Sergi González-Herrero; Dr. Dylan Reynolds; Prof. Michael Lehning
Project Title:	Understanding current and future snow climate regimes in Polar and High Mountain regions using CRYOWRF and SCHNAPS

Extended abstract

Background and Scientific Motivation

Polar and high mountain regions are among the regions of the Earth which are more susceptible to climate warming. Polar amplification and elevation-dependent warming locates them among the most rapidly warming regions on the Earth (Pepin *et al* 2015, Weller 2007). As a result, these regions are experiencing very fast changes. They have one element in common: they are covered, either seasonally or permanently by snow. This snow interacts directly with the atmosphere regulating fluxes with the soil and vegetation buried under. Snow itself is also crucial of human needs like water supply, energy production and tourism, but also for regulating the biosphere in cold ecosystems (Immerzeel *et al* 2019, Mankin *et al* 2015, Viviroli *et al* 2007). Therefore, to understand these regions, this component needs to be taken into account.

Unfortunately, snow is a very dynamic and complex component. Its physical description goes beyond than snow volume (height) and mass (snow water equivalent, SWE). Other physical properties like microstructure, temperature gradients and liquid water content modify how snow interacts with the atmosphere (Braun *et al* 2024, Würzer *et al* 2017, Wever *et al* 2020). Light-absorbing particles (LAPs) incorporated into the snow by natural (sand or algae) or artificial (black carbon) sources, add one more layer of complexity (Skiles *et al* 2018, Tuzet *et al* 2019). By changing the albedo and the absorbed radiation, they interact directly with snow and indirectly with the atmosphere. All this complexity with snow makes that most atmospheric and climate models, with coarse resolutions and very simplistic representation of the snow, struggle to accurately simulate snow and their interactions with the atmosphere (Notarnicola 2020, Mudryk *et al* 2020). In complex terrains, it becomes even more difficult to represent this component, due to the large heterogeneity of snow through preferential deposition and transport (Lehning *et al* 2008), that requires hectometric scales to properly represent it.

In order to fill this gap, project “SnowShifts: current and future shifts in snow regimes in extreme environments” funded by the European Research Council (ERC-Syn-2025; Pis: A. Kääb, F. Koch and M. Lehning) aims to reduce uncertainties in global estimates and changes of snow in such extreme regions. This will be achieved through a novel combination of in-situ and remote sensing observations (Koch *et al* 2019, 2024), along with new snow-atmosphere high resolution models. These models, developed by the groups Snow Processes in Davos and CRYOS in Sion, Switzerland couple the physics-based SNOWPACK (Lehning *et al* 1999) snow model with the weather and climate model WRF (Skamarock *et al* 2008) and the intermediate complexity weather model HICAR (Reynolds *et al* 2023), creating the models CRYOWRF (Sharma *et al* 2023) and SCHNAPS (Reynolds *et al* 2026), respectively. These two models are complementary: while the non-hydrostatic CRYOWRF allows to investigate in detail the interactions from the snow to the atmosphere including precipitation formation; SCHNAPS, thanks to its great efficiency, allows to investigate seasonal to climate temporal scales at hectometric spatial scales. These two models allow for the first time to represent and faithfully predict the current and future snow climate regimes in larger-scale weather and climate models.

Objectives

The general objectives of this computing project are embedded into SnowShifts project, which primary goal is to develop a new and comprehensive understanding of snow dynamics and their drastic changes through highly detailed spatio-temporal predictions in current and future snow regimes in polar and mountain regions. The computational part of the project aims therefore to:

- Characterize and elucidate observed trends and shifts in snow dynamics based on advanced numerical models
- Develop climate downscaling adapted for work on future snow dynamics
- Predict future snow regimes in polar and high mountain regions

More specifically, we will use the ECMWF computational resources to:

O1. Simulate snow-atmosphere interactions and their changes using a storyline framework for selected events in high-mountain and polar regions with CRYOWRF.

O2. Simulate current and future snow conditions in different mountain regions of the world using SCHNAPS.

O3. Representing and studying the effect of LAPs on snow in the models.

O4. Create a dataset of long-term kilometric-resolution snow and atmospheric variables in the Antarctic Peninsula, a region that combines both polar and mountain processes.

Model description and technical characteristics

CRYOWRF is an extension of WRF that includes the SNOWPACK model and a blowing snow scheme as an option for the land-surface scheme. With this model, it becomes possible to simulate an adequate number of computational snow layers, which has been shown to be a prerequisite for accurate snow modelling. In addition to the new land surface scheme, CRYOWRF includes a new blowing snow model based on (Vionnet *et al* 2014) with a double-moment hydrometeor class that considers mass and number mixing-ratios for blowing snow. This scheme incorporates recent scientific progress in understanding near surface snow transport and associated consequences for the atmospheric boundary layer, which have been achieved by the group (Sigmund *et al* 2024, Melo *et al* 2024) . More details about the model and a link to the publicly available code can be found in Sharma et al (2023).

SCHNAPS is – similar to CRYOWRF - an atmosphere – cryosphere model for dynamic downscaling a coarser-resolution model or reanalysis. It generates high-resolution atmospheric and surface outputs. SCHANPS is computationally highly efficient because it uses a simplified wind solver to advect heat, moisture and hydrometeors instead of solving the Navier-Stokes equations, while maintaining advanced physics parametrizations used in regional weather models like WRF (Reynolds *et al* 2023). Its high-resolution and advanced SNOWPACK capabilities together with its computational efficiency, makes it ideal for a topographically complex regions like the AP

Both WRF and SCHNAPS are written in Fortran90, while SNOWPACK is written in C++. A specialized coupling library, written in a combination of C, C++, and Fortran, makes SNOWPACK interoperable with WRF and SCHNAPS. The entire CRYOWRF framework was intensively tested with both Intel and GCC compilers for previous projects on Piz Daint and Eiger. The only required libraries for CRYOWRF are compatible NETCDF libraries. SCHNAPS similarly uses NETCDF, as well as FFTW and has been ported to GPUs.

Methodology

The project will combine different methodologies to analyse the processed dataset, from classic statistics to sensitivity analyses, and comparisons with our extensive observational datasets from

remote sensing and in-situ observations that the SnowShifts project foresees. More specifically, to analyse the impact of the thermodynamic effects of global warming on blowing snow, we will use the pseudo-global warming approach (Brogli *et al* 2023). Simulations will be forced with initial conditions from the ERA5 reanalysis for the control run. Then, we will add the ”delta” change for two future scenarios (SSP2-4.5 and SSP5-8.5) and a pre-industrial one, using the ensemble mean CMIP6 Global Climate Models, to the thermodynamic variables in ERA5, which are then used as the new initial conditions for PGW simulations. The role of global warming on blowing snow is then quantified by subtracting the control from the PGW simulations and have been already successfully used with CRYOWRF to attribute snow impacts (González-Herrero *et al* 2026). This approach allows us to investigate the changes in snow processes produced by thermodynamic changes. This method does not consider possible changes in atmospheric dynamics that may also occur from climate change, but this compromise is commonly accepted to be tractable problem. This approach allows for computationally demanding high-resolution climate projections using short duration simulations which reduce the computational and storage cost (Brogli *et al* 2023).

Computational resources justification

Resources estimated are based on benchmarks from the current CRYOWRF and SCHNAPS experiments. We estimate that:

- 1-day WRF simulation for a region of 1,000,000 km2 at 1km resolution requires approximatelly 250000 SBUs (C. Calvo; personal communication). CRYOWRF has a similar efficiency than WRF.
- 1-year SCHNAPS simulation for a region of 140,000 km2 at 1km resolution requires 1000000 GBUs (benchmark based on one Blackwell 6000 GPU simulation)

Based on these numbers we estimate a need of 50,000,000 SBUs per year to accomplish the CRYOWRF simulations and 6,000,000 GBUs to accomplish the SCHNAPS simulations needed. Finally, we request an accumulative of 100 TB per year to store the data produced.

The resources needs may change during the project, specific simulations still need to be set up, and presented estimates can be refined after specific benchmarks on ECMWF HPCF. In case our yearly estimates become significantly below to the requested allocation we will inform immediately to release resources into the reserve.

Expected outcomes

This project is expected to produce (1) event-based understanding of climate variables controlling snow changes, (2) current and future climate datasets of snow in different mountain regions, (3) a long-term dataset for the Antarctic Peninsula. The project will support 3 PhD theses (already funded through the ERC) and a set of peer-reviewed articles.

References

Braun A, Fourteau K and Löwe H 2024 A rigorous approach to the specific surface area evolution in snow during temperature gradient metamorphism *Cryosphere* **18** 1653–68

Brogli R, Heim C, Mensch J, Sorland S L and Schar C 2023 The pseudo-global-warming (PGW) approach: Methodology, software package PGW4ERA5 v1.1, validation, and sensitivity analyses *Geosci. Model Dev.* **16** 907–26

González-Herrero S, Deb P, Li S, Argüeso D, Engbers R, Matějka M, Wever N and Lehning M 2026 Impact attribution of the March 2022 Antarctic heatwave reveals amplification by cloud feedbacks and increased future meltwater *Communications Earth & Environment 2026* Online: https://www.nature.com/articles/s43247-026-03485-0

Immerzeel W W, Lutz A F, Andrade M, Bahl A, Biemans H, Bolch T, Hyde S, Brumby S, Davies B J, Elmore A C, Emmer A, Feng M, Fernández A, Haritashya U, Kargel J S, Koppes M, Kraaijenbrink P D A, Kulkarni A V., Mayewski P A, Nepal S, Pacheco P, Painter T H, Pellicciotti F, Rajaram H, Rupper S, Sinisalo A, Shrestha A B,

Viviroli D, Wada Y, Xiao C, Yao T and Baillie J E M 2019 Importance and vulnerability of the world's water towers *Nature 2019 577:7790* **577** 364–9 Online: https://www.nature.com/articles/s41586-019-1822-y

Koch F, Gascoin S, Achmüller K, Schattan P, Wetzel K F, Deschamps-Berger C, Lehning M, Rehm T, Schulz K and Voigt C 2024 Superconducting Gravimeter Observations Show That a Satellite-Derived Snow Depth Image Improves the Simulation of the Snow Water Equivalent Evolution in a High Alpine Site *Geophys. Res. Lett.* **51** e2024GL112483 Online: /doi/pdf/10.1029/2024GL112483

Koch F, Henkel P, Appel F, Schmid L, Bach H, Lamm M, Prasch M, Schweizer J and Mauser W 2019 Retrieval of Snow Water Equivalent, Liquid Water Content, and Snow Height of Dry and Wet Snow by Combining GPS Signal Attenuation and Time Delay *Water Resour. Res.* **55** 4465–87 Online: /doi/pdf/10.1029/2018WR024431

Lehning M, Bartelt P, Brown B, Russi T, Stöckli U and Zimmerli M 1999 SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations *Cold Reg. Sci. Technol.* **30** 145–57

Mankin J S, Viviroli D, Singh D, Hoekstra A Y and Diffenbaugh N S 2015 The potential for snow to supply human water demand in the present and future *Environmental Research Letters* **10** 114016 Online: https://iopscience.iop.org/article/10.1088/1748-9326/10/11/114016

Melo D B, Sigmund A and Lehning M 2024 Understanding snow saltation parameterizations: lessons from theory, experiments and numerical simulations *Cryosphere* **18** 1287–313

Mudryk L, Santolaria-Otín M, Krinner G, Ménégoz M, Derksen C, Brutel-Vuilmet C, Brady M and Essery R 2020 Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble *Cryosphere* **14** 2495–514

Notarnicola C 2020 Hotspots of snow cover changes in global mountain regions over 2000–2018 *Remote Sens. Environ.* **243** 111781 Online: https://www.sciencedirect.com/science/article/pii/S0034425720301516

Pepin N, Bradley R S, Diaz H F, Baraer M, Caceres E B, Forsythe N, Fowler H, Greenwood G, Hashmi M Z, Liu X D, Miller J R, Ning L, Ohmura A, Palazzi E, Rangwala I, Schöner W, Severskiy I, Shahgedanova M, Wang M B, Williamson S N and Yang D Q 2015 Elevation-dependent warming in mountain regions of the world *Nat. Clim. Chang.* **5** 424–30 Online: https://www.nature.com/articles/nclimate2563

Reynolds D, Gutmann E, Kruyt B, Haugeneder M, Jonas T, Gerber F, Lehning M and Mott R 2023 The High-resolution Intermediate Complexity Atmospheric Research (HICAR v1.1) model enables fast dynamic downscaling to the hectometer scale *Geosci. Model Dev.* **16** 5049–68

Reynolds D, Viaro S, Wever N and Lehning M 2026 Modeling with SCHNAPS: the Snow Cover and High-resolutioN Atmospheric Processes System *EGU26* Online: https://meetingorganizer.copernicus.org/EGU26/EGU26-12973.html

Sharma V, Gerber F and Lehning M 2023 Introducing CRYOWRF v1.0: multiscale atmospheric flow simulations with advanced snow cover modelling *Geosci. Model Dev.* **16** 719–49

Sigmund A, Melo D B, Dujardin J, Nishimura K, Lehning M and Sigmund A 2024 Parameterizing Snow Sublimation in Conditions of Drifting and Blowing Snow *J. Adv. Model. Earth Syst.* Online: https://essopenarchive.org/doi/pdf/10.22541/essoar.172304053.32270258/v1?redirectToLatest=false

Skamarock W C, Klemp J B, Dudhi J, Gill D O, Barker D M, Duda M G, Huang X-Y, Wang W and Powers J G 2008 *A Description of the Advanced Research WRF Version 3* Online: https://opensky.ucar.edu/islandora/object/technotes:500

Skiles S M K, Flanner M, Cook J M, Dumont M and Painter T H 2018 Radiative forcing by light-absorbing particles in snow *Nature Climate Change 2018 8:11* **8** 964–71 Online: https://www.nature.com/articles/s41558-018-0296-5

Tuzet F, Dumont M, Arnaud L, Voisin D, Lamare M, Larue F, Revuelto J and Picard G 2019 Influence of light-absorbing particles on snow spectral irradiance profiles *Cryosphere* **13** 2169–87

Vionnet V, Martin E, Masson V, Guyomarc'h G, Naaim-Bouvet F, Prokop A, Durand Y and Lac C 2014 The Cryosphere Simulation of wind-induced snow transport and sublimation in alpine terrain using a fully coupled snowpack/atmosphere model *Cryosphere* **8** 395–415 Online: www.the-cryosphere.net/8/395/2014/

Viviroli D, Dürr H H, Messerli B, Meybeck M and Weingartner R 2007 Mountains of the world, water towers for humanity: Typology, mapping, and global significance *Water Resour. Res.* **43** 7447 Online: https://onlinelibrary.wiley.com/doi/full/10.1029/2006WR005653

Weller G 2007 M.C. Serreze and R.G. Barry. 2005. The arctic climate system. Cambridge, Cambridge University Press. 385pp. ISBN 0 521 81418 9, hardback. £80. *Journal of Glaciology* **53** 519–519 Online: https://www.cambridge.org/core/journals/journal-of-glaciology/article/mc-serreze-and-rg-barry-2005-the-arctic-climate-system-cambridge-cambridge-university-press-385pp-isbn-0-521-81418-9-hardback-80/3C5DDB10214F8C4E167350882F46B61B

Wever N, Rossmann L, Maaß N, Leonard K C, Kaleschke L, Nicolaus M and Lehning M 2020 Version 1 of a sea ice module for the physics-based, detailed, multi-layer SNOWPACK model *Geosci. Model Dev.* **13** 99–119

Würzer S, Wever N, Juras R, Lehning M and Jonas T 2017 Modelling liquid water transport in snow under rain-on-snow conditions - Considering preferential flow *Hydrol. Earth Syst. Sci.* **21** 1741–56