SPECIAL 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	2024
Project Title:	Antarctic regional climate modelling: developing and running the HCLIM Polar High Resolution Regional Climate Model
Computer Project Account:	spdkmott
Principal Investigator(s):	Dr Ruth Mottram Dr Ole Bøssing Christensen, Dr Jose Abraham Torres Alavez, Dr Martin Olesen, Dr Fredrik Boberg, DMI.
Affiliation:	Danish Meteorological Institute
Name of ECMWF scientist(s) collaborating to the project (if applicable)	………………………………………………………….…… ………………………………………………………….……
Start date of the project:	01/01/2023
Expected end date:	31/12/2025

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)	9.5 million	10786062	20 million	9 million
Data storage capacity	(Gbytes)				

Summary of project objectives (10 lines max)

In this project we will examine the likely future evolution of Antarctica under climate scenarios out to 2100, as well as performing process studies, using a regional climate model. The project focuses on developing and optimising the HARMONIE-Climate (HCLIM) model for simulations in Antarctica, a region it has not previously been tested or run for, using a combination of in-situ and satellite data to test performance. Outputs are part of the Horizon 2020 project PolarRES and contribute to the Polar CORDEX regional climate model ensemble. Process studies focused on extreme precipitation in West Antarctica at high resolution (2km) and experiments using a new sea ice dataset provided by the ESA CCI have also been carried out. We have also supplied output datasets to partners in Ukraine, The Netherlands and Sweden and we are working on a common project looking at ice sheet processes over both ice sheets using these HCLIM outputs. Model evaluation against satellite and in-situ observations as well as development of ice shete mass budget using the DMI surface mass budget model are also planned in 2024 and 2025.

Summary of problems encountered (10 lines max)

Our most important problem is that the simulations planned in this special project use more resources than originally planned. An initial amendment has not proved to be sufficient to cover the full set of projections we plan and we have therefore requested a further increase in resources. The underestimate was due to several factors including a bigger domain, higher spatial resolution, the higher temporal outputs and increased requirements for outputs under the CORDEX protocol as well as the introduction of spectral nudging and a new dynamic sea ice component. The simulations now planned are well beyond the state-of-the-art and this special project therefore presents an opportunity for genuinely innovative science. We have been optimising our resource use and in particular we have managed to compress output size by optimising for compression, so that although we requested further storage, this has not increased as much as the SBUs.

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

The set-up and tuning of the model and hindcast downscaling ERA-5 were completed in 2023 and early 2024. We are now downscaling CMIP6 model outputs from the MPI-ESM global climate model and will shortly start the historical and projections downscaling with CESM2 outputs. We plan to downscale EC-Earth3 in 2025. Other models, including test downscaling the CMIP7 version of EC-EARTH4 are planned if resources are available. The focus in the last few months of this year and early 2025 will also be on process studies using a high resolution (2km) set-up in west Antarctica and Dronning Maud Land to examine extreme precipitation and other impacts agreed on with partners at different international institutes in the PolarRES project. We also plan to contribute to the SCAR (Scientific Committee on Antarctic Research) action groups ANTClimNOW and Antarctic RINGS (Matsuoka et al., 2022) where we plan to contribute to the semi-operationalised Antarctic climate indicators with surface mass balance from HCLIM, replacing our old HIRHAM5 outputs.

List of publications/reports from the project with complete references

Publications from this project are still in preparation but initial results were shown at the EGU Spring meeting in 2023 and 2024 and at the IUGG meeting in Berlin in July 2023. Presentations are also planned at the International Glaciological Society meeting in August 2024 and at the American Geophysical Union in December 2024.

Papers in preparation include:

1) High Resolution Polar Regional Climate Modelling: Experimental Protocol for a community approach Mottram et al., in prep. for Geoscientific Model Development
2) High-resolution regional climate modeling of atmospheric rivers over West Antarctic ice shelves, Gilbert et al., in prep.
3) Atmospheric structure and ice shelf impacts of atmospheric rivers in Antarctica, Kolbe et al., in prep.
4) Coastal Polynyas and katabatic winds from sea ice and high resolution climate modelling, Torres Alavez et al., in prep.
5) Assessing uncertainties in regional climate simulations with radar altimetry over ice sheets, Mottram et al., in prep.

Summary of results

This special project is contributing to a number of different research projects, besides running polar CORDEX projections. We separate out and enumerate some of these spin-off projects here but we note also that multiple other projects are already using the output from these simulations within the PolarRES project, or plan to use future projections when they are completed. We hope therefore that these projects currently in progress within our research group at DMI give a small flavour of some of the uses that they can be put to.

a. High resolution climate projections for Antarctica: evaluation with ESA CCI SEC

The set-up and tuning of the model (see Figure 1), testing of different physics and parameterisations, introduction of the spectral nudging scheme and hindcast downscaling ERA-5 were completed in 2023 and early 2024. We are now downscaling CMIP6 model outputs from the MPI-ESM global climate model and will shortly start the historical and projections downscaling with CESM2 forcing on the boundaries.

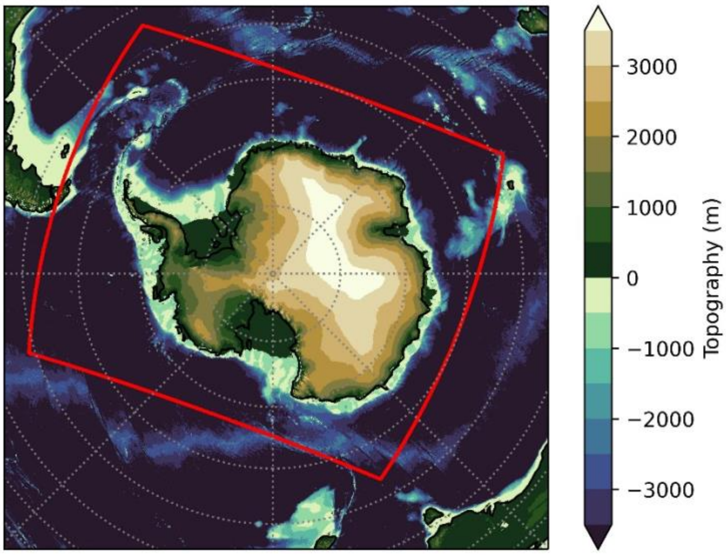

Figure 1. *Topography, bathymetry of the Antarctic domain (defined in the red box), from Mottram et al., in prep.*

In parallel, we are evaluating the model hindcasts with observational data. As part of this effort, we are experimentally using the ESA CCI ice sheet surface elevation change dataset. A similar comparison is shown for the HIRHAM5 model in Shepherd et al (2018), and we plan here to extend the approach not only to our new HCLIM model but also to other RCMs that are participating in the Horizon 2020 project PolarRES.
Surface elevation change over ice sheets is a result of surface mass budget processes (snowfall accumulating and compacting as well as snow and ice melt and runoff of meltwater) and ice dynamic processes. We plan to run the output through a full surface energy and mass budget model later this year to accurately calculate all processes (Hansen et al., 2022), and the surface mass budget will be used as a contribution to the IMBIE assessment of ice sheet mass budget (Otosaka et al., 2023). For the purposes of this progress report however, we show an initial assessment of the differences between the measured surface elevation change and the simple modelled precipitation minus evaporation and sublimation as shown in Figure 2 below.

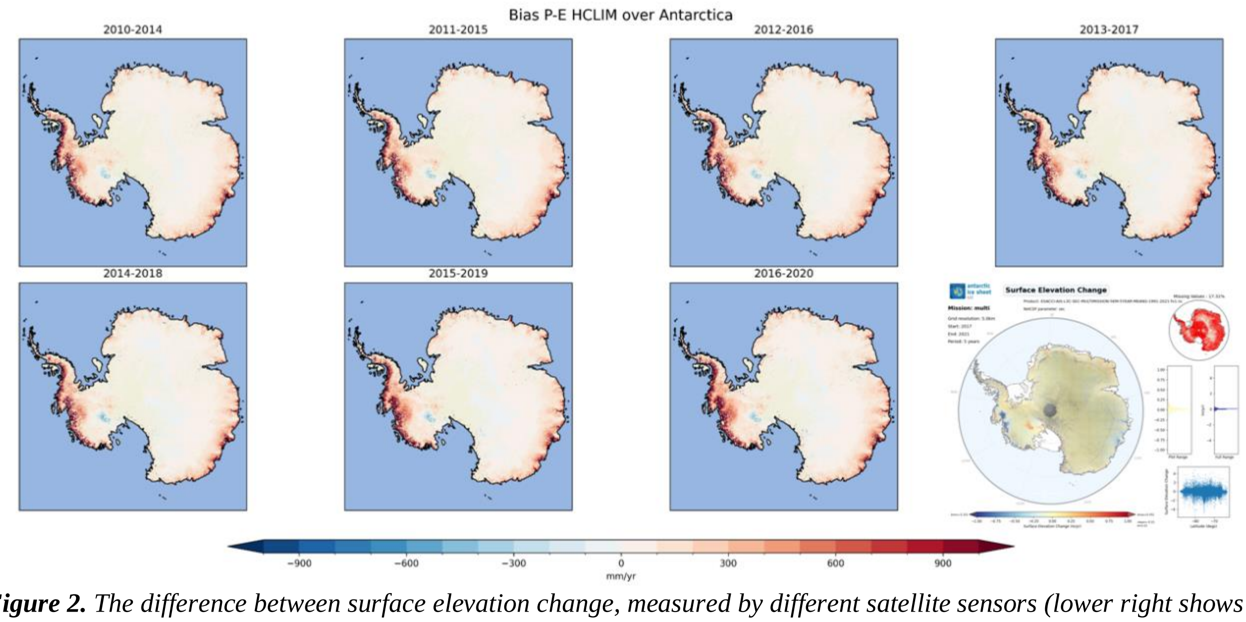

Figure 2. *The difference between surface elevation change, measured by different satellite sensors (lower right shows earth observation dataset) and modelled precipitation minus evaporation (including sublimation) for 5 year periods corresponding to the ESA CCI ice sheet dataset of surface elevation change. The area of negative bias (in blue colours) is likely related to ice sheet dynamical processes in the Siple coast ice streams and is one of the reasons that ice sheet velocity data products also need to be included in this analysis. The red colours show areas of high accumulation where compaction and densification processes need to be included in the analysis.*

In future, we plan to extend this work to evaluation of other models in the PolarRES/Polar CORDEX ensemble. In collaboration with the ESA climate modelling user group (CMUG), we will also account for elevation changes related to ice sheet dynamics, using satellite observed ice sheet velocities.

b. Coastal polynyas and the role of katabatic winds in Greenland and Antarctica

The set up of high resolution climate simulations in Antarctica has allowed us to contribute to a number of process studies including the role of katabatic winds in driving coastal polynyas and the use of high resolution satellite datasets in better defining these. In this project we use the high resolution HCLIM-AROME to resolve key processes during polynya events in both Antarctica and Greenland. Coastal polynyas in both polar regions are generally driven by katabatic winds and HCLIM-Arome, in combination with new high resolution satellite datasets is an ideal tool to characterise their development.
For this project we are running a set of nearly identical HCLIM-ALADIN and HCLIM-AROME at 4 km of horizontal resolution to test the different physical parameterisations. There are therefore four runs for northern Greenland, for February-March 2018, and four over Terra Nova Bay, Antarctica for October-November 2010. The lateral boundary-forcing (BC) data in each event are provided by the 3-hourly ERA5 data. The sea ice concentration (SIC) lower boundary forcing data are updated daily and represent the only difference in boundary conditions between the runs for each event. For each HCLIM dynamical core and each region the applied SIC lower boundary forcing data sets are (1) sea-ice fraction from ESA CCI+ sea ice at 12.5-km resolution, and (2) OSI SAF sea ice concentration dataset at 25 km resolution.

Figure 3 shows a 4km resolution simulation with HCLIM over Greenland during the 2018 polynya event (Moore et al., 2018). The 2018 storm produced large amounts of precipitation in Eastern Greenland, which later had dramatic ecosystem impacts in eastern Greenland (Schmidt et al., 2019). Very high katabatic winds over northern Greenland, leading to the opening of a new polynya off the northern coast of Greenland, as well as extraordinary high temperatures well above freezing point at Kap Morris Jesup weather station due to the föhn effect. This case study compares and contrasts the 2018 case study in Greenland with a similar event in Antarctica (Stewart., 2019) .

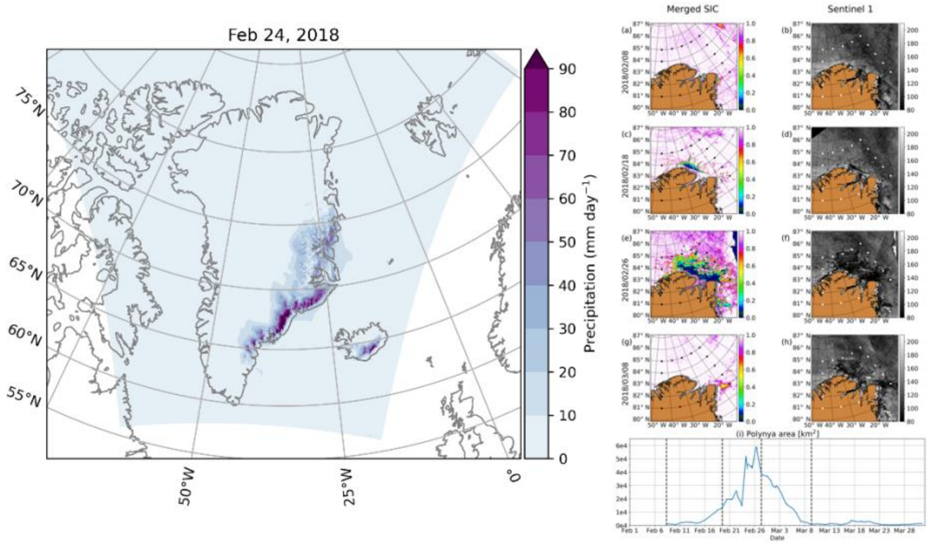

Figure 3 *(left)Output from control run during the February 2018 North Greenland polynya event showing the associated heavy snowfall over eastern Greenland (right) from Ludwig et al. (2019), merged sea ice concentration from different satellite sensors on the left and Sentinel-1 on the right showing the opening of the polynya in February.*

Currently this project has only had control runs with standard ERA-5 forcing on the boundaries run. Work later this year will incorporate outputs from the newly reprocessed data series of sea ice concentration produced by the ESA CCI for sea ice as described above. In addition, we intend to use OSI SAF sea ice drift product to assess if the internal simple sea ice model within HCLIM needs to be further refined to be able to handle these extreme events.

c. Characteristics and impacts of Antarctic atmospheric rivers

Amospheric rivers (ARs) are high impact extreme weather events that can occur anywhere in the world and are associated, in the polar regions with large and rapid temperature changes and large scale water vapour transport. Working with colleagues from KNMI, we identified five different atmospheric river events in Antarctica from the ERA-5 reanalysis using the techniques of Kolbe et al (2023). These occur on:

1) 13th to 22nd March 2022
2) 4th to 13th February 2020
3) 5th to 14th June 2019
4) 7th to 16th November 2023
5) 25th December 2023 to 3rd January 20024

For each AR case, we have run three simulations with HCLIM, one using ALADIN physics at 11 km horizontal resolution and two simulations with AROME physics at resolutions of 2.5 and 11 km. These different simulation allows us to disentangle the differences introduced by resolution and physical parameterisations. The project focuses not only on characterising the AR events in the atmosphere but also in examining the impacts on the ice sheet mass budget (Wille et al., 2019). The main impacts of ARs in atmospheric rivers in Antarctica are in enhanced accumulation over the ice sheet itself, but as the 2022 heatwave associated with an AR showed (Wille et al., 2024), they can also have an impact on the fringing ice shelves, where enhanced melting leads to hydrofracture and ice shelf collapse. Given the importance of ice shelves to the ice sheet in buttressing ice flow, future work is also making use of surface melt outputs, compared also with satellite data on surface melt, to assess the role of ARs in potentially destabilising ice shelves. Figure 4 below shows early analysis of one event, the March 2022 heatwave.

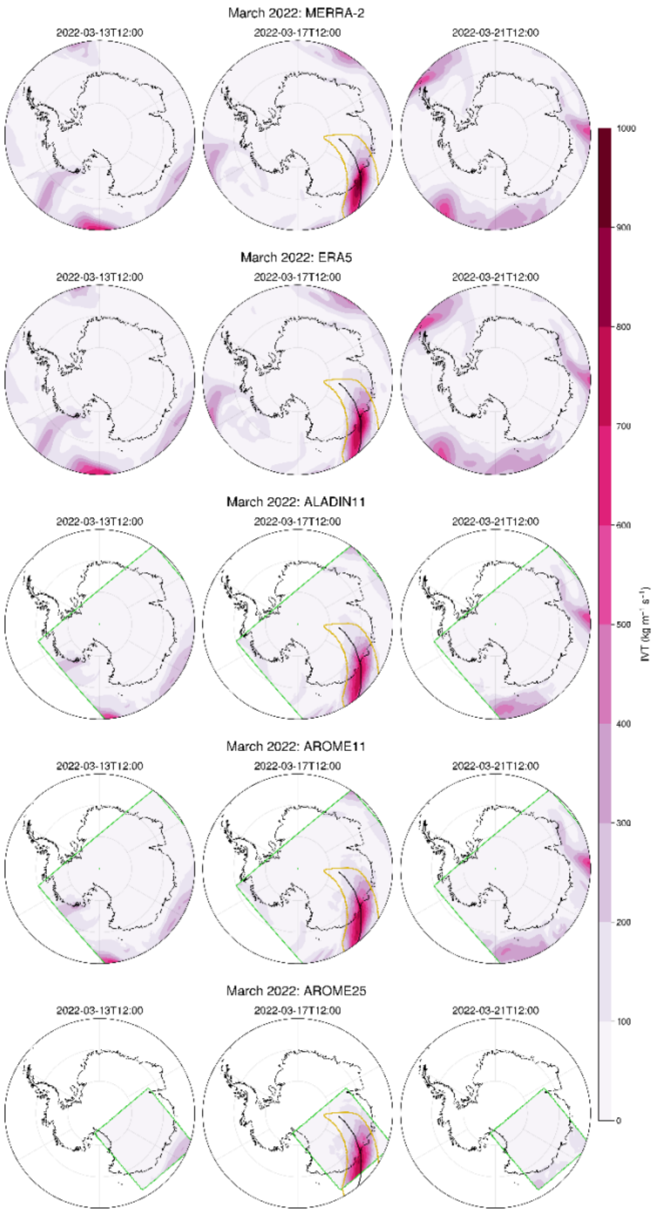

***Figure 4**: Integrated vapour transport during the March 2022 atmospheric river event in East Antarctica, visualised at three different time steps and compared between the two reanalysis datasets MERRA-2, ERA5, and downscaled with HCLIM using ALADIN 11km physics and AROME physics at 11 and 2.5km resolution. The yellow box shows the AR extent defined using the method of Kolbe et al. (2023). The green box shows the domain of the limited area downscaling.*

Within this project and in collaboration also with partners from the Horizon 2020 project PolarRES, we have also looked at events in west Antarctica and compared results from HCLIM with WRF and MetUM

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