# Shared frameworks for next-generation ice sheet modelling

## Developing a next generation ice sheet modelling framework through international collaboration and community building

Summary and Overall Motivation

Ice sheets respond to and influence the global climate on a variety of spatial and temporal scales. Their future evolution, especially the consequences for global sea level, is of great societal importance, and consequently numerical ice sheet models (ISMs) comprise a growing area of interest. The technical and scientific challenges inherent in ice sheet modelling are substantial, and are compounded by the need to couple ISMs to climate models in a physically-consistent and scientifically-useful way. The complexity and likely fragility of bespoke coupling code makes the development of flexible, generic couplers attractive. It would also enable new types of experiment to be conducted, leading to a deeper understanding of the effects of numerical and scientific uncertainties in these coupled models. This challenge requires a coordinated, international approach, with a high degree of participation from the broader academic and stakeholder communities.

We propose a project to bolster UK leadership in this rapidly developing field. We will build upon an existing unfunded international collaboration centred on an established ISM (Glimmer-CISM). Our primary aim is to advance a generic, sustainable technical framework for ice sheet-climate coupling, driven by international collaboration and community participation. This framework will handle coupling of ISMs to climate models in a transparent, flexible fashion. We will implement the framework using Glimmer-CISM, and demonstrate coupling to two world-leading climate models. Our second aim is directed at maintaining the position of Glimmer-CISM as an internationally-leading ISM: we will develop a set of standard software interfaces within Glimmer-CISM which will allow model components to be easily augmented or upgraded as modelling techniques improve. This is crucial for safeguarding future UK ice sheet modelling capability.

Community participation is essential if the potential benefits and impact of this proposal are to be maximised, and accordingly we focus the requested resources on activities which will foster deep engagement of the scientific user community in the development process. These activities will further allow the community to leverage other sources of funding to support future code maintenance and development. They will strengthen UK leadership in the field of coupled ISM-climate modelling, and it will cement the reputation of Glimmer-CISM as a leading ISM internationally. Overall, our focus is on capacity-building and providing value-for-money.

The project will be delivered by substantially strengthening an existing collaboration between groups in the UK (the Universities of Bristol, Edinburgh and Swansea, and the Hadley Centre) and the US (Los Alamos National Laboratory and the University of Montana). It will also draw in groups from across the US and Europe in a network of global significance. The team assembled for this project is of international standing, and brings an unrivalled set of skills and insight to this difficult and important problem. The aims are of high importance for international climate science capability.

1. Introduction

Prediction of the sea level change which will result from climate change is a key scientific challenge with major public policy implications. Numerical modelling of the global climate system using coupled Global Climate Models (GCMs) is the primary predictive tool used by climate scientists. GCMs need to incorporate the behaviour of the cryosphere, in particular the dynamics of the Earth’s large ice sheets (Greenland and Antarctica), but although numerous stand-alone ISMs exist, ISM-GCM coupling[[1]](#footnote-1) has historically been problematic for a number of scientific and technical reasons. In addition, ice sheet modelling is a rapidly-evolving field, and so the software architecture of ISMs themselves needs to be able to accommodate the addition of new or alternative model components if they are to remain scientifically-relevant. This goal of this proposal is to deliver a long-lasting software framework for ice sheet modelling and ISM-GCM coupling, through a vigorous international collaboration, informed by substantive community participation.

1. ISM-GCM Coupling

The scientific and technical challenges of coupling ISMs and GCMs are formidable. Scientifically, the most important problem is that the spatial and temporal scales concerned differ substantially between the two types of model. Ice sheets respond to climate change on timescales from decades to millennia: substantially longer than the timescales of interest in climate modelling, even considering the response of the deep ocean (typically a few thousand years).

Spatial scales also differ, with the narrow ablation region around the edge of an ice sheet typically being small compared to a GCM grid box. Because ISMs are typically regional models, and may be formulated on Cartesian grids with an associated map projection, interpolation may be necessary between the ISM and GCM grids; in these circumstances, achieving mass and energy conservation requires care. There are also decisions to be made about where quantities such as mass-balance are calculated, and how the ISM should interact with the land surface model in the GCM. Pollard (2010) discusses in detail the various techniques previous workers have used to address these issues, including various types of temporally asynchronous coupling and statistical climate downscaling.

The software implementation of ISM-GCM coupling is also complex, and comes with its own range of technical difficulties. Primarily, these are concerned with making the coupling code flexible enough to handle a useful range of coupling scenarios, while being structured to be robust and maintainable way. ISMs and GCMs are technically diverse codes: a generic coupler needs to take into account the possibility of different parallelisation strategies, different hardware/operating system platforms, and different grid definitions, among many other parameters. A degree of complexity in coupling code is therefore inevitable, and consequently requires sound software engineering if a long-lasting solution is to be devised.

1. Software Architecture Considerations

The key to the way a computer model can be used and re-used is its *interface* (sometimes known as the *Application Programming Interface*, or API), which is a description of how other pieces of code communicate with it, in whole or in part. For most programming languages, the API comprises definitions of subroutine/function names and their arguments. In object oriented languages, object hierarchies are also defined in the API. The purpose of a standardised API is to provide predictability and interoperability to users of a piece of code.

In the case of an ISM, a consistent API would allow a component module – or a whole ISM – to be swapped with another if the second module conformed to the API. The inner workings of the two modules may be different but the calling code doesn’t need to know that. For example, many ISMs include a model component dealing with ice shelves, which is usually tightly integrated with the main ice sheet code. The way the ice shelves are simulated can be done in a variety of different ways, however. An API can be written to define how the ice shelf and ice sheet are coupled; it is then possible to design a new ice shelf module such that, provided it conforms to the API, it can be used with an existing ice sheet code without need for substantial internal code redesign in both parts. This applies equally to other aspects of a given model, such as the stress solution, thermodynamics, etc. It also applies to the way the model is coupled to external components, most notably to the atmosphere.

The history of Glimmer-CISM (along with many similar codes) is such that it was not originally designed around a standardised API; instead, the code base has grown organically. This means that in many cases, while the code runs well as a whole, the interface between components is weakly specified, process modules are not always well encapsulated (they have embedded dependency with other parts of the code), and where external coupling has taken place, it has been crafted for a specific application rather than considered (or defined) in abstract. Existing coupling to HadCM3 and CESM is of this form.

The provision of a standardised API brings obvious benefits of flexibility and reusability, as well as opening up ways of performing more thorough model intercomparison and sensitivity studies. To bring this about, it will be necessary to engage deeply with all those involved in the design of ISMs and ISM-GCM coupling; this is the main purpose of this project, and we describe how in detail below how we will achieve it.

1. Glimmer-CISM

Our starting point for this project is Glimmer-CISM, an ISM with an international profile. The model’s origins lie in an ISM developed prior to 2003 by Payne. From 2003, the model was developed as an open-source community model (Glimmer), initially funded as part of GENIE (Payne, Rutt: NERC eScience ref. NER/T/S/2002/00221), and later though the National Centre for Earth Observation (NCEO), with significant unfunded contributions from Hagdorn and Hulton. Rutt *et al.* (2009) provides a full description of model physics, numerical methods and validation/verification exercises.

From 2006, Glimmer was adopted as the ice sheet model component of the Community Earth System Model (CESM, formerly CCSM[[2]](#footnote-2)), and subsequently renamed Glimmer-CISM. This work has been funded by the US Department of Energy (DOE), and at present this comprises the majority of funding supporting development of the model. While the US support has delivered significant benefits to the global ISM community, it is nevertheless understandably driven by the needs of CESM and US funders.

The scientific and numerical specification of Glimmer-CISM reflects the changing nature of contemporary ice sheet modelling. The model was initially based on the established Shallow Ice Approximation (Hutter, 1983), solved using the Finite Difference method. Thermomechanical coupling and a simple treatment of basal melt/sliding were also included in the model described in Rutt et al. (2009). However, Glimmer-CISM has recently gained a higher-order stress balance module developed by Price and Payne, using the approach of Blatter (1995) and Pattyn (2003), as well as other enhancements.

Glimmer-CISM has a relatively modular architecture. This means that the model can be embedded within other codes relatively easily. For example, the code can be coupled to a variety of climate drivers and landscape evolution models. It also allows multiple regional ice sheet instances within the same overall model. Model configuration can be controlled flexibly using standardised configuration files, including determining which numerical methods, ice physics and bed parameterisations are selected. Glimmer-CISM uses NetCDF for file IO, and there is significant freedom in the variables and frequency of output. An ISM-GCM coupling module is provided with Glimmer-CISM, but it has limited functionality.

Development of Glimmer-CISM is conducted on a public-access website, and is coordinated by a steering committee comprising Rutt (chair), Hagdorn, Johnson, Lipscomb, Payne and Price. However, UK involvement in model development, and the provision of functionality and support for non-CESM users (e.g. the Met Office, University of Reading), is presently hampered by a lack of funds.

Glimmer-CISM is the leading ISM with a UK provenance. The most prominent alternatives are PISM[[3]](#footnote-3), developed by groups at University of Alaska Fairbanks and Potsdam Institute for Climate Impact Research, and Elmer[[4]](#footnote-4), a multiphysics finite element code developed by the CSC, Espoo, Finland. There is a substantial potential European user group comprising scientists coupling ISMs to GCMs in FP7 who currently use PISM, in part because of concerns over Glimmer-CISM’s coupling environment. This project aims to ensure that ongoing developments by the international partnership working on the code can continue to address UK climate science needs.

1. Project Overview

The essence of this project is to make ice sheet models easy to use, to develop further and to integrate within a wide community of stakeholders. There are two distinct aspects to the implementation of this vision:

1. ***Development of a generic technical and scientific framework for ISM-GCM coupling, which will define a standard for ISMs and GCMs to use in the future.***
2. ***Implementation of the ISM part of the framework within Glimmer-CISM, and the GCM part within CESM and the Hadley Centre climate models.***

There are seven primary activities proposed:

* + - 1. ***Definition of scientific and technical requirements***
      2. ***Specification of ice sheet model internal and external interfaces, based on (1)***
      3. ***Architecture modification and interface implementation for Glimmer-CISM***
      4. ***GCM interface implementation: CESM and Hadley Centre models.***
      5. ***Improvements to Glimmer-CISM accessibility and usability.***
      6. ***Creation and delivery of training materials and courses for the user-community***
      7. ***Establishment of a longer-term community network to provide a forum for future developments.***

A detailed work plan follows below. We emphasise that the work outlined is targeted at providing better infrastructure and use of the existing code in the wider community. We aspire to continue to provide scientific enhancements to the core of Glimmer-CISM, but funding will be sought from other sources to allow this to happen, as well as falling within the scope of activities by our international partners.

1. Project Partners

Our project partners fall into three categories:

***Major developers.*** These are groups currently making major continued developments to Glimmer-CISM and its incorporation into other Earth System Models. There are two major partner groups which have been instrumental in developing Glimmer-CISM over the last four years: those at LANL (Lipscomb and Price) and the University of Montana (Johnson). In particular, the LANL group have provided significant sustained investment in the development of the code core as part of CESM. The work by these groups on the code base will continue (see letters of support) and is directly complementary to what is proposed here. We will continue to work closely with these partners as part of the framework development process (see below), and to assist their implementation of the framework in CESM. We will also work closely with the Hadley Centre and University of Reading (Ridley/Gregory) to conduct a parallel process concerning the suite of Hadley Centre models derived from the Met Office Unified Model (HadGEM3-ES and FAMOUS).

***Wider ISM/GCM users****.* This is a group (names here: see Letters of Support) which comprises scientists who use Glimmer-CISM to solve scientific problems, and who are interested in continuing to use ice sheet codes as they develop. This is the group of partners who are likely to benefit most directly from the proposed work. We need to ensure that this user community gains genuine benefits from the way the code is operated and can be interfaced, and the supporting materials provided . Through the Framework Development Workshops, their role is to inform us of their experience of using ISMs, what they perceive as desirable, the best kind of interfaces, and how the code can be improved to solve the problems they are interested in. The principle is to have a deeper conversation with the typical users of the code, and to identify shared aspirations and experiences.

***Developers of other ice sheet codes.*** (names here: see Letters of Support) Eventually, the current core of Glimmer-CISM and other ice sheet codes will become obsolete. Already there are new ice sheet codes (e.g. Elmer) which bring improvements in how the ice physics are solved yet arguably are less easy to use than Glimmer-CISM. What is important for the wider community is to avoid having to re-invent how models can be operated and coupled as these underlying codes evolve. By involving this group of partners, we will seek ways of standardising the ISM-GCM interface such that, provided any ice sheet code is equipped with such an interface, it can be operated in a similar way. This could lead to benefits now, since it would mean that different ice sheet models could be swapped in and out of larger models comparatively easily. In the future, it would mean that if there were an agreed interfacing standard, new models could be developed to conform to it. Consequently, it is essential to involve other model developers in this discussion.

1. Stakeholder Engagement Activities

***Framework Development Workshops.*** Community engagement and participation is essential if we are to achieve the goals listed in section 5 above. The main vehicle for this engagement will be three Framework Development Workshops. These will involve partners in each of the communities outlined above. The first two workshops are intended to be formative, in as much as intend that they should lead to the agreement on (at least) a prototype API standard for ice sheet models.

1. The first workshop will largely be one in which we seek to explain the overall concept behind the project, to engage participants in aspects of current practice, to identify core data-model needs to permit key scientific problems to be addressed, and to discuss ways of approaching this from a technical standpoint. An outcome of the workshop is that we will produce draft interface requirements (point 8.1 below), and seek feedback from participants and the wider community on the specification.
2. The second workshop will present the initial API to the community, and invite reflections on and refinements to this API. We will report on how the API has been implemented within Glimmer-CISM, and we will hold sessions that allow discussion and reflection on detailed aspects of the interfacing and its needs as specified in the requirements generated from Workshop 1.
3. The third workshop aims much more to be informative to a wider community and will therefore be scheduled towards the end of the project period. Our aim is to report on how the interface operates in practice and to identify where further developments will need to be targeted.

Throughout each of the workshops, we will allow time in some sessions to permit discussion on how best to establish a more permanent network to help steer development of the interface and associated activity across the community.

***Training Events.*** The development of a new ISM/GCM modelling framework will have maximum impact only if ice sheet and climate modellers are aware of it and know how to use it. To make sure these goals are achieved, we will run three training events, aimed at a broad constituency of scientific ISM users. These users will mainly comprise those wider ISM/GCM users referred to above. The training events will be run over two full days, and will provide a comprehensive introduction to the coupling framework in general, and its implementation in Glimmer-CISM in particular. Hands-on experience for the participants will be a central part of these events. Training materials and model documentation will be provided, which will also be published on the project website.

1. Detailed Work Plan
2. *Definition of scientific and technical requirements*

Before work can begin on a practical framework for ISM-GCM coupling, it is necessary to understand and define the range of functionality it is to have. The scientific aspects will include: the possible coupling fields and their calculation, interaction with the atmosphere, land surface and ocean components of the GCM, asynchronous coupling strategies, interpolation/downscaling techniques, etc. The technical aspects will encompass issues around computing platforms, compilers, language choice, parallelism, file IO, restart mechanisms, etc. A full technical and scientific specification will be drawn up by the project team, informed by community input at the first Framework Development Workshop. This part will involve the participation of all project partners.

1. *Specification of ice sheet model internal and external interfaces*

Having determined what the ISM and ISM-GCM APIs should be capable of doing, the next stage is to write a full API, sufficiently detailed that it can be used by other modellers to implement compatible interfaces in their own models. This task will take into account all the decisions made in part 9.1, as informed by the first Framework Development Workshop. It is likely that it will be conducted in tandem with 9.3: that is, a real implementation of the API will be developed in parallel with the specification. This part will be carried out by the UK project team in collaboration with Project Partners at LANL, University of Montana, Met Office/Hadley Centre and University of Reading.

1. *Architecture modification and interface implementation for Glimmer-CISM*

Following the work completed in 9.1 and 9.2 on API specification and design, we will modify the interface and structure of Glimmer-CISM to conform to the API. This will provide a working example of how the API should be implemented, and will demonstrate the practicability and usefulness of the approach. We will use the second Framework Development Workshop to review and refine the outcomes available at this point. This part will be carried out by the UK project team in collaboration with Project Partners at LANL and University of Montana.

1. *GCM interface implementation: CESM and Hadley Centre models*

We will implement the GCM side of the coupling API in CESM and the Hadley Centre models (HadGEM, etc.). This part will be carried out by Project Partners at LANL, University of Montana, Met Office/Hadley Centre and University of Reading, in consultation with the core UK project team.

1. *Improvements to Glimmer-CISM accessibility and usability.*

The most recent developments to Glimmer-CISM have tended to focus on improvements to the underlying physics, and have to some extent incurred further complexity in the use of the code. By contrast, the documentation and front-end accessibility to the code has lagged behind. For a specialist, use of Glimmer-CISM is not particularly complex, and permits relatively easy access to ice sheet models. However, for non-specialists or new users there is quite a technical hurdle to overcome. We propose first to further regularise the code branches into ‘development’ and ‘stable’ versions, the latter being well tested and bug free. Secondly, the code will be fully documented, and user-guides for non-specialists will be developed. Third, we will build a graphical ‘front-end’ to some versions of the code that will allow it to be driven for simple scenarios where the base topography, and climate options can be selected from particular options, or user-specified data. This latter functionality is particularly targeted at non-expert and student use so that we can extend awareness and use of the code. This part will be carried out by the UK project team in collaboration with Project Partners at LANL and University of Montana.

1. *Implementation of training materials and courses for the user-community.*

This element extends that provided in 9.5 but is more directly targeted at pro-active engagement of the user-community so that we can extend expertise in the use of the code, once the tools that enhance the code accessibility are prepared. In particular the training events will particularly be targeted to graduate student/ postdoctoral level, and we will generate structured training materials in support of a set of training events. Our aim is that these training events will persist beyond the time limit of the grant and be funded from additional sources. While we will provide training on the specific use of Glimmer-CISM as it stands, a specific aim is to educate users about the principles of utilising the standard interfaces, such that if they go on to work with other codes, they will be aware of this opportunity. This part will be carried out by the UK project team in collaboration with Project Partners at LANL and University of Montana.

1. *Establishment of a longer-term community network to provide a forum for future developments*

Glimmer-CISM is a community code operating under a public licence (currently the GNU GPL[[5]](#footnote-5), but soon to be released under GNU LGPL[[6]](#footnote-6)). It is therefore not ‘owned’ by anyone. The way in which it is used and is developed by various interest groups is in part dictated by those that have an interest in and resource to make it happen. The kind of development that is proposed in 9.1, also necessitates mutual agreement and benefits to those that participate in the further development of the code. For the most part, those interested in furthering ice sheet models do not want to get bogged down in huge bureaucracies or management systems; they want to get on and do the next bit of science. However, if an agreed specification of interfaces, and the efficient development of models is desirable, then the collegiate and consensual activity that implies requires a level of steerage and governance. We will explore via the workshops longer-term ways of establishing networks, centred around the existing Glimmer-CISM Steering Committee, which can continue to provide consensus on how ice sheet models can be more easily interfaced and accessible. This part will be carried out by the UK project team in collaboration with Project Partners at LANL and University of Montana.

1. Project Management Plan

The overall progress of the project will be managed by the existing Glimmer-CISM steering committee (Rutt, Hagdorn, Payne, Lipscomb, Price and Johnson), with the addition of Co-I Hulton. Overall operational responsibility rests with PI Rutt, but in practice decisions will be taken on a consensus basis within the committee. A number of work packages are identified within the scope of the proposal. These broadly mirror the structure of the detailed work plan given above, but are in some cases divided differently because of logistical considerations. Along with their associated coordinators, milestones and deliverables, they are as follows:

**WP1A – Organisation of First Framework Development Workshop** [Hulton]

**WP1B – Organisation of Second Framework Development Workshop** [Rutt]

**WP1C – Organisation of Third Framework Development Workshop** [Payne]

The structure and mechanics of the three Framework Development Workshops will be very similar. The division into three work packages reflects the desire to spread responsibility between the three UK institutions, as well as the distribution of the workshops across the timeframe of the project. Each workshop will require a planning phase, where participants will be invited, practical arrangements made, and a detailed schedule devised to facilitate best use of the available time. *Milestones:* First circular; second circular; programme confirmation; event takes place; follow-up with participants. *Deliverables:* D1A - Detailed workshop programme; D1B - successful practical arrangements; workshop report.

**WP2 – Definition of framework technical and scientific requirements** [Hulton]

This work package interacts strongly with WP1A, in that the technical and scientific requirements of the modelling framework will be informed substantially by the participants in the First Framework Development Workshop, but also because initial scoping of the requirements will provide information for the planning of the workshop. Hence, it makes sense for the same person to lead both work packages. In addition to Hulton, Hagdorn will have a major role in this work package. *Milestones/Deliverables:* D2A *-* scoping document for technical and scientific requirements; D2B - full draft of technical and scientific requirements.

**WP3 – Full specification of coupling and internal APIs** [Rutt/Hagdorn]

This work package interacts strongly with WP1A and depends on WP2. It will deliver outputs to WP1B. The main task in this work package is to turn the technical and scientific requirements into a detailed API specification. This task will be largely carried out by Rutt and Hagdorn, in consultation with other Co-Is and project partners. *Milestones/Deliverables:* D3 - full draft of API specification document.

**WP4 – Implementation of API in Glimmer-CISM** [Rutt/Hagdorn]

This work package will run alongside WP3, and will deliver outputs to WP1B and WP5. Glimmer-CISM will provide a testbed for API development, and the experience will inform decisions in WP3 as to which approaches are most practical and beneficial. Rutt and Hagdorn will deliver this work package in consultation with other Co-Is and project partners. *Milestones/Deliverables: D4 -* working implementation of API in Glimmer-CISM, including a suite of regression tests.

**WP5 – Implementation of API in CESM and Hadley Centre Models** [Payne]

This work package depends on WP3 and WP4. The parts of the API specification which relate to ISM-GCM coupling will be implemented in CESM and the Hadley Centre models. These changes will primarily be made by project partners Lipscomb and Price (CESM), and Ridley (Hadley Centre), coordinated by Payne. *Milestones/Deliverables:* D5 - Working coupling between Glimmer-CISM and these two GCMs.

**WP6 – Glimmer-CISM usability changes and documentation** [Rutt]

This work package depends on WP4, and provides outputs to WP7. In the light of any concerns raised in WP1A and WP1B (first and second Framework Development Workshops), changes to Glimmer-CISM will be made to enhance usability. Full documentation of the model will be generated, and a GUI front-end to the model will be written. The Glimmer-CISM website will be redesigned and improved to provide easy access to documentation, and to support the building of the community network of stakeholders. Programming tasks will be undertaken by a graduate programmer, under direction from Rutt. Website developments will be commissioned from commercial providers. *Milestones/Deliverables:* D6A - full documentation delivered (web/PDF); D6B - GUI front-end delivered, including relevant documentation; D6C - new website.

**WP7 – Training events** [Hulton/Rutt/Hagdorn]

This work package depends on all the other activities in the project. Nevertheless, to leverage maximum engagement and impact during the life of the project, we will initiate training events before work on the other work packages is complete. Three training events will be provided, one in the second year of the project, and two in the third. These will be led by Hulton, Rutt and Hagdorn, with input from Payne and project partners. *Milestones/Deliverables:* D7A - Training materials on website; D7B - training events advertised and successfully organised.

**Work Package schedule**

The following GANTT chart shows how the work packages will be scheduled across the 36 months of the project:

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Year | 2012 | | 2013 | | | | 2014 | | | | 2015 | |
| Quarter | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 |
| WP1 |  |  |  |  |  |  |  |  |  |  |  |  |
| WP2 |  |  |  |  |  |  |  |  |  |  |  |  |
| WP3 |  |  |  |  |  |  |  |  |  |  |  |  |
| WP4 |  |  |  |  |  |  |  |  |  |  |  |  |
| WP5 |  |  |  |  |  |  |  |  |  |  |  |  |
| WP6 |  |  |  |  |  |  |  |  |  |  |  |  |
| WP7 |  |  |  |  |  |  |  |  |  |  |  |  |

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Rutt IC, M Hagdorn, NRJ Hulton, AJ Payne (2009) The Glimmer community ice sheet model. *J. Geophys. Res.*

1. Note that when we refer to *ISM-GCM coupling* in this proposal, we always mean *two-way coupling*, entailing an exchange of model fields between the ISM and GCM over the course of the integration period. Coupling may involve spatial and/or temporal interpolation or averaging of model fields, and may necessitate other manipulation such as correction for temperature-elevation feedback. [↑](#footnote-ref-1)
2. http://www.cesm.ucar.edu/ [↑](#footnote-ref-2)
3. http://www.pism-docs.org/ [↑](#footnote-ref-3)
4. http://www.csc.fi/english/pages/elmer [↑](#footnote-ref-4)
5. http://www.gnu.org/licenses/old-licenses/gpl-2.0.html [↑](#footnote-ref-5)
6. http://www.gnu.org/licenses/lgpl.txt [↑](#footnote-ref-6)