**Development and applications of the new-generation ice-sheet model Elmer/Ice-sheet (EIS)**

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**Project summary**

By storing huge amounts of fresh water, ice sheets are the essential contributor to sea level changes on time scales up to a few thousands of years. Since the Last Glacial Maximum, mass loss of ice sheets has raised global sea level by about 130 m. Until recently, ice sheets were believed to respond on millennial time scales, i.e. to be too slow to have a significant impact in the coming centuries (Houghton et al., IPCC 2001). However, since the mid-nineties, and the observation of important and rapid dynamical changes of an increasing number of major outlet glaciers, ice sheets have proven to be much more dynamic than previously thought. . The currently observed acceleration of ice sheets mass loss, as well as records of tremendous rates of sea-level rise during past deglaciations, raise fears about the potential forthcoming contribution of Greenland and Antarctica. Unfortunately, as highlighted in the last IPCC reports, current ice-sheet models have difficulties in reproducing the contemporary observed changes in Greenland and Antarctica and current projections of sea-level rise still remain plagued with high uncertainties due to our poor ability to evaluate the evolution of the ice sheet dynamics, particularly for high-end scenarios.

The aim of this project is to complete the development of the new-generation ice sheet model Elmer/Ice-sheet, with unprecedented capabilities in modelling coastal ice-sheet dynamics, and propagate its use amongst the national and international climate community. A dedicated package built on top of the already existing and internationally recognized Elmer/Ice model will be completed during the course of the proposed project. Elmer/Ice-sheet will therefore fully use the previous and continuing Elmer/Ice developments and will be specifically designed to be easily handled by the climate and paleo-climate modelling communities. This will offer a unique scientific opportunity to revisit long-standing questions related to rapid changes of ice sheets and improve our ability to establish reliable projections of their coming evolution and associated contribution to sea-level rise in the context of the global climate change.

**Summary table of persons involved in the project:**

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**Any change that have been made in the full proposal compared to the pre-proposal**

EIS-PRC2017 is an updated and improved version of EIS-PRC2016; this latter was recommended for funding by the selection committee last year but finally not granted by ANR. Moreover, the EIS consortium was granted a 5k€ support by the French national programme LEFE/IMAGO-MANU (INSU CNRS) for the organisation of a meeting dedicated to answering this call. This meeting was held in Grenoble on March 21-22, 2017 and allowed the participation of all partners involved in EIS-PRC2017. As it will provide the necessary tool for a better estimate of ice-sheets contribution to SLR, the French LEFE IMPHALA consortium also supports this project.

This new version of the proposal accounts from the remarks of reviewers from the two calls. Regarding the PRC2017 first step review, the main criticism was that the numerical costs were not discussed, especially if the complete set of Stokes equations has to be solved. As mentioned in the pre-proposition, *Elmer/Ice* already includes not only the full Stokes equations but also all the classical lower-order Stokes approximations (*e.g.*, Fürst et al., 2016, Mosbeux et al., 2016). The type of equations which be solved is now clearly stated and a plan for numerical resources is presented.

Note also that since 1st January 2017 LGGE has merged with LTHE, and will appear in this proposal under its new denomination of Institut des Géosciences de l'Environnement (IGE).

# Proposal's context, positioning and objective(s)

***General aim***

**The aim of this 4-year-long project is to complete the development of the new generation ice-sheet model *Elmer/Ice-sheet*, with unprecedented capacities in modelling coastal ice-sheet dynamics, and spread its use amongst the national and international climate community. This will offer a unique scientific opportunity to revisit long-standing questions related to rapid changes of ice sheets and improve our ability to establish reliable projections of their coming evolution and associated contribution to sea-level rise in the context of global climate change**.

## Objectives and scientific hypotheses

***Background and specific aims***

Ice sheets are the main contributors to long-term sea-level changes. They have raised sea level by about ~130 m since the Last Glacial Maximum (LGM, Dutton et al., 2015) at a speed of up to 4 meters per century during the meltwater pulse 1a, which might have resulted from ice flow acceleration (Deschamps et al., 2012). Since the nineties, direct observations of unexpected, important and rapid dynamical changes of numerous outlet glaciers (Mouginot et al., 2014), together with the consequent increasing discharge of both Greenland and Antarctica (*e.g.*, Shepherd et al., 2012), have shed light on the vulnerability of contemporary human society to SLR. As highlighted in the last two IPCC assessments, **the major uncertainty in the projections of sea-level rise over the next centuries lies in our poor ability to model the coastal dynamics of ice sheets.**

Substantial progresses have been achieved during these last 5-10 years regarding our ability to model the flow of polar outlet glaciers. This gives the opportunity to both *(i)* revisit to what extent rapid dynamical changes of ice sheets flow were at the origin of documented fast SLR and *(ii)* benefit from paleo-reconstructions and contemporary observations to improve our ability to model the forthcoming contribution of ice sheets to SLR. This project specifically aims at completing the development of the new generation ice-sheet model *Elmer/Ice-sheet,* a model able to better reproduce past ice-sheet rapid changes and to improve projections of their evolution. Designed as an open and collaborative tool, the *Elmer/Ice-sheet* model will be rapidly and within the framework of this project used by the entire national scientific community interested in ice-sheet interactions with the climate system.

***Social and economic issues***

Besides strengthening the national climate community with a collaborative ice-sheet model, the general aim of this project is to provide a better estimation of SLR induced by ongoing climatic change. The economic implications of this project are therefore related to natural hazard mitigation strategies and insurance reliability (*e.g.*, Nicholls and Cazenave; 2010; Hauer et al. 2016). Numerous publications are available on the subject, providing prognostics of the costs induced by climatic change adaptation (*e.g.*, Stern 2007). Concerning the aspects related to SLR, they notably point out that *(i)* the worldwide population is concentrated close to the seas, *(ii)* SLR impacts will not be uniform and environmental refugees from affected locations could place significant political stress on even on remote regions not directly affected by SLR, *(iii)* the economic impact of flood defense building is highly non-linear, with the costs induced by 50-cm SLR being one order of magnitude smaller than by 1-m SLR (estimated to be 5.6% of the 1990 global world income; Nicholls and Mimura, 1998). These tremendous economic and societal impacts are based on IPCC SLR projections that remain poorly constrained particularly regarding higher-end scenarios (IPCC, 2013).

The present project proposes to bring together the French community around a unique and state-of-the-art ice-sheet model. The experts gathered in this project are certainly the most pertinent to provide valuable inputs to ongoing international debates on the future of ice-sheets mass balance and, ultimately to inform the scientific community and political stakeholders in discussions on coastal adaptation and sea-defense planning.

## Originality and relevance in relation to the state of the art

*A brief history of ice-sheet models*

Based on low order approximations of ice flow equations (asymptotic of the Stokes equations, the equations that govern the flow of an incompressible viscous material with low Reynolds number), ice-sheet models (ISM) were initially developed to explore the mechanisms driving the long-term and large-scale changes of ice sheets and in particular to analyse the feedbacks between ice sheet topography and surface mass balance (e.g. Ritz et al., 1997, 2001; Greve and Calov, 2002; Charbit et al., 2007; Roche et al., 2014; Robinson et al., 2012). However, these models were using low resolution (often coarser than 20 km) with simplified physics, and they failed to capture small-scale processes and to properly represent fast dynamical changes especially in coastal regions. At best, they had to use parameterizations to mimic these processes (Pollard and DeConto, 2009; Ritz et al., 2015). Besides not being capable of explaining rapid changes during deglaciations (Charbit et al., 2005, 2013; Bonelli et al., 2009), ISMs have further difficulties in reproducing the contemporary state of Greenland (Roche et al., 2014, Greve et al., 2011) and Antarctica (e.g. Maris et al., 2015). A lack of representation of small-scale processes required to confidently represent the dynamics of coastal outlet glaciers was clearly highlighted and, thus, improving capabilities of ISMs was identified as a priority for reliable projections (Solomon et al., 2007; Kirchner et al., 2011; Stocker et al., 2013, Durand and Pattyn, 2015).

In the light of these issues, new generation ice-flow models have recently started to be developed (e.g. Larour et al., 2012, Cornford et al., 2013, Gagliardini et al., 2013). Most of these developments were motivated by *(i)* improving the existing approximations of the ice flow equations, *(ii)* developing the capability to describe the movement of the grounding line (the boundary between the grounded and floating parts of the ice-sheet), a prerequisite before confidently modelling outlet glacier dynamics, and *(iii)* implementing data assimilation facilities. Stimulated by a number of international inter-comparison experiments (Pattyn et al., 2008, 2012, 2013; Asay-Davis et al., 2015), significant progresses have been made on the two first points. The ISMIP-HOM[[1]](#footnote-1) exercise has allowed the assessment of various lower-order Stokes approximations (Shallow Ice Approximation - SIA, Shallow Shelf Approximation - SSA, or hybrid, a superposition of SIA and SSA) with regards to their ability to reproduce typical ice flow conditions by comparison with the *full-*Stokes solution. The MISMIP[[2]](#footnote-2) and MISMIP3D[[3]](#footnote-3) experiments have highlighted general rules in terms of ice flow approximations and numerical methods to adequately solve grounding line dynamics. Developments in assimilation facilities were motivated by the increasing number of satellite data from which non-directly measurable parameters, such as basal friction and/or ice fluidity, can be inferred. The developed inverse methods are nowadays used to build initial states of transient simulations as close as possible to the observed ones (Gillet-Chaulet et al, 2012).

*French context: GRISLI versus Elmer/Ice*

C. Ritz developed the *GRISLI* ISM in the 1990s at IGE. *GRISLI* has been used for paleoclimate modelling, ice core interpretation, and projections over the next centuries, and collaborations between climate modelling and glaciology communities have been very fruitful, with ~40 publications. *GRISLI* is a hybrid model combining SIA and SSA, based on the finite difference method with a regular and structured grid over the whole domain but it does not include all the hierarchy of asymptotic expansions for the flow equations and does not offer mesh refinement facilities for regions of specific interest. *GRISLI* is therefore not able to reproduce standard grounding line reversibility tests (*e.g.*, as in MISMIP and MISMIP3D), making the model inappropriate to represent outlet glacier dynamics[[4]](#footnote-4). Finally, no assimilation method has been implemented.

In parallel, since 2004, increasing efforts have been deployed in the development, international recognition and dissemination of the ice-flow model *Elmer/Ice* (*e.g.*, Gagliardini et al., 2013). *Elmer/Ice* is the glaciological add-on package to *Elmer*, which is a multi-physics finite-element suite mainly developed by numerical experts at CSC[[5]](#footnote-5) in Finland. *Elmer/Ice* was initially developed to study processes at a local scale but it has progressively proved its ability to investigate large-scale ice flow evolution. Since 2004, almost 80 publications[[6]](#footnote-6) were based on simulations computed with *Elmer/Ice*. The worldwide recognition of *Elmer/Ice* is due to its physics completeness, its ability to be initialized to the actual ice-sheet state and simulate coastal changes (grounding line, calving). The comprehensive list of *Elmer/Ice* capabilities in terms of physics and numerical methods is detailed on a dedicated website[[7]](#footnote-7) and a wiki[[8]](#footnote-8). Most of these developments have been implemented by the IGE group so far, some being supported by successful past ANR fundings (see below for details). For the present proposal, the most relevant processes included within *Elmer/Ice* to be mentioned are:

* resolution of the Stokes equations and lower-order approximations (SIA, SSA and hybrid, ANR SUMER 2013-2017, Fürst et al., 2015, 2016),
* choice of various ice rheologies (Glen's law, anisotropic laws (Gillet-Chaulet et al., 2006) and damaged ice (Krug et al., 2014)),
* solvers for the evolution of internal variables, such as temperature (enthalpy conservation, Gilbert et al., 2014), damage (Krug et al., 2015) and age of ice layers,
* choice of various friction laws (*e.g.*, classical Weertman sliding law, effective-pressure dependent friction law (Gagliardini et al., 2007)),
* basal hydrology solvers (de Fleurian et al., 2014),
* data assimilation facilities (ANR ADAGe 2009-2013, Jay-Allemand et al., 2011),
* accurate treatment of grounding line dynamics (ANR DACOTA 2007-2011, Durand et al. 2009, Favier et al., 2012),
* iceberg calving for flow-line geometries (Krug et al., 2014).

Regarding numerical facilities, *Elmer/Ice*:

* is fully parallelised and has demonstrated its scalability (Gagliardini et al., 2013),
* is routinely used on various clusters (locally at IGE, on regional clusters, e.g. CIMENT[[9]](#footnote-9), national CINES clusters, and other clusters abroad by our international colleagues),
* uses unstructured meshes allowing focussing on regions of interest (Gillet-Chaulet et al., 2012),
* includes the possibility of using different meshes and interpolation from mesh to mesh facilities.

Since 2004, *Elmer/Ice* was first used on flow-line and/or synthetic geometries (e.g., Le Meur et al., 2004, Durand et al., 2009), providing reference results for the model inter-comparison projects ISMIP-HOM (Pattyn et al., 2008, Gagliardini and Zwinger, 2008), and more recently MISMIP (Pattyn et al., 2012), MISMIP3D (Pattyn et al., 2013) and MISOMIP (Asay-Davis et al., 2016). The use of *Elmer/Ice* has then progressed to fully 3d prognostic simulations applied to actual glaciers and ice sheets, using data assimilation facilities to better initialize the model with observed geometries and surface velocities. As illustrated in Fig. 1, the first Stokes prognostic simulations of Pine Island Glacier (Antarctica) with a free evolving grounding line (Favier et al., 2014), the first Stokes prognostic simulations over the whole Greenland ice-sheet (Gillet-Chaulet et al., 2012, Seddik et al., 2012), and more recently studies using SSA and state-of-the-art inverse methods over the whole of Antarctica (Fürst et al., 2015, 2016) demonstrate how the use of *Elmer/Ice* has matured to computing evolution of ice flow at a continental scale. However, few developments still remain to be implemented in order to provide to the climate community a fully operational new generation ISM able to encompass any application whatever the scale or the period of interest. They fall in two essential categories:

1. Implementing missing processes required for long-term simulations: lateral boundary evolution (*e.g.*, moving calving and terrestrial fronts) and isostasy.
2. Designing a user-friendly interface to facilitate usage by a broader community not limited to ice flow modelling experts.

## Methodology and risk management

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|  |  | **Figure 1**: Illustration of the evolution in applications performed with *Elmer/Ice* during the last years: **(a)** grounding line dynamics for 2d flow-line synthetical geometries (Durand et al., 2009), **(b)** grounding line retreat of Pine Island Glacier (Antarctica, Favier et al., 2014), **(c)** prognostic Stokes simulations of the whole of Greenland for the next 200 years (Gillet-Chaulet et al., 2012) and **(d)** SSA inversion of the basal drag and ice viscosity for the whole of Antarctica (Fürst et al., 2016). |

While a large number of groups are updating their previous generation models to incorporate part of the physics and numeric needed for simulating the coastal regions of ice sheets, this project has the ambition to move one step further by building a new ice-sheet model based on the highly physical and fine resolution ice flow model *Elmer/Ice*. Indeed, two options can be considered in building the new generation of ISMs required to improve our understanding of the consequences of imbalanced ice sheets to the climate system. First, to continuously improve the previous generation of ISMs initially designed for paleo-simulations (*e.g.*, Pennsylvania State University model: Pollard and Deconto, 2012 and PISM: Winkelmann et al., 2011). Second, to develop a new model based on an existing high-resolution ice flow model (*e.g.*, ISSM: Larour et al., 2012 and BISICLES: Cornford et al., 2013). At IGE, these two options have been evaluated: upgrading *GRISLI* or develop *Elmer/Ice*. Balancing the efforts between improving the old design of *GRISLI* (mainly parallelizing the code, enlarging the variety of flow equations, implementing grid refinement and data assimilation facilities) versus adjusting *Elmer/Ice* (mainly moving lateral boundary and implementing isostasy), we decided two years ago that *GRISLI* will not be further developed and efforts to turn *Elmer/Ice* into a comprehensive ISM have been engaged (Fürst et al., 2016). To achieve this strategy, a dedicated package built on top of *Elmer/Ice* will be completed during the duration of the proposed project (further denoted *Elmer/Ice-sheet*). *Elmer/Ice-sheet* will therefore fully use the previous, current and future developments of *Elmer/Ice* and will be specifically designed to be easily handled by the climate and paleo-climate modelling communities.

This project therefore focuses on: *(i)* implementing few missing processes in *Elmer/Ice, (ii)* completing the development of an easy-to-use package *Elmer/Ice-sheet* and promoting its usage, and *(iii)* completing timely applications. The proposed developments will be designed to last over the long term, allowing further developments of the physics and dissemination of the *Elmer/Ice-sheet* model in the climate community. In particular, *Elmer/Ice-sheet* will be integrated into the CNRM and IPSL Earth System Models in the course of this project and the necessary efforts required to couple *Elmer/Ice-sheet* with ocean and atmosphere models are already supported by the TROIS-AS ANR-JCJC project (2015-2019) led by N. Jourdain at IGE. Therefore, by the end of the present project, *Elmer/Ice-sheet* will complete the suite of physical models composed of *LMDz* and *ARPEGE* for the atmosphere and *NEMO* for the ocean. A labelling of *Elmer/Ice-sheet* as a national numerical tool will be requested. The new ***Elmer/Ice-sheet* ISM will allow long-standing questions** in which ice flow dynamics play a key role to be revisited. The proposed applications, by mixing past, present and future reconstructions of ice-sheets aim to evaluate the model with high-end scenarios of ice-sheet retreat documented from the past (LIG and BKIS after the LGM) in order to gain confidence in the ability of the model to perform reliable projections for the future. The newly developed model will contribute to the ISMIP6 project and obtained results will inform the next IPCC Assessment Report.

Regarding risks in general, it could be noted that the present project requires substantial efforts in terms of contractual engineers and PhDs (but of course in agreement with ANR rules with a tenuousness index of 24%). This is a necessity to have *Elmer/Ice-sheet* operational as soon as possible and benefit from the international schedule related to CMIP6 to efficiently promote the model in an ideal context. In any case, this does not put any risk on the achievement of *Elmer/Ice-sheet* in the course of the project and in the worst case it would only delay its dissemination within the international community. The corresponding work program and more specific risks related to each task are detailed in the next section.

# Project organisation and means implemented

As mentioned above, the objective of the proposal is to actively supplement the development of *Elmer/Ice-sheet* and propose the first applications of this new ISM. All along the project, technical developments and applications will be strongly intertwined. Each application will be preceded by specific model developments with the double objective of demonstrating the gain raised by these improvements and answering to specific open questions on ice sheets past, present and future evolutions. In parallel, a user-friendly framework for the *Elmer/Ice-sheet* package will be designed to ensure the promotion and uptake of the tool in the climate community. The development tasks are led by IGE whereas the application tasks are shared between all the partners. The EIS project is decomposed in 5 tasks: one for the management of the project, two for the development of *Elmer/ice-sheet* and two to perform applications using the newly developed tool.

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| --- | --- | --- | --- |
| **No** | **Task Name** | **Involved partners** | **Task leader** |
| 0 | Project **Management** | IGE | O. Gagliardini (IGE) |
| 1 | Processes and technical **developments** | IGE, LSCE | F. Gillet-Chaulet (IGE) |
| 2 | EIS **development** and distribution | IGE, LSCE | O. Gagliardini (IGE) |
| 3 | Paleo-ice-sheet **applications** | LSCE, CNRM | S. Charbit (LSCE) |
| 4 | Contemporary and future **applications** | IGE, LSCE, CNRM | G. Durand (IGE) |

## Scientific coordinator

***Project PI and leader of Tasks 0 and 2 -*** The PI **Olivier Gagliardini** is Professor at the University of Grenoble Alpes (UGA), nominated at Institut Universitaire de France (IUF) from 2010 to 2015. He launched the development of *Elmer/Ice* during his one-year visit at CSC (T. Zwinger, Finland, 2005-2006) and since then is the coordinator of the users community. He was PI of the ANR project ADAGe (2009-2013), which was dedicated to the development of inverse methods for ice flow model. He is Editor for The Cryosphere since 2012 and co-convenor of modelling sessions at EGU and AGU. He was the chair of the local organizing committee of an IGS International Symposium in Chamonix (26-30 May 2014) and the lead organizer of an international workshop on calving (IGE, 1&2 June 2014). He has organised 12 international courses on *Elmer/Ice* since 2008. He is co-author of 61 publications in peer-reviewed international journals (h-index: 23).

Detailed CVs of the project PI and all participants of the project are given in Appendix.

## Consortium

All French institutes studying ice-sheet dynamics and using ice-sheet models are involved in the proposed project. They further have a long history of fruitful collaborations through the use of the previous *GRISLI* ice-sheet model. The proposed project intertwines continuous developments of *Elmer/Ice-sheet* with dedicated applications in close interaction with all three partners. Even if not being part of the project, expertise on data/observation (E. Berthier) and SLR (B. Meyssignac) will be provided by our colleagues at LEGOS.

**UGA / IGE**

Institut des Géosciences de l'Environnement (IGE), based in Grenoble, is a Joint Research Unit (JRU) created in 2017 from the gathering of LTHE and LGGE. Within CNRS, IGE is primarily part of the Sciences of the Universe department (INSU). Within University Grenoble Alpes, IGE is part of the Observatory for Sciences of the Universe in Grenoble (OSUG). IGE has built its international scientific reputation on its research on the climate and the composition of the atmosphere. These studies deal with the present and the past based on the natural archives of ice and snow accumulated over the ages. IGE also boasts other very competitive research fields notably ranging from the physical and mechanical study of ice to the numerical modelling of glaciers and ice sheets. The Arctic and Antarctic Polar regions are the primary sites studied. ***Olivier Gagliardini***, PI of the EIS project, has a strong background in ice flow numerical modelling, and together with ***Fabien Gillet-Chaulet*** and ***Gaël Durand*** are the French core developers of the *Elmer/Ice* code. ***Catherine Ritz*** is a worldwide-recognized expert in polar ice sheet modelling and the main developer of the former model *GRISLI*. ***Nicolas Jourdain***, the PI of the TROIS-AS ANR project, has a recognized expertise on the ocean and atmosphere components and their coupling with an ice-sheet model. ***Emmanuel Le Meur*** has an expertise in ice flow and in isostasy models. ***Vincent Peyaud*** has an expertise in ISMs, and very interestingly a dual expertise on both *GRISLI* and *Elmer/Ice*.

**CNRS / LSCE**

Laboratoire des Sciences du Climat et de l'Environnement (LSCE) is a joint research unit (UMR 8212) of Commissariat à l’Énergie Atomique (CEA), Centre National de la Recherche Scientifique (CNRS) and the university of Versailles-Saint-Quentin. It is also attached to the Paris-Saclay University. LSCE employs ~300 persons in the fields of past, present and future climate studies, biogeochemical cycles modelling and observations. It is one of the 9 components of the Institut Pierre Simon Laplace (IPSL) on global environmental and climate studies. LSCE has also a strong expertise in past to future climate modelling from conceptual to fully coupled general circulation models (IPSL-CM) and in climate ice-sheet interaction modelling. On this basis, LSCE is very active in international projects such as PMIP (for the intercomparison of climate models for past climates, co-lead by LSCE), CMIP (inter-comparison of atmosphere-ocean general circulation models). ***Sylvie Charbit*** has built her expertise on the study of climate-ice sheet interactions for past Quaternary periods and future. She is also involved in the development of coupling methods between climate and ice-sheet models. ***Christophe Dumas***is an expert in ice-sheet dynamics and in the development of coupling methods between climate and ice-sheet models. ***Masa Kageyama***, head of the climate modelling team at LSCE, has developed her own research on glacial climates and their instabilities, as well as comparing them to future climates. She is also involved in developing the new version of the IPSL model and coupling it to ice-sheet models. ***Didier Roche*** focuses his research on paleoclimate applications of Earth system models, including cryospheric components. Over the past years, he has been the main developer and coordinator of the iLOVECLIM Earth System Model, using *GRISLI* as an ice-sheet component.

**CNRS / CNRM**

Centre National de Recherches Météorologiques (CNRM, mainly located in Toulouse and Grenoble) is a research centre affiliated to CNRS and Météo-France (the French national weather service), and has a staff of about 300 persons. The activities of CNRM within EIS will mostly rely on the use of *Elmer/Ice-sheet* and the CNRM-CM6 climate system model. CNRM-CM6 is developed in collaboration with CERFACS and IPSL and is maintained by a total of about 12 full-time permanent researchers and engineers. Most of its components are developed by CNRM (Crocus and ISBA-ES snow pack models, Gelato sea ice model, ARPEGE-Climat atmospheric climate model, and SURFEX land surface platform). ***David Salas y Mélia*** leads CNRM's climate research division. He has 20 years of experience in coupled climate modelling, with a particular interest in polar climates and sea-level changes. ***Silvana Buarque*** is a research engineer, with an expertise in modelling the surface mass balance of Greenland (Eemian and recent past climate).

## Tasks description

### Task 0 - Project Management

**Task leader:** O. Gagliardini (IGE), **recruited personnel:** Engineer Student (IGE)

**Objectives of the task**

**The general objectives of this task are the management of the EIS project regarding legal issues, the organisation of annual meetings of the working group, and promote *Elmer/Ice-sheet* and related results.**

The project manager will keep informed all the partners regarding legal issues of the project. He will be the natural interface with the ANR and produce the required reports, which will be written on the basis of contributions from all partners. A kick-off, two intermediates and a final meeting will be organised by the project manager. All participants of the project, as well as invited external experts, will contribute to stimulate the quality of the different contributions. The results presented and discussed during these meetings will be the basis of the annual reports to ANR. Potential external experts are F. Pattyn (ULB, Belgium), T. Edwards (Open University, UK), S. Cornford (Bristol University, UK), D. Goldberg (Edinburgh University, UK), T. Zwinger (CSC, Finland) and M. Morlighem (JPL, USA).

The project manager will design a website and set-up a twitter account at the very beginning of the project and update their contents continuously during the 4 years of the project. The website will contain a presentation of the main objectives of the EIS project, the job opportunities (postdoctoral positions / thesis) in the framework of the project, the partners and the scientific productions and news.

This news will be presented in a comprehensive form for a general audience and scientific journalists in particular. It will be efficiently spread through the EIS twitter account and supported by already established twitter networks (@ElmerIce1, @IGE\_Grenoble).

IGE has a long tradition of promoting its activities through regular visits of scholars and officials. EIS will benefit from this environment to promote its activities. An Augmented Reality Sandbox[[10]](#footnote-10) demonstrating ice flow processes will be developed and included in the routine of the IGE visits. In term, the AR Sandbox will become an efficient pedagogic support to introduce ice sheet and glacier flows to students of the University Grenoble Alpes.

**Deliverables**

**D0.1:** Design of the website and twitter account (T0+1), regular updates along the project

**D0.2:** Organisation of four annual meetings (T0+6, T0+18, T0+30 and T0+42)

**D0.3:** Writing of the ANR reports (T0+12, T0+24, T0+36 and T0+48)  
**D0.4:** Design and build of the Sandbox (T0+12)

### Task 1 - Processes and technical developments

**Task leader:** F. Gillet-Chaulet (IGE), **co-leader:** O. Gagliardini (IGE), **other permanents:** E. Le Meur (IGE), **recruited personnel:** Numerical engineer (IR IGE, 100%)

**Objectives of the task**

*Elmer/Ice-sheet* will be built upon *Elmer/Ice* and therefore benefit from all the existing *Elmer/Ice* capabilities (see the state-of-the-art section). **The aim of this task is to implement the processes and technical capabilities not yet implemented in *Elmer/Ice*.**

Ice-sheet scale applications using *Elmer/Ice* (Gillet-Chaulet et al., 2012, Seddik et al., 2012) have so far assumed a fixed position of the calving front and that terrestrial margins can only retreat. This is the main technical limitation of the model for the proposed applications. Improving this point requires associated numerical developments (moving boundaries and mesh adaptation, ST1.1) as well as implementing 3d calving criteria (ST1.2). In addition, a new module will have to be developed for long-term simulations (isostasy, ST1.3). We will ensure that these newly developed *Elmer/Ice* modules comply with defined standards and verify their numerical efficiency for the target simulations. Some work will be devoted to improve numerical efficiency of existing solvers. The required model developments will take place in the first phase of the project, in agreement with the timeline of the proposed applications.

**Detailed work plan**

**ST1.1: Moving ice margins and mesh adaptation**

Technically, solutions in *Elmer/Ice-sheet* will be computed on a 2d unstructured mesh in the horizontal plane (*e.g.*, asymptotic of Stokes equations) that will be internally vertically extruded for equations requiring a 3d mesh (e.g., temperature, damage). We will deal with moving boundaries in two different ways. For moderate margin migrations we will track the ice-sheet boundaries in a predefined and fixed mesh in the horizontal plane. For large migrations we will implement a remeshing module.

*Elmer/Ice* already includes routines to define passive elements, *i.e.* elements that are deactivated and do not contribute to the linear systems of equations, and to track the boundaries between passive and active elements. Deglaciated elements will be defined as passive. For land terminating glaciers, deglaciated elements are elements with null ice thickness and null or negative surface mass balance. For marine terminated glaciers, deglaciated elements will have to be defined from a calving criterion (see ST1.2). Using the passive elements method, the horizontal position of the mesh is fixed and boundaries can only follow the element edges. As a consequence, to insure a good accuracy, the mesh must be sufficiently refined near the margins of the active domain.

In order to maintain a fine mesh resolution near the boundaries during simulations involving large migrations of the margins, we will implement an adaptive mesh scheme. Remeshing libraries (*e.g.*, the anisotropic mesh adaptation code Mmg[[11]](#footnote-11)) and *Elmer/Ice* capabilities to interpolate variables between different meshes are already implemented. This method has already been evaluated on simple test cases and will have to be adapted on real geometry applications.

**ST1.2: Implementation of 3d calving laws**

We will implement various parameterizations for calving. We will start with simple calving criteria evaluated locally for each mesh elements. These pragmatic criteria will automatically calve elements where the ice thickness falls below a given threshold or elements with a predefined mask (e.g. ice shelves not allowed to extend into open-ocean). Although these parameterizations may sound over-simplistic, this remains a classical and standard approach in ice-sheet models (*e.g.*, Benn et al., 2007). Then, more advanced parameterizations computing a calving flux as a function of local stress or strain-rate state will be implemented following recent works by Levermann et al., (2012) and Morlighem et al., (2016) and also based on our expertise gained by the development of a calving law using damage and fracture mechanics for a 2d flow line configuration (Krug et al., 2014). In those approaches, the balance between ice flux and calving flux governs the horizontal position of the calving front, which needs to be tracked by solving a transport equation. This equation governing the movement of the calving front can be solved on the finite-element mesh using, *e.g.*, the level set method (Bondzio et al. 2016, Morlighem et al., 2016). *Elmer/Ice* already includes a level set solver such that implementing the 3d calving law should not imply significant technical developments.

**ST1.3: Implementation of the isostasy module** (voir la remarque review 2 là dessus)

Given the extreme sensitivity of the grounding line position to the free water depth, correct representation of isostatic readjustments in *Elmer/Ice-sheet* will become a necessary step in order to provide realistic simulations over paleo time periods. Different parameterizations of the complex bedrock response and its impact on ice sheet dynamics are now well established (Le Meur and Huybrechts, 1996). So far, *GRISLI* has adopted a cost effective representation assuming an elastic rigid lithosphere (accounting for the regional character of the earth response) overlying a viscously relaxing asthenosphere. As a first step, the *GRISLI* module will only need adjustments to be implemented in *Elmer/Ice* and this should already give realistic results (Le Meur and Huybrechts, 1996). In a second step, more sophisticated approaches like self-gravitating full visco-elastic models (Le Meur, 1996) will be considered so as to accurately reproduce both spatial and time-dependent specific aspects of the Earth response under glacial loading (notably the different viscous accommodation modes due to density and viscosity contrasts within the mantle). This later approach allows solving the sea-level equation dealing with the gravity field response to ice sheets evolution. In further work, this will give access to the feedbacks between ice sheets evolution and sea-level changes, including their respective spatial patterns.

**Deliverables**

**D1.1:** Adaptive remeshing solver based on an existing external library (T0+8)

**D1.2:** Implementation of 3d calving laws (T0+12)

**D1.3:** Implementation of isostasy modules (T0+12, T0+24)

**Risk of the Task**

For most of the developments proposed in this task, the feasibility has already been demonstrated through the design of simplified tests (adaptive remeshing), recently published developments and implementation of 3d calving laws (*e.g.*, Levermann et al., 2012 and Morlighem et al., 2016) and our experience in designing an original 2d calving law already implemented in *Elmer/Ice*. Therefore we do not anticipate any specific difficulties to rapidly implement these new features.

### Task 2 - *Elmer/Ice-sheet* package development and distribution

**Task leader:** O. Gagliardini (IGE), **co-leader:** C. Dumas (LSCE), **other permanents:** F. Gillet-Chaulet, N. Jourdain (IGE), S. Buarque (CNRM), **recruited personnel:** Numerical engineer (IE IGE, 50%)

**Objectives of the task**

The main objective of this task is to **design and build the *Elmer/Ice-sheet* package, maintain the code and ensure its distribution** with the most appropriate and up-to-date tools.

Thanks to the recent developments and applications performed at IGE (Gillet-Chaulet et al., 2012, Favier et al., 2014, Fürst et al., 2016), *Elmer/Ice* is now recognized as a very comprehensive code reaching maturity to engage ice-sheet scale applications. However, it has currently the drawback to offer a large set of possibilities and complexities when setting up a new problem, in terms of physical parameters, boundary conditions, ways of applying forcing and numerical choices, largely exceeding the needs of specific applications to ice-sheet flow and evolution. In short, *Elmer/Ice* is not convivial enough to be used efficiently by the modellers of the climate community. The *Elmer/Ice-sheet* package will therefore be built as an intermediate layer between *Elmer/Ice* and the users and specifically designed to solve ice-sheet flow problems, as shown in Fig. 3. The *Elmer/Ice-sheet* package will provide the required tools to setup predefined configurations, monitor the simulations while they are running and visualize results. As *Elmer/Ice-sheet* is designed to solve standard ice-sheet flow problems, standards for input/output of variables (I/O) will be developed to ease the reading of initial or forcing conditions as well as the monitoring and visualisation of the results.

|  |  |  |
| --- | --- | --- |
|  |  | **Figure 3***:* Conceptual design of the *Elmer/Ice-sheet* package, an ice-sheet model based on *Elmer/Ice*. Task 1 is devoted to the improvement of processes and numerical skills of Elmer/Ice. Task 2 will be dedicated to the design and development of the Elmer/Ice-sheet package. Link with the already funded ANR-JCJC project TROIS-AS on the coupling of *Elmer/Ice* with NEMO and MAR. |

*Elmer/Ice-sheet* will use unstructured meshes, which will offer much more possibilities than a structured grid, but will also bring more complexity in defining an optimal mesh for a given application. Indeed, an optimal mesh will be a compromise between the required minimal resolutions to account for the processes like the grounding line dynamics and the induced required CPU time. Different meshes will be produced and tested for Tasks 3 and 4, and delivered with a short description of their specificities (minimal and maximal resolution, maximal possible time-step, estimation of the CPU cost per year of simulation).

Forcing from the atmosphere and the ocean will be applied either in the form of parameterizations, from reading data in input files (typically reanalyses or CMIP model outputs) or by a true coupling with the ocean and/or atmosphere components (see Fig. 3). The first two possibilities already exist in *Elmer/Ice* capabilities but will be standardised (ST2.1), whereas the third option is being developed in the ANR-JCJC TROIS-AS project (2015-2019) led by N. Jourdain from IGE. The coupling is operated using OASIS with the ocean model NEMO and the Regional climate model MAR. All the functionalities developed in the framework of the ANR TROIS-AS will directly benefit the new *Elmer/Ice-sheet* package developed in this project.

The task leader will oversee the proper distribution of the newly developed package (ST2.2). To complete the promotion and uptake of the new package, a dedicated wiki will be set up and international *Elmer/Ice-sheet* courses organised, similar to the for *Elmer/Ice* courses at IGE[[12]](#footnote-12) (ST2.3). To allow an efficient distribution and appropriation of *Elmer/Ice-sheet*, validated test cases will be diffused to the community using shared Python notebook. Finally, an application to obtain a label of national numerical tool from INSU will be submitted.

**Detailed work plan**

**ST2.1: Design and build of the *Elmer/Ice-sheet* package**

We will design and build an easy-to-use interface to run the *Elmer/Ice* model on typical ice-sheet configurations by providing libraries of meshes, initial and boundary conditions and a simplified input file with limited choice for physical and numerical parameters. The number of meshes, initial and boundary conditions in the *Elmer/Ice-sheet* library will be increased all along the project. The first ones to be created will be those required in the applications proposed in Tasks 3 and 4 in interaction with all the partners involved by the applications.

I/O is important to apply initial conditions, external forcing and for processing and visualisation of the results for dedicated ice-sheet applications. As a first step, we will define different classes of I/O for scalar variables, field variables and flux variables to standardise reading and visualisation procedures. We will use existing standard formats and nomenclature (netcdf). For flexibility and performances reasons, many models (such as NEMO, MAR, LMDz) rely on external libraries that are run asynchronously to save the variables and operate arithmetic or temporal operations (*e.g.* XIOS[[13]](#footnote-13) developed at IPSL). Interfacing XIOS with *Elmer/Ice-sheet* will be done following XIOS developments as it is currently progressively integrating netcdf standards for unstructured grid.

On top of this, a monitoring and visualising tool will be developed. This tool will be developed with Python and the vtk library, which is already the preferred library chosen for saving unstructured outputs of *Elmer/Ice*. Moreover, to allow the continuity of the code and to coordinate developments with *Elmer/Ice*, the cmake tool will be used to control the software compilation process.

**ST2.2: Distribution of the *Elmer/Ice-sheet* package**

The task leader will take care that the newly developed package is adequately distributed. *Elmer/Ice-sheet* being built on *Elmer/Ice* (itself built on *Elmer*), it will be distributed as a branch of the *Elmer* depository under GitHub. This will ensure a proper management of the code (versioning), allowing further developments with a broader community than the one directly involved in the present project.

**ST2.3: Promotion and uptake of the *Elmer/Ice-sheet* package**

During the 4 years of the project, two *Elmer/Ice-sheet* courses will be organised. The first one (T0+15) will be mainly dedicated to the different partners and the 2 PhD students recruited for the project. The second one will take place at the end of the project (T0+42) with the aim of training new users from the whole international community. A dedicated wiki will be setup, in line with the already existing *Elmer/Ice* wiki[[14]](#footnote-14). The wiki will present the *Elmer/Ice-sheet* capabilities, a documentation for its use and examples of typical setups.

**Deliverables**

**D2.1:** Standardise classes of variables and formats for I/O (T0+6)

**D2.2:** Versioning and distribution of the new *Elmer/Ice-sheet* package (T0+12 and continuously updated)

**D2.3:** Setup of the documentation on the form of a wiki (T0+12 and continuously updated)

**D2.4:** Organisation of two *Elmer/Ice-sheet* courses (T0+15, T0+42)

**D2.5:** A paper ready for submission on the *Elmer/Ice-sheet* capabilities (T0+36)

**Risk of the Task**

The time to design and setup the first version of the Elmer/Ice-sheet package (D2.2) is rather short and depends on a timely recruitment of the numerical engineers that will contribute to Tasks 1 and 2. To minimize this risk, we will anticipate the recruitment of the engineers as soon as we have the confirmation that the project is funded, so that they can start at the very beginning of the project. Anyway, if the version 1 of the package cannot be released on time for a broad international diffusion at T0+12, application tasks will still have the opportunity to start working with a beta version, which will be distributed to the partner of the project. IGE has been leading the development of *Elmer/Ice* since its start and has gained an expertise in distributing the code by actively contributing to the wiki and organising beginner and experimented-users courses.

### Task 3 - Paleo-ice-sheet applications

**Task leader:** S. Charbit (LSCE), **co-leader:** D. Salas y Mélia (CNRM), **other permanents:** C. Ritz, V. Peyaud (IGE), S. Buarque (CNRM), C. Dumas, M. Kageyama, D. Roche (LSCE), **recruited personnel:** IE (IGE, 15%), PhD (LSCE), PhD (CNRM), M2 (LSCE), M2 (CNRM)

**Objectives of the task**

The overall objective of this task is to **take advantage of an adequate representation of fast dynamical changes to revisit long-standing questions related to the dynamics of paleo ice sheets**. We will focus on: *(i)* the last interglacial (LIG) period (~130 to 115 ka BP), a warm period with sea level higher than today, and *(ii)* the beginning of the last deglaciation of the Barents-Kara ice sheet (BKIS, 26 to 14 ka BP), which had some similarities with the present day conditions of West Antarctica.

We will first investigate if the accurate description of fast ice dynamics helps to represent large ice streams alternating with slow ice for the Greenland and West Antarctic ice sheets during the LIG period and for the BKIS during the LGM. In a second step, we will explore the potential mechanisms driving the retreat of the three ice sheets, with studies of the impacts of *(i)* sea-level rise *(ii)* atmospheric forcing and *(iii)* basal melting under the ice shelves. This will allow to disentangle the relative contributions of Greenland and Antarctica to SLR during the LIG time period and to investigate the processes leading to the BKIS deglaciation after the LGM.

**Detailed work plan**

To perform the *Elmer/Ice-sheet* simulations described hereafter, we will use climate forcings from three climate models: two atmospheric-ocean general circulation models, IPSL-CM (Dufresne et al., 2013) and CNRM-CM (Voldoire et al., 2013) which both take part in CMIP, and one model of intermediate complexity, iLOVECLIM (Roche et al., 2014), designed to perform long-term (~several millennia) climate simulations. An additional source of climate forcing is the PMIP project (Braconnot et al, 2012) in which M. Kageyama and D.M. Roche are working group leaders. Using more than one climate models will allow us to perform sensitivity experiments climate forcings and demonstrate that *Elmer/Ice-sheet* can be coupled with any climate models.

**Task 3.1: Reconstruction of ice-sheet geometries during the last interglacial period**

The dynamical response of the *Elmer/Ice-sheet* model obtained in Tasks 1 & 2 will be first investigated for the Antarctic and Greenland ice sheet domains for the LIG period. Transient *Elmer/Ice-sheet* simulations will be performed over the 130-115 ka period. Our target is to obtain geometries of both ice sheets compatible with available time-dependent sea-level data (Kopp et al., 2009, Dutton and Lambeck, 2012) and hence to evaluate the impact of fast ice sheet processes in this sea level evolution. The simulations will start with the present-day configurations of the ice sheets. Atmospheric and oceanic forcings will be obtained from climate model outputs available at LSCE and CNRM. A transient climate experiment spanning over the whole period will be run with iLOVECLIM. Due to their higher computational cost, IPSL-CM and CNRM-CM will be run for ~30 years every millennium. The climate forcings will be evaluated through a comparison against available simulations in the PMIP database and climatic proxy data **(**Capron et al., 2014). In addition, the model will be forced with sea-level scenarios from Kopp et al. (2009) who reconstructed both local and global sea levels from a compilation of local sea-level indicators. Similar simulations have already been computed using *GRISLI* model but showing inconsistencies with paleo reconstructions. This will allow to better characterize the added value of an improved representation of fast dynamical changes to simulate the changes in geometry of both Greenland and West Antarctic ice sheets.

To account for the uncertainties in SLR reconstructions during the LIG period (5 to 10 m) and to investigate the sensitivity of the Antarctic and Greenland ice sheets to SLR, *Elmer/Ice-sheet* will be forced *(i)* with various scenarios of sea-level evolution and (ii) with various scenarios of atmospheric and oceanic (subsurface) forcings from the available climate simulations. The basal melting under the ice shelves will be computed using simple parameterizations based on subsurface oceanic temperatures (Alvarez-Solas et al., 2011), or, if available, using more sophisticated methods elaborated within the framework of the TROIS-AS ANR project led by N. Jourdain.

**ST3.2: The Barents-Kara ice sheet (BKIS) during the LGM: an analogue to present-day West Antarctic ice sheet**

We will perform a set of *Elmer/Ice-sheet* simulations applied to the last glacial BKIS domain using available climate outputs for the LGM and different set of *Elmer/Ice-sheet* parameters. Our initial conditions will be the available LGM reconstructions used in PMIP (Kageyama et al., 2017, Ivanovic et al, 2016). Our first target is to obtain a BKIS geometry in good agreement with the recent geological reconstructions of the DATED-1 project (Hughes et al., 2016). Based on this model-data comparison, we will choose the most appropriate climate simulations to perform an in-depth analysis of the BKIS dynamics. Our model results will be compared to geophysical constraints compiled in Patton et al. (2015) that provide key information about the location and activity of paleo ice streams and ice flow routing. The comparison between these recent data and our model results will offer a good opportunity to test the *Elmer/Ice-sheet* model in paleo climatic contexts. This is particularly relevant for testing the mechanisms that could affect the West Antarctic ice sheet in the future since both the BKIS and West Antarctic ice sheets are characterized by large ice shelves.

The BKIS was one of the first paleo-ice sheets to retreat (~15-14 ka BP) after the LGM. Owing to its marine-based configuration, increased calving fluxes can be reasonably expected as the main driver for this early deglaciation. It has long been argued that SLR stemming from melting of other Northern hemisphere ice sheets was the main trigger (Lambeck, 1995; Winsborrow et al., 2010). Alternative hypotheses include changes in surface mass balance driven by changes in the atmospheric stationary waves in response to variations in the topography and extent of the North American ice sheet (Beghin et al., 2015). The stability of the ice sheet will be explored with different imposed sea-level scenarios. The impact of surface mass balance changes will be investigated by forcing *Elmer/Ice-sheet* with results from Beghin et al. (2015) providing various temperature and snow accumulation scenarios over the Eurasian region. This work will be completed by transient simulations of the early phase of deglaciation using available transient climatic forcings provided by the iLOVECLIM model or by the PMIP deglaciation working group. This work will improve our understanding of the role of the BKIS during the early phase of the deglaciation on the global climatic system during this crucial period. It will also allow us to determine the extent to which the processes involved in the BKIS deglaciation are those usually proposed for a possible retreat of the West Antarctic ice sheet.

Sharing the work performed in Task 3 between two students at LSCE and CNRM will offer them an excellent opportunity to work together and to collaborate with the different ANR EIS research teams.

**Deliverables**

**D3.1:** Achievement of LIG simulations (T0+30)

**D3.2:** Achievement of BKIS simulations at the LGM (T0+30)

**D3.3:** A paper ready for submission on LIG *Elmer/Ice-sheet* simulations for both Greenland and Antarctic ice sheets including sensitivity tests (T0+42)

**D3.4:** A paper ready for submission on BKIS simulations at the LGM and sensitivity tests to explore the mechanisms responsible for the ice sheet retreat (T0+42).

**Risk of the Task**

The main risk for the realization of the work proposed in this task is related to a delayed development of *Elmer/Ice-sheet* due to unexpected technical difficulties. However, if so, as previously specified, partners involved in application tasks would have the opportunity to use a beta version.

### Task 4 - Contemporary and future applications

**Task leader:** G. Durand (IGE), **co-leader:** C. Ritz (IGE), **other permanents:** O. Gagliardini, F. Gillet-Chaulet, N. Jourdain, V. Peyaud, C. Ritz (IGE), D. Salas y Mélia (CNRM), S. Charbit, C. Dumas, M. Kageyama (LSCE), **recruited personnel:** IE (IGE, 15%), PhD (LSCE), PhD (CNRM), M2 (LSCE), M2 (CNRM)

**Objectives of the task**

**This task is dedicated to the estimation of the forthcoming evolution of ice sheet dynamical losses and consequences on the climate system.** Our principal objective is to obtain the Greenland and Antarctic contributions to SLR for the coming two centuries. Associated efforts will contribute to the international ISMIP6-CMIP6 initiative. The later will feed the multi-model projections of the ice sheets contribution to SLR that will be synthetized in the next IPCC report. Using high-end scenarios, we will then investigate the impact of a massive fresh water release from polar ice sheets on coupled ocean-atmosphere general circulation models.

**Detailed work plan**

**ST4.1: Projections of Greenland and Antarctic contribution to SLR – ISMIP6 initiative**

The international community is coordinating for the first time an Ice Sheet Model Inter-comparison exercise embedded in the CMIP6 initiative (ISMIP6). ISMIP6 will bring together a consortium of international ice-sheet modelers and motivates the development ice sheet-climate models (AOGCM-ISM) in order to fully explore the SLR contribution of the Greenland and Antarctic ice sheets. Exercises for standalone ISMs (i.e. with no AOGCM) are being designed and IGE is involved in this international effort: *Elmer/Ice* is currently running the preliminary set of experiments dedicated to the initialization of the models to present-day conditions. In the framework of the EIS project, *Elmer/Ice-sheet* will be completed (see task 2) and will therefore be able to perform the entire set of ISMIP6 stand-alone experiments for both the Greenland and Antarctic ice sheets by 2020, which is the expected ISMIP6 deadline. Funding of the EIS project would greatly facilitate collaborations with international colleagues within the ISMIP6 initiative, which is today undertaken without any funding. Advancing the design of the new-generation ISM *Elmer/Ice-sheet* is timely and will help the French community to promote their new ISM to the international most relevant community.

We will put a particular attention on the consistency of our projections of West-Antarctica over the next two centuries with the paleo constraints obtained in ST3.2. We will more specifically focus our investigations on the impact of the representation of ice-sheet basal conditions within the models. Indeed, this has been recently indicated as one of the strongest sources of uncertainty in computing the forthcoming evolution of the Antarctic ice sheet (Ritz et al., 2015). A specific attention will also be put on the instability processes potentially at play (MISI and MICI) in rapid transitions. Forcing required for simulating ice sheets evolution will be provided through the CMIP6 database or through specific simulations computed by the CNRM and IPSL partners.

**ST4.2: Implication of massive fresh water release from polar ice sheets onto atmosphere and ocean circulation.**

All the experience gained through the ISMIP6 effort will allow the identification of the highest-end scenarios in terms of ice-sheet contributions to sea level rise. In this task, we will extend these highest-end simulations to 2300, and will use the corresponding grounding line and calving fluxes to constrain the freshwater release in ocean-atmosphere projections. These projections will be based on the CNRM and IPSL AOGCMs, and will make use of the new model capabilities to distribute the freshwater through a lagrangian iceberg model and a specific methodology to distribute ice-shelf melt (Merino et al. 2016). This will enable to investigate long-standing questions such as the potential of ice-sheet meltwater to slow down the Atlantic meridional overturning circulation, but we will also focus on the short-term effects pertaining sea ice coverage and its influence on air-sea fluxes.

**Deliverables**

**D4.1:** French contribution to ISMIP6 and submissions of related papers (T0+24 and all along the project until end of ISMIP6 ~2019)

**D4.2:** A paper submitted on ensemble simulations of Jakobshavn Isbrae 1900-2200 (T0+48)

**Risk of the Task**

The expertise required to achieve this task (ice-sheet data, forcing from atmosphere and ocean models and ice-sheet modelers with a more particular focus on projections) are all represented and proposed activities are the natural next step of previously completed work (Gillet-Chaulet et al., 2012; Favier et al. 2014; Ritz et al., 2015; Fürst et al. 2016). Therefore, the risk attached to this task stands essentially in the adjustment between the developments of Elmer/Ice-sheet and the schedule of the ISMIP6 stand-alone experiments (not yet finalized, presumably running until the end of 2019). In an optimistic but realistic perspective, stand-alone experiments will be finalized using the *Elmer/Ice-sheet* model. In any case our participation using *Elmer/Ice* is ensured and has already started with the preliminary phase (initMIP) devoted to develop initialization procedures of the ISMs. Risks are therefore essentially circumvented to a timely promotion of the new *Elmer/Ice-sheet* model within the international ice-sheet modeling community.

## Gantt diagram of the project



## Budget

As detailed below, most of the budget is dedicated to staff recruitments. The relatively high amount requested results from the manpower required for this project to be timely with international exercises and IPCC deadlines. Indeed, the development phase must be as short as possible to facilitate the transition from *GRISLI* to *Elmer/Ice-sheet*, and must be immediately followed by a number of applications demonstrating clearly the benefit of the new model to the whole climate community. The developments of the model will start at the beginning of the project with the help of two engineers at IGE. Three years of an IE will be dedicated to the development of the *Elmer/Ice-sheet* toolbox (Task 1 - 50%) and designing the first setups for the applications (Tasks 3 - 15% and 4 - 35%), for a total cost of 148k€. Two years of an IR will be dedicated to the implementation in *Elmer/Ice* of the moving margins capabilities, associated calving laws and the implementation of the isostasy module (Task 2), for a total cost of 116k€. Two PhDs will conduct the applications in Tasks 3, one at LSCE and one at CNRM, both in co-direction with IGE, for a total cost of 201k€. The staff recruitment is completed by two 6-months research master internships before the start of the two PhDs and a master engineer training to build the AR-Sandbox, for a total amount of 10k€.

The rest of the budget is 4k€/person-year for travels (including partner to partner exchanges and conferences), 1k€/person-year for equipment. The IGE will be in charge of organising the 4 annual meetings and two *Elmer/Ice-sheet* courses (20k€). For the whole project, a total of ~10 publications has been budgeted (15k€).

IGE and LSCE will apply to the French DARI call from the GENCI agency to request the necessary CPU hours to run the proposed simulations and CNRM will directly get CPU hours on the Météo-France clusters. A 10k€ support is asked for the local clusters in Grenoble. Outreach activities in general and the development of the AR-Sandbox in particular are budgeted at a cost of 3k€. Finally, the total amount requested is **707k€**.

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| --- | --- | --- | --- | --- | --- |
| **Partner** | **Salary** | **Equipment** | **Travels** | **Publication** | **Total\*** |
| IGE | 267 416€ | 28 000€ | 80 000€ | 9 000€ | 397 208€ |
| LSCE | 103 680€ | 6 333€ | 25 333€ | 3 000€ | 140 813€ |
| CNRM | 103 680€ | 5 083€ | 20 333€ | 3 000€ | 137 213€ |
| **Total** |  |  |  |  | **707 248€** |

*\*The total column includes the 4% management fees and 4% structure fees.*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Title of the call for proposals, source of funding | Project title | Name of coordinator | Starting date/End date | Grant amount | Part. | Name | Person. Month |
| Of the person involved in this proposal | | |
| LEFE INSU CNRS | EIS | Gagliardini |  | 5k€ | No. |  |  |

# Impact and benefits of the project

## Societal impacts

The EIS project aims to improve our understanding of ice sheet dynamics and our ability to model ice-sheet changes in the context of global warming, with the overall objective of increasing our confidence in their projected contributions to SLR for the future. Therefore, the EIS project is highly relevant regarding of the objective of **défi 1** of the present call. Indeed, as the contribution of ice sheets remains the main uncertainty in projection of SLR (IPCC, 2013), a better understanding of processes driving outlet glaciers and improved modelling capabilities will clearly contribute to improving the understanding of both the triggers and consequences of an important component of the climate system in the context of global change. In line with **orientation 1**, the EIS project will provide a tool to the climate community to better understand and predict ice-sheet mass changes and contribute to improving predictions of their impact on regional sea level.

## Scientific impacts and diffusion strategy

The scientific impacts of the EIS project will be both related to the model development itself and the conducted applications.

Indeed, the EIS project will provide to the national and international community the open-source state-of-the-art ice-sheet model *Elmer/Ice-sheet* and will mark its official launching. The EIS project will contribute to structure the *Elmer/Ice-sheet* users community by organising the two first *Elmer/Ice-sheet* courses, launching a documented wiki including pedagogic examples and developing the necessary tools for its efficient distribution. The important effort dedicated in this project to this task will ensure a long-standing life of the developed tool. The *Elmer/Ice-sheet* package will certainly also benefit from the already existing international community of *Elmer/Ice* users, and we can presume an efficient international uptake, certainly facilitated by our participation in the ISMIP6 international effort.

Regarding the selected applications proposed in the EIS project, the new model *Elmer/Ice-sheet* will allow long-standing questions regarding the impact of ice sheets to climate in the past to be revisited, for a better understanding of their potential impact in the near future. In parallel, we will improve the near past reconstruction at a local scale for a major glacier in Greenland (Jakobshavn Isbrae) and produce new projections at continental scale for both ice-sheets in an internationally important context (ISMIP6).

All these results, both from the model developments and the applications, will be presented during international conferences and symposia (AGU, IGS, EGU). We estimate that around 10 scientific publications will be directly produced from the EIS project, and we anticipate the potential for high profile papers. A number of these publications has already been identified and constitute named deliverables of the EIS project.

Polar missions and climate change are two subjects appreciated by the general public. For instance, all partners of the EIS project currently organize visits of school students to their laboratory. This project will contribute to these outreach activities. As explained in Task 0, the website of the EIS project will also present the project in a form accessible to the non-scientific public.

## Socio-economic impacts and valorisation strategy

The general aim of the EIS project is to provide a better estimation of sea-level rise induced by ongoing climate change. The economic implications of this project are therefore related to natural hazards mitigation, insurances liability and more generally sea-defence planning. Together with the work supported by the ANR-JCJC TROIS-AS project, the EIS project will offer the national community a state-of-the-art tool able to address the future challenges of ice sheet impact in the global system. The proposed applications of the EIS project are designed to improve quantification of SLR for the next century and will therefore directly inform international policy-makers through the next IPCC Assessment Reports.

1. Ice Sheet Model Intercomparison Project for Higher-Order ice sheet Models (http://homepages.ulb.ac.be/~fpattyn/ismip/) [↑](#footnote-ref-1)
2. Marine Ice Sheet Model Intercomparison Project (http://homepages.ulb.ac.be/~fpattyn/mismip/) [↑](#footnote-ref-2)
3. ice2sea MISMIP3D: Marine Ice Sheet Model Intercomparison Project for planview models (3D) (http://homepages.ulb.ac.be/~fpattyn/mismip3d/) [↑](#footnote-ref-3)
4. this pitfall has been circumvented in Ritz et al. (2015) by forcing the grounding line retreat [↑](#footnote-ref-4)
5. https://www.csc.fi/ [↑](#footnote-ref-5)
6. The complete list of Elmer/Ice publications can be obtained here: ttp://elmerice.elmerfem.org/publications. [↑](#footnote-ref-6)
7. http://elmerice.elmerfem.org/ [↑](#footnote-ref-7)
8. http://elmerice.elmerfem.org/wiki/doku.php?id=start [↑](#footnote-ref-8)
9. https://ciment.ujf-grenoble.fr/wiki-pub/index.php/Welcome\_to\_the\_CIMENT\_site! [↑](#footnote-ref-9)
10. http://idav.ucdavis.edu/~okreylos/ResDev/SARndbox/ [↑](#footnote-ref-10)
11. http://www.mmgtools.org/ [↑](#footnote-ref-11)
12. http://elmerice.elmerfem.org/wiki/doku.php?id=courses:courses [↑](#footnote-ref-12)
13. http://forge.ipsl.jussieu.fr/ioserver/wiki [↑](#footnote-ref-13)
14. http://elmerice.elmerfem.org/wiki [↑](#footnote-ref-14)