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GRANTSISM: An Excel™ ice sheet model for use in introductory Earth science courses

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ABSTRACT

GRANTISM (GReenland and ANTarctic Ice Sheet Model) is an educational Excel™ model introduced by Pattyn (2006). Here, GRANTISM is amended to simulate the Svalbard-Barents-Sea Ice Sheet during the Last Glacial Maximum, an analogue for the contemporary West Antarctic Ice Sheet. A new name, "GRANTSISM," is suggested; the added S represents Svalbard. GRANTSISM introduces students of bachelor's or master's programs in Earth sciences (first or second cycle program in the Bologna system for higher education), but with little or no background in numerical modeling, to basic ice sheet modeling. GRANTSISM provides hands-on learning experiences related to ice sheet dynamics in response to climate forcing, and fosters understanding of processes and feedbacks. GRANTSISM was successfully used in noncompulsory courses in which students have been able to reproduce paleo-ice sheet evolution scenarios discussed here as examples. Students progressed further by designing, developing, and analyzing their own modeling scenarios. Here, we describe GRANTSISM and report on how learning activities with GRANTSISM were assessed by students who had no prior experience in ice sheet modeling. The response rate for a noncompulsory survey of the learning activity was less than 40%. A subsequent control experiment with a compulsory survey, however, showed the same patterns of answers, so the student response is considered representative. First, GRANTSISM is concluded to be a highly attractive tool to introduce learners with an interest in ice sheet *behavior* to ice sheet *modeling*. Second, it triggers an interest for more in-depth learning experiences related to numerical ice sheet modeling.

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Introduction

An ice sheet is by definition a mass of glacier ice and snow that covers an area larger than 50,000 km^2 and flows outward from central thicker parts toward thinner margins (Bell et al., 2016). Two major ice sheets exist on Earth today: the Greenland Ice Sheet and the Antarctic Ice Sheet. The Antarctic Ice Sheet is subdivided into West and East components, as they are rather different in their characteristics. During the Last Glacial Maximum (LGM) between about 19 ka (kilo annum; 1000 years ago) and 23 ka, ice sheets covered large parts of Eurasia, North America, and the continental shelves bordering the central Arctic Ocean (Jakobsson et al., 2014; Svendsen et al., 2004; Stokes et al., 2015), see Figure 1. Also, the Antarctic Ice Sheet was substantially larger than today (Bentley et al., 2014).

Numerical simulation of ice sheet behavior comprises a research area within glaciology focused not only on today's cryosphere but also on simulating ice sheet configurations during past glacial and interglacial periods as well as in a future warmer climate (Colleoni, Kirchner, Niessen, Quiquet, & Liakka, 2015; deConto & Pollard, 2016; Nick et al., 2013; Stone et al., 2013). Ice sheets are complex, and the modeling community is confronted with a wide range of limitations in existing numerical ice

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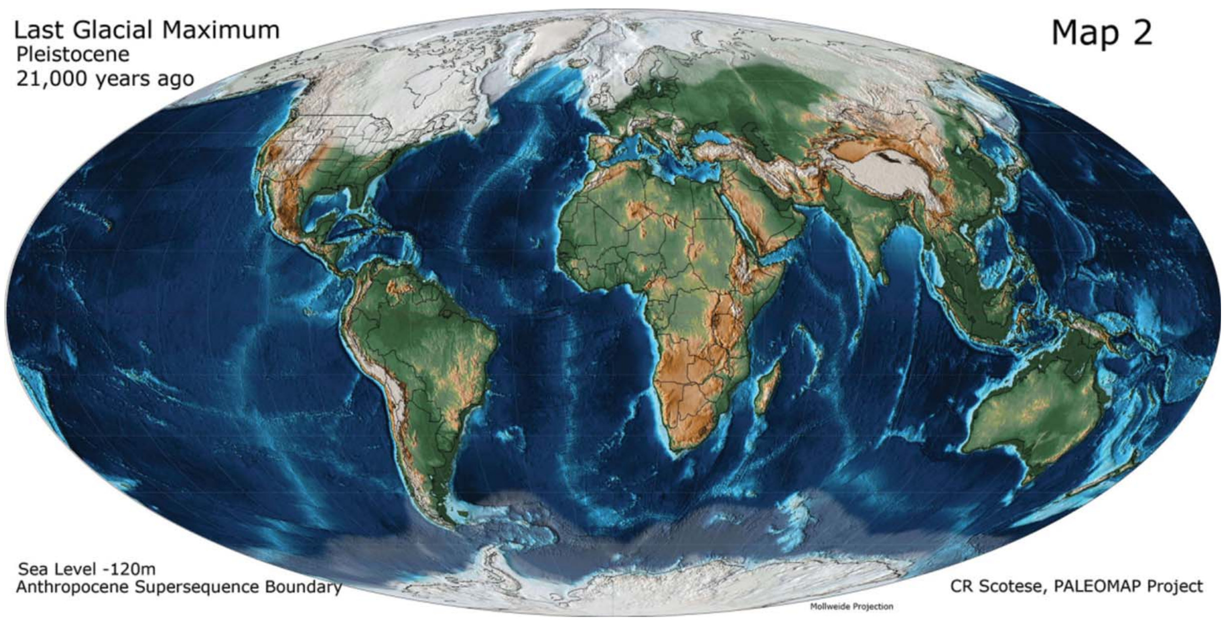

Figure 1. Illustration of the global ice cover during the Last Glacial Maximum, ca 21,000 years ago, as done within the PALEOMAP project. The figure is reprinted with permission from C. R. Scotese (Scotese, 2104), and unmodified ("Map 2" refers to the numbering of maps in the *Atlas of Neogene Paleogeographic Maps*).

sheet models (Kirchner et al., 2011, 2016). However, numerical modeling is the best instrument available to test and analyze the influence of climate and other physical parameters affecting ice sheet dynamics—for example, the underlying bed topography and geological composition.

Ice sheet modeling is rarely present in the curricula of higher education, despite its high societal relevance. Contemporary and former ice sheets are typically addressed in first and second cycle BSc and MSc programs[1] in Earth science (often, in geology or physical geography), in which the overall ice sheet *behavior* is in the focus. Yet the schedules often lack time and flexibility to introduce ice sheet *modeling*. An additional factor is that "conventional" numerical ice sheet models may not be completely straightforward to operate and understand by the common Earth science educator, even with some background in glaciology.

Note that exceptions exists: Specific courses in glaciology, including glacier and ice sheet modeling, can be taken at universities with a research tradition and/or geographical proximity to glaciers, such as the Swiss Federal Institute of Technology in Zurich, which hosts the Laboratory of Hydraulics, Hydrology, and Glaciology. Also, the University Centre in Svalbard provides an inspiring teaching and learning environment in which ice sheet modeling was recently introduced to selected courses. Teaching and learning in an environment that was formerly covered by a huge ice sheet made application of an ice sheet model for Svalbard during the courses a potentially highly attractive learning experience. Therefore, a Svalbard module was added to Pattyn's (2006) GRANTISM (Greenland and ANTarctic Ice Sheet Model) model, an Excel™ spreadsheet model to simulate the Greenland and Antarctic Ice Sheet. The amended model is referred to as GRANT<u>S</u>ISM, where the added S stands for Svalbard. Because the Svalbard-Barents Sea Ice Sheet has been regarded as an analogue to the contemporary West Antarctic Ice Sheet (Siegert et al., 2002), the new module also adds a specific actuality to GRANTSISM, as it highlights the importance of understanding mechanisms of past ice sheet behavior in making prognoses for future ones. For overviews on the history and recent developments in reconstructions of the Svalbard Barents Sea Ice Sheet, see Ingólfsson and Landvik (2013), Jakobsson and colleagues (2014), Patton and colleagues (2015) and Hughes, Gyllencreutz, Lohne, Mangerud, and Svendsen (2016) and the extensive references therein.

[1]Higher education in Sweden and Norway has adopted the Bologna system, in line with many other European countries. Bachelor studies belong to the first cycle of the system; MSc studies, to the second; and Licentiate and Ph.D. studies, to the third, and final, cycle. A completed BSc program requires acquisition of 180 European Credit Transfer System (ECTS) points, corresponding to three years of full-time (40 academic weeks) studies. MSc programs build on the BSc programs and comprise 60 ECTS or 120 ECTS.

Purpose and learning goals

The overall aim with GRANTSISM is to introduce students interested in general ice sheet behavior to ice sheet modeling, and to create and share a new, positive learning experience resulting in a deeper and wider interest in the use of models in Earth sciences, with benefits reaching beyond a particular learning activity and course.

The motivation is simple: Ice sheets, which are major features on the surface of the Earth and important components of the Earth's climate system, cannot be brought to the classroom. Nor can one bring a class of students to an ice sheet—obviously, the spatial scales of an ice sheet complicate the study of it (Kastens, 2008). Learning about ice sheets requires an advanced knowledge acquisition, and can be regarded as "learning … short of true experience" (Perkins, 2007). It can also pose inherent conceptual difficulties (Campbell et al., 2013; Feltovitch et al., 1993). Examples of dimensions of conceptual difficulty and their manifestation in the context of ice sheet behavior include sequentiality vs. simultaneity (e.g., of physical processes driving ice sheet dynamics), universality vs. conditionality (e.g., ice sheet behavior conditioned by specific boundary conditions), static vs. dynamic system behavior (e.g., the appreciation that dynamic systems may appear static on shorter timescales but are highly dynamic on longer ones), and concreteness vs. abstractness (e.g., the challenges of bringing Earth-scale features and processes to the classroom).

Introducing models to the learning process is therefore an attractive tool that can bring an ice sheet to the classroom. Learners can, guided by modeling instruction (Caballero et al. 2014; Jackson et al., 2008), explore and apply the model in the classroom, and make it a central component of their learning. Conceptual difficulties can be overcome through concrete, hands-on learning activities addressing dimensions of the difficulties mentioned above. Models can further help learners to approach and deal with what may be perceived as threshold concepts (Feltovitch et al., 1993; Meyer & Land, 2003). Mastering such a model can be a transformative learning experience, which, because of its irreversible and fundamental nature, will enable the student to apply the knowledge gained beyond ice sheet modeling—in the wider context of understanding Earth system processes through modeling (Cousin, 2006). Indeed, in our contemporary world, in which "geoscience uses equations, models and numbers in conjunction with observations, maps and words" (Manduca at al., 2008), it is imperative to enable learners to acquire a "model literacy" (Courtland et al., 2012) and with it a better-informed role in discussions concerning the changing face of the Earth in times of unprecedented global climate change.

In the teaching and learning process, several challenges (or "challenge features," see Olsen et al., 2011), addressing "content," "pedagogy," and "structure") have to be overcome: First, to spark the students interest in modeling to such an extent that they are willing to engage in descriptions of ice sheet behavior that include mathematical and numerical concepts that go beyond what is typically dealt with in introductory Earth science courses. Second, to provide them with a tool that combines this advanced knowledge acquisition with a true learning experience (here, the ice sheet model). Third, to offer students a knowledge base that enables them to acquire an increasingly complex contextual knowledge. If these aims can be achieved, students may change their perception of "dimensions of difficulty" and "threshold concepts" (Feltovitch et al., 1993; Meyer & Land, 2003), transforming an interdisciplinary and challenging learning situation and content into a stimulating and rewarding learning experience.

The learning activities are targeted at students of first and/or second cycle programs (BSc or MSc) in the Bologna system of higher education. Topically, the learners should have a basic knowledge of the cryosphere and its relation to the climate system before embarking on the learning experience. Also, experience using the Excel™ spreadsheet software is required in order to be able to participate in the learning activity. Standard presentation software is used so that results can be visually documented and shared among the learners and educators. Knowledge that is advantageous (but that also can be supplied during the learning activity if needed) comprises basic glaciological terminology such as accumulation, ablation, mass balance, equilibrium line altitude, lapse rate, and glacial isostasy.

The intended learning outcomes (LO) are as follow: Upon completion of the learning activity, learners shall, in general:

- LO1: be familiar with GRANTSISM, a numerical ice sheet flow-line model capable of simulating the large-scale dynamics of the Svalbard-Barents Sea Ice Sheet, and the contemporary Greenland and Antarctic Ice Sheet;
- LO2: be able to reproduce standard modeling scenarios described in written documentation provided by the instructor; and
- LO3: be able to follow more extensive descriptions of the GRANTSISM model (e.g., Pattyn, 2006), as well as similar, related literature, and to critically discuss and reflect on it.

Going beyond these initial accomplishments, learners should be able to:

- LO4: identify parameters and data representing "forcings" of the ice sheet model;
- LO5: investigate the impact of various choices of parameters and forcings on ice sheet evolution and decay;

- LO6: recognize and reflect on feedbacks and mechanisms that are relevant for dynamic ice sheet behavior;
- LO7: formulate hypotheses concerning ice sheet behavior in response to external forcings and changing (internal) parameters;
- LO8: design and conduct their own experiments in GRANTSISM to test a formulated hypothesis; and
- LO9: visualize and document results of their ice sheet modeling experiment, to facilitate a discussion in their learning peer group.

Achieving the learning outcomes is partly facilitated by providing a learning environment that stimulates active learning by the individual, empowering each student to become a self-regulated learner, and by engaging learners in collaborative efforts that produce knowledge leading to insight (Repko, 2008). Mostly, however, it is the opportunity to perform hands-on experiments ("a true learning experience") with a numerical model that enables the learner to achieve an understanding of how models work: Because the model allows for experimenting "in a nutshell," yet providing a range of possible experiments, simulations (a) can be performed with virtually no previous modeling experience, (b) can be run in the fraction of the time that full-fledged ice sheet models require, (c) produce a fraction of the output data which full-fledged ice sheet models produce, and (d) generate results that can be visualized with standard computer tools with which virtually every learner is familiar. Dimensions of difficulty—such as the simultaneity and/or conditionality of processes as well as the quasi-static in the short term, but ultimately dynamics nature of, for example, the isostatic uplift acting long after an ice sheet has vanished—are dealt with and likely to be overcome in the hands-on activities (see also the description of the learning activities below).

The Svalbard-Barents Sea Ice Sheet module in GRANTSISM

The model presented here, and its description, should be viewed as supplemental to the original version of Pattyn (2006), principally as material covered in the Pattyn (2006) version is not repeated here. Paleo-simulations based on a likely LGM configuration of the Svalbard Barents Sea Ice Sheet (Gowan et al., 2016; Hughes et al., 2016) can be performed, as can simulations starting from ice-free initial conditions. In both cases, ice sheet evolution is driven by a surface mass balance scheme derived from a specific climate forcing proposed by Pelto and colleagues (1990), which was also used by Siegert and colleagues (2001, 2004, and references therein) in more complex numerical ice sheet simulations of the Late Weichselian Eurasian Ice Sheet and the parts that covered the Barents Sea region.

The Svalbard-Barents Sea Ice Sheet module comprises two east–west cross-sections at 79°N and at 76°N, respectively (DATASET 3 and DATASET 4, respectively), and one north–south cross-section (DATASET 5) at 19°E, see Figure 2. GRANTSISM is an Excel™ spreadsheet model that has two sheets: The "Model" sheet, and the "Calculations" sheet. Model is the control and visualization interface, whereas Calculations contains the underlying code. Mandatory control parameters are RUN and TFOR, providing the option to run the model (with a choice of different initial conditions) and to specify the main forcing driving ice sheet evolution, represented by TFOR (atmospheric temperature) to be chosen from a given range. Optional parameters are BASALSL, TKOPP, BEDADJ, and SEALEV, allowing the user to make choices regarding "sliding at the base of the ice sheet," "thermal coupling within the ice sheet," "glacial isostatic adjustment at the ice sheet's bed," and "sea level." Mandatory and optional parameters are entered via the Model sheet, which also contains display panels for simulation results: the ice sheet profile as well as regions of mass loss and gain along the chosen cross-section, ice velocities, overall ice volume, and the time elapsed during the simulation. Choosing RUN = 1 and confirming by <ENTER> runs the model, and pressing F9 runs it forward through time while the selected output is displayed simultaneously. Model results are successively displayed after 50 iterations each; how this number is changed is described in the Supplemental Materials.

A detailed technical description of the module (addressing ice dynamics and thermodynamics, glacial isostasy, sea-level change, mass-balance treatment, model input in the form of topography and ice thickness, the numerical solution, and module parameters and module display) is provided in the Supplemental Materials. The GRANTSISM spreadsheet is available for download at http://homepages.ulb.ac.be/~fpattyn/grantism/.

Examples of learning activities with GRANTSISM

Practical ice sheet modeling is one of several modules in the portfolio of topically more general courses within which it is taught, focusing on the cryosphere and glaciology in a broader context. It is embedded in a series of conventional lectures focusing on modeling results published in the literature, and discussing the relevance of modeling results and connections to the broader course subject, with a specific focus on model capabilities and limitations (Kirchner et al., 2011, 2016).

Learning activities with GRANTSISM require that students have access to a computer with Excel™ installed.

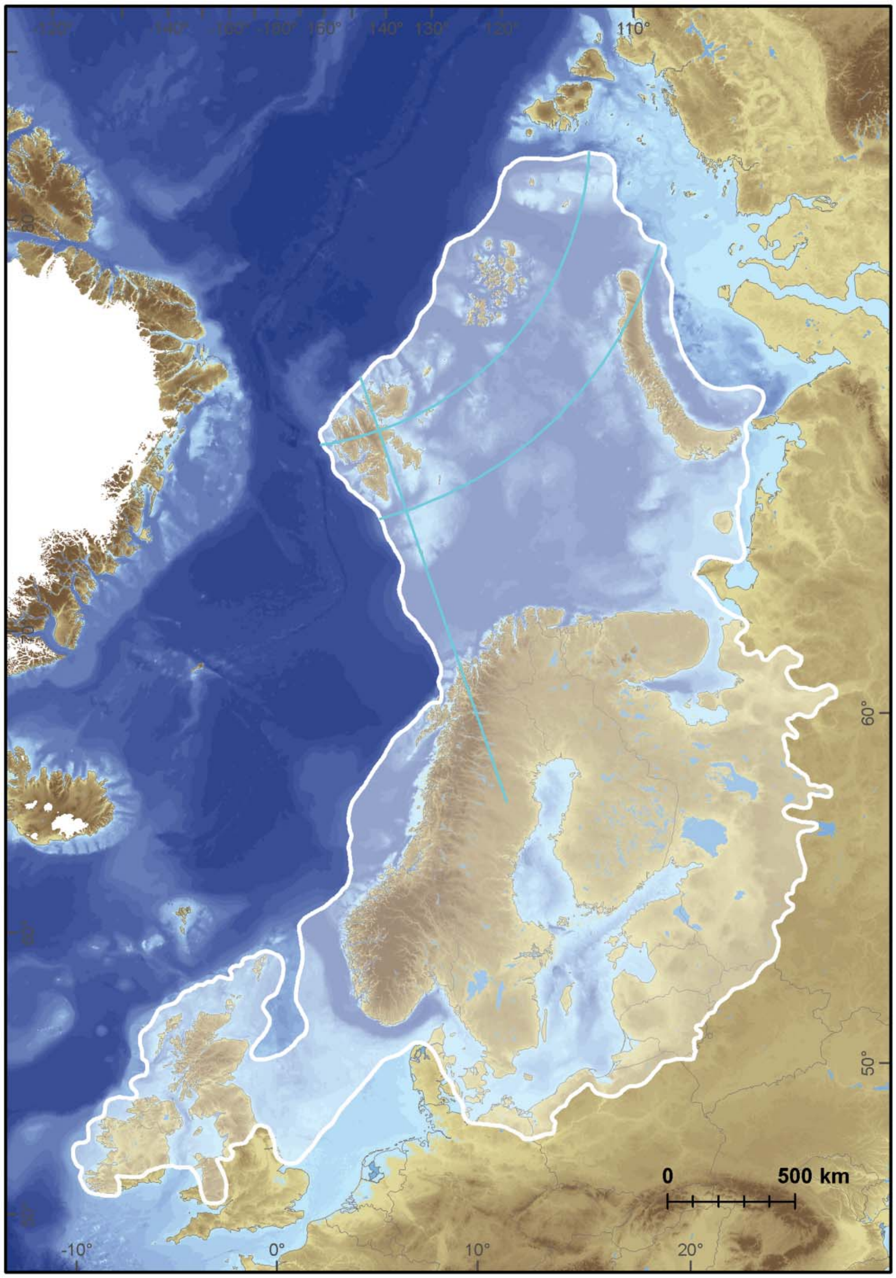

Figure 2. Most likely extent of the Svalbard-Barents Sea Ice Sheet at 20 ka (that is, 20,000 years before present), modified from Hughes et al. (2016). Turquoise lines indicate the cross-sections, which are now available in GRANTSISM to model ice sheet response to climate forcing. East–west cross-sections are located at 76°N and 79°N, respectively, and the north–south cross-section is located at 19°E.

Apart from that, no other equipment is required. If access to computers is limited, students can work in small groups, preferably not exceeding three learners. As a short introduction to the first learning activity, we recommend that the instructor sketch an ice sheet on a white- or blackboard, and recall that ice sheet behavior is mainly influenced by the background climate, often represented simplistically by the temperature above an ice sheet (see also Figure SD3 in the Supplemental Materials). Furthermore, the sketch will help to remind learners of where in (or around) the ice sheet processes take place that are steered via the optional model parameters briefly explained above (BASALSL, TKOPP, BEDADJ, SEALEV). The instructor can engage the learners into a discussion aimed at completing the sketch in the desired way, and develop it with input from the students. This creates a common point of departure before the students embark on familiarizing themselves with the model through Learning Activity 1.

Learning Activity 1 aims to fulfill learning goals LO1–LO3, and concerns simulating the decay of the Svalbard Barents Sea Ice Sheet at 76°N in response to climate warming (for a detailed description, see the section, “Description of selected learning activities” in the Supplemental Materials). Figure 3 shows snapshots of the thickness profile of the melting ice sheet, ice-free conditions after 3000 years of exposure to a warm climate, and the effects of isostatic rebound long after the ice sheet has disappeared, obtained from the numerical experiment in Learning Activity 1.

A second learning activity is dedicated to facilitate accomplishment of learning outcomes LO4–LO6, and focuses on simulating hysteresis in ice sheet behavior under reversed climate forcing. For details, see the section, “Description of learning activities” in the Supplemental Materials. Depending on the time available, a third activity can be structured along the lines of the second one (see the Supplemental Materials for a description).

The final learning activity is designed to address Learning Outcomes LO7–LO9, and comes in the form of a small project that is best performed in groups of up to five learners (this is a value based on our experience) who engage in discussions with their peers during the activity. Also, group work allows for splitting tasks, which may become relevant as the final learning activity may be more time consuming. Each group of students is tasked with formulating a hypothesis to be investigated with GRANTSISM, with designing the numerical experiment that will be used for this purpose, with running all necessary numerical experiments, and with presenting the results obtained to the class. The instructor supports hypothesis finding if necessary, and should be available to help if problems with the numerical model are encountered. At the time of the final presentation, the instructor will initiate and guide a short discussion, giving room for reflections and feedback.

Study population and setting

In total, 58 students enrolled in BSc and/or MSc programs (thus, first and/or second cycle programs according to the Bologna system) participated in learning activities with GRANTSISM. GRANTSISM was used in three courses at the University Centre in Svalbard, and in one course at Stockholm University. These courses were attended by a gender-balanced mix of students from European, U.S. and Russian universities, visiting, for example, through the ERASMUS program.

Student expectations, assessment of learning activities and outcomes, and comments

In order to assess student expectations, and the student’s perception of the learning activities and accomplished learning outcomes, students attending three courses at the Department of Arctic Geology at the University Centre in Svalbard in 2016 and 2017 were asked to provide feedback on the use of GRANTSISM by responding to a questionnaire comprising 12 questions (Q1–Q12; see

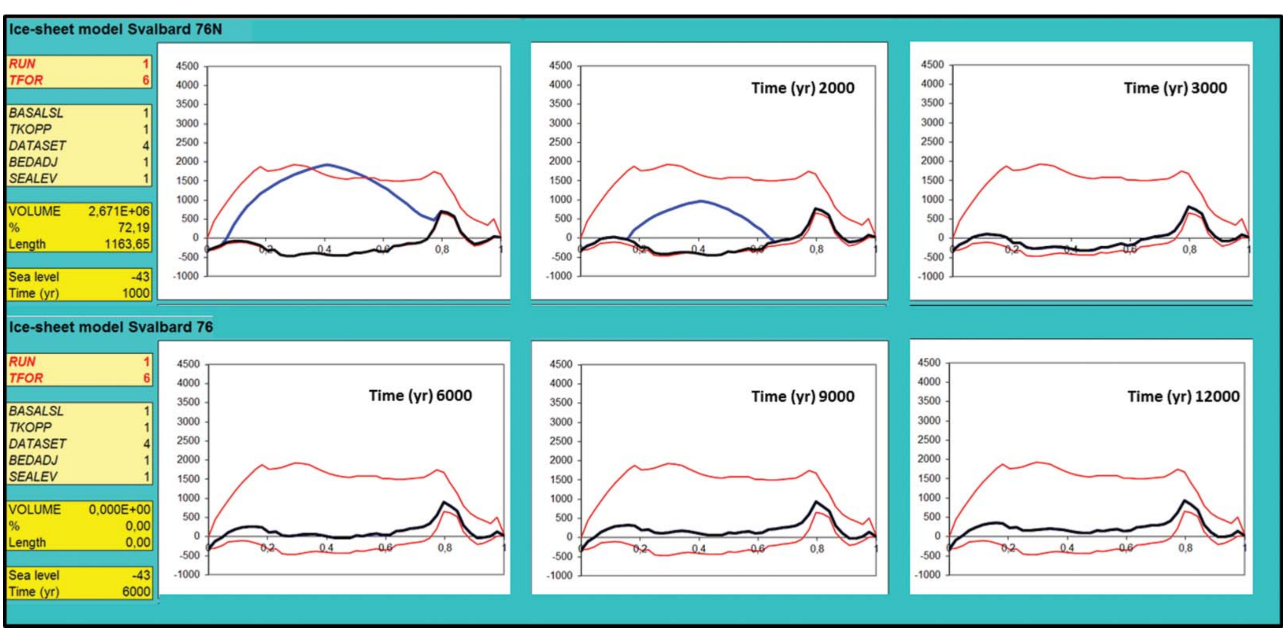

Figure 3. Ice sheet decay for dataset 4 (cross-section along 76°N) and TFOR = +6. Top panel from left to right: snapshots after 1000 years, 2000 years, and 3000 years (ice free). Lower panel from left to right: snapshots at 6000 years, 9000 years and 12,000 years. Red profile: observed initial conditions. Blue profile: modeled ice surface. Black profile: bedrock. Note the isostatic adjustment of the bedrock in (delayed) response to the changing ice load, especially in the lower panel.

Table 1). For a compilation of the responses, see the Supplemental Materials. Note that the survey focused solely on the courses' ice sheet modeling module with GRANTSISM, which was one of several modules in the course portfolio, and that responding to it was not compulsory. The reason for this was to not overload students, who also had to respond to extensive compulsory course evaluations. In addition, students attending a glaciology course at Stockholm University in 2017 participated in ice sheet modeling with GRANTSISM, and were asked to respond to the same survey; however, for this control group, responding was made compulsory, as no other compulsory course evaluations were scheduled at the same time.

Table 1. Student survey.

Questions (number of answers: $N = 26$, number of students participating in the courses: 58) Note one group (51 students, 19 respondents, 37%) responded to a noncompulsory survey, another (7 students, 7 respondents) responded to a compulsory one.

1. Have you ever used a numerical ice sheet model before?
Please answer "yes" or "no."
2. What were your expectations regarding the feasibility of actually performing numerical ice sheet modeling in class *before* we started modeling with GRANTSISM?
Please answer using the scale, "Strongly convinced it would not work / Convinced it would not work / Neutral / Convinced it would work / Strongly convinced it would work."
3. What were your expectations regarding your personal "gains" in terms of learning achievements *before* we started with the learning activity using GRANTSISM?
Please answer using the scale, "No gain at all—no new learning achievements and insights / Limited gain—some new learning achievements and insights / High gain—Plenty of new learning achievements and insights."
4. What were your expectations regarding the attractiveness of the learning activity, BEFORE we started modeling with GRANTSISM?
Please answer using the scale, "Very unattractive and not interesting at all / Unattractive and of very little interest / Neutral / Attractive and of some interest / Very attractive and of large interest."
5. What is your assessment of the feasibility of actually performing numerical ice sheet modeling in class *after* having completed the learning activity?
Please answer using the scale, "It did not work at all / It did not work very well / Neutral / It worked well / It worked very well."
6. What is your assessment regarding your personal "gains" in terms of learning achievements, *after* having completed the learning activity?
Please answer using the scale, *"No gain at all—no new learning achievements and insights /Limited gain—some new learning achievements and insights / High gain—plenty of new learning achievements and insights. Please specify which, if you like, in reply to Question 17.*
7. What is your assessment regarding the attractiveness of the learning activity in retrospect?
Please answer using the scale, "Very unattractive and not interesting at all / Unattractive and of very little interest / Neutral / Attractive and of some interest / Very attractive and of large interest."
8. Without GRANTSISM, I would not have come into contact with ice sheet modeling.
Please answer using the scale. "Strongly disagree / Disagree / Neutral / Agree / Strongly agree."
9. The hands-on learning activity with GRANTSISM provided a useful and simple introduction to ice sheet modeling.
Please answer using the scale. "Strongly disagree / Disagree / Neutral / Agree / Strongly agree."
10. The learning activity using GRANTSISM is a valuable course moment.
Please answer using the scale, "Strongly disagree / Disagree / Neutral / Agree / Strongly agree."
11. What did you like best with the GRANTSISM learning activity, and what did you like least?
Please provide a free text answer.
12. What would make the GRANTSISM learning activity even more interesting for future students?
Please provide a free-text answer.
13. Any other comments you would like to share?
Please provide a free-text answer.

The questionnaire is the single means by which the GRANTSISM learning activities were evaluated by the students and, due to a lack of time, it was not complemented by group discussions, self-reflecting essays, or other means. Because the number of students attending the courses is small (never exceeding 20), the questionnaire was rather informal and did not follow specific standards, as, for example, summarized by O'Neill (2010). The questionnaire should be regarded as a pilot survey, which was tested on the learners during the first times GRANTSISM was used in class. It focuses mainly on the learners' expectations, perception of, and satisfaction with the learning activities, and will be improved at later stages (e.g., following Brennan & Williams, 2004). In its present form, the survey is mainly designed to explore to what extent the attitudinal goals pursued with the use of GRANTSISM (introducing students to ice sheet modeling and triggering an interest for more in-depth learning) are accomplished. Note also that the survey does not contain specific questions regarding assessment. Students had to complete a written exam covering the contents of the entire course, including but going beyond questions related to (theoretical) ice sheet modeling, as the latter is only one of many modules of the course. Practical aspects of ice sheet modeling were not formally assessed, but the student project work and presentations (see the activity addressing learning outcomes LO7–LO9) provided learners with an opportunity for self- and peer-evaluation. A more formal and detailed assessment of how the specific learning goals (not only attitudinal ones) are accomplished, is to be done during forthcoming courses.

Of the 58 students attending courses in which GRANTSISM was used, 26 completed the questionnaire; this corresponds to 45%. Note that for one group (referred to as group 1; 51 students), responding to the survey was not compulsory; of this group, 19 students responded (37%). For a control group (referred to as group 2; 7 students), responding was compulsory, and 7/7 = 100% completed the survey. The student response to the survey provides the basis for the following discussion, and we report separately on the two groups to investigate whether responses from the larger group (51 students at the University Centre in Svalbard) were positively biased because study object and study location coincided geographically.

The results indicate that 85% (89% in group 1 and 71% in group 2) had never used a numerical ice sheet model before (see Q1), and that 62% (74% in group 1 and 29% in group 2) agreed that they foresee they would not have come into contact with ice sheet modeling if not exposed to GRANTSISM, see Q8 and Figure 4. Only 8% explicitly disagreed, 0% in group 1 and 29% (two students) in group 2.

Of the respondents, 88% (95% in group 1 and 71% in group 2) rated the learning activity as a useful and simple introduction to the subject, none disagreed, and the others had a neutral opinion (see Q9). Of all respondents, 77% (74% in group 1 and 86% in group 2) considered the ice sheet modeling moment a valuable module in the course curriculum, 15% (16% in group 1 and 14% in group 2) had a neutral opinion, and 8% disagreed (11% in group 1 and 0% in group 2), see Q10 and Figure 5. This provides an overall positive general feedback to the instructors, and also confirms that the assumed knowledge base among the learners matched the situation encountered in the classroom at the start of the course.

Prior to the learning activity, the majority of respondents expressed neutral expectations regarding both the feasibility of actually performing hands-on ice sheet modeling in class (73%: 74% in group 1 and 71% in group 2, see Q2), and their personal learning gains (77%: 79% in group 1 and 71% in group 2, see Q3). Only 4% of the respondents considered the planned learning activities with GRANTSISM unattractive, whereas 15% were indifferent (both groups responded identically), and 81% (79% in group 1 and 86% in group 2) rated the activity as attractive or even very attractive, see Q4 and the summarizing Figure 6. The student responses to Q4 lead us to conclude that we partly achieved our first aim—namely, to spark an interest for ice sheet modeling among learners who had neither prior exposure nor experience with the subject.

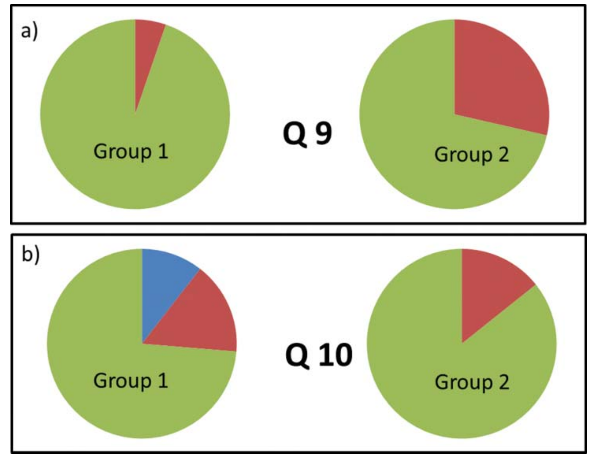

Figure 5. Student response to questions Q9 (panel a) and Q10 (panel b) of the questionnaire, reported separately for group 1 and group 2, respectively. Blue/red/green colors in both panels: disagreement/neutral opinion/agreement that GRANTSISM is a useful and simple introduction to ice sheet modeling (panel a), and that the practical ice sheet modeling activities were a valuable course moment (panel b).

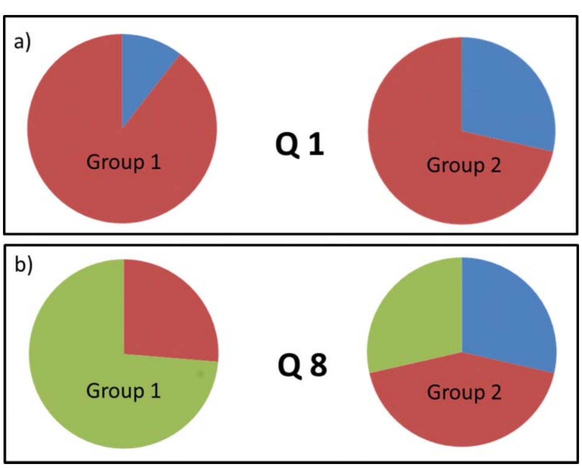

Figure 4. Student response to questions Q1 (panel a) and Q8 (panel b) of the questionnaire, reported separately for group 1 and group 2, respectively. Blue/red colors in panel a: Yes/No, student has/has not used an ice sheet model before. Blue/red/green color in panel b: Students disagree/are neutral/agree that without GRANTSISM, they would not have come into contact with ice sheet modeling.

Questions Q5–Q7 correspond to Q2–Q4, but ask for a feedback in hindsight, that is, after completion of the learning activity. In response to Q5, 69% of the respondents (68% in group 1 and 71% in group 2) reported that the activities with GRANTSISM worked well or very well, thus giving a higher ranking compared to their expectation prior to the hands-on exercise, when only 19% (21% in group 1 and 14% in group2) expected it to work well or very well (see Q2). The learning gain was not assessed differently prior to and after the learning activity: 77% reported some gain prior to the learning activity (Q2), and 73% reported some gain in hindsight, distributed as 79% and 57% between groups 1 and 2, respectively. In retrospect, 81% of the respondents (84% in group 1 and 71% in group 2) experienced working with GRANTSISM as attractive or very attractive, see Q7 and Figure 7.

Based on the replies to Q5–Q7, we conclude that we achieved our second goal to some extent: GRANTSISM became an appreciated learning tool to experience hands-on ice sheet modeling, but it becomes obvious from the respondents' replies that more efforts need to be made to enable the students to experience a high (rather than limited) personal learning gain.

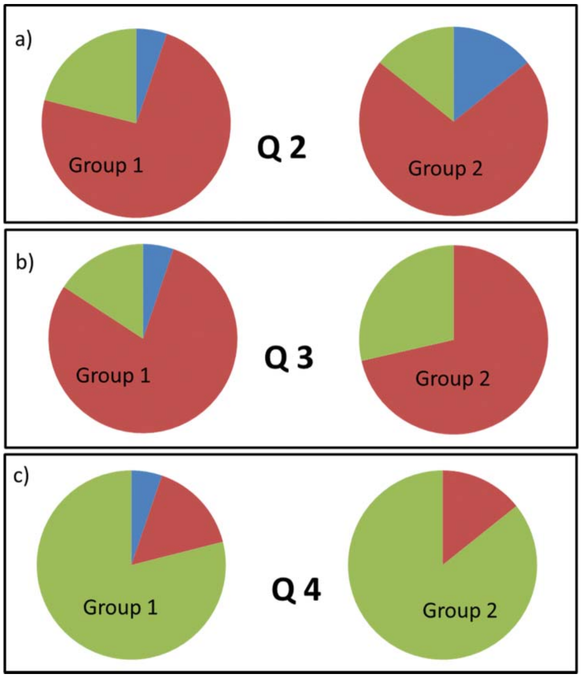

Figure 6. Student response to questions Q2 (panel a), Q3 (panel b), and Q4 (panel c) of the questionnaire, reported separately for group 1 and group 2. Blue/red/green colors: negative/neutral/positive expectation that GRANTSISM would work (panel a), expected low/limited/high personal "gain" in terms of learning achievements (panel b), ranking of the learning activity as unattractive/neutral/attractive (panel c).

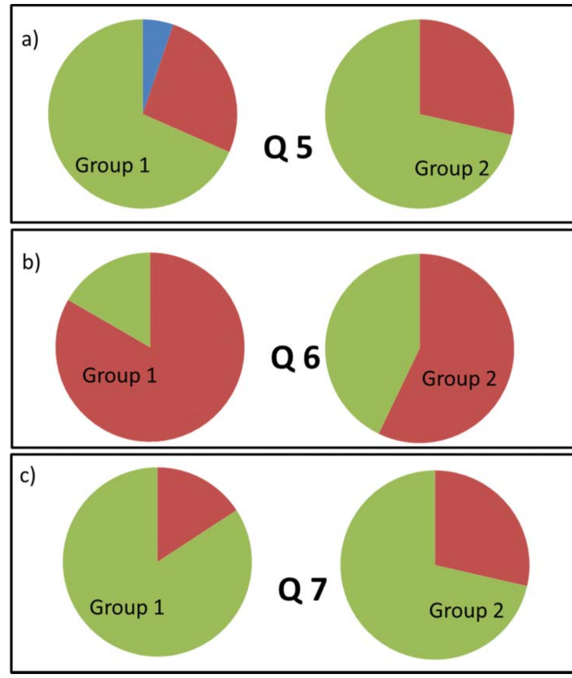

Figure 7. Student response to questions Q5 (panel a), Q6 (panel b), and Q7 (panel c) of the questionnaire, reported separately for group 1 and group 2. Blue/red/green colors: negative/neutral/positive experience of how GRANTSISM worked (panel a), experienced low/limited/high personal "gain" in terms of learning achievements (panel b), ranking of the learning activity as unattractive/neutral/attractive, in hindsight (panel c).

Comparing the answers from group 2 (mandatory student survey) with those from group 1 (noncompulsory response to the student survey), the same overall patters are observed in the replies, implying a low risk for a merely geographically induced bias when using GRANTSISM.

However, answers to Questions 11 and 12 indicate that we indeed have accomplished our first aim, because respondents express the wish to learn more about modeling details of GRANTSISM, and numerical processes in general, and about more complex numerical models, as the following selected quotations show:

> You can perform pretty cool experiments with an easy to operate model. Good way to get a "feel" for modeling and what it can do. What I liked less is that it was a bit of a black box and I did not know very well how it really worked.

> [The GRANTSISM learning activity would be even more interesting for future students if one could] go into the coding in order to better understand the numerical processes.

> [The GRANTSISM learning activity would be even more interesting for future students if one could go] a bit more in-depth with tweaking or entering some of the model code itself, in order to understand the nuts and bolts rather than just how to use it, but maybe that is impossible given the time-frame!

> [I wanted] more time to use it and more examples of practical applications and how it relates to larger models.

Also, answers to Q11 and Q12 help identify why the learning gain was overall only rated "limited" by the respondents: Too little time was set aside for the learning activity, which implied that the learning content was experienced as interesting, but "a bit shallow," as one respondent put it:

> Best: understanding how a numerical model can work. Least: the brief learning, maybe we could have practiced more.

> Best was simplicity of testing different scenarios. The time to actually play around with it was too limited.

> I wanted more time to learn it, and perhaps more "teaching" on it.

The extent to which students will use the ice sheet modeling knowledge gained using GRANTSISM in future learning environments is difficult to assess. However, from replies to Q11 and Q12 we conclude that thresholds for engaging in the topic of ice sheet modeling have been lowered, as two selected quotations illustrate:

> Really good introduction to ice sheet modeling—much less scary than I thought it would be!

> Before we started the lectures I was afraid I might not like your part of the course. But it was really interesting.

Positive student responses such as these lead us to suspect that students may also be receptive to increasingly complex concepts of ice sheet modeling when encountered in future occasions, where they would benefit from a curricular spiral effect (Olsen et al., 2011).

Implications

The students' learning experience with GRANTSISM is here summarized from three perspectives.

First, based on their self-reported feedback collected in the student survey: It illustrated that experimenting with GRANTSISM was highly appreciated by the students and well-suited as an introduction to ice sheet modeling, and that it triggered an interest for further subject-related in-depth learning experiences among the learners.

Second, based on instructors' observations in the classroom: Students were observed to actively engage in the hands-on learning activities, to participate in discussions, and to ask questions or to readily consult suggested literature if knowledge gaps needed to be filled. As almost all learners were new to ice sheet modeling, knowledge gaps concerned explicit knowledge mostly—tacit knowledge was built and shared by the learners while working individually, in pairs, or in groups with GRANTSISM. Performing numerical experiments simulating ice sheet growth and decay provided an opportunity for a true learning experience that brought ice sheets to the classroom and offered learning that was not short of true experience. Learning outcomes were achieved quickly by practicing with GRANTSISM, and discussing problems and progress with peers. Conceptual difficulties, if they existed, were observed to pose less challenge as modeling literacy increased.

Third, based on the educator's observations during the presentation of the project group work, and its subsequent discussion in class: Project works using GRANTSISM covered a wide range of hypothesis concerning ice sheet behavior, and addressed the Svalbard Barents Sea Ice Sheet, the Greenland Ice Sheet, and the Antarctic Ice Sheet alike. The numerical experiments designed and carried out demonstrated that learners had achieved the intended learning outcomes. On a few occasions, the presentation of the project work provided a prime example of traps encountered in explaining numerical model results. For instance, when a model result obtained for the Svalbard Barents Sea Ice Sheet along the north–south cross-section (DATASET 5) was regarded counterintuitive, an attempt was made to explain it in relation to lacking detail in the forcing or feedback mechanisms available in GRANTSISM. However, the solution was much simpler: Although referred to as a "north–south cross-section," GRANTSISM displays the cross section from south to north ("south" located at the leftmost and "north" at the rightmost endpoints of the cross section's length axis, respectively). Once this misunderstanding was resolved, the model results were no longer counterintuitive, and the class had experienced a situation that highlighted the importance of critical awareness with respect to model input and output, and visualization and interpretation of results.

From an educator's point of view, the lessons learned from the occasions when GRANTSISM was used in class represent an outcome we had aimed for: Learners recommending that more time be spend not only with the tool itself but also with a more in-depth introduction to ice sheet modeling, addressing more advanced topics that were beyond the scope of the module in its present, exploratory phase. The overall positive teaching experience may partly root in the special composition of the learning group, in which all individuals likely had a genuine interest in ice sheets (otherwise they would not have chosen the course). GRANTSISM has not yet been tested in mandatory courses potentially attended by learners who have no specific interest in ice sheets and modeling. Following the student's suggestions, future noncompulsory courses will give a more thorough introduction to the theory behind GRANTSISM, and include additional lectures on more theoretical aspects of ice sheet modeling.

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