GREENLAND IN PARALLEL

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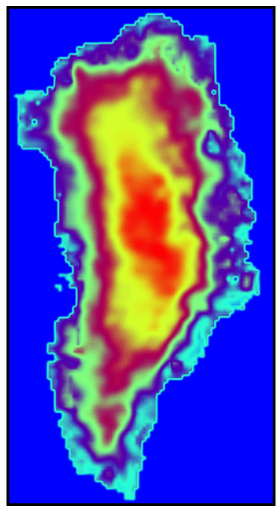

Abstract. Still in its infancy, PISM has been used successfully on the Antarctic ice sheet. The Greenland ice sheet, though, is unique in its own way and needs different modelling elements than Antarctica. This paper will discuss the implementation of the EISMINT-Greenland Intercomparison in PISM. There were several elements that needed to be added included a positive degree day model and climate controlling. Once implemented, the intercomparison was run to completion. Although the results cannot be verified, the process was used as a tutorial for the PISM user manual. In addition, a simple experiment of the regrowth of the Greenland ice sheet was performed.

1. Introduction

PISM (Parallel Ice Sheet Model) is an on going project that has been used to great success. In the past, PISM has been used to model the Antarctic ice sheet. It might seem that modelling Greenland would then be a trivial process. The European Ice-Sheet Modelling Initiative (EISMINT) has publicly available Greenland data which can be downloaded directly from their website. Once the data is obtained, one might think that using the same parameters as used with Antarctica would produce a sufficient model of Greenland. This is not the case, though. Generally speaking, Antarctica's climate is very cold, and well below freezing year round. As a result,

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the majority of the ice lost in Antarctica is due its ice flowing to the edges and calving off into the ocean. Greenland, on the other hand, has a much warmer climate. Much of the surface ice is at or just below its melting point. Thus, most of the ice lost on the Greenland ice sheet is through surface ablation. Because of this large difference certain elements needed to be implemented in PISM that were not needed for the Antarctic ice sheet. The first of these was a positive degree day model which would effectively allow PISM to take into account areas of ablation. In addition, included in the EISMINT-Greenland data, were some results from the GRIP ice core [1]. Using this data, a simple climate forcing element was able to be added to PISM. Once these elements were implemented in PISM it was possible to run the tests described in the EISMINT Intercomparison Experiment [4]. These runs are not for the purpose of making any predictions about the future of the Greenland ice sheet, but to simply perform some verifications on Greenland, to add more capabilities to PISM, and to also document the entire process in PISM's user manual as a tutorial for new users. After A. Letrèguilly's experiment in [2], it also seemed to be beneficial to replicate this experiment to see how PISM's results would compare.

2. Purpose of EISMINT-Greenland Intercomparison

The EISMINT-Greenland Intercomparison Experiment [4] was an attempt to check the consistancy of various ice sheet modelling programs. The experiment contains specific guidelines on how to run a chosen experiment on Greenland, and a good set of 20 kilometer gridded data including bedrock altitude, ice thickness, surface altitude, and accumulation. Further infomation was given in the experiment description to fill in other data. The results from each ice sheet modelling program would then be gathered and compared. Due to unforseen circumstances, the intercomparison never ran to completion. Since no results were ever published there is nothing to check the results from PISM against, but despite this, the data and description of the experiment is a chance to expand PISM's capabilities.

3. Formatting the Data

PISM is an open source project [3] which is available to download for anybody under the GNU General Public License. Since it is under the GNU General Public License, there are some items that cannot be distributed with PISM. One of these is other scientists' data. The main objective of this experiment is to use actual Greenland data in PISM, but the publically available EISMINT-Greenland data needs to be put in a format useable by PISM. This is done in the form of several python scripts and c code. These programs are part of the PISM source code, so they can therefore be distributed with PISM. Once PISM is downloaded, the user then needs to obtain the data sets from `http://homepages.vub.ac.be/~phuybrec/eismint/greenland.html`. After running the various scripts on these data sets, the user will have several NetCDF files useable by pism. The data type NetCDF was chosen for several reasons. First, NetCDF files are binary files. Thus, they are not as large as ASCII files and are also faster to read from and write to. In addition, the convention of NetCDF files is to take advantage of the metadata options. Instead of just having an ASCII file with a bunch of numbers, a NetCDF file can have descriptions of the data such as units and names.

4. Bootstrapping and Special Formulas

4.1. **Incomplete Model Description.** The EISMINT-Greenland data set contains data on the surface elevation, ice thickness, bedrock elevation, and accumulation rate of Greenland. Although this describes a great deal of Greenland, there is still other infomation needed by PISM in order to run. Thus, it was necessary to have a so-called "bootstrapping" function. This function has the ability to take an incomplete data set and fill in the empty fields with logical guesses. Although these guesses are going to be wrong, if they are not too extreme then PISM should still function fairly well. Some of these can actually be calculated more accurately by running PISM in special ways. This will be described more in Sections 5.1 and 5.2. So once the data is obtained and formatted as decribed in Section 3, PISM can use this incomplete data using the bootstrapping function.

4.2. **Surface Temperature.** In the EISMINT-Greenland Experiments, there are equations which, in some cases, replace missing data. The first pair help to fill in the surface temperatures as shown in Equation (1). Instead of supplying a single map of surface temperatures, the EISMINT-Greenland data supplies an equation that can be used to determine the surface temperature at any time during the run using the current latitude and surface elevation. Thus, the ability for PISM to update the surface temperature at each time step according to the following equation needed to be developed.

$$Ta = 49.13 - 0.007992 * Z - 0.7576 * latitude \tag{1}$$

where

$$Z = \max(SurfaceElevation, 20 * (latitude - 65)) \tag{2}$$

4.3. **Positive Degree Day Model.** In addition to not supplying a map of surface temperatures, the accumulation data supplied with the EISMINT Experiment describes only the amount of annual snowfall. It does not take into account any surface melting, and therefore does not show any areas of ablation. This was not a problem when PISM was used to model the Antarctic ice sheet because, as stated earlier, Antarctica is very cold, and thus there are only very small regions of surface melting and even smaller regions of ablation. But since Greenland is so much warmer, surface ablation needs to be taken into account. To do this a positive degree day model is used. The positive degree day model developed for PISM generates a sinusoidal curve describing the surface temperatures through out a single year. Then some random variations are applied and all the positive values are summed up. Using this sum, some snow and ice melt factors are used to determine if some of the annual accumulation will remain for the next year, or if all the snow fall will melt away and the region will actually ablate.

5. Running the EISMINT Experiments

In this section the four experiments described in [4] will be described in the context of PISM. The first two deal with running PISM until the ice sheet reaches a steady state (less than a 0.01% change in volume in 10,000 years). The second one uses the GRIP data mentioned earlier to force changes in temperature and sea level. Finally, the last run tries to simulate greenhouse warming by slowly increasing the surface temperature of the ice.

5.1. **Steady State Experiments.** The EISMINT Intercomparison describes two steady state runs. The first of which is fully described with all the standard parameters given. The second run is left up to the modeller to choose what modifications to the first run would be best. It might seem interesting why these steady state runs are to be performed. As stated earlier, a full description of the Greenland ice sheet is not given with the EISMINT data. One item of data that is very important to an ice sheet modelling program is the description of temperatures at depth. These are the temperatures below the surface. The formula given earlier only describes the temperatures at the surface of the ice sheet. By running the ice sheet to steady state, we can make a more educated guess about what the ice temperatures below the surface are. First, PISM interpolates the temperatures at depth using the surface temperatures and the fact that ice at the base is warmer than the surface ice due to geothermal flux, high pressures, and sheer stresses. Then, the ice sheet is modelled without allowing the mass to change. Thus only the internal temperatures change, and this will in turn allow the temperatures to even out a more realistic distribution. Once the temperatures are somewhat evened out, the ice sheet is allowed to deform again. Once the ice sheet changes less than 0.01% in 10,000 years, it is said to be in a steady state. Once this state is reached, the temperatures are what they would be if the ice sheet sat in the same climate for a very long time. This is the state the ice sheet is assumed to be at the beginning of the GRIP data which is used in Section 5.2.

5.2. **Climate Control Experiment.** As stated earlier, included with the EISMINT-Greenland data were some results from the GRIP data. From this data, some formulas were created to describe the change in sea level from present day and the change in surface temperatures from present day. The changes in sea level go back over 780,000 years and the changes in surface temperatures go back almost 250,000 years. Thus, if the steady ice sheet found in Section 5.1 is run from 250,000 years in the past to present day, these changes can be applied accordingly. The resulting ice sheet would contain the most realistic temperatures at depth than any of the states before.

5.3. **Greenhouse Warming Experiment.** Finally, the real prediction can take place. After running the data to steady state and using the past climate data to produce the most realistic ice sheet, a real experiment can take place. The Greenhouse Warming experiment is meant to simulate a projected increase in CO_2 in the air by increasing the surface temperature at a rate of $0.035°C$/year for the first 80 years, then at a rate of $0.0017°C$/year for the last 420 years.

6. Running Other Experiments

In addition to running the EISMINT-Greenland experiments, PISM was used to mimic an experiment described in [2]. Here, a modelling program was used to see if the Greenland ice sheet is actually a relect from a previous colder climate. In order to test this theory, a couple things needed to be done. First, it was necessary to remove all the ice from Greenland. Although it might seem that it would be sufficient to simply set the thickness to zero, this is not the case. According to the EISMINT-Greenland data, the Greenland ice sheet contains about 2.7 million giga-tons of ice. With such a large amount of ice contained in the ice sheet, there is a very large load on the earth's crust. This downward force deforms the crust and according to PISM's deformation model depresses the earth 822 meters at its maximum point. These changes in the crust will effect rebuilding the ice sheet in a couple ways. First it will result in a different climate. Since the surface temperatures for Greenland are computed using the equations from the EISMINT-Greenland experiments, they are dependant upon elevation. Thus, the changing bed elevations will change the temperature of the ice. Second, it will change the shape of the bed, and could possibly make a positive slope in one area that used to be a negative slope. This would change the flow of the ice as it begins to build up. In order to allow the bed to rebound, PISM's bed deformation model was used. Before the data was sent through PISM, the accumulation was set to a negative value. Thus, as PISM modelled the input, the ice sheet would disappear and at the same time the earth would rebound. To make sure the earth will rebound the full amount this first part was run for 100,000 years, while the ice disappeared during the first 5,000 years. Second, once all the ice melted away and the earth was fully rebounded, the original accumulation data needed to be replaced. Once this was done a steady state run like the one in the EISMINT-Greenland experiments was done.

7. Results

This section will describe the results of each run described in Section 5.

7.1. **Steady State and Climate Control.** In Figure 4 the evolution of the basel temperatures can be seen as they are run through each experiment described above. The basel temperatures from bootstrapping can be compared directly to the bedrock altitude shown in Figure 2. This is because, as stated before, the temperatures at depth (including basel temperatures) are interpolated using the surface temperature and the ice thickness. The other basel temperature maps show more, and more reasonable values for the basel temperatures. Running through the center of Greenland is the ridge where ice flows to one side or the other. Thus, at these places there is less sheering and therefore the ice is colder. As the ice flows to the edges, there is more motion and warmer ice. The Jakobshavn Isbræ is one of the fastest flowing outlets in Greenland. Results of this outlet glacier can be seen in the south western section of Greenland. Here, the basel temperatures should be as warm as possible. Looking at the map of basel temperatures after the climate controlled run, this is what is seen; the basel temperatures are right at melting point.

7.2. **Greenhouse Warming.** As stated earlier, the results from these runs are not meant to make any predictions about the future of the Greenland ice sheet. Not enough thought has been up into the physics behind PISM to be confident in any of these results. These experiments were run as an effort to further develop PISM and to document the process in the user manual as a tutorial for users to become familiar with PISM. Thus, this experiment was performed souly for the sake of completeness. The images in Figure 3 show the results of the Greenhouse Warming experiment. Through close inspection, you can see that there are slight changes Greenland's shape and thickness. An interesting result though, is that the total volume increased from 3.857 million giga-tons to 3.870 million giga-tons while the area decreased from 2.167 million km^2 to 2.137 million km^2. This gives the impression that the ablation areas around the edges moved inward, while the rest of Greenland continues to gain thickness. This is supported by the fact that the maximum thickness grew from 3295 m to 3302 m.

7.3. **Ice Sheet Regeneration.** The last experiment was not part of EISMINT-Greenland, but used the same data and parameters as the first steady state run. As stated earlier, the first part was to allow the earth to rebound. These results of the first part are shown in Figure 5 Here the difference between the starting and ending bed is shown. In the center, the bedrock lifted a total of 822 meters. This would show a significant change in surface temperature. After Greenland was run back to a steady state, what was noticed was a two step process. First, the ice began to accumulate very quickly. The inner parts of Greenland have no ablation, thus the ice was allowed to accumulate until it got to a thickness with the ability to flow. During this very fast accumulation, the bed stayed about the same. The defomation of the bed takes much longer than it does for ice to build up. After 30,000 years, the ice sheet did rebuild itself to look much like the original ice sheet.

It took a total of 70,000 years to reach a state of equilibium. The final map of the thickness is show in Figure 6.

8. Future Work

One item of future work could be a more structured set of runs. Instead of trying to predict what Greenland will do in the future, we can compare some data and look at what physics are the best to use. If a map of the surface velocities of Greenland can be obtained, then a group of runs with PISM can be set up. In these runs, a handful of variables could be varied within a certain range. After the runs have finished, the surface velocities could be compared to figure out what parameters are best for Greenland. Recently a set of data on a 5 km grid was obtained and formatted for PISM. This would be ideal for this future experiment. Also, PISM needs to be optimized. A full investigation of how long each part of PISM takes to run should be done. With these results, certain parts could be optimized and would allow PISM to model things faster. One example is the positive degree day model discussed in Section 4.3. Currently there is a noticible difference in speed with and without the positive degree day enabled. Very recently a more analytical solution to the problem was found, so if this were to be implemented, PISM would improve greatly. Finally, PISM could be expanded to look at the Mars polar cap. Even though the data for this ice sheet is not very good, it exists and some interesting results may come out.

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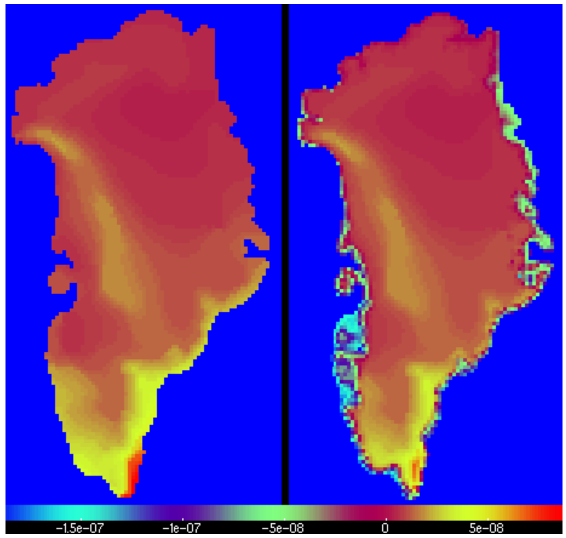

FIGURE 1. Demonstration of Positive Degree Day model. The map on the left is total snow fall over Greenland, while the map on the right is the accumulation with the PDD applied. The units of the scale are in m/s.

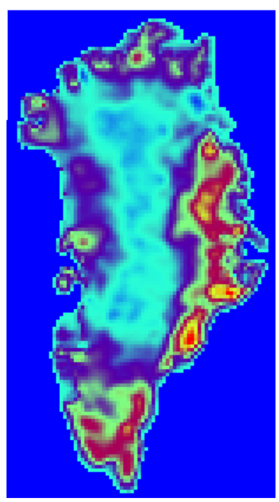

FIGURE 2. This figure shows the bedrock altitude underneath the Greenland Ice sheet.

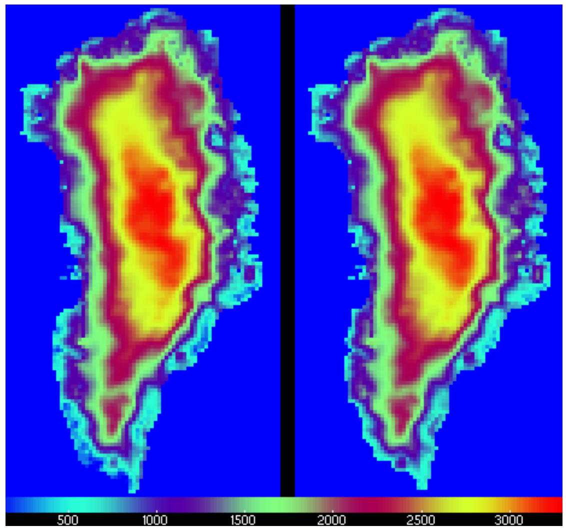

FIGURE 3. This figure shows the results of the Greenhouse Warming experiment. On the left is the map of the thickness of Greenland before the run, and on the right is after the run. The scale is in meters.

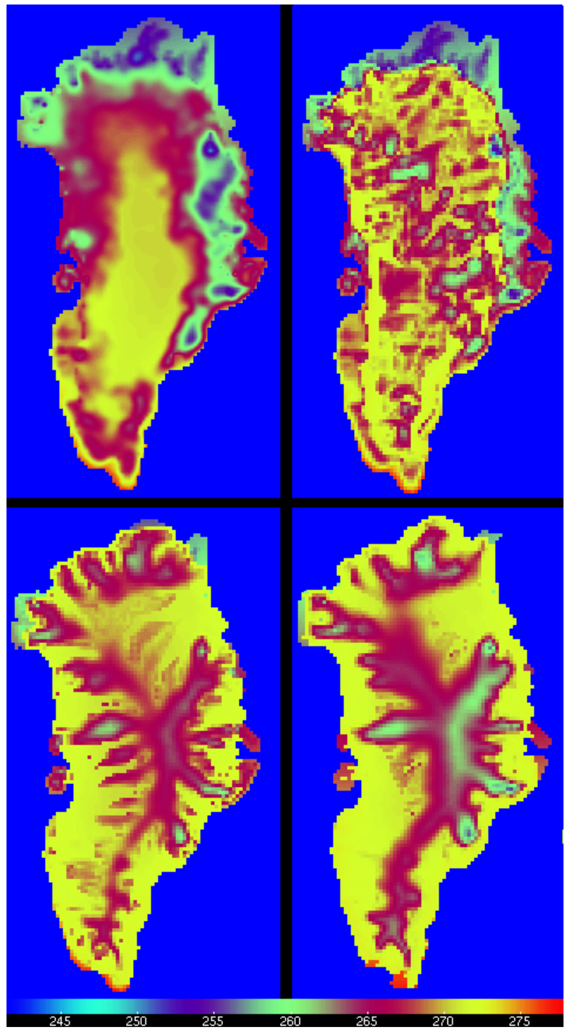

FIGURE 4. This figure shows the evolution of the basel temperatures. From top left to bottom right, the maps are the basel temperatures immediatly after bootstrapping, after the no mass run, after the second Steady State run, after the Climate Control run. The scale is in meters.

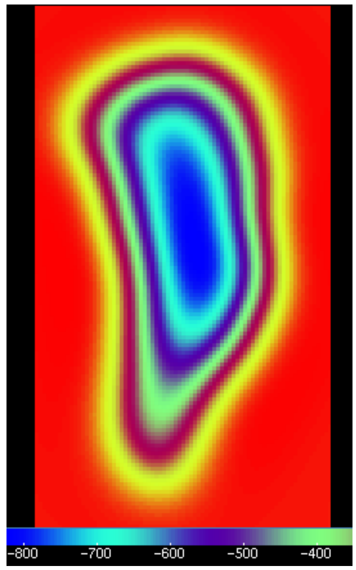

FIGURE 5. The bedrock before minus the bedrock after rebounded earth. The scale is in meters.

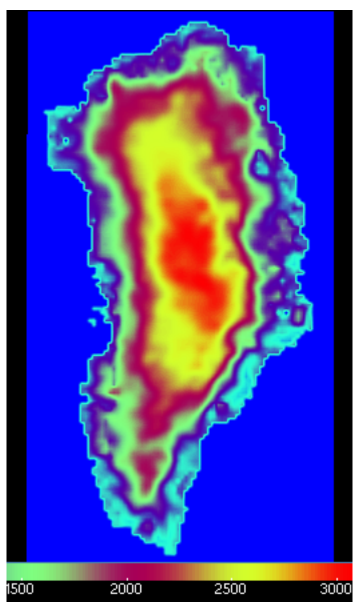

FIGURE 6. This figure shows the final thickness after the regeneration experiment. The scale is in meters.

References

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