PISM, A PARALLEL ICE SHEET MODEL:

USER'S MANUAL

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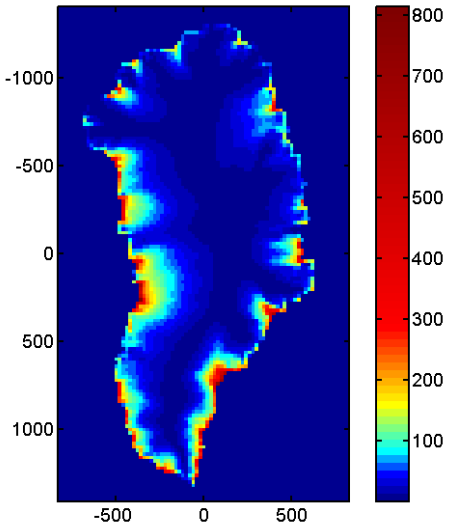

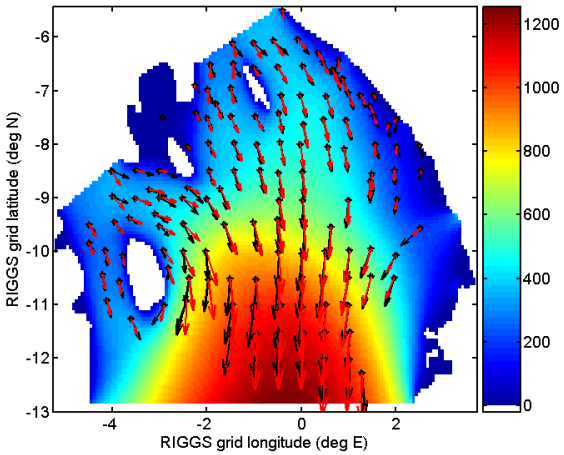

Date: February 11, 2008. *ffelb@uaf.edu.

Based on PISM version "`stable0.1`" and PETSC release 2.3.3-p2.

Get PISM by Subversion: `svn co http://svn.gna.org/svn/pism/branches/stable0.1 pism`.

Acknowledgements

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Contents

1. Introduction

Welcome to PISM!

This *User's Manual* describes how to download the PISM source code and install PISM. It describes how to run it for certain simplified geometry situations. It illustrates how PISM's numerical codes are verified. It describes how to use PISM as a modest Greenland ice sheet model or a modest Ross ice shelf model.

But that is all. Users who want to advance the science of ice sheets will need to go beyond what is described here. For such users there are two additional documents to know about:

(1) The *PISM Reference Manual* (`www.pism-docs.org/refman.pdf`) describes the most important pieces of the source code. It contains, or at least it is intended to contain, the minimum documentation of the PISM source code parts in order to include all the continuum models and numerical methods of PISM.

(2) The *PISM (HTML) Source Code Browser* gives a complete view of the class/object structure of the source code. It can be generated from the source by starting in the PISM directory and doing `cd doc/ && make`. Then use a web browser like Firefox to view `pism/doc/doxy/html/index.html`.

The *Reference Manual* and the *Source Code Browser* were automatically generated by `doxygen` (`www.doxygen.org`) from comments in the PISM source code. Thus they are not as user-friendly as this *User's Manual*.

WARNING: PISM is an ongoing project. Ice sheet modeling is complicated and not mature (in 2008, anyway). Please don't trust the results of PISM or any other ice sheet model without a fair amount of exploration. Also, please don't expect all your questions to be answered here. But do write to us with questions:

`ffelb@uaf.edu`.

2. Installation

Installing prerequisities.

1. You will need a UNIX system with internet access. A GNU/Linux environment will be easiest but other UNIX versions have been used successfully. Package management systems are useful for installing many of the tools below, *but* neither PISM itself nor up-to-date PETSc distributions are currently available in the Debian repositories. You will need Python and Subversion installed, but these are included in all current Linux distributions. To use the (recommended) graphical output of PISM you will need an (X Windows server.
2. As PISM is currently under rapid development, we distribute it only as compilable source code. On the other hand, there are several software libraries needed by PISM. Therefore the "header files" for these libraries are required for building PISM. In particular this means that the "developer's versions" of the libraries are needed if the libraries are downloaded from package repositories like Debian. (In summary, `xorg-dev`, `netcdfg-dev`, `libgsl0-dev`, and `fftw3-dev` are the Debian packages we—the PISM developers—have used in compiling and linking PISM.)
3. PISM uses NetCDF (= *network Common Data Form*) for an input and output file format. If it is not already present, install it using the instructions at the webpage or using a package management system.
4. PISM uses the GSL (= *GNU Scientific Library*) for certain numerical calculations and special functions. If it is not already present, install it using the instructions at the webpage or using a package management system.
5. PISM optionally uses the "FFTW" library (FFTW = *Fastest Fourier Transform in the West*) in approximating the deformation of the solid earth under ice loads [10]. If you want the functionality of this earth model, which is coupled to the ice flow and which we recommend, install FFTW or check that it is installed already. If FFTW is *not installed*, however, turn off PISM's attempt to build with it by setting the environment variable `WITH_FFTW=0`. If this library is absent, all of PISM will work *except* for the bed deformation model described in the paper [10].
6. You will need a version of MPI (= *Message Passing Interface*). Your system may have an existing MPI installation, in which case the path to the MPI directory will be used when installing PETSc below. Otherwise we recommend that you allow PETSc to download MPICH2 as part of the PETSc configure process (next). In either case, once MPI is installed, you will want to add the MPI `bin` directory to your path so that you can invoke MPI using the `mpiexec` or `mpirun` command. For example, you can add it with the statement

   `export PATH=/home/user/mympi/bin:$PATH` (for `bash` shell)

   or

   `setenv PATH /home/user/mympi/bin:$PATH` (for `csh` or `tcsh` shell).

   Such a statement can, of course, appear in your `.bashrc`, `.profile`, or `.cshrc` file so that there is no need to retype it each time you use MPI.

From now on this manual will assume use of bash.

7. PISM uses PETSc (= *Portable Extensible Toolkit for Scientific computation*). As mentions of this library will occur frequently in this manual, note "PETSc" is pronounced "pet-see". Download the PETSc source by grabbing the current gzipped tarball at

`www-unix.mcs.anl.gov/petsc/petsc-as/download/index.html`

PISM requires a version of PETSc which is `2.3.3-p2` or later.[1] The "lite" form of PETSc is fine if you are willing to depend on an internet connection for accessing the PETSc documentation.

You should configure and build PETSc *essentially* as described on the PETSc installation page, but it might be best to read the following comments on the PETSc configure and build process first:

(i) Untar in your preferred location, but note PETSc should *not* be configured (next) using root privileges. Note that you will need to define the environment variable `PETSC_DIR` before configuring PETSc (next). For instance, once you have entered the PETSc directory just untarred, `export PETSC_DIR=`\`pwd\`. (Note the use of the backprime (*accent-grave*) character, and not the single apostrophe `'`.)

(ii) When you run the configure script in the PETSc directory, the following options are recommended; note PISM uses shared libraries by default:

```
$  export PETSC_ARCH=linux-gnu-cxx
$  ./config/configure.py --with-shared --with-c-support \
   --with-clanguage=cxx --with-debugging=no
```

Turning off the inclusion of the debugging symbols gives a significant speed improvement.

Note that there is no PISM use of Fortran, and that it is sometimes convenient to have PETSc grab a local copy of BLAS and LAPACK rather than using the system-wide version. So one may add "`--with-fortran=0 --download-c-blas-lapack=1`" to the other configure options.

(iii) If there is an existing MPI installation, for example at `/home/user/mympi/`, one can point PETSc to it by adding the option `--with-mpi-dir=/home/user/mympi/`. The path used in this option must have MPI executables `mpicxx` and `mpicc`, and either `mpiexec` or `mpirun`, in subdirectory `bin/` and MPI library files in subdirectory `lib/`.

(iv) On the other hand, it seems common that one needs to tell PETSc to download MPI into a place it understands, even if there is an existing MPI. If you get messages suggesting that PETSc cannot configure using your existing MPI, you might try `configure.py` with option `--download-mpich=1`.

(v) Configuration of PETSc for a batch system requires special procedures described at the PETSc documentation site. One starts with a configure option `--with-batch=1`. See the "Installing on machine requiring cross compiler or a job scheduler" section of the PETSc installation page.

[1] A Debian package for PETSc may exist, but it should only be used if it is version `2.3.3-p2` or later.

(vi) Configuring PETSc takes many minutes even when everything goes smoothly. Note that a previously installed PETSc can be reconfigured with a new `PETSC_ARCH` if necessary.

(vii) After `configure.py` finishes, you will need to `make all test` in the PETSc directory and watch the result. If the X Windows system is functional some example viewers will appear; as noted you will need the X header files for this to work.

(viii) Finally, you will want to set the `PETSC_DIR` and the `PETSC_ARCH` environment variables in your `.profile` or `.bashrc` file. Also remember to add the MPI `bin` directory to your `PATH`. For instance, if you used the option `--download-mpich=1` in the PETSc configure, the MPI `bin` directory will have a path like `$PETSC_DIR/externalpackages/mpich2-1.0.4p1/$PETSC_ARCH/bin/`. Therefore the lines

```
export PETSC_DIR=/home/user/petsc-2.3.3-p2/
export PETSC_ARCH=linux-gnu-cxx
export PATH=$PETSC_DIR/externalpackages/mpich2-1.0.4p1/$PETSC_ARCH/bin/:$PATH
```

could appear in one of those files.

See Table 1 for a summary of the dependencies on external libraries, including those mentioned so far.

Installing PISM itself. At this point you have configured the environment which PISM needs. You are ready to build PISM itself, which is a much quicker procedure!

6. Get the source for the stable branch of PISM using the Subversion version control system:

```
svn co http://svn.gna.org/svn/pism/branches/stable0.1 pism
```

A directory called "`pism/`" will be created. Note that in the future when you enter that directory, `svn update` will update to the latest revision of PISM.[2]

7. Build PISM:[3]

```
cd pism
make
make install
```

Note that the "`make install`" puts executables, including `pismd`, `pismr`, `pismv`, and `pisms`, in the `pism/bin/` subdirectory and cleans up the junk from the build process. "`make install`" does *not* require root permission.

8. PISM executables can be run most easily by adding the directories `pism/bin/` and `pism/test/` to your `PATH`. The former directory contains the major PISM executables while the latter contains several useful scripts. For instance, this command can be done in the `bash` shell or in your `.bashrc` file:

```
export PATH=/home/user/pism/bin/:/home/user/pism/test/:$PATH
```

Quick tests of the installation. You are done with installation at this point. The next few items are recommended as they allow you to observe that PISM is functioning correctly.

[2]Of course, after `svn update` you will `make` and `make install` to recompile and relink PISM.

[3]Please report any problems you meet at this build stage by sending us the output: `ffelb@uaf.edu`.

10. Try a serial verification run of PISM:

```
pismv -test G -y 100
```

If you see some output and a final `Writing model state to file 'verify.nc' ... done` then PISM completed successfully. Note that at the end of this run you get measurements of the difference between the numerical result and the exact solution [9].

11. Try the MPI four processor version of the above run:

```
mpiexec -n 4 pismv -test G -y 100
```

This should work even if there is only one actual processor on your machine, in which case MPI will run multiple processes on the one processor, naturally. The reported errors should be very nearly the same as the serial run above, but the results should appear faster (if there really are four processors)!

12. Try a verification run on a finer vertical grid while watching the diagnostic views which use Xwindows:

```
pismv -test G -Mz 201 -y 2000 -d HTc
```

When using such diagnostic views and `mpiexec` the additional final option `-display :0` is sometimes required to enable MPI to use Xwindows:

```
mpiexec -n 2 pismv -test G -Mz 201 -y 2000 -d HTc -display :0
```

13. Run a verification test of the ice stream code:

```
pismv -test I -Mx 5 -My 401 -verbose
```

This runs a rather different part of the PISM code and then compares the numerical result to the exact solution appearing in [62].

14. Run a Python script for a basic suite of verifications:

```
verifynow.py
```

or, on an N processor machine,

```
verifynow.py -n N
```

If you would like us to confirm that PISM is working as expected please save the one page or so of output from this script and send it to us (`ffelb@uaf.edu`). See section 7 for more on PISM verification.

At this stage you can do the EISMINT II simplified geometry experiments (section 8) and run many verification tests (section 7) without further downloads. Section 9 is an example of using PISM to model the Greenland ice sheet using freely-downloadable data. Similarly one can model the Ross ice shelf using free data as described in section 10.

Setting up PISM to model real ice sheets will frequently require techniques not be covered in this manual. At the minimum, the user will need to convert ice sheet data to NetCDF format so that it can be read by PISM. Actual modeling may also require the writing of additional source code; see the *Reference Manual* for a description of the source code for PISM. Use of PISM for real ice sheet modeling is something we welcome questions about, and will attempt to help with, but we will not pretend it is routine. See the PISM Documentation web-page `www.pism-docs.org` for links to additional documentation.

A final reminder with respect to installation: Let's assume you have checked out a copy of PISM using Subversion, as in step 6 above. You can update your copy of PISM to the

latest version by `svn update` in the `pism/` directory. After doing so you will want to `make` and `make install` in order to rebuild the PISM executables using the updated source code files.

Have fun!

TABLE 1. Dependencies for PISM, listed alphabetically. These are needed to build a fully-functional PISM from source and to do all the examples in the manual.

Library /Program	**Site**	**Required?**	**Comment**
FFTW	`www.fftw.org`	*recommended*	if not present set `WITH_FFTW=0` for PISM build
GSL	`www.gnu.org/software/gsl`	*required*	
Matlab	`www.mathworks.com`	*recommended*	only used for alternate display of results
MPI	`www-unix.mcs.anl.gov/mpi`	*required*	
NetCDF	`www.unidata.ucar.edu/software/netcdf`	*required*	
`numpy`	`numpy.scipy.org`	*recommended*	used in Python scripts in sections 9 and 10
PETSc	`www-unix.mcs.anl.gov/petsc`	*required*	version $\geq$ 2.3.3-p2
Python	`python.org`	*required*	
`pycdf`	`pysclint.sourceforge.net/pycdf`	*recommended*	used in Python scripts in sections 9 and 10
Subversion	`subversion.tigris.org`	*required*	

TABLE 2. Additional dependencies for PISM *needed only for serious developers of PISM*, listed alphabetically.

Library /Program	**Site**	**Comment**
LaTeX	`www.latex-project.org`	only used for rebuilding manuals (both this User's Manual and the Reference Manual) from source
`doxygen`	`www.doxygen.org`	only used for rebuilding the Reference Manual and the Source Code Browser from the source code files
`ruby`	`www.ruby-lang.org`	only used when changing the NetCDF format for PISM output files

3. Getting started

3.1. **Running an EISMINT simplified geometry experiment.** PISM's purpose is the simulation of actual ice sheets. But actual ice sheet simulations require actual data.[4] For now, in order to avoid issues of data formats and data flaws in a first use of PISM, this section describes how to use PISM for experiment F in the "EISMINT II" simplified-geometry, thermomechanically-coupled ice sheet model intercomparison [51]. In this experiment one models an angularly-symmetric shallow, grounded ice sheet on a flat bed with relatively cold surface temperatures.

In EISMINT II the prescribed grid has 60 subintervals in each direction, with each subinterval of length 25km. Thus the total width of the computational box is 1500 km in both x and y directions. However, PISM always allows choice of the grid in all three dimensions. A runtime option chooses the number of grid points in each direction; note that the number of points is one greater than the number of subintervals (grid spaces). The vertical grid is not prescribed in EISMINT II. For a demonstration we choose this standard 25km grid in the horizontal and use 201 grid points in the vertical for a 25 m (equally-spaced) grid. (Note that the computational box is 5000 m high by default for EISMINT II experiment A in PISM.) Experiment A starts with zero ice, but the center thickness of the ice sheet grows to a peak near 5000 m before decaying to its equilibrium center thickness of about ??? m. All EISMINT II runs are for 200,000 model years. Here we start with a short 2000 year run for a quicker illustration. The executable is "`pisms`", for the "simplifed geometry mode" of PISM:

```
$ pisms -eisII A -Mx 61 -My 61 -Mz 201 -y 2000
PISMS (simplified geometry mode)
setting parameters for EISMINT II experiment A ...
initializing EISMINT II experiment A ...
  [computational box for ice: ( 1500.00 km) x ( 1500.00 km) x ( 5000.00 m)]
  [grid cell dims (equal dz): (   25.00 km) x (   25.00 km) x (   25.00 m)]
running EISMINT II experiment A ...
%ybp SIA SSA  # vgatdh Nr  +STEP
P         YEAR:     ivol   iarea    meltf     thick0     temp0
U        years 10^6_km^3 10^6_km^2 (none)          m         K
 $$$$             $$$$$ $$
S      0.00000:  0.00000  0.0000   0.0000      0.000  238.1500
 $$$ SIA        v$at$h 0m  +60.00000
S     60.00000:  0.01704  0.6281   0.0000     30.000  238.1500
. . .
 $$$ SIA        v$at$h 0e  +20.00000
S   2000.00000:  0.56790  0.6306   0.0000   1000.000  243.7518
done with run ...
Writing model state to file 'simp_exper.nc' ... done.
```

This should have taken less than one minute.

[4] Actual ice sheet and ice shelf data *are* freely available as part of the EISMINT intercomparison efforts. Section 9 is a tutorial on the use of PISM as a Greenland ice sheet evolution model and section 10 is a tutorial on PISM as an Ross ice shelf diagnosity model using the EISMINT data sets.

In a moment we will address the standard output information provided by PISM, as shown above, but for now we simply illustrate how to restart and complete the 200,000 year run. We see that the model state was stored in a NetCDF file with the `pisms` default name "`simp_exper.nc`". The next run will use a "`-o`" option to name the output file. Also, the above was a single processor run, but let's suppose we have a four processor machine. (The following should also work fine on a single processor machine but there is no speed-up, naturally.) Let's also run things in the background so we can continue to experiment:

```
$ mpiexec -n 4 pisms -eisII A -if simp_exper.nc -tempskip 5 -y 198000 \
  -o eisIIA200k >> eisIIA.out &
```

This run will take at least four processor-hours. It generates a NetCDF file `eisIIA200k.nc` at the end. The standard output in `eisIIA.out` can be tracked as the job is running in the background using `less`, for instance; `top` is a Linux tool to watch CPU and memory usage during the run.

To get the model state in the midst of a PISM run, send all running `pisms` processes (that's the executable in this case) a signal which causes PISM to write out the model state: `pkill -USR1 pisms`. The PISM model state is then saved in a NetCDF file with name `pism-`*year*`.nc`, using the year at that time step. On the other hand, terminatating the run with `pkill -TERM pisms` will will cause PISM to stop, but only after saving the model state using the `-o` specified name (though it will not hold the result of the completed run). See subsection 6.4 for a more complete description of how PISM catches signals.

While the four processor `pisms` run continues in the background, let's view the model state during a few time steps by restarting from the saved 2000 year state. We use PISM's "diagnostic viewers", which requires X Windows:

```
$ pisms -eisII A -if simp_exper.nc -y 1000 -d HTt
```

Three figures should appear and be refreshed at each time step. One figure is a map-plane view of thickness, another is a map-plane view of the basal temperature in Kelvin, and third there is a graph of height above the bed versus temperature. When the full 200,000 year run finishes, one may watch its evolving state, including the ice flow speed, by

```
pisms -eisII A -if eisIIA200k.nc -d HTc
```

for example. Figure 1 will appear.

3.2. **PISM's standard output.** As illustrated already, at each time step PISM shows a summary of the model state using a flags and a few numbers. The format of the summary is suggested by the three mysterious lines near the beginning of the run:

```
%ybp SIA SSA  # vatdh Nr  +STEP
P         YEAR:     ivol   iarea    meltf     thick0     temp0
U        years 10^6_km^3 10^6_km^2 (none)          m         K
```

The first line gives flags which indicate which physical models ran at the given time step, so it shows which quantities were updated. A dollar sign "`$`" appears if a given model did not run. From the left the first three positions are: `y` for basal yield stress model, `b` for bed deformation model, and `p` for plastic till yield stress. Then either "`SIA`" or "`SSA`" appear, or both, and the if the "`SSA`" flag is present it is followed by the number of iterations of the SSA model. (See

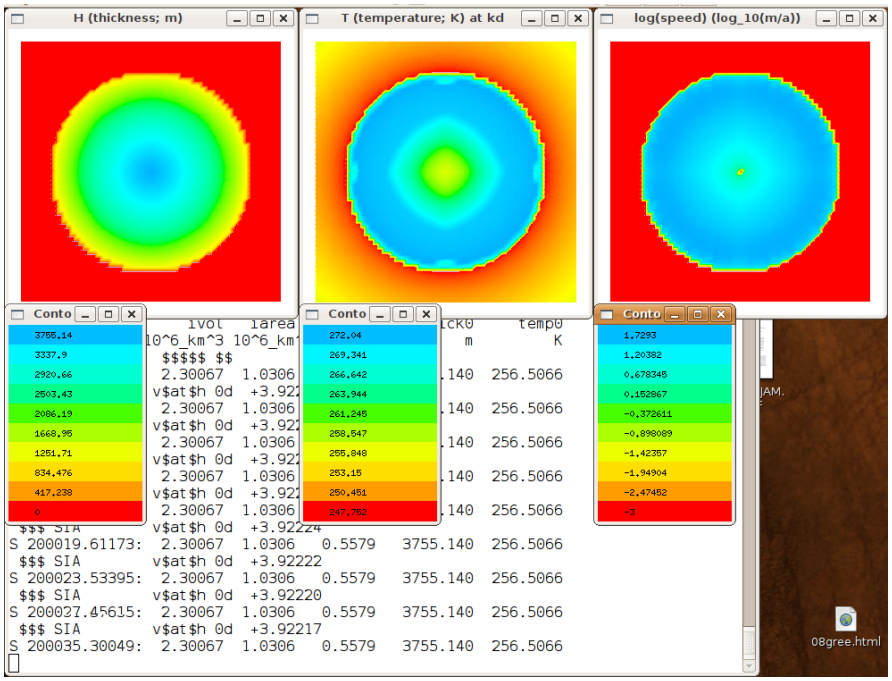

FIGURE 1. Screenshot of diagnostic figures for an EISMINT II experiment A run.

section 4 for an explanation of the SIA/SSA language.) Then there are six more positions: `v` for velocity updates (by SIA or SSA), `a` for age equation, `t` for temperature equation, `d` for positive degree day model, and `h` for mass continuity (which updates surface elevation and thickness).

Finally an integer `N` appears (it is most frequently zero), and another single character flag `r`. Then the time step itself is given (`STEP`). These all related to the decisions of the adaptive time-stepping scheme; described in subsection 6.3.

The next line starting with "`P`" is the prototype for the summary which appears at each time step. The third line starting with "`U`" is the units for this summary; it appears just once at the beginning of the run.

The time step `STEP` and the model year `YEAR`, which is the first entry in the summary line, are in units of years. The 200k year run above illustrates how the time-stepping in PISM adapts in order to maintain stability for its (mostly) explicit methods. At the beginning of the EISMINT II run, for instance, the ice has small thickness so the time step is 60 years, simply because that is the default maximum time step. Later in that run, after about 5000 years, the time step is made smaller because the flow is faster.

The next three entries in the summary report the volume of the ice in $10^6\,\mathrm{km}^3$, the area covered by the ice in $10^6\,\mathrm{km}^2$, and the basal melt fraction, that is, the fraction of the ice area where the basal temperature is at the pressure-melting temperature. The next two columns "`thick0`" and "`temp0`" are values at the center of the computational domain of the map plane, namely the ice thickness in meters and the absolute temperature of the ice at its base, in Kelvin. These five numbers are the ones reported in the tables in [51]. The summary of the model state can be

made more verbose by using the option `-verbose`. For more on the EISMINT II experiments see section 8.

3.3. **Visualizing the results.** There are four basic methods for visualizing the various quantities in PISM, namely

1) runtime viewers under Xwindows,
2) visualizing model state NetCDF files from the end of a run,
3) using MATLAB to view individual variables at the end of a run, and
4) turning the PISM standard output (above) into time series and viewing graphs of those.

As shown by the "`-d HTt`" option illustrated above, runtime viewers can be specified by options of the form `-d` *letters* or `-dbig` *letters*. The latter option shows larger windows but is otherwise identical. See Appendix C for the possible single letter names of each runtime viewer. These viewers are updated at each step. As they work under Xwindows, MPI must be told how to send data to the window, so PISM options are usually followed by "`-display :0`" when PISM is run under MPI and runtime viewers are desired.

The format is limited by the style of PETSc viewers, but these viewers often suffice for visualizing an ongoing PISM run. Note that some diagnostic viewers show slices of three-dimensional quantities in slices parallel to the bed. They are controlled by the option `-kd`. Those which show "soundings" are controlled by the options `-id`, `-jd`; see Appendices A and C.

Regarding method 2), when a PISM run is finished the state of the model is output in NetCDF format. The name can be specified by the option `-o`, so `-o foo` writes the NetCDF file `foo.nc`. NetCDF files can be viewed or modified with a variety of tools, some of which are mentioned in table 3. The PISM developers find `ncview` to be the fastest way to look at PISM output files, but `ncview` is not as sophisticated as many other scientific visualization programs which handle NetCDF files, such as IDV.

Regarding method 3), the user can add options of the form `-mato foo` and `-matv` *letters* to save certain variables in MATLAB-readable ASCII form at the end of the run. In particular, the saved file `foo.m` is a standard MATLAB script. The single letter arguments to `-d` and `-matv` are generally the same. See Appendix C.

Appendix D describes a Python script `series.py` which can post-process the standard output from a PISM run into a NetCDF file with the time series for the quantities listed in PISM standard output.

3.4. **Evolution runs versus "diagnostic" runs.** The main goal of a numerical ice sheet model like PISM is to be a dynamical system which evolves over time as similarly as possible to the modeled ice sheet. Such a goal assumes one starts with the right initial conditions and that one has the right climate and other inputs at each time step. Underlying an ice sheet model like PISM are evolution-in-time partial differential equations, and the obvious mode for a numerical ice sheet model is to take small time steps in approximating these differential equations; "small time steps" could mean several model years, of course. We will describe this usual time-stepping behavior as an "evolution run."

TABLE 3. Tools for viewing and modifying NetCDF files.

Tool	Site	Function
`ncdump`	*included with any NetCDF distribution*	dump as text file
`ncview`	`http://meteora.ucsd.edu/~pierce/ncview_home_page.html`	quick graphical view
`ncBrowse`	`www.epic.noaa.gov/java/ncBrowse/`	quick graphical view
`IDV`	`www.unidata.ucar.edu/software/idv/`	more complete visualization
`NCO` = NetCDF Operators	`nco.sourceforge.net/`	sophisticated manipulations at command line

See `www.unidata.ucar.edu/software/netcdf/docs/software.html` for additional tools.

Much of ice sheet, stream, and shelf modeling, however, requires only "diagnostic" solution of the partial differential equations which determine the velocity field. These are the balance of momentum equations for a slowly flowing fluid, and shallow approximations thereof [17]. In a diagnostic computation the temperature field and certain basal conditions, such as the yield stress of the till for instance, are held fixed. The goal of a "diagnostic run" is to compute the velocity field; this will be the definition used from now on in this manual.

Note that, as explained in the next section, the "shallow ice approximation" (SIA), on which the EISMINT II experiments are based, is only one of two forms of the balance of momentum equations solved by PISM. The other is the "shallow shelf approximation" (SSA). Both of these models can be solved in either evolution or diagnostic mode.

As a diagnostic example, using the quantities already computed in this section, try

```
pismd -if eisIIA200k.nc -o eisIIA200k_diag
```

The result of this command is a NetCDF file `eisIIA200k_diag.nc` which contains the full three-dimensional velocity field in the scalar NetCDF variables `uvel`, `vvel`, and `wvel`.

The velocity field saved by `pismd` is the one which would be computed at the *next* time step in an evolution run. That is, if we also run

```
pisms -eisII A -if eisIIA200k.nc -y 0.001 -o eisIIA200k_plus
```

then the horizontal velocity field computed in this single time step run is the same as that saved in `eisIIA200k_diag.nc`.[5]

This diagnostic mode is most frequently associated to the modeling of ice shelves and ice streams. Subsection 10 describes the use of `pismd` in modeling the Ross ice shelf [42].

Note that the NetCDF model state saved by PISM at the end of an *evolution* run does not, by default, contain the three-dimensional velocity field. Instead, it contains just the variables which are needed to restart the run, especially the ice geometry and temperature field. One can also force PISM to save the full velocity field at the end of a time-stepping run using the option `-f3d`. The diagnostic executable `pismd` saves the full three-dimensional velocity field by default. Either way, saving the full velocity field roughly doubles the size of the saved NetCDF file.

[5]For this example, one can use a NetCDF Operator to check that the two saved NetCDF files contain essentially the same vertically-averaged horizontal velocity field; just do `ncdiff -v cbar` ...

4. Ice dynamics in PISM

4.1. **Two different shallow models of ice flow.** PISM can numerically solve two significantly different sets of equations which determine the velocity field within the ice. In both cases the geometry of the ice, the temperature field within the ice, and the stress condition at the base of the ice are included into balance of momentum equations to determine the flow. But there are two different versions of the balance of momentum equations:

- the shallow ice approximation (SIA) [29], which describes ice flowing by shear in planes parallel to the geoid, with such shearing a local function of the driving stresses of classical glaciology [47], and
- the shallow shelf approximation (SSA) [65], which describes a membrane-type flow with the ice floating or sliding over a weak base [43, 41, 62].

PISM numerically solves both the SIA and SSA equations in parallel. Time-stepping solutions of the mass continuity equation are possible for both models.

The SIA equations are, as a rule, easier and quicker to numerically solve than the SSA. The SIA equations are also easier to parallelize. They can confidently be applied to those grounded parts of ice sheets for which the basal ice is frozen to the bedrock and the bed topography is relatively slowly-varying the map-plane [17]. We recommend only solving the SIA with a nonsliding base because the addition of a "sliding law" which switches on at the pressure-melting temperature tends to have deeply undesirable numerical consequences.

The SSA equations can confidently be applied to large floating ice shelves because such shelves have small depth-to-width ratio and because there is no shear stress at the base of the floating ice [43, 44].

Ice sheets have faster-flowing *grounded* parts, however. These are usually called "ice streams" or "outlet glaciers". Such features appear at the margin of, and even well into the interior of, the Greenland [37] and Antarctic [2] ice sheets. Describing these faster-flowing grounded parts of ice sheets requires something more than the non-sliding base SIA. Ultimately one might use the full Stokes equations which represent the balance of *all* tensor components [17], but there is still the issue of the appropriate sliding boundary condtion. Similarly one might use a "higher-order" but still shallow stress balance [5, 49], but again a proper choice of boundary condition is equally important.

Though they apply with greatest confidence to ice shelves, one may apply the SSA equations with additional basal resistance terms to grounded ice. This was justified in the context of the Siple Coast ice streams of Antarctica by MacAyeal [41, 27] using a linearly-viscous model for the underlying till. On the other hand, a free boundary problem with essentially the same (SSA) balance equations is the Schoof [62] model of ice streams. In Schoof's model ice streams emerge in those parts of the ice sheet where there is plastic till failure; see also [63].

These SSA equations with additional basal resistance are the models PISM uses to describe faster-flowing grounded ice. The SSA version of the balance of momentum equations with *linearly-viscous* till are solved as a fixed-boundary problem (at a particular time step), and thus the locations and extent of ice streams must be determined by some other criterion. For the SSA version of the balance of momentum equations with *plastic* till, as noted, the locations of

ice streams is determined as part of the free boundary problem. In fact we believe that the plastic till SSA of Schoof should be regarded as the best currently implementable "sliding law" for the SIA.

As noted, both the SIA and SSA models are *shallow* approximations. That is, the partial differential equations in these two approximations come by (different) small-parameter arguments, based on a small depth-to-width ratio, from the Stokes equations of a non-Newtonian fluid. For this small-parameter argument in the SIA case see [17]. For the corresponding SSA argument, see the appendices of [62].[6]

By default, PISM does not numerically solve the SSA when using the executables `pismr`, `pismd`, or `pisms`. The user must add the flag `-ssa`. The rules for verifying the SSA balance of momentum equations using the verification executable `pismv` are addressed in section 7.

4.2. **Tradition: Evolutionary SIA ice sheet versus diagnostic SSA ice shelf modeling.** Sections 9 and 10 illustrate the two traditional ice flow models, namely a time-stepping SIA-only model for the Greenland ice sheet and a diagnostic SSA model for the Ross ice shelf.

Note Tests A, B, C, D, E, F, G, H, and L in the verification suite are evolutionary runs using only the SIA. Tests I and J are diagnostic calculations using the SSA. See section 7.

All of the "EISMINT II" experiments documented in section 8 are evolutionary runs using only the SIA.

4.3. **The floating-grounded mask.** The most basic decision about ice dynamics made internally by PISM is to apply the "floatation criterion" to determine whether the ice is floating on the ocean or not.[7] In an evolution run this decision is made at each time step and the result is stored in the `mask`.

The possible values of the `mask` are given in Table 4. The mask does not by itself determine ice dynamics. For instance, when ice is floating (either value `MASK_FLOATING` or `MASK_FLOATING_OCEAN0`) the usual choice for ice dynamics is SSA, but the user can choose not to apply that model by leaving off the option `-ssa`.

TABLE 4. The PISM mask *along with user options* determines the dynamical model. This description gives only an incomplete view ...

Value	Name	Meaning
1	`MASK_SHEET`	ice is grounded (and the SIA is usually applied)
2	`MASK_DRAGGING`	ice is grounded (and the SSA is applied if option `-ssa` is given)
3	`MASK_FLOATING`	ice is floating (and the SSA is applied if option `-ssa` is given)
7	`MASK_FLOATING_OCEAN0`	same as `MASK_FLOATING`, but the grid point was ice free ocean at initialization of the model by `-bif`; ice with `MASK_FLOATING_OCEAN0` will calve off if option `-ocean_kill` is given.

[6]The references are, of course, the right place to examine the continuum equations and their physical motivation. This manual avoids serious discussion of continuum ice dynamics.

[7]See [65] for a definition and discussion of this criterion.

The remainder of this section gives an incomplete view, at best, of the dynamics in PISM. See sections 9 and 10 for examples which suggest the traditional modes of ice sheet and shelf modeling. Times they are a'changing, however, and PISM is too ...

4.4. **Schoof's plastic till free boundary problem for ice streams.** In [63] C. Schoof proposes a model for plastic failure of the basal till under flowing ice, and in [62] he recognizes this as a free boundary problem for the SSA. The result is a model for emergent ice streams within a larger ice sheet and ice shelf system. It explains the existence of ice streams by a combination of the plastic failure of the till and the SSA approximation of the balance of momentum.

PISM implements Schoof's model (among others, of course). The user gives the options `-ssa -plastic` to turn it on. All grounded points are immediately marked as SSA (i.e. as `MASK_DRAGGING`). At these points a yield stress is computed from the amount of stored basal water, a thermodynamic quantity, and from a (generally) spatially-varying till strength. See the description of option `-plastic` in Appendix A for a detailed description of the yield stress computation; see also the *PISM Reference Manual*.

A plastic till modification of EISMINT II experiment I. To demonstrate the Schoof model we describe an example based on EISMINT II experiment I.

The original EISMINT experiment I is only documented in [50], but not, however, in the published intercomparison [51]. (That reference says that for experiment I results were "straightforward ... with little variability between groups" but also that the results were "difficult to interpret".) Note that Section 8 describes using PISM to perform all the EISMINT II experiments documented in [50], including the original experiment I. Experiment I is identical to experiment A except for having "trough" bed topography.

As specified, the original experiment I has nothing to do with the SSA equations or plastic till failure, and indeed there is no basal motion at all. However, we use it to build an ice sheet which "ought" to have an ice stream, that is, along the trough. The script `test/eis2plastic.sh` gives a sequence which starts with the plain experiment I on a standard EISMINT II grid and builds an ice sheet modeled by SIA. It then turns on the plastic till SSA and superposes the velocity fields.

This plastic till modified experiment is for now only documented in [8]*, in preparation.*

Test I is an exact solution. Test I in the verification suite is an instance of the exact solution to the plastic till SSA published in [62]. It is a single diagnostic computation of the velocity of a highly-simplified ice stream. Here is an example run with some viewers:

```
pismv -test I -Mx 5 -My 121 -d ncqu
```

The boundary conditions are a uniform slab of ice on a bed with constant slope, but with a central minimum in a pre-specified distribution of till yield stress. There is zero yield stress at the very center. Thus the center of the slab slides. The ice flows under the SSA equations, because of the plastic failure, while at the margins the base of the ice does not slide. Thus we have an ice stream. The velocity only varies in the cross-slope direction. PISM's job is to compute the width and speed of the ice stream, "knowing" only the ice thickness, bed slope, and yield stress distribution. In this case we have the exact solution with which to compare the

numerically-computed velocities. This test, and convergence of PISM's numerical solution of it under grid refinement, are addressed in section 7.

5. Initialization and "bootstrapping"

5.1. **Initialization from a saved model state.** This phrase has a simple meaning in PISM. If a previous PISM run has saved a NetCDF file using "`-o`" then that file will contain complete initial conditions for continuing the run. The output file from the last run can be loaded with "`-if`", as in this example:

```
$ pisms -eisII A -y 100 -o foo
$ pisms -eisII A -if foo.nc -y 100 bar
```

Note that simplified-geometry experiments (section 8) and verification tests (section 7) do not need input files at all. They initialize from formulas in the source code, but they can be continued from saved model states using `-if`. As in the above example, however, specifying which simplified geometry experiment (or verification test) is in use *is* necessary. For instance, if the second line above is replaced by

```
$ pisms -if foo.nc -y 100 bar
```

then an error is generated.

5.2. **Bootstrapping.** "Bootstrapping" PISM means giving it less than complete data, and letting it fill in the needed data according to heuristics. These heuristics are applied before the first time step is taken, so they are part of an initialization process. Bootstrapping uses the option "`-bif`".

In some sense, bootstrapping is unprincipled inverse modelling. It is possible, for instance, to estimate the sliding state of the base of the ice through inverse models ([38] is an example[8]). It is also possible to use observed "isochrones" from ice-penetrating radar to estimate the velocity of ice [15].

Instead, however, most ice sheet modeling (using forward models like PISM) would do something like this to get "reasonable" temperature and velocity fields within the ice:

1) start only with observable quantities like surface elevation, ice thickness, and ice surface temperature,
2) "bootstrap" as described in this section, to fill in temperatures at depth and give a preliminary estimate of the basal sliding condition and the three-dimensional velocity field, and
3) *either* do a long run holding the current geometry and surface temperature steady, to evolve toward a "more physical" steady state which will have compatible temperature field, velocities, and age field,
4) *or* do a long run using an additional spatially-imprecise historical record from an ice core or a sea bed core (or both), to add apply forcing to the surface temperature or sea level (for instance), but with the same functional result of filling in a temperature, velocity, and age.

Subsection 9 does EISMINT-Greenland [55, 30] as an example of bootstrapping. That section shows examples of long runs of both types (3) and (4).

[8]The PISM authors are eager to work with principled (or at least, serious) inverse modelers. In particular, we would like to inverse-model-derived basal shear stresses to constrain a PISM forward model which would use both SIA and SSA models of ice flow.

When using `-bif` you will usually have to specify the height of the computational box for the ice with `-Lz` Z, and add option `-Lbz` Z_b if you want a bedrock thermal layer. This additional specification is natural: the data used in "bootstrapping" will usually be two-dimensional.

5.3. **Input file formats.** The NetCDF format of a PISM output model state file is described by the CDL file

`pism/src/netcdf/pism_state.cdl`

The file used with "`-if`" must have this format, but this is no difficulty for the user, as it will have been produced by a previous PISM run.

The allowed formats for a bootstrapping file are now relatively simple to describe. The NetCDF dimensions `t,x,y,z,zb` and corresponding variables must be present and match the choices in `pism_state.cdl`, or in a PISM output file. But any of the other two dimensional variables (depending on `t,x,y`) may be missing, and for those missing values some heuristic will be applied. All three dimensional variables (depending on `t,x,y,z` or `t,x,y,z`) will be ignored in bootstrapping.

The heuristics themselves are, for now, only documented in the source code:

`pism/src/base/iMbootstrap.cc`

Also see the *PISM Reference Manual*. Serious modeling is likely to start with the default bootstrapping method in `iMbootstrap.cc`, called by the option "`-bif`", but then add additional source code to add information. This additional source code is likely to be a derived class of `IceModel`. The code in

`pism/src/eismint/iceGRNModel.hh`

and

`pism/src/eismint/iceGRNModel.cc`

is an example of such a derived class; it does EISMINT-Greenland, as noted. Its function is fully documented in section 9.

6. More on usage

6.1. **The PISM coordinate system and grid.** PISM does all simulations in a computational box which is rectangular in the PISM coordinates.

The coordinate system has horizontal coordinates x, y and a vertical coordinate z. The z coordinate is measured positive upward from the base of the ice and it is exactly opposite to the vector of gravity. The surface $z = 0$ is the base of the ice, however, and thus is usually not horizontal in the sense of being parallel to the geoid. The surface $z = 0$ is the base of the ice both when the ice is grounded and when the ice is floating.

Bed topography is, of course, allowed. In fact, when the ice is grounded, the true physical vertical coordinate z', namely the coordinate measure relative to a reference geoid, is given by $z' = z + b(x, y)$ where $b(x, y)$ is the bed topography. The surface $z' = h(x, y)$ is the surface of the ice. Thus in the grounded case the equation $h(x, y) = H(x, y) + b(x, y)$ applies if $H(x, y)$ is the thickness of the ice.

In the floating case, the physical vertical coordinate is $z' = z - (\rho_i/\rho_s)H(x, y)$ where ρ_i is the density of ice and ρ_s the density of sea water. Again $z = 0$ is the base of the ice, which is the surface $z' = -(\rho_i/\rho_s)H(x, y)$. The surface of the ice is $h(x, y) = (1 - \rho_i/\rho_s)H(x, y)$. All we know about the bed elevations is that they are below the base of the ice when the ice is floating. That is, the *floatation criterion* $-(\rho_i/\rho_s)H(x, y) > b(x, y)$ applies.

The computational box can extend downward into the bedrock. As $z = 0$ is the base of the ice, the bedrock corresponds to negative z values regardless of the sign of its true (i.e. z') elevation.

The extent of the computational box, along with its bedrock extension downward, is determined by four numbers `Lx`, `Ly`, `Lz`, and `Lbz`. The first two of these are half-widths and have units of kilometers when set by options or displayed. The last two are vertical distances in the ice and in the bedrock, respectively, and have units of meters. See the sketch in figure 2.

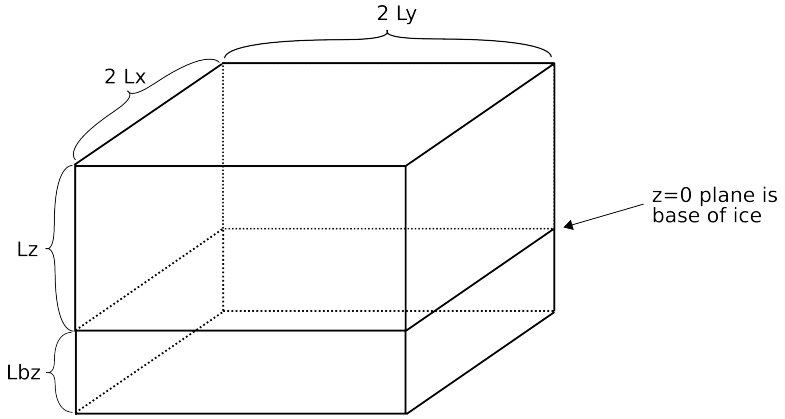

Figure 2. PISM's computational box.

The extent of the computational box for the ice is directly controlled by the options `-Lx`, `-Ly`, and `-Lz` as described in the Runtime options section. As noted `-Lx` and `-Ly` options should include values in kilometers while `-Lz` should be in meters.

The PISM grid covering the computational box is equally spaced in each of the three dimensions. Because of the bedrock extension, the grid of points is described by four numbers, namely the number of grid points in the x direction, the number in the y direction, the number in the z direction within the ice, and the number in the z direction within the bedrock. These are specified by options `-Mx`, `-My`, `-Mz`, and `-Mbz`, respectively, as described in the Runtime options section. The defaults for these four values are 61, 61, 31, and 1, respectively. Note that `Mx`, `My`, `Mz`, and `Mbz` all indicate the number of grid *points*. Therefore the number of grid *spaces* are, respectively, 60, 60, 30, and 0 (zero) in the default case. Note that the lowest grid point in a column of ice, that is the one at $z = 0$, coincides with the highest grid point in the bedrock. Also `Mbz` must always be at least one.

The distance `Lbz` is controlled by specifying the number `Mbz` of grid points in the bedrock, noting that the vertical spacing `dz` is the same within the ice and within the bedrock. To avoid conflicts, the distance `Lbz` cannot be set directly by the user. In particular, `Lbz` = `dz` (`Mbz` − 1) while `dz` = `Lz`/(`Mz` − 1), and so the distance `Lbz` into the bedrock is determined by setting `Lz`, `Mz`, and `Mbz`.

One is allowed to specify the grid when PISM is started *without* a pre-existing model state (i.e. as stored in a NetCDF input file output by PISM). For instance, a shortened EISMINT II experiment A [51] run, which will produce a convenient NetCDF file for our purposes here, is

```
$  pisms -eisII A -Mx 61 -My 61 -Mz 101 -y 5000 -o foo
```

If one initializes PISM from a saved model state then the input model state controls the parameters `Mx`, `My`, `Mz`, and `Mbz`. For instance, the command

```
$  pisms -eisII A -if foo.nc -Mz 201 -y 100
```

will give a warning that "`user option -Mz ignored; value read from file foo.nc`." To change the model grid one must explicitly "regrid", as described next.

6.2. **Regridding.** It is common to want to interpolate a coarse grid model state onto a finer grid or vice versa. For example, one might want to do the EISMINT II experiment as above, producing `foo.nc`, but then interpolate both the ice thickness and the temperature onto a finer grid. Speaking conceptually, the idea in PISM is that one starts over from the beginning of EISMINT II experiment A on the finer grid, but one extracts the thickness and ice temperature stored in the coarse grid file and interpolates onto the finer grid before proceeding with the actual computation. The transfer from grid to grid is reasonably general—one can go from coarse to fine or vice versa in each dimension x, y, z—but the transfer must always be done by *interpolation* and never *extrapolation*. (An attempt to do the latter will always produce a PISM error.)

Such "regridding" is done using the `-regrid` and `-regrid_vars` commands as in this example:

```
$  pisms -eisII A -Mx 101 -My 101 -Mz 201 -y 1000 \
     -regrid foo.nc -regrid_vars HT -o bar
```

By specifying regridded variables "`HT`", the ice thickness and temperature values from the old grid are interpolated onto the new grid. Note that one doesn't need to regrid the bed elevation, which is set identically zero as part of the EISMINT II experiment A description, nor the ice surface elevation, which is computed as the bed elevation plus the ice thickness at each time step anyway.

See table 5 for the regriddable variables.

A slightly different use of regridding occurs when "bootstrapping" as described in section 5 and illustrated by example in section 9.

TABLE 5. Regriddable variables. "`.nc` **Name**" gives the name of the variable in a PISM output NetCDF file. Use `-regrid_var` with given flag.

Flag	`.nc` **Name**	**Variable**	**Comment**
`a`	`acab`	(net annual) accumulation	*climate*; usually not regridded
`b`	`topg`	bed elevation	
`B`	`litho_temp`	temperature in bedrock	
`e`	`age`	age of the ice	
`g`	`bheatflx`	geothermal flux	*climate*; usually not regridded
`H`	`thk`	thickness	
`L`	`bwat`	thickness of basal melt water	
`s`	`artm`	ice surface temperature	*climate*; usually not regridded
`T`	`temp`	ice temperature	

6.3. **Understanding and controlling adaptive time-stepping.** Recall that at each time step the PISM standard output includes flags and a summary of the model state using a few numbers.:

```
%ybp SIA SSA  # vgatdh Nr  +STEP
P         YEAR:     ivol   iarea    meltf     thick0     temp0
```

Here we explain what '`Nr`' and '`STEP`'in the flag line mean.

`STEP` is the time step just taken by PISM, in model years. This time step is determined by a somewhat complicated adaptive mechanism. Note that PISM does each step explicitly when numerically approximating mass conservation in the map-plane. This, and the modeling of advection [9], requires and adaptive time-stepping scheme.

Note that most of the time '`N`' in the flag line will be zero. The exception is when the option `-tempskip` is used. If `-tempskip` M is used, then `N` will be at most M, and will countdown the mass conservation steps when the adaptive scheme determines that a long temperature/age evolution time step, relative to the diffusity controlled time step for mass conservation, would be allowed. To see an example, do:

```
$  pismv -test G -Mx 141 -My 141 -Mz 51 -tempskip 4
```

Table 6 explains the meaning of the one character adaptive-timestepping flag '`r`'.

6.4. **Using signals to control a running PISM model.** Ice sheet model runs sometimes take a long time and the state of the run needs checking. Sometimes they need to be stopped, but with the possibility of restarting. PISM implements these behaviors using "signals" from the POSIX standard. Such signals are included in Linux and most flavors of Unix. Table 7 below summarizes how PISM responds to signals.

TABLE 6. Meaning of the adaptive time-stepping flag '`r`' in standard output flag line.

Flag	Active adaptive constraint
`c`	3D CFL for temperature/age advection [9]
`d`	diffusivity for SIA mass conservation [9]
`e`	end of prescribed run time
`f`	`-dt_force` set; generally option `-dt_force`, which overrides the adaptive scheme, should not be used
`m`	maximum allowed Δt applies; set with `-max_dt`
`t`	maximum Δt was *t*emporarily set by a derived class; e.g. see effect of deliverables `-time`n in `pisms -ismip H \time`n
`u`	2D CFL for mass conservation in SSA regions (where mass conservation is *u*pwinded)

Here is an example. Suppose we start a long verification run in the background, with standard out redirected into a file:

```
pismv -test G -Mz 101 -y 1e6 -o testGmillion >> log.txt &
```

This run gets a Unix process id ("`pid`"); we will need that number. (One can get the `pid` by using the `ps` or `pgrep` utilities.)

If we want to observe the run without stopping it we send the `USR1` signal:

```
kill -USR1 8920
```

where "`8920`" happened to be the `pid` of the running PISM process. It happens that we caught the run at year 31871.5 or so because a NetCDF file `pism-31871.495239.nc` is produced. This intermediate state file can be viewed by `ncview pism-31871.495239.nc`. Note also that in the standard out log file `log.txt` the line

```
...
Caught signal SIGUSR1: Writing intermediate file 'pism-31871.495239.nc'.
...
```

appears around time step (i.e. `YEAR`) 31900.

Suppose, on the other hand, that the run needs to be stopped. One may use the interrupt "`kill -KILL 8920`" for this process, which is running in the background. (Foreground processes can be interrupted by Ctrl-C.) This brutal method, which a process cannot catch or block, stops the process but does not allow it time to save the model state. Therefore one will not be able to restart at the same place, nor inspect the model state more thoroughly. If one wants the possibility of restarting then one should used the `TERM` signal,

```
kill -TERM 8920
```

Then the PISM run is stopped and the lines

```
Caught signal SIGTERM: exiting early.
...
Writing model state to file 'testGmillion.nc' ... done
```

appear in the log file `log.txt`. In this case the NetCDF model state file `testGmillion.nc` appears; note this file has the original output name specified by the option `-o`. One can restart and finish the run by the command (for example)

```
pismv -test G -if testGmillion.nc -ye 1e6 -o testGmillion_finish >> log_cont.txt &
```

Finally we consider a multiple process (MPI) run of PISM. Here each of the processes must be sent the same signal at the same time. For example, consider the dialog

```
~/pism$ mpiexec -n 4 pismv -test C -y 100000 >> log.txt &
~/pism$ ps
PID TTY          TIME CMD
6761 pts/0    00:00:00 mpiexec
6762 pts/0    00:00:00 pismv
6763 pts/0    00:00:00 pismv
6764 pts/0    00:00:00 pismv
6765 pts/0    00:00:00 pismv
6770 pts/2    00:00:00 ps
~/pism$ kill -USR1 6762 6763 6764 6765
~/pism$ kill -TERM 6762 6763 6764 6765
```

Here the `kill` command sent the signal to all four of the running PISM processes simultaneously. The `kill -USR1` command caused the NetCDF file `pism-10852.037393.nc` to be written, while `kill -TERM` caused all four processes to end after (collectively, of course) writing `verify.nc`.

If, as in the above situation, one wants to send all `pismv` processes the `-TERM` signal then

```
pkill -TERM pismv
```

will have the same effect as `kill -TERM` followed by a list of all the `pid`s of `pismv` processes.

6.5. **Using the positive degree-day model.** By default the accumulation/ablation map in PISM is treated as net surface mass balance. (We are referring to the variable `acab` in saved model states, and to the view `-d a`.) The mass conservation equation for the ice sheet requires this surface balance, which is in units of meters ice-equivalent per time.

Also, the surface temperature variable in PISM is assumed to be the mean annual surface temperature, and without an additional model or input there is no yearly temperature cycle.

If the input data actually includes the annual snow-fall accumulation then one must *compute* the surface mass balance according to some model of how much of the snow is melted in each model year and according to a yearly temperature cycle. We call such a model a *positive degree day* model [12].

The model used by PISM in computing the amount of melting first assumes a sinusoidal temperature cycle over the course of the year, where the difference between the peak of this temperature cycle and its mean (average) is called the "summer warming." The default temperature cycle has a constant amount of summer warming. This constant is specified by `-pdd_summer_warming`. Note that the mean temperature is grid-point dependent, as specified by the input surface temperature map (data), so the cycle is different at each map-plane grid location, though the amplitude is the same at each grid point (in this default case). The peak of

TABLE 7. Signalling PISM. *pid* stands for list of all identifiers of the running PISM processes.

Command	**Signal**	**PISM behavior**
`kill -KILL` *pid*	`SIGKILL`	terminate with extreme prejudice; PISM cannot catch it and no state is saved
`kill -9` *pid*	(*same*)	(*same*)
Ctrl-C	(*same*)	same, but only for foreground process(es)
`kill -TERM` *pid*	`SIGTERM`	end process(es) but save the last model state using the user-given `-o` name or the default name
`kill -15` *pid*	(*same*)	(*same*)
`kill` *pid*	(*same*)	(*same*)
`pkill -TERM pismv`	(*same*)	(*same*); most convenient for MPI runs to terminate and save)
`kill -USR1` *pid*	`SIGUSR1`	allow process(es) to continue but save model state at current time using name `pism-`*year*`.nc`
`pkill -USR1 pismv`	(*same*)	(*same*); most convenient for MPI runs

the cycle occurs on August 1, which is Julian day 243, but the option `-pdd_summer_peak_day` can override this.

It is common to add "white noise" to the temperature cycle to simulate both the daily temperature cycle and additional variability associated to the vagaries of weather. More precisely, a normally-distributed, mean zero random temperature increment is added (or subtracted) from the temperature for each day. These increments are independent over the days of the year, though of course we only have pseudo-randomness ..., but they are the same over the whole sheet. Their standard deviation is controlled by `-pdd_std_dev`.

The number of positive degree days, denoted PDD, is computed as the sum of the product of the amount by which this temperature cycle, including the white noise variability, exceeds 0°C times the time (in days) during which it is above zero. In PISM there are two methods for computing PDD. The first is the expected value computed by the method described in [12]; this option is chosen by `-pdd`. The second is a monte carlo simulation of the white noise itself, chosen by `-pdd_rand`. (If one wants runs with repeatable randomness, use `-pdd_repeatable` instead of `-pdd_rand`.)

The PDD is multiplied by a coefficient (set by `-pdd_factor_snow`) to compute the amount of snow melted. Of this melted snow, a fraction (`-pdd_refreeze`) is kept as ice. This ice, plus all unmelted snow (measured as ice-equivalent) is added to the mass balance unless the PDD exceeds that required to melt all of the snow-fall in the year. In this latter case, in which there are excess PDD available for melting, the excess PDD is multiplied by a coefficient (`-pdd_factor_ice`) to compute how much ice is melted. In this latter case, ablation occurs at that location.

The PDD model is applied in section 9 to modeling the Greenland ice sheet.

To directly compare the two methods, try

```
$ pgrn -bif eis_green_smoothed.nc -Mx 83 -My 141 -Mz 201 \
    -ocean_kill -y 50 -o green_50yr_pdd -d Aa
```

versus

```
$ pgrn -bif eis_green_smoothed.nc -Mx 83 -My 141 -Mz 201 \
    -ocean_kill -y 50 -o green_50yr_pdd_rand -pdd_rand -d Aa
```

(See section 9 on how to create the file `eis_green_smoothed.nc` from publically available data. See the same section for the meaning of "`-bif`".)

7. Verification

> Two types of errors may be distinguished: modeling errors and numerical errors. modeling errors arise from not solving the right equations. Numerical errors result from not solving the equations right. The assessment of modeling errors is *validation*, whereas the assessment of numerical errors is called *verification* ... Validation makes sense only after verification, otherwise agreement between measured and computed results may well be fortuitous.
>
> P. Wesseling, (2001) *Principles of Computational Fluid Dynamics*, pp. 560–561 [66]

Ideas. "Verification" is a crucial task for a code as complicated as PISM. It is the exclusively mathematical and numerical task of checking that the predictions of the numerical code are close to the predictions of the continuum model (the one which the numerical code claims to approximate). One is not comparing model output to nature. Instead, one compares exact solutions of the continuum model, in circumstance in which they are available, to the numerical approximations of those solutions.

See [11] and [9] for discussion of verification issues for the isothermal and thermomechanically coupled shallow ice approximation (SIA), respectively, and for exact solutions to these models. See [62] for an exact solution to the SSA equations for ice streams using a plastic till assumption. Reference [58] gives a broad discussion of verification and validation in computational fluid dynamics.

In PISM there is a separate executable `pismv` which is used for verification. The numerical codes which are verified by `pismv` are, however, exactly the same lines of source code in exactly the same source files as is run by the non-verification executables `pismr`, `pisms`, `pgrn`, etc. In technical terms, `pismv` runs a derived class of the base class `IceModel`, and *all* PISM executables run `IceModel`.

Table 8 summarizes the many exact solutions currently available in PISM. Note that most of these exact solutions are solutions of *free boundary problems* for partial differential equations. (Tests A, E, J, and K are fixed boundary value problems.) Table 9 shows how to run each of them on modestly-refined grids (for relatively quick execution time).

Refinement. To meaningfully verify a numerical code one must go down a grid refinement path and measure numerical error for each grid [58]. By "a refinement path" we mean the specification of a sequence of grid cell sizes which decrease toward the refinement limit. For example, in the the two spatial and one time dimension case this means a sequence of triples $(\Delta x, \Delta y, \Delta t)$ which decrease toward the (unreachable) refinement limit $(\Delta x, \Delta y, \Delta t) = (0, 0, 0)$. By "measuring the error for each grid" we will mean computing a norm (or several norms) of the difference between the numerical solution and the exact solution. Concretely, we will typically compute both the *maximum* numerical error anywhere on the grid and the *average* numerical error on the grid.

The goal is not to see that the error is zero at any stage on the refinement path, or even that the error is small in a predetermined absolute sense, generally. Rather the goal is to see that the error is trending toward zero, and to measure the rate at which decays. Knowing the error

TABLE 8. Exact solutions for verification.

Test	Continuum model tested	Comments	Reference
A	isothermal SIA, steady, flat bed, constant accumulation		[11]
B	isothermal SIA, flat bed, zero accum	similarity soln	[11]
C	isothermal SIA, flat bed, growing accum	similarity soln	[11]
D	isothermal SIA, flat bed, oscillating accum	compensatory accum	[11]
E	isothermal SIA; as A but with sliding in a sector	compensatory accum	[11]
F	thermomechanically coupled SIA (mass and energy cons.), steady, flat bed	compensatory accum and comp heating	[7, 9]
G	thermomechanically coupled SIA; as F but with oscillating accumulation	ditto	[7, 9]
H	bed deformation coupled with isothermal SIA	joined similarity	[10]
I	stream velocity computation using SSA (plastic till)		[62]
J	shelf velocity computation using SSA		[IN PREPARATION]
K	pure conduction in ice and bedrock		[6]
L	isothermal SIA, steady, non-flat bed	numerical ODE soln	[IN PREPARATION]

TABLE 9. Running PISM to verify using the exact solutions listed in table 8.

Test	Example invocation
A	`pismv -test A -Mx 61 -My 61 -Mz 11 -y 25000`
B	`pismv -test B -Mx 61 -My 61 -Mz 11 -ys 422.45 -y 25000`
C	`pismv -test C -Mx 61 -My 61 -Mz 11 -y 15208.0`
D	`pismv -test D -Mx 61 -My 61 -Mz 11 -y 25000`
E	`pismv -test E -Mx 61 -My 61 -Mz 11 -y 25000`
F	`pismv -test F -Mx 61 -My 61 -Mz 61 -y 25000`
G	`pismv -test G -Mx 61 -My 61 -Mz 61 -y 25000`
H	`pismv -test H -Mx 61 -My 61 -Mz 11 -y 40034 -bed_def_iso`
I	`pismv -test I -Mx 5 -My 500 -ssa_rtol 1e-6 -ksp_rtol 1e-11`
J	`pismv -test J -Mx 60 -My 60 -Mz 11 -ksp_rtol 1e-12`
K	`pismv -test K -Mx 6 -My 6 -Mz 401 -Mbz 101 -y 130000`
L	`pismv -test L -Mx 61 -My 61 -Mz 31 -y 25000`

decay rate allows the modeler to have a sense of how fine a grid is necessary to achieve a small enough numerical error so that the numerical solution can be regarded as a (near) solution to the continuum model. See [11, 9, 58, 66].

For an example of a refinement path, consider the runs

```
pismv -test B -ys 422.45 -y 25000 -Mx 31 -My 31 -Mz 11
pismv -test B -ys 422.45 -y 25000 -Mx 61 -My 61 -Mz 11
pismv -test B -ys 422.45 -y 25000 -Mx 121 -My 121 -Mz 11
pismv -test B -ys 422.45 -y 25000 -Mx 241 -My 241 -Mz 11
```

These verify the basic function of the isothermal shallow ice approximation components of PISM in the case of no accumulation. The exact solution used here is the Halfar similarity solution [23]. Note that one specifies the number of grid points when running PISM, but this is equivalent to specifying the grid cell sizes if the overall dimensions of the computational box is fixed; see subsection 6.1. The refinement path is the sequence of triples $(\Delta x, \Delta y, \Delta t)$ with $\Delta x = \Delta y = 80, 40, 20, 10$ and where Δt is determined adaptively by a stability criterion (see subsection 6.3). Note that the vertical grid spacing Δz is fixed because this test is isothermal and no dependence of the error is expected from changing Δz.

The data produced by the above four runs appears in figures 7, 8, 9, and 10 of [11]. We see there that the isothermal mass conservation scheme does a reasonable job of approximating the evolving surface. Future improvements in the numerical scheme may make the error decrease faster or be smaller.

For thermocoupled tests one refines in three dimensions. For example, the runs

```
pismv -test G -max_dt 10.0 -y 25000 -Mx 61 -My 61 -Mz 61
pismv -test G -max_dt 10.0 -y 25000 -Mx 91 -My 91 -Mz 91
pismv -test G -max_dt 10.0 -y 25000 -Mx 121 -My 121 -Mz 121
pismv -test G -max_dt 10.0 -y 25000 -Mx 181 -My 181 -Mz 181
pismv -test G -max_dt 10.0 -y 25000 -Mx 241 -My 241 -Mz 241
pismv -test G -max_dt 10.0 -y 25000 -Mx 361 -My 361 -Mz 361
```

produced figures 13, 14, and 15 of [9]. (The last couple of these runs required a supercomputer! The $361 \times 361 \times 361$ run involves more than 100 million unknowns, updated at each of millions of time steps.)

Results. Figures 3 through 8 show a sampling of the results of verifying PISM using the tests described above. These figures were produced more-or-less automatically using Python scripts `pism/test/verifynow.py` and `pism/test/vnreport.py`. See appendix D.

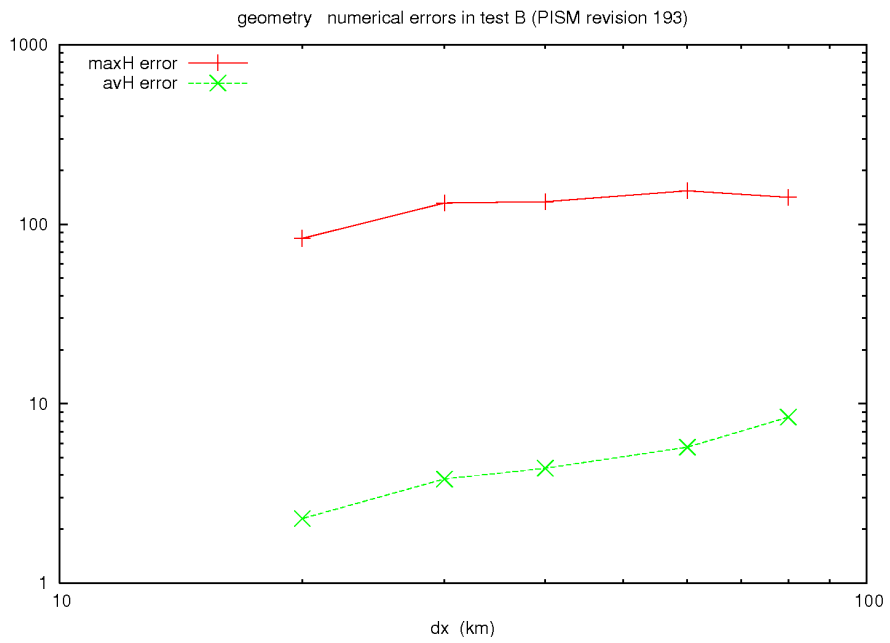

FIGURE 3. Numerical thickness errors in test B. Vertical axis is in meters. "maxH error" is the maximum thickness error anywhere on the grid, "avH error" is the average thickness error anywhere on the grid, and "centerH error" is the error at the center of the ice sheet. See [11] for discussion.

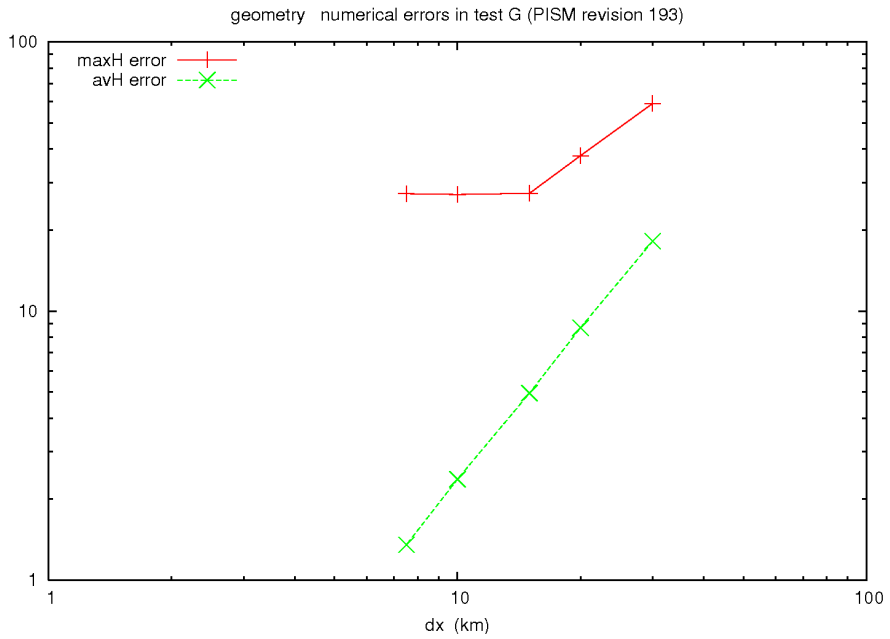

FIGURE 4. Numerical thickness errors in test G. Meaning exactly as in test C. See [9] and [11] for discussion.

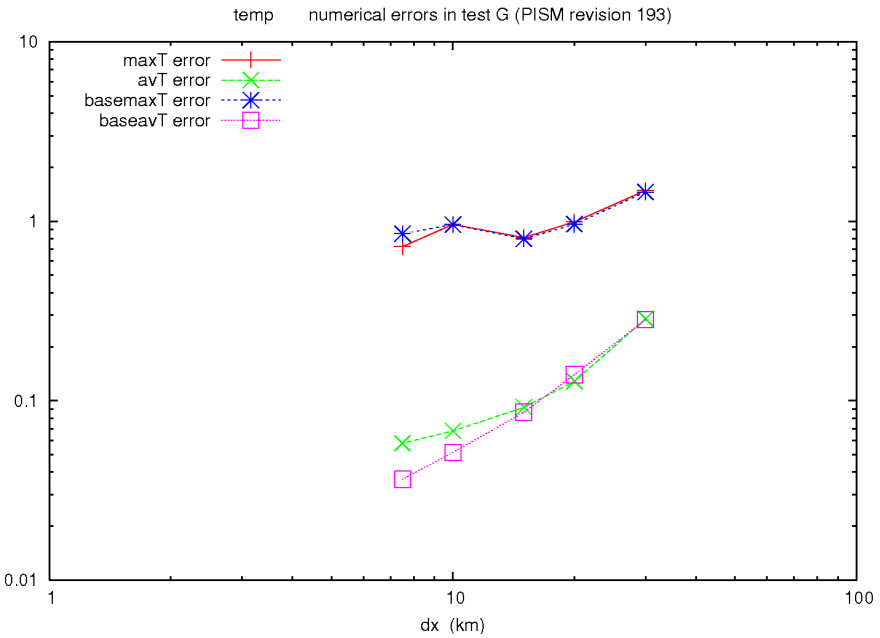

FIGURE 5. Numerical temperature errors in test G. Vertical axis is in Kelvin. "maxT" and "basemaxT" errors are maximum over all points within the ice and over all the basal points, respectively. Similarly for "avT" and "baseavT"; these are average errors. See [9] for discussion.

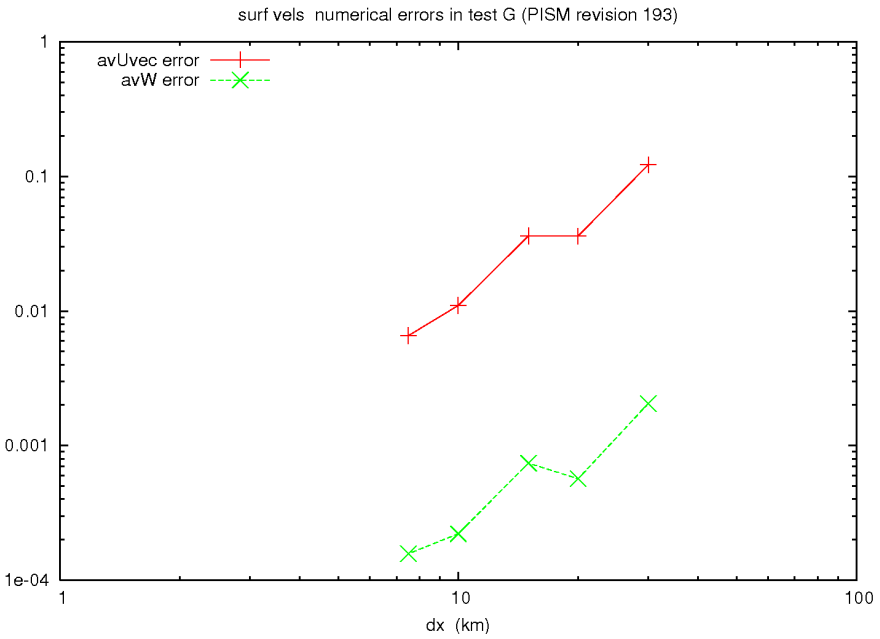

FIGURE 6. Numerical errors in computed surface velocities in test G. Vertical axis is in meters per year.

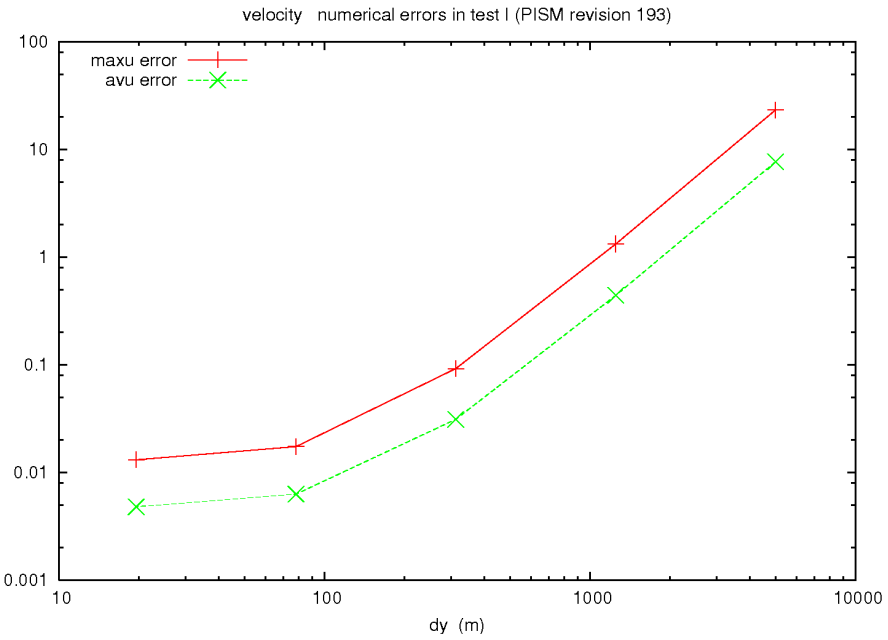

FIGURE 7. Numerical errors in horizontal velocities in test I, an ice stream. Vertical axis is in meters per year. See [62] for a description of the exact solution.

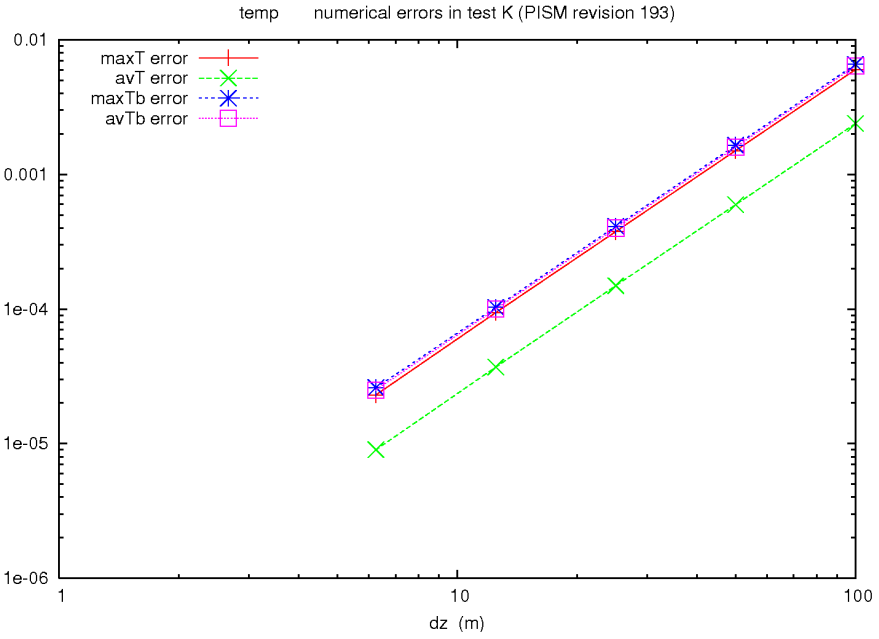

FIGURE 8. Numerical temperature errors in test K, which tests the thermal bedrock model. Vertical axis is in Kelvin. "maxT" and "avT" are errors computed over all points within the ice while "maxTb" and "avTb" are computed over all grid points within the bedrock. See [6] for a discussion.

8. Simplified geometry experiments

8.1. **Historical note.** There have been three stages of ice sheet model intercomparisons based on simplified geometry experiments since the early 1990s.

EISMINT[9] I [32] was the first of these and involved only the isothermal shallow ice approximation (SIA). Both fixed margin and moving margin experiments were performed in EISMINT I, and various conclusions were drawn about the several numerical schemes used in the intercomparison. EISMINT I is, however, superceded by *verification* using the full variety of exact solutions to the isothermal SIA. The reasons why EISMINT I can be fully replaced by verification are described in [11]. The "rediscovery", since EISMINT I, of the very useful Halfar similarity solution with zero accumulation [23] is a particular reason why the "moving margin" experiment in EISMINT I is, roughly speaking, irrelevant. For this reason there has been no attempt to support the EISMINT I experiments in PISM.

EISMINT II [51] was both a more significant and more controversial intercomparison. It pointed out interesting and surprising properties of the thermocoupled SIA. Here is not the place for a discussion of the interpretations which have followed the EISMINT II results, but references [9, 24, 25, 52, 60] each interpret the EISMINT II experiments and/or describe attempts to add more complete physical models to "fix" the perceived shortfalls of ice sheet models (as evidenced by their behavior on EISMINT II experiments). PISM has built-in support for all of the published and unpublished EISMINT II experiments; these are described in the next subsection.

The ISMIP[10] round of intercomparisons are ongoing at the time of this writing (January 2008). There are two components of ISMIP partially completed, namely HOM = Higher Order Models and HEINO = Heinrich Event INtercOmparison [22]. Of these ISMIP experiments, PISM has supported HEINO, but this ability is unmaintained (for reasons described in the next paragraph). There is no current plan to support HOM. The PISM developers plan to participate in the upcoming Marine Ice Sheet Model Intercomparison Project (MISMIP) and ISMIP-POLICE exercises.

The results from PISM for HEINO are not regarded by the PISM authors as meaningful. We believe the continuum problem described by HEINO to not be easily approximate-able because of a (large) discontinuous jump in the basal velocity field. The same problem applies to EISMINT II experiment H. This is a problem regardless of the details of the numerical schemes or even (roughly speaking) of the shallowness of the continuum model.

8.2. **EISMINT II in PISM.** There are seven experiments described in the published EISMINT II writeup [51]. They are labeled A, B, C, D, F, G, and H. As specified in the writeup, the common features of all of these experiments are:

- runs are of 200,000 years, with no prescribed time step;
- runs are on a prescribed 61×61 horizontal grid;

[9] "EISMINT" stands for European Ice Sheet Modeling INiTiative.
See `http://homepages.vub.ac.be/%7Ephuybrec/eismint.html`.

[10] "ISMIP" stands for Ice Sheet Model Intercomparison Project.
See `http://homepages.vub.ac.be/%7Ephuybrec/ismip.html`.

- the boundary conditions always have angular symmetry around the center of the grid;
- the bed is flat and does not move (there are no isostasy effects);
- the temperature in the bedrock is not modeled;
- only shallow ice approximation physics is included;
- the change in the temperature of ice is described by the shallow approximation of the conservation of energy [17];
- thermomechanical coupling is included, both because of the temperature dependence of the softness of the ice, *and* through the strain-heating (dissipation-heating) term in the conservation of energy equation;
- the ice is *cold* and not *polythermal* [19]; and finally
- though basal melt rates may be computed diagnostically, they do not contribute to the dynamics of the ice sheet.

The experiments differ from each other in their various combinations of surface temperature and accumulation parameterizations. Also, experiments H and G involve basal sliding, while the others don't. Four experiments start with zero ice (A,F,G,H), while the other experiments (B,C,D) start from the final state of experiment A.

In addition to the seven experiments published in [51], there were an additional five experiments described in the EISMINT II intercomparison description [50], labeled E, I, J, K, and L. These experiments share most features, itemized above, but with the following differences. Experiment E is the same as experiment A except that the peak of the accumulation, and also the low point of the surface temperature, are shifted by 100 km in both x and y directions; also experiment E starts with the final state of experiment A. Experiments I and J are similar to experiment A but with non-flat topography. Experiments K and L are similar to experiment C but with non-flat topography. See table 10 for how to run these experiments.

The vertical grid is not specified in the EISMINT II writeup. It seems that good simulation of the complex thermomechanically coupled conditions near the base of the ice requires relatively fine resolution there. Because PISM (currently) has an equally-spaced grid, we recommend the use of about 200 vertical levels. Thus a reasonable experiment A run on one processor is

```
pisms -eisII A -Mx 61 -My 61 -Mz 201 -y 200000 -o eisIIA
```

The SIA-only simulations parallelize well, and we see speedups up to 30 or more processors (for the standard 61×61 horizontal grid).

Table 10 shows how each of the EISMINT II experiments can be done in PISM.

The EISMINT II experiments can be run with various modifications of the default settings. Of course the grid can be refined. For instance, a twice as fine grid in the horizontal is "`-Mx 121 -My 121`". Table 11 lists some optional settings which are particular to the EISMINT II experiments. With the exception of "`-Lz`", these options will only work if option "`-eisII ?`" is also set.

Note that in PISM the height `Lz` of the computational box is fixed at the beginning of the run. On the other hand, changing the boundary conditions of the flow, as for instance by setting option `-Mmax` to a larger than default value (see table 11), may cause the ice sheet to thicken above the `Lz` height. If the ice grows above the height of the computational box then

TABLE 10. Running the EISMINT II experiments in PISM; the command is "`pisms`" plus the given options. Experiments below the horizontal line are only documented in [50].

Command: "`pisms`" +	**Relation to experiment A**
`-eisII A -Mx 61 -My 61 -Mz 201 -y 2e5 -o eisIIA`	
`-eisII B -if eisIIA.nc -y 2e5 -o eisIIB`	warmer
`-eisII C -if eisIIA.nc -y 2e5 -o eisIIC`	less snow (lower accumulation)
`-eisII D -if eisIIA.nc -y 2e5 -o eisIID`	only smaller area of accumulation
`-eisII F -Mx 61 -My 61 -Mz 201 -y 200000 -o eisIIF`	colder; famous spokes [9]
`-eisII G -Mx 61 -My 61 -Mz 201 -y 200000 -o eisIIG`	sliding (regardless of temperature)
`-eisII H -Mx 61 -My 61 -Mz 201 -y 200000 -o eisIIH`	melt-temperature activated sliding
`-eisII E -if eisIIA.nc -y 2e5 -o eisIIE`	shifted accumulation/temperature maps
`-eisII I -Mx 61 -My 61 -Mz 201 -y 2e5 -o eisIII`	trough topography
`-eisII J -if eisIII -y 2e5 -o eisIIJ`	trough topography and less snow
`-eisII K -Mx 61 -My 61 -Mz 201 -y 2e5 -o eisIIK`	mound topography
`-eisII L -if eisIIK -y 2e5 -o eisIIL`	mound topography and less snow

TABLE 11. Changing the default settings for the EISMINT II experiments in PISM.

Option	**Default values [expers]**	**Units**	**Meaning**
`-Mmax`	0.5 [ABDEFGHIK], 0.25 [CJL]	m/a	max value of accumulation rate
`-Rel`	450 [ABEFGHIK], 425 [CDJL]	km	radial distance to equilibrium line
`-Sb`	10^{-2} [*all*]	(m/a)/km	radial gradient of accumulation rate
`-ST`	1.67×10^{-2} [*all*]	K/km	radial gradient of surface temperature
`-Tmin`	238.15 [ACDEGHIJKL], 243.15[B], 223.15[F]	K	max of surface temperature
`-track_Hmelt`			compute effective thickness of basal melt water (override default for EISMINT II)
`-Lz`	4500 [AE], 4000 [BCD], 5000 [F], 3000 [G]	m	height of the computational box

a "`Vertical grid exceeded!`" or "`thickness overflow in SIA velocity: ks>Mz!`" error occurs. This can be fixed by restarting with a larger value for option `-Lz`.[11]

[11]Automatic rescaling of, or expansion of, the vertical grid is appropriate, but not yet implemented.

9. Example: Modeling the Greenland ice sheet

In this section we give an extended example of how to use PISM to model the Greenland ice sheet. We use somewhat stale data from the 1990s ice sheet modelling intercomparison known as EISMINT-Greenland [30, 55]. Though based on old data, EISMINT-Greenland serves as an excellent tutorial example.

The data for performing this experiment are freely available at

`http://homepages.vub.ac.be/~phuybrec/eismint/greenland.html`

The snow-fall accumulation map, ablation parameterization, surface temperature formula, surface elevation, and bedrock elevation maps are essentially as in the 1991 papers [39, 46]. Note that in the ice and sea floor-core driven "forced climate" run `-ccl3` described below, the ice sheet is forced by changes in temperature from the GRIP core [14] and by changes in sea level from SPECMAP [33]. A parameter-sensitivity study of a EISMINT-Greenland type ice sheet model is described in [56].

Substantial developments have occurred in modeling the Greenland ice sheet since the EISMINT-Greenland intercomparison. For example, the relation between a Greenland ice sheet flow model, Earth deformation under ice sheet loads, and the reconstruction of global ice loading is analyzed in [64]. The response of Greenland ice sheet models to climate warming is addressed in [31] and [20].

Obtaining and converting EISMINT-Greenland data. This subsection describes the use of two Python scripts to convert the EISMINT-Greenland data, which is in the form of several ASCII text files, into NetCDF files usable by PISM.

Python scripts `eis_green.py` and `eis_core.py` can be found in the `pism/test` directory. In order to use the scripts, you must have downloaded these text (ASCII) files from the EISMINT-Greenland web site above:

- `grid20-EISMINT`
- `suaq20-EISMINT`
- `specmap.017`
- `sum89-92-ss09-50yr.stp`

The Python libraries `numpy` and `pycdf` must be present for the scripts to work.

Run

```
$ eis_green.py
```

The NetCDF file `eis_green20.nc` will be created from the data in `grid20-EISMINT` and `suaq20-EISMINT`. It contains variables for the gridded latitude (`lat`), longitude (`lon`), surface altitude ("`usurf`" for *u*pper *surf*ace elevation), bedrock altitude (`topg`), and ice thickness (`thk`). These values can be viewed graphically with `ncview` or as (*quite large*) text files with `ncdump`.

Note that the script `eis_green.py` accepts option `--prefix=foo/` to specify that the downloaded data is in directory `foo/`; `eis_core.py` below also takes this option. The script `eis_green.py` also has option `-g` to specify the grid spacing. Use `-g 40` if you downloaded `grid40-EISMINT` and `suaq40-EISMINT` 40 km data; "`-g 20`" or no option specifies 20 km grid.

As an exercise, the NCO can be used on `eis_green20.nc` to compare the putative ice surface elevation to the sum of the ice thickness and the bed elevation:

```
$ ncap -O -vs "check=usurf-(thk+topg)" eis_green20.nc eis_green_check.nc
```

The variable `check` in the output file holds the difference of `usurf` and the sum `topg` + `thk`. Viewing `check` in `ncview` will show that `usurf` is within 1 meter of `topg`+`thk`. Thus the surface elevation `usurf` is consistent. It is also redundant because at bootstrapping, described below, PISM reads ice thickness and bed elevation and computes ice surface elevation as the sum of these two.

The bed elevation in the original data effectively contains a missing value attribute of 0.0, because in several places—deep fjords, mostly—the observed bed elevation was not measured or the measured value was not trusted. When viewing `eis_green20.nc` with `ncview`, these values show as white spots. If these missing values are left as is then the bed elevation map is extraordinarily rough and this makes reasonable ice flow predictions more difficult. We therefore suggest smoothing the bed elevations. This can be done with another script named `fill_missing.py`, found in directory `pism/test/`. To use this script, the following command can be run:[12]

```
$ fill_missing.py -i eis_green20.nc -v topg -o eis_green_smoothed.nc
```

Here, `eis_green20.nc` is the input file, `topg` is the variable with missing values, and `eis_green_smoothed.nc` is the output file. The script will look for an attribute named `missing_value` and fill in the missing values according to the averages of its neighbors.[13]

In addition to getting the EISMINT gridded data into NetCDF format and filling missing values, there is an issue with Ellesmere Island. Ellesmere Island is very close to Greenland, and so it would be possible for the modeled ice sheet to flow onto to it. (Indeed this presumably occurred at the last glacial maximum.) Since we don't, however, have correct topography or accumulation rates for Ellesmere Island among the downloaded data, we want to prevent this from happening. Therefore special code is executed by the relevant PISM executable `pgrn` (see below). It says that all points northwest of the line connecting the points $(68.18°E, 80.1°N)$ and $(62°E, 82.24°N)$ are removed from the flow simulation. The same applies to anything east of $30°E$ and south of $67°N$ so that the flow could not spread to the tip of Iceland (not likely anyway ...). The phrase "removed from the flow simulation" actually means that the points are marked as ice-free ocean; note the use of option `-ocean_kill` below.

We mentioned the script `eis_core.py`. Now we execute it:

```
$ eis_core.py
```

This script converts the data files `specmap.017` and `sum89-92-ss09-50yr.stp` to PISM readable NetCDF form. Two NetCDF files with one-dimensional (time series) data will be created, namely `grip_dT.nc` and `specmap_dSL.nc`. The executable `pgrn` will be called with an option `-forcing` for the "CCL3" run below, which will make PISM read these two NetCDF files for the climate forcing. Using `ncview` on `grip_dT.nc` gives the graph of temperature shown in Figure 10.

[12] If this script doesn't work, recall this: the Python libraries `numpy` and `pycdf` must be present.

[13] `fill_missing.py` is a general tool for smoothly removing missing values from variables in NetCDF files; see Appendix D.

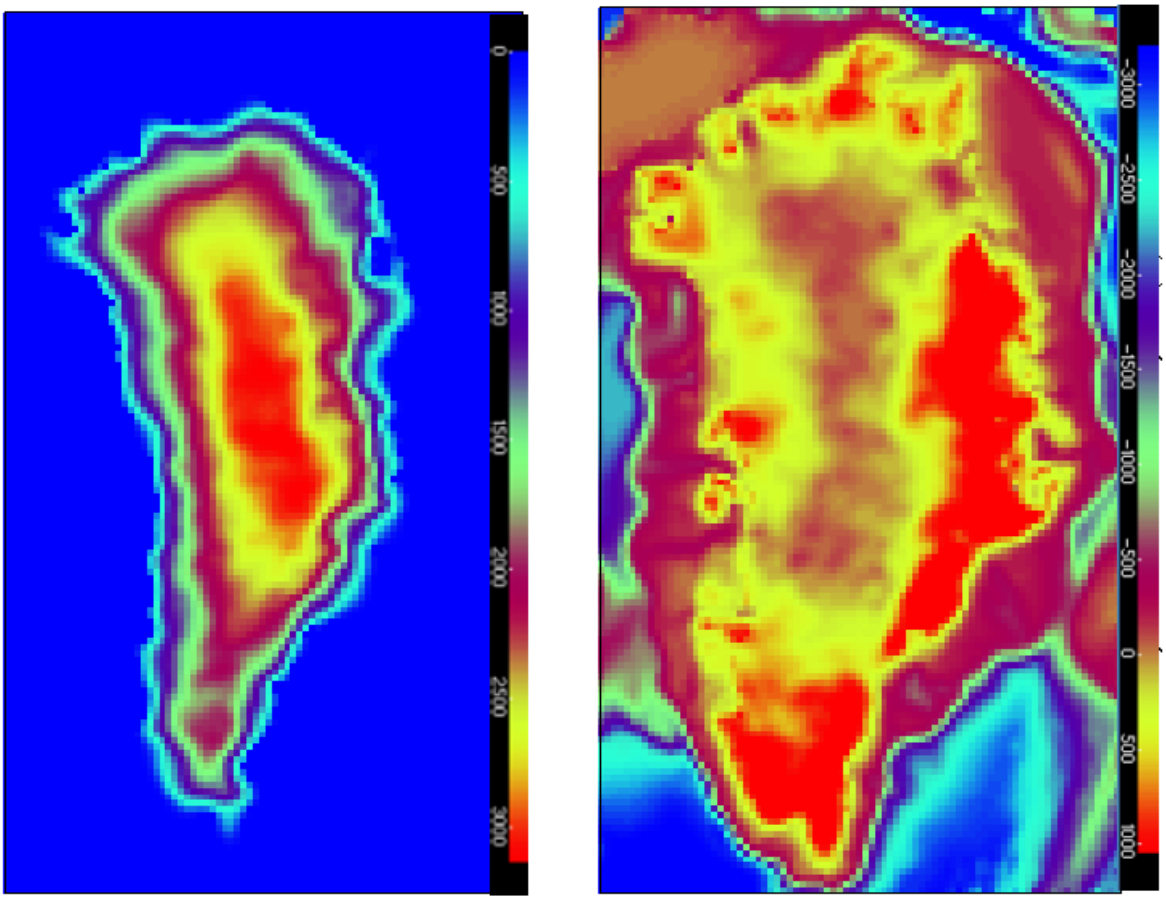

FIGURE 9. Views of the thickness (left) and smoothed bed elevation (right) for EISMINT-Greenland. The coastal topography around several fjords has been smoothed. These views are produced by `ncview` applied to `eis_green_smoothed.nc`.

Bootstrapping from EISMINT-Greenland data. Once the EISMINT Greenland data is obtained and converted to NetCDF, as above, "bootstrapping" can begin. By "bootstrapping" we mean the creation, by heuristics and simplified models, of the kind of full initial conditions needed for the continuum model (differential equations) inside PISM.[14]

Table 9 shows the entire PISM output for a one model year run using option `-bif` to "bootstrap" from file `eis_green_smoothed.nc`

```
$ pgrn -bif eis_green_smoothed.nc -Mx 141 -My 83 -Lz 4000 -Mz 51 -quadZ \
  -ocean_kill -y 1 -o green20km_y1
```

The run takes a few seconds of real time.

[14]Section 5 will explain, once written, that "bootstrapping" is a form of inverse modeling, and that we must inevitably do inverse modeling to do prognostic ice sheet modeling.

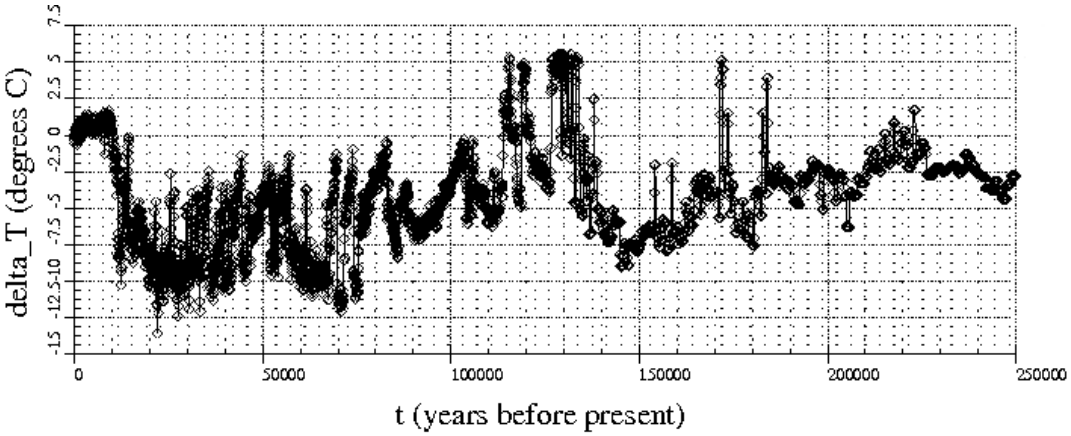

FIGURE 10. Change in temperature from present, from the GRIP core. A famous graph produced, in this case, by applying `ncview` to `grip_dT.nc`

Let's explain what has happened. The EISMINT-Greenland data, as with *all* real ice sheet data, does not contain certain variables necessary to initialize PISM in the sense of complete initial values for time-dependent partial differential equations. For instance, the data do not include the temperature of the ice anywhere but at the surface. The data also do not include the amount of water stored in the till, for instance. These are not omissions from the data sets but rather inevitable facts; one cannot observe ice sheets as fluids very well.

Therefore PISM fills in the unknown initial conditions based on some default guesses, as indicated by the messages to standard out.

Note that EISMINT-Greenland specifies an 83 by 141 point grid. But there is a transpose: In order to make the diagnostic viewers described in Appendix C have the correct orientation, the x and y axes are switched internally in PISM. Of course the physics approximated by PISM does not care about orientation. The consequence of using "`-Mx 83 -My 141`", instead of the correct pair shown, would be to have grid cells which are far from square, and to have squashed viewers.

You may use other numbers for `-Mx` and `-My` if desired. In such cases the data will be linearly interpolated onto your grid.

Note the choice of the height of the computational box ("`-Lz 4000`"), of the number of vertical levels ("`-Mz 21`"), and of a not-equally-spaced grid ("`-quadZ`"). The messages to standard out show that the vertical spacing is less than 30 m near the base and more than 130 m at the top of the computational box (where it matters less to have a fine grid).

The option `-bif` stands for "bootstrapping input file". This option is an alternative to `-if` (stands for "input file") which is used for a file which has full initial conditions. In practice, `-if` is only used with a NetCDF file which was previously saved by PISM; that is, `-if` is used to continue a run.

Regarding the temperature within the ice, bootstrapping applies an interpolation scheme to the surface temperatures and geothermal fluxes. It is based on a heuristic for the amount of

```
$  pgrn -bif eis_green_smoothed.nc -Mx 141 -My 83 -Lz 4000 -Mz 51 -quadZ -ocean_kill -y 1 -o green20km_y1
PGRN (EISMINT Greenland mode)
bootstrapping by PISM default method from file eis_green_smoothed.nc
  polar stereographic found: svlfp = -41.14, lopo =  71.65, sp =  71.00
  time t = 0.0000 years found in bootstrap file; setting current year to this value
  rescaling computational box *for ice* from defaults, -bif file, and
    user options to dimensions:
      [-1400.00 km, 1400.00 km] x [-820.00 km, 820.00 km] x [0 m, 4000.00 m]
  WARNING: vertical  dimension of target computational domain not a subset of
    source (in NetCDF file) computational domain;  either  -bdy[5] = -0.0000 < Lbz = -0.0000
    or  bdy[6] = 0.0000 < Lz = 4000.0000; ALLOWING ONLY 2D REGRIDDING ...
  WARNING: ignoring values found for surface elevation 'usurf'; using usurf = topg + thk
  WARNING: surface temperature 'artm' not found; using default  263.15 K
  WARNING: geothermal flux 'bheatflx' not found; using default  0.042 W/m^2
  WARNING: uplift rate 'dbdt' not found; filling with zero
  WARNING: effective thickness of basal melt water 'bwat' not found; filling with zero
  determining mask by floating criterion; grounded ice marked as 1; floating ice as 7
  filling in temperatures at depth using surface temperatures and quartic guess
bootstrapping by PISM default method done
resetting vertical levels base on options and user option -Lz ...
geothermal flux set to EISMINT-Greenland value 0.050000 W/m^2
computing surface temperatures by EISMINT-Greenland elevation-latitude rule
filling in temperatures at depth using surface temperatures and quartic guess
removing extra land (Ellesmere Island and Iceland) using EISMINT-Greenland rule
  [computational box for ice: ( 2800.00 km) x ( 1640.00 km) x ( 4000.00 m)]
  [hor. grid cell dimensions: (   20.00 km) x (   20.00 km)]
  [vertical grid spacing in ice not equal: 27.733333 m < dz < 132.266667 m]
  [fine equal spacing used in temperatureStep():  Mz = 146,  dzEQ =    27.59 m]
%ybp SIA SSA  # vgatdh Nr  +STEP
P         YEAR:     ivol   iarea    meltf     thick0     temp0
U        years 10^6_km^3 10^6_km^2 (none)          m         K
 $$$            $$$$$ $$
S      0.00000:  2.82500  1.6708   0.2071   3042.000  270.5156
 $$$ SIA        vatdh 0d  +0.18293
S      0.18293:  2.82515  2.2300   0.1683   3041.888  270.5156
 $$$ SIA        vatdh 0d  +0.23570
S      0.41863:  2.82534  2.2296   0.1681   3041.704  270.5157
 $$$ SIA        vatdh 0d  +0.27029
S      0.68893:  2.82520  1.6836   0.2057   3041.458  270.5159
 $$$ SIA        vatdh 0d  +0.30049
S      0.98942:  2.82526  1.6852   0.2053   3041.175  270.5161
 $$$ SIA        vatdh 0e  +0.01058
S      1.00000:  2.82526  2.2292   0.1681   3041.165  270.5163
done with run ...
Writing model state to file 'green20km_y1.nc' ... done.
```

TABLE 12. Bootstrapping from the EISMINT-Greenland data and running for one model year.

downward flow in a column. Thus bootstrapping creates a temperature field at depth. See the PISM *Reference Manual*.

This bootstrapping mode also fills in several default values. For instance, the variables `bheatflx` (geothermal flux), `dbdt` (bed uplift rate), and `bwat` (effective thickness of basal water) were not found in the input file, whereas they would be in a saved PISM model state (i.e. those saved by `-o` and loaded with `-if`). Thus, these variables were filled with defaults `0.042` $\mathrm{mW/m^2}$, `0` m/s, and `0` m respectively. Also, note that the EISMINT Greenland data had redundant surface elevation values; PISM bootstrapping includes the computation "`usurf = topg + thk`" of the surface elevation from the ice thickness and the bed elevation.

Continuing with the above output, after default bootstrapping there are additional settings special to EISMINT-Greenland. For instance, because there is no EISMINT-Greenland gridded data set for surface temperature [55], at the surface there is a formula which determines the temperature as a function of altitude and latitude. The derived class of PISM corresponding to the executable `pgrn` knows this formula and uses it. Also, the constant value for geothermal flux is reset, and the above-mentioned Ellesmere Island issue is resolved.

Relaxing the temperature field. Before seeking a good steady state for the entire thermomechanically-coupled ice sheet, it is helpful to do a better job of filling in the temperatures within the ice (than has already been done by the heuristic formula used in bootstrapping). One way to do this is to have the temperature field and velocity field co-evolve according to the thermomechanical flow model, but while holding the upper ice surface stationary. This is really a continuation of the "bootstrapping" idea, because the effect is to replace the heuristic temperature field applied above by one which is approximately stationary with respect to advection and conduction. The resulting temperature field is still not the fully physical temperature field, however, because it comes from a steadiness assumption about position of the surface of the ice.

We create this temperature field by running for 10000 years with non-evolving surface, using the option `-no_mass` to turn off the map-plane mass continuity scheme:

```
$ mpiexec -n 2 pgrn -if green20km_y1.nc -no_mass -y 10000 -o green20km_Tsteady
```

This last run takes a significant amount of computer time (on the order of four processor hours). In fact a much longer run should be done for serious modeling because the exponential time constant for decay of the thermomechanically-coupled system toward equilibrium is probably about 100k years.

This is a case where many more processors *are* effective, up to perhaps peak real time speed with 40 to 80 processors for this 83 by 141 grid. (Finer grids give greater parallel benefits, in terms of the maximum attainable speedup, in wall clock time, over one processor.)

The EISMINT-Greenland experiments [55] specify a positive degree day (PDD) model which is automatically turned on when using the `pgrn` executable. (Other executables require option `-pdd` or `-pdd_rand` to turn on the PDD model.) The PDD model is, by default, implemented by the deterministic scheme described in [12], but the user can add option `-pdd_rand` to use a stochastic PDD model.

Running the EISMINT-Greenland steady state experiments. Now that we have initial conditions including a vaguely-credible temperature field, our first experiment is the steady state run "SSL2". This experiment uses the parameters specified in the EISMINT-Greenland description [55]. If 8 processors are used, a ten thousand model year run might look like this:

```
mpiexec -n 8 pgrn -ssl2 -if green20km_Tsteady.nc -y 10000 -ys 0 -ocean_kill \
     -tempskip 3 -o green_SSL2_10k >> ssl2.txt
```

We can continue for another ten thousand years by

```
mpiexec -n 8 pgrn -ssl2 -if green_SSL2_10k.nc -y 10000 -ocean_kill \
     -tempskip 3 -o green_SSL2_20k >> ssl2.txt
```

These runs took [HOW LONG?] on an 4 processor (8 core) Opteron cluster (2006 technology).

Note the option "`-ocean_kill`". This forces all floating ice to immediately calve off (i.e. to have thickness zero). Compare the Ross ice shelf model in the next section.

For these runs we add "`-tempskip 3`" to speed things up. The effect of this option is to allow the explicit time-stepping scheme to not update the temperature field for up to three time-steps of the mass continuity scheme, *if* this is allowed by the stability conditions appropriate to the conservation of energy equation and the (diffusive in this case) mass continuity equation; see subsection 6.3 for more detail.

This simulation is, however, intended to go until the model reaches a "steady state", a phrase which [55] defines as a small volume change rate, namely less than a .01% change in volume in 10,000 years.

One can look at the standard output text file by a minimal method like "`less ssl2.txt`". But, to more clearly see the behavior over time of the volume, area, basal melt fraction, and so on, one can generate a time series file in NetCDF form and then use various tools to view and manipulate that file. Use the Python script `test/series.py`, documented in Appendix D, like this:

```
$  series.py -f ssl2.txt -o ssl2_series.nc
```

View using `ncview`, for instance. One sees that the volume shows a consistent growing-but-leveling-out trend, with a final volume expected to be a bit more than $4 \times 10^6\,\text{km}^3$.

In fact that is what happens with a long run. If we run the SSL2 experiment with the specified "0.01% change in 10k years" criterion, then the run ends at 110k years with a volume change of about 0.001% between the 100k and 110k model states. This steady state criteria can be most easily determined by examining the time series NetCDF file produced by `series.py` (from a completed partial run or even during an ongoing run). The final volume was $4.087 \times 10^6\,\text{km}^3$. The time series for volume and melt fraction (the fraction of the base where the temperature is at pressure-melting) are shown in Figures 11 and 12. The volume time series is boring, but the melt fraction indicates something interesting: measured by basal melt fraction, the temperature field resulting from bootstrapping and relaxing the temperature field (above) gave a pretty good estimate of the basal melt fraction for the fully coupled steady state.

The command that completed the full 110k model year run is

```
mpiexec -n 8 pgrn -ssl2 -if green_SSL2_20k.nc -y 90000 -ocean_kill \
     -tempskip 3 -o green_SSL2_110k >> ssl2.txt
```

We will use the final NetCDF file `green_SSL2_110k.nc` to continue the EISMINT-Greenland experiments below. The saved ice thickness and homologous basal temperature maps are shown in Figure 13. The vertically-averaged horizontal velocity is shown in Figure 14.

In addition to the more standardized EISMINT-Greenland intercomparison called "SSL2", a "SSL3" intercomparison was performed allowing each participant to choose parameters in the

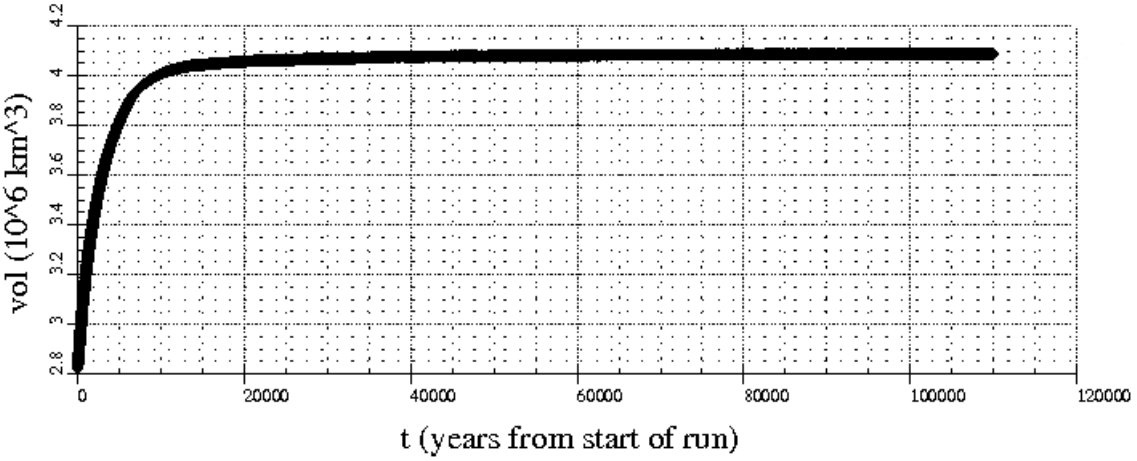

FIGURE 11. Volume time series for a 110k model year EISMINT-Greenland run; units of $10^6\,\mathrm{km}^3$.

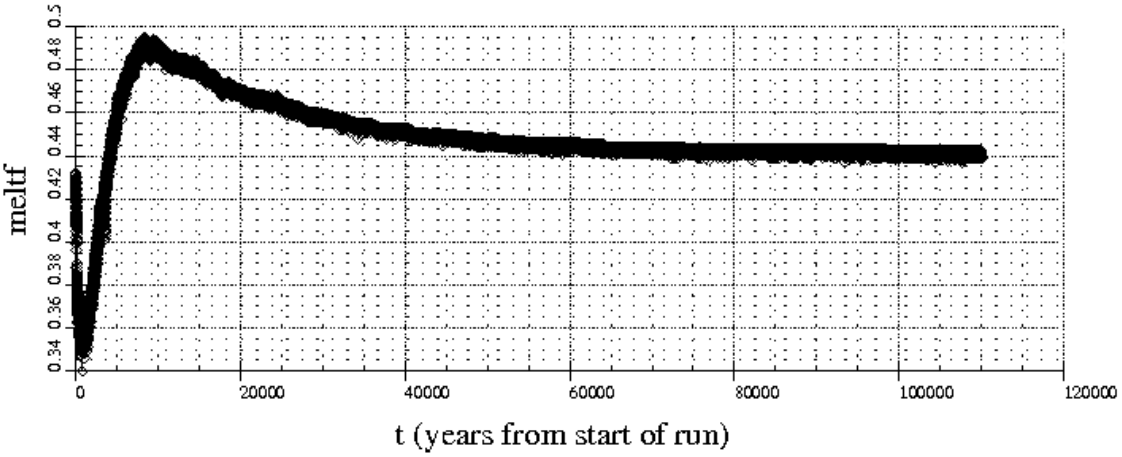

FIGURE 12. Time series for the fraction of the base which is at the pressure-melting temperature from a 110k model year EISMINT-Greenland run. See the right hand part of Figure 13 for a map of the basal temperature.

model. The PISM interpretation of the SSL3 experiment is the same as SSL2 with these two modificiation:

- use Goldsby-Kohlstedt flow law [18] with an enhancement factor of 1.0, and
- the Lingle and Clark [10, 40] two layer, flat earth bed deformation model is used, assuming zero uplift rate at time zero.

There is no particular assertion that these are superior modeling choices. We give "SSL3" this interpretation merely for illustration. A 100k year run starting over with these choices would be

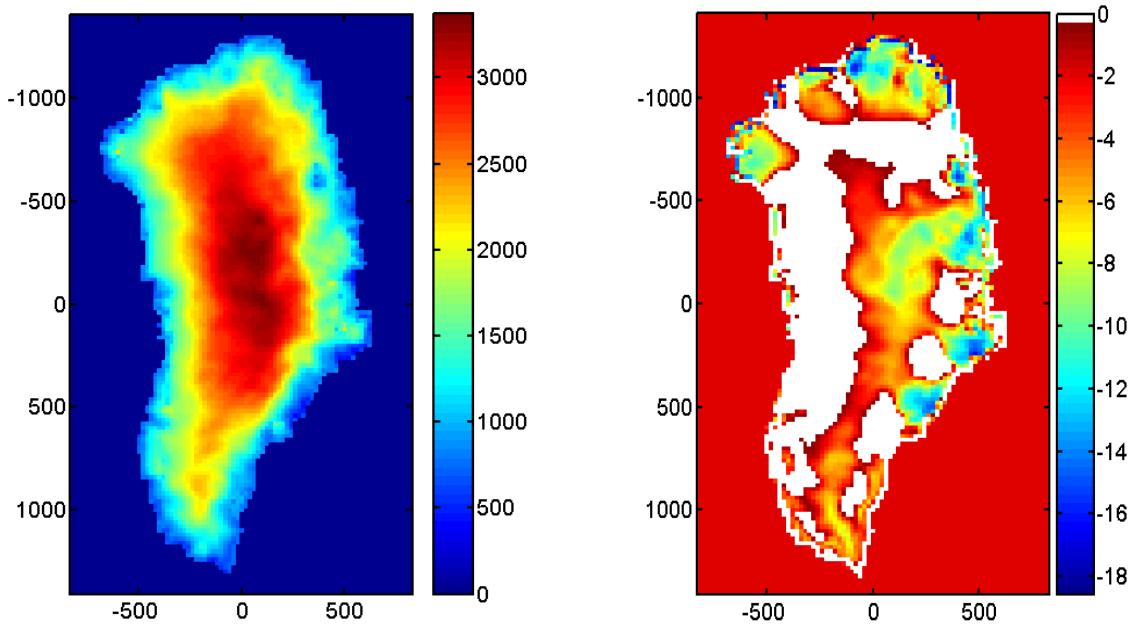

FIGURE 13. Ice thickness (meters; left) and homologous basal temperature (degrees C below 0; right) at the end (110k model years) of a EISMINT-Greenland SSL2 run. Note that in the temperature graph the pressure-melting temperature areas are white.

```
mpiexec -n 8 pgrn -ssl3 -gk -if green20km_Tsteady.nc -y 100000 -ys 0 -ocean_kill \
     -tempskip 3 -o green_SSL3_100k >> ssl3.txt
```

Climate forcing from GRIP and SPECMAP. The next experiment is intended to be carried out after the completion of the SSL2 steady state run above.

Recall that the NetCDF files `grip_dT.nc` and `specmap_dSL.nc` contain time series data for change in surface temperature and the change in sea level. The options `-dTforcing` and `-dSLforcing` for `pgrn` can use these data for a "CCL3" climate forced run [55, 30] under PISM. Before every time step, `pgrn` adds in a change to the surface temperature and sea level in order to incorporate the effects of global climate changes stored in the GRIP ice core and a collection of sea bed cores. The data in `grip_dT.nc` goes about 250,000 years into the past, while the data in `specmap_dSL.nc` goes back about 780,000 years, but EISMINT-Greenland specifies that the run will start at the beginning of the GRIP data. Thus we manually set the starting year using the option `-ys`. The CCL3 experiment can be run using the following command:

```
$  pgrn -ccl3 -gk -if green_SSL2_110k.nc -dTforcing grip_dT.nc \
      -dSLforcing specmap_dSL.nc -ys -249900 -ye 0 -o green_CCL3_y0
```

The resulting thickness difference, relative to the end of the SSL2 run, and the homologous basal temperature, are shown in Figure 15.

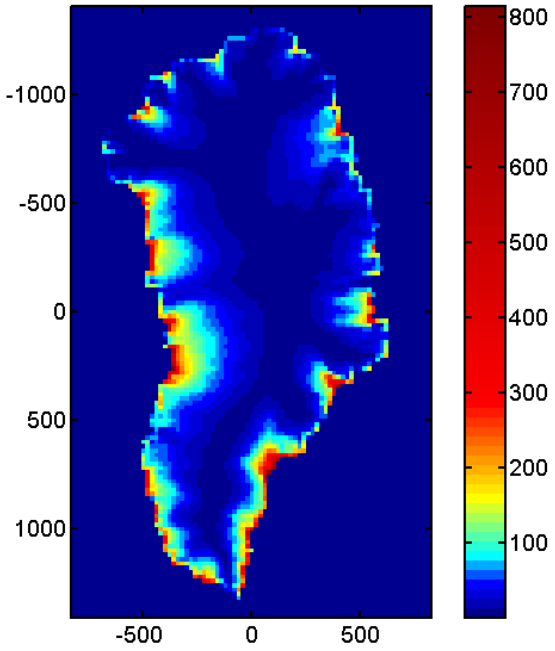

FIGURE 14. Vertically-averaged horizontal velocity in meters per year at the end (110k model years) of a EISMINT-Greenland SSL2 run.

EISMINT-Greenland also calls for a baseline run for another 500 years which starts from the end of the CCL3 run and has steady current climate forcing. If `pgrn -ccl3` is run past year 0, and thus past the end of the GRIP and SPECMAP data, this baseline run will occur by default. So the previous command can be run for another 500 years, and the forcing can be omitted:

```
$  pgrn -ccl3 -gk -if green_CCL3_y0.nc -y 500 -o green_CCL3_y500
```

A greenhouse warming scenario. A final "greenhouse warming" experiment "GWL3" is described in the EISMINT-Greenland [55]. It uses the model state obtained for present day from the CCL3 run. The GWL3 experiment runs for 500 years with the temperature increasing by $0.035°C$/year for the first 80 years, then at a rate of $0.0017°C$/year for the last 420 years:

```
$  pgrn -gwl3 -gk -if green_CCL3_y0.nc -y 500 -o green_GWL3_y500
```

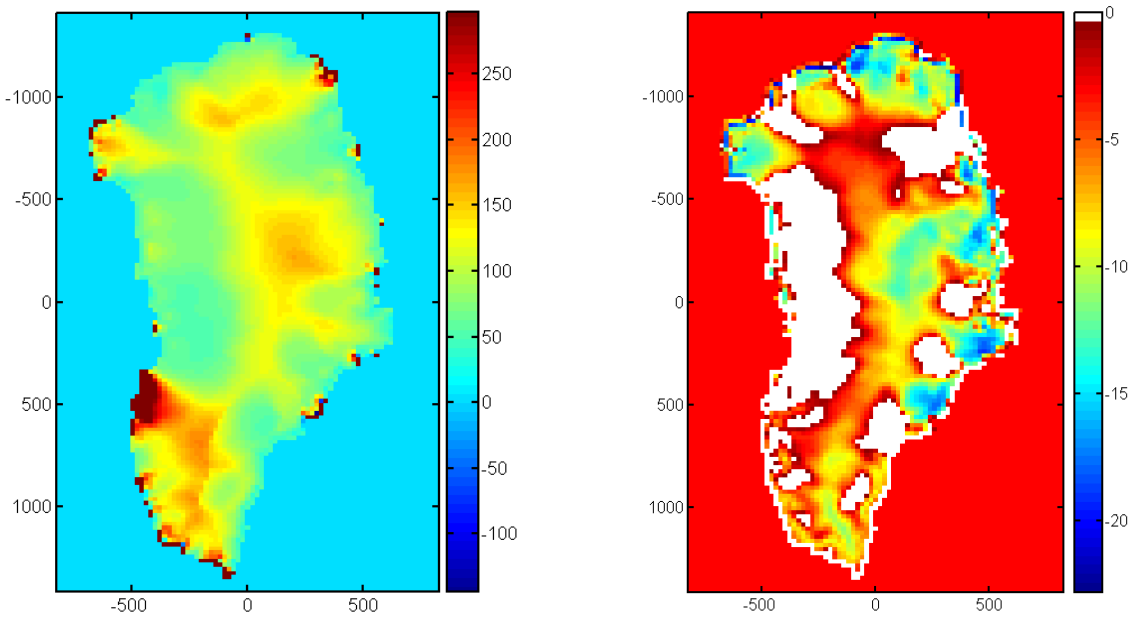

FIGURE 15. Left: Ice thickness difference between end (year zero) of a CCL3 run and the end of an SSL2 run (meters). Right: Ice homologous basal temperature (degrees C below 0; right) at the end of a EISMINT-Greenland CCL3 run. Compare Figure 13.

10. Example: Validating PISM as a flow model for the Ross ice shelf

The term "validation" describes the comparison of model output with physical observations in cases where those physical observations are believed to be sufficiently complete and of sufficient quality so that the performance of the numerical model can be assessed [58, 66]. Roughly speaking, validation can happen when the observations or data are better than the model, so the comparison informs one of the quality of the numerical model, not merely the lack of confidence in, or incompleteness of, the data.

As part of the first EISMINT series of intercomparisons, MacAyeal and others [42] validated several ice shelf numerical models using the Ross ice shelf as an example. We will refer to this intercomparison and its associate write-up [42] as "EISMINT-Ross". The models were compared to data from the RIGGS (= Ross Ice shelf Geophysical and Glaciological Survey) [3, 4], data acquired in the period 1973–1978. The RIGGS data include the (horizontal) velocity of the ice shelf measured at a few hundred locations in a reasonably regular grid across the shelf; see figure 18 below for an indication of these positions.

Substantial developments have occurred in the modeling of the Ross ice shelf since the EISMINT-Ross intercomparison. For example, inverse modeling techniques were used to recover depth-averaged viscosity of the Ross ice shelf from the RIGGS data in [59]. A parameter-sensitivity study was performed for a particular Ross ice shelf numerical model in [28].

Grabbing the data. Download data files from the website

`http://homepages.vub.ac.be/~phuybrec/eismint/iceshelf.html`

to do the validation:

- `111by147Grid.dat`
- `kbc.dat`
- `inlets.dat`

We will assume that these three text files are in a directory `eisDownload/`. The reader might want to look at them in a text editor; their idiosyncratic format is handled by the python script `pism/test/ross/eis_ross.py` (more below); a very significant part of repeating EISMINT-Ross is the step of converting these text files into machine-readable and metadata-containing NetCDF. Note that these data are for a particular rectangular grid with 6.822km spacing in both x and y directions, but, as usual, the fineness of th PISM computational grid is determined by the user.

The script `eis_ross.py` in subdirectory `pism/test/ross/` reads the above three `.dat` files and it creates a NetCDF file:[15]

```
$ eis_ross.py -o ross.nc
```

If the data files are not in the current directory but instead in `eisDownload/` then add option `--prefix=eisDownload/` when invoking `eis_ross.py`.

Note that the NetCDF file `ross.nc` can be reconverted to text (CDL) using `ncdump` or it can be viewed graphically with `ncview`. For example,

```
$ ncdump -h ross.nc
```

[15] If the script doesn't work, recall this: the Python libraries `numpy` and `pycdf` must be present. Also, depending on which directory you are in, you may want to do something like this: `export PATH=~/pism/test/ross/:$PATH`.

shows the "header" (the metadata) for `ross.nc`. The script `eis_ross.py` has added this metadata. Writing such a script means, among other things, reading the appropriate papers to understand the data and its format [3, 4, 42]—attention to detail is unavoidable!

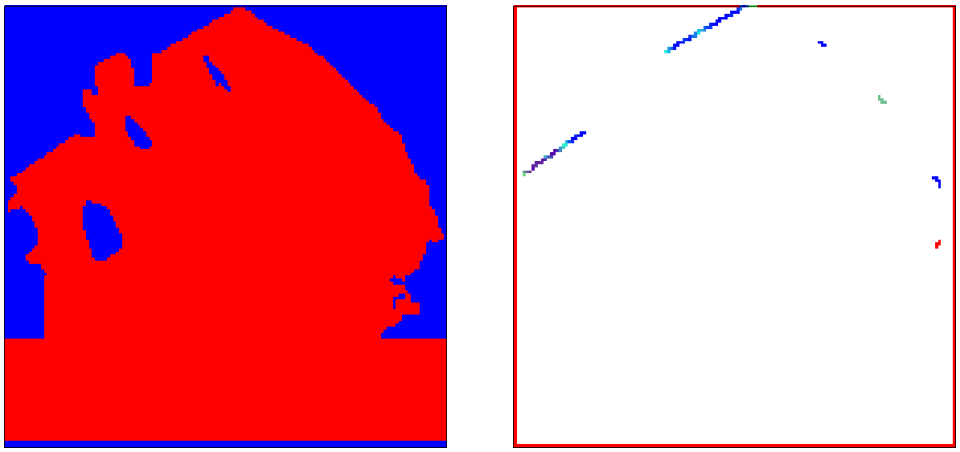

FIGURE 16. Two views from `ncview` of the EISMINT-Ross data in the NetCDF file `ross.nc`. The floating-versus-grounded mask (left; red areas are floating ice shelf) and the x-component of the non-zero kinematic (Dirichlet) boundary condition for velocity (right).

The NetCDF file `ross.nc` contains ice thickness, bed elevations, surface temperature, and accumulation. Values for latitude and longitude from the RIGGS survey grid [4] are given. All of these are typical of ice sheet modeling data, both in evolution and diagnostic runs.

`ross.nc` also has variables `ubar` and `vbar`. These give the boundary values which are needed for the diagnostic computation of velocity, and they are only valid at grounding line locations. They are the measured velocities of the ice flow inputs to the ice shelf. Also present are integer variables `mask`, which shows the domain where the ice shelf is modeled, and `bcflag`, which shows the locations where the boundary conditions are to be applied.

Finally, `ross.nc` contains variables which allow us to partly validate our computation. There is an interger variable `accur` which flags the region where the interpolated measured velocities are believed to be accurate enough for validation.[16] The variables `azi_obs` and `mag_obs` are believed to be accurate in this region.

The original EISMINT-Ross data are on a 111 by 147 grid but `eis_ross.py` extends this grid to a more convenient 147 by 147 grid with the same 6.822 km spacing in each coordinate direction. This grid has ice-free ocean beyond the calving front; the calving front is straightened in the EISMINT-Ross intercomparison [42].

Diagnostic computation of ice shelf velocity. A basic Ross ice shelf velocity computation from these data is:

```
$ pismd -ross -bif ross.nc -ssaBC ross.nc -Mx 147 -My 147 -Lz 1000 -Mz 11 \
    -ssa -o rossComputed
```

[16] `111by147.dat` has a "Reliable Velocity Obs" flag.

Here we bootstrap (`-bif`; see section 5) from `ross.nc`. We also use a special option `-ssaBC` to specify `ross.nc` as the source of the boundary value data for the ice shelf equations, as mentioned in the last paragraph. The computational grid specified here is the 6.822 km data grid in EISMINT-Ross with 147 grid points in each direction. The maximum thickness of the ice is 874 m so we choose a height for the computational box (`-Lz`) large enough to contain the ice. Note that using a small number of vertical levels (`-Mz 11`) is reasonable because the EISMINT-Ross intercomparison specifies that the temperature at each depth is just the surface temperature [42]. In fact there is no thermocoupling issue because the ice hardness used here is constant.

At the end of this run the computed velocity field is compared to the interpolated observed velocities stored in `ross.nc`. The value called "average relative error in vector vel" is most relevant. A value of 0.07 here means that the averaged absolute difference between the computed and the observed velocity, in the "accurate" region, is 7%.

The output file `rossComputed.nc` contains vertically-averaged horizontal speed in the variable `cbar`. Viewing that variable will show a picture like the one on the cover page of this *User's Manual*, and like that in figure 17.

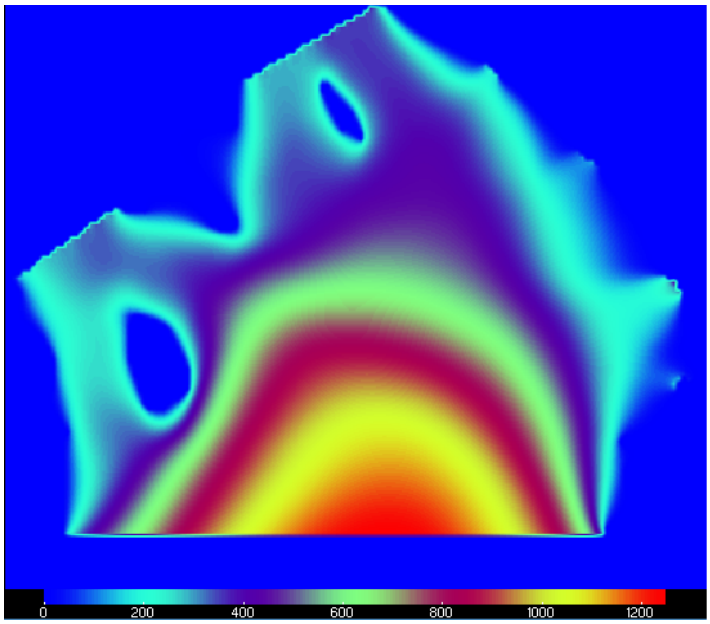

FIGURE 17. Computed horizontal ice speed of the Ross ice shelf. Color gives velocity in m/a; see scale.

There are many variations on this basic "`pismd -ross`" run above. First of all one can get more information during the run by adding diagnostic viewers and a more complete (verbose) report to standard out:

```
$ pismd -ross -bif ross.nc -ssaBC ross.nc -Mx 147 -My 147 -Lz 1000 -Mz 11 \
    -ssa -d cnmu -verbose -pause 10
```

Secondly one might want to do the run in parallel and do it on a finer grid. For example,

```
$ mpiexec -n 4 pismd -ross -bif ross.nc -ssaBC ross.nc -Mx 201 -My 201 \
    -Lz 1000 -Mz 3 -ssa
```

The result is very similar, as it should be. On the other hand, since the data is only on a 6.8 km grid we expect no added accuracy on this new 5km grid.

Alternately one might want to experiment with different values of the hardness parameter. Its default value is $\bar{B} = 1.9 \times 10^8\,\mathrm{Pa\,s}^{1/3}$ as in [42]. We can also use lower (more severe) tolerances for the nonlinear iteration (`-ssa_rtol`) and the linear iteration (`-ksp_rtol`) to get more confidence in the numerical scheme:

```
$ pismd -ross -bif ross.nc -ssaBC ross.nc -Mx 147 -My 147 -Lz 1000 -Mz 11 -ssa \
    -constant_hardness 1.8e8 -ssa_rtol 1e-6 -ksp_rtol 1e-10 -o ross_out_1p8
```

Table 13 lists some of the options which are useful for this kind of diagnostic velocity computation.

TABLE 13. Non-obvious options available and/or recommended with `pismd -ross`.

Option	**Explanation/Comments**
`-d cnmu`	a good way to see what is going on
`-mato foo -matv cnmuvH`	writes some model results to Matlab-readable file `foo.m`
`-pause N`	pause for N seconds when refreshing viewers
`-ross`	only use with executable `pismd`
`-verbose 4`	shows information on nonlinear iteration and Krylov solve and parameters related to solving the ice shelf equations

Comparison to RIGGS data. The file `riggs_clean.dat` in directory `pism/test/ross/` is a cleaned-up version of the original RIGGS data [4, 3].[17] To convert this data to a NetCDF file, as needed next, do

```
$ cp ~/pism/test/ross/riggs_clean.dat .
$ eis_riggs.py -o riggs.nc
```

A file `riggs.nc` will be created. This data is one-dimensional; it is just a lists of values which have an index dimension `count` in the NetCDF file `riggs.nc`.

Now, `pismd -ross` can read this data and compute a χ^2 statistic comparing computed PISM output to the data:

```
$ pismd -ross -bif ross.nc -ssaBC ross.nc -Mx 147 -My 147 -Lz 1000 -Mz 3 -ssa -riggs riggs.nc
PISMD (diagnostic velocity computation mode)
initializing EISMINT Ross ice shelf velocity computation ...
. . .
maximum computed speed in ice shelf is   1249.107 (m/a)
. . .
comparing to RIGGS data in riggs.nc ...
Chi^2 statistic for computed results compared to RIGGS is   3625.099
 ... done.
```

[17](See `pism/test/ross/README` for more explanation on this RIGGS data.

Naturally, the question is "does this χ^2 value of 3625.099 represent a good fit of model result to observations"? Also naturally, there is no objective answer. For comparison, Table 1 in [42] is reproduced here as Table 14. As noted, all these results are with a constant hardness parameter $\bar{B} = 1.9 \times 10^8\,\mathrm{Pa\,s^{1/3}}$ [42]. The maximum computed horizontal ice speed above of 1249.107 m/a is lower than the maximum velocities reported by the other models but, on the other hand, the maximum measured speed in the RIGGS data set is 1007 m/a (near the calving front, of course). The χ^2 result is essentially as good as the best in the Table, noting smaller χ^2 is better.

TABLE 14. Model performance index, χ^2 (non-dimensional). *(Reproduction of Table 1 in* [42]*.)*

Model	χ^2	*Maximum velocity* $\mathrm{m\,a^{-1}}$
Bremerhaven1	3605	1379
Bremerhaven2	12 518	1663
Chicago1	5114	1497
Chicago2	5125	1497
Grenoble	5237	1508

Tuning the ice hardness for a better fit to RIGGS. Because there is a relatively rich data set from RIGGS on ice velocity, it is reasonable to ask whether the PISM computed velocities can fit the data better if the hardness parameter $\bar{B}$ is adjusted. There is a Python script `pism/test/ross/tune.py` which (by default) runs `pismd -ross` with six values of $\bar{B}$ ranging from $\bar{B} = 1.5\times10^8$ to $\bar{B} = 2.0\times10^8\,\mathrm{Pa\,s^{1/3}}$. It uses smaller values for the convergence tolerances (by default), and it can be run with multiple processors:[18]

```
$ tune.py -n 2
TUNE.PY (for EISMINT Ross; compare to table 1 in MacAyeal et al 1996)
trying "mpiexec -n 2 pismd -ross -bif ross.nc -ssaBC ross.nc -riggs riggs.nc
-ksp_rtol 1e-08 -ssa_rtol 1e-05 -Mx 147 -My 147 -Lz 1000 -Mz 3 -ssa
-constant_hardness 1.5e8"
  finished in 116.7409 seconds; max computed speed and Chi^2 as follows:
  |maximum computed speed in ice shelf is   2355.752 (m/a)
  |Chi^2 statistic for computed results compared to RIGGS is  28157.4
. . .
trying "mpiexec -n 2 pismd -ross -bif ross.nc -ssaBC ross.nc -riggs riggs.nc
-ksp_rtol 1e-08 -ssa_rtol 1e-05 -Mx 147 -My 147 -Lz 1000 -Mz 3 -ssa
-constant_hardness 1.8e8"
  finished in 114.4815 seconds; max computed speed and Chi^2 as follows:
  |maximum computed speed in ice shelf is   1437.704 (m/a)
  |Chi^2 statistic for computed results compared to RIGGS is   3967.9
trying "mpiexec -n 2 pismd -ross -bif ross.nc -ssaBC ross.nc -riggs riggs.nc
```

[18] If the script doesn't work, recall that you need `tune.py` to be on your `PATH`: `export PATH=~/pism/test/ross/:$PATH`.

```
-ksp_rtol 1e-08 -ssa_rtol 1e-05 -Mx 147 -My 147 -Lz 1000 -Mz 3 -ssa
-constant_hardness 1.9e8"
  finished in 104.6139 seconds; max computed speed and Chi^2 as follows:
  |maximum computed speed in ice shelf is   1249.716 (m/a)
  |Chi^2 statistic for computed results compared to RIGGS is   3624.1
. . .
```

We see that hardnesses $\bar{B} = 1.8, 1.9 \times 10^8\,\mathrm{Pa\,s}^{1/3}$ give the best fits. This fitting exercise is a first small step towards inverse modelling of the spatially-distributed effective viscosity. More steps in such directions are found in [28, 59]

Additional visualization using MATLAB *output from PISM.* The visualization abilities of PISM's runtime viewers and of `ncview` (applied to the PISM output NetCDF file) are limited. PISM can save certain variables in a MATLAB-readable form, however, and this is a situation where it might be useful.

```
$ pismd -ross -bif ross.nc -ssaBC ross.nc -riggs riggs.nc \
    -ksp_rtol 1e-08 -ssa_rtol 1e-05 -Mx 147 -My 147 -Lz 1000 -Mz 3 -ssa \
    -constant_hardness 1.9e8 -mato ross1p9 -matv cuvHm
```

When this completes, make sure MATLAB can find `ross1p9.m` and also files `ross_plot.m` and `riggs_clean.dat` (both in directory `pism/test/ross/`). Execute the `m`-files at the MATLAB command line:

```
>> ross1p9
>> ross_plot
```

Figure 18 is the result. We have succeeded in modeling a real ice shelf.

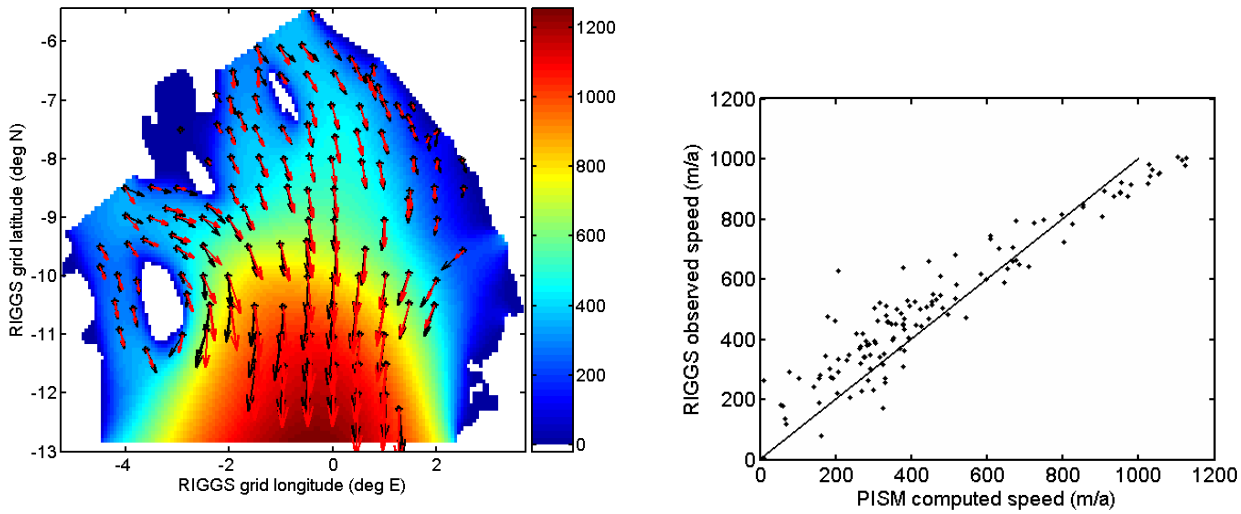

FIGURE 18. *Left*: Color is speed in m/a. Arrows are observed (black) and computed (red) velocities at RIGGS points. *Right*: Comparison between modeled and observed speeds at RIGGS points; compare figure 2 in [42].

11. Inside PISM: overviews of continuum models and numerical schemes

This section is an executive summary. Technical documentation of the continuum models, numerical methods, and the source code structure is in the *PISM Reference Manual*.

11.1. **The continuum models in PISM.** Significant features of the continuum model approximated by the PISM include:

- The thermocoupled shallow ice approximation equations [17] is verifiably [11, 9] solved.
- Ice shelves and ice streams are modeled by shallow equations which describe flow by longitudinal strain rates and basal sliding. These equations are different from the shallow ice approximation. In shelves and streams the velocities are independent of depth within the ice. The equations were originally established for ice shelves [43, 44, 42, 65]. They were adapted for ice streams, as "dragging ice shelves," by MacAyeal [41]; see also [27, 62]. The solution is verifiable using ice stream and ice shelf exact solutions.
- The regions of grounded ice in which the ice stream model is applied can be determined from a plastic till assumption and the associated free boundary problem [62].
- A three dimensional age field is computed.
- A temperature model for the bedrock under an ice sheet is included and geothermal flux which varies in the map-plane can be used.
- Within the shallow ice sheet regions the model can use the constitutive relation of Goldsby and Kohlstedt [18, 54]. For inclusion in this flow law, grain size can be computed using a age-grain size relation from the Vostok core data [16], for example.
- The Lingle-Clark [10, 40] bed deformation model can be used. It generalizes the better known elastic lithosphere, relaxing asthenosphere ("ELRA") model [21]. This model can be initialized by an observed bed uplift map [10], or even an uplift map computed by an external model like that in [34].

Many of the parts of the model described above are optional. For instance, options can choose between five different flow laws; see Appendix A and B for options.

The following features are *not* included in the continuum model, and would (or will) require major additions:

- Inclusion of all components of the stress tensor through either an intermediate order scheme (e.g. [5, 25, 49]) or the full Stokes equations [17].
- A model for water–content within the ice. In the current model the ice is *cold* and not *polythermal*; compare [19]. (On the other hand, in the current model the energy used to melt the ice within a given column, if any, is conserved. In particular, a layer of basal melt water evolves by conservation of energy in the column. This layer can activate basal sliding and its latent heat energy is available for refreezing.)
- A model for basal water mass conservation in the map-plane; compare [36].
- A fully spherical Earth deformation model, for example one descended from the Earth model of [53].

11.2. **The numerical schemes in PISM.** Significant features of the numerical methods in PISM include:

- Verification [58] is a primary concern and is built into the code. Nontrivial verifications are available for isothermal ice sheet flow [11], thermocoupled sheet flow [7, 9], conservation in ice and bedrock [6], the earth deformation model [10], the coupled (ice flow)/(earth deformation) system in an isothermal and pointwise isostasy case [10], ice shelf flow (preprint), and ice stream flow based on a plastic bed [62].
- The code is *structurally* parallel because the PETSc toolkit is used at all levels [1]. PETSc manages the MPI-based communication between processors. It provides an interface to parallel numerical linear algebra.
- The grid can be chosen at the command line. Regridding can be done at any time, for example taking the result of a rough grid computation and interpolating it onto a finer grid or vice versa.
- A moving boundary technique is used for the temperature equation which does not stretch the vertical in a singular manner; the Jenssen [35] change of variables is not used.
- The shallow shelf approximation (SSA) [65] is used to determine velocity in the ice shelf and ice stream regions. Like the full non-Newtonian Stokes equations, they are nonlinear and nonlocal equations for the velocity given the geometry of the streams and shelves and given the ice temperature. They are solved by straightforward iteration of linearized equations with numerically-determined (vertically-averaged) viscosity. Either plastic till or linear drag is allowed. As with all of PISM, the numerical approximation is finite difference. The linearized finite difference equations are solved by any of the Krylov subspace methods in PETSc [1], choosable at the command line.
- The model uses an explicit time stepping method for flow and a partly implicit method for temperature. Advection of temperature is upwinded [45]. As described in [9], reasonably rigorous stability criteria are applied to the time-stepping scheme, including a diffusivity-based criteria for the explicit mass continuity scheme and a CFL criteria [45] for temperature/age advection. The contributions to mass continuity from sliding of the base, including essentially all of the flow in the ice shelves, is approximated by an upwinding scheme.
- The local truncation error is generically first order (i.e. $O(\Delta x, \Delta y, \Delta z, \Delta t)$).
- The bed deformation model is implemented by a new Fourier collocation (spectral) method [10].
- Implementation is in C++ and is object-oriented. For example, verification occurs in a derived class of the base class. Also EISMINT II, EISMINT-Greenland, and EISMINT-Ross are each derived classes.

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Appendix A. PISM command line options

Much of the behavior of PISM can be set at the command line by options. For example, the command

```
$  pismv -test C -Mx 61 -gk -e 1.2 -o foo
```

includes five options "`-test`", "`-Mx`", "`-gk`", "`-e`", and "`-o`", The first of these options includes a single character argument, the second an integer argument, the third has no argument, the fourth has a floating point argument, and the fifth has a string argument.

The format of the option documentation below is

"`-optionname` [*A*] [`B` *only*]: Description."

Here "A" is the default value and "`B`" is a list of the allowed executables. The option applies to all executables (`pismr`, `pisms`, `pismv`) unless the allowed executables are specifically stated by giving "[`B` *only*]".

As PISM is a PETSc program, all PETSc options are available [1]. See the next section, which recalls some of these PETSc options.

`-adapt_ratio` [*0.12*]: Adaptive time stepping ratio for the explicit scheme for the mass balance equation.

`-bed_def_iso`: Compute bed deformations by simple pointwise isostasy. Assumes that the bed at the starting time is in equilibrium with the load so the bed elevation is equal to the starting bed elevation minus a multiple of the increase in ice thickness from the starting time, roughly: $b(t,x,y) = b(0,x,y) - f[H(t,x,y) - H(0,x,y)]$. Here f is the density of ice divided by the density of the mantle. See Test H in Verification section.

`-bed_def_lc`: Compute bed deformations, caused by the changing load of the ice, using a viscoelastic earth model. Uses the model and computational technique described in [10], based on the continuum model in [40].

`-bif` [`pismr, pgrn` *only*]: The model can be "bootstrapped" from certain NetCDF files using less than the full initial values for the system of evolution partial differential equations. See sections 5 for generalities and 9 for an example. Compare `-if`.

`-bmr_in_cont` [`pisms -eisII` *only*]: By default `pisms -eisII` does not include the basal melt rate in the continuity equation because EISMINT II specifies that it should not be included. This option makes `pisms -eisII` behave like the generic PISM cases (e.g. `pismr`).

`-chebZ`: Specify Chebyshev-spaced grid in the vertical. *This grid is extremely fine near the base*, and choice `-quadZ` is probably better justified (by current understanding of the thermo-coupling and age problems) than is `-chebZ`. Use only in combination with the option `-bif` or with executables `pisms` and `pismv`. That is, use only when creating a vertical grid from scratch. For a detailed description of the spacing of the grid, see the documentation on `IceGrid::setVertLevels()` in the *PISM Reference Manual*.

`-constant_hardness`: If this option is used then the velocities in ice shelves and streams (see `-mv` below) are computed with a constant, temperature-independent hardness parameter $\bar{B}$. In particular, the viscous stress term in the x-component (for example) of the SSA equations

for ice shelves and ice streams is

$$\frac{\partial}{\partial x}\left(2\nu H\left(2\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right)$$

where

$$\nu=\frac{\bar{B}}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\frac{1}{4}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}\right]^{(1-n)/(2n)}.$$

Generally $\bar{B}$ is computed by a vertical-integral of a function of the temperature field. If `-constant_hardness` is used then $\bar{B}$ is set to the given value.

In the case of `pismd -ross`, which performs the EISMINT Ross ice shelf intercomparison, a constant value $\bar{B}=1.9\times10^8\,\mathrm{Pa\,s}^{1/3}$ is the default [42].

`-constant_nu` [*30.0*]: If this option is used then the velocities in ice shelves and streams (see `-mv` below) are computed with a constant viscosity ν; see the option `-constant_hardness` above. Generally the viscosity is computed by a nonlinear iteration. With option `-constant_nu`, this iteration does not occur. If `-constant_nu` is set then `-constant_hardness` is ignored. The argument is given in units of MPa a, and the default value is 30 MPa a, the value given in [57].

`-ccl3` [`pgrn -forcing` *only*]: Run EISMINT-GREENLAND climate control experiment. See section 9

`-d`: Specifies diagnostic (X Windows) viewers. See Appendix C.

`-datprefix` [*PISM*] [`pisms -ismip H` *only*]: Specify base name for ISMIP-HEINO deliverable `.dat` files. See also `-no_deliver`.

`-dbig`: Specifies larger (about twice linear dimensions) diagnostic viewers. See Appendix C.

`-e` [*1.0*]: Flow enhancement factor.

`-eo` [`pismv` *only*]: Only evaluate the exact solution (don't do numerical approximation at all). See section 7.

`-eisII` [*A*] [`pisms` *only*]: Choose single character name of EISMINT II [51] simplified geometry experiment. Allowed values are A, B, C, D, E, F, G, H.

`-forcing` [`pgrn` *only*]: Uses a NetCDF file to apply changes in surface temperature and sea level. See section 9 for an example.

`-f3d`: Save the model state with additional full velocity field. That is, save all scalar components $u(x,y,z)$, $v(x,y,z)$, $w(x,y,z)$ of the velocity field for (x,y,z) everywhere in the three-dimensional computational box. Not needed when using `pismd`, for which saving the full three-dimensional velocity field is the default. Has the effect of (roughly) doubling the size of the output model state NetCDF file.

`-gk` [`pisms,pismr` *only*]: Sets the flow law to Goldsby-Kohlstedt. Same as `-law 4`. See `-law` for more complete option choice of flow law.

`-grad_from_eta`: The surface gradient is usually computed by simple centered-differences on the surface elevation. With this option it is computed by first transforming the thickness H

by $\eta = H^{(2n+2)/n}$ and then differentiating the sum of the thickness and the bed:

$$\nabla h = \nabla H + \nabla b = \frac{n}{(2n+2)} \eta^{(-n-2)/(2n+2)} \nabla \eta + \nabla b.$$

Here b is the bed elevation and h is the surface elevation. Note that only $n = 3$ is used in this transformation regardless of the chosen flow law. The transformation may have benefits in that the surface value of the vertical velocity may be better behaved near the margin, e. .g. as in EISMINT II experiments, but this is not yet clear. See [13] for the technical explanation of this transformation and compare [61].

`-hold_tauc`: Keep the current values of the till yield stress τ_c. That is, do not update them by the default model using the stored basal melt water. Only effective if `-ssa` and `-plastic` are also set. See documentation of option `-plastic` for a description of the till yield stress model.

`-gwl3` [`pgrn` *only*]: Run EISMINT-GREENLAND greenhouse warming. See section 9.

`-id`: Sets the x grid index at which a sounding diagnostic viewer (section C) is displayed. The integer argument should be in the range $0, \ldots,$ `Mx` $- 1$. The default is (`Mx` $- 1)/2$ at the center of the grid. For example, `pismv -test G -d t -id 10`.

`-if`: The model can be initialized (restarted) from a NetCDF file `foo.nc` written by the model, e.g. `foo.nc` from `-o foo -of n`. Compare `-bif`.

`-jd`: Sets the y grid index at which a sounding diagnostic viewer (section C) is displayed. The integer argument should be in the range $0, \ldots,$ `My` $- 1$. The default is (`My` $- 1)/2$ at the center of the grid. For example, `pismv -test G -d t -jd 10`.

`-kd` [*0*]: Sets the z grid index at which map-plane diagnostic views are shown. Compare `pismv -test G -Mz 101 -d T` and `pismv -test G -Mz 101 -d T -kd 50`. See section C.

`-law` [*0*]: Allows choice of thermocoupled flow law. The options are in table 15 below. Note that a "flow law" here means the function $F(\sigma, T, P, d)$ in the relation

$$\dot{\epsilon}_{ij} = F(\sigma, T, P, d)\, \sigma'_{ij}$$

where $\dot{\epsilon}_{ij}$ is the strain rate tensor, σ'_{ij} is the stress deviator tensor, T is the ice temperature, $\sigma^2 = \frac{1}{2}\|\sigma'_{ij}\|_F$ so σ is the second invariant of the stress deviator tensor, P is the pressure, and d is the grain size. That is, we are addressing isotropic flow laws only, and one can choose the scalar function. Note that the inverse form of such a flow law in needed for ice shelves and ice streams:

$$\sigma'_{ij} = 2\nu(\dot{\epsilon}, T, P, d)\, \dot{\epsilon}_{ij}$$

Here $\nu(\dot{\epsilon}, T, P, d)$ is the effective viscosity. The need for this inverse form of the flow law explains the "hybrid" law `-law 4` (or `-gk`).

`-low_temp` [*200.0*]: Set the temperature which PISM will regard as "too low". Units in Kelvin. Note that one kind of numerical error associated to the advection part of the conservation of energy scheme is for the maximum principle to be violated. In that case temperatures appear at the next step which are outside the range of current temperatures. PISM attempts to count such violations, and if the number is too great then the run is stopped. See option `-max_low_temps`.

TABLE 15. Choosing the flow law.

Flow Law	**Option**	**Comments and Reference**
Paterson-Budd law	`-law 0`	Fixed Glen exponent $n = 3$. There is a split "Arrhenius" term $A(T) = A\exp(-Q/RT^*)$ where $(A = 3.615 \times 10^{-13}\,\mathrm{s}^{-1}\,\mathrm{Pa}^{-3}, Q = 6.0 \times 10^4\,\mathrm{J\,mol}^{-1})$ if $T^* < 263$ K and $(A = 1.733 \times 10^3\,\mathrm{s}^{-1}\,\mathrm{Pa}^{-3}$, $Q = 13.9 \times 10^4\,\mathrm{J\,mol}^{-1})$ if $T^* > 263$ K and where T^* is the homologous temperature [48].
Cold part of Paterson-Budd	`-law 1`	Regardless of temperature, the A and Q values for $T^* < 263$ K in the Paterson-Budd law apply. This is the flow law used in the thermomechanically coupled exact solutions Tests **F** and **G** described in [9, 7] and run by `pismv -test F` and `pismv -test G`.
Warm part of Paterson-Budd	`-law 2`	Regardless of temperature, the A and Q values for $T^* > 263$ K in Paterson-Budd apply.
Hooke law	`-law 3`	Fixed Glen exponent $n = 3$. Here $A(T) = A\exp(-Q/(RT^*) + 3C(T_r - T^*)^\kappa)$; values of constants as in [26, 52].
Hybrid of Goldsby-Kohlstedt and Paterson-Budd	`-law 4`	Goldsby-Kohlstedt law with a combination of exponents from $n = 1.8$ to $n = 4$ [18] in grounded shallow ice approximation regions. Paterson-Budd flow for ice streams and ice sheets. See mask for SIA versus stream versus shelf by `-d m`.

`-Lx`: The x direction half-width of the computational box, in kilometers. See section 6.

`-Ly`: The y direction half-width of the computational box, in kilometers. See section 6.

`-Lz`: The height of the computational box for the ice (excluding the bedrock thermal model part). See section 6.

`-mato` [*pism_views*]: Specifies the name of the MATLAB-readable file in which to save the views. Use with `-matv`, to set which views to save; if `-matv` is not set then `-mato` has no effect.

`-matv`: Specifies which MATLAB "views" to save at end of run. See Appendix C for list of single character names of the views. The default is for *no* MATLAB views. See `-mato` for setting the name of the MATLAB-readable file in which to save the views. Typically the user will write `-mato foo -matv HT0c` to save four views in the MATLAB-readable ASCII file `foo.m`.

`-max_dt` [*60.0*]: The maximum time-step in years. The adaptive time-stepping scheme will make the time-step shorter than this as needed for stability, but not longer. See section 6.

`-max_low_temps` [*10*]: Specify the number (a nonnegative integer) of allowed low temp violations per time step. Note these are reported in detail (i.e. with location) if `-verbose` is set. Note that one kind of numerical error associated to the advection part of the conservation of energy scheme is for the maximum principle to be violated. In that case temperatures appear at the next step which are outside the range of current temperatures. PISM attempts to count

such violations, and if the number is too great then the run is stopped. See option `-low_temp` for the cutoff low temperature.

`-Mbz` [*1*]: Number of grid points in the bedrock for the bedrock thermal model. The highest grid point corresponds to the base of the ice $z = 0$, and so `Mbz`> 1 is required to actually have bedrock thermal model. Note this option is unrelated to the bed deformation model (glacial isostasy model); see option `-bed_def` for that.

`-Mmax` [`pisms -eisII` *only*]: Set value of $M_{\max}$ for EISMINT II.

`-mu_sliding` [*0*]: The sliding law parameter in SIA regions of the ice. This kind of sliding is used in experiments G and H of EISMINT II [51], but note that executable `pisms -eisII` ignors this parameter and uses the right amount of sliding for the given experiment.

`-Mx` [*61*]: Number of grid points in x horizontal direction.

`-My` [*61*]: Number of grid points in y horizontal direction.

`-Mz` [*31*]: Number of grid points in z (vertical) direction.

`-no_mass`: Forces PISM not to change the ice thickness. No time steps of the mass conservation equation are computed.

`-no_report` [`pismv` *only*]: Do not report errors at the end of a verification run.

`-no_temp`: Do not change temperature or age values within the ice. That is, do not do time steps of energy conservation and age equation.

`-o` [*unnamed.nc*]: Give name of output file: `-o foo` writes an output file named `foo.nc`. See the description of option `-if`. Default name is `unnamed.nc` under `pismr`, `simp_exper.nc` under `pisms`, and `verify.nc` under `pismv`.

`-ocean_kill`: If used with input from a NetCDF initialization file which has ice-free ocean mask, will zero out ice thicknesses in areas that were ice-free ocean at time zero. Has no effect when used in conjunction with `-no_mass`.

`-of` [*n*]: Format of output file(s). Possible values are `n` for model state written to a NetCDF file `foo.nc` and `m` for selected variables written to an ASCII Matlab file `foo.m`. PISM can be restarted using `-if` from the output `.nc` files. Multiple files can be written, for instance, `-o foo -of nm` writes both `foo.nc` and `foo.m`.

`-pause` [`pismd -ross,pismv -test I,pismv -test J` *only*]: Pause for given number of seconds at the end of the run when the results are displayed.

`-pdd`: Turns on the positive degree day model (which is off by default for `pismr`, `pisms`, and `pismv`). Use the method described in [12], which computes the expected number of positive degree days. See subsection 6.5.

`-pdd_rand`: Turns on the positive degree day model (which is off by default for `pismr`, `pisms`, and `pismv`). Use a monte carlo method based on a random number generator. Note that if `-pdd_std_dev 0.0` is set then the additional randomness is not active. See subsection 6.5.

`-pdd_rand_repeatable`: Same effect as `pdd_rand` but additionally sets the "seed" for the random number generator to a default. This makes runs based on the monte carlo method repeatable.

`-pdd_factor_ice` [*0.008*]: The amount of ice, measured in meters, which is melted per positive degree day. In units of m °C^{-1}day^{-1}. See subsection 6.5.

`-pdd_factor_snow` [*0.003*]: The amount of snow, measured in meters ice-equivalent, which is melted per positive degree day. In units of m °C^{-1}day^{-1}. See subsection 6.5.

`-pdd_refreeze` [*0.6*]: Fraction of melted snow, from positive degree day melting, which locally refreezes as ice (and therefore adds to accumulation). See subsection 6.5.

`-pdd_std_dev` [*5.0*]: Standard deviation of temperature increment added each day to temperature cycle in positive degree day model. Units of °C. See subsection 6.5.

`-pdd_summer_peak_day` [*243.0*]: Julian day of peak summer temperature. Default of August 1st is clearly not appropriate to Antarctica! See subsection 6.5.

`-pdd_summer_warming` [*15.0*]: Difference between peak summer temperature and mean annual temperature at each grid location. Units of °C. See subsection 6.5. Note `pgrn` ignors this option; see section 9.

`-plastic`: Use Schoof's plastic till model for ice streams at all grounded points on the ice sheet. Must be used along with `-ssa` to turn on the solution of the SSA (shallow shelf approximation). See subsection 4.4. See options `-plastic_reg`, `-plastic_c0`, `-plastic_phi`, and `-plastic_pwfrac`, all of which control the plastic till model in various ways.

Indeed, we describe the role of the parameters for the plastic till model as follows: The effective pressure N on the till is

$$N = P - p = (1 - (\texttt{pwfrac})\lambda)P$$

where $P = \rho g H$ is the overburden or hydrostatic pressure at the base (see Paterson [47], pp. 168–169) and $p = (\texttt{pwfrac})\lambda P$ is the pore water pressure in the till. Here λ is a pure number, $0 \le \lambda \le 1$, measuring the amount of available basal water. In particular, $\lambda = 0$ if the base is frozen, while λ is a linear function of the stored basal melt water (see `-d L`), up to the fixed maximum amount of stored basal melt water. Thus our model says that when there is a lot (the maximum) amount of available basal water, $p = (\texttt{pwfrac})P$; the default value for `pwfrac` is 0.95.

Note that Paterson gives this formula for the till yield stress

$$\tau_c = c_0 + \mu N, \qquad \mu = \tan\phi,$$

while Schoof [62] formula (2.4) gives this one

$$\tau_c = \mu N,$$

with zero till cohesion. We allow a positive till cohesion, though the default is zero, and we describe μ as the tangent of the friction angle ϕ.

`-plastic_c0` [*0.0*]: Set the value of the till cohesion in the plastic till model. The value is a pressure, given in kPa. Only effective if used with `-plastic` and `-ssa`.

Note Schoof [62] formula (2.4) uses $c_0 = 0$.

`-plastic_pwfrac` [*0.95*]: Set what fraction of overburden pressure is assumed as the till pore water pressure. Only relevant at basal points where there is a positive amount of basal water. The value is a pure number. Only effective if used with `-plastic` and `-ssa`.

`-plastic_reg` [*0.01 m/a*]: Set the value of ϵ regularization of plastic till; this is the second "ϵ" in formula (4.1) in [62]. Only effective if used with `-plastic` and `-ssa`.

`-plastic_phi` [*30.0*]: Set the till friction angle. The value is an angle ϕ, given in degrees, and the coefficient μ in formula (2.4) in [62] is computed from θ by this formula:

$$\mu = \tan\left(\frac{\pi}{180}\theta\right).$$

Only effective if used with `-plastic` and `-ssa`.

`-quadZ`: Specify quadratically-spaced grid in the vertical. Use only in combination with the option `-bif` or with executables `pisms` and `pismv`. That is, use only when creating a vertical grid from scratch. For a detailed description of the spacing of the grid, see the documentation on `IceGrid::setVertLevels()` in the *PISM Reference Manual*.

`-regrid`: See section 6.

`-regrid_vars`: See section 6.

`-reg_length_schoof` [*1000 km*]: Set the "L" in formula (4.1) in [62]. To use the regularization described by Schoof, one must set `-ssa_eps 0.0` to turn off the other regularization mechanism, otherwise there is a double regularization.

`-reg_vel_schoof` [*1 m/a*]: Set the *first* "ϵ" in formula (4.1) in [62]. To use the regularization described by Schoof, one must set `-ssa_eps 0.0` to turn off the other regularization mechanism, otherwise there is a double regularization. Use `-plastic_reg` above to set the second "ϵ" in formula (4.1) of [62].

`-Rel` [`pisms -eisII` *only*]: Set value of R_{el} for EISMINT II.

`-ross` [`pisms` *only*]: Run the EISMINT Ross ice shelf validation [42]. Requires data from `http://homepages.vub.ac.be/~phuybrec/eismint/iceshelf.html`.

`-Sb` [`pisms -eisII` *only*]: Set value of S_b for EISMINT II.

`-ssa`: Use the equations of the shallow shelf approximation [41, 43, 62, 65] for ice shelves and dragging ice shelves (i.e. ice streams) where so-indicated by the mask. To view the mask use `-d m`. See also `-plastic` and `-super`.

`-ssa_eps` [*1.0e15*]: The numerical scheme for the shallow shelf approximation [65] computes an effective viscosity which which depends on velocity and temperature. After that computation, this constant is added to the effective viscosity (to keep it bounded away from zero). The units are kg $\text{m}^{-1}\,\text{s}^{-1}$.

In fact there is a double regularization by default because the Schoof regularization mechanism described in equation (4.1) of [62] is also used. Turn off this lower bound mechanise by `-ssa_eps 0.0` to exclusively use the Schoof regularization mechanism; see `-reg_vel_schoof` and `-reg_length_Schoof` below. Note `-ssa_eps` is set to zero automatically when running `pismv -test I`.

`-ssa_maxi` [*300*]: This option sets the maximum allowed number of nonlinear iterations in solving the shallow shelf approximation. One should usually use option `-ssa_rtol` to control convergence of the nonlinear iteration.

`-ssa_rtol` [*1.0e-4*]: The numerical scheme for the shallow shelf approximation [65] does a nonlinear iteration wherein velocities (and temperatures) are used to compute a vertically-averaged effective viscosity which is used to solve the equations for horizontal velocity. Then the new velocities are used to recompute an effective viscosity, and so on. This option sets the relative change tolerance for the effective viscosity.

In particular, the nonlinear part of the iteration requires that successive values $\nu^{(k)}$ of the vertically-averaged effective viscosity satisfy

$$\frac{\|(\nu^{(k)} - \nu^{(k-1)})H\|_2}{\|\nu^{(k)}H\|_2} \le \text{ssa\_rtol}$$

in order to end the iteration with $\nu = \nu^{(k)}$. See also `-ksp_rtol`, a PETSc option below, as one may want to require a high relative tolerance for the linear iteration as well.

`-ssl2` [`pgrn` *only*]: Run EISMINT-GREENLAND steady state experiment level 2. See section 9.

`-ssl3` [`pgrn` *only*]: Run EISMINT-GREENLAND steady state experiment level 3. Use with option `-gk`: "`pgrn -ssl3 -gk`. See section 9.

`-ST` [`pisms -eisII` *only*]: Set value of S_T for EISMINT II.

`-super`: Superpose the velocity fields from the SIA and SSA models. That is, add the velocity fields which result from the SIA and SSA versions of the balance of momentum equations. Also has the effect of the option `-mu_sliding 0.0`, that is, the SIA-type sliding law is set to zero so that all basal sliding is controlled by the SSA model. Only effective if used with `-ssa`.

`-tempskip` [*1*]: Number of mass-balance steps to perform before a temperature step is executed. Only effective if the time step is being limited by the diffusivity time step restriction associated to mass continuity using the SIA, or by the CFL restriction associated to SSA-type mass continuity. A maximum value of `-tempskip 5` is recommended to avoid too many CFL violations.

`-test` [*A*] [`pismv` *only*]: Choose which verification test to run by giving its single character name. See section 7.

`-till_phi` [*20.0,5.0*] [`pisms -eisII I -ssa -plastic` *only*]: Set the till friction angle map special to the modification of EISMINT II experiment I discussed in subsection 4.4.

`-Tmin` [`pisms -eisII` *only*]: Set value of $T_{\min}$ for EISMINT II.

`-track_Hmelt` [`pisms -eisII` *only*]: Turn on the part of the conservation of energy model which accumulates (tracks) locally-stored basal melt water.

`-verbose`: Increased verbosity of standard output. Can be given without argument ("`-verbose`") or with a level which is one of the integers 0,1,2,3,4,5 ("`-verbose 2`"). The full scheme is given in table 16.

`-vverbose`: See table 16.

TABLE 16. Controlling the verbosity level to standard out.

Level	Option	Meaning
0	`-verbose 0`	never print to standard out *at all*; no warnings appear
1	`-verbose 1`	only warning messages and other high priority messages will appear
2	[`-verbose 2`]	default verbosity
3	`-verbose 3`	somewhat verbose; expanded description of grid at start
	or `-verbose`	and expanded information in summary
4	`-verbose 4`	
	or `-vverbose`	more verbose
5	`-verbose 5`	
	or `-vvverbose`	maximally verbose

`-vvverbose`: See table 16.

`-y` [*1000*]: Number of model years to run.

`-ye`: Model year at which to end the run.

`-ys` [*0*]: Model year at which to start the run.

Appendix B. PETSC command line options (for PISM users)

All PETSc programs accept command line options which control the manner in which PETSc distributes jobs among parallel processors, how it solves linear systems, what additional information it provides, and so on. The PETSc manual (`http://www.mcs.anl.gov/petsc/petsc-as/snapshots/petsc-current/docs/manual.pdf`) is the complete reference on these options. Here we list some that are perhaps most useful to PISM users.

`-da_processors_x`: Number of processors in x direction.

`-da_processors_y`: Number of processors in y direction.

`-display`: The option `-display :0` seems to frequently be needed to let PETSc use Xwindows when running multiple processes. *It must be given as a* final *option, after all the others.*

`-help`: Gives PISM help message and then a brief description of many PETSc options.

`-info`: Gives excessive information about PETSc operations during run. Option `-verbose` for PISM (above) is generally more useful, except possibly for debugging.

`-ksp_rtol` [*1e-5*]: For solving the SSA equations with high resolution on multiple processors, it is recommended that this be tightened (set lower than the default). For example,

```
$  mpiexec -n 8 pismv -test I -Mx 5 -My 769
```

works poorly on a certain machine, but

```
$  mpiexec -n 8 pismv -test I -Mx 5 -My 769 -ksp_rtol 1e-10
```

works fine.

`-ksp_type` [*gmres*]: Based on one processor evidence from `pismv -test I`, the following are possible choices in the sense that they work and allow convergence at some reasonable rate: `cg`, `bicg`, `gmres`, `bcgs`, `cgs`, `tfqmr`, `tcqmr`, and `cr`. It appears `bicg`, `gmres`, `bcgs`, and `tfqmr`, at least, are all among the best.

`-log_summary`: At the end of the run gives a performance summary and also a synopsis of the PETSc configuration in use.

`-pc_type` [*ilu*]: Several options are possible, but for solving the ice stream and shelf equations we recommend only `bjacobi`, `ilu`, and `asm`. Of these it is not currently clear which is fastest; they are all about the same for `pismv -test I` with high tolerances (e.g. `-ssa_rtol 1e-7 -ksp_rtol 1e-12`).

`-v`: Show version number of PETSc.

Appendix C. PISM viewers: Graphical and Matlab

Viewing the PISM state. Basic graphical views of the changing state of a PISM ice model are available at the command line by using the options "`-d`" and "`-dbig`" with additional arguments. For instance:

```
$  pismv -test G -d hTf -dbig 0
```

shows a map-plane views of surface elevation ("`h`"), temperature at the level specified by `-kd` ("`T`"), rate of change of thickness ("`f`") and of horizontal ice speed at the surface ("`0`", i.e. zero).

The option `-d` is followed by a space and then a list of single-character names of the diagnostic viewers. The option `-dbig` works exactly the same way, with the same list of single-character names available. The bigger viewers take precedence, so that "`-d hT -dbig T`" shows only two viewers, namely a regular size viewer for surface elevation and a larger viewer for temperature.

The same views of the PISM model can be saved *at the end of the run* to a Matlab-readable ASCII file by the same single character names. (At this point, *most* of the names are allowed; see the list below.) We will call these "Matlab views". For instance,

```
$  pismv -test G -mato foo -matv hTf0
```

will save surface elevation ("`h`"), temperature at the level specified by `-kd` ("`T`"), rate of change of thickness ("`f`") and of horizontal ice speed at the surface ("`0`") in an ASCII file `foo.m`. To use `foo.m` at the Matlab command line, make sure the Matlab path includes the directory with `foo.m`. Then just do

```
>> foo
```

You will be able to plot the surface elevation (for example) by

```
>> imagesc(x,y,flipud(H')), axis square, colorbar
```

but you can also use the Matlab tools `contour`, `surf`, and so on. (*The necessity to do* "`flipud(H')`" *to get the expected orientation, that is, the necessity of doing both do a transpose* and *a* `flipud`, *is for various deep reasons too complicated to explain here. Feel free to enquire, but* sorry *in the meantime.*)

Single character names (for each view). The single character diagnostic viewer and Matlab views names are:

`0`: Map-plane view of horizontal ice speed (magnitude of velocity) at the surface of the ice in meters per year.

`1`: Map-plane view of x-component of horizontal ice velocity at the *surface* of the ice in meters per year.

`2`: Map-plane view of y-component of horizontal ice velocity at the *surface* of the ice in meters per year.

`3`: Map-plane view of vertical ice velocity at the *surface* of the ice in meters per year; positive values are upward velocities.

`4`: Map-plane view of x-component of horizontal ice velocity at the *base* of the ice in meters per year.

`5`: Map-plane view of y-component of horizontal ice velocity at the *base* of the ice in meters per year.

`A`: Map-plane view of snow accumulation in ice-equivalent meters per year. Viewer `-d A` is different from `-d a` only if positive degree day model is turned on; see viewer `A` below.

`B`: Map-plane view of basal drag coefficient β for ice stream regions. β has units of Pa s m^{-1}. Displayed as log base ten of β.

`C`: Map-plane view of basal till yield stress τ_c, under plastic till ice stream model. Units of kPa.

`D`: (*NOT available as a* MATLAB *view.*) Map-plane view of diffusivity coefficient D in mass balance equation in m^2/s. Meaningful only in regions of shallow ice flow.

`E`: Map-plane view of age of the ice, in years.

`F`: Map-plane view of basal geothermal heat flux, in milliWatts per meter squared.

`H`: Map-plane view of thickness in meters.

`L`: Map-plane view of basal melt water *thickness* in meters.

`P`: (*NOT available as a* MATLAB *view.*) (*ONLY available for* `pismv`.) Map-plane view of comPensatory heating term Σ_C in thermocoupled verification tests F and G. Displayed at chosen elevation above base; see option `-kd`.

`Q`: Map-plane view of basal driving stress $f_{\text{basal}} = \rho g H |\nabla h|$. Units of kPa. Note that this quantity is the effective shear stress at the base in the SIA. It is also the (magnitude of the) driving source term in the SSA, for both ice streams and ice shelves. Compare to `-d C`, the view of the till yield stress, when using the plastic till ice stream model.

`R`: Map-plane view of basal frictional heating in milliWatts per meter squared.

`S`: Map-plane view of strain heating term Σ in temperature equation, in Kelvin per year. Displayed at chosen elevation above base; see option `-kd`.

`T`: Map-plane view of absolute ice temperature in Kelvin. Displayed at chosen elevation above base; see option `-kd`.

`U`: Map-plane view of vertically averaged horizontal velocity in the x-direction *on the staggered grid* which is offset by positive one in i direction; in meters per year. (*Meaningful only in technical/numerical context*; use `u` generally.)

`V`: Map-plane view of vertically averaged horizontal velocity in the y-direction *on the staggered grid* which is offset by positive one in j direction; in meters per year. (*Meaningful only in technical/numerical context*; use `v` generally.)

`X`: Map plane view of x-component of horizontal velocity, in meters per year. Displayed at chosen elevation above base; see option `-kd`.

`Y`: Map plane view of y-component of horizontal velocity, in meters per year. Displayed at chosen elevation above base; see option `-kd`.

`Z`: Map plane view of vertical velocity, in meters per year. Displayed at chosen elevation above base; see option `-kd`.

`a`: Map-plane view of ice surface mass balance in ice-equivalent meters per year. Note `-d A` gives snow accumulation rate but `-d a` shows melting included in the surface balance if the positive degree day model is turned on; see options `-pdd` and `-pdd_rand` in Appendix A. If positive degree day model is off then `-d a` and `-d A` give the same view.

`b`: Map-plane view of bed elevation in meters above sea level.

`c`: Map-plane view of horizontal speed, namely the absolute value of the vertically-averaged horizontal velocity. Displayed as log base ten of speed in meters per year.

`e`: Age in a vertical column (sounding); in years. See `-id`, `-jd` to set sounding location.

`f`: Map-plane view of thickening rate of the ice, in meters per year.

`h`: Map-plane view of ice surface elevation in meters above sea level.

`i`: Map-plane view of vertically-averaged effective viscosity times thickness; on i offset grid. Only meaningful in ice streams and shelves.

`j`: Map-plane view of vertically-averaged effective viscosity times thickness; on i offset grid. Only meaningful in ice streams and shelves.

`k`: (*NOT available as a* MATLAB *view.*) Iteration monitor for the Krylov subspace routines (KSP) in Petsc. Shows norm of residual versus iteration number. Has same effect as PETSc option `-ksp_monitor_draw`.

`l`: Map-plane view of basal melt *rate* in meters per year.

`m`: Map-plane view of mask for flow type: **1** = grounded shallow ice sheet flow, **2** = dragging ice shelf, **3** = floating ice shelf, 7 = ice free ocean (in original input file).

`n`: Map-plane view of the log base ten of the vertically-averaged effective viscosity times thickness on the regular grid. Only meaningful in ice streams and shelves.

`p`: Map-plane view of bed uplift rate in meters per year.

`q`: Map-plane view of basal sliding speed. Displayed as log base ten of speed in meters per year.

`r`: Map-plane view of surface temperature in Kelvin.

`s`: Strain heating term Σ in vertical column (sounding). See `-id`, `-jd` to set sounding location.

`t`: Absolute ice temperature in vertical column (sounding). Note this sounding extends into the bedrock, unlike the other soundings (e.g. `-d egsxyz`). See `-id`, `-jd` to set sounding location.

`u`: Map-plane view of vertically averaged horizontal velocity in the x-direction; in meters per year.

`v`: Map-plane view of vertically averaged horizontal velocity in the y-direction; in meters per year.

`x`: x-component of horizontal velocity in vertical column (sounding). See `-id`, `-jd` to set sounding location.

`y`: y-component of horizontal velocity in vertical column (sounding). See `-id`, `-jd` to set sounding location.

`z`: Vertical velocity (w-component of velocity) in vertical column (sounding). See `-id`, `-jd` to set sounding location.

Appendix D. Python scripts for PISM modeling

The following scripts, among others, are found in subdirectory `pism/test/`.

fill_missing.py. This script uses an approximation to Laplace's equation

$$\nabla^2 u = 0$$

to smoothly replace missing values in two-dimensional NetCDF variables with the average of the "nearby" non-missing values.

This example of filling the missing values in several variables is probably complete documentation (if not, see the source code):

```
fill_missing.py -i data.nc -v b,H,Ts -o data_smoothed.nc
```

Note that *each* of the listed variables must have an attribute named `missing_value`.

series.py. This Python script postprocesses the standard output of `pismr`, `pisms`, `pgrn`, or `pismv` if it is stored in a text file. (That is, standard output from the PISM *evolution* executables. Output from `pismd`, an executable for diagnostic runs, is not supported.)

Time series are extracted from the text file containing the standard output. Typically this means time series for ice sheet volume, area, melt fraction, thickness at the center of the grid, and temperature of the base of the ice at the center of the grid. Also the time series for the time step length itself is extracted. These time series are put into a one-dimensional NetCDF file.

An example usage is

```
$  pisms -eisII A -Mx 61 -My 61 -Mz 201 -y 5000 >> eisIIA.out
$  series.py -f eisIIA.out -o eisIIA_series.nc
$  ncview eisIIA_series.nc
```

For temperature-dependent SIA `pismv` output (tests F,G,K) run as above, but for isothermal SIA `pismv` output (tests A,B,C,D,E,L) add the option "`-i`":

```
$  pismv -test C >> testC.out
$  series.py -i -f testC.out -o testC_series.nc
```

In this case `series.py` only extracts time series for volume, area, and central thickness.

Note that the small number of digits reported in the standard output from the PISM executables may limit the utility of the resulting time series. That is, the time series may mostly show discrete steps which result from the small number of digits reported rather than from the (unreported) full precision volume, area, etc.

`series.py` takes the following options. They have both a short form and a long form, *a la* GNU; the default is in brackets:

`-f`, `--file=` [*foo.txt*]: Specify the name of the text file.

`-i`, `--isopismv=` [*False*]: If "`-i`" is given then `series.py` assumes the text file came from using `pismv` on an isothermal SIA verification test.

`-o`, `--out=` [*series_out.nc*]: Give the full name, including the `.nc` extension, of the output NetCDF file.

ssl_exper.py. This Python script is actually special to the EISMINT-Greenland experiment described in section 9. It is worth documenting here in part because it is an example of using scripts with NCO, and in part because we need to document its options to help readers of section 9.

[FIXME: DOCUMENT THE OPTIONS!]

verifynow.py. This Python script organizes the process of verifying PISM. It specifies standard refinement paths for each of the tests described in section 7. It runs the tests, times them, and summarizes the numerical errors reported at the end.

Three example usages are

- "`verifynow.py`" without options will use one processor and do three levels of refinement; this command is equivalent to `verifynow.py -n 1 -l 3 -t CGIJ`
- "`verifynow.py -n 8 -l 5 -t J --prefix=bin/ --mpido=mpirun/`" will use `mpirun -np 8 bin/pismv` as the command and do five levels (the maximum) of refinement only on test J
- "`verifynow.py -n 2 -l 3 -t CEIJGKL -u 1`" uses the two cores on my laptop and runs in about two hours; the vertical spacing is not equal (its `-quadZ`)
- "`verifynow.py -n 40 -l 5 -t ABCDEFGIJKL`" will use forty processors to do all possible verification as managed by `verifynow.py`; don't run this unless you have a big computer and you are prepared to wait

`verifynow.py` takes the following options. They have both a short form and a long form, *a la* GNU; the default is in brackets:

`-l`, `--levels=` [*3*]: specifies number of levels of refinement; $1, 2, 3, 4, 5$ are allowed values

`-m`, `--mpido=` [*mpiexec*]: how to run PISM as an MPI program

`-n`, `--nproc=` [*1*]: specify number of processors to use

`-p`, `--prefix=` []: where the PISM executable `pismv` is located

`-t`, `--tests=` [*CGIJ*]: which tests to run

`-u`, `--unequal=` [*0*]: spacing in vertical: `-u 0` is default equal spacing, `-u 1` adds option `-quadZ` to `pismv` call, and `-u 2` adds option `-chebZ` to `pismv` call; see documentation on options `-quadZ` and `-chebZ`

Note that timing information is also given in the `verifynow.py` output. Therefore performance, including parallel performance, can be assessed along with accuracy.

The exact meaning of the various errors reported by `pismv`, which appear in a `verifynow.py` output as well, is currently only documented in the source files `pism/src/verif/iceCompModel.cc`, `pism/src/verif/iCMthermo.cc`, and `pism/src/verif/iceExactSSAModel.cc`.

vnreport.py. This Python script postprocesses the standard output of `verifynow.py` above. The output is converted into graphs using `gnuplot`. Example graphs are Figures 3 through 8 in section 7.

The basic use is this:

```
$  verifynow.py -n 2 -l 3 -t BGIK >> foo.txt
```

```
$  vnreport.py -f foo.txt -t B -e 'geometry' -o thickerrs
```

(Figures 3 through 8 in section 7 were actually generated by a level five ("`-l 5`") `verifynow.py` run, but that takes a lot of computer time.)

The `verifynow.py` run will take a while. The `vnreport.py` run will (quickly) look at `foo.txt` and extract the geometry (thickness) numerical errors and refinement path and build a `.eps` (encapsulated Postscript) image like that in Figure 3.

The `Makefile` in the documentation directory `pism/doc/` gives more example usages. In fact, `vnreport.py` is primarily used to automate the creation of this manual. This `Makefile` also shows how to use Ghostscript to convert the `.eps` images to `.png` (Portable Network Graphics) format.

`vnreport.py` takes the following options:

`-e`, `--error=` [*'geometry'*]: which kind of error to look for; for example, with test E the valid possibilities are `'geometry'` and `'base vels'`

`-f`, `--file=` [*foo.txt*]: name of the text file containing the `verifynow.py` report

`-o`, `--out=` [*report*]: prefix of output file name; if "`-t G -o bar`" then output file is named "`bar_G.eps`"

`-t`, `--test=` [*A*]: the test for which to find the `verifynow.py` report; only one value allowed

`-x`, `--exclude=` []: specify tags of errors to exclude from the figure