The CESM Land Ice Model: Documentation and User's Guide

William Lipscomb
Los Alamos National Laboratory
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1. Introduction

This document accompanies the Community Earth System Model (CESM) User's Guide and is intended for those who would like to run CESM with dynamic ice sheets and/or an improved surface mass balance scheme for glaciated regions. Users running CESM fully coupled should also refer to the CESM User's Guide.

The rest of this section describes the scientific motivation for improved land-ice models and gives a brief history of land-ice model development within CESM. Section 2 describes Glimmer, the Community Ice Sheet Model (Glimmer-CISM), the dynamic ice sheet model in CESM. Section 3 gives a detailed description of the surface-mass-balance scheme for ice sheets in the Community Land Model (CLM). Section 4 lists some anticipated model improvements.

It should be emphasized that this is an initial implementation with a number of scientific limitations that are detailed below. Model developers are keenly aware of these limitations and are actively addressing them. Several major improvements are planned for the next one to two years and will be released as they become available.

This documentation is itself in progress. If you find errors, or if you would like to have some additional information included, please contact the lead author at lipscomb@lanl.gov.

1.1 Scientific background

Historically, ice sheet models were not included in global climate models (GCMs), because they were thought to be too sluggish to respond to climate change on decade-to-century time scales. In the Community Climate System Model (CCSM), as in many other global climate models, the extent and elevation of the Greenland and Antarctic ice sheets were assumed to be fixed in time. Interactions between ice sheets and other parts of the climate system were largely ignored.

Recent observations, however, have established that both the Greenland and Antarctic ice sheets can respond to atmospheric and ocean warming on time scales of a decade or less. Satellite gravity measurements show that both ice sheets are losing mass at rates of more than 200 Gt/yr, roughly double the values from earlier this decade (Velicogna 2009). (A mass loss of 360 Gt corresponds to global sea-level rise of 1 mm.) Greenland mass loss is caused by increased surface melting and the acceleration of large outlet glaciers (van den Broeke et al. 2009). In Antarctica, mass is being lost primarily because of the acceleration of outlet glaciers, especially in the Amundsen Sea Embayment of West Antarctica (Rignot et al. 2008).

Small glaciers and ice caps (GIC) also have retreated in recent years. Although the total volume of GIC (~0.6 m sea-level equivalent; Radić and Hock 2010) is much less than that of the Greenland ice sheet (~7 m) and the Antarctic ice sheet (~60 m), glaciers and ice caps can respond quickly to climate change. Mass loss from GIC has grown during the past decade and is now about about 400 Gt/yr (Meier et al. 2007). GCMs generally assume that the mass of glaciers and ice caps, like that of ice sheets, is fixed.

Global sea level is currently rising at a rate of about 30 cm/century, with primary contributions from land ice retreat and ocean thermal expansion. One recent study (Cazenave et al. 2008) suggests that land ice accounts for about 80% of recent sea-level rise. Estimates of 21^{st} century ice-sheet mass loss and sea-level rise are highly uncertain. The IPCC Fourth Assessment Report (Meehl et al. 2007) projected 18 to 59 cm of sea-level rise by 2100 but specifically excluded ice-sheet dynamical feedbacks, in part because existing ice sheet models were deemed inadequate. A widely cited semi-empirical study (Rahmstorf 2007) estimated 40 to 150 cm of 21^{st} century sea-level rise, based on the assumption that the rate of rise is linearly proportional to the increase in global mean temperatures from preindustrial values. This assumption may not be valid as additional land-ice processes come into play.

Modeling of land ice has therefore taken on increased urgency. Many recent workshops (e.g., Little et al. 2007; Lipscomb et al. 2009) have called for developing improved ice sheet models. There is general agreement on the need for (1) “higher-order” flow models with a unified treatment of vertical shear stresses and horizontal-plane stresses, (2) finer grid resolution (~5 km or less) for ice streams, outlet glaciers, and other regions where the flow varies rapidly on small scales, and (3) improved treatments of key physical processes such as basal sliding, subglacial water transport, iceberg calving, and grounding-line migration. These improvements are beginning to be incorporated in a number of ice sheet models. One such model is Glimmer, the Community Ice Sheet Model (Glimmer-CISM), which has been coupled to CESM and is described below.

Although much can be learned from ice sheet models in standalone mode, coupled models are required to capture important feedbacks. For example, surface ablation may be underestimated if an ice sheet model is forced by an atmospheric model that does not respond to changes in surface albedo and elevation (Pritchard et al. 2008). At ice sheet margins, floating ice shelves are closely coupled to the ocean in ways that are just beginning to be understood and modeled (Holland et al. 2008a, 2008b). Also, changes in ice sheet elevation and surface runoff could have significant effects on regional and global circulation of the atmosphere and ocean.

1.2 Ice sheets in CESM

Since 2006, researchers in the Climate, Ocean and Sea Ice Modeling (COSIM) group at Los Alamos National Laboratory (LANL) have worked with scientists at the National

Center for Atmospheric Research (NCAR) to incorporate an ice sheet model in the CCSM/CESM framework. This work was funded primarily by the DOE Scientific Discovery through Advanced Computing (SciDAC) program, with additional support from NSF. The Glimmer ice sheet model (Rutt et al. 2009), developed by Tony Payne and colleagues at the University of Bristol, was chosen for coupling. Although Glimmer's dynamical core was relatively basic, a higher-order dynamics scheme was under development. In addition, the model was well structured and well documented, with an interface (GLINT) to enable coupling to GCMs.

Glimmer was initially coupled to CCSM version 3.5. The surface mass balance (SMB; the difference between annual accumulation and ablation) was computed using Glimmer's positive-degree-scheme, which uses semi-empirical formulas to relate surface temperatures to summer melting. It was decided that the PDD scheme was not appropriate for climate change modeling, because empirical relationships that are valid for present-day climate may not hold in the future. Instead, a surface-mass-balance scheme for ice sheets was developed for the Community Land Model (CLM). This scheme computes the SMB in each of ~10 elevation classes per gridcell in glaciated regions. The SMB is passed via the coupler to the ice sheet component, where it is averaged, downscaled, and used to force the dynamic ice sheet model at the upper surface. When the CCSM4 framework became available, the coupling was redone for the new framework. Details of the SMB scheme are given in Section 3.

In 2009 the U.K. researchers who had created Glimmer joined efforts with U.S. scientists who were developing a Community Ice Sheet Model (CISM), and the model was renamed Glimmer-CISM. Model development is overseen by a six-member steering committee including Magnus Hagdorn (U. Edinburgh), Jesse Johnson (U. Montana), William Lipscomb (LANL), Tony Payne (U. Bristol), Stephen Price (LANL), and Ian Rutt (U. Swansea). The model resides on the BerliOS repository (http://glimmer-cism.berlios.de/). It is an open-source code governed by the GNU General Public License and is freely available to all. The version included in the initial CESM release is a close approximation of Glimmer-CISM version 1.6.

The ice sheet model in the initial CESM release has several limitations that should be noted by users:

- The model is technically supported but is still undergoing scientific testing. We cannot guarantee that the default values of model parameters will yield an optimal simulation. Scientific validation is under way, and optimized configuration files will be included in releases later in 2010.
- Glimmer-CISM has been coupled to CLM, but the current coupling is one-way. That is, the surface mass balance computed by CLM is passed to Glimmer-CISM and used to drive ice sheet evolution, but the resulting ice sheet topography is not used to update the surface elevation or landunit types in CLM. Two-way coupling is under development and should be ready later in 2010.
- The dynamical core is similar to that in the original Glimmer code and is based on the shallow-ice approximation (SIA). The SIA is valid in the interior of ice sheets, but not in fast-flowing regions such as ice shelves, ice streams, and outlet

glaciers. A higher-order scheme that is valid in all parts of the ice sheet is being tested and will become part of CESM later in 2010 with the release of Glimmer-CISM version 2.0.

- The current Glimmer-CISM code is serial. This is not a limitation for the SIA model, which is computationally fast, but will be an issue for the higher-order model. A parallel version of the code is under development and is expected to be available by 2011.
- The ice sheet model has not been coupled to the ocean model. That coupling is under development, with plans for release in 2011. For this reason the initial implementation is for the Greenland ice sheet only. Since ice-ocean coupling is critical for the dynamics of the Antarctic ice sheet, it was decided that Antarctic simulations without ocean coupling would be of limited scientific value.

2. The dynamic ice sheet model

This section gives a brief overview of ice flow modeling and of Glimmer-CISM, the dynamic ice sheet model in CESM. For more details, including a technical description of the model, please see Rutt et al. (2009) and the Glimmer-CISM documentation. The documentation is slightly out of date but still provides a useful description of Glimmer-CISM's dynamical core (GLIDE) and climate model interface (GLINT). Updated documentation will be provided with the release of Glimmer-CISM 2.0 later in 2010.

2.1. Equations of ice flow

Here we give a brief overview of the equations of ice flow. For more details, see, e.g., Greve and Blatter (2009) and the Glimmer-CISM documentation.

An ice sheet is typically modeled as an incompressible, heat-conducting, viscous, non-Newtonian fluid. The basic field equations can be written as (e.g., Pattyn 2003)

$$\nabla \bullet \mathbf{u} = 0 , \tag{1}$$

$$\rho \frac{d\mathbf{u}}{dt} = \nabla \bullet \sigma + \rho \mathbf{g} , \tag{2}$$

$$\rho \frac{d(c_p T)}{dt} = \nabla (k \nabla T) + \Phi , \tag{3}$$

where ρ is the ice density, $\mathbf{u}$ is the 3D velocity, T is the temperature in degrees Celsius, $\mathbf{g}$ is the gravitational acceleration, σ is the stress tensor, c_p is the specific heat of ice, k is the thermal conductivity, and Φ is the deformational heat source. These three equations express conservation of mass, linear momentum, and energy, respectively. The continuity equation (1) implies that glacier ice is incompressible.

In Cartesian coordinates (x, y, z) with $\mathbf{g} = (0, 0, -g)$, the continuity equation becomes

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\,, \tag{4}$$

where $\mathbf{u}=(u,v,w)$. The momentum equations are

$$\frac{\partial \sigma_{xx}}{\partial x}+\frac{\partial \sigma_{xy}}{\partial y}+\frac{\partial \sigma_{xz}}{\partial z}=0\,, \tag{5}$$

$$\frac{\partial \sigma_{xy}}{\partial x}+\frac{\partial \sigma_{yy}}{\partial y}+\frac{\partial \sigma_{yz}}{\partial z}=0\,, \tag{6}$$

$$\frac{\partial \sigma_{xz}}{\partial x}+\frac{\partial \sigma_{yz}}{\partial y}+\frac{\partial \sigma_{zz}}{\partial z}=\rho g\,, \tag{7}$$

where σ_{ij} is the force per unit area in the j direction on the plane normal to the i direction, and acceleration terms (which are small for ice sheets) have have neglected. Equations (5)–(7) are known as the full-Stokes equations. Since the stress tensor is symmetric (ensuring conservation of angular momentum), only six of the nine components are independent. It is convenient to write σ as

$$\sigma_{ij}=\tau_{ij}-p\delta_{ij}\,, \tag{8}$$

where τ_{ij} is the stress deviator tensor, δ_{ij} is the Kronecker delta, and p is the static pressure, defined as

$$p=-\frac{1}{3}(\sigma_{xx}+\sigma_{yy}+\sigma_{zz})\,. \tag{9}$$

This definition implies that $p>0$, since the three normal stresses are negative for an ice sheet at rest. The stress deviator tensor is traceless: $\tau_{xx}+\tau_{yy}+\tau_{zz}=0$.

The components of τ are related to the strain rate by means of a constitutive law. The standard constitutive law is Glen's flow law:

$$\dot{\varepsilon}_{ij}=A(T)\tau_e^{\,n-1}\tau_{ij}\,, \tag{10}$$

where the strain rate tensor $\dot{\varepsilon}_{ij}$ is the symmetric part of the tensor $\nabla\mathbf{u}$:

$$\dot{\varepsilon}_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right). \tag{11}$$

Equation (1) implies that $\dot{\varepsilon}_{ij}$, like τ_{ij}, is traceless. The effective stress τ_e is a function of the second invariant of the stress deviator tensor and may be written as

$$\tau_e^2=\frac{1}{2}\tau_{ij}\tau_{ij}=\frac{1}{2}(\tau_{xx}^2+\tau_{yy}^2+\tau_{zz}^2)+\tau_{xy}^2+\tau_{yz}^2+\tau_{xz}^2\,. \tag{12}$$

The exponent is (10) is usually chosen as $n = 3$. The rate factor $A(T)$ is typically computed using an Arrhenius relation (Payne et al. 2000):

$$A(T^*) = a \exp\left(-\frac{Q}{RT^*} \right), \tag{13}$$

where a is a proportionality constant, Q is the activation energy for creep, R is the universal gas constant, $T^* = T - T_{pm} + T_0$ is the absolute temperature relative to the pressure melting point T_{pm}, and $T_0 = 273.15$ K is the triple point of water. Often it is desirable to express the deviatoric stress in terms of the strain rate. Using the relation $\dot{\varepsilon}_e = A\tau_e^n$, equation (10) can be inverted to give

$$\tau_{ij} = B(T)\dot{\varepsilon}_e^{(1/n-1)}\dot{\varepsilon}_{ij}, \tag{14}$$

where $B = A^{-1/n}$. This expression is of the standard form for a viscous fluid,

$$\tau_{ij} = 2\mu\dot{\varepsilon}_{ij}, \tag{15}$$

where $\mu = B(T)\dot{\varepsilon}_e^{(1/n-1)}$ is the effective viscosity.

Using (8)–(14), the full-Stokes equations (5)–(7) together with the continuity equation (4) can be written as a system of four coupled equations with four unknowns: *u*, *v*, *w*, and *p*. Since these equations are hard to solve, most numerical ice sheet models solve the momentum equation in approximate form. For example, Pattyn (2003) neglects the first two terms on the LHS of (7) and uses a hydrostatic approximation,

$$\frac{\partial \sigma_{zz}}{\partial z} \cong \rho g, \tag{16}$$

to eliminate σ_{zz}. After some algebraic manipulation, the resulting momentum equations are

$$\frac{\partial}{\partial x}(2\tau_{xx} + \tau_{yy}) + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = \rho g \frac{\partial s}{\partial x}, \tag{17}$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial}{\partial y}(\tau_{xx} + 2\tau_{yy}) + \frac{\partial \tau_{yz}}{\partial z} = \rho g \frac{\partial s}{\partial y}, \tag{18}$$

where s is the surface elevation. This is a set of two coupled equations in two unknowns, *u* and *v*, which are easier to solve than the full-Stokes equations. Once *u* and *v* are determined, *w* and *p* are found using the continuity equation (given that $w = 0$ at the lower boundary) and the hydrostatic relation.

Equations (17)–(18) are often referred to as a "higher-order" approximation of the full-Stokes equations. Other higher-order approximations exist; for example, Schoof and Hindmarsh (2010) used an additional simplification to obtain a vertically averaged higher-order model. In this model, *u* and *v* are solved in a single layer (rather than three dimensions as in the Pattyn model), and the velocities at other elevations are found by vertical integration.

Two lower-order approximations are widely used. The most common is the so-called shallow-ice approximation (SIA), in which lateral and longitudinal stresses (the first two terms on the LHS of (17) and (18)) are neglected. The SIA is valid in the slow-moving interior of ice sheets, where basal sliding is small and the motion is dominated by vertical shear. Another is the shallow-shelf approximation (SSA), in which vertical shear stresses (the third terms on the LHS of (17) and (18)) are ignored. The SSA is valid for floating ice shelves, where the basal shear stress is negligible and there is little or no vertical shear. The SSA is sometimes used in modified form to model flow in regions of rapid sliding, such as ice streams, where the basal shear stress is small but nonzero (e.g., MacAyeal 1989).

2.2. Glimmer, the Community Ice Sheet Model

Glimmer-CISM is a thermomechanical ice sheet model that solves the equations of ice flow, given suitable approximations and boundary conditions. The source code is written primarily in Fortran 90 and 95. The model resides on the BerliOS repository (http://glimmer-cism.berlios.de/), where it is under active development. Glimmer-CISM is an open-source code governed by the GNU General Public License and is freely available to all.

The initial release of CESM contains source code from Glimmer-CISM version 1.6. The main differences from version 1.0 are that (1) the directory structure has been reorganized, and (2) the GLINT climate model interface has been significantly changed to support coupling to CESM and other GCMs.

The dynamical core of the model, known as GLIDE, solves equations (1)–(3) for the conservation of momentum, mass, and internal energy. The version of GLIDE currently in CESM uses the shallow-ice approximation. However, a higher-order model is under development and will be included in future releases.

The surface boundary conditions (e.g., the surface temperature and surface mass balance) are supplied by a climate driver. When Glimmer-CISM is run in CESM, the climate driver is GLINT, which receives the temperature and SMB from the coupler and downscales them to the ice-sheet grid. The lower boundary conditions are given by an isostasy model, which computes the elevation of the lower surface, and by a geothermal model, which supplies heat fluxes at the lower boundary.

The model currently has simple treatments of basal hydrology and sliding. More complex schemes for subglacial water hydrology and evolution of basal till strength are under development. Glimmer-CISM also provides several simple schemes for calving at the margins; these will be replaced by more realistic lateral boundary conditions in the future.

For a detailed description of Glimmer-CISM's dynamical core and software design, please see Rutt et al. (2009) and the latest model documentation.

2.3. Directory structure

In the CESM directory structure, each model component sits under a directory with a three-letter acronym: e.g., *atm* for the atmosphere model, *lnd* for the land surface, *ocn* for the ocean, and *ice* for sea ice. The ice sheet component resides in a directory called *glc*. Within the *glc* directory are three subdirectories: *sglc* (a stub model), *xglc* (a "dead" model), and *cism* (the physical model).

Inside the *cism* subdirectory are several more subdirectories:

- *source_glimmer_cism*, which contains source code from Glimmer-CISM. Most modules begin with the prefix "glide" (for GLIDE modules), "glint" (for GLINT modules), or "glimmer" (for general-purpose modules).
- *source_glc*, which contains wrapper modules that link Glimmer-CISM to the CESM coupler.
- *source_slap*, which has source code for the SLAP (Sparse Linear Algebra Package) solvers used by Glimmer-CISM to solve implicit equations
- *drivers*, which contains two versions of the *glc* driver: one for use in the MCT coupling framework and the other for the ESMF framework. The ESMF driver is currently a placeholder.
- *bld*, which contains files required to build the code and create namelist files
- *input_templates*, which has config files for simulating the Greenland ice sheet at various grid resolutions. Resolutions of 20 km, 10 km, and 5 km are currently supported.
- *tools*, which contains tools for generating land/ice-sheet grid overlap files
- *doc*, which contains model documentation
- *mpi* and *serial*, which have appropriate versions of source code that can be used for parallel and serial runs, respectively. Currently, only serial runs are supported, and the only module used is glc_communicate.F90.

The code of most interest to users lies in the *source_glimmer_cism*, *source_glc*, and *input_templates* directories. To change parameters in the config files that are read by Glimmer-CISM at runtime, users should edit the appropriate file in *input_templates*. If the file is edited before configuring the model, then the case directory will contain a namelist script that will build a namelist with the desired parameters. Once the model has been configured, runtime parameters can be changed by editing the namelist scripts themselves.

The safest way to change source code in the *source_glimmer_cism* and *source_glc* directories is to copy the file to the *SourceMods/src.cism* subdirectory within the case directory and edit the file there. When the code is built, the contents of *src.cism* will automatically overwrite any files of the same name in the model source code directories.

2.4. *Coupling to CLM*

GLINT, the climate model interface of Glimmer-CISM, is designed to accumulate, average, and downscale fields received from other climate model components. These fields are interpolated from a global grid to the individual ice sheet grid(s). In general there can be multiple non-overlapping ice sheet grids, but only Greenland is currently enabled. The global grid must be a regular lat-lon grid, but the latitudes need not be equally spaced. For CESM the global grid is assumed to be the same as the CLM grid.

GLINT needs to know (1) one or more 2D fields necessary for computing the surface mass balance, (2) an upper boundary condition, usually surface temperature, and (3) the latitudes and longitudes of the grid cells where these fields are defined. There are two general ways of computing the surface mass balance:

1. a positive-degree-day (PDD) scheme, either annual or daily, for which the required inputs to GLINT are the 2m air temperature and the precipitation. This is the default scheme for Glimmer-CISM, but it may not be appropriate for climate change studies. The PDD option is not currently enabled for CESM runs, but will soon be added as an option for comparison with the surface-mass-balance scheme.

2. a surface-mass-balance (SMB) scheme for land ice embedded in CLM. In this case the required input to GLINT is the SMB itself. This is the preferred strategy for climate experiments. The mass balance is computed for a specified number of elevation classes for each cell on the coarser land grid (~100 km). This is much less computationally expensive than computing the SMB for each cell on the finer ice sheet grid (~10 km). Values of 1, 3, 5, and 10 elevation classes are currently supported, with 10 being the default.

For the SMB scheme, the fields passed to GLINT are (1) the surface mass balance, *qsmb* (kg/m^2/s, positive for ice growing, negative for ice melting), (2) the surface temperature, *Tsfc* (deg C), and (3) the surface elevation, *topo* (m) for each elevation class.

These fields are received from the coupler once per simulation day, accumulated and averaged over the course of a mass balance accumulation time step (typically one year) and then are downscaled to the ice sheet grid. The downscaling occurs in two phases. First, the values on the global grid are interpolated in the horizontal to the local ice sheet grid. Next, for each local grid cell, values are linearly interpolated between adjacent elevation classes. For example, suppose that at a given location the coupler supplies a surface mass balance at elevations of 300 and 500 m, whereas the local gridcell has an elevation of 400 m. Then the local SMB is computed to be equal to the average of the SMB at 300 and 500 m.

In some parts of the ice sheet grid the fields supplied by CLM are not valid, simply because there are no land-covered global gridcells in the vicinity. For this reason, GLINT computes a mask on the global grid at initialization. The mask has a value of 1 for global gridcells that have a nonzero land fraction (and hence supply valid data) and is zero otherwise. GLINT then computes a local mask for each gridcell on the ice sheet grid. The local mask has a value of 1 if one or more of the four nearest global neighbors supplies valid data (i.e., has a global mask of 1). Otherwise, the local mask has a value of zero. In this case ice sheets are not allowed to exist, and in output files, the SMB and temperature fields are given arbitrary values, typically zero. This masking has not yet proved to be a restriction in practice, since the Greenland ice sheet does not extend far from the land margin. Alternatives may need to be considered for modeling the Antarctic ice sheet.

After downscaling the surface mass balance to the ice sheet grid, GLINT calls the ice sheet dynamics model, which returns a new profile of ice sheet area and extent. The following fields can be upscaled to the global grid and returned from GLINT to the coupler: (1) the ice area fraction, *gfrac*, (2) the ice sheet elevation, *gtopo* (m), (3), the frozen portion of the freshwater runoff, *grofi*, (4) the liquid portion of the runoff, *grofl*, and (5) the heat flux from the ice sheet interior to the surface, *ghflx*. These fields are computed for each elevation class of each grid cell. The frozen runoff corresponds to iceberg calving and the liquid runoff to basal meltwater. Surface runoff is not supplied by GLINT because it has already been computed in CLM. Upscaling is not enabled in the current release but will be included in the near future.

There are two modes of coupling Glimmer-CISM to CLM: one-way and two-way. For one-way coupling, Glimmer-CISM receives the surface mass balance from CLM via the coupler, and the ice sheet extent and thickness evolve accordingly. However, the land surface topography is fixed, and the fields received by CLM from the ice sheet model are ignored. In this case CLM computes surface runoff as in earlier versions of CCSM: Excess snow is assumed to run off, and melted ice stays put at the surface. (See Section 3 for more details.) For two-way coupling, the CLM surface topography is modified based on input from the ice sheet model. In this case, surface runoff is computed in a more realistic way; excess snow remains in place and is converted to ice, and melted ice runs off. In either case, CLM computes the surface runoff, which is directed toward the ocean by the river routing scheme. Only one-way coupling is currently enabled, but two-way coupling is under development and will be added later in 2010.

2.5. *Configuring and running the model*

Timesteps: There are several kinds of timesteps in Glimmer-CISM.

1. The *forcing timestep* is the interval in hours between calls to GLINT. Currently, the forcing timestep is the same as the *coupling interval*, which is 24 hours. GLINT is called every time information is passed from the coupler to GLC, i.e., once per day.
2. The *mass balance timestep* is the interval over which accumulation/ablation forcing data is summed and averaged. The current default is one year. This means that GLINT will accumulate forcing data from the coupler over 365 daily forcing timesteps and average the data before downscaling it to the local ice sheet

grid. The mass balance timestep must be an integer multiple of the forcing timestep.

3. The *ice sheet timestep* is the interval in years between calls to the dynamic ice sheet model, GLIDE. The ice sheet timestep must be an integer multiple of the mass balance timestep.

Two optional runtime parameters can be used to make the time-stepping more intricate:

1. The mass balance accumulation time, *mbal_accum_time* (in years), is the period over which mass balance information is accumulated before calling GLIDE. By default, the mass balance accumulation time is equal to the ice sheet timestep. But suppose, for example, that the ice sheet timestep is 5 years. If we set mbal_accum_time = 1.0, we accumulate mass balance information for 1 year and use this mass balance to force the ice sheet model (thus avoiding 4 additional years of accumulating mass balance data).
2. The timestep multiplier, *ice_tstep_multiply*, is equal to the number of ice sheet timesteps executed for each accumulated mass balance field. Suppose that the mass balance timestep is 1 year, the ice sheet timestep is 1 year, and ice_tstep_multiply = 10. GLINT will accumulate and average mass balance information for 1 year, then execute 10 ice sheet model timesteps of 1 year each. In other words, the ice sheet dynamics is accelerated relative to the land and atmosphere. This option is likely to be useful in CESM for multi-millennial ice-sheet simulations where it is impractical to run the atmosphere and ocean models for more than a few centuries.

These various options are set in the ice configuration file (e.g., *ice.config.gland20*) in the *input_templates* directory. This file contains (or may contain) the following timestep information:

1. The ice sheet timestep *dt* (in years) is set in the section [*time*] in the ice config file.
2. The mass balance time step is not set directly in the config file, but is related to the accumulation/ablation mode, *acabmode*, which is set in the section [*GLINT climate*]. If *acabmode = 1* (the default value for CESM runs), then the mass balance time step is set to the number of hours in a year (i.e., 8760 hours for a 365-day year).
3. The values of *ice_tstep_multiply* and *mbal_accum_time*, if present, are listed in the section [*GLINT climate*].

See the Glimmer-CISM documentation for more details.

Note that the total length of the simulation is not determined by Glimmer-CISM, but is set in the file *env_run.xml* in the case directory.

Input/output: All model I/O is in netCDF format. Near the end of the config file, there are sections labeled [*CF input*] and [*CF output*]. The CF input section contains the name of the ice sheet grid file used for initialization. This file typically includes the ice thickness and surface elevation, or equivalent information, in each grid cell. Other information (e.g., internal ice temperature) may be included; if not, then these fields are set internally by Glimmer-CISM.

The CF output section determines the names of the various output files, the variables to be written to each file, and the frequency with which files are written. The defaults are to write output to a history file (suffix ‘h’) and a restart file (suffix ‘hot’, denoting a Glimmer-CISM hotstart file) once a year. Among the standard fields written to the history file are the ice thickness (*thk*), upper surface elevation (*usurf*), temperature (*temp*), and velocity (*uvel*, *vvel*) fields, along with the surface mass balance (*acab*) and surface air temperature (*artm*) downscaled to the ice sheet grid.

The restart or hotstart file contains all the fields required for exact restart. However, the restart will be exact only if the file is written immediately after an ice dynamics time step. This will normally be the case for restart files written at the end of any model year.

Many other fields can be written out if desired, simply by adding them to variable list in the config file. The source files with names “*_io.F90” specify the fields than can be written out. The easiest way to write out new variables is to add them to a file ending in “vars.def” and then rebuild the “*_io.F90” files using a python script. These files and scripts are not part of the standard CESM release but can be obtained by checking out Glimmer-CISM from the BerliOS repository.

Grids: GLINT can downscale fields from any global lat/lon grid. The latitude lines need not be equally spaced. Three global grid resolutions are currently supported: T31 (spectral), FV2 (~2^o finite-volume), and FV1 (~1^o finite-volume). The global resolution (i.e., the resolution of the land and atmosphere) is set when a case is created.

Local ice sheet grids must be rectangular; typically they are polar stereographic projections. For Greenland, three grids are currently supported, with resolutions of 20 km, 10 km, and 5 km, respectively. The current default is 20 km. This can be changed by modifying GLC_GRID to the desired value (e.g., gland10 or gland5) in env_conf.xml before configuring the case. When the model is configured, config files values are taken automatically from the appropriate file (e.g., *ice.config.gland10* for 10-km resolution) in *input_templates*. Each local grid is compatible with any of the three supported global resolutions.

Simulating the Greenland Ice Sheet: A primary motivation for having a CESM ice sheet model is to do climate change experiments with a dynamic Greenland Ice Sheet (GrIS). The first step is to simulate a present-day (or preindustrial) ice sheet that is in steady-state with the CESM climate and is not too different in thickness, extent, and velocity from the real GrIS. If we cannot do this, then either we will start climate change simulations with an unrealistic GrIS, or we will start with a realistic GrIS that is far from steady state, making it difficult to distinguish the climate-change signal from model transients.

It may be challenging to generate a realistic ice sheet, for several reasons: (1) The surface mass balance computed in CESM could be inaccurate; (2) Glimmer-CISM currently uses the shallow-ice approximation, which is not accurate for fast outlet glaciers; and (3) the present-day GrIS may not be in steady-state with the present-day (or preindustrial) climate. Our working hypotheses are that (1) If the SMB is reasonably accurate, we can obtain a reasonable large-scale thickness and extent for the GIS; (2) With a higher-order dynamics scheme and some judicious tuning, we can generate ice streams and outlet glaciers in the right locations with realistic velocities; and (3) The present-day GrIS is not far from steady-state with the preindustrial climate. These hypotheses are now being tested; results will be reported in an upcoming special issue of the *Journal of Climate*.

Obtaining an accurate surface mass balance may require some tuning in CLM; see Section 3 for details. We are also experimenting with different dynamics settings in the ice config file. The current default settings may not be optimal. The config files will be updated when we have more experience in running the model.

3. Ice sheets in the Community Land Model

This section describes changes made in CLM4 to accommodate ice sheets. For more information, see the CLM4 documentation.

3.1. *CLM and the surface mass balance of ice sheets*

The surface mass balance of a glacier or ice sheet is the net annual accumulation/ablation of mass at the upper surface. Ablation is defined as the mass of water that runs off to the ocean. Not all the surface meltwater runs off; some of the melt percolates into the snow and refreezes. Accumulation is primarily by snowfall and deposition, and ablation is primarily by melting and evaporation/sublimation.

Two kinds of surface mass balance schemes are widely used in ice sheet models:

- positive-degree-day (PDD) schemes, in which the melting is parameterized as a linear function of the number of degree-days above the freezing temperature. The proportionality factor is empirical and is larger for bare ice than for snow.
- surface energy-balance (SEB) schemes, in which the melting depends on the sum of the radiative, turbulent, and conductive fluxes reaching the surface.

The current version of Glimmer-CISM has only a PDD scheme. It is generally believed that PDD schemes are not appropriate for climate change studies, because empirical degree-day factors could change in a warming climate. Comparisons of PDD and energy-balance schemes (e.g., van de Wal 1996; Bougamont et al. 2007) suggest that PDD schemes may be overly sensitive to warming temperatures. Bougamont et al. (2007) found that a PDD scheme generates runoff rates nearly twice as large as those computed by an SEB scheme.

In CESM, the ice sheet surface mass balance is computed using an SEB scheme in CLM. Before discussing the scheme, it is useful to describe CLM's hierarchical data structure. Each gridcell is divided into one or more landunits; landunits can be further divided into columns; and columns can be subdivided into plant functional types, or PFTs. Each column within a landunit is characterized by a distinct snow/soil or snow/ice temperature and water profile. PFTs within a column have the same vertical profiles but can have different surface fluxes. In the current version, landunit areas in each gridcell are fixed at initialization, but PFT and column areas can evolve during the simulation.

Previously, CLM supported up to five landunits per grid cell: soil, urban, wetland, lake, and glacier landunits. Each of these landunits generally contains a single column, and soil columns (but not urban, wetland, lake, and glacier columns) consist of multiple PFTs. The ice-sheet-friendly version of CLM supports a sixth landunit, *glacier_mec*, where "mec" denotes "multiple elevation classes". Each glacier_mec landunit is divided into a user-defined set of columns based on surface elevation. The default is 10 elevation classes whose lower boundaries are 0, 200, 400, 700, 1000, 1300, 1600, 2000, 2500, and 3000 m. Each column is characterized by a fractional area and surface elevation that are read in during model initialization. The fractional area and elevation in each column are allowed to evolve during the run. Each glacier_mec column within a grid cell has distinct ice and snow temperatures, snow water content, surface fluxes, and surface mass balance.

These elevation classes provide a mechanism for downscaling the surface mass balance from the relatively coarse (~100 km) land grid to the finer (~10 km) ice sheet grid. The SMB is computed for each elevation class in each grid cell and is accumulated, averaged, and passed to the GLC (dynamic ice-sheet) component via the coupler once per day. The mass balance is downscaled by GLINT to the ice-sheet grid as described in Section 2 above.

There are several reasons for computing the surface mass balance in CLM rather than in Glimmer-CISM:

1. It is much cheaper to compute the SMB in CLM for ~10 elevation classes than in Glimmer-CISM. For example, suppose we are running CLM at a resolution of ~50 km and Glimmer at ~5 km. Greenland has dimensions of about 1000 x 2000 km. For CLM we would have 20 x 40 x 10 = 8,000 columns, whereas for GLIMMER we would have 200 x 400 = 80,000 columns.
2. We take advantage of the sophisticated snow physics parameterization already in CLM instead of implementing a separate scheme for Glimmer-CISM. When the CLM scheme is improved, the improvements are applied to ice sheets automatically.
3. The atmosphere model can respond during runtime to ice-sheet surface changes. As shown by Pritchard et al. (2008), runtime albedo feedback from the ice sheet is critical for simulating ice-sheet retreat on paleoclimate time scales. Without this feedback, the atmosphere warms much less, and the retreat is delayed.
4. Mass is conserved, in that the rate of surface ice growth or melting computed in CLM is equal to the rate seen by the dynamic ice sheet model.

5. The improved surface mass balance is available in CLM for all glaciated grid cells (e.g., in the Alps, Rockies, Andes, and Himalayas), not just those which are part of ice sheets.

3.2. *Details of the surface-mass-balance and coupling schemes*

When the model is initialized, CLM reads a high-resolution data file classifying each point as soil, urban, lake, wetland, glacier, or glacier_mec. For runs with dynamic ice sheets, the default is to classify all glaciated regions as glacier_mec. If there are no dynamic ice sheets, then these regions are normally classified as glacier landunits with a single column per landunit. Glacier_mec columns, like glacier columns, are initialized with a temperature of 250 K. While glacier columns are initialized with a snow liquid water equivalent (LWE) equal to the maximum allowed value of 1 m, glacier_mec columns begin with a snow LWE of 0.5 m so that they will reach their equilibrium mean snow depth sooner.

Surface fluxes and the vertical temperature profile are computed independently for each glacier_mec column. Each column consists of 15 ice layers and up to 5 snow layers, depending on snow thickness. As for other landunits with a snow cover, surface albedos are computed based on snow fraction, snow depth, snow age, and solar zenith angle. The bare ice albedo is prescribed to be 0.50 by default; this is lower than the values assumed by CLM for glacier landunits (0.80 for visible radiation and 0.55 for near IR). The latter values are higher than those usually assumed by glaciologists.

The atmospheric surface temperature, potential temperature, specific humidity, density, and pressure are downscaled from the mean gridcell elevation to the glacier_mec column elevation using a specified lapse rate (typically 6.0 deg/km) and an assumption of uniform relative humidity. At a given time, lower-elevation columns can undergo surface melting while columns at higher elevations remain frozen. This results in a more accurate simulation of summer melting, which is a highly nonlinear function of air temperature. The precipitation rate and radiative fluxes are not currently downscaled, but could be in the future if care were taken to preserve the cell-integrated values.

CLM has a somewhat unrealistic treatment of accumulation and melting on glacier landunits. The snow depth is limited to a prescribed depth of 1 m liquid water equivalent, with any additional snow assumed to run off to the ocean. (This amounts to a crude parameterization of iceberg calving.) Snow melting is treated in a realistic fashion, with meltwater percolating downward through snow layers as long as the snow is unsaturated. Once the underlying snow is saturated, any additional meltwater runs off. When glacier ice melts, however, the meltwater is assumed to remain in place until it refreezes. In warm parts of the ice sheet, the meltwater does not refreeze, but stays in place indefinitely.

In the modified CLM with glacier_mec columns, snow in excess of the prescribed maximum depth is converted to ice, contributing a positive surface mass balance to the ice sheet model. When ice melts, the meltwater is assumed to run off to the ocean, contributing a negative surface mass balance. The net SMB associated with ice formation (by conversion from snow) and melting/runoff is computed for each column, averaged over the coupling interval, and sent to the coupler. This quantity, denoted *qice*, is then passed to GLINT, along with the surface elevation *topo* in each column. GLINT downscales the SMB (renamed as *qsmb*) to the local elevation on the ice sheet grid, interpolating between values in adjacent elevation classes. The units of *qice* are mm/s, or equivalently km/m^2/s. If desired, the downscaled quantities can be multiplied by a normalization factor to conserve mass exactly. (This normalization is not yet implemented.)

Note that the surface mass balance typically is defined as the total accumulation of ice and snow, minus the total ablation. The *qice* flux passed to GLINT is the mass balance for ice alone, not snow. We can think of CLM as owning the snow, whereas Glimmer owns the underlying ice. The snow depth can fluctuate between 0 and 1 m LWE without Glimmer-CISM knowing about it.

In addition to *qice* and *topo*, the ground surface temperature *tsfc* is passed from CLM to GLINT via the coupler. This temperature serves as the upper boundary condition for Glimmer-CISM's temperature calculation.

Given the SMB from the land model, Glimmer-CISM executes one or more dynamic time steps and then has the option to upscale the new ice sheet geometry to the global grid and return it to CLM via the coupler. The fields passed to the coupler for each elevation class are the ice sheet fractional area (*gfrac*), urface elevation (*gtopo*), liquid (basal meltwater) runoff *grofl*, frozen (calving) runoff *grofi*, and surface conductive heat flux *ghflx*.

The current coupling is one-way only. That is, CLM sends the SMB and surface temperature to GLINT but does not do anything with the fields that are returned. Thus the CLM surface topography is fixed in time. This is permissible for century-scale runs in which ice-sheet elevation changes are modest. For longer runs with larger elevation changes, two-way coupling is highly desirable. A two-way coupling scheme is under development.

3.3. *Model controls*

The number of elevation classes is *glc_nec*, an integer declared in module *clm_varctl.F90*. This number is set equal to the value specified for *GLC_NEC* in the file *env_build.nml* in the case directory. Values of 1, 3, 5, and 10 elevation classes are currently supported, with 10 classes being the default. The number of classes cannot exceed *maxpatch_glcmec*, an integer parameter set in *clm_varpar.F90*. Currently, *maxpatch_glcmec* = 10.

The array *glc_topomax*, which is set in subroutine *clmvarctl_init*, defines the maximum elevation (in meters) in each class. For 10 elevation classes, glc_topomax is set to (0, 200, 400, 700, 1000, 1300, 1600, 2000, 2500, 3000, 10000).

At initialization, CLM reads a data file specifying the areal percentage of each grid cell classified as wetland, vegetation, lake, urban, glacier, or glacier_mec. For glacier_mec cells, the area and surface elevation are specified in each elevation classes. The area and surface elevation in each elevation class may change during the course of the run, but the total glacier_mec area in a given gridcell is fixed; glacier_mec landunits cannot change to vegetated landunits or vice versa. This restriction will be relaxed in future model releases.

The fundamental control variable is *create_glacier_mec_landunit*, a logical variable that is declared in *clm_varctl.F90*. It is false by default, but is automatically set to true when we create a case that includes a dynamic ice sheet component (e.g., IG, FG, or BG). If *create_glacier_mec_landunit* = T, the following occurs:

- The array *glc_topomax* is defined appropriately based on *glc_nec*.
- Memory is allocated for the areal percentage (*pct_glcmec*) and surface elevation (*topo_glcmec*) in each elevation class, and these values are read in from a netCDF file**.** The sum of *pct_glcmec* in each grid cell is checked to make sure it agrees with *pctgla*, the total glaciated fraction in each gridcell.
- Glacier_mec landunits and columns are defined for all gridcells where either (1) the fractional glacier area is greater than zero or (2) the dynamic ice sheet model may require a surface mass balance, even if CLM does not have glacier landunits in that location. To allow for case (2), grid overlap files have been precomputed. For given resolutions of CLM and Glimmer-CISM, these files identify all CLM cells that have nonzero ice area and overlap with any part of the ice sheet grid. In these overlapping cells, glacier_mec columns are defined in all elevation classes. Columns with zero area are known as "virtual" columns. These columns do not affect energy exchange between the land and the atmosphere, but are included for potential forcing of Glimmer-CISM.

The logical variable *glc_smb* determines what kind of information is passed from CLM to the ice sheet model via the coupler. If *glc_smb* is true, then the surface mass balance is passed. Specifically, *qice* is interpreted by the ice sheet model as a flux ($kg/m^2/s$) of ice freezing/melting. If *glc_smb* is false, then the ice sheet model should compute the surface mass balance using a positive-degree-day scheme, with *qice* interpreted as the precipitation and *tsfc* as the 2-m air temperature. (The PDD option is not currently supported, but will be included in a future release.) In either case, *tsfc* is downscaled and applied as the upper boundary condition for the dynamic ice sheet.

The logical variable *glc_dyntopo* controls whether CLM surface topography changes dynamically as the ice sheet evolves (i.e., whether the coupling is one-way or two-way). The default (and the only option currently supported) is *glc_dyntopo* = F, in which case the land topography is fixed. In this case the surface runoff for glacier_mec landunits is computed as for glacier landunits: (1) Any snow in excess of 1 m LWE runs off to the ocean, and (2) Melted ice remains in place until it refreezes. Excess snow and melted ice still contribute to positive and negative values, respectively, of *qice*, but only for the purpose of forcing Glimmer-CISM.)

If *glc_dyntopo* = T, then CLM receives updated topographic information from the ice sheet model. In this case the CLM surface runoff is computed in a more realistic way: (1) Any snow in excess of 1 m LWE is assumed to turn to ice and does not run off. (2) Melted ice runs off.

Two physical parameters may be useful for tuning the surface mass balance: (1) the surface bare ice albedo, *albice*, which is set in SurfaceAlbedoMod.F90, and (2) the surface air temperature lapse rate, *lapse_glcmec*, which is used for downscaling temperature and is set in *clm_varcon.F90*. By default, the bare ice albedo is 0.80 for visible wavelengths and 0.55 for near IR, but for glacier_mec columns the bare ice albedo is automatically reduced to 0.50 in the namelist. The default lapse rate is 6.0 deg/km.

The snow albedo is not easily tunable. It is computed in a complicated way based on snow fraction, snow depth, snow age, and solar zenith angle. Snow albedo in glacier_mec columns is treated identically to snow in other landunits.

Another possible tuning mechanism is to convert rain to snow and vice versa as a function of surface temperature. This conversion would violate conservation of latent heat, but might give more realistic precipitation fields in columns with elevations much higher or lower than the grid-cell mean.

The default values of *albice*, *create_glacier_mec_landunit*, *glc_smb*, and *glc_dyntopo* may each be overwritten by specifying the desired values in the namelist. This is done automatically for *albice* and *create_glacier_mec_landunit* when a case is created with dynamic ice sheets.

4. Future developments

This section lists model features that are planned or desirably but not yet implemented. Many of these are mentioned in the text above, but are included here for reference. In each section, future developments are listed roughly in order from easy, near-term improvements to more extensive, long-term improvements.

4.1. *Bug fixes*

One major bug was identified after the code for the initial CESM release was frozen. The config files for the 10-km and 5-km Glimmer-CISM grids (*ice.config.gland10* and *ice.config.gland5*) contain incorrect settings for the map projection. The sections labeled [GLINT projection] should be deleted and replaced by the following:

```
[projection]
type = 'STERE'
centre_latitude = 90.0
centre_longitude = 321.0
false_easting = 800000.0
false_northing = 3400000.0
standard_parallel = 71.0
```

The existing 20-km config file is correct. The other two files will be fixed in the next code release.

4.2. *Glimmer-CISM*

- Add ESMF capability. (Coupling currently is supported for MCT only.)
- Enable exact restart when restart files are written in mid-year (requires writing some GLINT variables to restart files).
- Enable short (~5-day) tests that exercise GLIDE.
- Define elevation classes by reading CLM surface data files (to guarantee consistency).
- Enable the PDD scheme for comparison to the surface mass balance received from CLM.
- Upscale GLC→CLM coupling fields (*gfrac*, *gtopo*, *grofi*, *grofl*, *ghflx*) correctly to the global grid.
- Support creation of *_io.F0 files from *vars.def files with supported software (i.e., an alternative to python scripts). Similarly for glimmer_vers file.
- Restructure the GLINT interface, reducing the number of extraneous arguments.
- Modify Greenland configuration files to optimize agreement with present-day thickness and extent.
- Upgrade to Glimmer-CISM 2.0 (serial version) with higher-order dynamics and Trilinos solver capabilities.
- Develop a suitable Greenland initial condition for higher-order simulations.
- Upgrade to a parallel version of Glimmer-CISM.
- Implement coupling to the POP ocean model.

4.3. *CLM*

- Add a switch for making frain/fsnow dependent on surface temperature.
- For glacier_mec landunits, specify distinct bare ice albedos for visible and near IR.
- Add diagnostics to track mass balance terms (e.g., total runoff, refreezing, and total melt).
- Add some daily diagnostics (e.g., for melting and albedo).
- Evaluate sensitivity to maximum snowpack depth; perhaps increase to > 1 m.
- Develop a modified surface data file with ice-free gridcells near northern margin (in agreement with other ice-sheet datasets)
- Develop data sets to force CLM with output from other GCMs.
- Enable two-way coupling of CLM and Glimmer-CISM.
- Implement parameterization for area and volume evolution of glaciers and ice caps.

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