Research Papers
Issue RP0249
January 2015

Ocean Modeling and Data assimilation Division

GRenoble Ice-Shelf and Land-Ice model: a practical user guide

By **Florence Colleoni**
Centro Euro-Mediterraneo sui i Cambiamenti Climatici, Bologna (Italy)
flocolleoni@gmail.com

SUMMARY GRISLI has been developed by Ritz et al. (2001) at LGGE (CNRS, France). It is able to simulate both grounded and floating ice. The grounded part uses the Shallow Ice Approximation (SIA, Hutter, 1983) whereas ice shelves and ice streams are simulated following the Shallow Shelf Approximation (SSA, MacAyeal, 1989). The ice shelf formulation in GRISLI allows for a more realistic calculation of the ice sheet growth, and particularly of the advance of ice onto the shallow continental shelves in both hemispheres high latitudes. GRISLI has been validated over Antarctica, Greenland and successfully applied to study the inception of ice sheets during the last glacial cycle. At CMCC, GRISLI has been used to simulate the glacial inceptions of the last two glacial cycles and the penultimate glaciation in the framework of the climate service in contract with the Swedish Nuclear Fuel and Waste and Management Company. The following document provides a detailed description of the model and some indications to set up and run simulations.

We thank Catherine Ritz for providing the GRISLI code and for the helpful discussions and Claudia Wekerle on the description of the model physics. We gratefully acknowledge the support of Italian Ministry of Education, University and Research and Ministry for Environment, Land and Sea through the project GEMINA.

Table of Contents

Preamble

GRISLI stand for “GRenoble Ice-Shelf and Land-Ice model”. It has been developed by Ritz et al. (2001) at LGGE in Grenoble. It is able to simulate both grounded and floating ice. The grounded part uses the Shallow Ice Approximation (SIA, Hutter, 1983) whereas ice shelves and ice streams are simulated following the Shallow Shelf Approximation (SSA, MacAyeal, 1989). The ice shelf formulation in GRISLI allows for a more realistic calculation of the ice sheet growth, and particularly of the advance of ice onto the shallow continental shelves in both hemispheres high latitudes. GRISLI has been validated over Antarctica (Ritz et al., 2001) and successfully applied to study the inception of ice sheets during the Early Weichselian period (Peyaud et al., 2007; Alvarez-Solas et al., 2011). In the following document, we give a detailed description of the model and some indication to set-up and run simulations.

This guide is by far non exhaustive and is related to a version of GRISLI that might not be up to date. The purpose of this guide is purely descriptive and the implementation performed at CMCC are indicated in the text. Finally, GRISLI is not open-source, therefore, CMCC is not authorised to diffuse the code. The code is available on request to Catherine Ritz (LGGE, Grenoble).

User Guide

1 Before installing

GRISLI is a suite of Fortran 90 routines that need three distinct numerical tools to compile and run properly. Before running the model, the user might check the installation of the following tools.

- **A fortran compiler**: GRISLI has been developed originally using the IBM fortran and C++ compilers, namely *ifort* and *icc*. GRISLI has been successfully tested with the open-source GNU Fortran and C++ compiler *gfortran* and *gcc*. The results produced by both compilers are almost identical when using the appropriate compiling and optimisation options.
- **Basic Linear Algebra Subprograms (BLAS) fortran libraries**: those libraries are needed to perform some of the mathematical calculations needed by GRISLI. While this libraries came originally along with the IBM compilers, an open-source version available for download here http://www.netlib.org/blas/. The routines have been developed in Fortran 77. The open-source libraries might not be included within GRISLI code and the user might have to download it.
- **NetCDF fortran libraries**: As GRISLI outputs are produced both in ASCII and NetCDF format, the user should compile the NetCDF Fortran and C++ libraries, available for download on the main NetCDF website, with their own Fortran compiler. Note that the NetCDF releases after 4.2 does not include Fortran and C++ libraries in the same package, which have to be installed separately.

GRISLI runs under UNIX environment and has been successfully run on Macintosh operative systems. GRISLI runs in serial, on one single processor, and has not been optimised to use multi-threads processes.

To post-process and visualise GRISLI outputs, the user might use the following tools (only indicative):

- **NCVIEW**: available at http://meteora.ucsd.edu/∼pierce/ncview_home_page.html. This tool allows for quick visualisation of the Netcdf, both during run time and after the simulation. This tools requires the installation of Netcdf.
- **NCO**: NetCDF Climate Operators, available at http://nco.sourceforge.net/. This tool allows for direct operations on the output files, such as the extraction of a single variable, the merging of several files, arithmetic basic operations etc...
- **CDO**: Climate Data Operators, available at https://code.zmaw.de/projects/cdo. This tool is similar to NCO, but might also offer more options to perform high-level arithmetic operations on the files.
- **NCL**: NCAR Command Language , available at http://www.ncl.ucar.edu/. This open-source software, developed and maintained by NCAR, is an advanced tool to plot and perform high-level mathematical calculations on netcdf files. This tools handle the Cartesian native grid, which are the grids used by GRISLI, which allow the user to draw projected maps.

- **GMT**: Generic Mapping Tools, available at http://www.soest.hawaii.edu/gmt/. This software is similar to NCL, but does not handle very easily Netcdf files and allows for only limited mathematical operations on the variables. However, this tools handles perfectly all the Cartesian projections on sphere and ellipsoid. It also handles very easily ASCII files.

Note that only open-source software are listed here, and this list is by far not comprehensive, other tools such as **GNUplot**, **R**, **Ferret** or **GRADS** might also work.

2 GRISLI directory structure

The GRISLI main directory includes six sub-directories (Figure 1):

- `GRISLI/SOURCES`: contains all the routines of the model, the Makefile and the namelists to be set up by the user before running the model.
- `GRISLI/INPUT`: contains all the input files needed by GRISLI to initialise a simulation, such as the model grids, the climate forcing, and other forcing files.
- `GRISLI/RESULTATS`: contains all the output files in ASCII and NetCDF format.
- `GRISLI/Fichier-CPTR`: contains the restart file in ASCII format.
- `GRISLI/Param`: contains a copy of the namelist options created during the initialisation phase of the simulation.
- `GRISLI/bin`: contains the model executable created during the compilation as well as the log file containing all the run time informations.

When getting the code for the first time, `GRISLI/Param`, `GRISLI/bin`, `GRISLI/Fichier-CPTR` and `GRISLI/RESULTATS` does not exit and have to be created by the user.

3 Compiling and running

Before compiling the routines, the user has to edit the `Makefile` located in `GRISLI/SOURCES`. There are four steps to execute:

- **STEP 1 - NetCDF libraries**: setting the path of the NetCDF include files and libraries in the variables `NCDF_INC` and `NCDF_LIB` respectively such that:
  `NCDF_INC = /usr/local/netcdf-4.1.3_ifort/include`
  `NCDF_LIB = /usr/local/netcdf-4.1.3_ifort/lib`

- **STEP 2 - Compiler**: setting the name of the compiler in the variable `IFORT`:
  `IFORT = gfortran`, for example.

```
GRISLI/
├─ SOURCES/
│   ├─ BLAS/
│   ├─ Eurasie20_files/
│   ├─ Fichiers-parametres/
│   ├─ Hemin40_files/
│   ├─ Netcdf-routines/
│   └─ New-remplimat/
├─ INPUT/
│   ├─ HEMIN40/
│   ├─ EURASIE20/
│   └─ Forcage/
├─ RESULTATS
│   └─ Netcdf-Resu
├─ Param/
└─ bin/
```

Figure 1:
Description of GRISLI main directories.

- **STEP 3 - Compilation options**: setting the options to compile the model according to your compiler and your operative system in the four variables `ARITHM`, `FT`, `LK`, `F_NETCDF`. For example, to compile GRISLI using the IBM Fortran and C++ compilers on 64 bits Macintosh architecture:

```
ARITHM          = -O2  -xHost  -no-prec-div  -mkl  -m64
FT              = $(IFORT) $(ARITHM) -c -I$(NCDF_INC) -g
LK              = $(IFORT) $(ARITHM) -g
F_NETCDF        = $(IFORT) $(ARITHM) -c -I$(NCDF_INC)
```

Note that in the `ARITHM` variable, we include `-mkl` option corresponding to the famous IBM mathematical `MKL` libraries provided with the IBM Fortran compiler. Those libraries contains the BLAS routines which are necessary to run GRISLI. To compile GRISLI using the GNU Fortran and C++ compilers on 64 bits Macintosh architecture:

```
ARITHM          = -O2 -ffree-line-length-none -mtune=native -mfpmath=sse
FT              = $(IFORT) $(ARITHM) -c -I$(NCDF_INC)
LK              = $(IFORT) $(ARITHM)
F_NETCDF        = $(IFORT) $(ARITHM) -c -I$(NCDF_INC)
```

Note that the `MKL` option is not specified. In this case, the user will have to follow **STEP 4**.

- **STEP 4 - BLAS library**: include or not the BLAS library in the compilation options. If the user does not use the IBM Fortran and C++ compilers, some of the mathematical functions needed to solve the elliptic matrix included within the `MKL` libraries will be missing. Therefore, the user will have to compile the `GRISLI/SOURCES/BLAS` routines provided with the code (if the directory is missing, please report to the previous sections). The routines needed by GRISLI are already listed within the `Makefile`. To compile them, the user will have to manually remove all the `*.o` files and execute the compilation. At last, the user will have to manually include the `Liste_BLAS` libraries in the compilation lines of the selected grid domain of the Makefile. For example, to compile the routine to run over the Northern Hemisphere:

```
Hemin-40 : $(Dim_hemin40) $(mod_communs)  $(mod_ell)  $(Liste_hemin40) \
        $(diagnoshelf) $(Liste_Netcdf) $(routines_communes) \
        $(routine_elliptiques) $(Liste_BLAS)


       $(LK) -o  $(RUND)/Hemin-40  $(Dim_hemin40) $(mod_communs) $(mod_ell) \
       $(Liste_hemin40) $(diagnoshelf) $(Liste_Netcdf) $(routines_communes) \
       $(routine_elliptiques) -L$(NCDF_LIB) -lnetcdf \
       -L$(NCDF_LIB) -lnetcdff $(Liste_BLAS)
```

In the case of using the IBM Fortran and C++ compilers, the `BLAS` libraries are included through the `-mkl` compilation option and the user has to modify the compilation block such that:

```
Hemin-40 : $(Dim_hemin40) $(mod_communs)  $(mod_ell)  $(Liste_hemin40) \
        $(diagnoshelf) $(Liste_Netcdf) $(routines_communes) \
        $(routine_elliptiques)


       $(LK) -o  $(RUND)/Hemin-40  $(Dim_hemin40) $(mod_communs) $(mod_ell) \
       $(Liste_hemin40) $(diagnoshelf) $(Liste_Netcdf) $(routines_communes) \
       $(routine_elliptiques) -L$(NCDF_LIB) -lnetcdf \
       -L$(NCDF_LIB) -lnetcdff
```

Finally to compile and run the model for the Northern Hemisphere domain:

```
> cd GRISLI/SOURCES
> make Hemin-40
```

This will create and executable located in `GRISLI/bin/`.

```
> cd ../bin/
> ./Hemin-40
```

The other grids included with GRISLI are listed at the beginning of the Makefile.

4 GRISLI grid domain

The equations governing ice flow, ice thickness and ice temperature evolution are discretised with the finite difference method.The prognostic variables are computed on a rectangular regular grid. The grids are created off-line using any spherical or ellipsoidal geographical projection of the topography decided by the user. The projection informations are not needed by GRISLI but are useful in case the user wants to reproject the outputs from the simulations on a standard (longitude,latitude) map.

The number of points in X and Y directions depends on the size of the domain and on the horizontal resolution. Those numbers are decided by the user and have to be provided to the model (see Tutorial section). The (X,Y) coordinates of the grid must be provided in a separate coordinate ASCII file in native Cartesian distances (km), also containing the index number of each pixel (i,j), as well as the corresponding projected longitude and latitude (Lon,Lat).

For example, the GRISLI grid covering part of Northern Eurasia, projected into Lambert Equal Area geographical projection (centre of projection: 0°; 90°N, Figure 2 for an example), at 20 km resolution contains 210 in the X direction and 270 points in the Y direction. The corresponding coordinate file, located under `GRISLI/INPUT/EURASIE20/` has to be structured as follows:

i	j	X	Y	Lon	Lat
1	1	-830000.00000000000	-4320000.0000000000	349.12431166414439	49.734095498049626
2	1	-810000.00000000000	-4320000.0000000000	349.38034472384487	49.769806622114523
3	1	-790000.00000000000	-4320000.0000000000	349.63680754375133	49.804671832343111
4	1	-770000.00000000000	-4320000.0000000000	349.89369090450970	49.838689334153315
5	1	-750000.00000000000	-4320000.0000000000	350.15098548888295	49.871857370085763
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
210	270	3350000.0000000000	1060000.0000000000	107.55830413905845	58.100928066994435

The file contains **no header** and the red letters are only indicated here for a better understanding:

- `i` and `j` correspond to the number of points in the X and Y directions respectively.
- `X` and `Y` correspond to the coordinates of the grid, expressed in native Cartesian distances (km) in the Lambert Equal Area projection.
- `Lon` and `Lat` correspond to the longitudes and latitudes of the Cartesian coordinates (X,Y) in the Lambert Equal Area projection.

In the vertical, both the domain has 21 levels evenly spaced along the Z-axis, scaled to the ice thickness. Furthermore, there are 4 vertical levels in the bedrock layer.

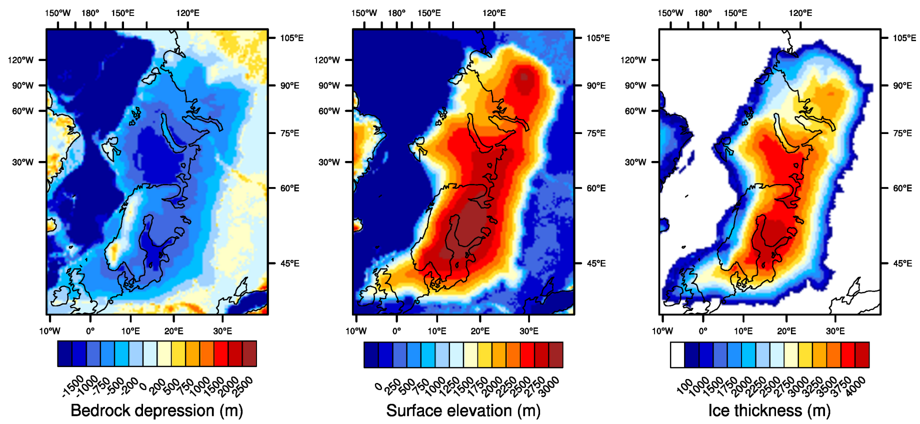

Figure 2:
Example of projected initial topography over the Eurasian domain at 20 km resolution: bedrock topography, surface elevation and ice thickness.

5 GRISLI initial conditions

The following initial conditions, i.e. topography and climate forcing, have to be projected on the horizontal grid before running. GRISLI does not directly handle the projection procedure.

Initial topography

GRISLI needs three initial topographic conditions, namely surface topography, bedrock topography, i.e. topography below the existing ice sheets (over ice free regions, bedrock equals surface topography) and ice thickness if some ice sheets already exist in the initial topography. For example, if you consider running GRISLI over present-day Northern Hemisphere topography, you will have to provide Greenland ice thickness, and the bedrock topography below Greenland. In Figure 2 we provide the example of an initial topography corresponding to a glaciation period over the Eurasian domain described in the previous section.

For each of the grid point, the three topography variables have to be provided in meters and written in the topography_file, located under `GRISLI/INPUT/EURASIE20` as follows:

```
Eurasia: present-day topo interpolated by grid-maker
        56700   3          210           270      20.0000
 S   H   B0
 -240.116241       0.00000000      -240.116241
 -146.568726       0.00000000      -146.568726
 -126.997734       0.00000000      -126.997734
 -113.883545       0.00000000      -113.883545
...
```

S corresponds to the surface topography, H is the ice thickness and B0 is the bedrock topography. The values are ordered exactly as in the coordinate file described in the previous section.

The three first lines of the file are mandatory and are red by GRISLI during the initialisation of the grid. In the second line, some grid informations are indicated: total number of points (X*Y), the number of columns contained in the file, number of X points, number of Y points, horizontal resolution (in km).

Climate forcing

The ice-sheet model is forced by steady-state monthly air temperatures and monthly total precipitation (water equivalent) from any climate data provider (observations, simulations). Both climate fields have to be provided for each of the 12 month of the year. Climatic means, when needed by GRISLI are performed during run time.

- Temperatures have to be provided in degree Celsius
- Precipitations have to be provided in meter/year, in water equivalent. The conversion into snow and ice is performed during run time, using the appropriate density.
- Both climate fields have to be projected and interpolated on the GRISLI horizontal rectangular grid before running.
- Both variables have to be written in an ASCII files containing 3 headers and 24 columns: 12 column for precipitations first followed by 12 columns for temperatures. GRISLI reads the file following the Fortran format (24(e12.5, 1x)):

```
 -140000.000     Hemisphere Nord: climate forcing CESM fv09 B_case
      56700          24          210         270    20.000000000000000
Monthly precip (m/an) and monthly T2M(C)
  2.066    1.887     ...    2.181    5.430    4.537    ...     6.504
```

.
.
.

The climate forcing generally comes on a standard Mercator longitude-latitude grid at a resolution varying from 0.5° to 1°. The original climate forcing grid resolution is generally coarser than the horizontal resolution of the ice-sheet model. As a consequence, the surface elevation at which the climate forcing was computed or interpolated to (in case of reanalysis), presents some discrepancies with the finer surface topography of the ice-sheet model. Therefore, a correction of the climate variables is necessary before giving it to the ice-sheet model for simulation.

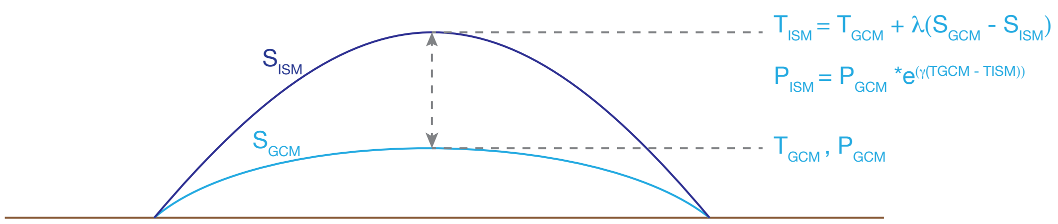

Figure 3:
Example of downscaling from a coarse climate model (GCM) onto a finer resolution ice-sheet model (ISM). Initial GCM topography (S_{GCM}) is less resolved than initial ice-sheet topography (S_{ISM}) and in this example, S_{GCM} is lower than S_{ISM}. To correct the simulated GCM temperatures (T_{GCM}), the downscaling is performed by means of an atmospheric lapse rate λ. Simulated GCM precipitations (P_{GCM}) can be corrected following an exponential relationship accounting for the temperature correction due to elevation changes. This procedure is the standard procedure applied to run an ISM. However more sophisticated methods could be use, for example to conserve the mass during the interpolation.

Downscaling procedure

1. The temperature field from the CESM simulation is horizontally interpolated on the higher resolution Eurasian ice-sheet model (ISM) grid:

$$T_{GCM}(1^\circ \times 1^\circ) \rightarrow T_{GCM-on-ISM}(20 \text{ km } \times 20 \text{ km}). \tag{1}$$

2. Interpolation of the surface elevation field from the coarse resolution CESM grid onto the ice-sheet model grid introduces small differences in elevation. Temperature fields have to be corrected for these elevation changes by means of a lapse rate value (downscaling):

$$T_{ISM-cor} = T_{GCM-on-ISM} + \lambda(S_{GCM-on-ISM} - S_{ISM}) \tag{2}$$

where $T_{ISM-cor}$ and $T_{GCM-on-ISM}$ are the final downscaled temperature field and the interpolated temperature field, respectively. S_{ISM} denotes the elevation of topography on the high resolution ice-sheet model grid, and $S_{CESM-on-ISM}$ is the elevation of the CESM topography interpolated on the high resolution ice-sheet model grid. At last, λ corresponds to the atmospheric lapse rate (°C/km) used to correct temperature for elevation difference.

The same procedure can be used to correct precipitations. The correction can be performed using various methods. Here we apply the same method as GRISLI uses during run time, based on Charbit et al. (2002).

$$P_{ISM-cor} = P_{GCM-on-ISM} \cdot \exp(\gamma \cdot (T_{GCM-on-ISM} - T_{ISM-cor})), \quad (3)$$

where P_{cor} and P_0 stand for the corrected and initial precipitation, respectively; γ corresponds to the precipitation correction factor. Note that the use of exponential function in the precipitation formulation (eq. 5) is motivated by the saturation pressure of water vapour in the atmosphere (Clausius-Clapeyron relationship), which increases roughly exponentially with temperature.

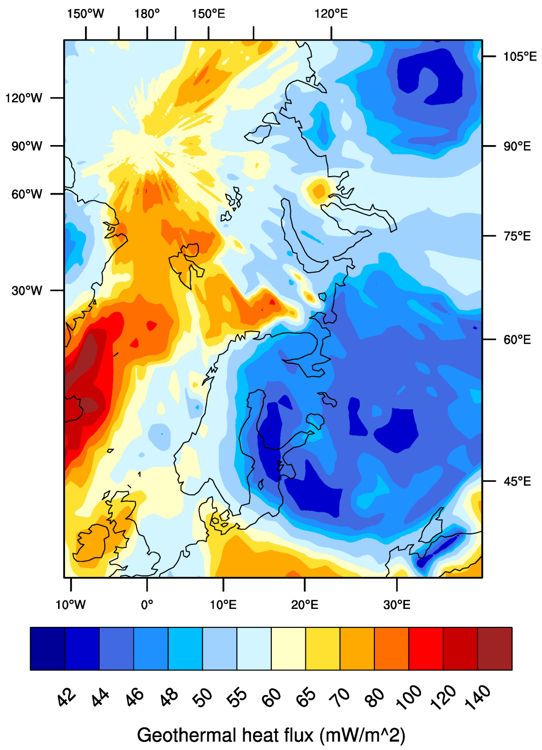

Figure 4:
Map of geothermal heat flux (mW/m^2) from Shapiro and Ritzwoller (2004) interpolated on the Eurasian 20 km grid.

Climate correction during run time

Similarly to the off-line downscaling procedure, changes in ice sheet elevation during run time affect input temperature and precipitation. In GRISLI, temperatures account for elevation changes at each time step, by means of a lapse rate value:

$$T_{cor}(t) = T_0 + \lambda(S(t) - S_0), \tag{4}$$

where T_{cor} and T_0 are the corrected and initial temperature fields, respectively, S is the elevation at time step t, and S_0 is the initial elevation. The lapse rate λ, as described above, takes different values for annual mean and July temperatures.

Precipitation is also corrected for changes in elevation:

$$P_{cor}(t) = P_0 \cdot \exp(\gamma \cdot (T_{cor}(t) - T_0)), \tag{5}$$

where P_{cor} and P_0 stand for the corrected and initial precipitation, respectively.

6 GRISLI boundary conditions

As boundary condition, GRISLI uses a map of present-day geothermal heat flux (GHF) reconstructed by Shapiro and Ritzwoller (2004) (Figure 4a). The original GHF file is available at http://ciei.colorado.edu/∼nshapiro/MODEL/ASC_VERSION/. It has to be interpolated onto GRISLI grid before running and written in an ASCII file located in `GRISLI/INPUT/HEMIN40` for example:

```
  1        1    72.5903244
  2        1    73.8195953
  3        1    76.1473999
  .
  .
241      241    84.9069672
```

where the first column corresponds to the i index coordinate number, the second column corresponds to the j index coordinates number and the third column holds the GHF values given in mW/yr.

A second boundary condition used by GRISLI is a map of present-day sediment thickness taken from Laske and Masters (1997). The original file is available at http://igppweb.ucsd.edu/∼gabi/sediment.html. The data are provided on a grid of $1^\circ \times 1^\circ$ horizontal resolution and have to be interpolated on the GRISLI grid before running (Figure 5a).

The sediment map is used by GRISLI to determine the possible areas where ice streams might occur. The sediment map is related to the basal hydrology conditions (see the section about Basal Hydrology below).

7 GRISLI namelist example

To each of the grid implemented in GRISLI corresponds a namelist encompassing all the parameters that the user may change. An example of namelist is displayed below. See the Tutorial section for the explanation of each namelist block.

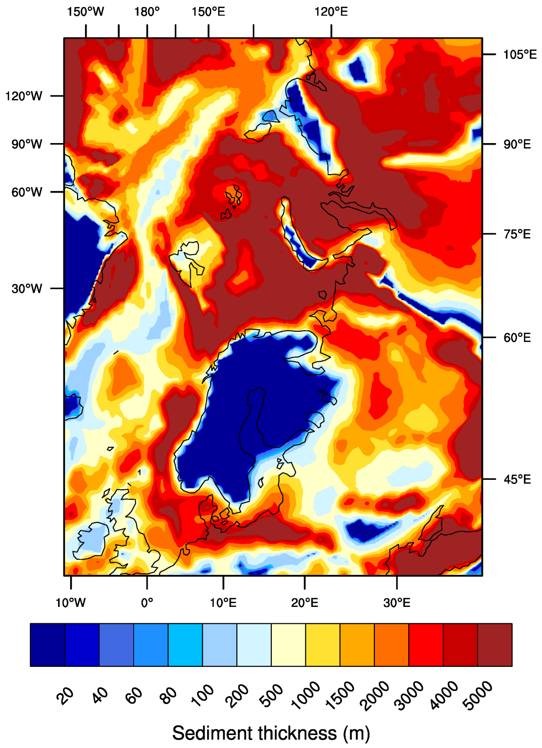

Figure 5:
Map of sediment thickness from Laske and Masters (1997) interpolated on the Eurasian 20 km grid.

```
!  Parametres du run : Hemin40!

!___________________________________________________________
&runpar                    ! nom du bloc  parametres du run

 runname      =  "shelf002"
 icompteur    = 0
 reprcptr     =  " " !"d31Apvi5+k0100.CPTR" pour depart a 0
 itracebug    =  0
 num_tracebug = 166
 comment_run  = "SPIN-UP_1: NH40_035 200k, SPIN-UP_2: NH40_41b 200k"
/
! runname    : nom de l experience (8 caracteres)
! icompteur  : reprise dans un fichier  0 -> non, 1 -> oui, 2 -> T et Hwat
!              3-> T seulement
! reprcptr   : nom du fichier

!___________________________________________________________
&netcdf                    ! bloc netcdf

 dtncdf      =      10.
 /
! dtncdf :espace en temps entre les sorties

!___________________________________________________________
&grdline                   ! bloc grounding line

 igrdline     =            0
 /
```

```
! igrdline :  1 ligne d echouage fixée, sinon 0

!_____________________________________________________________
&timesteps                  ! bloc timestep

 tend      =   30000.
 tbegin    =   0.
 dtmin     =   2.e-2
 dtmax     =   1.
 dtt    =   5.   ! 5
 testdiag  =   0.02 ! 0.016
 /
! tous les temps en annees. tbegin et tend : debut et fin du run
! pour equation masse, pas de temps mini -> dtmin, maxi -> dtmax
! dtt : pas de temps long
! testdiag, pour gérer le pas de temps dynamique dt
! ordres de grandeur (a moduler selon dx) :
! 40 km dtmin=2.e-2, dtmax=1., dtt=5., tesdiag=0.02

!_____________________________________________________________
&topo_file
 file1          = "NH_40km_140k_topo2_withice_GRISLI.xyz"
 file2 = "NH_40km_140k_topo2_withice_GRISLI.xyz"
 filecoord      = "Coordinates_NH_40km_GRISLI.xyz"
/
! file1 : topo de depart "topo-21k.g40"
! file2 : topo de reference hemin2.g40
! coordfile : grid coordinates'

!_____________________________________________________________
&eaubasale1                ! nom du premier bloc eau basale

 ecoulement_eau =  T
 hwatermax      =    5000.000
 infiltr        =   1.0000001E-03
 /
! ecoulement eau : .false. -> modele bucket, sinon equ. diffusion
! hwatermax :  hauteur d eau basale maximum dans le sediment (m)
! infiltr est la quantite d eau qui peut s infiltrer dans le sol (m/an)

!_____________________________________________________________
&param_hydr              ! nom du  bloc parametres hydrauliques

 hmax_till      =    20.00000
 poro_till      =   0.5000000
 kond0          =   1.000000E-06
/
! hmax_till (m) : epaisseur max du sediment
! poro_till : porosite du sediment
! conductivite du sediment :  kond0 (m/s)

!______________________________________________________________
&drag_hwat_cont              ! nom du bloc dragging hwater contigu

hwatstream = 50.
cf = 1.e-5              ! 1.e-4
tobmax = 1000.
toblim = 0.7e5               ! 0.25e5
/
! hwatstream (m) :  critere de passage en stream en partant de la cote'
! si hwater > hwatstream '
! cf coefficient de la loi de frottement fonction Neff'
! tobmax : (Pa) frottement maxi '
! toblim : (Pa) tes pour les iles '

!______________________________________________________________
&drag_hwat_sedim              ! nom du bloc dragging hwater sediment

filesedim       = "nosediment_ij_hemin40.dat"
hwatstream      =       50.
cf              =       2.e-5              ! 1.e-4
tobmax          =       1000.
toblim          =       0.7e5               ! 0.25e5
seuil_hwater    =       250.
```

```
seuil_sedim     =       150.
seuil_neff      =       350.e5
/
! hwatstream (m) :  critere de passage en stream en partant de la cote'
! si hwater > hwatstream '
! cf coefficient de la loi de frottement fonction Neff'
! tobmax : (Pa) frottement maxi '
! toblim : (Pa) tes pour les iles '
! seuil_hwater (m) : seuil hwater pour avoir glissement sur zone sediment'
! seuil_sedim (m) : seuil epaisseur sediment pour avoir glissement sur zone sediment'

!___________________________________________________________
&drag_jorge              ! nom du bloc dragging_jorge

filesedim       = "nosediment_ij_hemin40.dat"
hwatstream      =       50.
cf              =       2.e-5             ! 1.e-4
tobmax          =       1000.
toblim          =       0.7e5              ! 0.7e5
seuil_sedim     =       1.             ! 0.0001
/
! hwatstream (m) :  critere de passage en stream en partant de la cote'
! si hwater > hwatstream '
! cf coefficient de la loi de frottement fonction Neff'
! tobmax : (Pa) frottement maxi '
! toblim : (Pa) tes pour les iles '
!___________________________________________________________
&ghflux                                ! geothermal heat fluxes

fileghf       = "ijphi_hemin40.dat"
coefghf         = 1.
/
! fileghf : input geothermal heat fluxes map
! coefghf : to modulate the amplitude of the geothermal heat fluxes

!___________________________________________________________
&calving            !   nom du bloc calving méthode Vincent

Hcoup  = 200.
ifrange = 3
meth_Hcoup = 0
/

! Hcoup epaisseur de coupure
! ifrange=0 -> NO CALVING
! ifrange=1 -> traitement de Vincent avec ice shelves frangeants' (biased)
! ifrange=2 -> ice shelves frangeant seulement si bm-bmelt positif (biased)
! ifrange=3 -> option 2 corrected, but no test on ice thickness of upstream point
! ifrange=4 -> option 3 but with test on upstream point ice thickness point
! meth_Hcoup -> Hcoup depends on surface temperature. If=0 then use namelist Hcoup value
!____________________________________________________________
! loi de deformation 1          module deformation_mod_2lois
&loidef_1

 exposant_1       = 3.
 temp_trans_1     = -6.5
 enhanc_fact_1    = 3.
 coef_cold_1      = 1.660E-16
 Q_cold_1         = 7.820E+04
 coef_warm_1      = 2.000E-16
 Q_warm_1         = 9.545E+04
/
! exposant (glen), temperature de transition (ttrans)
! enhancement factor (sf)
! pour les temperatures inf. a Temp_trans :
!            coef_cold (Bat1) et Q_cold (Q1)
! pour les temperatures sup. a Temp_trans :
!            coef_warm (Bat2) et Q_warm (Q2)
!________________________________________________________
! loi de deformation 2          module deformation_mod_2lois
&loidef_2

 exposant_2       = 1.
 temp_trans_2     = -10.
```

```
 enhanc_fact_2    = 10.
 coef_cold_2      = 8.313E-08
 Q_cold_2         = 4.000E+04
 coef_warm_2      = 8.313E-08
 Q_warm_2         = 6.000E+04
/
! exposant (glen), temperature de transition (ttrans)
! enhancement factor (sf)
! pour les temperatures inf. a Temp_trans :
!            coef_cold (Bat1) et Q_cold (Q1)
! pour les temperatures sup. a Temp_trans :
!            coef_warm (Bat2) et Q_warm (Q2)
!____________________________________________________________
&diagno_rheol              ! nom du bloc  diagno_rheol

sf01           =  0.2
sf03           =  0.03
pvimin         =        1.e3
/
! coefficients par rapport a la loi glace posee
! sf01 : coefficient viscosite loi lineaire
! sf03 : coefficient viscosite loi n=3
! pvimin : valeur de pvi pour les noeuds fictifs ~ 1.e3
! tres petit par rapport aux valeurs standards ~ 1.e10

!___________________________________________________________
&bmelt_nor_depth                      ! module bmelt_nor_depth

bmelt_type = 1
bmelt1 = 0.
bmelt2 = 0.
depthlimit = 2000.
ocn_profile = "TEMP_vert_Chukchi.dat"
ocn_map = "Tocn_B140_topo1_artic_20km_noice_GRISLI.xyz"
/
! bmelt_type=1 -> prescribed basal melting depending on depthlimit
! bmelt_type=2 -> basal melting calculated using an ocean temperature vertical profile
! bmelt_type=3 -> as for 2 but using bidimensional ocean vertical temperature
! bmelt1 : basal melting above depthlimit
! bmelt2 : basal melting below depthlimit
! depthlimit: depth threshold to precribe basal melting!
! ocn_profile: ocean temperature vertical profile
! ocn_map: vertical ocean temperature map

!___________________________________________________________
&bmelt_nor_reg1                                  ! nom du bloc

!bmelt_Ross = 0.5
!bmgrz_Ross   = 0.2
!bmelt_FRis = 2.4
!bmgrz_FRis   = 5.6
/
!___________________________________________________________
&clim_forcage                                    ! nom du bloc

forcage_file1 = " "
forcage_file2 = " "
mincoefbmelt  =  0.
maxcoefbmelt  =  2.
rapbmshelf    = 5.
filforc       = "b140_topo1_150.dat"
tempgrad      = 0.0
tempgrjul     =  0.0
! forcage_file1 : snapshot climat 1
! mincoefbmelt : borne mini de coefbmshelf
! maxcoefbmelt : borne maxi de coefbmshelf
! filforc : fichier de forcage
! tempgrad : lapse rate annuel
! tempgrjul : lapse rate d'ete
/
!___________________________________________________________
&clim_act

file1       = "Snapshots-GCM/clim_B140_topo2_NH_40km_withice_GRISLI_lapse5.xyz" ! reference climate
```

```
annual       = .false.
type_precip  = .true.
/
! file1  : reference climate
! annual : .true. if climate file contains Tann Tjja
! type_precip : .true. if liquid precip (.false. snow)
!____________________________________________________________
&clim_pert                                    ! nom du bloc

rappact      = 0.05 ! 0.05 pour Antartique
retroac      = 0
rapbmshelf   = 5.
mincoefbmelt = 0.
maxcoefbmelt = 2.
filforc      = "b140_topo1_150.dat"
tempgrad      =         0.005  ! Annual lapse rate (C/m)
tempgrjul     =         0.004  ! Summer lapse rate (C/m)
/
!-----------------------------------------------------------
&ablation_ann                                 ! PDD base Tann et Tjuly

 Cice          = 0.008
 Csnow         = 0.003
 Sigma         = 5.
 csi           = 0.6
/

! Cice and Csnow, melting factors for ice and snow
! sigma variabilite Tday
! csi proportion of melted water that can refreeze
!-----------------------------------------------------------
&meca_SIA_L1                         ! bloc resol_meca

i_resolmeca  =  2
/
! i_resolmeca type d association entre SIA et L1'
! i_resolmeca=0  chacun dans sa zone'
! i_resolmeca=1  dans les zones stream, addition si uxdef > uxL1 (MIS11 Cairns)
! i_resolmeca=2  addition systematique dans les zones stream
```

8 Output variables and output frequency

The output variables that have to be written during run time in the output NetCDF and ASCII files are listed in the file LISTE-VAR-NETCDF.dat and LISTE-VAR-HZ.dat, respectively. Those files are located under GRISLI/SOURCES/Fichiers − parametres/.

The variables are listed according to their dimension and the user may decide the frequency of output of those variables by switching on some flags. For example:

```
-------------------------------------------------------------
S                      ! name of the variable in GRISLI
1                      ! index number of the variable
1 1 1                  ! isortie  ,  dtncdf , interv
-------------------------------------------------------------
H                      ! ice thickness
2
1 1 1
-------------------------------------------------------------
```

where the frequency of output is determined according the three flags `isortie`, `dtncdf`, `interv`:

- `isortie`: determines whether or not the variable will be output.
  If isortie = 1 -> output; if isortie = 0 -> no output
- `dtncdf`: indicates the periodicity of output for the variables. For example:
  dtncdf = 1 means that the variables will be output at the first time step frequency `ndtsortie` indicated in the TEMPS-NETCDF.dat
  dtncdf = 2 means that the variables will be output at the second time step frequency `ndtsortie` indicated in the TEMPS-NETCDF.dat
  dtncdf = 0 means that the output will occur only on the intermediate time steps `npredeft` indicated in the TEMPS-NETCDF.dat
- `interv`: indicates the time interval at which outputs are written:
  interv = -1 the outputs are written at the first and last time steps only.
  interv = 0 the outputs are written at the first time step only.
  interv = 1 the outputs are written at all time steps specified in the file TEMPS-NETCDF.dat

For example:

`1 1 0` outputs written for the first time step and all intermediate time steps specified in TEMPS-NETCDF.dat
`1 0 -1` outputs written at the first and last time step
`0 1 1` no output written
`1 0 0` outputs written at the first time step only
`1 1 1` outputs written at all time steps: first, intermediate and last

The time step frequency is defined in the TEMPS-NETCDF.dat and TEMPS-HZ.dat, located under `GRISLI/SOURCES/Fichiers-parametres/`:

```
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ fin des commentaires~~~~~~~~~~~
2                       number of classes to be written
1   2   3    4   5   class    (see variables class in LISTE_VAR_NCDF.dat)
------------------------------------------------------------------------
3       ndtsortie      lecture de dtncdf de sortie
20.
1000.
2000.
------------------------------------------------------------------------
4       npredeft        lecture de predef_tsort
25
35
65
```

```
85
------------------------------------------------------------------------
```

Three sections have to be parametrised:

1. variable class: the variables in the file LISTE-VAR-NETCDF.dat have been classified according to their dimensions in five distinct classes.

   1 = Var 2D to be output regularly
   2 = Var 2D to be output regularly and in case of debugging
   3 = Var 3D to be output regularly
   4 = Var of debugging only
   5 = Var output only once at the beginning and once at the end of the simulations

   In the example above, 2 classes will be output, i.e class 1 and class 2. The order of the classes is not important and if the user wants to output class 3 and class 4 then this section will look like:

   ```
   ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ fin des commentaires~~~~~~~~~~~
   2                       number of classes to be written
   3    4    5    1    2 class    (see variables class in LISTE_VAR_NCDF.dat)
   ------------------------------------------------------------------------
   ```

2. `ndtsortie` = corresponds to the regular frequency of output given in years. In the example above, three frequencies have been set, 20 years, 1000 years and 2000 years. Those frequencies can be assigned to the variables in the file LISTE-VAR-NCDF.dat:

   ```
   ------------------------------------------------------------
   S
   1
   1 1 1                 ! the variable will be output each 20 years
   ------------------------------------------------------------
   ```

   Another example:

   ```
   ------------------------------------------------------------
   S
   1
   1 2 1                 ! the variable will be output each 1000 years
   ------------------------------------------------------------
   ```

3. `ndtpredeft` = corresponds to intermediate time steps given in years. In the example above, outputs will also occur at model-year 25, model-year 35, model-year 65 and model-year 85.

Numeric and theory

GRISLI is able to simulate both grounded and floating ice. The grounded part uses the Shallow Ice Approximation (SIA, Hutter, 1983) whereas ice shelves and ice streams are simulated following the Shallow Shelf Approximation (SSA, MacAyeal, 1989). The ice shelf formulation in GRISLI allows for a more realistic calculation of the ice sheet growth, and particularly of the advance of ice onto the shallow continental shelves in both hemispheres high latitudes. GRISLI has been validated over Antarctica (Ritz et al., 2001) and successfully applied to study the inception of ice sheets during the Early Weichselian period (Peyaud et al., 2007; Alvarez-Solas et al., 2011). In the following, we give a detailed description of the model. Notation of the main variables is listed in Table 1 and Table 2.

DEFINITION OF ICE FLOW IN GRISLI

In GRISLI, three different regions of ice flow are considered: ice sheets, ice stream zones and ice shelves. Ice sheets and ice stream zones are regions with grounded ice, whereas ice shelves are regions with floating ice (Figure 6). During the simulation, the location of these different regions is determined in every time step. The three different regions are characterised by distinct flow behaviour:

1. Ice sheets (inland ice) are areas of grounded ice where ice flow results from deformation. In addition, basal sliding might occur in areas where the base is at the pressure melting point. Here, the SIA applies.

2. Ice streams are regions of fast flowing ice. In reality ice streams are glaciological features with widths of a few kilometres, much smaller than our grid size (20 to 40 km). In GRISLI, the effect of these features is parametrised by treating areas which have the large scale characteristic of ice streams differently, i.e. narrow valleys, thick sediment layer saturated by melt water, high effective basal pressure. In these areas we apply the SSA, a different set of momentum equations than for the slow-flowing ice sheet, following the approach by MacAyeal (1989).

3. Ice shelves are large floating ice plates in contrast to ice sheets and streams which are grounded, and are fed by inland ice. The line where ice begins to float is called the grounding line, and once the flow passes this line, the ice mass does not contribute to sea level anymore. Ice shelf nodes must satisfy a flotation criterion, and velocities in these grid points are computed from the same set of equations as the velocities in ice stream nodes but assuming a zero basal drag.

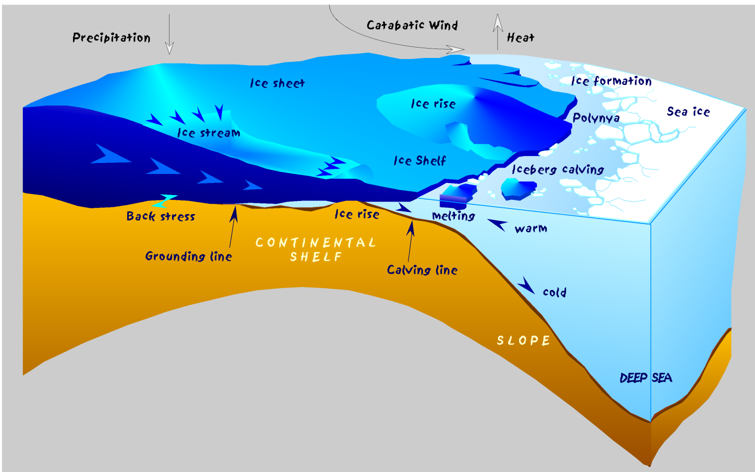

Figure 6:
Sketch illustrating the different regions considered in GRISLI: ice sheets, ice streams and ice shelves. Figure from H. Grobe, AWI.

FUNDAMENTAL EQUATIONS

The governing equations of ice sheet dynamics are based on the conservation of mass, momentum and energy:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \tag{6}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \tau + \rho \mathbf{g}, \tag{7}$$

$$\rho c \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla (\kappa \nabla T) + Q_i, \tag{8}$$

where ρ stands for the ice density, $\mathbf{u}$ for the ice velocity, τ for the stress tensor, g for the gravitational acceleration, c for the heat capacity of ice, T for the ice temperature, κ for the thermal conductivity of ice, and Q_i for the deformational heat.

If we consider ice as an incompressible fluid with a constant density, the continuity equation (6) simplifies to

$$\nabla \cdot \mathbf{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \tag{9}$$

This equation is used to diagnose the vertical velocity from horizontal velocities (the computation of the horizontal velocity will be described later on).

The vertical integration of equation (6) from the base of the ice sheet B to the surface elevation S leads to an equation for the ice thickness. Defining the ice thickness H as surface elevation minus the base of the ice sheet ($S - B$), assuming that the ice density is constant and accounting for ablation and accumulation (Surface Mass Balance, SMB) at the ice surface as well as melting at the ice base (F) leads to:

$$\frac{\partial H}{\partial t} + \frac{\partial (H\,u)}{\partial x} + \frac{\partial (H\,v)}{\partial y} = SMB + F \tag{10}$$

The fundamental contributions that govern the mass balance of the ice sheet are:

- The surface mass balance SMB (accumulation minus ablation) which depends on climatic conditions (surface air temperature and precipitation).
- The basal melting rate F, which depends on the pressure melting point below the ice sheet and the geothermal heat flux. Below ice shelves, basal melting results from oceanic heat flux, and is denoted by b_{melt}.
- Calving of the ice shelf, which depends on a thickness criterion.

EQUATION OF MOTION: GROUNDED ICE

Velocities within the ice sheet are rather small, and thus acceleration can be ignored: Assuming typical values for an ice sheet geometry and typical flow velocities, the ratio between acceleration and horizontal pressure gradient is $\sim 10^{-15}$, see Greve and Blatter (2009). Equation (7) can then be written as:

$$\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = 0, \tag{11}$$

$$\frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0, \tag{12}$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} = \rho \mathbf{g}. \tag{13}$$

We split up the stress tensor into a deviatoric part τ' and an isotropic pressure:

$$\begin{aligned} \tau_{ij} &= \tau'_{ij} - \frac{1}{3}(\tau_{xx} + \tau_{yy} + \tau_{zz})\,\delta_{ij} \\ &= \tau'_{ij} - p. \end{aligned}$$

We assume that the shear stresses τ_{zx} and τ_{zy} are small compared to the vertical normal stress τ_{zz}. This reduces the vertical momentum equation to a balance between the vertical gradient of τ_{zz} and the gravity force (hydrostatic approximation). Integration gives the hydrostatic pressure equation:

$$p = \rho g (H - z). \tag{14}$$

In GRISLI, like in other large-scale ice-sheet models, the shallow ice approximation (SIA, Hutter (1983)) is used. The SIA is a simplification which is reasonable when the horizontal length scale is much larger than the ice thickness. We assume that the flow regime is mainly characterised by bed-parallel shear. Thus the relevant components of the deviatoric stress tensor are the shear stresses in the horizontal plane, τ_{xz} and τ_{yz}. Then the horizontal components of the momentum balance simplify to:

$$\frac{\partial \tau_{xz}}{\partial z} = \frac{\partial p}{\partial x} = \rho g \, \frac{\partial H}{\partial x} \tag{15}$$

$$\frac{\partial \tau_{yz}}{\partial z} = \frac{\partial p}{\partial y} = \rho g \, \frac{\partial H}{\partial y} \tag{16}$$

The deviatoric stress τ_{xy} is related to the strain rate $\dot{\epsilon}_{xy}$ by a nonlinear Glen-type flow law (an equivalent expression holds for τ_{yz} and $\dot{\epsilon}_{yz}$):

$$\dot{\epsilon}_{xy} = \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) = B_{AT}(T_{pmp})\tau_*^{n-1}\tau_{xy}, \tag{17}$$

where B_{AT} is the temperature dependent flow law coefficient, n is the flow law exponent (here we use n=3). τ_* is the effective shear stress given by

$$\tau_* = \sqrt{\tau_{xz}^2 + \tau_{yz}^2}. \tag{18}$$

The ice temperature T_{pmp} is the absolute temperature corrected for the dependence on the melting point on pressure:

$$T_{pmp} = T + 9.76 \cdot 10^{-8} \rho \, g(S - z). \tag{19}$$

The flow law coefficient B_{AT} follows an Arrhenius relationship:

$$B_{AT} = B_{AT0} \exp\left(\frac{E_a}{R}\left(\frac{1}{T_{pmp}} - \frac{1}{T}\right)\right), \tag{20}$$

where B_{AT0} is a coefficient, E_a is the activation energy and R the universal gas constant.

Combining the above equations and integrating over z gives an equation for the horizontal velocity $\mathbf{u}$:

$$\mathbf{u} = -(\rho g)^n (\nabla S.\nabla S)^{\frac{n-1}{2}} \nabla S \, E_f \int_B^z B_{AT}(T_{pmp})(S - z')^n \, dz' + \mathbf{u}_B. \tag{21}$$

E_f is a parameter, the flow enhancement factor, set to 3 in this model version.

We assume that sliding of ice over the bedrock occurs only if the basal ice temperature reaches the melting point. The basal velocity $\mathbf{u_B}$ is expressed as a function of basal shear stress and effective pressure N, following Weertman (1957):

$$\mathbf{u}_B = k(\rho g H)^3 \, (\nabla S.\nabla S)^{\frac{1}{2}} \, \nabla S \, N^{-1}, \tag{22}$$

where k is an adjustable parameter, set to 5·10^{-11} in this version of GRISLI. The effective pressure N is given by

$$N = \rho g H - p_w, \tag{23}$$

where p_w is the sub-glacial water pressure. Again, equation (22) is only valid for regions where the basal ice temperature reaches the melting point. If the basal ice temperature is below the melting point, the basal velocity is set to zero. In GRISLI, the sliding law described above is only valid for small velocities (< 50 m/yr). Regions with larger velocities are considered as "fast flowing areas" and treated separately (see next section).

EQUATION OF MOTION: FAST FLOWING AREAS

Ice streams and ice shelves are characterised by fast flow and low surface slopes. The sliding velocity (eq. (22)) depends strongly on the surface slope, and thus fast flowing areas would not be represented well in the model. For that reason, we treat ice stream and ice shelf areas separately in the model by applying the shallow shelf approximation (SSA MacAyeal, 1989). Those regions are called "fast flowing areas". Due to the fact that we use a horizontal resolution of 20 km and 40 km in our model setup, GRISLI cannot resolve individual ice streams. Thus, a grid point in GRISLI is considered as "ice stream grid point" if it has the large-scale characteristics of an ice stream area.

With the SSA, the horizontal velocity is independent from depth, which is reasonable for ice shelves and fast flowing ice stream areas. This leads to the following elliptic equation for horizontal vertically averaged velocity $\bar{\mathbf{u}}$:

$$\frac{\partial}{\partial x}\left[2\bar{\eta}H\left(2\frac{\partial u}{\partial x}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\bar{\eta}H\left(2\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]=\rho g H\frac{\partial S}{\partial x}-\tau_{bx}, \tag{24}$$

$$\frac{\partial}{\partial y}\left[2\bar{\eta}H\left(2\frac{\partial v}{\partial y}+\frac{\partial u}{\partial x}\right)\right]+\frac{\partial}{\partial x}\left[\bar{\eta}H\left(2\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]=\rho g H\frac{\partial S}{\partial y}-\tau_{by}. \tag{25}$$

where $\bar{\eta}$ is the ice viscosity, vertically averaged over the ice thickness. τ_{bx} and τ_{by} stand for the basal drag. This set of equations is used both for ice stream areas and ice shelves.

Ice shelves
In case of ice shelves, the basal drag $\tau_{\mathbf{b}}$ is set to zero (since ice shelves are floating on the water without any resistance). In every time step, the position of ice shelves is determined with a flotation criterion, which is based on Archimedes' principle of floating bodies:

$$\rho_w(SL-B)=\rho H, \tag{26}$$

where ρ and ρ_w are the ice and water density, respectively. SL and B stand for sea level and the base of the ice sheet, respectively.

Calving of the ice shelf is determined by a thickness criterion. As soon as the ice thickness in an ice shelf node at the front reaches a certain threshold H_{calv}, the node is "cut off". We set H_{calv} to 200 m, which corresponds to values observed at the large ice shelves of Antarctica. The oceanic basal meting rate below the ice shelf, b_{melt}, is determined by the temperature of the ocean. In this version of GRISLI we use a simplified approach assuming a melting rate which only depends on the water depth. Above 450 m, b_{melt} is set to 0.2 m/yr, while below 450 m depth b_{melt} is set to 2.45 m/yr .

Ice streams
In case of ice streams, the basal drag in equations (24) and (25) is described by a friction law. It depends on the vertically averaged velocity $\bar{\mathbf{u}}$ and the effective pressure N (eq. (23)), scaled with the basal drag coefficient c_f:

$$\tau_{\mathbf{b}}=-c_f\,N\,\bar{\mathbf{u}}, \tag{27}$$

The position of the "ice stream grid points" is determined with the following three criteria, from which at least one has to be fulfilled:

- The grid point is located in a narrow valley.
- First, the sediment layer has to be thick (h_{sed} > 150 m). However, this threshold is ad-hoc and no direct evidence exists to constrain it better (see Discussion). Second, it has to be saturated by meltwater. This saturation is determined by the hydraulic head h_w, which has to exceed 250 m (the hydraulic head is calculated with a Darcy flow law, see section). Third, the effective pressure N has to be lower than 3.5 10^7 Pa.
- The grid point is located on an ice rise with low ice thickness and low surface slope. It has to hold that: $\rho\, g\, H\, \nabla S\ \leq 7{\cdot}10^6$ Pa.

BASAL HYDROLOGY

One criterion for determining the position of ice streams is the basal water head h_w. In the following, we describe how basal hydrology is implemented in GRISLI.

The basal hydrology is characterised by different hydrological features, ranging from drainage through a thin film of water (< 1 mm) to flow through a network of cavities and rivers. Also percolation of basal water into the porous sub-glacial sediment plays an important role. Nonetheless, due to a lack of observations we still do not fully understand the hydrological processes occurring below ice sheets. Thus, the representation of basal hydrology in an ice-sheet model is one of the most arguable components, but indeed one of the most important processes for the dynamics of the whole ice sheet.

The basal hydrology in GRISLI was implemented by Peyaud (2006), and is based on a Darcy-type flow law. The drainage of sub-glacial water depends on the pressure imposed onto the base. This pressure can be expressed as a potential, and the flow of melt water follows its gradient. The potential can be written as:

$$\Phi = p_w + \rho_{fw} g B + \rho g H + \Phi_O. \tag{28}$$

p_w stands for the sub-glacial water pressure. The second term represents the influence of the altitude of the base, while the third term represents the pressure resulting from the weight of the ice. Φ_O is an arbitrary constant. Then, the gradient of Φ can be expressed as

$$\nabla\Phi = \nabla p_w + \nabla(\rho_{fw} g B + \rho g H) = \nabla p_w + \rho g \left[(\frac{\rho_{fw}}{\rho} - 1)\nabla B + \nabla S \right]. \tag{29}$$

Note that the magnitude of the surface gradient ∇S is around 10 times larger than that of the bedrock. Darcy's law states that flow through a porous medium is proportional to a hydraulic gradient, which corresponds to the variation of the hydraulic head, h_w. This leads to an equation for the flow velocity, and with expressing the hydraulic head as $h_w = \Phi/\rho_{fw} g$ we obtain

$$V_e = -K\nabla h_w = -\frac{K}{\rho_w g}\nabla\Phi, \tag{30}$$

with the proportionality constant K (the hydraulic conductivity). This parameter depends on the property of the soil (e.g. clay: <10^{-9} m/s, till: 10^{-12} to 10^{-5} m/s, fine sand: 10^{-7} to 10^{-5} m/s). In GRISLI, K is set in the following way: If the base is cold (with the ice temperature below the pressure melting point), we make the assumption that the ground is impermeable and thus K is set to zero. If the base is warm (with the ice temperature above the pressure melting point) and the effective pressure is high, we choose a constant value of $K_0 = 10^{-6}$ m/s. If the effective pressure is low, the hydraulic conductivity increases:

$$K = \begin{cases} K_0 & \text{if } N > 100 \text{ bar} \\ K_0 \cdot \frac{1000}{N} & \text{if } N \leq 100 \text{ bar} \end{cases} \quad (31)$$

The variation of the hydraulic head with time is governed by the horizontal variation of the water flux and by two source terms, the basal melting rate b_{melt} (computed from the heat equation (eq. 8)), and the infiltration rate into the soil $I_{infiltr}$:

$$\frac{\partial h_w}{\partial t} + \frac{\partial V_{ex}}{\partial x} + \frac{\partial V_{ey}}{\partial y} = F - I_{infiltr}. \quad (32)$$

ICE TEMPERATURE

The ice temperature is required to calculate the flow law coefficient B_{AT}, the basal melting rate F below the grounded regions, and the basal ice velocity $\mathbf{u_B}$, since sliding occurs only in areas where the basal ice temperature is at the melting point. The time-dependent heat equation (8) is solved in the ice sheet, and accounts for horizontal and vertical advection of ice, vertical diffusion and production of heat through deformation.

At the surface, the ice temperature is determined by climatic conditions (which also depend on surface elevation). The ice temperature 10 m below the ice surface is almost similar to the annual mean surface air temperature T_{ann}. Thus we use T_{ann} as a surface boundary condition for ice temperature. At the base of the ice sheet, a geothermal heat flux (GHF) is prescribed. At the ice-bedrock interface we distinguish between warm and cold conditions: Below the melting point, the heat flux at the interface consists of geothermal heat, which is transmitted by vertical diffusion into the ice. At the melting point, the melting rate depends on the difference between the heat fluxes on both sides, including heat generated by friction during the sliding. If basal temperatures T_b are at the melting point, they are held constant:

$$T_b = T_{pmp} \quad \text{if } T_b \geq T_{pmp}, \quad (33)$$

and the excess in heat is used for basal melting F. This basal melting rate F is one of the components of the mass conservation equation (eq. (6)).

CALVING

The spatial extent of ice shelves is controlled by the calving process. In GRISLI, the position of the ice shelf front is based on a thickness criterion H_{coup}. The ice shelf front corresponds to the pixels where the ice thickness at the ice-ocean boundary equals 0. A grid node is considered as part of the front if all the three following conditions are fulfilled:

- floating

- the ice thickness is not equal to zero
- if a neighbour point has an ice thickness equals to zero and is located in the ocean domain

The method implemented by Peyaud (2006) consists in determining if a new ice shelf point should be cut or should thicken and become part of the ice shelf ($H > H_{coup}$). Ih this node is not calved, it will be considered as the new ice shelf front. This process is computed at each time step and when the thickness of the ice shelf front is lower than the calving criterion, GRISLI tests the status of the front.

The ice-shelf thickness variations are computed by means of a Lagrangian scheme:

$$\frac{dH}{dt} = bm - bmelt - H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \tag{34}$$

where H is the ice thickness, u and v are horizontal velocities, bm corresponds to the surface mass balance and $bmelt$ corresponds to the fusion at the base of the ice shelf (prescribed in the namelist). This equation is applied to the upstream node of the pixel tested for calving. The upstream node has an ice thickness $H_{upstream}$ greater than the thickness criterion H_{coup}. The time used by the ice in the upstream node to flow to the neighbour ice shelf front point is given by:

$$\tau_f = \frac{\partial x}{\partial u} \tag{35}$$

Therefore, the ice thickness variation during this time τ_f is:

$$\tau_f * \frac{dh}{dt} \tag{36}$$

This quantity is generally negative because the upstream point lose some mass in favour of the ice shelf front node. Using this quantity, the thickness at the front H_{front} can be deduced:

$$H_{front} = H_{upstream} + \tau_f * \frac{dh}{dt} \tag{37}$$

If H_{front} is lower than H_coup, calving occurs in the node. In the case that no calving occurs, the condition to maintain and develop the ice shelf front is given by:

$$\frac{dH}{dt}|_{upstream} \geq \frac{\vec{u}}{dx}(H_{coup} - H_{upstream}) \tag{38}$$

As reported by Peyaud (2006), a physical problem arises when ice shelves develop from coastal grounded ice. In the coastal areas, the grounded ice is generally thinner than H_{coup}. As a consequence, when the ice starts to float, some calving occurs. As the horizontal velocities increase substantially in the floating part, the ice flux is too large, which does not allow the ice to reach a thickness larger than H_{coup}. Therefore, an additional test is performed in that case and the testing procedure is applied only if none of the neighbour point is grounded.

At last, if some nodes, in the middle of the ice shelves have an ice thickness lower than H_{coup}, some polynias develop locally. Those polynias can grow and divide the ice shelf. This issue is avoided by applying calving only if a point is located at the front of the ice shelf.

In GRISLI, there are 5 different options to treat the calving. For example. one of the option is to test whether or not the ice thickness in the upstream point is larger than H_{coup} or the mass balance $bm - bmelt$ is positive. Those options are described more into details in the Tutorial section.

BASAL MELTING UNDER THE SHELVES

Because they are floating over oceans, the ice shelves are naturally affected by the ocean warmth at their base. The basal melting is generally important near the grounded line area because the depth of the ice shelves is large and therefore reaches area were ocean temperature is more elevated than at the surface. The fresh water resulting from the ice melting, is less dense than the sea water and flows toward to surface following the base of the ice shelves. This fresh water mass is deviated by the Coriolis strength and exchange of mass, temperature and salinity occurs with the surrounding sea water. This fresh water mass mixes up completely when its density reaches that of the sea water. Basal melting decreases gradually from the grounded line toward the front of the ice shelves and some refreezing can occur in the central part. At the front, the basal melting is generally high because this part of the ice shelf is located far away from the ice sheets and is therefore subject to warmer oceanic currents.

While several parametrisations of basal melting under the ice shelves have been developed in the ocean general circulation models, most of the ice-sheet models are not coupled with ocean, therefore it is difficult to properly calculate the basal melting accounting for ocean temperature changes. In GRISLI, basal melting follows the work of Dumas (2002) who calculates the basal melting in function of surface temperature and an ocean depth criterion. A distinction is made between the grounded line (`bmgrz`) and the rest of the ice shelf (`bmshelf`):

1. according to the depth criterion set in the namelist, two different values of basal melting can be attributed: one above this limit (`bmelt1`) and one below (`bmelt2`). During the initialisation phase:

$$bmshelf = bmelt1 \tag{39}$$

$$bmgrz = bmelt1 \tag{40}$$

   or $bmelt2$ if appropriate.

2. the basal melting occurring at a depth above the defined limit is a function of surface temperature, set as a coefficient:

$$bmelt = coeftemp * bmshelf \tag{41}$$

   If the depth is larger then the defined value then:

$$bmelt = bmshelf \tag{42}$$

3. At the grounded line, for the point located along this line but which are still floating, the basal melting is also set as a function of surface temperature since the depth of the grounded line might vary in function of the area:

$$bmelt = coeftemp * bmgrz \tag{43}$$

If the point is at the grounded line and is not floating, the basal melting is a combination between the grounded zone value `bmgrz` and the basal melting of the floating part:

$$bmelt = (ngr/4) * bmgrz * coeftemp + (1 - ngr/4) * bmshelf * coeftemp \tag{44}$$

where `ngr` corresponds to the number of grounded neighbour points.

In the last version of GRISLI, no difference is made for the grounded zone and central ice shelf basal melting values if the grid domain is not Antarctica. The user may easily edit the basal melting routine to account for different values between those two areas.

SURFACE MASS BALANCE

The surface mass balance (SMB) in the ice-sheet model is composed of accumulation and ablation:

SMB = Accumulation - Ablation

The accumulation corresponds to the mean annual total precipitation obtained from CESM, which is turned into snow using a density of 917 g/cm^3.

In GRISLI, ablation is parametrised using the Positive-Degree-Day (PDD) semi-empirical method (Reeh, 1991). This method is based on an empirical relationship between the number of positive degree days, computed from annual mean and July surface air temperature, and the snow and ice melting rates which depend on the melting factors C_{snow} and C_{ice}, derived from observations. The number of positive degree days (PDD) is given by:

$$PDD = \frac{1}{\sigma\sqrt{2\pi}} \int_{1yr} \int_0^{\infty} \exp\left(\frac{-(T - T_d)^2}{2\sigma^2}\right) dT dt \tag{45}$$

where T_d is the daily temperature and σ the standard deviation of the daily temperature, usually set to 5°C. This formulation allows for positive temperatures even when the average daily temperature is below the melting point. As a consequence, it may also overestimate melting in general (Bougamont et al., 2007). The daily temperature T_d is reconstructed from annual mean and July temperatures, T_{Ann} and T_{July}, by assuming that the annual temperature cycle follows a cosine function (Figure 7):

$$T_d(t) = T_{Ann} + (T_{July} - T_{Ann}) \cos(2\,\pi\,t/\,365). \tag{46}$$

Ablation is then calculated in several steps:

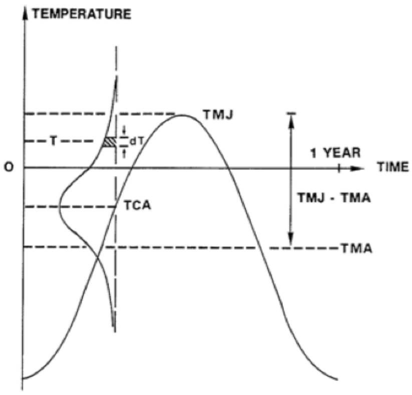

Figure 7:
Reconstructed annual temperature cycle used to calculate the number of positive degree days. The annual cycle is retrieved from the annual mean temperature and the July temperature. Figure from Reeh (1991).

1. Snow, if it is present, is melted at rate C_{snow}. Melt water is supposed to percolate into the snow layer and refreezes as superimposed ice. Runoff occurs when the amount of superimposed ice exceeds 60% of the yearly snowfall.
2. Superimposed ice is melted at rate C_{ice}.
3. Glacier ice is melted.

Depending on the available energy, not all steps or even none of the steps will be carried out. The melting factors C_{snow} and C_{ice} are typically set to 0.003 and 0.008 mm d^{-1} °C^{-1}. C_{snow} and C_{ice} take different values to account for the difference in albedo between snow and ice. The portion of melted water that can refreeze, denoted by csi, is usually set to 60%, but can reach values up to 70% (Pfeffer et al., 1991).

ISOSTATIC RESPONSE

The bedrock reacts to changes in ice load (Figure 8). In GRISLI, this isostatic response is described by the ELRA (elastic lithosphere-relaxed asthenosphere) method (Le Meur and Huybrechts, 1996). The lithosphere is treated as a thin elastic plate. This allows a regional response to the ice load, so that the bedrock in a certain distance from the imposed ice load can still be affected (in contrast to the rather simple "local lithosphere"-method which accounts only for a local response). The underlying asthenosphere is assumed to be viscous. Due to its viscous property the asthenosphere responds to an imposed ice load with a time lag, the characteristic relaxation time τ_r. In GRISLI the default value of this parameter is 3000 years (Turcotte and Schubert, 2002).

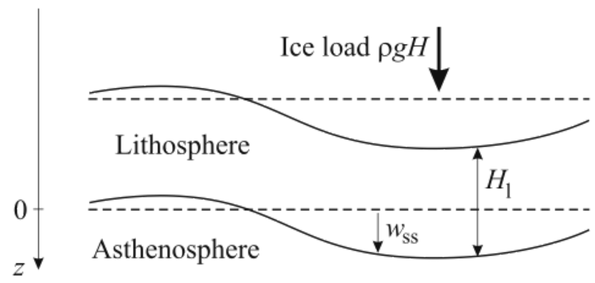

Figure 8:
Sketch of the ELRA-method. Figure from Greve and Blatter (2009).

Tutorial: setting a Northern Hemisphere simulation

In this section, the setting of a run over a Northern Hemisphere grid is detailed and explained. There are five mains step to run a simulation:

1. Selecting some aspects of the physics
2. Compilation
3. Namelist settings
4. Output variables and frequency
5. Running

For each of the grid domain implemented in GRISLI, a short name related to the geographical domain is set and reused within the routines. The Northern Hemisphere domain implemented in GRISLI has been projected using the Lambert Equal Area projection with a 40 km horizontal resolution. This domain covers all the Northern mid-latitudes from about 20°N to the North Pole. The short name attributed to this domain, or geoplace, in GRISLI is: $hemin40$ and will be used in the following instruction to refer to the domain.

PHYSICS OPTIONS

In the previous section, the main aspects of the physics embedded in GRISLI has been described. Some of those aspects present several options that may be set in the namelist or in a module related to the grid domain, and in which some of the parametrisation can be selected. In the case of the Northern Hemisphere domain, the file is called module_choix-hemin40-0.4.f90 and is located under GRISLI/SOURCES/Hemin40_files/:

```
! This module allows to choose some physical and practical aspect of the model
!

MODULE MODULE_CHOIX

!-------------- Reading initial topography ------------------------
! use lect_topo_anteis     ! For Antarctica 40 km
  use lect_topo_hemin40    ! For Northern Hemisphere 40 km
! use lect_topo_eurasie    ! For Eurasia  (toute resolutions)

!-------------- Reference Climate type  ------------------
! use lect_clim_act_anteis
  use lect_clim_act_hemin40   ! For Northern Hemisphere
! use lect_clim_act_eura20    ! For Eurasia

!-------------- Climate forcing type --------------------
```

```
  use climat_perturb_mod
! use climat_forcage_mod
! use climat_profil_mod
!  use climat_regions_delta

!------------- Proglacial lakes -------------------------------
! use lakes_prescribed_mod
  use no_lakes

!-------------- Isostasy --------------------------------------
  use isostasie_mod               ! module accounting for isostaty
! USE NOISOSTASIE_MOD  ! no isostasy

!-------------- Ice deformation law ---------------------------
  use deformation_mod  ! deformation law

!-------------- Ice thermal properties ------------------------
  use  prop_thermiques_ice
! use prop_therm_ice_heino

!-------------- Basal water hydrology -------------------------
  use eau_basale

!-------------- Basal sliding ----------------------------------
! use module sliding_vitbal
  use sliding_Bindschadler
! use sliding_dragging_heino

!-------------- Basal dragging ----------------------------------
! use dragging_vitbil
! use dragging_hwatstream
! use dragging_hwat_cont
! use dragging_hwat_contmaj  ! friction streams Cat Antarctique
  use dragging_hwat_sedim    ! friction with sediments maps
!  use dragging_jorge              ! friction stream Jorge Sediments

!------------- Elliptique equation -----------------------------
! use eq_elliptique_mod   ! old version (remplimat-5)
  use eq_ellip_sgbsv_mod  ! new version July 2008

!------------- Calving ------------------------------------------
! use calving_vincent ! old version
  use calving_frange   ! new version

!------------- Mass Conservation --------------------------------
  use equat_adv_diff_2D          ! with advection-diffusion

!-------------- Basal Melting ----------------------------------
! use bmelt_ant_regions     ! For Antarctica with regions
! use bmelt_nor_regions     ! For Northern Hemisphere with regions
```

```
  use bmelt_nor_depth       ! For Northern Hemisphere with water depth criterion
! use bmelt_eurasie_regions ! For Eurasia with regions
! use bmelt_eurasie_depth   ! For Eurasia with water depth criterion

!-------------- Fake routines for compatibility ----------------
! use fake_heino
!  use fake_eurasie
 use fake_nor

!-------------- Outputs-----------------------------------------
  use out_profile   ! ASCII vertical profiles
  use out_cptr      ! ASCII restart files
  use out_hz        ! ASCII variable outputs

!-------------- Time outputs -----------------------------------
 use output_hemin40_mod
!  use output_eurasie20_mod

!-------------- Debugging --------------------------------------
  use printtable

end module module_choix
```

Some of those routines are located under GRISLI/SOURCES/Hemin40_files/, namely all the routines related to initial topography, grid and climate forcing, basal hydrology and basal melting, while the others are located with the other routines in GRISLI/SOURCES/.

COMPILATION

One the user has defined the modules that will be compiled for the geoplace, the routines may be compiled through the Makefile as follow:

```
>  cd GRISLI/SOURCES
>  make Hemin-40
```

Hemin-40 is the name of the executable that will be produced by the compilation of the various routines contained in the Makefile. This executable will be placed in GRISLI/bin/. See the next section for a more detailed explanation of the Makefile.

NAMELIST SETTINGS

The setting of the namelist options can be done after the compilation. In the following, we provide a detailed description of the various blocks of the namelist. Each grid domain in GRISLI has its own namelist file located under GRISLI/SOURCES/Fichiers-parametres. In the case of the Northern Hemisphere, the namelist file is hemin40_param_list.dat.

Run name and restart procedure:

```
!_____________________________________________________________
&runpar                      ! name of the run parameters block

 runname       =  "NHtest1"   ! 8 characters at maximum
 icompteur     = 0
 reprcptr      =  " "
 itracebug     =  0
 num_tracebug = 166
 comment_run   = "Northern Hemisphere test run"
/
! runname     : nom de l experience (8 caracteres)
! icompteur   : restart in a file  0 -> no
!                      1 -> yes,
!                      2 -> only restarting from T and Hwat
!                      3-> T only
! reprcptr    : name of the restart file
!_____________________________________________________________
```

This block is the first block of the whole namelist and includes all the parameters to be set related to the name of the simulation and the restart process:

- `runname`: name of the simulation. MUST HAVE 8 characters at maximum.
- `icompteur`: switch to restart or not from a pre-existing restart file.
- `reprcptr`: name of the restart file. The restart files have the extension `.cptr` and are written during run time in GRISLI/Fichier-CPTR/ at a frequency that have to set manually in the routines `GRISLI/SOURCES/out_cptr_mod.F90`. To restart from one of those files, the user may set the name of the restart file in this variable and change the `.cptr` extension to `.CPTR`.

  For example, if a previous simulation called `NHtest0` was run for 30 kyrs, then the last restart file produced during run time will be `NHtest0+k030.cptr`. To restart from this file, the user may set:

  ```
  icompteur = 1   (or 2 or 3)
  reprcptr = "NHtest0+k030.CPTR"
  ```

  then the user may change the extension of the restart file to:

  ```
  > cd GRISLI/Fichier-CPTR
  > mv NHtest0+k030.cptr  NHtest0+k030.CPTR
  ```

In addition, the user will have to set the initial model time (in years) to the time written in the first line of the restart file. In the example above, this initial model time will be set to 30000. See the explanations for the `timesteps` namelist block.

- `itracebug`: switch to debugging mode. 0 –> no, 1 –> yes
- `num_tracebug`: corresponds to the number of the call within the routine for debugging. The call to the debugging function is used to to print some matrix and arrays during run time and check the values and dimensions.
- `comment_run`: character chain written in the ASCII output file and set by the user to write specific comment about the simulation.

Netcdf output frequency:

```
!___________________________________________________________________
&netcdf                      ! bloc netcdf

 dtncdf      =       10.
 /
! dtncdf :espace en temps entre les sorties
!___________________________________________________________________
```

This block is overwritten by the file `GRISLI/SOURCES/Fichiers − parametres/hemin40_TEMPS − NETCDF.dat` where the frequency of output is defined **(See Section 8)**. The user may therefore set an ad-hoc value.

Grounded line physics:

```
!___________________________________________________________________
&grdline                     ! bloc grounding line

 igrdline     =             0
 /
! igrdline :  fixed -> 1 , free -> 0
!___________________________________________________________________
```

This blocks determines whether or not the grounded line will be fixed, i.e. not dynamic or will be able to move during the simulation. Fixed grounded line is typically used to spin-up Greenland to present-day topography for example and avoid that the expansion of the ice sheet beyond the observed limit. This has consequences on the ice shelves and on the mass conservation.

Model time steps:

```
!________________________________________________________________
&timesteps                ! bloc timestep

 tend       =   30000.
 tbegin     =   0.
 dtmin      =   2.e-2
 dtmax      =   1.
 dtt     =   5.    ! 5
 testdiag   =   0.02 ! 0.016
 /
! tous les temps en annees. tbegin et tend : debut et fin du run
! pour equation masse, pas de temps mini -> dtmin, maxi -> dtmax
! dtt : pas de temps long
! testdiag, pour gérer le pas de temps dynamique dt
! ordres de grandeur (a moduler selon dx) :
! 40 km dtmin=2.e-2, dtmax=1., dtt=5., tesdiag=0.02
!________________________________________________________________
```

In this blocks, the user determines the length of the run and set the time steps related to the resolution of the grid to satisfy the CFL conditions.

- `tend`: corresponds to the length or the run expressed in years. If the user needs to perform a run of 100 kyrs, then $\texttt{tend} = 100000.$. Alternatively, the model also handles real time, i.e. for example, if the user wants to perform a transient simulation based on input data evolving from the Last Glacial Maximum until today, $\texttt{tend} = 0.$ and $\texttt{tbegin} = -21000.$.

- `tbegin`: same as above. For a 100-kyrs run long, $\texttt{begin} = 0.$.

- `dtmin`: corresponds to the minimum time step needed by the mass equation and expressed in year. At 40 km, $\texttt{dtmin} = 2.\texttt{e} - 2$.

- `dtmax`: maximum time step required by the mass equation. At 40 km, $\texttt{dtmax} = 1.$., i.e. one year

- `dtt`: corresponds to the time step at which all the variables will be calculated and at which all the routines will be called in the main fortran routine $\texttt{main3D} - 0.4 - 40\texttt{km.F90}$. It can be different from dtmax. For example, if $\texttt{tbegin} = 0.$, then the next step will be $\texttt{tbegin} + \texttt{dtt}$ until `tend` is reached.

- `testdiag`: is a time step needed to diagonalise the elliptic matrix and modulated by the mass conservation routine. In case of crash, the user may change this value to adjust the dynamical time step `dt` calculated within the mass conservation routine. The values is also function of the grid resolution and a typical value for a 40 km grid is about 0.02.

Grid topography:

```
!________________________________________________________________
&topo_file
 file1          = "NH_40km_GRISLI.xyz"
 file2          = "NH_40km_GRISLI.xyz"
 filecoord      = "Coordinates_NH_40km_GRISLI.xyz"
/
! file1 : initial topo
! file2 : reference topo
! filecoord : grid coordinates
!________________________________________________________________
```

In this block, the user can set the file containing the initial and reference topography on the GRISLI grid:

- `file1`: contains the initial topography interpolated on the GRISLI grid. This can corresponds to a climate model topography, horizontally interpolated on the GRISLI grid for example, but showing a less resolved topography than the GRISLI topography contained in file2.
- `file2`: contains the reference topography of GRISLI, which is a high resolution topography.
- `filecoord`: contains the grid coordinates, i, j, X, Y, lon, lat. see Section 4.

Those two topographic files are used to correct the climate variables during run time. As described in Section 5, because the climate fields might not have been computed at the GRISLI horizontal high resolution, a correction accounting for the differences in elevation between the climate model and the ice sheet model grids is necessary. This correction can be performed off-line, as described in Section 5, or during run time.

In the case the correction is performed off-line, the user may set:

```
file1 = "NH_40km_GRISLI.xyz"
file2 = "NH_40km_GRISLI.xyz"
```

Therefore, no climate correction of the climate field will be performed during the initialisation since the correction will be equal to zero. Following Equation 4 in which S_0 would correspond to file2 and $S(t)$ would correspond to file1 for $t = 0$:

$$\lambda(S(t) - S_0) = 0 \tag{47}$$

Therefore:

$$T_{cor}(t) = T_0 \tag{48}$$

with T_0 corresponding to the initial input downscaled surface temperature. On the contrary, if the correction is not performed off-line, the user will have to provide the climate model topography interpolated on the GRISLI grid domain and set:

```
file1 = "NH_40km_GCM-on-GRISLI.xyz"
file2 = "NH_40km_GRISLI.xyz"
```

Since the two topographies are different, a climate correction will be performed during the initialisation:

$$\lambda(S(t) - S_0) \neq 0 \tag{49}$$

Therefore:

$$T_{cor}(t) = T_0 + \lambda(S(t) - S_0) \tag{50}$$

Basal water:

```
!_________________________________________________________________
&eaubasale1               ! nom du premier bloc eau basale

 ecoulement_eau =  T
 hwatermax      =    5000.000
 infiltr        =   1.0000001E-03
 /
! ecoulement eau : .false. -> modele bucket, sinon equ. diffusion
! hwatermax :  hauteur d eau basale maximum dans le sediment (m)
! infiltr est la quantite d eau qui peut s infiltrer dans le sol (m/an)
!_________________________________________________________________
```

Those parameters control the amount of basal water at the base of the ice sheet:

- `ecoulement_eau`: is a logical. If set to false, the bucket model is used, otherwise, the water flow is handle by diffusion
- `hwatermax`: corresponds the maximum water level contained in the sediments (sediment map input also in the namelist), in meters.
- `infiltr`: is the maximum amount of water able to penetrate in the ground in m/yr.

Hydraulic parameters:

```
!_________________________________________________________________
&param_hydr              ! nom du  bloc parametres hydrauliques

 hmax_till      =    20.00000
 poro_till      =   0.5000000
 kond0          =   1.000000E-06
```

```
/
! hmax_till (m) : max sediment thickness
! poro_till : sediment porosity
! kond0: sediment conductivity (m/s)
!_______________________________________________________________
```

This block set the hydraulic parameters used to drain sub-glacial waters. The basal hydrology in GRISLI is based on a Darcy-type flow law stating that water flows through a porous medium (till sediments) proportional to a hydraulic pressure gradient. This is why the properties of this till sediment layer at the base of the ice sheet have to be set:

- `hmax_till`: is the maximum sediment thickness considered in the drainage of the sub-glacial waters
- `poro_till`: is the porosity of this sediment layer at the base. This can be varied if the user changes the nature of the till.
- `kond0`: is the sediment conductivity depending on the nature of the till.

Basal dragging and ice streams:

```
!________________________________________________________________
&drag_hwat_cont               ! nom du bloc dragging hwater contigu

hwatstream = 50.
cf = 1.e-5             ! 1.e-4
tobmax = 1000.
toblim = 0.7e5              ! 0.25e5
/
! hwatstream (m) :  critere de passage en stream en partant de la cote'
! si hwater > hwatstream '
! cf coefficient de la loi de frottement fonction Neff'
! tobmax : (Pa) frottement maxi '
! toblim : (Pa) tes pour les iles '

!________________________________________________________________
&drag_hwat_sedim               ! nom du bloc dragging hwater sediment

filesedim       = "nosediment_ij_hemin40.dat"
hwatstream      =       50.
cf              =       2.e-5             ! 1.e-4
tobmax          =       1000.
toblim          =       0.7e5              ! 0.25e5
seuil_hwater    =       250.
seuil_sedim     =       150.
seuil_neff      =       350.e5
/
! hwatstream (m) :  critere de passage en stream en partant de la cote'
```

```
! si hwater > hwatstream '
! cf coefficient de la loi de frottement fonction Neff'
! tobmax : (Pa) frottement maxi '
! toblim : (Pa) tes pour les iles '
! seuil_hwater (m) : seuil hwater pour avoir glissement sur zone sediment'
! seuil_sedim (m) : seuil epaisseur sediment pour avoir glissement sur zone sediment'

!____________________________________________________________
&drag_jorge               ! nom du bloc dragging_jorge

filesedim        = "nosediment_ij_hemin40.dat"
hwatstream       =       50.
cf               =       2.e-5               ! 1.e-4
tobmax           =       1000.
toblim           =       0.7e5                ! 0.7e5
seuil_sedim      =       1.              ! 0.0001
/
! hwatstream (m) :  critere de passage en stream en partant de la cote'
! si hwater > hwatstream '
! cf coefficient de la loi de frottement fonction Neff'
! tobmax : (Pa) frottement maxi '
! toblim : (Pa) tes pour les iles '
!____________________________________________________________
```

Those three blocks are related to the sediment and basal water thresholds needed to trigger basal dragging and in particular the ice streams, i.e. the criteria to treat grounded ice with the SSA. Each of them correspond to fortran routine located under GRISLI/SOURCES/Hemin40_files. The choice of the dragging routine has to be made in the routine GRISLI/SOURCES/Hemin40_files/module_choix-hemin40-0.4.f90 BEFORE compiling the model.

The first block `drag_hwat_cont` contains parameters to trigger ice streams based on the melt water level at the base of the ice sheet. The two following blocks, `drag_hwat_sedim` and `drag_jorge`, account for sediment thickness at the base of the ice sheet and the amount of water contained in those sediments to trigger ice streams.

- `filesedim`: is the sediment map interpolated on GRISLI grid and located under GRISLI/INPUT/HEMIN40/
- `hwatstream`: is the minimum water level above which ice streams are trigger if `hwater` $>$ `hwatstream`.
- `cf`: if the dragging coefficient, function of the effective pressure $Neff$.
- `tobmax`: maximum basal dragging in Pascal
- `toblim`: maximum pressure for islands in Pascal
- `seuil_hwater`: water level threshold to allow for ice stream over the sediment area to be combined with `seuil_sedim`

- `seuil_sedim`: minimum sediment thickness above which ice stream are triggered if `seuil_hwater` is reached concomitantly.
- `seuil_neff`: minimum effective pressure to trigger ice streams in Pascal

Geothermal heat flux:

```
!______________________________________________________________
&ghflux                                 ! geothermal heat fluxes

fileghf        = "ijphi_hemin40.dat"
coefghf          = 1.
/
! fileghf : input geothermal heat fluxes map
! coefghf : to modulate the amplitude of the geothermal heat fluxes
!______________________________________________________________
```

In this block, the user can prescribed the geothermal heat flux file. As for the sediment map, it has to be interpolated on the GRISLI grid domain.

- `fileghf`: input file of geothermal heat flux located under GRISLI/INPUT/HEMIN40
- `coefghf`: coefficient set to modulate the geothermal heat fluxes. $\mathtt{coefghf} = 1.$ implies no changes in the input geothermal heat flux values. In the routine, $\mathtt{ghf} = \mathtt{ghf} * \mathtt{coefgfh}$.

Calving:

```
!______________________________________________________________
&calving             !   nom du bloc calving méthode Vincent

Hcoup   = 200.
ifrange = 3
meth_Hcoup = 0
/

! Hcoup epaisseur de coupure
! ifrange=0 -> NO CALVING
! ifrange=1 -> traitement de Vincent avec ice shelves frangeants' (biased)
! ifrange=2 -> ice shelves frangeant seulement si bm-bmelt positif (biased)
! ifrange=3 -> option 2 corrected, but no test on ice thickness of upstream point
! ifrange=4 -> option 3 but with test on upstream point ice thickness point
! meth_Hcoup -> Hcoup depends on surface temperature. If=0 then use namelist Hcoup value
!______________________________________________________________
```

The calving is parametrised according to if the Lagrangian scheme described in the theory above fulfils some of the tests upon the flux and the mass balance of the ice shelves. The calving occurs if the ice shelf front thickness reaches the critical value `Hcoup`. This value can be prescribed directly in the namelist or can be determined based on the climate forcing.

- `Hcoup`: threshold for ice shelf front thickness cut in meters
- `ifrange`: type of tests performed on the Lagrangian ice flux. Option 1 and option 2 are biased and should not be used
- `meth_Hcoup`: if =1 Hcoup depends on surface temperature. If=0 then the calving routine uses namelist Hcoup value

Deformation law:

```
!_____________________________________________________________
! loi de deformation 1          module deformation_mod_2lois
&loidef_1

 exposant_1        = 3.
 temp_trans_1      = -6.5
 enhanc_fact_1     = 3.
 coef_cold_1       = 1.660E-16
 Q_cold_1          = 7.820E+04
 coef_warm_1       = 2.000E-16
 Q_warm_1          = 9.545E+04
/
! exponent (glen), transition temperature (ttrans)
! enhancement factor (sf)
! for temperatures lower than Temp_trans :
!            coef_cold (Bat1) et Q_cold (Q1)
! for temperatures greater than Temp_trans :
!            coef_warm (Bat2) et Q_warm (Q2)
!_________________________________________________________
! loi de deformation 2          module deformation_mod_2lois
&loidef_2

 exposant_2        = 1.
 temp_trans_2      = -10.
 enhanc_fact_2     = 10.
 coef_cold_2       = 8.313E-08
 Q_cold_2          = 4.000E+04
 coef_warm_2       = 8.313E-08
 Q_warm_2          = 6.000E+04
/
! exponent (glen), transition temperature (ttrans)
! enhancement factor (sf)
```

```
! for temperatures lower than Temp_trans :
!           coef_cold (Bat1) et Q_cold (Q1)
! for temperatures greater than Temp_trans :
!           coef_warm (Bat2) et Q_warm (Q2)
!____________________________________________________________
```

The deformation block handles the parameters of the Glen flow law (see Numeric and theory section) applied to the grounded ice (SIA). In this version of GRISLI, the flow law uses two sets of parameters reported in the namelist. The use of the first or the second law depends on the temperature of transition: if the ice temperature at the base of the ice sheet drops below -6.5°C then the second table of parameters `loidef_2` are used.

Ice viscosity for Shallow Shelf Approximation:

```
!____________________________________________________________
&diagno_rheol              ! nom du bloc  diagno_rheol

sf01           =  0.2
sf03           =  0.03
pvimin         =        1.e3
/
! coefficients related to the flow law of grounded ice
! sf01 : viscosity coefficient linear law
! sf03 : viscosity coefficient law n=3
! pvimin : pvi value for ghost nodes ~ 1.e3
! very small relative to standard values ~ 1.e10
!____________________________________________________________
```

This blocks is linked with the previous one and is part of the Glen flow law calculation (see Numeric and Theory). It calculates the thermo-mechanically coupled integrated ice viscosities between the grounded ice (SIA) and the floating ice (SSA). `sf01` and `sf03` correspond to the enhancement factors of the floating part.

Basal Melting under ice shelves:

```
!___________________________________________________________
&bmelt_nor_depth                    ! module bmelt_nor_depth

bmelt_type = 1
bmelt1 = 0.
bmelt2 = 0.
depthlimit = 2000.
ocn_profile = "TEMP_vert_Chukchi.dat"
ocn_map = "Tocn_B140_topo1_artic_20km_noice_GRISLI.xyz"
/
! bmelt_type=1 -> prescribed basal melting depending on depthlimit
```

```
! bmelt_type=2 -> basal melting calculated using an ocean temperature vertical profile
! bmelt_type=3 -> as for 2 but using bidimensional ocean vertical temperature
! bmelt1 : basal melting above depthlimit
! bmelt2 : basal melting below depthlimit
! depthlimit: depth threshold to precribe basal melting!
! ocn_profile: ocean temperature vertical profile
! ocn_map: vertical ocean temperature map

!_____________________________________________________________________
&bmelt_nor_reg1                                   ! nom du bloc

!bmelt_Ross = 0.5
!bmgrz_Ross   = 0.2
!bmelt_FRis = 2.4
!bmgrz_FRis   = 5.6
/
!_____________________________________________________________________
```

In the namelist, two blocks are associated with ice shelves basal melting, namely `bmelt_nor_depth` and `bmelt_nor_reg1`. The choice of the basal melting module is operated in the `module_choix`. The first block can be use for any grid domain, except Antarctica, while the second block is related to Antarctica grid domain exclusively. In the case of Antarctica, `bmelt_nor_reg1` attributes a melting value to some specific ice shelves grounded line and central area (Dumas, 2002). In the block `bmelt_nor_depth`, on the contrary, three methods, two out of three implemented at CMCC, to prescribe basal melting can be chosen:

- `bmelt_type`: define the way of accounting for ocean heat fluxes. `bmelt_type` $= 1$ corresponds to the standard method to prescribe basal melting depending on a depth limit. The `depthlimit` option has to be filled with an ocean depth in meters and two basal melting values `bmelt1`, applied for depths above the prescribed limit, and `bmelt2`, applied for depth below the limit, can be set in m/yr.
- `bmelt_type = 2`: is the basal melting calculated using the quadratic parametrisation of (Holland et al., 2008) in which a vertical ocean temperature profile is prescribed. In their paper, Holland et al. (2008) review the different parametrisations used in the Ocean General Circulation Model to calculate the ice melting under the ice shelves in Antarctica and its interaction with the surrounding ocean waters in terms of temperature and salinity. Comparing observations with the various peer-reviewed parametrisations, they show that the relationship between basal melt rates and vertical ocean temperature below the shelves is quadratic. They propose the following relationship:

$$c_0 \gamma_T |\mathbf{u}| (T_{ML} - T_b) = m' L + m' c_I (T_b - T_I) \tag{51}$$

where m' corresponds to the melting rate; $c_0 = 3974\ Jkg^{-1}\ {}^{\circ}C^{-1}$ and $c_I = 2009\ Jkg^{-1}\ {}^{\circ}C^{-1}$ are the specific heat capacities of water and ice, respectively; $|\mathbf{u}|$, and T_{ML} are the speed and temperature of the ocean mixed layer; T_b is the temperature of the ice-ocean interface, i.e. at the base of the ice shelf; γ_T is a coefficient representing the transfer of heat and salt through the boundary layer; $L = 3.35 \times 10^5 Jkg^{-1}$ is the latent heat of ice fusion; $T_I = -25°C$ is the core temperature of the ice shelf.

In their ocean model, the ice shelf basal temperatures T_b is calculated using a relationship dependent on salinity (not shown). In GRISLI, we use a vertical ocean temperature profile T_{oc} from a climate simulation to interpolate the temperature at the base of the ice shelf. By doing so, the computed vertical temperature profile already account for the variation in temperature and salinity with depth. However, this does not account for the variation in salinity caused by the melting of the ice shelf itself. Our approach here is therefore simplified. The input vertical profile file is bi-dimensional and should have three columns: the depth of each vertical level given in centimetres, the index number of each level and the temperature at each level extracted at the chosen location. The forcing file is located under GRISLI/INPUT/Forcage.

At each time step, the depth of the base of the ice shelf is known:

$$H_{base}(t) = -H(i,j,t) * \frac{\rho_i}{\rho_w} \tag{52}$$

which calculates the ice thickness $H(i,j,t)$ below the sea level based on Archimedes's law (accounting for floatation with ρ_i as ice density and ρ_w as water density). The temperature at the corresponding depth is interpolated between the ocean vertical levels:

$$T_b(i,j,t) = T_{oc}(z) - (T_{oc}(z+1) - T_{oc}(z)) * \frac{H_{base}(i,j,t) - ocdepth(z)}{ocdepth(z+1) - ocdepth(z)} \tag{53}$$

where $ocdepth$ corresponds to the depth of each of the ocean levels prescribed in the input vertical temperature profile. The melt rate is calculated as follow:

$$m'(t) = \frac{c_0 \gamma_T |\mathbf{u}| (T_{ML} - T_b(t))}{L + c_I (T_b(t) - T_I)} \tag{54}$$

where $|\mathbf{u}|$ takes an averaged value for the area of interest (m/s), T_{ML} is also set with an averaged value at a depth of interest, γ_T is set to the ad hoc value of 10^{-4}, following literature values. For example, in the Arctic ocean, there is no mixed layer, as in the North Atlantic or around Antarctica, therefore, an averaged temperature below the halocline at 500m seems reasonable.

- `bmelt_type = 3`: Same as for `bmelt_type = 2` but using three-dimensional vertical temperature maps, one for each of the ocean level, i.e. $T_{oc}(lon, lat, z)$. The file has the same structure as for the previous option, but has $n\ column$ containing temperature for each ocean vertical level. The file is located under GRISLI/INPUT/Forcage. This option is still being tested and might not work properly.

Reference climate forcing:

```
!_____________________________________________________________
&clim_act

file1        = "Snapshots-GCM/clim_B140_topo2_NH_40km.xyz" ! reference climate
annual        = .false.
type_precip  = .true.
/
! file1  : reference climate
! annual : .true. if climate file contains Tann Tjja
! type_precip : .true. if liquid precip (.false. snow)
!_____________________________________________________________
```

The climate forcing, i.e. surface temperature and precipitation, is specified in this block. The structure of the forcing file has been described in Section 5.

- `annual`: if set to `false`, the climate forcing file has to have monthly values (24 columns, 12 for precipitation and 12 for temperatures). In this case, the annual mean is computed during run time. If set to `true` the file should have mean annual values (1 column for precipitation and 1 column for temperature).
- `type_precip`: corresponds to the nature of precipitation. If set to `true`, the prescribed precipitation corresponds to the total liquid precipitation, while if set to `false`, the routine assumes that the user provided the snowfall.

Transient climate forcing:

```
!_____________________________________________________________
&clim_forcage                                    ! nom du bloc

forcage_file1 = "clim-anoml-21k-0k.dat "
mincoefbmelt  =  0.
maxcoefbmelt  =  2.
rapbmshelf   = 5.
filforc       = "b140_topo1_150.dat"
tempgrad      = 0.005
tempgrjul     =  0.004
! forcage_file1 : snapshot climat 1
! mincoefbmelt : borne mini de coefbmshelf
! maxcoefbmelt : borne maxi de coefbmshelf
! filforc : fichier de forcage
! tempgrad : lapse rate annuel
! tempgrjul : lapse rate d'ete
/
!_____________________________________________________________
```

In GRISLI, it is possible to perform steady-state and transient simulations. The choice of `clim_forcage` in the module_choix leads to transient simulations. Transient simulations consist in interpolating the climate forcing between two snapshots, modulated by a climate index varying in time ($\delta^{18}O$ for example or sea-level etc...). In this case, the user may specify one or several climate snapshots representative of two different periods, between which to interpolate the climate. To use this module, the forcing file might be computed as an anomaly relative to the prescribed reference climate, i.e. the climate forcing file set in the `clim_act` block. Therefore, the structure of the forcing file should be:

```
 -21000.00    H.Nord: forcage climatique k115-k125 CESM
        58081  4        241      241  40.0   0.
MK0   rap-precip  deltaTann    deltaTjuly
0   0.487772   -0.2986   -0.2491
0   0.467371   -0.2968   -0.2527
.
.
.
```

where the first line should states the date of the snapshot, here -21 000 years (real paleotime) and the rest of the line is a comment about the climate forcing; the second line should states the total number of lines in the file (NX*NY), the number of column (4), the grid domain dimensions, i.e. NX and NY, the horizontal resolution dx (40 km) and the sea-level (here 0. m); the third line is a header line where `MK0` correspond to the land-sea mask and has to bet set to 0 everywhere for all Northern Hemisphere simulations, `rap` $-$ `precip` corresponds to the precipitation ratio between the reference precipitation and the snapshot prescribed in this block, `deltaTann` is the mean annual anomaly between the snapshot and the reference climate and `deltaTjuly` is the July temperature anomaly between the snapshot and the reference climate. For example, in the case of a transient simulation performed between the Last Glacial Maximum (-21000 years) and today, the precipitation ratio will be:

$$\Delta P_{LGM} = \frac{P_{LGM}}{P_{0k}} \tag{55}$$

the temperature anomalies will be computed as:

$$\Delta T_{LGM}^{ann} = T_{LGM}^{ann} - T_{0k}^{ann} + \lambda(S_{LGM} - S_{0k}) \tag{56}$$

$$\Delta T_{LGM}^{July} = T_{LGM}^{July} - T_{0k}^{July} + \lambda(S_{LGM} - S_{0k}) \tag{57}$$

Note that they both account for elevation difference between the two snapshot. During run time, the temperature is then modulated by the climate index:

$$T(t) = T_{0k}(t) - \lambda(S(t) - S_{0k}) + \Delta T_{LGM} \times climindex(t) \tag{58}$$

Similarly, precipitation is interpolated and modulated by the same climate index. The climate index must be computed such as for $t = 0$, $climindex$ = 1, therefore $T(t_0) = T_{LGM}$ and for $t = n$, $climindex$ = 0, therefore $T(t_n) = T_{0k} - \lambda(S(t) - S_{0k})$. The structure of the index file should be located under GRISLI/INPUT/Forcage and should look like:

```
nb_lines 71
     -21000  -0.00000000       -0.00000000        0.00000000
     -20900  -3.80087309E-02  -3.80087309E-02    0.00000000
     -20800  -5.28201908E-02  -5.28201908E-02    0.00000000
     .
     .
```

where `nb_lines` corresponds to the total number of lines contained in the file. The first column corresponds to the `time` in years BP, the second column contains the temperature index `Tindex`, the third column contains the precipitation index `Pindex` (which is similar to `Tindex` in this case) and the last column contains the sea-level index `SLindex` (here = 0, which implies that the sea-level value will not be varied during run time). The climate index only depends on time and is informally applied to the whole grid domain. In this example, the values in the file have a time step of 100 years. GRISLI time step is 1 year, therefore, during run time, the climate index values are also linearly interpolated on GRISLI time step. Note that for transient experiments, the time red in the headers of the climate forcing snapshots corresponds to the real time of the model. The model is able to account for negative paleotimes, therefore, the namelist variables has to bet set such that `tbegin` = -21000 and `tend` = 0.

- `forcage_file1`: corresponds to the climate snapshot, expressed as anomaly relative to the reference climate. Climate will be interpolated linearly during run time between this climate and the reference climate.
- `mincoefbmelt`: corresponds to the climate-related coefficient to modulate the ice shelves basal melting when `meth_Hcoup` option is set to 1 in the `calving` namelist block.
- `maxcoefbmelt`: same as for `mincoefbmelt`.
- `rapbmshelf`: only use for Antarctica. modulate the melting of the ice shelves as well
- `filforc`: corresponds to the input climate index file.
- `tempgrad`: is the mean annual atmospheric lapse rate value (°C/m)
- `tempgrjul`: is the July atmospheric lapse rate value (°C/m)

Perturbation of the reference climate forcing:

```
!_______________________________________________________________
&clim_pert                                   ! nom du bloc

rappact       = 0.05 ! 0.05 pour Antartique
retroac       = 0.
rapbmshelf     = 5.
mincoefbmelt   = 0.
maxcoefbmelt   = 2.
filforc        = "b140_topo1_150.dat"
tempgrad       =         0.005   ! Annual lapse rate (C/m)
tempgrjul      =         0.004   ! Summer lapse rate (C/m)
/
!_______________________________________________________________
```

To perform a steady-state simulation, this module must be commented out in the module_choix. In this module, GRISLI also offers to perturb the reference climate using some time-varying values prescribed in the `filforc`, similarly to the previous namelist block. However, this forcing file is slightly different and must follow the structure:

```
nb_lines   2
0.       0.   0.
20000. 0.   0.
.
.
```

where `nb_lines` corresponds to the number of lines contained in the file. The first column is the time, the second corresponds to temperature value used to perturb the reference climate (in °C) and the last column is a sea-level value used to perturb the sea-level. In the example shown above, the file is set to perform a steady-state simulation for a duration of 20 000 years, with no temperature and sea-level increments. Those two values are nevertheless interpolated during run time at GRISLI time step. In this case, interpolation result is always 0.

- `rappact`: corresponds to the precipitation factor γ used to correct precipitation for elevation (in %) in the accumulation routine.
- `retroac`: is not used anymore.
- the other options are similar to that set in the `clim_forcage` namelist block.

Positive Degree Day parameters: ablation

```
!_______________________________________________________________
&ablation_ann                                ! PDD base Tann et Tjuly
```

```
 Cice           = 0.008
 Csnow          = 0.003
 Sigma          = 5.
 csi            = 0.6
/

! Cice and Csnow, melting factors for ice and snow
! sigma variabilite Tday
! csi proportion of melted water that can refreeze
!___________________________________________________________
```

This block sets the value of the parameters for the ablation calculation through the Positive Degree Day semi-empirical method (See the Numeric and Theory section).

- `Cice`: is the ice melting coefficient
- `Csnow`: is the snow melting coefficient
- `Sigma`: is the amplitude of the daily temperature cycle (in °C)
- `csi`: is the fraction of melting that can refreeze over the ice sheet

Coupling between SIA and SSA mechanics:

```
!___________________________________________________________
&meca_SIA_L1                         ! bloc resol_meca

i_resolmeca  =  2
/
! i_resolmeca type d association entre SIA et L1
! i_resolmeca=0  no overlapping between the two mechanics
! i_resolmeca=1  in the stream areas, addition if uxdef > uxL1
! i_resolmeca=2  systematic addition in stream areas
!___________________________________________________________
```

This option is usually set on 2.

Tutorial: how to implement a new grid domain

To implement a new grid domain in GRISLI there are several steps to follow:

1. create a new input repository in GRISLI/INPUT/ to put the grid, the geothermal heat flux, the sediment map and the climate forcing interpolated on the new grid. For example GRISLI/INPUT/NEWGRID/.
2. create a new repository in GRISLI/SOURCES/, copying the routines located under one of the pre-existing implemented domain into the new grid repository. For example GRISLI/SOURCES/NEWGRID.
3. edit the various routines to give the dimension of the grid and point to the right input boundary and initial conditions files.
4. edit the Makefile located under GRISLI/SOURCES/ to add the new domain, compile the corresponding routines and create the executable.

In this guide, the GRISLI repository contains two different grid domains, one covering the entire Northern Hemisphere from about 16°N and one covering Northern Eurasia.

- The grid and climate forcing related to those grids are located under GRISLI/INPUT/HEMIN40 and GRISLI/INPUT/EURASIE20
- The routines specific to those two domains are located under GRISLI/SOURCES/Hemin40_files and GRISLI/SOURCES/Eurasie20_files. Those directories contains the main information related to each grid in the paradim-hemin40_mod.f90 and paradim-euras20_mod.f90:

```
module module_nord

  implicit none

  character(len=7), parameter :: geoplace='hemin40'    ! geoplace
  character(len=200), parameter  :: dirnameinp='/Users/GRISLI/INPUT/HEMIN40/'
  character(len=200), parameter  :: dirforcage='/Users/GRISLI/INPUT/Forcage/'

! dimensionnement grilles
!-------------------------
  integer, parameter :: nx=241           ! dimension selon x (indice i)
  integer, parameter :: ny=241           ! dimension selon y (indice j)
  integer, parameter :: nlmin=141        ! min(nx,ny), pour matrice elliptique
  integer, parameter :: nz=21            ! dimension selon z (indice k)
  integer, parameter :: nzm=4            ! nb de points verticaux dans le socle
  integer, parameter :: nn=241           ! pour des sorties
!cdc integer, parameter :: nx1=nx-1,ny1=ny-1,nz1=nz-1
```

```
! pas horizontal
!-----------------
  real, parameter :: dx=40000.0
  real, parameter :: dy=40000.0              ! pas en X et Y en m


end module module_nord
```

The user has to adapt the various dimensions, name and repository to its new grid. Other routines, such as the ones reading the input grid, input geothermal heat fluxes file, the sediment map and the climate forcing has to be edited. The user may not forget to also edit the module_choix.

The Makefile, is structured as follows:

- NetCDF libraries, compilers, and compiling options. The user has to modify those options to adapt them to his own operative system and compiler:

```
# NETCDF libraries
NCDF_INC = /usr/local/netcdf-4.1.2_ifort/include
NCDF_LIB = /usr/local/netcdf-4.1.2_ifort/lib

#Compiler
IFORT = ifort

# Compiling options and FLAGS
ARITHM =  -O2 -xHost -no-prec-div -mkl -m64

# debug : -g -CB -fp-stack-check -check all
FT         = $(IFORT) $(ARITHM) -c  -I$(NCDF_INC) -g
LK         = $(IFORT) $(ARITHM)  -g
F_NETCDF   = $(IFORT) $(ARITHM) -c -I$(NCDF_INC)
```

- The list of the routines and modules that are compiled whatever is the grid domain:

```
mod_communs =  runparam_mod.o 3D-physique-gen_mod.o pdd_declar_mod.o \
        iso_declar_mod-0.3.o isostasie_mod-0.3.o noisostasie_mod-0.3.o \
        .
        .

routines_communes = tracebug.o ablation_Thompson_1997.o ablation-annual-month.o\
.
.
```

- The routines associated with the selected grid domain. When implemented a new grid, the user has to duplicate this part of the Makefile to create the list of routine associated with his new grid domain.

```
Liste_hemin40 = output_hemin40_mod-0.5.o \
        lect-clim-act-hemin40_mod.o lect-hemin40_mod.o  \
        .
        .
```

- The detailed list of fortran routines. The user will have to add the routines associated with his new grid
- The compilation instructions, duplicated for each of the grid domains implemented in the model. The user has to create the same block for his own new grid:

```
Hemin-40 : $(Dim_hemin40) $(mod_communs)  $(mod_ell)  $(Liste_hemin40) $(diagnoshelf)$(Liste_Netcdf) \
        $(routines_communes) $(routine_elliptiques) $(Liste_BLAS)

        $(LK) -o  $(RUND)/Hemin-40  $(Dim_hemin40) $(mod_communs) $(mod_ell)  $(Liste_hemin40) \
        $(diagnoshelf) $(Liste_Netcdf) \
        $(routines_communes) $(routine_elliptiques) -L$(NCDF_LIB) -lnetcdf -L$(NCDF_LIB) -lnetcdff $(Liste_BLAS)
```

Appendix

Table 1
Notation used in this report.

Geometric and physical variables		
$S(x, y, t)$	Surface elevation	m
$S_0(x, y)$	Initial surface elevation	m
SL	Sea level	m
$B(x, y, t)$	Bedrock elevation	m
$B_0(x, y, t)$	Initial bedrock elevation	m
$H(x, y, t)$	Ice thickness: H = S - B	m
$H_0(x, y, t)$	Initial ice thickness	m
$p(x, y, z)$	Hydrostatic pressure	Pa
$T(x, y, z, t)$	Ice temperature	$^\circ$C
$T_b(x, y, z, t)$	Basal ice temperature	$^\circ$C
$T_{pmp}(x, y, z, t)$	Ice temperature relative to the melting point of pressure	$^\circ$C
$\mathbf{u}(x, y, z, t)$	Ice velocity	m/yr
$\bar{\mathbf{u}}(x, y, t)$	Vertically averaged horizontal ice velocity	m/yr
$\mathbf{u_B}(x, y, t)$	Sliding velocity at the base of the ice	m/yr
Mass balance and Climate		
$Abl(x, y, t)$	Ablation rate	m/yr
$Acc(x, y, t)$	Accumulation rate	m/yr
C_{ice}	Melting factor of ice	mm/d/$^\circ$C
C_{snow}	Melting factor of snow	mm/d/$^\circ$C
$P(x, y, t)$	Precipitation	m/yr
PDD	number of positive degree days	
$SMB(x, y, t)$	Surface mass balance	m/yr
T_{Ann}	Annual mean surface air temperature	$^\circ$C
T_{Jul}	Mean July surface air temperature	$^\circ$C
T_d	Daily surface air temperature	$^\circ$C
b_{melt}	Melting rate at the base of the ice shelf	m/yr
csi	fraction of ice that refreezes	-
λ_{Ann}	Lapse rate for annual mean air temperature	$^\circ$C/km
λ_{July}	Lapse rate for July air temperature	$^\circ$C/km
γ	Precipitation correction factor	$^\circ$C^{-1}
σ	Standard deviation of the daily air temperature	$^\circ$C

Table 2
Notation used in this report.

Thermal properties		
Q_i	deformational heat	W m^{-2}
c	heat capacity of ice	J mol^{-1} kg^{-1}
κ	thermal conductivity of ice	W $°C^{-1}$ m^{-1}
Ice deformation		
$B_{AT}(T)$	Coefficient of the Glen flow law	Pa
E_f	Enhancement factor of the flow law	J mol^{-1}
τ	Stress tensor	Pa
τ'	Deviatoric stress tensor	Pa
$\dot{\epsilon}$	Strain rate	s^{-1}
n	exponent in the Glen flow law	-
$\bar{\eta}$	Vertically integrated viscosity of the ice	Pa/yr
Sliding and dragging		
c_f	Basal dragging coefficient	-
N	Effective pressure at the base of the ice	Pa
$\tau_{\mathbf{b}}$	Basal drag	Pa
Basal hydrology		
K	Hydraulic conductivity	m/s
V_e	Sub-glacial flow velocity	m/yr
p_w	Subglacial water pressure	Pa
h_w	Hydraulic head	m
Physical constants		
ρ	Density of ice	910 kg m^{-3}
ρ_w	Density of sea water	1028 kg m^{-3}
ρ_{fw}	Density of fresh water	1000 kg m^{-3}
g	Gravitational acceleration	9.81 ms^{-2}
R	Ideal gas constant	8.3145 J mol^{-1} $°C^{-1}$

References

Alvarez-Solas, J., Montoya, M., Ritz, C., Ramstein, G., Charbit, S., Dumas, C., Nisancioglu, K., Dokken, T., and Ganopolski, A. (2011). Heinrich event 1: an example of dynamical ice-sheet reaction to oceanic changes. *Clim. Past*, 7:1297–1306.

Bougamont, M., Bamber, J. L., Ridley, J. K., Gladstone, R. M., Greuell, W., Hanna, E., Payne, A. J., and Rutt, I. (2007). Impact of model physics on estimating the surface mass balance of the Greenland ice sheet. *Geophys. Res. Lett.*, 34(L17501).

Charbit, S., Ritz, C., and Ramstein, G. (2002). Simulations of Northern Hemisphere ice-sheet retreat: sensitivity to physical mechanisms involved during the Last Deglaciation. *Quaternary Science Reviews*, 21:243–265.

Dumas, C. (2002). *Modélisation de l'évolution de l'Antarctique depuis le dernier cycle glaciaire-interglaciaire jusqu'au futur: importance relative des différents processus physiques et rôle des données d'entrée*. PhD thesis, Université Joseph-Fourier-Grenoble I.

Greve, R. and Blatter, H. (2009). *Dynamics of Ice Sheets and Glaciers*. Springer-Verlag Berlin.

Holland, P. R., Jenkins, A., and Holland, D. M. (2008). The response of ice shelf basal melting to variations in ocean temperature. *J. Climate*, 21(11):2558–2572.

Hutter, K. (1983). *Theoretical glaciology: material science of ice and the mechanics of glaciers and ice sheets*. Reidel Publishing Company, Dordrecht, The Netherlands.

Laske, G. and Masters, G. (1997). A Global Digital Map of Sediment Thickness.

Le Meur, E. and Huybrechts, P. (1996). A comparison of different ways of dealing with isostasy: examples from modeling the Antarctic ice sheet during the last glacial cycle. *Annals of Glaciology*, 23:309–317.

MacAyeal, D. (1989). Large-Scale Ice Flow Over a Viscous Basal Sediment: Theory and Application to Ice Stream B, Antarctica. *J. Geophys. Res.*, 94:4071–4087.

Peyaud, V. (2006). *Role of the Ice Sheet Dynamics in major climate changes*. PhD thesis, Laboratoire de Glaciologie et de Géophysique de l'Environnement, Université Grenoble I.

Peyaud, V., Ritz, C., and Krinner, G. (2007). Modelling the Early Weichselian Eurasian Ice Sheets: role of ice shelves and influence of ice-dammed lakes. *Clim. Past*, 3:375–386.

Pfeffer, W. T., Meier, M. F., and Illangasekare, T. H. (1991). Retention of Greenland runoff by refreezing: Implications for projected future sea level change. *J. Geophy. Res.*, 96(C12):22117–22124.

Reeh, N. (1991). Parameterization of Melt Rate and Surface Temperature on the Greenland ice Sheet. *Polarforschung*, 59(3):113–128.

Ritz, C., Rommelaere, V., and Dumas, C. (2001). Modeling the evolution of Antarctic ice sheet over the last 420,000 years: Implications for altitude changes in the Vostok region. *J. Geophy. Res.*, 106(D23).

Shapiro, N. and Ritzwoller, M. (2004). Inferring surface heat flux distributions guided by a global seismic model: particular application to Antarctica. *Earth and Planetary Science Letters*, 223:213–224.

Turcotte, D. L. and Schubert, G. (2002). *Geodynamics*. Cambridge Univ. Press, New York.

Weertman, J. (1957). On the sliding of glaciers. *CJ. Glaciol.*, 3:33–38.