Integration of the land ice model (CISM) in the Norwegian Earth System Model (NorESM)

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1. Introduction

Recent observations show that Greenland and Antarctic ice sheet are losing mass in response to atmosphere and ocean warming (Shepherd et al. 2012, Church et al. 2013), The current ice sheet contribution to global mean sea level rise is about 1 mm/yr, with somewhat greater losses from Greenland than from Antarctica. Glaciers outside the two ice sheets also have retreated in recent years, accounting for almost 1 mm/yr as well (Vaughan et al. 2013). Understanding the interaction between land ice and the rest of the earth system is essential, and the integration of land ice as an active component in earth system models has become urgent. In particular, coupled ice sheet and earth system models are required to capture important feedbacks (e.g. Vizcaino et al., 2014), such as the effects of changes in albedo and elevation on (regional) atmospheric circulation and effect of freshwater fluxes from the ice sheets on ocean circulation.

In this report, we describe the first efforts of integrating the Community Ice Sheet Model into the Norwegian Earth System Model. After technical information, such as the compset definition, gid information, case set-ups and asynchronized coupling, we provide a short evaluation of the first coupled simulations.

1.1.CISM 2.1

The Community Ice Sheet Model (CISM) is a next-generation ice sheet model used for predicting ice sheet evolution and sea level rise in a changing climate. In previous versions of CESM with CISM coupling capabilities, the shallow-ice dynamical core of the model was used, known as Glide (Rutt et al. 2009). CISM2.1 introduces a new high-order dynamical core, known as Glissade (Lipscomb et al. 2019). The CISM calculates mass, momentum, and energy conservation for ice sheets and glaciers using a serial, thermomechanically-coupled, shallow-ice representation of ice dynamics (Lipscomb et al., 2019).

1.2.NorESM2.1

The Norwegian Earth System Model version 2.1 (NorESM2.1) is based on the Community Earth System Model version 2.1 (CESM2.1). NorESM2.1 is designed to contribute to phase 6 of the Climate Model Intercomparison Project (CMIP6), while its predecessor, NorESM1, is the released version for the CMIP5. NorESM is based on the CESM framework, but differs with CESM in its ocean component, its chemistry-aerosol-cloud-radiation interactions in the atmospheric module, and its biogeochemical ocean module (e.g. Bentsen et al., 2013; Iversen et al., 2013; Tjiputra et al., 2013).

1.3.Coupling of CISM2.1 and NorESM2.1

Within the CISM-NorESM framework, CISM2.1 can be run with or without coupling to the earth system model. In standalone mode (no coupling to other earth system components), it should be forced by output from a previous, coupled run. In NorESM2.1, only the Greenland ice sheet is dynamically incorporated, not the Antarctic ice sheet, nor any paleo ice sheet (e.g. Scandinavian or Laurentide ice sheets).

CISM can be coupled interactively to CLM (the land model in NorESM2.1). The surface mass balance of the ice sheets (SMB) is computed by CLM in multiple elevation classes for ice sheets (default), and changes in ice sheet extent and thickness feed back to land surface elevation and surface types in CLM. Offline scripts have been developed to support coupling to the Community Atmosphere Model (CAM), adjusting CAM's notion of surface topography; however, this atmosphere coupling is not available out-of-the-box and is not officially supported yet. At present, interactions between the ice sheet and the ocean is very limited as well. The ice sheet model can send calving fluxes to the ocean, but there is currently no mechanism to compute sub-ice-shelf melt rates based on ocean conditions, and ocean boundaries do not evolve in response to ice-shelf or ice sheet changes.

2. Set up CISM within NorESM2-framework

2.1.Define compset

We added a new compset in $NorESM_ROOT/cime_config/config_compsets.xml:

```
<compset>
<alias>N1850G</alias>
<lname>1850_CAM60%PTAERO_CLM50%BGC-CROP_CICE_MICOM_MOSART_CISM2%EVOLVE_SWAV</lname>
</compset>
```

This compset, N1850G, includes an active ice sheet for Greenland. The N1850G compset is a counterpart to the fully coupled NorESM preindustrial compset, N1850OCBDRDDMS, except that ocean biogeochemical process (i.e., the carbon cycle model, HAMOCC) is switched off to save computational and storage resources. However, since there is no direct coupling between the land ice and ocean biogeochemistry modules, we fully expect both subcomponents to be compatible and able to run simultaneously.

There are two modes for the CISM: CISM2%NOEVOLVE and CISM2%EVOLVE. When CISM2%NOEVOLVE is in the compset name, CISM is not evolving. CLM does compute a SMB (downscaled on the CISM grid) and sends it to CISM, but CISM's ice sheet geometry remains fixed over the course of the simulation. No fluxes are send from CISM to other NorESM components. However, CISM does define glacier areas and topographic elevations thereby overriding the values of CLM's surface dataset. Using CISM2%EVOLVE, CISM is fully active, receiving SMB from CLM and evolving dynamically. In addition, by default, CISM feeds information back to other climate system components in this configuration, i.e., it is two-way coupled. Specifically, it sends (1) glacier areas and elevations to CLM and (2) ice and liquid runoff to the ocean. The default ice albedo values in CLM5.0 are 0.5 and 0.3 for visible and near-infrared spectrum. To change the ice albedo to for example 0.55 and 0.45, add the following line to user_nl_clm:

```
albice = 0.55,0.45
```

After creating a case, you can switch between NOEVOLVE and EVOLVE by setting the xml variable, CISM_EVOLVE, in env_run.xml

2.2.Define CISM grid information

Information on the NorESM and CISM grid is needed to create and run a case with active ice sheet model. Currently, three grid configurations are tested:

1) **f19_g16_gl4**, a 2-deg atmosphere, 1-deg bipolar ocean and 4 km ice sheets model grid configuration,
2) **f19_tn14_gl4**, a 2-deg atmosphere, 1-deg tripolar ocean and 4 km ice sheets model grid configuration,
3) **f09_tn14_gl4**, a 1-deg atmosphere, 1-deg tripolar ocean and 4 km ice sheets model grid configuration,

where the ice sheet model grid, gland4, has dimension of 416*704, covering Greenland with rectangular grid cells of 4 km resolution with a polar stereographic projection.

Other combinations of grid configuration with 2-deg and 1-deg atmosphere grid, f19 and f09, and 1-deg bipolar and 2-deg tripolar ocean grid, g16 and tn14, and 4 km, 5 km and 20 km ice sheets grid, gl4, gl5 and gl20, can possibly be supported, but not all of them are implemented.

The model grid description, grid domain and re-mapping information among different model components is defined in $CIMEROOT/config/cesm/config_grids.xml. Some snippets are shown as example in the following:

- <model_grid> entry

```
<model_grid_defaults>
<grid name="glc"    compset="CISM2"    >gland4</grid>
</model_grid_defaults>
             ...
<model_grid alias="f09_tn14_gl4" not_compset="_POP">
<grid name="atm">0.9x1.25</grid>
<grid name="lnd">0.9x1.25</grid>
<grid name="ocnice">tnx1v4</grid>
<grid name="glc">gland4</grid>
<mask>tnx1v4</mask>
</model_grid>
```

- <domain> entries

```
<domain name="gland4">
<nx>416</nx> <ny>704</ny>
<desc>4-km Greenland grid, for use with the glissade dycore</desc>
</domain>
```

- <gridmap> entries

```
<gridmap lnd_grid="0.9x1.25" glc_grid="gland4" >
<map name="LND2GLC_FMAPNAME">cpl/gridmaps/fv0.9x1.25/map_fv0.9x1.25_TO_gland4km_aave.170429.nc</map>
<map name="LND2GLC_SMAPNAME">cpl/gridmaps/fv0.9x1.25/map_fv0.9x1.25_TO_gland4km_blin.170429.nc</map>
```

```
<map name="GLC2LND_FMAPNAME">cpl/gridmaps/gland4km/map_gland4km_TO_fv0.9x1.25_aave.170429.nc</map>
<map name="GLC2LND_SMAPNAME">cpl/gridmaps/gland4km/map_gland4km_TO_fv0.9x1.25_aave.170429.nc</map>
</gridmap>
<gridmap ocn_grid="tnx1v4" glc_grid="gland4" >
<map name="GLC2OCN_LIQ_RMAPNAME">cpl/gridmaps/gland4km/map_gland4km_to_tnx1v4_nnsm_e1000r300_181030.nc</map>
<map name="GLC2OCN_ICE_RMAPNAME">cpl/gridmaps/gland4km/map_gland4km_to_tnx1v4_nnsm_e1000r300_181030.nc</map>
</gridmap>
```

Notes:

1) The actual grid file of the gl4 grid containing latitude, longitude, mask, topography etc. is located at FRAM: /cluster/shared/noresm/inputdata/glc/cism/Greenland/glissade/init/greenland_4km_epsg3413_c171126.nc, and is prescribed in: $NorESM_ROOT/components/cism/bld/namelist_files/namelist_defaults_cism.xml.
2) As stated in Subsection 1.3, the CISM is two-way coupled with the land model, remapping from glacier to land (GLC2LND) and land to glacier (LND2GLC) are both needed. Coupling between ice sheets and ocean is only one way from glacier to ocean, so only GLC2OCN remapping is required. The remapping file was generated following the guideline and tools described in CISM online documentation (https://escomp.github.io/cism-docs/cism-in-cesm/versions/master/html/new-grids.html). A script is created to generate the remapping file: noresm-dev/cime/tools/mapping/gen_mapping_files/runoff_to_ocn/make_mapping_files_gl4_tnx1v4.sh, and the generated remapping file is located at: /cluster/shared/noresm/inputdata/cpl/gridmaps/gland4km/map_gland4km_to_tnx1v4_nnsm_e1000r300_181030.nc
3) The treatment of liquid and ice from glacier to ocean are the same, so GLC2OCN_LIQ_RMAPNAME and GLC2OCN_ICE_RMAPNAME uses identical mapping file. POP (the ocean model in CESM) treats the liquid from glacier in the coast and open ocean cells differently, so it uses different remapping files in POP configuration in CESM.

2.3. Create a case for the CISM

A new case is created with the standard tool using the appropriate compset:

```
./create_newcase --case N1850G_f09_tn14_gl4_test4 --compset N1850G --res f09_tn14_gl4 --mach fram --project nn2345k --run-unsupported
```

2.4. Asynchronous coupling

It is possible to asynchronously couple the ice sheet model to NorESM by setting the time step multiplier, ice_tstep_multiply, which will speed up the ice sheet model. This option may be useful for multi-millennial ice-sheet simulations where it is impractical to run the atmosphere and ocean models for more than a few centuries. The time step multiplier is equal to the number of ice sheet timesteps executed for each accumulated mass balance field. Suppose that the mass balance timestep is 1 year, the ice sheet timestep is 1 year, and ice_tstep_multiply = 10. The climate model interface *Glad* will accumulate and average mass balance information for 1 year, then execute 10 ice sheet model timesteps of 1 year each applying the same annual mass balance repeatedly. In other words, the ice sheet dynamics is accelerated relative to the land and atmosphere.

The time step multiplier, ice_tstep_multiply, is defined in:
$NorESM_ROOT/components/cism/bld/namelist_files/namelist_definition_cism.xml, but it is currently hard-coded in:
components/cism/source_cism/libglad/glad_type.F90
or
components/cism/source_cism/libglint/glint_type.F90,
depending on which core of dynamic ice sheet model is active. The impact of using an accelerated coupling on the evolution of the Greenland ice sheet is shown in Figure 3 in Section 3.3.

2.5.Performance metric

The fully coupled N1850G compset with 1-deg atmos/lnd, 1-deg ocean/sea ice and 4 km ice sheet model grid system, f09_tn14_gl4, is configured with a total of 1024 CPU cores (32 nodes in FRAM). The overall model performance is:

```
Overall Metrics:
Model Cost:           3281.10      pe-hrs/simulated_year
Model Throughput:     7.72         simulated_years/day
```

The ice sheet model component itself is quite efficient:

```
TOT Run Time:        30.645 seconds/model-day          7.72 model-years/wall-day
GLC Run Time:         0.039 seconds/model-day       6131.66 model-years/wall-day
```

3. Evaluation of simulated Greenland Ice Sheet

3.1.Configuration of simulations

A test case with above-described configurations is set up with “-compset N1850G” and “-res f09_tn14_gl4”. The NorESM source code version is noresm-dev branch “origin/featureCESM2-OsloDevelopment”, version tag 1c6baba. The model is initialized from year 211 of a NorESM2 spinup (reference case name: N1850OCBDRDDMS_f09_tn14_2rosc1dp).

The CLM is initialized from a previous CESM spinup, and user_nl_clm is set as:

```
finidat =
'/cluster/shared/noresm/inputdata/cesm2_init/b.e20.B1850.f09_g17.pi_control.all.
297/0308-01-01/b.e20.B1850.f09_g17.pi_control.all.297.clm2.r.0308-01-01-
00000.nc'
use_init_interp = .true.
reset_snow = .true.
```

The configuration of this simulation, N1850G_f09_tn14_gl4_test3, is listed in Table.1, together with configurations of other standalone and coupled CISM simulations.

CASE NAME	*COMPSET*	*RESOLUTION*	*DESCRIPTION*
T1850G_f09_g17_gl4_test1	*T1850G*	*atm/lnd, 0.9x1.25* *ocn/ice, gx1v7* *glacier, 4km*	*standalone CISM model*
J1850G_f19_g17_gl4_test1	*J1850G*	*atm/lnd,1.9x2.5* *ocn/ice, gx1v7* *glacier,4km*	*data atm/lnd models, active ocean/crop/wave models of CESM*
B1850GWs_f19_g17_gl4_test1	*B1850GWs*	*atm/lnd,1.9x2.5* *ocn/ice,gx1v7* *glacier, 4km*	*fully coupled with CESM, and CISM2 is set as NOEVOLVE*
N1850G_f19_g16_gl4_test1	*N1850G*	*atm/lnd,1.9x2.5* *ocn/ice,gx1v7* *glacer, 4km*	*fully coupled with NorESM, low resolution*
N1850G_f09_tn14_gl4_test1	*N1850G*	*atm/lnd, 0.9x1.25* *ocn/ice,tnx1v4* *glacer, 4km*	*full coupled with NorESM, high resolution; cold initialization*
N1850G_f09_tn14_gl4_test2	*N1850G*	*atm/lnd, 0.9x1.25* *ocn/ice,tnx1v4* *glacer, 4km*	*as N1850G_f09_tn14_gl4_test1, but initialized from previous spinup*
N1850G_f09_tn14_gl4_test3	*N1850G*	*atm/lnd, 0.9x1.25* *ocn/ice,tnx1v4* *glacer, 4km*	*as N1850G_f09_tn14_gl4_test2, but with asynchronous coupling* ice_tstep_multiply = 10.

3.2.Limitations on model output

Due to some unresolved bugs, currently there are some limitation of the CISM output: it can only support restarts on day boundaries; the model only supports no-leap years and only instantaneous fields are supported, i.e., snapshots of model results.

3.3.Simulation results

The land ice component is initialized with observed ice and bed topographies, which leads to a good representation of the flow pattern at the beginning of the simulation (Fig. 1a). All major drainage basins are found, and the ice divide is at the correct location. After 100 years of (asynchronous) simulation, i.e., the climate model ran for 10 years, the ice topography changes notably but not to the point that the ice dynamics are fundamentally different (Fig. 2, 1b). The pattern of ice velocities is smoother than at initialization and the velocity of outlet glaciers is higher. Ice thicknesses are reduced near the western margin while the southern part of the ice sheet gains mass equivalent to more than 100 m of ice in large regions. This suggests a large imbalance in the surface mass balance and is likely the reason for the increasing ice volume (equivalent to a drop in global sea level) that is present in all simulations (Fig. 3). The anomalous ice thickness field shows a slight checkerboard pattern in particular in regions with steep surface gradients that suggest numerical issues in the ice dynamics code (Fig. 4).

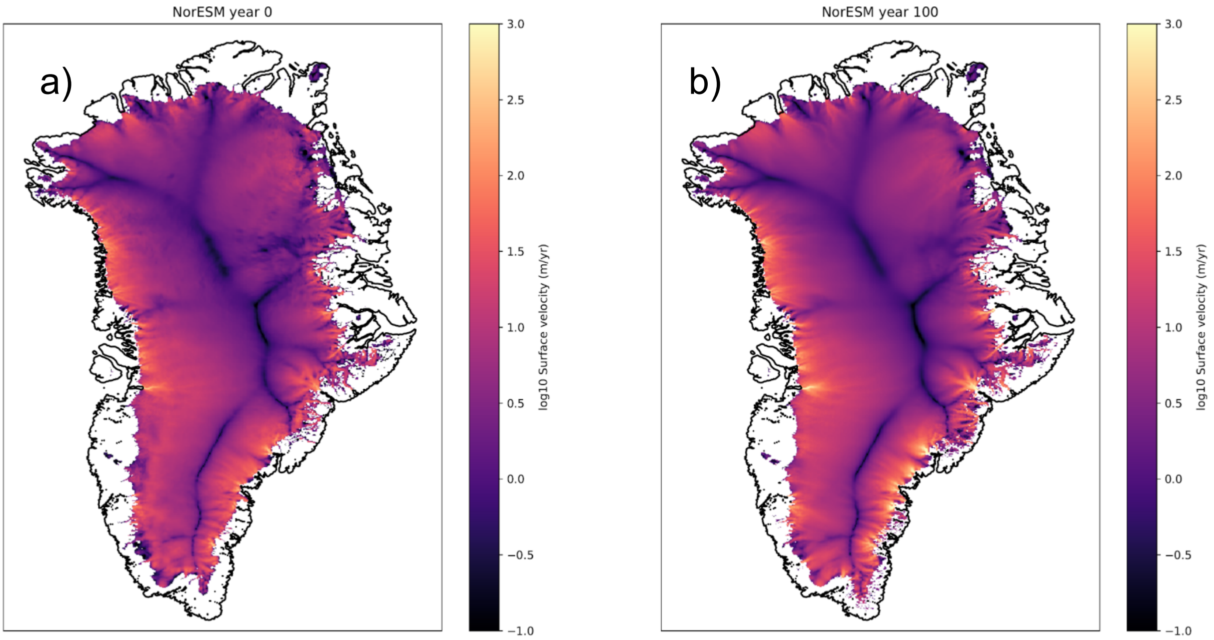


Figure 1: Surface ice velocity at the time of initialization (a) and at the end of the simulation after 100 years (b).

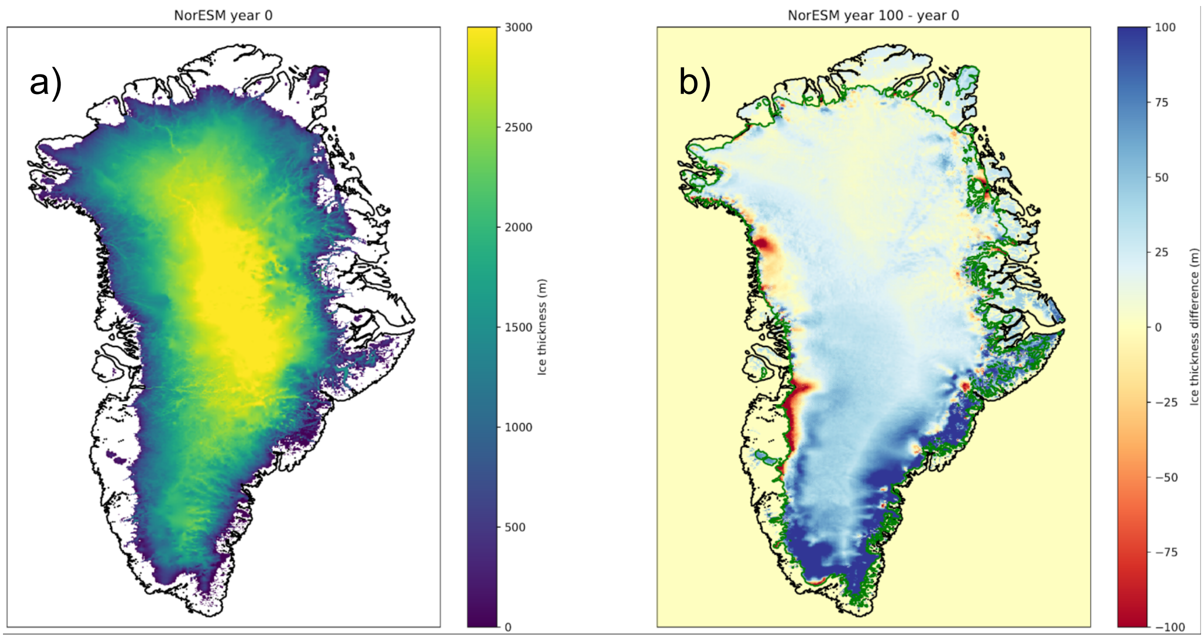


Figure 2: Ice thickness at the time of initialization (a) and anomalies at the end of the simulation after 100 years (b).

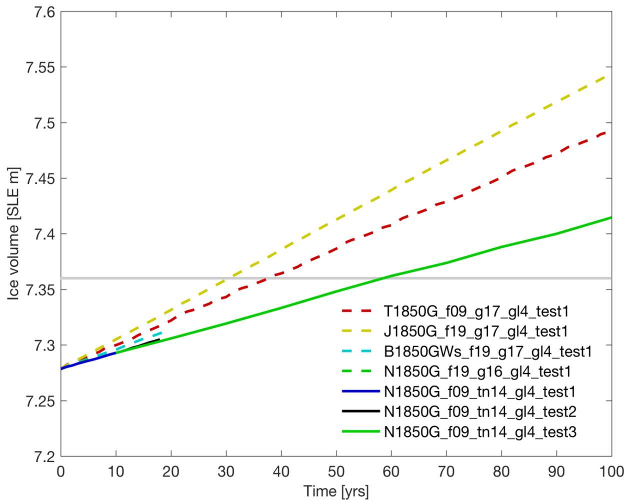
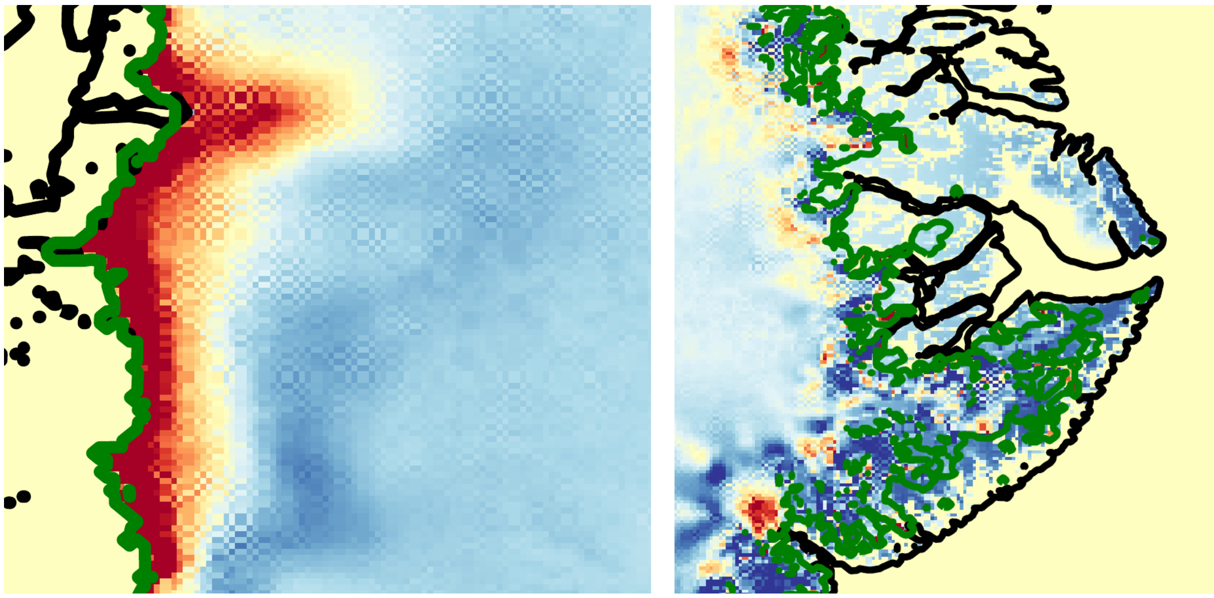


Figure 3: Time series of ice volume for various simulations.



Figre 4: Checkerboard pattern in anomalous ice thickness field.

All simulations show a positive imbalance in the mass balance of the Greenland ice sheet, which leads to a growth in ice volume equivalent to about 1.35 mm/yr of global sea level rise (Fig. 1). To further analyze the performance of NorESM, we compare the surface mass balance to that of a state-of-the-art simulation for Greenland with the regional and purpose-build atmosphere model RACMO2.3 (pers. comm. B. Noël, U Utrecht). An important caveat is that NorESM is forced with preindustrial boundary conditions (1850) while RACMO2.3 was run for the recent period for which reanalysis datasets can be used (1958-2017). In order to avoid the recent most severe warming trend on Greenland, only RACMO data for 1958-1990 was used here.

This comparison with the regional model reveals that NorESM does capture the overall pattern of mass balance realistically, but that its lower resolution makes the the result much smoother (Fig. 5). In addition, there is a notable bias in the simulation that creates surplus accumulation in the southern part of Greenland and a moderate negative bias in the northwest. Melting at the western margin is underestimated in NorESM. The integrated surface mass balance in NorESM is equivalent to 1.28 mm/yr sea level decrease, so that it accounts for virtually the entire imbalance that is observed in the total ice mass.

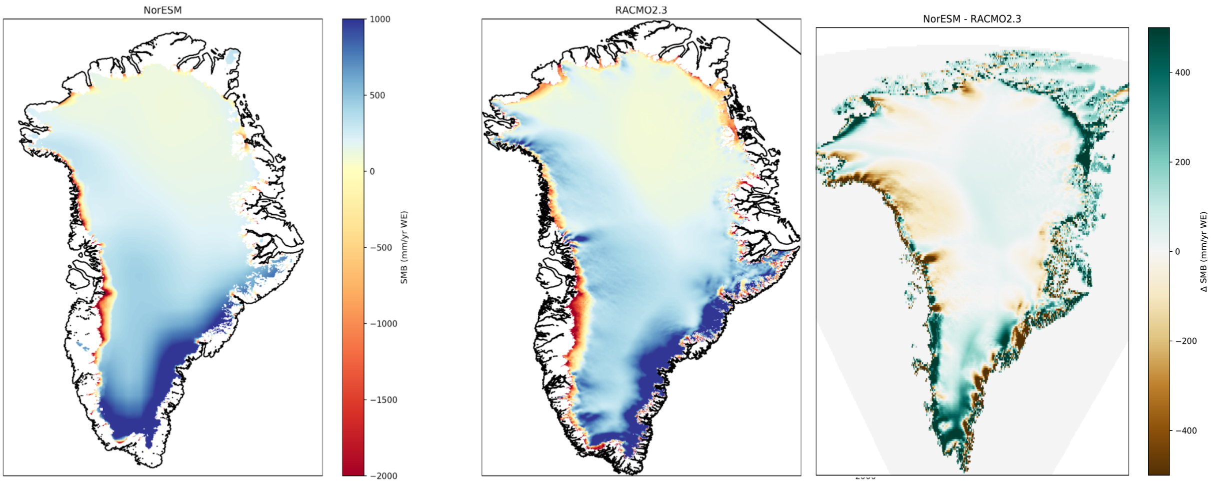


Figure 5: Average surface mass balance for NorESM, RACMO2.3, and the difference between the two. For the latter, the data of both models was interpolated to a regular latitude-longitude mesh.

The difference in mass balance can be attributed to both biases in snowfall as well as melting of snow (Fig. 6, 7). Since these quantities are calculated by the atmosphere subcomponent of NorESM at 1° resolution, the level of detail is much less than in RACMO2.3, which was run at 5 km resolution and statistically downscaled to 1 km (Fig. 8). Snowfall in northwestern Greenland is underestimated in NorESM in both seasons. The same is true for the overestimation of accumulation in the southeastern part of the island. A large systematic bias is also observed in the melting of snow during the summer (Fig. 7). In particular mass loss in the south is too low, which contributes to the positive mass balance anomaly in this region (Fig. 5). Note, however, that it is possible that melting may have been less in preindustrial climate than during the period 1958-1990.

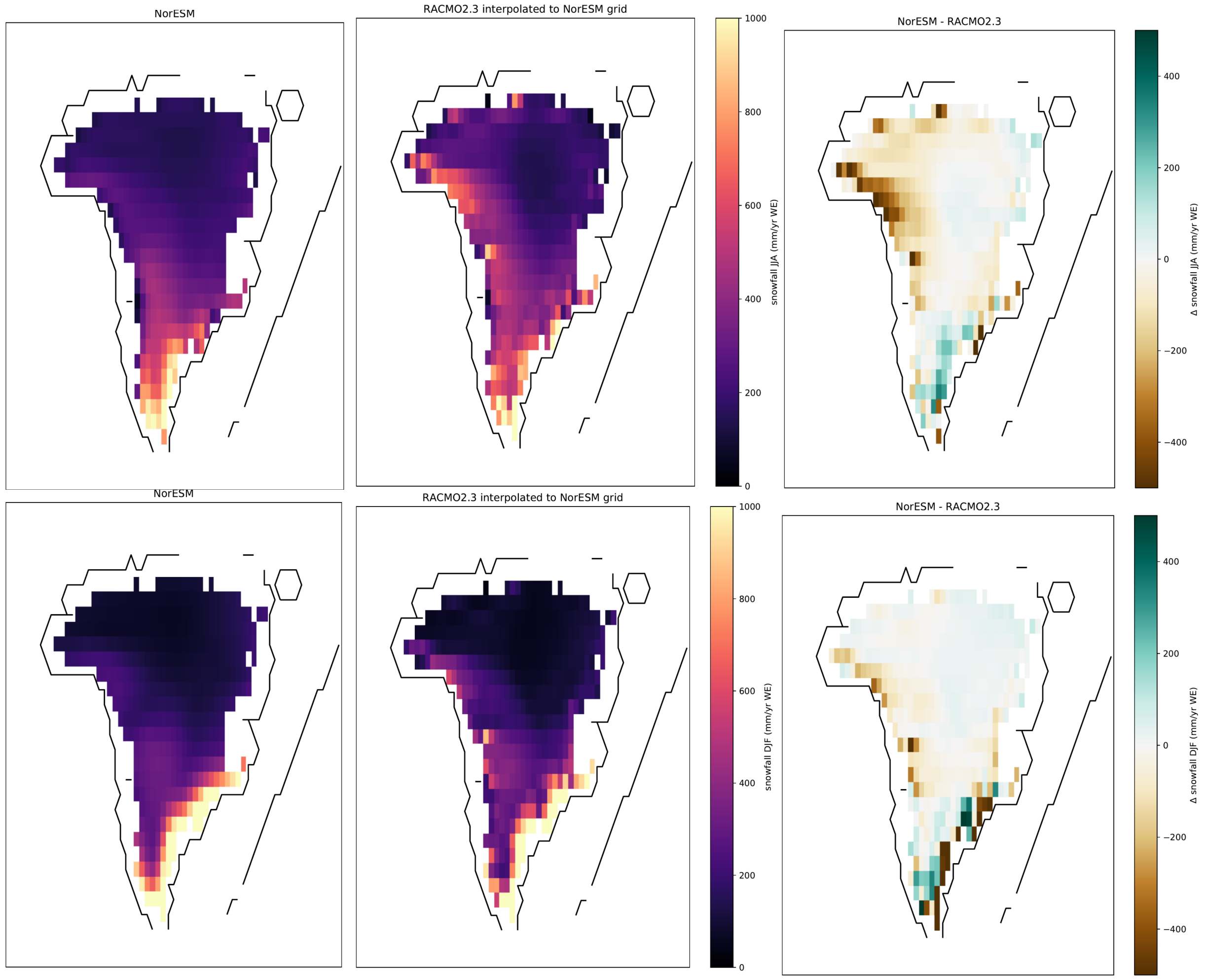


Figure 6: Snowfall for JJA (upper row) and DJF (lower row) in NorESM (left), RACMO2.3 (interpolated, middle), and the respective differences (right).

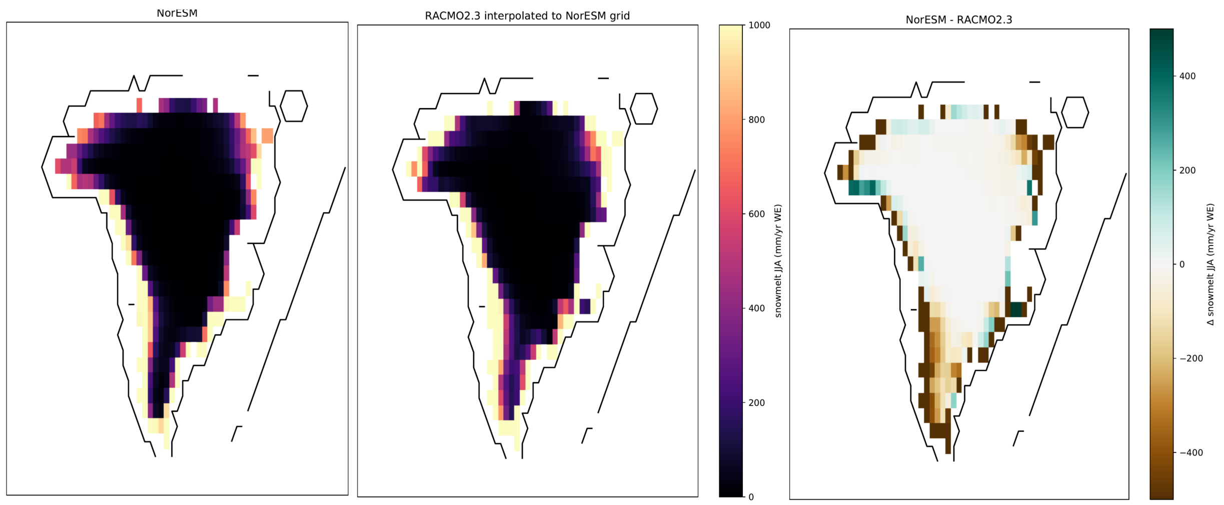


Figure 7: Surface melting for JJA in NorESM (left), RACMO2.3 (interpolated, middle), and the difference (right).

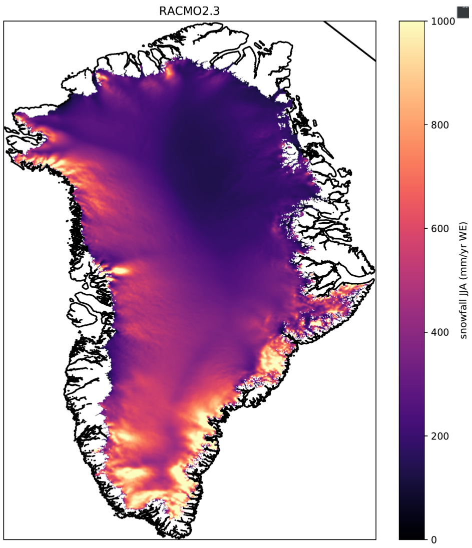


Figure 8: Average snow fall in RACMO2.3 for the months June, July and August, at a statistically downscaled resolution of 1 km.

4. Outlook

As a result of this initiative, we were invited to join a national consortium on climate modeling and development of NorESM. The work of this consortium won support from the Norwegian research Council in late 2018 and will soon start working under the KeyCLIM project. A Born will lead the synthesis work package of this project and will employ a postdoctoral research assistant to continue the work presented here. Y He receives funding from both the INES (Infrastructure for Norwegian Earth System Modelling) and KeyCLIM projects to continuously contribute to the development of NorESM and identify key climate process in determining climate change at northern high latitudes. P Langebroek is also involved in INES and KeyCLIM and will hire a postdoctoral research assistant to support the more in-depth testing and further development of the coupled CISM-NorESM system.

5. References:

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