SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2022
Project Title:	Impact of Greenland melt water on EC-Earth high-resolution simulations
Computer Project Account:	spnldrij
Principal Investigator(s):	Dr. Sybren S. Drijfhout
Affiliation:	Royal Netherlands Meteorological Institute (KNMI)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	André Jüling, Philippe Le Sager, Rein Haarsma (all at KNMI)
Start date of the project:	2020
Expected end date:	2024

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	10,000,000	10,000,000	10,000,000	0
Data storage capacity	(Gbytes)	240,000	240,000	240,000	0

Summary of project objectives (10 lines max)

The project aims to ascertain the impacts of freshwater fluxes from the melting Greenland ice sheet in an eddy-permitting version of the EC-Earth3 under a high emission scenario up to 2100. We focus on changes to the North Atlantic Ocean circulation, in particular the Atlantic Meridional Overturning Circulation, and their impacts on dynamic sea level as well as regional and global climate. A freshwater forcing protocol is developed to mitigate the lack of an active ice sheet component in the model. This protocol uses both the simulated temperatures above Greenland from the standard, no-freshwater-forcing simulations to drive a more realistic future Greenland surface mass balance and dynamic ice loss results from the recent ice sheet model intercomparison project for freshwater flux estimates.

Summary of problems encountered (10 lines max)

The implementation of a new NEMO subroutine to read in spatially-heterogeneous freshwater forcing patterns has been challenging, but this has been solved now.

Summary of plans for the continuation of the project (10 lines max)

While short test simulations have been performed, the full-length simulations until 2100 still have to be completed. The analysis of the results will be published afterward. A full simulation is ready to run now.

List of publications/reports from the project with complete references

None yet.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

All three EC-Earth3P-HR simulations have been continued to 2100 past the HighResMIP end date of 2050. The freshwater forcing protocol is developed, the forcing files have been created, and new NEMO subroutines have been implemented.

We use the European Consortium Earth System Model in its PRIMAVERA setup which precedes the EC-Earth3 version of CMIP6 in its standard- and high-resolution setup. The atmosphere component is cycle 36r4 of the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF), the ocean model is NEMO3.6 (Barnier et al., 2006), the land model HTESSEL (Balsamo et al., 2009), and the Louvain-la- Neuve sea-ice model version 3 (LIM3; Vancoppenolle et al., 2012).

The standard-resolution version, EC-Earth3P, is 1°in the atmosphere (IFS grid T255) and 1°in the ocean (NEMO grid ORCA1 with 75 vertical levels). Here, we employ the eddy-permitting

configuration, EC-Earth3P-HR, which uses the 0.25°ORCA025 ocean grid (Barnier et al., 2006) together with a 0.5°IFS grid (Haarsma et al., 2020).
As part of the HighResMIP there are three EC-Earth3P-HR simulations: (1) control simulations using 1950 radiative forcing, (2) historical simulations from 1950-2015, and (3) projections of future climate change under the RCP8.5 scenario from 2015-2050 (Haarsma et al., 2016). There are three ensemble members each for each of the simulations (Haarsma et al., 2020); all the future simulations have since been extended to 2100.

Freshwater budget
Ice sheets change their mass though the surface mass balance, marine and grounded-ice basal melt, and solid ice discharge. Sea level is determined through changes in the ice-sheet mass above flotation. The surface mass balance is determined through the difference in precipitation, evaporation, sublimation, runoff (and snow drift). The freshwater forcing that enters the ocean is the sum of runoff, basal melt, and discharge.
$MB = SMB - B - D$ (1)
$SMB = PREC - R - EVAP - SUBL$ (2)
$FWF=R+B+D$ (3)
SLC = MB above flotation (4)

EC-Earth freshwater budget
In EC-Earth3, the ocean receives both runoff and calving fluxes.
Ice sheets are represented as fixed topography with a finite snow-layer depth of 10 m. Any precipitation that falls in excess of this is immediately rerouted to the ocean, in effect simulating discharge. This discharge together with liquid runoff is distributed in the ocean around the Greenland and Antarctic ice sheets. Assuming long-term changes in freshwater storage in the finite-depth snow layer is negligible, the freshwater forcing in the model is
$FWF = PREC - EVAP - SUBL$ (5)
There are two masks: the ”near” mask where runoff and basal melt is distributed to, and the ”far” masks where solid discharge are distributed over a larger area as iceberg melt. In the default EC-Earth3P-HR setup they are the same and the freshwater forcing is applied at the surface. The same two masks are also used for the standard resolution EC-Earth3P simulations and the CMIP6 EC-Earth3 simulations.
In both Greenland and Antarctica the warming climate results in increased snowfall. In the original implementation this additional water is rerouted into the ocean. Over Antarctica, the SMB is severely overestimated in the present-day climate due to the warm bias of EC-Earth. Under increasing radiative forcing in the hist-1950 and highres-future simulations, precipitation, evaporation, and sublimation increase. As precipitation changes dominate and freshwater storage is finite in the model, the freshwater fluxes to the ocean increase in these scenarios.

Freshwater Forcing Protocol
To include the effects of shrinking ice sheets, we propose a protocol which uses model information for a plausible high-end melt water input scenario.
Greenland FWF contributors
Runoff R With anthropogenic warming, runoff is expected to increase significantly. Some increase in freshwater flux is captured by the default EC-Earth freshwater rerouting mechanism due to the increased precipitation, but they still significantly underestimate the additional melt water input. For future projections, we use a quadratic calibration between mid-tropospheric temperature anomalies (with respect to 1970-2000) and GrIS runoff (Lenaerts et al., 2015). For the historical period we use the runoff as estimated by Bamberet al. (2018).
Discharge D As glaciers are retreating, the GrIS solid discharge as icebergs will decrease. We use the quadratic fit to the simulated discharge amount by Muntjewerf et al. (2021). In contrast to other simulations, like Choi et al. (2021), the simulated discharge amount matches historical observations (Marsh et al., 2015).

Basal melt in Greenland is relatively small. Observations have only been performed on a small number of glaciers (n = 3 in study cited by Golledge et al. (2019)). - marine basal melt - grounded ice basal melt - included in Choi et al. (2021).
Total freshwater forcing FWF
The total amount of freshwater is very similar to the amount proposed by van den Berk and Drijfhout (2014), but the relative contributions of discharge and runoff differ. Runoff as calculated from the parametrization is larger, while discharge is smaller than in the previous forcing protocol.

Antarctic FWF contributors
In Antarctica, freshwater fluxes to the ocean comprise basal melt and solid ice discharge or iceberg calving in about equal parts. Both Antarctic basal melt and solid discharge are expected to increase with warming ocean temperatures. Like with Greenland, we use observational estimates until 2015 and a physically plausible scenario from then to 2100. For the historical period, we use the estimates of discharge covering 2007-2008 (Rignot et al., 2013). We also use the time-dependent estimates of basal melt Adusumilli et al. (2020) from 1994 to 2018, averaging 1200 Gt/yr, and assume their steady state basal melt from 1985 to 1993 of 1100 Gt/yr. Surface runoff in Antarctica is very small compared to other freshwater sources and will remain so until 2100.
For future freshwater forcing, we use the freshwater anomalies based on LARMIP2 mass loss response functions Levermann et al., 2020. In this approach, regional ocean temperature anomalies are translated to basal melt anomalies which results in a dynamic response of the Antarctic Ice Sheet. The focus of LARMIP2 was the impact on sea level and hence the response functions published concern mass above flotation, but here we use the response functions concerning total mass loss. Temperature anomalies are taken in the five regions defined by Levermann et al. (2020) from the EC-Earth3P-HR historical and highres-future simulations. As we start calculating anomalies only from 2015, we use 2000-2029 as a reference period. The temperature anomalies are related to the basal melt via a melt sensitivity parameter, and we use the median of the uniform range given by Levermann et al. (2020), 11.5 m/yr/K. We further choose one of the response functions, namely IMAU-ICE, as it results in mass loss slightly above the median of all models' response functions. Furthermore, both total and above-flotation mass loss response functions are available for this model. We then model the additional mass loss rate on top of the observed present-day rates as a quadratic fit with zero slope in 2015 and the same integrated total mass loss until 2100 as derived from the response functions. The total mass loss for each of the five sectors is split according to the present-day ratio of calving to basal melt (Rignot et al. (2013); Table 1).

Spatio-temporal FWF distribution
Table 1: Fraction of calving/basal melt per region as Region Calving East Antarctic 50% Ross 68% Amundsen 29% Weddell 62% Peninsula 27%
By default, EC-Earth redistributes freshwater via the runoffmapper module uniformly at the surface of the ocean. The default Greenland runoff-map includes Ellesmere, Devon, and Axel Heiberg islands.

Our modifications include

a) an improved horizontal distribution taking the difference between basal melt and runoff (local freshwater release) and calving via icebergs (distributed over observed iceberg tracks) into account.
b) vertical redistribution of freshwater due to basal melt in a layer of 200m below floating ice-shelves
c) seasonality
d) energy conservation by accounting for cooling via latent heat uptake for melt
e) a time-dependent total freshwater release, partly interactive and partly prescribed by using results from ice-sheet models and observations.

References:

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