REQUEST FOR A SPECIAL PROJECT 2025–2027

MEMBER STATE: Italy

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Project Title: LIMALOC: Long-term Impact of Meltwater from Antarctica on Large-scale Oceanic Circulations

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** _________________	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2025	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for the years: (To make changes to an existing project please submit an amended version of the original form.)		**2025**	**2026**	**2027**
High Performance Computing Facility	(SBU)	7.75 million	10.95 million	11 million
Accumulated data storage (total archive volume)[2]	(GB)	17500	36250	52750

[1] The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide annual progress reports of the project's activities, etc.

[2] These figures refer to data archived in ECFS and MARS. If e.g. you archive x GB in year one and y GB in year two and don't delete anything you need to request x + y GB for the second project year etc.

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Extended abstract

1. Motivation and scientific goals of the project

The Antarctic Ice Sheet (AIS) is projected to lose an increasing amount of mass under climate change injecting freshwater into the Southern Ocean (Fox-Kemper and Hewitt 2021). This is believed to have effects on the stratification of the water column around the Antarctic continent, potentially influencing deep water formation (Chen et al. 2023), both with respect to the location of the deep water formation sites and the intensity of convection, with potential effects on large scale ocean currents as the Antarctic Circumpolar Current (ACC) and the Atlantic Meridional Overturning Circulation (AMOC) (Loriani et al. 2023). Although in the last decades most of the attention has been directed to the effects of meltwater from the Greenland Ice Sheet on the AMOC, a rising number of studies are investigating the impact of meltwater from Antarctica (N. C. Swart and Fyfe 2013), mostly in idealized setups.
With this project we use the Earth system model Ec-Earth3 and the intermediate complexity global circulation model Speedy-NEMO to investigate the sensitivity of the Southern Ocean and of large scale ocean currents to climate change-induced meltwater input from the Antartic Ice Sheet in different configurations.

In particular, we aim at addressing two research questions:

- (*R1) how does the meltwater input from Antarctica change when using a coupled ice sheet - climate model?*
  The meltwater from ice sheets is usually computed by running stand-alone ice sheet models, in which the feedback of the climate on the ice sheet model is not taken into account. Here we aim at assessing the impact of including a somewhat simplified two-way coupling between the ice sheet model and the ocean model on the meltwater flux.

- *(R2) does a more realistic meltwater input from Antarctica under SSP scenarios result in appreciable differences in the behaviour of the ACC and/or the AMOC on centennial scales?*
  A number of hosing experiments was performed under the SOFIAMIP initiative (Neil C. Swart et al. 2023) to investigate the impact of the freshwater input of Antarctica on the Sothern Ocean. Although these experiments allow for the investigation of the sensitivity of the models to freshwater, they do not account for the feedbacks between the ice sheet and the climate model. Only few studies (Golledge et al. 2019; Park et al. 2023; Siahaan et al. 2022)
  include a realistic meltwater input in the Southern Ocean in a two-way coupled ice sheet model-climate model. To our knowledge, although some studies with realistic meltwater for the Northern Hemisphere have been carried out before (e.g., Mehling et al. 2024), coupled and uncoupled simulations have not yet been compared yet in terms of the meltwater-induced changes on the large scale ocean currents. In addition, we notice that, although an effect on the Southern Ocean is to be expected already in the first centuries after the meltwater forcing, the quantification of changes in the ACC or AMOC may require longer timescales **REF** that we investigate here by means by multicentennial simulations.

2. Models and experimental design

In this project we aim at exploiting the climate model Ec-Earth3, described in the following, along with the ice sheet model PISM. EC-Earth3 (Döscher et al. 2022) is a state-of-the-art climate model which participated in the CMIP6 Intercomparison project. In the version 3.3, that we intend to employ here, it includes an atmosphere component IFS (Integrated Forecasting System, cycle 36r4), based on the European Centre for Medium-Range Weather Forecasts (ECMWF) dynamical core, the ocean model NEMO version 3.6 (Madec et al. 2017) with its built-in sea ice model LIM version 3 (Rousset et al. 2015), and the H-TESSEL surface scheme (Balsamo et al. 2009). The coupling between the atmosphere and the ocean-sea ice is performed via the Ocean Atmosphere Sea Ice Soil coupler version 3 (OASIS, Craig et al, 2017). We run EcEarth in global configuration with the atmospheric component in the standard CMIP6 resolution, with a spectral truncation of T255, corresponding to a resolution of about 80 km, and the ocean component NEMO uses an ORCA1 configuration with a spatial resolution of about 1° around Antarctica and 75 vertical levels. In this project, two modeling approaches are employed and compared to another to account for the impact of freshwater injection into the Southern Ocean and on the large scale ocean currents. These are hosing and coupling with an ice sheet model, and are described in the following.

2.1 Hosing

We apply hosing, that is imposing a freshwater anomaly by applying a virtual salinity flux of the form:

$$F(t,x,y) = -h\frac{S_0(x,y,z)}{dz_0(x,y)},$$

where S0 is the local salinity in the upper layer, dz_0 is the upper layer thickness, and h = H/Ar is the water hosing field. Here, the denominator Ar is the area of the region in which the water hosing is applied, and the numerator (H) is the strength of the freshwater flux anomaly in Sverdrups (1 Sv= 10^6 m3s^-1).
It has to be noted that in the hosing simulations a correction must be applied to the 3D salinity field to conserve the total amount of salt throughout the rest of the ocean. This is of the form

$$\frac{dS\,(t,x,y,z)}{dt} = \frac{h\int S_0\,(t,x,y)\,dxdy}{V_o},$$

where Vo is the total volume of the ocean. Hosing was employed in EcEarth3 before for both the Northern and Southern Hemisphere (Bellomo et al. 2021, Mehling et al. 2024, A. Jueling pers. comm., 2024), hence we plan to employ already existing modifications to the EcE3 code to run our simulations.

2.2 The ice sheet model PISM and the ECE3-PISM coupling scheme

The Parallel Ice Sheet Model (PISM, version 1.2) is a hybrid ice sheet-ice shelf model (Bueler and Brown 2009; Winkelmann et al. 2011) that we intend to run on a 16 km equidistant polar stereographic grid. PISM has been used to model the AIS in a number of studies (Winkelmann et al. 2011, Rodehacke et al. 2020), that showed its ability in reproducing the historical development and the current condition of the AIS. As a result, PISM can be effectively integrated with EC-Earth to investigate potential alterations in the AIS in the future. The coupling between PISM and Ec-Earth3 is under development at the Daenish Meteorlological Institute (DMI). The coupling is operated by a script that handles the two-way exchange of fields between the ice sheet model (that receives ocean temperature and salinity fields, as an input) and the climate model (that receives the surface elevation, the ice sheet mask and the total meltwater flux), after remapping to the respective grids. In the available configuration, the exchange of fields occurs once per year (asynchronous coupling). We note that, due to the warm bias of EcEarth3 in the Southern Ocean the input fields from the ocean model are exchanged as anomalies with respect to a reference state (Rodehacke et al., 2021). Although the coupling between Ec-Earth and PISM allows for a computation of the Surface Mass Balance (SMB) of the ice sheet from atmospheric fields, we decide to use climatological SMB. Indeed, as the loss of ice from Antarctica is driven primarily by oceanic processes at the bottom of the ice shelves (Hanna et al. 2024), we neglect having an interactive SMB in order to keep the computational cost of the simulations low, allowing us to run long simulations. Regarding the interface between the ice sheet and the ice shelves and the ocean model NEMO we note that, as the NEMO version employed here has vertically-uniform boundaries at the interface with the land and with the ice sheet, the circulation of the ocean waters in the cavities under the shelves is not represented. The computation of melting at the bottom of floating ice shelves is rather handled via the PICO box model (Reese et al. 2018). PICO includes a parametrization of the circulation in ice shelf cavities calculated from temperature and salinity fields.

2.3 Simulations

To address the research questions outlined in Section 1 we perform two sets of simulations, one set with prescribed meltwater from stand-alone ice sheets (*antwaterPRS*) and one set (*antwaterCPL*) with the coupled EcE-PISM model.
For *antwaterPRS* we follow the protocol of the *tier2* of the SOFIAMIP initiative (Neil C. Swart et al. 2023). *tier2* includes two simulations (*ssp126-ismip6-water* and *ssp585-ismip6-water* respectively, in the SOFIAMIP protocol) where the climate is forced under the SSP1-2.6 and SSP5-8.5 scenarios and the freshwater is prescribed. The freshwater flux is taken from the ISMIP6 ensemble mean as the mean freshwater input from stand-alone ice sheet model run under CMIP5 boundary conditions for the equivalent CMIP5 scenarios (RCP2.6 and RCP8.5), displayed in Figure A1c of Swart et al. 2023. The freshwater is injected into the ocean uniformly over the zonal direction at the closest gridbox to the Antarctic continent. The simulation is restarted branching off the CMIP6 historical simulation and is run from 2015 to 2100. To complete the *tier2* of the EcEarth contribution to SOFIAMIP we run the remaining historical simulations.

We run two additional *antwaterPRS* experiments by injecting freshwater from a stand-alone PISM simulation run under SSP scenarios, instead than from the ISMIP6 ensemble mean run under CMIP5 scenarios that we extend here to year 2300 to investigate the long-term response. The main motivation for these additional runs is to allow for a more direct comparison with the coupled simulations.

For *antwaterCPL* we plan to run the simulations with the ECE3-PISM coupled configuration, i.e. forcing both the climate and the ice sheet with the SSP1-2.6 and SSP5-8.5 scenarios and allowing the exchange of fields as described in Section 2.2. This means that in this latter case the meltwater is being computed interactively (although the coupling is asynchronous) rather than being prescribed. The simulation is run with a 16 km resolution for the Antarctic Ice Sheet and is restarted from the spin up for the present-day model configuration described in (Rodehacke et al., 2021). This was performed by first spinning up the stand-alone ice sheet for about 350 000 years and then spinning up the coupled configuration until quasi-equilibrium was reached.

In addition, we intend to perform the full set of the SOFIAMIP experiments by adapting the hosing procedure to SPEEDY-NEMO. SPEEDY-NEMO (Kucharski et al. 2016; Ruggieri et al. 2024), is an intermediate complexity model that combines a simplified atmosphere (Molteni, 2003; Kucharski et al., 2006) to the comparatively more complex ocean model NEMO version 3 (Madec et al., 2008), that is an older version of the same ocean component of EC-Earth3. Since the amount and the rate

of melting of the Antarctic Ice Sheet is believed to be mostly linked to feedbacks related to oceanic processes (Armstrong McKay et al., 2022), SPEEDY-NEMO is a reasonable choice, as it allows to capture the relevant mechanisms while retaining a low computational cost.
In particular, we exploit the low computational cost of the model to run extended versions of the simulations of the SOFIAMIP initiative in order to investigate the multicentennial response to freshwater injection by performing 1000-years long simulations with SPEEDY-NEMO.
In addition, we exploit SPEEDY-NEMO to investigate the role of centennial variability in the Southern Ocean in shaping the response to meltwater forcing. As noted in Swart et al. (2023), the magnitude and patterns of this latter response of meltwater may depend on the phasing of Southern Ocean's centennial variability, though this dependence is still poorly understood. As it is conceivable that Speedy-NEMO might show a similar type of variability, after testing this feature of the model, we perform an ensemble of simulations following the specifications of the Appendix A3 of the SOFIAMIP protocol.

Finally we stress that a low-resolution (LR) version of EC-Earth4 is being developed with a TL63L31-ORCA2Z31 configuration (ECE-FAST, Davini pers. comm., 2023 and SPLTUNE, ECMWF Special Project by S. Yang, 2022). Depending on the availability of this version of the climate model, we will consider performing the experiments with ECE-FAST which has a higher resolution than SPEEDY-NEMO while having a similar computational cost (200 SYPD for ECE-FAST, i.e. in a gain of almost 40x in SBU with respect to EcEarth3 in standard configuration, vs 300 SYPD for SPEEDY-NEMO).

3. Justification of the computer resources requested

Scaling tests performed in the framework of the SPLTUNE Project by P. Davini have determined that the optimal configuration for the EC-Earth 3 in the resolution used here (TL255L91-ORCA1) is obtained with 286 cores for IFS and 108 cores for NEMO. In the above-mentioned conditions, one year of simulation of EC-Earth3 corresponds to about 19,000 SBU.

For PISM, we consider 500 SBU per simulation year, according to the statistics of PISM on the DKRZ machines[2]. Yet, for the calculation of computational resources for the coupled EC-Earth-PISM model, it is to note that, to calculate the SBU, the real elapsed time needs to be factored in. In our case, this strongly depends on the timestep of the asynchronous coupling. We therefore request 1000 SBU per year and will perform testing the optimal coupling configuration within a trade-off between computational resources and increments in the exchanged fields.

For SPEEDY-NEMO, on the Atos machine, it is possible to run 1 year of simulation with SPEEDY-NEMO (parallelized on 18 cores) in 0.29 hours (A. Bellucci, SPITBEAL), corresponding to ~100 SBU per simulation year.

We save the climate model data in monthly resolution. Regarding storage, we estimate a need of 30 GB/year for EC-Earth3 and 0.5GB/year for SPEEDY-NEMO (inferred from A. Bellucci, SPITBEAL), considering monthly averages. For PISM we consider again 25% of the resources needed for EC-Earth3, that is 7.5GB/year.

Year	Model	Experiment	Model Years	Ensemble members	Total model years	SBU/ model year
Year 1	EC-Earth3	antwaterPRS	75	2	150	19000
	EC-Earth3	tier2 hist SOFIA MIP	50	4	200	19000

[2] statistics provided by Christian Rodehacke, https://docs.dkrz.de/doc/levante/configuration.html

	Speedy-NEMO	tier2 SOFIA MIP	1000	14	14000	100
SBU Year 1						**7750000 SBU**
Storage after Year 1						**17’500 GB**
Year 2	EC-Earth3	antwaterPRS_PISM	275	2	550	19000
	PISM	to produce meltwater timeseries for antwaterPRS_PISM	275	2	550	1000
SBU Year 2						**10’950’000 SBU**
Storage after Year 2						**36’250 GB**
Year 3	EC-Earth3 - PISM	antwaterCPL	275	2	550	20000
SBU Year 3						**11000000 SBU**
Storage after Year 3						**52’750 GB**
Total SBU						**29’700’000 SBU**
Total storage						**52’750 GB**

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