LATE REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: Italy

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Project Title: Tipping points of the Antarctic Ice Sheet in EC-Earth-PISM

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.)	2024	
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.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	-	21500000	23100000
Accumulated data storage (total archive volume)[2]	(GB)	-	32250	105750

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[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. Introduction

1.1 Background and motivation

The Antarctic Ice Sheet (AIS) is the largest reservoir of freshwater on the Earth, amounting to about 60 m of sea level equivalent (Fretwell et al., 2013). Substantial loss of ice mass from Antarctica has been already observed during the last century as a consequence of global warming (Eyring et al., 2021), with an acceleration over the last decades (Rignot et al., 2019). Together with the recording of the collapse (e.g. Larsen A and B ice-shelves, Wang et al., 2023) and accelerated retreat (Rignot et al., 2014; Milillo et al., 2019) of large ice-shelves, this has raised concerns on the stability of the ice sheet on a larger scale (Feldmann and Levermann, 2015), and on the related socio-economic implications in terms of Sea Level Rise (SLR).

The current and projected near-future contribution of Antarctic ice loss to SLR is of secondary importance when compared to the other sources, that are thermal expansion, Glaciers, and meltwater from the Greenland ice sheet (Fox-Kemper et al., 2021). Yet, the presence of amplifying feedbacks related e.g. to the specific bedrock structure of large areas of Antarctica, as the marine ice sheet instability (Schoof, 2007), combined to the inertia of the ice sheets, have the potential to determine an ice loss to global warming unfolding over centuries to millennia (e.g. Klose et al., 2023). Together with indications of rapid ice loss during past warm climates (Alley et al., 2015; Turney et al., 2020), this has led to the classification of the West Antarctic ice sheet (WAIS) and the subglacial basins in East Antarctica (EASB) as tipping elements of the Earth system (Lenton et al., 2008; Armstrong McKay et al., 2022).

Thresholds for the occurrence of such abrupt transitions have been provided in terms of Global Mean Surface Temperature (GMST) with respect to pre-industrial temperature, amounting to 1.5°C (1 to 3°C, high confidence) for the WAIS and 3°C (2 to 6°C, medium confidence) for the EASB (Armstrong McKay et al. 2022). These thresholds are likely to be overcome by the end of the 21st century, even if current pledges in terms of emission reductions are met (Wiltshire et al., 2022). It is to note that the Six Assessment report (AR6) of the IPCC attributes only medium and low confidence, respectively, in simulating some key processes (e. g. the marine ice sheet instability) at the core of the tipping behaviour of the ice sheet (Fox-Kemper et al., 2021). Given that this uncertainty about the processes is combined to an extremely large and in practice irreversible (Garbe et al., 2020) ice mass loss and related SLR (Golledge et al., 2015; Klose et al., 2023), the IPCC has described the tipping of areas of the AIS as being characterized by deep uncertainty.

A notable source of uncertainty in the simulation of long-term Antarctic mass loss stems from the common practice of running ice sheet models without coupling them with a general circulation climate model (GCM). As a result, these models neglect ice-ocean-atmosphere feedbacks, posing the risk of potentially underestimating the extent of Antarctic mass loss, as indicated by the experiments conducted by Golledge et al., (2019). In the study, incorporating the coupling resulted in doubling of the AIS's SLR contribution under mid to high emission scenarios, even on the short term (end of the 21th century). This amplification can be attributed to the coupling's ability to capture the interaction between meltwater and the warm ocean currents responsible for sub-shelf melting, considered to result in a self-reinforcing mechanism (Alley et al., 2015; Hellmer et al., 2017). At the same time, including the meltwater flux in climate models, allows for the investigation of the effects of meltwater on projected SH climate change (Bronselaer et al., 2018). In addition, it enables capturing the impact of AIS loss on the long-term behaviour of other subsystems of the Earth, such as the Antarctic Overturning Current (AOC) and the Atlantic Meridional Overturning Circulation (AMOC), that have both been classified as tipping elements (Loriani et al., 2023).

1.2 Scientific goals of the project

In this project, we aim at investigating some key aspects and consequences of the tipping behaviour of the West Antarctic ice sheet and the East Antarctic subglacial basins by addressing two research questions:

(R1) What are the temperature thresholds of the WAIS and EASB? To what extent is it possible to temporarily overshoot these thresholds, without implying an irreversible ice loss?
Given the relatively large timescales (centuries-to-millennia) over which ice sheets respond to a forcing, exceeding a temperature threshold could lead to prolonged and irreversible changes, and hence, long-term committed sea level rise. On the other hand, such large timescale of response might allow to temporarily overshoot a temperature threshold, without necessarily resulting in irreversible ice loss (Ritchie et al., 2021; Bochow et al., 2023). This possibility can be investigated in the so-called "overshoot" scenarios. These are scenarios that follow a high-emission pathway for the first half of the 21st century and exhibit fast reduction of emissions and negative CO2 emissions throughout the late 21st and early 22nd centuries (O'Neill et al., 2016).

(R2) does the meltwater input from Antarctica result in abrupt changes of the AOC and/or the AMOC?
The inclusion of the freshwater contribution from ice mass loss is currently neglected in CMIP6 models, although several studies on past meltwater-induced climate changes have analyzed the sensitivity of the climate system to such forcings (Kageyama et al., 2013). In particular, only a few simulations (Golledge et al., 2019; Park et al., 2023) include a realistic meltwater input in the Southern Ocean in a coupled ice sheet model-climate model. In addition, to our knowledge, while some studies exist on the potential initiation of tipping cascades via meltwater input in the North Atlantic (e.g. Lohmann and Ditlevsen, 2021), such possibilities remain unexplored for the Southern Hemisphere. In our study we aim at investigating the potential of meltwater input from Antarctica to induce abrupt changes in the AOC and the AMOC, giving rise to a tipping cascade (Wunderling et al., 2023).

2. Proposed activities

We plan to perform simulations with the state-of-the-art ice sheet model PISM coupled to the general circulation (GCM) climate model EC-Earth. In addition, a subset of simulations will be run with the intermediate complexity GCM SPEEDY-NEMO. The main features of the models are summarized in the following.

2.1 Models

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 -OASIS3 (Craig, Valcke, and Coquart, 2017). The atmospheric component is run 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.

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 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. Most importantly for this project, that aims at capturing abrupt changes in ice loss, believed to be closely related to the position of the grounding line (Schoof, 2007), PISM parametrizes grounding line migration on a sub-grid scale (Feldmann et al., 2014). For the computation of melting at the bottom of floating ice shelves, the PICO box model (Reese et al., 2018) is employed. PICO includes a parametrization of the circulation in ice shelf cavities calculated from temperature and salinity fields.

2.2 Coupling

The coupling between the two models occurs via exchange of fields between the ice sheet model (that receives atmospheric and oceanic 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 every year (asynchronous coupling), but it is possible to adjust the time step of exchange. It is to note that, due to EC-Earth's warm bias in the atmosphere over the Southern Ocean, for Antarctica it is necessary to adopt anomaly coupling (Roedehacke, pers. comm., 2023). Although this introduces an arbitrary choice for the reference state, it does not represent a limitation for calculating thresholds and investigating the effect of meltwater on reinforcing abrupt ice mass loss.

The coupling of EC-Earth to a PISM model of the Greenland ice sheet has been been proven to realistically represent the current state of the ice sheet and climate (Madsen et al., 2022), and recent advancements have been made in coupling EC-Earth to the PISM model of the Antarctic ice sheet (Rodehacke, Madsen, and Gierz, 2021). Both PISM and EC-Earth are already installed on the Atos machine, on which first runs of the PISM model of the Greenland ice sheet have been performed. Currently, the coupling scheme is being updated in order to run with the latest version of EC-Earth (EC-Earth4) (Rodehacke, pers. comm. 2023). In addition, a low-resolution (LR) version of EC-Earth4 is being developed with a TL63L31-ORCA2Z31 configuration (Davini pers. comm., 2023 and SPLTUNE, ECMWF Special Project by S. Yang, 2022). Depending on the availability of these new versions for the climate model, we will consider performing the experiments with LR EC-Earth4 coupled to PISM, as this would allow for longer simulations with reduced computational cost.

Alternatively, we intend to perform a subset of the simulations by coupling PISM to SPEEDY-NEMO. SPEEDY-NEMO (Kucharski et al., 2016; Ruggieri et al., 2023) 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 tipping behaviour of the WAIS and EASB 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.

2.3 Simulations

To address the scientific goals outlined above, we carry out simulations with EC-Earth3-PISM as described in the following. Starting from an available spin up of EC-Earth3-PISM for pre-industrial conditions (Roedehacke, pers. comm., 2023), we extend it to the historical period up to year 1990.

Subsequently, we run the following simulations, based on the Shared Socioeconomic Pathways (SSPs) from the Scenario Model Intercomparison Project (ScenarioMIP, O'Neill et al. 2016):

- **SSP5-8.5 abrupt stabilization:** we perform a first run of the high-emission scenario SSP5-8.5, that we extend for 1000 years keeping the climatic conditions at 2300 fixed. In addition, we perform six 1000-long abrupt stabilization scenarios branching off from SSP5-8.5 at 1990, 2025, 2050, 2065, 2080 and 2100 as in Fabiano et al., (2023). Since such stabilization runs result in GMST ranging from 1.4 to 9.6°C anomaly with respect to the pre-industrial baseline (Fabiano et al., 2023), this allows to explore the temperature thresholds for Antarctica over a wide range. In addition, it could lead to a reduction of the bias introduced by the melting of large parts of the AIS in the uncoupled EC-Earth3 simulations, as reported by Fabiano et al., (2023).

- **SSP1-1.9 overshoot:** we follow two selected scenarios from the C1 and C2 set of scenarios described in Riahi et al., (2022). These scenarios are believed to limit warming to 1.5°C (i.e. the current best estimate of the threshold for the tipping of the WAIS (Armstrong McKay et al., 2022)) by 2100, after a limited or high overshoot. Similarly to the first set of experiments, after 2100, we keep the climatic conditions constant for 1000 years.

Regarding research question R2, which aims to evaluate the impact of meltwater in potentially triggering abrupt changes in the AMOC and AOC after stabilization, we conduct a comparison between the states of these systems in the SSP5-8.5 abrupt stabilization runs and those in the runs conducted by Fabiano et al., (2023), where meltwater is not included.

3. Justification of the computer resources requested

EC-Earth

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 corresponds to about 19,000 SBU.
Regarding EC-Earth 4 LR (TL63L31-ORCA2Z31 configuration), preliminary tests on 256 cores show that one year corresponds to ~500 SBU (Davini, pers. comm. 2023). Given that the optimal configuration and the final resolution for the EC-Earth 4 LR model has not been yet defined, we consider 750 SBU/year.
As mentioned in the previous section, alternatively to Ec-Earth4-LR, we consider using SPEEDY-NEMO. On the Atos machine, it is possible to run 10 years of simulation with SPEEDY-NEMO (parallelized on 34 cores) in 0.29 hours, equivalent to corresponding to 5.29 core hours (Bellucci, pers. comm. 2023). This is of the order of about two times faster than the current estimates for EC-Earth4 LR (1.11 h for 10 years). Yet, in case the most computationally expensive simulations will be run with SPEEDY-NEMO, testing of the coupling scheme between SPEEDY-NEMO and PISM will be needed. Therefore, we consider the same amount of SBU than for EC-Earth4 LR.

For PISM, since tests for the AIS model will be performed for the first time within this project, we consider only a rough estimate of about 25% of the computational resources needed for EC-Earth3 (i.e. 5,000 SBU per model year). Regarding 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 some resources for testing the optimal coupling configuration within a trade-off between computational resources and increments in the exchanged fields.

Regarding storage, we estimate a need of 30 GB/year for EC-Earth3 and of 650MB/year for EC-Earth4 LR, 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	PISM	First test runs of PISM for the Antarctic ice sheet	50	2	100	5’000
	EC-Earth3 - PISM	historical (1850-1990)	140	1	140	24’000
	EC-Earth3 - PISM	Testing (asynchronous coupling)	50	3	300	24’000
	EC-Earth4LR - PISM	Testing (asynchronous coupling)	50	3	300	24’000
	EC-Earth3 - PISM	SSP5-8.5 (1990-2100)	110	1	110	24’000
SBU Year 1						**21’500’000 SBU**
Storage after Year 1						**32’250 GB**
Year 2	EC-Earth4 LR - PISM (alternatively SPEEDY-NEMO - PISM)	tests on stabilization times of AIS	1	1	3000	5’750
	EC-Earth4 LR - PISM (alternatively SPEEDY-NEMO - PISM)	SSP5-8.5 extended (abrupt stabilization) (2100-3100)	1000	6	6000	5’750
	EC-Earth3 - PISM	SSP1-1.9 overshoot (1990-2100)	110	2	222	24’000
	EC-Earth4 LR - PISM (alternatively SPEEDY-NEMO - PISM)	SSP1-1.9 extended (2100-3100)	1000	2	2000	5’750
SBU Year 2						**23’100’000 SBU**
Storage after Year 2						**73’500 GB**
Total SBU (Year 1 + Year 2)						**44’600’000 SBU**
Total storage (Year 1 + Year 2)						**105’750 GB**

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