<u>LATE</u> REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: Italy

Principal Investigator[1]: Oliver Mehling

Affiliation: DIATI, Politecnico di Torino

Address: Corso Duca degli Abruzzi 24

10129 Torino

Italy

Other researchers: Katinka Bellomo & Jost von Hardenberg (PoliTo/ISAC-CNR)

Project Title: AMOC decline and recovery under strong warming and overshoot scenarios

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.)	2023	
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)	22,500,000	20,000,000	–
Accumulated data storage (total archive volume)[2]	(GB)	45,000	90,000	–

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

[2] 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.

Principal Investigator: Oliver Mehling

Project Title: AMOC decline and recovery under strong warming and overshoot scenarios

Extended abstract

1. Introduction

1.1 Background and motivation

In the present-day climate, the North Atlantic is the only region of deep-water formation in the northern hemisphere and therefore a major driver of the global thermohaline circulation. The resulting circulation, the Atlantic Meridional Overturning Circulation (AMOC), plays an important role in governing the climate of the North Atlantic region. It is therefore of both scientific and societal importance to understand changes of the AMOC under global warming, as modelling studies have shown that a regime change of the AMOC could have important impacts on temperature and hydroclimate not only in the North Atlantic region (e.g., Jackson et al., 2015; Bellomo et al., 2022), but also globally (e.g., Vellinga & Wood, 2002; Zhang & Delworth, 2005; Stouffer et al., 2006; Vellinga & Wood, 2008; Liu et al., 2020).

Coupled global climate models (GCMs) of the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) robustly project a decline of the AMOC over the 21st century, but there are large uncertainties about the magnitude of this change (Weijer et al., 2020). Whether this decline can induce an abrupt transition (e.g., faster than the timescale of anthropogenic forcing) or "tipping" of the AMOC to a weak state – or even a complete AMOC shutdown – has been especially debated. None of the CMIP6 models shows a collapse of the AMOC during the 21st century or under a more idealized abrupt quadrupling of CO2 concentrations from preindustrial levels (Bellomo et al., 2021). However, it has been suggested that the CMIP ensemble as a whole has common biases that may lead to unrealistic stability of the AMOC (Liu et al., 2017). CMIP6 models also neglect meltwater input from ice sheets, which has the potential to exacerbate AMOC weakening (Golledge et al., 2019). In particular, Lohmann & Ditlevsen (2021) demonstrated using a low-resolution ocean GCM that increasing rates of meltwater input from the Greenland Ice Sheet (GrIS) can induce a collapse of the AMOC.

Overall, based on these factors the Sixth Assessment report (AR6) of the IPCC frames AMOC shutdown as a "low-likelihood, but high-impact" scenario for the 21st century (Arias et al., 2021) and assigns only "medium confidence" that an abrupt collapse of the AMOC will not occur before 2100 (Fox-Kemper et al., 2021). A recent review of tipping points in the Earth system (Armstrong McKay et al., 2022) estimated that about 4°C (best estimate; confidence interval 1.4 to 8°C; low confidence) of global warming above preindustrial level would trigger an AMOC collapse. This threshold is expected to be crossed for high-emission scenarios around 2100 (O'Neill et al., 2016). Although the uncertainty on this estimate is large, the question of a potential AMOC collapse would become especially relevant for the 22nd century. Despite the availability of protocols up until 2500 (Meinshausen et al., 2020) only few currently available CMIP6 simulations extend beyond 2100, which adds uncertainty in the assessment of a potential AMOC collapse.

1.2 Scientific goals of the project

In this project, we first aim at addressing two core questions regarding a potential collapse of the AMOC in a state-of-the-art climate model: (a) does a high-emission scenario, in which the AMOC declines but does not collapse by 2100, imply an AMOC collapse in the 22nd century? And (b), does accounting for meltwater input from the GrIS significantly enhance AMOC weakening or even induce a collapse?

Second, we note that (b) becomes an especially relevant question in case of an "overshoot" scenario, i.e., a scenario that follows a high-emission pathway until the middle of the 21st century followed by fast emission reductions and negative CO2 emissions throughout the late 21st and early 22nd centuries (O'Neill et al., 2016). Because ice sheets are among the most inert components of the climate system, we expect meltwater input to have an impact onto the weakening and recovery of the AMOC following a CO2 overshoot.

While the AMOC is the main focus of our project, we highlight that the simulations carried out here will also be of use for other studies on the long-term effects of strong global warming or overshoot scenarios, and the extended SSP scenarios with the default model configuration will be made available as part of the CMIP6 contribution for EC-Earth3.

2. Proposed activities

2.1 Model

We plan to perform model experiments with EC-Earth3 (Döscher et al., 2022), a state-of-the-art developed by a consortium of European research institutions which participates in CMIP6. EC-Earth3 comprises of the atmospheric model ECMWF IFS cy36r4, the ocean model NEMO3.6 (Madec & NEMO team, 2016) including the LIM3 sea ice component (Rousset et al., 2015), the land surface scheme H-TESSEL (Balsamo et al., 2009) and the coupler OASIS3-MCT (Valcke, 2013). Because we build on existing simulations carried out for CMIP6, we use the standard resolution of EC-Earth3: a spectral truncation of TL255 with 91 vertical levels for the atmosphere and an ORCA1 grid with 75 vertical levels for the ocean. This corresponds to a horizontal resolution of about 80 km in the atmosphere and 100 km in the ocean, with a grid refinement to about 40 km in the tropical ocean.

2.2 Idealized meltwater forcing

Ideally, the influence of GrIS meltwater on AMOC weakening would be examined using interactively coupled ice sheets within EC-Earth, but this version is still under development within the EC-Earth Consortium. Therefore, we plan to simulate the effect of runoff from GrIS melt via a more idealized temperature-dependent meltwater flux into the ocean, keeping GrIS extent and orography constant from an atmospheric perspective. We plan to closely follow the experimental setup of the AMOCMIP project (Bakker et al., 2016), which was carried out with a number of CMIP5 models. AMOCMIP in turn followed the methodology of Lenaerts et al. (2015), who used meltwater output from a high-resolution future GrIS simulation and scaled it with the GCMs' summer temperature anomalies at 500 hPa to parametrize GrIS runoff. To account for spatial variations in meltwater runoff, it was calculated separately over eight glacial drainage sections.

If similar high-resolution simulations of future Antarctic Ice Sheet runoff have now become available, we plan to include a similar parametrization for Antarctica into our runs. However, we do not intend to run additional regional simulations as part of this project, and hence the meltwater calculations themselves will be inexpensive as they rely on existing data.

2.3 Simulations

To address the scientific goals outlined above, we carry out simulations with EC-Earth3 for two standardized future emission scenarios, represented by Shared Socioeconomic Pathways (SSPs) from the Scenario Model Intercomparison Project (ScenarioMIP; O'Neill et al., 2016) as part of CMIP6:

- SSP5-85, a high-emission scenario in which future economic development is primarily based on fossil fuels, implying a CO2 concentration of about 1100 ppm by 2100 and about 2000 ppm by 2200
- SSP5-34-OS, an overshoot scenario which follows SSP5-85 until 2040, followed by a fast reduction of greenhouse gas emissions and negative CO2 emissions for a duration of about 100 years

Because ScenarioMIP simulations have been a core part of CMIP6 activities leading up to the IPCC AR6, simulations covering the period 2015-2100 are available with standard forcings for both scenarios. In fact, both SSP5-85 and SSP5-34-OS are part of the 50-member SMHI Large Ensemble (SMHI-LENS; Wyser et al., 2021) carried out with the same version of EC-Earth3. To address objective (a), we will therefore extend a subset of SMHI-LENS ensemble members for SSP5-85 from 2100 to 2200, and at least one ensemble member to 2300.

To address objective (b), we plan to carry out a new set of simulations with idealized meltwater forcing (Section 2.2). This necessitates a new ensemble of simulations that cannot be branched off from the existing

SMHI-LENS. In line with the SMHI-LENS setup, we initialize these simulations in 1970 and integrate them until 2100 using historical and SSP5-85 forcings and including idealized meltwater. The SSP5-34-OS simulations with idealized meltwater are branched off from this set of simulations in 2040 following the ScenarioMIP protocol. Finally, we plan to integrate at least one SSP5-85-meltwater ensemble member up to the year 2300 to enable a comparison with AMOCMIP.

3. Justification of the computer resources requested

First runs on the new Atos machine have determined that the optimal configuration for the standard resolution of EC-Earth3 (TL255L91-ORCA1L75) is obtained using five nodes (490 cores for IFS and 148 cores for NEMO, with one core each for the runoff mapper and the XIOS server). We estimate that one model year using the standard configuration of EC-Earth3 will use about 19,000 SBU. Accounting for 6-hourly outputs for IFS and monthly outputs for NEMO, we estimate a need for about 40 GB of storage per model year – 90 TB in total which will be split equally over the two years.

Since EC-Earth3 exhibits strong multicentennial AMOC variability in its preindustrial control simulation (Meccia et al., 2022) and we expect a potential AMOC collapse to be inherently stochastic, ideally every model experiment would be conducted with several ensemble members. However, given the high computational cost of the model, in terms of ensemble members we prioritize the most important scenarios for our scientific goals as well as those in which we expect internal variability to have the largest influence.

In summary, for the experiments perform within the project the following resources will be required:

Year	**Configuration**	**Experiment**	**Model years**	**# Ensemble members**	**Total model years**
Year 1	Default	SSP5-85 extension (2100–2300)	200	4	800
		SSP5-34-OS extension (2100–2300)	200	1	200
	Meltwater	Testing (meltwater)	50	1	50
		historical (1970–2014)	45	3	135
				Total model years Year 1	**1185**
				SBU Year 1	22,500,000
				Storage after Year 1	45 TB
Year 2	Meltwater	SSP5-85 (2015–2100)	85	3	255
		SSP5-34-OS (2040–2100)	60	3	180
		SSP5-85 extension (2100–2300)	200	2	400
		SSP5-34-OS extension (2100–2300)	200	1	200
				Total model years Year 2	**1035**
				SBU Year 2	20,000,000
				Storage after Year 2	90 TB

Bibliography

Arias, P. A., et al. (2021). Technical Summary. In V. Masson-Delmotte et al. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 33−144). Cambridge University Press. https://doi.org/10.1017/9781009157896.002

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), eabn7950. https://doi.org/10.1126/science.abn7950

Bakker, P., Schmittner, A., Lenaerts, J. T. M., Abe-Ouchi, A., Bi, D., van den Broeke, M. R., Chan, W.-L., Hu, A., Beadling, R. L., Marsland, S. J., Mernild, S. H., Saenko, O. A., Swingedouw, D., Sullivan, A., & Yin, J. (2016). Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting. *Geophysical Research Letters*, *43*(23), 12,252-12,260. https://doi.org/10.1002/2016GL070457

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., van den Hurk, B., Hirschi, M., & Betts, A. K. (2009). A Revised Hydrology for the ECMWF Model: Verification from Field Site to Terrestrial Water Storage and Impact in the Integrated Forecast System. *Journal of Hydrometeorology*, *10*(3), 623–643. https://doi.org/10.1175/2008JHM1068.1

Bellomo, K., Angeloni, M., Corti, S., & von Hardenberg, J. (2021). Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. *Nature Communications*, *12*(1), 3659. https://doi.org/10.1038/s41467-021-24015-w

Bellomo, K., Meccia, V. L., D'Agostino, R., Fabiano, F., Larson, S. M., von Hardenberg, J., & Corti, S. (2022). *Impacts of a weakened AMOC on precipitation over the Euro- Atlantic region in the EC-Earth3 climate model* [Preprint]. In Review. https://doi.org/10.21203/rs.3.rs-2013367/v1

Döscher, R., et al. (2022). The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6. *Geoscientific Model Development*, *15*(7), 2973–3020. https://doi.org/10.5194/gmd-15-2973-2022

Fox-Kemper, B., et al. (2021). Ocean, Cryosphere and Sea Level Change. In V. Masson-Delmotte et al. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1211–1362). Cambridge University Press. https://doi.org/10.1017/9781009157896.011

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., & Edwards, T. L. (2019). Global environmental consequences of twenty-first-century ice-sheet melt. *Nature*, *566*(7742), 65–72. https://doi.org/10.1038/s41586-019-0889-9

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*, *45*(11), 3299–3316. https://doi.org/10.1007/s00382-015-2540-2

Lenaerts, J. T. M., Le Bars, D., van Kampenhout, L., Vizcaino, M., Enderlin, E. M., & van den Broeke, M. R. (2015). Representing Greenland ice sheet freshwater fluxes in climate models. *Geophysical Research Letters*, *42*(15), 6373–6381. https://doi.org/10.1002/2015GL064738

Liu, W., Fedorov, A. V., Xie, S.-P., & Hu, S. (2020). Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. *Science Advances*, *6*(26), eaaz4876. https://doi.org/10.1126/sciadv.aaz4876

Liu, W., Xie, S.-P., Liu, Z., & Zhu, J. (2017). Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate. *Science Advances*, *3*(1), e1601666. https://doi.org/10.1126/sciadv.1601666

Lohmann, J., & Ditlevsen, P. D. (2021). Risk of tipping the overturning circulation due to increasing rates of ice melt. *Proceedings of the National Academy of Sciences*, *118*(9), e2017989118. https://doi.org/10.1073/pnas.2017989118

Madec, G. & NEMO team. (2016). *NEMO ocean engine*. Notes Du Pôle de Modélisation de l'Institut Pierre-Simon Laplace (IPSL) No. 27. https://doi.org/10.5281/zenodo.3248739

Meccia, V. L., Fuentes-Franco, R., Davini, P., Bellomo, K., Fabiano, F., Yang, S., & von Hardenberg, J. (2022). Internal multi-centennial variability of the Atlantic Meridional Overturning Circulation simulated by EC-Earth3. *Climate Dynamics*. https://doi.org/10.1007/s00382-022-06534-4

Meinshausen, M., et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Rousset, C., Vancoppenolle, M., Madec, G., Fichefet, T., Flavoni, S., Barthélemy, A., Benshila, R., Chanut, J., Levy, C., Masson, S., & Vivier, F. (2015). The Louvain-La-Neuve sea ice model LIM3.6: Global and regional capabilities. *Geoscientific Model Development*, *8*(10), 2991–3005. https://doi.org/10.5194/gmd-8-2991-2015

Stouffer, R. J., et al. (2006). Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *Journal of Climate*, *19*(8), 1365–1387. https://doi.org/10.1175/JCLI3689.1

Valcke, S. (2013). The OASIS3 coupler: A European climate modelling community software. *Geoscientific Model Development*, *6*(2), 373–388. https://doi.org/10.5194/gmd-6-373-2013

Vellinga, M., & Wood, R. A. (2002). Global Climatic Impacts of a Collapse of the Atlantic Thermohaline Circulation. *Climatic Change*, *54*(3), 251–267. https://doi.org/10.1023/A:1016168827653

Vellinga, M., & Wood, R. A. (2008). Impacts of thermohaline circulation shutdown in the twenty-first century. *Climatic Change*, *91*(1), 43–63. https://doi.org/10.1007/s10584-006-9146-y

Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters*, *47*(12), e2019GL086075. https://doi.org/10.1029/2019GL086075

Wyser, K., Koenigk, T., Fladrich, U., Fuentes-Franco, R., Karami, M. P., & Kruschke, T. (2021). The SMHI Large Ensemble (SMHI-LENS) with EC-Earth3.3.1. *Geoscientific Model Development*, *14*(7), 4781–4796. https://doi.org/10.5194/gmd-14-4781-2021

Zhang, R., & Delworth, T. L. (2005). Simulated Tropical Response to a Substantial Weakening of the Atlantic Thermohaline Circulation. *Journal of Climate*, *18*(12), 1853–1860. https://doi.org/10.1175/JCLI3460.1