REQUEST FOR A SPECIAL PROJECT 2023–2025

MEMBER STATE: Italy

Principal Investigator[1]**:** Katinka Bellomo

Affiliation: Polytechnic University of Turin

Address: Corso Duca degli Abruzzi 24
10129 Torino, Italy

Other researchers: Virna Meccia, Paolo Davini, Jost von Hardenberg, Federico Fabiano

Project Title: Mechanisms and impacts of an abrupt decline in the Atlantic Meridional Overturning Circulation (AMOC) strength

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** ITBELL	
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 **X**	NO ☐

Computer resources required for 2023-2025: (To make changes to an existing project please submit an amended version of the original form.)		**2023**	**2024**	**2025**
High Performance Computing Facility	(SBU)	10,000,000	10,000,000	10,000,000
Accumulated data storage (total archive volume)[2]	(GB)	18TB	36TB	54TB

[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.

Principal Investigator: Katinka Bellomo

Project Title: Mechanisms and impacts of an abrupt decline in the Atlantic Meridional Overturning Circulation (AMOC) strength

Extended abstract

The aim of this project is to use the EC-Earth general circulation model to investigate mechanisms of precipitation change associated with changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC), with and without the influence of increasing concentration of greenhouse gases. This is a continuation of the existing project 'Impacts of Atlantic Meridional Overturning Circulation (AMOC) decline on European climate'.

1. Background and motivation

The Atlantic Meridional Overturning Circulation (AMOC) is a global scale system of ocean currents that redistributes heat, carbon and salinity (e.g., Buckley and Marshall 2016). Previous work has showed that changes in the AMOC affect the global climate in terms of precipitation, temperature and wind circulation anomalies (e.g., Zhang and Delworth 2005, Brayshaw et al. 2009, Jackson et al. 2015). It has been shown that abrupt shifts in the AMOC are possible, and that a sudden decline in the AMOC strength leads to widespread cooling over the northern hemisphere, amplifying or even leading to ice ages (e.g., Clement and Peterson 2008, Lenton et al. 2013, Johnson et al. 2019). The AMOC is also thought to be involved in multidecadal climate variability, such as the Atlantic Multidecadal Variability (AMV) mode, which is responsible for long-time scale anomalies in water availability and temperature over land, and is associated with the number and intensity of tropical and extra-tropical cyclones (e.g., Zhang et al. 2019).

Previous studies have shown that an abrupt decline in the AMOC leads to a southward shift in the Intertropical Convergence Zone (ITCZ), associated with a southward shift in the Hadley cell (Frierson et al. 2013, Marshall et al. 2014). Mechanistically, the climate system responds to a reduced ocean heat transport by the AMOC with an increased atmospheric heat transport, which is accomplished with the aforementioned shifts in the Hadley cell and ITCZ. Alongside the southward migration of the ITCZ, reduced AMOC strength is also linked to widespread drying over the northern hemisphere. However, our results (Bellomo et al. in prep.) show that there are some regions, such as north western Europe, in which precipitation increases despite the widespread drying. This is related to an increase in NAO+ events and an intensification and eastward enhancement of the jet stream.

In response to increasing concentration of greenhouse gases, there are also important changes in precipitation, which are affected by the response of the AMOC. Bellomo et al. 2021 showed that in models in which the AMOC declines less, precipitation changes according to the 'wet-get-wetter, dry-get-drier' pattern (Collins et al. 2013). However, in models in which the AMOC declines more, there is a southward shift in the ITCZ and widespread northern hemisphere drying, despite the increase in greenhouse gases. Hence, the response of precipitation to climate change strongly depends on the response of the AMOC.

Here we propose a series of climate model experiments that build upon our previous work and aim at elucidating the interplay of anthropogenic radiative forcing, AMOC decline and the precipitation response. We plan to apply the atmospheric moisture budget originally developed by Seager et al. (2010) to assess the relative contributions of dynamic and thermodynamic processes to the simulated precipitation changes, and to investigate the links between dynamic changes in the atmospheric circulation and precipitation patterns by explicitly computing changes in weather regimes using the clustering algorithm developed in Fabiano et al. (2020).

2. Proposed activities

2.1 Model

We plan to perform model experiments with EC-Earth3, a state-of-the-art global climate model participating in CMIP6 and developed by a consortium of European research institutions (Hazeleger et al. 2010). EC-Earth3 includes the ECMWF IFS cy36r4 atmospheric model, the land-surface scheme H-TESSEL (Balsamo et al., 2009), the NEMO 3.6 ocean model (Madec, 2008) and the LIM3 sea-ice component (Fichefet and Morales Maqueda 1997). The OASIS3-MCT (Valcke, 2013) coupler version 3.0 exchanges fields between the atmosphere and the other components. We use the standard resolutions of TL255L91 for the atmosphere and ORCA1L75 for the ocean (same as in CMIP6). These settings correspond to an atmospheric horizontal resolution of ~80 Km and 91 vertical levels, and an oceanic horizontal resolution of ~100 Km and 75 vertical levels. We note that EC-Earth3 is already installed and being used at ECMWF. We will also test the model experiments with the newer version of the model (EC-Earth4) and we will attempt to couple EC-Earth with a slab-ocean model (motionless ocean, coupled to the atmosphere through thermal fluxes only) to further test the role of AMOC on precipitation patterns.

Previous experiments performed on CCA at ECMWF suggest that the best configuration for the EC-Earth standard resolution (TL255L91-ORCA1L75) is using 240 cores for IFS and 118 cores for NEMO, with one additional core for the runoff mapper and the XIOS server. We estimate that one model year of the fully-coupled model will use about 19,000 SBU, while one model year of the slab-ocean, similarly to the atmosphere-only model, will use 15,000 SBU. Accounting for 6-hourly outputs for IFS and monthly outputs for NEMO, we estimate a need for roughly 30 GB storage for each year of simulation.

2.2 Simulations

In addition to control simulations, we plan to run three kinds of experiments within this project:

1) Water hosing (salinity anomaly) is applied in the North Atlantic and Arctic Oceans to inhibit deep-water formation and suppress the AMOC circulation.
2) Water hosing in conjunction with increased concentration of greenhouse gases (following the CMIP6 protocols for ssps and abrupt CO_2 experiments).
3) Experiments with a slab-ocean, where the so-called 'q-flux' (i.e., calculated ocean heat transport) is modified to test the role of AMOC.

Similar to previous experiments (Bellomo et al. in prep.), we will carry out water hosing experiments by applying freshwater anomaly of 0.3 Sv uniformly above 50°N over the North Atlantic and Arctic oceans. Once the AMOC has halted, or stops declining, we will end the hosing and we will let the model to freely evolve. The freshwater anomaly will be applied as a virtual salinity flux:

$$F(t,j,i) = -\frac{h(j,i)S_o(t,j,i)}{dz_0(j,i)} \qquad (1)$$

where S_0 is the local salinity in the upper layer, dz_0 is the upper layer thickness, and h is the water hosing field:

$$h(j,i) = \frac{H}{\int_R dxdy} \qquad (2)$$

for $(j,i) \in R$, the region in which the water hosing is applied (the North Atlantic and the Arctic in our case), and 0 otherwise. H is the strength of the freshwater anomaly (0.3 Sv = 0.3×10^6 $m^3 s^{-1}$), and dx and dy are the zonal and meridional grid spacings. Then, we will apply a water hosing correction throughout the rest of the ocean to the 3D salinity field to conserve the total amount of salt:

$$\frac{\int h(j,i)S_0(t,j,i)dxdy}{\int_{global} dxdydz} \qquad (3)$$

which represents the total added flux divided by the total ocean volume.

To investigate the added effects of greenhouse gases, we will run experiments in which we add to the freshwater hosing also increasing concentrations of greenhouses, according to CMIP6 protocols (we will attempt to use the ssp585 and abrupt-2xCO_2 designs). We will also perform experiments in which concentrations of greenhouse gases are modified, but there is no water hosing.

Finally, we will work on developing and coupling a slab-ocean model, adapted from PlaSIM (Fraedrich et al. 2005) for EC-Earth3. This model development is funded by a MSCA-IF fellowship agreement ('CliMOC'). With EC-Earth3 coupled to a slab-ocean we will test the role of AMOC strength by modifying the implied ocean heat transport ('q-flux'). This part of the project will reveal whether using the slab-ocean for testing the role of AMOC leads to similar results as the water hosing simulations, which would save computational time for future experiments. While we strongly suspect this will not be the case, this exercise will inform future users on the pros and cons of using the slab-ocean to investigate mechanisms related to ocean circulation processes, which has been the subject of debate (Zhang et al. 2019). We will also attempt to couple the slab-ocean to EC-Earth4. We note that while the slab-ocean might lack realism in ocean processes, it retains a fully functional atmospheric component and thermal coupling, which could be used to investigate the impacts of imposed ocean heat transport patterns on future climate change.

3. Summary table of the experiments and relative computer resources

Legend: Fully-coupled (FC), Slab-ocean (SOM)

	Model configuration	**Experiments**	**Duration**	**SBUs**	**Storage**
Year 1	FC	Control experiment (FC)	250 years	10,000,000	18TB
		Water hosing (FC)	300 years		
		Extra (for testing)	25 years		
Year 2	FC, SOM	Water hosing +GHG forcing (FC)	250 years	10,000,000	36TB
		Slab-ocean testing and control (SOM)	300 years		
		Extra (FC, SOM, for testing)	50 years		
Year 3	FC, SOM	Water hosing + GHG forcing (FC)	250 years	10,000,000	54TB
		Slab-ocean experiments (SOM)	300 years		
		Extra (FC, SOM for testing)	50 years		

4. References

Balsamo, G., Beljaars, A., Scipal, K., Viterbo, P., van den Hurk, B., Hirschi, M., and 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. Hydrometeorology, 10:623–643. https://doi.org/10.1175/2008JHM1068.1

Bellomo, K., Angeloni, M., Corti, S., and J. von Hardenberg, 2021: Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. Nat Commun 12, 3659. https://doi.org/10.1038/s41467-021-24015-w.

Bellomo K., Meccia V. L., D'Agostino R., Fabiano F., Larson S., von Hardenberg J., Corti S., in prep.: Climate impacts of a weaker AMOC over the Euro-Atlantic region in the EC-Earth3 climate model.

Brayshaw DJ, Woollings T, Vellinga M, 2009: Tropical and extratrop- ical responses of the North Atlantic atmospheric circulation to a sustained weakening of the MOC. J Clim 22(11):3146–3155. doi: 10.1175/2008jcli2594.1

Clement, A. C., and Peterson, L. C., 2008: Mechanisms of abrupt climate change of the last glacial period, Rev. Geophys., 46, RG4002, doi:10.1029/2006RG000204.

Collins M., Knutti R., Arblaster J., et al., 2013: Long-term climate change: Projections, commitments and irreversibility. In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, pp. 1029-1136, https://doi.org/10.1017/CBO9781107415324.024.

Fabiano, F., Christensen, H.M., Strommen, K. et al., 2020: Euro-Atlantic weather Regimes in the PRIMAVERA coupled climate simulations: impact of resolution and mean state biases on model performance. Clim Dyn 54, 5031–5048 https://doi.org/10.1007/s00382-020-05271-w

Fichefet, T., and M.A. Morales Maqueda, 1997: Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics, J. Geophys. Res., 102:12609-12646.

Fraedrich K, Jansen H, Kirk E, et al. 2005: The Planet Simulator: Towards a user friendly model. Meteorol Z 14(3):299–304. https://doi.org/10.1127/ 0941-2948/2005/0043

Frierson D., and Coauthors, 2013: Contribution of ocean overturning circulation to tropical rainfall peak in the Northern Hemisphere, Nature Geoscience 6, 940–944, https://doi.org/10.1038/ngeo1987.

Hazeleger, W. et al., 2010: EC-Earth: a seamless earth system prediction approach in action. Bull. Am. Meteorol. Soc., 91:1357-1363.

Jackson L.C., Kahana R., Graham T. et al., 2015: Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, Climate Dynamics, 45, 3299–3316, https://doi.org/10.1007/s00382-015-2540-2.

Johnson, H. L., Cessi, P., Marshall, D. P., Schloesser, F., and Spall, M. A., 2019: Recent contributions of theory to our understanding of the Atlantic Meridional Overturning Circulation. Journal of Geophysical Research: Oceans, 124, 5376– 5399. https://doi.org/10.1029/2019JC015330

Lenton T. M., Held H., Kriegler E., Hall J.W., Lucht W., Rahmstorf S., and Schellnhuber H.J., 2013: Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences of the USA, 105, 1786-1793, https://doi.org/10.1073/pnas.0705414105.

Madec, G., 2008: NEMO ocean engine. Note du Pole de modelization, Institut Pierre-Simon Laplace (IPSL), France, No 27 ISSN No 1288-1619.

Marshall J., Donohoe A., Ferreira D., and McGee D., 2014: The ocean's role in setting the mean position of the Inter-Tropical Convergence Zone, Climate Dynamics, 42, 1967–1979, https://doi.org/10.1007/s00382-013-1767-z.

Seager, R., Naik, N., Vecchi, G.A., 2010. Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. J. Clim. 23, 4651e4668.

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

Zhang, R., and Delworth T.L., 2005: Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation, J. Climate, 18, 12, 1853–1860, https://doi.org/10.1175/JCLI3460.1.

Zhang R., Sutton R., Danabasoglu G., Kwon Y.-O., Marsh R., Yeager S. G., et al., 2019: A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic Multidecadal Variability and associated climate impacts. Reviews of Geophysics, 57, 316– 375, https://doi.org/10.1029/2019RG000644.