# REQUEST FOR A SPECIAL PROJECT 2021–2023

**MEMBER STATE:** Italy

**Principal Investigator**[1]**:** Virna Loana Meccia

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**Project Title:** AMOC hysteresis in the EC-Earth model

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|---|---|---|
| If this is a continuation of an existing project, please state the computer project account assigned previously. | **SP** ________________ | |
| Starting year:<br>(A project can have a duration of up to 3 years, agreed at the beginning of the project.) | 2021 | |
| Would you accept support for 1 year only, if necessary? | YES ☒ | NO ☐ |

| **Computer resources required for 2021-2023:**<br>(To make changes to an existing project please submit an amended version of the original form.) | | **2021** | **2022** | **2023** |
|---|---|---|---|---|
| High Performance Computing Facility | (SBU) | 9,500,000 | 9,500,000 | - |
| Accumulated data storage (total archive volume)[2] | (GB) | 22,500 | 45,000 | - |

*Continue overleaf*

[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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**Project Title:** **AMOC hysteresis in the EC-Earth model**

# Extended abstract

**Overview**

In this special project, we plan to explore the bi-stability of the Atlantic Meridional Overturning Circulation (AMOC) in a state-of-the-art climate model by applying different water hosing forcing in the North Atlantic. This work will be carried out with the EC-Earth climate model at its standard resolution, which is represented by a horizontal resolution of approximately 80 km in the atmosphere and 100 km in the ocean. Our experiments will take part in a Multi-model Inter-comparison Project (MIP) to better understand the likelihood of the AMOC collapse in the future with the last generation climate models or earth system models.

## 1. Introduction

### *1.1 Scientific Context*

The Atlantic Meridional Overturning Circulation (AMOC) represents a crucial component of our climate because it contributes to the heat redistribution around the globe. It is constituted by a shallow-layers northward component of warm and salty waters and a deep-layers southward component of cold waters in the Atlantic (Buckley & Marshall, 2016). This ocean circulation system transports a substantial amount of heat from the south, including the Southern Hemisphere and the Tropics, toward the North Atlantic (Bryan, 1962; Ganachaud & Wunsch, 2000; Jackson et al., 2015; Weijer et al., 2020).

Since the pioneering work of Stommel (1961), it is thought that the AMOC has a bi-stable equilibrium state, either *on,* corresponding to our current climate, or *off*. A transition between these two states could be irreversible. The term hysteresis is used to refer to this irreversibility. Furthermore, through a simple conceptual model, Rahmstorf (1996) has found that the response of the oceanic circulation to changes in the freshwater input takes the form of a hysteresis curve. Then, a mechanism that can disrupt the current stable state of the AMOC might be the addition of freshwater into the North Atlantic. This would yield surface seawater to be less dense and therefore more difficult to sink, slowing down the thermohaline circulation.

Indeed, an increase in the freshwater input to the North Atlantic is likely to occur as a response to global warming due to increased precipitation on oceans, increased runoff, sea-ice melting and the melting of Greenland. In light of this, state-of-the-art climate models project a weakening of the AMOC in response to global warming. The Fifth Report of the Intergovernmental Panel on Climate Change (IPCC) concludes that a weakening of the AMOC before 2100 is very likely, with a range of weakening of 12-54% for a high-range scenario (Collins et al, 2013). It was also found that an AMOC collapse is very unlikely to occur in the 21$^{st}$ century (Schmittner et al., 2005; Cheng et al., 2013; Stocker et al., 2013; Schleussner et al., 2014). However, the future projections in the previous comprehensive climate model simulations have either neglected or highly idealized the mass loss of the Greenland ice-sheet in terms of magnitude, spatial, and temporal characteristics. In addition, there remains a suggestion that climate models as a whole may be biased towards a too-stable AMOC (Valdes, 2011; Mecking et al., 2017).

### *1.2 Current status*

Paleoclimate records suggest that input of freshwater from the ice-sheet melting into the North Atlantic produced abrupt changes in the AMOC. Those changes are believed to be linked to changes in the climate (Broecker et al., 1985; Bond et al., 1997; Rahmstorf 2002; McManus et al. 2004; Clement & Peterson 2008; McNeall et al. 2011), supporting the view of the classic bi-stability structure and hysteresis behaviour. From a more theoretical viewpoint, the bi-stability of the AMOC equilibrium state was first exhibited in box models and a range of climate models of low complexity (Stommel, 1961; Manabe & Stouffer, 1988; Gregory et al., 2003). Moving forward into model complexity, Rahmstorf et al. (2005) have obtained a qualitatively similar hysteresis response of the thermohaline circulation to the freshwater forcing in 11 climate models of intermediate complexity. Yet, testing the AMOC hysteresis response in coupled climate models is extremely challenging due to the computational constraints.

Hawkins et al., (2011) showed for the first time an AMOC bi-stability response to freshwater perturbations in the complex climate model FAMOUS. More recently, Jackson & Wood (2018) have found hysteresis of the AMOC (quasi-irreversible shutdown) in a climate model with an eddy-permitting ocean. In particular, authors have shown that if the AMOC weakening due to freshening is sufficiently high, the AMOC remains in a weak state even when the hosing is stopped. However, a weak AMOC can recover if the hosing is applied for a limited time. Their model experiments were conducted with a sixth Coupled Model Intercomparison Project (CMIP6) generation model, resulting in the most complex model to show the AMOC hysteresis behaviour.

There are still open questions as to whether the same results regarding the AMOC behaviour found by Jackson & Wood (2018) would be reproduced by other CMIP6 generation climate models and whether the feedback mechanisms would change in a warmer climate. In that context, Laura Jackson from the MetOffice is launching a proposal for a new Multi-model Inter-comparison Project (MIP) to understand the processes and feedbacks controlling the AMOC response in the last (CMIP6) generation climate models. The combination of insights under a MIP effort will contribute to a better understanding of the most important feedbacks controlling the AMOC stability and how those feedbacks vary across models.

### *1.3 Objective and expected contributions to the field*

The main aim of this special project is to participate in the multi-model inter-comparison project studying the AMOC hysteresis with the EC-Earth model. In this way, this project will contribute to a better understanding of the likelihood of AMOC collapse in the future. Additionally, we aim at assessing the feedbacks in a warmer climate.

As part of a multi-model inter-comparison project, data produced during this project might be shared with the climate modelling community to allow for a large range of studies focused on the AMOC mechanism responses to different hosing forcing.

## 2. Methodology

### *2.1 The General Circulation Model*

We will use the CMIP6-generation General Circulation Model (GCM) EC-Earth version 3 (Doescher et al. 2020). The atmospheric component consists of a modified version of cycle 36r4 Integrated Forecast System (IFS; ECMWF, 2009), and includes the land-surface scheme H-TESSEL (Balsamo et al., 2009). The ocean model consists of the Nucleus for European Modelling of the Ocean (NEMO; Madec, 2008) version 3.6, which includes the Louvain la Neuve (LIM3; Vancoppenolle et al., 2012) sea-ice model. The OASIS3-MCT (Valcke, 2013) coupler version 3.0 is used to exchange fields between the atmosphere and ocean components. The IFS spatial resolution is T255 L91, which corresponds to a horizontal resolution of about 80 km at the equator and 91 vertical levels represented in a hybrid coordinate system. The model configuration in NEMO is the ORCA1L75, a tripolar grid with an average horizontal resolution of 1° × 1° and 75 vertical levels.

### *2.2 The experiments*

The first part of the project is intended to be performed during the first year and it aims at understanding the feedback mechanisms controlling the AMOC hysteresis under the current climate. Therefore, starting from an initial state corresponding to the CMIP6 *piControl* run (steady pre-industrial forcing), a set of water hosing experiments will be run. The hosing will be applied as an additional freshwater flux uniformly over the region between 50°N in the Atlantic and the Bering Strait. The planned experiments are the following:

a) moderate water hosing of 0.3 Sv for 150 years;
b) moderate water hosing of 0.3 Sv for 20 years, stop the hosing and continue the simulation for 130 years with no hosing;
c) moderate water hosing of 0.3 Sv for 50 years, stop the hosing and continue the simulation for 100 years with no hosing.

Note: If a) results in an AMOC collapse, the experiment will be repeated with weaker water hosing.

The second part of the project is planned for the second year and it will address the same issue as the first part but in a warmer climate. Therefore, the experiments a) to c) will be run starting from an initial condition corresponding to the CMIP6 *abrupt4xCO$_2$* experiment (steady 4x$CO_2$ forcing).

## 3. Justification for the resources requested

Considering the simulations described above, we need to run 450 model years per set of experiments. Some additional years will be needed to test the water hosing set-up and some additional computing time to cmorize the output. We estimate, therefore, 500 model years to be run per year of the project. From scaling tests already performed in CCA, the optimal configuration for EC-Earth version 3 in its standard resolution (the one we intend to use) is obtained with 360 cores (240 for IFS, 118 for NEMO, 1 for the runoff mapper and 1 for XIOS server). With that configuration, each model year costs around 19000 SBU. Therefore, for running 500 model years we need roughly 9.5 millions of SBU per year of the project.

With regards to the storage, considering 6-hourly output for IFS and monthly means for NEMO, the requirements for the storage are around 50 GB/model-year. Saving 900 model years would imply the total amount of required space at the end of the project of around 45 TB. Storage resources will be split into equal parts between the two years of the project.

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