REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: Italy

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Project Title: Impacts of Atlantic Meridional Overturning Circulation (AMOC) decline on European climate

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.)	2021	
Would you accept support for 1 year only, if necessary?	**YES X**	NO ☐

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	9,880,000	9,450,000	-
Accumulated data storage (total archive volume)[2]	(GB)	18,000	33,000	-

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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Extended abstract

The aim of this project is to use the EC-Earth general circulation model to investigate the decline of the Atlantic Meridional Overturning Circulation (AMOC) in response to carbon dioxide (CO_2) forcing, and its impacts over the European climate.

1. Background and motivation

The AMOC is the Atlantic portion and most prominent part of the convection-driven global ocean meridional overturning circulation (Buckley and Marshall 2016, Johnson et al. 2019). The AMOC transports warm and salty waters in the upper layer of the ocean from the southern hemisphere into the North Atlantic. Once these waters cool at high latitudes in the North Atlantic, the combined effects of salinity and colder temperature make them sink and return to the southern hemisphere. The overall effect of this overturning circulation is a heat transport from the southern to the northern hemisphere, which is thought to be responsible for the northerly position of the Intertropical Convergence Zone (ITCZ) at 6°N in the annual mean (Frierson et al. 2013, Marshall et al. 2014).

Dramatic declines in the AMOC have been associated with global cooling of the earth and a shift of the ITCZ to the southern hemisphere (Zhang and Delworth 2005, Jackson et al. 2015) at times in which the earth was actually warming, such as during the Dansgaard-Oeschger ("D-O") events (Zhang et al. 2019). In present times, the continued warming of the earth could as well release in the North Atlantic enough freshwater to potentially shut-down the AMOC, as it is believed to have happened during the D-O events. If the AMOC does shut-down, an overall cooling of the earth, as large as 8°C in the northern hemisphere, could happen, possibly leading to a partial glaciation of the northern hemisphere (Zhang et al. 2019). For these reasons, an AMOC collapse is considered to be a 'tipping point' in the climate system (Liu et al. 2017).

Previous model simulations have shown that even in the most dramatic future climate change scenarios, such as the RCP8.5 and abrupt-4xCO_2 forcing in the CMIP5 archive (Taylor et al. 2012), the AMOC doesn't completely collapse (Cheng et al. 2013, Gregory et al. 2005). Nevertheless, there is large inter-model spread in the projections of AMOC decline rates, which contributes to the amplitude of North Atlantic Ocean warming (Drijfhout et al. 2012): in the models where the AMOC declines the most, the amount of warming in the North Atlantic and in the world is significantly reduced compared to models in which the AMOC declines less (Bellomo et al. in prep.). We found that some models, such as GISS-E2-1-G, exhibit huge jumps in AMOC decline rate going from 2xCO_2 forcing to 4xCO_2, with associated differences in the simulated SST change over the North Atlantic Ocean as big as 5°C.

What is not clear from these previous inter-model comparisons is:
1) whether there is a nonlinearity in the AMOC response to increasing concentrations of CO_2, which would suggest the presence of a tipping point, or at least, of a significant shift in the strength of the AMOC, passed a certain threshold
2) what are the weather impacts caused by different AMOC decline rates

Resolving these two outstanding issues would help us better understand the dependence of the AMOC on anthropogenic forcing, as well as quantify and better prepare for climate impacts in Europe due to the AMOC decline.

2. Scientific project

In order to address these questions, we plan to run simulations with EC-Earth using both the fully-coupled and the atmosphere-only configurations.

2.1 Model

We will use the EC-Earth model version 3.3.1.1. EC-Earth is a state-of-the-art earth system model developed by a consortium of European research institutions, including CNR-ISAC (Hazeleger et al., 2010). The version of the model that we will use is the one that participates in the CMIP6 archive. EC-Earth includes the ECMWF IFS cy36r4 atmospheric model, the NEMO 3.6 ocean model (Madec 2008), the LIM3 sea ice component (Fichefet and Morales Maqueda 1997) and the H-Tessel land component (Balsamo et al. 2009). We will run the model in the standard resolution TL255L91- ORCA1L75, the same used for CMIP6, which features for the atmosphere a horizontal resolution of 80 km and 91 vertical levels, while for the ocean a horizontal resolution of about 100 km and 75 vertical levels. We note that EC-Earth is already installed and being used at ECMWF.

2.2 Simulations

- **Fully-Coupled simulations forced with increasing concentrations of CO_2 (Year 1)**

In the first part of the project, we will perform a series of experiments in which we impose an abrupt CO_2 forcing throughout the simulation using the fully-coupled EC-Earth in standard configuration. We plan to perform 4 experiments. These 4 experiments will be each 130 years long and we will impose abrupt CO_2 forcing of respectively: 2xCO2 (560 ppm), 2.5xCO2 (700 ppm), 3xCO2 (840 ppm), and 3.5xCO2 (980 ppm). The base CO_2 forcing (or 1xCO_2) is 280 ppm and is the value used in the pre-industrial control experiments in CMIP6. These simulations will be complemented with the abrupt-4xCO_2 (1120 ppm) simulation, which is already available from CMIP6. Changes in the climate system will be computed relative to the pre-industrial control simulation at 1xCO_2, which is also already available in CMIP6. We will branch these new simulations off the same year of the pre-industrial control simulation as the existing 4xCO_2 simulation in CMIP6. Ideally these experiments should be 150 years long, as in the CMIP6 archive, but previous work has shown that the many climate aspects equilibrate after 100 years, hence 130 years should be sufficient. If needed, we will request additional computing time to extend these runs.

These simulations will be used to investigate the response of the AMOC to different CO_2 forcings, and the associated impacts over the European weather and climate statistics. However, the impacts on weather patterns in future climate change are highly dependent on internal variability. In other words, even given the same AMOC decline and the associated SST change in the North Atlantic, there may be very different climate impacts due to atmospheric noise. Therefore, to quantify the climatic impacts of an AMOC decline, a probabilistic approach needs to be used. This means that we would need to run very long coupled climate simulations with each different CO_2 forcings. However, an alternative but nonetheless valid approach exists, and it is to run ensembles of atmosphere-only simulations perturbing the initial conditions, thus significantly reducing computational costs.

- **(AMIP-style) Atmosphere-Only simulations forced with the SST patterns resulting from different CO_2-induced rates of AMOC decline (Year 2)**

From the experiments in Year 1, we can obtain a pattern of global SST change for each CO_2-forced experiment. From our preliminary research, we can tell with enough confidence that while the rest of the world keeps warming, the North Atlantic doesn't keep up. This is because the AMOC declines and the heat transport to the North Atlantic is reduced. We will choose the 3 most significant SST pattern changes, among the 5 from Year 1. While we consider all of the proposed increasing CO2 forced experiments necessary to study the possible nonlinearity of the AMOC response, we believe that it will suffice to quantify the details of weather impacts for a subset of them. For each of these 3 patterns of SST change, we want to be able to tell what are the impacts over the European climate, to both improve resilience by advising policymakers but also to investigate the consequences of crossing certain thresholds in terms of the response of the AMOC decline to CO_2 (or in the extreme, an AMOC collapse, that is, a tipping point).

In order to be able to study the probability and statistics of characteristic weather events (e.g.,: atmospheric blocking, warm and cold spells, droughts, heat waves, etc.) associated with the SST patterns calculated from the simulations in Year 1, we need to generate an ensemble of AMIP-style simulations using the forced atmosphere-only component of EC-Earth. By AMIP-style we mean forced simulations in which the 12 month climatology of SST is repeated throughout the simulation. This way, the atmospheric model sees the annual cycle of the SST at each grid point, but SSTs do not change from year to year.

We plan to run an ensemble of 7 members for each of the 3 chosen SST patterns. Each experiment will be run for 30 years to be able to obtain solid statistical significance on the results. The atmospheric model will be run using the standard resolution of IFS used for CMIP6.

Each member in an ensemble will be generated by initializing the model from different atmospheric conditions. Perturbing initial atmospheric conditions to generate an ensemble of simulations characterized by differently evolving storylines is a consolidated technique and is used worldwide to generate "large ensembles" (Deser et al. 2012). Taking the mean of an ensemble effectively isolates the forced mean response from the internal variability, while the probabilities for individual extreme events can be estimated from the ensemble spread (Bellomo et al. 2018).

3. Technical specifications and justification of the computer resources requested

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 atmosphere-only model will use 15,000 SBU.

For the fully-coupled model experiments we estimate 9,880,000 SBU, while for the atmosphere-only model experiments we estimate 9,450,000 SBU, for a total of 19,330,000 SBU to be split over the course of 2 years. 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. Hence, we estimate a need for a cumulative storage of 33TB, 18TB in the first year and 15TB to be added in the second year.

Summary table for requested computer resources:

	Model configuration	**Experiments**	**Number Length**	**SBUs**	**Storage**
Year 1	fully-coupled (TL255L91-ORCA1L75)	abrupt-2xCO2 abrupt-2.5xCO2 abrupt-3xCO2 abrupt-3.5xCO2	4 simulations, 130 years each	9,880,000	18 TB
Year 2	atmosphere-only (TL255L91)	SST-forced1 SST-forced2 SST-forced3	21 simulations, 30 years each	9,450,000	15 TB
				total: 19,330,000	total: 33 TB

4. References

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