REQUEST FOR A SPECIAL PROJECT 2022–2024

MEMBER STATE: Italy

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Project Title: AddRessing iMpact of lArGe- and small-scale biases of North Atlantic SSTs on the mid-latitude Circulation (ARMAGNAC)

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.)	2022	
Would you accept support for 1 year only, if necessary?	YES ☐	NO ☒

Computer resources required for 2022-2024: (To make changes to an existing project please submit an amended version of the original form.)		**2022**	**2023**	**2024**
High Performance Computing Facility	(SBU)	26 million	32 million	32 million
Accumulated data storage (total archive volume)[2]	(GB)	20000	42000	64000

[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

Objectives

Within ARMAGNAC we aim at exploring the impact that different patterns and biases of North Atlantic sea surface temperatures (SSTs) - at different spatial and temporal scales - have on the mid-latitude circulation, using the newly developed version 4 of the EC-Earth Global Climate Model (GCM). Making use of a set of atmosphere-only integrations at three different horizontal resolutions (~100 km, ~50 km and ~25 km) we will 1) explore the effect of the most common large-scale SST bias featured by GCMs, such as the ones participating to the CMIP6 effort, 2) assess to what extent spatial and temporal resolution of the SST boundary forcing are relevant for a high resolution atmosphere, and 3) explore what are the impacts of different topologies of the Gulf Stream front, comparing *elongated* (non-meandering) vs. *convoluted* (meandering) Gulf Stream configurations on the local and downstream atmospheric circulation. Overall, ARMAGNAC aims at providing a deeper understanding of the influence that North Atlantic SST biases exert on the mid-latitude circulation dynamics, providing insightful indications for future pathways of bias reduction and model development.

Introduction

Despite the notable improvements achieved in the recent decades, state-of-the-art Global Climate Model (GCM) still feature large biases affecting both the mean climate (i.e., systematic error) and its variability, especially over the mid-latitudes: this applies, with different degrees, to essentially every single GCM participating to the Coupled Model Intercomparison Project - Phase 6 (CMIP6, Eyring et al, 2016). A realistic representation of the storm tracks, atmospheric blocking or weather regimes is still a considerable issue in both atmosphere-only and coupled GCMs (Priestly et al, 2020, Davini and D'Andrea, 2020, Fabiano et al, 2020). Improved parametrizations and grid refinement has led to reduced biases in the atmospheric component (Schiemann et al. 2017, Davini and D'Andrea. 2020), but it is still quite unclear to what extent the bias of the underlying ocean affects the jet stream dynamics. Indeed, over the North Atlantic it has been shown that the shape, position and strength of the meridional SST gradient induced by the Gulf Stream (GS) can have a marked influence on the downstream dynamics over the Euro-Atlantic sector (e.g., Minobe et al, 2008; O'Reilly et al 2016, 2017; Parfitt et al, 2016; Parfitt and Kwon 2020). Moreover, for mid-latitude variability events as atmospheric blocking, the spatial pattern and intensity of the SST biases might not interact linearly with the overlying atmospheric processes: even if it is true that in some instances improved SSTs lead to improved atmospheric response (Scaife et al. 2011), it has been shown that in the mid-latitudes coupled runs not always underperform their correspondent atmosphere-only integrations (Davini and D'Andrea 2016).

To this day, the standard nominal resolution adopted for the oceanic component of most global climate models - around one degree - does not allow to resolve mesoscale eddies and realistically reproduce the structure of eddy-rich regions of the world oceans such as the Western Boundary Currents (WBC; e.g., the Gulf Stream or the Kuroshio current systems). One typical issue related to such limitation is a misrepresented path for the GS front, - typically detaching from the US coastline far beyond the observed latitude (Hewitt et al., 2020) - leading in turn to SST biases (e.g. Keeley et al, 2012, Lee et al, 2018) that can reach up to 10K locally. This has a notable impact on the surface heat fluxes, determining an anomalous heat source/sink with non-negligible implications on many aspects of the overlying atmosphere, such as low-level tropospheric baroclinicity, the local vertical circulation and/or rainfall patterns.

In order to reduce these persistent SST biases, in recent years much effort has been placed to achieve eddy-permitting (or even eddy-resolving) resolution in the ocean components: this seems to have alleviated the above-mentioned mean biases (e.g., Roberts et al, 2020; Bellucci et al., 2021). As a downside, a refined oceanic mesh has a huge impact in terms of computational effort, due to both the cost of integrations and to the time needed to reach deep ocean equilibrium (i.e., the spin up time).

It appears therefore critical to investigate to what extent and in which way the present-day biases most commonly identified in the CMIP model ensemble are able to affect the atmospheric circulation, in order to understand how much the global climate community is required to invest in high-resolution, mesoscale-resolving ocean models to achieve a high-quality simulation of the mid-latitude atmosphere. Are the large-scale biases seen in eddy-parameterized/laminar ocean GCM SSTs and Sea Ice Concentrations (SIC) relevant for the mid-latitude climate variability? Which spatial scale matters when discussing the improvements coming from the high-resolution ocean simulation, i.e. is the mean SST state or is the small scale meandering of the WBC which has an impact on the atmospheric variability? Does the spatial and temporal resolution of the SST/SIC forcing matter? These and other fundamental dynamical questions will be investigated within the ARMAGNAC set of experiments. Furthermore, since the sensitivity to the SST biases might depend on the atmospheric resolution (e.g., Smirnov et al. 2015) - considering that only a high-resolution atmosphere might be able to exploit a high-resolution ocean - a set of different atmospheric horizontal grids will be employed.

Methodology

ARMAGNAC will be based on a set of atmosphere-only integrations at different horizontal resolutions carried out with the EC-Earth4 Earth System Model. The runs will be based on present-day conditions, in terms of both greenhouse gases and aerosol and ozone forcing, derived from CMIP6 forcing. The most resolved and realistic SSTs - available at the start date of the project - will be used: in this sense, the choice will likely fall on the latest available version of the HadISST2 dataset (Titchner and Rayner, 2014) that allows for daily (pentad-based) data at a 0.25x0.25 degree resolution: this dataset has been used for similar atmosphere-only experiments within the HighResMIP protocol (Haarsma et al, 2016).

Since one of the goals of ARMAGNAC is to explore the sensitivity to the bias at different horizontal resolutions, we will make use of three model configurations, namely Tco95, Tco199 and Tco399, which roughly correspond to 100, 50 and 25km respectively. The three resolutions are based on the new cubic octahedral grid developed by ECMWF that will be available in EC-Earth for the first time in the version 4. The project will be divided in four chunks, described here below:

0. TEST integrations

Considering that we will run on the new Atos HPC machine and that EC-Earth4 has - to this date - a limited amount of performance metrics available, we plan to dedicate a reasonable amount of core hours to test, scale, and tune the three different resolutions. Indeed, if tuned higher resolution configurations as Tco199 and Tco399 will not be made available by the EC-Earth Consortium, those configurations will undergo minor tuning aimed at ensuring a reasonable radiative budget during the ARMAGNAC project, using very short integrations. In this direction, we will exploit the gratuity of the core hours for the first four months of the project (before the 1st of May) in order to port the model on the new machine. However, a moderate amount of core hours might be reserved to this task. We estimate that about 8 model years (~100 months of integrations) for each resolution should be enough to fulfill this goal.

1. CTRL integrations

The first active part of the project will therefore be a set of AMIP-like integrations, 40-year long from 1980-01-01 to 2019-12-31 at the three different resolutions. As mentioned above, they will use realistic SST/SIC and radiative forcing: GHG/aerosol/ozone data from CMIP6 (historical up to year 2014 and then SSP2-4.5 scenario) will be used. This will identify the control integrations for the following simulations. A total of three simulations, performed at Tco95, Tco199 and Tco399 resolutions, will be run.

2. BIAS integrations

The second part of the project will tackle the impacts of those SST/SIC biases that chronically affect coupled climate models. As a first step, we will examine the SST biases in the CMIP6 models and apply a k-means clustering over specific regions of the globe, with a focus on the North Atlantic. This methodology will allow us to identify the more recurrent patterns of SST bias, as shown in Figure 1 with an example of k-means with k=3 for the North Atlantic. The biases will then be superimposed on the realistic HadISST2 dataset. A smoothing will be applied on the edge of the domain to avoid abrupt discontinuities. SIC will be modified accordingly. 40-year long integrations, each with a specific bias, will be run and then compared against the CTRL integrations. The goal is therefore to assess what is the influence of the most common SST bias on the mid-latitude atmospheric circulation. A comparison with CMIP6 data will be carried out, in order to see to what extent those large-scale SST biases are dominating the atmospheric variability and what is the role of the coupled feedbacks in shaping the mid-latitude climate. This analysis will be process-oriented and will primarily (but not exclusively) focus on diagnostics such as atmospheric blocking and weather regimes.

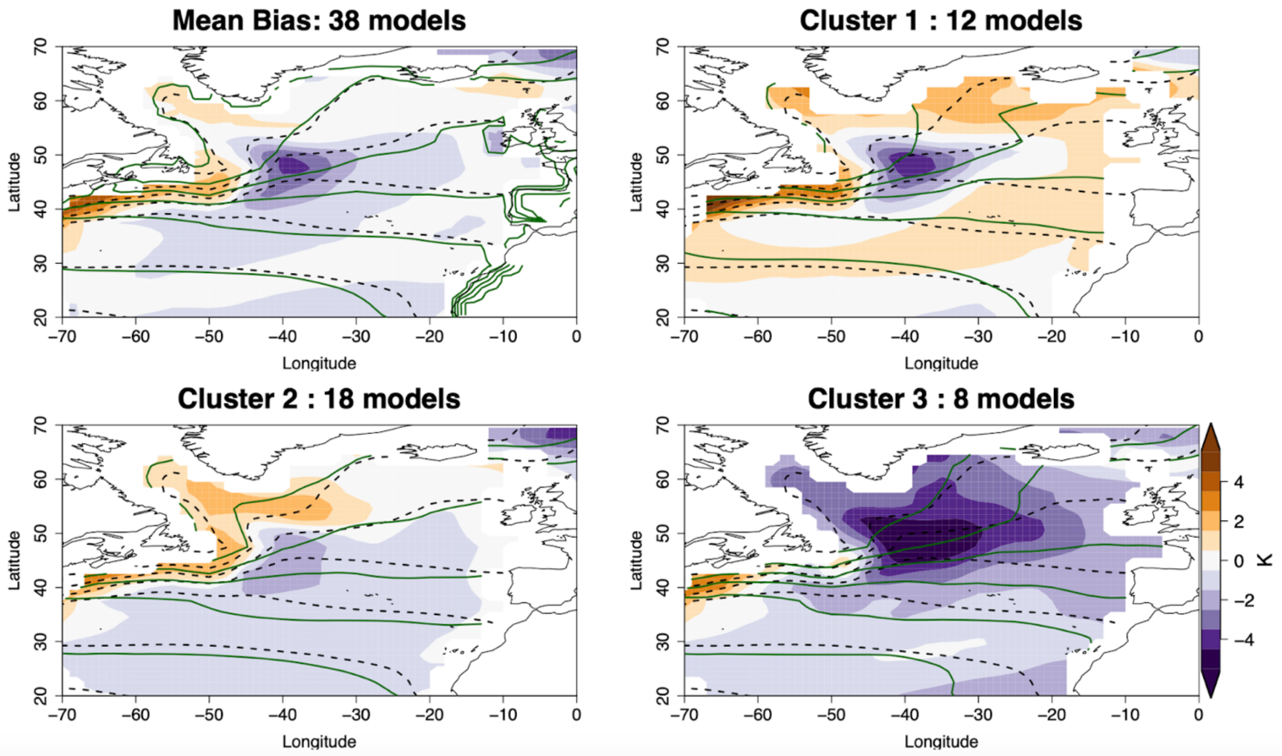

Figure 1: The mean bias of SST in CMIP6 models over the North Atlantic and a k-means clustering with k=3 showing three different relevant bias patterns, showing the typical cold blob in the subpolar gyre and the corresponding GS displacement. The number of models within each cluster is shown in the title. SST field is shown for the models in green and for HadISST1 reanalysis in dashed black.

Since for this task the atmospheric high resolution is not at the center of our attention (only a few HighResMIP models achieved a 25km horizontal resolution), for this specific subset of runs we will make use of Tco95 and Tco199 configurations only. The main focus will be the North Atlantic, but we would like to extend the approach to the North Pacific and to the Tropical Pacific, based on the outcomes of the regional k-means clustering. In the same sense, the optimal choice for the definition of k (i.e. how many clusters and how many runs we will run) will be assessed in the first period of the project after manual inspection of the CMIP6 SST/SIC biases. Overall, we estimate 15 40-year long runs at both Tco199 and Tco95 runs, in order to cover a wide set of possible patterns - perhaps also tuning their magnitude - over a few selected regions.

3. RESOLUTION integrations

This part of the project will be devoted to exploring the sensitivity of the high-resolution model configurations to the spatial and temporal resolution of the SST/SIC boundary forcing. In the first set of simulations, we will downgrade the SST/SIC boundary condition from the original ¼° horizontal resolution to a more standard 1° grid, and use them to force a high-resolution atmosphere (i.e. Tco199 and Tco399). In a second set, we will average on a monthly timescale the daily HadISST2 dataset and then linearly interpolate it back to daily timescale as usually done in climate models (e.g. CMIP6). The differences in the forcing field, for both the spatial and temporal downgrading, as shown by Figure 2, are quite relevant, and expected to affect the baroclinicity over the GS region with a significant impact on the overlying Atlantic jet stream dynamics. A total of four 40-year long simulations, two at Tco199 and two at Tco399 will be run.

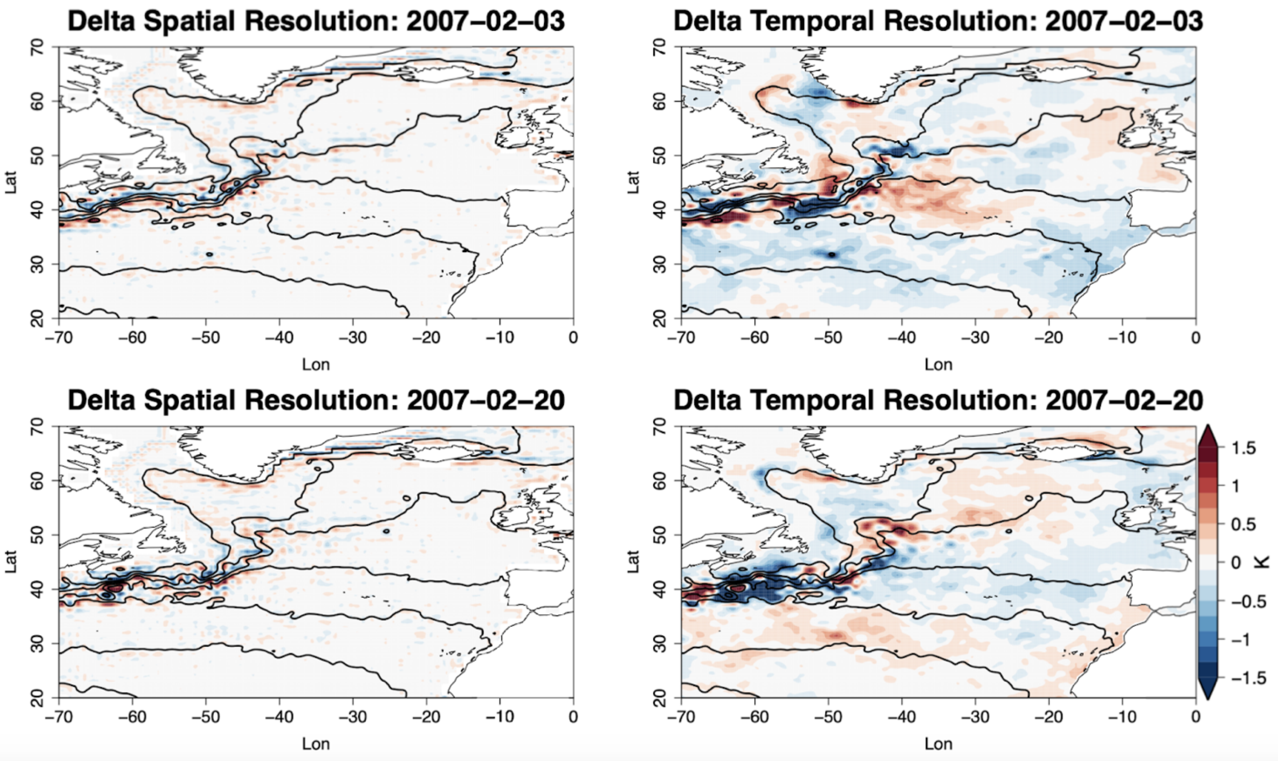

Figure 2: For two random days of February 2007 HadISST2 SST (left column) the SST anomalies induced by downgrading the spatial resolution from 0.25x0.25 to 1x1 deg and (right column) the SST anomalies caused by downgrading the temporal resolution from daily to monthly.

4. MEANDERING integrations

The last part of the ARMAGNAC project will explore to what extent the meandering of the Gulf Stream affects the overlying atmosphere. Therefore, we will design a set of shorter experiments (2-year long) where we impose different, time-invariant SST patterns corresponding to either 1) an "elongated" state where the GS shows a straight, non-meandering jet or to 2) a "convoluted" state where the GS exhibits large scale meanders. These two configurations portray different observed conditions of the inter-annually varying GS jet (e.g., Anders 2016) and will guide the design of two sets of integrations, using consistent boundary conditions, to sample the phase space of the oceanic state.

These twin ensembles will be then compared in order to assess whether the synoptic-scale variability of the atmosphere is significantly affected by the lower and higher degree of topological complexity associated with the above described, elongated versus convoluted states of the GS system. Note that the two selected topologies for the GS front (non-meandering vs meandering) do not only sample two possible states of the observed GS signature, but they also reflect the typical structure of the GS front in eddy-parameterized and eddy-permitting/resolving ocean models, respectively.

For this set of numerical integrations, we will make use of the highest resolution model configuration (Tco399) and an adequate number of ensemble members. At least 20 2-year long members will be run for both the elongated and for the convoluted state for a total of 80 years of integration.

Workflow

We will organize our work plan in detail as follows:

- Month 1-6: Setup of the EC-Earth4 model on the Atos HPC, transfer of the initial conditions, numerical optimizations, and scaling exercise.
- Month 6-12: Running of the CTRL integrations and setup of the BIAS boundary conditions.
- Month 10-24: Running of the BIAS integrations.
- Month 20-30: Running of the RESOLUTION integrations.
- Month 28-36: Running of the MEANDERING integrations.
- Month 4-36: Post Processing and data transfer to CNR machines. Analysis of the output.

Resources and technical development

The project is grounded on the EC-Earth4 Earth System Model, the successor of EC-Earth3 (Doescher et al 2021) which has been part of the CMIP6 campaign. The new model is based on the oIFS cy43 atmospheric model so that it presents a considerable step ahead to its predecessor (based on cy36r4).
To this day, the new model configuration is technically running, and it has been tested by the PI on the ECMWF CCA HPC at Tco95 and Tco199. The model is supported by an interface for processing output (XIOS v2.5) and an interface to read daily SST and SIC forcing (amip-reader). An intense development is carried out by the EC-Earth Consortium in these months so that the main configuration of the model, that will be based on a Tco95 grid, will be tested and tuned before the end of the year. All runs will be made with the default L91 vertical level configuration.

Expectedly, the transition from CCA to Atos HPC will affect the ARMAGNAC project. A few computational tests have been carried out on CCA - thanks to the SPITDAV2 special project - so that a basic scaling and performance evaluation allows for an estimation of the required computing hours. However, the actual speed of the new AMD-based machine might affect - either in positive or in negative - the computing time and the number of resources consumed. In the unlikely possibility that the Atos HPC shows a lower performance than CCA, as a contingency plan, we will reduce the length of our experiments. In a symmetric fashion, we plan to increase/extend the number of integrations in case the new computational facility will show better performance than expected.

Scaling test with EC-Earth4 has only been carried out in a partial way, but it is possible to assess the estimated computing time making use of a couple of a few emerging relations - considering the present relation of 18.84 SBUs for each core hour for Atos HPC:

1. Tco95L91: With 144 cores (5 CCA nodes, 142 cores for IFS, 1 for amip-reader and 1 for XIOS) EC-Earth4 runs one model year in approximately 3.15 hours. This means about 500 core hours, i.e. ~9500 SBUs per year.
2. Tco199L91: with 288 cores (10 CCA nodes, 286 cores for IFS, 1 for amip-reader and 1 for XIOS) EC-Earth4 runs one model year in approximately 8 hours. This means about 2500 core hours, i.e. 47500 SBUs per year.
3. Tco399L91: this configuration has not been tested yet. Noticing that the increase in computational cost scales roughly with the square of the number of latitude points and with the inverse of the timestep, it is possible to assume a slightly larger increase in cost than the one seen going from Tco199 to Tco95 (indeed, this is an equivalent doubling in resolution). We can thus estimate ~13500 core hours per year, i.e 255000 SBUs per year.

Summing together the different planned experiments, we will have that:

- TEST: 2.5 million SBUs
- CTRL: 12.47 million SBUs
- BIAS: 34.02 million SBUs
- RESOLUTION: 20.4 million SBUs
- MEANDERING: 20.4 million SBUs

This will sum up to 89.8 million SBUs over the three years. Of course, as mentioned in the introduction, we expect to encounter differences between CCA and Atos HPC, which cannot be completely addressed now. We might face reduced computational efficiency or extra work at the beginning of the project to improve the speed of the model. It is well-known that oIFS can benefit from the OpenMP parallelization, which has not yet been implemented on EC-Earth4 and might improve the performances especially at high resolution. In this direction, we will exploit the gratuity of the core hours for the first four months of the project (before the 1st of May) in order to port the model on the new machine. This should therefore not affect the required computing hours and might allow for a proper choice of computing configuration at each resolution.

A great novelty of EC-Earth4 compared to its predecessor is the adoption of the XIOS server in order to process in real time the output, directly into NetCDF files. This feature considerably reduces the amount of required data since raw Grib data is no longer needed. Our estimates for required storage are therefore only 10GB/year at Tco95 resolution, which will increase to 40GB/year and to 160 GB/year at Tco199 and Tco399 respectively. Considering that we plan to archive about 640 model years at Tco95 and Tco199 and 200 model years at Tco399, we estimate the total occupied space to be 64TB at the moment of maximum occupancy.

As an extra risk management plan, if it turns out that the model is considerably slower than expected on Atos HPC, we might want to run high resolution integration at Tco319 (~32 km) instead of Tco399: this could save between 10 and 12 million SBUs (assuming the same scaling proportional to square number of latitudes and the inverse of the timestep). As a last resort, if it turns out that EC-Earth4 is not suitable for the goal due to its low computational efficiency, numerical instabilities or lack of model development, we might want to roll back to EC-Earth3. Four different horizontal resolutions have been widely tested, ranging for TL159 to TL799, so that it will be possible to pick the right set of three resolutions which satisfy the core hours requirements.

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