REQUEST FOR A SPECIAL PROJECT 2020–2022

MEMBER STATE: Italy

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Project Title: State- and forcing-dependence of Equilibrium Climate Sensitivity in EC-Earth

If this is a continuation of an existing project, please state the computer project account assigned previously.		
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2020	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2020-2022: (To make changes to an existing project please submit an amended version of the original form.)		**2020**	**2021**	**2022**
High Performance Computing Facility	(SBU)	9,600,000	9,700,000	9,000,000
Accumulated data storage (total archive volume)[2]	(GB)	17,000	34,000	50,000

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 special project is to study the dependence of Equilibrium Climate Sensitivity (ECS) on the mean state and on forcing in a Global Circulation Model (GCM), using the EC-Earth model.

1. Introduction and motivation

Equilibrium Climate Sensitivity (ECS) is defined as the equilibrium response of global mean temperature to a doubling of the CO_2 concentration with respect to preindustrial levels.
The problem of determining ECS in the climate system is probably still one of the most relevant in climate science, and yet we are far from a final answer. Indeed, it is quite striking to observe that the AR5 likely range for climate sensitivity of 1.5 to 4.5 K (Collins et al., 2013) is the same as the original first guess by Charney and colleagues in 1979 (NRC, 1979). Preliminary results from CMIP6 models show an increased range of 2.8-5.6 K (CB, 2019), suggesting an important role of recent improvements in the models, such as the representation of cloud-aerosol interactions.

Limits of the linear response framework, dependence on the mean state.
This large uncertainty in ECS can be traced back to several causes. One of the most relevant is a systematic bias between the estimates from studies based on the observed warming and the estimates based on GCMs simulations, with the first ones being systematically lower. The cause of this discrepancy has been identified by recent studies (Knutti et al., 2018) and may be associated with the limits of the linear response theory approach usually used to determine the feedbacks from the observations (Gregory, 2004; Andrews, 2012). In fact, there is now convincing evidence that ECS and its related climate feedbacks are not constant but they depend on the global mean temperature and more generally on the climate mean state: with increasing global temperature some feedbacks may amplify (e.g. the water vapour and cloud feedbacks) or decrease (e.g. the ice albedo feedback) (Jonko, 2013; Armour, 2017).

Spread in models, emergent constraints.
However, even if considering only the results from GCMs, the spread in the estimated ECS remains large. Andrews et al. (2012) analyzed the CMIP5 inter-model spread in ECS and showed that the main reason behind the differences was the disagreement amongst different models on the intensity - and even on the sign - of the cloud feedback. Many authors investigated the different behavior of models in simulating clouds and their response to climate change (Bony, 2015) and tried to determine whether some models were more credible than others, based on their skill in simulating several dynamical processes (for a review, see Caldwell, 2018). In this context, Sherwood (2014) pointed at differences in the atmospheric convective mixing in the tropical region and found that the models showing a better agreement with observations have systematically larger ECS.

Role of tuning in determining ECS.

While many studies have focused on the inter-model differences, less attention has been devoted to the role of model tuning in defining the model mean climate and ECS. One of the first studies focusing on this topic has been the participatory science experiment 'climateprediction.net', in which thousands of people run a member of a Perturbed Parameters Ensemble (PPE) of the HadGEM3 model, each with a different set of tuning parameters (Stainforth, 2005). The results showed a spread in climate sensitivities ranging from 2 to 10 K, although many of the members were strongly out of equilibrium and gave unrealistic mean states.

A more recent example in this sense is the work by Mauritsen et al. (2012), in which they accurately reported on the process of tuning of the MPI-ESM for CMIP5. They also produced three different "worlds" with slightly different sets of tuning parameters and mean climates, with pre-industrial global mean temperatures ranging from 13 to 14 K. The climate sensitivities of the three worlds were found to be different, in the range between 2.8 and 3.4 K.

Recent advances, dependence on warming pattern and on forcing.

More recently, a wider perspective on the problem of ECS has been emerging. There is an overall agreement now in recognizing that the climate feedbacks, and consequently the ECS, depend on the state of the climate system. Moreover, new studies pointed out that the feedback strengths depend also on the external forcing applied: CMIP5 models show systematically larger ECS in 4xCO_2 runs than in 1%CO_2 runs (Armour, 2017) and the same behavior has been observed in models of intermediate complexity (Pfister, 2017).

These forcing-dependence of the feedbacks is suspected to be linked with changes in the spatial pattern of warming (the so called "pattern effect"; see Gregory, 2016; Andrews, 2015). One of the most sensible regions is the Tropical Pacific: an increased warming on the West Pacific Warm Pool with respect to the Eastern Tropical Pacific produces more low clouds in the Eastern Pacific, thus reducing the shortwave radiation reaching surface (Mauritsen, 2016; Zhou, 2016). The opposite happens when the warming pattern is reversed. A recent work by Andrews et al. (2018) showed that forcing atmosphere-only simulations with the observed SST warming pattern (warm West, cold East Tropical Pacific) produces smaller ECS than that of the same models run in coupled mode under 4xCO_2 forcing.

2. Scientific project

The aim of this project is to tackle two fundamental questions regarding the Equilibrium Climate Sensitivity in EC-Earth:

- the role of the model tuning and of the model mean state in determining ECS. The direct effect of the tuning parameters on ECS and the indirect effect due to changes in the mean climate are inextricably related.
- the response of the climate feedbacks and ECS to different warming patterns.

The experimental setup we intend to follow is described below.

Model.

The climate model used for simulations will be EC-Earth model version 3.3.1.1, a state-of-the-art, high-resolution earth-system model, developed by a large consortium of European research institutions and researchers of which CNR-ISAC is a core partner (Hazeleger et al., 2010; http://www.ec-earth.org). EC-Earth includes advanced, robust and validated components for the atmosphere (the ECMWF IFS model cy36r4) the ocean (NEMO 3.6; Madec 2008), sea ice (LIM3; Fichefet and Morales Maqueda 1997) and land processes (H-Tessel; Balsamo et al. 2009). The model will be run in both atmospheric-only and coupled mode. It is worth to note that v3.3.1.1 is the same version currently used for the CMIP6 intercomparison project.

The model has been already implemented and tested on many supercomputing platforms, including CCA at ECMWF. The coupled model will be used in the standard CMIP6 resolution TL255L91-ORCA1, with a horizontal resolution of approximately 80 km and 100 km for the atmosphere and the ocean, respectively. In the vertical, the atmosphere uses 91 levels and the ocean 75 levels. The atmosphere-only model will be used in the corresponding TL255L91 resolution.

Simulations.

a) The role of model tuning and mean state. (Project Year 1 and 2)

The first part of the project will focus on the role of model tuning and of the consequent change in the model mean state in determining ECS, following the approach by Mauritsen et al. (2012). The recent tuning process of the EC-Earth model for CMIP6 has further motivated this proposal since the CMIP6 version of the model has a larger ECS than the CMIP5 version. More specifically, the CMIP6 version appears to have an ECS around 4.2 K, while the corresponding CMIP5 version of EC-Earth had an ECS of 3.3 K. One of the possible explanations for this large difference (0.9 K) could be the presence of a new aerosol-cloud indirect effect parameterization, which has been introduced in the CMIP6 version.

This first part of the project will proceed along the following steps:

- perturb one tuning parameter from EC-Earth v3.3.1.1 and then change other parameters accordingly, in order to maintain a neutral TOA flux. This exercise can be done largely offline using a “tuning simulator” matrix developed in earlier projects (spitvonh, spnltune), based on known sensitivities of the model radiative fluxes to changes in a set of predetermined tuning parameters (mainly convective and microphysical parameters). This exercise will be repeated 3 times for different tuning parameters. We will then have 3 Perturbed Parameter (PP) “worlds” as in Mauritsen (2012), plus the control version represented by the CMIP6 simulation. Tests will be initially done in atmosphere-only mode and then extended to the coupled configuration.

- Perform a preindustrial and a 4xCO_2 coupled run for each PP world. The length of the runs will be limited to 65 years for the first year of this project, as better explained in Section 3 below. The control runs for preindustrial CO_2 and 4xCO_2 climates in this regard will be the

EC-Earth CMIP6 pi-Control and 4xCO_2 simulations, with the definitive tuning of version v3.3.1.1.

- The runs will be extended in the second year of the project, in order to better evaluate ECS and its variation while the model approaches equilibrium. The extension will last other 85 years for all runs, in order to be in line with the CMIP6 abrupt 4xCO_2 standard procedure (150 years). Depending on the results of the first year, we may also decide to extend only one or two simulations for more years, in order to look for the long-term behaviour of ECS.

b) The pattern effect. (Project Year 3)

The second part of the project, which focuses on the effect of the warming pattern in determining climate feedbacks and ECS, will consider atmosphere-only simulations and will be started in the third year of this project.

The second part will follow these steps:

- identification of two SST warming patterns, one in the historical and one in the 4xCO_2 CMIP6 run of EC-Earth. These 2 warming patterns will be used as forcing for the atmosphere-only runs. More patterns will be obtained modifying the intensity of the patterns (enhancing regional differences) and reversing them. In this way we will have a set of 8 warming patterns (2 patterns x 2 intensities x 2 signs). The number of patterns could be increased to 10, adding another intensity perturbation only for the 2 positive patterns.

- Perform a set of 10 atmosphere-only simulations, each adopting a different SST warming pattern from the above set and lasting 30 years. These simulations will use the reference EC-Earth v3.3.1.1 version of the model tuning.

- Estimate the fast climate feedbacks (water vapor, lapse rate and cloud feedbacks) from these runs following the approach in Andrews et al. (2018) and Jonko et al. (2013), which adopts the radiative kernels technique. Use the value of the feedbacks calculated in this way to give an estimate of ECS in each run and then assess the strength of the pattern effect in EC-Earth.

- The same approach will then be repeated with a different configuration of the model, chosen among the 3 PP worlds obtained in the first part of the project. In this way we aim to test whether the pattern effect is modulated by the model mean state.

3. Justification of the computer resources requested

Scaling tests performed on CCA at ECMWF in the framework of the SPITDAVI project have determined that the optimal configuration for the EC-earth standard resolution (TL255L91-ORCA1) is obtained with 286 cores for IFS and 108 cores for NEMO, with one core each for the runoff mapper and the XIOS server. One year of integration with the coupled model in the abovementioned conditions is completed in about 19,000 SBU. The expected model performance with the CMIP6 atmosphere-only version is instead 15,000 SBU per modeled year.

1. First project year.

The first step in the project requires the calibration and testing of the 3 PP worlds, with different tuning parameter configurations. The tests will be performed initially in atmosphere-only configuration and then extended to the coupled model. We estimate about 10 years of simulation per each re-tuned version in atmosphere-only and 30 years in coupled configuration. These estimates account for the fact that several tuning tests will probably be needed to obtain a satisfactory tuning. The tuning tests will require approximately 2.2 million SBUs.

For the first project year we then propose 6 experiments of 65 years each with the coupled model. This sum up to 390 modeled years. Following these estimates, we will need 7.4 million SBUs for the six simulations. The total amount of SBUs for the first year is then 9.6 million SBUs.

2. Second project year

The plan of the second project year will be to extend the 6 experiments by additional 85 years each, so as to reach the CMIP6 standard of 150 years for the $4xCO_2$ experiments. These simulations will require additional 9.7 million SBUs.

3. Third project year

The third year will be dedicated to the second part of the project, regarding the pattern effect. We plan to perform a set of 10 atmosphere-only simulations forced with the different warming patterns identified. Each simulation will last 30 years. These runs will be performed both for the reference EC-Earth version and for one of the 3 PP worlds built in the first part of the project.
These two sets of simulations will require approximately 9 million SBUs.

The following table summarizes the resources estimated.

#Year	Experiment	Model config.	Set-up	SBUs
Year 1	PP Tuning	Both	10 yrs atm-only, 30 yrs coupled, 3 versions	2.2 millions
Year 1	ECS of PP worlds	TL255L91-ORCA1	65 yrs, 6 runs	7.4 millions
Year 2	ECS of PP worlds	TL255L91-ORCA1	85 yrs, 6 runs (extension)	9.7 millions
Year 3	Pattern effect	TL255L91	30 yrs, 10 patterns, 2 sets	9 millions

So the request is for 9.6, 9.7 and 9 millions SBUs for the three years respectively.
Considering 6-hourly output for IFS and monthly means for NEMO, the requirements for the storage are around 30 GB/model-year. Consequently, the total amount of required space at the end of the project is around 50 TB. Storage resources will be split in equal parts between the three years.

5. References

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