SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2021
Project Title:	State- and forcing-dependence of Equilibrium Climate Sensitivity in EC-Earth
Computer Project Account:	spitfabi
Principal Investigator(s):	Federico Fabiano (S. Corti, P. Davini, J. von Hardenberg)
Affiliation:	ISAC-CNR (Bologna)
Name of ECMWF scientist(s) collaborating to the project (if applicable)	-
Start date of the project:	01/01/2020
Expected end date:	31/12/2022

Computer resources allocated/used for the current year and the previous one
(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	9,600,000	9,600,000	9,600,000	6,362,033
Data storage capacity	(Gbytes)	17,000	40,000	17,000	30,000

Summary of project objectives (10 lines max)

The aim of this project is to explore how the Equilibrium Climate Sensitivity (ECS) of a climate model (i.e. the mean global temperature increase in response to a CO_2 doubling with respect to preindustrial levels) might depend on the model tuning and mean state.
In a first part of the project we explored the tuning parameters' space to find suitable combinations that would modify the model climate feedbacks and sensitivity to CO2 forcing. Then, two coupled simulations were run both in pre-industrial and 4xCO2 conditions, with one "cold" and one "warm" parameter set respectively. The effective climate sensitivity and feedbacks of the climate system in the two configurations are finally studied.

Summary of problems encountered (10 lines max)

Nothing to report.

Summary of plans for the continuation of the project (10 lines max)

Preliminary analysis of the simulations performed has highlighted the necessity of an additional set of atmosphere-only simulations to account for non-linear effects arising from the simultaneous modification of two tuning parameters. Also, the impact of the tuning parameters on the effective radiative forcing (ERF) needs to be evaluated in order to better predict the change of the equilibrium climate sensitivity (ECS) following a change of the parameters. Depending on the results, we will decide whether to perform a new 4xCO2 coupled simulation with a different set of "cold" parameters, or to move on to the estimation of the climate feedbacks in the runs already performed.

List of publications/reports from the project with complete references

No publication is available for this project yet.

Summary of results

1. Atmosphere-only sensitivity runs to different tuning parameters

In the first part of the project, the sensitivity of the radiative balance of the system to a set of tuning parameters was assessed through an ensemble of short atmosphere-only simulations. All parameters considered are involved in the atmospheric parametrizations inside the IFS model and are mainly linked to cloud and precipitation processes. More specifically, we focused on the following set:

- ENTRORG: organized entrainment in deep convection
- RPRCON: rate of conversion of cloud water to rain
- DETRPEN: detrainment rate in penetrative convection
- RMFDEPS: fractional massflux for downdrafts
- RVICE: fall speed of ice particles
- RSNOWLIN2: snow autoconversion constant in large scale precipitation
- RCLDIFF: diffusion coefficient for evaporation by turbulent mixing
- RLCRIT UPHYS: cloud to rain critical radius (autoconversion)

The short atmosphere-only experiments (5 years) have been performed perturbing one parameter at a time, for 4 different values above and below the nominal value used in the CMIP6 version of EC-Earth3. This was done both with a pre-industrial SST boundary condition and with a 4xCO2 SST climatology calculated from the last 30 years of the EC-Earth 4xCO2 run of CMIP6. These runs were used to obtain the sensitivity of the radiative fluxes at TOA to the change of each parameter, both in pre-industrial and 4xCO2 conditions. The results are shown in Figure 1 below.

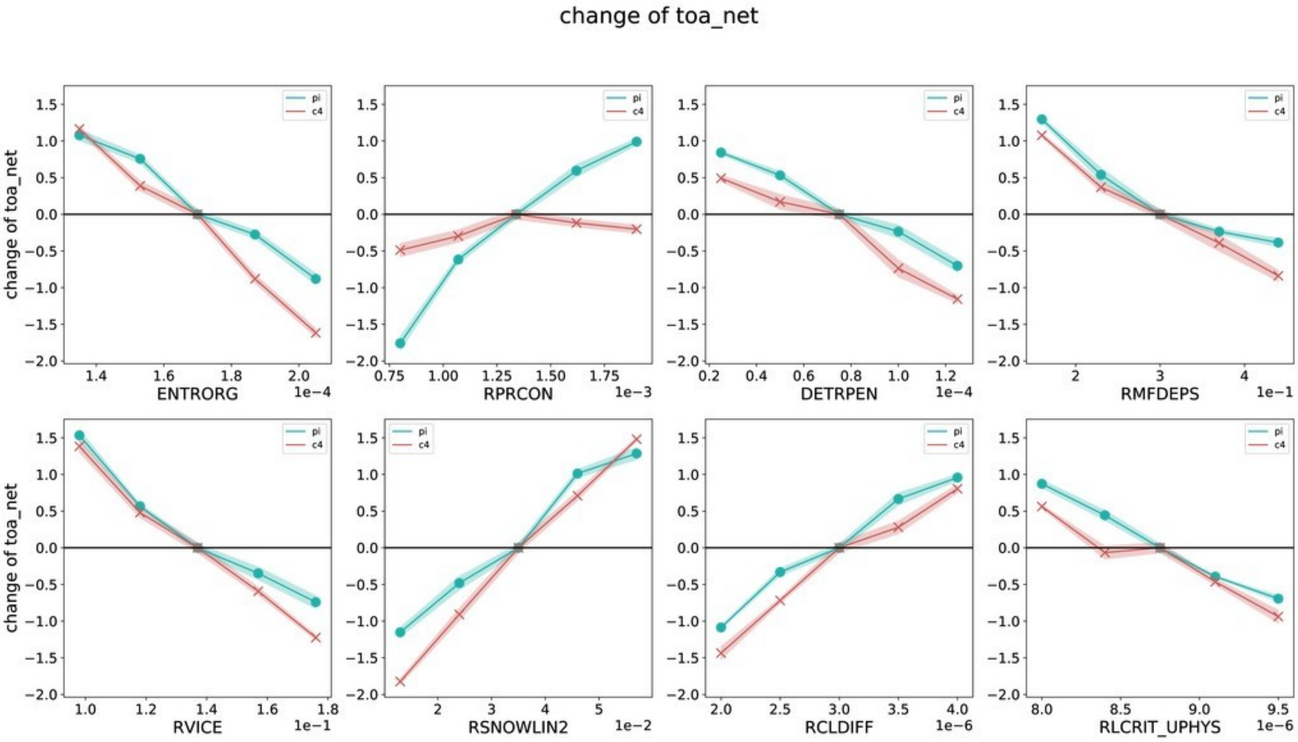

Figure 1. Change in the net TOA flux following perturbation of the respective parameter, for both pre-industrial (pi) and 4xCO2 conditions (c4).

The analysis showed that, for some parameters, the effect on the radiative balance is different depending on the underlying SST field. The most interesting parameter in this sense is the RPRCON parameter, which modifies the global precipitation and cloud distribution, and has a large impact on the balance for pre-industrial SSTs, but a much reduced effect for warmer SSTs. In a linear feedback approach (as in Gregory et al., 2004), it can be shown that the parameters that impact pre-industrial and 4xCO2 net TOA fluxes in a different way, also affect the climate feedbacks and equilibrium climate sensitivity (ECS).

Assuming that the effect of each parameter on the net TOA flux is independent from the others, we looked for the two parameter sets that would maximize and minimize the net TOA flux in the 4xCO2 simulation, while leaving the pre-industrial net TOA almost unchanged (abs. val. < 0.1 W/m2). Also, to avoid unphysical behaviours, we imposed a 30% limit on the parameter variation with respect to its original value in the CMIP6 version of EC-Earth3. In this way, we were able to define a "cold" and "warm" parameter set, that have been used to perform two coupled simulations, as explained in the next section.

2. Coupled simulations for the cold and warm worlds

A 20 years spinup + 30 years coupled pre-industrial simulation have been run for both the cold and warm set of parameters. Although the climate is close to radiative balance in both cases (-0.12 W/m2 and 0.17 W/m2 net TOA for the cold and warm worlds respectively), a small drift in the global mean temperature is seen, with the two pre-industrial worlds ending at about 13.5 and 14.3 degrees Celsius. Such a drift was not expected, but still both pre-industrial temperatures are acceptable and inside the multi-model CMIP6 range.
Then, two 4xCO2 abrupt simulations were performed, starting from the end of the spinup runs. The two simulations were run for 150 years each, as in the CMIP6 4xCO2 protocol. The equilibrium climate sensitivity in the two configurations has been estimated with the usual method based on linear feedback theory (Gregory et al., 2004; Andrews et al., 2012).
Preliminary results show that the warm world has a larger ECS than the nominal configuration (about 0.5 K), while the cold world ends up having a very similar ECS to the control run. While the result for the warm world was in line with the expectations based on the atmosphere-only simulations, the response of the cold world is much smaller than expected. A possible explanation to this fact is that the reduction of the climate feedback parameter in the cold world is partly balanced by an increase in the effective radiative forcing (ERF) exerted on the climate at the beginning of the abrupt 4xCO2 simulation.

3. Limits of the current framework and future developments

Some limits of the first formulation of the problem have emerged during the first year of the project. In particular, most attention had been given to the change in the climate feedbacks and possible impacts on the ERF were at first neglected. The cold world experiment however shows that modifications to the ERF due to a different cloud distribution and cloud screening effect can counterbalance the change in the climate feedbacks, even leading to a null net effect on the resulting ECS. To better understand which climate feedbacks have been modified most by the alternative tunings, a more in-depth analysis through radiative kernels (Soden et al., 2008; Zelinka et al., 2020) is currently being carried out.

Also, some evidence has emerged that the original assumption of linear independency of the tuning parameters may not hold, at least for some particular combinations. Indeed, the change in the TOA radiative fluxes predicted from the linear framework differs consistently from the actual values calculated in test atmosphere-only runs. Therefore, we plan to perform an additional set of atmosphere-only sensitivity runs, computing also second-order cross derivatives to the change of two parameters at a time for a subset of the parameters. These will be used to correct the linear framework and have a better prediction of the impact of the parameters on the climate feedbacks and ERF.

References

Andrews, T., Gregory, J. M., Webb, M. J., & Taylor, K. E. (2012). Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models. Geophysical Research Letters, 39(9).

Gregory, J. M., Ingram, W. J., Palmer, M. A., Jones, G. S., Stott, P. A., Thorpe, R. B., ... & Williams, K. D. (2004). A new method for diagnosing radiative forcing and climate sensitivity. Geophysical research letters, 31(3).

Soden, B.J., Held, I.M., Colman, R., Shell, K.M., Kiehl, J.T. and Shields, C.A., 2008. Quantifying climate feedbacks using radiative kernels. *Journal of Climate*, *21*(14), pp.3504-3520.

Zelinka, M.D., Myers, T.A., McCoy, D.T., Po-Chedley, S., Caldwell, P.M., Ceppi, P., Klein, S.A. and Taylor, K.E., 2020. Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters*, *47*(1), p.e2019GL085782.