# 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** | 2023 |
| **Project Title:** | State- and forcing-dependence of Equilibrium Climate Sensitivity in EC-Earth |
| **Computer Project Account:** | spitfabi |
| **Principal Investigator(s):** | Federico Fabiano<br>(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) | 9,000,000 | **6,229,721** | 0 | 0 |
| **Data storage capacity** | (Gbytes) | 17,000 | 30,000 | 0 | 0 |

## 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)

The project is completed in its computational part. Analysis is ongoing and a publication is in preparation.

## List of publications/reports from the project with complete references

A publication is in preparation.

## Summary of results

We briefly recall here the work performed during the entire course of the special project.
First, 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 with two sets of climatological SSTs corresponding to a pre-industrial and a 4x$CO_2$ climate. The tuning parameters considered in the experiment are: 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 sensitivity estimates were used to build a tuning simulator (to predict the impact of a multiple parameter change on the radiative balance, both for PI and 4xCO2) and an ECS simulator (to estimate the impact on ECS). The simulators relied on the following hypothesis:
- linearity of the response when multiple parameters are modified;
- negligible impact of the perturbation on the effective radiative forcing (ERF).

A set of 9 perturbed parameter sets has been tested, but most of them were discarded in that the linearity hypothesis did not hold. Out of the 9 sets, a "cold" and a "warm" set were selected, which were in reasonable agreement with the expectations from the simulator (linearity hypothesis holding true).

With the perturbed "cold" and "warm" sets, two 150-year coupled abrupt-4xCO2 simulations were run, accompanied by one 50-year pre-industrial control each. The two simulations were then studied to assess the impact of tuning on the effective climate sensitivity and individual climate feedbacks. The main result is summarized in Figure 1 below from previous report.

The feedback parameter and 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). The difference in ECS between the cold and warm configurations is estimated in about 0.5 K. This is less than expected from the "ECS simulator" under the two hypothesis summarized above. In particular, we find that:
- hypothesis 1 (linearity) does hold only partially, and a better simulator would require a more complete mapping of the parameter space and a nonlinear fitting;
- hypothesis 2 (negligible impact on ERF) does not hold, since the impact on ERF is of the same order as the impact on ECS (ERF varies from 3.3 W/m2 in the warm set to 3.7 W/m2 in the cold set), possibly masking a larger difference in the feedback parameter.

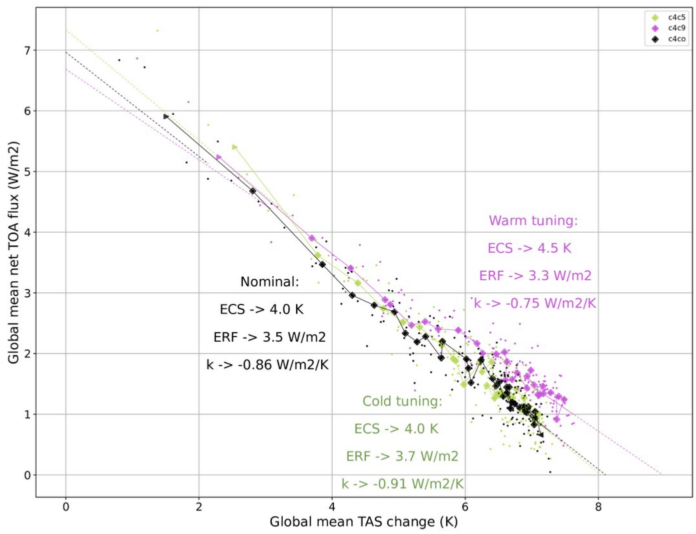


Figure 1. Fit of the feedback parameter and ERF for the "cold" set, "warm" set and the nominal configuration.

**Impact on individual feedbacks**

The two coupled abrupt-4xCO2 simulations with the perturbed cold and warm tuning were further analyzed to assess the impact on individual feedbacks, which could give more insight on the processes that are significantly impacted by the perturbation. The feedbacks were calculated following Soden et al. (2008), and separated in two "Planck" terms (warming response of surface and uniform vertical warming of the atmosphere), the lapse-rate, the water-vapor, the albedo and the cloud feedbacks. Cloud feedbacks were estimated as outlined in Soden et al. (2008) as a residual of the total feedback computed for full and clear sky conditions.

The preliminar results are shown in Table 1. The impact of the perturbed tuning parameters on the individual feedbacks is generally small, particularly for the Planck feedbacks, but can have a non negligible impact on some of them. In particular, the lapse-rate term is quite impacted (about 50% less in the "warm" tuning set), probably connected with the large impact on the deep convection regions in the tropics. Water-vapor and albedo feedbacks are also modified by about 5% their original value. The cloud feedback is also slightly different, but the difference is inside the uncertainty.

| Feedback (W/m2/K) | "Cold" tuning | "Warm" tuning |
|---|---|---|
| Planck (surface) | -0.68 +/- 0.01 | -0.69 +/- 0.01 |
| Planck (atmo) | -2.76 +/- 0.01 | -2.78 +/- 0.01 |
| lapse-rate | 0.21 +/- 0.02 | 0.13 +/- 0.02 |
| water-vapor | 1.87 +/- 0.03 | 1.96 +/- 0.02 |
| albedo | 0.70 +/- 0.01 | 0.66 +/- 0.01 |
| cloud | 0.25 +/- 0.04 | 0.27 +/- 0.04 |

Table 1. Assessment of individual feedbacks in the two simulations.

**Future steps**

Currently, work is ongoing to discard the initial hypotheses (linearity + negligible impact on ERF) and be able to make a more general claim. In particular, as described in last year's report, a Sobol mapping of the parameter space has been performed and expanded during the last year of the project. Results have not yet been analyzed, but will allow to build a better tuning simulator, able to consider also nonlinear terms.

On the other side, studying the impact of the perturbed tuning on the ERF (necessary to predict impact on ECS and feedbacks) required a new set of atmosphere-only simulations, with prescribed pre-industrial SSTs but 4xCO2 concentration in the atmosphere. These were performed for both the individual perturbation sets and the Sobol mapping of the parameters. Results have not been analyzed yet.

In the meanwhile, a first publication is being drafted on the topic, outlining the method and a first assessment of the results. Reference to this special project will be added to the manuscript.

**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, Brian J., Isaac M. Held, Robert Colman, Karen M. Shell, Jeffrey T. Kiehl, and Christine A. Shields. “Quantifying Climate Feedbacks Using Radiative Kernels.” *Journal of Climate* 21, no. 14 (July 15, 2008): 3504–20. https://doi.org/10.1175/2007JCLI2110.1.