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	……………………2025……………………………..……
Project Title:	…Linear response theory and stochastic parametrizations for the investigation of response and sensitivity: A case study with an intermediate-complexity model …
Computer Project Account:	………spitlemb……………………………………..……
Principal Investigator(s):	……Valerio Lembo…………………………………..……
	……………………………………………………..……
Affiliation:	…ISAC-CNR……………………………………..……
Name of ECMWF scientist(s) collaborating to the project (if applicable)	……………………………………………………..……
	……………………………………………………..……
Start date of the project:	…01/01/2024……………………………………..……
Expected end date:	…31/12/2026……………………………………..……

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)	2869200	2776321	7012500	21582
Data storage capacity	(Gbytes)	91500	0	157500	2464

Summary of project objectives (10 lines max)

The sensitivity of internal variability to external forcings, as it can be distinguished from the long-term climate response, is studied in model PlaSim-LSG, with and without a Stochastically Perturbed Parametrization Tendencies (SPPT) scheme (Buizza et al. 1999). The computational advantage provided by such EMIC-class models is exploited to investigate the asymptotic response of the modelled climate in a systematic way. An experimental protocol adopting the LRT in the context of climate modelling (Ragone et al. 2016) is tested in its performance to predict the asymptotic response of a chosen observable, highlighting several crucial aspects of the climate forced response, such as the equilibrium climate sensitivity, the transient climate response etc., the reduction of the Atlantic Meridional Overturning Circulation (AMOC) or the emergence of the North Atlantic cold bloc (cfr. Lembo et al. 2020).

Summary of problems encountered (10 lines max)

The production phase of the PlaSim-LSG modelling system was shared between the Atos machine and other HPC infrastructures; for this reason, the computational resources in the first part of 2025 have not been extensively used, while they will be in the second part of the year. The daily resolution output has posed some challenge to the usage of storage space. In fact, for each millennial run, the output had to be transferred to ECFS tape, limiting the capability to perform several runs in parallel.
This will be hopefully overcome by a more extensive usage of the SCRATCH partition. Besides this, it has been found that the model conserves energy in a different way, whether its atmospheric vertical discretization features 10 or 15 levels. An existing issue that has not been yet resolved in year 2 is the numerical instability of T31 and T63 resolutions.

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

The totality of runs 1pct_xCO2_t21, xCO2_ens_t21, 2CO2_ens_t42, hist_ens_t42_d, hist_ens_t42_s have been now completed. The next steps, starting in the second half of 2025, will be running the remaining historical runs at T21 resolution, investigating the impact of the different vertical discretization in the atmosphere by switching to 10 levels instead of 15 and checking that the model better conserves energy. Together with the model developers, we then plan to run more tests with T31 and T63 resolutions, that have proven to be numerically unstable, and enter the production phase of the ctrl_t31, ctrl_t63, 2CO2_ens_t31, 2CO2_ens_t63, hist_ens_t31_d, hist_ens_t31_s, hist_ens_t31_d, hist_ens_t31_s ensembles.

Summary of results

The first major task required porting the adopted version of the PlaSim-LSG model to Atos, setting the right compiler and compiler's flags and make it run. Once this was achieved, the first tests were carried out to assess the model's performances and scalability. We verified that the scaling was coherent with what illustrated in the project proposal, as this what achieved with a different HPC system.
During the production phase, we deployed resources on Atos mainly for the ensemble run with 8CO2_ens_t21 and 1pct_8CO2_t21. Despite the very coarse spatial resolution, a major bottleneck was determined by the necessity to provide outputs at the daily temporal resolution. A total of about 1.2TB of data was produced for each 8CO2_ens_t21 run, and 600 GB for each 1pct_8CO2_t21 run. With the help of the /scratch/ partition and progressively transferring data to ECFS, we managed to complete the 40 runs by the end of 2024. In the meantime, we worked on another HPC infrastructure to compute the historical runs (hist_d and hist_s), but this required running a new pre-industrial control run for the hist_s ensemble, given that the equilibrium state of the model with these options was not the same as for the hist_d settings.
At the moment, all but two hist_s runs have been completed, and this allows us to draw some conclusions about how PlaSim runs differ when SPPT is applied and when it is not.

Preliminary results suggest that the global mean near-surface air temperature anomaly wrt. to the preindustrial period is nearly identical in the ensemble mean of the two experiments, as show in Figure 1. We notice, though, that the hist_s ensemble appears to be slightly colder than the hist_d, and this prompted us to look more closely into the evolution of regional patterns.

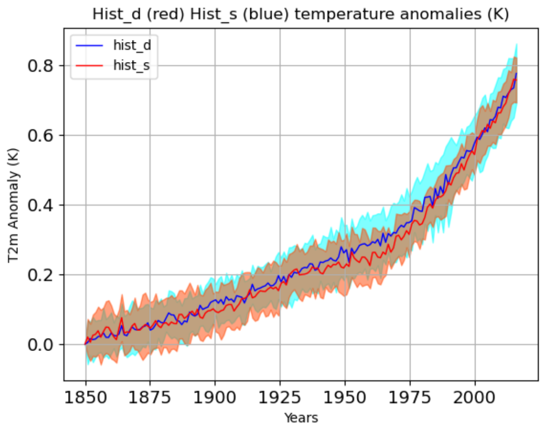

Figure 1:

From Figure 2, we notice that the difference is not spatially homogeneous, with largest differences of opposite sign in the polar regions. This is made clearer in Figure 3, comparing the temperature differences averaged north of 75 N and south of 75 S respectively.

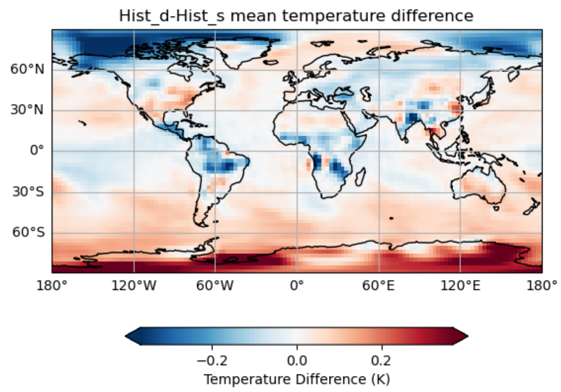

Figure 2: 1850-2014 time-averaged difference of near-surface temperature in the ensemble mean of hist_d minus hist_s.

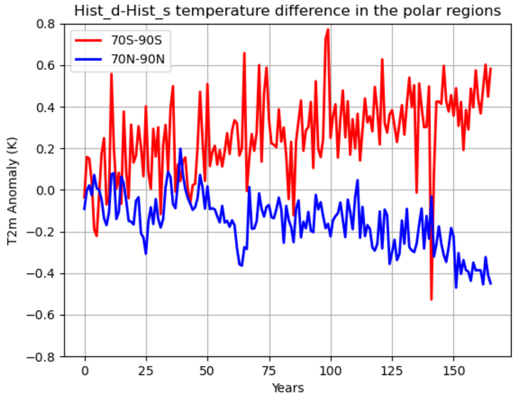

Figure 3: hist_d-hist_s difference of ensemble-mean temperatures poleward of 70S (in red) and 70N (in blue).

Another aspect that is currently under investigation is the role of clouds and precipitation. We know from previous studies (e.g. Strommen et al. 2019) that the inclusion of stochastic parametrizations may result in a decreased climate sensitivity of the model, and that this happens through a change in the low level cloud feedbacks. As those arguments were resulting from a multi-model intercomparison of CMIP-class models, we aim to compare these with what we obtain from PlaSim intermediate complexity model.
This investigation will proceed in parallel with new model simulations aimed at addressing the role of a different atmospheric vertical discretization for the energy conservation of the model. A challenging aspect that we need to investigate is in fact the reason why the energy conservation of the model is deteriorated by the addition of vertical levels, therefore being much worse when run with 15 vertical levels (a total imbalance of +4.5 Wm-2) than with 10 vertical levels. This can potentially affect not only the stability of the model and its climate sensitivity, but also the role of SPPT through a different effect on feedbacks.

On a separate note, we started evaluating the capability to predict the long-term climate response with the linear response theory, given a first order Green's function trivially computed as an output of the xCO2 ensemble. Given some inconsistencies in some 8CO2 runs, we only show years preliminary results about 2CO2 and 4CO2.
Figure 3 shows the ensemble mean evolution of these step forcing experiments along 2000 years, with shadings encompassing all ensemble members. Figure 4 shows the time evolution of the ensemble mean 1000-year long ramp-up experiments until doubling (in red) and quadrupling of pre-industrial CO2 concentrations, respectively. We notice that after 2000 years the system is evolving to its statistically steady state, although the warming is very slow at the end of the run. We also notice that the warming achieved at the end of the 4xCO2 step forcing experiment is less than twice the warming achieved at the end of the 2xCO2 experiment. This is even more evident for the ramp-up experiments (1pct2CO2 and 1pct4CO2, respectively). At the end of the 1% increase period, both experiments still have a substantial pace of warming, that is entirely ascribed to slow (mostly oceanic) feedbacks. Remarkably, the warming in the1pct4CO2 experiment becomes warmer than the 1pct2CO2 already in the ramp-up part of the experiment.
Looking at these plots, we also realized that there was a substantial amount of warming at the beginning of the simulation, that was due to different model settings adopted for the pre-industrial control run and for the ramp-up forced runs. As a consequence, we were forced to adapt the linear response algorithm to reflect this. The predicted evolution of ramp-up experiments is shown in Figures 6-10. We compare the prediction obtained with the Green's function from the corresponding step forcing experiment (i.e. Figures 6a,c for 1pct2CO2 and 1pct4CO2, respectively) and the prediction obtained rescaling the Green's function from the other step forcing experiment (i.e. Figures 6b,d, scaling the Green's function from the 4CO2 and 2CO2 experiments, respectively). We notice that, with the appropriate scaling, it does not matter what is the step forcing experiment used for the computation of the Green's function, to obtain an accurate prediction of the long-term response to a given forcing. This is a signature of the fact that the climate response to forcings of this intensity can be explained through the linear response theory.
Given that the response function retrieved through the Green's function assumes an initial statistically steady state (cfr. Ragone et al. 2016; Lucarini et al. 2017; Lembo et al. 2020), its value is underestimated at the beginning of the simulated period, and in particular during the ramp-up period. Nevertheless, the long-term statistically steady state that is achieved by the system after a sufficiently long time is correctly captured, confirming the relevance of the methodology for the study of the asymptotic climate response (Lucarini and Chekroun, 2023). At the same time, though, additional analyses are required to investigate the initial imbalance of the model and how this can be reduced to increase the performance of the prediction in the transient.

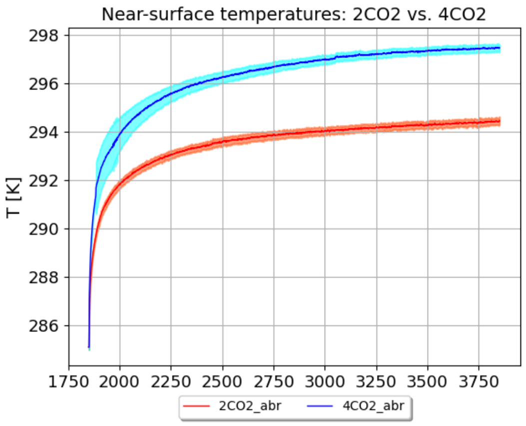

Figure 4: ensemble mean (thick) and ensemble spread (shaded area) of global mean near-surface temperatures for a 2x (in red) and 4x (in blue) step-increase in CO2 concentrations at time t=0 of the simulation, over 2000 years.

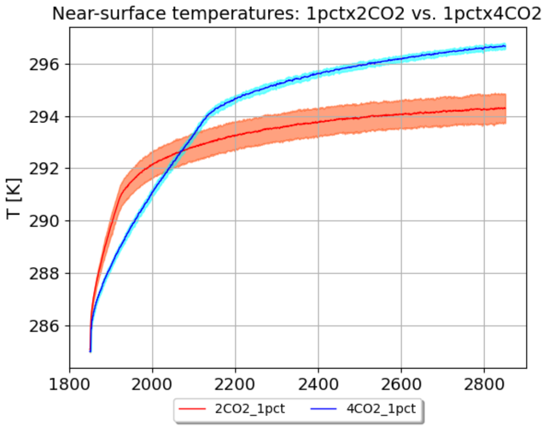

Figure 5: ensemble mean (thick) and ensemble spread (shaded area) of global mean near-surface temperatures for a 2x (in red) and 4x (in blue) step-increase in CO2 concentrations at time t=0 of the simulation, over 1000 years.

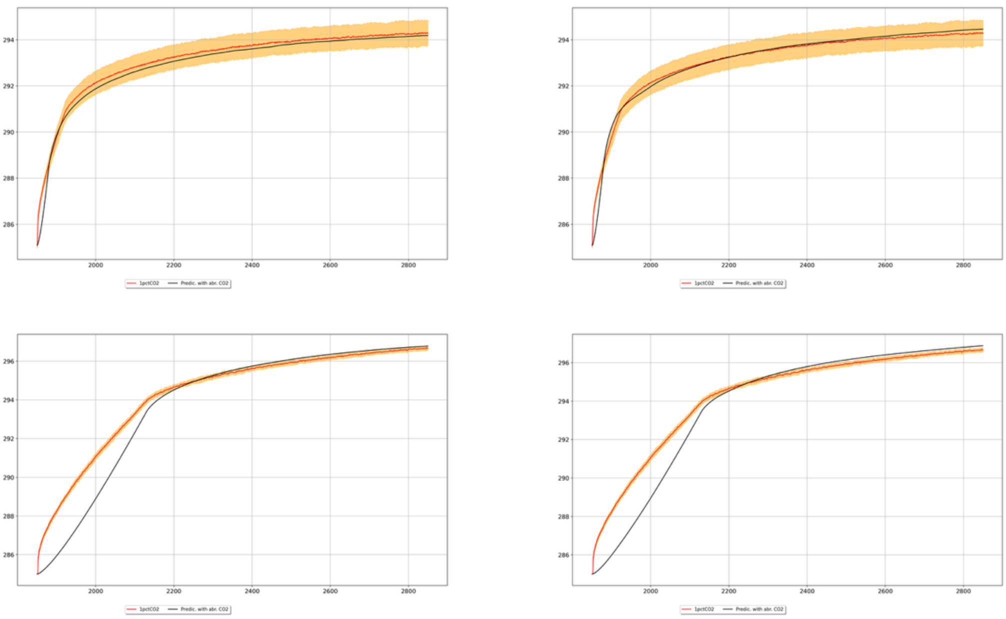

Figure 6: global mean near-surface temperature evolution simulated with an ensemble of ramp-up simulations until (a,b) 2CO2 (c,d) 4CO2, then stabilizing until year 1000 (ensemble mean, thick red line; ensemble spread, orange shading) and predicted via the linear response theory (black solid line). The Green's function computed from the 2CO2 (a,d) and from the 4CO2 (b,c) step forcing experiments (see Figure 4) are used for the linear prediction.

References

- Lembo, V., Lucarini, V. & Ragone, F. Beyond Forcing Scenarios: Predicting Climate Change through Response Operators in a Coupled General Circulation Model. *Sci Rep* **10**, 8668 (2020). https://doi.org/10.1038/s41598-020-65297-2
- Lucarini, V., Ragone, F. & Lunkeit, F. Predicting Climate Change Using Response Theory: Global Averages and Spatial Patterns. *J Stat Phys* **166**, 1036–1064 (2017). https://doi.org/10.1007/s10955-016-1506-z
- Lucarini, V., Chekroun, M.D. Theoretical tools for understanding the climate crisis from Hasselmann's programme and beyond. *Nat Rev Phys* **5**, 744–765 (2023). https://doi.org/10.1038/s42254-023-00650-8
- Ragone, F., Lucarini, V. & Lunkeit, F. A new framework for climate sensitivity and prediction: a modelling perspective. *Clim Dyn* **46**, 1459–1471 (2016). https://doi.org/10.1007/s00382-015-2657-3
- Strommen, K., Watson, P. A. G., & Palmer, T. N. (2019). The impact of a stochastic parameterization scheme on climate sensitivity in EC-Earth. *Journal of Geophysical Research: Atmospheres*, 124, 12726–12740.. https://doi.org/10.1029/2019JD030732
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