REQUEST FOR A SPECIAL PROJECT 2021–2023

MEMBER STATE: United Kingdom

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Project Title: The Impact of Stochastic Parametrisations in Climate Models: EC-EARTH System Development and Application

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** GBTPSP	
Starting year: (A project can have a duration of up to 3 years, agreed at the beginning of the project.)	2021	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2021-2023: (To make changes to an existing project please submit an amended version of the original form.)		**2021**	**2022**	**2023**
High Performance Computing Facility	(SBU)	15,000,000	10,000,000	9,000,000
Accumulated data storage (total archive volume)[2]	(GB)	10000	10000	10000

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.

Principal Investigator: Prof Tim Palmer

Project Title: The impact of stochastic parametrizations in the EC-EARTH climate model

Extended abstract

Introduction

Current global climate models achieve closure of the model equations by explicitly parameterising the unresolved sub-grid scale processes. These processes are not fully constrained by the grid scale flow, so conventional parameterisation schemes aim to represent the bulk effect of these small-scale processes on the resolved flow. A parameterisation scheme involves a conceptual representation of the physics involved, and necessarily introduces simplifications and approximations to represent these complex processes. The deterministic nature of these simplified schemes is typically associated with a lack of sufficient sub-grid scale variability. The resulting uncertainty is the dominant source of error in climate model simulations.

Stochastic schemes in atmospheric models have been used for 20 years as a means of addressing these errors. They provide a way to represent model uncertainty by aiming to represent the variability of unresolved sub-grid scale processes. It has been demonstrated (Buizza et al. 1999, Palmer et al. 2009) that they have a beneficial effect on the spread and mean state for medium- and extended-range forecasts. In recent years, there is growing evidence that stochastic schemes are beneficial also for the long-term climate of a model. Notably, improvements have been reported for the El Nino-Southern Oscillation (Christensen et al. 2017) the Madden Julian Oscillation (Wang et al. 2016), the Indian monsoon (Strommen et al. 2017) and the representation of heat-waves (MacLeod et al. 2016). Very recently, stochastic physics has been found to improve the representation of tropical cyclones to a degree comparable with an increase in horizontal resolution (Vidale et al. 2020; in preparation). In terms of more elementary changes to the model mean state and variability, Strommen et al. (2019a) found that stochastic schemes reduced the common `split intertropical convergence zone' bias in precipitation, as well as notably reducing surface temperature and cloud cover biases. In Watson et al. (2017), the distribution of tropical precipitation extremes was also found to improve, with deterministic models (i.e. models without stochasticity) typically under-representing the frequency of extremes. Stochasticity has even been found to impact on a model's climate sensitivity (Strommen et al. 2019b and Meccia et al. 2020), by modulating cloud feedbacks. A common theme in these last three studies is the crucial role played by non-linear interactions of the stochastic scheme with convective processes, which allow even a mean-zero perturbation to profoundly impact the model attractor.

Much work on the representation and implementation of stochastic parametrisations in ocean models (Brankart et al. 2013), ocean/atmosphere coupling in a coupled atmosphere ocean system (Williams et al. 2012) and ocean ice models (Juricke and Jung 2014) has also been undertaken. Brankart (2013) and Williams (2012) show significant impact of stochastic parametrisations on mean climate. Brankart (2013) investigated the impact of unresolved variability in salinity and temperature on the equation of state and demonstrated that it has a considerable effect on the mean model state in the areas of intense meso-scale activities. Williams (2012) showed that there is a significant impact of stochastic perturbations in air-sea fluxes on mixed layer depth and the variability of ENSO. Juricke and Jung (2014) found that stochastic parametrisation in a sea ice model behaves differently in coupled and uncoupled systems. In a coupled system, stochastic parametrisation led to a redistribution of the thickness of the Arctic sea ice volume, whereas in an uncoupled simulation it led to ice volume increase.

Summary of previous incarnation of the project

The last incarnation of this project was mostly taken up with the generation and analysis of a suite of ensemble simulations with various stochastic schemes (developed in earlier cycles of this Special Project), as part of a contribution to the PRIMAVERA Horizon 2020 Project. Using the units from the project, we ran 3-member ensembles covering 1950-2015 (the hist-1950 PRIMAVERA protocol) with the following configurations of EC-Earth3P: CTRL (default deterministic EC-Earth), SPPT (with the standard SPPT scheme), OCE (with stochastic ocean and sea-ice schemes), FESM (with SPPT, stochastic ocean and sea-ice schemes and the stochastic H-Tessel land-scheme developed by D. MacLeod in a previous version of this special project) and PESM (with the new ISPPT scheme developed by Hannah Christensen in a previous version of this project, stochastic ocean and sea-ice and the stochastic H-Tessel scheme). All these were coupled, representing the first test of all of these configurations (save SPPT) in long, coupled simulations. One member of each ensemble was further integrated out to 2050. The simulations were all at spectral resolution T255, 91 levels, and a 1 degree, 75 levels in NEMO.

The FESM and PESM configurations were particularly noteworthy as they represent the first attempt at running EC-Earth with a stochastic scheme added to all the major components: atmosphere, ocean, sea-ice and land. While the benefits of this `full stochasticity' were broadly positive, some surprising impacts were also found. In the PESM configuration, run first, it was found that while it significantly improved mean-state and variance biases, the ENSO in the model became extremely strong and excessively periodic. This prompted the follow-up ensemble FESM, which was found to have a more modest impact on the global mean/variance, but a much better representation of ENSO. The FESM configuration therefore represents the first stable example of the Probabilistic Earth-System Model envisaged in Palmer (2012).

Results from the analysis carried out on these schemes and further details of the simulation process can be found in the most recent spgbtpsp Special Project report.

Objectives for the Project renewal

We have 6 big goals we wish to tackle in this project renewal. These can be summarised as follows:

1. Improve our understanding of the impact of stochastic schemes on climate feedbacks and climate sensitivity in EC-Earth by generating abrupt-4xCO2 simulations;
2. Tune the Independent SPPT scheme (ISPPT) to have more realistic ENSO's and thereby obtain a much more flexible variant of the Probabilistic Earth-System Model with greater improvements to the climate mean state and variability;
3. Implement an improved 'humidity fix' to SPPT (and ISPPT) which makes the scheme more physically consistent without the need for a global mass fix;

4. Understand how stochastic schemes alter the representation of Euro-Atlantic weather regimes using long pre-industrial control simulations with/without stochastic schemes;
5. Understand how the improved teleconnection from Arctic sea-ice to the NAO when turning on stochastic sea-ice/ocean schemes influences projections of European climate change using transient and abrupt forcing scenarios;
6. Explore the creation of adding a stochastic component to the cloud microphysics component of the model.

Some of this work (points 1 and 3) is already underway in the final year of the current Special Project, but would be continued onwards in the renewal. We briefly justify each point of investigation now.

For 1), the paper Strommen et al. (2019b) first looked at the impact of SPPT on climate sensitivity, showing a robust reduction in the transient response between 1850 and 2100, amounting to a reduction in transient sensitivity of around 10% compared to the deterministic model. This was attributed to a change in cloud feedbacks. However, a follow-up study, Meccia et al. (2020), which extended the EC-Earth integrations used (from the Climate SPHINX Project) out to 2160, found a change in the transient response following the year 2100, with the net result being that SPPT seemed to have a somewhat *higher* sensitivity: see Figure 1. Again, cloud feedbacks were implicated as important; in Strommen et al. (2019b) it was low and mid-level clouds that were key up to the year 2100 (with high level clouds playing little/no role), while in Meccia et al. (2020), high level clouds were found to exert a dominant impact in the following 60 years. This puzzling situation points to non-linearities in either the climate response of the deterministic EC-Earth, the impact of SPPT on climate feedbacks, or both, and leaves open the question of what the outcome would be if the model were run to equilibrium. We aim to tackle this question by performing a robust abrupt-4xCO2 simulation (including the corresponding spin-up and pre-industrial control) with a selection of stochastic EC-Earth configurations. By letting the model run to equilibrium and analysing the explicit feedbacks with a radiative kernel method, we aim to resolve the question of how SPPT impacts on climate sensitivity. We will be using the CMIP6 version of EC-Earth3 to take full advantage of the fact that the control (deterministic) simulation for comparison has already been generated for the 6th IPCC Report: this data is freely available on the CMIP6 ESGF.

The motivation of 2) is clear, in that ISPPT had by far the best impact on the mean and variance of the model (as detailed in earlier reports), with its only obvious limitation being its poor ENSO performance. Analysis of the ISPPT ensemble members suggests that the presence of excessive ENSO events is clearly visible within the first 20 years of simulation. Tuning the scheme to have more realistic ENSO events will therefore require a number of 20 year simulations to assess the impact of parameter changes.

For 3), work by other members of our research group and colleagues abroad (Prof. Aneesh Subramanian in particular) has led to the creation of a better way to fix the issue of lack of water-conservation in SPPT (and ISPPT). This amounts to adding perturbations also to the surface level water fluxes (precipitation and evaporation). It has been tested to work in some cycles of the IFS, but not in the current version of EC-Earth3. We aim to implement this fix to the latest version of EC-Earth3. In order to understand its potential impact on results concerning climate sensitivity (discussed above) we will also be performing an abrupt-4xCO2 run with SPPT and this new fix on to untangle any impact the earlier global mass fixer may have been having.

For 4), understanding changes on weather regimes with SPPT in climate models has been hampered for a long time by the large amount of internal variability exhibited in coupled simulations and the lack of sufficient ensemble members to overcome this. Recently developed techniques (Dorrington and Strommen 2020) suggest that these difficulties stem from the large decadal variability in the speed of the North Atlantic eddy-driven jet, which projects strongly on the Euro-Atlantic circulation. Performing clustering algorithms after this influence has been removed results in regimes that are significantly more stable across centennial timescales; this technique, along with the now substantial number of ensemble members (across both Climate SPHINX and PRIMAVERA) will allow us to address this question. We will also be crucially utilising the long pre-industrial control simulations generated for the abrupt-4xCO2 simulation experiments (discussed above) in order to robustly account for internal variability and the impact of greenhouse forcing.

The motivation for 5) comes from two results. The first is discussed in the latest Project Report: the deterministic EC-Earth shows no real teleconnection between Arctic sea-ice and the North Atlantic Oscillation (NAO), unlike what is observed in reanalysis (e.g. Koenigk et al. 2008). However, turning on the stochastic sea-ice and ocean schemes leads to the emergence of a statistically robust teleconnection, concomitant with improved mean and variance of the Arctic sea-ice field itself. The second result is from analysis in Meccia et al. (2020) using SPPT, showing that stochastic schemes can change the timing of abrupt sea-ice decline in transient forcing scenarios. These two suggest that stochastic schemes may have a big impact on regional climate change projections over Europe, which we aim to understand better through transient runs: concretely, we aim to compare coupled deterministic simulations with coupled stochastic simulations to understand changes in future projections, and with AMIP-style simulations (i.e. with prescribed sea-ice conditions) to understand the extent to which atmospheric variability influences the results.

The 6th objective is deliberately left open-ended and exploratory. It is known that cloud microphysics schemes substantially influence climate projections, as has become even clearer in the latest CMIP6 projections, where cloud microphysics has been implicated in the overall increased climate sensitivity compared to CMIP5. It is therefore of interest to represent the uncertainty associated in the microphysics scheme via stochastic methods. Conversations on this topic and how such schemes may be created are underway with colleagues at NCAR, including Prof. Berner and Prof. Gettelman.

Proposed Integrations and Unit Estimation

The last CMIP6-generation version of EC-Earth3 (namely version 3.3.3) in its standard resolution is intended to be applied. It consists of T255 L91 for IFS and ORCA1L75 for NEMO. Unit estimates are based on experience from experiments conducted already with the same configuration, suggesting that 1 model-year costs approximately 19000 SBU’s; adding a stochastic scheme increases this cost by at most 4%.

Storage space is estimated based on experience from the PRIMAVERA simulations, and is mostly there for the temporary storage of raw model output while CMOR-ization algorithms are run and then validated for errors. Data will be deleted from tape on an annual basis to stay within targets.

Year 1 will be devoted to the abrupt-4xCO2 simulations. An abrupt-4xCO2 simulation requires at least 50-year spin-up, followed by a pre-industrial control and abrupt-4xCO2 scenario both lasting 165 years each, adding up to ~7 million SBUs. In order to test 2 configurations (SPPT+the old global mass fixer and SPPT+the new humidity fix), we therefore require ~14 million SBUs, which we round up to 15 million to account for leeway and the small extra cost of the stochastic schemes.

Year 2 will be dedicated to tuning ISPPT and running standard CMIP6 simulations with the improved PESM configuration (tuned ISPPT, stochastic ocean/sea-ice and stochastic H-Tessel). Running a historical, future and pre-industrial scenario is estimated to require around 250-300 model years (depending on the length of the pre-industrial control). We estimate around 240 model years in addition for tuning a coupled model and checking its ENSO periodicity (since it takes around 20 model years to robustly assess changes to ENSO, as discussed earlier), adding up to around 500 simulated years. The cost of this is rounded to an even 10 million SBUs.

Year 3 is devoted to the further testing of how stochastic sea-ice and ocean schemes impact on climate change projections in the mid-latitudes, as well as exploratory simulations of a stochastic cloud microphysics scheme. For the former, we currently plan to do transient runs between 2000 and 2160 in an RPC8.5-equivalent scenario, in order to capture the full decline in Arctic sea-ice and subsequent changes in mid-latitude circulation (with the year 2160 estimated based on Meccia et al. 2020). Because Arctic signals are well-known to be noisy, we anticipate the need to add extra ensemble members, and therefore estimate the need for ~300 model years in total.

For the stochastic cloud microphysics experiments, we estimate 100 model years for tuning purposes and assessment over a historical period, and a further 100 years to assess future changes in a transient high-forcing scenario.

We therefore estimate around 500 model years to be sufficient to cover all desired experiments, rounded down to 9 million SBUs.

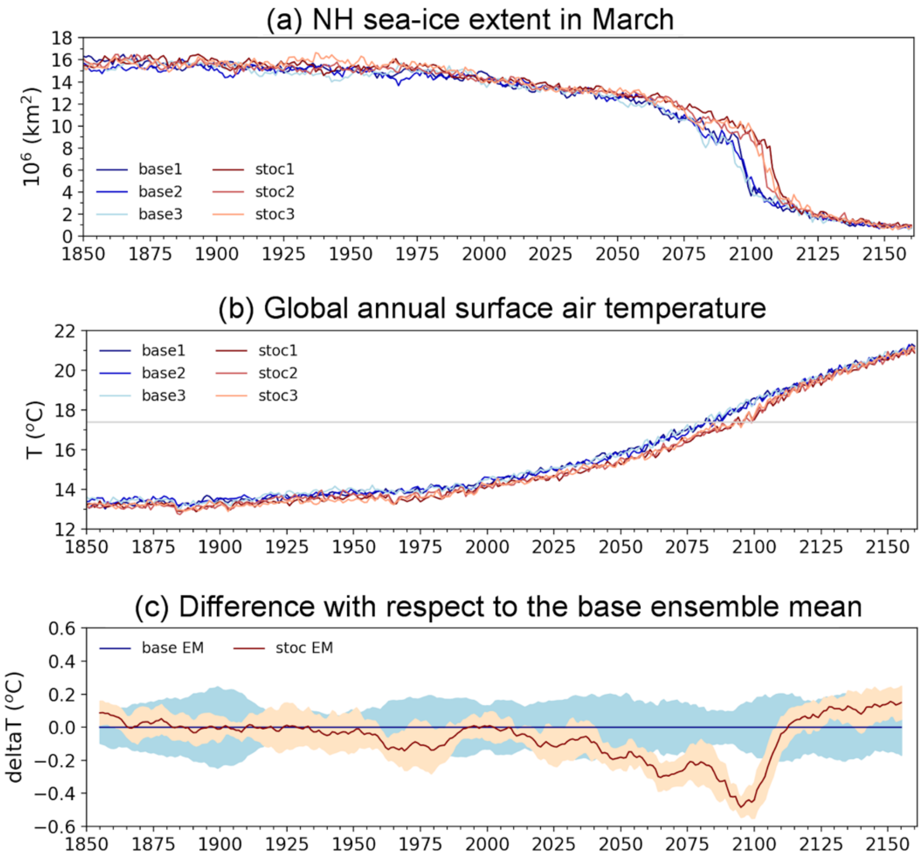

Figure 1: From Meccia et al. (2020). The evolution of 3 deterministic EC-Earth ensemble members (base1 to 3) and 3 members with SPPT turned on (stoc1 to 3). In a) for Northern Hemisphere sea-ice extent in March, b) for global mean temperatures and c) differences in ensemble mean global temperatures. Note the change in behaviour from 2100 onwards.

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