SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Impact of atmospheric stochastic physics in high-resolution climate simulations with EC-Earth
Computer Project Account:	spitvonh
Start Year - End Year :	2016 - 2018
Principal Investigator(s)	Jost von Hardenberg
Affiliation/Address:	Institute of Atmospheric Sciences and Climate, National Research Council (ISAC-CNR), Italy
Other Researchers (Name/Affiliation):	ISAC-CNR: Paolo Davini, Susanna Corti, Elisa Palazzi, Chunxue Yang Oxford University: Antje Weisheimer, Kristian Strommen, Tim Palmer

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

In this special project we explored the impact of Stochastic Physics (in the atmosphere) in long climate integrations with the EC-Earth model as a function both of model resolution and stochastic parametrizations in coupled and uncoupled configurations. Particular attention has been placed on tuning of the model EC-Earth model and on checking energy and mass conservation of the SPPT atmospheric stochastic parameterization for climatic applications, with the goal of reaching a realistic representation of the main radiative fluxes and conservation of energy and humidity in the atmosphere.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

No particular issues related to the ECMWF computing environment. The rapid development of the EC-Earth model in recent years, particularly in preparation of CMIP6 has required periodic adaptation of our run scripts in order to maintain them aligned with the default EC-Earth job templates and frequent model changes (due to bug fixes and implementation of CMIP6 forcings) have required several and frequent retuning of the model.

Experience with the Special Project framework

The current progress reporting scheme and the online interface to submit reports, together with friendly periodic email reminders of important deadlines work well and make it easy to prepare and submit reports.

Summary of results

Model tuning and development

The timeframe of the project (2016-2018) coincided with the intense and rapid development of the EC-Earth model in preparation for CMIP6 in the past years, leading to the currently released version 3.3 of EC-Earth, an activity to which this project contributed significantly. In particular the following model developments related to tuning were implemented in the framework of SPITVONH and explored with dedicated model experiments.

- *Energy and mass conservation in the SPPT stochastic physics scheme*

Part of the tuning activities have focused on the specific case of stochastic physics: the standard SPPT and SKEB schemes were designed for use at NWP timescales. When implemented in a climate model, the original SPPT scheme was found to systematically reduce humidity in the atmosphere which was compensated by overly strong evaporation. The global P-E imbalance in the stochastically perturbed simulations was increased by a factor of 10 to approx. -0.16 mm/day. This led to substantial imbalances in the whole climate system, in particular to significant changes in the radiative balance. In T255L91 simulations the failure to conserve humidity alone had a significant impact on the energy budget (a loss of about 4.2 W/m2). Additionally, energy was found not to be conserved in the SPPT scheme when applied to temperature, leading to an excess energy production of about 2.2 W/m2. In fact the SPPT scheme was not designed specifically to conserve water vapour, leading to a water vapour sink in the atmosphere.

We developed a fix, requiring that the global average of relevant stochastic parameterization tendencies (i.e. winds, temperature and more importantly specific humidity) before and after the SPPT perturbation are conserved, applying a global correction. To constrain the global average perturbed tendencies by the unperturbed ones, the difference of tendencies before and after SPPT is distributed based on the amplitude of the local change in tendency due to SPPT. This results in a redistribution of the perturbed tendencies such that the global net average change between the perturbed and unperturbed tendency is zero.

The new scheme removes the imbalance in P-E, which is now the same as in runs where the SPPT scheme is disabled. Fig. 1 reports shows the improvement in the P-E imbalance in a 10-year long run. The fix has been included in the EC-Earth trunk in release 3.2.1, after careful testing. The fix guarantees that the global average of the tendencies (i.e. winds, temperature and more importantly specific humidity) before and after the SPPT perturbation are conserved. In particular, runs in the historical period showed that the inclusion of the scheme does address the imbalance of precipitation minus evaporation, which is now the same as for EC-Earth without stochastic physics. Further it was found that the inclusion of the scheme did not meaningfully alter the overall energy balance. Computing difference between the TOA energy balance and surface energy balance provides the same averages for deterministic runs and for runs using the SPPT fix.

This activity has led to further work by the PI of this project (reported in Lang et al. 2016) to implement the same SPPT fix also in a recent cycle of IFS. Development was performed on cy41r1 and the fix was later included in cy43r1.

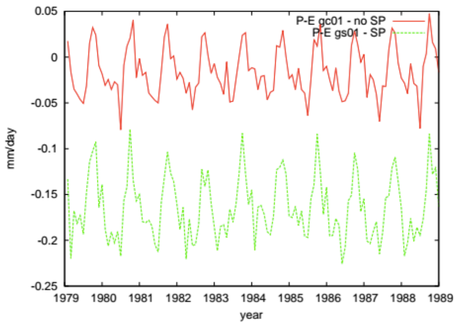

Figure 1: *Precipitation-Evaporation imbalance in SPPT runs with (red) and without the SPPT fix discussed above.*

- *Non-orographic gravity wave drag*

Further tuning has been performed in project in order to produce a realistic Quasi-Biennial Oscillation (QBO) also at higher resolutions. The EC-Earth 3 non-orographic gravity waves scheme is characterised by a momentum flux that is continuously launched at in the mid-troposphere to simulate the effect of gravity waves. The latitudinal profile of this momentum flux governs the correct parameterisation of gravity waves: a too high amplitude of the momentum flux will disturb the QBO in equatorial zones, particularly at high resolutions, while a too low value will lead to unrealistic eddy-driven jets, especially in the southern hemisphere, where orographically induced wave drag is low. With the current latitudinal profile, the QBO was simulated only at standard resolution (T255 with 91 vertical levels). Following advice from ECMWF staff, a resolution-dependent parameterisation of non-orographic gravity wave drag replaced the version-dependent parameterisation present in EC-Earth 3. Namely, instead of using a low momentum flux average value (GFLUXLAUN=0.02) with a positive Gaussian peak at 50°S, we use a higher value (GFLUXLAUN=0.0375) which is reduced with a Gaussian shape at the equator. This negative peak is slightly deeper for stochastic runs than for deterministic simulations to compensate the effect of the stochastic noise. The average value of the momentum flux was further reduced with increasing resolution (starting from T799) according to the ECMWF specification for IFS cy40r1. The new non-orographic gravity wave scheme allows the simulation of the QBO also at higher resolutions, without deteriorating the jet streams (see Fig. 2). Please see Davini et al. 2017a for more details.

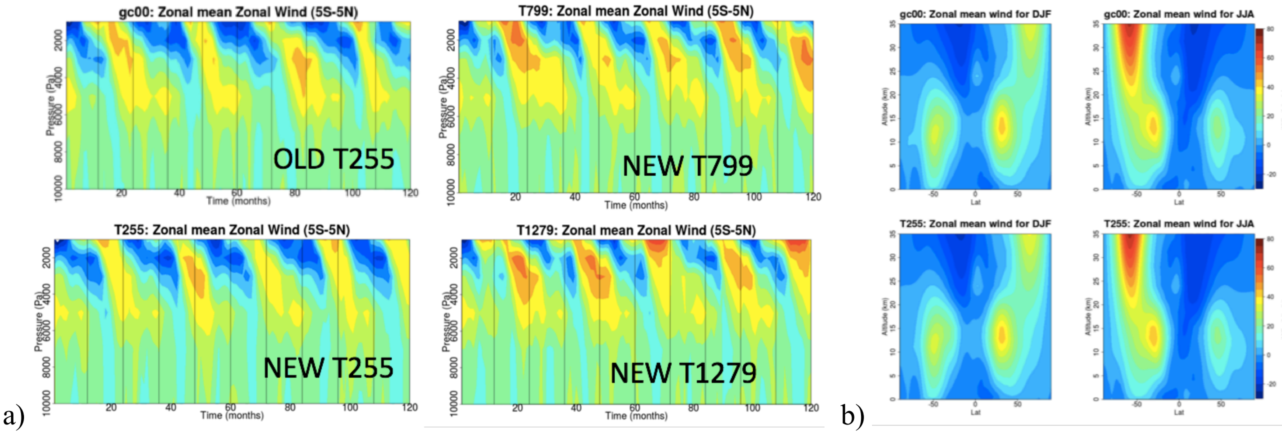

Figure 2: *Improved representation of the QBO in the model at different resolutions. Panel a) shows equatorial mean zonal wind profiles at different model resolutions. Panel b) shows that the changes do not affect significantly the model zonal mean winds.*

- *Coupled model energy and mass conservation*

The original coupled model at the start of the project (3.2.1) was found to not be energy conserving. More specifically, we found a strong mismatch between the net surface heat flux computed from IFS and the heat the ocean was actually receiving, as revealed both by the integrated change in ocean heat content and by the output diagnostic files written by NEMO. In particular, at standard resolution, NEMO was found to be receiving 1.04 W/m2 (as an average over the ocean only) more than what actually sent by IFS (as recorded in its diagnostic output files). High-resolution runs showed an even worse mismatch of about + 3W/m^2. A detailed investigation of this issue required several coupled runs over periods of 20 years. In particular it was possible to break down this imbalance into individual contributions due to different effects. +1.6 W/m^2 were found to be associated with the non-solar flux (STR+SLHF+SSHF). Investigation revealed in particular a problem associated with the longwave flux sent by IFS to NEMO (the sum of the tile-specific fluxes did not correspond to the total grid-cell average assumed by IFS). Consultation with ECMWF has permitted to identify the problem, which had been corrected in recent cycles of IFS. Backporting from cy41r2 the relevant fix has allowed to resolve this particular problem.
The particular choice of conservation options used for OASIS (multiplicative conservation, GLBPOS, vs. additive conservation- GLOBAL) was responsible for an additional small difference of +0.09 W/m^2 for the solar component of the radiative flux. In the end GLBPOS was adopted as an option for all radiative fluxes.
Finally, also through discussion with the NEMO developers, it was verified that, in addition to geothermal heating (a source of about 0.065 W/m^2), since NEMO takes into account the heat content associated with the temperatures of rainfall, evaporation and runoff, and since IFS does not take into account of these effects, a sink of energy in the oceans results, equivalent to -0.23 W/m^2 (for T255L91/ORCA1L75). It was decided to simply acknowledge the existence of this issue in the coupled system, in keeping with the strategy adopted also by other CMIP modeling groups.

The original coupled ocean-atmosphere system (3.2.0) was further found to present a very unrealistic freshwater deficit (about 0.06 m per year). Investigation of the issue allowed to identify a series of problems in the NEMO coupling interface related to river runoff and sublimation. Additionally, it was found that there was a problem in the sublimation over ice calculated by IFS and sent to NEMO Fixing these issues allowed to recover an excellent mass-conservation in the coupled system. A remaining imbalance associated with a global average Evaporation – Precipitation imbalance in the atmosphere (about -0.016 mm/day) has been fixed adjusting the river runoff flux to compensate.

- *Model radiative imbalance*

Successive versions of the EC-Earth model had been tuned to take into account the availability of updated CMIP6 forcings, including updated CMIP6 GHG concentrations, solar forcing and the MacSPv2 simplified aerosol forcing and changes and bug-fixes in model physics. We have attempted to maintain at all times a well-tuned version of the model after each change and, where possible, to establish the impact of the changes in terms of global energy fluxes, also in model versions with stochastic physics and at high resolution. The tuning

strategy aimed at achieving realistic equilibrium temperatures in long forced fixed-year runs and realistic temperatures and radiative fluxes in transient present-day runs, particularly in AMIP experiments.
Using the sensitivities to a set of atmospheric tuning parameters (mainly convective and cloud-related parameters), it has been possible to prepare several new improved tuning parameter sets by "simulating" their impact in terms of radiative fluxes, even before performing actual runs. The already known sensitivities of an initial set of tuning parameters have later been integrated with additional tuning parameters (such as RCLDIFF – mixing coefficient for turbulence - which has a significant impact on cloud cover, or RLCRIT_UPHYS which controls the radiative impact of secondary cloud effects). To this end, sensitivities have been determined using a series of short (6 years) AMIP runs. A series of short test runs (20 years each) with each new estimated parameter set has allowed to rapidly converge onto improved tuned versions of the model, which show, for transient present-day runs, realistic surface energy fluxes and cloud forcing.

In coupled runs the climate sensitivity estimated from previous long coupled runs has been used to estimate equilibrium temperatures based on current net surface fluxes and mean global temperature and to suggest tuning corrections (using so-called Gregory plots). Using resources from this project, in addition to EC-Earth tuning performed in other projects (SPNLTUNE), additional tuning effort has been dedicated to model changes related to the parameterization of background surface albedo as a function of vegetation cover, the impact of different past, present and future land vegetation covers, sensitivity to different boundary and initial conditions, in particular orography, the implementation of stratospheric aerosol forcing, fixes in atmosphere-ocean coupling and energy conservation issues and the impact of different cloud activation scheme.

Model energy fluxes and cloud cover are resolution dependent, so that the high-resolution model version required a separate tuning, also in AMIP runs. Using the same parameter sensitivities measured at low resolution, and through a series of short runs (5/6 years each), we were able to develop a new set of atmospheric tuning parameters for the T511L91 model version. The runs were performed for anthropogenic forcing conditions in the year 1950 (of interest for the HighResMIP protocol and late used for simulations in the H2020 PRIMAVERA project).

Finally, a series of tuning runs have been performed in collaboration with Oxford University aimed at tuning the model when the SPPT stochastic physics scheme is active. Tuning was necessary since SPPT leads to significantly reduced net surface energy fluxes (a contribution of the order of -0.8 W/m2). Use of the same climate sensitivities measured for the standard low-resolution model allowed to estimate rapidly an improved set of atmospheric tuning parameters, confirmed by a series of short AMIP simulations over a few decades of years.

Impact of the Stochastic Physics on ENSO in past and future coupled simulations

We evaluated the impact of stochastic physics in past-to-future (PFC) simulations with IFS at the T255L91 configuration, coupled with NEMO using the ORCA1 grid (a tripolar grid with resolution of 1 longitudinally and refinement to 1/3 at the Equator) with 46 vertical levels. Six ensemble members were run, three with the stochastic parameterisation active and three control members without stochastic parameterisation, from 1850 to 2100 (from 2005 to 2100 the forcing is consistent with the RCP8.5 scenario). The Stochastic Physics schemes used in the Atmospheric component of the EC-Earth Model are the same used in the operational ECMWF Seasonal Forecast System (System 4).

The PFC experiment consisted of six ensemble members: three ensemble members use stochastic physics schemes in the atmospheric component of the EC-Earth Model (STO_PHY); three ensemble members were run without including stochastic physics (CTRL). In our analysis we tried to assess the impact of stochastic physics on ENSO simulations and discuss the mechanisms leading to such an impact. The main motivation of this analysis was the result by Christensen et al. 2017, where it is shown that the use of the multiplicative Stochastically Perturbed Parameterization Tendencies (SPPT) scheme in the Community Atmosphere Model (the atmospheric component of CCSM4) improves significantly the ENSO power spectrum by reducing the excessive power at periods of three-four years and increasing the power with periods less than three years.

By comparing an ensemble of three members of control historical simulations with three ensemble members that include stochastic physics in the atmosphere, we find that the implementation of stochastic physics in the atmosphere improves the excessively weak representation of ENSO in EC-Earth. Specifically, the amplitude of both El Niño and, to a lesser extent, La Niña increases (Fig 3i).

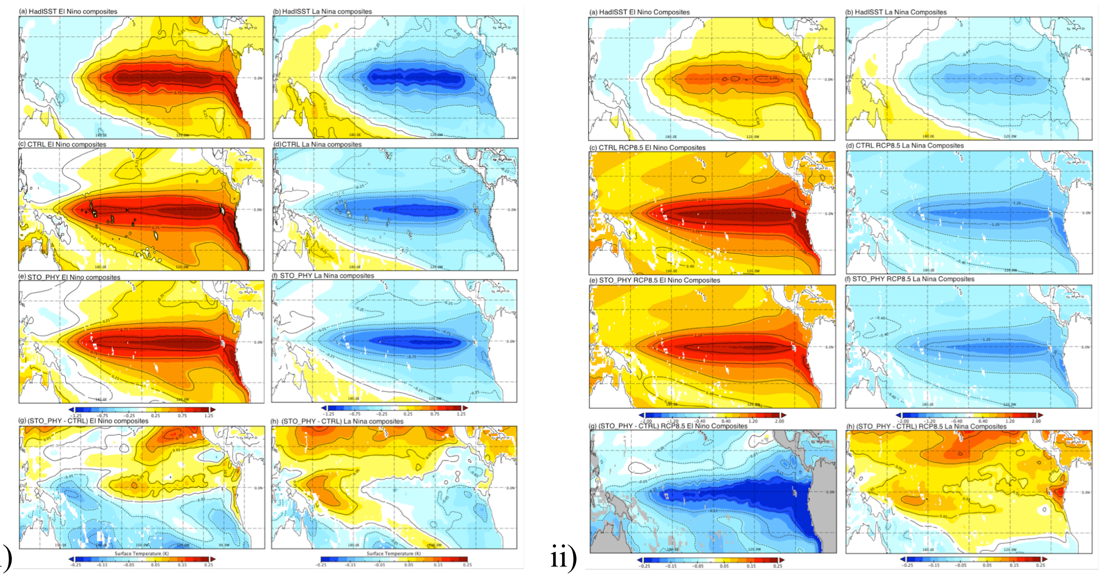

Figure 3: *i) Sea Surface Temperature (SST) composites (1870-2005) of El Niño events in (a) HadISST1 (c) CTRL and (e) STO_PHY runs and composites of La Niña events in (b) HadISST1, (d) CTRL and (f) STO_PHY runs. ii) As panel i) but for CTRL_RCP8.5 and STO_PHY_RCP8.5 and HadISST1.*

Stochastic physics ameliorates the temporal variability of ENSO at interannual time scales, demonstrated by the emergence of peaks in the power spectrum with periods of 5-7 years and 3-4 years (Fig 4a).

The impact of stochastic physics on the amplitude of ENSO in EC-EARTH is opposite to that found on CCSM4 and shown in Christensen et al. 2017. However, in both cases the inclusion of stochastic physics in the atmospheric component of the coupled model seems to lead to an improved representation of ENSO variability and amplitude. This apparent "paradox" can be explained by analogy with an idealized Delayed Oscillator (DO) model with stochastic noise. In the DO model stochastic perturbations increase the ENSO amplitude when the atmosphere-ocean coupling is weak, while they decrease the ENSO amplitude when the atmosphere-ocean coupling is strong. The "weakness" of the power spectrum in the EC-Earth CTRL suggests that this model might fit in the weak coupling "category". (While the prominent power spectrum in CCSM4 suggests that CCSM4 might fall in the strong coupling "category"). This would imply that a too weak atmosphere and ocean coupling might be responsible for the underestimated ENSO variability in the EC-Earth control runs.
The stochastic physics in the atmosphere increases Westerly Wind Burst (WWB) occurrences (i.e.

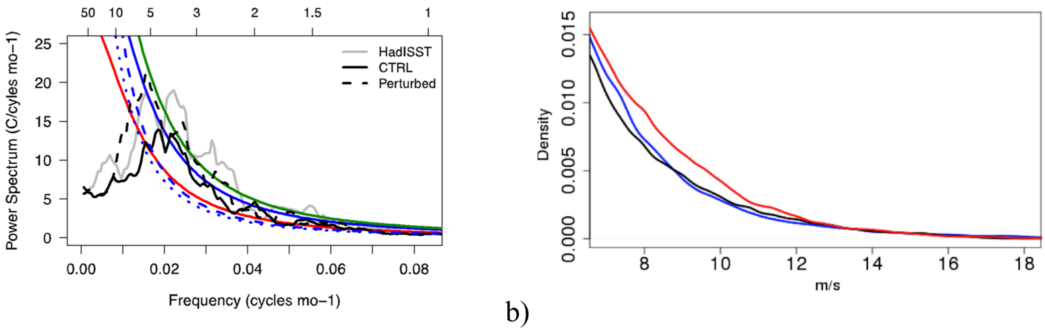

***Figure 4**: a) The power spectrum of the Niño 3.4 timeseries in ensemble mean CTRL (solid black), ensemble mean STO_PHY (dashed black) and HadISST1 (grey). The best fit AR(1) spectrum (red) and its 95% (blue) and 99% (green) confidence bounds for HadISST. Dashed and dotted blue lines are the 95% confidence bounds for STO_PHY and CTRL; b) The distribution of U850 (westerly wind) anomalies (m s^{-1}) from the ERA-Interim dataset (black), ensemble mean CTRL (blue), and ensemble mean STO_PHY (red). The data are first smoothed using a 5-day running mean and low frequency variability (over 1 year) is filtered, and the PDFs are constructed using all spatial points between 5N and 5S and between 130E and 260E.*

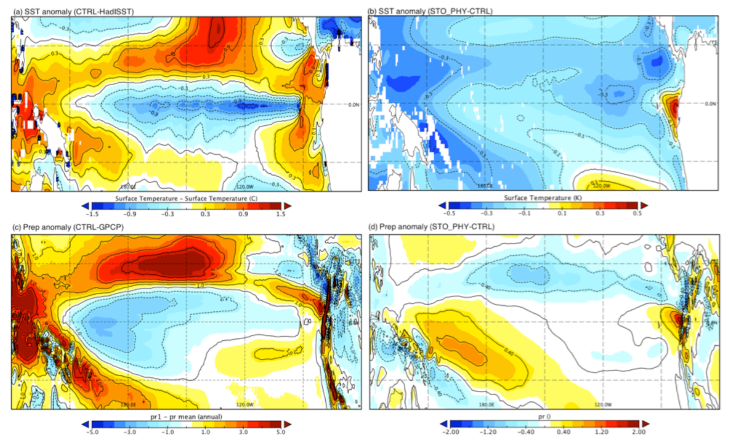

Figure 5*: (a) The SST bias (CTRL-HadISST1) in EC-Earth and (b) the SST difference between STO_PHY and CTRL. Unit is °C (c) The precipitation bias (CTRL-GPCP) and (d) the precipitation difference between STO_PHY and CTRL. Units: mm/day.*

amplification of noise amplitude) that would trigger more and stronger El Niño events (i.e. increase of ENSO oscillation) in the coupled EC-Earth model (see Fig. 4b). Further analysis of the mean state bias of EC-Earth suggests that a cold SST and dry precipitation bias in the central tropical Pacific together with a warm SST and wet precipitation bias in the western tropical Pacific are responsible for the coupled feedback bias (weak coupling) in the tropical Pacific that results in the weak ENSO simulation in EC-Earth (Fig. 5).

In order to strengthen the argument that the mean state is one of the possible reasons for the deficiency of ENSO simulation in climate coupled models, the same analysis was performed considering the impacts of stochastic physics on ENSO with future scenario coupled runs. The future scenario runs (CTRL_RCP8.5) are forced following the RCP8.5 scenario thus simulating a global warming world. Therefore, these EC-Earth simulations can be treated as if they were performed using a coupled model with an even larger mean state bias with much warmer SST anomalies compared to historical experiments. In CTRL_RCP8.5 the amplitude of both El Niño (Figure 3ii,c) and La Niña (Figure 3ii,d) is stronger than the CTRL historical experiments. With stochastic physics, the amplitude of El Niño decreases significantly but the amplitude of La Niña decreases less, as shown for historical experiments.

The change of the temporal variability of ENSO is shown in Figure 6 for CTRL_RCP8.5, STO_PHY_RCP8.5 and HadISST1. CTRL_RCP8.5 has sharp and narrow ENSO power spectrum: applying stochastic physics the power spectrum decreases for the time period between 3 to 4 years.

Overall the impact of stochastic physics on ENSO behaviour in the EC-Earth RCP8.5 scenario is the opposite to that seen in historical experiments. Indeed, in the "climate change" simulation the impact of stochastic physics on ENSO is somehow in agreement with that found by Christensen et al. 2017 (doi:10.1175 /JCLI-D-16-0122.1) in the CCSM model.

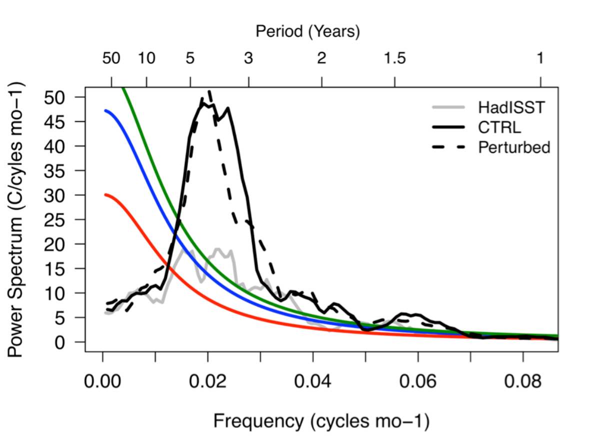

Figure 6*: As Figure 2 but for CTRL_RCP8.5 (black solid), STO_PHY_RCP8.5 (black dashed) and HadISST1 (grey solid).*

The above results suggest that the impact of stochastic physics on ENSO for the EC-Earth model depends on the mean state. When a different external forcing is applied to the EC-Earth model, the mean state changes accordingly and this leads to an almost reverse outcome when stochastic physics is included.
The details of the mechanisms that explain how the stochastic physics affect ENSO are clearly dependent on the biases of the coupled climate models, especially on the coupled feedback in the tropical Pacific. The representation of unresolved sub-grid scale variability through stochastic physics schemes can interact with the resolved scales improving low frequency aspects of the simulated climate. These results are described in more detail in the paper Yang et al. 2019.

Further scientific results

Analysis of recent EC-Earth model runs, in part performed in the framework of this special project, has allowed to develop scientific studies on a wide range of topics. In particular, 2017 saw the publication of the paper Davini et al 2017a, in which, analysing a large set of high-resolution simulations we found an improvement in the simulation of Euro-Atlantic atmospheric blocking following resolution increase. The same paper also showed that including stochastic parameterisation in the low-resolution runs helps to improve some aspects of the tropical climate – specifically the Madden–Julian Oscillation and tropical rainfall variability.
These findings have been further explored more in detail in two follow-up papers. In Davini et al. 2017b we find that increasing resolution leads to a negligible bias in blocking frequency over Europe when resolution reaches or exceeds 40km. A combined effect by the more resolved orography and by a change in tropical precipitation is identified as the source of an upper tropospheric planetary wave. At the same time, a weakening of the meridional temperature gradient reduces the upper level baroclinicity and the zonal mean winds. Following these changes, in the high-resolution configurations the Atlantic eddy-driven jet stream is weakened and less penetrating over Europe. This favours the breaking of synoptic Rossby waves over the Atlantic ridge and thus increases the simulated European blocking frequency. However, the Atlantic jet stream is too weak and the blocking duration is still underestimated, suggesting that the optimal blocking frequencies are achieved through a compensation of errors.
In Watson et al. 2017, the impact on the statistics of tropical rainfall of the stochastically perturbed parameterization tendency scheme (SPPT) and of the stochastic kinetic energy backscatter scheme (SKEB) were evaluated. The schemes generally improve the statistics of simulated tropical rainfall variability, particularly by increasing the frequency of heavy rainfall events, reducing its persistence and increasing the high-frequency component of its variability.

List of publications/reports from the project with complete references

- Yang, C., Christensen, H. M., Corti, S., von Hardenberg, J. and Davini, P. (2019). The impact of stochastic physics on the El Niño Southern Oscillation in the EC-Earth coupled model. *Climate Dynamics* https://doi.org/10.1007/s00382-019-04771-8
- Watson, P. A. G., J. Berner, S. Corti, P. Davini, J. von Hardenberg, C. Sanchez, A. Weisheimer, and T. N. Palmer (2017). The impact of stochastic physics on tropical rainfall variability in global climate models on daily to weekly time scales, J. Geophys. Res. Atmos., 122, 5738–5762, https://doi.org/10.1002/2016JD026386
- Davini, P., von Hardenberg, J., Corti, S., Christensen, H. M., Juricke, S., Subramanian, A., Watson, P. A. G., Weisheimer, A., and Palmer, T. N. (2017a). Climate SPHINX: evaluating the impact of resolution and stochastic physics parameterisations in the EC-Earth global climate model, Geosci. Model Dev., 10, 1383-1402, https://doi.org/10.5194/gmd-10-1383-2017
- Davini, P., Corti, S., D'Andrea, F., Rivière, G., & von Hardenberg, J. (2017b). Improved Winter European Atmospheric Blocking Frequencies in High-Resolution Global Climate Simulations. Journal of Advances in Modeling Earth Systems, 9, 2615-2634. https://doi.org/10.1002/2017MS001082
- S. Lang, A. Weisheimer, J. von Hardenberg, L. Magnusson, M. Bonavita. Modification of SPPT to improve global conservation properties of momentum, energy and moisture. ECMWF Research Department Memorandum, May 2016

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

The impacts of stochastic physics parameterization schemes in EC-Earth are currently being further investigated in the framework of project WHERE (spitmavi) dedicated to analyzing the capability of the model in reproducing realistic Euro-Atlantic and Pacific North American atmospheric weather regimes and associated teleconnection patterns, with and without stochastic physics.