https://doi.org/10.5194/gmd-2019-282
Preprint. Discussion started: 11 November 2019

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On the increased climate sensitivity in the EC-Earth model from CMIP5 to CMIP6

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Abstract. Many modelling groups that contribute to CMIP6 (Coupled Model Intercomparison Project phase 6) have found a larger equilibrium climate sensitivity (ECS) with their latest model versions compared to the values obtained with earlier versions for CMIP5. This is also the case for the EC-Earth model, and in this study we investigate what developments since the CMIP5 era could have caused the increase in the ECS in this model. Apart from increases in horizontal and vertical resolution, the EC-Earth model also has substantially changed the representation of aerosols, and in particular it has introduced a more sophisticated description of aerosol indirect effects. After testing the model with some of the recent updates switched off, we find that the ECS increase can be attributed to the more advanced treatment of aerosols, with the largest contribution coming from the effect of aerosols on cloud microphysics (cloud lifetime or second indirect effect). The increase in climate sensitivity is unrelated to model tuning as all experiments have been performed with the same tuning parameters and only the representation of the aerosol effects has been changing. These results cannot be easily generalised to other models as their CMIP5 and CMIP6 versions may differ in other aspects than the aerosol-cloud interaction, but the results highlights the strong sensitivity of ECS to the details of the aerosol forcing.

1 Introduction

The equilibrium climate sensitivity (ECS) is the average change in global and annual mean near-surface air temperature (tas) following an instantaneous doubling of the CO_2 concentration compared to preindustrial levels, after the climate has reached a new equilibrium. It is a widely used metric in the climate change context to illustrate the warming from increased CO_2 levels including feedbacks in the climate system. The ECS is also highly relevant for climate policy: Matthews et al. (2009) found that global warming mainly depends on the total cumulative anthropogenic emission of carbon to the atmosphere and that the details of the emission pathways are of secondary importance for the warming. The larger the ECS the smaller the

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amount of carbon that still can be emitted in order to limit the warming to a value below a given level, e.g. warming levels suggested by the Paris treaty.

Despite the simple definition of the ECS it is not easy to constrain its value, neither with observations nor with models (Roe and Armour, 2011; Knutti et al. 2017). The majority of CMIP5 models was found to have an ECS in the range between 2.1 and 4.7 K (IPCC 2013). With the first results from CMIP6 models becoming accessible, it has been found that for a number of models the ECS has increased substantially compared to the values that were found for CMIP5 with the predecessors of the very same models (e.g. Valdoire et al. 2019), which has already led to discussions about possible implications of higher climate sensitivity (Voosen 2019, https://www.carbonbrief.org/guest-post-why-results-from-the-next-generation-of-climate-models-matter). Our EC-Earth model also shows an increased sensitivity: EC-Earth2 which has been used for CMIP5 had an ECS of 3.3 K that has increased to 4.3 K in the newer model version EC-Earth3-Veg used for CMIP6. An important question is if we understand the reason for this increase. Can we identify and quantify the contributions from the various developments and updates when going from EC-Earth2 to EC-Earth3-Veg? Unfortunately the complex nature of the model development process makes it impossible to turn back the development in a systematic and continuous approach. Some of the newly introduced processes or forcings can only be switched on or off in combination with others, for example the more advanced treatment of aerosol indirect effects can only be used in combination with the aerosol representation of EC-Earth3 and has no counterpart in EC-Earth2. Nevertheless, we hope to shed some light on the reasons for the increased ECS of EC-Earth3-Veg with systematic model sensitivity experiments to test the contributions from new developments.

The goal of this study is neither to justify the higher ECS of EC-Earth3-Veg nor that of CMIP6 models in general; we only investigate possible reasons for the increase of the ECS in the EC-Earth model family when advancing from the CMIP5 to the CMIP6 version of the model. General constraints on the ECS are outside the range of this study as well as general findings on the ECS for all CMIP6 models. Strictly speaking any conclusion is valid only for the EC-Earth3 model, but since many climate models share model components and/or forcings the findings presented here could hint at possible reasons for higher ECS even in other models.

2 Method

2.1 The EC-Earth model

The EC-Earth global climate model has evolved from the seasonal prediction system of ECMWF (Hazeleger et al., 2010). The CMIP5 version of EC-Earth is based on the ECMWF integrated forecasting system (IFS) cy31r1 and the NEMO version 2 ocean model (OPA9 with the LIM2 sea ice model), see Hazeleger et al (2012) for details. All components have been upgraded for the new EC-Earth3 model that is used for CMIP6. A detailed description of EC-Earth3 is in preparation (Döscher et al., 2019). The basic differences between EC-Earth2 and the EC-Earth3 model family are listed in Table 1. In addition to the differences between model versions there are also differences in the forcing datasets when going from CMIP5

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to CMIP6, e.g. the greenhouse gases (GHGs) or aerosol forcing datasets, but the impact of the changes in the external forcing on the ECS is not investigated here.

The EC-Earth3 model contributes to CMIP6 in several configurations. For the work here we have used the EC-Earth3-Veg configuration which couples the dynamic vegetation model LPJ-Guess (Smith et al. 2014) to the atmosphere and ocean model.

A noteworthy difference between EC-Earth2 and EC-Earth3-Veg is the way the aerosols are treated. In EC-Earth2, aerosols are prescribed as mass concentration fields following the CMIP5 time series from the Community Atmosphere Model (CAM, Lamarque et al., 2011). The provided aerosol components are mapped onto the types used in IFS, and fed into the short- and longwave radiation scheme. The calculation of cloud droplet number concentrations and effective radius is done as in IFS cy31r1 following Martin et al. (1994), independently of the CMIP5 forcing dataset. Hence, EC-Earth2 accounts only for the direct (and semi-direct) radiative effects of the prescribed changes in aerosol concentrations, but has no representation of the indirect effects via their impacts on clouds.

EC-Earth3 includes the climate forcing from both direct and indirect aerosol effects. For the direct aerosol effects in the shortwave the model uses the optical properties of the aerosol plumes provided by the MACv2-SP simple plume model (Stevens et al. 2017) in combination with monthly climatologies of the optical properties of the pre-industrial background aerosol levels that have been obtained from an off-line simulation using the atmospheric composition model TM5 (Van Noije et al. 2014; Bergman et al. 2019) forced with pre-industrial emissions for CMIP6 (Hoesly et al., 2018; Van Marle et al., 2017). The aerosol effects in the longwave are calculated based on the background aerosol mass concentrations obtained from the same TM5 simulation. For the indirect aerosol effect cloud droplets are allowed to form from aerosols with the aerosol activation scheme from Abdul-Razzak and Ghan (2000) and both the effective radius as well as the autoconversion efficiency depend on the number of cloud droplets. A power-law dependence is assumed for the autoconversion rate (Rotstayn and Penner, 2001). The aerosol number and mass concentration fields that serve as input to the activation scheme are climatologies from the off-line run with TM5. The changes in aerosol concentrations since the pre-industrial era in transient runs are accounted for by multiplying the resulting cloud droplet number concentration by the multiplication factor provided by MACv2-SP. Note however that the piControl and abrupt-4xCO2 experiments in this study require pre-industrial aerosol concentrations and no multiplication factor has been used.

2.2 Experiment design

ECS is assessed by comparing the response of the net top-of-the-atmosphere (TOA) radiative flux (Q_{net}) and tas from the abrupt-4xCO2 experiment (hereafter denoted as 4xCO2) against the steady climate of the pre-industrial control experiment (piControl) with its baseline CO_2 concentration. Each model modification therefore requires two long model simulations, one with baseline and one with quadrupled CO_2 concentration. The CMIP6 protocol requires the 4xCO2 experiments to be 150 years long, but in order to save computational resources we test if simulations of only 75 years length could give an acceptable estimate for the ECS.

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In another attempt to save computational resources we investigate if the ECS depends on the model resolution. The horizontal and vertical resolution of the atmosphere model in EC-Earth3 is reduced to the resolution that was used for CMIP5. The reduction of the simulation length and the lower resolution would allow us to perform substantially more experiments with the available computational resources but we first need to validate that these modifications have only a small impact on the ECS of the model.

Apart from the changes in model resolution, the most important updates of the model are likely those related to the revised treatment of the aerosols. In addition to the tests related to changes in horizontal and vertical resolution we also test the impact from the newly implemented aerosol-cloud interaction parameterizations on the ECS in a number of sensitivity experiments. The question is if and possibly how much any of these changes have contributed to the increase in ECS that we find when comparing the CMIP5 and the CMIP6 version of the EC-Earth model.

2.3 Assessing the equilibrium climate sensitivity

ECS is defined as the increase in the global mean tas between a steady-state climate with pre-industrial levels of CO2 concentrations and the steady-state climate with doubled CO_2 concentrations, with all other forcings (GHGs, aerosols, land-use etc.) remaining at pre-industrial conditions. Despite this simple and straightforward definition of the ECS the practical task to assess the ECS of a model is a real challenge because it would require the model to run with increased CO_2 concentration until it reaches equilibrium. However, the brute force approach to run the model until equilibrium is not very practical as it would take thousands of years of model integration to bring the deep ocean into equilibrium and to find the steady-state equilibrium temperature. For this reason modellers often use the shortcut proposed by Gregory et al. (2004) to estimate the equilibrium temperature response from shorter experiments, e.g. the 4xCO2 experiments for CMIP6. When doing a simulation with increased CO_2 concentrations the global mean Q_{net} and tas asymptotically approach the equilibrium state, and by extrapolating a linear fit of the data points to the Q_{net}=0 level one can obtain an estimate of the equilibrium temperature that would be reached when the model reaches its new equilibrium that is characterized by a zero TOA energy balance. Since models may present a not perfectly closed energy balance, resulting in a non-zero equilibrium TOA net flux, the preindustrial equilibrium values are typically removed from the 4xCO2 values before proceeding with the fit to determine ECS.

ECS by definition is the temperature change with doubled CO_2 concentrations. However, the DECK (Diagnostic, Evaluation and Characterization of Klima) experiments for CMIP6 comprise the abrupt4xCO2 experiment with instantaneously quadrupled CO_2 (Eyring et al., 2016). It is a common assumption that the equilibrium temperature responds linearly with the CO_2 concentration. Therefore we divide the estimate for the equilibrium temperature in the 4xCO2 experiment by 2 to obtain an estimate for the ECS.

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2.3.1 Correction for model drift

A basic assumption of the Gregory method is a well-tuned model with a steady state control climate in the piControl experiment. It is then straightforward to evaluate the TOA radiation imbalance and temperature response at the surface in a sensitivity experiment with changed forcing relative to the control climate. The control climate and response to changed forcing are evaluated in corresponding time periods in the control and sensitivity experiment, respectively. However, when testing the sensitivity of the ECS to recent model changes we switch on/off some model features, which may result in an ill-tuned model and introduce a drift. In principle one would have to first make a new spin-up run with the modified model before starting new piControl and 4xCO2 experiments, yet limited computational resources don't allow us to make several long spin-up runs with slightly modified model configurations. To overcome this difficulty we assume that the model modifications lead only to a small drift in the piControl climate that we can correct for. After making the piControl experiments with each model modification we first make linear fits of the Q_{net} and tas time series and then use these fits to correct the corresponding time series of the 4xCO2 experiment (Fig 1), following common practice (e.g. Andrews et al., 2012). We applied a similar correction also to the unperturbed control experiment. Since the largest shock caused by a model modification occurs right at the start of the simulation and may give rise to a non-linear response we exclude the first 5 annual means when computing the linear fit for the model drift. For the same reason we also exclude the first 5 years of the net radiation and temperature time series when computing the linear regression for estimating the ECS. We have verified that the resulting ECS estimates are very close to the values obtained with more advanced linear regression methods that are more robust against outliers (e.g. Theil-Sen regression), confirming that the strongest deviations from the linear relation are indeed observed during the first few years.

3 Results

3.1 Reducing the length of the simulation

Reducing the length of the piControl and 4xCO2 simulations would free valuable computational resources, yet only if it has a marginal impact on the ECS. In order to test this, we compute the ECS from our DECK experiments (EC-Earth Consortium 2019) by taking 150 and of 75 years of the annual mean timeseries, respectively. In both cases the model configuration is EC-Earth3-Veg with the full T255L91-ORCA1L75 resolution used for CMIP6. The ECS is found to be 4.3 K irrespective of including 150 or 75 years in the linear regression (Table 2). We therefore conclude that we can safely reduce the length of the sensitivity experiments with minimal impact on the ECS.

3.2 Reducing the model resolution

Table 2 also lists the results from a reduction of the horizontal and vertical resolution. For these experiments we change the resolution only in the atmosphere in two steps to bring it into agreement with the resolution that was used for CMIP5. The

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ECS changes slightly from 4.3 K to 4.2 or stays at 4.3 K when only the horizontal or both the horizontal and vertical resolution are changed. These changes in ECS are small compared to the difference in ECS between the CMIP5 and CMIP6 model versions. The change in model resolution thus cannot explain the increase in ECS. Since resolution changes don't contribute much to the ECS difference all further sensitivity experiments with modified aerosol-cloud interaction are made with the low resolution configuration of EC-Earth3-Veg. The resulting ECS will not be fully accurate for the full-resolution CMIP6 model; nevertheless the estimates obtained with low resolution will allow us to make a qualitative assessment of the impact of the newly implemented aerosol scheme.

3.3 Sensitivity to the description of aerosols and their impacts on clouds

Table 3 presents the results from a series of sensitivity experiment with the aerosol scheme in EC-Earth3-Veg. When reverting the newly implemented simple plume representation of MACv2-SP in combination with a pre-industrial background climatology back to the scheme with prescribed aerosol concentrations used for CMIP5, we find that the ECS drops to 3.3 K which is suspiciously close to the value that was found for the CMIP5 version of EC-Earth. A significant difference between EC-Earth2 and EC-Earth3-Veg is the presence of a dynamic vegetation model in the latter that could play a role for the ECS. However, the first analysis from the DECK experiments with the configuration with prescribed vegetation reveals that the ECS is only marginally lower (4.2 K). Changing the source of the aerosol forcing from the CMIP5 data set to the new representation of aerosol optical properties in CMIP6 but without aerosol indirect effects - effective radius and autoconversion are parameterised as in the CMIP5 version of the model and do not depend on the number of activated aerosol particles calculated from the pre-industrial climatology of aerosol concentrations - the ECS increases slightly to 3.5 K. The change is small and may not be significant with all the simplifications of the experimental design in mind. When the coupling between the explicit aerosol activation is switched on and impacts the effective radius (1^{st} indirect effect) the ECS increases further to 3.8 K, and if in addition the activated aerosol particles are also allowed to impact cloud microphysics the ECS becomes 4.3 K. This last value is similar to the ECS from the CMIP6 experiments with EC-Earth3-Veg performed at higher atmospheric resolution (T255L91).

This series of sensitivity experiments suggests that the increase of the ECS from CMIP5 to CMIP6 is mainly caused by the change in the representation of aerosol and their impacts on clouds and radiation. The implementation of MACv2-SP as it is suggested for CMIP6 models without explicit aerosol scheme has fundamentally changed the way how aerosols are prescribed in the model, yet this change has little effect on the ECS as long as cloud effective radius and autoconversion are independent of the aerosol concentration. The ECS increases when the more advanced treatment of the first and second indirect effect is introduced, with the largest contribution coming from the latter.

Kiehl (2007) has shown a correlation between stronger aerosol forcing and higher climate sensitivity in climate models. Thus, by introducing a more advanced treatment of aerosols in the EC-Earth3 model and subsequent tuning to match a realistic preindustrial equilibrium and present-day climate in the model we may have altered the model's sensitivity. However, tuning is likely a 2^{nd} order effect as all our results here were obtained with the same tuning of the model, the only

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changes in the sensitivity experiments are related to the linkage between cloud droplet number concentrations and effective radius or autoconversion efficiency.

4 Conclusions

The ECS of the EC-Earth model has increased from 3.3 K in CMIP5 to 4.3 K in CMIP6. In this work we show that this increase can be explained by the revised description of aerosol processes in EC-Earth3, in particular the implementation of the first and second indirect aerosol effect. In fact, cloud feedbacks have been identified among the most important sources of uncertainty for ECS for the past generation of climate models (Andrews et al. 2012). Interestingly the analysis by Chylek et al. (2016) suggested that only CMIP5 models including indirect aerosol effects present a correlation between radiative forcing and equilibrium climate sensitivity similar to that discussed in Kiehl (2007). Further, more complexity in a model has the potential to modify the sensitivity to external forcing because of the increased degree of freedom. Thus, a higher ECS when going from a model with no indirect aerosol effects in CMIP5 to a model with these effects included for CMIP6 could be expected and is not surprising.

Of course, the question has to be asked how good is the representation in EC-Earth3 of specific processes such as the activation of aerosols, how realistic are the parameterisations of effective radius and autoconversion efficiency as a function of the activated cloud droplets, and how will all these changes affect the ECS of the model. Hopefully the coming CMIP6 experiments in AerChemMIP will help us to better understand how well the EC-Earth3 model represents such aerosol-cloud interactions. All results from this study are strictly speaking only valid for the EC-Earth3-Veg model. Many of the other climate models already had indirect aerosol effects in their CMIP5 version and therefore they cannot easily explain an increase of the ECS with the introduction of a more sophisticated aerosol scheme. However, many models have updated their aerosol representation since CMIP5 and some have implemented the new MACv2-SP scheme. It is possible – but impossible to prove here – that the changes in the aerosol treatment could make a substantial contribution to the increase in ECS that many modelling groups have found.

Code and data availability

The EC-Earth model is restricted to institutes that have signed a memorandum of understanding or letter of intent with the EC-Earth consortium and a software license agreement with ECMWF. Confidential access to the code can be granted for editor and reviewers, please use the contact form at http://www.ec-earth.org/about/contact. The data from the piControl and abrupt4xCO2 for CMIP5 are available from https://doi.org/10.5281/zenodo.3459914 while the CMIP6 data can be downloaded from any ESGF dataportal (cf. reference EC-Earth Consortium 2019). The results of the sensitivity experiments with EC-Earth3-Veg used in this study are available from https://doi.org/10.5281/zenodo.3454079.

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Author contribution

All co-authors are part of the EC-Earth consortium that develops the EC-Earth model. The experiments with EC-Earth3 were done by K. Wyser while the experiments with EC-Earth2 were done by S. Yang. All co-authors have participated in the analysis of the results. K. Wyser prepared the manuscript with contributions from all co-authors.

Acknowledgement

This work was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 641816 (CRESCENDO). The EC-Earth simulations were performed on resources provided by the Swedish National Infrastructure for Computing (SNIC) at PDC and NSC.

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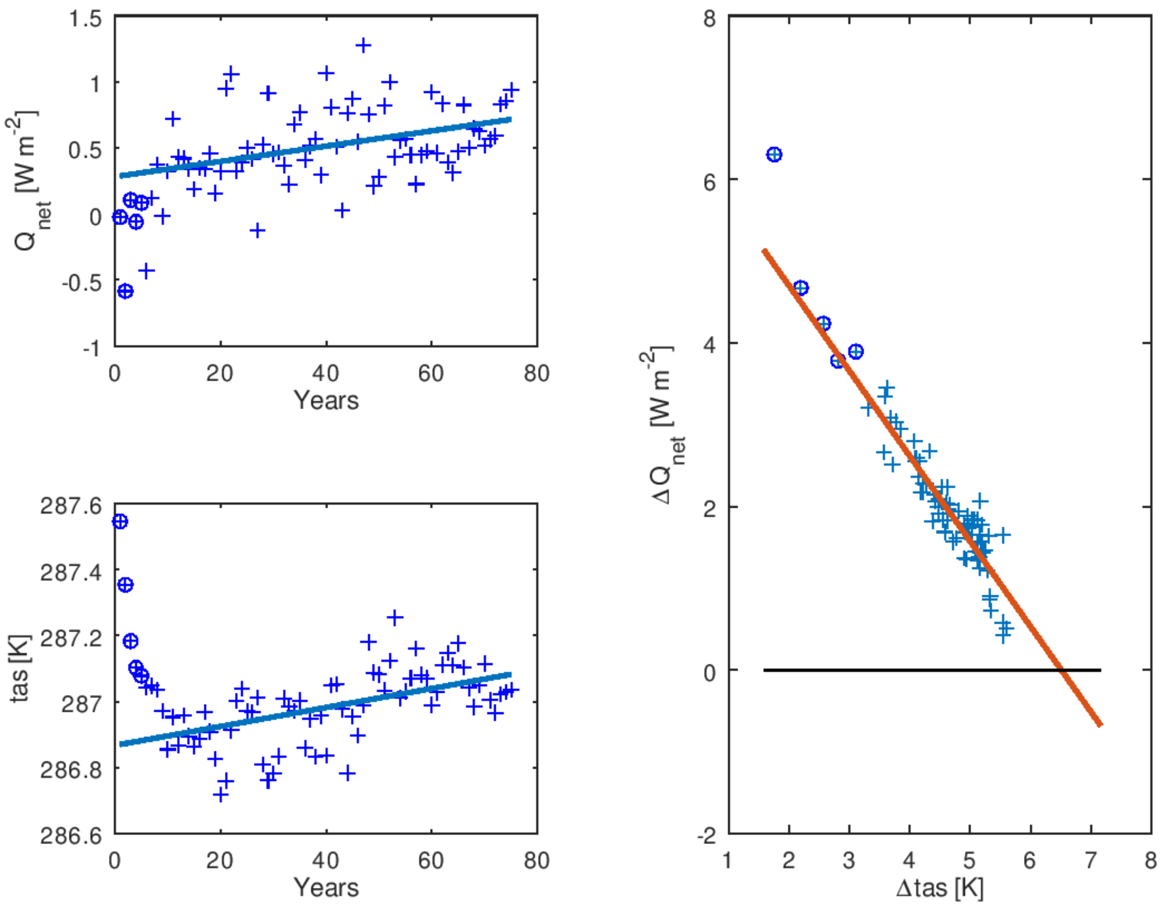

Figure 1, left: Timeseries of Q_{net} and tas in the piControl run with CMIP5 aerosols and without explicit cloud activation. The model isn't tuned for this configuration and experiences a drift over time. The linear fit (solid) in the Q_{net} and tas plot provides the offset and drift correction- that are later subtracted from the 4xCO2 experiment with the same model configuration. The first 5 years (marked "o" in the plot) are excluded when computing the linear fit. Right: Gregory plot from the 4xCO2 experiment for this model configuration after correcting for offset and drift in the corresponding piControl experiment. A regression line is fitted to the data points (red) and extrapolated, again excluding the first 5 years marked "o"). The intersection of this line with the ΔQ_{net}=0 line is an estimate for the equilibrium temperature response in the 4xCO2 experiment. This value has to be divided by 2 to yield an estimate for the ECS.

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		EC-Earth2	EC-Earth3
Atmosphere model		IFS cy31r1	IFS cy36r4
Ocean model		NEMO2 (OPA9)	NEMO 3.6
Sea-ice model		LIM2 with 1 sea ice category	LIM3 with 5 sea ice categories
Resolution	Atmosphere	T159L62	T255L91
	Ocean	ORCA1L42	ORCA1L75

Table 1: Basic differences between the CMIP5 and CMIP6 versions of the EC-Earth model family

Model	Length (years)	Resolution	ECS	Remarks
EC-Earth2	150	T159L62-ORCA1L42	3.3	CMIP5
EC-Earth3-Veg	150	T255L91-ORCA1L75	4.3	CMIP6
	75	T255L91-ORCA1L75	4.3	Reduced length
		T159L91-ORCA1L75	4.2	Reduced length + reduced horizontal resolution
		T159L62-ORCA1L75	4.3	Reduced length + reduced horizontal and reduced vertical resolution

Table 2: Impact of a reduced simulation length and reduced model resolution on the ECS. The ECS value for EC-Earth2 is shown for comparison.

Experiment	Aerosol direct radiative effect	First indirect effect	Second indirect effect	ECS
EC-Earth2 (control)	As for CMIP5	As for CMIP5	As for CMIP5	3.3
EC-Earth3-Veg (control)	As for CMIP6	As for CMIP6	As for CMIP6	4.3
Prescribed aerosol concentrations from CMIP5	As for CMIP5	As for CMIP5	As for CMIP5	3.3

https://doi.org/10.5194/gmd-2019-282
Preprint. Discussion started: 11 November 2019

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Aerosols as in CMIP6	As for CMIP6	As for CMIP5	As for CMIP5	3.5
	As for CMIP6	As for CMIP6	As for CMIP5	3.8
	As for CMIP6	As for CMIP6	As for CMIP6	4.3

Table 3: Sensitivity of ECS to different realisations of the aerosol-cloud interaction processes. All experiments except those labelled "control" are with the low resolution (T159L62) configuration of EC-Earth3-Veg and 75 years long.