“On the increased climate sensitivity in the EC-Earth model from CMIP5 to CMIP6” by Klaus Wyser et al.

Author comments to referees #1 and #2

We’d like to thank the two anonymous reviewers for many helpful comments and suggestions that have helped us to improve the manuscript. Both reviewers acknowledge that the climate sensitivity of CMIP6 models is an important topic, and that it is important to understanding the differences to the models from CMIP5.

The reviewers agree in their criticism that the submitted manuscript was incomplete and lacked much of the essential analysis. We have tried to address the reviewers’ point by substantially extending the analysis and not only look at the ECS but also at changes in clouds and the cloud radiative forcing, and discuss the impact of these changes to explain the change in the ECS in the CMIP5 and CMIP6 version of the EC-Earth model. The analysis is now also covering regional aspects and not only global means. We hope the extension of the analysis pleases the reviewers and makes the message of the study more clear.

Both reviewers also mention the lack of references to recent papers that discuss climate sensitivity in other CMIP6 models. We agree on that point and have added references to other studies where suitable. However, we’d also like to make a point that both reviewers have given examples of missing references and cite papers that have been published several months after our manuscript was submitted (end of September 2019), and we therefore were not aware of these references (e.g. the excellent paper by Zelinka et al.)

We would like to emphasize that our submitted manuscript isn’t intended to replace the full documentation of the EC-Earth3 model. The details of the changes when going from the CMIP5 to the CMIP6 version of the model, the model tuning, and changes in the model climate will be documented in a model reference paper. Thus, we have decided to not dive deeper into explicit details of individual steps in the model development, but keep the discussion at a general level and focus on the impact of the developments on the ECS instead.

Detailed replies to the comments from reviewer 1:

Major comments

1) The paper could be easily improved by describing the changes to the model code in terms which can be understood by non-aerosol specialists, e.g. somebody who might be interested model weighting and query your paper for understanding why ECEarth model version X has a higher sensitivity that EC-Earth model version Y; which of the two to include in a certain assessment and how much weight to give each model version. Such a person should be able to take more away from your paper than ". . . [the change] is mainly caused by the change in the representation of aerosols and their impact on clouds and radiation" (line 179), isn't it? It would help to flesh out line 65-88 (not necessarily in length but in readability for non-experts).

We have reworked the model description (2.1) and describe the differences between ECE2 and ECE3 clearer. As stated above, it's not the intention that this study replaces a detailed model description, we try to keep the description at a general level.

2) I my eyes, a main conclusion of the paper is "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" (line 177-184 or so)

The paper would profit from putting actual numbers behind these claims, which are now only expressed in Table 1 and 2 (the only actual results of the paper). Simply showing the relative contributions locally, some spatial fields of how the second indirect effect is expressed, and the different contributions (short and long wave, clear and full sky) to Delta Q net (as in Fig. 1), which is standard in climate sensitivity papers, e.g. Andrews et al. 2012 or 2015, or Zelinka et al. 2020 "Causes of higher climate

sensitivity in CMIP6 models" (which goes much deeper in the discussion but does not replace papers like this one). However, there should be more depth than "it's likely the second indirect effect".

Why? Where? How trustworthy is it (which model versions should I use for which *purpose)? Why did you include it into the model? What do we learn from it about climate sensitivity and projections of warming (and precipitation) in the next century? With the men power of six co-authors you should be able to go into a little bit more depth (e.g. compare Gettleman 2019 "High Climate Sensitivity in the Community Earth System Model Version 2 (CESM2)".*

We have extended the analysis and now include also discuss the differences in ERF and feedback parameter between between ECE2 and ECE3. We also look at the differences in the sensitivity of clouds and the cloud forcing in the two model versions, and show that the largest difference are found over the Northern Hemisphere Atlantic and Pacific Ocean.

3) The paper discusses changes in ECS of 1K and smaller changes between the model versions. There should be uncertainty estimates for all ECS estimate and a discussion in how far differences are even statistically detectable (I'm guessing the difference in line 155 between 4.3 and 4.2K is not even significant (as you also argue, but you should show it)).

We have added uncertainty estimates to all numbers in the table with estimates given as standard deviation of the parameter estimates in the linear regression of the Gregory method.

Minor comments

line 21: delete "easily" (of course this can't be generalized to any other model (?))

Agree.

Line 27: what's "the climate change context" (?)

Replaced with "…widely used metric in climate modeling…"

line 30: . . . for the warming. I guess in the next century? Are there more recent papers on this discussion?

No, the warming in this context is not bound to a fixed point in time (e.g. end of the century). The idea is that the equilibrium temperature at any point in time is determined by the cumulative emission up to this point. To our knowledge, Matthews et al were the first to describe this and we therefore think it makes sense to cite their work. Since then many papers have appeared in the literature that look at the relationship between cumulative emissions and temperature change (e.g. Frölicher 2016, Seshadri 2017, Miller and Friedlingstein 2018, Matthews et al 2018), but we consider the discussion of this topic to be outside the scope of our work and therefore don't add more references.

line 34: "was found"

and "has been found" sounds as if these models fell from the sky onto your desk. The models were made more sensitivity (by people like you, changing the model), this is active human action and doesn't passively happen.

We haven't tuned the ECS in the EC-Earth model and get its value first after having done some of the CMIP6 simulations. So yes, for us it "fell from the sky". The same is probably true for other modeling groups too, otherwise there wouldn't have been so much discussion about higher ECS in the new climate models about a year ago at the CMIP6 analysis workshop in Barcelona (which among other things resulted in the Carbonbrief guest post: https://www.carbonbrief.org/guest-post-why-results-from-the-next-generation-of-climate-models-matter)

line 40: "An important question is if we understand the reason for this increase" This statement is very sadly showing the level of climate science these days. I hope you are able to understand the reason for this increase and both the user and the wider public want to know it. If you don't understand the reason, why should I trust you, your model, the IPCC assessment using the model, . . . ?

This sentence has been removed.

line 43: "Unfortunately the complex nature of the model development process makes it impossible to turn back the development in a system-

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*atic and continuous approach." What about starting systematically in the first place (!?) *You* developed the model and made these decisions only a few years or even months ago. I know this is a hard process, but the necessity for careful documentation has been openly discussed now for several years (e.g. Hourdin et al., 2016, "The art and science of climate model tuning.", but also already Mauritsen et al. 2012 "Tuning the climate of a global model"). You at least have to blame yourself (or colleagues) for following this approach and not take it as passively given.*

The EC-Earth model is developed by a broad and heterogeneous consortium. Some developments can be easily reverted, others not. Sometimes it's just not possible (or very difficult) to maintain different versions of process descriptions in the same model. This has nothing to do with model tuning.

line 56: This is the last time I'm making that comment: "The EC-Earth global climate model has evolved from . . ." You did evolve the model (actively) and should be able to confidently explain me why *things change, isn't it?*

This sentence was there to document the legacy of the EC-Earth model, not to explain any of its characteristics. Nevertheless we have removed this sentence as it's not necessary for the ECS.

line 71: Explain how (what is in Martin 1994).
line 71-73: More
explanation and depth is necessary for a reader not familiar with the model or aerosols
in general

We have added a short sentence about the Martin et al parameterization of the effective radius. It would be beyond the scope of this study to go into the technical details of this – or other – parameterisations, the interested reader can easily find the formulae in the cited references.

line 75: Again more explanation necessary. How are these plumes prescribed?
Do they change in time in the historical but not in the step forcing (the same
way as in the control simulation)? A non-aerosol expert would profit here from some
plots visualizing the changes in the model.

The aerosol concentrations do not change in time, neither in the pre-industrial control nor in the 4xCO2 simulations. We have added a statement that the aerosol concentrations don't change over time (l.89f in the revised manuscript)

*line 79: the *direct* aerosol effect? What's*
the background aerosol mass concentration?

The background aerosol concentration is from the off-line run with TM5, this is described in l.85ff

line 81: shortly explain effective radius,
auto conversion-efficiency, activation scheme in laymen's terms

We don't think it is necessary to explain these basic concepts of coud microphysic and radiative transfer in a paper about climate model sensitivity.

line 91: What's the baseline CO2
concentration? Is it the same in all models in CMIP6? I think that wasn't the case for
CMIP5? How did you deal with this in your model development?

Yes, the prescribed CO2 concentration is the same in all concentration driven models, this has been the case for CMIP5 and it still is for CMIP6.

line 126: No that's

not a basic assumption of the Gregory method. It is very common to detrend models,

e.g. Proistosescu and Huybers 2017 or Andrews et al. 2015. (rest of the section is

fine though)

Agree, the detrending is widely used and we have removed this statement.

line 139: In how far does discarding the first five years change the results?

See comments on uncertainty above.

The ECS estimates are changing a lot when the first few years are included in the regression, but we don't find any difference if we exclude 5 or 10 years. We have added a sentence about that (l.148)

line 169: Does the lower value refer to the fixed

vegetation version?

The paragraph has been reworded.

*line 181: as long as cloud *droplet(?)* effective radius . . .*

Added droplet.

line 184:

What's the reason for the correlation in the Kiel 2007 paper? Are there any updates of

the discussion in the literature?

line 183: This is great that the tuning is discussed

Kiehl et al argue that tuning change the ECS of a model, and we are not opposing their finding. However, our sensitivity experiments show that the ECS can also change without changing the tuning of the model, and this is the point we like to make here because we heard the argument in the discussion that higher ECS is just the result from the tuning.

line

189: add maps of these quantities or short wave cloud radiative effects or other feed-

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backs here (?)

Figs 2+3 have been added

line 205: delete "strictly speaking" (or explain how "loosely speaking" *your results are valid for any other model (of course they are not (?)))*

This sentence has been changed according to the reviewer's suggestion.

line 310: Express resolution also in approximate km units

Done.

References to statements missing throughout the text (e.g. line 62, whole section 2.3, especially line 110, line 113, line 124, and other places)

Sorry, but we don't understand what the reviewer is asking here? For example l.110 reads "concentration until it reaches equilibrium. However, the brute force approach to run the model until equilibrium is not very", what statement on that line would require a reference?

Detailed replies to the comments from reviewer 2:

Major comments:

The authors present climate sensitivity estimates from a series of simulations including all or subsets of the aerosol related changes between the CMIP5 and CMIP6 versions. Simulation results indicate that as well direct aerosol effects from the new climatology as the inclusion of different indirect aerosol effects contribute to the higher climate sensitivity. However, no attempt is made to understand why and how these effects come about, which I think would be crucial to make this paper useful for readers beyond the notion that differences in climate sensitivities simulated by different EC-Earth version may be related to the treatment of aerosols. There should be an attempt to attribute the changes to different types of climate feedbacks, as well as to identify possible regional patterns and mechanisms that affect the feedbacks. One could e.g. imagine that the modifications affect ECS rather indirectly, e.g. by modifying the climatological cloud distribution which then reacts differently to an increased GHG concentration. It would be important to figure these things out.

We address the concerns with an extended analysis of the differences between the CMIP5 and CMIP6 version of the model by looking at the response of clouds and the cloud forcing, see new Section 3.1.

There have been other publications on increased or tuned climate sensitivities in CMIP6 models (at least Andrews et al., JAMES, 2019, Gettelman et al., GRL, 2019; Mauritsen et al., JAMES, 2019; Zelinka et al., GRL, 2020, but there may be more I'm not aware of). I find it surprising that the authors ignore all of these publications. Their own work needs to be put into the context of these earlier studies.

Indeed, there are many publications about changes in the climate sensitivity of CMIP6 models. We made an attempt to update references in the paper and put our results in a wider context.

To estimate the climate sensitivities in different model configurations the authors deviate from the common approach of branching a simulation with instantaneously increased CO2 concentration from a control run with a climate in equilibrium. Instead, the authors start control runs with modified configurations at the same time as the runs with increased CO2 and use anomalies of the latter with respect to the former. The sentence where this is described (L134) cites Andrews et al. (2012) which is a bit misleading as this reference is not appropriate for the use of anomalies. My hypothesis is that likely the use of anomalies is unproblematic, but If there is no reference confirming this I think the authors should show that, e.g. by using other common approaches as slab ocean models or +4K experiments which also don't require long spin-up runs. I'm a bit concerned about the applied method because of the strong initial (over five years or so) adjustment due to the change of configuration and the change of sign in the temperature trend afterwards.

We are sorry for having put the wrong reference for the detrending of the results before evaluating the ECS, the correct reference is Andrews at el (2015) and this has corrected. We are aware that we deviate from the standard protocol by not letting the model run to equilibrium in its different configurations before starting the 4xCO2 experiment. We explain all this in the manuscript and motivate it with the expensive computational resources that would be needed to run the model to equilibrium for each configuration. Please not also that this deviation from the CMIP6 protocol is only used for the sensitivity experiments in Sec 3.4, the piControl and 4xCO2 experiments for CMIP6 have been started from a properly spun-up state.

Minor comments: L60: The table doesn't show "basic differences" between the different EC-Earth versions but version numbers (and resolutions) of the subcomponents.

Agree, changed in the text and table caption.

L89: I don't like the use of "tas"

for near surface air temperature. I know it is a CMIP variable name, but it looks odd *in a written text, isn't used for the global mean in CMIP, and is inconsistent with other names (Qnet).*

We prefer to use CMIP variable names when possible. There are no CMIP names for net radiation or cloud forcing and for these variables we use Qnet and CF.

L100 "most important updates are likely those related to the revised aerosols". I guess "most important" is meant in the sense of ECS. Why is that likely? Other authors have e.g. documented that also tuning of model physics may affect ECS strongly. Can this be excluded a priori.

No, tuning may also play a role as suggested by Kiehl (2007), this is mentioned at the end of Sec 3.4. However, here we show that for the ECE3 model we can get back the ECS from ECE2 by switching of the updates in the aerosol-cloud interaction that were not present in ECE2. In all the sensitivity experiments we don't change the model tuning, it only is an effect of having the indirect aerosols effect switched on or off. We also try to be clear that this is only true for the EC-Earth model, we cannot say anything about if this would have the same effect in other models.

L117 "Since models may present a not perfectly closed energy balance : : :" Is that the case for EC-Earth?

Many models can experience a small drift, or long-term climate variability in long runs such as piControl. In the CMIP6 version of the EC-Earth model the decadal or even multi-decadal variability is surprisingly strong for reasons yet unknown.

L123 "Therefore we divide : : :" This is common practice.

Yes, but still it has to be mentioned here to explain how we get from the 4xCO2 experiment to a value that corresponds to a 2xCO2 experiment.

L126 Why is a "well-tuned" model a basic assumption of the Gregory method? And how can good tuning be characterized?

Indeed, "well-tuned" is not necessary for the Gregory method. We have updated the text accordingly.

L134 The new control experiments are no piControl experiments, which are supposed to start after a spin-up. I'd suggest to name them differently.

Agree, we now only use piControl where we refer to the proper CMIP6 (and CMIP5) piControl experiment.

L185 The authors speak of "subsequent tuning to match a realistic preindustrial equilibrium and present-day climate". This sounds like the model's climate sensitivity was tuned? Or is this just a misunderstanding?

We tuned the model with the goal to get a stable pre-industrial climate and a present-day climate close to observations. We did not tune the climate sensitivity explicitely. However, when the new treatment of aerosols was introduced we had to re-tune the model to again come close to our tuning goals.

L193 I don't find it easy to understand why a change in complexity would have the "potential to modify the sensitivity" beyond the fact that any model change has this potential. I would also like to see an explanation for the statement in the following sentence. Would the assumption be that the addition of an indirect effect would lead overall to a larger aerosol forcing and the attempt to compensate for that by tuning the model to a higher climate sensitivity to obtain a better fit to the historical temperature trend?

The reviewer is correct, any model change can change the sensitivity and it's not a priori given that the sensitivity increases in a more complex model. We therefore have removed this paragraph.

Code and Data availability: I don't know the exact policy of GMD. But usually these days journals require the availability of primary data, which to my understanding is the model code and the scripts and input files needed to run the model, not only for editors and reviewers.

Unfortunately we cannot freely distribute the EC-Earth code but are bound by license agreements with the ECMWF (for the IFS code). GMD has accepted this restriction and allows the distribution of the code only to editor and reviewers. Hopefully this restrictive policy of ECMWF will change with the next version of EC-Earth that will be based on OpenIFS and can be distributed more freely.

Table 2: The "experiment" column should contain more information. E.g. it would be nice to be able to identify quickly which experiment in table 3 belong to which in table 2.

Tables have been reorganized and split, and should be easier to read now.

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~~modeling 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 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~~was found that for a number of models the ECS has increased substantially compared to the values that were found for CMIP5 (Zelinka et al 2020) with the predecessors of the very same models (e.g. Mauritsen et al. 2019, Gettelman et al. 2019, 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 (hereafter ECE2) 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~~ (hereafter ECE3). The goal of this ~~increase. Can we~~study is to identify and quantify the contributions from ~~the various developments and~~model updates when going from ~~EC-Earth2~~ECE2 to ~~EC-Earth3-Veg?~~ECE3. Unfortunately the complex nature of the model development process makes it impossible to turn back the development steps in a systematic and continuous approach. Some of the newly introduced processes or ~~forcings~~forcing datasets 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 new aerosol representation ~~of EC-Earth3 and~~in ECE3 that has ~~no counterpart~~nothing corresponding in ~~EC-Earth2~~ECE2. Nevertheless, we ~~hope~~attempt to ~~shed some light on~~analyse the reasons for the ~~increased~~ ECS ~~of EC-Earth3-Veg~~increase with systematic model sensitivity experiments to test the contributions from ~~new~~the various steps during the model developments.

The goal of this study is neither to justify the higher ECS of ~~EC-Earth3-Veg~~ECE3 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~~ that have been addressed elsewhere (Zelinka et al. 2020, Flynn and Mauritsen 2020). Any conclusion presented here 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 the EC-Earth model 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~~ECE3 is in preparation (Döscher et al., ~~2019~~2020). The ~~basic~~ differences ~~between EC-Earth2 and the EC-Earth3~~in model

~~family~~components and resolutions of ECE2 and ECE3 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 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~~outside the scope of this study.

The ~~EC-Earth3~~ECE3 model ~~contributes~~is used to contribute 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, yet the performance of EC-Earth3 and EC-Earth3-Veg is very similar.

A noteworthy difference between ~~EC-Earth2~~ECE2 and ~~EC-Earth3-Veg~~ECE3 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 aerosol types used in IFS~~,~~ and fed into the short- and longwave radiation scheme~~.~~ (direct effect). The ~~calculation of~~ cloud ~~droplet number concentrations and~~ effective radius is ~~done as in IFS cy31r1~~computed by distributing the cloud water on a fixed number of droplets following Martin et al. (1994~~), independently~~) and is thus independent of the CMIP5 ~~forcing dataset.~~aerosol data. Hence, ~~EC-Earth2~~ECE2 accounts only for the direct ~~(and semi-direct)~~ radiative effects of the prescribed changes in aerosol concentrations in the forcing dataset, but has no representation of the indirect effects via ~~their impacts~~the aerosol impact on clouds.

~~EC-Earth3~~ECE3 includes a representation of 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~~concentration 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~~pre-industrial TM5 simulation. For the indirect aerosol effect cloud droplets ~~are allowed to~~ form ~~from~~on activated aerosols with the aerosol activation scheme taken from Abdul-Razzak and Ghan (2000~~) and both~~). Indirect aerosol effects are accounted for by making the effective radius ~~as well as the~~and autoconversion efficiency depend on the ~~number~~concentration of cloud droplets~~. A power-law dependence~~ (CDNC). The effective radius is ~~assumed for the~~still computed following Martin el al. (1994) yet with the climatological (constant) droplet concentration replaced by CDNC. The autoconversion ~~rate (~~efficiency is a linear function of cloud water above a given threshold following Sundqvist (1978), multiplied by a power-law correction following 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 pre-industrial run with TM5. The changes in aerosol concentrations since the pre-industrial era in transient ~~runs~~simulations for CMIP6 are accounted for by multiplying the resulting cloud droplet number concentration by the multiplication factor provided by MACv2-SP. Note however that in the piControl and abrupt-4xCO2 experiments ~~in~~for this study ~~require~~the pre-industrial aerosol concentrations and noare used without any multiplication factor has been used, following the experimental protocol for these CMIP6 experiments.

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. In a first step we compare ECS between the CMIP5 and CMIP6 version of the EC-Earth model. We then analyse changes in the global means and in the regional distribution of clouds and their impact on the cloud forcing (CF, the difference between all-sky and clear-sky net radiation) to investigate the difference in climate sensitivity between ECE2 and ECE3.

To better understand the role of the various improvements during the development process of ECE3 we roll back some of the changes and measure the impact on CF and ECS in a series of sensitivity experiments. Apart from the changes in model resolution, the most relevant updates of the model are those related to the revised treatment of the aerosols and their interaction with clouds. 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.

The CMIP6 protocol requires the 4xCO2 experiments to be 150 years long, but in order to save computational resources we test if simulationssensitivity experiments of only 75 years length could give an acceptable estimate for the ECS.

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. TheA reduction of the simulation length and the lower resolution would allowallows us to perform substantially more experiments with the available computational resources but of course we first need to validateestablish 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. Apart from ECS the Gregory method allows one to estimate two other important model: the intercept of the linear fit the ordinate indicates the effective radiative forcing (ERF) for a quadrupling of the CO_2 concentration, while the slope of the linear regression is known as radiative feedback parameter (λ) that expresses the strength of the feedback. 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~~ that results from a doubling of the 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 and effective radiative forcing in the 4xCO2 experiment by 2 to obtain ~~an estimate~~comparable estimates for ~~the~~ ECS and ERF.

2.3.1 Correction for model drift

~~A basic assumption of the Gregory method is a well-tuned model with~~With a steady state control climate in the piControl experiment~~. It~~ 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~~pre-industrial control climate that we can correct for. After making the ~~piControl experiments~~experiment with pre-industrial forcing with each model modification we first make linear fits of the Q_{net} and tas time series and then use these ~~fits~~regressions to correct the ~~corresponding~~ time series of the corresponding 4xCO2 experiment (Fig. 1), following common practice (e.g. Andrews et al., ~~2012~~2015). 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 tested the impact on the ECS when excluding a few years from the data, and find that the result doesn't change any longer if 4 or more years are excluded. 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

3.13.1 Climate sensitivity in ECE2 and ECE3

Table 2 presents the ECS, net feedback and ERF for the CMIP5 and CMIP6 version of the EC-Earth model. ECS increases from 3.34 K to 4.31 K. Zelinka et al (2020) conclude that the higher ECS of many CMIP6 models is due to a combination of higher ERF and weaker net feedback compared to the model versions that have been used for CMIP5. However, the EC-Earth model is slightly different compared to other models because its ERF doesn't change much between the CMIP5 and CMIP6 version and therefore the different ECS in ECE2 and ECE3 is mainly caused by a different net feedback parameter. The small change of ERF from ECE2 to ECE3 can explain the comparably weak increase of ECS in the EC-Earth model, other models show considerably larger increase between their CMIP5 and CMIP6 versions yet Zelinka et al. (2020) conclude that the differences are not significant.

To analyse the causes for the change in the net feedback parameter look at the response in the 4xCO2 experiments in ECE2 and ECE3. Fig. 2 shows the change in clouds at the end (years 131 to 150) of the in the 4xCO2 experiment relative to the piControl experiment. We find a different behaviour in the versions of the model: ECE2 shows a weaker response in the cloud cover than ECE3, in particular over North Hemisphere Atlantic and Pacific Ocean, while ECE2 shows a stronger response in cloud liquid water path (LWP) in the extratropics. The response of the vertically integrated cloud ice has a similar pattern in ECE2 and ECE3 but is somewhat stronger in ECE3 (not shown). These differences in the response of the cloud fraction and LWP due to a quadrupling of CO2 have also an impact on the cloud forcing (Fig. 3). In ECE2 the response in the CF is weak except at high latitudes which results from the melting of sea-ice in a warmer climate. In contrast ECE3 shows a more pronounced response in the cloud forcing. In the tropics CF becomes more negative and over the Northern Hemisphere Atlantic and Pacific Ocean the response is positive leading to a less negative cloud forcing.

These changes in the response of clouds and subsequently cloud forcing can explain the change in the climate sensitivity of the EC-Earth model when going from the CMIP5 version to the CMIP6 version. The question is then what modifications of the cloud parameterisation during the development of ECE3 play an important role for the changes in the response to an increased CO2 forcing, and what impact these model updates have on the ECS. To study the effects from different model development steps, we roll back the developments that are related to the aerosol and cloud interaction, and then repeat the piControl and abrupt4xCO2 experiments in a series of sensitivity studies.

3.2 Reducing the length of the simulation

Reducing the length of the piControl and 4xCO2 simulations would ~~free valuable computational resources, yet~~make the sensitivity experiments computationally cheaper, but it could only be done if ~~it has a marginal~~the impact on the ECS is small. 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~~not significantly different 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~~3 Reducing the model resolution

~~Table 2 also lists~~In another attempt to reduce the ~~results from a reduction~~computational costs of the sensitivity simulations we test if the horizontal and vertical resolution~~. For~~ of ECE3 could be reduced to that of ECE2 (Table 3). In these ~~experiments~~tests we ~~change~~have changed the resolution (only in the atmosphere) first only in ~~two steps to bring it into agreement with the resolution that was used for CMIP5.~~the horizontal and then in both horizontal and vertical. The ECS changes slightly from 4.3 K to 4.2 or stays ~~at~~close to 4.3 K when only the horizontal or both the horizontal and vertical resolution ~~are~~has been changed. These changes in ECS are small compared to the difference in ECS between ~~the CMIP5 and~~ECE2 and ECE3. An important result of these tests is that the change in the resolution of the EC-Earth model from CMIP5 to CMIP6 ~~model versions. The~~is not responsible for the change in ~~model~~the climate sensitivity and the reasons have to be sought elsewhere, Because the changes in the resolution ~~thus cannot explain the increase in ECS. Since resolution changes~~ don't ~~contribute much to~~have only a marginal impact on the ECS ~~difference all further~~the 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~~4 Sensitivity to the description of aerosols and their impacts on ~~clouds~~the cloud forcing

~~Table 3 presents the~~The results from a series of sensitivity experiment with the aerosol scheme in ~~EC-Earth3-Veg~~ECE3 are shown in Table 4. 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~~25 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 3.554 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 (1st indirect effect) the ECS increases further to 3.881 K, and if in addition the activated aerosol particles are also allowed to impact cloud microphysics the ECS becomes 4.328 K. This last value is similar to the ECS from the CMIP6 experiments (4.31 K) 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 droplet 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. This finding is further supported by the change in the net CF in these sensitivity experiments. The largest change in the CF is found when the 2nd indirect aerosol effect is activated. In that case the cooling by clouds becomes less strong (CF increases) which reduces the feedback from the warming induced by the quadrupled CO2 concentrations resulting in a higher ECS.

Kiehl (2007) has shown a correlation between stronger aerosol forcing and higher climate sensitivity in climate models. Thus, byBy 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 2nd order effect as all our resultswe have shown here were obtained withthat the same tuning ofECS can also change without changing the model, tuning. It is possible to get back the only changes in the climate sensitivity experiments are related to of ECE2 with the new ECE3 model when reverting the linkage betweenchanges in the representation of the aerosol cloud droplet number concentrations and effective radius or autoconversion efficiency. interaction without any retuning of ECE3.

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-Earth3when going from ECE2 to ECE3, 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~~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 only. 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.

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.

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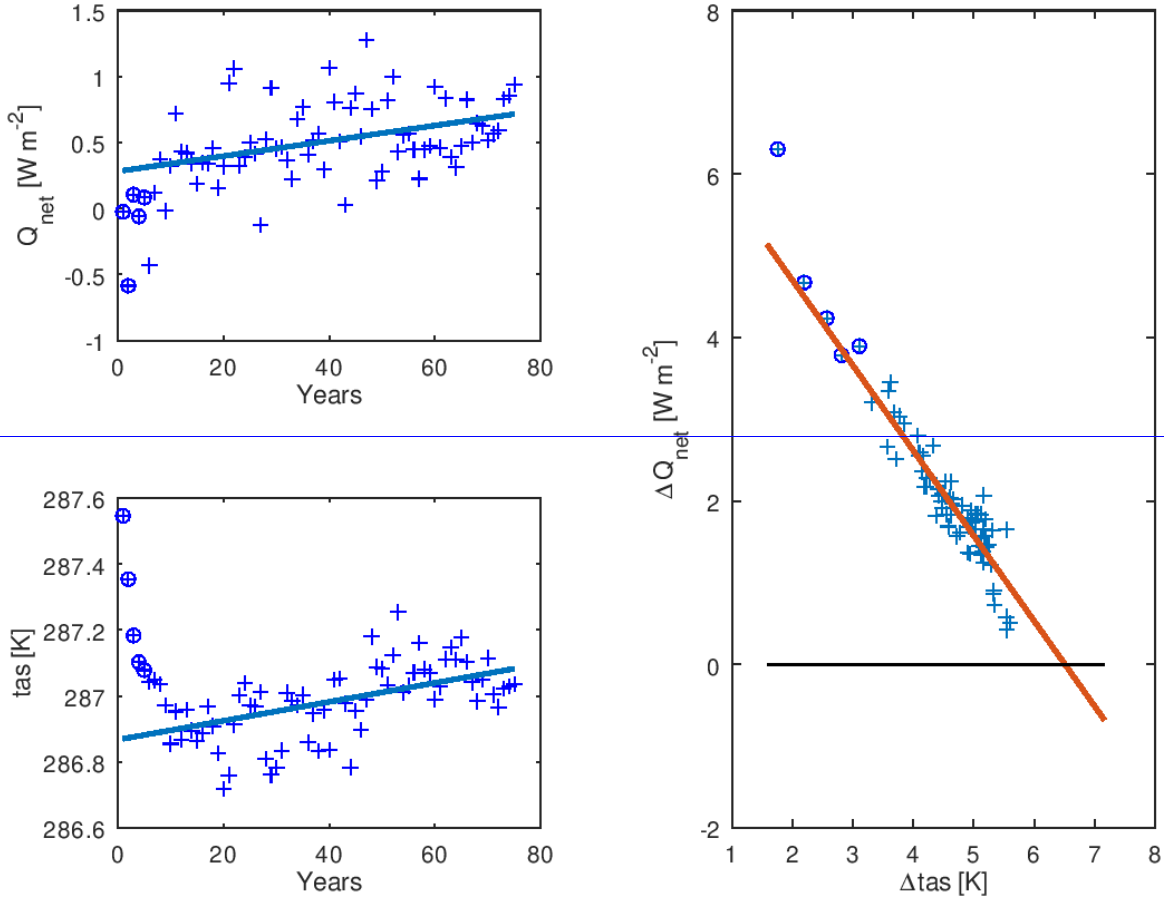

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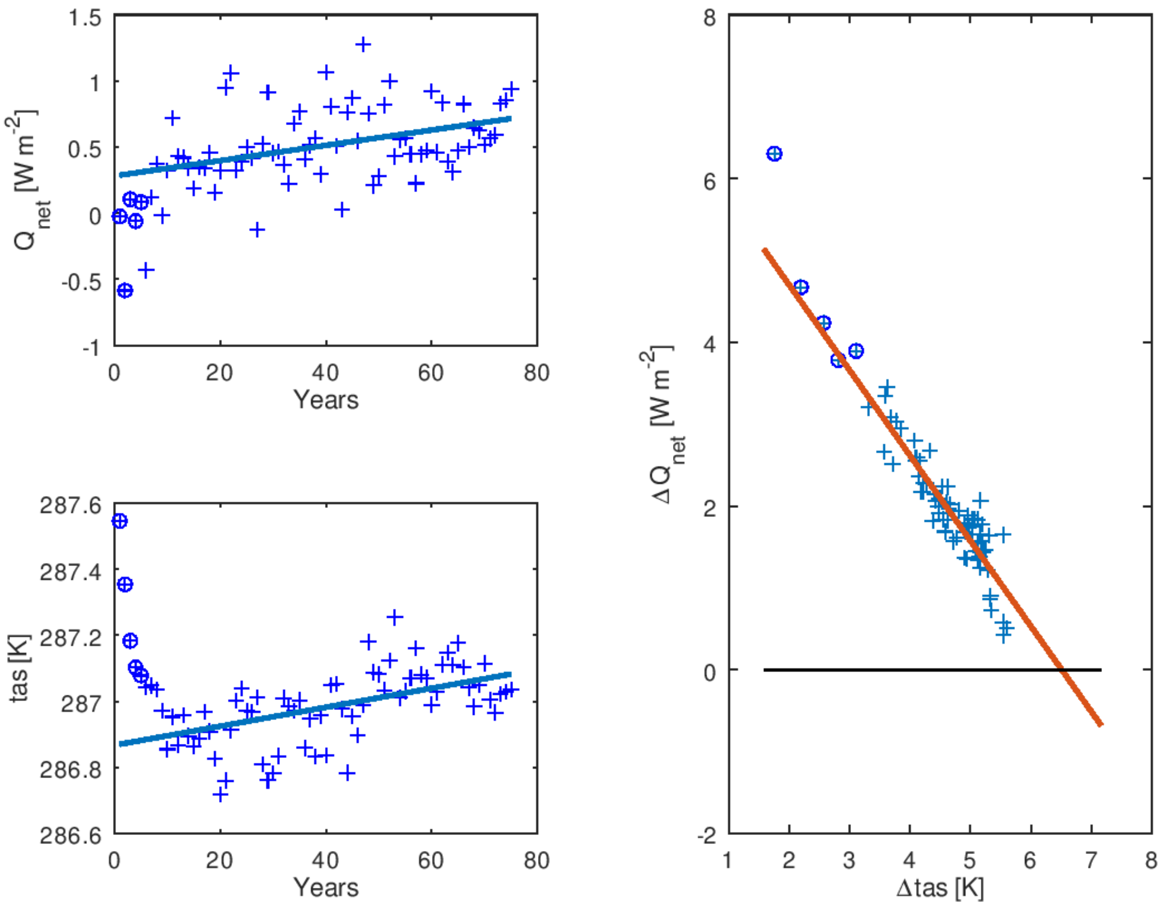

Figure 1, left: Timeseries of Q_{net} and tas in ~~the piControl run~~a pre-industrial simulation with CMIP5 aerosols and without explicit cloud droplet activation. The model isn't tuned for this configuration and therefore experiences a drift over time. The linear ~~fit~~regression (solid) in the Q_{net} 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 with "o" in the plot) are excluded when computing the linear fit. Right: Gregory plot from the 4xCO2 experiment for ~~this~~the same model configuration after correcting for offset and drift in the corresponding ~~piControl~~ experiment with pre-industrial forcing. 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.

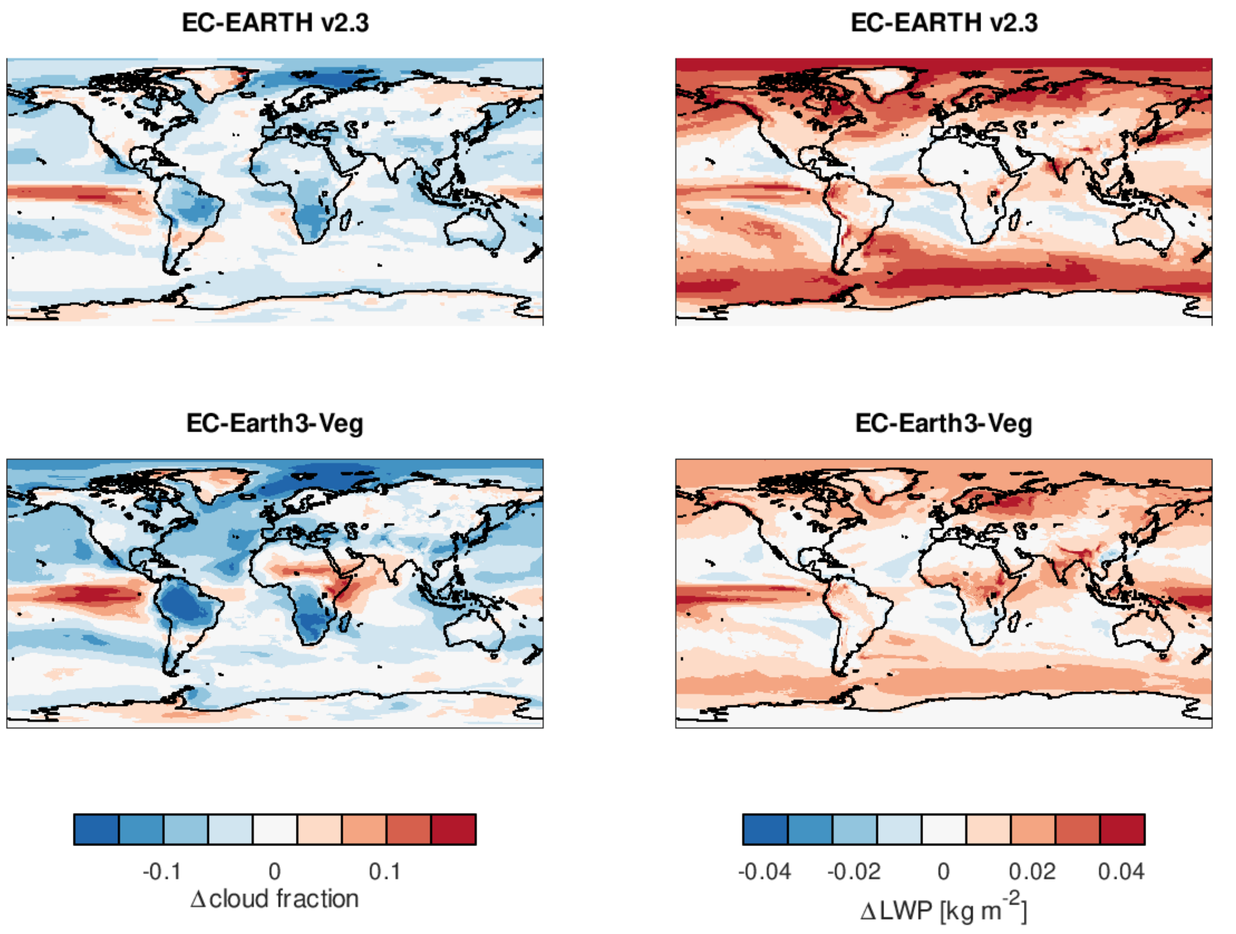

Figure 2. Response of cloud fraction (left) and LWP (right) to a quadrupling of CO_2 in ECE2 (top) and ECE3 (bottom).

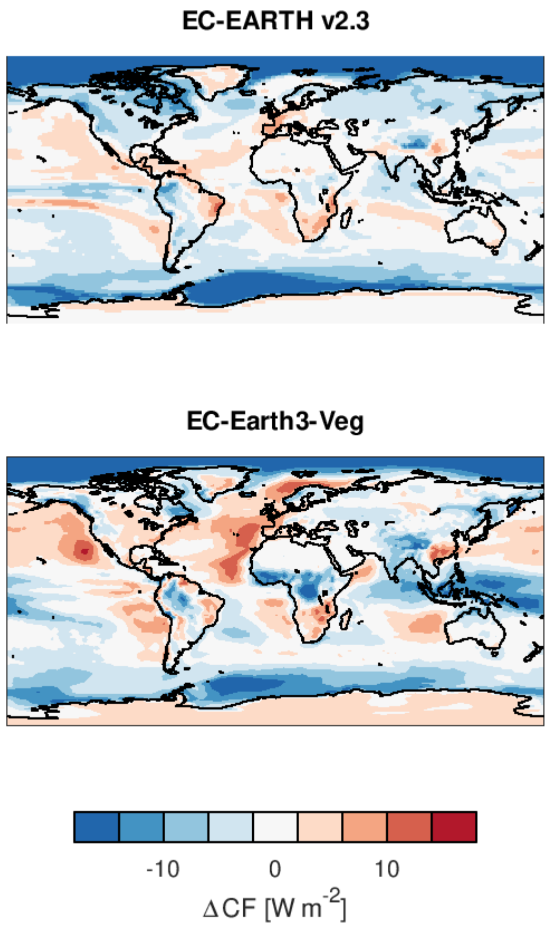

Figure 3. As Fig. 2 but for net cloud forcing.

		EC-Earth2 (ECE2)	EC-Earth3 (ECE3)
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 (125 km)	T255L91 (80 km)
	Ocean	ORCA1L42 (1 deg)	ORCA1L75 (1 deg)

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

MIP	**Model**	**ECS**	**λ**	**ERF**
CMIP5	EC-Earth2	3.34 ± 0.05	-1.01 ± 0.03	3.37 ± 0.13
CMIP6	EC-Earth3-Veg	4.31 ± 0.08	-0.79 ± 0.03	3.41 ± 0.17

Table 2: Equilibrium climate sensitivity (ECS in K), net feedback parameter (λ in W m^{-2} K^{-1}), and effective radiative forcing (ERF in W m^{-2}) in the CMIP5 and CMIP6 version of the EC-Earth model

Model	**Length (years)**	**Resolution**	**ECS**	**Remarks**
EC-Earth2	150	T159L62-ORCA1L42	3.334 ± 0.05	Used in CMIP5
EC-Earth3-Veg	150	T255L91-ORCA1L75	4.331 ± 0.08	Used in CMIP6
	75	T255L91-ORCA1L75	4.327 ± 0.15	Reduced length
		T159L91-ORCA1L75	4.203 ± 0.12	Reduced length + reduced horizontal resolution
		T159L62-ORCA1L75	4.311 ± 0.12	Reduced length + reduced horizontal and reduced vertical resolution

Table 23: 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 (K)	Net CF ($W\ m^{-2}$)
~~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~~25 ± 0.07	-21.54 ± 0.32
Aerosols as in CMIP6	As for CMIP6	As for CMIP5	As for CMIP5	3.~~5~~54 ± 0.12	-21.31 ± 0.34
	As for CMIP6	As for CMIP6	As for CMIP5	3.~~8~~81 ± 0.12	-21.69 ± 0.26
	As for CMIP6	As for CMIP6	As for CMIP6	4.~~3~~28 ± 0.12	-18.07 ± 0.28

Table ~~3~~4: Sensitivity of ECS and net CF to different realisations of the aerosol-cloud interaction processes. All experiments ~~except those labelled “control” are~~were done with the low resolution (T159L62) configuration of EC-Earth3-Veg and stretch over only 75 years ~~long~~.