

Dear Holger,  
Below please find a point-by-point response to the reviews as well as the marked-up manuscript.  
Cheers, Ulrike

**Response to reviewer 1:**

We thank the referee for his/her valuable comments and suggestions. We marked the responses to the comments in italics.

General Comments:

1. Model Configuration. Several aspects of the model set-up and experiments section are not sufficiently explained and as a result it is unclear how the way the models were set up and run might impact the results. Specifically:

Page 7 Line 25: How are the ALL\_ICE and ALL\_LIQ simulations set up?

The simulation ALL\_ICE is set-up such that ice crystals grow at the expense of cloud droplets, which evaporate at temperatures  $\geq 0$  °C, that all cloud water that is advected to colder temperatures is forced to freeze instantaneously and all the detrained cloud condensate is in the form of ice at temperatures  $\geq 0$  °C. The simulation ALL\_LIQ is set-up such that heterogeneous freezing is turned off in the temperature range between 0 and -35 °C and detrainment of ice crystals from convective clouds is restricted to temperatures below -35 °C. Ice crystals sedimenting from colder into warmer cloud layers melt at -35 °C. The number of cloud droplets which freeze at temperatures below -35 °C had to be reduced by a factor of 100 in order to keep the ice crystal number concentration realistic in simulation ALL\_LIQ. We added this description.

- How do the methods used to modify the model here compare to those in Tan et al. (2016)?

The simulations ALL\_ICE and ALL\_LIQ are as similar as possible as in Tan et al., 2016, but we were more thorough in strictly enforcing this set-up. However, there is one difference such that Tan et al. used results from a fully coupled simulation, while we were using a mixed-layer ocean. We added this.

- Are the changes in ALL\_ICE and ALL\_LIQ applied to all types of clouds globally?

The changes are applied to all layer clouds. Convective clouds in ECHAM are not radiatively active, thus we didn't change the simple microphysics of them. However, we ensured that the detrained condensate, which is a source for large-scale clouds, is detrained in the phase corresponding to the ALL\_LIQ and ALL\_ICE set-ups. We added this as mentioned above.

It was unclear to me why these seven specific configurations (other than ALL\_ICE and ALL\_LIQ), which contain multiple differences other than SLF, were selected given the goal of the study is to determine the impact of SLF on ECS.

You are right. Our primary goal is the impact of SLF on ECS. As also the second reviewer commented on this, we have deleted the section of the aerosol radiative forcing and the two simulations that were exclusively done for this, namely GFAS3.4 and 10/cc. We decided to keep the simulations HET and NOCONV because they influence the distribution of clouds and shed light into ECS.

Page 8 Line 7-10. It is unclear how the various simulations were set up and run. You state that “To calculate ECS, ECHAM6-HAM2 has been coupled to a mixed-layer ocean. (MLO). These simulations were spun up for 25 years and then run for another 25 years, over which the results were averaged.”

- How was the mixed-layer ocean set up (i.e. how are mixed-layer depths and q-fluxes generated) for each of the seven different versions of the model?

A mixed-layer depth of 50 m is used in all simulations. The deep ocean heat flux Q is computed from 25 year-simulations with fixed SSTs (AMIP climatology 2000-2015), which were run for each of the seven different set-ups separately. We added that.

- Are mixed-layer depth and q-fluxes different for the seven different versions of the model? If not, how might this impact results (e.g. Frey et al. (2017) showed that ocean heat uptake changes in response to differences in clouds similar to those, for example, between ALL ICE and REF).

Mixed-layer depths are the same (50 m) but Q-fluxes are different (see our reply to the previous question). We agree that the deep ocean heat fluxes will adjust to the different set-ups, therefore we computed them for each set-up separately.

- How many and what types of simulations were run?

All different simulations are listed in table 1. All of them were run in three different set-ups: (i) atmosphere-only simulations with prescribed SST and sea ice cover using the AMIP 2000-2015 climatology with present-day aerosol emissions and greenhouse gas concentrations, (ii) atmosphere-MLO simulation at 1xCO<sub>2</sub> concentrations with pre-industrial aerosol emissions and pre-industrial levels of the other greenhouse gas and (iii) as (ii) but with 2xCO<sub>2</sub> concentrations. We added that.

- Was a 1xCO<sub>2</sub> (pre-industrial) simulation run for each model configuration?

Yes.

- Was a 2xCO<sub>2</sub> simulation run for each model configuration?

Yes.

- When was CO<sub>2</sub> doubled? Was it before or after the 25-year spin up period?

The CO<sub>2</sub> concentration was doubled before the 25-year spin up period. We added that.

- You state that results were averaged over 25 years after model spin up. In the 2xCO<sub>2</sub> case, were those 25 years all after the model had reached a new

equilibrium after doubled CO2?

Yes.

- Were fixed-SST runs accomplished as stated in Table 2? If so, which years? Were observed SSTs used?

Yes, the results in Table 2 are from 20-year atmosphere-only simulations with present-day CO2 concentrations, present-day aerosol emissions and prescribed SSTs and sea ice cover. The present-day reference year is 2008. A climatology for the years 2000-2015 of AMIP SSTs and sea ice cover was used. Greenhouse gas emissions are for the year 2008. Aerosol emissions are for the years 2003 to 2012 and after that year 2008 values were used.

- Were any fully-coupled model runs accomplished?

No.

Table 1 could be expanded to include information to clarify many of the points above.

We added the information in the main text.

Page 8 Line 11-15: Model Tuning. Two parameters which impact precipitation efficiency were used to tune the various model configurations. Several places in the paper (e.g. Page 11 Lines 405, Page 12 Lines 6-7, Page 22 Lines 26-28) reference these tuning changes to explain differences between the model configurations, but a discussion of if and how tuning might impact ECS or cloud feedbacks is not included. Does model tuning impact ECS or cloud feedbacks? According to the study by Klocke et al. (2011), only the entrainment rate for shallow convection and the cloud mass flux above the level of neutral buoyancy noticeably influence climate sensitivity. While they did not change the conversion rate from cloud water to rain in stratiform clouds, they did that for convective clouds and found a negligible influence. Judging from our results in Figure 6, we do not expect a large influence. Testing this, would be a study on its own and is thus beyond the scope of the present study.

2. Comparison of results with Tan et al. (2016) The results from this paper are contrasted with Tan et al. (2016) who showed a monotonic increase in ECS with increasing SLF in CAM5. In two places (Page 3 L20-21 and Page 25 L1-2) the authors state that the Tan et al. results should be treated with caution because the climate in their models was not “the most realistic”, citing Gettelman and Sherwood (2016). This brings up two comments:

a) What about the Tan et al. (2016) model climate(s) is unrealistic that would impact ECS estimates? Are the model climates assessed in this paper more realistic? The authors compare their models to observations several ways in Table 2, but no direct comparison to Tan et al. is mentioned. The only direct comparison I could make is precipitation rate, which is similar in the Tan et al. models (their Table S2) and the model realizations presented here.

As far as we know their clouds over the Southern Ocean consist of too much ice, i.e. their negative cloud phase feedback is too strong. The global mean temperature in their CALIOP-SLF1 and CALIOP-SLF2 is 2-3 degrees lower than in their reference simulation. As climate feedbacks are state dependent, especially those related to ice, a colder reference climate will have implications for their estimates of ECS.

b) Gettelman and Sherwood (2016) also reference another version of CAM (Kay et al., 2016) which they state has a more realistic climate than that of Tan et al. (2016). Frey and Kay (2017) assessed the ECS of this “more realistic” version of CAM and showed an ECS increase similar to that in Tan et al. The Frey and Kay (2017) result may suggest that the Tan et al. result is not an artifact of an unrealistic climate, and should be discussed along with the Tan result.

Thanks for pointing this out. We now refer to Frey and Kay (2017) in this context and revised this paragraph in question.

Specific Comments:

1. Page 2 Lines 9-10: “Here we evaluate the increase in the global annual mean surface temperature ( $\Delta T_s$ ) at the time of a doubling of carbon dioxide ( $CO_2$ ) with respect to pre-industrial concentrations”

- This is misleading. The only warming metric assessed in this paper is ECS, which is the equilibrium global mean surface warming resulting from a doubling of  $CO_2$ . Not the warming at the time of doubling  $CO_2$ .

We changed that.

2. Page 2 Line 10: The forcing due to a doubling of  $CO_2$  is model-dependent (e.g. Forster et al. 2013). Is the 3.7 W m<sup>-2</sup> listed here an average value among IPCC AR4 (Solomon et al., 2007) or the value from ECHAM6-HAM2?

We used this value just to indicate the magnitude of the  $CO_2$  forcing. We know mention that it is an average value from the IPCC AR4 models.

3. Page 2 Lines 11-14. This discussion of TCR and ECS is misleading as it appears to imply that they are both in part defined by the model runs used to estimate them.

- “ $\Delta T_s$  can be calculated in different ways”. This is confusing. I think you mean that there are two metrics that describe the temperature response to a doubling of  $CO_2$ . TCR (warming at the time of  $CO_2$  doubling after a 1%/yr increase in a fully-coupled model) and ECS (warming at equilibrium after a doubling of  $CO_2$ ).

We changed that.

- “or it can be obtained from coupled atmosphere - mixed layer ocean (MLO) simulations that are abruptly exposed to a  $CO_2$  doubling relative to pre-industrial concentrations and then run until a new equilibrium has been established (equilibrium climate sensitivity, ECS)”

- This definition of ECS is misleading. A MLO is not necessary to estimate ECS. ECS is the global, annual mean warming at equilibrium after a doubling of CO<sub>2</sub>. It is commonly estimated using MLO models (e.g. in IPCCAR4 Meehl et al., 2007) or fully coupled models (e.g. Gregory et al., 2004; and in IPCC AR5 Flato et al., 2013).

We changed that.

- When comparing results to Tan et al. (2016), it is important to note that they did not use a MLO to estimate ECS. This could impact the comparison because different methods can produce differing ECS estimates (e.g. Frey et al., 2017).

Thanks for pointing this out. We now refer to Frey et al., 2017 for this.

4. Page 3 Lines 6-15: This paragraph should cite some of the extensive literature on the negative optical depth feedback. Some relevant papers are Mitchell et al., 1989; McCoy et al., 2015; Ceppi et al., 2016; and the review paper by Storelvmo et al, 2015.

Thanks for the references, we added some.

5. Page 3 Line 25: The transition between ECS and aerosol radiative forcing could be improved. It was unclear why aerosol forcing was being discussed until the last sentence of this paragraph.

As mentioned above, we deleted the entire section to make the paper more concise.

6. Page 3 Lines 30-35: Are the simulations ALL\_ICE and ALL\_LIQ discussed here from this paper or from a previous paper? Please clarify.

They are from the Lohmann (2002) study. We made that clearer.

7. Page 7 Line 19: Please define the acronym GFAS.

Not relevant any longer as we deleted this simulation.

8. Section 4 (Pages 8-14): “Comparison of ECHAM6-HAM2 with observations” This section contains a lot of information and details on the observations used. I found it hard to pick out the comparisons of the model with observations among all of these details. It might be easier to read if the information on the observations used are presented first, and then the comparison with observations is done in a more compact way.

We prefer to keep the description of the observations where they are introduced.

A summary of the different observations can be found in Table 2 and Figure 1.

9. Page 9 Line 35: “Nl,oc,top reaches values of  $> 100$  cm<sup>-3</sup> between 30 N and 80 N in the observations (Figure 1).” I do not see observed data north of 60 degrees North in Figure 1d.

Thanks for spotting this. We corrected that.

10. Page 12 Line 6: In Figure 1 it does not appear that ALL\_ICE underestimates cloud ice in the extratropics, especially in the Southern Hemisphere.

You are right. We corrected that.

11. Page 12 Line 31 and Page 13 Line 4: Please state which simulation is “the one with the extreme changes in SLF.”

We now explicitly refer to simulation ALL\_LIQ.

12. Page 13 Lines 9-10: Does the fact that all seven model simulations overestimate the net negative radiative effect of clouds have an impact on the cloud feedbacks predicted by the models?

That is a good question. We do not have any simulations in which the net CRE is smaller so we have no way to answer this question. We would speculate similarly as we did for the last question of your major comments, that we do not anticipate a large sensitivity because our model is generally not that sensitive to model changes as seen in Figure 6.

13. Page 14 Line 2: Here Figure 3, which shows how SLF varies between models, is introduced. Is it possible to include SLF comparisons in Table 1 and Figure 1 along with all of the other comparisons with observations?

This would be possible but we find this visual comparison more appealing than adding 6 rows to Table 1. We prefer to keep this figure separately.

14. Page 14 Line 19: ECS is the temperature at equilibrium after a CO<sub>2</sub> doubling. Not “at the time of CO<sub>2</sub> doubling”

We corrected that.

15. Page 15 Line 3: First reference to table 3. In Table 3, how are the changes defined? Are they the changes in response to doubled CO<sub>2</sub>? If so, which years from which simulations are used?

Yes, these are the changes in response to CO<sub>2</sub> doubling from the years 26-50. We added this in the table caption.

16. Page 16 Lines 1-5: The hypothesis put forward here is very similar to the hypothesis of Frey and Kay (2017). From Frey and Kay 2017: “Climate models overestimate the magnitude of the negative cloud phase feedback at extratropical southern latitudes because they overestimate the amount of cloud ice present in the mean state. Further, since negative feedbacks reduce warming, models with negative cloud phase feedbacks that are too large may underestimate the amount of warming resulting from greenhouse gas forcing, quantified by their equilibrium climate sensitivity.”

Thanks for pointing us to this paper, we now cite them when discussing our hypothesis.

17. Page 16 Line 9: First reference to Figure 5. In Figure 5, why is the cut off for the extratropics 60 degrees North and South? The negative cloud phase feedback acts poleward of these latitudes, especially in the Southern Hemisphere (e.g. Zelinka et al., 2012, Figure 4d).

For consistency, we now show Figure 5 polewards of 40°.

18. Page 22 Lines 1-2: The fact that the cloud feedback increases between

simulations without impacting ECS is an interesting finding. If the mixed-layer oceans are different between the different simulations, do differences in heat uptake impact this result? Are you able to assess other feedbacks (e.g. lapse rate, water vapor, surface albedo, etc.) to determine if there is compensation?

We did not diagnose any other feedbacks and because of this need to speculate about the compensating processes. The heat uptake by the ocean is only relevant for TCR because it vanishes in equilibrium as we discuss in the introduction.

19. Page 25 Lines 12-15: This section is unclear. How is shortwave radiation at high latitudes related to the tops of deep convective clouds and low level tropical clouds? In the next sentence, what are “all of these other clouds”?

We want to make the point that only mixed-phase clouds with tops between 0 and  $-35^{\circ}\text{C}$  matter for climate sensitivity but arguing why all other cloud types do not matter. We will make that clearer.

Technical Comments: All Figures: Please specify which years from each model run (e.g. years x-y from 1xCO<sub>2</sub> runs, years a-b from 2xCO<sub>2</sub> runs) were used to create each figure? Which years were used for the observations presented?

We added the details in all figures.

Page 1 Line 13: Change “frequent” to “frequently” Page 2 Line 27: Change “not” to “nor” Page 2 Line 30: Change “somehow” to “somewhat” Page 2 Line 31: Change “contributor” to “contributors” Page 2 Line 32: Change “positiv” to “positive” Page 8 Line 5: insert comma after ERF<sub>ari+aci</sub>

These typos have been corrected.

Page 10 Figure 1: Label the panels a, b, c, etc. Are these model runs the MLO runs or fully-coupled runs?

The panels are now labeled with a,b,c,etc. The results are from the atmosphere-only simulations for the present-day climate. We will add that.

Page 11 Table 2: What years are used for the observations presented here? The caption specifies some of the data sets but not all. Are the same years used in the model runs?

We added the details about the observations in Figure 1 and refer to Figure 1 for this. The majority of the observations is averaged over 2003-2012. Therefore, we also use the average over the years 2003-2012 from the atmospheric-only present-day simulations for this comparison.

Page 14 Figure 2: What years are used for the observations presented here? Are the same years used in the model runs?

As mentioned above, we added that.

Page 17 Line 22: The sentence beginning on this line is very long and hard to follow.

We rewrote this sentence and split it in two.

Page 20 Line 6: Is “this region” the subtropics?

Yes, we now say that explicitly.

References:

Klocke, D., R. Pincus, and J. Quaas (2011), On constraining estimates of climate sensitivity with present-day observations through model weighting, *J. Clim.*, 24, 6092-6099, doi:10.1175/2011JCLI4193.1.

**Response to reviewer 2:**

We thank the referee for his/her valuable comments and suggestions. We marked the responses to the comments in red. Specific Comments

1. Page 1, Line 13: should be “most frequently”

Changed

2. Page 1, Line 19: dominate what? Inter-member spread in ECS?

Other feedbacks dominate the overall cloud feedback. We specified that.

3. Page 2, Line 1: “uncertainty” should be plural

Changed

4. Equation 1:  $\Delta H$  should be deleted. It is not a separate term in the global TOA energy budget, and is roughly equivalent to  $\Delta R$

We would argue that  $\Delta H$  matters for the global TOA energy budget. Before equation (2), we acknowledge that it vanishes when a new equilibrium is reached.

We prefer to keep it as is.

5. Page 2, Line 9: suggest replacing “at the time of” with “in response to”

Changed

6. Introduction section: there are many references to the IPCC reports rather than to the original literature.

We now refer to the original papers by Dufresne and Bony (2008) and to Yokohata et al. (2010).

7. Page 2, Line 12: TCR is specifically defined for runs in which CO<sub>2</sub> is increased 1

We added that.

8. Page 2, Lines 5-20: I find it odd that there is no mention of the standard method for computing ECS in fully coupled AOGCMs used in CMIP5: that of Gregory et al. (2004).

We now mention the Gregory method.

9. Page 2, Lines 22-23: this line about reversing the sign of feedbacks is confusing and unnecessary

We deleted this sentence.

10. Page 2, Line 23-24: the residual term (which does not appear in any equation, so it is unclear what it refers to), I believe, also includes errors in the kernel method. Also, the citation is missing.



We added that the residual term also includes errors in the kernel method and added references to Soden et al. (2008) and Shell et al. (2008).

11. Page 2, Line 27: “not” should be “nor”

Corrected

12. Page 2, Line 31: “contributor” should be plural; “are” should be “is”, or rephrase sentence appropriately

Corrected

13. Page 2, Line 33: “positive” is misspelled; seems like there is a missing word(s) after “with”

Corrected

14. Page 3, Lines 12-13: please provide references for this statement about precipitation efficiency

We added references.

15. Page 3, Line 21: should be “viewed with caution”

Corrected

16. Page 3, Line 28: strictly speaking, ECS and TCR are completely independent of aerosol forcing. Perhaps you mean observational estimates of ECS and TCR?

We deleted everything related to aerosol forcing to make the paper more precise.

17. Figure 1: this has no (a), (b) labels, though the panels are referred to as such in the caption

Labels have been be added to Figure 1.

18. Page 12, Line 15: “to initially to”

Corrected

19. Page 12, Line 30: reference to Loeb should be updated to the latest EBAF product (Loeb et al. 2017)

We added reference to Loeb et al. (2018).

20. Page 13, Line 27: “noticeable” should be “noticeably”

Corrected

21. Page 13, Line 29: “too high” - suggest restating as “too large” so as to not confuse magnitude of the peak with vertical location in the atmosphere

Corrected

22. Page 14, Line 20 - Page 15, line 3: rephrase/combine to remove redundancy  
The redundant sentence has been removed.

23. Page 16, Line 1: what hypothesis? Is there are reference to a paper, or to something stated earlier?

The hypothesis is explained in the abstract. We added a more thorough description here and referenced two new studies on this topic (Frey and Kay, 2017 and Bodas-Salcedo, 2018).

24. Page 16, Line 2: “absorbed in clouds” - do you really mean this? Or not enough SW reflected back to space by clouds?

You are right, we meant not sufficient SW is reflected back to space, we changed that.

25. Page 16, Line 6: “proof” should be “prove”

Corrected

26. Page 16, Line 10: I think “single column” refers to each sub-column, as in those generated by COSP; probably need to be more clear here, and refer to COSP (Bodas- Salcedo et al. 2011)

We added the reference to COSP-ISCCP and Bodas-Salcedo et al. (2011) and refer to the sub-columns of the simulator.

27. Figure 5: These all look very different to me, and suggest that there are major differences in mean-state clouds as a function of CTP and tau that may be as important or more important in driving feedback differences than can be gleaned from looking at Figs 1-3 and Table 2. I suggest showing the mean-state histograms too.

We added mean-state histograms.

28. Page 17, Lines 5: question mark before citation; also the original citations for this technique are Zelinka et al. (2012a, b), unless you are performing the decomposition separately for low clouds vs non-low clouds, in which case this citation is appropriate

We do not see a question mark....We changed the citation to Zelinka et al. 2012a,b because we don't look at the differences in low vs. non-low clouds.

29. Page 17, Line 21: suggest inserting “liquid” before “cloud droplets”

Liquid cloud droplets would be redundant because cloud droplets are always liquid. Therefore, we kept cloud droplets.

30. Page 20, Lines 3-6: it is not obvious to me that stronger entrainment drying should lead to decreased low cloud optical depth rather than low cloud coverage; also “thin” should be “thin”.

A decrease in cloud coverage will also lead to a decrease in cloud optical depth. We kept that but corrected “thin” to “become thinner”.

31. Page 21, Line 3: “optical” should be “optically” (twice)

Corrected

32. Page 21, Lines 4-8: is the altitude feedback computed just for free tropospheric clouds as advocated in Zelinka et al (2016), or is it done for all clouds?

We used both methods (feedbacks calculated for all clouds and for low and non-low clouds separately) and found qualitatively similar results. For simplicity we use the feedbacks from all clouds but mention new that the decomposition by low and non-low clouds gives qualitatively similar results.

33. Page 21, Line 12: should “affected” be “compensated”?

We think that both adjectives would do, but compensated sounds more precise. We changed that.

34. Page 21, Lines 9-21: It is not clear whether this paragraph is mostly speculation, or if the authors have performed analysis to convince themselves but are not showing it to the reader. The notion that the latent heat of fusion provides additional buoyancy allowing clouds to penetrate higher has been shown to be incorrect, since the atmosphere adjusts its temperature profile to closely match the temperature profile of convection (Seeley & Romps 2016). Moreover, when I look at Figure 5, I see huge CTP anomalies for thick clouds in ALL\_LIQ, which are not seen for the other three simulations shown. Is this because the other simulations have few clouds at these large tau values in the mean state, so there is no way of getting a strong altitude feedback, or is the upward shift truly different in the ALL\_LIQ case? The change in cloud fraction profile (Figure 7) looks roughly the same in all models, so my sense is that the larger altitude feedback in ALL\_LIQ comes from the fact that clouds are optically thicker (higher emissivity) in the mean-state, not something to do with how much the clouds rise in that simulation vs other simulations.

Thanks for your comments. You are right that ALL\_LIQ has more thicker clouds in the mean state (as also seen in the vertical profile of cloud liquid water in Figure 2). At the same time, the change in cloud liquid water profile in the warmer climate is very different in this simulation. This causes the altitude increase in optically thicker clouds as you suggested. We corrected our argumentation.

35. Page 21, line 35: “large increase in cloud top pressure” should be “large increase in cloud altitude feedback” I think.

You are right, we meant “cloud top pressure feedback”. We added “feedback”.

36. Page 22, first paragraph, also page 24, lines 17-18: I found this paragraph very hard to follow, and it seems like a lot of speculation to me (though not acknowledged as such). First, models run at GCM resolution typically cannot simulate convective aggregation, so it is doubtful that that is playing a role here. Second, Figure 9 (which also lacks a caption) does not really help elucidate the processes described. A zonal mean  $\Delta$ OLR figure would be a step in the right direction, so the different runs could be compared more easily. I am not aware of anything in Hartmann and Larson (2002) describing convective aggregation or a negative feedback from decreased high cloud coverage. I think the better citation is Bony et al. 2016, which relies on principles from Hartmann and Larson (2002).

On page 22, line 2 of the original manuscript we hypothesize why ECS is not changing, i.e. we acknowledged that we speculate, but we rewrote the paragraph to make that clearer.

In our version, OLR had a caption. Anyhow instead of showing maps of changes in OLR, we now show zonal mean changes of all radiative fluxes in order to provide a complete picture.

You are right that the clustering of convective clouds in the warmer climate is best described by Bony et al. 2016. We added that. We also now refer to an older study with ECHAM which showed a clustering of convection in a simulation in which cirrus scheme had an emissivity of one, i.e. where their infrared optical thickness was highest.

37. Section 6: It is never described how  $ER_{Fari+aci}$  is computed, and with what type of experiments (fixed SSTs but modified aerosol loading, as in CMIP5?). Can the ari and aci components be separated to get better insights about direct and indirect effects?

As stated above, we removed the entire section on  $ER_{Fari+aci}$  to make the paper more concise.

38. Page 24, lines 1-9: In and of itself, a large present-day aerosol forcing does not guarantee large TCR or ECS. I think you need to insert words to clarify that “given the observed change in surface temperature and ocean heat uptake, a large present-day aerosol forcing. . .” Similarly, TCR as strictly defined does not depend on  $ER_{Fari+aci}$ ; it is simply the temperature change at the time of doubling for a simulation with  $CO_2$  increasing at 1% per year. I think you mean “TCR inferred from observations”.

As stated above, we removed the entire section on  $ER_{Fari+aci}$  to make the paper more concise.

39. Page 24, line 11: Suggest replacing “faster” with something clearer.

As stated above, we removed the entire section on  $ER_{Fari+aci}$  to make the paper more concise.

40. Page 24, line 12: it is not clear what “that” refers to, or if it is shown in the paper.

As stated above, we removed the entire section on  $ER_{Fari+aci}$  to make the paper more concise.

41. Page 24, line 32: “variable values” is a little awkward. Also “in contrary” should be “in contrast”

Changed to “calculated values”. The spelling has been corrected.

42. Page 24, lines 6-7: Is this Southern Ocean bias really getting to the heart of the matter, or is it just another symptom of the fundamental issue? My understanding is that SW reflection by clouds in models whose clouds are too optically thin (e.g., due to having too low SLF) is overly sensitive to phase changes because phase changes in these models can actually have a non-negligible effect on cloud optical depth. In contrast, phase changes in in models whose mean-state clouds are not too optically thin have a negligible effect on cloud optical depth.

Is this correct, and if not, could this important point be stated more clearly in the paper? It would be nice if this could be shown more unambiguously in the paper. Is it demonstrated anywhere that the models with larger SLFs actually have LWPs that put them in the range of optical depths where albedo is saturated and hence insensitive to phase changes?

Yes, you are right that this problem is not limited to clouds over the Southern Ocean, but there it is most obvious. Albedo only saturates when optical depth exceeds 500 (Kokhanovsky et al., ACP, 2007). Thus, it is not so much the actual saturation than it is the sensitivity of albedo to changes in optical depth that becomes much less at high optical depths.

43. Page 24, lines 8 and 10: “absorbed in clouds” - I don’t think this is what you mean

Corrected

44. Page 24, line 32: as far as I can tell, Forster et al (2013) only plots ECS against the total radiative forcing, not ERFari+aci.

As stated above, we removed the entire section on ERFari+aci to make the paper more concise.

45. General comment: It seems that there should be some mention of the various studies finding observational support for a model overestimate of the cloud optical depth feedback at middle latitudes (Gordon & Klein 2014, Ceppi et al. 2016, Terai et al. 2016). Currently the Tan et al study is cited alone but it is really one among several studies that are suggesting a bias, one that likely implicates the too-strong phase feedback.

Agreed. We added more references.

### Response to reviewer 3:

We thank the referee for his/her valuable comments and suggestions. We marked the responses to the comments in red.

General Comments:

It is nice to see that more modeling groups are now looking into the issue of cloud phase and its importance for the overall cloud feedback and climate sensitivity. As such, this paper is a timely and important contribution, but it needs additional work before publication because of the following main reasons: 1) The comparison of supercooled liquid fraction (SLF) with CALIOP, which in many ways forms the foundation for the study, is not done correctly (see comment below).

Sorry, this was written incorrectly. We did do it correctly and now explained it properly.

2) The claim in the abstract that the findings are contrary to those of Tan et al. are not supported by the results. Tan et al. found a systematic change

in equilibrium climate sensitivity (ECS) with changing cloud phase. The same relationship between cloud phase and ECS is found here, but ECHAM6 appears to lie elsewhere on the SLF scale (has higher SLF) to begin with than the model used in Tan et al. (CESM). Many of the model experiments presented are not designed to differ from REF predominantly in their cloud phase, so they shed very little light on this relationship. In my opinion, the experiments that are relevant in this respect are ALL\_ICE, REF and ALL\_LIQ, but for ALL\_LIQ and ALL\_ICE there is at present not enough information provided on how these simulations were designed.

We added a more thorough description of the design of the ALL\_ICE and ALL\_LIQ experiments in section 3. You are right that experiments GFAS3.4 and 10/cc were not designed to address ECS, therefore we removed these two experiments. Cloud phase does change profoundly in simulation NOCONV so we kept this simulation. Likewise, we kept simulation HET because a change in ice cloud optical thickness could impact ECS.

In addition to the above comments, I have the following additional ones (chronologically, so minor and major comments are interspersed):

Page 1, line 13: frequent should be frequently

Corrected

Page 1, line 16: Remove one 'is'

Corrected

Page 2, line 2: uncertainty should be uncertainties

Corrected

Page 2, line 15: Emphasize that TCR is most relevant to present-day/modern climate change.

Done

Page 2, lines 9-17: ECS is really the surface temperature change in response to a doubling of CO<sub>2</sub> once the fully coupled atmosphere ocean have reached a new equilibrium state. Therefore, simulations with an atmosphere and a MLO are only an approximation of that equilibrium state, and that should be acknowledged here. There are papers that compare the differences in equilibrium climate state depending on whether simulations are run with MLO or full ocean. It is important to point out here that the experiments in this paper differ from those of Tan et al. in this respect.

Point well taken, we now acknowledge both aspects.

Page 2, line 29-30: It wasn't the spread that varied between 1.4 and 4.1 K, but the estimates themselves.

Thanks for noting this. It's now corrected.

Page 2, line 30: Do you mean "somewhat higher" here? Page 2, line 31: positiv should be positive

Both error are corrected.

Page 3, line 3: Maybe clarify that it is the mid-latitude storms that shift poleward?

Added

Page 3, lines 16-24: Tan et al. used the fully coupled CESM model, not just the atmospheric CAM5. Please clarify here what aspect of the climate of the CESM simulations in Tan et al. was not realistic. This was not specified in Sherwood and Gettelman (2017), so instead of repeating their unsubstantiated claim it would be better to here explain what specifically was unrealistic in those simulations. Tan et al. also did not claim that ECS in CESM was too low (it is actually quite high), but that the cloud phase bias in isolation would bias ECS low. Other biases in CESM could potentially bias ECS high.

Agreed. We now state explicitly that we are referring to the cold bias of 2-3 K in those simulations in Tan et al., that best matched the CALIOP results. This would lead to more ice in the present-day climate and bias the cloud phase feedback high.

Page 5, line 13: What is “cloud blinking”?

Cloud blinking occurred in ECHAM6.1 because of a bug in the cloud cover scheme. The cloud cover was either 0 or 1 in a grid box but almost never any fractional cloud cover was produced. This on and off in cloud cover is called cloud blinking. In later model versions (including ECHAM6.3) this bug was removed and fractional cloud cover in grid boxes is simulated.

Page 7, lines 25-27: How were the ALL\_ICE and ALL\_LIQ simulations designed? Did you switch off heterogeneous ice nucleation in ALL\_LIQ? And in ALL\_ICE, did you increase ice nucleation, increase ice crystal growth (through e.g. the WBF process), or both? What about detrained ice/liquid from convection, did you modify that?

We now describe our simulations in more detail.

Page 8, line 3: I’m guessing this should be “horizontal resolution”?

Yes, corrected.

Page 11, line 35 - Page 12, line 1 2: This is a widespread problem in GCMs in general, not just in CAM5/CESM.

You are right. We changed that and added more references.

Page 13, line 35 -Page 14, line 1: This is not the appropriate way to sample the simulated SLF to compare with CALIOP. CALIOP measures SLF for ALL cloud tops, irrespective of their optical depth, but if the cloud top layer has an optical depth  $\geq 3$  it will ALSO be able to retrieve cloud phase from the cloud layer below cloud top. That is very different from only sampling SLF from optically thin clouds ( $\tau < 3$ ) in the simulations, so the comparison to CALIOP in Fig. 3 is not meaningful at this point.

We actually did it correctly but wrote it wrongly. We corrected that.

Page 14, line 8: Do you mean “detrainment” here? It would actually be very helpful to know exactly how ECHAM handles the cloud phase of detrained clouds.

Yes, we meant detrainment. We now explain how we handle cloud phase from detrainment in section 3.

Fig. 4 and related discussion: The simulations presented here are not comparable to the experiments in Tan et al, for the following reasons: With the exception of ALL\_LIQ and ALL\_ICE, the differences between REF and the other experiments go far beyond just cloud phase. Whatever difference (or lack of difference) in ECS relative to REF can therefore not be attributed to cloud phase changes alone. In addition, as pointed out above, SLF is not extracted from the simulations in an appropriate manner, so it is hard to say how SLF would compare if they had been, and since it is unclear how ALL\_LIQ and ALL\_ICE were constructed it is hard to make an informed comparison with the corresponding simulations in Tan et al.

As mentioned above, we did extract SLF correctly, thus the comparison to Tan et al. is justified.

Page 16, line 6: proof should be prove.

Corrected

Table 3: Give two decimals consistently in this table.

We actually prefer to keep the number of decimals according to the value of the quantity. We have 2 decimals for precipitation, where they are needed because the different global mean values are rather similar. For all other quantities 1 decimal is sufficient. To respond to your request, we added one decimal for the oceanic cloud top cloud droplet number concentration.

Fig. 5 shows that there are a lot of other things going on in these simulations other than the cloud phase feedback. Clearly, the ALL\_LIQ cloud changes are very different from those in REF, so the fact that they have a similar ECS is the result of multiple compensating differences between them, cloud phase only being one of them.

We agree. We are now discussing this in more detail.

Fig. 7 and related discussion: This figure, if anything, confirms the findings of Tan et al. if you focus on the simulations here that differ ONLY in their cloud phase. The cloud optical depth feedback changes quite dramatically (becomes less negative) from ALL\_ICE to REF, and a small additional change is seen from REF to ALL\_LIQ. The total change of  $0.5\text{K/Wm}^{-2}$  is very strong. The main difference is that the default ECHAM6 is closer ALL\_LIQ in its behavior, while CESM was more similar to the equivalent of ALL\_ICE. The other experiments have lots of other changes in them beyond cloud phase and are not relevant for



the discussion of the impact of cloud phase on climate sensitivity.

We actually mention that at the very end of section 4. We now discuss that again in the conclusions.

Page 20, line 5: thinnen should be thin

Changed

Page 21, line 3: optical should be optically

Corrected

Page 22, lines 1-2: The only way that a marked increase in the overall cloud feedback can not correspond to a marked change in ECS is if either: i) The simulations had not equilibrated in the analyzed 25 year time periods, or ii) Other climate feedbacks compensate for the change in the cloud feedback. I'm guessing it's the latter, but both aspects should be addressed in the paper. In other words, what was the radiative balance for the respective experiments for the 25 yr time periods analyzed, and how did the other (non-cloud) climate feedbacks change between the experiments?

Unfortunately, we did not diagnose other feedbacks. What we can say is that our simulations are in equilibrium after 25 years, so that is not the problem. We now discuss the hypothesized compensating feedback in more detail.

Page 24, line 31 -33: These findings are not contrary to Tan et al. - the SLF is higher in ECHAM6 than in CESM/CAM, so there is a smaller ECS increase associated with increasing SLF. It is completely consistent with Tan et al., as far as I can tell. A caveat here is obviously that in the ECHAM6 simulations SLF is not calculated the way it has to be in order to be comparable to CALIOP, so once that's corrected the SLF comparison may look different.

See answers to both points above.

# The importance of mixed-phase clouds for climate sensitivity in the global aerosol-climate model ECHAM6-HAM2

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**Abstract.** Clouds are important in the climate system because of their large influence on the radiation budget. On the one hand, they scatter solar radiation and with that cool the climate. On the other hand, they absorb and re-emit terrestrial radiation, which causes a warming. How clouds change in a warmer climate is one of the largest uncertainties for the equilibrium climate sensitivity (ECS). While a large spread in the cloud feedback arises from low-level clouds, it was recently shown that also  
5 mixed-phase clouds are important for ECS. If mixed-phase clouds in the current climate contain too few supercooled cloud droplets, too much ice will change to liquid water in a warmer climate. As shown by Tan et al. (2016), this overestimates the negative cloud phase feedback and underestimates ECS in the CAM global climate model (GCM). Here we are using the newest version of the ECHAM6-HAM2 GCM to investigate the importance of mixed-phase clouds for ECS.

Although we also considerably underestimate the fraction of supercooled liquid water globally in the reference version  
10 of ECHAM6-HAM2 GCM, we do not obtain increases in ECS in simulations with more supercooled liquid water in the present-day climate, contrary to the findings by Tan et al. (2016). We hypothesize that it is not the global supercooled liquid water fraction that matters, but only how well low- and mid-level mixed-phase clouds with cloud top temperatures in the mixed-phase temperature range between 0 and -35 °C ~~are~~ that are not shielded by higher-lying ice clouds are simulated. These occur most ~~frequent~~ frequently in mid-latitudes, in particular over the Southern Ocean where they determine the amount of  
15 absorbed shortwave radiation. In ECHAM6-HAM2 the amount of absorbed shortwave radiation over the Southern Ocean is only significantly overestimated if all clouds below 0 °C consist exclusively of ice and only in this simulation is ECS ~~is~~ significantly smaller than in all other simulations ~~-Hence, the negative cloud phase feedback seems to be important only if the optically thin low- and mid-level mid-latitude clouds have the wrong phase (ice instead of liquid water) in the absence of overlying clouds and the cloud optical depth feedback plays is the dominant cloud feedback.~~ In all other simulations, the  
20 cloud optical depth feedback is weak and changes in cloud feedbacks associated with cloud amount and cloud top pressure, dominate the overall cloud feedback. However, apart from the simulation with only ice below 0 °C, differences in the overall cloud feedback are not translated into differences in ECS in our model. This insensitivity to the cloud feedback in our model is explained with compensating effects in the clear-sky.

# 1 Introduction

Changes in clouds remain one of the largest ~~uncertainty~~ uncertainties for the calculation of the response of the climate system to a given radiative forcing  $\Delta F$  (~~Flato et al., 2013~~) (Dufresne and Bony, 2008). This response can be described with the following equation:

$$5 \quad \Delta F = \Delta R + \Delta H + \lambda \Delta T_s. \quad (1)$$

Here  $\Delta R$  represents the net radiative imbalance at the top-of-the-atmosphere (TOA),  $\Delta H$  is the heat taken up by the ocean,  $\Delta T_s$  is the net change in global annual mean surface temperature and  $\lambda$  is the climate feedback parameter in  $\text{W m}^{-2} \text{K}^{-1}$ .  $\Delta R$  and  $\Delta T_s$  change over time. In addition, some studies suggest that also the heat uptake by the ocean is time-dependent and even  $\lambda$  is not a constant parameter (e.g., Knutti and Rugenstein, 2015).

10 Here we evaluate the increase in ~~the global annual mean surface temperature ( $\Delta T_s$ ) at the time of~~, which results from a doubling of carbon dioxide ( $\text{CO}_2$ ) with respect to pre-industrial concentrations, ~~which amounts to i.e. from a  $\Delta F_{2x\text{CO}_2} =$  on the order of  $3.7 \text{ W m}^{-2}$  (Solomon et al., 2007).  $\Delta T_s$  can be calculated in different ways. It can be taken~~ There are two metrics that describe the temperature response to a doubling of  $\text{CO}_2$ , the transient climate response (TCR) and the equilibrium climate sensitivity (ECS). TCR is estimated at the time of  $\text{CO}_2$  doubling from atmosphere GCM simulations in which the  $\text{CO}_2$  concentration increases by 1% per year and that are coupled to a dynamic ocean at the time of  $\text{CO}_2$  doubling (transient climate response, TCR, (e.g., Flato et al., 2013)) or it can be (e.g., Flato et al., 2013). ECS is obtained from coupled atmosphere - mixed layer ocean (MLO) ocean simulations that are abruptly exposed to a  $\text{CO}_2$  doubling relative to pre-industrial concentrations and then run until a new equilibrium of the climate system has been established (equilibrium climate sensitivity, ECS). This requires coupling of the atmosphere GCM to a fully coupled dynamic ocean model (e.g., Gregory et al., 2004; Flato et al., 2013). As such a coupled system takes a long time to reach a new equilibrium, sometimes ECS is approximated from coupled atmosphere - mixed-layer ocean (MLO) climate models (e.g., Meehl et al., 2007; Randall et al., 2007).

15 ECS can also be determined from the so-called Gregory method (Gregory et al., 2004), in which the top-of-the-atmosphere radiative flux is regressed against the annual global averaged surface air temperature change. While TCR is more relevant to present-day climate change because it is obtained from transient simulations that at the time of  $\text{CO}_2$  doubling have not reached a new equilibrium climate, it is more expensive to calculate because it requires fully coupled atmosphere-ocean models model simulations over the whole period. Therefore we focus on ECS in this paper. At the time of the new equilibrium in the coupled atmosphere-MLO simulations,  $\Delta R$  and  $\Delta H$  vanish and eq. (1) reduces to:

$$25 \quad \Delta F_{2x\text{CO}_2} = \lambda \Delta T_s. \quad (2)$$

and  $\Delta T_s$  equals the ECS.  $\lambda$  can be decomposed into different feedbacks (e.g., Soden et al., 2008; Shell et al., 2008). It is the sum of the Planck feedback, the water vapor feedback, the lapse rate feedback, the surface albedo feedback, the cloud feedback  $\lambda_c$ , that will be discussed further below, and a residual term. ~~The convention is that the individual feedbacks are multiplied by -1 so the positive cloud feedback has a positive value. The~~ (Shell et al., 2008). The residual term considers the interactions between the different components ~~and the~~, non-linear dependencies of ECS from the forcing (Vial et al., 2013) and errors in

[the radiative kernel method \(Shell et al., 2008\)](#). This term needs to be small for the decomposition into individual feedbacks to explain the vast majority of the feedback. The average  $\lambda$  value from the GCMs that participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5) is  $1.1 \text{ W m}^{-2} \text{ K}^{-1}$  with a 90% uncertainty range of  $\pm 0.5 \text{ W m}^{-2} \text{ K}^{-1}$  (Flato et al., 2013). The uncertainty in  $\lambda$  induces the uncertainty in ECS. Neither the average ECS of approximately 3 K (Collins et al., 2013) ~~not nor~~ its uncertainty has changed much over time.

In a first model intercomparison paper by Cess et al. (1989), the ~~spread in ECS between different estimates of ECS in~~ GCMs varied between 1.4 and 4.1 K. Estimates from the GCMs used in CMIP5 are ~~somehow somewhat~~ higher with 2.1 and 4.7 K (Forster et al., 2013; Flato et al., 2013), but the range in estimates remains similar. One of the prime ~~contributor contributors~~ to this range in uncertainty are intermodel differences in the ~~changes of low-level clouds (Boucher et al., 2013)~~ [shortwave cloud feedback \(Yokohata et al., 2010\)](#). While the overall cloud feedback is ~~positiv positive~~ with  $0.3 \text{ W m}^{-2} \text{ K}^{-1}$ , the spread in  $\lambda_c$  is larger than that of the overall climate feedback parameter and varies by  $\pm 0.7 \text{ W m}^{-2} \text{ K}^{-1}$  between the CMIP5 models (Flato et al., 2013). This means a negative  $\lambda_c$  cannot be ruled out and the careful conclusion from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) was that  $\lambda_c$  is likely (with a probability of 66%) positive. Contributors to the positive net cloud feedback are a poleward shift of the [mid-latitude](#) storms and decreases in the coverage of low-level clouds, both of which result in less scattering of solar radiation ~~, as well as increases in the top of high clouds which increase the longwave cloud radiative effect (Boucher et al., 2013)~~ [\(Boucher et al., 2013\)](#). [Another positive cloud feedback that operates mainly in the longwave radiation regime is the increase in the height of deep convective outflow. Because the troposphere warms but the cloud top temperature remains at roughly the same temperature \(fixed anvil-temperature, \(Hartmann and Larson, 2002\)\), the rate of longwave emission to space from these cloud tops does not keep pace with that of underlying atmosphere, causing more longwave radiation to remain in the Earth-atmosphere system.](#)

One of the more uncertain cloud feedbacks is the negative cloud optical depth feedback [\(e.g., Mitchell et al., 1989; Gordon and Klein, 2014; McCoy et al., 2015; Ceppi et al., 2016\)](#). The cloud optical depth  $\tau$  is proportional to the cloud water path over the effective cloud particle size. Therefore changes in  $\tau$  can occur due to changes in the cloud water path, which in turn originate from changes in the hydrological cycle, changes in the size of the cloud droplets/ice crystals and changes in cloud phase from ice to water or vice versa. The negative cloud optical depth feedback is related to a shift from cloud ice in the present-day climate to cloud liquid water at the same altitude in the warmer climate. Because cloud droplets are generally smaller and more numerous than ice crystals and they have a different refractive index, the optical depth of liquid clouds is larger than that of ice clouds for a constant cloud water path. Precipitation formation is also less efficient for liquid clouds than for ice clouds [\(e.g., Lohmann, 1996; Hoose et al., 2008\)](#), further increasing cloud lifetime and  $\tau$  of liquid clouds. If, in addition, the cloud water path increases in a warmer climate,  $\tau$  will be further enlarged. All of these aspects result in a negative cloud optical depth feedback.

Tan et al. (2016) analyzed the ratio of supercooled liquid water to the sum of cloud liquid water and cloud ice (supercooled liquid fraction, SLF) between 0 and  $-35 \text{ }^\circ\text{C}$  in the CAM5 GCM. They found SLF to be systematically underestimated with respect to CALIOP observations, i.e. too much condensate to be in the form of ice at these temperatures. This led to a too negative cloud phase feedback and in the CAM5 GCM to a too low ECS. When constraining the present-day SLF by

satellite observations, their ECS increased by up to 1.3 °C. ~~However, as pointed out by Gettelman and Sherwood (2016), their results~~ A similar increase in ECS of 1.5 °C was found by Frey and Kay (2017) when increasing the fraction of supercooled liquid clouds over the Southern ocean. Gettelman and Sherwood (2016) point out that the results by Tan et al. (2016) should be viewed by caution because the version with caution because their versions of CAM5 used by Tan et al. (2016) did not

5 ~~have the most realistic climate and could have been overly sensitive to changes in that were constrained by the CALIOP observations of SLF, had a 2-3 K colder present-day climate than their reference simulation. This could have impacted ECS because climate feedbacks depend on the state of the system, especially those related to ice, such as the cloud phase feedback and would bias it high. This argument can, however, not be made for the study by Frey and Kay (2017) using the same model. Terai et al. (2016) analyzed the low-cloud optical depth feedback from eight CMIP5 models with that inferred from ISCCP, MODIS and PATMOS satellite data. They also concluded that the low-cloud optical depth feedback is likely too negative at mid and high latitudes in climate models. Motivated by these studies and to understand how universal the findings of the change in ECS using extreme assumptions about the liquid water/ice phase in mixed-phase clouds. Motivated by their study and to understand how universal the findings of Tan et al. (2016) are, here we use the clouds of Tan et al. (2016) are, here we use the ECHAM6-HAM2 GCM to calculate the impact of mixed-phase clouds on ECS.~~

10 ~~There have been suggestions that there is an inverse relationship between ECS and the magnitude of the anthropogenic aerosol forcing (Kiehl, 2007). Such a relationship was also found in those newer CMIP5 models that match the observed temperature record (Forster et al., 2013) and underlines that uncertainties in the aerosol forcing remain a key driver of uncertainty for both TCR and ECS (e.g., Mauritsen and Pineus, 2017; Knutti et al., 2017). Lohmann (2002) found a large impact of SLF on the anthropogenic aerosol radiative forcing using the ECHAM4 GCM. Here we define the aerosol radiative forcing as the effective radiative forcing due to aerosol radiation and aerosol-cloud interactions (ERFari+aci, Boucher et al. (2013)). In simulations with only ice below 0 °C (ALL\_ICE), ERFari+aci was only half as large as when no ice formed at temperatures above -35 °C (ALL\_LIQ). This was attributed to the three times higher increase in liquid water path (LWP), which is the vertically integrated liquid water content, between pre-industrial and present-day in simulation ALL\_LIQ as compared to simulation ALL\_ICE. Since that study, parameterizations in the host model ECHAM and in the cloud microphysics scheme have been improved and the one-moment aerosol scheme has been replaced by the two-moment aerosol scheme HAM (Stier et al., 2005). Therefore, we re-evaluate the impact of SLF on ERFari+aci in this paper~~ clouds on ECS.

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## 2 Description of the model and the sensitivity studies

In this paper we use the latest version of the aerosol-climate model ECHAM6.3-HAM2.3, which assembles the most recent versions of the atmospheric general circulation model ECHAM (namely ECHAM6, as described in Stevens et al. (2013) with the most recent changes described below) and the aerosol module HAM based on the HAM2 version as described in Zhang et al. (2012), Neubauer et al. (2014) and Schultz et al. (2017) and summarized below. As our simulations are conducted with

30

monthly mean oxidant fields instead of with interactive chemistry as in HAMMOZ (Schultz et al., 2017), we refer to it as ECHAM6-HAM2.

## 2.1 ECHAM6

ECHAM6 is the latest generation of the atmospheric general circulation model developed by the Max Planck Institute for Meteorology (Stevens et al., 2013). As its predecessors, ECHAM6 employs a spectral transform dynamical core and a flux-form semi-Lagrangian tracer transport algorithm from Lin and Rood (1996). Vertical mixing occurs through turbulent mixing, moist convection (including shallow, deep, and mid-level convection), and momentum transport by gravity waves arising from boundary effects or atmospheric disturbances. Sub-grid scale cloudiness (stratiform clouds) is represented using the scheme of Sundqvist et al. (1989), which calculates diagnostically the grid cell cloud fraction as a function of the relative humidity in the given grid cell, once a threshold value is exceeded. Cloud liquid water and cloud ice mixing ratios are treated prognostically following Lohmann and Roeckner (1996). In ECHAM6-HAM2, additional prognostic equation for the numbers concentrations of cloud droplets and ice crystals are included (Lohmann et al., 2007). The two-moment cloud microphysics scheme and the aerosol scheme are described in section 2.2. Radiative transfer in ECHAM6 is represented using the radiation transfer broadband model PSrad (Pincus and Stevens, 2013), which considers 14 and 16 bands for the shortwave ( $820$  to  $50000$   $\text{cm}^{-1}$ ) and longwave ( $10$  to  $3000$   $\text{cm}^{-1}$ ) parts of the spectrum, respectively (Iacono et al., 2008).

Radiative transfer is computed based on the amount of gases, aerosols and clouds in the atmosphere and their related optical properties. Trace gas concentrations of long-lived greenhouse gases are specified in the model. Optical properties of aerosol particles and clouds are pre-calculated for each band of the RRTMG scheme using Mie theory offline and read from a look-up table based on the concentration of cloud droplets and ice crystals as computed by the two-moment scheme.

ECHAM6 includes a new land-surface model JSBACH (Reick et al., 2013). JSBACH assumes that each grid box is composed of two fractions, one representing bare soil and the other being covered with vegetation, this one being further sub-divided into tiles, one for each of the 11 plant functional types distinguished in JSBACH. Soil hydrology is represented with a single-layer bucket model. A new treatment of the surface albedo (Brovkin et al., 2013) is included, which accounts for the different sections of bare and vegetated areas.

In addition to the improved representation of solar radiative transfer by the RRTMG scheme and the improved surface albedo, smaller changes are included. The vertical discretization within the troposphere (in particular in the upper troposphere and lower stratosphere) is slightly different, the representation of convective triggering has been improved, and the tuning of various model parameters was adjusted. In contrast to ECHAM5, ECHAM6 is more commonly used in a middle-atmosphere configuration, i.e., with the two verticals grids L47 and L95 that resolve the atmosphere from the surface up to  $0.01$  hPa (roughly  $80$  km).

Changes from ECHAM6.1, as coupled to HAM2 in Neubauer et al. (2014), to ECHAM6.3 used here include small changes in convection, in the middle atmosphere, concerning the seawater albedo, improvements in snow- and sea ice coverage, an improved aerosol climatology (Kinne et al., 2013) combined with a simple plume implementation of anthropogenic aerosols (Stevens et al., 2017) and an improved submodel interface. ECHAM6.3 uses the Monte-Carlo independent column approxima-

tion radiation scheme with the option for spectral sampling in time (Pincus and Stevens, 2013). The land model JSBACH has been updated with an improved hydrology and soil model. Changes in the cloud cover scheme were made to improve cloud cover in stratocumulus regions. ~~Also, in ECHAM6.3 the 1 suffered from artificial cloud blinking that occurred due to a bug in the cloud cover scheme, causing the (fractional) cloud cover to be either 0 or 1. This cloud blinking has been removed and it is now energy conserving in the physics part in ECHAM6.3.~~

As in previous versions of ECHAM-HAM, ECHAM drives the aerosol and chemistry modules through the generic sub-model interface by providing meteorological conditions such as wind, temperature, pressure, specific humidity and conditions pertaining to the land surface (taken from JSBACH) such as Leaf Area Index. Aerosol particles and their precursors are transported in the same way as water vapor and cloud species.

## 10 2.2 Aerosol and cloud microphysics scheme

The aerosol module HAM predicts the evolution of an aerosol ensemble considering five components: sulfate, black carbon, particulate organic matter, sea salt, and mineral dust. The aerosol spectrum is described by the superposition of seven log-normal modes ranging from  $0.005$  to  $> 0.5 \mu\text{m}$ . Aerosol particles within a mode are assumed to be internally mixed, in the sense that each particle can consist of multiple components. Aerosols of different modes are externally mixed, meaning that they co-exist in the atmosphere as independent particles. The seven modes of the aerosol number distribution are grouped into four geometrical size classes, including the nucleation, Aitken, accumulation and coarse modes. Particles in four of the modes contain at least one soluble compound, thus they can take up water and are referred to as soluble. The particles in the other three modes consist of compounds with no or low water-solubility and are referred to as insoluble. Through aging processes, insoluble particles can become soluble. Each mode of the aerosol size number distribution is described by the three moments, the aerosol number  $N$ , the number median radius  $r$ , and the standard deviation  $\sigma$ . The standard deviation is assumed to be constant and is set to 1.59 for the nucleation, Aitken, and accumulation modes and to 2 for the coarse modes. The median radius of each mode is calculated from the aerosol number and aerosol mass, which are transported as tracers. For more details, please refer to the description of HAM in Stier et al. (2005) and Zhang et al. (2012).

The two-moment cloud microphysics scheme that predicts the number concentrations and mass mixing ratios of cloud droplets and ice crystals in stratiform clouds as implemented in ECHAM5 is ~~originally~~ described in Lohmann et al. (2007) and Lohmann and Hoose (2009). The microphysics scheme includes all phase changes between the water components (condensation, evaporation, freezing, melting, deposition and sublimation) and precipitation processes (autoconversion of cloud droplets, accretion of raindrops with cloud droplets and snow flakes with cloud droplets and ice crystals, aggregation of ice crystals). Moreover, evaporation of raindrops and melting and sublimation of snowflakes are considered, as well as sedimentation of cloud ice. The cloud microphysics scheme is coupled to the aerosol scheme HAM through the processes of cloud droplet activation and ice crystal nucleation (Lohmann et al., 2007) as well as through in-cloud and below-cloud scavenging (Croft et al., 2009, 2010). Convective clouds are not radiatively active and have much simpler conversion rates (Tiedtke, 1989). The detrained condensate from convective clouds is a source for the stratiform cloud scheme.

Heterogeneous freezing in mixed-phase clouds occurs by contact and immersion freezing as discussed below. In the standard configuration, cirrus clouds are assumed to form by homogeneous freezing of supercooled solution droplets (Lohmann and Kärcher, 2002). Homogeneous and heterogeneous nucleation strongly depends on the vertical velocity that results in supersaturation. The vertical velocity is a superposition of the grid-scale vertical velocity and a subgrid-scale component, which is linked to the turbulent kinetic energy (Lohmann and Kärcher, 2002).

Since the ECHAM-HAM model validation in Lohmann and Hoose (2009), the cloud microphysics scheme has undergone the following scientific improvements:

1. While in the previous ECHAM6-HAM version cloud droplet activation followed the empirical scheme by Lin and Leaitch (1997), it now uses a parameterization of cloud droplet activation based on Köhler theory by Abdul-Razzak and Ghan (2000) as discussed in Stier (2016).
2. Previously, the increase in cloud droplet number concentration (CDNC) from cloud droplets that were detrained from convective clouds, was applied everywhere in the grid box. We now weight the detrained CDNC by the detrained mass and add it to the mass-weighted CDNC of the stratiform part. In addition the split of the detrained cloud water mass into liquid water and ice was made consistent between the number concentrations and mass mixing ratios of cloud droplets and ice crystals.
3. We now assume the shape of ice crystals to be hexagonal plates of crystal type P1a following Pruppacher and Klett (1997). Before we used the empirical mass-size relationships from their Table 2.4, which is only valid for crystals between 0.3 and 1.5 mm. We replaced that by their empirical relationship in Table 2.2, which is valid from 10  $\mu\text{m}$  to 3 mm and with that covers the whole size range. Also while we assumed that all ice crystals are hexagonal plates in the cloud microphysics scheme, cirrus crystals were treated as spheres for the calculation of the effective ice crystal radius and ice cloud optical properties in Zhang et al. (2012). This inconsistency has been eliminated and ice crystals are now hexagonal plates everywhere in the module.
4. The heterogeneous nucleation scheme in the mixed-phase cloud regime between temperatures between 273.15 K and 238.15 K considers contact nucleation by mineral dust and immersion nucleation by black carbon and mineral dust following Lohmann and Hoose (2009). However because there is no evidence that Aitken mode particles contribute to freezing (Marcolli et al., 2007), we now limit the immersion freezing of black carbon to particles in the accumulation mode or larger.
5. The temperature dependence of sticking efficiency used for accretion of ice crystals by snow has been changed to the expression used in Seifert and Beheng (2006).
6. In previous versions, the minimum CDNC (CDNC<sub>min</sub>) was set to 40  $\text{cm}^{-3}$ . The justification for this choice was twofold: First, while observations of clouds with a lower CDNC exist, (e.g, Terai et al., 2014), these smaller concentrations normally occur in clouds or pockets in clouds that are much smaller than our grid boxes. Second, so far we do not



account for nitrate aerosols and our treatment of secondary organic aerosols is rather simplistic and likely underestimates the organic aerosol concentration (Zhang et al., 2012). Therefore we are likely to underestimate CDNC, which we partly buffer by using  $CDNC_{min} = 40 \text{ cm}^{-3}$ . However,  $CDNC_{min}$  has a large impact on ~~ERFari+aci~~ the aerosol radiative forcing (Hoose et al., 2009). Therefore we introduced the option to have two ECHAM6.3-HAM2.3 versions, one that  
5 keeps the  $CDNC_{min}$  at  $40 \text{ cm}^{-3}$  and one in which we lower  $CDNC_{min}$  to  $10 \text{ cm}^{-3}$ .

In addition to the scientific improvements, we removed smaller inconsistencies, such that cloud droplets/ice crystals could both grow and evaporate/sublimate in one timestep, non-zero CDNC below 238.15 K, non-zero ice crystal number concentrations above 273.15 K, inconsistencies in the calculation of cloud cover, condensation and of the ice crystal number concentration in cirrus clouds. Moreover, the two-moment cloud microphysics scheme is now energy-conserving and has been  
10 modularized.

### 3 Model set-up and experiments

In this paper, we compare results from the ~~two release versions~~ release version of ECHAM6-HAM2 ~~the one~~ with  $CDNC_{min}=40 \text{ cm}^{-3}$  (simulation REF) and the ~~one with  $CDNC_{min}=10 \text{ cm}^{-3}$  (simulation 10/cc)~~. ~~Another uncertainty is related to the choice of the biomass burning emissions. It was suggested that the GFAS biomass burning emissions needed to be scaled up by a factor of 3.4 (Kaiser et al., 2012; Veira et al., 2015). They argued that this factor partly arises because of the uncertain conversion of organic carbon to organic matter and by missing ageing because interactions of aerosol particles with gas-phase species are not included in the treatment of aerosols in the ECMWF aerosol forecast model MACC. Therefore we use the GFAS biomass burning emissions as they are in our reference simulation, but perform one simulation in which these emissions are increased by a factor of 3.4 (simulation GFAS3.4).~~  
15 sensitivity simulations discussed below with observations.

To address the impact of SLF on ~~ERFari+aci~~ and ECS in ECHAM6-HAM2, we conducted one simulation with no supercooled liquid water below  $0^\circ\text{C}$  (simulation ALL\_ICE) and one simulation with no ice formation at temperatures  $> -35^\circ\text{C}$  (simulation ALL\_LIQ) similar to what has been done in Tan et al. (2016) and Lohmann (2002). ~~Another aspect to the possible impact of ice on ERFari+aci is the~~ The simulation ALL\_ICE is set-up such that all cloud droplets that are advected to colder temperatures are forced to freeze instantaneously and all the detrained cloud condensate is in the form of ice at temperatures  $< 0^\circ\text{C}$ . The simulation ALL\_LIQ is set-up such that heterogeneous freezing is turned off in the temperature range between 0 and  $-35^\circ\text{C}$  and detrainment of ice crystals from convective clouds is restricted to temperatures below  $-35^\circ\text{C}$ . Ice crystals sedimenting from colder into warmer cloud layers melt at  $-35^\circ\text{C}$ . The number of cloud droplets which freeze at temperatures below  $-35^\circ\text{C}$  had to be reduced by a factor of 100 in order to keep the ice crystal number concentration realistic in simulation ALL\_LIQ.  
25

In this paper we go beyond the study by Tan et al. (2016) and also test the impact of other aspects of clouds on ECS, such as the type of nucleation in cirrus clouds. There are discussions if cirrus ~~clouds~~ are mainly formed by homogeneous nucleation as we assume in our reference simulation or are ~~formed~~ nucleated heterogeneously (Cziczo et al., 2013; Spichtinger and Krämer, 2012; Kärcher, 2017). We investigate the impact of homogeneous vs. heterogeneous freezing in cirrus clouds by performing one  
30

simulation in which all cirrus clouds form heterogeneously (simulation HET) instead of homogeneous nucleation in simulation REF. Heterogeneously nucleated cirrus are optically thinner (Lohmann, 2008). Thus, with this simulation we aim to address the impact of cirrus on ECS that so far remains uncertain (Boucher et al., 2013).

5 Last but not least we investigate the impact of parameterized convection on ~~ERFari+aei and~~ECS by performing a simulation in which we completely switched off convection (simulation NOCONV) as was done in Webb et al. (2015). This is normally done only in simulations run at horizontal resolutions of less than 10 km, where the vertical motions associated with deep convection start to be resolved. While our horizontal ~~simulation-resolution~~ is much coarser and thus a convective parameterization is needed, there are some inconsistencies in terms of microphysics between convective and stratiform clouds. Therefore we evaluate how the cloud fields, the climate in general, ~~ERFari+aei and~~ ECS are simulated if only large-scale clouds are allowed  
10 to form.

All ~~the~~simulations were performed in T63 spectral resolution which corresponds to  $1.875^\circ \times 1.875^\circ$  and 31 vertical layers with a top at 10 hPa. The ~~simulations for the calculations of ERFari+aei~~ present-day atmosphere-only simulations were run over ~~20-25~~ years after a three-months spin-up with fixed SSTs and sea-ice cover (averaged over the atmosphere model intercomparison project (AMIP) climatology for the years 2000-2015). To calculate ECS, ECHAM6-HAM2 has been coupled to a ~~mixed-layer ocean (MLO).~~ MLO of 50 m depth. The deep ocean heat flux is computed from the atmosphere-only simulations. Because the deep ocean heat flux adjusts to the different set-ups, we computed it individually for each of the five different set-ups separately. These simulations were spun up for 25 years ~~and then run~~ after which the simulations were in equilibrium. We then ran for another 25 years, over which the results were averaged.  
15

The sensitivity studies conducted for our studies are summarized in Table 1. For the calculations of ECS, all simulations  
20 need to be in radiative equilibrium at TOA. This requires retuning. To keep the different simulations as comparable as possible, we only adjusted two parameters inside the two-moment cloud microphysics scheme.  $\gamma_r$  speeds-up the autoconversion rate of cloud droplets to grow to raindrops by collision-coalescence and accounts for the missing subgrid-scale variability in cloud water and CDNC (Wood, 2002).  $\gamma_s$  is the corresponding process in the ice phase, which enhances the aggregation of ice crystals to form snow flakes (Lohmann and Ferrachat, 2010). The values of these two parameters also included in Table 1. In addition  
25 to the changes in the tuning parameters, we needed to decrease the time-step from 7.5 to 5 minutes in simulation NOCONV because of numerical stability.

All of simulations listed in Table 1 were run in three different set-ups: (i) atmosphere-only simulations with prescribed SST and sea ice cover using the AMIP 2000-2015 climatology with present-day aerosol emissions and greenhouse gas concentrations for comparison with observations, (ii) atmosphere-MLO simulations at  $1\times\text{CO}_2$  concentrations with pre-industrial aerosol emissions and pre-industrial levels of the other greenhouse gas and (iii) atmosphere-MLO simulations at  $2\times\text{CO}_2$  concentrations, keeping everything else as in (ii). For simulations (iii) the  $\text{CO}_2$  concentration was doubled before the 25-year spin up period.  
30

**Table 1.** Set-up of the simulations together with the two tuning parameters that differ between the simulations.

Simulation	Description
REF	Reference simulation
10/ce-as-REF, but with $CDNC_{min} = 10 \text{ cm}^{-3}$	As REF, only hom
2.8-900-GFAS3.4-as-REF, but with 3.4 higher biomass burning emissions	As REF,
10.6-900-ALL_ICE	As REF,
ALL_LIQ	
HET	
NOCONV	

#### 4 Comparison of ECHAM6-HAM2 with observations

An overview of the annual, global mean state of the climate in the different simulations is given in Table ??-2 together with observations, where available. The observations of global LWP range between 30-90  $\text{g m}^{-2}$  (Stubenrauch et al., 2013; Platnick et al., 2015, 2017; Stengel et al., 2017a; Poulsen et al., 2017). Elsaesser et al. (2017) restricted the LWP retrievals to ocean regions ( $LWP_{oc}$ ) and estimated  $LWP_{oc}$  from a combination of the SSM/I, TMI, AMSR-E, WindSat, SSMIS, AMSR-2 and GMI satellite data (MAC-LWP) as 81.4  $\text{g m}^{-2}$ . Limiting the other retrievals to ocean regions yields a global  $LWP_{oc}$  of 42.9  $\text{g m}^{-2}$  from MODIS (Platnick et al., 2015, 2017), 43.9  $\text{g m}^{-2}$  from ATSR2-AATSR (Stengel et al., 2017a; Poulsen et al., 2017) and 41  $\text{g m}^{-2}$  from AVHRR-PM (Stengel et al., 2017b), illustrating the huge uncertainty of estimating  $LWP_{oc}$ . All simulations except for ALL\_LIQ fall within this range. In simulation ALL\_LIQ,  $LWP_{oc}$  amounts to 110  $\text{g m}^{-2}$  because no ice is formed at temperatures  $> -35^\circ\text{C}$ .

The annual zonal mean LWP and ice water path (IWP) from all simulations as well as from satellite observations for LWP from multiple satellite sensors (Elsaesser et al., 2017), the MODIS satellite (Platnick et al., 2015, 2017) and the ATSR2-AATSR satellites (Stengel et al., 2017a; Poulsen et al., 2017) and IWP from Calipso/CLOUDSAT (Li et al., 2012) are shown in Figure 1. Because the MAC-LWP observations are only available over oceans, we limit the comparison of LWP to ocean regions. Both, retrievals from visible/near infrared sensor-sensors as well as microwave sensor have biases in retrieving LWP (Seethala and Horvath, 2010; Lebsock and Su, 2014). Lebsock and Su (2014) mentioned four biases in LWP retrievals for MODIS (visible/near infrared sensor) and AMSR-E (microwave sensor): a bias at large solar zenith angle (MODIS), missing of some pixels of low-lying clouds that are not detected (MODIS), LWP retrievals in cloud free scenes (AMSR-E) and the partitioning of the microwave signal between cloud and precipitation signals (AMSR-E). The LWP bias of microwave sensor based products in clear-sky scenes has been recently corrected by Elsaesser et al. (2017). The LWP estimates of microwave retrieval products are most reliable in regions where LWP is much larger than the rain water path (RWP). Thus, Elsaesser et al. (2017) recommend to restrict the LWP satellite data to regions in which  $LWP/(LWP+RWP) > 0.8$ . This  $LWP_{oc,low\_pr}$  covers areas dominated by stratocumulus, tradewind cumulus regions in the subtropics, the southern ocean, high latitude in

**Table 2.** Global annual mean of oceanic  $LWP_{oc}$ ,  $LWP_{oc,low\_pr}$ , IWP, vertically integrated cloud droplet globally ( $N_l$ ), CDNC at cloud top over oceans ( $N_{l,oc,top}$ ) and ice crystal number concentration ( $N_i$ ), total cloud cover (CC), precipitation rate ( $P$ ), shortwave (SW), longwave (LW) and net cloud radiative effect (CRE) from observations and ~~the 20-years atmosphere-only~~ present-day model simulations with prescribed SST as described in Table 1 ~~for 2003-2012~~. The satellite observations of  $LWP_{oc}$ , are taken from Platnick et al. (2015, 2017); Stengel et al. (2017a); Poulsen et al. (2017); Elsaesser et al. (2017), of  $LWP_{oc,low\_pr}$  from Elsaesser et al. (2017), of IWP from the CloudSat/CALIPSO satellites (Li et al., 2012), of  $N_{l,oc,top}$  from Bennartz and Rausch (2017) of total cloud cover from Stubenrauch et al. (2013); Matus and L’Ecuyer (2017), precipitation rate ~~is averaged over 1981–2010~~ from the GPCP version 2.3 data set (Adler et al., 2003, 2012), the CRE satellite data are averaged over the period 2001–2011 from the Clouds and the Earth’s Radiant Energy System Energy Balanced and Filled Ed2.6r data set (Boucher et al., 2013) and are described in (~~Loeb et al., 2009~~)~~Loeb et al. (2009, 2018)~~. For the uncertainty range of the SW CRE also data from CloudSat and CALIPSO are considered (Matus and L’Ecuyer, 2017) and for LW CRE also data from the TOVS satellite Susskind et al. (1997). See legend of Figure 1 for details of the observations.

	OBS	REF	<del>10/ee-GFAS3.4</del> ALL_ICE	ALL_LIQ	HET	NOCONV
$LWP_{oc}$ , $g\ m^{-2}$	81.4 (30-90)	70.6	<del>90.0</del> <u>75.9</u>	<del>72.5</del> <u>111.3</u>	<del>76.1</del> <u>62.5</u>	<del>111.2</del> <u>62.6</u> <del>53.2</del> <u>53.3</u>
$LWP_{oc,low\_pr}$ , $g\ m^{-2}$	73.5±5.5	76.2	<del>100.4</del> <u>78.1</u> -70.4	<del>140.8</del> <u>141.1</u>	<del>68.2</del> <u>68.1</u>	42.0
IWP, $g\ m^{-2}$	25±7	14.8	<del>14.9</del> <u>14.8</u> -16.5	8.6	26	11.7
$N_l$ , $10^{10}\ m^{-2}$	<del>???</del> <u>—</u>	3.1	<del>2.9</del> <u>3.3</u> -2.4	6.4	2.9	4.5
$N_{l,oc,top}$ , $cm^{-3}$	72±38	<del>78</del> <u>78.3</u>	<del>73</del> <u>95.6</u>	<del>84</del> <u>69.6</u>	<del>96</del> <u>77.4</u>	<del>69</del> <u>77</u> <del>74</del> <u>74.2</u>
$N_i$ , $10^8\ m^{-2}$	–	7.9	<del>8.0</del> <u>7.9</u> -8.4	9.3	10.7	5.8
CC, %	68±5	68.1	<del>68.4</del> <u>68.3</u> -67.8	70.6	66.3	71.2
$P$ , $mm\ d^{-1}$	2.7±0.2	2.99	<del>3.00</del> <u>2.92</u>	<del>2.98</del> <u>2.93</u> -2.87	<del>3.04</del> <u>3.03</u>	<del>3.01</del> <u>3.00</u>
SW CRE, $W\ m^{-2}$	-47.3 (-44 to -53.3)	-49.9	<del>-49.6</del> <u>-50.2</u> -48.2	-62.6	<del>-50.0</del> <u>-49.9</u>	-52.2
LW CRE, $W\ m^{-2}$	26.2 (22 to 30.5)	<del>24.2</del> <u>24.3</u> -24.1	22.4	35.6	24.6	24.7
Net CRE, $W\ m^{-2}$	-21.1 (-17.1 to -22.8)	-25.8	<del>-25.4</del> <u>-26.2</u> -25.8	<del>-27</del> <u>-26.9</u>	-25.4	-27.5

the Northern Hemisphere and parts of north Atlantic and north Pacific.  $LWP_{oc,low\_pr}$  from MAC-LWP should thus have the smallest retrieval biases. Therefore we use it to evaluate the model LWP as shown in Figure 1.

The new multi-satellite observations of  $LWP_{oc}$  by Elsaesser et al. (2017), averaged over the years 1988-2016, show a maximum LWP in the tropics and, on average, their estimate is twice as high as the retrievals from MODIS and ~~AATSR~~AATSR2-AATSR both for the years 2003-2012.  $LWP_{oc}$  from MODIS and ~~AATSR~~AATSR2-AATSR on the contrary increases towards the poles and only a weak secondary maximum is indicated near the equator. All observations show high values of  $LWP_{oc}$  in the storm tracks on both hemispheres, but the exact location varies between the different observations. The most noticeable difference between  $LWP_{oc}$  and  $LWP_{oc,low\_pr}$  is the absence of data in the intertropical convergence zone (ITCZ). In fact, the agreement of simulations REF ~~,GFAS3.4~~ and HET in terms of the zonal mean structure of  $LWP_{oc,low\_pr}$  with observations is very good everywhere and better than with  $LWP_{oc}$ .  $LWP_{oc,low\_pr}$  is too low at high latitudes in simulation ALL\_ICE and the maxima in the extratropics are overestimated in ~~simulations~~simulation ALL\_LIQ ~~and 10/ee~~.  $LWP_{oc,low\_pr}$

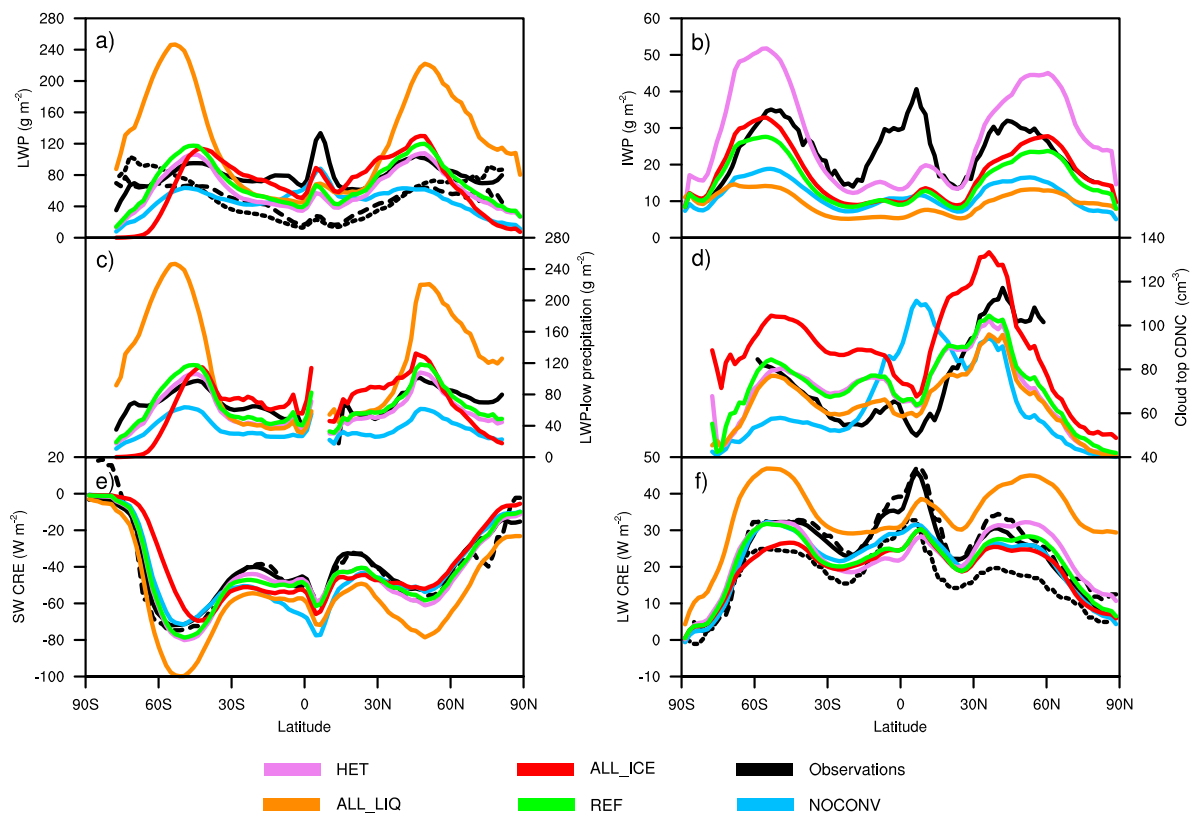
is everywhere underestimated in simulation NOCONV, because of the large speed-up of the autoconversion rate required to reach radiative equilibrium at TOA in this set-up.

The cloud-top CDNC for oceanic clouds ( $N_{l,oc,top}$ ) with temperatures between 268 and 300 K has also been obtained from satellite data (Bennartz and Rausch, 2017) ~~and for the years 2003-2015. From the model simulations, oceanic cloud-top~~  
5 ~~CDNC were used for~~ temperatures  $> 273.2$  K ~~from the model simulations~~.  $N_{l,oc,top}$  is less zonally symmetric than LWP as a result of the higher emissions in the Northern Hemisphere.  $N_{l,oc,top}$  reaches values of  $> 100 \text{ cm}^{-3}$  between  $30^\circ\text{N}$  and ~~80~~60 $^\circ\text{N}$  in the observations (Figure 1). All model simulations fail to produce such high values north of  $40^\circ\text{N}$ , probably because of an insufficient transport of aerosol particles to the Arctic (Bourgeois and Bey, 2011), missing nitrate aerosols and underestimating particulate organic aerosols (Zhang et al., 2012) all of which contribute to underestimating the concentration of  
10 cloud condensation nuclei.  $N_{l,oc,top}$  is well simulated south of  $30^\circ\text{N}$ , especially in ~~simulations 10/ee and simulation~~ ALL\_LIQ.  $N_{l,oc,top}$  is highest in simulation ALL\_ICE (Table ??2) and overestimated with respect to the observations. This is caused by the lower speed-up of the autoconversion rate in simulation ALL\_ICE (Table 1), which reduces the ~~sinks~~ sink of cloud droplets in this simulation and causes higher ~~cloud droplet number concentrations~~ CDNC at all altitudes as compared to simulation REF (not shown).

15 The zonal distribution of  $N_{l,oc,top}$  in simulation NOCONV differs from the other simulations. It peaks near the equator because the clouds here cannot form by convection and instead the stratiform cloud scheme needs to take over. As the rain formation depends on CDNC only in the stratiform cloud microphysics scheme but not in the convective one, warm rain is less efficiently formed in the tropics in the stratiform scheme, causing a build-up of cloud droplets in simulation NOCONV as portrayed in Figure 1. The CDNC peak in the tropics in simulation NOCONV deviates strongly from observations as do the  
20 lower than observed values in the extratropics.

~~The IWP peak in the tropics is related to liquid-origin cirrus clouds (Wernli et al., 2016; Kraemer et al., 2016; Gasparini et al., 2017) formed in the anvils from deep convection in the ITCZ as well as in the warm conveyor belt in the storm tracks. The peak in the ITCZ is not captured in any of the model simulations suggesting that the model severely underestimates the detrained cloud ice in deep convective clouds. Cloud ice in the extratropics is underestimated in all simulations but simulation HET, where the IWP is largest due to retuning as discussed above.~~

ECHAM6-HAM2 in general has problems to simulate IWP values in the observed range. This deficiency can largely be attributed to an underestimation in the ice crystal size in simulation REF at least for clouds with cloud optical depth  $< 3$  (Gasparini et al., 2017). The only simulation in which IWP in the global mean agrees with the observations is simulation HET (Table 2), because the heterogeneous nucleation is limited by the number concentration of dust aerosols. The dust number  
30 concentration is smaller than the number concentration of soluble aerosols that can freeze homogeneously and freezing commences at a lower relative humidity and a higher temperature in simulation HET. Because of the limited number concentration of dust aerosols and the faster depositional growth at higher temperatures, the heterogeneously nucleated ice crystals are larger than the ones nucleated homogeneously. Because of this, they sediment and aggregate more rapidly, causing simulation HET to initially be out of radiative balance. Here retuning was necessary to slow down the rate of aggregation and at the same



time, speed up the rate of autoconversion. This resulted in one of the lowest LWPs of all simulations and highest IWP with the highest ice crystal number concentration.

The IWP peak in the tropics in Figure 1 is related to liquid-origin cirrus clouds (Wernli et al., 2016; Kraemer et al., 2016; Gasparini et al., 2017) forming the anvils from deep convection in the ITCZ as well as in the warm conveyor belt in the storm tracks. The peak in the ITCZ is not captured in any of the model simulations suggesting that the model severely underestimates the detrained cloud ice in deep convective clouds. Cloud ice in the extratropics is underestimated in all simulations but simulations HET and ALL\_ICE. IWP is largest in simulation HET due to retuning as discussed above. Its zonal distribution shows that the underestimation of IWP in the tropics is compensated by an overestimation in the extratropics. Simulation ALL\_ICE best matches the magnitude of IWP in the extratropics but shifts the peaks slightly polewards from the observations.

The total cloud cover in ECHAM6-HAM2 is that of large-scale clouds because convective clouds are considered to be short-lived and to decay within one model timestep except for the detrained condensate in the anvils that is taken as a source for the stratiform cloud scheme. The global mean total cloud cover does not vary much between the different simulations and it falls within the observed range of  $68 \pm 5\%$  (Stubenrauch et al., 2013) in all simulations. It is second-largest in simulation ALL\_LIQ because of its large LWP. It is highest in simulation NOCONV because here all clouds are large-scale and contribute to the cloud cover.

The observed precipitation rate from GPCP (Adler et al., 2003) averaged over 1981–2010 of  $2.7 \text{ mm d}^{-1}$  is overestimated by 6–13 % in all simulations, a feature that ECHAM6-HAM2 shares with its host model ECHAM6 (Stevens et al., 2013). As discussed in Stevens et al. (2013), GPCP seems to underreport precipitation and higher precipitation rates are more consistent with the best observational estimates of the surface energy budget (Stephens et al., 2012).

The cloud radiative effect (CRE) is the difference between the all-sky radiation at TOA and the clear-sky radiation. The shortwave (SW) CRE amounts to  $-47.3 \text{ W m}^{-2}$  with a range from  $-46$  to  $-53.3 \text{ W m}^{-2}$  in the satellite data (Loeb et al., 2009; Zelinka et al., 2017). ~~All (Loeb et al., 2009, 2018; Zelinka et al., 2017). In all simulations, except the one with the extreme changes in SLF predict a value of~~ ALL LIQ SW CRE amounts to about  $-50 \text{ W m}^{-2}$  ~~that, which~~ lies within the observed range. SW CRE is most negative and outside the observational range in simulation ALL\_LIQ because of its high LWP and total cloud cover (see also Figure 1). On the contrary, it is least negative in simulation ALL\_ICE, where LWP is rather small and hence  $\tau$  is smallest. Here SW CRE is severely underestimated south of  $40^\circ\text{S}$  due to the lack of supercooled liquid water. While too much absorption of shortwave radiation over the southern ocean has been a problem in the ~~CAM5-GCM many GCMs~~ because of insufficient supercooled liquid water (Kay et al., 2016) (e.g., Williams et al., 2013; Bodas-Salcedo et al., 2014; Kay et al., 2016), in our model this problem only arises in the extreme simulation ALL\_ICE.

LW CRE amounts to  $26.2 \text{ W m}^{-2}$  with a range from 22 to  $30.5 \text{ W m}^{-2}$  in the satellite data (Loeb et al., 2009; Susskind et al., 1997; Zelinka et al., 2017) (Loeb et al., 2009, 2018; Susskind et al., 1997; Zelinka et al., 2017). As for SW CRE, all simulations but ~~the one with the extreme assumptions in SLF predict~~ ALL LIQ calculate LW CRE to be about  $24\text{--}25 \text{ W m}^{-2}$  in good agreement with ~~the~~ observations. Again LW CRE is smallest in simulation ALL\_ICE and highest

and outside the observational range in simulation ALL\_LIQ (see also Figure 1). Due to the severe underestimation of cloud ice in the tropics in all simulations, LW CRE is systematically underestimated in the tropics. The exception is simulation ALL\_LIQ where the underestimation in tropical cloud ice is compensated for by the thickest high level clouds (Figure 2).

5 The global mean observed net CRE ranges between  $-17.1$  and  $-22.8 \text{ W m}^{-2}$ . Here all simulations are more negative than observed, i.e. they overestimate the net negative radiative effect of clouds.

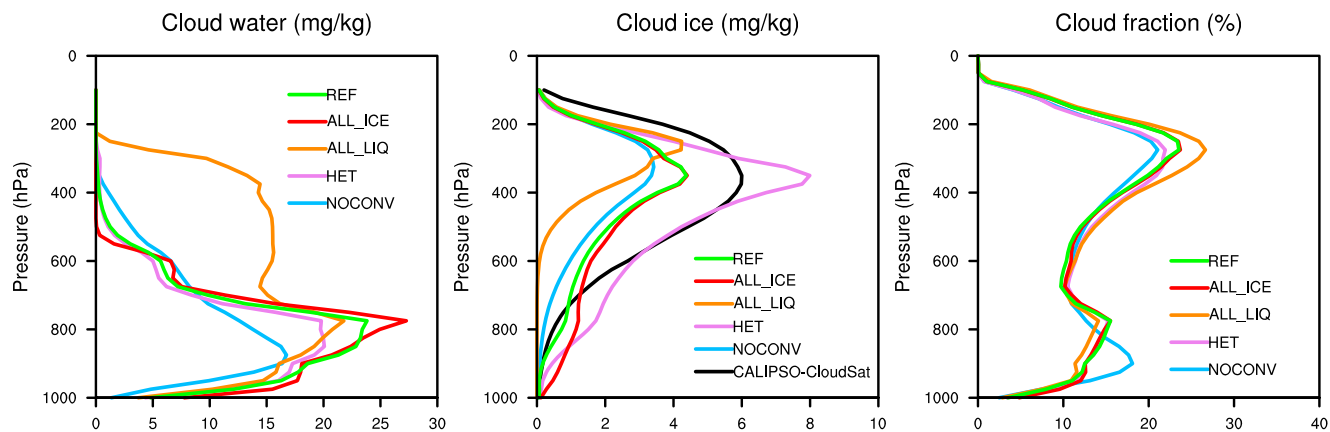
The vertical distribution of the globally and annually averaged cloud liquid water and cloud ice is shown in Figure 2. Cloud liquid water has its maximum at around 800 hPa associated with low clouds where it varies between 20 and 30  $\text{mg kg}^{-1}$  in the different simulations. It is ~~highest in simulation 10/ce because of the reduced autoconversion rate and~~ lowest in simulation NOCONV because of the drastically enhanced autoconversion rate (Table 1). Cloud liquid water decreases to zero  
10 at around 400 hPa except in simulation ALL\_LIQ where ice formation is limited to temperatures  $< -35^\circ\text{C}$ . Unfortunately no observational data of the vertical distribution of cloud liquid water are available.

The vertical distribution of cloud ice has been derived from Calipso/CLOUDSAT (Li et al., 2012). It peaks at 400 hPa with  $6 \text{ mg kg}^{-1}$  and becomes negligible at altitudes above 100 hPa and below 900 hPa (Figure 2). Here the differences between the sensitivity experiments are more pronounced. In simulations REF, ~~10/ce, GFAS3.4~~ and NOCONV the shape of the distribution  
15 looks similar to the observed, but the peak value is underestimated by 30-50% and in ~~simulations REF, 10/ce and GFAS3.4~~ simulation REF a secondary maximum is present at around 780 hPa. This peak is related to cloud ice over the Southern Ocean and Antarctica (not shown). In simulation ALL\_LIQ, where the global annual mean IWP is smallest due to suppressed ice formation in mixed-phase clouds, cloud ice peaks at 250 hPa and drops to zero at 600 hPa. This simulation differs most from the observations. It also has the lowest cloud cover in the lower troposphere and the highest cloud fraction between 200 and 400  
20 hPa (Figure 2). On the contrary, simulation NOCONV has the highest coverage of low-level clouds and the smallest coverage of cirrus clouds.

In simulation ALL\_ICE the comparison of cloud ice with observations is also less favorable as compared to simulation REF because more cloud ice than observed is simulated in the lower atmosphere while the underestimation of cloud ice at higher altitudes has not ~~noticeable~~ noticeably improved. The overall best agreement with observations is seen in simulation HET. This  
25 is the only simulation in which the global annual mean IWP lies within the observational uncertainty (Table ~~??~~2). However, the peak in cloud ice at 400 hPa is 25% too high large and too narrow. Although the freezing mechanism was only changed for cirrus clouds, the overall higher amount of cloud ice extends to lower altitudes causing an overestimation in cloud ice between 600 and 900 hPa. This is mainly a result of the reduced speed-up of the aggregation rate that affects cloud ice also in mixed-phase clouds.

30 SLF has been obtained from the CALIOP satellite and has been compared to an earlier version of ECHAM6-HAM2 (Komurcu et al., 2014). At that time ECHAM6-HAM2 seriously underestimated SLF. This can partly be explained by differences in the definition of SLF in the satellite data and in the model. In addition, some of the model improvements mentioned above were added after the study by Komurcu et al. (2014). As the lidar signal gets attenuated at cloud optical depth (COD)  $> 3$ , the CALIOP satellite data are only representative for ~~thin~~ all cloud tops not overlaid by clouds with COD  $< 3$ , ~~to which we now~~  
35 ~~limit~~  $> 3$ . SLF of the model data as well is diagnosed similar as the ratio of supercooled liquid water to the sum of cloud liquid





**Figure 2.** Annual global mean cloud liquid water content (left panel), ice water content (middle panel) in  $\text{mg kg}^{-1}$  and cloud cover (right panel) in % as a function of pressure in hPa from the various sensitivity [atmosphere-only present-day](#) simulations [for the years 2003-2012](#) described in Table 1 and observations of the ice water content [from CALIPSO-CloudSat for the years 2006-2010](#) by Li et al. (2012).

[water and cloud ice of the cloud layers starting from the highest cloud layers as long as the cumulative COD of these cloud layers is less or equal to 3.](#) As shown in Figure 3, ECHAM6-HAM2 still underestimates SLF but on average simulates twice as

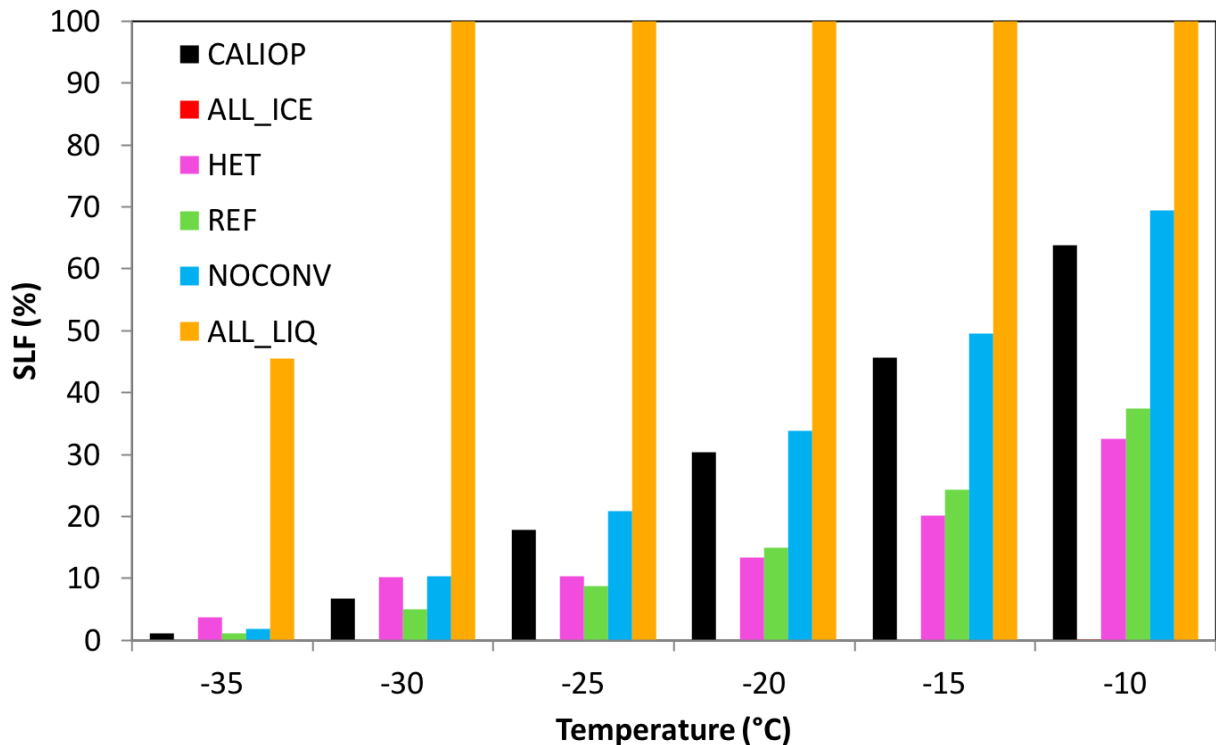
high SLFs as presented in Komurcu et al. (2014). At  $-10^\circ\text{C}$  SLF amounts to 63% in CALIOP, but only 37% in simulation REF.

5 SLF with decreasing temperature.

SLF from all ECHAM simulations is significantly underestimated except for simulations ALL\_LIQ and NOCONV. Simulation NOCONV actually matches the observed SLF rather well, mainly because supercooled liquid water exists at higher altitudes than in simulation REF (Figure 2). This points to a potential deficiency as to how we handle [entrainment detrainment](#) from convective clouds or convection itself. In simulation REF we assume that if we are in the Wegener-Bergeron-Findeisen (WBF) regime, following the definition of Korolev (2007) as described in Lohmann and Hoose (2009), and cloud ice is already present, the detrained condensate will be in the form of ice. It is only detrained as supercooled liquid water if the vertical velocity is sufficiently high to exceed saturation with respect to liquid water. This assumption seems to cause a too efficient WBF process, thus depleting the supercooled liquid water too rapidly. We will rethink our approach in the future.

15 The control simulation in CESM from Tan et al. (2016) simulates a SLF of only 20% at  $-10^\circ\text{C}$ . Based on their hypothesis that an underestimation in SLF translates into an underestimation in ECS, a smaller underestimation of SLF in simulation REF should lead to a [lower-smaller](#) underestimation of ECS in ECHAM6-HAM2. [Based on the simulated SLFs, we expect ECS to be lowest in simulation ALL\\_ICE and to successively increase in simulations HET, REF, NOCONV and ALL\\_LIQ.](#)

## 5 Equilibrium climate sensitivity



**Figure 3.** Frequency of occurrence of SLF in % for clouds with COD < 3 in different temperature bins from CALIOP observations [for the years 2006-2010](#) and the various sensitivity simulations [from the atmosphere-only present-day simulations for the years 2003-2012](#) described in Table 1.

~~As mentioned above, ECS refers to the temperature that results from having established a new equilibrium climate with a balanced TOA radiation budget at the time of CO<sub>2</sub> doubling. In the~~ In a warmer climate, the saturation specific humidity increases by 7% per °C warming according to the Clausius-Clapeyron equation. Because the relative humidity has been found to remain rather constant (Soden et al., 2002), this causes an increase in the specific humidity and speeds up the hydrological cycle leading to higher liquid water contents in clouds and higher precipitation rates as summarized in Table 3.

~~The change in~~ ECS from all our sensitivity simulations is shown in [Figure ??](#). [ECS Table 3](#). It ranges between 1.8 and ~~2.82,6 K in all our simulations (Table 3)~~ and with that lies on the lower side of the range of ECS estimated in the last IPCC report (Collins et al., 2013; Flato et al., 2013) and from CMIP5 models (Forster et al., 2013). Similar to Tan et al. (2016), ECS increases by ~30% when increasing SLF from almost zero to one (simulations ALL\_ICE and ALL\_LIQ in this paper vs. Low-SLF and High-SLF in Tan et al. (2016)). Contrary to their large increase of ECS from their reference simulation to simulation

**Table 3.** Global annual mean changes of surface temperature ( $\Delta T_s$ ), liquid water path ( $\Delta LWP$ ), ice water path ( $\Delta IWP$ ), vertically integrated cloud droplet ( $\Delta N_l$ ) and ice crystal number concentration ( $\Delta N_i$ ), total cloud cover ( $\Delta CC$ ), SW CRE ( $\Delta SW CRE$ ), LW CRE ( $\Delta LW CRE$ ) and precipitation-rate-net CRE from the radiative kernel method ( $\Delta PRK$ ) and as normally diagnosed that are established in equilibrium after a  $CO_2$  doubling from years 26-50 of the coupled atmosphere - MLO model simulations. The individual simulations are described in Table 1. Different from Table ~~???~~, here the changes in LWP are global and not limited to ocean regions.

	REF	<del>10/ee-GFAS3.4</del> ALL_ICE	ALL_LIQ	HET	NOCONV
$\Delta T, K$	2.5	<del>2.78-2.61</del> 1.83	2.51	2.58	2.56
$\Delta LWP, g m^{-2}$	2.54	<del>2.75-2.59</del> 4.75	0.80	3.18	0.72
$\Delta IWP, g m^{-2}$	-0.40	<del>-0.47-0.45</del> -0.40	-0.54	-1.06	-0.31
$\Delta CC, \%$	-1.43	<del>-1.67-1.53</del> -0.82	-1.13	-1.23	-1.15
<u><math>\Delta SW CRE (RK), W m^{-2}</math></u>	<u>1.13</u>	<u>-0.51</u>	<u>1.00</u>	<u>0.87</u>	<u>1.69</u>
<u><math>\Delta LW CRE (RK), W m^{-2}</math></u>	<u>-0.34</u>	<u>-0.20</u>	<u>0.46</u>	<u>-0.17</u>	<u>-0.35</u>
<u><math>\Delta net CRE (RK), W m^{-2}</math></u>	<u>0.78</u>	<u>-0.71</u>	<u>1.45</u>	<u>0.69</u>	<u>1.34</u>
<u><math>\Delta SW CRE, W m^{-2}</math></u>	<u>1.03</u>	<u>-0.11</u>	<u>0.78</u>	<u>0.65</u>	<u>1.51</u>
<u><math>\Delta LW CRE, W m^{-2}</math></u>	<u>-1.58</u>	<u>-1.30</u>	<u>-1.22</u>	<u>-1.45</u>	<u>-1.49</u>
<u><math>\Delta net CRE, W m^{-2}</math></u>	<u>-0.54</u>	<u>-1.42</u>	<u>-0.44</u>	<u>-0.80</u>	<u>0.03</u>

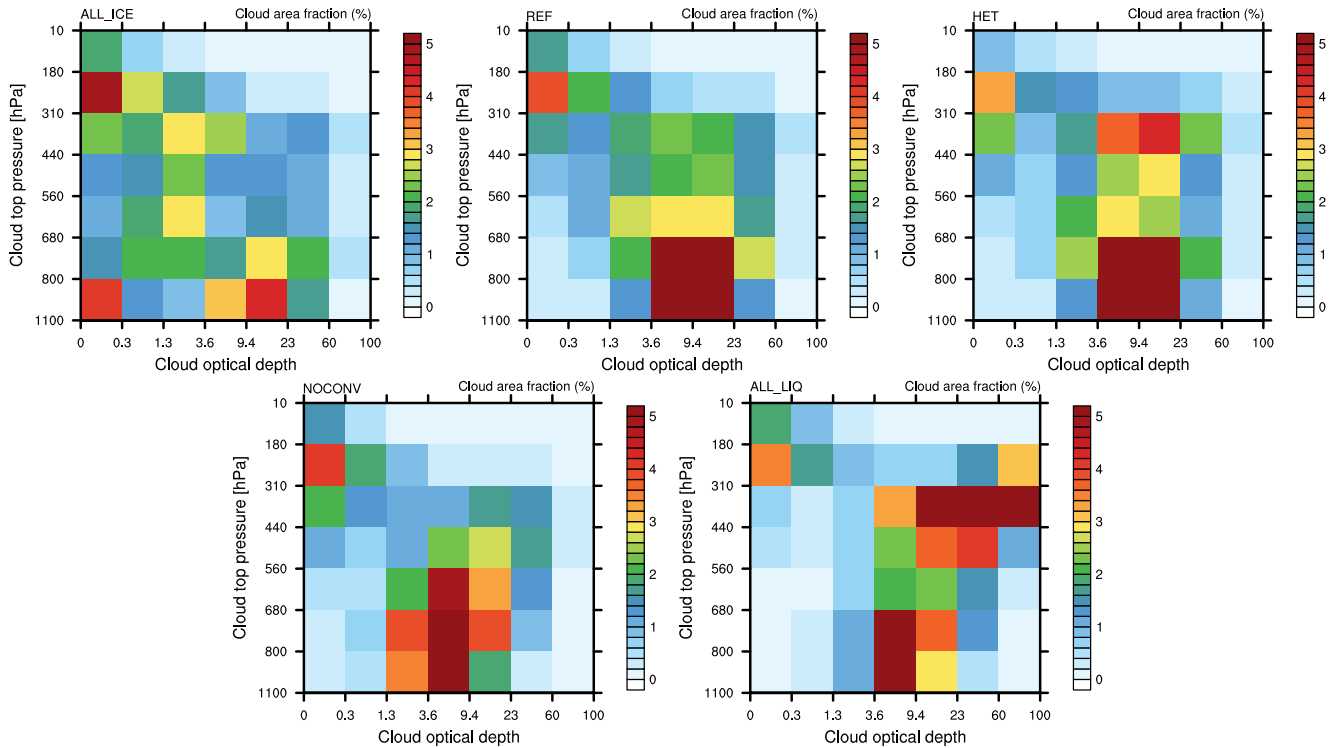
High-SLF, ECS does not ~~increase~~ change between simulations REF, NOCONV and ALL\_LIQ but remains at  $\sim 2.5$ -~~2.6~~ K despite the increase in SLF at  $-10^\circ C$  from  $\sim 30\%$  in HET,  $\sim 40\%$  in REF to  $\sim 70\%$  in NOCONV and 100% in ALL\_LIQ. ~~Instead the ECHAM6-HAM2 simulations show a larger difference in ECS between simulations REF and ALL\_ICE of 0.7 K, i.e. only ECS in simulation ALL\_ICE is noticeably different. This suggests that ECHAM6-HAM2 seems to be is~~ more sensitive at low SLF. These results seems to support the hypothesis that an increase in ECS is only sensitive to SLF if too ~~much~~ little shortwave radiation is ~~absorbed in~~ reflected back to space from mixed-phase mid-latitude clouds, i.e. when they are composed of ice instead of liquid water. This has also been suggested by Frey and Kay (2017), who modified CAM5 to detrain more liquid water at colder temperatures in shallow convective clouds, which occur e.g. in the cold sector of mid-latitude cyclones. It is important that these mixed-phase clouds are not shielded by ice clouds in order for a change in their cloud phase to affect ECS (Bodas-Salcedo, 2018). Since in ECHAM6-HAM2 this ~~is only the case~~ shortwave bias is most pronounced in simulation ALL\_ICE, this is the only simulation with a distinctively lower ECS. In the reference version of CAM5, too much shortwave radiation is absorbed over the Southern Ocean in their present-day climate (Kay et al., 2016), which explains why ECS is also sensitive to an increase in SLF in the study by Tan et al. (2016) this model (Tan et al., 2016). In addition, Tan et al. (2016) did not use a MLO, but a fully coupled dynamic ocean, which could impact the comparison with our results, because different methods can lead to differing ECS estimates (Frey et al., 2017).

~~Effective radiative forcing due to aerosol-radiation and aerosol-cloud interactions (ERFari+aci) and equilibrium climate sensitivity for the various sensitivity simulations described in Table 1.~~

In order to ~~proof~~prove our hypothesis for the different relationship between SLF and ECS in ECHAM6-HAM2, we evaluate the changes in cloud fraction as a function of cloud top pressure and cloud optical depth between the 2xCO<sub>2</sub> and 1xCO<sub>2</sub> climates. Because mixed-phase clouds are more prevalent in mid- and high latitudes than in the tropics and subtropics (Matus and L'Ecuyer, 2017), ~~the histograms in Figure~~we expected the largest differences there. The histograms in Figures 4 and 5 are taken ~~between 20° polewards of 40° S–60°S and 20°N–60°N latitude in both hemispheres.~~ They are taken from a satellite perspective, ~~i.e. by using the COSP-ISCCP simulator (Bodas-Salcedo et al., 2011).~~ This means that the cloud top pressure refers to the highest cloud in each single ~~column.~~sub-column used by the simulator. Subcolumns are used in the simulator to account for subgrid scale variability of the cloud (top) distribution. Here a phase change from cloud ice to cloud liquid water in the 2xCO<sub>2</sub> climate should be most pronounced. From Figure ~~5~~4 we see that only in simulation ALL\_ICE there is a ~~marked decrease~~large abundance of low- and mid-level optically thin extratropical clouds (with  $\tau < 1.3$ )~~accompanied by.~~ These clouds show a marked decrease accompanied with a marked increase of medium optical depth clouds ( $3.6 < \tau < 60$ ) between 560 and 800 hPa. ~~These in the 2xCO<sub>2</sub> climate (Figure 5). These clouds and their changes are absent in the all other simulations with a higher SLF, here shown for REF, (REF, HET, NOCONV and ALL\_LIQ).~~ Only in simulation ALL\_ICE ~~do~~are these optically thin ~~clouds consist of ice and hence are the ones that are ice clouds not shielded by higher clouds prevalent in the present-day climate (not shown) and are~~ converted to low- and mid-level liquid water clouds of medium optical depth in the ~~warmer~~2xCO<sub>2</sub> climate.

To estimate the radiative effect of this increase in cloud optical depth, we calculate the different components of the global cloud feedback parameter  $\lambda_c$  using the radiative kernel decomposition method described in ~~Zelinka et al. (2013, 2016)~~Zelinka et al. (2012a, b). This method decomposes  $\lambda_c$  into feedbacks that are associated with changes in cloud amount  $\lambda_{amt}$ , cloud top pressure  $\lambda_{ctp}$  and cloud optical depth  $\lambda_\tau$  as shown in Figure 6 for all simulations.  $\lambda_{ctp}$  is positive because of the shift of clouds to higher altitudes in the warmer climate (see also Figure 7) that enhances their LW CRE. At the same time, the total cloud amount decreases in a warmer climate, most noticeable at lower altitudes (Figure 7). This decrease in low/mid level clouds reduces the negative net CRE and also constitutes a positive feedback.  $\lambda_\tau$  is negative in most simulations and smaller than other cloud feedbacks so that  $\lambda_c$  is positive in most simulations.  $\lambda_c$  is negative ~~(-0.4 W m<sup>-2</sup> K<sup>-1</sup>)~~ only in simulation ALL\_ICE because of its large negative  $\lambda_\tau$ . In all other simulations  $\lambda_c$  ranges between 0.3 W m<sup>-2</sup> K<sup>-1</sup> and 0.6 W m<sup>-2</sup> K<sup>-1</sup>. The value of 0.6 W m<sup>-2</sup> K<sup>-1</sup> corresponds to the mean of the analyzed GCMs in AR5 (Boucher et al., 2013). The estimates from the other simulations (except ALL\_ICE) fall within the 90% range of the cloud feedback of -0.2 to 0.6 W m<sup>-2</sup> K<sup>-1</sup> as assessed in AR5 (Boucher et al., 2013).

The largest differences between the simulations are associated with changes in  $\lambda_\tau$ , which varies between -0.6 W m<sup>-2</sup> K<sup>-1</sup> in simulation ALL\_ICE and 0.1 W m<sup>-2</sup> K<sup>-1</sup> in simulation NOCONV. In simulation ALL\_ICE, the large negative value of  $\lambda_\tau$  can be explained with the largest increase in the liquid water path of 4.8 g m<sup>-2</sup> (Table 3) due to the phase change from cloud ice to cloud liquid water mainly in low- and mid-level mid-latitude clouds (Figure 5). This causes a negative optical depth feedback in all regions, but most pronounced polewards of 40° (Figure 8). Note that simulation ALL\_ICE is the only simulation in which the overall cloud feedback parameter is dominated by changes in cloud optical depth. The results of simulation ALL\_ICE agree qualitatively to the results from Bodas-Salcedo (2018) for regions with large-scale subsidence where optically thin ice

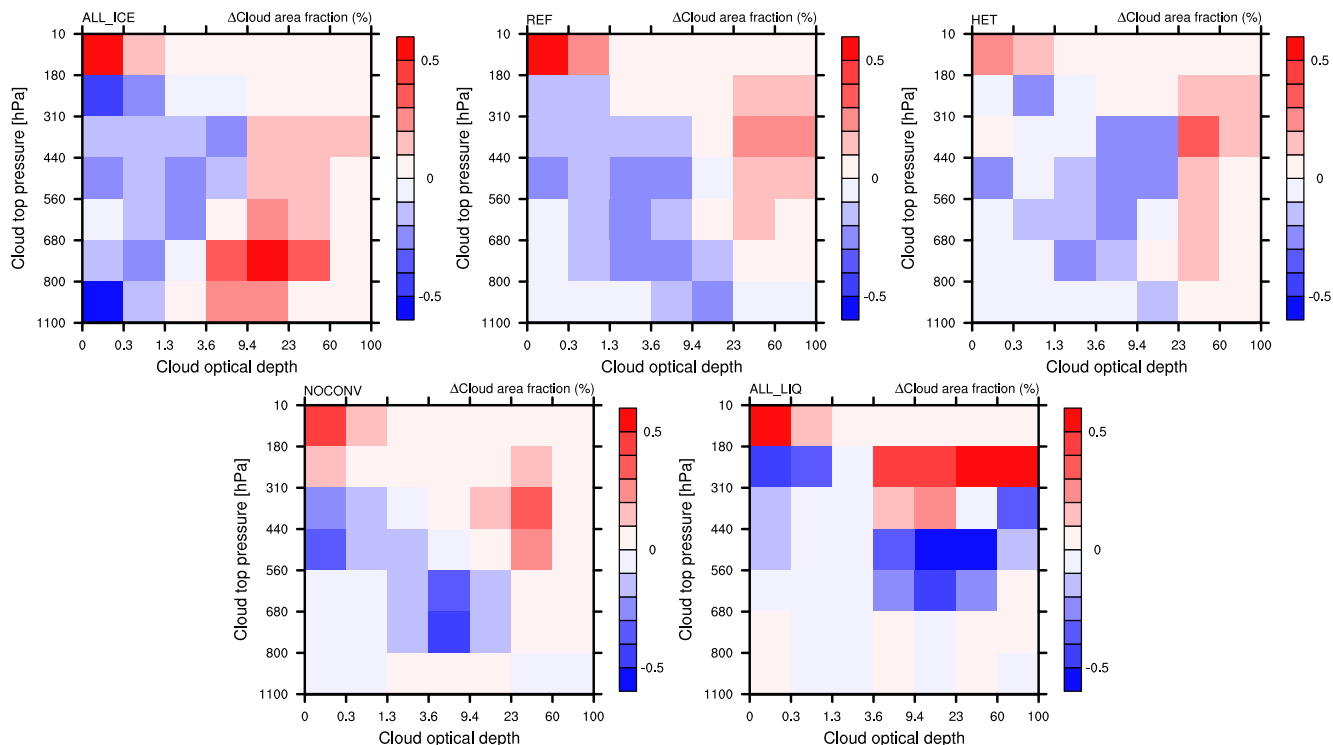


**Figure 4.** Distribution of cloud fraction in the extratropics ( $> 40^\circ\text{S/N}$ ) as a function of cloud optical depth and cloud top pressure between the  $2\times\text{CO}_2$  and the  $1\times\text{CO}_2$  climate in simulations ALL\_ICE, HET, REF, NOCONV and ALL\_LIQ from the last 25 years of the MLO simulations described in Table 1.

clouds in the present-day climate are not shielded by higher clouds and hence for which the cloud optical depth feedback is most important. In all other simulations, the cloud feedback is dominated by changes in cloud amount and cloud top pressure (Figure 6).

In the other simulations, shown in Figure 5 for simulations REF, NOCONV and ALL\_LIQ mid- and high latitudes, a rather different picture emerges. Here  $\tau$  of low clouds hardly changes or decreases as the majority of them is already composed of cloud droplets in the present climate and only a small phase change from ice to liquid occurs due to the doubling of  $\text{CO}_2$ . In all simulations, but for simulation NOCONV, the a negative cloud phase feedback shows up is also visible in the tropics. This negative feedback arises because some tropical clouds that glaciate at the tops either due to the presence of ice nucleating particles in the mixed-phase temperature regime or because their tops extend to altitudes with temperatures  $< -35^\circ\text{C}$  in the present climate will remain supercooled in the warmer climate and hence become optically thicker (Figure 8 Figures 8 and 9).

In the warmer climate, the static stability increases in areas with marine stratus, stratocumulus and tradewind cumuli in all simulations. This is accompanied by a stronger moisture gradient which promotes stronger drying by more entrainment (Gettelman and Sherwood, 2016), which in turn causes the marine subtropical clouds to thin become thinner and their

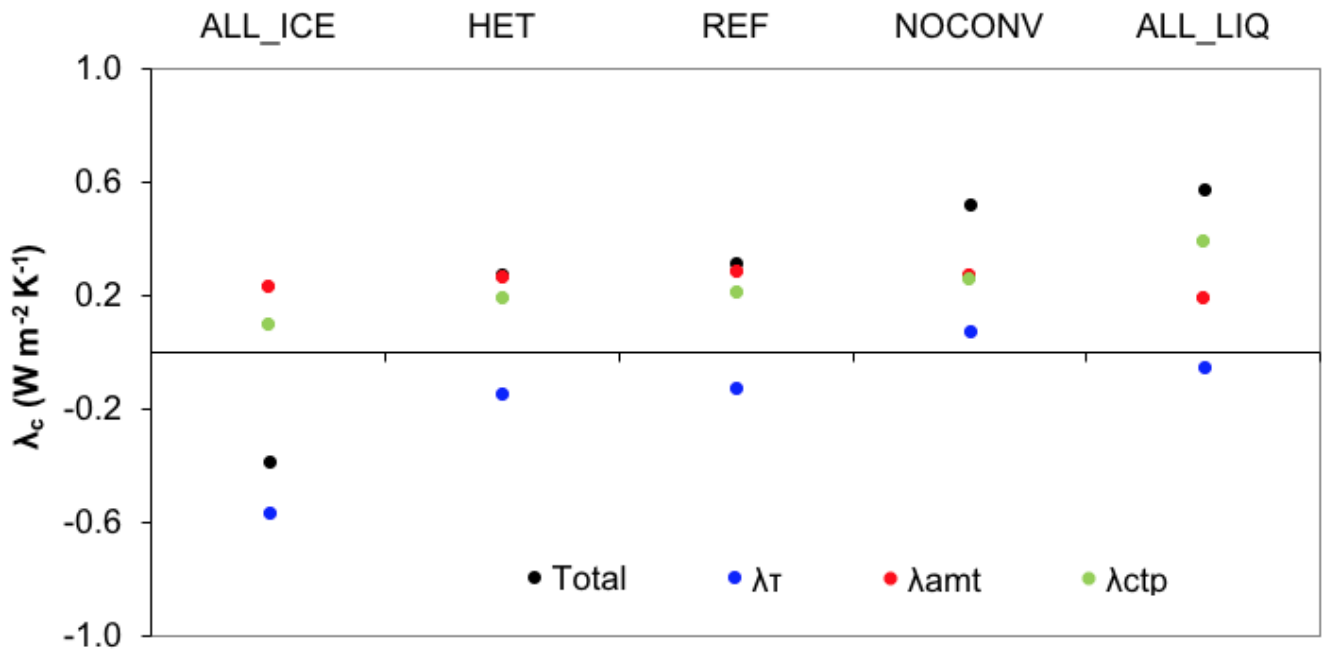


**Figure 5.** Changes in the distribution of cloud fraction in the extratropics ( $20^{\circ}\text{S} > 40^{\circ}\text{S}$ – $60^{\circ}\text{S}$  and  $20^{\circ}\text{N}$ – $60^{\circ}\text{N}$ ) as a function of cloud optical depth and cloud top pressure between the  $2\times\text{CO}_2$  and the  $1\times\text{CO}_2$  climate in simulations ALL\_ICE (upper-left), HET, REF (upper-right), NOCONV (lower-left) and ALL\_LIQ (lower-right) from the last 25 years of the MLO simulations described in Table 1.

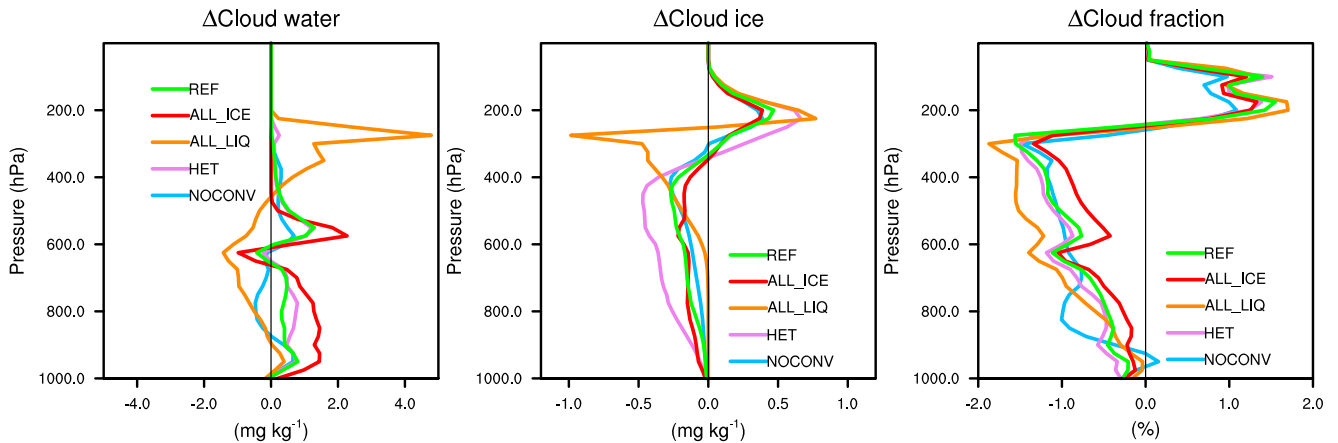
optical depth to decrease leading in most simulations to a positive cloud optical depth feedback in this region the subtropics as shown in Figure 8.

~~Tropical, subtropical, extratropical and global cloud optical depth feedback parameter  $\lambda_{\tau}$  in  $\text{W m}^{-2} \text{K}^{-1}$  for the sensitivity simulations described in Table 1.~~

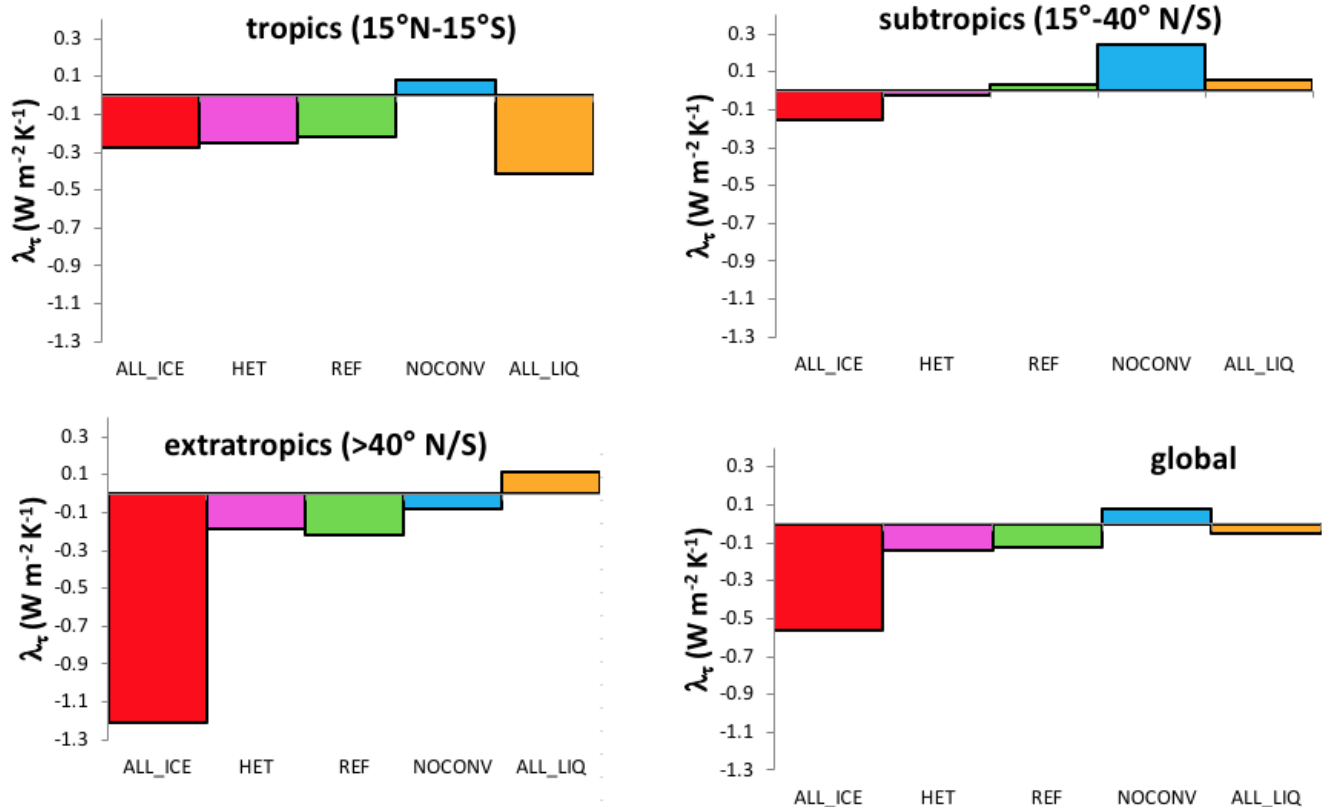
- 5 The parameterization of convective clouds in ECHAM6-HAM2 assumes that they form and dissipate in one timestep. During their lifetime, they can detrain cloud water and ice in the environment. Thus the negative cloud optical depth feedback in the tropics and mid-latitudes indicates that more cloud condensate is detrained in the form of liquid or supercooled liquid water rather than as cloud ice in the warmer climate. Thus, next to the rise of the melting level in the warmer climate also the rise of the homogeneous freezing level is important for the negative cloud phase feedback. This is best seen in simulation ALL\_LIQ
- 10 where no ice exists at mixed-phase temperatures, yet the negative cloud phase feedback still operates in the tropics (Figure 8 Figures 8 and 9). In the global mean, this negative cloud phase feedback is visible in all our simulations as a simultaneous increase in cloud liquid water and decrease in cloud ice in the warmer climate at a given pressure level (Figure 7). In mid-



**Figure 6.** Components of the globally averaged cloud feedback parameter  $\lambda_c$  in  $\text{W m}^{-2} \text{K}^{-1}$  for the ~~sensitivity~~ simulations described in Table 1.  $\lambda_\tau$  accounts for changes in cloud optical depth,  $\lambda_{amt}$  accounts for changes in cloud amount and  $\lambda_{ctp}$  accounts for changes in cloud top pressure.



**Figure 7.** Change in the annual global mean cloud liquid water content (LWC, left panel) and ice water content (IWC, right panel) in  $\text{mg kg}^{-1}$  as a function of pressure in hPa between the  $2x\text{CO}_2$  and  $1x\text{CO}_2$  climate ~~from for~~ the ~~various sensitivity~~ simulations described in Table 1.



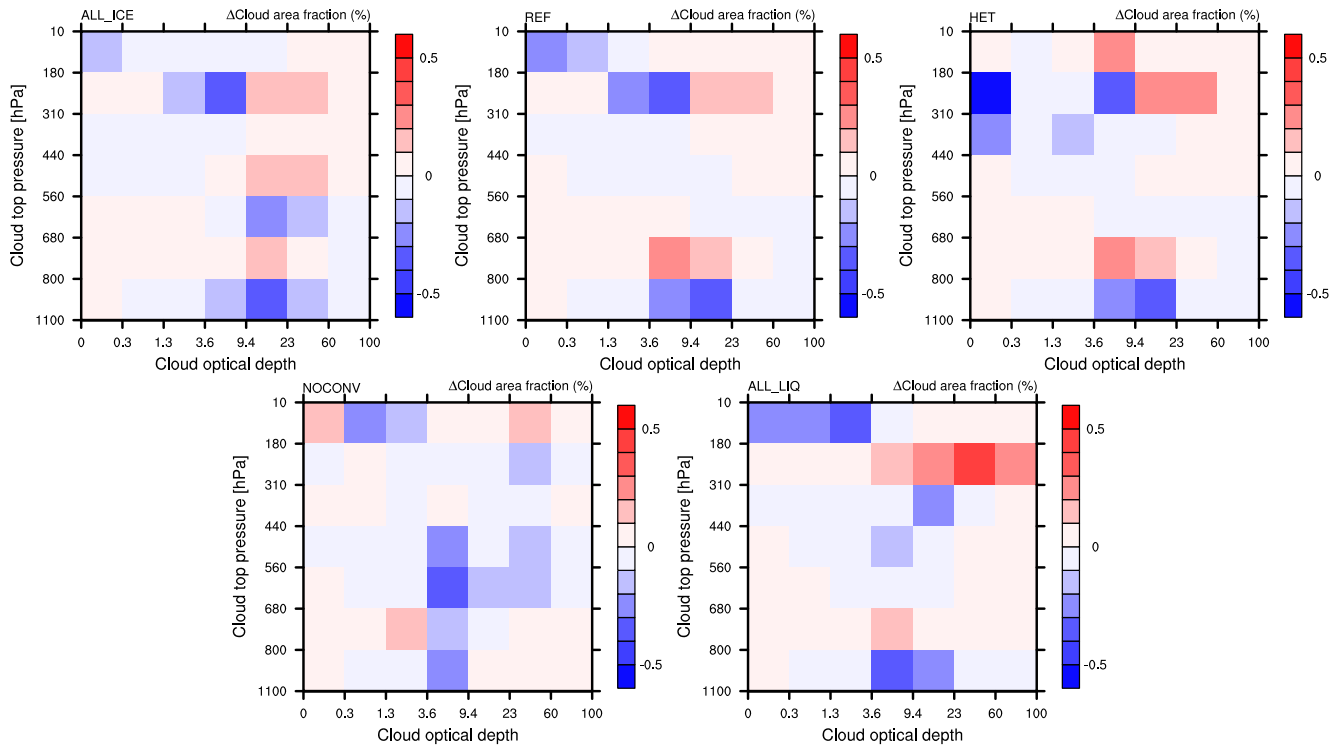
**Figure 8.** [Tropical, subtropical, extratropical and global cloud optical depth feedback parameter  \$\lambda\_{\tau}\$  in  \$\text{W m}^{-2} \text{K}^{-1}\$  for the sensitivity simulations for the simulations described in Table 1.](#)

latitudes [and the tropics](#) it shows up as an increase in [optical-optically](#) thicker clouds and decrease in [optical-optically](#) thinner clouds for the same cloud top pressure ([Figure 5](#) [Figures 5 and 9](#)).

The second most important contributor to the differences in the overall cloud feedback between ~~the~~ simulations ALL\_ICE and ALL\_LIQ is the change in cloud top pressure ( $\lambda_{ctp}$ ).  $\lambda_{ctp}$  varies between  $0.1 \text{ W m}^{-2} \text{ K}^{-1}$  in simulation ALL\_ICE and  $0.4 \text{ W m}^{-2} \text{ K}^{-1}$  in simulation ALL\_LIQ. The cloud top pressure feedback is mainly related to cirrus clouds and has been estimated from satellite observations to amount to  $0.2 \text{ W m}^{-2} \text{ K}^{-1}$  (Zhou et al., 2014). We obtain a cloud top pressure feedback of about this value in all other simulations. [We also computed the cloud feedbacks separately for low and non-low clouds following the decomposition by Zelinka et al. \(2016\), which leads to a weaker cloud top pressure feedback but in general qualitatively similar results for all simulations \(not shown\).](#)

10  $\lambda_{ctp}$  is largest in simulation ALL\_LIQ where the global mean changes in cloud liquid water and cloud ice are distinctively different from all other simulations (Figure 7). It is the only simulation in which cloud liquid water decreases throughout the lower and mid troposphere because here the poleward shift of the storm tracks and the upward shift of convective clouds are least [affected-compensated](#) by changes from cloud ice to cloud liquid water. ~~These~~ [The](#) changes in simulation ALL\_LIQ are





**Figure 9.** As Figure 5 but for the tropics ( $15^{\circ}\text{S} - 15^{\circ}\text{N}$ ).

accompanied with the largest decrease in cloud cover between 750 hPa and 370 hPa. Cloud liquid water increases between 250 and 400 hPa at the expense of cloud ice in simulation ALL\_LIQ. In all other simulations, the concurrent increase in cloud liquid water and decrease in cloud ice occurs at altitudes below 400 hPa. The different vertical structure of cloud liquid water and cloud ice in simulation ALL\_LIQ is a consequence of the **less efficient formation of rain as compared to precipitation formation via the ice phase** design of this simulation. Because cloud ice only forms at temperatures below  $-35^{\circ}\text{C}$ , cloud droplets are carried upwards to this temperature and the latent heat of fusion is released here. This additional buoyancy causes the highest cloud tops already in the present-day climate. In the, such that the optically thick clouds extend to higher altitudes in the  $2\times\text{CO}_2$  climate with higher specific humidity and more latent heat release, the buoyancy is higher and causes a further rise in cloud top pressure (see also Figure 5 for the extratropics) and (see Figures 5 and 9) causing the largest cloud top pressure feedback as shown in Figure 6.

The opposite effect can be seen in simulation ALL\_ICE, where all cloud water is converted to ice already at  $0^{\circ}\text{C}$  and the latent heat is released lowest in the cloud. As aggregation of ice crystals and accretion of snow flakes with ice crystals are more efficient at warmer temperatures, precipitation is formed much lower in the cloud. Therefore less condensate is carried into higher altitudes and the. The increase in cloud liquid water in low and mid-level clouds in the warmer climate is largest in this simulation (Figures 5, 7 and Table mainly because of the negative cloud phase feedback (Figure 7 and Tables 1 and 3). This

combined with only a modest increase in cloud ice and cloud cover between 250 hPa and 100 hPa (Figure 7) causes the cloud top pressure feedback to be smallest in this simulation (Figure 6).

Simulation NOCONV is the only simulation in which  $\lambda_\tau$  is slightly positive.  $\lambda_\tau$  is negative in all other simulations in the tropics (Figure 8) because more cloud condensate is detrained in the form of liquid or supercooled liquid water in the warmer climate. The absence of a convection parameterization and hence detrainment in simulation NOCONV on average leads to a positive tropical  $\lambda_\tau$ , i.e. the tropical and subtropical clouds in simulation NOCONV become optically thinner.

To summarize, the negative cloud optical depth feedback only dominates the overall cloud feedback if the low- and mid-level midlatitude clouds consist of ice in the present climate and change to liquid in the 2xCO<sub>2</sub> climate as in simulation ALL\_ICE. However, this does not imply that the overall cloud feedback remains more or less constant in the other simulations. In fact,  $\lambda_c$  almost doubles from simulation REF-simulations REF and HET to simulation NOCONV and ALL\_LIQ, caused by the large increase in cloud top pressure feedback in simulation ALL\_LIQ and a positive  $\lambda_\tau$  in simulation NOCONV as explained above. This marked increase in the overall cloud feedback from simulations HET and REF to simulations NOCONV and ALL\_LIQ is, however, does not lead to not reflected in an increase in ECS.

We hypothesize that different reasons are responsible for this behaviour in the different simulations processes contribute to the rather similar ECS in all simulations but ALL\_ICE: In simulation ALL\_LIQ, this is seems to be caused by the increase in optically optical thick clouds that cause convective aggregation in the ITCZ with less outgoing longwave radiation (OLR; see Figure ??) tend to cluster in the tropics and become optically thicker there. This is apparent from Figure 9, where the upward shift in cirrus clouds with an increase in cirrus optical depth between 180 and as seen in the most negative  $\lambda_\tau$  in the tropics in this simulation (Figure 8). This convective aggregation is associated with a 310 hPa is much more pronounced than in simulation REF. In addition, the negative cloud phase feedback is restricted to ice clouds that formed at altitudes with temperatures  $< -35$  °C in the 1xCO<sub>2</sub> climate that are now liquid clouds (Figure 7).

This increase in optical depth of high clouds causes their SW CRE to be more negative and completely offsets the reduction in LW CRE from the decrease in clouds elsewhere especially in the mid troposphere cloud cover in the tropics (Figure 10). Such a clustering of convective clouds was found by Lohmann and Roeckner (1995) using the ECHAM4 model when the emissivity of cirrus clouds was set to one (black cirrus), i.e. when the infrared optical depth was increased. No convective clustering was seen in the reference simulation where the cirrus emissivity was calculated as a function of ice water path and in a simulation with transparent cirrus in the infrared. In a warmer climate, convective clouds have been found to cluster further (Bony et al., 2016). The clustering of convective clouds in the warmer climate arises because clouds remain at nearly the same temperature in a warmer climate (e.g., Hartmann and Larson, 2002) but are in a more stable environment, which decreases anvil outflow in the upper troposphere and decreases the anvil cloud fraction (Bony et al., 2016). In ECHAM this decrease is most pronounced at altitudes below 250 hPa (Figure 7) from where more longwave radiation is emitted to space. This leads to an overall negative feedback (e.g., Hartmann and Larson, 2002; Mauritsen and Stevens, 2015) because of the much larger clear-sky area and offsets the positive cloud feedback limiting ECS in simulation ALL\_LIQ to have the same value as in simulation REF. Whereas reductions in OLR are restricted to the tropics in most of the simulations, in simulation ALL\_ICE also less LIQ, the least amount of outgoing longwave radiation is emitted from clouds over the Southern Ocean due

to the negative cloud-phase feedback. In simulation NOCONV hardly any reduction in OLR is visible, not even in the tropics, because of the absence of convection. The associated absence of detrainment slows down the Wegener-Bergeron-Findeisen process on the one hand, but speeds up the autoconversion rate on the other hand. The latter causes the increase in cloud liquid water in the warmer climate to be smallest (Table 3), which explains the overall positive  $\lambda_T$  and second-largest  $\lambda_C$ , but not why ECS does not increase as compared to simulation REF. The absence of convection seems to limit the increase in cirrus clouds (increase to space because the clouds are optically thickest in this simulation. In a warmer climate, these clouds cluster further in the intertropical convergence zone as can be seen from the largest increase in LW CRE as diagnosed from the radiative kernel (RK) method (Figure 10). Because these clouds are optically thick, this large increase in LW CRE (RK) is overcompensated by a decrease in SW CRE (RK) causing the net CRE (RK) in the intertropical convergence zone to be as negative in simulation ALL\_LIQ as in simulation REF.

The cloud top pressure feedback in the extratropics that operates in all simulations but ALL\_ICE (not shown) is overcompensated by decreases in cloud cover at altitudes above 250 hPa, Figure 7), and allows more OLR to be emitted to space basically everywhere on the globe (Figure ??). Differences in increases in Arctic OLR between the sensitivity simulations point to different Arctic amplification in these simulations, but that is less important for ECS.

Change in the annual mean outgoing longwave radiation in  $\text{W m}^{-2}$  between the  $2\times\text{CO}_2$  and  $1\times\text{CO}_2$  climate from the various sensitivity simulations described in Table 1. Negative values denote higher values of OLR in the  $2\times\text{CO}_2$  climate.

## 6 Aerosol radiative forcing

The aerosol radiative forcing  $\text{ERF}_{\text{ari+aci}}$  between the simulation with present-day aerosol emissions from the year 2008 and pre-industrial emissions from the year 1850 is shown in Figure ?? .  $\text{ERF}_{\text{ari+aci}}$  varies between  $-0.7 \text{ W m}^{-2}$  in simulation ALL\_LIQ and  $-1.7 \text{ W m}^{-2}$  in simulation 10/ce. Contrary to earlier results obtained with ECHAM4 (Lohmann, 2002), where  $\text{ERF}_{\text{ari+aci}}$  was twice as large in simulation ALL\_LIQ than . As shown in Figure 10, SW CRE and SW CRE (RK) become less negative in the extratropics and dominate over the decrease in LW CRE and LW CRE (RK) causing a positive  $\Delta$  net CRE at mid latitudes. The generally smaller positive and larger negative changes in net CRE than in net CRE (RK) are caused by compensating changes in non-cloud climate components as described in detail in Shell et al. (2008). In high latitudes, the decrease in surface albedo due to melting of Arctic sea ice causes especially large negative  $\Delta$  SW CRE and  $\Delta$  net CRE values polewards of  $70^\circ\text{N}$ . In the clear-sky, water vapor and  $\text{CO}_2$  absorb more longwave radiation in the warmer climate than in the present-day. This decreases the difference between all-sky and clear-sky fluxes and causes the LW CRE to be less positive. Differences in surface temperature operate in opposite ways. While more longwave radiation is emitted to space in the warmer climate (negative Planck feedback), also more longwave radiation is absorbed by clouds and re-emitted to the surface (positive cloud feedback). This clear-sky compensation in the longwave is most pronounced in simulation ALL\_ICE, there is not a large difference in  $\text{ERF}_{\text{ari+aci}}$  between these two simulations. In Lohmann (2002), the twice as large  $\text{ERF}_{\text{ari+aci}}$  in LIQ, which is the only simulation in which the global mean  $\Delta$  LW CRE (RK) is positive (Table 3).

The changes between simulation REF and ALL\_LIQ resulted from a three-times-as-large LWP in the present-day and also a three-times-as-large increase in LWP between pre-industrial and present-day conditions than in simulation are qualitatively comparable to the ones from Lohmann and Roeckner (1995), where the difference in climate sensitivity was rather small between the reference simulation and the black cirrus simulation, which both had a positive cloud feedback and an increase in net CRE. There was a noticeable difference between the transparent cirrus and the reference simulation because only the transparent cirrus simulation produced a negative cloud feedback and a decrease in net CRE. While in our simulation  $\Delta$ CRE is always negative or close to zero, it is most negative in simulation ALL\_ICE. In the current simulations, we retuned each simulation to be in radiative equilibrium at the top-of-the-atmosphere, which reduces the difference in LWP between these two simulations in the present-day climate to less than a factor of two, which corresponds to the transparent cirrus simulation.

For ERFari+aci the minimum CDNC is more important than differences in SLF. When reducing the minimum CDNC from  $40\text{ cm}^{-3}$  to  $10\text{ cm}^{-3}$ , ERFari+aci increases from  $-1$  to  $-1.7\text{ W m}^{-2}$  in accordance with the findings by Lohmann et al. (2000) and Hoose et al. (2009). On the contrary, ERFari+aci decreases from  $-1$  to  $-0.8\text{ W m}^{-2}$  when the biomass burning emissions are higher as in simulation GFAS3.4 because this increases the natural background (Carslaw et al., 2013). Whether cirrus clouds are formed by homogeneous or heterogeneous nucleation (simulations HET vs. REF) has no impact on ERFari+aci. ECS in simulation HET is also similar to simulation REF, but differences in  $\Delta$  LW CRE (RK) exist. As in simulation ALL\_LIQ, also in simulation HET the increase in  $\Delta$  LW CRE (RK) in the tropics is larger than in simulation REF (Figure 10) because of the upward shift of ice clouds (Figure 7) and their increase in optical depth (Figure 9). Because these ice clouds are of medium optical depth, the large  $\Delta$  LW CRE (RK) is overcompensated by a decrease in  $\Delta$  SW CRE (RK), causing  $\Delta$  net CRE (RK) and  $\Delta$  net CRE to be similar as in simulation REF (Table 3).

ERFari+aci is important for the transient climate response (TCR), because a large present-day aerosol forcing implies a larger warming when greenhouse gases become more important and emissions of aerosol particles are reduced (Andreae et al., 2005). However, since TCR and ECS are related (e.g., Otto et al., 2013; Knutti et al., 2017), and TCR is affected by ERFari+aci (e.g., Ekman, 2014), also a connection between ERFari+aci and ECS seems plausible. As discussed in the introduction, such a correlation between ERFari+aci and ECS was found in earlier versions of fully coupled atmosphere-ocean GCMs (Kiehl, 2007) and can also be seen in those newer CMIP5 models that are consistent with the observed temperature record during the instrumental period (Forster et al., 2013). However, that does not imply a causal relationship between ERFari+aci and ECS but says that GCMs which for whatever reason have a higher TCR need to have a higher ERFari+aci in order to match the observed temperature evolution.

When conducting different sensitivity simulations with a given model, a correlation between ERFari+aci and ECS can only be expected if there is a physical mechanism that affects both. In general, a doubling of  $\text{CO}_2$  leads to a faster hydrological cycle which reduces the lifetime of aerosols, but it does that similarly in all simulations. In our simulations, In simulation NOCONV the outgoing longwave clear-sky radiation is increased the most. While it is also slightly decreased in the coefficient of determination ( $r^2$ ) between ERFari+aci and ECS is only 0.2, i. e. no correlation exists (see Figure ??). I.e. the differences in SLF in low- and mid-level midlatitude clouds that influence ECS are not the main determinant for ERFari+aci. Vice versa, the differences in pre-industrial climate that strongly influence ERFari+aci are secondary for ECStropics, the decrease is smallest

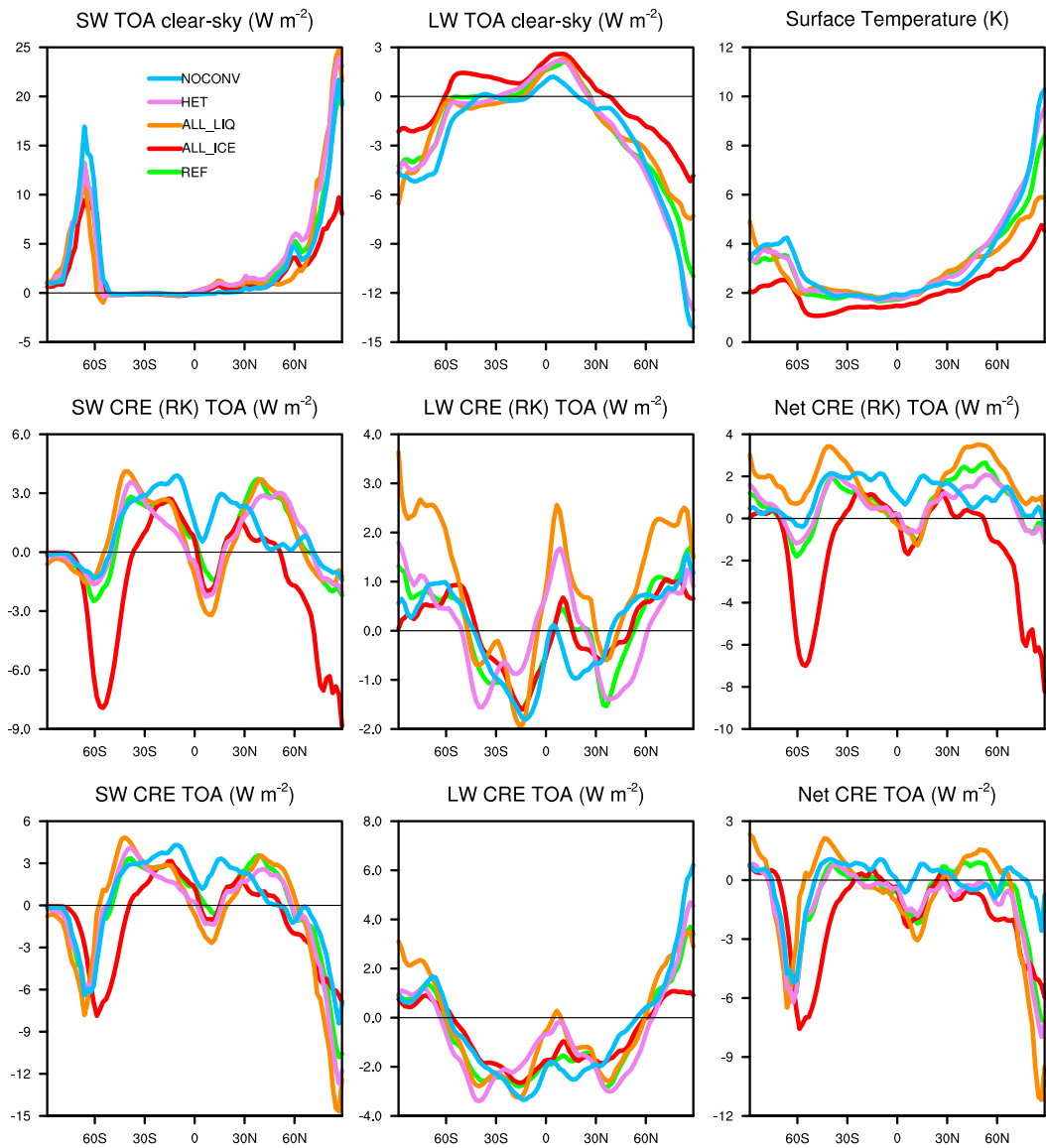
in this simulation, because of the absence of convection (Figure 10). The associated absence of detrainment slows down the Wegener-Bergeron-Findeisen process on the one hand, but required the largest speed-up of the autoconversion rate on the other hand (Table 1). The latter causes the present day cloud liquid water and its increase in the warmer climate to be smallest (Tables 2 and 3). This explains the overall positive  $\lambda_T$  and the second-largest  $\lambda_C$ . The most negative clear-sky LW radiation changes in NOCONV explain why ECS does not increase as compared to simulation REF. The absence of convection seems to limit the increase in cirrus clouds (increase in cloud cover at altitudes above 250 hPa, Figure 7).

## 6 Conclusions

In this study we used the newly developed ECHAM6.3-HAM2.3 coupled global aerosol-climate model to assess the influence of different factors for ECS. This work was motivated by the findings of Tan et al. (2016) using CAM5, who showed a large influence of correcting the underestimated SLF in present-day mixed-phase clouds on ECS. An underestimate of SLF has also been found in other models (Komurcu et al., 2014; Barrett et al., 2017a, b) and in a different version of CAM5 (Kay et al., 2016). The SLF was found to be most sensitive to the glaciation rate, which in turn is influenced by ice microphysics and the model's vertical resolution (Barrett et al., 2017a, b). In ECHAM6-HAM2, SLF could be improved when switching off the convective parameterization entirely. The absence of convection and hence detrained cloud ice slows down the glaciation rate in ECHAM6-HAM2, which corroborates the findings by Barrett et al. (2017a) on the importance of the glaciation rate for SLF.

In ECHAM6-HAM2, ECS is much smaller than in the CAM5 GCM used by Tan et al. (2016). It varies between 1.8 to 2.5 K in ECHAM6-HAM2 versus between 3.9 to 5.7 K in CAM5 (Tan et al., 2016). Thus, while ECS is at the low side of the ECS range between 2.1 and 4.7 K in IPCC AR5 (Forster et al., 2013; Flato et al., 2013) in ECHAM6-HAM2, it is on the high side in CAM5. Note that the percentage increase in ECS of 30% between the extreme scenarios (ALL\_ICE to ALL\_LIQ in ECHAM6-HAM2 vs. Low-SLF to High-SLF in CAM5) is similar, indicating that the relative contribution of the negative cloud phase feedback to the overall ECS is comparable in both GCMs.

However, important differences between the two GCM studies are apparent: Increasing SLF in ECHAM6-HAM2 from its variable-calculated values in the reference simulation to one as in simulation ALL\_LIQ does not increase ECS in contrary contrast to the findings by Tan et al. (2016). This supports the hypothesis put forward by Gettelman and Sherwood (2016) that the increase in ECS by increasing SLF in the CAM5 version used by Tan et al. (2016) is overestimated because its mean climate is not the most realistic. More specifically, as discussed in Kay et al. (2016), CAM5 overestimates the Part of this difference could be caused by the overestimation of shortwave absorption over the Southern Ocean because of due to too efficient freezing in low- and mid-level cloudsshallow convective clouds in CAM5 (Kay et al., 2016). We hypothesize that it is the SLF of these optically thin low- and mid-level mid-latitude clouds in the absence of overlying clouds that matters for ECS, because the cloud top temperature of these clouds is in the mixed-phase temperature range. Hence, the cloud phase at the cloud top of these clouds plays an important role for the TOA radiation budget. If the absorption of shortwave radiation over the Southern Ocean is correctly simulated, then SLF in other clouds does not matter for ECS. At least this is what the ECHAM6-HAM2 results show, because only in simulation ALL\_ICE too much significantly less shortwave radiation is absorbed in reflected back to



**Figure 10.** Changes in the annual zonal SW and LW net clear-sky radiation in  $W m^{-2}$  at the top-of-the-atmosphere, surface temperature [K] (upper row); changes in SW, LW and net cloud radiative effects between the  $2xCO_2$  and  $1xCO_2$  climate calculated based on the radiative kernel method (middle row) and normally diagnosed (lowest row) for the simulations described in Table 1. Negative values for the change in clear-sky outgoing longwave radiation denote higher values in the  $2xCO_2$  climate.

space from clouds over the Southern Ocean and this is the only simulation in which ECS is significantly smaller than in all other simulations. In all other simulations sufficient or even too little much shortwave radiation is ~~absorbed in~~ reflected back to space from clouds over the Southern Ocean and all of them have similar values of ECS.

The reason why an underestimation of SLF in ~~other cloud types~~ cloud types other than thin mid-latitude clouds with cloud  
5 top temperatures between 0 and -35 °C does not seem to matter is because ~~the reflection of shortwave radiation saturates with~~  
~~increasing optical depth~~ radiative changes in clouds in the warm sector of extratropical cyclones are masked by ice clouds above  
them (A. et al., 2016). In addition, ~~there is too little shortwave radiation in higher latitudes~~, the tops of tropical deep convective  
and deep frontal clouds consist of ice and low-level that will not change in a warmer climate. Low-level clouds in the tropics  
and subtropics already consist of liquid water ~~. Thus, the cloud phase at the tops of all these other clouds will and therefore~~  
10 their cloud phase will also not change in the future climate. ~~Nevertheless~~

In our model, it is not only the cloud phase feedback and the overall cloud feedback that matters for ECS. If ~~that this~~ were the  
case, ECS should be largest in simulation ALL\_LIQ, where the cloud ~~optical depth~~ feedback parameter is highest ~~and positive~~.  
It seems that in simulation ALL\_LIQ tropical deep convective clouds tend to aggregate, which causes a negative feedback  
by increasing the clear-sky area and with that the longwave emission from clear-sky regions to space (e.g., Hartmann and  
15 Larson, 2002; Mauritsen and Stevens, 2015). This negative feedback ~~offsets~~ reduces the positive cloud feedback and causes  
the changes in the net cloud radiative effect and ECS to be the same in simulations REF and ALL\_LIQ. Also in simulation  
NOCONV, where we switched off the convection parameterization, SLF is higher than in simulation REF, because of a reduced  
Wegener-Bergeron-Findeisen process. Again, ECS remains the same because of the smallest increase in cirrus cloud cover in  
this simulation that allows more longwave clear-sky longwave radiation emission to space ~~. than in the reference simulation.~~

20 As discussed by Frey et al. (2017), while cloud phase improvements in the extratropics affect ECS in their model, they  
do not seem to matter for the warming during the 21st century in the Community Earth System Model (CESM) because of  
compensating responses in ocean circulation. If this is also the case in other Earth System Models, will be subject to future  
investigations.

~~An analysis of the different simulations in terms of their aerosol radiative forcing (ERFari+aci) showed that this is largely~~  
25 ~~determined by the pre-industrial aerosol concentration and hence is largest when the minimum cloud droplet number is smallest~~  
~~and smallest when assuming higher biomass burning emissions in pre-industrial times. No correlation has been found between~~  
~~SLF and ERFari+aci, contrary to earlier findings with a previous version of ECHAM-HAM (Lohmann, 2002), where the~~  
~~simulations were not re-tuned to be in TOA radiation balance and hence had much larger differences in cloud water that~~  
~~influenced ERFari+aci. Also, no correlation has been found between ERFari+aci and ECS, suggesting that the relationship~~  
30 ~~between ERFari+aci and ECS found by Forster et al. (2013) in the CMIP5 models seems to be related to structural uncertainties~~  
~~between different models rather than parametric uncertainties within one model.~~

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10 6.1: NASA Goddard (<https://ladsweb.nascom.nasa.gov>). Model data are available from the authors upon request.



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