Author's response

Below, the Author's comments are extended with a more specific description of the changes in the manuscript, highlighted in orange

In addition to the corrections detailed below, major changes have been made on the order of presentation in Section 4 induced by the necessary corrections to account for the Reviewer comments: Section 4 has been divided into 3 subsections in the revised version. Cloud properties, radiation and the effects of retuning are explained separately in Section 4.1-4.3, respectively, in order to clarify the presentation of our results.

1. Author's responses to Reviewer comments

We gratefully thank the three Reviewers for their suggestions and comments. Below we present our response to each Reviewer. General comments are considered first, which are followed by point-to-point answers to specific comments provided by each of the Reviewers. (The Reviewer comment is shown in *italics* highlighted with yellow, which is followed by our response).

In the process of revising our analysis, a small bug was found from the code for autoconversion which on rare occasions caused the CNDC to be increased. Luckily, it had an almost negligible impact on the results (e.g. impacts on global-mean radiation fluxes were on the order of 0.01 W m^{-2}). The bug has been corrected for all the results presented in the manuscript, and this results in some very small differences in some of the reported numerical values as compared to the initial submission.

As a general note about the revised manuscript, much of Section 4 has been revised, with corresponding changes in the Conclusions. Section 3 also includes some more specific corrections, which are outlined in our replies below.

1.1 Reviewer #1

General comments

1.
The manuscript needs to better illustrate the differences between simulations in a quantitative way (probably with zonal mean figures) as noted below.

2.
In addition, given the prominence of autoconversion as a process for the results, it is probably necessary to show some process rates for autoconversion.

3.
Vertical velocity distributions and activation rates would also be useful to explain some of the more confusing aspects of the relationship between vertical velocity variance and cloud drop number noted in the text.

The Reviewer highlighted the need for more quantitative illustration of the results: our results are now presented in zonal means. The process rates for autoconversion and cloud activation are now also shown (Figures 2 and 3 in the revised manuscript), and used to provide more detailed understanding of several processes leading to our results. The revised manuscript also includes more discussion about the influence of the subgrid vertical velocity distribution

All figures are now given in zonal means, with the addition of Figures 2 and 3 for microphysical process rates. The relationship between subgrid vertical velocity and CDNC is further analysed and explained on page 8, line 18 – page 9, line 15

Specific comments

1.
P15524,L6: should the ACI be negative?

Yes, this has been corrected.

Page 2, line 6. The change from -1.30 to -1.28 is due to the bug correction.

2.
P15228,l25: what type of cloud is the high cloud cover due to? You are using the ISCCP simulator, so you can discriminate thin and thick clouds, and high and low clouds? Also in Tontilla et al 2013? Or is that a feature of the nudging?

The high total cloud cover is not a feature of nudging; similar features were present in Tonttila et al. 2013 as well, where nudging was not used. In general, the cloud-top pressure is too low in our model runs as compared to ISCCP-data, suggesting an overestimation in high-level cloud cover. However, low level cloud cover at mid-latitudes is also larger than in ECHAM5 simulations without the HAM2 aerosol module. Moreover, comparison of the global mean cloud radiative effects with CERES-EBAF data (presented in Table 4 in the revised manuscript) shows too strong cloud radiative effect for both SW and LW radiation in our model, which would be consistent with an overestimation of both high- and low-level clouds.

Corresponding discussion has been added on page 7, lines 17-25.

3.
P15529,L29: note that reducing autoconversion might also impact accretion. What is the relative importance of these processes in ECHAM-HAM?

Autoconversion plays the key role for the differences between the model versions considered in the manuscript, yet it is agreed that autoconversion and accretion rates do interact. Their relative importance is also strongly controlled by model tuning which, however, has not been considered for accretion rate in this manuscript.

4.
P15530,L6: but above you said sensitivity was low Inge S.H. and higher in the NH. Please clarify.

The following explanation will be added to the revised manuscript:

"In the southern hemisphere the autoconversion rate is sensitive to changes in CDNC due to the generally low CCN concentration over the oceans. Thus, the slightly increased CDNC shown by ACT is accompanied by increased LWP as compared to REF, since reduced droplet size reduces the amount of water that is converted to drizzle and rain. In comparison, in the northern hemisphere subtropics and mid-latitudes, CDNC is lower in ACT than in REF, especially over land, but LWP is similar to REF. This likely relates to the low sensitivity of autoconversion to small changes in CDNC in regions with high CCN concentration”

The text given above has been added to page 9, lines 16-23.

5.
P15330,l25: again, do the earlier simulations show this with ECHAM ham (high cloud amounts and high tau). Or is this a feature of nudging? From Tontilla et al 2013 it looks like cloud amounts stay high.

Also: perhaps you should show microphysical process rates for autoconversion here.

As already mentioned in the text, the high cloud cover is present in all our runs using the McICA and the stochastic cloud generator in conjunction with ECHAM5-HAM2, also in Tonttila et al. 2013. Earlier papers using the McICA and stochastic cloud generator in standard ECHAM5 (without HAM) did not show this feature. It is not caused by nudging. This will be elaborated in the revised manuscript. The process rates for autoconversion and cloud activation are given in Figures 2 and 3, respectively, in the revised manuscript.

Autoconversion rate is shown in Figure 2 and commented on page 8, lines 3-8.

6.
P15531, L3: these need to be more quantitative. Perhaps zonal means would be better?

7.
P15531,L11: the difference is not easily visible. See comment above.

8.
P15332,L1: can you demonstrate with zonal mean difference plots? I also think an analysis of the microphysical process rates would be wise.

9.
P15532,L5: why not show the microphysical process rates for autoconversion and other processes?

11.
P15541: figure 2 and 3 would be better as zonal means. In figure 2 I cannot see any differences. These could be made more quantitative for figure 3 with zonal means. Could maybe separate land and ocean as well.

Since the same general issues are repeated in comments 6, 7, 8, 9 and 11 here, we provide a collective response to them. All the figures are now given in zonal means and new figures 2 and 3 have been included for autoconversion and nucleation rates.

10.
P15533,L5: useful to state that ACI seem to follow deltaLWP, not deltaCDNC.

12.
P15543: figure 4. Again, this is hard to see any quantitative differences. Perhaps

showing a zonal mean on the same plot would be better. Where are differences? Assume this is mentioned in the text.

The plot has been converted to zonal means. Clearly, the strongest differences in the aerosol indirect effect are seen for the northern mid-latitudes, collocated with the significant differences in the anthropogenic perturbation of cloud properties.

The following discussion will be added in the revised manuscript:
"The zonal mean net AIE is shown in Figure 6. The bulk of the difference between REF and ACACT occurs in the midlatitudes of the northern hemisphere. It is also noted that the global distribution of AIE follows rather tightly the anthropogenic perturbation in LWP, which along with the difference in the global mean AIE highlights the importance of how autoconversion is calculated in the model."

The text above is found on page 13, lines 14-18.

1.2 Reviewer #2

1.
The authors should clarify how the model configurations REF, ACT, ACACT differ from the configurations REF, SUBW, SUBWRT, W_ADJ1, W_ADJ2 in T2013.

REF and ACACT are similar to REF and SUBW respectively, except that the former ones are now run for both pre-industrial and present-day conditions, and they are performed as nudged runs, unlike in Tonttila et al 2013. This will be described more clearly in the manuscript

This is now described more clearly on page 6, lines 22-25.

2.
There is no mention of retuning for radiation balance. If REF is in radiation balance, then ACACT must not be. I would suggest to add a retuned version of ACACT to the comparison. In T2013, the retuning involved adjusting the autoconversion scaling factor. There is ample evidence in the literature that altering autoconversion can have a large impact the magnitude of the indirect effect, so this should be discussed and investigated.

A retuned model configuration ACACTRT has been added in the revised manuscript. The autoconversion rate scaling factor was reduced from 3.0 to 1.5. This results in quite similar radiation budget in REF and ACACTRT in pre-industrial conditions (net radiation balance within 0.3 W m^{-2}, and also similar LWP). The net aerosol indirect effect (AIE) in ACACTRT is -1.37 W m^{-2}, which is approximately 0.09 W m^{-2} stronger than in the un-tuned ACACT configuration. Thus, the difference in AIE between ACACTRT and REF is -14 %, which is smaller than that between ACACT and REF (-19% after the bug correction mentioned above), but it is still a significant effect.

The question of the initial basic state of the different model configurations is an interesting one, yet rather difficult to answer definitively. On one hand, when we are tuning the model closure parameters, we are directly tampering with the model physics, thus adding additional effects on the model results besides the ones we are actually interested in. On the other hand, the argument about differing model basic state is of course valid. Thus, we interpret the result such that the 19 % reduction of AIE in the un-tuned model setup represents the direct impact of the subgrid parameterizations, whereas the 14 % reduction after retuning more closely resembles an operational implementation. Discussion on this will be added to the concluding section (Section 5) of the revised manuscript.

It is also worth noting that to a large extent the change in AIE due to subgrid treatment of microphysics eventually stems from the change in autoconversion rate, and is thus related to precipitation formation and LWP (more in-depth discussion of this will be added to Section 4 of the revised manuscript. Please consult also our responses to comments 8 and 11 of Reviewer #3). This is consistent with earlier studies about the importance of precipitation formation in representing the anthropogenic aerosol effects in large-scale models.

A retuned model configuration is now presented and analysed: page 6, 7-10; page 13, line 25 – page 14, line 15. The radiative fluxes for each model configuration are given in Tables 3 and 4 for PI and PD conditions, respectively. The effect of autoconversion on the simulated aerosol indirect effect is discussed on page 15, lines 15-24.

3.
Panels in Figures 2, 3, and 4 are very small and difficult to read. In the difference panels, most regions are probably not statistically significantly different from one configuration to another. Maybe it would be better to plot zonal averages and then highlight which regions of the zonal averages are statistically significant.

These figures are replaced by zonal mean plots. Please refer to our responses to Reviewer #1. The zonal distribution of statistical significance was analysed and is commented in Section 4 of the revised manuscript accordingly.

All figures 1-6 are now given in zonal means. The regional distribution of statistically significant differences are given in the text on page 11, lines 9-18; page 12, lines 5-6 and 9-10; page 15, lines 7-9.

4.
West et al. (2014, doi:10.5194/acp-14-6369-2014) found a strong relationship between the variance of the subgrid vertical velocity distribution and the magnitude of the indirect effect.

The citation will be included in the revised manuscript.

On page 16, line 26.

5.
P15525, lines 1-6: this is an incomplete description of the state-of-the-art. A very large number of climate models do not use a single effective vertical velocity for activation, but rather explicitly integrate over a vertical velocity distribution. This was first proposed in 1997 and has been adopted in many contemporary climate models (see for example dois: 10.1029/97JD00703, 10.1029/96JD03087, 10.1029/2005JD006300, 10.1175/2010JCLI3945.1). ACT follows the same basic idea.

We will account for this comment, and add the suggested references, in the Introduction of the revised manuscript.

The references and related discussion is now found on page 3, lines 13-19.

6.

P15526, lines 16-17. Even if one were to assume that all the TKE was confined to vertical motions (which is physically impossible), the upper bound on the proportionality coefficient would be 1.41 (sqrt(2)). Is the 1.68 value simply treated as a tuning parameter?

Agreed. The value 1.68 is indeed considered as a type of tuning parameter, as also discussed in Tonttila et al. (2013). For clarity, a short discussion is now included also in the current manuscript. It states that the value 1.68, although unphysical as the Reviewer states, is selected in order to match the magnitude of the GCM grid-cell mean vertical velocity with the effective velocity in REF, in order to isolate the effects of subgrid variability alone. This point will be elaborated on in Section 2 of the revised manuscript.

Improvements in the text have been added on page 4, lines 22-27.

7.
P15526: choosing sigma to be the same as the single effective velocity in REF almost automatically guarantees that CDNC will be smaller with subgrid variability than without, since the majority of sample points will have velocities smaller than the effective velocity.

Please note that we choose sigma so that the mean vertical velocity over the positive side of the PDF matches the single effective vertical velocity, i.e. the mean magnitude of the subgrid vertical velocity samples used for cloud activation approximately matches the effective vertical velocity. For a Gaussian distribution, with the distribution peak at zero, the mean over the positive side is ~0.79*sigma. Thus sigma needs to be larger than the effective vertical velocity in REF in order to match the average magnitude of the vertical velocity for cloud activation, and to isolate the impact of subgrid variability. As it is suggested in the text, in many cases it still results in smaller CDNC with subgrid variability than without, since small velocities still gain more weight in terms of the mean CDNC, if CCN concentration is high enough so that cloud activation is sensitive to variations in vertical velocity.

8.
Section 2: mention the number of sub-columns and the additional associated cost compared to REF.

We use 50 subcolumns which increases the computational cost by 20-25 % on a Cray XC30 computer. This will be mentioned at the end of section 2 in the revised manuscript.

Added on page 6, lines 16-19.

9.
Table 2: add CERES-EBAF observation for SWCRE and LWCRE. Also add net TOA radiation values.

We have separated the cloud properties to Table 2 and radiation quantities to new Tables 3 and 4 in the revised manuscript. Table 3 shows the radiation quantities for the pre-industrial runs of each model configuration. Table 4 shows present-day radiation quantities, also including the CERES-EBAF observations.

TOA radiation values are given in Tables 3 and 4 for PI and PD conditions, respectively. In addition, the CERES-EBAF observations are also given in Table 4.

10.
In T2013, Sect 6, there is a brief discussion about an imposed minimum cloud drop number of 40 cm-3 in ECHAM5.5. If this minimum value is still being imposed, it would be relevant to discuss it in the present manuscript.

The issue of minimum CDNC will be noted in Section 5 of the revised manuscript.
The existence of the minimum CDNC is noted on page 5, lines 4-6, and its potential effects are briefly considered on page 16, lines 9-11 and 26-29.

1.3 Reviewer #3

Major comments
1.
The differences in the basic states in three configurations. The differences in the basic states of three configurations are large. For example, LWP is 67.4 g/m2 in ACT and reduces to 50.2 g/m2 in ACACT, about 25% decrease. The same large differences are also true for column-integrated droplet number concentrations. Therefore when the authors discuss the differences in aerosol indirect effects, the large differences in the basic states need to be accounted for. The relative difference therefore may be more meaningful. For example, although increase in in-cloud CDNC at the 890 hPa is the largest in REF (36.42/cm3), with smaller increase in ACT (31.83 /cm3) and ACACT (30.7/cm3), the relative increase (compared to the PI CDNC) is the largest in ACACT (44.5%), with smaller relative increase in REF (41.7%), and Act (40.5%). The same can be applied to LWP and aerosol indirect forcing as well. When the relative differences are used, the picture can be quite different. Accordingly, many discussions in Section 4 and 5 will need to be revised.

2.
The physical mechanisms behind simulated changes in anthropogenic aerosol effects on LWP needs to be better understood, especially between ACACT and ACT. The large difference in LWP change from PI to PD between ACACT and ACT is probably one of the most important results of this manuscript, but the reason behind this is not clear at all. On the other hand, if the relative change is used, the difference is much more moderate, and not sure whether the difference is still statistically significant.

The differences in the initial model states have now been accounted for by 1) analysing both the absolute and relative changes between PI and PD conditions and 2) by including a new retuned model version, where the radiation balance and e.g. LWP are quite close to those in REF in PI conditions. The new results are considered in Section 4 and the Conclusions. We have also added a more detailed explanation about the underlying reasons for especially the differences in the LWP change from PI to PD. A more detailed list of changes can be found in our responses to the Specific comments.

Relative changes and their significance are analysed in Sections 4.1 and 4.3 of the revised manuscript. Results from a retuned model configuration are considered in Section 4.3. The reason for differences in the anthropogenic LWP change are also further explained in Section 4.1.

Specific comments

1.
line 17, page 15524: Results from climate model simulations that account for cloud-

scale motion (Wang et al., 2011, doi:10.5194/acp-11-5431-2011; Wang et al., 2012, doi: 10.1029/2012GL052204) also contribute to the weaker aerosol indirect forcing estimate, as discussed in IPCC AR5. Wang et al. (2012) is particularly relevant to this paper, as that paper is also about understanding aerosol indirect effect differences in different models, and how differences in cloud microphysics might help to explain model differences.

The references will be included in the revised manuscript.

Added on page 3, lines 1-2 and page 13, lines 21-24.

2.
Lines 22-24, page 15525: Not sure I would agree with this statement ("a significant part of model-based overestimation of aerosol indirect effect can be explained by omitting subgrid variability in cloud microphysical processes") and a similar statement in the abstract. I think the paper needs to provide more evidence to support this statement. One thing is that tthe differences in the basic states are needed to be accounted for. Another thing is that the physical mechanisms that lead to the large reduction of aerosol indirect forcing from ACT to ACACT needs to be further explored.

A new model run with retuned autoconversion scaling parameter has been added to the manuscript. It shows that even after retuning the net indirect radiative effect due to subgrid variability is approximately 14 % weaker than in REF. We interpret this so that for an operational setup the impact of subgrid parameterizations is most likely at least 14 %. Please refer also to our answer to comment no. 2 of Reviewer #2.

The difference in the indirect radiative forcing between ACT and ACACT follows quite closely the difference in LWP between those model configurations, which in turn is seen to be tightly coupled with the treatment of autoconversion, and for which we can provide an explanation. Regarding this, please refer to our answer to comments 8 and 11 below.

Furthermore, we have moderated the wording of the above-mentioned sentence to reflect the fact that retuning slightly reduces the difference in indirect effects between ACT and REF. It now reads: "These simulations demonstrate directly that omitting subgrid variability in cloud microphysics contributes to the overestimation of model-based aerosol indirect effect". A corresponding change will be included in the abstract.

The modified versions of the statements referred by the Reviewer are found on page 2, lines 14-16 and page 3, lines 29 – page 4, line 2. Results from the retuned model version are given on page 13, line 25 – page 15, line 15. Discussion about the key physical mechanisms affecting the reduction of AIE is added on page 11, lines 22-29 and on page 12, lines 11-27.

3.
Lines 21-23, page 15526: It is not clear to me how the subgrid distribution of CDNC is purely determined from the subgrid distribution of vertical velocity. To my knowledge, grid-mean CDNC is a prognostic variable in ECHAM5-HAM2, which accounts for both source and sink terms such as droplet activation, advection and precipitation. So how can the PDF of CDNC is directly determined by the PDF of sugbrid vertical velocity?

Indeed, the grid-scale CDNC is the result of source and sink terms, but the subgrid distribution of CDNC operates in the subcolumn space, which is stochastic. Thus, the subgrid variability is a diagnostic property generated for each timestep. Of course, during that timestep the distribution is also affected by the subgrid autoconversion in the case of ACACT and ACACTRT. This is done also in part for computational reasons, since having each subcolumn prognostic would increase the number of tracers to an unpractical level.

The following explanation will be added to Section 2 of the revised manuscript:
“The subgrid vertical velocity samples from the PDF are used to calculate cloud droplet activation, which yields the distribution of CDNC in the stochastic subcolumn space. Note that the subcolumn CDNC distribution is treated as a a diagnostic property, while a prognostic formulation (Lohmann et al., 1999) is retained for the grid-scale mean CDNC.”

The text quoted above has been added on page 5, lines 1-4.

4.
Lines 25-26, page 1526: Please also elaborate how the model account for the correlations between LWC and CDNC in their subcolumn generator (or, more precisely, the correlation between LWC and the subgrid vertical velocity). This can be elaborated either here or in the description of the case of ACACT on page 15527.

Since these parameterizations operate on turbulent stratiform clouds, we do not assume any correlation between the cloud properties and vertical velocity, following the discussion in Tonttila et al. 2013 and e.g. Morales and Nenes 2010. For cumulus clouds the situation would be different since in that case the in-cloud thermodynamics are important in driving the updrafts.

We will add the following sentence in Section 2:
“Since our focus is on stratiform clouds, the vertical motions to be parameterized are highly turbulent and thus presumably weakly correlated with the thermodynamical properties of the cloud (in contrast to convective cumulus clouds), as also noted in e.g. Morales and Nenes (2010). Therefore, we do not assume any correlation between vertical velocity (and thus CDNC) and LWC.”

The new sentences have been added on page 5, lines 9-14.

5.
Page 15527, the case of ACT: Please clarify whether the subgrid CDNC in ACT is used in radiation calculation.

Yes, it is. This is stated explicitly in the revised manuscript.

The statement has been added on page 6, lines 1-2. Similar addition was also made on page 6, lines 5-6.

6.
Figure 1c and 1d, page 15529: I understand the decrease in CDNC from REF to ACT, as activated droplet number concentration increases non-linearly with increasing vertical velocity and this non-linearity is mainly caused by the competition of water vapor from more activated droplets. However, there is also a significant decrease in CDNC around 60S from REF to ACT. This is not clear to me.

7.
Line 20, page 15529: “even slightly increased CDNC”. The increase at around 60S is quite significant. What causes this increase?

The most likely explanation is that as shown by Figure 3 in the revised manuscript, the nucleation rate is slightly increased in ACT and ACACT over the southern hemisphere oceans, where CCN concentration is low, as compared to REF. This is in contrast to regions with higher CCN concentration, where subgrid treatment decreases the cloud droplet nucleation rate. While virtually all suitable accumulation and coarse mode particles are activated already at very weak updrafts when the aerosol concentration is low, ACT and ACACT showed an additional boost in the number of activated aerosols in small Aitken mode particles due to some subcolumns having a very strong vertical velocity compared to the effective velocity in REF.

The slight increase in CDNC in ACT then stands out, because the autoconversion rate is very similar between ACT and REF, while ACACT displays stronger autoconversion due to the subgrid calculations. The stronger autoconversion compensates for the effects of cloud activation in ACACT, resulting in lower CDNC at 60 S, than what is seen for ACT. This point will be discussed in Section 3 of the revised manuscript.

Explanation for this feature has been added on page 9, lines 4-15.

9.
Lines 10-17, page 15531: see the major comment #1. As the basic states are quite different in three configurations, the absolute difference in CDNC can be misleading sometimes, and a relative difference can be more meaningful. See the approach used in Wang et al. (2012). If the relative difference is used here, the picture can be quite different (see the major comment #1). Accordingly, many statements and discussions in this section will need to be revised. For example, I do not think you can attribute 80% of this difference to subgrid cloud droplet activation alone. I also do not think you can conclude that "the type of autoconverion is not important for the anthropogenic perturbation in CDNC in our model".

10.
Lines 5-15, page 15532: see my last comment and the major comment #1. The same argument can be applied to LWP as well. The relative change in LWP is 11.0% in ACTACT, and 12.8% in ACT. The difference between ACACT and ACT is therefor much moderate than 35% cited in the paper based on the absolute change.

The relative differences between PI and PD for CDNC and LWP are now shown in figures 4 and 5, respectively and considered in the text. Even though the subgrid parameterizations do clearly reduce the CDNC for both PI and PD conditions even after retuning, it is true that the relative change between PI and PD is not very significant. This is discussed in Section 4 of the revised manuscript.

For LWP, the relative PD-PI changes are more considerable and statistically significant, although indeed not as strong as the 35% difference obtained using the absolute change. In the retuned model (ACACTRT) the absolute LWP change is about 19% lower than in REF, with very similar initial LWP between the two in PI conditions. Taking the difference in the relative LWP change between ACACT and REF gives 18 %. These results will be discussed in Section 4 of the revised manuscript.

Analysis of the relative change in CDNC has been added on page 11, lines 3-18, and the relative change in LWP on page 12, lines 2-10. Changes in cloud properties after retuning has been analysed on page 13, line 26 – page 15, line 4. Accordingly, changes have been made in the conclusions on page 15, line 22 – page 16, line 5.

8.
Lines 1-7, page 15530: I am a little bit surprised by the difference in LWP between REF and ACT. The almost identical LWP in the NH is particularly puzzling. Does this mean that LWP in the NH is dominated by those over oceans in your model? Is this result consistent with Tonttila et al. (2013)?

11.
Lines 5-15, page 15532: the differences in LWP between ACTAC and ACT clearly needs more explanation. It is not immediately clear to me why accounting for the subgrid variation of LWC and CDNC leads to smaller LWP change in ACACT. Given that the relative difference is now quite moderate, I am not sure whether the relative difference is still statistically significant.

First, regarding comment 8, over the midlatitudes of both hemispheres the LWP is much higher over oceans than over continents (revised Figure 1), which is expected. However the difference between ACT and REF is quite small in both. One explanation for the NH, that is most heavily influenced by anthropogenic aerosol in present-day conditions, is that CDNC is generally high, so that the difference in CDNC between ACT and REF would yield rather small differences for the cloud water removed by autoconversion (both use grid-mean values of CDNC and cloud water to calculate the autoconversion rate!). This is backed up by Figure 2 in the revised manuscript, which shows the autoconversion rates.

Second, regarding the PI-PD change in LWP in ACACT and ACT (comment 11), the smaller change in LWP due to the subgrid treatment of autoconversion is also visible in the relative change. The smaller change in ACACT is likely connected to the spread of the subgrid values of CDNC, which can easily be larger than the difference in the grid-mean CDNC between ACACT and ACT. The mechanism can be explained as follows: First, in PD conditions, cloud activation is limited by the available CCN less frequently than in PI conditions. Therefore, the subgrid variability of vertical velocity plays a larger role in PD conditions, which results in a larger spread of the subgrid CDNC in PD conditions both for ACT and ACACT. Second, in ACACT the autoconversion rate is calculated using subgrid values of CDNC (and LWC), while ACT uses grid-mean values. It is expected that, due the non-linear dependence of autoconversion on CDNC, the consideration of subgrid variations in CDNC acts to increase the grid-mean autoconversion rate, and does so more effectively in PD conditions where the spread of CDNC is larger. This compensates for part of the decrease in autoconversion that is associated with the PD-PI change in the grid-mean CDNC. Consequently, the reduction in the autoconversion rate from PI to PD conditions is smaller for ACACT than for ACT. It is shown in Figure 2 of the revised manuscript that not only is the autoconversion rate consistently stronger (more negative) in ACACT than in ACT, but also the relative change between PI and PD is slightly weaker for ACACT, i.e. the decrease in autoconversion rate from PI to PD is indeed smaller for ACACT than for ACT in the northern hemisphere. This behaviour is seen throughout the lower troposphere and can thus explain the reduced anthropogenic change of LWP in ACACT. The difference in the PI-PD LWP change between ACT and ACACT is significant also in terms of the relative change at the 99 % confidence level.

The corresponding discussion will be included in Section 4 of the revised manuscript.

The difference in LWP between REF and ACT is now explained on page 11, lines 22-29. The difference in LWP change between ACT and ACACT is explained on page 12, lines 11-27.

12.
Lines 16-23, page 15532: the smaller aerosol indirect effects in ACTAC can be partly explained by the smaller SWCRE in this case (-52.75 W m-2) than in REF (-55.92 W m-2).

The new retuned model configuration ACACTRT is used to investigate this issue as the SWCRE is quite similar to REF after retuning. Even for ACACTRT the global mean indirect effect is 14% smaller than in REF. This supports our basic conclusion: consideration of subgrid effects yields a relatively strong reduction in the model representation of the aerosol indirect effects. Please refer also to our response to comment no. 2 by Reviewer #2.

The effects of model basic state on the estimation of AIE has now been accounted for on page 15, lines 5-15. The new results are now also considered in the Abstract and the Conclusions (page 2, lines 9-12 and page 16, lines 14-22).

[1,3]J.Tonttila [3]H.Järvinen [2]P.Räisänen
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Explicit representation of subgrid variability in cloud microphysics yields weaker aerosol indirect effect in the ECHAM5-HAM2 climate model

Finnish Meteorological Institute, Atmospheric Research Centre of Eastern Finland,
P.O. Box 1627, 70211 Kuopio, Finland

Finnish Meteorological Institute, P.O. Box 503, 00101 Helsinki, Finland

University of Helsinki, Department of Physics, P.O. Box 48, 00014 Helsinki, Finland

Correspondence to: J. Tonttila (juha.tonttila@fmi.fi)

Abstract

Impacts of representing cloud microphysical processes in a stochastic subcolumn framework are investigated, with emphasis on estimating the aerosol indirect effect. It is shown that subgrid treatment of cloud activation and autoconversion of cloud water to rain reduce the impact of anthropogenic aerosols on cloud properties and thus reduce the global mean aerosol indirect effect by 18%, from 1.59 to 1.30 $\mathrm{W\,m^{-2}}$. Although the 19%, from -1.59 to $-1.28\,\mathrm{W\,m^{-2}}$. This difference is partly related to differences in the model basic state; in particular, the liquid water path (LWP) is smaller and the shortwave cloud radiative forcing weaker when autoconversion is computed in the subcolumn space. However, when the model is retuned so that the differences in the basic state LWP and radiation balance are largely eliminated, the global-mean aerosol indirect effect is still 14% smaller (i.e., $-1.37\,\mathrm{W\,m^{-2}}$) than for the model version without subgrid treatment of cloud activation and autoconversion. The results show the importance of considering subgrid variability in the treatment of autoconversion, representing . Representation of several processes in a self-consistent subgrid framework is emphasized. This paper provides direct evidence that omitting subgrid variability in cloud microphysics significantly contributes to the apparently chronic overestimation of the aerosol indirect effect by climate models, as compared to satellite-based estimates.

1 Introduction

Aerosol–cloud interactions and their changes due to anthropogenic aerosol emissions represent a major uncertainty in climate projections. In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the uncertainty range for the effective radiative forcing due to aerosol-cloud interactions is given as -1.2 to $0.0\,\mathrm{W\,m^{-2}}$, with the best estimate at $-0.45\,\mathrm{W\,m^{-2}}$, based on expert judgement judgment supported by satellite studies (Boucher et al., 2013). The high uncertainty in this estimate stems to a large extent from the difficulty in separating the effects of aerosol-cloud interactions from other contributing feedbacks and processes. In addition, comparisons between general circulation models (GCM) and satellite studies have indicated that models typically overestimate the sensitivity of clouds to aerosol perturbations (Quaas et al., 2009), especially in terms of precipitation susceptibility and thus the anthropogenic increase in LWP (Wang et al., 2012) . The median forcing value for estimates based on GCMs in AR5 ($-1.4\,\mathrm{W\,m^{-2}}$) is indeed much larger in magnitude than the best estimate. The reasons for this overestimation are not fully understood.

The key topics in the model-based estimates of the aerosol indirect effects are those related to the parameterization of cloud microphysical processes, such as cloud activation of aerosols and the formation of drizzle and rain. Model In many GCMs, the representation of aerosol-cloud interactions and cloud droplet activation in particular has relied heavily on the use of parameterized effective vertical velocity in order to estimate the maximum supersaturation in a cloud layer for cloud droplet activation (?) . (e.g. Lohmann et al., 1999) . This approach aims to provide a single, suitable vertical velocity value for the climate model grid cell, which is reminiscent of the typical small scale variability of the turbulent vertical motions and is the method used in the ECHAM model. Another popular approach is to use a probability density function (PDF) to describe the subgrid variation of vertical velocity, where the grid-mean number of activated droplets is obtained by integration over the PDF (Chuang et al., 1997; Ghan et al., 1997; Storelvmo et a Tonttila et al. (2013) developed a more elaborate approach, where a using a PDF in the footsteps of Ghan et al. (1997) to extend the stochastic subcolumn framework (Räisänen et al., 2004) was extended with subgrid by Räisänen et al. (2004) . Instead of integrating over the PDF for a grid-mean cloud droplet number concentration (CDNC), random vertical velocity samples drawn from a probability distributionwere drawn from the PDF. This enabled the calculation of the cloud droplet number concentration (CDNC) CDNC individually in each cloudy subcolumn, yielding an explicit representation of the variability of cloud structure and the distribution of the microphysical properties inside the climate model grid cells. The cloudy subcolumns can be directly used in the radiation calculations by the use of the Monte Carlo Independent Column Approximation method (MCICA; Pincus et al., 2003). This is a significant advantage, as now the entire chain of processes from formation of cloud droplets to radiative transfer can be considered consistently using the same subgrid framework. In addition, it provides an innovative approach for estimating the aerosol indirect effects, which is the main topic of this paper.

A series of climate model simulations using the modified model version from Tonttila et al. (2013) is presented in this study. These simulations are used to directly demonstrate that a significant part of the model-based overestimation of the These simulations demonstrate directly that omitting subgrid variability in cloud microphysics contributes to the overestimation of model-based aerosol indirect effectcan be explained by omitting subgrid variability in cloud microphysical processes. . A description of the model used in this study and the experimental setup is outlined in Sect. 2. Impacts of the subcolumn-based cloud microphysics on the present-day cloud properties are reported in Sect. 3. In Sect. 4, the impact of the subcolumn microphysics on the perturbation in cloud properties and radiation due to anthropogenic aerosol emissions is estimated, before drawing conclusions in Sect. 5.

2 Model description and experimental setup

The experiments in this study are performed using the ECHAM5-HAM2 aerosol-climate model (the model is thoroughly described in Roeckner et al., 2003, 2006; Zhang et al., 2012). The model version considered here has been modified to include the Monte Carlo Independent Column Approximation radiation scheme (Pincus et al., 2003) and a stochastic cloud generator (Räisänen et al., 2004, 2007) with the subgrid treatment of cloud microphysical processes (Tonttila et al., 2013). The model uses the large-scale condensation scheme by Tompkins (2002) to calculate the cloud fraction inside the GCM grid-box, and it also provides the statistical information about the subgrid variability of the total water amount needed by the stochastic cloud generator. To summarize the operation of the stochastic subgrid framework, subgrid columns created inside the GCM grid-columns by the stochastic cloud generator are used to describe the subgrid cloud structure and varying cloud condensate amount. Vertical velocity is assigned to each cloudy subcolumn based on samples drawn from a Gaussian probability density function (PDF) $P(\mu,\sigma)$, with the mean μ taken as the GCM grid-scale vertical velocity and the standard deviation given as $\sigma = 1.68\sqrt{TKE}$, where TKE is the turbulent kinetic energy provided by the GCM. The coefficient 1.68 is chosen in order to match the average magnitude of the vertical velocity from the subcolumn parameterization with the effective vertical velocity according to Lohmann et al. (2007) in the default model, thus isolating the effect of explicit subgrid variability alone when comparing the results obtained using the two approaches(Tonttila et al., 2013) . It is worth noting that the coefficient 1.68 is treated here as a tuning parameter for this particular comparison; physically it allocates too much energy to the turbulent vertical motion, as also discussed in (Tonttila et al., 2013) . The subgrid vertical velocity samples from the PDF are used to calculate cloud droplet activation, which yields the distribution of CDNC in the subcolumn space. stochastic subcolumn space. Note that the subcolumn CDNC distribution is treated as a a diagnostic property, while a prognostic formulation (Lohmann et al., 1999) is retained for the grid-scale mean CDNC. For radiation calculations, CDNC is constrained by an assumed minimum concentration of $40\,\mathrm{cm}^{-3}$, which is also applied in the subcolumns. The parameterization used for cloud activation is that presented in Abdul-Razzak and Ghan (2000). Moreover, the autoconversion of cloud water into rain (Khairoutdinov and Kogan, 2000) can be treated separately for each subcolumn as well, since both liquid water content (LWC) and CDNC are known in the subcolumn space. Since our focus is on stratiform clouds, the vertical motions to be parameterized are highly turbulent and thus presumably weakly correlated with the thermodynamical properties of the cloud (in contrast to convective cumulus clouds), as also noted in e.g. Morales and Nenes (2010) . Therefore, we do not assume any correlation between vertical velocity (and thus CDNC) and LWC.

Three Four model configurations are used in this study, as summarized in Table 1. All of them use subgrid columns for radiation calculations, such that each layer of the subcolumns has a cloud fraction of 0 or 1, and cloud water content varies from one subcolumn to another (Räisänen et al., 2007). Furthermore, with the exception of the last experiment (ACACTRT), model closure parameters were not changed so that the only difference between the configurations is lies in the treatment of cloud microphysics.

1. In REF, cloud droplet activation is computed using an effective vertical velocity (Lohmann et al., 2007). Consequently, subgrid-scale variations in CDNC are not considered. Furthermore, subgrid-scale cloud variability in LWC is considered in radiation calculations, but not in cloud microphysics.

2. In ACT, subgrid-scale variability of vertical velocity is considered in computing cloud activation, such that CDNC varies from one subcolumn to another. The width of the PDF for vertical velocity (σ) was fixed such that the sample mean value corresponds to the effective vertical velocity in REF (Tonttila et al., 2013). In contrast, autoconversion is evaluated based on the grid-mean values of LWC and CDNC, similarly to REF. The subgrid distributions of both LWC and CDNC are used in the radiation calculations.

3. In ACACT, vertical velocity and cloud activation are calculated in the subcolumn space, similar to ACT. Furthermore, autoconversion is now also computed in the subcolumns, considering the subgrid-scale variations in LWC and CDNC. Similar to ACT, the subgrid distributions of LWC and CDNC are used in the radiation calculations.

4. ACACTRT is similar to ACACT, but the scaling factor for autoconversion rate has been tuned down to the value 1.5 from 3.0 used in the other configurations. This model configuration will be used for estimating to which extent the indirect radiative effects of aerosols are influenced by differences in model basic states between the untuned configurations.

A 5 year simulation for the years 2001–2005 was performed with configurations ~~1–3~~1–4, each preceded by a 3 month spin-up. The simulations were nudged towards ERA-Interim reanalysis data (Dee et al., 2011) to suppress the impact of model internal variability, involving four model fields: vorticity (relaxation time scale 6 h), divergence (48 h), atmospheric temperature (24 h) and logarithm of surface pressure (24 h). The model horizontal resolution was T42 (corresponding to a grid-spacing of $\approx 2.8°$) with 19 layers in the vertical. Following Räisänen et al. (2007) , we use 50 subcolumns for the McICA calculations and the subgrid cloud description. Calculating cloud microphysics in the subcolumn space adds about 25 % to the computational cost of the model, compared to the REF configuration. All simulations were run twice, separately ~~with~~ for pre-industrial (PI) and present-day (PD) conditions in terms of aerosol emissions. These were obtained using the AEROCOM emission inventories (Dentener et al., 2006) for the years 1750 and 2000, respectively. The model configurations REF and ACACT are similar to the experiments REF and SUBW presented in Tonttila et al. (2013) , except that here the simulations are nudged and also include runs with pre-industrial aerosol emissions. The ACT and ACACTRT configurations presented in this paper do not have a direct counterpart in Tonttila et al. (2013) .

3 Impact of subgrid-scale parameterizations on cloud properties

In general, the differences between REF and ACACT for present-day conditions are similar to the results presented in Tonttila et al. (2013): adding subgrid treatment of cloud activation and autoconversion typically decreases CDNC and LWC, especially over industrialized areas. Nevertheless, a brief recap of these effects is presented since the model experiments in the current paper are run in the nudged configuration and the sensitivity of cloud properties to different parameterized components is analysed.

Figure 1 shows the zonal mean present-day cloud properties for the model experiments~~and observations, where available. Further,~~ , and corresponding global mean values ~~for related cloud parameters and the longwave and the sortwave cloud radiative effects for each model configuration are given in Table 2. The simulated vertically integrated~~ are given in Table 2. Further, observations of the total (i.e., vertically integrated) cloud fraction and cloud optical depth from the International Satellite Cloud Climatology Project (ISCCP) D1 dataset (Rossow and Due averaged over the years 2001–2005, are included in Figure 1. The corresponding simulated quantities were obtained using the ISCCP simulator (Klein and Jakob , 1999; Webb et al., 2001) , which has been slightly modified in order to operate consistently with the subcolumns created by the stochastic cloud generator. The simulated total cloud fraction (Fig. 1a) is higher than ~~the~~ observed (global mean at approximately 0.73 vs. 0.63 in the observations) especially at high latitudes and over the tropics, and similar between the different model configurations. ~~The observations are from the International Satellite Cloud Climatology Project (ISCCP)~~ A comparison with the ISCCP D1 ~~dataset (Rossow and Dueñas, 2004) averaged over the years 2001–2005. Note~~ data further indicates that the simulated ~~cloud fraction is obtained using the ISCCP simulator (Klein and Jakob , 1999; Webb et al., 2001) , which has been slightly modified in order to operate consistently with the subcolumns created by the stochastic cloud generator~~average cloud top pressure is too low (not shown), suggesting that high clouds contribute to the overestimated total cloud fraction. Other modelling studies using ECHAM5 (without HAM2) with the Tompkins (2002) cloud cover scheme but without HAM2 (e.g. Räisänen and Järvinen, 2010) show lower global global-mean cloud fraction than our experiments. Therefore the high Therefore the overestimated total cloud cover appears to be an issue associated with a feature arising from the use of the HAM2 aerosol module together with the Tompkins (2002) cloud scheme. This issue is not influenced significantly by the inclusion of subgrid microphysics. , nor is it caused by nudging (a similar feature was also present in Tonttila et al. (2013)).

The liquid water path (LWP; Fig. 1b,c over land and oceans, respectively) is clearly decreased in ACACT as compared to both REF and ACT, which shows that the LWP is mostly controlled by the stronger autoconversion of cloud water to rain due to the subgrid treatment(Larson et al., 2001; M Instead, in the experiment ACT, LWP remains similar to REF in the Northern Hemisphere northern hemisphere and over the continents, and is even slightly increased over southern mid-latitudes over the ocean. Figure 2 shows the autoconversion rate for cloud water in each experiment. It is evident that the autoconversion rate is stronger in ACACT than in ACT or REF, which explains the smaller LWP in ACACT. This difference is expected when subgrid variation in cloud properties is accounted for when calculating the grid-mean autoconversion rate, since, due to its exponential formulation, including variations about the mean for LWP and CDNC tends to put more weight on higher process rates (Larson et al., 2001; Morales and Nenes, 2010; Tontti Overall the differences in LWP between the different configurations are larger over the oceans than over continents due to larger droplet size and thus higher sensitivity to the treatment of autoconversion.

The zonal mean lower tropospheric CDNC sampled over land and oceans is shown in Fig. 1c and d Figs. 1d and 1e, respectively. It is evident that At most latitudes, the subgrid treatment of cloud activation decreases the mean CDNCsubstantiallyCDNC, as indicated by the difference between ACT and REF. The largest difference occurs over land in the northern mid-latitudes, near the primary anthropogenic emission sources, while in . In more pristine regions , especially the differences are more modest, and over the southern oceans, the differences are more modest. Tonttila et al. (2013) explained this behaviour by CDNC is even larger in ACT than in REF.

Tonttila et al. (2013) explained the behaviour of CDNC in terms of the modulated weighting caused by explicit subgrid variability in vertical velocity for cloud activation and its interaction with the aerosol size distribution, as the GCM grid-scale average magnitude of vertical velocity is kept similar regardless of the type of parameterization in our experiments. In ~~the Southern Hemisphere and over the oceans, the low number of potential~~ regions with a high concentration of cloud condensation nuclei (CCN)~~is depleted at fairly low water vapour supersaturations, which reduces the sensitivity of cloud activation to vertical velocity variability. Therefore, explicitly accounting for the subgrid distribution of vertical velocity instead of using the effective value results in similar or even slightly increased CDNC. In comparison, in the northern mid-latitudes and especially~~ , most prominently at the northern hemisphere midlatitudes over land, ~~with higher CCN due to more numerous anthropogenic sources, the~~ there is a strong competition for water vapour between the ~~potential CCN is stronger and the CDNC is more~~ CCN-sized particles. This makes the CDNC sensitive to the level of supersaturation and thus the treatment of vertical velocity. ~~Thus~~Therefore, the high frequency of occurrence of low vertical velocities in the subgrid distribution dominates in terms of CDNC, relative to the use of an effective vertical velocity, which yields a decrease in the mean ~~CNDC~~CDNC. Moreover, CDNC is even further reduced in ACACT as compared to ACT, owing to the above-mentiond enhancement of the autoconversion process due to ~~subgrid treatment as mentioned above~~the subgrid treatment, which also influences the CDNC. Analysis of the rate of cloud droplet nucleation in Figure 3 shows, as anticipated, that the subgrid treatment of cloud activation in ACT and ACACT decreases the nucleation rate over polluted regions compared to REF.

In contrast, in the southern hemisphere and over the oceans, there is much less competition for water vapour among the relatively few CCN available. Thus, a sufficiently high water vapour supersaturation for the bulk of suitable aerosol particles to activate is obtained at rather low updraft speeds. This makes the CDNC relatively insensitive to variations in updraft speed at the low end of the vertical velocity spectrum. However, Figure 3 shows that around 60° S, the nucleation rate in both ACT and ACACT slightly exceeds that in REF. The likely explanation for this is that when the subgrid distribution of vertical velocity is accounted for, some subcolumns will get considerably higher vertical velocity than the grid-scale mean, which allows for even smaller interstitial particles (typically small Aitken mode particles in our model) to activate. However, in terms of the resulting CDNC, this is compensated in ACACT by the enhanced autoconversion due to the subgrid treatment. Thus, the CDNC around 60° S is similar between REF and ACACT, and slightly increased in ACT.

Contrasting the impacts seen on CDNC and LWP shows that the behaviour between the two is fairly consistent. In the ~~Southern Hemisphere~~southern hemisphere the autoconversion rate is sensitive to changes in CDNC due to the generally low CCN concentration over the oceans. Thus, the slightly increased CDNC shown by ACT ~~over the oceans requires higher LWP for autoconversion to become effective,~~ is accompanied by increased LWP as compared to REF, since reduced droplet size reduces the amount of water that is converted to drizzle and rain. In comparison, in the ~~Northern Hemisphere~~ northern hemisphere subtropics and mid-latitudes, ~~the CDNC is slightly lower for ACT~~ CDNC is lower in ACT than in REF, especially over land, but LWP is similar to REF. This likely relates to the low sensitivity of autoconversion to small changes in CDNC in regions with high CCN concentration. Instead, for ACACT, the impact of subgrid treatment of autoconversion dominates the resulting LWP, for the most part masking out other effects.

The impact of the results above on the cloud optical properties are summarized by investigating the cloud optical depth (τ). The zonal means of ~~cloud optical depth (τ)~~calculated separately using data over land areas and over the oceans are shown in Fig. 1e and f, respectively (again using the ISCCP simulator). ~~Observations in these figures are provided by the ISCCP dataset.~~ Compared to REF, τ is clearly decreased in ACACT at all latitudes, with a larger difference over the oceans. The results from ACT are close to REF with a small increase in southern mid- and high latitudes over the oceans, and a slight decrease over Northern Hemisphere continents. The changes shown by both ACT and ACACT correspond well with the changes in LWP and CDNC discussed above. The comparison of the model results with ISCCP data shows that REF and ACT overestimate τ over the oceans and underestimate it over the continents. In ACACT, τ is underestimated over the continents as well, similar to REF and ACT. However, over the oceans, τ in ACACT agrees better with ISCCP data than in the other experiments. The most outstanding improvements also coincide with the smallest bias in total cloud fraction (i.e., in the lower midlatitudes of each hemisphere), which makes this an encouraging result.

4 Anthropogenic aerosol effects

The In this section, the impact of anthropogenic aerosols on cloud properties, and finally the aerosol indirect radiative effect, is evaluated as the difference between the PD and PI runs, separately for each model configuration. The impact on CNDC at We first focus on the direct impacts of subgrid treatment of cloud microphysics, and consider the model versions with the same closure parameters, namely REF, ACT and ACACT. The impact of retuning the model in ACACTRT is considered toward the end of the section.

4.1 Cloud properties

The impact of subgrid parameterizations on the change of CDNC between PI and PD aerosol conditions at the $890\,\mathrm{hPa}$ pressure level is considered in Fig. ?? 4 and the impact on LWP change in Fig. ??5. Consistent with the distribution of anthropogenic aerosol emissions, the anthropogenic impacts on changes in both the CDNC and the LWP are larger over the Northern Hemisphere than the Southern Hemispherenorthern hemisphere than the southern hemisphere, in the vicinity of the main anthropogenic emission sources. The results show that It is also seen, especially in terms of the absolute differences, that the subgrid treatment of the cloud microphysical parameterizations generally decreases mostly reduces the sensitivity of cloud properties to the anthropogenic aerosol perturbation.

For CDNC (Fig. ??), the weaker sensitivity to increasing aerosol concentration is easily visible The absolute change in CDNC from PI to PD aerosol conditions is smaller in both ACT and ACACT as compared to REF than in REF (Fig. 4b). The global mean increase in CDNC between the PD and PI conditions is $30.7\,\mathrm{cm^{-3}}$ in ACACTand $31.8\,\mathrm{cm^{-3}}$ anthropogenic increase of CDNC is $30.5\,\mathrm{cm^{-3}}$ in ACACT, $32.1\,\mathrm{cm^{-3}}$ in ACT, which are clearly lower than the corresponding change in REF($36.4\,\mathrm{cm^{-3}}$). Thus, and $37.4\,\mathrm{cm^{-3}}$ in REF. While the differences between the different model configurations are considerable and significant at the 99% confidence level according to the two-tailed t-test, it should be noted that the average CDNC is smaller for ACT and ACACT than for REF in both the PI and PD simulations (Fig. 1d,e). Consequently, the inter-configuration differences in the relative CDNC change (i.e., ΔCDNCpertubation in ACACT is smaller than that in REF by 5.7cm^{-3}. Most of this difference (about 80%) is explained by the subgrid cloud droplet activation alone,as shown by ACT, while the type of treatment of autoconversion has only a minor impact on the /CDNC) between the PI and PD conditions are moderate (Fig. 4c). In terms of global-mean anthropogenic CDNC perturbation.Accordi to a two-tailed Student's t test, the difference between ACACT and REF is significant at the 99.9% confidence level and that between ACT and REFat the 99% level, while the difference between ACACT and ACT is values, ΔCDNC/CDNC for ACT is 4% smaller than that for REF, but for ACACT it is 1% larger. These differences are not statistically significant. Thus, the type of treatment for autoconversion is not important for , but some of the zonal-mean features are. First, the relative change in CDNC in the mid and high latitudes of the northern hemisphere is larger for ACACT than REF at the 99% confidence level, which most likely occurs due to the suppression of the initial CDNC in the anthropogenic perturbation in CDNC in our model.

Understanding why the anthropogenic perturbations in CDNC are decreased by subgrid cloud activation can be derived from the results in Sect. 3 and the discussion in Tonttila et al. (2013) . The PI by the subgrid treatment of autoconversion. Second, around 30° N, both ACT and ACACT show a smaller relative CDNC change than REF. This can be explained by the potentially increasing sensitivity of CDNC to subgrid variability of vertical velocity is highest in areas with high CCN concentration, where subgrid treatment of cloud activation acts to decrease the average number of activated droplets. Therefore, it can be expected that the substantial anthropogenic increase in CCN yields less increase in CDNC in from low to high CCN concentrations (Tonttila et al., 2013) : at high CCN concentrations, the experiment ACT than in REF. In addition, ACACT shows a small reduction in the anthropogenic CDNC perturbation as compared to ACT. This represents a feedback from the subgrid autoconversion on the mean CDNC , yet, as stated above, the difference is not statistically significantconsideration of subgrid variations in vertical velocity reduces the grid-mean CDNC more effectively than at low CCN concentrations, which acts to curb the increase in CDNC from PI to PD conditions.

~~Perhaps a more meaningful view of the significance~~ The importance of the subgrid treatment ~~of autoconversion is obtained~~ for autoconversion is best illustrated through an examination of the anthropogenic impact on LWP ~~. Similar to CDNC,~~ (Figure 5). The anthropogenic perturbation in LWP is considerably weaker in ACACT ($4.95\,\mathrm{g\,m^{-2}}$) than in REF ($7.62\,\mathrm{g\,m^{-2}}$) due to accounting for subgrid variability in the cloud microphysical parameterizations~~yields weaker increase in LWP due to anthropogenic aerosols. However, unlike for CNDC, REF and ACT show similar changein~~ . In contrast, ACT shows an almost identical change in the global-mean LWP with REF. This may be surprising considering the difference in CDNC between the two configurations, but most of the changes in cloud properties between PI and PD conditions in general manifest themselves over the northern mid-latitudes, where CDNC is high. In such conditions, the autoconversion rate is most likely not particularly sensitive to relatively small changes in CDNC, such as the difference between ACT and REF. As both configurations use the grid-scale mean cloud properties to calculate the autoconversion rate, this results in a very small difference, as shown by Fig. 2, explaining the similarity in the LWP change.

As with CDNC, to better account for the LWP differences in the model basic state, the relative LWP change between PI and PD ~~runs (7.62 and $7.63\,\mathrm{g\,m^{-2}}$, respectively), while the~~ is calculated and shown in Fig. 5c for each model configuration. In the global mean, the relative PI-to-PD changes are 13.3% for REF and 12.8% for ACT, respectively. Thus the difference between the two is small, and the respective zonal mean differences are also small and mostly not statistically significant. In contrast, for ACACT, the relative change in global-mean LWP is 10.9%, which is approximately 18% smaller than that in REF. Globally, the difference in the relative LWP change ~~in ACACT is 35% weaker ($4.96\,\mathrm{g\,m^{-2}}$). The difference in LWP response~~ between ACACT and ~~the two other simulations~~ REF is significant at ~~the 99.9% confidence level. Accounting for subgrid variability in cloud microphysics therefore yields weaker anthropogenic perturbation in LWP, which is primarily due to accounting for the subgrid variability in CDNC and LWC in autoconversion~~ higher than 99% level. In the zonal mean values, statistically significant differences are mainly found between 20° and ~~drizzle formation~~50° N.

A deeper insight into why the LWP change between PI and PD runs is smaller in ACACT than in ACT is obtained by considering how the anthropogenic aerosol emissions alter the interaction between subgrid-scale variability of cloud properties and the cloud microphysical processes. The suggested mechanism goes as follows. First, in PD conditions, cloud activation is limited by the available CCN less frequently than in PI conditions. Therefore, the subgrid variability of vertical velocity plays a larger role in PD conditions, which results in a larger spread of the subgrid CDNC in PD conditions both for ACT and ACACT. Second, in ACACT the autoconversion rate is calculated using subgrid values of CDNC (and LWC), while ACT uses grid-mean values. It is expected that, due to the non-linear dependence of autoconversion on CDNC, the consideration of subgrid variations in CDNC acts to increase the grid-mean autoconversion rate, and does so more effectively in PD conditions where the spread of CDNC is larger. This compensates for a part of the decrease in autoconversion rate that is associated with the PI-to-PD change in the grid-mean CDNC. Consequently, the reduction in the autoconversion rate from PI to PD conditions is smaller for ACACT than for ACT, as indeed shown in Fig. 2b in the northern mid-laditudes. This effect is stronger at altitudes near the top of the boundary layer than near the surface, which is consistent with the expected vertical LWC distribution of stratocumulus clouds, and yields the weaker LWP change shown for ACACT.

4.2 Indirect radiative effect of aerosols

The aerosol indirect radiative effect ~~is primarily~~ (AIE) is estimated as the perturbation in the net cloud radiative effect (CRE) at the top of the atmosphere (TOA) between the PI and PD simulations. This includes the combined effects of changing cloud lifetime, cloud extent and cloud albedo, but disregards the direct radiative effect of aerosols. The global mean radiation fluxes and cloud radiative effects for PI and PD are given in Tables 3 and 4, respectively. The global mean indirect effect for each model configuration is given in Table ~~3~~5, also separately for longwave and shortwave radiation. ~~The net CRE perturbation for each model configuration is shown in Fig. ??.~~

As expected based on the results for ~~CDNC and LWC~~cloud properties, ACACT promotes weaker global mean ~~aerosol indirect effect ($-1.30\,\mathrm{W\,m^{-2}}$~~AIE ($-1.28\,\mathrm{W\,m^{-2}}$) compared to REF ($-1.59\,\mathrm{W\,m^{-2}}$). ~~Interestingly, only a small difference is seen between ACT ($-1.52\,\mathrm{W\,m^{-2}}$)~~Thus, the subgrid treatment of cloud microphysics reduces the net AIE by $19\,\%$, with higher than $99\,\%$

statistical significance. This reduction stems primarily from the perturbation in the shortwave cloud radiative effect (SWCRE), as indicated by Table 5. The difference between ACT and REF is much weaker, only 5%, and not significant. The zonal mean net AIE is shown in Figure 6. The bulk of the difference between REF and ACACT occurs in the midlatitudes of the northern hemisphere. It is also noted that the global distribution of AIE follows rather tightly the anthropogenic perturbation in LWP, which along with the difference in the global mean AIE highlights the importance of how autoconversion is calculated in the model. Nevertheless, subgrid treatment for cloud activation cannot be judged unimportant because it is essential in considering the subgrid variability in autoconversion rate.

This result is qualitatively similar to a study by Wang et al. (2011) , who found that accounting for subgrid variability in cloud properties using a multi-scale modelling framework reduced the aerosol indirect effect, and that this reduction was also related to a weaker response in LWP to the anthropogenic aerosol increase, compared to a traditional modelling approach.

4.3 Impacts of retuning

A caveat regarding the results presented in Sections 4.1 and REF, even though the anthropogenic increase in CDNC is significantly weaker over the industrialized areas. The differencesin the radiative perturbation between ACACT 4.2 is that the basic state of the model, in particular the climatology of LWP and radiative fluxes, is different. In the PD simulations, the global-mean LWP for ACT is only $50.3\,\mathrm{g\,m^{-2}}$, as compared with $65.0\,\mathrm{g\,m^{-2}}$ in REF (Table 2), and the SWCRE is weaker ($-52.81\,\mathrm{W\,m^{-2}}$ vs. $-55.92\,\mathrm{W\,m^{-2}}$; Table 4). The impacts of the differing basic states of the model can be partially addressed by analysing the relative differences, but retuning of the model is necessary for robust estimation of especially the aerosol indirect radiative effect. In addition, the global-mean TOA net radiation in ACACT differs significantly from REF, by $2.67\,\mathrm{W\,m^{-2}}$ in the PD simulations and by $2.98\,\mathrm{W\,m^{-2}}$ in the PI simulations (Tables 3 and REF, 4). If subgrid treatment of cloud microphysics were implemented in an operational setting, especially in a coupled atmosphere-ocean GCM, such large changes in the TOA radiation budget would need to be eliminated through model retuning.

Therefore, the PI and PD runs were repeated with a retuned version of the ACACT configuration, denoted as ACACTRT, whose results are now analysed. The primary target of tuning in this case is the TOA net radiation in the REF simulation rather than in observations. Specifically, the scaling parameter for autoconversion was reduced from the value 3.0 used in the original experiments to 1.5 in ACACTRT. This yields a substantial increase in LWP as compared with ACACT, so that the global-mean value for ACACTRT is quite close to REF in the PD simulation (Table 2), and in fact almost identical (within $0.1\,\mathrm{g\,m^{-2}}$) in the PI simulation. All global-mean radiative fluxes in Tables 3 and ACACT and ACT are 4 are within $0.3\,\mathrm{W\,m^{-2}}$ from REF. Compared to the CERES EBAF satellite dataset (Loeb et al., 2009) , the global-mean TOA net flux both in REF and ACACTRT in PD conditions is more negative by over $2\,\mathrm{W\,m^{-2}}$, and the magnitude of both shortwave and (to a lesser extent) longwave CRE is overestimated (see Table 4). Presumably, the overestimated cloud cover present in all our simulations contributes to these differences.

The PI-to-PD change in CDNC at 890 hPa in ACACTRT is very similar to ACACT in almost every respect, even though the global mean CDNC in ACACTRT is slightly larger both in the PI and PD runs (Fig. 4). In comparison, the global-mean PI-to-PD change in LWP in ACACTRT is $6.15\,\mathrm{g\,m^{-2}}$, which is larger than that in ACACT, but the relative change is very similar, both in terms of the meridional distribution (Fig. 5) and the global mean values (10.7% for ACACTRT and 10.9% for ACACT). Thus, while retuning increases significantly the global-mean LWP for both the PI and PD conditions, it has little effect on the relative change between the two. The physical behaviour of cloud processes in ACACTRT therefore stays quite similar to ACACT, despite the retuning, which is understandable since the tuning parameter for autoconversion rate in ECHAM-HAM is a linear scaling coefficient. Importantly, the LWP change between PI and PD conditions in ACACTRT is substantially smaller than that in REF, by 19% both in absolute and relative terms.

Finally, as shown by Figure 6 and Table 5, the net AIE remains significantly lower in ACACTRT than in REF, with a global mean of $-1.37\,\mathrm{W\,m^{-2}}$. This yields a relative difference of -14% to REF, which is significant at the 99.9% level, while the difference between ACT and REF is not significant even at 99% level. Regionally, the 95% confidence leveldifferences between ACACTRT and REF are highly significant at latitudes 20°–50° N, which is expected given the distribution of the cloud property perturbations and Fig 6. As a conclusion, the retuning yields only a limited compensation to the influence that subgrid variability in cloud microphysics exerts on the aerosol indirect effects. This result highlights is strongly related to the similar finding on LWP. The results presented here highlight the non-linearity inherent in the processes controlling the aerosol-cloud-radiation interactions, which is are now more accurately sampled since the different parameterizations from clouds to radiation are considered using the common subgrid framework . Although subgrid cloud activation alone has a relatively small impact on the aerosol indirect effect, it does influence the indirect effect when autoconversion is computed in the subcolumn space(Tonttila et al., 2013) .

5 Conclusions

In this paper, we used the ECHAM5-HAM2 climate-aerosol model augmented with a stochastic subcolumn framework for cloud microphysics and radiation to study the aerosol indirect effects. Compared to a reference model configuration with GCM grid-scale cloud microphysics and thus uniform CDNC inside the GCM grid-cells, calculating cloud activation and autoconversion explicitly in the subcolumn space generally decreased the difference change in cloud properties between pre-industrial (PI) and present-day (PD) aerosol emission conditions. In more detail, it was determined that The impact of subgrid cloud microphysical parameterizations on anthropogenic CDNC change was found moderate, even though subgrid treatment for cloud activation alone explained most of the decrease in anthropogenic perturbation of cloud droplet number concentration (CDNC) compared to GCM-scale microphysics. Adding subgrid treatment also for autoconversion had only a small already resulted in a significant decrease especially for present-day conditions. Instead, the impact on the CDNC perturbation between the PI and PD conditions, although it did yield lower global mean CDNC for the lower troposphere when examined separately for PI and PD model runs. For cloud liquid water path (LWP), the anthropogenic perturbation was reduced by anthropogenic LWP change was found more significant. After retuning the model to account for differences in the basic state radiation balance between the different model configurations, the use of subgrid parameterizations for both cloud activation and autoconversion decreased the PI-PD change of LWP by 19%. Even though these results highlight the importance of subgrid treatment for autoconversion, it is important to note that subgrid ~~microphysics as well; however, now autoconversionhad the largest effect, while subgrid cloud activation alone had a statistically insignificant impact. However, it should be noted that the subgrid treatment~~ treament for cloud activation ~~is one of the key elements~~ does significantly alter the representation of CDNC, and is a key element in order to ~~consider subgrid variability in the autocoversion process~~provide a subgrid treatment for autoconversion.

The indirect radiative effect of anthropogenic aerosols was investigated by analysing the perturbation in the net cloud radiative forcing between the PI and PD conditions. Interestingly, with subgrid treatment for cloud droplet activation alone, the difference in the aerosol indirect effect to the reference simulation was relatively small ~~.~~ and not statistically significant. This may be, in part, related to a minimum value of CDNC ($40\,\mathrm{cm}^{-3}$) imposed in the radiation calculations. When both cloud droplet activation and autoconversion were considered in the subcolumn space, the anthropogenic perturbation in cloud radiative forcing was reduced by approximately ~~18%~~19% in the untuned model configuration as compared to the reference with grid-scale parameterizations. Retuning the model so that the difference in the basic state radiation budget was essentially eliminated partially compensated for this reduction, but nevertheless, the indirect effect remained 14% weaker than in the reference. Giving a single best estimate for the impact of subgrid parameterizations on the aerosol indirect effect is somewhat difficult, on one hand due to the strong modulation of the model basic state caused by the subgrid treatment and on the other hand due to the fact that the impact of subgrid parameterizations can not be isolated if the model is retuned. It is concluded, that the results above provide the range from the direct impact of subgrid cloud microphysical parameterizations (without retuning) to what more closely resembles an operational setup (with retuning).

Given that the vertical velocity for cloud activation in ECHAM5.5-HAM2 is in general quite high, reflecting to the high value of σ_w used with the PDF of vertical velocity for the comparisons in this paper, it is possible that reducing σ_w to more realistic values would produce an even larger reduction in the model estimate of the indirect effect (West et al., 2014) . Another aspect that possibly restricts the differences in the aerosol indirect effect between the analysed model configurations is the minimum CDNC, which is also appplied in cloud microphysical calculations. This potentially has a strong effect on e.g. the autoconversion rate. It has been documented that climate models in general tend to overestimate the magnitude of the indirect radiative effects of anthropogenic aerosols (Quaas et al., 2009), especially the interaction between the amount of aerosols and the cloud liquid water path. The results of this paper provide tangible evidence that omitting subgrid variability in the model representation of cloud microphysical ~~properties~~ processes significantly contributes to this overestimation.

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Table 1. Experimental setup indicating whether the parameterized components marked on the top row are calculated in the GCM-scale (–) or in the subcolumn-space (+).

Experiment	Radiation	cloud activation	autoconversion
REF	+	–	–
ACT	+	+	–
ACACT	+	+	+
ACACTRT	+	+	+

Table 2. Present-day global mean values in each model configuration for (from top to bottom) total cloud cover (C_{tot}), liquid water path (LWP), ice water path (IWP) , and CDNC burden, shortwave cloud radiative effect (SWCRE) and longwave cloud radiative effect (LWCRE).

	REF	ACT	ACACT	ACACTRT
C_{tot}	73.5	73.8	72.8	73.5
LWP $[\mathrm{gm}^{-2}]$	65.0	67.4	50.2 50.3	63.4
IWP $[\mathrm{gm}^{-2}]$	7.1	7.0	7.0	7.0
CDNC burden $[\mathrm{cm}^{-2}]$	3.96×10^6	3.77×10^6	2.86×10^6	3.22×10^6

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Table 3. Pre-industrial global mean values in each model configuration for (from top to bottom) the net radiation balance, net shortwave (SW) radiation, net longwave radiation (LW), SW cloud radiative effect (SWCRE) and LW cloud radiative effect (LWCRE) in $\mathrm{W\,m^{-2}}$.

	REF	ACT	ACACT	ACACTRT
Net	0.75	−0.13	3.42	0.49
SW	232.22	231.52	235.23	231.96
LW	−231.47	−231.65	−231.81	−231.47
SWCRE	−54.10	−54.76	−51.26	−54.39
LWCRE	27.51	27.29	27.20	27.50

Table 4. Present-day global mean values in each model configuration for (from top to bottom) the net radiation balance, net shortwave (SW) radiation, net longwave radiation (LW), SW cloud radiative effect (SWCRE) and LW cloud radiative effect (LWCRE) in $\mathrm{W\,m^{-2}}$.

	REF	ACT	ACACT	ACACTRT	CERES-EBAF
Net	−1.36	−2.21	1.62	−1.42	0.79
SW	229.83	229.09	233.16	229.80	240.51
LW	−231.20	−231.30	−231.54	−231.22	−239.72
SWCRE ~~$\mathrm{W\,m^{-2}}$~~	−55.92	~~−56.63~~ −56.62	~~−52.75~~ −52.81	−56.01	−47.26
LWCRE ~~$\mathrm{W\,m^{-2}}$~~	27.74	~~27.64~~ 27.63	27.47	27.76	26.18

Table 5. Global mean aerosol indirect radiative effect in each model configuration given in terms of the shortwave (AIE_{SW}), longwave (AIE_{LW}) and net (AIE_{Net}) radiative forcing in $\mathrm{W\,m^{-2}}$.

	REF	ACT	ACACT	ACACTRT
AIE_{SW}	~~−1.82~~ −1.82	~~−1.86~~ −1.86	~~−1.56~~ −1.55	−1.62
AIE_{LW}	~~0.23~~ 0.23	~~0.34~~ 0.35	~~0.26~~ 0.27	0.25
AIE_{Net}	~~−1.59~~ −1.59	~~−1.52~~ −1.51	~~−1.30~~ −1.28	−1.37

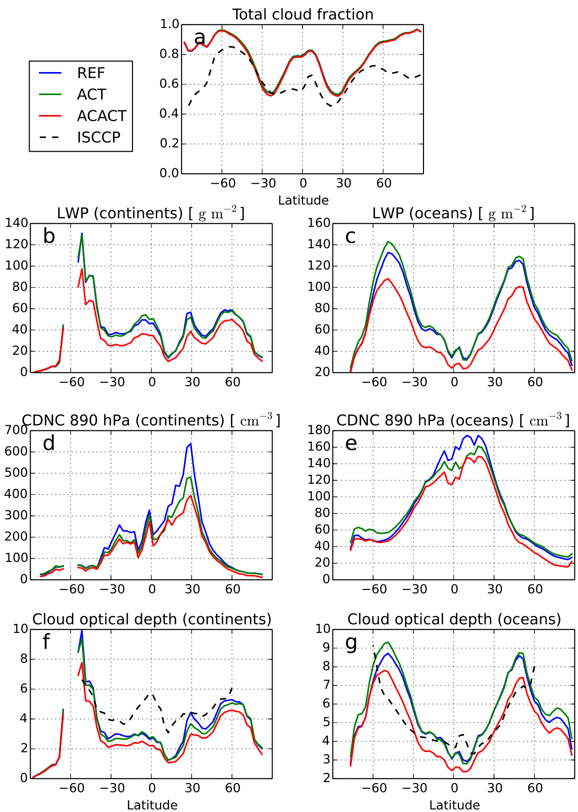

Fig. 1. Zonal mean cloud properties for present-day conditions for different model configurations (summarized in Table 1) and observations from ISCCP. **(a)** Vertically integrated total cloud fraction, **(b)** liquid water path (LWP) sampled over continents, **(c)** ~~in-cloud CDNC at the 890level~~ LWP over ~~land~~oceans, **(d)** ~~in-cloud~~ CDNC sampled over continents at the 890 hPa level, **(e)** CDNC over ~~the~~ oceans, ~~**(e)**~~ **(f)** cloud optical depth (τ) over ~~land~~ continents and ~~**(f)** cloud optical depth~~ **(g)** τ over ~~the~~ oceans. Note that the ISCCP simulator was used to obtain the model estimates for **(a)**, ~~**(e)** and~~ **(f)** and **(g)**.

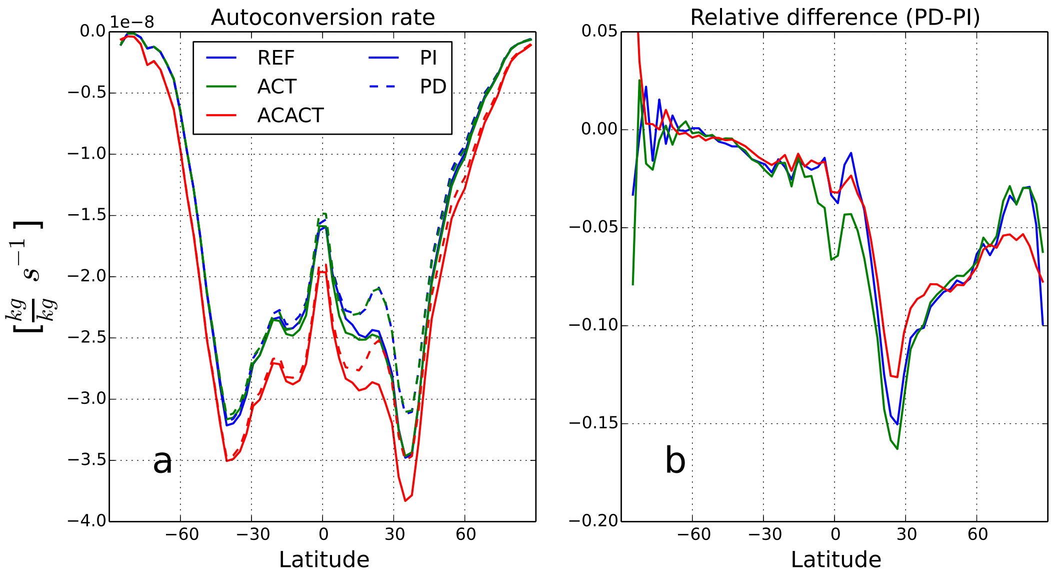

Fig. 2. ~~Comparison of in-cloud CDNC~~ **(a)** Autoconversion rate for PI and PD conditions in s^{-1} at ~~the~~ 890 hPa ~~pressure level (cm^{-3}) between pre-industrial (PI)~~ and ~~present-day (PD) conditions~~ **(b)** the relative anthropogenic change for each model configuration~~as indicated in the panels. The global mean is given in the parentheses~~.

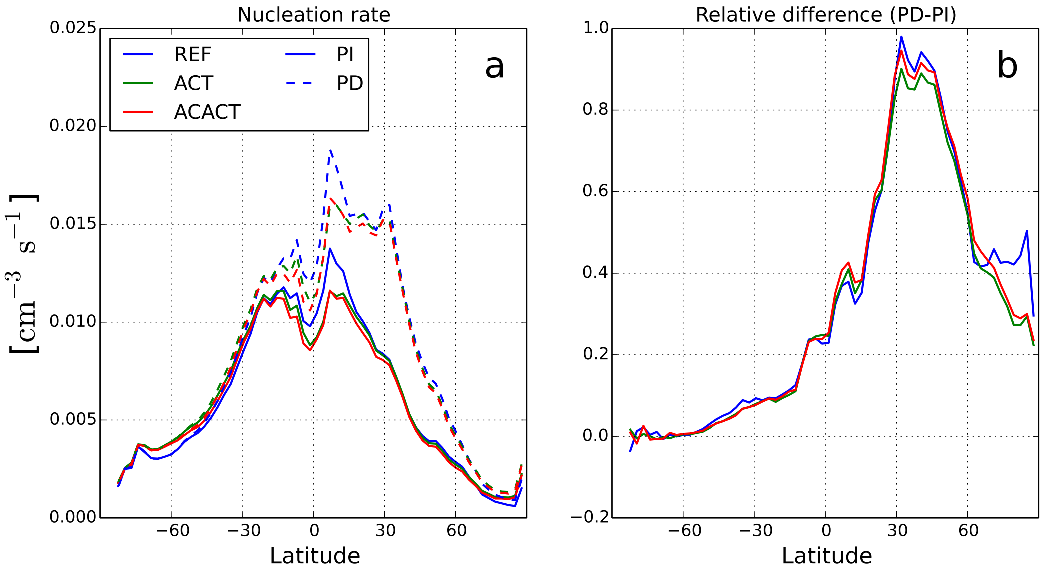

Fig. 3. Comparison of the LWP ($g\,m^{-2}$) between pre-industrial (**(a)** Cloud droplet nucleation rate for PI) and present-day (PD) conditions in $cm^{-3}\,s^{-1}$ at 890 hPa and **(b)** the relative anthropogenic change for each model configurationas indicated in the panels. The global mean is given in the parentheses.

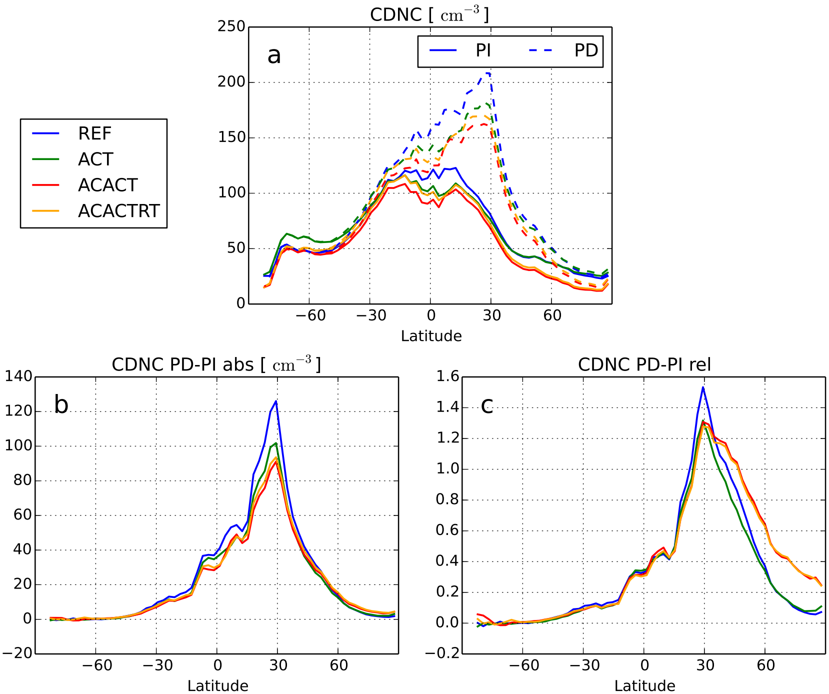

Fig. 4. ~~Aerosol indirect effects estimated as the perturbation in~~ **(a)** CDNC at the ~~net cloud radiative effect (Net CRE, W m^{-2}) between pre-industrial (~~890 hPa pressure level for PI ~~)~~ and ~~present-day (~~PD ~~)~~ conditions ~~for REF, ACT~~in cm^{-3}, and ~~ACACT~~**(b)** the absolute and **(c)** relative anthropogenic changes in CDNC.

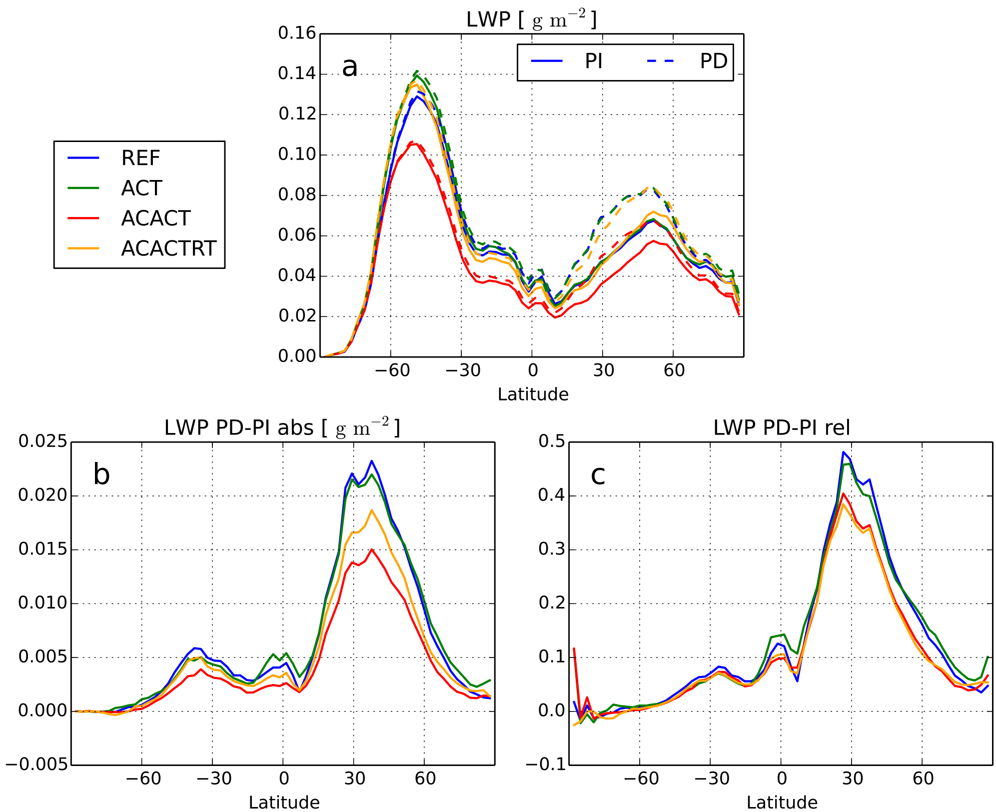

Fig. 5. **(a)** LWP for PI and PD conditions in $\mathrm{g\,m^{-2}}$, and **(b)** the absolute and **(c)** relative anthropogenic changes in LWP.

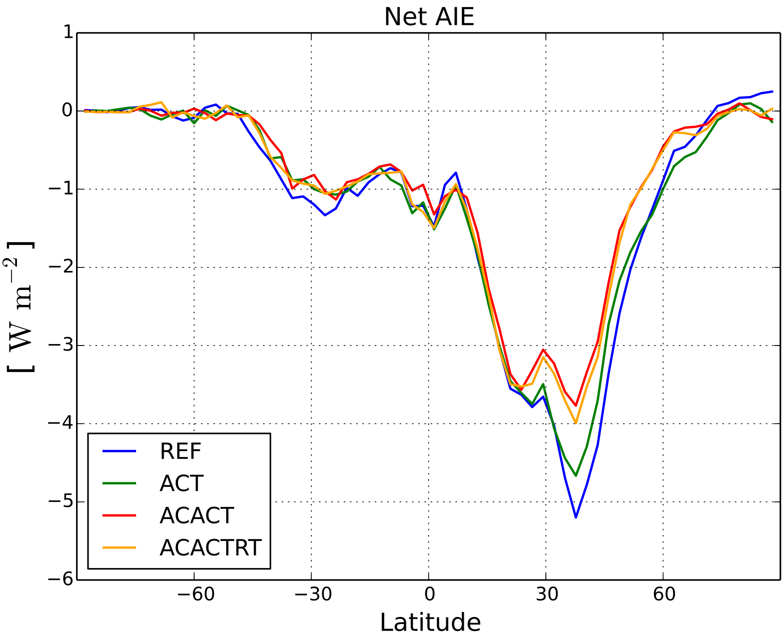

Fig. 6. The net aerosol indirect effect (AIE) for each model configuration in $\mathrm{W\,m^{-2}}$.