Author’s response for comments on *Impact of the representation of marine stratocumulus clouds on the anthropogenic aerosol effect*, ACPD 14, 13681–13729

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For the point-to-point response to the reviewers comments see the “Response to comments on *Impact of the representation of marine stratocumulus clouds on the anthropogenic aerosol effect”* below.

List of relevant changes:

- page 2, lines 3-6: we included the values for global, annual mean anthropogenic aerosol effect (AAE) in the abstract
- page 2, lines 15-30: we added a discussion of the feedback of increased aerosol concentration on entrainment in cloud topped boundary layers
- page 3, lines 7-18: the paragraph has been rewritten to clarify which cloud climatologies and ISCCP data were used, to remove a wrong statement about cloud number concentrations and to better motivate it
- page 4, lines 18-21: better motivation of our definition of the stratocumulus regime
- page 5, line 20-22: we added a statement that we have seen no significant differences between the original CFMIP-OBS ISCCP data product and our extended version
- page 6, line 6-8: we added that AAE is evaluated globally and in the stratocumulus regime
- page 6, line 15-18: rewritten to clarify that internal variability is more important for mean values in the stratocumulus regime than global mean values
- page 6, line 26-page 7, lines 10: rewritten to clarify how test for statistical significance and compute mean values in the stratocumulus regime
- page 7, lines 19-21: clarification that we compute differences not only for AAE but also for other variables
- page 8, lines 1-5: short discussion how aerosol effects on convective clouds are represented in the model
- page 8, lines 20-23: reference for the ‘sharp’ stability function and statement that changes due to the new stability function occur at stable conditions
- page 10, line 23: added years used for the experiments
- page 11, lines 1-4: added details about the simulation and the climatology used for sea surface temperature and sea ice cover
- page 11, lines 8-9: removed the confusing ‘free mode’
- page 11, lines 16-19: added details about the tuning and the autoconversion parameterization used
- page 11, line 25-page 12, line 7: quantification of the lower tropospheric stability and the subsidence criteria and area covered by the stratocumulus regime
- page 12, lines 10-14: rewritten to point out the separation of the influence of the large-scale environment and other factors to the formation of stratocumulus clouds
- page 13, lines 1-2: details on what the UWisc LWP climatology is based on
- page 13, lines 30-31: we added the reason why we used one month for our computation

- page 14, lines 10-11: changed to point out that we compared a monthly mean diurnal cycle
- page 15, lines 20-25: added details for the tuning of the VRES experiments
- page 15, line 29-page 16, line 22: added a discussion for simulations with the reference setup and reduced time step as suggested by one of the reviewers
- page 16, lines 26-29: rewritten to explain in part the smaller low cloud cover in the VRES experiments
- page 17, lines 4-8: added to better point at the too large convective transport later in the section
- page 17, lines 9-12: added to explain what looks like a shift of the cloud forcing
- page 18, lines 3-12: removed the discussion of the boundary layer height and added a discussion of aerosol changes in the VRES experiments
- page 19, lines 20-25: added values for present day CLIM simulations and to point out that focus of this study lies on the stratocumulus regime
- page 20, lines : 21-24: added to point out that the important ‘entrainment-evaporation’ is not explicitly represented in our model
- page 21, lines 5-19: added to discuss the influence of changes in cloud properties on aerosol
- page 22, line 8-page 25, line 13: this section has been renamed, restructured and rewritten to better point out the main findings
- page 22, lines 15-16: added to point out the separation of the influence of the large-scale environment and other factors to the formation of stratocumulus clouds
- page 23, lines 10-16: the discussion of the results of the study by Nam et al. (2014) has been rewritten
- page 24, lines 11-14: added to quantify differences in environmental conditions between the reference simulation and ERA-Interim
- page 24, lines 19-20: changed to point out that we compared a monthly mean diurnal cycle
- page 25, lines 1-3: quantification of the change in AAE due to aerosol processing
- page 25, lines 3-7: rewritten to clarify that this is a result in our simulations
- page 25, lines 8-9: quantification of the change in AAE due to the ‘sharp’ stability function and increased vertical resolution
- page 26, line 1-page 28, line 2: Appendices added to define terms in the stratocumulus regime, add Tables for the statistical significance of results in the stratocumulus regime and a Figure for changes in the frequency of shallow convection in the experiments
- page 38: new Table 2 showing aerosol, cloud and forcing parameters for present day CLIM simulations for all experiments
- page 49: added the VRES47+STAB simulation to Figure 8
- page 55: new Figure 14 showing the change in wet deposition of aerosol mass and the change in production of SO_4 by wet chemistry between the VRES95 and the REF experiment
- pages 56-57: added stippling for 90% significance level to Figures 15,16
- page 58: new Figure A1 showing the stratocumulus regime in January and July 2006
- page 59: new Figure A1 showing the requency of the activation of the shallow-convection scheme in the REF, STAB, VRES47 and VRES95 experiments

Response to comments on *Impact of the representation of marine stratocumulus clouds on the anthropogenic aerosol effect*, ACPD 14, 13681–13729

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We would like to thank the reviewers for the helpful comments and suggestions. They have helped to improve the structure and content of the paper. The original comments are provided in *italics* for reference. Modifications to the text are highlighted.

Reply to referee #1

General concerns:
1.The use of in cloud and regional averages in stratocumulus regions is confusing.

We agree that the use of the terms stratocumulus regime and stratocumulus regions as well as in-regime values and in-cloud values can be confusing. As it is necessary for the analysis in the study to use these terms we have added an appendix (A) where the different terms are explained and examples are given.

2. I am concerned that the tuning parameters may have an influence on AAE, and not enough detail is provided.

It is true that tuning parameters may have an influence on AAE but this depends on the physical parameterisations e.g. the autoconversion parameterisation that is used in the model. In Lohmann and Ferrachat, 2010 it was shown with the relevant model physics in ECHAM5-HAM (which are also used in ECHAM6-HAM2) that tuning has only a minor influence on AAE. Two sentences have been added to the description of the simulations in Sect. 3.2 to clarify this: Lohmann and Ferrachat (2010) varied ccraut between 1 and 10, in this study ccraut values between 3.5 and 12 are used (see Table 1). In this study the same autoconversion parameterization (Khairoutdinov and Kogan 2000) as in Lohmann and Ferrachat (2010) is used.

3. I am not certain that looking at global AAE while just focusing on the stratocumulus regions is helpful. Model biases do not appear to be confined to low clouds, and the response to aerosols and AAE may also not be confined to low stratocumulus clouds.

We agree that model biases appear not only in the stratocumulus regime and that model changes can influence also other cloud regimes. Although it would be interesting to study the response of clouds, aerosol and AAE also in other cloud regimes the focus of this study lies on the stratocumulus regime. We have added two sentences in Section 4.3 to clearly say this: The focus of this study lies on the representation of marine stratocumulus clouds. Therefore AAE is computed also in the stratocumulus regime.

4. Some further analysis of the he effects of the tuning parameters and time stepping probably needs to be performed or assessed in more detail.

A detailed analysis of the effects of the tuning parameters on AAE is provided in Lohmann and Ferrachat (2010).
Further analysis of the time stepping is a very good point. As suggested in a specific comment below the analysis was repeated for the reference simulations with reduced time steps of 300 s and 180 s. This was added in Sect. 3.1:
The effect of reducing the time step alone is presented in Sect. 4.2.2.
and Sect. 4.2.2:
To estimate the effect of the reduction of the time step the present day reference simulation (L31) was repeated with reduced time steps of 300 s and 180 s. This leads to significant increases in condensation and deposition rates at shorter time steps and reduced vertical velocities due to reduced turbulent kinetic energy (TKE). This time step dependence will be fixed in newer versions of the ECHAM6 GCM (ECHAM6.2 onwards; Mauritsen T., pers. comm.), but unfortunately they are not yet coupled to the aerosol scheme. The reduced TKE leads to a reduced vertical velocity, which then favors depositional growth of ice crystals at the expense of condensational growth of cloud droplets (Wegener-Bergeron-Findeisen process). In stratocumulus regions the reduced TKE reduces the cloud cover significantly when the time step is reduced. The reduction in cloud cover in the stratocumulus regime in the VRES experiments can therefore be attributed to the reduction of the time step and the subsequent reduction of TKE. The changes in condensation/deposition/TKE also lead to changes in convection. Mid-level convection in the storm tracks is replaced by shallow convection. In the tropics and subtropics shallow convection is replaced by deep and mid-level convection. These changes in convection correlate with changes in AAE. AAE increases from -1.19 W/m^2 @ 720 s to -1.50 W/m^2 @ 300 s and to -1.33 W/m^2 @ 180 s. Changes in the aerosol are small when the time step is reduced and they do not correspond to the changes in AAE. The only exception are strong decreases in dust emissions by -35% (720 s – 300 s) and -37% (720 s – 180 s) but this also do not seem to affect AAE. The dust emissions are very sensitive to changes in wind velocities (and to lesser extent to soil moisture) and the threshold friction velocity may have to be adjusted to a different model setup.

Specific Comments are below:
P13683, L 23: unclear. Did Carslaw use microphysical retrievals from ISCCP in their model?

Carslaw et al. (2013) used only surface albedo and cloud optical depth from ISCCP and assumed a constant liquid water path between present day and pre-industrial simulations. The paragraph has been rewritten to clarify which cloud climatologies and ISCCP data were used by Carslaw et al. (2013). We removed the wrong statement about the cloud number concentrations in stratocumulus regions:
Surface albedo and cloud optical depth fields from International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999) D2 data for low level stratiform clouds was used in their study. To evaluate the uncertainty stemming from the simulation of clouds Carslaw et al. (2013) did extra simulations with the 1983–2008 multi-annual ISCCP cloud climatology but found that the sensitivity to the cloud climatology was very small.

P13685, L 13: do you discuss sensitivity to the choice of empirical thresholds (e.g. LTS)? What is the area of the planet you are addressing with stratocumulus clouds?

We only have a short discussion about the low sensitivity we found for adding another criterion for the vertical velocity closer to the inversion height. As these empirical thresholds have been used in several studies e.g Medeiros and Stevens (2011), Bogenschutz et al. (2013),

Nam and Quaas (2013) and were discussed there we took values from the literature. For example Gettelman et al. (2012) found no change in their results by adjusting the LTS threshold.
We have added the discussion of the LTS and of the values for the fraction of the global area covered by the stratocumulus regime in Sect. 4.1:
The stratocumulus regime covers 4.8% of the global area in the reanalysis data, 4.4% in REF, 4.2% in STAB, 3.0% in VRES47 3.0% in VRES95 and 4.5% in AP. Gettelman et al. (2012) altered the stability threshold to adjust the area covered by the stratocumulus regime in their simulations to the same area fraction as in the reanalysis data but found that the results did not change. Due to the smaller area (compared to reanalysis) covered by the stratocumulus regime in our simulations cloud properties like cloud cover, liquid water path or cloud radiative effect will therefore be too low compared to observations.

P13686, L16: is AAE evaluated everywhere? Can you isolate AAE to stratocumulus regions? What does this mean and is there compensation? If this is discussed later, you might need to mention it here.

Done. AAE is evaluated globally and in the stratocumulus regime. It can be calculated only for the stratocumulus regime but a specific methodology has to be used to get statistically significant results, which are discussed later. We have added two sentences to mention it here:
AAE is evaluated globally and in the stratocumulus regime. Results for this are presented in Sect. 4.3. The computation of AAE in the stratocumulus regime is described in the following paragraph.

P13686, L27: what does internal variability can become comparable to model changes mean?

The change in a model variable due to internal variability alone can be as large as the change in this variable due to the changes one is interested in such as changes in the model resolution or to changing aerosol emissions. We have rewritten two sentences to better explain this:
Global differences by changes in the model physics or resolution or the global anthropogenic aerosol effect are typically much larger than internal variability. In the stratocumulus regime however due to the conditional sampling internal variability can become as large as changes in variables due to model changes or the anthropogenic aerosol effect.

P13687,L7: these should probably not be in a supplement if they are important to the paper.

We have moved the Tables S1 and S2 to the appendix (B).

P13687, L24: it is not clear to me what you will be comparing for differnces. Is it just AAE or many variables?

All differences in variables in Table 3 (formerly Table 2) are computed as explained in this paragraph. We added a sentence at the end of Sect. 2 to clarify this:
This methodology is used for all variables for which differences between present day and pre-industrial simulations are computed e.g. AAE, the change in liquid water path or cloud cover.

P13690,L9: what is the effect of timestepping alone? Can you repeat the analysis with L31 but dt=300s and 180s?

A very good idea. We repeated the analysis with L31 and dt=300 s and dt = 180 s. See our reply to the general concern above.

P13691, L16: if the AMIP simulations have annual varying SSTs, then what years were used? I assume the CLIM experiments are an average? I'm not certain I believe that 5 years with variable SST is enough: I think it is with CLIM SSTs.

The years for which the AMIP simulations were done should have been in the text but were missing. Thank you for spotting this. The years 2006-2010 were used to cover the same time period as most of the observations.

This was added in Sect. 3.2:

The length of the simulations was 5 years (2006-2010) for L31 after 3 months spin-up.

The climatological values are an average for each calendar month of the years 1979-2008. This was also added in Sect. 3.2:

For the evaluation of the anthropogenic aerosol effect the experiments were repeated (5 years after 3 months spin-up) with climatological values for sea surface temperatures and sea ice cover (CLIM simulations; the climatological values are an average for each calendar month of the years 1979-2008) to decrease the natural variability in the experiments (see also Sect. 2)

The significance of the results was tested and the results are in Table B2 (formerly Table S2). For changes in the model (STAB/VRES/AP) 5 years with variable SST and sea ice cover are enough to obtain significant results. Only for the anthropogenic aerosol effect in the stratocumulus regime the 5 years AMIP simulations the results were not significant. This is why we used 5 years climatological simulations for assessing AAE in the stratocumulus regime. We also performed 10 years climatological simulations but this did not improve the statistical significance of AAE in the stratocumulus regime.

P13691, L21: what is 'free mode'. It seems like everything is run in the same way (fixed SST and ice and free atmosphere). Is there something other than free mode, which would imply nudging? Or did I misunderstand something?

Climatological SST and sea ice cover and a free atmosphere were used in the simulations. The confusing 'free mode' was deleted from the sentence:

Both simulations were run with climatological sea surface temperatures and sea ice cover for one year with present day greenhouse gas and aerosol emissions.

P13692, L1: in other models the autoconversion tuning parameter has a large effect on AAE (e.g. Work with the GFDL model by Golaz). Are you sure this is true in the version of ECHAM you have? Typically autoconversion is related to drop number, so it directly links to aerosols.

ECHAM6-HAM2 uses the autoconversion parameterization developed by Khairoutdinov and Kogan (2000) which was used also in the simulations in Lohmann and Ferrachat (2010). Lohmann and Ferrachat (2010) showed that tuning has only little effect on AAE.

A sentence has been added to the experiments description in Sect. 3.2 for this: In this study the same autoconversion parameterization (Khairoutdinov and Kogan 2000) as in Lohmann and Ferrachat (2010) is used.

Please see also our reply to the general concern above.

P13692, L11: please be quantitative throughout this section: how much more frequently.

The global area fraction where the LTS criterion is met is 6.24% in the reanalysis data and 6.22% in ECHAM6-HAM2. The subsidence criterion is met 28% in reanalysis data and 30% in ECHAM6-HAM2. It is most interesting to focus on areas where both conditions are met. For these areas we computed weighted values (weighted by the frequency of occurrence of

stratocumulus conditions) for the frequency of occurrence of the LTS and subsidence criteria in areas where both conditions are met. This revealed that both the LTS and the subsidence criteria occur less frequently in ECHAM6-HAM2 than in ERA-Interim. We have changed the relevant sentences accordingly:
This is because large values of LTS occur 12% less often in ECHAM6-HAM2 than in the reanalysis data (the same is true for other GCMs, see Medeiros and Stevens, 2011) in areas where both stratocumulus conditions are met. The criterion for subsidence is met 9% less often in ECHAM6-HAM2 than in ERA-INTERIM in these areas.

P13692,L22: this is unclear to me. Do you mean in-cloud properties, or just properties when clouds occur?

We mean in-regime values. We have added an appendix (A) where in-regime values and the total uncertainty are explained.

P13693,L10: this is difficult to understand: on the one hand LWP is lower, and then it is higher. The words seem to say the same thing : LWP in stratocumulus areas and LWP in the stratocumulus regime. I think you need new terms for this.

We have added an appendix (A) to explain the difference between in-regime values and values in stratocumulus areas. We use two values to separate uncertainty due to large-scale dynamics and other model parts. LWP in the stratocumulus regime (in-regime value) represents the value of LWP when the large-scale environment is (almost) similar in ECHAM6-HAM2 and ERA-Interim. This value therefore excludes uncertainty due to large-scale dynamics. In-regime values are average values for the stratocumulus regime and are shown in Figs. 5, 6, 7, 10 (formerly 9), 12, 15 (formerly 14), 16 (formerly 15), C1 below the panels. Values in stratocumulus areas also include the difference in large-scale environmental conditions (by including the frequency of occurrence of stratocumulus conditions). These values represent the total model uncertainty and are typically shown in the figures.

P13693,L22: then this bias cannot be fixed with changes to the low cloud scheme. Or is the inversion going to help that?

We focus in this study on marine stratocumulus clouds and do not address this bias.

P13694,L5: figure 10 mentioned before figure 8 and 9?. Given the disparity in regions in the observations, the model should be represented by dotted lines for each region.

We changed the figure numbers.
The diurnal cycle was computed from output for every time step for October 2006. Because of the large amount of data involved we were not able to compute the output for longer time periods. We chose October as the stratocumulus cloud cover in the SE Pacific and in the SE Atlantic is largest in this month and Wood et al. (2002) found the most pronounced diurnal cycle in these regions. We have added this in the text:
We therefore chose for a comparison the month of October (2006) when in the SE Pacific and in the SE Atlantic the stratocumulus cloud cover is large (because of the large amount of data involved we were not able to compute the output for longer time periods).

P13696,l12: how far out was the radiative balance? It seems you are going to be shifting the cloud forcing around spatially with these changes. Are you use they do not affect AAE? Again, I am not sure whether you are using a local or global AAE.

All present day simulations were tuned to be in radiative balance (see the new Table 2). We use 5-year simulations with climatological sea surface temperatures and sea ice cover to obtain statistically significant results. What appears to be a shift of the cloud forcing is likely the results of a decrease in stratocumulus clouds due to decreased TKE (see our reply to the general concern above) and an increase in stratocumulus clouds further off coast due to a less active shallow convection scheme at the increased vertical resolution. We have rewritten the text to clarify this:
The pattern appears like a spatial shift of the clouds but actually there are two changes partly compensating each other. The increase in cloud cover and LWP is in areas where also shallow cumulus clouds may appear (the shallow convection frequency is reduced in the VRES95 experiment see Fig. C1) and not in the 'core' stratocumulus regions, where the same decrease of cloud cover and LWP as in the VRES47 simulation occurs (due in part to reduced turbulent vertical velocity).

P13697:l10: what is the effect of timestep alone? Can you separate that from the vertical resolution change?

As suggested in the specific comment above we repeated the analysis with L31 and dt=300 s and dt = 180 s. See our reply to the general concern above.

P13699,L20: I worry strongly about the significance of these changes given the relatively short (5 year) runs. What is the significance level for table 2 and figures 14 and 15.

The significance level for the values in Table 3 (formerly Table 2) is 90% (see also Tables B1(S1) and B2(S2)). We have added stippling to figures 14 and 15 for the 90% significance level. We also tried 10-year simulations with climatological SST and sea ice cover but this did not improve the statistical significance of the results.

P13700, l27: are there aerosol effects in deep convection? How could that affect AAE? Are the changes in deep convective regimes? In the VRES Experiments, do the same susceptibilities act as in the other Experiments? Does aerosol decrease? It is not clear this is the case from table 2. Please clarify.

Aerosol effects in deep convection are not included in ECHAM6-HAM2. But there is a dependence of cloud droplets detrained from convective clouds on aerosol. Some sentences have been added in Sect. 3.1 to clarify this:
Aerosol effects on convective clouds are not included. But there is a dependence of cloud droplets detrained from convective clouds on aerosol. The condensate detrained from convective clouds is added to that of the existing stratiform clouds. For liquid clouds the cloud droplet number added from detrainment depends on the number of aerosol particles that can be activated at the convective cloud base.
In Lohmann (2008): "Global anthropogenic aerosol effects on convective clouds in ECHAM5-HAM", ACP, aerosol effects on convective clouds were investigated. The change in the geographical pattern of precipitation since pre-industrial times better matched observations when aerosol effects on convective clouds are included. Also the sensitivity of LWP to AOD decreased and convective precipitation increased suggesting more vigorous convection. But the effect on AAE was small, it decreased from -1.6 W/m^2 to -1.5 W/m^2 when aerosol effects on convective clouds were included.
There is a small increase in the frequency of the deep convection scheme and convective precipitation is increased in the VRES experiments. This was also found in Lohmann and

Ferrachat (2010) when the entrainment for deep convection was decreased and could therefore be the results of the different tuning and not the different vertical resolution so we do not expect it to have a strong influence on AAE as in Lohmann and Ferrachat (2010) no large dependence of AAE on tuning was found. Precipitation, aerosol and other variables for the present day simulations of all experiments are now presented in the new Table 2. The aerosol load decreases for almost all aerosol components in the VRES experiments. For VRES47 this seems to be due to increased wet deposition (new Fig. 14) and for VRES95 also due to increased dry deposition (not shown).

Whether susceptibilities change in the VRES experiments is an interesting question. The increased wet deposition in the VRES47 experiment could be due to changed susceptibilities. But this is beyond the scope of the current study and. We will investigate this in further studies. We have added a discussion of the changes in the aerosol in the VRES experiments in Sect. 4.2.2:

The aerosol burden decreases for all aerosol species except sulfate (SO_4) (see Table 2) in the VRES experiments compared to the reference simulation. Although the emission rates are quite similar the aerosol particles are removed faster from the atmosphere in the VRES experiments. This is due to increased wet deposition rates in the VRES experiments (cf. Fig. 14). In the VRES95 experiment also the dry deposition rate is increased. One exception is mineral dust (DU) for which the emission is reduced by -36 % in the VRES47 experiment and by -49 % in the VRES experiment. As mentioned above dust emissions are very sensitive to wind velocities. Although the monthly mean 10m wind velocities do not change much between the experiments, shorter fluctuations in the wind velocities could considerably alter the dust emissions.

P13701:l8; given the bias in middle and high clouds, might these be contributing to the effects seen? Please comment.

The high and mid-level cloud cover is low in the reference experiment and does not change much in any other experiment (less than 2%), so we do not expect a contribution of high and mid-level clouds to the strong increase of AAE_{Sc}.

P13792,L3: does it change mid and high level cloudiness biases? I am assume not from the comment, but please clarify.

No, high and mid-level cloudiness changes less than 2% in any of the experiments.

P13703,L1: what is the AAE when shallow convection is turned off? Are their aerosol effects in shallow convection? If not, then more regimes are treated by stratiform clouds with aerosol effects. Please comment.

AAE increases to -2.64 W/m^2 with shallow convection turned off (-1.19 W/m^2 in REF). This is due to a very strong increase in LWP (almost 50%) with shallow convection turned off and maybe also to increased nucleation of SO_4 as compared to the reference simulation Condensation of SO_4 is likely decreased as SS and DU burdens are decreased. DU is decreased because of reduced emissions and SS is reduced because of stronger wet deposition.

Aerosol effects in shallow convection are not included in ECHAM6-HAM2. But the cloud droplet number concentration detrained from convective clouds depends on the activated aerosol number concentration at the cloud base of convective clouds (see our reply to the specific comment about deep convection above). By this mechanism there are also aerosol effects in ‘convective’ regimes in our simulations. We do not expect a large influence on AAE because of this (see Lohmann (2008) and our reply to the specific comment above).

P13704’L14: I think the supplement could be incorporated and integrated into the manuscript.

Done. We have moved Tables S1 and S2 to the appendix (B).

P13729: figures 14 and 15 need to have some estimate of significance: what changes are significant?

Done. We have added stippling to Figures 15 (formerly Fig. 14) and 16 (formerly Fig. 15) to indicate the 90 % significance level.

Reply to referee #2

General comments
1.The fact that the aerosol effects, and in particular the aerosol cloud interactions, are poorly represented in GCMs should be stressed out in the introduction. The authors acknowledge that there is a lot of uncertainty in the prediction of these effects among the climate models, and that part of this is related to a poor representation of stratocumulus clouds. But it is important to also point out that the complex interactions between aerosol and clouds are represented very crudely in models, usually through a dependency of the precipitation rate on the cloud droplet number. While other dependencies which have been shown to play an important role in the response of the cloud to the change in aerosol loading in LES studies are still missing, for e.g. the dependency of the entrainment rate on the droplet number, or interactions between evaporative cooling of precipitation and absorption of solar radiation.

We agree that it is important to point out also the problems with representing aerosol-cloud interactions in GCMs. We have added a paragraph to the introduction to mention some issues: It is also challenging to represent the complex interaction between aerosol and clouds in a global climate model. Recent high resolution large eddy simulations (LES) studies showed that the liquid water path may either increase or decrease with increased cloud droplet number concentrations (N_d) in contrast to the thickening from reduced precipitation efficiency (Ackerman et al., 2004; Bretherton et al., 2007; Hill et al., 2008; Sandu et al., 2008; Ackerman et al., 2009; Petters et al., 2013). The thinning is due to increased entrainment of dry free atmospheric air that is associated with increased N_d (Ackerman et al., 2009; Petters et al, 2013). The drying of the boundary layer occurs when the free atmosphere is dry (Ackerman et al., 2004). The increased entrainment is explained either by increased evaporative cooling at cloud top due to stronger turbulence (Ackerman et al., 2004; Hill et al., 2008; Ackerman et al., 2009) or a stronger evaporative cooling efficiency (Bretherton, 2007). The increase in entrainment is substantially reduced when cloud water sedimentation is included in the simulation (Bretherthon et al, 2007; Ackerman et al, 2009). Global climate models typically only represent the reduced precipitation efficiency via an autoconversion parameterisation of cloud water (depending also N_d) to precipitation but no parameterisation of the other interactions.

2. The authors do not manage to convey clearly enough how much changes in model physics and resolution influence in the end the aerosol effects simulated with the model they use, which is the main focus of the paper according to the title.

We included the values for global, annual mean AAE in the abstract:
In-cloud aerosol processing in ECHAM6-HAM2 leads in the global, annual mean to a decrease of the anthropogenic aerosol effect from -1.19 W/m^2 in the reference simulation to -1.08 W/m^2 while using a 'sharp' stability function leads to an increase to -1.34 W/m^2. The results from the simulations with increased vertical resolution are diverse but increase the anthropogenic aerosol effect to -2.08 W/m^2 at 47 levels and -2.30 W/m^2 at 95 levels.
We have added some discussion of changes in the aerosol emission and processes Section (4.2.2):
The aerosol burden decreases for all aerosol species except sulfate (SO_4) (see Table 2) in the VRES experiments as compared to the reference simulation. Although the emission rates are quite similar the aerosol particles are removed faster from the atmosphere in the VRES experiments due to increased wet deposition rates (cf. Fig. 14). In the VRES95 experiment also the dry deposition rate is increased. One exception is mineral dust (DU) for which the

emission is reduced by -36 % in the VRES47 experiment and by -49 % in the VRES experiment. As mentioned above dust emissions are very sensitive to wind velocities. Although the monthly mean 10m wind velocities do not change much between the experiments, shorter fluctuations in the wind velocities could considerably alter the dust emissions.

These changes alone do not seem to explain the large changes in AAE. In the AP experiment we have not seen much influence of the aerosol on the cloud properties. Vice versa, changes in clouds, as they occur for example in the VRES experiments, can also change the atmospheric aerosol by changing wet deposition or production of SO_4 by wet chemistry and thereby amplify the changes in the cloud properties with respect to AAE. We have added a discussion of this in Sect. 4.3:

In the VRES experiments there is a strong increase in *AAE*. As discussed in Sect. 4.2.2 there are changes in aerosol emission and removal in the VRES experiments compared to the reference simulation leading to smaller aerosol burdens. These changes seem not to be the direct result of the changed model resolution but of the changes in the clouds. Changes in clouds, as they occur in the VRES experiments, change also the atmospheric aerosol by changing wet deposition or production of SO_4 by wet chemistry. Reduced wet deposition of large aerosol particles would decrease the condensation rate of SO_4 to atmospheric aerosol particles and increase the nucleation rate of SO_4 leading to increased CCN. Also increased production of SO_4 would lead to increased CCN. With these two mechanisms changes in aerosol cloud interactions due to changes in the clouds could be amplified by subsequent changes in aerosol. In Fig. 14 the change in wet deposition of aerosol mass and the change in production of SO_4 by wet chemistry between the VRES95 and the REF experiment are shown. There seems to be a correlation between the increase of wet deposition and the increase of SO_4 production and the stronger *AAE* in the VRES95 experiment in many regions.

3. the authors should as well explain more clearly how much the tuning done in the various experiments to close the radiative budget matters for differences we see between each experiment and the control run. My concern is that the changes in stratocumulus we see between two simulations are not only due to the sensitivity test but also an outcome of the tunning of some parameters. The authors could avoid this controversy by saying that the changes we see between an increased VRES experiment for eg and the control one are not due only to the increased vertical resolution, but to the new model configuration necessary for the increased vertical resolution.

We agree that the tuning could have an effect on changes in the stratocumulus regime and that this should be pointed out in the text. We do not expect a strong impact for our simulations as the impact of tuning on global AAE in our model is small (see Lohmann and Ferrachat, 2010). Also we have chosen tuning parameters for the experiments where we found in sensitivity simulations the smallest impact on stratocumulus cloud cover. We have added some sentences in Sect. 4.2.2 to point out the necessary new model setup:

The different tuning and the reduced time steps are necessary for increasing the vertical resolution. The effects of changing the vertical resolution described below are not entirely due to the change in the vertical resolution alone but also to these necessary changes in the model setup.

4. The authors should mention that the frequency of occurence of stratocumulus discussed in the paper, depends of course on the way they defined stratocumulus. As well, the authors conclude that the cloud lack in the model because the LTS is too weak. This is certainly not the only reason, the formation of clouds depends on many factors not ony the LTS.

This is a good point. To better motivate our definition of the stratocumulus regime we have added a sentence to Sect. 2:

This definition of the stratocumulus regime allows, to the extent possible in a global climate model simulation, to separate dynamical (large-scale environment) and other influences on the simulation of stratocumulus clouds.

To point out the separation of the influence of the large-scale environment and other factors to the formation of stratocumulus clouds with our definition of the stratocumulus regime we have added and rewritten text in Sect 4.1:

The regime based analysis allows to investigate cloud properties only when the environmental conditions for stratocumulus clouds are met (see Sect. 2. and Appendix) and therefore to separate between in-regime uncertainties (all influences on stratocumulus clouds formation excluding large-scale dynamical factors) and total uncertainties (in-regime plus frequency of occurrence uncertainty; all influences on stratocumulus clouds formation including dynamical factors).

and Sect. 5:

The formation of stratocumulus clouds depends on many factors. Their representation in large-scale models requires a correct simulation of the large-scale environment.

and in the new Appendix A.

5. The results and discussions parts could be more focused and concise, bringing forward the lessons learned by the authors rather than describing the results.

We changed the title of section 5 to Summary and conclusions and changed the structure of the text. It reads now:

We have performed several simulations to identify cloud biases in the stratocumulus regime and to improve the representation of stratocumulus clouds and the aerosol in the stratocumulus regime. The impact of these changes on the anthropogenic aerosol effect have also been investigated. The biases in ECHAM6-HAM2 are typical for global models: the clouds form too low and are too shallow, low cloud cover, liquid water path and the shortwave cloud radiative effect are underestimated. In the stratocumulus regime (diagnosed by environmental conditions) these biases are reduced.

The formation of stratocumulus clouds depends on many factors. Their representation in large-scale models requires a correct simulation of the large-scale environment. The main reasons for the cloud biases in regions with high stratocumulus cloud cover in ECHAM6-HAM2 as follows:

- Too strong turbulent mixing at stable conditions: At high vertical resolution the vertical cloud properties indicate a too strong mixing at the top of stratocumulus clouds in ECHAM6-HAM2 and too much convective transport. The turbulent mixing at stable conditions can be reduced by using a ‘sharp’ stability function in the TKE scheme of ECHAM6. This improves the stratocumulus cloud cover and liquid water path but changes the vertical cloud properties only modestly. The stratocumulus clouds in ECHAM6-HAM2 at high vertical resolution have a larger vertical extent but their coverage is smaller at lower altitudes than in ERA-Interim. This may be explained by too strong entrainment of warm, dry free tropospheric air into the PBL, which is reduced with the ‘sharp’ stability function, and too much convective transport of moisture to higher levels. The improvement by using a ‘sharp’ stability function is not sufficient to reconcile the simulated low cloud cover with that of satellite observations.
- Too ‘active’ shallow convective scheme: Another reason for the lack of stratocumulus clouds appears to be the over-active shallow convection scheme in ECHAM6-HAM2. Isotta et al. (2011) have shown that the Tiedtke-shallow-convection scheme (Tiedtke,

1989) used in ECHAM5-HAM (Roeckner et al., 2003; Stier et al., 2005; also used in ECHAM6-HAM2) activates too frequently compared to large eddy simulations and observations of the frequency of cumulus clouds. Their transient shallow-convection scheme decreased the frequency of shallow convection which was compensated by increased stratus and stratocumulus (a similar decrease of shallow-convection frequency and increase of LWP in the stratocumulus regime was observed in the VRES95 experiment, see Fig. C1). In a recent study Nam et al. (2014) compared three boundary layer cloud schemes in ECHAM5 to the standard scheme used in ECHAM5 and CALIPSO and CloudSat satellite observations. All three schemes improved low cloud cover and precipitation in the (sub)tropics compared to the standard scheme (note that their ECHAM5_Trig model is similar to what is used in ECHAM6). Two of the new schemes reduced the frequency of shallow convection compared to standard ECHAM5. The third new scheme does not compute shallow convection separately.

By turning off shallow convection completely in a sensitivity study we found that stratocumulus clouds were forming higher up and were thicker. The improvement is almost as large as by increasing the vertical resolution. Turning off shallow convection also increased the low cloud cover in the stratocumulus regime. Changing the shallow convection scheme in ECHAM6 would probably be beneficial for representing stratocumulus clouds.

- The relative humidity based cloud cover scheme: A sensitivity study where precipitation in the stratocumulus regime was turned off showed an impact mainly on liquid water path, cloud optical properties and cloud radiative effects. LWP and cloud optical depth (COD) approximately double in the stratocumulus regime without precipitation compared to the reference simulation and SWCRE is increased by 21% resulting in a more negative net cloud radiative effect (NETCRE in worse agreement with observations). The low cloud cover increases only by 3% from 47.7% to 50.7 %. This strong increase in LWP by turning off precipitation which hardly affects low cloud cover indicates that the relative humidity based cloud cover scheme used for the simulations produces not enough cloud cover in the stratocumulus regime (see also Fig. 5).
- Lack of vertical resolution: Stratocumulus clouds in ECHAM6-HAM2 form too low and are too shallow. With an increased vertical resolution the clouds are forming higher up and are quite similar to the clouds in the ERA-Interim stratocumulus regime. A simple increase of the vertical resolution (at unchanged horizontal resolution) improves the vertical cloud properties in the stratocumulus regime but affects other parts of the model and leads to a degradation of the simulation. Diagnosing the actual inversion height (cloud top) in stratocumulus regions as in the schemes of Grenier and Bretherton (2001; applied to ECHAM5-HAM in Siegenthaler-Le Drian, 2010) could improve stratocumulus clouds while keeping the interaction with other parts of the model at a minimum.
- Possibly too low subsidence rates: Environmental conditions suitable for stratocumulus clouds appear 8% less frequent in ECHAM6-HAM2 (4.4 % of the global area in the REF experiment) as in reanalysis data (4.8%) due to a too low LTS and too low subsidence rates. The underestimation of the frequency of stratocumulus conditions appears in all simulations conducted in this study, in particular also in the simulations with reduced turbulent mixing at the top of the stratocumulus clouds and increased vertical resolution. Subsidence rates are lower in ECHAM6-HAM2 than in ERA-Interim which might explain the lack of inversions.
- The monthly average diurnal cycle of liquid water path of stratocumulus clouds modeled in ECHAM6-HAM2 on the other hand agrees well with observations.

Our simulations indicate that no single measure brings the simulated stratocumulus clouds in ECHAM6-HAM2 in agreement with observations. Changes to three parts of the model will be necessary to further improve the simulation of stratocumulus clouds in ECHAM6-HAM2:

- Changes in the cloud cover scheme,
- Changes in the shallow convection scheme and
- Changes in the boundary layer scheme.

From our simulations with changes in model resolution and physics to better represent clouds and aerosol in the stratocumulus regime we conclude that the anthropogenic aerosol effect (AAE) is sensitive to changes in (stratocumulus) clouds:

Aerosol processing in stratiform clouds has only a small impact on cloud properties in ECHAM6-HAM2 but it reduces the anthropogenic aerosol effect globally from -1.19 W/m^2 in the reference simulation to -1.08 W/m^2. In the simulations performed in this study the cloud droplet number concentration is quite stable in the stratocumulus regime as it increased only by 23 % in the sensitivity study with precipitation turned off in the stratocumulus regime and by only 13 % in the aerosol processing experiment where the cloud condensation nuclei concentration (CCN) approximately doubles.

The 'sharp' stability function leads to an increase in AAE of 0.15 W/m^2 to -1.34 W/m^2. In simulations VRES47 and VRES95 AAE strongly increases to -2.08 W/m^2 and -2.30 W/m^2 respectively. AAE in the stratocumulus regime is generally stronger than in the global mean and so are the changes between the different experiments. These sensitivity studies show the importance of a good representation of stratocumulus clouds for simulations of the anthropogenic aerosol effect.

Minor comments

1.introduction, page 13863 - the last paragraph feels out of place here

We have rewritten and moved this paragraph to better motivate it:

… Stratocumulus cloud regions were identified to be among the regions responsible for the largest host model uncertainty in the direct aerosol effect and can therefore be expected to be important for the total anthropogenic aerosol effect.

For the first indirect aerosol effect (cloud albedo effect), Carslaw et al. (2013) systematically evaluated the sources of uncertainty for the simulation of aerosol. Uncertainties in natural emissions cause most uncertainty in cloud radiative forcing, followed by uncertainties in anthropogenic emissions and aerosol processes. Stratocumulus regions were identified as regions with a strong cloud albedo effect and large model uncertainty. Surface albedo and cloud optical depth fields from International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999) D2 data for low level stratiform clouds was used in their study. To evaluate the uncertainty stemming from the simulation of clouds Carslaw et al. (2013) did extra simulations with the 1983–2008 multi-annual ISCCP cloud climatology but found that the sensitivity to the cloud climatology was very small.

As stratocumulus regions are areas of a strong anthropogenic aerosol effect, simulations of the anthropogenic aerosol effect can be expected to depend on the representation of stratocumulus clouds. …

2. page 13687, line 8 to 13 - not clear, it should be rephrased

Done. The text reads now:

The differences in a variable between two simulations are considered statistically significant if the p-value < 0.1 (i.e. the probability that there are no "real" differences in the variable between the simulations and that observed differences are only due to natural variability is less than 10%, i.e. the null hypothesis is rejected for p<0.1). Results of the t-test for variables changes between different experiments and present day and pre-industrial simulations are presented in the Appendix Tables B1 and B2. For differences due to model changes (see Sect. 3, i.e. changes between different experiments) the mean values over the stratocumulus regime are computed as a mean over all grid boxes belonging to the stratocumulus regime at once as the mean values computed this way were found to be statistically significant (or for some variables in the case of including aerosol processing too small to be statistically significant independently of the averaging method). Taking the average over such a large area as the stratocumulus regime can average out differences. Differences in model variables due to anthropogenic aerosol were found to be smaller than the differences between different present-day experiments. We therefore did not average over the whole stratocumulus regime at once but used a different averaging method for the anthropogenic aerosol effect in the stratocumulus regime. We computed yearly mean values in six stratocumulus regions (see Fig. 4) and compared the differences in these six regions between simulations with present day and pre-industrial aerosol emissions and then took a weighted average (Nam and Quaas, 2013 used a similar approach to evaluate boundary layer clouds in satellite and model data).

3. page 13688, point 1 : it should be stated that this formulation is for stable conditions

Done. We have inserted two sentences in Sect 3.1, point 1 to state this:
We replaced the 'long-tail' stability function with a 'sharp' stability function (King et al., 2001; Brown et al., 2008; see Fig. 1). As the stability functions differ the most for large Richardson numbers the largest differences in the simulations occur at stable atmospheric conditions.

4. page 13691, lines 14 to 18: not clear, I thought the sst' s were fixed

SST's and sea ice cover in the CLIM simulations are averages for each calendar month over the years 1979-2008. The text was rewritten to clearly state this:
For the evaluation of the anthropogenic aerosol effect the experiments were repeated (5 years after 3 months spin-up) with climatological values for sea surface temperatures and sea ice cover (CLIM simulations; the climatological values are an average for each calendar month of the years 1979-2008) to decrease the natural variability in the experiments (see also Sect. 2)

5.page 13692, first paragraph: other processes that LTS matter for the cloud formation. Same for page 13693 lines 12 to 13.

To point out that LTS and w_{500} are just one factor (large-scale environment) controlling stratocumulus cloud formation we have added a sentence to Sect 4.1:
Note that with the frequency of occurrence of stratocumulus conditions the simulation of the large-scale environment can be investigated separately from other factors controlling stratocumulus cloud formation, which are discussed below.
And to point out that in-regime values refer to similar large-scale environmental conditions we have rewritten two passages:
When looking only at in-(stratocumulus)regime values, i.e. similar large-scale environmental conditions, the underestimation is less severe: …
On the other hand when looking only at the LWP in the stratocumulus regime, the (in-regime) values for LWP are higher in the reference simulation than in ERA-Interim.

6. page 13693, what is the LWP climatology from the Univ of Wisconsin based on?

The UWisc LWP climatology is based on passive microwave satellite observations for the time period 1988-2005. We have added this to Sect. 4.1:
ERA-Interim reanalysis data agrees fairly well with Moderate Resolution Imaging Spectroradiometer (MODIS; MYD08_D3 daily mean level 3 cloud product; King et al., 2003) data and the LWP climatology of the University of Wisconsin (UWisc; O'Dell et al., 2008) derived from satellite-based passive microwave observations (1988-2005) over oceans.

7. page 13694, lines 4 to 14 - not clear what message this paragraph intends to emphasize

We want to point out in this paragraph that ECHAM6-HAM2 reasonably well simulates the monthly mean diurnal cycle of LWP in the stratocumulus regime (see also our reply to the minor comment below).

8. page 13694, last paragraph - the statement about the diurnal cycle is too strong. It is not that obvious that there is good agreement with the observations. Moreover, these are monthly means, it may well be that if you would look at individual times the model would perform much worse.

The multiyear average in LWP shown in Fig. 6 and the difference in the morning maximum and the afternoon minimum of LWP, normalized to the mean LWP, are quite similar in ECHAM6-HAM2 and Wood et al. (2002). Also the phase of the diurnal cycle agrees qualitatively with the TMI data (formerly Fig. 8; now Fig. 9). We therefore believe that the statement is justified.
We changed the last sentence to point out that we compared here a monthly mean diurnal cycle:
The monthly average diurnal cycle of stratocumulus clouds simulated with ECHAM6-HAM2 agrees well with observations.

9. section 4.2.2 - this whole subsection would benefit from some revisions trying to emphasize more strongly the main points; the discussion about the PBL height could be removed, as the PBL height can be diagnosed in a 100 ways and conclusions that are drawn may depend on the diagnostic that is chosen. If the authors really want to discuss the experiment VRES47+STAB, why not support it by a figure? The last phrase of the section is an important finding, but it is drowned in rest of the text.

We agree that the PBL height depends on the diagnostic that is chosen and as we have not seen significant changes in PBL height between different experiments we have removed the discussion.
We have added a discussion of changes in aerosol emissions and processes (see our reply to the general comment above), which better puts the results in this section into context.
Vertical variable profiles in the stratocumulus regime for the VRES47+STAB experiment have been added to Fig. 8 (formerly Fig. 10).
We have added some sentences in Sect 4.2.2 to the discussion of the VRES47 experiment and rewritten the last sentence of the section so that the finding stands out better:
…The clouds seem to form higher up in the atmosphere but the cloud cover and the liquid water content are reduced. Around 800 hPa the liquid water content is larger than in the reanalysis data. This is the result of too much vertical transport as the cloud cover in the simulation with L47bl is not significantly larger around 800 hPa as in the reanalysis data. ...
… Around 800 hPa the liquid water content in the VRES47+STAB and VRES47 experiments is too large compared to reanalysis, irrespective of the stability function used. This indicates

that not only turbulent but also convective transport is too large around 800 hPa in the stratocumulus regime.

10. page 13700, lines 10 to 12 - this conclusion is controversial. The strong negative AAE in stratocumulus regions can be just an artefact of poor parameterizations in GCMs.

True. We added a discussion of this in Sect. 4.3:
Note that the impact of aerosol processing may be different in high resolution e.g. large eddy simulations of stratocumulus clouds as in our GCM simulation the important 'evaporation-entrainment' feedback (Xue and Feingold, 2006) is not accounted for explicitly.

11. page 13700, last phrase: where is this conclusion inferred from?

We are not sure to which conclusion this comment is referring to.

12. page 13701, lines 5-6: why is the aerosol load lower in the high vertical resolution experiment

The aerosol load is lower in the VRES experiments because of faster removal of the aerosol and to a lesser extent changed emissions. Wet deposition rates are increased in the VRES experiments and in the VRES95 experiment also the dry deposition rate is increased. This is now also discussed in the text (see our reply to the general comment above).

13. page 13702, lines 20-25 - the discussion of the results of the study by Nam et al is not clear.

The discussion of the results of the study by Nam et al. (2014) has been rewritten and reads now:
In a recent study Nam et al. (2014) compared three boundary layer cloud schemes in ECHAM5 to the standard scheme used in ECHAM5 and CALIPSO and CloudSat satellite observations. All three schemes improved low cloud cover and precipitation in the (sub)tropics compared to the standard scheme (note that their ECHAM5_Trig model is similar to what is used in ECHAM6). Two of the new schemes reduced the frequency of shallow convection compared to standard ECHAM5. The third new scheme does not compute shallow convection separately.

14. page 13703, lines 25-27, the droplet concentration does not only depend on the aerosol loading but also on the vertical velocity and the available supersaturated water vapour

True. Including aerosol processing in the simulation did not significantly change any cloud property in the stratocumulus regime except the cloud droplet number concentration. As changes in vertical velocity and available supersaturated water vapour would also change the mass mixing ratios of the clouds vertical velocity and available supersaturated water vapour can be assumed to remain fairly similar in the AP and REF experiments. When precipitation is turned off on the other hand, this will likely change (turbulent) vertical velocity due to changed cloud top radiative cooling and changed evaporation fluxes and supersaturation. Therefore changes in vertical velocity and supersaturation are implicitly included in the statement the cloud droplet number concentration is quite stable in the stratocumulus regime. We have rewritten the sentence to clarify that this is a result in our simulations:
In the simulations performed in this study the cloud droplet number concentration is quite stable in the stratocumulus regime as it increased only by 23 % in the sensitivity study with

precipitation turned off in the stratocumulus regime and by only 13 % in the aerosol processing experiment where the cloud condensation nuclei concentration (CCN) approximately doubles.