Impacts of emission reductions on aerosol radiative effects

Author's Response

The paper describes experiments with the ECHAM-HAM aerosol-climate model where four emission scenarios of the year 2030, representing increasingly efficient emission reduction measures, are used to assess their impact on aerosol burden and radiative forcing compared to the year 2005. The results are interesting and the link between emission and burden changes is well made (section 3.1).

The paper has weaknesses however. The emission scenarios, which are central to the study, need to be better described, both qualitatively and quantitatively. The writing should be more rigorous, and references to previous studies should be accompanied with a quick summary of the relevant finding. Figures and their captions can be improved. Finally, although the level of English language is good, minor improvements will be required by a native speaker.

We thank the reviewer for valuable comments for improving the manuscript. We have rewritten the descriptions of emissions and improved the English language of the manuscript. Throughout the text reviewers comments are marked with boldface and after each comment follows our reply.

Main comments

The use of four emission scenarios to 2030 is a strength of the paper. Unfortunately, section 2.2.1 does a rather poor job at describing those scenarios, as it assumes that the reader is familiar with many scenarios, projections, and legislation. To improve the situation, the authors must:

- **Show a Table similar to Table 2, but for emission rates of aerosol and precursor species in the reference dataset, and how those change in the four scenarios. That Table will help the reader determine the size of the different emission reductions considered.**

  The Table requested has been made based on old Table 1.

- **Are the aerosol emissions the only thing that changes in the perturbed simulation? It sounds like the CLECC simulations also include changes in CO2 , and also other climate forcers (methane?).**

  In our simulations, only BC, OC and SO_2 are changing as we only concentrate on aerosol forcing. It is true that the scenarios themselves include more changing species (e.g. CO_2).

- **Why is the BCAdd scenario called like that if it targets short-lived climate forcers in general? What are those "most important measures" (31904, line 22) that are included, and the "principles of such scenario" (31904, line 23)? It must be possible to summarise the key points of UNEP (2011) and Shindell et al. (2012) in a couple of sentences.**

  We have modified the second paragraph of Section 2.2.1: "..details of such scenario has been described in UNEP (2011) and Shindell et al. (2012). In short, the principles behind the development of the BCAdd scenario are a selection of measures which result in net reduction of radiative forcing calculated using pollutant-specific Global Warming Potential (GWP) values (UNEP , 2011). The measures reduce the emissions of BC, but also OC, carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NOx), and the reduced amounts vary across the measures. Key air pollutant measures include advanced emission standards on diesel engines (including diesel particulate filters), clean cookstoves, pellet stoves and boilers, more efficient brick kilns, and ban of agricultural burning. Thus, in terms of species used here, the reductions target BC and OC emissions. Measures with a relatively small net impact or increase in radiative forcing have been excluded from this portfolio. Lastly, the maximum technically feasible reduction (MTFR) scenario implements the maximum reduction potential of anthropogenic aerosol and SO2 emissions with currently available technologies by the year 2030 (simulation MTFR2030). The MTFR scenario introduces the best available technology to a maximum extend while ignoring any potential economic and political barriers. In this

scenario, no consideration is given to the direction of the change in aerosol radiative forcing, so also measures that reduce strongly the emissions of SO2 , e.g., fuel gas desulphurization, are included. The emission model used includes the end of pipe measures that remove pollutants from the exhaust. This means that it assumes that the use of most advanced particulate filters will reduce emissions of primary particular matter (PM), selective catalytic reduction (SCR) installations will bring NOx emissions down from industrial boilers, etc. For more detailed description of the current legislation and the MTFR scenarios, see e.g. Cofala et al. (2007) and Klimont et al. (2009). More information about an overall emission scenario comparison can be found from Amann et al. (2013)."

– **Same remark for the MTFR scenario, but for Cofala et al. (2007) and Klimont et al. (2009). Those "end-of-pipe measures" are quite mysterious.**

Please see previous answer.

– **Table 1 needs to be extended to include emissions discussed in 2.2.2, and 2.2.3. In the present version of the paper, the reader has no idea of the size of aviation and biomass-burning emissions.**

These are now in Table 1.

Figures 2, 3, 4, 5, 6, and supplementary Figures: please give the global average alongside each panel. Please also avoid using acronyms in the captions: all Figures should be stand-alone. Figures S1, S2, and S3 should show differences in emissions compared to the 2005 reference: at the moment, it is difficult to determine precisely where emissions have changed, and whether aerosol burden changes (Figures 2, 3, 4) are consistent.

We have changed all the figures as requested.

The last paragraphs of sections 3.1.1 (31910, lines 3-12), 3.1.2 (31911, lines 21-29), and 3.1.3 (31912, line 27 to 31913 line 4) should be moved to section 2.1, because they suggest that the reference simulation is in line with previous model runs. Of course, I am sure that the authors are aware that such a comparison is a poor measure of skill: previous simulations are biased against observations in diverse ways. The section should also mention aerosol residence times for the three species studied in the paper. Residence times are key to understand aerosol transport and radiative effects, and how they differ among models.

An interesting suggestion, but as Section 2 concentrates more on tools and methods, we do not see the point of moving the comparison part from the results sections to Section 2. This would require some initial explanation of the simulations and we believe that the current structure is clear already as it is. The comparison we show should not be taken as an detailed evaluation of the model as this was partly done before in Henriksson et. al. 2014 (this information has been added to the text in Section 2.1) and partly by ourselves (not shown).

Including the information about residence times is an excellent suggestion. We have calculated it for all of the species and simulations. Now chapters 3.1.1-3.1.3 include information about the residence time of the reference simulations and comparison to previous studies.

Page 31916, lines 4-5: This is a big surprise, and that limitation should have been mentioned earlier, including in the abstract. Why not give the all-sky DRE? That should be straightforward in a climate model.

In this work, the clear sky approach for DRE was chosen, because we wanted to show how the aerosol changes translate into overall radiative effect. Including the clouds, changes in cloudiness would change the total DRE estimates. Although the purpose here is to show how the radiative effect are changing in current day climate conditions, all-sky DRE would be partly "twisted" for the scenario simulations due to clouds. Thus, the clear-sky was considered to give more information about the future DRE changes (it is quite commonly used). Nevertheless, we will add the information about using clear-sky values to the abstract.

Other comments

Abstract, line 3: The authors use of the terms "radiative effect" and "radiative forcing" is inconsistent. The title uses the former, the abstract and the rest of the paper use both without a clear logic. I recommend using a consistent convention throughout. The IPCC terminology could be used: "radiative effect" refers

to the contribution of aerosols in general to the radiative budget, while "radiative forcing" is reserved to anthropogenic aerosols, or for changes with respect to a reference state. Under that definition, "radiative effect" would be used for 2005 reference numbers, while "radiative forcing" would be reserved to changes with respect to that reference. Changes are needed throughout the paper, including Table and Figure captions. A good example of the confusion are lines 21-23 of page 31915: the first sentence is indeed a definition of the direct radiative effect, but the second is in fact a definition of the direct radiative forcing (see e.g. Myhre et al., Atmos. Chem. Phys., 2013).

We have checked and corrected the manuscript for any inconsistencies related to this comment.

Abstract, line 9: A good way to summarise the results of the study is to remark that burden changes, and consequently radiative forcings, basically follow changes in primary and precursor emissions. Of course, to have a more complete assessment, one would need to include interactive chemistry (to account for possible changes in aerosol oxidants, e.g. Rae et al. [2007]) and consider the impact of climate change on atmospheric circulation.

We have modified the abstract: "ased on our results, aerosol burdens show an overall decreasing trend as they basically follow the changes in primary and precursor emissions. However, in some locations, such as India, the burdens could increase significantly..."

Abstract, lines 12-13: "The global values": Which global values? The DRE? And the "lowest" is ambiguous, as DRE is negative. "Weakest" is probably a better word.

Changed to: "The global changes in the DRE depends on the scenario and are smallest in...

Abstract, line 13: "The cloud radiative effect": Again, the wording needs to be more accurate, as "cloud radiative effect" has a specific meaning (contribution of clouds to the radiative budget) which is probably not what the authors mean. Here, I guess the authors mean "aerosol indirect radiative effect" (or forcing, see above), since it is a shortwave effect (31919, line 11).

Changed to: "aerosol indirect radiative effect"

Page 31901, line 4: "global dimming" is not an "enhanced aerosol cooling effect". It is the reduction of shortwave radiation reaching the surface caused by increases in aerosol loading. It may lead to a cooling.

Changed to: "i.e. the reduction of shortwave radiation reaching the surface"

Page 31902, lines 1-2: "the role of different regions in these effects" is unclear. Do the authors mean the contribution of emissions from different regions to global aerosol radiative effects?

Yes, we mean the emissions. We have changed this to: "...the direct and indirect aerosol effects, the role of different world regions' emissions in these effects, and contrasting emission changes reflecting alternative emission control strategies."

Page 31902: Is the model an atmosphere-ocean coupled model? If not, does it matter, and how are sea-surface temperature fields prescribed?

No, it is not coupled. In our approach (using current day climate conditions), this does not matter as the sea surface temperatures were taken from the Atmospheric Model Intercomparison Project (AMIP II). We have added this information to Section 2.3. When prescribed SSTs are used, the aerosol influence is somewhat included in the forcing data and does not change even if the aerosol concentrations would change. As mentioned, we wanted to examine the burdens and forcing in current day climate conditions so the prescribed SSTs are not a problem.

Page 31902, lines 20-21: HAM and M7 are not two different components of ECHAM. Rather, HAM is an implementation of the M7 framework.

Indeed a bit confusing, now: "... (Zhang et al., 2012). This model version has the HAM aerosol module (Stier et al., 2005), which includes the M7 aerosol microphysical module by Vignati et al. (2004). ECHAM-HAMMOZ..."

Page 31903, line 3: "stratiform cloud scheme". So there is no aerosol indirect effects on clouds other than stratiform?

Ice phase clouds are also influenced. Changed to: "...large scale cloud scheme (no influence on convective microphysics)..."

Page 31903, lines 6-16: The evaluation studies need to be summarised in more useful details than just saying that the model is "realistic". For example, Zhang et al. (2012) lists in its abstract important deficiencies: "(i) positive biases in AOD over the ocean, (ii) negative biases in AOD and aerosol mass concentration in high-latitude regions, and (iii) negative biases in particle number concentration, especially that of the Aitken mode, in the lower troposphere in heavily polluted regions." Those deficiencies (and those identified by the other studies) likely have an impact on the results discussed here, so it is important that they are stated clearly.

We have added the deficiencies reported by Zhang et. al 2012. The model version used here is exactly the same as in Zhang et. al 2012 so the deficiencies noted there are overall a good summary.

Page 31905, lines 8-9: What are those "other SO2 emissions not covered separately"?

There are mostly industrial sources that are not included in the industrial sector. This information has been added to the manuscript.

Page 31906, line 14: "same approach as was used by Dentener et al.": please specify which approach you are talking about.

We have added: "In this approach, based on location and type, the emissions are divided into six altitude regimes: 0-100 m, 100-500 m, 0.5-1 km, 1-2 km, 2-3 km and 3-6 km."

Page 31908, line 22: The traffic sector doubles in CLEC2030, but not in the other scenarios? Why not? Pollution growth is presumably similar in all scenarios.

The activity scenario underlying the growth of number of cars (fuel consumption), etc., is the same for all included emission scenarios. However, the penetration of control measures varies significantly. The CLEC/C includes current legislation and so after the current fleet is replaced with new vehicles complying with existing standards, emissions start to grow proportionally to activity growth. In BCAdd and MTFR scenarios, more stringent controls are introduced everywhere, e.g., diesel particulate filters, and so emissions of several of pollutants will decline compared to the baseline CLEC/C.

We have modified the sentence: "Over India, the increase comes mainly from the traffic sector, which approximately doubles in CLEC2030. Even though the CLEC scenario includes current legislation measures, i.e. after some time new vehicles complying with existing standards will be in use, emissions start eventually to grow proportionally to the activity growth."

Page 31908, line 23: I m not sure why this fact is "noteworthy". Would the different measures included in the four scenarios impact traffic emissions more than domestic emissions?

Although the increase over India comes from the traffic sector (which almost doubles in CLEC2030), the biggest source sector is still domestic one. This should be mentioned to show the potential for further emission modifications.

Page 31908, line 25: BC burden decreases everywhere in those two scenarios. Why mention Eastern China specifically? It should be mentioned in the next paragraph.

It explains the decreases mentioned for these regions already in the lines 20 and 21.

Page 31909, line 15: "due to atmospheric transport" - this implies that changes in transport to the South Hemisphere are dominated by changes made over India. Is that expected? How then to explain the increase in BC burden over Greenland in CLEC2030?

As was commented before, the emission maps in supplementary material were not very informative for the scenarios and have been now updated. From the new maps, it is obvious that the emissions overall increase in Southern Hemisphere and the atmospheric transport increases the area of influence (as can be seen from Fig. 2). However, you point out Greenland, which has slightly increased burden in CLEC2030. As CLECC2030 does not show any increase in BC burden over Greenland, changes in shipping emissions does not cause the difference. The reason here is the increased emissions around India, which are higher in CLEC2030. These emissions cause increased BC concentration at higher altitudes (lifting) which are eventually transported to the Arctic area. Based on our analysis (not shown), the lower tropospheric burden change in

CLEC/CLECC2030 compared to reference run is negative, but the transport to higher altitudes make the overall change of burden positive in CLEC2030. This pathway for BC transport to Arctic regions was also reported by Stohl. et al (2006).

Based on this comment, we have modified the paragraph: "...border area of Indonesia and Papua New Guinea. There changes are caused by the overall emission increases over land areas in the Southern Hemisphere, as can be seen in Fig. S1. Partly due to atmospheric transport from continental areas and partly due to increased shipping emissions, the BC burden also increases over Antarctica as well as over most oceanic regions in the Southern Hemisphere. Although the absolute BC values in these regions are low, the increased burdens could lead to changes in the surface albedo over snowy and sea ice covered areas. In the CLEC2030 scenario, the burden also increases over the Arctic region. This is due to transport coming from southeastern Asia (around India), where the increased emissions cause increased values of BC at higher altitudes (lifting) which are eventually transported to the Arctic regions. In our analysis (details not shown here, but for more information, please visit http://www.maceb.fi/result_viewer.html), we found that the lower tropospheric BC burden decreases in CLEC and CLECC over the Arctic, but the transported BC from southeastern Asia makes the overall burden change quite small, or even positive in the case of CLEC2030. A similar pathway for upper tropospheric Arctic BC from southeastern Asia has been discussed already in a previous study by Stohl (2006). In any case, since the albedo change due to BC deposition is not included in the current model version, further investigation concerning BC effects on snowy regions is left for future studies.

Page 31909, lines 26-27: This sentence is ambiguous, as it suggests that BCAdd includes MTFR measures. What the authors mean is that the additional MTFR measures have only a small impact on BC emissions.

Changed to: "The differences between the burdens in these two scenarios are quite modest also on regional scales (Table 2), which means that the targeted sectors (transport and especially residential combustion) in BCAdd include most of the reduction potential of BC and very little further reductions can be obtained with additional technological measures (as in MTFR)."

Page 31910, line 21: This is the first time we hear of significant natural emissions of organic aerosols in the model. Wildfire emissions would not dominate in the North Hemisphere, so where do they come from? Biogenic processes? Those emissions need to be mentioned (including their annual rates) in section 2.1.

The text in the original manuscript was unclear, so it was changed to: "...reference run than the BC burdens (Figures 2 and 3). The main reason for this is that the current legislation measures do not have a major impact on domestic and agricultural sectors, which are two biggest sectors emitting OC (domestic is 5 times bigger than agricultural sector). This, together with unperturbed natural emissions, diminishes the differences seen in Fig. 3. On the other hand, the domestic sector will change quite dramatically (down to one fifth of the reference) in the BCAdd and MTFR scenarios, which mainly explains the larger differences in the OA burden for these scenarios. Furthermore, the difference between BCAdd and MTFR can be explained by the agricultural sector, which, as was mentioned before, does not include any emissions in MTFR."

Page 31912, lines 7-9: Interesting statement here on the impact of solar radiation on the distribution of sulphate aerosol burden. I would have expected atmospheric transport to compensate for that effect.

This sentence was not correct and has been changed to: "The latitudinal dependence of the burden over the continents follows directly the emission pattern (Fig. S3)."

Page 31912, lines 25-26: Duly noted, but it would be more helpful to tell the reader why changes are so small over China, for example.

Actually, as BCAdd targets mostly BC and OC, it does not include much additional reductions when compared to CLEC2030 SA burden (CLEC is the baseline of SO_2 in BCAdd). Therefore, this sentence is not relevant and was removed.

Page 31915, lines 12-19: I think this paragraph is more confusing than helpful. Basically, positive changes in DRE (a positive forcing) would translate into a weaker cooling by aerosols. However, it is improper to say that the difference plots show "change in the cooling" – if that were really the case, they would be in units of temperature. The authors should refrain from using "cooling" as a synonym for "DRE" (31916, line 17; 31916, line 20, and so on...). They are different concepts: DRE is the trigger, which is quantified by the authors, cooling is the response, which is not quantified in the study.

Thank you for this comment. Based on it, we have changed this part to: "As the radiative effects presented in the following sections are mostly negative, i.e. they have a cooling effect, positive changes in radiative effects translate into a weaker cooling by aerosols, and vice versa."

Page 31917, line 28: Note that this is not happening over India only: the competition between the opposite

sign of BC and sulphate DREs happens everywhere, but it is particularly obvious over India in those simulations.

This is true. Based on this comment, we added a sentence to the end of the paragraph: "Naturally, the same counteracting effects from absorbing BC and scattering sulphate can occur in other locations, but is particularly obvious over India in our simulations."

Last paragraph of Conclusion, page 31924: This paragraph should mention the limitations of the studies, in particular that changes in atmospheric chemistry and atmospheric circulation are not included, and would affect the results. The lack of nitrate aerosols in the model is also an important limitation, as decreases in sulphate aerosol formation can favour nitrate formation and compensate for the change in sulphate aerosol radiative forcing.

We changed to first sentence to: "Our simulations predict a notable positive radiative forcing change in the current day climate conditions..." and added to the end of the paragraph: "Moreover, the use of coupled aerosol-chemistry models with more detailed aerosol description (e.g. including nitrates) would give more detailed estimates of the future forcing of aerosols."

References:

Henriksson, S. V., Pietikäinen, J.-P., Hyvärinen, A.-P., Räisänen, P., Kupiainen, K., Tonttila, J., Hooda, R., Lihavainen, H., O'Donnell, D., Backman, L., Klimont, Z., and Laaksonen, A.: Spatial distributions and seasonal cycles of aerosol climate effects in India seen in a global climateaerosol model, Atmos. Chem. Phys., 14, 10177-10192, doi:10.5194/acp-14-10177-2014, 2014.

Impacts of emission reductions on aerosol radiative effects

Author's Response

Pietikäinen et al. estimate changes in the aerosol radiative effect (direct+indirect) due to projected reductions in emission of SO2, black carbon, and organic carbon, following four future scenarios. The authors discuss regional to global changes in atmospheric burden and radiation. The scenarios include current legislated and maximum feasible emission reductions.

While the results of this work are of great interest to the community, more detail is needed in some sections (as discussed below). The manuscript is generally well-written, but an edit by a native English speaker is recommended. This paper is within the scope of ACP and I believe it will meet its standards once the following comments are addressed.

We thank the reviewer for valuable comments for improving the manuscript. We have improved the English language of the manuscript. Throughout the text reviewers comments are marked with boldface and after each comment follows our reply.

General comments

The magnitude of emission changes in the four future scenarios is not specified, globally or regionally. A table of regional emission changes for each scenario would be useful for future comparisons and better understanding of changes in burden/radiative effect. In addition, it is not clear what emissions are being modified. Are CO, VOCs, NOx, methane, etc. also being modified?

This was also pointed out by the referee 1 and hence the Table 1 has been modified to include all emissions species. Only the BC, OC and SO_2 emissions are included in this study.

The choice of 2005 as a reference year is an improvement over many studies that default to 2000. However, there have been significant emission-driven changes in aerosol distributions between 2005 and 2015. I recommend a couple sentences discussing the impacts of 2005 vs. 2015 as a reference year. Similarly, discussing changes between 2005 and 2020 as "future" changes is interesting since we're already 2/3 of the way to 2020.

There are some changes between 2005 and 2015, but in terms of BC and OC the changes are not very big. SO_2 is estimated to have changed slightly more, but not more than by 10-15% globally. Regionally, the SO_2 emissions seems to be decreasing in western countries and increasing in India and China. We have modified the end of first paragraph on Section 2.2.1: "...(FAO). We have used the 2005 as a reference year as emissions in this year have been well evaluated and the emissions do not change significantly between 2005 and 2015 for BC and OC (Granier et al., 2011). Over the same time period, SO2 emissions have been estimated to slightly decrease globally (10-15%), although regionally, e.g. in India and China, the emissions may have increased (Klimont et al., 2013). For comparison of GAINS emissions against for example Representative Concentration Pathways (RCP), see Granier et al. (2011)."

The 2020 scenarios are very near-future estimates, but give valid information about the pathway to 2030. For example, from Tables 2 and 3 it can be seen (and is discussed in the manuscript) that some trends from 2005 to 2020 continue from 2020 to 2030, whereas some decrease or even change their sign.

Also, it would be interesting to know how close (or far) the 2005 to 2030 reductions are from pre-industrial levels. For example, are we at 50

Lamarque et al. 2010 (ACP, 10, 7017-7039) estimated global anthropogenic emissions in 1850's to be about 1 Tg, 5 Tg and 3 Tg for BC, OC and SO2, respectively. These compare with our BCadd 2030 values 2.74 Tg, 4.97 Tg and 77.84 Tg for BC, OC and SO2, respectively.

Comparing simulated burdens to Schulz et al. (2006) is great, but AeroCom simulated year 2000 conditions, which should differ from 2005. This should be mentioned. More recent multi-model intercomparisons include AeroCom II (Myhre et al., 2013) and AC- CMIP (Shindell et al., 2013). These intercomparisons also commonly default to 2000 as a "reference", but represent the most up to date multi-model estimates.

We made it more clear that Schulz et al. (2006) used 2000 conditions. Myhre et al., 2013 unfortunately only include the anthropogenic burden (and forcing), but from Shindell et al., 2013 we have included BC and SO_4 burdens. Based on the comments from referee 1, we also included a comparison of residence time of BC and SO_4 from Shindell et al., 2013. Moreover, all the results from other sources include the standard deviation (if it was given).

The calculation of the aerosol radiative effect needs a more thorough explanation. Nudging the model to ERA-Interim is fine, but then an effective radiative effect may not be particularly meaningful. However, it is unclear if the authors are estimating true radiative effect (parallel calls to radiation schemes) or the effective radiative effect (difference in TOA radiation between paired simulations). I believe it is the latter.

The aerosol radiative effects come from parallel calls of radiation scheme (with and without aerosols/clouds). These are then compared between different simulations.

We have changed the last sentence of the Chapter 3.2: "Additionally, the values given in the following sections refer to the top of the atmosphere and are obtained directly from the radiation scheme (parallel calls with and without aerosols/clouds). "

Terminology needs to be clearer as well. The direct radiative effect is presented in Fig. 5. This is different from radiative forcing and should be defined in the methods section, ideally when the forcing (or radiative effect) calculation algorithm is spelled out.

Also partly based on referee 1 comments, we have made the terminology more clear.

Changes in burden and DRE are compared to previous studies throughout this paper and it is rightly pointed out that comparisons are complicated by differing models, emissions, future scenarios, etc. But I think an important comparison would be to the more commonly used RCP scenarios, i.e., Shindell et al. (2013), which make different assumptions.

We have added comparison of burdens and aerosol residence time against Shindell et al. (2013), but as they use all-sky values for radiative forcing, comparison would not be straightforward and has not been added.

The authors may also be interested in comparing to a similar study by Kloster et al. (2008) using the same model.

A very good point. We have now added the comparison with Kloster et al. (2008) result in terms of burdens, residence times and radiative effects.

- The manuscript could be greatly improved with a more thorough discussion of the implications of the various scenarios for climate and air quality. Such an analysis, or a comparison of the four scenarios to the RCP scenarios (previous point), would strengthen the current paper.

From the air quality point of view such an analysis would be interesting. However, in this paper we are focusing on forcing and related magnitudes. We only briefly discuss about air quality (mainly in terms of burden, which cannot be linked directly with surface concentrations, but gives indications how the atmospheric concentration overall change). For more information about the air quality implications, please see Anenberg et. al (2012).

We have also added two sentences telling where to find information about how the GAINS emissions historical comparison and how the scenarios compare against other pathways, such as RCP. We have added the following in the end of first paragraph on Section 2.2.1: "For comparison of GAINS emissions against for example Representative Concentration Pathways (RCP), see Granier et al. (2011)." and in the end of second paragraph: "More information about an overall emission scenario comparison can be found from Amann et al. (2013)."

Specific comments

The sign convention in the abstract and throughout the text is difficult to follow since aerosol RF is negative. Perhaps saying the magnitude decreases will provide clarity.

The text was thoroughly revised in this respect according to this comment and the comment by the oher reviewer.

- In the abstract I am left wondering what the 2005 vs. pre-industrial RF is, i.e., what percentage of the overall magnitude is a 0.06-0.4 W/m2 decrease?

We have not calculated this. However, estimate from Kloster et al. (2008) is -0.82 W/m^2 (TOA clear-sky, 2000).

- The penultimate sentence of the abstract is a bit puzzling. Does this include air quality considerations or just climate effects?

In a way both, although air quality comes mainly from burden point of view. We have also analysed surface concentrations, for example, but this analysis in not shown here. Besides these, no further air quality analysis has been done.

Page 31901, line 3-6: But some models have been unable to simulate the magnitude of dimming with only aerosols [Wild et al., 2009; Koch et al., ; Leibensperger et al., 2012].

True, but the phenomenon still exists.

Page 31901, line 9: "Loosing" should be "losing"

Corrected as suggested.

Page 31902, line 10: "How these" should be "How do these"

Corrected as suggested.

Page 31902, line 12: "To what extent these patterns can be influenced by..." should be "To what extent are these patterns influenced by..."

Corrected as suggested.

Page 31904: Is the difference, in terms of aerosols, between CLEC2020 and CLECC2020 the additional reductions in aerosols occurring because of decreases in co-emitted precursors? A sentence should be added here to clarify since only CO2 is currently referenced.

We have added: "scenario relies on the 2 °C (450 ppm) energy scenario developed by IEA (IEA, 2009). The main reductions in aerosol species between CLEC and CLECC occur in the residential, transport, energy and industry sectors and are the result of shifts away from the use fossil fuels as well as improvements in energy efficiency (IEA, 2009). In addition, two more..."

Page 31910, lines 6: Redundant word "models models" and "resorting to" should likely be replaced with "using"

Corrected as suggested.

Page 31916, line 14: Also see IPCC AR5 for more recent DRE estimates.

We are using here clear-sky diagnostics which is not the case with AR5 report. This is why the comparison has been omitted.

Page 31917, last paragraph: This is a very interesting paragraph, but I am having difficulty following the logic. I suggest a bit of editing.

We have edited the paragraph to make it more logical.

Figure captions: Acronyms (e.g., SA) should be spelled out

This was also mentioned by referee 1 and has been now corrected.

References:

Anenberg et al: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. Environ Health Perspectives, Vol. 120, issue 6, DOI:10.1289/ehp.1104301, 2012.

Klimont, Z., Smith, S. J., and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions, Environmental Research Letters, 8, 014 003, doi:10.1088/1748-9326/8/1/014003, http://stacks. iop.org/1748-9326/8/i=1/a=014003,

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Impacts of emission reductions on aerosol radiative effects

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Abstract. The global ~~aerosol–climate~~ aerosol-climate model ECHAM-HAMMOZ ~~is used to study~~ was used to investigate changes in the aerosol burden and ~~forcing changes~~ aerosol radiative effects in the coming decades. Four different emissions scenarios ~~are~~ were applied for 2030 (two of them applied also for 2020) and the results ~~are compared against~~ were compared against the reference year 2005. Two of the scenarios are based on current legislation reductions, one shows the maximum potential of reductions that can be achieved by technical measures, and the last one is targeted to short-lived climate forcers (SLCFs). We have analysed the results in terms of global means and additionally focused on 8 sub-regions. Based on our results, aerosol burdens ~~overall show decreasing trend, but~~ show an overall decreasing trend as they basically follow the changes in primary and precursor emissions. However, in some locations, such as India, the burdens could increase significantly. ~~This has~~ The declining emissions have an impact on the clear-sky direct aerosol effect (DRE), ~~which could reduce~~ i.e. the cooling effect. The DRE could decrease globally 0.06~~–0.4Wm^{-2}~~ -0.4 W/m^2 by 2030 ~~, but can increase~~ with some regional increases, for example, over India (up to 0.84 ~~Wm^{-2}~~W/m^2). The global ~~values depend~~ changes in the DRE depends on the scenario and are ~~lowest with~~ smallest in the targeted SLCF simulation. The ~~cloud~~ aerosol indirect radiative effect could decline 0.25~~–0.82by 2030 and occurs mostly over~~ -0.82 W/m^2 by 2030. This decrease takes place mostly over the oceans, whereas the DRE ~~effect is mostly over land~~changes are greatest over the continents. Our results show that targeted emission reduction measures can be a ~~-~~much better choice for the climate than overall high reductions globally. Our simulations also suggest that more than half of the near-future forcing change is due to the radiative effects associated with aerosol-cloud interactions.

1 Introduction

The net radiative forcing caused by atmospheric aerosol particles originating from human activities is currently negative, thereby offsetting a ~~-~~major, yet poorly-quantified fraction of the global warming caused by anthropogenic greenhouse gas emissions (Boucher et al., 2013; Smith and Mizrahi, 2013). The lifetime of atmospheric aerosol particles is relatively short, which has two major implications. Firstly, the climatically important aerosol properties vary greatly in both space and time in the atmosphere ~~(e.g. Kaufman et al., 2002)~~ (e.g. Kaufman et al. (2002)). Secondly, and perhaps even more importantly, atmospheric aerosol concentrations respond rapidly to any changes in emissions of either primary aerosol particles or aerosol precursor gases.

Overall increases in aerosol emissions during the past decades have contributed to the so-called global dimming, i.e. ~~enhanced aerosol cooling effect~~the reduction of shortwave radiation reaching the surface, followed by some brightening due to later emission reductions in many regions of the world ~~(e.g. Wild, 2009; Cermak et al., 2010; Haywood et al., 2011)~~ (e.g. Wild (2009); Cermak et al. (2010); Haywood et al. (2011)) In near future, there is a ~~-~~pressure for further aerosol and aerosol precursor emission reductions due to the adverse health effects by atmospheric aerosol particles ~~(e.g. Pope and Dockery, 2006; Rao et al., 2012)~~ (e.g. Pope and Dockery (2006); Rao et al. (2012)). This has raised concerns about ~~loosing a~~ losing a significant fraction of the current aerosol cooling effect (Brasseur and Roeckner, 2005; Arneth et al., 2009; Raes and Seinfeld, 2009), and generated discussions on how to optimally realize future emission reductions (Löndahl et al., 2010; Shindell et al., 2012; Shoemaker et al., 2013; Smith and Mizrahi, 2013; Partanen et al., 2013).

The discussed mitigation strategies focus on reduction of black carbon (BC). While BC itself has an apparent warming effect in the present-day climate ~~(e.g. Jacobson, 2010; Jones et al., 2011; Bond et al., 2013; Boucher et al., 201~~ Jacobson (2010); Jones et al. (2011); Bond et al. (2013); Boucher et al. (2013)), the usually co-emitted sulphur and organic compounds are effective cooling agents, substantially complicating the design of optimal emission reductions ~~(Kopp and Mauzerall, 2010; Ramana et al., 2010)~~ (Kopp and Mauzerall, 2010; Ramana et al., 2010; Wa Furthermore, besides having a ~~-~~direct radiative effect on solar radiation, particles containing BC can act as cloud condensation and ice nuclei ~~(Prenni et al., 2009; Leaitch et al., 2010)~~ (Prenni et al. (2009); Leaitch et al. (2010)). The influence of BC emission changes on clouds and climate is potentially important yet poorly quantified ~~(Chen et al., 2010a; Bahadur et al., 2012; Bond et al., 2013)~~ (Chen et al., 2010a; Bahadur et al., 2012; Bond et al., 2013)

The relation between future aerosol emission changes, radiative forcing and climate has been investigated both globally ~~(Menon et al., 2008; Unger et al., 2009; Chen et al., 2010b; Bellouin et al., 2011; Makkonen et al., 2012; G~~ over some continental regions (Mickley et al., 2012; Péré et al., 2012; Sillmann et al., 2013). While demonstrating potentially large regional effects, ~~none~~ very few of these studies have simultaneously considered the following issues together: the direct and indirect aerosol effects, the role of different world regions' emissions in these effects, and contrasting emission changes reflecting alternative emission control strategies. In this paper, we aim to bring new insight into these issues by investigating near-future changes in the aerosol direct and indirect radiative forcing globally as

well as over a ~~-~~number of selected world regions as a ~~-~~result of emission changes according to four recently-developed emission scenarios. The specific questions ~~,~~ we are searching answers for are the following:

- how much is the ~~global negative aerosol forcing expected to be reduced~~ aerosol radiative effect, or the radiative forcing by aerosols, expected to change during the next couple of decades ~~from~~ compared with the present day value?
- how do these changes differ over different world regions?
- what are the relative roles of direct and indirect effects?
- to what extent ~~these patterns can be~~ are these patterns influenced by targeted emission reductions?

The paper is structured as follows: first, the model and the emission modifications are described in ~~Sect. 2; Sect.~~ Section 2; Section 3 presents a ~~-~~detailed analysis of the results and explains the emission reductions influences to the climate, followed by ~~Sect.~~ Section 4, where the main conclusions are listed and further steps are discussed.

2 Methods

2.1 Model description

The main tool in this work is the global aerosol–climate model ECHAM-HAMMOZ (version ECHAM5.5-HAM2.0) (Zhang et al., 2012)~~, which uses~~ . This model version has the HAM aerosol module (Stier et al., 2005)~~and~~ , which includes the M7 aerosol microphysical module ~~(Vignati et al., 2004)~~ by Vignati et al. (2004) . ECHAM-HAMMOZ simulates all the major aerosol sources (both natural and anthropogenic), microphysical processes and sinks. It predicts the evolution of seven interacting internally- and externally-mixed aerosol modes in terms of their size distribution and composition. The simulated aerosol components are sulphate, BC, organic carbon (OC), sea salt and mineral dust. The aerosol module is coupled with the host model's ~~stratiform cloud scheme~~ large scale cloud scheme (no influence on convective microphysics) and radiation module; thus, both the direct and indirect aerosol effects are simulated online (Lohmann and Hoose, 2009). The cloud droplet activation is calculated using a ~~parametrization by Abdul-Razzak and Ghan (2000)~~ parametrization by Abdul-Razzak and Ghan (2000) .

The aerosol characteristics simulated by ECHAM-HAMMOZ have been evaluated in several previous studies. For example, ECHAM-HAMMOZ was included in the AeroCom model intercomparison exercise analyzing the life cycles of dust, sea salt, ~~sulfate~~sulphate, black carbon and particulate organic matter in 16 global aerosol models (e.g Huneeus et al., 2011; Mann et al., 2014; Tsigaridis et al., 2014). Furthermore, ~~Zhang et al. (2012)~~ Zhang et al. (2012) evaluated the ECHAM5-HAM2

version, which is used in this study, against the AeroCom models and a ~~-~~large range of atmospheric measurements. These studies have shown that ECHAM-HAMMOZ can reproduce the main aerosol characteristics realistically. ~~Thus~~ There are, however, still some deficiencies in the model, as was pointed out by the study from Zhang et al. (2012) : "(i) positive biases in AOD over the ocean, (ii) negative biases in AOD and aerosol mass concentration in high-latitude regions, and (iii) negative biases in particle number concentration, especially that of the Aitken mode, in the lower troposphere in heavily polluted regions." However, in this study, we do not concentrate on model evaluation as such (this has been already partly done in Henriksson et al. (2014)), although we do compare our simulated aerosol burdens, lifetime and radiative effects to several previous model studies.

2.2 Emissions

~~For~~ In this work, ~~some of the emission modules of ECHAM-HAMMOZ were updated and some new ones implemented~~new emission modules were implemented to ECHAM-HAMMOZ and some of the old ones were updated. In the following sections, the ~~modified and new~~ new and modified modules are described in more detail. The global emissions maps for BC, OC and sulphur dioxide (SO_2) based on the new emissions are shown in the ~~Supplement~~ supplementary material (Figs. ~~S1–S3~~S1, S2 and S3). Note that volcanic, dimethyl sulphide (DMS), dust and sea salt emissions are left unmodified and follow the methods presented in ~~Stier et al. (2005) and Zhang et al. (2012)~~ Stier et al. (2005) and Zhang et al. (2012) .

We analyzed the emissions and simulation results both globally and over 8 different geographical regions. These regions, i.e. western United States (W-USA), eastern United States (E-USA), South America (S-America), Europe, Africa, India, western China (W-China) and eastern China (E-China), are shown in Figure 1. The emission fluxes for different sources, scenarios and years are represented in Table 1.

2.2.1 Continental anthropogenic emissions

~~For~~ For continental anthropogenic emissions, we applied gridded datasets based on the GAINS (Greenhouse ~~gas–Air~~ gas - Air pollution Interactions and Synergies) model (Amann et al., 2011), operated by the International Institute for Applied Systems Analysis (IIASA, http://gains.iiasa.ac.at). Globally, ~~this~~ the GAINS model considers 162 geographical regions and includes all the major economic sectors. The principal statistical data used in the model for the base year (2005) in our simulations (simulation Refe2005) originates from the International Energy Agency (IEA) and ~~EUROSTAT~~The Statistical Office of the European Communities (EUROSTAT), whereas for agriculture the data ~~is from FAO (UN~~ are from United Nations Food and Agriculture Organization ~~).~~ (FAO). We have used the 2005 as a reference year as emissions in this year have been well evaluated and the emissions do not change significantly between 2005 and 2015 for BC and OC (Granier et al., 2011) . Over the same time period, SO_2 emissions have been estimated to slightly decrease globally (10-15%),

although regionally, e.g. in India and China, the emissions may have increased (Klimont et al., 2013) . For comparison of GAINS emissions against for example Representative Concentration Pathways (RCP), see Granier et al. (2011) .

In addition to the reference simulation, we considered four scenarios drawing on the energy projections presented in the World Energy Outlook 2009 (IEA, 2009) and including different assumptions of legislative and technological developments in the next few decades. The CLEC scenario includes all currently agreed air pollution policies and legislation and estimates impacts on emissions in 2020 and 2030 (simulations CLEC2020 and CLEC2030, respectively). The CLECC scenario includes these same policies, but is further designed to keep the total forcing due to long-lived greenhouse gases at 450 ppm CO_2-equivalent level by the end of the century via CO_2 mitigation measures mostly targeting the energy and industrial sectors (simulations CLECC2020 and CLECC2030) – this scenario relies on the 2 °C (450 ppm) energy scenario developed by IEA (IEA, 2009). The main reductions in aerosol species between CLEC and CLECC occur in the residential, transport, energy and industry sectors and are the result of shifts away from the use fossil fuels as well as improvements in energy efficiency (IEA, 2009) . In addition, two more scenarios for 2030 were used. The BCAdd scenario targets the short-lived climate forcers (SLCFs) by including a portfolio of most important measures that could yield the largest reductions in their global radiative forcing in 2030 (simulation BCadd2030). The ~~principles~~ details of such scenario has been described in ~~UNEP (2011) and Shindell et al. (2012) . In terms of aerosols, this means targeting~~ UNEP (2011) and Shindell et al. (2012) . In short, the principles behind the development of the BCAdd scenario are a selection of measures which result in net reduction of radiative forcing calculated using pollutant-specific Global Warming Potential (GWP) values (UNEP , 2011) . The measures reduce the emissions of BC, but also OC, carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NOx), and the reduced amounts vary across the measures. Key air pollutant measures include advanced emission standards on diesel engines (including diesel particulate filters), clean cookstoves, pellet stoves and boilers, more efficient brick kilns, and ban of agricultural burning. Thus, in terms of species used here, the reductions target BC and OC emissions. Measures with a relatively small net impact or increase in radiative forcing have been excluded from this portfolio. Lastly, the ~~MTFR~~ maximum technically feasible reduction (MTFR) scenario implements the maximum reduction potential of anthropogenic aerosol and SO_2 emissions with currently available technologies by the year 2030 (simulation MTFR2030). The MTFR scenario ~~includes primarily end-of-pipe measures and excludes any further efficiency or fuel switching potential~~ introduces the best available technology to a maximum extend while ignoring any potential economic and political barriers. In this scenario, no consideration is given to the direction of the change in aerosol radiative forcing, so also measures that reduce strongly the emissions of SO_2, e.g., fuel gas desulphurization, are included. The emission model used includes the end of pipe measures that remove pollutants from the exhaust. This means that it assumes that the use of

most advanced particulate filters will reduce emissions of primary particular matter (PM), selective catalytic reduction (SCR) installations will bring NOx emissions down from industrial boilers, etc. For more detailed description of the current legislation and the MTFR scenarios~~see for example Cofala et al. (2007) and Klimont et al. (2009)~~ , see e.g. Cofala et al. (2007) and Klimont et al. (2009) . More information about an overall emission scenario comparison can be found from Amann et al. (2013) .

In this study, the ~~GAINS detailed~~ detailed GAINS sectoral emissions were aggregated into six key categories: ~~(~~1) agriculture (waste burning on fields), ~~(~~2) residential and commercial combustion, ~~(~~3) power plants, energy conversion, extraction, ~~(~~4) industry (combustion and processing), ~~(~~5) surface transportation and ~~(~~6) waste. In addition, an extra sector for other SO_2 emissions not covered separately in GAINS was included (mainly industrial sources not included in the 4th category). Each of the sectors ~~are allocated into $0.5° \times 0.5°$~~ were allocated into a $0.5° \times 0.5°$ grid. The emissions from agriculture, residential and commercial combustion, surface transportation and waste sectors ~~are~~ were emitted at the surface level. The energy sector emissions ~~are released into~~ were released into the following model levels: 51.25~~to 2nd~~ % to 2^{nd} lowest level, 45.3~~to 3rd~~ % to 3^{rd} lowest level and 3.45~~to 4th~~ % to 4^{th} lowest level. The industrial sector and the extra sector for ~~emissions have~~ SO_2 emissions had the same vertical emission height distribution: 95% to surface and 5~~to 2nd~~ % to 2^{nd} lowest level. The emission heights ~~are based on Bieser et al. (2011)~~ were based on Bieser et al. (2011) .

By default, GAINS provides only the total annual emissions for all sectors. Considering the importance of temporal resolution for few key sectors, we ~~have~~ developed monthly estimates for power plants and residential combustion~~, and used GFED (see Sect. 2.2.3) temporal pattern for agricultural residue burning~~. Specifically for ~~residential combustion we have~~ the latter, we applied the method developed by ~~Streets et al. (2003)~~ Streets et al. (2003) , who calculated the operating hours for stoves based on monthly mean temperature, i.e., ~~$< 0C$~~ $< 0°C \Rightarrow 16$ ~~, 0–5C~~ hr/d, $0 - 5°C \Rightarrow 12$ ~~, 5–10C~~ hr/d, $5 - 10°C \Rightarrow 6$ ~~and $> 10C$~~ hr/d and $> 10°C \Rightarrow 3$ hr/d. In our approach, the monthly mean temperatures were obtained from the Climatic Research Unit (CRU) TS 3.1 dataset (Harris et al., 2014) and the calculations were done in each gridbox separately. Since our aim ~~is~~ was to study the scenarios in current day climate conditions, the temperatures from 2005 were used ~~for all GAINS emissions~~also for the scenarios.

2.2.2 Aviation emissions

We ~~also~~ implemented into ECHAM-HAMMOZ the monthly aviation emission ~~data~~ produced in QUANTIFY (Quantifying the Climate Impact of Global and European Transport Systems) project (Lee et al., 2005; Owen et al., 2010). Concerning the aerosol species and precursors of interest in our work, only BC mass and number concentration are available (no data for OC or SO_2). The data ~~is~~ are provided on a ~~1resolution and at~~ ° resolution grid and on 23 levels using 610 m vertical steps. Since the QUANTIFY database provides emissions only for year 2000, we scaled the emission by

1.3355 in 2005, by 2.4 in 2020 and by 3.1 in 2030. These scaling factors were estimated based on Fig. Figure 6 in Lee et al. (2010) Lee et al. (2010) .

2.2.3 Wildfire emissions

The Global Fire Emissions Database (GFED) dataset for the wildfire emissions was updated to the version 3 (Giglio et al., 2010; van der Werf et al., 2010). The data has a 0.5° spatial resolution and is on a monthly time resolution. To make the emissions height dependent, the same approach as was used by Dentener et al. (2006) used by Dentener et al. (2006) with AeroCom emissions was applied. In this approach, based on location and type, the emissions are divided into six altitude regimes: 0-100 m, 100-500 m, 0.5-1 km, 1-2 km, 2-3 km and 3-6 km. GFED 3 dataset includes six different sectors: (1) deforestation and degradation fire emissions, (2) savanna fire emissions, (3) woodland fire emissions, (4) forest fire emissions, (5) agricultural waste burning, and (6) tropical peatland burning (confined to Indonesia and Malaysian Borneo) (van der Werf et al., 2010). The 5th 5th sector can be also found in the GAINS model output (see Sect. Sec. 2.2.1) and in this work the GAINS agriculture sector was used. Moreover, for all simulated years, the 2005 GFED emissions were used. The yearly emissions are represented in Table 1.

2.2.4 Shipping emissions

The international ship emissions are used here were based on the improved ICOADS (International Comprehensive Ocean–Atmosphere Ocean-Atmosphere Data Set) data by Wang et al. (2008) . In this work, the Wang et al. (2008) . The ICOADS dataset presents only a proxy grid on a 0.1° horizontal resolution, i.e. the dataset gives the fraction of total global ship emissions that is emitted at each grid cell. The final gridded emissions were obtained by using the global proxy with the values from RCP 8.5 (Riahi et al., 2007) emission estimates for the years (for 2005, 2020 and 2030 were usedseparately). The sensitivity of the results to the chosen RCP was tested by repeating the reference simulation (Refe2005) using RCP 2.6 emissions. However, the difference between the two RCPs was found to be so small that no further analysis will be shown from RCP 2.6 simulations.

The annual global emissions from shipping according to RCP 8.5 are represented in Table **??**. Since the ICOADS dataset presents only a proxy grid on a 0.1horizontal resolution, i.e. the dataset gives the fraction of total global ship emissions that is emitted at each grid cell, final gridded emissions were obtained by using the global proxy with the values from Table **??**. Since the proxy does not include estimates on how the shipping routes will change in the future, the same emission pattern is used for all was used in all the simulations.

In the Arctic, we have used an additional high resolution emission inventory by Corbett et al. (2010) Corbett et al. (2010) . In this inventory, the data is are given on a seasonal scale in a 5 km × 5 km 5 km × 5 km horizontal grid for year 2004, including 2020 and 2030 as scenario years. We used the emission values for 2004 in our reference simulation for year 2005 without any modifications; it . It can be assumed that the er-

ror from this approach lies within the uncertainty limits of the emissions. For the scenario years 2020 and 2030, the Business As Usual (BAU) approach was chosen. The scenarios also include changes in the shipping route patterns ~~(details in Corbett et al., 2010)~~ (details in Corbett et al. (2010)). If there were overlapping grid boxes between ICOADS and Arctic emission datasets, the latter was chosen. The yearly shipping emissions are represented in Table 1.

2.3 Simulations

Each simulation was run for 5 years (~~2003–2007~~2003-2007) preceded by a ~~6month~~ 6-month spin-up. In order to minimize the variation in the model meteorology, all the simulations were nudged~~(~~, i.e. divergence, vorticity, surface pressure and temperature were ~~forced to follow)~~ nudged towards the ERA-Interim reanalysis data (Dee et al., 2011). The ~~5year~~ sea surface temperatures (SST) were taken from the Atmospheric Model Intercomparison Project (AMIP II) (Taylor et al., 2000) . The 5-year monthly data was furthermore averaged to one year monthly data (multi-year monthly mean), which minimizes the influence of the internal variability of the model. All simulations were conducted at a ~~-~~T63 horizontal resolution (~~~ 200~~~200 km) with 31 vertical terrain following levels (top reaching 10 hPa).

We ~~have also done~~ also made shorter simulations where the aerosol characteristics were compared to simulations with original emissions (not shown here). Based on these simulations, the new version reproduces closely the aerosol fields of the original model version.

3 Results and discussion

Below, we concentrate mainly on the 2030 simulation results, and discuss ~~year~~ briefly 2020 ~~only~~ when it reveals additional information about the time scale of the emission reductions. All the absolute and relative changes presented are calculated as the difference between the scenario and reference simulation (Refe2005) values. In addition to global results, we analyse the simulations separately for the 8 regions shown in ~~Fig. 1, i.e. Western United States, Eastern United States, South America, Europe, Africa, India, Western China and Eastern China~~Figure 1. The column burdens and aerosol radiative effects for these regions are summarized in Tables ~~-~~2 and 3.

3.1 Aerosol burdens

3.1.1 BC burden

The annual mean BC column burden ~~results are~~ is shown in Fig. ~~-~~2. In all the simulations, the BC burden peaks in the Amazon region and central Africa (biomass burning areas), India (residential biomass burning area) and ~~Eastern~~ eastern China (industrial area). In these peak areas, changes in the BC burden are relatively modest in most of the scenarios apart from CLEC2030 ~~,~~ which shows a ~~-~~32% increase over India, ~~and~~ as well as BCAdd2030 and MTFR2030 ~~,~~ which both show nearly

60decreases over Eastern % decreases over eastern China (Table -2). Over India, the increase comes mainly from the traffic sector, which approximately doubles in CLEC2030and reflects estimated growing population. Even though the CLEC scenario includes current legislation measures, i.e. after some time new vehicles complying with existing standards will be in use, emissions start eventually to grow proportionally to the activity growth. However, it is noteworthy that the domestic sector will still have the biggest emissions over India. The decrease over Eastern eastern China in the two mitigation scenarios (BCAdd and MTFR) is primarily due to declining use of solid fuels (mostly coal) for cooking and heating in the residential combustion sector. The high BC burden areas in the biomass burning regions of South America and Africa show negligible change in all the scenario runs since because the GAINS scenarios do not predict reductions for this sector (and the wildfire emissions from GFED are the same for all simulated years).

Concerning In regions with lower absolute BC burden values, all the scenarios predict significant decreases by 2030 over Europe (−24 to −66-24% to -66%, mainly from residential combustion and traffic sectors) and North America (−3 to −-3% to - 54%, mainly traffic sector), although in CLECC2030 the burden slightly increases over Mexico and southern parts of USA U.S. (increment over Western US western U.S. 8%, caused by residential combustion sector). Furthermore, in the CLEC and CLECC scenarios, the BC burden increases over Africa (9 and 5%, respectively; from residential combustion sector) and Western western China (28 and 15%, respectively; from residential combustion, traffic and industrial sectors). In these scenarios, small increases are seen also in Southern southern Argentina, the west coast and southern parts of Africa, and the border area of Indonesia and Papua New Guinea. Due There changes are caused by the overall emission increases over land areas in the Southern Hemisphere, as can be seen in Fig. S1. Partly due to atmospheric transport from continental areas and partly due to increased shipping emissions, the BC burden also increases over Antarctica as well as over most oceanic regions in the Southern Hemisphere. Although the absolute BC values in these regions are low, the increased burdens could lead to changes to in the surface albedo over snowy and sea ice covered areas. HoweverIn the CLEC2030 scenario, the burden also increases over the Arctic region. This is due to transport coming from southeastern Asia (around India), where the increased emissions cause increased values of BC at higher altitudes (lifting) which are eventually transported to the Arctic regions. In our analysis (details not shown here, but for more information, please visit http://www.maceb.fi/result_viewer.html), we found that the lower tropospheric BC burden decreases in CLEC and CLECC over the Arctic, but the transported BC from southeastern Asia makes the overall burden change quite small, or even positive in the case of CLEC2030. A similar pathway for upper tropospheric Arctic BC from southeastern Asia has been discussed already in a previous study by Stohl (2006) . In any case, since the albedo change due to BC deposition is not included in the current model version, further investigation concerning this effect BC effects on snowy regions is left for future studies.

The two ~~more extreme scenarios , i.e.~~ other scenarios (BCAdd and MTFR~~, show~~) show a decreased BC burden over the whole globe (~~-26 and -27~~ -26 and -27%, respectively). The differences between the burdens in these two scenarios are quite modest also on regional ~~scale (Table~~ scales (Table 2), which means that the targeted sectors (transport and especially residential combustion) in BCAdd include most of the reduction potential of BC ~~, even when all technologically available measures are used~~ and very little further reductions can be obtained with additional technological measures (as in MTFR). ~~The additional reductions in MTFR~~ These additional measures come from waste disposal and treatment ~~, and~~ as well as from agricultural waste burning. In the latter sector, the MTFR scenario assumes that all activity ~~in these sectors~~ can be stopped and thus ~~their~~ the emissions are set to zero.

Our reference simulation can be compared ~~to~~ with previous model estimates ~~of~~ on the atmospheric aerosol burden. ~~Schulz et al. (2006)~~ Schulz et al. (2006) reported results from a ~~-~~multi-model comparison for global BC, ~~OA and burdens . For~~ organic aerosol (OA) and SO_4 burdens for the year 2000. In the sub-set of models using AeroCom emissions~~(2000)~~, the global ensemble mean for BC was 0.25 ~~. For models models resorting to~~ mg/m^2 (standard deviation σ = 0.08 mg/m^2), whereas in the sub-set of model using other emission inventories, the global ensemble mean was 0.37 ~~for BC~~mg/m^2 (σ = 0.08 mg/m^2). In addition, ~~Bond et al. (2013)~~ Bond et al. (2013) collected results from recent publications ~~(some same as in Schulz et al., 2006, details in the papers)~~ (some the same as in Schulz et al. (2006) , details in the paper) and calculated a ~~-~~mean burden of 0.26 mg/m^2. These results are in good agreement with our result ~~(~~of 0.25 ~~, Table 2)and show that the new~~ mg/m^2 (Table 2). Shindell et al. (2013) evaluated the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) models and calculated the multi-model mean of BC burden in 2000 to be 0.16 Tg (σ = 0.07 Tg). Our equivalent value is 0.13 Tg for the year 2005. In a similar study (using older versions of both the ECHAM model and the IIASA emissions) Kloster et al. (2008) calculated the BC burden in 2000 to be 0.12 Tg. These results show that our updated emissions can reproduce ~~the global BC burden realistically~~similar global BC burdens. Kloster et al. (2008) also included two IIASA emission scenarios for 2030: a current legislation (CLE) scenario and a maximum feasible reduction (MFR) scenario. They reported burdens of 0.11 Tg and 0.10 Tg, respectively, for the two scenarios. Our values are 0.13 Tg for CLEC2030 and CLECC2030, and 0.09 Tg for BCAdd and MTFR. The results do not differ much, so the different estimates are consistent with each other.

The residence time of aerosols is also one factor worth mentioning. In the reference simulation, we get a residence time of 6.0 days for BC. This compares well with earlier results, as shown by Textor et al. (2006) , who did a multi-model comparison of the AeroCom models (simulating the year 2000). Authors reported that the BC residence time for ECHAM was 5.3 days while the mean for all the AeroCom models was 7.1 days (σ = 33%). In addition, Shindell et al. (2013) reported the multi-model mean residence time of BC for 2000 to be 7.4 days (σ = 3.4 days), while Kloster et al. (2008) got 5.6 days in their year 2000 reference run, 5.8 days in 2030 CLE and 6.1 days in 2030 MFR.

Our results indicate BC residence times of 6.3 days in CLEC2020 and CLECC2020, 6.4 days in CLEC2030 and CLECC2030, 6.6 days in BCAdd, and 6.8 days in MTFR. The higher residence times in the scenarios reflect mainly the decreased washout due to less clouds, mainly caused by sulphate reductions (Lohmann and Feichter, 1997) .

3.1.2 Organic aerosol burden

The absolute values of ~~organic aerosol (OA)~~ OA burden in the reference simulation (Fig. ~~-~~3) are higher than those for the BC burden (almost by a ~~-~~factor of 10), but overall the burden maps are very similar. This reflects the fact that these two compounds are often co-emitted from the same sources~~but~~ , although organic emissions dominate in magnitude, especially in the residential combustion sector. The OA burdens differ less between the different scenarios and show overall much smaller relative changes from the reference run than the BC burdens (~~compare Figs.~~ Figures 2 and 3). The main reason for this is ~~the significant contribution of natural sources to the overall OA emissions, which diminish the influence of anthropogenic emission changes~~that the current legislation measures do not have a major impact on domestic and agricultural sectors, which are two biggest sectors emitting OC (domestic is 5 times bigger than agricultural sector). This, together with unperturbed natural emissions, diminishes the differences seen in Fig. 3. On the other hand, the domestic sector will change quite dramatically (down to one fifth of the reference) in the BCAdd and MTFR scenarios, which mainly explains the larger differences in the OA burden for these scenarios. Furthermore, the difference between BCAdd and MTFR can be explained by the agricultural sector, which, as was mentioned before, does not include any emissions in MTFR.

The CLEC2030 and CLECC2030 scenarios predict the largest changes in the OA burden over ~~Eastern China (−25 and −31~~eastern China (-25 and -31%, respectively), mainly from the residential combustion sector due to reduction of solid fuel use and effective decline of stove emissions. On the other hand, changes over India, Europe and North America are very small, in contrast to the BC burden changes. The differing ~~behavior~~ behaviour of BC and OA burdens ~~over India~~ can be explained by the traffic sector, ~~which increases the BC emissions more strongly in the future. The opposite can be seen in Europe and North America, where the reductions in BC emissions in the traffic sector are quite high whereas the OC reductions are much more moderate~~in which BC emissions are impacted much more strongly than OC emissions. This is because the ~~reduction for~~ reductions in the traffic sector are ~~focused on~~ targeted to diesel emissions, which ~~for aerosol emissions are mainly BC~~ is a high BC emitter.

In the BCAdd simulation, the OA burden decreases globally and the highest reductions are over Europe (~~−25~~-25%, mainly from residential combustion and traffic sectors), India (~~−50~~-50%, mainly residential combustion sector), ~~Western China (−47~~western China (-47%, residential combustion sector) and ~~Eastern China (−53~~eastern China (-53%, residential combustion and energy sectors). The geographical pattern of the change is similar in MTFR, although the decrement is higher; the highest

reductions occur over China, Japan, India, Middle-East and Europe reaching a ~~21~~ 21% decrement globally (all sectors decrease, residential combustion sector having the biggest reductions). In these two scenarios, the pattern of the OA burden change is again quite different from ~~pattern of~~ the pattern of the BC burden change (~~compare Figs.~~ Figures 2 and 3). The OA burden change is much ~~more significant~~ larger over India due to a ~~very~~ large contribution from both stoves and agricultural burning, and these two sources have a high share of OC. On the other hand, larger BC changes are seen over Europe and North America as there are less stoves with high OC emissions, and instead most mitigation will be in diesel controls with a high BC share and some in the residential combustion sector. It is also noticeable that changes over the Southern Hemisphere are small in all the scenarios.

The values for ~~global OA from Schulz et al. (2006) are also~~ the global OA burden from Schulz et al. (2006) are in good agreement with our results. Again, if only the models which used AeroCom based emissions are taken into account, the global mean is 1.32 mg/m^2 (σ = 0.32 mg/m^2). For the other models, ~~Schulz et al. (2006) reported a~~ Schulz et al. (2006) reported a mean of 2.40 mg/m^2 (σ = 0.39 mg/m^2). Our results show a ~~global~~ OA burden of 2.01 mg/m^2, which falls into the range of the values reported in ~~Schulz et al. (2006) . The~~ Schulz et al. (2006) . Kloster et al. (2008) reported the OA burden to be 1.08 Tg in 2000, 1.00 Tg in 2030 CLE and 0.47 Tg in 2030 MFR. Our values are 1.03 Tg for 2005 and for 2030 they are 1.04 Tg in CLEC, 1.02 Tg in CLECC, 0.86 Tg in BCAdd and 0.81 in MTFR. Overall, the relatively large uncertainties in simulating the global and regional ~~organic~~ OA burdens arise from poorly quantified primary emissions and secondary organic aerosol formation, together with uncertainties in the sufficient complexity of the OA parameterizations (Tsigaridis et al., 2014).

The residence time of OA in our reference simulation was 5.8 days. Textor et al. (2006) reported for ECHAM a residence time of 5.4 days and overall AeroCom multi-model mean of 6.5 days (σ = 27%), whereas Kloster et al. (2008) got 5.7 days. This means that, similar to BC, the residence times of OA in our simulations are in good accord with previous studies. Our future estimates show an OA residence time of 5.8 days in CLEC2020 and CLECC2020, 5.8 days in CLEC2030, 5.9 days in CLECC2030, 5.9 days in BCAdd and 6.0 days in MTFR. These are similar to Kloster et al. (2008) estimates: 5.8 days in CLE and 5.9 days in MFR.

3.1.3 Sulphate burden

The absolute sulphate aerosol (SA) burden map in Fig. ~~4~~ differs from the BC and OA maps, because the anthropogenic emission sources are more similar between BC and OC ~~than compared with~~ compared with SO_2. For BC and OC, the biggest source is the residential combustion sector, whereas SO_2 is mainly emitted from the industrial and energy sectors.

~~Figure~~ Fig. 4 shows that the highest absolute values of the SA burden are over ~~Eastern~~ eastern China, India, Middle-East, North Africa, ~~Southern Europe and Eastern USA~~southern Europe and

eastern U.S. The latitudinal dependence of the burden over the continents ~~is explained by the amount of solar radiation, which is needed for oxidation of to sulphate~~follows directly the emission pattern (Fig. S3).

In Europe, it is well known that sulphate precursor (SO_2) emissions have decreased over the last ~~2–3~~ 2-3 decades (Hamed et al., 2010, and references therein). The same decreasing trend is also visible in the current legislation based simulations, which have reductions from 26% (CLEC2030) to 35% (CLECC2030) over Europe. In North America, the reductions in the SA burden are even higher, especially over ~~Eastern and Central parts of USA~~eastern and central parts of U.S. CLEC2030 gives ~~−33decrement over Western US and −40over Eastern US~~-33% decrement over western U.S. and -40% over eastern U.S., whereas in CLECC2030 the values are ~~−41 and −48~~-41% and -48%, respectively. These significant decreases in both Europe and North America are mainly from the energy sector, although ~~,~~the industrial sector has also reductions that influence the results.

Quite the opposite can be seen over India, where the ~~burden values~~ SA burden will increase in all the scenarios, except in MFTR. The increment is smallest in the CLECC2030 scenario ~~being~~ (12%) and the highest in the CLEC2030 scenario (62%), although almost as high increase (58%) is simulated in the BCAdd scenario. On the other hand, in ~~MTFR scenario~~ the MTFR scenario, the SA burden decreases by 60%. These features come from the industrial and energy sectors and mean that the SA burden over India could be controlled with technical measures, such as flue gas desulphurization. ~~It is noteworthy that in BCAdd the change is not significant in areas outside India, South Africa, Europe and US.~~

The global ~~sulphate aerosol~~ SA burden was also reported by ~~Schulz et al. (2006) . For AeroCom emissions based model~~Schulz et al. (2006) . For model using AeroCom emissions, the global mean burden ~~is~~ was 2.12 ~~and for~~ mg/m^2 (σ = 0.82 mg/m^2) and for the other models 2.70 ~~. Our results are slightly lower~~g/m^2 (σ = 1.09 mg/m^2). The SA burden from our simulation is slightly lower, being 1.85 mg/m^2. Shindell et al. (2013) got the multi-model mean of 2.0 Tg (σ = 0.5 Tg) for the SA burden. Our equivalent value is 0.95 Tg, which is more than two times smaller. However, our result is ~~well in range of the modelled results shown by Schulz et al. (2006) and~~ close to the Kloster et al. (2008) estimate of 0.86 Tg. For the near future, Kloster et al. (2008) estimated that sulphate burden will be 0.94 Tg in CLE and 0.53 Tg in MFR. Our simulations show 0.90 Tg in CLEC2030, 0.78 Tg in CLECC2030, 0.88 Tg in BCAdd and 0.60 Tg in MTFR. Despite of all these differences, we feel confident to say that our result shows a realistic global SA burden as there are differences in sources and sinks (e.g. different emission years, deposition modules etc).

For sulphate, the residence time in the reference simulation was 3.8 days. From Textor et al. (2006) , ECHAM sulphate residence time was the same 3.8 days, while the AeroCom multi-model mean was 4.1 days (σ = 18%). Shindell et al. (2013) reported that their multi-model mean for sulphate residence time was 5 days (σ = 2 days), whereas Kloster et al. (2008) got 4.4 days. Our results are comparable with all the previous studies. Our future estimates show a sulphate residence time of

3.9 days in CLEC2020 and CLECC2020, ~~we feel confident to say that our result shows a realistic global SA burden~~4.0 days in CLEC2030, 4.1 days in CLECC2030, 4.0 days in BCAdd and 4.3 days in MTFR. These result are also in accord with Kloster et al. (2008) , who simulated 4.6 days for CLE and 4.7 days for MFR.

3.1.4 Aerosol burdens in 2020

In order to explore the timeline of the emission reductions, we will ~~show next results from~~ shortly summarize the current legislation scenarios ~~for the~~ changes between 2005 and 2020. ~~Summary of~~ Details about the burden changes between these years ~~is included in Table 2 and Fig.~~ are shown in Table 2 and Figure S4.

Regarding the BC burden, the same general features which were visible in the CLEC2030 simulation can also be seen in CLEC2020. While the changes from 2005 through 2020 to 2030 do not follow a ~~-~~linear path, the CLEC2020 simulation shows overall the same global pattern as the CLEC2030 simulation (Fig. ~~-~~S4). Globally, the BC burden increases 2% between 2005 and 2020, and 5% between 2005 and 2030, indicating an accelerated BC emission rate in the 2020s mainly from the traffic sector. Regionally, the biggest contributors to the increased BC burden in the 2020s are India and ~~Western~~ western China (Table ~~-~~2). In both of these regions, the relative BC burden change (from the reference year 2005) almost doubles between 2020 and 2030. On the other hand, there is a ~~-~~significant decrease in the BC burden in ~~Eastern~~ eastern China after 2020 (~~burden change of -4~~-4% between 2005 and 2020, ~~and -15~~-15% between 2005 and 2030). This is caused by the reductions in the residential combustion and energy sectors, although it should be mentioned that the traffic sector increases between 2020 and 2030 in ~~Eastern~~ eastern China roughly as much as energy sector decreases.

In the CLECC scenario, the global ~~values of BC burden decrease~~ BC burden decreases slightly between 2005 and 2020 (~~-0.2) and increase~~ -0.2%) and increases between 2005 and 2030 ~~by~~ (1%). The reason for this is the same as in the CLEC scenario, i.e. the traffic sector. The geographical patterns of BC burden change are quite similar for the CLECC2020 and CLECC2030 ~~; however,~~ scenarios, even though there are some significant differences over North America. At the border area of Mexico and ~~USA~~U.S., the BC burden change shows no clear signal by 2020, but there is an increase by 2030. This can be also seen from ~~the Table~~ Table 2, where over ~~Western US BC burden is decreased by~~ western U.S. the BC burden decreases 13% by 2020, but increases 8% by 2030. ~~The difference~~ This feature comes from the residential combustion sector, which is estimated to increase quite significantly by 2030. The reason for this is that in CLECC the underlying idea is to move from fossil fuels to bio fuels and residential burning, which ~~happens~~ takes place mainly between 2020 and 2030. Another ~~place with big~~ region with a large difference in CLECC between 2020 and 2030 is ~~Eastern~~ eastern China, where the ~~decrement~~ BC burden change (with respect to 2005) ~~increases from -9 to -25and~~ will increase from -9% to -25% and this comes from the reductions in

residential combustion and energy sectors. Similarly as in CLEC, the reduction in the energy sector are roughly balanced out by the increased traffic sector.

The global OA burden changes are small in both scenarios. However, in the CLEC scenario, the burden increases 1.0~~between years~~ % between 2005 and 2020, and 0.9 ~~between years~~ % between 2005 and 2030, indicating a ~~-~~slight reduction during the 2020s. On the other hand, a ~~-~~much stronger reduction after 2020 takes place in the CLECC scenario as the OA burden change is ~~smaller than −0.05~~-0.05% by 2020 and ~~−1~~-1% by 2030. Regionally, the ~~biggest~~ largest differences are over ~~Eastern~~ eastern China and the ~~Mexico–USA~~ Mexico-U.S. border. The decrement over ~~Eastern~~ eastern China increases between 2020 and 2030 in CLEC from ~~−10 to −25~~-10% to -25% and in CLECC from ~~−15 to −31, mainly coming~~ -15% to -31% and mainly comes from the residential combustion sector. Over the ~~Mexico–US~~ Mexico-U.S. border, the scenarios show no signal by 2020, but by 2030 both have a strong positive sign; over ~~Western USA~~ western U.S. the burden change in CLEC is ~~−2~~-2% by 2020 and 4% by 2030, and in CLECC ~~−2~~ -2% and 13%, respectively. As explained above, this is caused by the increases in residential combustion sector. In other regions the changes are quite small and do not show significant changes in the pattern of OA burden.

In terms of the global SA burden, most of the reductions take place already before 2020 in both scenarios ~~, andin fact~~ and, in fact, the CLEC scenario predicts an increase of SA in the 2020s (change from year 2005 burden is ~~−9~~-9% by 2020 and ~~−5~~-5% by 2030). This increase in ~~burden happens~~ the SA burden takes place mainly because of the increment over India (from 25% change in 2020 to 62% change in 2030) and ~~Western~~ western China (from 15% to 42~~)~~%), and is caused by higher industrial and energy sector emissions. At the same time, Europe and ~~the Americas~~ both North and South America experience very low emission reductions, or even slight emission increases, in the 2020s. In the CLECC scenario, the decreasing global trend in the SA burden continues throughout the 2020s, although it slightly slows down: the change from 2005 burden is ~~−12~~-12% by 2020 and ~~−18~~-18% by 2030. This global decrease is mainly caused by the decreasing trend in ~~energy sector emissions~~emissions from the energy sector. In this scenario, all studied regions show decreasing SA burdens between 2020 and 2030, with the largest decrease taking place in ~~E China~~ E-China (burden change of ~~−10~~-10% in 2020 and ~~−33~~-33% in 2030). Over the other regions, the reductions after 2020 are at most 6 percentage units.

3.2 Radiative effects

We will next investigate how the simulated changes in the aerosol burden translate into aerosol radiative effects. As the radiative effects presented in the following sections are mostly negative, i.e. they have a ~~-~~cooling effect, ~~the difference plots represent the change in the cooling. This means, that if the cooling increases in a scenario, the difference will be negative (more negative minus less negative gives a negative value). Naturally, if cooling decreases, the values are positive~~positive changes in radiative effects translate into a weaker cooling by aerosols, and vice versa. This should

be kept in mind when the radiative effect plots are analysed. Additionally, the values given in the following sections refer to the top of the atmosphere and are obtained directly from the radiation scheme (parallel calls with and without aerosols/clouds).

3.2.1 Direct radiative effect

Aerosols scatter and absorb the incoming solar radiation and the sum of these is called the direct radiative effect (DRE). ~~DRE allows us to study how the radiation budget is changing in different scenarios due to aerosols~~Investigating changes in the DRE between two time periods, or years, tells us how the direct radiative forcing by aerosols changes between these years in different emission scenarios. Besides short wave radiation permutations, aerosols (especially large particles, for example dust) can also influence the long wave radiation through absorption and emissivity~~(especially large particles, for example dust)~~. However, this is ~~has a minor significance for the smaller~~ of minor importance for the small anthropogenic aerosols (Ramanathan and Feng, 2009). We have conducted tests to estimate the magnitude of the long wave component in our simulations and, based on the results, the impact was found to be ~~insignificant~~not important. Thus, the DRE in our analysis is only calculated for the short wave radiation. It should also be noted that the DRE values are clear-sky values, which means that they are calculated assuming a zero cloud cover.

~~Figure~~

Figure 5 shows the annual mean DRE for the reference run and the difference plots for the scenarios. The reference run shows that overall, the DRE is negative around the world (global mean ~~−3.94~~-3.94 W/m^2). Previous studies ~~show similar estimates, for example, Yu et al. (2006) presented a~~ have shows similar estimates. For example, Yu et al. (2006) presented a review of DRE estimates and concluded it to be ~~−4.9 ± 0.7~~-4.9 ± 0.7 W/m^2 over land and ~~−5.5 ± 0.2~~-5.5 ± 0.2 W/m^2 over oceans. Since many of the satellite measurements only give estimates over oceans, we have also calculated ~~this value from our simulations and got −4.68~~the equivalent value and got -4.68 W/m^2 (globally). This can be compared with ~~Zhao et al. (2008)~~ Zhao et al. (2008) , who estimated an oceanic DRE of ~~−4.98 ± 1.67~~-4.98 ± 1.67 W/m^2, and with ~~Forster et al. (2007)~~ Forster et al. (2007) , who estimated from satellite remote sensing studies a ~~value of −5.4(with SD of~~ value of -5.4 W/m^2 (σ = 0.9 W/m^2) over the oceans. Therefore, our simulations seem to give realistic values and are in ~~accord~~ good agreement with previous studies.

In the reference simulation, the strongest cooling effect caused by DRE takes place over the Atlantic ocean near the coast of ~~East Africa~~East-Africa; this is mainly because of the dust transport from Sahara. The overall aerosol burden is ~~also~~ high over the polluted areas, ~~for example Eastern China~~including eastern China, where it leads to ~~cooling of −5.16~~a DRE of -5.16 W/m^2. Over Europe, India, Africa and ~~Eastern US~~ eastern U.S., the values are quite close to the global mean, whereas in ~~Western China and Western US~~ western China and western U.S., they are only approximately half of it. Over ~~smaller regionsDRE can be also~~ limited regions, the DRE can also be positive

(Fig. ~~-~~5). This happens when the underlying surface has a high albedo and the aerosols above are absorbing. This occurs mainly over Sahara, Antarctica and Greenland. Seasonally, positive DRE could ~~be simulated also over~~ also be seen over the Arctic and other snow-covered regions. Note that DRE could be ~~also positive~~ positive also if the absorbing aerosol are above clouds, but here we use only clear-sky values.

Consistent with reductions in aerosol emissions, all the scenario simulations predict a ~~decreasing trend of DRE over Europe and North America~~decreasing cooling effect by aerosols due to DRE over both Europe and North-America. The decrease in the magnitude of the DRE is predicted to be 0.5~~–1.0~~-1.0 W/m^2 over Europe, 0.9~~–1.3over Eastern US~~-1.3 W/m^2 over eastern U.S., and 0.5~~–0.8over Western US~~-0.8 W/m^2 over western U.S. The smallest ~~decreases~~ changes are seen in the CLEC and CLECC scenarios, and the largest in the MTFR scenario. These changes are mainly caused by reductions in SO_2 emissions, which lead to lower aerosol concentrations and thus, decrease the cooling effect. The main sector causing these reductions is the energy production and distribution sector, which has the highest reductions in ~~CLECC and MTRF~~ the CLECC and MTFR scenarios. These reductions are also visible over ~~Eastern~~ eastern China, where BCAdd and CLEC scenarios show modest reduction in ~~DRE cooling~~ the cooling effect due to DRE change (0.07 and 0.29 W/m^2, respectively), ~~but much higher values in CLECC and MTRF~~ whereas they are much higher in the CLECC and MTFR scenarios (1.18 and 2.38 W/m^2, respectively).

The simulated ~~DRE~~ changes over India show significant variation between the different scenarios. Our simulations predict that the cooling effect will increase in BCAdd and CLEC (~~–1.32 and –0.84~~-1.32 and -0.84 W/m^2, respectively), no significant changes will occur in CLECC, whereas in MTFR, the cooling effect will decrease (1.15 W/m^2). The reason for this behavior can be searched from the changes in aerosol component burdens (Figs. ~~-~~2 ~~–~~2 - 4).

~~As~~ It was shown in ~~Sect. 3.1.1~~ Section 3.1.1 that over India, the BC burden increases in the CLEC and CLECC scenarios and decreases in ~~BCAdd and MTRF scenarios. Thus~~the BCAdd and MTFR scenarios. Since the DRE change does not follow this pattern, it is obvious that ~~the sign of DRE~~ its sign does not directly follow the changes ~~of~~ in the BC burden. ~~In addition, the~~ The OA burden changes over India ~~quite similarly than~~ are fairly similar with the BC burden ~~, and besides the overallOA changes are small compared to the other two components. This indicates that the role of OA in driving the DRE sign over India is not significant. Meanwhile, SA burden shows significant increases in BCAdd~~ changes, but overall, both changes are so small that they do not influence the DRE significantly. On the other hand, the SA burden increases in the BCAdd (58%) and CLEC scenarios ~~, is quite modest in CLECC~~ (62%), has small changes in CLECC (12%) and decreases in ~~MTRF. Thus~~ MTFR (-60%). It is clear that apart from CLECC, the ~~SA burden changes can explain the signal of DRE over India. In~~ changes in the DRE follow quite systematically the changes in the SA burden. In the CLECC simulation, the increased absorption coming from the increased BC burden eliminates the cooling entirely (absorption maps are in the ~~Supplement~~supplementary material;

Fig. ~~-~~S5). This means that, based on our model simulation predictions, the sign of DRE change over India is a ~~-~~combination of a ~~warming component~~warming component, for which the changes are mainly caused by the residential combustion sector, and a ~~cooling component~~cooling component, for which the changes are mainly due to energy production and distribution sector. Naturally, the same counteracting effects from absorbing BC and scattering sulphate can occur in other locations, but is particularly obvious over India in our simulations.

It is not straightforward to compare the simulated DRE changes to previously published estimates due to different baseline and scenario years, and differences in emission scenarios between the studies. ~~Unger et al. (2009)~~ Unger et al. (2009) undertook sensitivity studies with NASA Goddard Institute for Space Studies (GISS) model for the future DRE change using 1995 as a reference year and 2050 as a scenario year. The authors reported a global net reduction of 0.179 W/m^2 between these years. ~~Out of our scenario runs, CLEC~~ Our CLEC simulation shows slightly lower reductions from 2005 to 2030 (0.11 W/m^2), and a ~~-~~decreasing trend in the 2020s (change from 2005 to 2020 is 0.13 W/m^2). On the other hand, CLECC shows somewhat higher values (0.24 ~~) than Unger et al. (2009)~~ W/m^2) than Unger et al. (2009) , and no sign of a changing trend. The predicted DRE changes in BCAdd and MTFR are clearly lower and higher, respectively, than simulated in ~~Unger et al. (2009)~~ Unger et al. (2009) . When comparing these two studies, it should be noted that some of the reductions assumed by ~~Unger et al. (2009) may have happened~~ Unger et al. (2009) may have taken place already before 2005, which we use as the reference year.

~~Szopa et al. (2013)~~ Szopa et al. (2013) simulated with a ~~global earth~~ global Earth system model the present day climate and future climate based on different RCP scenarios. Based on Fig. ~~-~~14 in their work, we calculated the global and European forcing change between years 2005 and 2030. Globally, the change is 0.0~~-0.125~~-0.125 W/m^2 (depending on the RCP scenario), whereas our simulations show a 0.06~~-0.4~~-0.4 W/m^2 change (or 0.11~~-0.24~~-0.24 W/m^2 if only CLEC and CLECC ~~is~~ are considered). In Europe, ~~Szopa et al. (2013) estimates a~~ Szopa et al. (2013) estimate a DRE change of 0.3~~-0.7~~-0.7 W/m^2, whereas our simulations predict a 0.51~~-0.95~~-0.95 W/m^2 change (0.54~~-0.7~~-0.7 W/m^2 for CLEC and CLECC). On the other hand, ~~Smith and Bond (2014)~~ Smith and Bond (2014) used the Global Change Assessment Model (GCAM) to estimate the future forcing ~~changes~~change, and calculated a ~~global DRE~~ global DRE change of 0.175 W/m^2 between 2005 and 2030. Overall, our estimates of DRE change are well in line with the previous studies, especially given that there are many differences between the models and simulation set-ups used.

Kloster et al. (2008) did not calculate absolute values of DRE, but they did calculate the forcing between 2000 and 2030 (equivalent to our Δ(DRE)). The authors showed that in their simulations Δ(DRE) is -0.10 W/m^2 for CLE and 0.58 W/m^2 for MFR. Our results show a similar magnitude as CLE for the CLEC and CLECC scenarios, but with opposite signs. This can due to the different reference year, model version and overall emissions in the two studies. For MTFR, our prediction of 0.4 W/m^2 change is in a relatively good agreement with the Kloster et al. (2008) estimate for MFR.

Our simulations were limited to the coming few decades; however, there are earlier published estimates on how the aerosol effect will change by the end of the century. ~~Chen et al. (2010b) reported a~~ Chen et al. (2010b) reported a reduction of 0.12 W/m^2 between 2010 and 2100 based on three different models. ~~Bellouin et al. (2011)~~ Bellouin et al. (2011) showed that for the time period of ~~2000–2090~~2000-2090, HadGEM2-ES model gives a 0.32 W/m^2 reduction without nitrate and 0.83 W/m^2 when nitrate is included. Based on ~~Szopa et al. (2013)~~ Szopa et al. (2013) , the change between 2005 and 2090 was estimated to be 0.15~~–0.26~~-0.26 W/m^2, and based on ~~Smith and Bond (2014)~~ Smith and Bond (2014) , the change between 2005 and 2100 was estimated to be 0.47 W/m^2. These examples give some estimates on how DRE changes might continue after 2030.

3.2.2 Cloud radiative effect

~~Cloud~~ The cloud radiative effect (CRE) is ~~also a sum of two components:~~ a sum of the short wave and long wave cloud radiative effects. ~~As~~ Since the short wave radiative effect is more dominant, the following analysis only includes the short wave component and makes the CRE analysis more consistent with the DRE analysis. Therefore~~as~~ , as was with DRE, ~~from this point forward we will use the abbreviation CRE only for~~ we only include the short wave component when discuss the CRE.

~~CRE is~~ The CRE was calculated based on the method proposed by ~~Ghan (2013)~~ Ghan (2013) , which removes the effects of aerosol scattering and absorption. The ~~double-moment~~ double–moment cloud scheme used in this work takes into account cloud droplet activation (~~Sect.~~ Sec. 2.1). Freshly emitted insoluble BC ~~can~~ may act as ice nuclei and thus, influence ice clouds directly~~, but in~~ . In case of warm clouds, only soluble aerosols have the potential to act as cloud condensation nuclei (CCN). BC is emitted as insoluble, but can in our model become hygroscopic through condensation of sulphuric acid and coagulation with soluble particles.

~~Figure~~

Figure 6 shows the simulated global distribution of CRE and the difference plots between the reference year and scenarios. The largest values of CRE are seen over oceans (~~> 100~~> 100 W/m^2), mostly in temperate latitudes. Several continental areas, ~~e.g. over~~ including Europe, China, Central Africa, North America and South America, ~~have also~~ also have quite high CRE. ~~Based on all~~ All the scenario simulations ~~, the cooling from CRE will decrease in the future~~show cooling due to future changes in the CRE. This takes place mainly in the Northern Hemisphere, where the change in CRE cooling effect is over 2.5 W/m^2 in some areas. The reason for this is that most of the reductions in emissions are located in the Northern Hemisphere. In all ~~scenarios, CRE changes~~ the scenarios, the CRE cooling effect decreases over North Atlantic Ocean, North Pacific Ocean and Europe. ~~Furhermore~~Furthermore, BCAdd2030 and MTFR2030 show decreases also over ~~Eastern~~ eastern China and the coast of Peru~~, and~~ . There are also other locations in MTFR2030 ~~for example over East and West~~ where decreases in CRE cooling effect can be seen, for example, east and west coasts of Africa and South coast of Brazil. Some minor changes also ~~takes place in MTRF~~ take

place in MTFR over the Southern Hemisphere, but the values are very low (~~< 0.5~~<0.5 W/m^2). It is noteworthy that globally the ~~changes in the absolute values of~~ absolute changes in CRE are approximately twice as large as the changes in the DRE (except for BCAdd, for which the CRE change is about six times as large as the DRE change). However, regionally ~~,~~ large variability in the relative ~~magnitude~~ magnitudes of CRE and DRE changes can be seen.

The simulated ~~reduction patterns in CRE~~ patterns of CRE changes follow approximately the ~~reduction patterns of~~ patterns of the BC and SA ~~burdens~~ burden changes (Figs. ~~-~~2 and 4). Over Northern Pacific Ocean and west coast of ~~South America, BC burden~~ South-America, the BC burden change seems to be a ~~-~~more dominant contributor to ~~CRE~~the CRE change, whereas over Atlantic Ocean and coastal areas of Africa, the SA burden changes are the dominant factor. On the other hand, over India in the BCAdd scenario, the increased SA burden does not lead to an increment in CRE values, because the influence is limited by reductions in BC.

Previously~~Szopa et al. (2013)~~ , Szopa et al. (2013) estimated the indirect forcing ~~to change~~ change to be 0.05-0.1 W/m^2 between 2005 and ~~2030 by 0.05–0.1.~~ 2030. For the same time period, the estimate ~~from Smith and Bond (2014)~~ by Smith and Bond (2014) is 0.1 ~~. These estimated~~ W/m^2. These values are less than half of our simulated CRE change (0.25~~–0.82, Table~~ -0.82 W/m^2, Table 3). However, our model includes a ~~-~~sophisticated aerosol activation scheme that takes into account the aerosol number and composition size distribution, and simulates both the first and second aerosol indirect effects. ~~On the other hand, Szopa et al. (2013) include~~ For example, Szopa et al. (2013) included only the first aerosol indirect effect ~~, and calculate~~ and calculated the cloud droplet number concentration in a ~~simplified way~~ more simplistic way (based on soluble aerosol mass~~. Smith and Bond (2014) do~~). Smith and Bond (2014) did not utilize a ~~-~~global atmospheric model at all~~but obtain~~ , but obtained their CRE estimates via direct scaling of aerosol emissions. Therefore, these two previous studies are not directly comparable to our simulations.

It should be stressed that the approach here only tells how the clouds react to aerosol concentration changes in current climate conditions ~~(we use~~ as we used year 2005 meteorology in all simulations~~)~~. Furthermore, some error is introduced by the nudging method because it restricts some of the feedback processes. For example, if emission reductions change the regional or global cloud features in a ~~-~~way that it should impact the overall circulation, these feedback processes will not be fully realized in our simulations. Nevertheless, our approach does show how clouds and their properties react to emission changes in current climatological conditions and gives indications on how the future cloud radiative effect might change.

3.2.3 ~~Forcings~~ Changes in aerosol radiative effect by the year 2020

~~Again, we investigate the timeline of changes in aerosol radiative effects by looking at the two simulations for~~ We investigated the changes in radiative effects realized by year 2020 by looking

into the current legislation simulation results (CLEC2020 and CLECC2020). The results ~~from these simulations~~ are summarized in Table ~~3~~) and ~~Fig.~~ Figure S6.

Our model results show that in CLEC, the reduction of global cooling ~~from DRE~~ due to DRE change takes place prior to 2020; the cooling effect even slightly increases between 2020 and 2030 (change from 2005 is 0.13 W/m^2 by 2020 and 0.11 W/m^2 by 2030). On the other hand, in CLECC, the decrease in the global direct aerosol cooling ~~(i.e. warming)~~ effect continues after the 2020s; the DRE cooling effect change is 0.16 W/m^2 between 2005 and 2020, and 0.24 W/m^2 between 2005 and 2030. However, regional differences are large in both of the scenarios. For example, our model predicts that in the CLEC scenario the ~~cooling trend~~ trend in the cooling effect will significantly accelerate between 2020 and 2030 ~~in India and Western~~ over India and western China. On the other hand, ~~the warming trend accelerates in Eastern Chinaover the same time period~~for the same time period, the trend in the aerosol warming effect accelerates in eastern China. In the CLECC scenario, ~~Eastern and Western~~ eastern and western China experience 3 and 5 times larger DRE change, respectively, from 2005 to 2030 than from 2005 to 2020. Over India, the negative change in DRE in 2020 (i.e. cooling effect with respect to 2005) turns into a ~~-~~positive change by 2030 (i.e. warming effect).

CRE changes after 2020 show somewhat different behaviour in the CLEC and CLECC scenarios. There is no further change in the global CRE in CLEC in the 2020s, whereas in CLECC the ~~CRE values continue decreasing changing~~ cooling effect due to CRE changes continues decreasing from 0.29 W/m^2 (between 2005 and 2020) to 0.39 W/m^2 (between 2005 and 2030). The global change in CLECC from 2020 to 2030 is mainly caused by the change over ~~Eastern~~ eastern China, where the ~~change of CRE increases~~ CRE cooling effect changes from 0.26 W/m^2 by 2020 to 0.75 W/m^2 by 2030. This is caused by overall reductions in all aerosol species. Otherwise, the changes after 2020 are rather small in both of the scenarios, which means that most of the emission reduction based on CRE changes already takes place by 2020.

4 Summary and Conclusions

~~We have~~ We used the global ~~aerosol–climate~~ aerosol-climate model ECHAM-HAMMOZ to evaluate how ~~the aerosol forcing is~~ changes in the aerosol radiative effects, and hence forcing, are expected to decrease during the next couple of decades~~and how it can be~~ , and how they are influenced by emission reductions. This ~~has been~~ was done by modifying the model to use new and updated emission modules. The ~~biggest update was to include GAINS model anthropogenic emissions~~ most important update was the application of continental anthropogenic emissions produced by the GAINS model. With this version, four different emissions scenarios were investigated for the year 2030, and ~~the~~ two of the scenarios where also run for the year 2020. Year 2005 was used as a ~~-~~reference year. The scenarios included two different current legislation scenarios (CLEC and CLECC), one targeted

to ~~black carbon emission reductions~~ short-lived climate forcers' emissions (BCAdd)~~and~~ , and the last one introducing the maximum reduction potential of aerosols and SO_2 with currently available technologies (MTFR).

With the current legislation scenarios, the global black carbon (BC) aerosol burden was estimated to increase by 2030 compared with the current (2005) situation, the sulphate aerosol (SA) burden was estimated to decrease and the organic aerosol (OA) burden may change either way. In the same scenarios, the BC and OA burdens showed increase over India, ~~Western~~ western China, Africa and ~~South America~~ South-America, and the SA burden showed increases over India and ~~Western~~ western China. The residential combustion and traffic sectors ~~cause the major~~ caused the majority of changes for BC and OC, while energy and industrial sectors ~~cause~~ caused most of the SA changes. Over South America, increases in the agricultural waste burning ~~explain~~ explained the higher burden for BC and OA in 2030. The targeted and maximum technological reductions ~~show~~ showed decreasing trend for all species globally and regionally, except over India and ~~Western~~ western China. There, the BC targeted simulation ~~increases the~~ increased SA burden due to emission increases in industrial and energy sectors.

The magnitude of negative aerosol ~~forcing~~ radiative effect will decrease on a ~~-~~global scale in all the scenarios. Based on the current legislation scenarios, the cooling ~~coming from the~~ effect resulting from the clear-sky direct radiative effect (DRE), compared to the year 2005, will decrease by 0.11~~-0.24~~-0.24 W/m^2 by 2030. The technical maximum potential for DRE reductions is globally 0.4 W/m^2 by 2030. Regionally, the cooling effect ~~of DRE~~ from DRE changes can also increase, for example over India and ~~Western~~ western China. These changes follow mainly the BC and SA concentrations, which ~~have different signswhen the impact to DRE is considered. SA , having higher concentration,~~ cause DRE changes of different signs. SA that has higher concentrations is more dominant and causes ~~cooling~~ a cooling effect through scattering, while BC has the ability to absorb solar radiation and causes ~~heating~~a heating effect. For example, over India, the cooling effect from DRE was estimated to increase due to ~~increases~~ the increased SA burden, although in one ~~current legislation simulation~~ of the current legislation simulations the warming effect coming from the increased BC burden ~~seems to have an extinctive~~ canceled out the cooling effect.

~~The~~ Our simulations suggest that the magnitude of the cloud radiative effect (CRE) ~~,~~will decrease globally by 0.25~~-0.82~~-0.82 W/m^2 by 2030 compared with the year 2005. These changes and patterns are again connected to the BC and SA burden changes. ~~Major changes mostly happen~~ Many of the changes occur already by 2020. ~~Overall, CRE is more dominant globally than DRE and has bigger changes . On the other hand, regionally~~ Globally, the changes in the CRE cooling effect are roughly double the changes in DRE ~~can be bigger, for example~~in most scenarios, but regionally large variability in the relative changes can be seen. For example, over India and ~~Western China~~ western China the DRE change is larger than the CRE change. The changes in CRE ~~occur mostly~~ take place over oceans, whereas ~~in terms of DRE , most influence is seen~~ the DRE changes are seen mostly

over the continents. ~~Globally, the changes in DRE are roughly half of the changes in CRE in most scenarios, but regionally large variability in the relative change can be seen.~~

Regionally, India and western China are the only areas where the cooling effect from DRE and CRE ~~will increaseover India and Western China, whereas elsewhere the cooling effect decreases~~is expected to increase. This is because of the aerosol burden increases over ~~India and Western China, and decreases elsewhere. The residential combustion and traffic sector causes the major changes for BC and OC, while energy and industrial sector causes most of the SA changes~~these two regions.

Our simulations predict a ~~-~~notable positive radiative forcing change in the current day climate conditions, up to about 1 W/m^2 globally and > 5 W/m^2 regionally, due to the reductions in aerosol and their precursor gas emissions that will take place during the next couple of decades. The magnitude of this forcing depends strongly on the chosen emission pathway. We have shown that targeted BC emission reductions are clearly the most beneficial for climate, making it even possible to achieve further enhancements in the negative direct radiative forcing (i.e. cooling effect) in some of the world regions (e.g. India and ~~West~~ western China). To the contrary, reducing aerosol and their precursor emissions as much as it is technically feasible could ~~probably~~ be harmful for climate practically in all continental regions, although potentially beneficial from human health protection point of view. Finally, our simulations suggest that more than half of the near-future aerosol forcing change is due to the radiative effects associated with aerosol-cloud interactions. Noting this and the large uncertainties associated with this phenomenon (Boucher et al., 2013), more work is clearly needed for investigating the sources of cloud active aerosol particles into the atmosphere, aerosol-cloud-precipitation interactions and associated feedbacks in the climate system.

Moreover, the use of coupled aerosol-chemistry models with more detailed aerosol description (e.g. including nitrates) would give more detailed estimates of the future forcing of aerosols.

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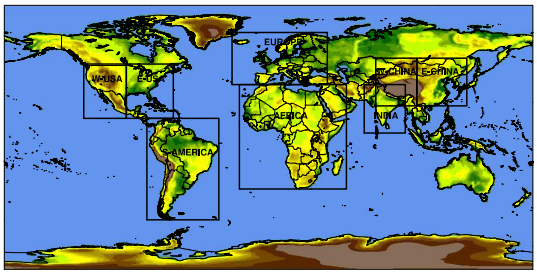

Figure 1. The separately analysed areas: ~~Western~~ western United States (W-USA), ~~Eastern~~ eastern United States (E-USA), South America (S-America), Europe, Africa, India, ~~Western~~ western China (W-China) and ~~Eastern~~ eastern China (E-China).

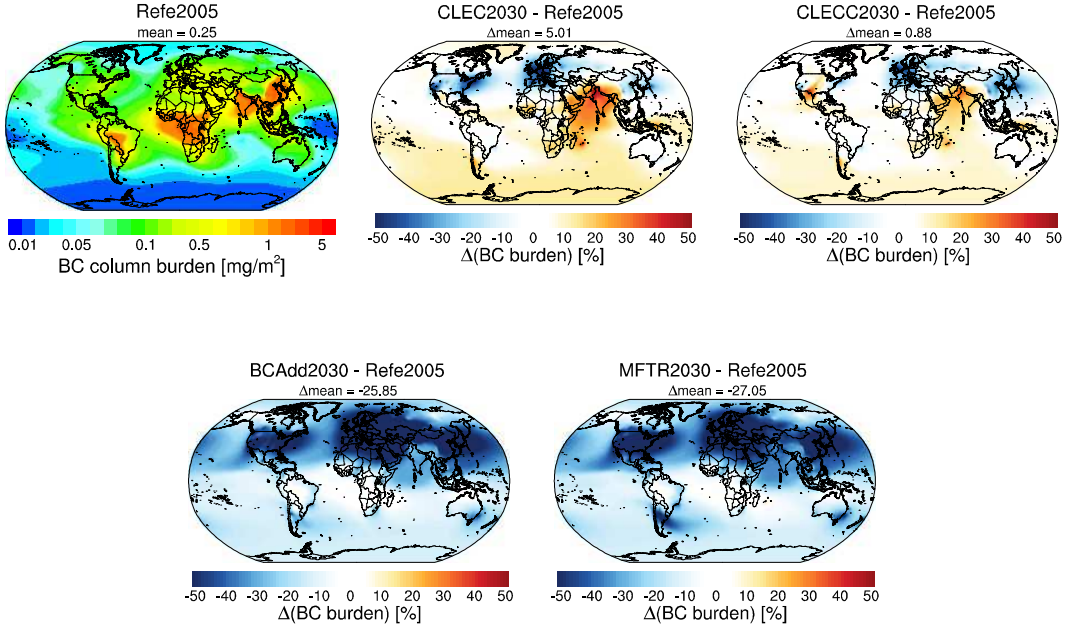

Figure 2. The annual mean black carbon (BC) burden ~~from~~ in the reference run and the relative differences between the scenarios and the reference run.

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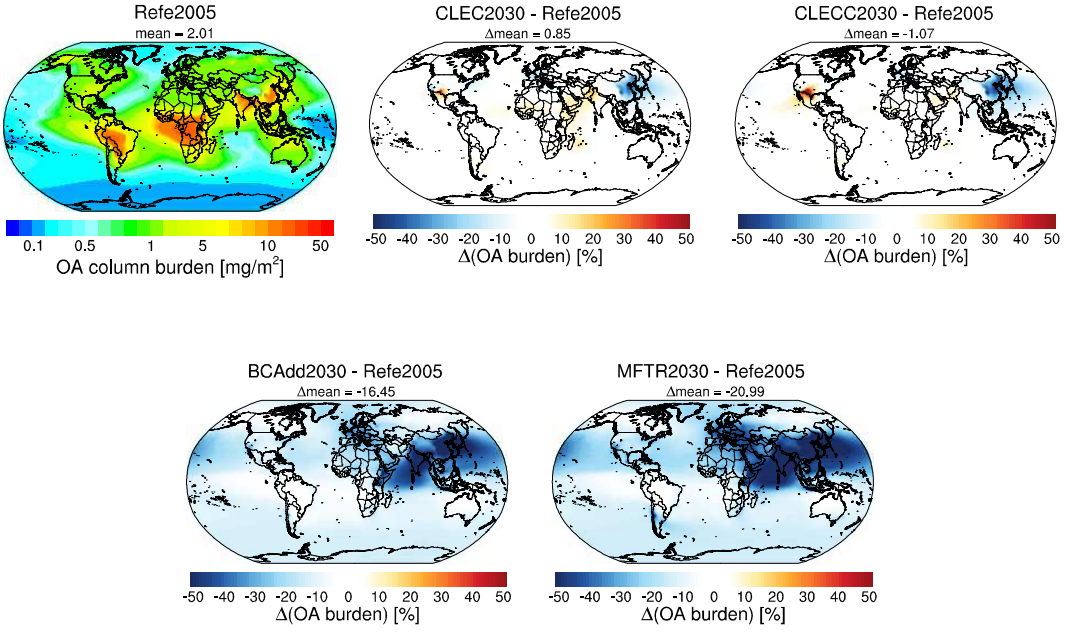

Figure 3. Like Fig. -2, but for organic aerosol (OA) burden.

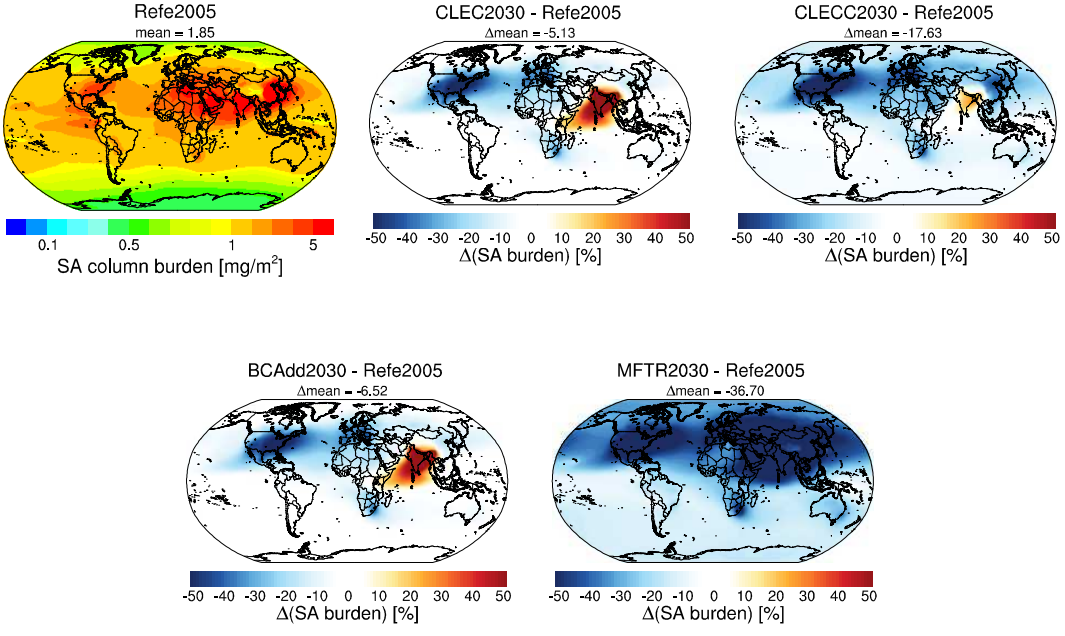

Figure 4. Like Fig. -2, but for sulphate aerosol (SA) burden.

Table 1. Yearly emissions fluxes for different sources, continental anthropogenic emission scenarios and and aerosol species (GFED denotes the wildfire emissions): black carbon (BC), organic carbon (OC) and sulphuric dioxide (SO_2) . The different geophysical areas are shown in Figure 1. Note: the GFED emissions do not include agricultural waste burning sector because it is included in the GAINS emissions.

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Refe2005 [Tg/a]

~~Year~~ **SO_2 emissions**

Refe2005 [Tg/a]

Table 2. The ~~areal~~ global and regional mean burdens of black carbon (BC), organic aerosols (OA) and sulphate aerosols (SA) for the reference simulation and ~~for~~ the difference of the mean burden between the scenarios and the reference simulation.

	Globe	Eu	India	W-China	E-China	Africa	E-USA	W-USA	South-America
BC burden									
Refe2005 [mg/m^2]	0.25	0.26	1.20	0.72	1.03	0.72	0.20	0.17	0.34
CLEC2020 Δ[%]	2.2	-27.5	17.0	14.6	-4.4	5.1	-22.8	-15.3	0.7
CLEC2030 Δ[%]	5.0	-30.3	31.9	28.4	-15.0	8.9	-23.1	-10.2	2.0
CLECC2020 Δ[%]	-0.2	-27.5	10.9	8.7	-9.0	2.9	-17.7	-13.5	0.2
CLECC2030 Δ[%]	0.9	-24.1	17.9	15.0	-24.6	4.7	-3.1	8.4	1.2
BCAdd2030 Δ[%]	-25.8	-63.5	-30.7	-33.2	-58.6	-13.5	-47.2	-40.5	-9.5
MTFR2030 Δ[%]	-27.1	-66.3	-35.8	-37.9	-58.2	-13.7	-54.5	-48.3	-12.6
OA burden									
Refe2005 [mg/m^2]	2.01	1.02	6.25	3.87	4.54	6.34	1.67	1.51	4.59
CLEC2020 Δ[%]	1.0	-6.3	5.3	4.8	-10.4	3.1	-3.1	-1.9	0.1
CLEC2030 Δ[%]	0.9	-7.4	6.1	5.5	-24.9	4.4	-3.8	4.3	0.5
CLECC2020 Δ[%]	-0.0	-6.1	0.4	0.2	-14.6	2.1	-2.0	-2.1	0.3
CLECC2030 Δ[%]	-1.1	-4.7	-3.7	-3.7	-30.7	2.3	-0.0	12.6	0.5
BCAdd2030 Δ[%]	-16.5	-25.1	-49.7	-47.1	-53.5	-11.9	-12.4	-13.2	-3.7
MTFR2030 Δ[%]	-21.0	-34.1	-63.1	-60.9	-64.8	-15.2	-18.8	-20.2	-5.3
SA burden									
Refe2005 [mg/m^2]	1.85	2.37	4.35	2.73	5.31	2.88	2.98	2.60	1.54
CLEC2020 Δ[%]	-8.7	-27.6	25.1	14.6	-1.1	-13.2	-38.8	-31.5	-4.9
CLEC2030 Δ[%]	-5.1	-26.0	62.2	42.1	-6.9	-9.5	-40.1	-32.9	-2.8
CLECC2020 Δ[%]	-12.3	-30.8	13.0	4.4	-10.2	-16.4	-42.1	-34.0	-5.9
CLECC2030 Δ[%]	-17.6	-35.1	11.8	0.8	-33.2	-20.8	-48.3	-40.8	-7.2
BCAdd2030 Δ[%]	-6.5	-27.2	57.5	37.4	-10.3	-10.9	-40.7	-33.5	-3.6
MTFR2030 Δ[%]	-36.7	-50.4	-59.5	-60.0	-66.3	-39.2	-58.5	-51.5	-15.9

Table 3. The ~~areal~~ global and regional mean ~~forcings~~ clear-sky direct radiative effect (DRE) and cloud radiative effect (CRE) at the top of the atmosphere for the reference simulation, and ~~for the difference between~~ the ~~scenarios and~~ changes in these (i.e. changes in aerosol radiative forcing) from the reference simulation to the future in different emission scenarios.

	Globe	Eu	India	W-China	E-China	Africa	E-USA	W-USA	South-America
DRE									
Refe2005 [W/m^2]	-3.94	-4.35	-4.16	-2.01	-5.16	-4.08	-3.97	-2.36	-3.59
CLEC2020 Δ[W/m^2]	0.13	0.56	-0.33	-0.04	0.07	0.16	0.90	0.51	0.05
CLEC2030 Δ[W/m^2]	0.11	0.54	-0.84	-0.20	0.29	0.15	0.95	0.54	0.03
CLECC2020 Δ[W/m^2]	0.16	0.61	-0.13	0.03	0.36	0.17	0.98	0.55	0.05
CLECC2030 Δ[W/m^2]	0.24	0.70	0.04	0.15	1.18	0.25	1.15	0.68	0.06
BCAdd2030 Δ[W/m^2]	0.06	0.51	-1.32	-0.60	0.12	-0.03	0.94	0.51	0.01
MTFR2030 Δ[W/m^2]	0.40	0.95	1.15	0.51	2.38	0.31	1.31	0.76	0.13
CRE									
Refe2005 [W/m^2]	-48.10	-51.05	-33.61	-37.14	-55.61	-31.55	-38.64	-33.87	-55.39
CLEC2020 Δ[W/m^2]	0.25	1.21	-0.10	-0.04	0.20	0.15	0.69	0.87	0.05
CLEC2030 Δ[W/m^2]	0.25	1.26	-0.16	-0.11	0.33	0.14	0.75	0.94	0.00
CLECC2020 Δ[W/m^2]	0.29	1.23	-0.02	0.07	0.26	0.17	0.76	0.89	0.03
CLECC2030 Δ[W/m^2]	0.38	1.42	-0.02	0.07	0.75	0.25	0.95	1.05	0.05
BCAdd2030 Δ[W/m^2]	0.38	1.59	0.18	0.24	1.07	0.40	0.78	1.02	0.18
MTFR2030 Δ[W/m^2]	0.82	2.51	0.98	0.98	2.77	0.70	1.47	1.72	0.55

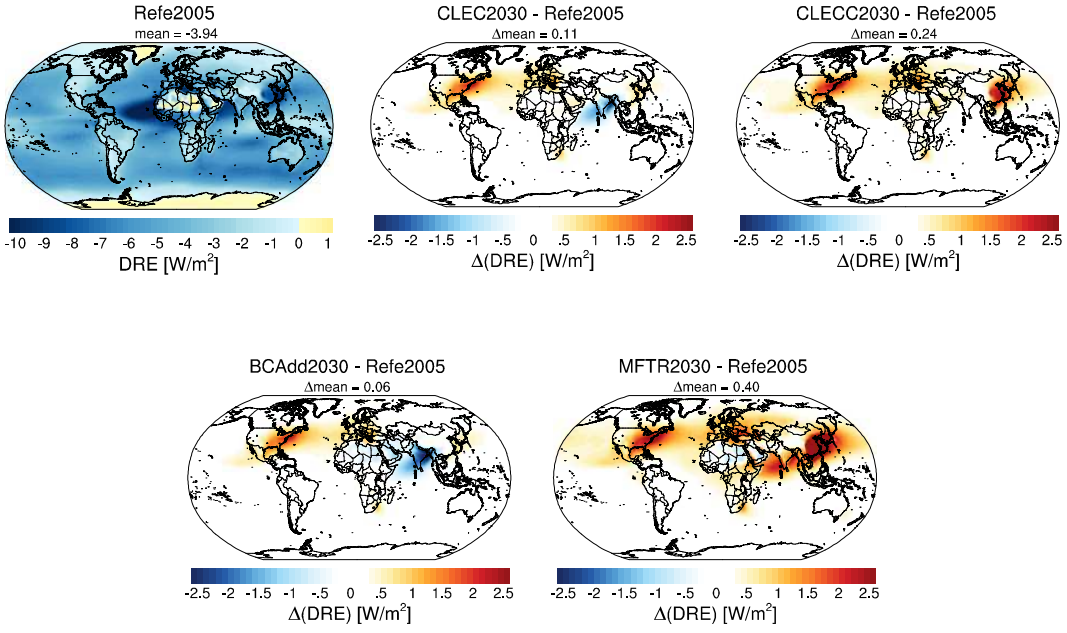

Figure 5. The yearly mean clear-sky direct radiative effect (DRE) at the top of the atmosphere ~~(TOA) from~~ in the reference run and the difference between scenarios and the reference run.

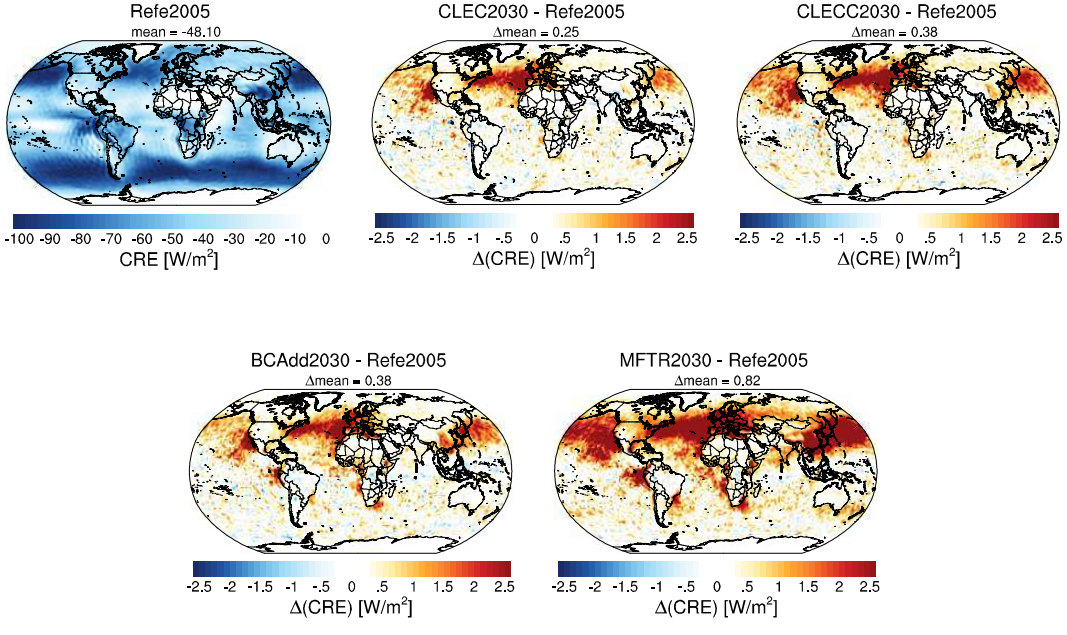

Figure 6. The yearly mean cloud radiative effect (CRE) at the top of the atmosphere ~~(TOA) from~~ in the reference run and the difference between scenarios and the reference run.