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Atmospheric Chemistry and Physics Discussions

Interactive comment on "

Modeling the climate impact of road transport, maritime shipping and aviation over the period 1860–2100 with an AOGCM" *by* D. J. L. Olivié et al.

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Answer to reviewer #1

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We thank the reviewer for the constructive comments on the manuscript. Please find below our responses to the comments.

Specific comments:

1. *P19773 - the impact of NO_x on O_3 and CH_4 concentrations occurs on different timescales. This is important when calculating the net effect of NO_x emissions and should be mentioned here.*

Tropospheric NO_x emissions lead to a large, short-lived regional increase in O_3, and a smaller, long-lived, global decrease in CH_4 and O_3. We mention this in Sect. 1 and refer to Stevenson et al. (2004) (their Fig. 2 is also shown in Lee et al. (2010)).

2. *P19773, l22 - It is true that the estimates of contrail and contrail cirrus radiative forcing lie between 10–80 $mW\,m^{-2}$, however the most recent ('best') estimates with the most detailed models of contrail cirrus are at the lower end, around 31 $mW\,m^{-2}$ (e.g. Burkhardt and Karcher, 2011). This is worth mentioning.*

We added in Sect. 1 that the best estimate is currently around 0.031 $W\,m^{-2}$ and mention the reference.

3. *P19776, l18 and P19805, l35. Specify 'ice' supersaturation.*

We changed "supersaturation" into "ice supersaturation". Also on page 19785 we have changed this.

4. *P19777, l23. State that the observed trend over the 20th century was 0.8K.*

We have added in Sect. 2.1 between brackets the observed trend: (0.8 K, Brohan et al. (2006)).

5. *Section 2.2 Tables 2, 3 and 4 seem to be referenced before Table 1. The first reference I found to Table 1 was on P19787. Re-order the tables?*

We have reordered the tables: Tables 2, 3 and 4 have been put before Table 1.

6. *P19778, l11–13. It would be useful to summarise what the specific emission scenarios are, for each transport sector. i.e. for aviation: what growth rate is assumed and is this globally uniform, do you assume more fuel-efficient aircraft, or different fuel types?*

The detailed emission estimates for the 21st century are based on traffic demand estimates (which are assumed to be mainly driven by gross domestic product (GDP) and population development), fuel efficiency estimates, and emission factor estimates. These estimates reflect, e.g., changes in fuel composition, changes in aircraft or ship size, and developments in technology. Estimates on the short term (up to the year 2020 or 2025) on fuel efficiency and emission factors are often based on current observed trends. The assumptions for the 2050–2100 period are necessarily

more uncertain, and therefore based on more simplified modeling approaches (Eide et al., 2007). The A1B scenario describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. In estimating the traffic emissions, distinction is made between different world regions, different vehicle, ship and aircraft types, different engine types and different fuel types.

For road traffic, the fuel demand is going to increase strongly over the next decades. Uherek et al. (2010) assume that emission standards are further tightened in the OECD (Organisation for Economic Co-operation and Development) regions. It is further assumed that these standards are then adopted in other world regions, notably in Asia where the transport growth is expected particularly strong. Although these more stringent emission controls worldwide, for the NO_x emissions this only balances the volume growth up to the year 2030 (see Fig. 1), as the fleet renewal needs some time before it becomes effective.

For aviation (Lee et al., 2009, 2010; Owen et al., 2010), ICAO (International Civil Aviation Organisation) suggests traffic growth of the order of 5 % yr^{-1} over the next 20 years, and one assumes fuel efficiency continuing todays trends and NO_x improvements commensurate with insertion of the best of todays technology. After 2020, the predictions in traffic are based on the SRES GDP. Up to 2050, one assumes moderate to good fuel efficiency improvement (1 % yr^{-1}), and good NO_x improvements. For the 2050–2100 period, the 1 % yr^{-1} in fuel efficiency continues. Assumptions on NO_x (and BC) are that 2050 emission indices remain unchanged to 2100. For aviation, there are few prospects at the moment for alternative fuels such as liquid hydrogen to make substantial emissions savings (Lee et al., 2010). Also, the use of biofuels in the aviation sector remains uncertain because of the strict requirements on fuel composition for reasons of safety.

As shipping (Eyring et al., 2005; Eide et al., 2007; Eyring et al., 2010) is one of the least regulated sources of anthropogenic emissions, it has a high reduction potential through technological improvements, alternative fuels and ship modifications (propeller, rudder, hull). For the QUANTIFY emissions, it was assumed that technological barriers will be overcome rapidly, and new technologies become available at an early stage. One assumes that gas usage will increase rapidly and strongly, but there is only a moderate use of biofuels due to slow introduction of CO_2 legislation. Legislation for reduced emission factors will be implemented at a moderate pace. The reduction factors for the years 2025 and 2050 are based on current emission regulations and trends in regulation, technological opportunities and environmental and technological profiles specific for the A1B scenario. The emission factors and reduction potential used for scenario B1 (which is an SRES scenario assuming clean and resource-efficient technologies) from the year 2050 have been applied universally for the period 2050–2100 in scenario A1B, indicating that this level is assumed to have fulfilled the full potential for emission reduction for the given engine types and fuel types.

A reduced version of this has been implemented in Sect. 2.2 of the manuscript:

"The transport emission estimates for the 21st century are based on traffic demand estimates (which are assumed to be mainly driven by the gross domestic product (GDP) and population development), fuel efficiency estimates, and emission factor estimates (emission factors indicate how much NO_x/SO_2/BC/... is emitted per unit fuel burnt). A distinction is made between different world regions, different vehicle, ship and aircraft types, different engine types and different fuel types. In scenario A1B, fuel consumption is assumed to grow for all three sectors, with some stabilization for road transport in the second half of the 21st century. For road transport (Uherek et al., 2010) it is assumed that emission standards will be taken over in the next decades on a global scale such that it will ultimately lead to a net decrease in NO_x emissions from 2030 on, despite the sustained increase in fuel consumption. For aviation (Lee et al., 2009, 2010; Owen et al., 2010), a sustained fuel efficiency improvement is

projected over the whole period 2020–2100 ($1\,\%\,yr^{-1}$), and the emission factor for NO_x is assumed to decrease up to 2050 and remain constant thereafter. For shipping (Eyring et al., 2005; Eide et al., 2007; Eyring et al., 2010), it is assumed that gas usage will increase rapidly and strongly, and legislation for reduced emission factors will be implemented at a moderate pace. One assumes that around 2050 maritime shipping will have fulfilled the full potential for emission reduction for the given engine types and fuel types (Eide et al., 2007). The estimated use of biofuels is moderate for shipping and low for aviation."

7. *P19779, l21. How is the data 'slightly modified' and why is this necessary (why is there a such a gap between the observed and modeled concentration?)? I suggest changing to wording from 'slightly modify' to something more specific.*

With the simple carbon-cycle model, one can calculate the evolution of the atmospheric CO_2 burden when the anthropogenic CO_2 emissions are known. Based on best estimates for the CO_2 emissions in the 19th and 20th century, and based on scenarios for the 21st century, the expected CO_2 concentration is calculated. For the 19th and 20th century best estimates for the atmospheric CO_2 concentration exist, based on direct observations or proxies. Comparing them with the results from the carbon-cycle model showed good correspondence over the 20th century, with a deviation of 3.5 ppmv at around 1990–2000. Whereas we used for the 21st century the results from the simple carbon-cycle model in the AOGCM, we preferred to use the observed values for the 19th and 20th century. To avoid a small discontinuity in the prescribed CO_2 concentration in CNRM-CM3.3 around the year 2000, we decided to make a gradual transition from the observed to the modeled CO_2 concentrations.

We have replaced the text by:

"In our simulation, we use observed CO_2 concentrations until 2000 and the SCM modeled CO_2 concentrations from 2000 onwards. To avoid a discontinuity due to a small difference of around 3.5 ppmv between the observed and modeled CO_2 concentrations around 2000, we phase out this transition over the period 1990–2010."

8. *P19780, l15. By 'goes up to around' do you mean 'can be as large as' (does not imply an increase with time)?*

Indeed, we don't mean that it increases in time but that its impact can be as large. Therefore we replaced "goes up to around" by "can be as large as".

9. *P19780, l22. Are these the emission periods shown in Figure 2?*

The main emission period for CFC-12 is 1970–2010 (with a peak in 1993), and for HFC-134a it is 1993–2053 (peak around 2015) (see Table 2). Taking into account their lifetime, one can calculate their atmospheric burden and radiative forcing, which is shown in Fig. 1. As the lifetime of HFC-134a is rather short, the temporal evolution of its atmospheric burden reflects slightly the temporal evolution of its emission history. Due to its long lifetime, this is not the case for CFC-12.

We now mention also the emission periods for CFC-12 and HFC-134a in the text.

10. *P19782, l24–26. The sentence is unclear; I think there is a word missing. Suggest: 'also leads to changes'.*

The original sentence is: "In addition to the impact on OH, these simulations calculated for the years 2000, 2025 and 2050 also changes in O_3, NO_x, CO, and many other atmospheric components."
We have modified the sentence in: "From these simulations, the impacts of transport

on O_3, NO_x, CO, and many other atmospheric components (e.g., OH, see Sect. 2.2.3) were obtained for the years 2000, 2025 and 2050."

11. *P19784, l25. State the best estimate from the Burkhardt and Karcher paper.*

We changed "Recently, modeling studies have been performed which model the evolution and aging of contrails (Burkhardt and Kärcher, 2009, 2011)."
into "Recently, modeling studies have been performed which model the evolution and aging of contrails: Burkhardt and Kärcher (2009, 2011) derived a radiative forcing of 31 mW m^{-2}."

12. *P19786, l16 and Figure 3. In figure 3, is the contribution of aviation to the distribution of BC actually zero (the figure panel is blank), or just smaller than the lowest contour interval used in the figure? A non-zero TOA forcing from aviation BC is quoted in the text.*

In our simulations, the contribution from aviation to BC is small but different from zero, while the aviation contribution to OC is zero. Table 1 in Balkanski et al. (2010) contains the atmospheric aerosol loads which are used in our model and are shown in our Fig. 3. For BC, Balkanski et al. (2010) indicate for road, shipping and aviation respectively 18.9, 0.79 and 0.03 μg m^{-2}. It means that there is still some BC from aviation, but its mixing ratio is lower than the lowest contour interval in our Figure 3. This contrasts indeed with the OC perturbation from aircraft which is assumed 0 in our model.

13. *P19787, l26 and Figure 5. I found this figure confusing. The figure caption does not describe all the elements of the figure (what is the solid line, dashed line, and error bars?) and gives too much detailed explanation that belongs in the text. Importantly, I*

did not understand how the figure represents the effect of using ensemble simulations?

We have limited the explication in the figure caption to the description of the figure, and we have put some more explanation and interpretation in the text.

14. *P19788, l15. Also, the effect of water vapour emissions from aviation is not considered here.*

Fortuin et al. (1995) estimated this impact in 1992 to be rather small, 0.0015 $W m^{-2}$, making this factor a minor uncertainty in subsonic climate forcing. It is further assumed that this value scales linearly with fuel use. This low impact from (current) subsonic aircraft contrasts with the possible impacts of supersonic aircraft with cruise altitudes around 20 km altitude: they might build up much greater H_2O enhancements in the stratosphere. Penner et al. (1999) suggest that this would even be the dominant climate impact from supersonic aircraft.

We mention now shortly in the text in Sect. 2.3 that we do not take this into account.

15. *P19789, l21. The impact from aviation is smaller in the SH than the NH due to there being much fewer flights in the SH than the NH and the relatively short lifetime of ozone?*

There are indeed much fewer flights in the SH than in the NH. As the lifetime of ozone in the troposphere is much shorter than the characteristic time for hemispheric exchange (exchange rate 0.3–0.5/year), and as the SH NO_x emissions are much lower than in the NH, we obtain rather small ozone perturbations in the SH.

We changed "The impact from aviation in the SH is almost a factor of 5 smaller

than in the NH."
into "The impact from aviation in the SH is almost a factor of 5 smaller than in the NH, a consequence of the much stronger emissions in the NH, the short tropospheric O_3 lifetime and the slow inter-hemispheric mixing."

16. *P19795, l5–8 and Fig 11. The figure caption is missing a description of the thinner lines (stated in the text as 95% confidence intervals), and that the thick line is the mean over all the ensemble members.*

We have added this information in the caption of Fig. 11.

17. *P19795, l20. 'From shipping the non-CO_2 impact is negative everywhere' - except the SH poles for the period 2011–2030 when it is weakly positive.*

In Fig. 11, it is indeed positive in the region 60°S-90°S for the period 2011–2030. However the lower limit of the 95% uncertainty interval is close to 0.

We have modified the text accordingly: we added "(except at southern high latitudes for the period 2011–2030 when it is weakly positive)".

18. *P19797, l1. This is difficult to see from figure 13, as there are so many different lines on the figure. A solution may be to have separate figure panels for each period, so that the difference between the dashed and solid lines could be clearly seen.*

We have made a separate plot for each period. In addition, the plot showing the time evolution of the annual global mean surface air temperature is now in a separate first figure, and the 4 plots showing the zonal behaviour are in a second figure.

19. *Figure 16, left panel. At the moment it is difficult to distinguish the lines from the dots. The clarity of this figure could be improved by making the dots smaller.*

We have reduced the size of the dots.

20. *P19803, l24. It is informative to quote the temperature from transport as a percentage of the total anthropogenic temperature change. E.g. In 2000, the CO_2 impact from transport sectors was 0.1K (12.5% of the total anthropogenic temperature change), increasing to 16.7% in 2100.*

We have added these %-values.

21. *Figures - on some of the multi-panel figure, it may be useful to label individual panels (a), (b) etc to make it easier to refer to them (and for the reader to more easily understand which panel you are referring to!).*

We have labeled the individual panels in the Figs. 1, 6, 7, 9, 11, 12, 13 (now 14), 15 (now 16), 16 (now 17), 18 (now 19), 19 (now 20), 20 (now 21) and 21 (now 22), and labeled rows in Figs. 3, 8, 10, 14 (now 15) and 17 (now 18). We have accordingly modified the captions of the figures and the text referring to these figures.

Technical comments:

1. *P19775, l23. Correct the spelling of 'geographical'.*

We corrected "geographcial" into "geographical".

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