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Responses to Reviewer #1

This study concerns the climate response of black carbon (BC) emissions in a fully- coupled climate model. The study is motivated by the potential for BC emissions reductions, and the authors evaluate the non-linearity of emission perturbations and the transient response. As BC has received attention from a policy-perspective to reduce global warming (e.g. CCAC and the Arctic Council), investigating possible non- linearities in emission perturbations and the transient response of BC is important and highly relevant for ACP.

We thank the reviewer for all the insightful comments. Below, please see our point-by-point responses (in blue) to the specific comments and suggestions and the changes that have been made to the manuscript to take into account all the comments raised here.

Unfortunately, I think the study fails to answer these questions. Since the authors do not find any significant climate change from present-day BC emissions, the authors conclude that BC emission cuts may not be detectable and that the climate impact of BC should be expressed directly in terms of emissions.

Indeed, we do conclude that there may be no detectable surface **temperature** change impacts from present-day BC over much of the world (note we do not conclude there are no *climate* impacts, since BC will impact other variables). Note, our specific wording on this point:

> *These results indicate that even substantial BC emissions reductions from current levels may lead to detectable surface temperature changes for only limited regions of the globe. (line 560)*

Which we believe accurately reflects our findings and does, indeed, address the questions raised by many on this topic (albeit from one model of course).

We did not intend to say that the impact of BC should be expressed as emissions, we apologize for the misunderstanding. This portion of the discussion section has been re-written to clarify as:

> *We suggest that impacts of BC on climate should be expressed directly in terms of impacts per unit emissions (e.g. table 1), and not only relative to forcing given the complex relationship between BC climatic impacts and top of the atmosphere forcing. In addition, BC impacts should be re-evaluated using coupled models, and provided with measures of response variability, such as standard deviation.*

First; Do the authors mean that we cannot say anything about the climate impact of BC? I would argue that emissions are not climate impacts. As this paper is clearly motivated by policy-relevant questions, I am confused about what the authors are trying to conclude.

Response:

We can indeed say something about BC impacts on climate. We can say that, over most of the globe, BC impacts on surface temperature are very small.

Second; I agree that cutting BC emissions would not be detectable on a thermostat in the real world. As a matter of fact; few things would, except radical changes like cutting CO2-emissions to zero. Is this relevant? As researchers, we must use models (this is why we use them) to provide our best estimate on the climate impact of e.g. cutting BC emissions, and then it is up to the policy-makers to decide if it is worth it in terms of costs, feasibility, co-emitted species etc.

Response:

This statement by the reviewer that only changes such as cutting CO2 emissions to zero would be detectable is not correct. For example, differences in climate variables between a RCP8.5 and RCP4.5 scenario begin to be statistically detectable as early as 25–30 years after scenarios diverge (Tebaldi and Friedlingstein 2013), well before CO_2 emissions are zero. Cutting SO_2 emissions to zero, for example, also leads to detectable changes in surface temperature over much of the world (Baker et al. 2015). However, the impact of reducing BC emissions on surface temperature is much smaller due, in part, to the counteracting cooling and warming effects of fast feedbacks that are only present in coupled model simulations (as demonstrated in a number of models recently by Stjern et al. 2017).

Note that we did not provide any recommendation on the desirability of reducing BC emissions. We have, however, found in our simulations that the impact of reducing BC emissions, even to the point of eliminating all anthropogenic emissions, is small and statistically undetectable across most of the globe.

Third; the simulating period for these runs are too short to make these conclusions. If the simulation period was long enough, I argue that the authors would 1) be able to detect a signal from present-day emissions and 2) quantify the non-linearity of different emissions perturbations. Are the temperature sensitivities in Figure 8 significantly different from each other? The authors refer to natural variability as error bars, which I find a bit odd.

Response:

The runs were as long as computationally feasible (e.g. multiple 100-year coupled simulations), and our results are provided with the uncertainty estimates derived from these simulations. To reduce uncertainty further, a far longer set of runs would be required since noise in this case would reduce as 1/sqrt(Neff), where Neff equals the simulation length divided by the correlation time-scale for the processes in question.

We have added statistical tests in Figure 8 and Table 2 as shown below and modified the manuscript adding these tests.

Note that we did not "refer to natural variability as error bars", the error bars represent one standard deviation of the signals derived from our runs to indicate uncertainty. We do, however, conclude that the root of this variability in our signal likely stems from internal variability in the model due to the statistical properties we find in our analysis.

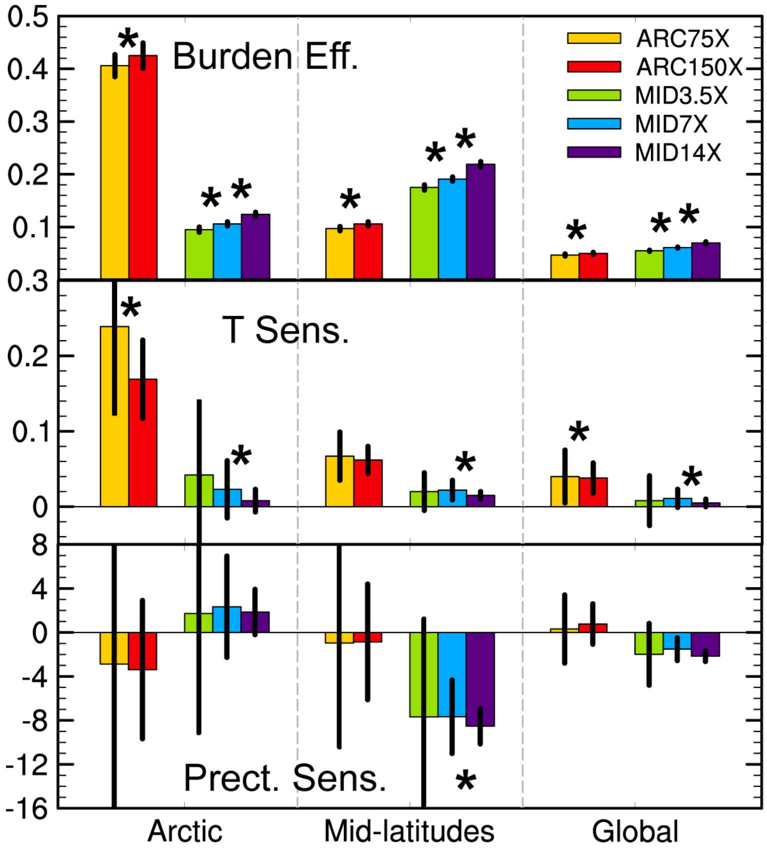

Figure 8. Burden efficiencies, temperature and precipitation sensitivities over the Arctic, mid-latitudes and the whole globe for ARC75X, ARC150X, MID3.5X, MID7X and MID14X. Burden efficiencies, temperature sensitivity and precipitation sensitivity are calculated as changes in regional mean BC column burden, surface temperature and total precipitation rate divided by changes in global total BC emissions between perturbed and PD simulations, respectively. Error bars represent 1-σ for 80-annual means. Asterisk between two bars (ARC75X/ARC150X, MID3.5X/MID7X, and MID7X/MID14X) indicates statistically significant changes with 95% confidence from a two-tailed Student's t test.

Table 2. BC burden, DRE, CRE, and snow/ice-albedo forcing efficiencies, T sensitivity and P sensitivity over the Arctic (60–90°N), mid-latitudes (28–60°N) and the globe between perturbed (ARC75X/ARC150X/MID3.5X/MID7X/MID14X) and PD simulations. 1-σ for 80-annual means is shown in the parentheses. Bold values between two simulations (ARC75X/ARC150X, MID3.5X/MID7X, and MID7X/MID14X) indicates statistically significant changes with 95% confidence from a two-tailed Student's t test.

		ARC75X	ARC150X			MID3P5X	MID7X	MID14X
		Burden Eff. (mg m^{-2} (Tg yr^{-1})$^{-1}$)						
60–90°N		**0.406 (±0.021)**	**0.425 (±0.024)**			**0.095 (±0.005)**	**0.106 (±0.004)**	**0.124 (±0.004)**
28–60°N		**0.097 (±0.004)**	**0.106 (±0.004)**			**0.175 (±0.005)**	**0.191 (±0.004)**	**0.219 (±0.005)**
Global		**0.047 (±0.002)**	**0.050 (±0.002)**			**0.055 (±0.001)**	**0.061 (±0.001)**	**0.070 (±0.002)**
		DRE Eff. (W m^{-2} (Tg yr^{-1})$^{-1}$)						
60–90°N		**0.346 (±0.036)**	**0.312 (±0.031)**			**0.146 (±0.014)**	**0.140 (±0.009)**	**0.137 (±0.006)**
28–60°N		**0.069 (±0.005)**	**0.066 (±0.003)**			**0.129 (±0.006)**	**0.120 (±0.004)**	**0.112 (±0.003)**
Global		**0.038 (±0.003)**	**0.035 (±0.003)**			**0.051 (±0.003)**	**0.048 (±0.002)**	**0.046 (±0.001)**
		CRE Eff. (W m^{-2} (Tg yr^{-1})$^{-1}$)						
60–90°N		**–0.533 (±0.232)**	**–0.303 (±0.078)**			–0.091 (±0.166)	**–0.111 (±0.046)**	**–0.015 (±0.029)**
28–60°N		0.010 (±0.222)	–0.037 (±0.067)			**0.070 (±0.203)**	**–0.152 (±0.043)**	**0.129 (±0.035)**
Global		**–0.028 (±0.071)**	**–0.017 (±0.043)**			0.013 (±0.058)	**–0.061 (±0.025)**	**0.035 (±0.010)**
		Snow/ice-albedo Eff. (W m^{-2} (Tg yr^{-1})$^{-1}$)						
60–90°N		**0.151 (±0.011)**	**0.099 (±0.006)**			**0.030 (±0.003)**	**0.026 (±0.002)**	**0.020 (±0.002)**
28–60°N		**0.013 (±0.003)**	**0.010 (±0.002)**			**0.011 (±0.002)**	**0.009 (±0.001)**	**0.007 (±0.001)**
Global		**0.012 (±0.001)**	**0.008 (±0.001)**			**0.004 (±0.001)**	**0.003 (±0.000)**	**0.003 (±0.000)**
		T Sensitivity (K (Tg yr^{-1})$^{-1}$)						
60–90°N		**0.239 (±0.116)**	**0.169 (±0.052)**			0.042 (±0.098)	**0.023 (±0.038)**	**0.008 (±0.015)**
28–60°N		0.067 (±0.032)	0.062 (±0.018)			0.020 (±0.025)	**0.022 (±0.013)**	**0.015 (±0.005)**
Global		**0.040 (±0.035)**	**0.038 (±0.020)**			0.008 (±0.033)	**0.011 (±0.012)**	**0.005 (±0.005)**
		P Sensitivity (μm day-1 (Tg yr^{-1})$^{-1}$)						
60–90°N		–2.88 (±13.39)	–3.38 (±6.29)			1.73 (±10.85)	2.34 (±4.61)	1.86 (±2.06)
28–60°N		–0.96 (±9.45)	–0.86 (±5.26)			–7.69 (±8.90)	**–7.67 (±3.34)**	**–8.53 (±1.61)**
Global		0.31 (±3.10)	0.77 (±1.84)			–1.99 (±2.81)	–1.52 (±1.04)	–2.15 (±0.49)

The most important finding in this study, I think, is the short transient response of 2-3 years and the lack of a long-term response that the authors find for BC. This contradicts the much-used study by Boucher and Reddy (2007) where it is shown that BC both has a short-term response and a long-term response (ocean). If this is true it will be important for policy-makers, as a rapid BC mitigation will not be crucial for reaching e.g. the 2-degree target and can be delayed for some time. Physically, this means that BC emissions mostly influences the boundary layer over land surface, and do not warm the ocean due to a stabilization of the marine stratocumulus clouds. Would this be specific or sensitive to the model and the cloud scheme? In Boucher and Reddy (2007), they use an impulse temperature response function with both a short-term and a long term. How certain are the authors that there is no long-term response? In L404 you state that ‘by our observation that there is no detectable long-term trend after the initial transient period’. This is a bit vague. Can you perform a hypothesis test to see if there is no long-term trend? But, again, the simulation period is too short to estimate any long-term responses.

Response:

We note that Boucher and Reddy (2008), and much other previous work, use a GHG impulse response function for the BC response. This was an implicit assumption that the system responds similar to a BC impulse as to a GHG inputs. This is known not to be the case for aerosols in general, since their forcing is not uniformly distributed in space (e.g., the “geometric effect” as noted by Meinshausen et al. (2011) and Shindell (2014)). As we note in the text, a similar result for BC (for a global emission perturbation) was found by Sand et al. (2015).

We did indeed statistically test for a long-term response and we have amended the text to cite the result of our linear fit showing there is no long-term response. We have amended the text to indicate that, as the reviewer points out, that we can only conclude there is no significant response over a 100-year time horizon. We cannot draw conclusions for longer-time scales.

I suggest that the authors either extend their simulation period or significantly tone down their conclusions. But if the latter; I am not sure how much added value this study will provide. However, if the authors do extend their simulation period (yes, this will require some extra work), I think this study can be an important contribution to the field.

Response:

We disagree that it is necessary to extend the simulations to draw relevant conclusions. While it would be interesting to do so, it is not clear if the computational costs could be justified. 100-years is a standard length for model diagnoses of this sort (e.g. Baker et al. 2015) and provides sufficient statistics for analysis.

Reference:

Boucher, O. and Reddy, M. S.: Climate trade-off between black carbon and carbon dioxide emissions, Energ. Policy, 36, 193–200, doi:10.1016/j.enpol.2007.08.039, 2008.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic Change, 109, 213 – 241, doi:10.1007/s10584-011-0156-z, 2011.

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Sand, M., Iversen, T., Bohlinger, P., Kirkevåg, A., Seierstad, I., Seland, Ø., and Sorteberg, A: A standardized global climate model study showing unique properties for the climate response to black carbon aerosols, J. Climate., 28, 2512–2526, doi:10.1175/JCLI-D-14-00050.1, 2015.