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Atmospheric Chemistry and Physics Discussions

Interactive comment on "The effect of sea ice loss on sea salt aerosol concentrations and the radiative balance in the Arctic" *by* H. Struthers et al.

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We thank the reviewer for their effort in reviewing this paper. Their comments and corrections have significantly improved the manuscript.

Referee #1 Specific comments

1. The Måttensson scheme cut off at dry radius of 1.4 μm, while the optical depths are usually dominated by sea salt particles with larger sizes. I suggest the authors considering extending the sea salt spectrum to larger sizes using Monahan source function. It could result in different optical depth thus influence the estimation of the direct climate effect.

Response: The description of the modal fitted source function was not clear but in the creation of the modal source function we started from a combination of the Mårtensson and the Monahan parameterization, following Mårtensson et al. (2010). The Mårtensson parameterization is indeed not valid above 1.4 μm dry Rd, and the Monahan code should not be used below 0.45 μm dry Rd. However, they result in about the same emissions in the overlapping size range. In the current paper, for particles larger than 1.4μm in Rd the modes are indeed constrained by the Monahan source function, hence the quadratic temperature dependence for the largest mode included in the present work. In any case, the explanation of the fitting procedure has been altered in the text.

Section 3 (Parameterization of sea salt emissions), the beginning of paragraph 2 has been changed to:-

'To simplify the implementation of the size distribution of the sea salt aerosol flux in CAM-Oslo, three log-normal modes were fitted to the Mårtensson parameterization combined with the parameterization of Monahan et al. (1986) for particles with radii greater than 1.4μm. The modal radii and geometric standard deviations ...' The appropriate Monahan et al. (1986) reference has also been added to the bibliography.

2. Since also important for the sea salt burden, the removal and hygroscopic growth scheme used in the model should be described in more detail.

Response: The hygroscopic growth of particles is modeled using a lookup table of growth factors for different particle types which is a function of relative humidity.

Section 2 (CAM-Oslo model), first paragraph has been changed to:-

'... aerosol and cloud optics and water uptake (Kirkevåg and Iversen, 2002). For relative humidities below 100%, the hygroscopic growth of particles is modeled using a pre- calculated lookup table for the estimate of dry deposition. Large look-up tables are also used for the calculation of aerosol optics in the model, using relative humidity and a range of process specific aerosol concentrations as input parameters.'

3. Wind speed is the dominant effect of sea salt emission. Suggest highlighting in the text ahead of the conclusion session that the influence of wind speed on sea salt emission under 2100 climatology is negligible as implied in Figure 5 e,f.

Response: The first paragraph of Section 6 (Conclusions) has been altered:-

'The implications of a reduction in Arctic sea ice extent on sea salt aerosol emissions and the resulting natural radiative forcing has been examined through a series of model simulations using the CAM-Oslo global climate model. Over the open ocean, sea salt aerosol emissions are primarily determined by U10 although the average U10 over the Arctic cap was relatively insensitive to the applied changes in sea ice extent and SST. This means that the prescribed changes in sea ice extent and SST are the main drivers of the modeled change in sea salt aerosol over the Arctic in this study. Considering the sea ice/sea salt aerosol system in isolation, the chain of response ...'

4. I think some clarification is needed about the climatology used in the perturbation runs. For example, P1-ICE is "identical to CTL but with northern hemisphere sea ice fraction replaced with 2095-2100 climatology : : :". As a reader, I might wonder if P1-ICE run uses 2000 climatology with nothing different but 2100 sea ice extend, or with feedbacks of the climate system due to the sea ice extend change? As I interpret from Figure 5 and the aim of the simulation, should it be the latter? I brought this to attention because although the sea salt emission is not related to sea ice extend change in P1-ICE, changes of wind speed, SST, cloud fraction, and boundary layer height due to the snow/ice-albedo feedback could still influence the sea salt emission, though the magnitude, I believe, is trivial compare to the sea ice extend contribution.

Response: The description and nomenclature used to describe the model simulations has been rewritten to clarify the actual model setup and give a better motivation for the different model experiments:-

Section 4 (model simulations)

Four model simulations were completed for this study. Well-mixed greenhouse gas concentrations were fixed at values representative of the year 2000 for all model simulations. – Control simulation (CTL). CAM3: 2000 sea ice, Aerosol module: 2000 sea ice. A 6 year integration forced by an annually repeating sea surface temperature (SST) and sea ice fraction climatology (hereafter denoted as the 2000 climatology) obtained from the data set of Hurrell et al. (2008). This data set is a blend of the observationally constrained Hadley Centre sea ice and SST data set version 1 (HadISST1) and version 2 of the National Oceanic and Atmospheric Administration (NOAA) weekly optimal interpolation (OI) SST analysis. – Perturbation simulation 1 (P1). CAM3: 2100 sea ice, Aerosol module: 2000 sea ice. Similar to the CTL simulation but with a northern hemisphere sea ice climatology representative of the late 21st century (hereafter denoted as the 2100 climatology) in place of the 2000 sea ice climatology. The sea salt aerosol emissions remain constrained by the 2000 sea ice climatology. This simulation will show how the CAM3 model meteorology responds to changes in the northern hemisphere sea ice extent. Within the aerosol module, the sea ice extent is the same as in the CTL simulation. Even so, the sea salt aerosol emissions may in any case be slightly different due to differences in U10. The 2100 sea ice climatology was calculated from a three member ensemble of twenty first century CCSM3 simulations under the Special Report on Emissions Scenarios (SRES) A1B greenhouse gas forcing scenario. Arctic sea ice extent from the CCSM3 model was compared with other AR4 climate models and measurements by Stroeve et al. (2007). – Perturbation simulation 2 (P2). CAM3: 2100 sea ice, Aerosol module: 2100 sea ice. The same as P1, with the exception of the sea salt emissions which are constrained by the 2100 sea ice climatology. All the boundary conditions in the CAM3 climate model for this simulation are the same as the P1 simulation. Since the aerosol model is run off-line from the climate model, the meteorological fields including the cloud fraction and liquid water path, are identical to the P1 fields. Results from this simulation along with the CTL and P1 results can be used to contrast the effects of surface albedo and emission changes on the aerosol radiative forcing (see Fig. 1). – Perturbation simulation 3 (P3). CAM3: 2100 sea ice, Aerosol module: 2100 sea ice and 2100 SST. The same as P2 with the exception of the sea surface temperatures which were also taken from the 2100 CCSM3 climatology (both in the CAM3 model and the aerosol module). The response of sea spray emissions to changes in both ice cover and sea surface temperature can then be examined based on this simulation (see Fig. 1).

5. P28870, L10. Since the model sets the sea salt emission linearly change with the sea ice extent, the _100 factor is not reflected in the model, these comment is somewhat problematic.

Response: Yes the reviewer is correct, thanks for pointing this out. It should read by a factor of $\sim$2 (or 100%). The text has been corrected:-

'... model simulations can increase sea spray emissions by a factor of approximately 2.'

6. Could the authors mention more about how the uncertainty of CAM3.1 in polar-ward transportation effects the simulations?

Response: There are known biases in the large scale circulation of the Arctic in CAM3 (e.g. see Hurrell et al. (2006) J. Clim., 19, pp2162, Hack et al. (2006), J. Clim., 19, pp2267, DeWeaver and Bitz, (2006) J. Clim., 19, pp2415) which in turn may affect the simulated background concentration of sea salt concentration although it is difficult to quantify how these biases will influence the results presented. Whilst the majority of the results and discussion is focused on changes in sea salt (with respect to the CTL simulation) driven by local sea ice change, it is true that there should be some mention of the effect of circulation biases on the results.

Added to the end of Section 2 (CAM-Oslo model):-

'Arctic atmospheric circulation biases in CAM3 have previously been noted (e.g. Hurrell et al. 2006, Hack et al. 2006, DeWeaver and Bitz, 2006). These biases in turn may affect the results presented below due to unrealistic meridional transport of aerosols

into or out of the Arctic region. In addition, there are inherent problems in the representation of atmospheric transport in general circulation models (GCMs), in particular vertical transport, which adds to the uncertainty in the modeled aerosol distributions. It is difficult to directly quantify how these issues will influence the results shown below. We thus simply note that the conclusions drawn here are based on output from a single model which, in common with all GCMs, is not completely unbiased with respect to the real atmosphere.'

7. In section 5.1, the authors constrain the model performance of U10, turbulent heat flux, boundary layer height, and the low cloud fraction with observations. However, the model performance on sea ice extend and SST against observations are not provided. Is there any reason such as satellite data not available for the model years? It might be more comprehensive investigation if uncertainty in the modeled ice extend and SST can be mentioned.

Response: The 2000 climatology prescribed in the model is calculated from the 1980-2000 average of the data set of Hurrell et al. (2008). This data set is based on Hadley Centre sea ice and SST dataset version 1 (HadISST1) and version 2 of the National Oceanic and Atmospheric Administration (NOAA) weekly optimum interpolation (OI) SST analysis. Both these contributing data sets are constrained by observations, including satellite data. To make it clear that the 2000 SST and sea ice climatology is based on observations the text describing the Hurrell et al. (2008) 2000 climatology has been altered.

Section 4 (Model simulations), in the description of the control simulation:-

'A 6 year integration forced by an annually repeating sea surface temperature (SST) and sea ice fraction climatology (hereafter denoted as the 2000 climatology) obtained from the data set of Hurrell et al. (2008). This data set is a blend of the observationally constrained Hadley Centre sea ice and SST data set version 1 (HadISST1) and version 2 of the National Oceanic and Atmospheric Administration (NOAA) weekly optimal interpolation (OI) SST analysis.'

8. P28876 L27 "The increase in magnitude of the aerosol forcing in the P2-ICE-SALT and P3-ICE/SST-SALT simulations arises due to the local increase in sea salt aerosol emissions, and is of the order of 50% of the ice-albedo effect as measured by the difference in aerosol forcing between the P1 and CTL simulations." I think this is a very important conclusion relating to the purpose of this investigation – identifying the relative contribution of ice extend-aerosol effect to snow/ice-albedo effect. Maybe more analysis for P2 and P3 analysis will make the argument more interesting. In the abstract, the authors mention that the direct forcing is estimated to be between -0.2 to -0.4 W/m2. I think it is worth mentioning again in this section.

Response: Text has been added as suggested.

Section 5.2.1 (Natural aerosol direct radiative forcing), paragraph 3:- 'The increase in magnitude of the aerosol forcing in the P2 and P3 simulations arises due to the local increase in sea salt aerosol emissions, and is approximately 50% ($\sim$ -0.1Wm-2) of the ice-albedo effect, the latter represented by the difference in aerosol forcing between the P1 and CTL simulations. The combined effect of decreasing surface albedo and increasing the sea salt aerosol burden leads to an overall aerosol direct forcing change that peaks around -0.2 to 0.4 Wm-2 in June. It is worth ...'

9. P28877 L3. Could the author explain why P3 is closer to P1 than P2?

Response: A brief suggestion as to why the P3 simulation is closer to the P1 than the P2 simulation has been added in the text.

Section 5.2.1 (Natural aerosol direct radiative forcing), paragraph three:-

'It is worth pointing out that the P3 simulations are for the most part closer to the P1 than the P2 simulations (Fig. 12), especially for spring which can also seen in the AOD results (Fig. 10). The likely reason for this is the decrease in the residence time for sea salt aerosol particles (see Figs. 9g and 9h) which in turn is dependent on the wet

deposition efficiency (Section 5.1.2). Even though the sea-ice cover was reduced from CTL to P1 and P2, the sea surface temperature was kept below freezing in the ice free regions. The cold ocean temperature inhibits the occurrence of warm clouds (see Fig. 9e and 9f). An increase in SST increases the amount of warm clouds thus making the scavenging process more efficient.'

Technical corrections

10. P28867, L5. Is the 6 year integration forced by sea ice fraction of a period of 6 year during 1980-2000?

Response: The 1980-2000 average was used, repeating the annual cycle over the six years of the simulation. The description of the integrations has been revised (see point 4 above) to more clearly explain the way the model was set up and used.

11. Figure 5, caption: (a)(b) should be "open ocean area", instead of "sea ice area"

Response: Caption altered as suggested.

12. Is the ERA-Interim reanalysis the same as ECWMF? Should use the consistent terminology.

Response: The ERA-Interim fields are produced by ECMWF. 'ECMWF ERA-Interim' is now used to describe the reanalysis data consistently throughout the manuscript.

13. P28869, L27, indicate what SHEBA stands for.

Response: SHEBA acronym (Surface Heat budget of the Arctic Ocean) added to text.

14. P28870, L15, compare with Fig. 1 -> refer to Fig. 1

Response: Text altered as suggested.

15. P28876, L13, suggest move (0.7 to >0.9) after high albedo.

Response: Text altered as suggested.

16. P28877, L2, “already mentioned” -> “as already mentioned”

Response: This sentence has been removed.

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