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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Global model simulations of the impact of ocean-going ships onaerosols, clouds, and the radiation budget" *by* A. Lauer et al.

A. Lauer et al.

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Reply to anonymous referee #2

We thank the referee for the comments on our manuscript, which helped us to significantly improve the quality of the paper.

General comments

In the introduction, both the first and second indirect effect are defined. I could not find in this manuscript a mention of whether both indirect effects were taken into account in

the study. Moreover, in the conclusion, the authors discuss the effect of "the change in cloud reflectivity", from which I inferred that only the 1st effect is treated. The authors should clearly state it.

The reviewer is right, a clear statement is missing whether only the first indirect effect or also the second indirect effect is considered by the model. To make this clearer, we added the following paragraph to the model description (Sect. 2.1):

"In principle, the microphysical cloud scheme is able to capture both, the first and second indirect aerosol effect. The precipitation formation efficiency is linked to the calculated cloud droplet number concentration applying the formulation of Khairoutdinov and Khogan (2000). However, the effect of aerosol emissions on cloud life-time resulting from changes in the precipitation formation efficiency cannot be resolved accurately by the model. Cloud life-time is limited to a multiple of the time step length of the GCM (30 minutes in the configuration used). Thus, small changes in average cloud life-time cannot be resolved. Moreover, GCMs do not capture the microphysical processes in detail which could cause different responses in cloud properties to aerosol increases than obtained by detailed cloud models, e.g. Ackerman et al. (2004)."

Figure 10 shows that in the Southern Hemisphere the indirect aerosol forcing differs significantly for the 3 inventories A, B and C. Unfortunately, the model underestimates the observed aerosol number concentrations by several folds in the 20S to 70S region (Figure 2). For the simulated low aerosol number concentrations, a change due to shipping emissions will greatly influence the indirect effect due to the non-linearity of this effect. I would like the authors to present a sensitivity simulation that imposes aerosol number concentrations in the range of observations (circa 700 to 900 cm^{-3}) and then add the emissions from shipping. This would allow to quantify the effect of this non-lineatiry on the results presented here. It will help constrain the amplitude of

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the indirect aerosol effect due to shipping.

We agree with the reviewer that the indirect aerosol effect due to ship emissions differs significantly between the 3 emission inventories used. This is particularly the case for the Southern Hemisphere. This diversity can be explained by the large differences in the emission totals in the 3 ship emission inventories in the Southern Hemisphere. SO_2 emissions south of 20°S, for instance, in inventory A amount to 1.12 Tg/yr, 0.18 Tg/yr in inventory B, and 0.62 Tg/yr in inventory C, which is a factor of 6 between the lowest and the highest SO_2 emissions in the Southern Hemisphere.
The reviewer is right, Fig. 2 shows that the model clearly understimates the total aerosol number concentration in the Southern Hemisphere. Nevertheless, we think our model should be able to capture the indirect aerosol effect in the Southern Hemisphere reasonably well. To point this out, we extended Sect. 3.1 as follows:

"We also compared the model data to measurements obtained during the campaign INCA (Interhemispheric Differences in Cirrus Properties from Anthropogenic Emissions, not shown) (Minikin et al., 2003). These measurements provide vertical profiles of the aerosol number concentration in the Southern Hemisphere for 3 different lower cut-off diameters. This comparison showed, that in particular the Aitken mode (d$>$14 nm) and the accumulation mode (d$>$120 nm) particle number concentrations calculated by the model nicely fit the observations, i.e. the modeled particle number concentration lies completely within the 25% and 75% percentiles of the observations up to about 500 hPa (Aitken mode) and up to 350 hPa (accumulation mode). For cloud formation in particular these size-regimes are relevant, whereas the very small particles that often dominate the total aerosol number concentration are less important. For this reason, we think that the model should be able to capture the indirect aerosol effect in the Southern Hemisphere reasonably well. This is further confirmed by the quite good agreement of cloud droplet number concentrations calculated by the model and retrieved from satellite observations for low marine clouds in this region as

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discussed in Sect.3.4."

Thus, we do not think the additional sensitivity study proposed by the reviewer would provide many new insights but we extended Sect. 3.1 accordingly.

Specific comments

The following result stated in the abstract: "emissions from ships significantly increase the cloud droplet number concentration of low maritime water clouds." needs to be quantified.

We agree and added the following sentence to the abstract:

"These changes amount up to 5% to 30% depending on the ship emission inventory and the geographic region."

P 9428; lines 22-25: "In the lower troposphere of the Southern Pacific (Fig. 2, left panel), E5/M1-MADE underestimates the mean particle number concentration, which could be related to the omission of sea salt particles in the size range of the Aitken mode in the model." The incidence of the underestimation of the mean particle number concentration should be studied through a sensitivity run proposed above.

For the reasons given above (general comments), we do not think such a sensitivity study would provide many new insights.

p. 9428, line 16: "For the Pacific measurement sites Coconut Island, Midway Island, and Lanai as well as for the Indian Ocean site Amsterdam Island and the Atlantic Ocean site Azores, the simulated AOT are mostly within the inter-annual variability of

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the Aeronet measurements, given by the standard deviation." Midway Island should not be included in this list of AERONET station since the simulated AOT does not fall within the inter-annual variability of the measurements.

The reviewer is right, "Midway Island" has been accidentially included in list of Aeronet measurements sites for which simulated AOT falls within the measured standard deviation. This has been corrected now.

Page 9430: Please indicate the altitude range at which the measurements of Bennartz [2007] were made.

Unfortunately, Bennartz (2007) does not specify an altitude range of the cloud top heights investigated. The cloud top height of marine stratiform clouds lies typically below 1.5 km.

Page 9431, lines 6-10: "The effective cloud droplet radii derived from the satellite data lie between 11 μm to 13 μm. Here the model gives slightly smaller values ranging from 10 μm to 11 μm for the regions North America, North Africa, South America, and Southern Africa. For the region Northeast Asia, the average effective radii calculated by the model range from 8 μm to 9 μm, whereas the satellite data suggest 11 to 12 μm." The incidence on the indirect effect of a difference of 1 to 2 μm radius should be computed.

We do not exactly understand what the reviewer means by "incidence on the indirect effect". In most cases except "Northeast Asia", the lower effective cloud droplet radii in the model coincide with higher cloud droplet number concentrations than shown by the satellite data. A higher than observed background cloud droplet number concentration should result in a lower relative contribution of ship emissions to the cloud droplet number concentration. Thus, we expect that the indirect aerosol effect

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due to shipping calculated here might be slightly reduced compared to a scenario with lower background cloud droplet number concentrations and thus larger cloud droplet effective radii.

Page 9431: When comparing the GCM with ERBE data, did you use the same resolution as you sampled the two datasets?

The ERBE satellite data depicted in Fig. 5 (now Fig. 6) has a horizontal resolution of 2.5°, the model data is on its native grid (2.8°). When calculating the global averages discussed in Sect. 3.5, both data sets have been upsampled to 1°x1°.

Page 9435: If you applied equation 1 to the 3 inventories it is surprising that for clear skies you get: 0.038, 0.012, and 0.030 W/m^2 for scenarios A, B and C respectively. For cloudy skies you infer values of 0.014, 0.010, and 0.009 W/m^2 from equation 1, please check your numbers.

Because of the concerns of reviewer #1 regarding our approximation for the calculation of the direct aerosol effect, we decided to run each of the 4 model experiments (inventory A, B, C, and without ship emissions) again. In these new model experiments, the radiation scheme is called twice, with and without taking into account aerosols. The difference between the two radiation calculations is the signal from the direct aerosol effect, which now can be calculated for all-sky conditions. We revised the corresponding paragraph of Sect. 4.1 accordingly and removed our approximation, we had used previously to assess the direct aerosol effect. In addition, the updated numbers of the direct aerosol effect from shipping are summarized by the new Tab. 4.

Page 9436, line 24: "In the Atlantic Ocean, for instance, the average decrease in the cloud droplet effective radius is 0.42 μm (A), 0.17 μm (B), and 0.25 μm (C) at an altitude of 0.4 km." Do you have an explanation as to why this decrease in cloud

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droplet radius over the Atlantic is larger for scenario A compared to C or B?

Inventory A has the highest SO_2 emissions above the Atlantic (5.0 Tg/yr), followed by inventory B (4.7 Tg/yr) and C (3.4 Tg/yr). This indicates that not only the emission total, but also the geographic distribution is an important factor for the impact of ship emissions on clouds. SO_2 emissions above the Atlantic are most widespread in inventory A, followed by inventory C. In contrast, emissions are confined to narrow lines in inventory B. According to the model results, more widespread emissions facilitate a larger impact of aerosol and precursor emissions from shipping on the marine boundary layer clouds. To point this out, we added the following sentences to Sect. 4.2:

"This larger impact on average cloud droplet radii above the Atlantic by ship emissions from inventory A compared to inventories B and C cannot be explained by the emission totals only. The emission total of SO_2 from inventory A (5.0 Tg/yr) is similar to that from inventory B (4.7 Tg/yr). This indicates that the geographic distribution of the emissions plays an important role, too: Emissions are much more widespread in inventory A compared to B, resulting in a larger impact on the cloud microphysical properties averaged over a larger domain."

Page 9436, line 10-12: "The increased reflectivity of the low marine clouds results in an increased shortwave cloud forcing, calculated as the difference between the whole sky value and the clear-sky value of the net shortwave radiation at the ToA." Reorganize the paper with a paragraph explaining the computation of the direct radiative forcing and the indirect. This sentence indicates that you treat only the 1st indirect effect. Is it the case?

As explained above, the model also considers the effect of aerosol emissions on the precipitation formation efficiency (2nd indirect aerosol effect). However, because of the coarse temporal resolution of the model, we do not expect small changes in

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average cloud life-time (2nd indirect aerosol effect) to be resolved. In fact, we do not see any changes in the average cloud cover or precipitation which are statistically significant. To make this clearer, we added the following sentences to Sect. 4.2:

"The changes in the cloud forcing include both, changes in the cloud reflectivity due to altered cloud droplet number concentration (1st indirect effect), as well as changes due to altered precipitation formation efficiency (2nd indirect effect). However, no statistically significant changes in the precipitation patterns or total precipitation have been encountered."

Page 9437, line 1: You should write -0.60 W m^{-2} and not -0.6 W m^{-2} (not the same precision).

We agree with the reviewer and changed the manuscript accordingly.

Page 9437, Line 7 These values are within the range of previous model estimates (-0.9 to -2.9 W/m^2) (Lohmann and Feichter, 2005) of the total anthropogenic indirect effect. In chapter 2 of the last IPCC report (http://ipccwg1.ucar.edu/wg1/Report/AR4WG1_Pub_Ch02.pdf) it is stated that: "Based on the results from all the modelling studies shown in Figure 2.14, compared to the TAR it is now possible to present a best estimate for the cloud albedo RF of -0.7 W m^{-2} as the median, with a 5 to 95% range of -0.3 to -1.8 W m^{-2}." This should be stated in this paper. It also allows to contrast the range you propose of -0.19 to -0.60 W m^{-2} with not only the papers included in Lohmann and Feichter [2005] but also a several papers that have been published since.

We agree with the reviewer that the results of the latest IPCC report should be be discussed. Thus, we have extended Sect. 4.2 by the following paragraph:

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"The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) reports a best estimate for the cloud albedo effect (1st indirect aerosol effect) of -0.7 W/m^2 with a 5% to 95% range of -0.3 to -1.8 W/m^2 (IPCC, 2007). The results of E5M1-MADE (-1.1 to -1.5 W/m^2) are in the upper range of these uncertainties. However, it should be kept in mind, that most models consider ships in a simplified manner such as inventory B only. Thus, the total indirect forcing using inventory B (-1.1 W/m^2) should be considered only when comparing E5M1-MADE to the IPCC results."

Finally I recommend that you improve the paragraph of conclusions in your manuscript. They seem to have been written to hastily.

We went through the conclusions and improved this section.

Interactive comment on Atmos. Chem. Phys. Discuss., 7, 9419, 2007.