We thank the reviewer for the constructive comments and suggestions for improvement of our manuscript. The comments from the reviewer followed by our responses to the comments can be seen below.

Major comment

The paper is well organized and well written. The result is important, but a little more insight is needed. The current results suggest another question: to what degree is optimization of particle injections necessary? Despite the factor of four difference in the mean size representation of the particle size distribution of the GISS model compared with the other two models, differences in the clear-sky forcing among the models appear to be relatively small (e.g. Fig. 2b). Considering the injection sizes, should greater differences be expected if the forcing is direct? Neither question can be considered because relatively simple explanations of fundamental particle representations used in each model are missing: 1) sub-saturated hygroscopic growth; 2) cloud activation; 3) deposition processes; 4) vertical distributions of the injected particles; 5) number size distributions of the simulated injections. The complexities and subtleties of the many aerosol processes, including effects on cloud, may offset to some degree. For example, as you know, if you try to optimize for the indirect effect by injecting particles smaller than 100 nm you expect to reduce the direct component. However, it may be difficult to either avoid spraying some larger particles or the presence of natural sea salt particles, either of which will tend to reduce the indirect effect by competition for water vapour. There is some discussion at the top of page 8, but it focuses on activation only. Some additional discussion of these processes with a focus on why the clear-sky forcing is not so different despite the substantial difference in particle representations between GISS and the other models, as well as a figure comparing injected number size distributions, would offer some insight.

Response:

We agree with the reviewer that the size of the injected particles is relevant for the clear-sky effective radiative forcing (ERF). The injected sea salt particles within the G4sea-salt experiment have a median dry radius of 0.13 µm in NorESM1-M, 0.44 µm in GISS-E2-R, and 0.10 µm in HadGEM2-ES. However, the fact that the clear-sky global-mean ERF in Fig. 2b in the manuscript (Fig. 3b in the updated version) is similar in magnitude for the three models does not imply that the difference in particle size between the models has a negligible effect on the clear-sky ERF. The reason that such a conclusion cannot be drawn is that the sea salt injection rates are not equal for the three models, since the injection rates have been set to generate a total global-mean ERF of -2.0 W m^{-2} in each model. The injection rates are 250 Tg yr^{-1} in NorESM1-M, 590 Tg yr^{-1} in GISS-E2-R, and 200 Tg yr^{-1} in HadGEM2-ES, as mentioned in Sect. 3.2. Thus, the injection rates vary with almost a factor of three across the three models.

The size distributions of the sea salt injection are shown in Figure 1 for particle number (Fig. 1a), particle surface area (Fig. 1b), and particle mass (Fig. 1c). This figure is now included in the updated manuscript as suggested by the reviewer. The mass scattering efficiency of homogeneous spheres of sea salt (refractive index = 1.544) for light with a wavelength of 550 nm peaks for a particle radius of ~0.3 µm (Seinfeld and Pandis, 1998). Thus, for a constant mass concentration, maximum scattering efficiency is expected for particle sizes somewhere in between the median dry radius of the injections in GISS-E2-R and the median dry radii of the injections in NorESM1-M and HadGEM2-ES. However, as mentioned above (and shown in Fig. 1c below), mass concentrations are not equal in the models since the injected sea salt mass is larger in GISS-E2-R than in the other two models. On top of this, aerosol processing in the atmosphere, transport, and deposition will affect the clear-sky forcing, as pointed out by the reviewer. We have added some more description of these processes into Sect. 2.1 of the updated version of the manuscript.

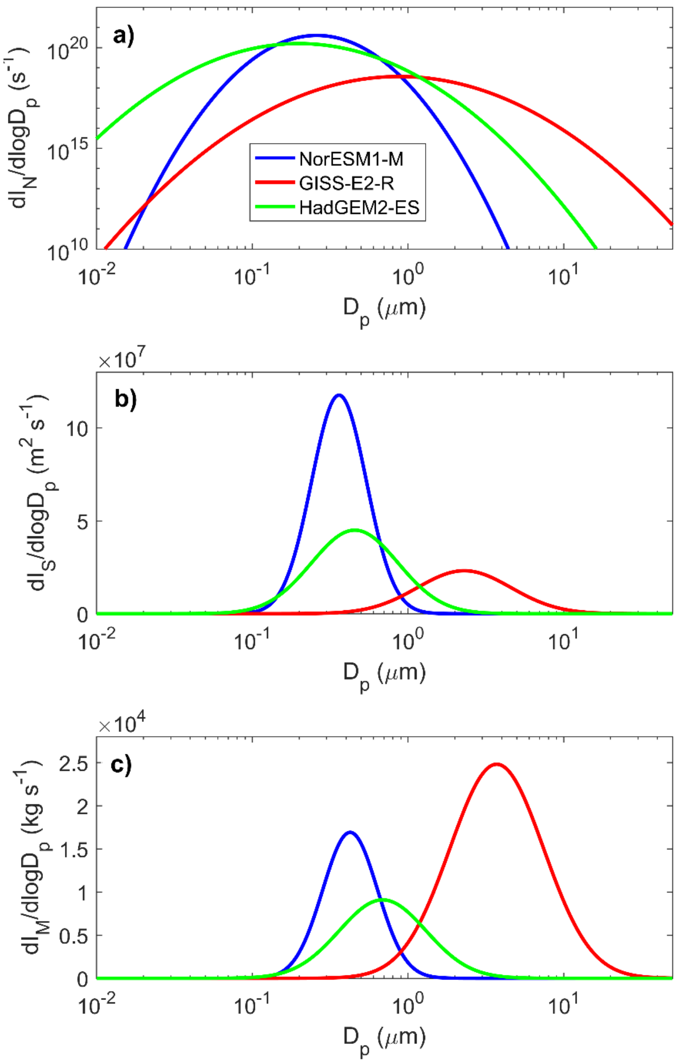

Figure 1. Size distributions for the total sea salt injections (30°N and 30°S) of a) particle number I_N, b) particle surface area I_S, and c) particle mass I_M for NorESM1-M (blue), GISS-E2-R (red), and HadGEM2-ES (green).

In Fig. 1 above, the particle surface area (Fig. 1b) is the variable that is closest related to the amount of light scattered by the sea salt particles (and thereby the clear-sky ERF in Fig.

2b in the manuscript, or Fig. 3b in the updated version). For a full description of Mie scattering, however, one needs to take into account also variations in the scattering coefficient with particle size, which is done in the radiative transfer calculations in the models. The total particle number injections (integrated over the number size distributions in Fig. 1a) are $1.8 \cdot 10^{20}$, $2.7 \cdot 10^{18}$, and $1.1 \cdot 10^{20}$ s^{-1} for NorESM1-M, GISS-E2-R, and HadGEM2-ES, thus almost two orders of magnitude smaller number injection in GISS-E2-R compared to the other models. The corresponding particle surface injections (integrated over the particle surface distributions in Fig. 1b) are $5.2 \cdot 10^{7}$, $1.7 \cdot 10^{7}$, and $3.1 \cdot 10^{7}$ m^2 s^{-1} for NorESM1-M, GISS-E2-R, and HadGEM2-ES. Thus, although the difference in total particle number injection between GISS-E2-R and the other two models is large, the difference in total particle surface area injection is considerably smaller. Based on these numbers it is not so surprising that the clear-sky ERF is rather equal in magnitude for the three models.

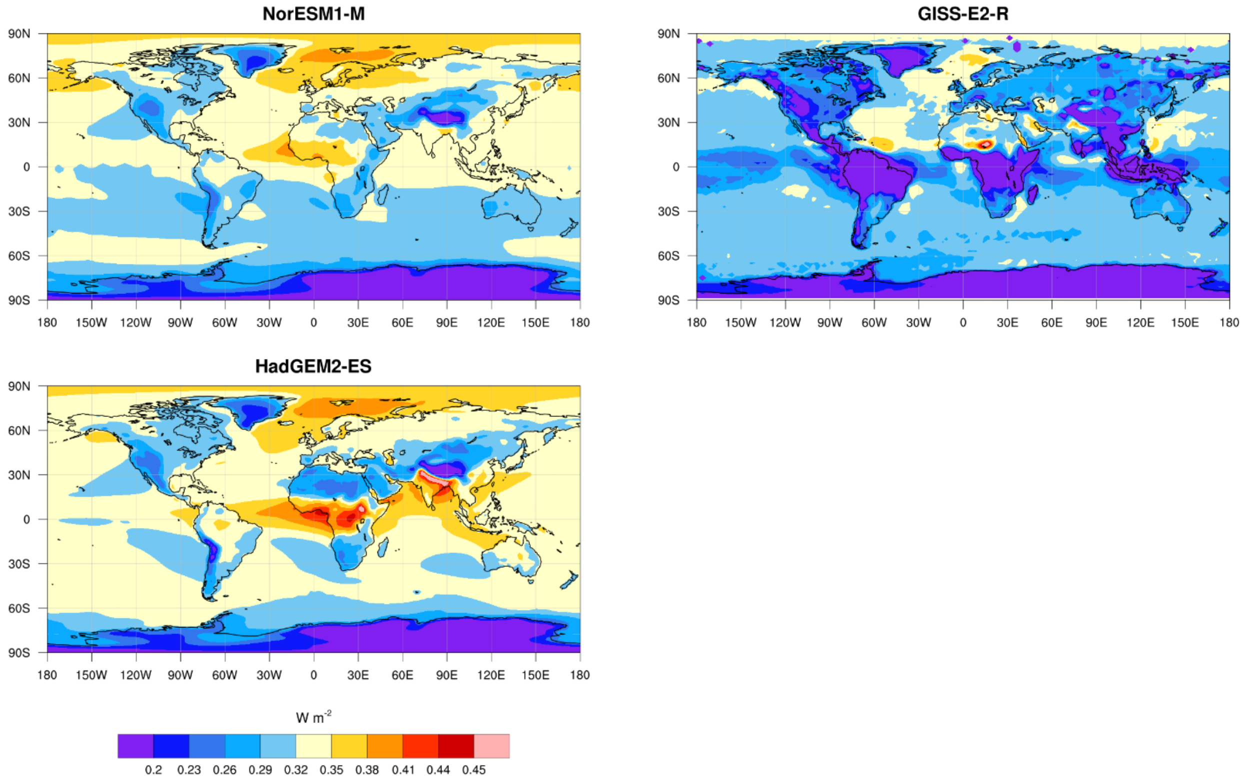

Figure 2. Mean clear-sky optical depth of the atmosphere for RCP4.5 between 2035 and 2065 for a) NorESM1-M, b) GISS-E2-R, and c) HadGEM2-ES.

When it comes to the processes listed by the reviewer, dry deposition of the injected particles should be slightly faster in GISS-E2-R than in the other two models, since the injected particles are larger in GISS-E2-R, which implies somewhat higher dry deposition velocities due to more efficient interception and impaction, and even gravitational settling for the largest particles. Vertical mixing is more efficient in NorESM1-M than in the other models, but this is likely of minor importance for the clear-sky ERF, although it may be relevant for the aerosol direct effect if a fraction of the injected sea salt particles can be transported above the stratocumulus layers.

However, the main reason that the somewhat smaller particle surface injections in GISS-E2-R still generates a clear-sky ERF as large as the other two models (or even slightly larger) is likely due to GISS-E2-R having the lowest background clear-sky atmospheric optical depth of the three models (Fig. 2). This means that GISS-E2-R is more sensitive to injections than the two other models. The lower clear-sky atmospheric optical depth in GISS-E2-R is at least to some extent related to lower background sea salt concentrations. The background sea salt mass concentrations within the injection area for RCP4.5 (2035-2065) at the lowest model layer are 14.4, 7.9, and 54.1 µg m^{-3} for NorESM1-M, GISS-E2-R, and HadGEM2-ES, respectively. The impact of mineral dust outflow from Africa over the Atlantic Ocean on the clear-sky optical depth (Fig. 2) is also less pronounced in GISS-E2-R than in the other two models, which should also contribute to a higher sensitivity to sea salt injections in GISS-E2-R. Some of this discussion has been added to the updated version of the manuscript.

Minor comments

Comment #1

Page 2, line 31 – Should this be "an uncertainty" rather than "the uncertainty"?

Response:

Thanks, we have changed this.

Comment #2

Page 4, line 32 – Perhaps use "low-cloud amounts".

Response:

Thanks, changed.

Comment #3

Page 5, lines 24-25 - How frequent are clear-sky conditions in each model?

Response:

This is a relevant question because if there were large regions frequently dominated by clear-sky, it would not be surprising that the ERF by the injected particles in these areas are similar in total and in clear-sky conditions. However, from Fig. 1 in the paper (Fig. 2 in the updated version) we know that almost everywhere within the injection area, the mean cloud fraction of low-level clouds is larger than 40% and 30% in NorESM1-M and HadGEM2-ES, respectively. As mentioned in the manuscript, the low-level cloud fraction is considerably smaller in GISS-E2-R than in the other two models.

As we only have cloud cover model output as monthly mean values, it is not possible to tell how frequent clear sky conditions are. During a period of a month, there will be days with clouds in all locations which implies that the monthly mean cloud fraction is never zero in any marine location. However, Fig. 2 below shows the percentage fraction of all months between 2035 and 2065 with a total cloud fraction less than 50% within the injection area for RCP4.5 for the three models. As seen in the figure, months with a mean total cloud fraction below 50% are most frequent in HadGEM2-ES. Note that the total cloud fraction includes cloud layers at all heights. If only low-level clouds are included, GISS-E2-R has the highest frequency of low cloudiness, as discussed in Sect. 3 in the paper.

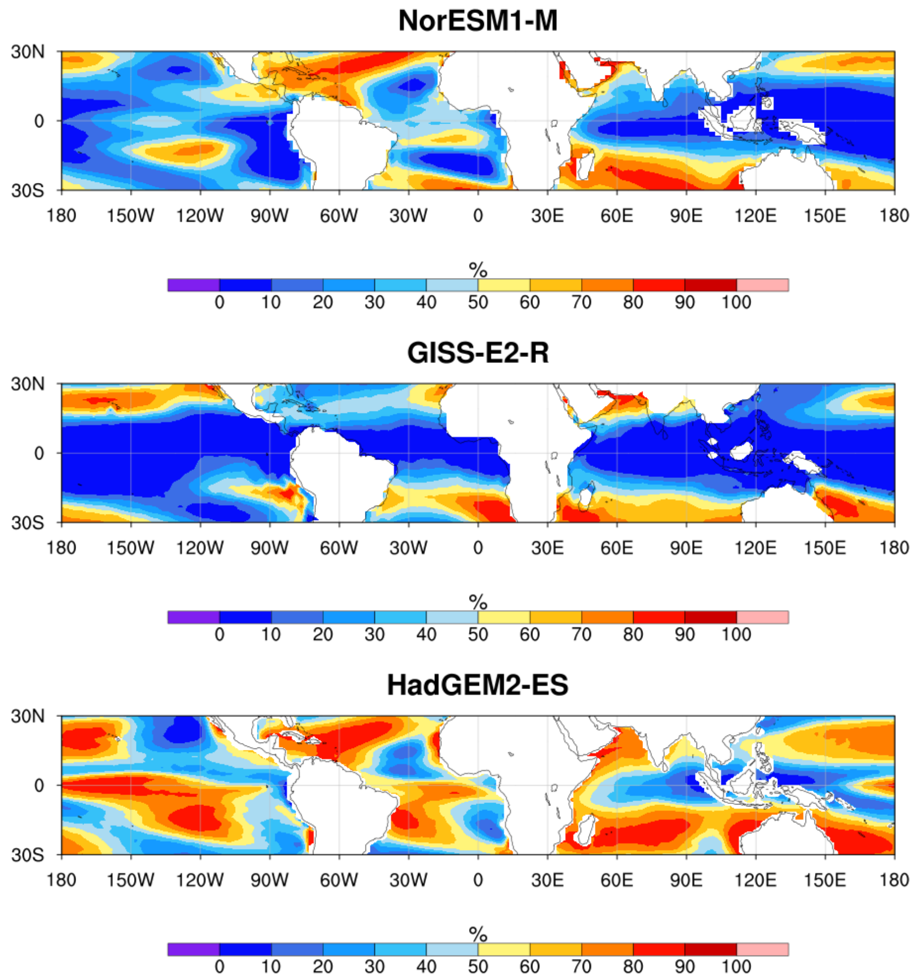

Figure 2. Percentage of all months between 2035 and 2065 with a mean total cloud cover below 50% in the injection area for NorESM1-M, GISS-E2-R, and HadGEM2-ES.

Comment # 4

Page 7, lines 11-12 and Figure 4 - Is it truly increasing or just altering the mechanism, since the ERF-TOF is held constant?

Response:

We do not fully understand this comment by the reviewer. What is held constant is the sea salt injection rates. These constant injection rates generate an ERF that is more or less constant with time. The global-mean clear-sky ERF is not held constant at a certain value, but happens to be almost equal in magnitude to the global-mean cloudy-sky ERF. However, the fact that the global-mean total ERF is almost equal to the corresponding clear-sky ERF does not imply that these are equal in all locations. In the subtropical high pressure cells, the presence of low-level clouds increases the regional ERF compared to clear-sky conditions, in particular in HadGEM2-ES. In contrast, closer to the equator the presence of high-level clouds decreases the ERF compared to clear-sky conditions, in particular in GISS-E2-R.

Comment #5

Page 7, line 31 - It would be more instructive to include changes in number concentrations of sea-salt particles.

Response:

We agree with the reviewer. Unfortunately, the particle number concentration is only diagnosed in NorESM1-M, which is the reason why this variable is not shown in the paper. The change in number concentration due to sea spray climate engineering in NorESM1-M is shown in Fig. 3 below. As can be seen in this figure, the sentence that the reviewer refers to in the manuscript ("In NorESM1-M (Fig. 5a), comparatively large increases in sea salt concentration occur in the subtropical high pressure regions") is valid also for the particle number concentration.

Comment #6

Page 8, lines 11-14 - What are the ranges of background CDNC in each model? Why does CDNC over northern Greenland reduce so much in NorESM, and over the high Arctic in HadGEM2?

Response:

The background CDNC within the injection area at an altitude of ~1000 m averaged over 2035-2065 for RCP4.5 varies for NorESM1-M from 10-20 cm^{-3} in the remote areas of Pacific and reaches a maximum of ~100 cm^{-3} south of Mexico, west of Northern Africa, south-east of China, and over the northern parts of the Indian Ocean. HadGEM2-ES has its maxima in CDNC at similar locations within the injection area. However, HadGEM2-ES has somewhat higher concentrations with a typical CDNC of 20-40 cm^{-3} in the remote Pacific Ocean and CDNC reaching 250 cm^{-3} at coastal locations closer to continental sources. GISS-E2-R has higher background CDNC than the other models with concentrations of 50-100 cm^{-3} in the remote Pacific Ocean and concentrations higher than 1000 cm^{-3} in some coastal regions influenced by continental sources. Whereas NorESM1-M and HadGEM2-ES predict CDNC close to estimates using MODIS data for cloud top CDNC (e.g. Wood, 2012), GISS-E2-R predicts higher background CDNC than estimated from MODIS. The relatively high background CDNC in GISS-E2-R is the reason for the smaller percentage increase in CDNC due to sea spray climate engineering in GISS-E2-R compared to the other two models.

Concerning the reduction in CDNC over the Arctic region in NorESM1-M and HadGEM2-ES, the variable CDNC represents the number concentration of cloud liquid water particles in the air, and the CDNC is lower than 1 cm^{-3} over Greenland in NorESM1-M and just slightly higher than 1 cm^{-3} in HadGEM2-ES. Thus, a very small absolute change in concentration can result in a very large relative change in CDNC. The explanation for the reduction in CDNC is probably that the G4sea-salt experiment results in a cooling of the Arctic region, which implies less liquid water in the clouds over e.g. Greenland. Another mechanism for the reduction of CDNC in the Arctic is also related to the cooling induced by the sea-salt: the cooling increases the sea-ice cover in the Arctic and therefore reduces the source of natural sea salt and Dimethyl sulphide (DMS), both of which cause a reduction in CDNC. We have added this information to the manuscript.

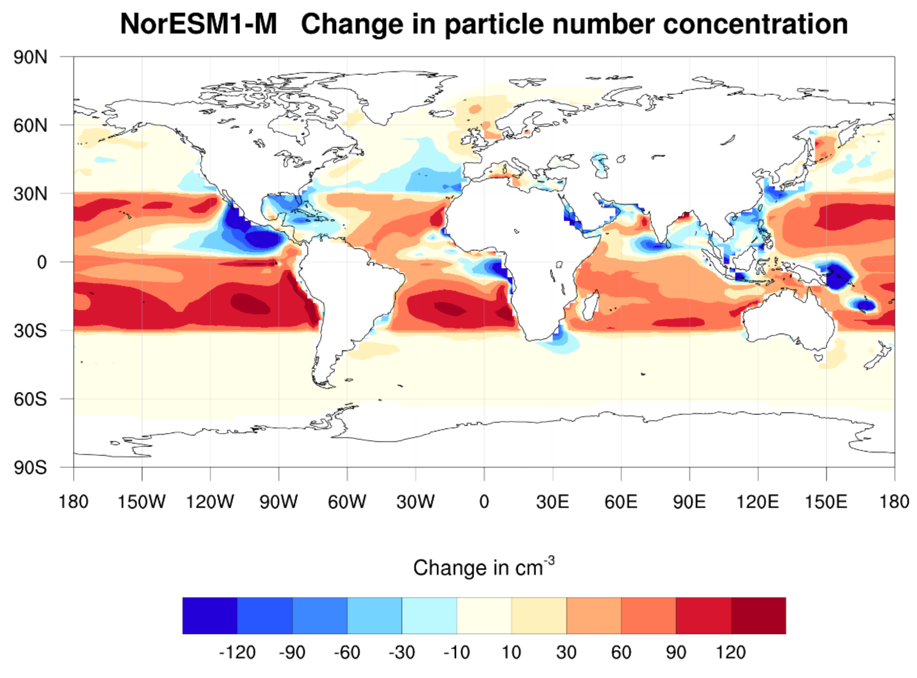

Figure 3. Difference in particle number concentration between G4sea-salt and RCP4.5 in NorESM1-M averaged over the period 2035-2065.

Comment #7

Page 9, lines 8-10 - Of course the relative impact of LWP is well known. What would be helpful is to know how Figures 9c and 9d compare with observations, if there are sufficient data to do that.

Response:

The point we want to make with Fig. 9 is that for these long time scales (sea spray climate engineering for 15-45 years), changes in the atmospheric circulation and the resulting changes in LWP will be the main controller of the cloud optical depth in a certain location, rather than changes in CDNC. Therefore, this is not something that can be compared to observations.

Comment #8

A note - Sea salt particles of 0.88 um diameter (GISS) or larger will be very hard to activate (by definition) in clouds. To reach their activation point they need to take up a very large amount of water, and that may not happen.

Response:

We agree with the reviewer that the aerosol indirect effect would likely be favoured by injections of particles with a smaller size than those injected in GISS-E2-R. However, a benefit of applying somewhat varying sizes for the sea salt injections in the different models is that it allows us to incorporate a study of model spread in our analyses.

References

Wood, R.: Stratocumulus clouds, Monthly Weather Review, 140, 2373-2423, 2012.