# Anonymous Referee #1

General comments

"Climate engineering and the ocean: effects on biogeochemistry and primary production" by Lauvset et al. provides a single-model assessment how three different climate engineering methods (stratospheric aerosol injections, marine sky brightening and cirrus cloud thinning) affect ocean biogeochemistry. This is one of the first studies on the topic and comparing different methods within the same model is a valuable addition to previous works. They concentrate on four key variables in ocean biogeochemistry: sea surface temperature, oxygen, pH and net primary production. For NPP, they complement the interactive Earth System Model simulations with offline calculations that make possible to disentangle different drivers of NPP change. This method adds to the value of the manuscript, although I have some concerns and questions about the method (see specific comments). The manuscript is mostly clearly structured and written, and thus easy to read. However, some more commas when dependent clauses start sentences would enhance readability. For example, I would insert a comma in "When only phytoplankton concentration is allowed to vary temporally in the offline calculation there is a decrease of ~8% by 2100 in RCP8.5." (Lines 369-371) and similar sentences. Also, the use of present tense throughout the manuscript differs from the general practice of using past tense to describe the results and methods. Overall, I would recommend this manuscript for publication if my comments below are adequately addressed.
**Thank you for this nice summary and comments about the manuscript. Since the results and discussion are combined into one section we feel that present tense is the most appropriate. The tense has been changed in the methods section.**

Major comments

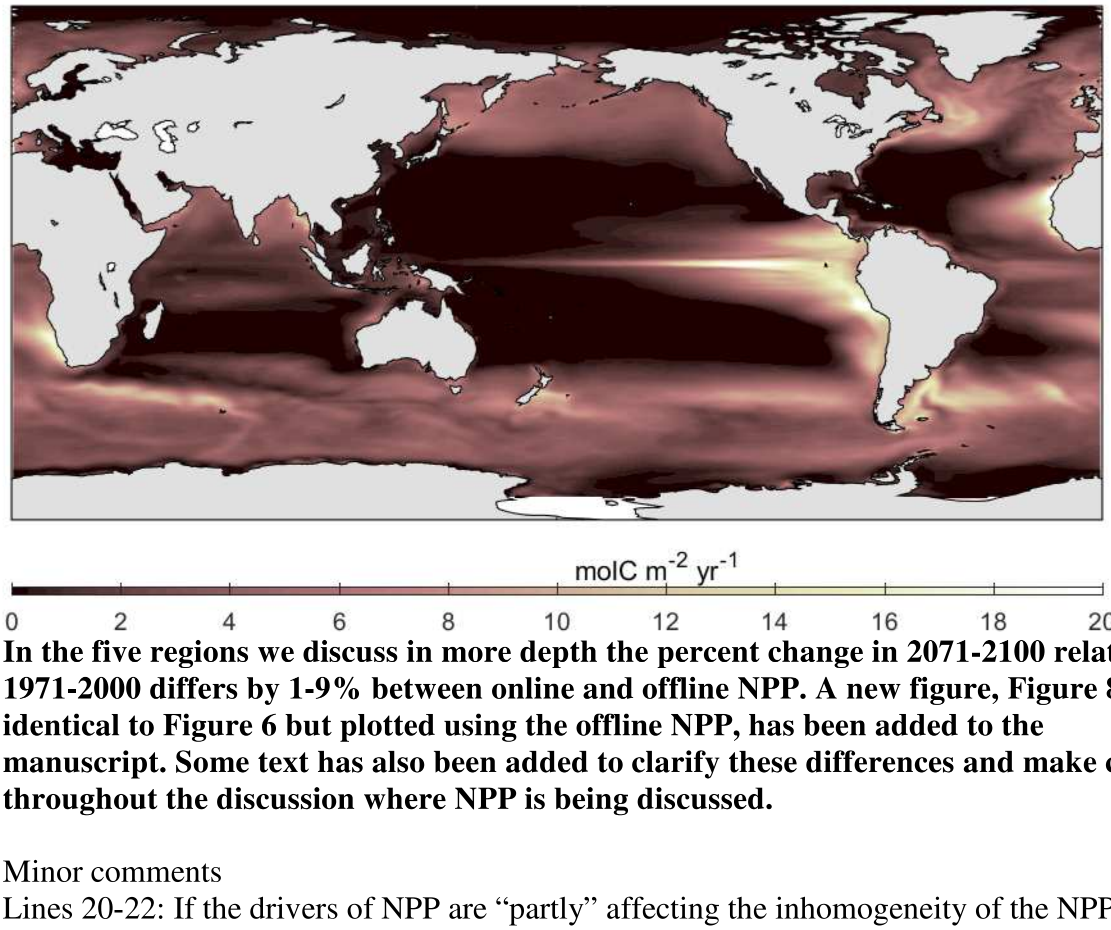
The offline model for NPP calculations needs more precise explanation and evaluation. In Lines 139-149, you imply that monthly-mean values are used for nutrients. On the other hand, on Lines 362-364 you write that phytoplankton concentration is used as a proxy for nutrient availability. Moreover, on Line 417, phytoplankton concentration is said to be a proxy for circulation changes. The last two statements are in my understanding consistent with each other (but it would be good to explain explicitly why they are related), but please clarify how the first statement of monthly-mean nutrient fields should be understood.
**Upon rereading these sections we see that our description of both the method and the interpretation of results could have been better. We believe some of the confusion comes from the difference between phytoplankton growth rate and primary production, and the text has been revised to clarify this. The growth rate of phytoplankton is a function of temperature, light, and the concentration of the limiting nutrient (in our case either nitrate, phosphate, or dissolved iron). The growth rate is expressed as the first two terms in Equation 1 in the original paper [$r(T,L)*(N/(N+N_0))$]. In this equation, monthly mean nutrient data from the model are used. As is seen from this formulation, any change in the limiting nutrient has a very small impact on the growth rate. NPP is the growth rate multiplied by the phytoplankton biomass (expressed as a concentration), i.e. Equation 1 in entirety. To help clarify this we have, in the revised paper, split Equation 1 into one equation for growth rate and one for NPP.**

Also, doesn't NPP significantly affect phytoplankton concentration? Using phytoplankton concentration to calculate NPP sounds circular reasoning to me and I see a risk that the method overestimates the contribution of circulation changes to NPP changes. For example, if temperature increased phytoplankton in the online simulations and this in turn increases NPP in offline calculations, don’t you attribute this increase to circulation in the offline calculations instead of to temperature?

**The reviewer is correct, and we appreciate this being pointed out. As described above, NPP is driven by temperature, light, nutrient and phytoplankton concentrations. Since the last two drivers depend on each other, in the revised manuscript, we have quantified the changes in NPP (i.e., through the offline calculation) due to changes in temperature, light, and residual parameters. The residual term is approximately represents an integrated circulation-induced changes in phytoplankton and limiting nutrient as described in the revised manuscript. We believe this will avoid confusions on the ‘circular effects’ as the reviewer pointed out.**

I think it would also be good to provide some short evaluation of the offline NPP calculation method to show whether it provides similar results as the online calculation. The value of offline calculations is to disentangle different drivers of NPP change, but how well does the offline version compare to online version when all drivers are accounted for (both regionally and at global mean level)? Specifically, comparing Fig. 5 to Fig. 7a would be helpful.

**We agree with the reviewer that comparing the offline NPP with the online is useful. Given the method used to calculate NPP offline (see my reply above) we expect there to be some differences between the offline and online estimates. The figure below shows a comparison between the 2006-2020 NPP in the model and the 2006-2020 NPP calculated offline. In 2020, the offline global average NPP is 75% of the online global average. Text has been added to the revised manuscript to reflect this comparison.**



**In the five regions we discuss in more depth the percent change in 2071-2100 relative to 1971-2000 differs by 1-9% between online and offline NPP. A new figure, Figure 8, identical to Figure 6 but plotted using the offline NPP, has been added to the manuscript. Some text has also been added to clarify these differences and make clear throughout the discussion where NPP is being discussed.**

Minor comments

Lines 20-22: If the drivers of NPP are “partly” affecting the inhomogeneity of the NPP changes, what is responsible for the rest of the inhomogeneity?

**We agree with the reviewer that this sentence was unclear and have revised to:**

**"The spatially inhomogeneous changes in ocean NPP are related to the simulated spatial change in the NPP drivers (incoming radiation, temperature, availability of nutrients, and phytoplankton) depending in the RM methods." In addition, we have added some text with concrete examples of how the different RM methods affect NPP differently.**

Line 93: Spell out SST as it's used here for the first time.
**Done**

Line 118 and throughout the manuscript: You apparently use NPP and primary production interchangeably. I would recommend using NPP (shorter and more precise) everywhere consistently or explain if there is some subtle difference between NPP and primary production in the manuscript.
**Done**

Line 165: I think it would more precise to say that you scaled AOD to match the level of a 20 TgS/year injection as you don't explicitly model the aerosol injection here.
**The text has now been clarified to:**
**"As the NorESM1-M model does not include an interactive aerosol scheme in the stratosphere, the dataset of Tilmes et al. (2015) was used. The stratospheric zonal aerosol extinction, single scattering albedo and asymmetry factors resulting from $SO_2$ injections in the tropics were prescribed such that the prescribed aerosol layer in year 2100 corresponds to an $SO_2$ injection strength of 40 Tg $yr^{-1}$ (Muri et al. 2017)."**

Line 172: Maybe good to say here explicitly that the other two methods had -4.0 W m-2 forcing.
**Done**

Line 193: SST should be defined on Line 93 already. Maybe not necessary to repeat it here.
**Done**

Lines 207-209: You use a high emission scenario. I would add that RM does not prevent long-term impacts in a scenario where CO2 emissions don't go to net zero. If they did, the situation would probably look a lot different.
**Done.**

Lines 230-232: Are there many areas where changes are greater with RM than without? If the results in RCP8.5 with RM are spatially highly variable, the changes can't be attributed to RM.
**We are unsure what the reviewer asks here since Figures 2, 3, and 6 all show the spatial variability in changes incurred by adding RM to RCP8.5. As shown in Figures 2 and 3, RM induced changes are always smaller, or in a few cases in the opposite direction, than the results in the RCP8.5 reference simulation. We have rephrased "(…) possibly lead to new and detrimental (…)" to now read "(…) still lead to similar albeit weaker detrimental (…)"**

Lines 291-292: I'm not sure what this sentence means. What is smaller than in RCP8.5? The exhibited decrease of NPP or the changes in NPP in RM simulations? Please, clarify.
**The temporal decrease in global ocean NPP is smaller in experiments with RM than in RCP8.5. The sentence has been rewritten for clarity and now reads:**

**"All RM methods also exhibit decreases in ocean NPP, but the decrease is never as strong as that in RCP8.5."**

Line 332-334: Isn't the increase in NPP with CCT only present in offline calculations? In Fig. 5, NPP decreases in all simulations, and I think the online calculations are more reliable.
**Yes, this is present only in the offline calculations and it is right that the online calculations are more "correct". However, on lines X-Y (previously 332-334) it is the results from the offline calculation that are being discussed. This is now clarified in the text which now reads:**
**"In fact, CCT results in an increased productivity by 2100 (Figure 7a) in the offline calculation". While we agree that this statement was misplaced, we maintain that the effect of CCT on NPP is an interesting result and have moved this discussion to section 3.3.**

Line 363: As discussed earlier, please explain here or elsewhere what you mean by using phytoplankton as a proxy for nutrient availability.
**See earlier reply.**

Line 378: Is this section based on online of offline NPP calculations? If you use only offline calculations, could you provide some evaluation how well the offline results match the online results at regional level?
**Since the online NPP cannot be decomposed into its individual drives this section is based entirely on the offline calculations. This is clarified in the text, which now reads "For a more detailed analysis, five regions have been identified and analyzed based on the offline calculations of NPP and its drivers."**
**We have evaluated how the offline calculated NPP compares to the online model output. Depending on region, the total percent change in 2071-2100 relative to 1971-2000 differs by 1-9% between online and offline. The online change is higher in 3 of the 5 regions, while offline changes are higher in the remaining 2 regions. The new Figure 8 allows for comparison between the spatial variations of the online and offline NPP.**

Line 388-390: What do you exactly mean by being consistent with CMIP5? Consistent with the sign of model ensemble mean or do all CMIP5 models give the same sign for these regions?
**Our results are consistent with the CMIP5 model ensemble mean. This has been clarified in the text.**

Lines 403-409. Why higher NPP would not lead to higher fish catches but lower NPP would decrease fish catches? Is this based on some dynamics of the ecosystem or are you just more careful to predict any increases than to predict decreases?
**NPP is the building block of the food web. It is therefore straight forward to predict that if this decreases there is less food for all higher trophic levels. It is not, however, as straight forward to predict what happens to higher tropic levels if NPP increases. In addition, higher tropic levels in the ocean is more than just fish. We have reworded this section for clarity, and added the following statement: "The IPCC-AR5 states that due to lack of consistent observations it remains uncertain how the future changes in marine ecosystem drivers (like productivity, acidification, and oxygen concentrations) will alter the higher trophic levels (Pörtner et al., 2014)."**

Lines 411-414: Splitting this to several sentences would make it easier to understand. Also, “do” on Line 413 seems redundant.

**Done**

Line 422: I don’t understand what you mean by “Radiation changes become more important in driving changes with RM”.

**The reviewer is correct that this was a poorly worded sentence. The sentence is now revised for clarity and reads: “When RM is applied, shortwave radiation changes at the surface become more important in driving NPP changes than they are in RCP8.5 and RCP4.5”.**

Line 463: Why is this unusual? Compared to what? Doesn’t increased temperature lead to increased NPP in other regions as well?

**The unusual part is how large the temperature component is. The sentence has been revised for clarity and now reads: “The temperature changes lead to an unusually large, compared to other regions, increase in ocean NPP of 4% in 2121-2150 in all experiments.”**

Line 467: Considering the low number of previous studies on the topic, could you write something about the results of Hardman-Mountford et al (2013) that you mention in the introduction? I know that comparing an ESM to single-column model is challenging, but it would be interesting to know how the results compare.

**A brief description of the Hardman-Mountford et al (2013) results and how they compare with our study has been added at the beginning of section 3.6 (before the comparison with Partanen et al (2016)).**

Lines 494-497: I would add here that the potential interaction of SST and the clouds is missing in Partanen et al. (2016). Their forcing is calculated with an AGCM that has a fully interactive aerosol scheme and takes thus into account interactions with clouds and sea salt aerosol, but with prescribed SST, the model might miss some relevant feedbacks.

**Thank you for pointing this out. A comment on this has been added: “Partanen et al. (2016) take their SRM forcing from Partanen et al. (2012), which use an atmosphere only version of their model and hence neglect important feedbacks, including SST/ocean feedbacks. Partanen et al. (2016) furthermore prescribe their SRM forcing in terms of changes to the radiation, and hence miss out on further feedbacks, that we include in our fully coupled Earth system simulations. E.g., as seen in Ahlm et al., (2017) and Muri et al. (2017), MSB may lead to an increased sinking of air over the oceans and hence a reduction in cloud cover.”**

Lines 497-500: Could you speculate, what are the implications of using a high emission scenario (RCP8.5) instead of a low emission scenario (RCP4.5)?

**Generally, the global mean and rate of change of ecosystem drivers in RCP4.5 are smaller than RCP8.5 (Henson et al., 2017). Applying the same RM forcing on RCP4.5 projection would yield a global mean state that is closer to the pre-industrial state with model-dependent regional variations. A short sentence has been added reflecting this.**

Table 2: I would write that AOD is modified to reflect a sulphur injection not to give an impression that the sulphur injection is calculate online in the current study.

**The table has been updated with a more precise definition of the experiments.**

Figure 2 and other maps: Could you move labels a,b,c,… outside the plots? They are a bit hard to see and I first thought they were missing altogether.
**Done**

All line plots: The lines are a bit hard to tell apart. I know that with so many overlapping lines it's hard to make them easy to distinguish, but I think there could be some room for improvement using dashed lines or slightly thicker lines or something.
**We have altered the figures slightly so that they now, hopefully, are easier to read.**

Figure 5. The legend is missing. Also, why is there a gap in the line of CCT around 2100?
**The gap is a glitch in the making of a .png figure, it does not exist in the higher quality .pdf figure. The .pdf version will be included in the revised submission. The legend is added.**

Figure 6: Standard deviation of what? Inter-annual variability of annual means of the reference period?
**One standard deviation is defined as the standard deviation of the mean of the 1971-2000 period in the historical run. This is now clarified in the text and in all relevant figure captions.**

Figure 7. Could the legend be included in sub figure a already?
**Done.**

Technical corrections – **All have been changed accordingly.**
Line 34: temperatures -> temperature
Line 39: I think "induced" is redundant here.
Line 235: continue -> continues (if you keep the present tense)
Line 408: decreases -> decrease
Lines 472-473: A verb is missing. (in -> are ?)

## Anonymous Referee #2

The manuscript by Lauvset at al. analyses the effects of three proposed solar radiation schemes for geo-engineering on ocean carbon cycling (CC) and net primary productivity (NPP), using a fully coupled earth system model which includes an aerosol and a radiation scheme, a description of atmospheric and oceanic circulation, and land and ocean biogeochemical models. The question investigated is highly relevant, both for understanding possible feedbacks in the system (changes in radiative climate forcing incurred by changes in oceanic carbon uptake) and for possible effects of (engineered or un-engineered) climate change on food security: primary production of the ocean can serve as a (admittedly crude) measure of possible fisheries yields. Three geoengineering schemes, all affecting the radiation balance, two mainly on the incoming shortwave radiation, and the third mainly on the outgoing long-wave radiation are applied in this study, in such a way that globally they all lead to a reduction of the radiative flux by 4 W $m^2$, bringing the radiative forcing of the RCP8.5-scenario down to that of RCP4.5. In addition to these coupled model runs, the manuscript uses offline calculations to investigate which factors drive changes in NPP. These

help in interpreting the results, but as outlined further below I have some issues with the methodology here.
Overall, this is a well thought-through study, the results are relevant, and the manuscript is besides some minor points very well written. I would therefore support publication in Biogeosciences after addressing the points listed below.

Major comments
The description of the offline calculations (lines 139 ff) is missing important information, and also some justification. To me it is not clear at all to which equations the expression ’makes use of the same set of equations as the online calculation’ (line 141) refer to: Does the offline model consider three-dimensional transport (advection and diffusion) of the non-prescribed equations? Which equations exactly are those?
**We thank the reviewer for pointing out that our description of this method was unclear. Upon rereading we realize that it sounds like we have used an offline model, but this is not the case. We have merely performed a simple offline calculation using the output from the NorESM1-ME model. We took the monthly three-dimensional model output (x,y,depth) and put it into Equations 1-3 (in the revised version) to solve for NPP. We assumed a constant euphotic depth of 100m and therefore averaged the inventory over the top 100m for nitrate, phosphate, and dissolved iron to calculate the limiting nutrient in each month. We also used the average temperature in the top 100m and light was attenuated to 50m (in the middle of our depth layer). There are no other equations in our offline calculation than Equations 1-3. The text has been revised to clarify this method.**

Why is the light in the offline calculations attenuated to a constant depth of 50 m, is the offline model two- dimensional or does it resolve depth?
**No, we do not resolve depth. We calculate a value for NPP in the top 100m of the ocean and assume that the light at 50m is a good approximation of average light concentration over the 100m layer.**

One issue that I found particularly confusing in the description of the offline experiments is that N stands for the most-limiting nutrient (phosphate/nitrate/iron). But which nutrient is most limiting is likely to change in the online runs. Are all nutrients prescribed in the offline runs, is there a climatology of the most limiting nutrient?
**In the offline calculation, the most limiting nutrient is computed based on the monthly outputs of nitrate, phosphate, and dissolved iron concentrations. See also my reply above.**

I also have a similar problem with the interpretation of the results of the offline calculations as the first reviewer. The authors use phytoplankton biomass as proxy for assessing the impact of changes in nutrient supply to the euphotic zone due to changes in upper ocean stratification (lines 363-364). What one would really like to use as a control variable in these calculations is the vertical flux of nutrients. I see that nutrient concentrations are probably not a good tracer for this nutrient flux, since they are drawn down to limiting values (assuming sufficient light) regardless of the flux. But the phytoplankton biomass is also just an indirect indicator: Firstly it is also affected by other losses such as zooplankton grazing (as the authors also mention, line 366), to which I would add the sinking losses of biomass through aggregation and sinking: Assume that the only loss of phytoplankton was a quadratic loss through aggregation and sinking. Then biomass would be proportional to the square root of nutrient supply.

**The reviewer is correct and these are very good points. As explained in our reply to reviwer #1 we now calculate a residual term which approximately represents the integrated circulation-induced changes in phytoplankton and limiting nutrient. To a first order this term thus includes the advection of nutrients. The discussion is revised to reflect this. Unfortunately, the vertical fluxes of nutrients are not available as model outputs. And since the ocean model is based on isopycnic vertical coordinates, the computation of surface-deep exchange of nutrients is not straightforward.**

Also, phytoplankton growth rate is affected by both nutrients and temperature, which however is considered as a separate driver. To me it is thus nor completely clear how well these two factors can be separated with the offline experiments.
**This point was also raised by reviewer #1. We agree that the presentation of NPP variation due to changes in phytoplankton was confusing. We now only compute the total, temperature- and light-induced NPP variability, and discuss the residual. The residual term predominantly represents the NPP change due to circulation-induced changes in nutrient and phytoplankton. See also our reply to reviewer #1.**

A smaller question that I didn't find the answer to in the model description (lines 129-138), and that may affect the interpretation of the manuscript slightly, is whether the model considers direct effects of ocean acidification (line 536) on carbon cycling through the marine ecosystem, e.g. by reductions in calcification.
**No. In the HAMOCC model, calcification is indirectly determined by the silicate availability. In regions of high silicate, biogenic opal production dominates, and when silicate is low, calcium carbonate production dominates. In the interior ocean, ocean acidification induced changes in carbonate ion saturation governs the dissolution rate of calcium carbonate.**

Also, the description of how the different RM methods have been implemented in the model (Lines 163-173) is quite short: to me it was for example a bit unclear how the SAI scenario was modelled. It is said that a layer of sulfate aerosols was prescribed, but then the next sentence states an injection strength, which to me implies that the layer was not prescribed, but calculated as resulting from a balance between injection and some unclear losses.
**The description of the implementation of the RM methods has been clarified. We prescribed a layer in the stratosphere with optical properties representing an injection strength of 20 Tg(S) per year in year 2100, to offset -4.0 W m$^{-2}$. The aerosol layer was represented by stratospheric zonal aerosol extinction, single scattering albedo and asymmetry factors, as derived from the Tilmes et al. (2015) data set.**

Minor comments
Line 42: At least the CCT method does not act to 'increase the amount of solar radiation reflected' but rather to increase the loss of long-wave radiation passing through the atmosphere.
**This is true, and is the reason for our definition and use of the term Radiation Management (RM) on line 65.**

Line 66 ff: I found this sentence quite confusing: Is it maybe two sentences in one?
**The sentence is revised for clarity and now reads: "As pointed out by Irvine et al. (2016) there are several gaps in the research on the impact of RM on both global climate and the global environment, especially considering that only a few modelling studies to date systematically compare multiple RM methods."**

Line 100: contrary to the statement on line 100 I have not found any presentation of impacts on inorganic carbon in the manuscript, only impacts on air-sea carbon flux. They are of course closely related, but be precise.

**The reviewer are correct that we do not discuss changes in inorganic carbon content by itself, but we do discuss changes in pH as well as air-sea fluxes, which is a part of the inorganic carbon cycle. We agree this was unclear and now state that we look at changes in the inorganic carbon cycle (which is also the title of section 3.2).**

Line 138: It is stated that seawater carbonate chemistry formulation follows the OCMIP protocol. But which one, OCMIP 2 or 3? OCMIP 3 corrected a few smaller errors in the OCMIP 2 protocols.

**The model uses the OCMIP2 protocols and this is now reflected in the text.**

Line 223-225: This result could be emphasised a bit more, it shows why we need full coupled atmosphere-ocean-biogeochemistry models to study this type of effects

**It is indeed important to use full Earth system models to address the climate responses and implications of RM scenarios. The so-called "monsoon-like" response to the tropical and extra-tropical circulation as a result of the MSB forcing has been discussed in several papers before, and we will hence not spend too much time on it in this paper.**

Line 297: 'production' missing after 'increasing primary'

**This is now changed, and primary production is replaced with NPP throughout.**

Line 299-300: 'after termination it takes less than 5 years': What sets the timescale, the atmosphere (radiation), or the ocean biology?

**This timescale is set by the atmosphere. The ocean biology reacts to the (very) fast atmospheric response to termination of RM. We have added a sentence reflecting this.**

Line 327: 'Only CCT significantly changes..': Does that not contradict what has been said before? Maybe I did not understand what should be said here.

**This section discusses the offline calculations only, the results of which differ somewhat from the model experiment. The sentence is revised to clarify this and now reads: "For the top 100 m of the ocean, the offline calculation shows that only CCT significantly changes NPP compared to RCP8.5."**

Line 336-337: insert 'the' in 'once terminated, CCT method..'

**Done**

Line 441: Is 18 percent really a 'minor change' compared to 13 percent?

**Considering the uncertainties in NPP change I'd say these numbers are very similar. However, I agree with the reviewer that the statement may be misleading so "marginally" has been removed.**

Line 447 ff: This and the next paragraph talk about reduction on NPP; it would be clearer if the percent changes would therefore have a negative sign also.

**That is true and the paragraphs have been changed accordingly.**

Line 477: 'are quite different': It would be good to have a short summary of the differences, so the reader does not have to read Partanen et al. (2016) herself.

**This is a good suggestion from the reviewer and we have now added a brief description of the major differences between our results and those of Partanen et al (2016), as follows "Overall, the effects of MSB in this study and that of Partanen et al. (2016) are quite different. Spatially, Partanen et al. (2016) sees a very strong correlation between the regions where the MSB forcing was applied and the regions of strongest NPP change which is not apparent in this study. Temporally, the change in NPP in Partanen et al. (2016) comes in form of a relatively rapid decrease over the first ten years MSB is applied while in this study the change is more even throughout the period of MSB forcing."**

Line 563 ff, references: It the Ahlm paper still in the discussion forum or is there a citable full reference by now?
**A revision is now in review.**

## Short comment by R. SEITZ

In reaching their abstract's conclusion, ave the authors considered and compared to SRM models circumglobal natural albedo variations like those seen in the calcite belt or created by the extensive summer plactonic blooms that annually cover a significant percentage of Northern seas? The radiative forcings resultng from them may rival or exceed humanity's continental albedo footprint
**In this study we have only evaluated the effects and impacts of artificial albedo changes in the form of radiation management. The model we use, NorESM1-ME, also does not include albedo changes due to changes in plankton blooms so this is not possible to study with this particular model.**

# Climate engineering and the ocean: effects on biogeochemistry and primary production

Siv K. Lauvset[1], Jerry Tjiputra[1], Helene Muri[2],

[1]Uni Research Climate, Bjerknes Center for Climate Research, Jahnebakken 5, Bergen, Norway

[2]University of Oslo, Department of Geosciences, Section for Meteorology and Oceanography, Oslo, Norway

## ABSTRACT

Here we use an Earth System Model with interactive biogeochemistry to project future ocean biogeochemistry impacts from large-scale deployment of three different radiation management (RM) climate engineering (also known as geoengineering) methods: stratospheric aerosol injection (SAI), marine sky brightening (MSB), and cirrus cloud thinning (CCT). We apply RM such that the change in radiative forcing in the RCP8.5 emission scenario is reduced to the change in radiative forcing in the RCP4.5 scenario. The resulting global mean sea surface temperatures in the RM experiments are comparable to those in RCP4.5, but there are regional differences. The forcing from MSB, for example, is applied over the oceans, so the cooling of the ocean is in some regions stronger for this method of RM than for the others. Changes in ocean net primary production (NPP) are much more variable, but SAI and MSB give a global decrease comparable to RCP4.5 (~6% in 2100 relative to 1971-2000), while CCT give a much smaller global decrease of ~3%. Depending on the RM methods, t~~T~~he spatially inhomogeneous changes in ocean NPP are related to the simulated spatial change in the NPP drivers (incoming radiation, temperature, availability of nutrients, and phytoplankton biomass), but mostly dominated by the circulation changes ~~depending in the RM methods~~. In general, the SAI and MSB - induced changes are largest in

the low latitudes, while the CCT - induced changes tend to be the weakest of the three. ~~The spatially inhomogeneous changes in ocean primary production are partly linked to how the different RM methods affect the drivers of primary production (incoming radiation, temperature, availability of nutrients, and phytoplankton) in the model.~~ The results of this work underscores the complexity of climate impacts on ~~primary production~~NPP, and highlights that changes are driven by an integrated effect of multiple environmental drivers, which all change in different ways. These results stress the uncertain changes to ocean productivity in the future and advocates caution at any deliberate attempt for large-scale perturbation of the Earth system.

## 1 INTRODUCTION

Human emissions of carbon dioxide to the atmosphere is unequivocally causing global warming and climate change (IPCC, 2013). At the 21st United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties, it was agreed to limit the increase in global mean temperature~~s~~ to 2˚C above pre-industrial levels and to pursue efforts to remain below 1.5°C. Reaching this goal will not be possible without radical social transformation. Solar radiation management (SRM) has been suggested as both a method of offsetting global warming and to reduce risks associated with climate change, substituting some degree of mitigation (Teller et al., 2003, Bickel and Lane, 2009), or to buy time to reduce emissions (Wigley, 2006). Reducing the otherwise large anthropogenic~~-induced~~ changes in the marine ecosystem drivers (*e.g.*, temperature, oxygen, and primary production) could also be beneficial for vulnerable organisms that need more time to migrate or adapt (Henson et al., 2017). SRM is the idea to increase the amount of solar radiation reflected by Earth in order to offset changes in the radiation budget due to the increased greenhouse effect from anthropogenic emissions, *i.e.* a form of climate engineering – or geoengineering.

Here we have performed model experiments with stratospheric sulfur aerosol injections (Crutzen, 2006; Weisenstein et al., 2015), ~~and ~~marine sky brightening (Latham, 1990), and cirrus cloud thinning (Mitchell and Finnegan, 2009) applied individually. Stratospheric aerosol injections (SAI) would involve creating a layer of reflective particles in the stratosphere to reduce the amount of solar radiation reaching the surface. The most widely discussed approach to SAI is to release a gaseous sulfate precursor, like $SO_2$, which would oxidize to form sulfuric acid and then condensate to reflective aerosol particles (e.g. Irvine et al. 2016). Marine sky brightening (MSB) aims to reflect the incoming solar radiation at lower levels in the atmosphere. Here, the idea is to spray naturally occurring sea salt particles into low-lying stratiform clouds over the tropical oceans to increase the available cloud condensation nuclei, thus increasing the concentration of smaller cloud droplet and increase the reflectivity of the clouds (Latham, 1990). The sea salt aerosols are reflective in themselves (*e.g.*, Ma et al., 2008), adding to the cooling potential of the method. Cirrus cloud thinning (CCT) on the other hand, aims to increase the amount of outgoing longwave radiation at the top of the atmosphere. This is envisioned done by depleting the longwave trapping in high ice clouds by seeding them with highly potent ice nuclei (*e.g.*, Mitchell and Finnegan, 2009; Storelvmo et al., 2013). In the absence of naturally occurring ice nuclei, the seeded material would facilitate freezing at lower supersaturations, enabling the growth of fewer and larger ice crystals. These would eventually grow so large that they sediment out of the upper troposphere reducing the lifetime and optical thickness of the cirrus clouds leading to a cooling effect. Together these three methods are referred to as Radiation Management (RM).

As pointed out by Irvine et al. (2017~~6~~), there are several gaps in the research on the impact of RM on both global climate and the global environment, especially considering that only a few modelling studies to date systematically compare multiple RM methods. Aswathy et al. (2015) and Niemeier et al. (2013) compared stratospheric sulfur aerosol injections to brightening of marine clouds in terms of the hydrological cycle and extremes in temperatures and precipitation. Crook et al. (2015) compared the three methods used in this study, but restricted the study to temperatures and precipitation. This study focuses on the impact on the ocean carbon cycle, which could feedback to climate~~has several potential climate feedbacks~~ (Friedlingstein et al., 2006), and in particular on ocean primary production (NPP), which is known to be temporally and spatially complex.

The effect RM has on the ocean carbon cycle and ocean productivity has been studied previously, but limited to the use of simple one-dimensional models (Hardman-Mountford et al., 2013) or with global models but focusing on a single method of RM (Partanen et al., 2016; Tjiputra et al., 2016~~5~~, Matthews et al., 2009). Due to the many uncertainties and open questions associated with RM impacts, a systematic comparative approach is necessary. The three different methods of RM used in this study are likely to have different effects on both the climate and the ocean, due to the differences in the type of forcing being applied. A~~n~~ ~~aspect~~ concern of RM is that it may allow for continued $CO_2$ emissions in the future without the accompanied temperature increases and that it does not directly affect the atmospheric $CO_2$ concentrations. Ocean acidification, a direct consequence of increased $CO_2$ concentrations in the atmosphere, would therefore continue with RM, unless paired with mitigation and / or carbon dioxide removal (CDR).

This manuscript is the first to evaluate and compare the effect and impact of multiple RM techniques on ocean biogeochemistry using a fully coupled state-of-the-art Earth system model, and furthermore extends previous studies by looking into impacts introduced by three different large-scale RM deployment scenarios both during and after deployment periods. It is also the first study to assess the impacts of cirrus cloud thinning on ocean biogeochemistry. Our focuses are on impacts on sea surface temperature (SST), oxygen, pH, and ~~primary production~~ ~~(~~NPP~~)~~, which are the four climate drivers identified by the Intergovernmental

Panel on Climate Change (IPCC), significantly affecting marine ecosystem structure and functioning. In a wider perspective, ocean ~~primary production~~NPP is often used as an indicator for marine food availability, such as fisheries, so furthering our understanding has direct societal implications and a strong connection to the United Nations Sustainable Development Goals.

The model and experiments are described in detail in Section 2, the impacts on ocean temperature, oxygen content, the inorganic carbon cycle, and NPP~~primary production~~ are presented and discussed in Section 3, in addition to a comparison of our results to previous studies, while Section 4 summarizes and concludes the study.

## 2 METHODS

### 2.1 Model description

Three RM methods ~~a~~were simulated using the Norwegian Earth System Model (NorESM1-ME; Bentsen et al., 2013). The NorESM1-ME is a fully coupled climate-carbon cycle model, which has contributed to the fifth assessment of the IPCC and participated in numerous Coupled M~~m~~odel I~~i~~ntercomparison P~~p~~roject phase 5 (CMIP5) analyses. For a full description of the physical and carbon cycle components of the model, the readers are referred to Bentsen et al. (2013) and Tjiputra et al. (2013), respectively. Here, we only briefly describe some key processes in the ocean carbon cycle that are relevant for this study.

The ocean carbon cycle component of the NorESM1-ME originates from the Hamburg Oceanic Carbon Cycle Model (HAMOCC; Maier-Reimer et al., 2005). In the upper ocean, the lower trophic ecosystem is simulated using an NPZD-type (Nutrient-Phytoplankton-Zooplankton-Detritus) module. The ~~primary production~~NPP depends on phytoplankton growth and nutrient availability within the euphotic layer (for some of our calculations assumed to be 100 m). In addition to multi-nutrient limitation, the phytoplankton growth is light- and temperature-dependent. The ~~net primary production~~NPP~~ (NPP)~~ in NorESM1-ME is parameterized using the equations of Six and Maier-Reimer (1996) (Equation 1).

$$G = r(T,L) * \frac{N}{N+No}$$ Equation 1

Where $G$ is the growth rate and

$$r(T,L) = \frac{f(L)*f(T)}{\sqrt{(f(L)^2+f(T)^2)}}$$ Equation 2

$N$ is the concentration of the limiting nutrient (either phosphate, nitrate or dissolved iron), $f(L)$ is the function determining light-dependency, and $f(T)$ is the function for temperature-dependency. Both $f(L)$ and $f(T)$ were defined in Six and Maier-Reimer (1996).

$$NPP = \cancel{r(T,L) * \frac{N}{N+No}} G * P$$

Equation 3~~1~~

~~where~~ $\cancel{r(T,L) = \frac{f(L)*f(T)}{\sqrt{(f(L)^2+f(T)^2)}}}$ ~~Equation 2~~

~~$N$ is the concentration of the limiting nutrient (either phosphate, nitrate or dissolved iron), $f(L)$ is the function determining light-dependency, $f(T)$ is the function for temperature-dependency,~~ where ~~and~~$NPP$ is the net primary production and ~~-~~$P$ is the phytoplankton concentration. ~~Both $f(L)$ and $f(T)$ are defined in Six and Maier-Reimer (1996).~~

In addition to the growth through NPP, the phytoplankton has several sink terms due to mortality, exudation, and zooplankton grazing. All nutrients, plankton, and dissolved biogeochemical tracers are prognostically advected by the ocean circulation. The model adopts~~ a~~ generic bulk phytoplankton and zooplankton compartments. The detritus is divided into organic and inorganic materials: particulate organic carbon, biogenic opal, and calcium carbonate. Organic carbon, once exported out of the euphotic layer, is remineralized at depth – a process that consumes oxygen in the ocean interior. Non-remineralized particles reaching the seafloor undergo chemical reactions with sediment pore water, bioturbation, and vertical advection within the sediment module. The model calculates air-sea $CO_2$ fluxes as a function of seawater solubility, gas transfer rate, and the gradient of the gas partial pressure ($pCO_2$) between atmosphere and ocean surface, following Wanninkhof (1992). Prognostic surface ocean $pCO_2$ is computed using inorganic seawater carbon chemistry formulation following the Ocean Carbon-cycle Model Intercomparison Project (OCMIP2).

In this study, we mad~~k~~e use of ocean ~~primary production~~NPP simulated by the~~calculations made both online by~~ NorESM1-ME ~~model~~ (hereafter referred to as “online calculations”), as well as ~~and~~ calculations using the monthly averaged model ~~results~~outputs (hereafter referred to as “offline calculations”)~~, using the monthly averaged output from the model~~. The offline calculations also mad~~k~~e use of ~~the same set of equations as the~~ Equations 1-3, same as the model,~~ online calculation~~, but unlike in the model (i), the average value over the top 100 m wa~~i~~s used for $N$, $T$, and $P$ alike; (ii) $L$ wa~~i~~s approximated as incident light at surface attenuated to a constant depth of 50 m; (iii) the monthly mean wa~~i~~s used for $N$, $T$, $L$, and $P$. The offline calculations allowed~~s~~ us to decompose and identify the dominant drivers for the simulated changes. The decomposition wa~~i~~s done by choosing to keep all but one parameter, $x$, constant at a time to quantify the contribution of~~ parameter~~ $x$ to the total change. Table 1 describes how this was done. The parameters being kept constant we~~a~~re kept at the long-term (80 year) monthly mean, as calculated from the pre-industrial model experiment (with constant atmospheric $CO_2$ concentrations).

### 2.2 Experiment setup

SAI, MSB, and CCT were applied individually to the RCP8.5 (Representative Concentration Pathway) future scenario (Table 2). The target of the simulations were to reduce the global mean top of the atmosphere (TOA) radiative flux imbalance of RCP8.5 down to RCP4.5. In each experiment, the forcing is applied over the years 2020 to 2100. To study the termination effect, the simulations we~~a~~re continued for another 50 years following the cessation of each RM method.

Here, the SAI, MSB, and CCT experiments are analyzed and compared to the RCP4.5 and RCP8.5 scenarios (Riahi et al., 2011; Thomson et al., 2011) (Table 2). All simulations we~~a~~re run with interactive biogeochemistry and used prescribed anthropogenic $CO_2$ emissions. The atmospheric $CO_2$ concentrations are therefore prognostically simulated accounting for land-air and sea-air $CO_2$ fluxes.

As the NorESM1-ME model does not include an interactive aerosol scheme in the stratosphere, the dataset of ~~Tilmes~~Niemeier and Timmreck~~ et al.~~ (2015) was used to implement the SAI. The stratospheric zonal sulfate aerosol extinction, single scattering albedo and asymmetry factors resulting from $SO_2$ injections in the tropics were prescribed such that the prescribed aerosol layer in year 2100 correspond~~s~~ to an $SO_2$ injection strength of 40 Tg $SO_2$ yr$^{-1}$ (Muri et al., 2017). ~~The SAI was implemented by prescribing a global layer of sulfate aerosols in the stratosphere, and the optical properties were taken from the ECHAM dataset described in Tilmes et al. (2015). The injection strength was scaled up to 20 TgS in year 2100.~~ The MSB follows the method of ~~Alterskjaer~~ Alterskjær et al. (2013), where the emissions on accumulation mode sea salt was increased over the oceans. Here we cho~~o~~se to apply this to a latitude band of ±45°. The tropospheric aerosol scheme is fully prognostic, thus allowing the full interactive cycle with clouds and radiation. As for the CCT, we adopted the approach of Muri et al. (2014), where the terminal velocity of ice crystals at typical cirrus forming temperatures of colder than -38 °C is increased. The maximum effective radiative forcing was found to be limited at about -3.8 W m$^{-2}$ for CCT, resulting in a somewhat higher top of the atmosphere (TOA) radiative flux imbalance in this simulation at 2100 compared to the other simulations, ~~in which~~where an effective radiative forcing of -4.0 W m$^{-2}$ in 2100 was reached.

# 3 RESULTS AND DISCUSSION

## 3.1 Global changes in ocean temperature and oxygen concentration

Relative to the 1971-2000 historical period, the ocean oxygen content in the 200-600 m depth interval is projected to decrease by ~6% globally in 2100 in RCP8.5 (Figure 1a). In RCP4.5 on the other hand, the ~~inventory of~~ oxygen inventory in the 200-600 m interval shows only a minor decrease of 2% by 2100 (Figure 1a). This difference stems partly from lower oxygen solubility as the ocean warms and partly from changes in ocean stratification and circulation (not shown). When applying RM to RCP8.5, the oxygen concentration in this depth interval follows the RCP4.5 development closely for all three RM methods (ranging from 2-2.6% decrease in 2100 compared to the 1971-2100 average). There are, however, differences between the methods, with SAI yielding slightly larger decreases after 2060 (Figure 1a). After termination of RM, the rate of oxygen reduction accelerates rapidly for the first ten years, before stabilizing at a new rate of decrease of similar magnitude to that in RCP8.5. The projected oxygen reductions do not drop as low as in RCP8.5 after termination of the RM during our simulation period, but had the simulations been continued for some further decades, the oxygen levels would most likely have converged to the RCP8.5 levels. In 2150, RCP8.5 shows a global mean oxygen decrease globally of 9.5%, while the simulations with terminated RM show a global mean oxygen decrease of 8-8.5% (Figure 1a).

In RCP8.5, the global mean ~~sea surface temperatures (~~SST~~)~~ are projected to increase by ~2.5 °C by 2100 relative to 2010 (Figure 1b), and ~3 °C relative to the 1971-2000 average. With RM, the changes in SST are kept similar to RCP4.5, with an increase ranging from 0.8

to 1.1°C over the time period between 2020 (start of RM deployment) and 2100 (end of RM deployment). After termination, there is a very rapid SST increase in the subsequent decade before the SST increases more gradually towards that in RCP8.5. Similar to the development in oxygen content, the absolute change in SST in the model runs with terminated RM is still smaller than the absolute change in RCP8.5 (Figure 1b) in 2150. This is mainly due to the slow response time of the ocean, so the SST would eventually converge had the simulations been carried out for a longer period of time after termination. It should be noted that all methods of RM used in this study have been implemented~~designed~~ to produce the global mean radiative forcing at the end of the century that is equivalent to offsetting the difference in the anthropogenic radiative forcing between ~~RCP4~~RCP8.5 and ~~RCP8~~RCP4.5, *i.e.* -4 W m$^{-2}$. This means that the globally averaged sea surface temperature changes, and changes in large-scale physical variables such as oxygen, are expected to be close to those in RCP4.5. The results presented here imply that applying RM does not prevent the long-term impacts of climate change, which is also not expected as long as $CO_2$ emissions are not simultaneously reduced, but would on average delay them. In the case of oxygen concentrations in the 200-600 m depth interval, the changes incurred in RCP4.5~~,~~ as well as when the three different methods of RM are applied, are mostly not significantly different ~~(*i.e.* they are smaller than one standard deviation)~~ from the 1971-2000 average (*i.e.* they are smaller than one standard deviation of the 1971-2000 mean, Figure 2). There are a few exceptions where the oxygen changes are significant. These regions, however, highlight how differently the RM methods affect the ocean.

The spatial absolute change in SST in 2071-2100 relative to 1971-2000 is shown in Figure 3b for RCP8.5 and Figure 3c for RCP4.5. The changes are significantly smaller in RCP4.5, but the spatial variations are the same in RCP8.5 and RCP4.5. When applying RM, the changes in SST are everywhere smaller than in RCP8.5 at the end of the century. ~~As~~

~~for~~Similar to thermocline oxygen, the spatial patterns are altered in some regions, as seen in the zonally averaged temperature changes (Figure 3a). The SAI method yields the temperature change most similar to that in RCP4.5, which is also mirrored in the near surface air temperatures (Muri et al., 2017~~in prep~~). MSB yields the SST changes that are most different compared to RCP4.5. For this method there is a strong bimodal pattern in the SST changes in the North Pacific (Figure 3e), which is also seen in oxygen (Figure 2e). The tropical and subtropical changes in SST with MSB are linked to an enhancement of the Pacific Walker cell, which is induced when MSB is applied, which has been found in previous studies such as Bala et al. (2011), ~~(~~Alterskjær et al.~~,~~ (2013),~~;~~ Ahlm et al.~~,~~ (2017), Stjern et al. (2017), and Muri et al. (2017).

Regardless of the RM method, some regions, in particular the northwestern Pacific, will still experience levels of warming (cooling) and oxygen loss (gain) exceeding those in RCP4.5. With SAI, the North American west coast, an important region for aquaculture, will, for example, experience enhanced deoxygenation, which is not projected to happen in RCP4.5. The large spatial heterogeneity in how RM affects ocean temperatures and oxygen concentrations highlights that RM can still lead to similar, albeit weaker, detrimental ~~possibly lead to new and detrimental~~ conditions regionally even if beneficial in the global mean.

### 3.2 Global changes in the inorganic ocean carbon cycle

The atmospheric $CO_2$ concentration continues to rise in all experiments in which RM is applied at ~~the same~~similar rate as in RCP8.5 (Figure 4a), given no simultaneous mitigation efforts in these cases. The atmospheric $CO_2$ concentration in 2100 in RCP8.5 is 1109 ppm and in 2150 it is 1651 ppm. In 2100 there is a minor reduction in $CO_2$ concentrations when RM is applied of 13 -21 ppm compared to RCP8.5, depending on method. MSB gives the largest decrease in atmospheric $CO_2$. The termination of RM does not significantly affect the atmospheric $CO_2$ evolution and in 2150 there is a marginal reduction of -15 to -26 ppm depending on method, again with MSB giving the largest reduction. The reductions in atmospheric $CO_2$ concentrations when applying RM are due to the decreasing ocean temperatures leading to larger air-sea flux of $CO_2$ (Figure 4b). Note that the land carbon sinks also increase slightly when RM is applied (Tjiputra et al., 2016, Muri et al., 2017). The lower $CO_2$ concentration with MSB is due to the forcing from MSB being applied over the oceans, and the cooling of the ocean in many regions thus being stronger for this method of RM (Figure 3e).

While RM leads to a small increase in global mean oceanic $CO_2$ uptake from the atmosphere, due to increased solubility, the difference introduced by each method is not outside of the interannual variability of RCP8.5 up to 2075. By 2100, the different RM methods give an additional $CO_2$ uptake of ~0.5 PgC $yr^{-1}$. After termination, the uptake anomaly quickly drops and returns to the same level as RCP8.5 within only two years. Future surface ocean pH is forced by the increasing atmospheric $CO_2$ concentrations, which drive the uptake of $CO_2$ in the surface ocean. Thus RM could possibly worsen future ocean acidification, unless atmospheric $CO_2$ concentrations are dealt with. However, given the small changes in both atmospheric concentrations and ocean uptake stemming from RM, the surface pH is not greatly affected by RM (Figure 4c). Hence, termination does not considerably affect the pH decrease on the surface ocean.

Anthropogenic changes in the ocean inorganic carbon content comes from the top down, so it takes a long time for these changes to be observable in the deep ocean. Therefore, the globally averaged deep ocean (>2000 m) pH changes by only 0.06 pH units between 2010 and 2150 in RCP8.5 (Figure 4d). The only region where pH changes significantly in the deep ocean is the North Atlantic north of 30°N, where the strong overturning circulation brings anthropogenic carbon to great depths in a relatively short timeframe. Here there is a significant decrease in deep ocean pH between 2010 and 2150 in RCP8.5, as well as the three RM cases (Figure 4e). In RCP8.5, the pH is projected to decrease by ~0.2 pH unit in 2100. RM leads to an additional acidification of 0.02-0.045 (depending on the method of RM) in the deep North Atlantic Ocean, which is large enough to marginally, but not significantly, affect the global average (Figure 4d). A similar result was found by Tjiputra et al. (2016~~5~~). After termination of RM, the pH keeps decreasing – now at a rate comparable to RCP8.5. This change in rate of decrease after termination happens within ~10 years, indicating that the changes in the inorganic carbon cycle are very quick in the North Atlantic. Both the rapid decrease of deep ocean pH in this region and the rapid recovery towards RCP8.5 development after termination of RM, are likely linked to changes in the Atlantic Meridional Overturning Circulation due to climate change and RM (not shown, see Muri et al., 2017~~in prep.~~). While the global mean pH below 2000m in RM experiments rebound to that of the RCP8.5, this is not the case for the North Atlantic. In the latter, all RM methods lead to and remain at lower pH than the RCP8.5 by 2150. It is possible~~likely~~ that the deep pH in the North Atlantic would recover to that in RCP8.5 had the simulations been continued for another few decades~~, but we have no way of analyzing how long that would take~~.

### 3.3 Global changes in ocean ~~primary production~~NPP

The direct effects of RM on surface shortwave radiation and temperature directly affect photosynthesis through the light and temperature dependence of the phytoplankton growth rate. The ocean productivity, and by extension ocean biological carbon pump, is thus indirectly affected by RM. There is a lot of interannual variability in the ~~primary production~~NPP changes hence Figure 5 shows the 5-year running averages of relative changes to the 1971-2000 average. In RCP8.5, there is a decrease in global NPP of ~10% by 2100

(Figure 5), which is within the range of the decrease projected by CMIP5 models of -8.6±7.9% (Bopp et al., 2013) and mainly due to the overall warming leading to a more stratified ocean where there are less nutrients available in the euphotic zone. All RM methods also exhibit decreases in ocean NPP~~primary productivity~~, but the~~se~~ decrease is never as strong as that~~ are all smaller than those~~ in RCP8.5. The shortwave-based methods, *i.e.*, SAI and MSB, which reduce the amount of downward solar radiation at the surface, have the largest decreases (~6% in 2100) of the RM methods, which is ~~more of a~~a stronger decrease than in RCP4.5. The longwave-based CCT method, however, yields only a minor decrease of ~3% in 2100, *i.e.* less than in RCP4.5. As the cirrus clouds are thinned or removed, more sunlight reaches the surface ocean, thus promoting and increasing NPP~~primary~~ above the RCP4.5 levels. ~~The divergence between methods is particularly strong in the period 2070-2100, as the radiative forcing by RM approaches -4 Wm$^{-2}$. After termination, it takes less than five years for the development of ocean primary production to return to RCP8.5 levels again.~~

The fact that CCT shows a significant global increase in ocean NPP relative to RCP8.5 and even an increase relative to RCP4.5 is a very interesting result of this study. It suggests that when considering the global ocean NPP changes alone, implementation of CCT may offer the least negative impact of the three tested methods. The side effect, however, is that ~~once~~if terminated suddenly at a large-scale deployment with no simultaneous mitigation or CDR efforts, the CCT method w~~e~~ould lead to the most drastic change in NPP over very short period. The divergence between methods is particularly strong in the period 2070-2100, as the radiative forcing by RM approaches -4 Wm$^{-2}$. After termination, it takes less than five years for the development of ocean NPP to return to RCP8.5 levels again. This is consistent with the rapid warming seen after termination (Figure 1b), and is driven by the fast atmospheric response to the termination.

On average there are some interesting spatial features in how ~~primary production~~NPP changes. Figure 6a shows the zonally averaged difference between 2071-2100 and 1971-2000. In the Northern Hemisphere, ~~primary production~~NPP decreases everywhere, and decreases less in RCP4.5 and with RM than in RCP8.5. In the Southern Hemisphere, on the other hand, the changes in ~~primary production~~NPP are much more spatially variable, and the response to the different methods of RM is more variable. Between the Equator and 40°S there is a reduction in ~~primary production~~NPP in 2071-2100 relative to 1971-2000, while south of 40° there is generally an increase (except in a narrow band at 60°S). In the Southern Hemisphere the impact of CCT is quite different from the impact of SAI and MSB. This is probably due to the change in radiative balance, which is much stronger for CCT in the southern high latitudes than for the other methods (not shown, see Muri et al., 2017~~in prep.~~). Because of the large spatial and inter-annual variability, the changes incurred to ocean ~~primary production~~NPP in the future are frequently not significantly different ~~(*i.e.* the absolute change is smaller than one standard deviation)~~ from the 1971-2000 average (*i.e.* the absolute change is smaller than one standard deviation of the 1971-2000 mean, Figure 6b-f). This means that when RM is applied, the ocean ~~primary production~~NPP does not change in most of the ocean. However, it is clear that the changes in ~~primary production~~NPP in 2071-2100 relative to 1971-2000 are smaller in RCP4.5 than in RCP8.5 (Figures 6b and 6c), and that the spatial variations in all experiments mainly come from the nutrient availability (not shown), which is furthermore dependent on ocean stratification. There are also some regions of significant change in ocean ~~primary production~~NPP, which are discussed further in Section 3.5.

### 3.4 Drivers of global changes in ocean ~~primary production~~NPP

To further evaluate how RM affects ocean ~~primary production~~NPP, we have made offline calculations using Equations 1-3. From the NorESM1-ME model ~~runs~~outputs we used ~~and~~ the monthly mean ~~model output of~~ nitrate, phosphate, iron, and phytoplankton concentration over the top 100 m, average temperature in the top 100 m, and shortwave radiation input attenuated to 50 m depth~~at the surface, as described in Section 2~~. The resulting offline NPP is therefore an approximation of the NPP in the top 100 m of the ocean. The offline global average is 75% of the full water column NPP inventory as simulated by the model, and spatially the offline calculated NPP is larger than the model output in oligotrophic regions and smaller than the model output in coastal and upwelling region as expected (not shown). In addition, the temporal rate of change is somewhat smaller for the offline calculated NPP (not shown). Note that the following results and discussion concerns only the offline NPP calculations and therefore only the top 100 m of the ocean. ~~For the top 100 m of the ocean,~~ The offline calculation shows that in the top 100 m only CCT significantly changes ~~primary production~~NPP$_{total}$ compared to RCP8.5. In fact, CCT results in an increased productivity by 2100 (Figure 7a) in the offline calculation, which is linked to the increase in the incoming~~ shortwave~~ solar radiation in some regions, since the shortwave reflection from ice clouds is reduced. After termination of CCT, the ~~primary production~~NPP$_{total}$ drops to the same level as RCP8.5 within two years. The RCP4.5 scenario yields little change by 2100. ~~The fact that CCT shows a significant global increase in ocean primary production relative to RCP8.5 and even a positive change at the end of the century is a very interesting result of this study. It suggests that when considering the global ocean primary production changes alone, implementation of CCT may offer the least negative impact of the three tested methods. The side effect, however, is that once terminated, CCT method could lead to most drastic change in primary production over very short period.~~

Warmer temperatures increase growth rates.~~-~~ Thus ~~primary production increases~~ when only temperature is allowed to change, $\mathrm{NPP}_{\mathrm{temp}}$ increases in the offline calculation (Figure 7b), as temperature increases in all scenarios considered here (Figure 1~~7~~b), even though less in simulations with RM than RCP8.5. All methods of RM yield an increase in ~~primary production~~$\mathrm{NPP}_{\mathrm{temp}}$ of ~1% from 2020 to 2100, comparable to RCP4.5~~, is allowed toin this calculation~~. This is consistent with SST being comparable between RCP4.5 and RM (Figure 1b). After termination, ~~the temperature-induced primary production~~$\mathrm{NPP}_{\mathrm{temp}}$ increases rapidly for the first five years, before stabilizing with the same rate of change as that in RCP8.5. Just like SST (Figure 1b), the absolute change in ~~primary production~~$\mathrm{NPP}_{\mathrm{temp}}$ does not quite recover to~~ the quite~~ the same absolute level as that in RCP8.5, but all simulations show an increase in ~~primary production~~$\mathrm{NPP}_{\mathrm{temp}}$ of ~3% by 2150.

Reduced shortwave radiation at the surface decreases growth rates and thus lead to decreased ~~primary production~~NPP. In RCP4.5 and RCP8.5, light constraints do not change much, hence when using the output from these experiments and only shortwave radiation changes in the offline calculation, ~~the primary production~~$\mathrm{NPP}_{\mathrm{light}}$ ~~also~~ does not considerably change~~ when only shortwave radiation is allowed to vary in the offline calculation~~ (Figure 7c). Both SAI and MSB decrease the amount of global mean direct shortwave radiation at the surface, however, which negatively affect the phytoplankton growth rate and ~~primary production~~$\mathrm{NPP}_{\mathrm{light}}$ in the ocean (Figure 7c). The result ~~of allowing only shortwave radiation to vary~~ is therefore a decrease in ~~primary production~~$\mathrm{NPP}_{\mathrm{light}}$ of ~2% by 2100 for SAI and MSB (Figure 7c). When reducing the optical thickness and the lifetime of the cirrus clouds in the model, the shortwave reflection by these clouds is reduced, allowing more shortwave radiation to reach the surface and increasing the growth rate. CCT thus results in an increase in ~~primary production~~$\mathrm{NPP}_{\mathrm{light}}$ of ~2% by 2100 (Figure 7c). It is this increase in available shortwave radiation that causes the majority of the increase in ocean productivity with CCT, with some contribution from the elevated temperatures (Figure 7b). Within two years of the termination of RM, the ~~simulated primary production~~NPP$_{light}$ has completely returned to the baseline conditions.

There cannot be any growth of phytoplankton without nutrients. However, changes in the concentration of the limiting nutrient (either phosphate, nitrate, or dissolved iron) has a small effect on the growth rate (not shown). NPP is the product of growth rate and phytoplankton concentration (Equation 2), but phytoplankton concentration is also a function of growth rate, as well as grazing, aggregation, and ~~sinking~~mortality. In the model, the time step is small and the relationships are fully dynamic within the NPZD framework. However, since we use monthly model output in the offline calculation, the phytoplankton concentration is not independent of either the nutrient availability or the growth rate. Therefore we look at the residual NPP$_{residual}$ (NPP$_{total}$ – NPP$_{temp}$ – NPP$_{light}$). This residual approximates the integrated circulation--induced changes in phytoplankton concentration and the concentration of the limiting nutrient. The latter is an~~Inorganic nutrients are also~~ important limiting factor~~s~~ for NPP, especially in the low latitude regions, and ~~will change with~~is largely influenced by circulation changes. ~~Given the formulation of Equation 1, we use phytoplankton concentration as a proxy for nutrient availability when calculating primary production. Note though, that the relationship between nutrients and phytoplankton is not exactly one to one because phytoplankton are also grazed by zooplankton in the model. However, temporal changes in phytoplankton concentration give a strong indication of how the stratification limits access to nutrients in the surface ocean.~~ Figure 7d shows that ~~phytoplankton~~ NPP$_{residual}$ dominates over the growth rate in~~is the dominant factor~~ determining changes in ocean ~~primary production~~NPP~~, except when CCT is applied~~. ~~When only phytoplankton concentration is allowed to vary temporally in the offline calculation there is~~Overall, NPP$_{residual}$ – accounts for a decrease of ~8% by 2100 in RCP8.5. The SAI and MSB methods of RM also exhibit a change in ~~primary production~~NPP$_{residual}$, but the change of ~5% is less than that in RCP8.5. With CCT there is no significant change in ~~primary production~~NPP$_{residual}$ by 2100 relative to 1971-2000. After termination, ~~the phytoplanktoncirculation-driven change of ocean~~ NPP$_{residual}$~~productivity~~ decreases rapidly and after 4-5 years it continues changing at a rate comparable to that in RCP8.5, reaching a global mean reduction of greater than -10% in 2150.

### **3.5 Regional changes in ocean ~~primary production~~NPP**

As seen in Figure 6, the projected changes in ocean ~~primary production~~NPP exhibit large spatial variation. These spatial ~~variation~~ patterns~~s~~ are comparable to ~~the same for~~ the NPP calculated offline (Figure 8). Applying RM does not change the large-scale spatial heterogeneity, but rather works to enhance or weaken the change magnitude (Figures 6 and 8). These regional differences are important, since regional changes are much more important than global changes when determining the impact ~~changes in~~ ocean ~~primary production~~NPP has on human food security (Mora et al., 2013). For a more detailed analysis, five regions have been identified and analyzed using the offline calculations of NPP and its drivers. These regions are chosen based on:

(i) a significant change, i.e. outside of ±1 standard deviation, in ~~primary production~~NPP in RCP8.5 in years 2071-2100 relative to 1971-2000;

(ii) the sign of the change in ocean ~~primary production~~NPP projected by NorESM1-ME being consistent with that of the CMIP5 models ensemble mean (Bopp et al., 2013; Mora et al., 2013);

(iii) the impact the different methods of RM has on this increase or decrease in the online simulations; and

(iv) their relative importance for fish catches, as identified in Zeller et al. (2016).

The regions are outlined in black in Figure 6b, and labeled the Equatorial Pacific, Equatorial Atlantic, Southern Atlantic, Indian Ocean, and Sea of Okhotsk in Figure 9~~8~~. In RCP8.5, the Sea of Okhotsk and Southern Atlantic exhibit a significant increase in ~~primary production~~NPP in 2071-2100 relatively to 1971-2000, while the Equatorial Pacific, Indian Ocean, and Equatorial Atlantic show a significant weakening (Figure 9~~8~~).

The IPCC’s -Assessment Report 5(AR5) states that, due to lack of consistent observations, it remains uncertain how the future changes in marine ecosystem drivers (like productivity, acidification, and oxygen concentrations) will alter the higher trophic levels (Pörtner et al., 2014). Given the lack of complexity and lack of higher trophic level organisms in the NorESM1-ME, we are unable to directly link changes in ~~primary production~~NPP to impacts on the higher tropic levels in this study. ~~But given the changes in Arctic biodiversity observed today due to temperature changes (*e.g.* Bucholz et al., 2012; Fossheim et al., 2015), respective changes in migration pattern would be likely to happen with RM.~~ It therefore cannot be assumed from our results that increased ~~primary production~~NPP will lead to increased fish stocks and thus potential for higher fish catches, because the driving factors leading to higher ~~primary production~~NPP (*i.e.* temperature, light availability, and stratification) could also lead to biodiversity changes. ~~But g~~Given the changes in Arctic biodiversity observed today due to temperature changes (*e.g.* Bucholz et al., 2012; Fossheim et al., 2015), respective changes in migration pattern would be likely to happen also with RM ~~though~~. Nevertheless, ~~H~~higher ~~primary production~~NPP does lead to more food for higher trophic level ~~organisms,~~organisms; therefore a significant decrease in regional ~~primary production~~NPP ~~is likely to~~ could decrease~~s~~ higher tropic organisms due to less food availability in those regions. Based on the model projections, it is possible that there will be less fish catches in the Indian Ocean and Equatorial Atlantic in the future than today. The different methods of RM also lead to different effects on ocean ~~primary production~~NPP (Figures 6 and 9~~8~~).~~, and i~~ Only in the Equatorial Atlantic, and in the shaded regions where there are~~is~~ no significant changes, do all three methods give changes in ~~primary production~~NPP comparable to those in RCP4.5.

In the Equatorial Pacific, RCP8.5 leads to a decrease in ocean ~~primary production~~NPP of -21% in 2071-2100 relative to 1971-2000, driven by circulation - induced changes ~~in~~ in phytoplankton concentration and nutrient availability ~~(our proxy for circulation changes)~~. Circulation - induced changes ~~in circulation~~ dominates the change of -12% ~~incurred~~ in RCP4.5 too. This region is today a very productive fishery area (Zeller et al., 2016), so a significant decrease in ~~primary production~~NPP could have adverse effects on fish catches. It is therefore noteworthy that all RM methods yield ~~primary production~~NPP changes only marginally smaller than those in RCP8.5, and not nearly as small as those in RCP4.5. When RM is applied, shortwave ~~R~~radiation changes at the surface become more important in driving NPP changes ~~with RM~~ than they are in RCP8.5 and RCP4.5, which is consistent with changes in cloud fraction (not shown, see Muri et al., 2017~~in prep.~~). With CCT, the radiation changes yield an increase in ~~primary production~~NPP of 5%, indicating that this is one of the regions that drive the global mean increase in ~~primary production~~NPP ~~with CCT~~ (Figure 7a). After termination, the change in ~~primary production~~NPP is comparable to that in RCP8.5 in all experiments, and the warming results in ~~incur~~ a small increase in ~~primary production~~NPP of ~2% (Figure 7b).

The Southern Atlantic has the largest changes in 2071-2100 relative to 1971-2000, where RCP8.5 results in an increase in ocean ~~primary production~~NPP of 39% and RCP4.5 leads to an increase of 25%. SAI leads to changes in ~~primary production~~NPP comparable to that in RCP8.5, while MSB and CCT yield~~ing~~ changes more in line with RCP4.5. For all experiments, the circulation-induced changes ~~in phytoplankton concentration is~~are the dominant factor ~~indicating that changes in circulation will be substantial here~~. Changes in temperatures contribute ~5% to the total change, which is consistent with a significant warming in all experiments (Figure 3). This alleviates the temperature limitation of the~~phytoplankton~~ growth rate, which is consistent with the other CMIP5 models (Bopp et al., 2013). After termination, the increase continues in the Southern Atlantic, and in 2121-2150 the changes in ~~primary production~~NPP are 6~~5~~0-7~~6~~0% higher than in 1971-2000 in all experiments.

~~Like~~As in all other regions, ~~I~~in the Sea of Okhotsk, the circulation~~-~~-induced changes dominate. ~~changes in temperature yield changes in primary production comparable with that in RCP4.5 (13%), which is marginally smaller than that in RCP8.5 (18%).~~ SAI and MSB both yield changes comparable to that in RCP4.5, while CCT, on the other hand, is comparable to RCP8.5. In all experiments, temperature changes are an important driver of the overall increases in ~~primary production~~NPP, ~~which is~~ consistent with the strong warming in this region (Figure 3). After termination, all experiments yield comparable increases in ~~primary production~~NPP, with a very strong contribution from ~~and~~ the temperature changes. ~~have the largest contribution to the overall increase, which is consistent with strong warming when RM is terminated.~~

In the Equatorial Atlantic, there is a reduction of ocean ~~primary production~~NPP in RCP8.5 of -19% in 2071-2100 relative to 1971-2000. Circulation~~-~~-induced changes ~~in phytoplankton concentration~~ dominate this change, with a minor negative contribution of <-5% from radiation changes. All methods of RM yield changes in ocean ~~primary production~~NPP more in line with that in RCP4.5 (-11%), but changes in radiation are more important with SAI and MSB. After termination, all experiments result in the same decrease in ocean ~~primary production~~NPP of -25%.

In the Indian Ocean, there is also a reduction of ocean ~~primary production~~NPP in RCP8.5. Here the total change in 2071-2100 is -21%, but unlike in any other regions the temperature~~-~~-induced changes lead to only a small increase of 1-2% in all experiments. This is consistent with parts of this region experiencing only a small ~~decrease~~ increase in SST (Figure 3). Both SAI and MSB yield changes in ~~primary production~~NPP comparable to that in RCP8.5 (-19% and -18% respectively), but where changes in radiation contribute ~-2% to the total reduction. There is, however, no corresponding change in cloud cover (see Muri et al., 2017~~in prep.~~) to explain the apparent importance of radiation changes in this region. The Indian Ocean is also one of the regions where CCT is able to sustain (i.e., induce least changes in) the contemporary ~~primary production~~NPP. After termination, the ocean ~~primary production~~NPP continues to decrease and is in 2121-2150 30% lower than in 1971-2000 in all experiments. ~~Unusually, the temperature changes lead to an increase in ocean primary production of 4% in 2121-2150 in all experiments.~~

### 3.6 Comparison with previous studies

Very few other studies have been published on the impact on ocean biogeochemistry due to RM. One such study is ~~the study~~ by Hardman-Mountford et al. (2013), which used a one-dimensional water column model to study the effect of reduced light availability on phytoplankton growth. Their results imply that even a significant reduction (90%) of solar radiation barely affects total column biological productivity, but can alter considerably vertical distribution of productivity. However, their study did not consider how other processes, such as local cooling or horizontal transport of nutrients, would affect the marine ecosystems, and their simplistic model setup was also unable to capture broader effects on the ocean carbon cycle. The magnitude of regional changes in NPP found in this study differs from the results of Hardman-Mountford et al. (2013), but the NPP changes ~~we observe~~seen in

~~NPP in~~ the oligotrophic gyres are very small and not statistically significant. Given the very large differences in method, no in depth comparison of this study and Hardman-Mountford et al. (2013) has been undertaken.~~,~~ ~~but t~~Two other recent studies, which are both more comparable to this one,~~ones~~ are Tjiputra et al. (2016) and Partanen et al. (2016). Tjiputra et al. (2016), who used the same model as in this study, identified changes in ocean ~~primary production~~NPP and export production in a simulation with SAI. The implementation of SAI is different here, both in methodology somewhat and ~~amplitude~~ magnitude of forcing, but the spatial pattern and sign~~al~~ of surface climate response and the overall impact on global ocean ~~primary production~~NPP are~~in~~ broadly ~~comparable~~consistent. Nevertheless, our study provides a more extended and in-depth analysis based on different RM methods as well as ~~in~~ ~~and~~ identif~~ying~~ies ~~the~~ dominant drivers of changes in ~~primary production~~NPP in key ocean regions. Partanen et al. (2016), on the other hand, analyzed the effects on ocean ~~primary production~~NPP from ~~MSB~~ marine cloud brightening (MCB) only. Overall, the effects ~~of MSB~~ in this study and that of Partanen et al. (2016) are quite different.~~ both spatially and as a function of time.~~ Spatially, Partanen et al. (2016) sees a very strong correlation between the regions where the ~~MSB~~cloud brightening forcing was applied and the regions of strongest NPP change, which is not apparent in this study. Temporally, the change in NPP in Partanen et al. (2016) comes in form of a relatively rapid decrease over the first ten years, when ~~MSB~~the cloud brightening forcing is applied, while in this study the change is more even throughout the period of MSB forcing. This is likely due to the several noteworthy differences between their method and the one used here:

(i) Partanen et al. (2016) uses the UVic ESCM model, an Earth system model of intermediate complexity (EMIC), while here we use the fully coupled NorESM1-ME Earth system model;

(ii) Here, we increase oceanic sea salt emissions over ±45° latitude not only brightening the marine stratocumulus decks, but also reflecting more shortwave radiation with the increased in bright aerosols through the direct effect. Partanen et al. (2016), on the other hand, prescribe changes in radiation over three marine stratocumulus areas inferred from model output from Partanen et al. (2012).

~~(i)~~

~~(ii)~~(iii) the RM forcing applied by Partanen et al. (2016) is -1 $Wm^{-2}$ annually, while here it is ~~scaled~~ ramped up to -4 $Wm^{-2}$ in 2100;

~~(iii)~~(iv) Partanen et al. (2016) applies RM to RCP4.5, while here we apply RM to RCP8.5;

(v) Partanen et al. (2016) applies RM for 20 years before termination, while here we apply RM for 80 year before termination, which, combined with the higher forcing, means that the Earth system takes longer to recover in this study than in the Partanen et al. (2016) study.

~~(iv)~~

The biggest and most important of these differences is that Partanen et al. (2016) use an EMIC, while we use an ESM with the forcing applied over a much larger area. ~~The ecosystem module in NorESM1-ME is not substantially more complex than that of the UViC ESCM model, but differences could arise due to better representation of the ocean physical circulation (owing to higher spatial resolution) and air-sea interactions. Differences in the aerosol-cloud-climate interactions will also affect the results.~~ NorESM1-ME has a fully interactive tropospheric aerosol scheme, accounting for both the direct and the indirect effects of the aerosols, which is of key importance when evaluating the impact of changes in shortwave radiation reaching the surface from changes to clouds. Partanen et al. (2016) take their ~~SRM~~ forcing from Partanen et al. (2012), which use an atmosphere-only version of their model and hence neglect important feedbacks, including SST~~/~~ and ocean feedbacks. Partanen et al. (2016) furthermore prescribe their ~~SRM~~ forcing in terms of changes to the radiation, and hence miss out on further feedbacks with their one layered atmosphere with prescribed circulation, ~~that we include~~processes that are much more comprehensively represented in our fully coupled Earth system ~~simulations~~model. MSB may, *e.g.*, lead to an increased sinking of air over the oceans and hence a reduction in cloud cover, as seen in both Ahlm et al. (2017), Stjern et al. (2017) and Muri et al. (2017). The ecosystem module in NorESM1-ME is not substantially more complex than that of the UViC ESCM model, but differences could arise due to better representation of the ocean physical circulation (owing to higher spatial resolution) and air-sea interactions. Partanen et al. (2016) identify a decrease in global mean ocean ~~primary production~~NPP relative to their reference case (RCP4.5), while in our MSB simulation we simulate an increase in ocean ~~primary production~~NPP relative to our reference case (RCP8.5). This likely impacts the differences in results since the global mean and rate of change of ecosystem drivers in RCP4.5 are smaller than RCP8.5 (Henson et al., 2017). These methodological differences and the large differences in the spatial impact can partly be explained by the differences in the applied RM forcing and method, but is mostly explained by the fundamental differences between the models~~ and especially how clouds are modelled~~. Another important difference between Partanen et al. (2016) and this study, is the timing of termination, since this is a very important aspect of all climate engineering studies. Partanen et al. (2016) applies RM for 20 years before termination, while we apply RM for 80 years before termination. This means that in our study the impact on temperature and ocean circulation is greater than in the Partanen et al. (2016) study, as the slow climate feedbacks are allowed to pan out. This could explain the differences in termination effect between the studies, where the ~~primary production~~NPP fully recovers and exceeds that in RCP4.5 in the Partanen et al. (2016) study, but remain within the variability of RCP8.5 here. The larger magnitude of the forcing applied in our simulations (-4 $Wm^{-2}$ in 2100) also means that it takes much longer for the climate system to recover back to the RCP8.5 state.

## 4 CONCLUSIONS

In this study, we use the Norwegian Earth System Model with fully interactive carbon cycle to assess the impact of three radiation management climate engineering (RM) methods on marine biogeochemistry. The model simulations indicate that RM may reduce perturbations in SST and thermocline oxygen driven by anthropogenic climate change, but that large changes in ~~primary production~~NPP remain and are even intensified in some regions. It must be noted, that we use only one model, and that such models are known to have large spread in their projections of future ocean ~~primary production~~NPP (*e.g.* Bopp et al., 2013). However, this single-model study does show some clear tendencies:

(i) A clear mitigation of the global mean decrease in ocean ~~primary production~~NPP from 10% in 2100 in RCP8.5 and ~5% in RCP4.5 to somewhere between 3% and 6%, depending on the method of RM.

(ii) Strong regional variations in the changes, and what primarily drives the changes, in ocean ~~primary production~~NPP. The different methods of RM do not have the same effects in the same regions, even though SAI and MSB yield similar global averages.

(iii) Spatially MSB yields the largest changes relative to RCP4.5, which is consistent with MSB being applied over the ocean and therefore likely affects the ocean more strongly than the other methods.

The effect of future climate change on ocean ~~primary production~~NPP is uncertain, and is driven by an integrated change in physical factors, such as temperature, radiation, and ocean mixing. Additionally, changes in ocean oxygen concentrations and ocean acidification are likely to affect ocean ~~primary production~~NPP. ~~So i~~It is noteworthy that with RM, the way the scenario is designed in this study, anthropogenic $CO_2$ emissions are not curbed, so ocean acidification would continue. The results presented in this study show that future changes to ocean ~~primary production~~NPP would likely be negative on average, but exhibit great variation both temporally and spatially, regardless of whether or not RM is applied.

This study also show that for the first five to ten years after a sudden termination of large-scale RM with no mitigation or CDR efforts, the SST, oxygen, surface pH, and ~~primary production~~NPP all experience changes that are significantly larger than those projected without RM implementation or mitigation. While there is still large uncertainty in how marine habitats respond to such rapid changes, it is certain than they will have less time to adapt or migrate to a more suitable location and potentially have higher likelihood to face extinction, if RM was suddenly halted during large-scale deployment and with no mitigation.

The results of this work does nothing to diminish the complexity of climate impacts on ~~primary production~~NPP, but rather highlights that any change in ocean ~~primary production~~NPP is driven by a combination of several variables, which all change in different ways in the future, and subsequently are affected differently when RM is applied. The importance of ocean ~~primary production~~NPP for human societies, however, lies in its impact on food security in general and fisheries in particular, for which regional changes are much more important than global changes (Mora et al., 2013).

## ACKNOWLEDGEMENTS

The authors acknowledge funding from the Norwegian Research Council through the project EXPECT (229760). We also acknowledge NOTUR resource NN9182K, Norstore NS9033K and NS1002K. Helene Muri was also supported by RCN project 261862/E10, 1.5C-BECCSy.

JT also acknowledges RCN project ORGANIC (239965). The authors want to thank Alf Grini for his technical assistance in setting up and running model experiments, ~~and~~ as well as the rest of the EXPECT team

## REFERENCES

Ahlm, L., Jones, A., Stjern, C. W., Muri, H., Kravitz, B., and Kristjánsson, J. E.: Marine cloud brightening – as effective without clouds, Atmos. Chem. Phys. Discuss., 2017, 1-25, 2017. doi:10.5194/acp-2017-484.

Alterskjær, K., Kristjansson, J. E., Boucher, O., Muri, H., Niemeier, U., Schmidt, H., Schulz, M., and Timmreck, C.: Sea-salt injections into the low-latitude marine boundary layer: The transient response in three Earth system models, J. Geophys. Res.-Atmos., 118, 12195-12206, 2013. doi:10.1002/2013jd020432.

Aswathy, N., Boucher, O., Quaas, M., Niemeier, U., Muri, H., Mulmenstadt, J., and Quaas, J.: Climate extremes in multi-model simulations of stratospheric aerosol and marine cloud brightening climate engineering, Atmospheric Chemistry and Physics, 15, 9593-9610, 2015. doi:10.5194/acp-15-9593-2015

Bala, G., Caldeira, K., Nemani, R., Cao, L., Ban-Weiss, G., and Shin, H.-J. Albedo enhancement of marine clouds to counteract global warming: impacts on the hydrological cycle. Climate Dynamics 37(5-6), 915–931, 2011. doi: 10.1007/s00382-010-0868-1.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., Roelandt, C., Seierstad, I. A., Hoose, C., and Kristjánsson, J. E.: The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate, Geosci. Model Dev., 6, 687-720, 2013. doi:10.5194/gmd-6-687-2013

Bickel J, and Lane L. An Analysis of Climate Engineering as a Response to Climate Change. Frederiksberg: Copenhagen Consensus Center. 2009.

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Seferian, R., Tjiputra, J., and Vichi, M.: Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models, Biogeosciences, 10, 6225-6245, 2013. doi:10.5194/bg-10-6225-2013

Buchholz, F., Werner, T., and Buchholz, C.: First observation of krill spawning in the high Arctic Kongsfjorden, west Spitsbergen, Polar Biology, 35, 1273-1279, 2012. doi:10.1007/s00300-012-1186-3

Crook, J. A., Jackson, L. S., Osprey, S. M., and Forster, P. M.: A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes, J. Geophys. Res.-Atmos., 120, 9352-9373, 2015. doi:10.1002/2015jd023269

Crutzen, P. J.: Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma? Climatic Change, 77, 211-219, 2006. doi:10.1007/s10584-006-9101-y

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., and Dolgov, A. V.: Recent warming leads to a rapid borealization of fish communities in the Arctic, Nat. Clim. Chang., 5, 673-677, 2015. doi:10.1038/nclimate2647

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Kindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.-G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate-Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison, Journal of Climate, 19, 3337-3353, 2006.

Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., Tjiputra, J., and Sarmiento, J. L.: Rapid emergence of climate change in environmental drivers of marine ecosystems, Nat. Commun., 8, 14682, 2017. doi:10.1038/ncomms14682

Hardman-Mountford, N. J., Polimene, L., Hirata, T., Brewin, R. J. W., and Aiken, J.: Impacts of light shading and nutrient enrichment geo-engineering approaches on the productivity of a stratified, oligotrophic ocean ecosystem, J. R. Soc. Interface, 10, 9, 2013. doi:10.1098/rsif.2013.0701

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Irvine, P. J., Kravitz, B., Lawrence, M. G., and Muri, H.: An overview of the Earth system science of solar geoengineering. WIREs Climate Change 7: 815–833, 2016. doi: 10.1002/wcc.423.

Irvine, P. J., Kravitz, B., Lawrence, M. G., Gerten, D., Caminade, C., Gosling, S. N., Hendy, E., Kassie, B., Kissling, W. D., Muri, H., Oschlies, A., and Smith, S. J.: Towards a comprehensive climate impacts assessment of solar geoengineering, Earth's Future, 2016. doi:10.1002/2016EF000389.

Kristjansson, J. E., Muri, H., and Schmidt, H.: The hydrological cycle response to cirrus cloud thinning, Geophysical Research Letters, 42, 10807-10815, 2015. doi:10.1002/2015gl066795

Latham, J.: Control of Global Warming, Nature, 347, 339-340, 1990. doi:10.1038/347339b0

Lynch, D. K.: Cirrus, Oxford University Press, 2002.

Ma, X., von Salzen, K., and Li, J.: Modelling sea salt aerosol and its direct and indirect effects on climate, Atmospheric Chemistry and Physics, 8, 1311-1327, 2008.

Maier-Reimer, E., Kriest, I., Segschneider, J., and Wetzel, P.: The Hamburg Oceanic Carbon Cycle Circulation model HAMOCC5.1, Max Planck Institute for Meteorology, Hamburg, Germany, 2005.

Matthews, H. D., Cao, L., and Caldeira, K.: Sensitivity of ocean acidification to geoengineered climate stabilization, Geophysical Research Letters, 36, 2009. doi:10.1029/2009gl037488

Mitchell, D., L. and Finnegan, W.: Modification of cirrus clouds to reduce global warming, Environmental Research Letters, 4, 045102, 2009. doi:10.1088/1748-9326/4/4/045102

Muri, H., Kristjansson, J. E., Storelvmo, T., and Pfeffer, M. A.: The climatic effects of modifying cirrus clouds in a climate engineering framework, J. Geophys. Res.-Atmos., 119, 4174-4191, 2014. doi:10.1002/2013jd021063

Muri, H., Tjiputra, J. Otterå, O. H., Adakudlu, M., Lauvset, S. K., Grini, A., Schulz, M., and Kristjansson, J. E.: Climate response to aerosol injection geoengineering: a multi-method comparison. Journal of climate (under review), 2017. doi: 10.1175/JCLI-D-17-0620.1.

Niemeier, U., Schmidt, H., Alterskjaer, K., and Kristjansson, J. E.: Solar irradiance reduction via climate engineering: Impact of different techniques on the energy balance and the hydrological cycle, J. Geophys. Res.-Atmos., 118, 11905-11917, 2013. doi:10.1002/2013jd020445.

Niemeier, U. and Timmreck, C.: What is the limit of climate engineering by stratospheric injection of $SO_2$?, Atmos. Chem. Phys., 15, 9129-9141, https://doi.org/10.5194/acp-15-9129-2015, 2015.

Partanen, A.-I., Kokkola, H., Romakkaniemi, S., Kerminen, V. M., Lehtinen, K. E. J., Bergman, T., Arola, A., and Korhonen, H.: Direct and indirect effects of sea spray geoengineering and the role of injected particle size, J. Geophys. Res., 117, D02203, 2012. doi:10.1029/2011JD016428.

Partanen, A.-I., Keller, D. P., Korhonen, H., and Matthews, H. D.: Impacts of sea spray geoengineering on ocean biogeochemistry, Geophysical Research Letters, 43, 7600-7608, 2016. doi:10.1002/2016gl070111

Pörtner, H.-O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., Schmidt, D. N., and Zavialov, P. O.: Ocean systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C. B. Field et al., pp. 411–484, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 2014

Riahi, K., Rao, S., Krey, V., Cho, C. H., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rafaj, P.: RCP 8.5-A scenario of comparatively high greenhouse gas emissions, Climatic Change, 109, 33-57, 2011. doi:10.1007/s10584-011-0149-y

Six, K. D. and Maier-Reimer, E.: Effects of plankton dynamics on seasonal carbon fluxes in an ocean general circulation model, Global Biogeochemical Cycles, 10, 559-583, 1996. doi:10.1029/96gb02561

Stjern, C. W., Muri, H., Ahlm, L., Boucher, O., Cole, J. N. S., Ji, D., Jones, A., Haywood, J. M., Kravitz, B., Lenton, A., Moore, J. C., Niemeier, U., Phipps, S. J., Schmidt, H., Watanabe, S., and Kristjánsson, J. E.: Response to marine cloud brightening in a multi-model ensemble. Atmospheric Chemistry and Physics Discussions. 2017. doi: 10.5194/acp-2017-629.

Storelvmo, T., Kristjansson, J. E., Muri, H., Pfeffer, M., Barahona, D., and Nenes, A.: Cirrus cloud seeding has potential to cool climate, Geophysical Research Letters, 40, 178-182, 2013. doi:10.1029/2012gl054201

Teller, E., Hyde, R., Ishikawa M., et al. Active Stabilization of Climate: Inexpensive, Lowrisk, near-Term Options for Preventing Global Warming and Ice Ages Via Technologically Varied Solar Radiative Forcing. Lawrence Livermore National Library, 30 November. 2003

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E., and Edmonds, J. A.: RCP4.5: a pathway for stabilization of radiative forcing by 2100, Climatic Change, 109, 77-94, 2011. doi:10.1007/s10584-011-0151-4

~~Tilmes, S., Mills, M. J., Niemeier, U., Schmidt, H., Robock, A., Kravitz, B., Lamarque, J. F., Pitari, G., and English, J. M.: A new Geoengineering Model Intercomparison Project (GeoMIP) experiment designed for climate and chemistry models, Geoscientific Model Development, 8, 43-49, 2015. doi:10.5194/gmd-8-43-2015~~

Tjiputra, J. F., Grini, A., and Lee, H.: Impact of idealized future stratospheric aerosol injection on the large scale ocean and land carbon cycles, Journal of Geophysical Research: Biogeosciences, 120, doi: 10.1002/2015jg003045, 2016. doi:10.1002/2015jg003045

Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, O., and Heinze, C.: Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), Geoscientific Model Development, 6, 301-325, 2013. doi:10.5194/gmd-6-301-2013

Wanninkhof, R.: Relationship between wind speed and gas exchange over the ocean, Journal of Geophysical Research, 97, 7373-7382, 1992.

Weisenstein, D. K., Keith, D. W., and Dykema, J. A.: Solar geoengineering using solid aerosol in the stratosphere, Atmospheric Chemistry and Physics, 15, 11835-11859, 2015. doi:10.5194/acp-15-11835-2015

Wigley, T.M.L., A combined mitigation/geoengineering approach to climate stabilization, Science 314:452-454. 2006. doi:10.1126/science.1131728

Xia, L., Robock, A., Tilmes, S., and Neely Iii, R. R.: Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate, Atmospheric Chemistry and Physics, 16, 1479-1489, 2016. doi:10.5194/acp-16-1479-2016

Zeller, D., Palomares, M. L. D., Tavakolie, A., Ang, M., Belhabib, D., Cheung, W. W. L., Lam, V. W. Y., Sy, E., Tsui, G., Zylich, K., and Pauly, D.: Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility, Marine Policy, 70, 145-152, 2016. doi:10.1016/j.marpol.2016.04.046

# FIGURES AND TABLES

**Figure 1. Time series of global average change in (a) oxygen content at 200-600m depth (%), and (b) SST (°C). The oxygen change is relative to the 1971-2000 average in the historical run.**

**Figure 2. The absolute change in oxygen concentration (200-600m) in 2071-2100 relative to 1971-2000 (in moles $O_2$ $m^{-2}$). Panel (a) shows zonally averaged (in 2° latitude bands) change for all simulations. Global maps of (b) RCP8.5, (c) RCP4.5, (d) RCP8.5 with SAI, (e) RCP8.5 with MSB, (f) RCP8.5 with CCT. Gray shading in b)-f)**

indicates areas where the change is not significantly different from the 1971-2000 average (*i.e.* within one standard deviation of the 1971-2000 mean).

**Figure 3.** The absolute change in sea surface temperature (SST) in 2071-2100 relative to 1971-2000 (in °C). Panel (a) shows zonally averaged (in 2° latitude bands) change for all simulations. Global maps of (b) RCP8.5, (c) RCP4.5, (d) RCP8.5 with SAI, (e) RCP8.5 with MSB, (f) RCP8.5 with CCT. Gray shading in b)-f) indicates areas where the change is not significantly different from the 1971-2000 average (*i.e.* within one standard deviation of the 1971-2000 mean).

**Figure 4.** Time series of global average change in (a) atmospheric $CO_2$ (ppm), (b) air-sea $CO_2$ flux (PgC $yr^{-1}$), (c) global surface ocean pH, (d) global deep ocean (>2000 m) pH, and (e) deep (>2000 m) North Atlantic Ocean (north of 30°N) pH.

**Figure 5.** Time series of changes global ocean ~~primary production~~NPP (~~PP, ~~%). The ~~primary production~~NPP change is relative to the 1971-2000 average in the historical run.

**Figure 6.** The percent changes in ~~primary production~~NPP in 2071-2100 relative to the 1971-2000 average in the historical run. (a) ~~z~~Zonally averaged (in 2° latitude bands) change for all simulations. (b) RCP8.5, (c) RCP4.5, (d) RCP8.5 with SAI, (e) RCP8.5 with MSB, (f) RCP8.5 with CCT. Gray shading in b)-f) indicates areas where the change is not significantly different from the 1971-2000 average (*i.e.* within one standard deviation of the 1971-2000 mean). The outlined areas in panel (b) indicate regions plotted in Figure 10~~8~~.

**Figure 7.** Time series of the 5-year running mean of globally averaged ~~primary production~~NPP (~~PP, ~~%) calculated offline using Equations 1-3, plotted as the percent change relative to the 1971-2000 average in the historical run. The residual (NPP$_{total}$ – NPP$_{temp}$ – NPP$_{light}$) represents the circulation-induced changes. ~~–total~~Note the different scales on the y-axes. See Table 1 for an explanation of the different calculations shown.

**Figure 8.** The percent change in the offline calculated NPP in 2071-2100 relative to the 1971-2000 average in the historical run. (a) Z~~z~~onally averaged (in 2° latitude bands) change for all simulations. (b) RCP8.5, (c) RCP4.5, (d) RCP8.5 with SAI, ~~€~~(e) RCP8.5 with MSB, (f) RCP8.5 with CCT. Gray shading in b)-f) indicates areas where the change is not significantly different from the 1971-2000 average (*i.e.* within one standard deviation of the 1971-2000 mean). The outlined areas in panel (b) indicate regions plotted in Figure 9.

**Figure 9~~8~~.** Offline calculated ~~primary production~~NPP change (~~PP, ~~%) in five different regions (as indicated on Figure 6b) for RCP4.5, RCP8.5, and RCP8.5 with three different RM methods. The residual (NPP$_{total}$ – NPP$_{temp}$ – NPP$_{light}$) represents the circulation-induced changes.~~–total~~

**Table 1.** Description of the offline calculations of ocean ~~primary production~~NPP and ~~its ~~primary drivers using Equations 1-3. T is the average temperature in the top 100 m, L is shortwave radiation attenuated to 50 m depth~~at the surface~~, N is the concentration of the limiting nutrient (either nitrate, phosphate~~, silicate~~, or dissolved iron) in the top 100 m, and P is the concentration of phytoplankton cells in the top 100 m. $\overline{X}$ denotes the long-term (80 year) mean of the given variable.

| Calculation | |
|---|---|
| NPP$_{total}$ Everything changes | T, L, N, P |
| NPP$_{temp}$ Only temperature changes | T, $\overline{L}$, $\overline{N}$, $\overline{P}$ |
| NPP$_{light}$ Only shortwave radiation changes | L, $\overline{T}$, $\overline{N}$, $\overline{P}$ |
| ~~Only phytoplankton concentration changes~~NPP$_{residual}$ | ~~P, $\overline{L}$, $\overline{N}$, $\overline{T}$~~NPP$_{total}$ – NPP$_T$ – NPP$_L$ |

**Table 2.** General description of model experiments used in this study.

| Experiment | Description | Time period |
|---|---|---|
| RCP4.5 | Reference RCP4.5 scenario | 2006-2100 |
| RCP8.5 | Reference RCP8.5 scenario | 2006-2150 |
| SAI | RCP8.5 scenario ~~where~~with a layer of~~ sulfur~~ sulfate particles ~~are injected ~~is ~~into the atmosphere to~~ | 2020-2100 |

| | | |
|---|---|---|
| | ~~scatter~~prescribed in the stratosphere to reflect incoming shortwave radiation and bring down global average temperatures | |
| SAI$_{\text{EXT}}$ | The extension of the SAI run after termination of climate engineering in 2100 | 2101-2150 |
| MSB | RCP8.5 scenario where salt particles are ~~added~~emitted at the sea surface ~~to the marine boundary layer~~ between 45°S and 45°N to make both the sky and clouds brighter, thus increasing the Earth’s albedo thereby lower global average temperatures | 2020-2100 |
| MSB$_{\text{EXT}}$ | The extension of the MSB run after termination of climate engineering in 2100 | 2101-2150 |
| CCT | RCP8.5 scenario where cirrus clouds are thinned out. Cirrus clouds have a net heating effect so less ice~~thinner~~ clouds will result in lower global average temperatures | 2020-2100 |
| CCT$_{\text{EXT}}$ | The extension of the CCT run after termination of climate engineering in 2100 | 2101-2150 |