Anonymous Referee #1

We would like to thank referee 1 for his/her constructive and detailed review.

This is a mostly well written manuscript with interesting new results identifying a stratospheric mechanism impacting the Atlantic Meridional Oscillation. Therefore, it is potentially suitable for publication in the Earth System Dynamics journal. I have, however, a few concerns which I would like the authors to address before I can recommend the publication.

My major concerns are:

1. What would be the impact of aerosols? Your model does not include aerosol interactions, you just simply reduce the solar radiation. This seems a critical simplification to me. You should at least discuss how aerosol interactions would modify the AMOC response if taken into account in your model.

We agree, that the response of the coupled atmosphere-chemistry-ocean model to stratospheric aerosols is the next follow up question, which should be addressed. In this study, however, we focus on response of the system to a direct reduction in the solar energy input (i.e. total solar irradiance). A reduction of the TSI takes place during grand solar minima (e.g., Dalton Minimum) or in the case of solar radiation management techniques taking place in space (e.g., reduction of the TSI by mirrors in space). The model includes also aerosol interactions and indeed a number of modelling studies on the response to stratospheric aerosols from volcanic eruption have been performed earlier (e.g., Anet et al, 2013, Muthers et al. 2014 and 2015).

A comparison between both approaches, a reduction of the TSI in space and through stratospheric aerosols is, however, highly relevant. We therefore discuss possible effects of radiation management by stratospheric aerosols at the end of the submitted manuscript.

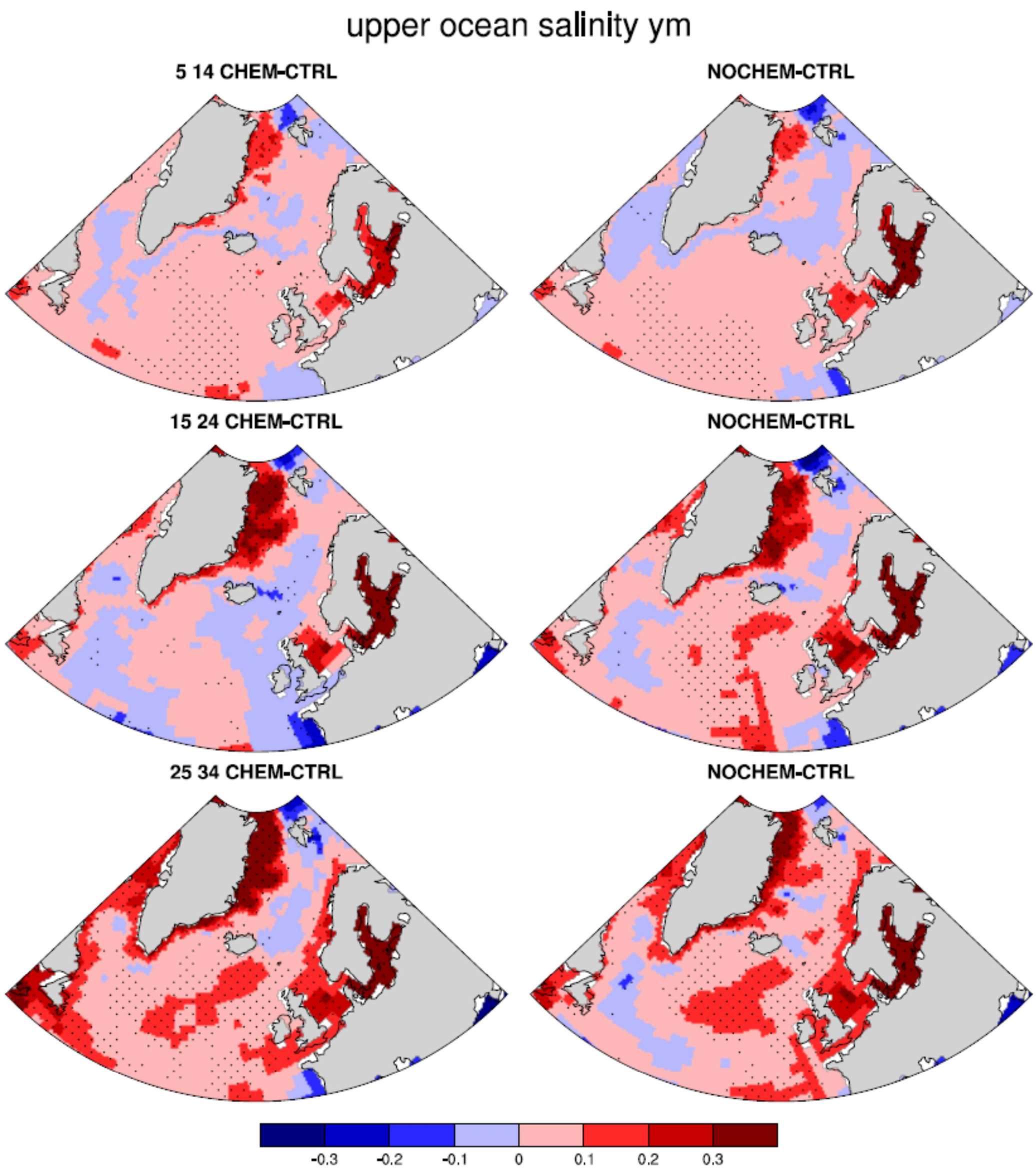
"The dynamical effect is expected to change, however, when the solar radiation is reduced in the Earth's atmosphere, for instance, by stratospheric sulphate aerosols. In this case a strengthening of the NH polar vortex and a positive phase of the AO may develop, analogous to the response to strong tropical volcanic eruptions (Graf et al., 1993; Kodera, 1994; Stenchikov et al., 2002; Muthers et al., 2014a, 2015). This effect of the positive AO phase may, in turn, lead to an intensification of the AMOC. Future studies shall address the influence of stratospheric sulphate geoengineering on the AMOC and the possible role of chemistry-climate interactions."

2. I think in reality the salt rejection from the sea-ice growth is rather small and mainly occurs north from the regions of deep convection. Therefore, it has only a minor importance to the deep convection and the AMOC compared to the heat loss and possibly the net precipitation (precipitation minus evaporation) at the ocean surface. At the moment, the reader is led to understand that the salt rejection is at least as important as the heat loss. The increase of the sea-surface salinity could also be due to a decreased net precipitation related to changing storm tracks, for example. To better support the salt rejection argument, you need to quantify the salt rejection to the surface density and compare it to other factors. Can you check the ocean surface fluxes from your model output and their relation to the T and S, not only density, anomalies? How realistic these modelled fluxes then

are, depend on your model skill and are related to your model configuration, such as the sea-ice salinity scheme.

Figure 4 (formerly S2) of the revised manuscript shows, that salinity changes contribute substantially to the density changes in both deep water formation regions, in particular in the second half of the reduction period. Figure R1 (below), furthermore shows the spatial pattern of the anomalies. Both, sea-ice growth and precipitation changes contribute to this increase of the salinity. So far, we cannot answer, which process is more important for the increasing salinity, therefore we mention both processes in the revised manuscript.

Figure 4 furthermore shows, that heat loss is clearly more important in the first half of the reduction period. We therefore, carefully rewrote the results section of our manuscript and took care not to overemphasize the importance of sea ice growth.



R 1: Upper ocean (0-100m) salinity anomalies in S2_CHEM (left) and S2_NOCHEM (right) for the first (top), second (middle), and last (bottom) 10 years of the solar reduction period. Ensemble mean anomalies are calculated relative to the corresponding control ensemble mean. Dots denote significant differences ($p<0.05$).

3. I have a problem when you treat the AO and NAO identically. Although the AO and NAO correlate, they are not identical, not even from the AMOC perspective. I agree that the AO behaves largely like the NAO in winter. If, instead of the AO, you based your analysis on the NAO, how would the results look like? What would be their significance after taking into account the possible year-to-year autocorrelation?

See in comments below.

Minor comments:

- Page 1, line 16. I would rather say that ’surface currents transport water into the northern North Atlantic’ rather than to ’Northern high latitudes’ which sounds more like to the Arctic Ocean.

We changed 'Northern high latitudes' to 'North Atlantic'.

- Page 2, line 7. I don’t think the AO is the hemispheric equivalent of the NAO. The NAO is a regional index and correlates with the AO, but their definitions differ substantially.

We have deleted the phrasing 'hemispheric equivalent'

- Page 2, lines 18. ’... by increasing SSTs and enhancing freshwater input ...’

Rewritten to: “An increase in the solar forcing has been found to weaken the AMOC by increasing SSTs and enhancing freshwater input (Cubasch et al., 1997; Latif et al., 2009; Otterå et al., 2010; Swingedouw et al., 2011)”

- Page 2, line 32. As you focus on the AO in this paper, would be clearer not to talk about the NAO, but the AO, after Page 2, line 7.

We agree and focus on the AO in the revised manuscript. Note, that the results are very similar, when the analysis is performed using the NAO index. Some of the relevant literature, however, focuses on the NAO, therefore we cannot completely remove the NAO from the manuscript.

- Page 3, line 19. ’... uses temperature data ...’

Done.

- Page 4. line 3. You provide very little details on the model configuration. For example, what was the time step you used? How about the sea-ice salinity, was it constant? Or what sea-ice thermodynamics scheme was deployed? This information is important to assess how realistically the sea-ice salt rejection was modelled.

The model used is a configuration of the widely used ECHAM5-MPIOM (COSMOS model), which has been applied in various modelling studies and the IPCC AR4. The only difference between our version and the COSMOS version is the coupled atmospheric-chemistry module and this configuration is described in great detail in Muthers et al. (2014b).

The requested information has been included in the model description of the revised manuscript:

- Sea ice thermodynamics: “Sea ice dynamics are based on the viscous-plastic rheology formulated by Hibler (1979).”

- “A constant sea ice salinity of 5 psu is assumed.”
- Time-step: ”The time-step of the atmospheric component is 15 minutes, with the full radiation and the chemical computations updates are performed every 2 hours.” Ocean: “The time-step of the oceanic component is 2 hours and 24 minutes.”

- Page 4, line 20. You should mention here how long model simulations continued after the 30 year SSR period.

Rewritten to: “The reduction of the solar forcing is switched on in year 5 of a simulation and lasts for 30 years when it is switched off and the simulation is continued for 25 years.”

- Page 4, line 27. Explain the acronym TSI.

The acronym TSI is now defined at its first occurrence.

- Page 4, line 32. Explain more in detail how the AO index was calculated and provide references. For example, a common way to calculate the AO is based on the PC1 of 1000 mb pressure height anomaly data north of 20N. Your method seems to differ from that. Why? How robust your results are based on the AO calculation method?

We compared both AO methods, the EOF based way and the simplified AO index using the sea level pressure (SLP) north of 70°N. Both indices are closely related, for the CHEM_CTRL we find a Pearson correlation coefficient of 0.81 (0.85 for NOCHEM_CTRL). When calculating the AO based on sea level pressure data a common approach is based on the difference in the zonal mean SLP between around 40°N and 65°N (e.g. similar to Li and Wang (2003)). We also compared our index (SLP field north of 70°N) to the index using the SLP difference between 40°N and 65°N and found very similar results. We therefore conclude that the exact definition of the AO index is not important for the results of this study.

However, for a better agreement with previous studies we modified the manuscript and apply an AO index based on the SLP difference between 40°N and 65°N in the revised manuscript. In comparison to the EOF based definition we prefer this approach for its simplicity.

- Page 5, line 18. ’... are related ...’

Done.

- Page 5, lines 21-22. This sentence is hard to understand. How is the slight initial reduction of the global mean temperature related to the initial conditions of the ocean when the ocean initial conditions are from a 1300 year long simulation? Why rather not related to the atmospheric initial conditions which presumably started from an observation based, physically less consistent initial state?

The oceanic restart file is identical in all ensemble simulations. The atmosphere is perturbed by slight time difference between the restart files. Therefore, there is a considerable amount of “memory” in the ocean, which dominates the behaviour of the AMOC during the first years. We rewrote the relevant sentences for the revised manuscript:

“A slight initial reduction of the global mean temperature is also found in the reference ensemble experiments and is related to the initial conditions of the ocean. With all ensemble simulations sharing the same oceanic conditions in the beginning, the AMOC evolution of the first years is dominated by the oceanic memory.”

- Page 5, line 31. 'during the second half'

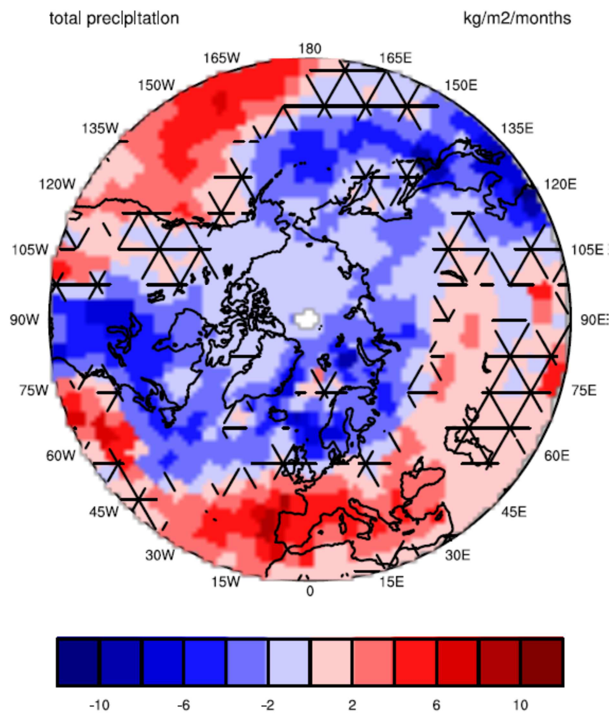
Thank you.

- Page 6, line 7. Do you mean that sea-ice patterns look similar but their anomalies are (presumably) weaker in the S1 experiments?

Exactly. Rewritten to "In the S1 experiments similar but weaker temperature and sea ice anomalies are found and S1_CHEM experiment is characterized by an amplified temperature reduction as well (not shown)."

- Page 6, line 13. Is the reduction in precipitation related to a shift in the main storm track and, as a result, a colder and dryer atmosphere?

It is mainly due to the shift in the storm track. The negative anomalies in the North Atlantic and Northern Europe occur along with positive anomalies in Southern Europe (compare Fig. R1).



R 2: Precipitation anomalies in S2_CHEM relative to CTRL_CHEM averaged over the 30 year SRR period

We changed this sentence in the manuscript accordingly: "Additionally, a shift of the storm track and a significant reduction of precipitation is found in the North Atlantic, which further increases the salinity."

- Page 6, lines 15-16. I think you need to verify the significance of the salt rejection to the surface density. It is typically small compared to the cooling effect. Also, not much freezing occurs at the eastern side of Greenland, but the Arctic ice flows south and melts along the eastern boundary of the East Greenland Current.

We rewrote this part of the result section focusing more on the density changes in the deep water formation regions of the North Atlantic and the Nordic sea.

- Page 6, lines 26-27. You should mention that these density and mixed layer depth anomalies are not reflected in the AMOC.

We have added: “These changes during the first 15 years are not reflected in the AMOC index.”

- Page 6, line 30. ’... the North Atlantic (Fig. 3a).’

Done.

- Page 6, lines 33-34. You must mean ’the central North Atlantic’ here.

Thank you.

- Page 7, line 2. The ’dominance’ is based on very speculative assumptions. Just say ’Salinity changes, nevertheless ...’

Changed accordingly.

- Page 8, line 1. Add a literature reference that proofs the linkage between the downward propagating wind anomalies and the AO phases.

At this point in the manuscript we discuss Fig. S4, which shows a connection between the AO and zonal mean wind anomalies. The pattern of the zonal wind composite suggests downward propagation of the wind anomalies. A similar pattern has been found by Baldwin and Thompson (2009, compare their Fig. 11) and we have added this reference to the manuscript.

- Page 8, lines 13-14. You don’t show this in Fig. 6, which should be mentioned, or plot CTRL_NOCHEM in Fig. 6.

The boxplots of the AO index for all experiments in Fig. 6 c and d (Fig 7 in the revised manuscript) show the behaviour discussed in the manuscript. In the revised manuscript we have added an explicit reference to Fig. 7 d to the corresponding explanation.

- Page 8, line 16. ’... which affects the wind ...’

Done.

- Page 8, line 29. ’... the AO phase has a long lasting effect ...’

Done.

- Page 8, line 33. This should be ’... the weakening of the Northern polar vortex ..’, right?

Right, thank you.

- Page 8, lines 34-35. I suggest you to write ’... dynamical changes decrease the density of the surface ocean waters South of Greenland, ...’

Applied as suggested.

- Page 9, lines 11-13. Don’t these citations analyse the impact of the increase in GHGCs? Seems like you are cutting corners here. Wouldn’t it be more correct to say e.g. ’... Swingedouw et al., 2011).

Related to increasing global greenhouse gas concentrations and associated surface warming, it is also one of the dominant ...’

We agree that our explanation was a bit oversimplified. We changed this as suggested to: “This response of the overturning to solar radiation changes has been identified in earlier studies (Cubasch et al., 1997; Latif et al., 2009; Otterå et al., 2010; Swingedouw et al., 2011). Related to increasing global greenhouse gas concentrations and associated surface warming, it is also one of the dominant mechanisms for the projected future weakening of the AMOC (Stocker and Schmittner, 1997; Manabe and Stouffer, 1999; Mikolajewicz and Voss, 2000; Gregory et al., 2005; Stocker et al., 2013).”

- Page 9, line 17. ’... may reduce the projected 21st century ...’

Done.

- Page 9, line 18. ’... stronger than in the late 21st century than [today?], when a grand ...’

We rewrote this to: “This is confirmed by experiments of Anet et al. (2013b). The AMOC is significantly stronger in the late 21th century, in ensemble simulations including a grand solar minimum in the second half of the 21th century in comparison to ensemble simulation without a decline of the solar activity (Fig. S7).“

- Page 9, line 23. ’... the AMOC by anomalous …

Done.

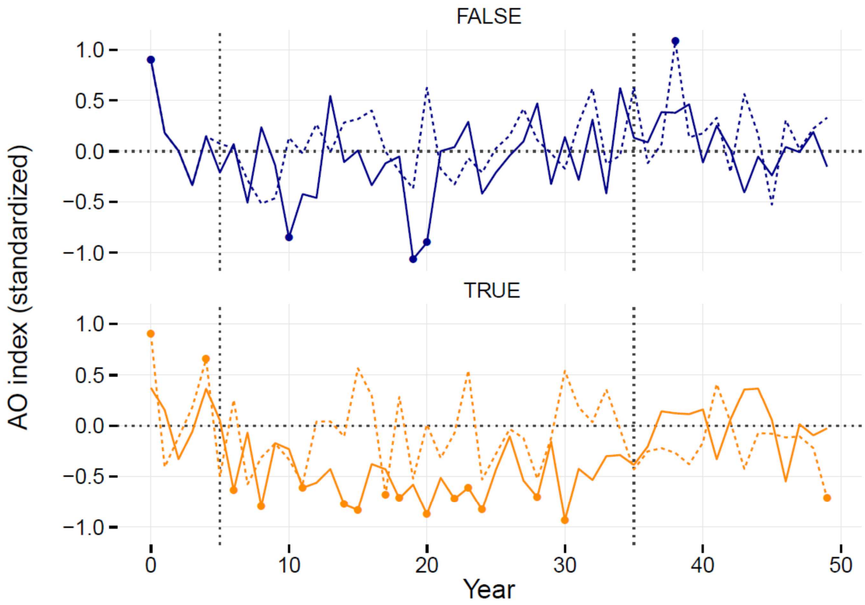
- Page 9, lines 23-25. This sentence is not clear to me. I suggest rewriting ’The dynamical effect is enabled by chemistry climate interactions, which result in amplified stratospheric temperature responses.’

We rewrote this to: “The dynamical effect is amplified by chemistry climate interactions, which result in amplified stratospheric temperature responses.” We prefer the term amplified, since the same dynamical effects is also present without chemistry-climate interactions, but much weaker.

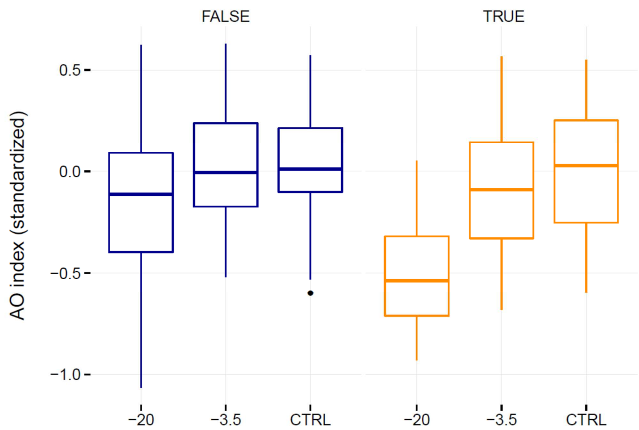
- Page 9, lines 28-29. The literature you cite here include three studies analysing NAO and only one analysing AO. This indicates to me, that NAO would have been a more appropriate index for this study as well, although its relation to the polar vortex is not as clear as the one of the AO.

For the analysis of the stratosphere-troposphere interactions the AO index is the more appropriate parameter. The AMOC index, however, is stronger influenced by the NAO. In our study, the influence of the stratosphere on the AMOC is analysed and therefore, we have to decide for one of the two indices to draw a consistent picture, from the stratosphere down to the ocean.

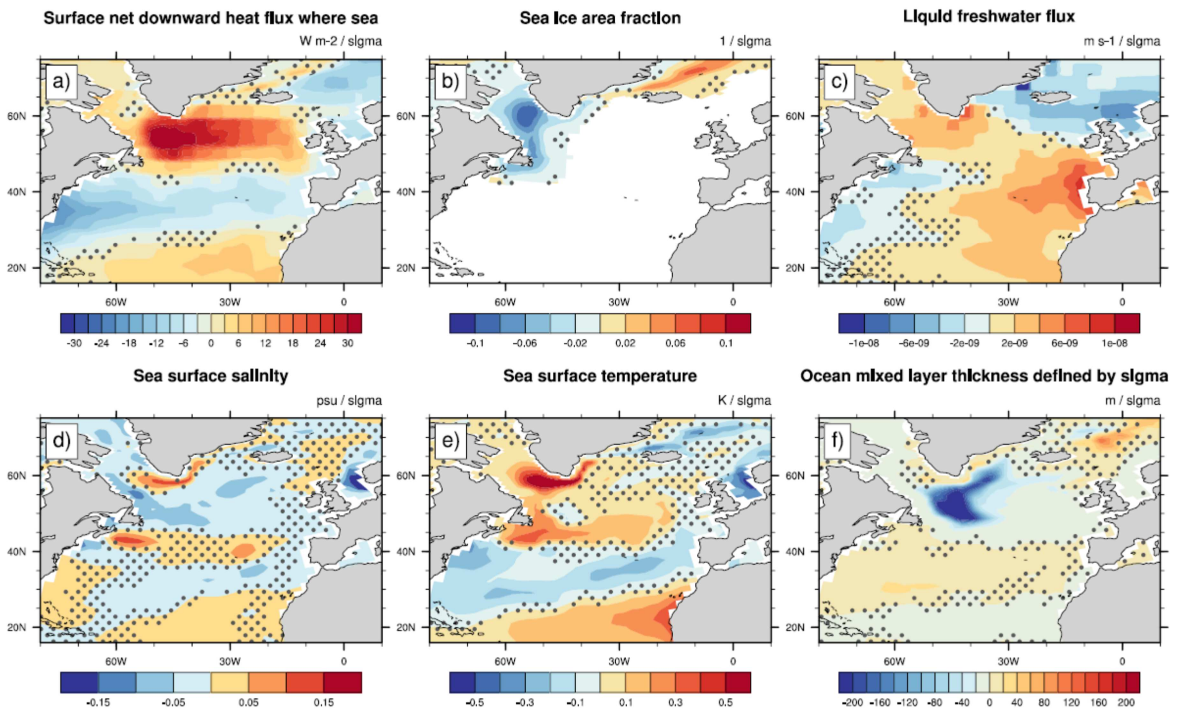
We argue, however, that the decision for one index or the other does not affect the conclusions of our study. Both indices are closely related in SOCOL-MPIOM. For CHEM_CTRL we find correlation coefficient of about 0.71 (0.68 in NOCHEM_CTRL.) For comparison we also performed our analysis with the NAO index (defined by the pressure difference between Iceland and the Azores). The results are given below and do not differ substantially between the results for the AO index.



R 3: Similar to Fig 6 a/b of the submitted manuscript, but for the ensemble mean winter (Nov. – Mar.) NAO index. The NAO is defined by the sea level pressure difference between Iceland and the Azores. Blue lines correspond to the NOCHEM experiments, orange lines to the CHEM experiments. Solid lines resemble the S2 and dashed lines the S1 experiments. Dots indicate winters with significant differences to the CTRL ensemble (Student t-test p ≤ 0.05).



R 4: Similar to Fig 6 d/e of the submitted manuscript, but for the ensemble mean winter (Nov. – Mar.) NAO index. Blue boxplots correspond to the NOCHEM experiments, orange boxplots to the CHEM experiments.



R 5: Similar to Fig 7 of the submitted manuscript, but for the ensemble mean winter (Nov. – Mar.) NAO index.

- Page 9, line 31. 'the modelled response of the AMOC ...'

done.

- Page 10, line 5. '... weakening of the AMOC with climatic ...'

done.

- Page 10, line 10. What do you mean by 'Future studies'. Be more explicit. Are you planning to do this work?

We currently do not plan to study these questions, since generating an appropriate aerosol forcing for SOCOL-MPIOM is a complicated task, which requires simulations with an external aerosol microphysical model. Therefore, this sentence is meant as a general suggestion to the community and we would like to keep this sentence as is.

- Figure 1. Write out the TSI acronym in the figure caption. As you used t-test for significance, did you check the autocorrelation or did you just treat each year as an independent variable? If years correlate, it affects your significance estimates. Explain more in detail what you did.

The TSI acronym is defined in the caption of the revised manuscript.

Dots in Fig. 1 represent year, where the SSR ensemble (e.g., S2_CHEM, 10 simulations) differs significantly from the control ensemble (e.g., CTRL_CHEM, 10 simulations). We therefore do a comparison of two data sets with 10 values each against each other. There is no autocorrelation, since we do not include any temporal information and the 10 experiments can be considered to be independent.

- Figures 2-4, 7, S1, S3, S5. Dots are not dark grey, but black. Better to say 'Black dots denote non-significant ...'

We changed this to "Dotes denote…"

- Figure 2. More correct to say 'The sea-level pressure contour interval is ...'

Done.

- Figure S2. Indicate latitude and longitude locations of these T & S profiles.

We did not use a latitude longitude box to calculate the T & S profiles. Instead the grid cells were selected by their averaged mixed layer depth. We state this in the caption of the figure:

"The deep water formation regions cover all grid cells with an annual mean mixed layer depth ≥ 250 m in the corresponding ocean basins".

References:

- Anet, J. G., Muthers, S., Rozanov, E., Raible, C. C., Peter, T., Stenke, A., Shapiro, A. I., Beer, J., Steinhilber, F., Brönnimann, S., Arfeuille, F., Brugnara, Y., and Schmutz, W.: Forcing of stratospheric chemistry and dynamics during the Dalton Minimum, Atmos. Chem. Phys., 13, 10951-10967, doi:10.5194/acp-13-10951-2013, 2013.
- Baldwin, Mark P., and David W J Thompson. 2009. "A Critical Comparison of Stratosphere – Troposphere Coupling Indices." Quarterly Journal of the Royal Meteorological Society 1672: 1661–1672. doi:10.1002/qj.
- Li J, Wang JXL. 2003. A modified zonal index and its physical sense. Geophys. Res. Lett. 30: 1632, DOI:10.1029/2003GL017441.
- Muthers, S., Arfeuille, F., Raible, C. C., and Rozanov, E. (2015): "The impacts of volcanic aerosol on stratospheric ozone and the Northern Hemisphere polar vortex: separating radiative-dynamical changes from direct effects due to enhanced aerosol heterogeneous chemistry". Atmos. Chem. Phys., 15, 11461-11476. 10.5194/acp-15-11461-2015
- Muthers, S., J. G. Anet, C. C. Raible, S. Broennimann, E. Rozanov, F. Arfeuille, T. Peter, A. I. Shapiro, J. Beer, F. Steinhilber, Y. Brugnara, W. Schmutz (2014): "Sensitivity of the winter warming pattern following tropical volcanic eruptions to the background ozone climatology", Journal of Geophysical Reseach, 199, 3, 1340-1355, 10.1002/2013JD020138.
- Muthers, S., Anet, J. G., Stenke, A., Raible, C. C., Rozanov, E., Brönnimann, S., Peter, T., Arfeuille, F. X., Shapiro, A. I., Beer, J., Steinhilber, F., Brugnara, Y., and Schmutz, W. (2014b): "The coupled atmosphere-chemistry-ocean model SOCOL-MPIOM", Geosci. Model Dev., 7, 2157–2179, doi:10.5194/gmd-7-2157-2014.

Anonymous Referee #2

We would like to thank referee 2 for his/her constructive and detailed review.

This paper examines the physical processes responsible for the AMOC response to reduced solar radiation and assesses the importance of chemistry-climate in modulating this response. By comparing two sets of climate model experiments, with and without interactive chemistry, the study demonstrates that climate models which do not consider stratospheric -namely ozone -chemistry may overestimate the sensitivity of the AMOC to solar forcing since the "top-down" influence (stratospheric influence on tropospheric circulation) is underestimated.

In my opinion, this work constitutes a very nice contribution for the broad climate research readership as it demonstrates, using the specific example of the AMOC, the prominent and complex connections between the different components which drive climate variability (going from the stratosphere chemistry to the ocean circulation). The work is well-framed in the current literature. I found the paper mostly clear, well written and scientifically sound. I think however that some improvements and clarifications could be made before publication. Please find my main comments/suggestions below:

Main comments/questions:

1. It has already long been recognized that atmospheric chemistry interacts with dynamics and that its consideration in climate models is crucial to adequately simulate climate variability (e.g. influence of the ozone hole recovery on the SAM trends in CMIP3 simulations by Son et al. (2008)). As a consequence, historical and projection climate simulations in CMIP5 for models without interactive chemistry were designed by prescribing chemical fields that consider long-term trends (Cionni et al., 2011). For CMIP6, the ozone prescription fields should be even further improved. So I would say that the current question regarding chemistry-climate interactions is: do we really need interactive chemistry? or can it just be prescribed? The other question is then how to prescribe it in the most accurate way (see e.g. Nowack et al. (2015)).

In my opinion, given the frame, the results and the conclusion of the present study, I think that the introductory part of the paper should –at least partly –review the recent advances regarding chemistry climate interaction. A lot has been done already and should not be ignored.

We rewrote large parts of the introduction and include now a state of the art on chemistry climate interactions:

"Still, most of these studies are based on models without interactive atmospheric chemistry. The influence of climate changes on the state of the ozone layer has been recognized already long time ago. The cooling of the stratosphere by greenhouse gases (GHG) slows down catalytic ozone oxidation cycles leading to ozone increase (e.g. Haigh and Pyle, 1982; Revell et al., 2012). The greenhouse warming accelerates Brewer Dobson circulation reducing ozone in the tropical lower stratosphere and enhancing its abundance over middle to high latitudes (Deckert and Dameris, 2008; Zubov et al., 2013). On the other hand, the ozone changes have substantial implications for the climate. The influence of the ozone recovery associated with the implementation of the Montreal Protocol limitations on the production of ozone destroying substances on the southern hemisphere has been identified in the observations and model simulations (e.g. Son et al., 2008; Robinson and Erickson, 2015). Recently it was suggested that the use of interactive chemistry instead of prescribed ozone climatology can influence climate model properties. Dietmüller et al. (2014) showed that the application of interactive chemistry reduces the climate sensitivity by 3-8%. Similar reduction of the climate sensitivity was also found by Muthers et al. (2014b). A more substantial reduction of the model response to 4xCO_2 by up to 20% due to taking into account interactive chemistry was reported by Nowack et al. (2014). All these studies attributed the reduction to the changes of ozone, water vapour and clouds in response to climate warming. These conclusions were not confirmed by very recent results of CESM1-WACCM model (Marsh et al. 2016), which have found similar ozone response to 4xCO_2 but no changes in climate sensitivity. In contrast, Chiodo and Polvani (2016) applied the same model and demonstrated the interactive ozone represents negative feedback leads to a weaker surface warming caused by an enhancement of the solar irradiance. These results require further experiments to define the reasons behind the model disagreements. Despite of some issues the understanding and treatment of the ozone feedback is important for the simulation of future climate change under influence of different natural and anthropogenic factors."

We prefer not to address the question how the chemistry can be prescribed in the introduction, since this is not a topic of our paper.

2. In the light of my previous comment, I would suggest the authors to explain more thoroughly how the combined UV+ozone effects modulate the heating rates in the stratosphere which is the starting point of the stratospheric mechanism discussed in the paper. The thermal modulation of the stratosphere through UV variations comes from two main effects: (1) direct shortwave heating through incoming UV absorption by ozone (λ~200-300 nm), (2) ozone change (λ<242 nm) which also affect shortwave heating rates. Both effects count significantly. Basically, and if I understood correctly, their NOCHEM experiment account for effect (1) only while CHEM account for effects (1) + (2). I think such clarifications are easy to make and necessary since they help understanding the basic difference between the two experimental configurations (at least regarding stratospheric ozone which is the major solar effect). In the present version of the paper too few information are given on UV-ozone-temperature interactions and their implication on experimental setting (e.g. P2L32-P3L1, P5L12-14).

We have included a detailed description of the chemistry-temperature interactions in the revised manuscript (see our answer to your comment on + P2L34-P3L1). In the experiment section, the following description of the experiments is included.

"In the CHEM experiments, ECHAM5 and MEZON are coupled and the atmospheric chemistry responds to the solar radiation changes. In NOCHEM, temporal and spatial ozone variations need to be prescribed. Therefore, a daily 3D ozone climatology is applied, based on a 1600 AD control simulations."

3/-A very recent study by Chiodo and Polvani (2016) has just been released in *Journal of Climate* and deal with –somewhat -similar problematics. They performed simulations that also present some similarities with those perform in the present work. While both studies have their own relevance and focus on different aspects, they also nicely complement each other. The authors may consider comparing results of both studies: are they consistent?

Thank you. We have added a comparison to the results of Chiodo and Polvani to the discussion section of the revised manuscript:

"Recently, Chiodo and Polvani (2016) assessed the role of the interactive chemistry on the temperature and precipitation response to increasing SSI. They identified a reduced sensitivity with interactive chemistry due to the effect of the ozone increase on the short-wave radiation balance. Our results for a SSI reduction indicate a slightly larger temperature sensitivity with interactive chemistry owing to the effect of the stratospheric water vapour and ozone changes on the long-wave radiation balance. These differences may be attributed to model differences or differences in the response of the climate system to increasing and decreasing solar forcing. A possible effect of the differences in the atmospheric response on the AMOC is not discussed by Chiodo and Polvani (2016)."

4/-In light again of my first comment, there is currently a debate about the need of having interactive chemistry in climate model or if it is sufficient to prescribe chemistry. The concern is real given the heavy computational costs that interactive chemistry requires. This question could have been addressed here by using the chemistry outputs of the CHEM experiments as a chemistry forcing for a say "prescribed-CHEM" experiment with solar-induced ozone changes. Both effects (1)+(2) (see comment 2/) could thus have been considered without including interactive chemistry. Did the authors perform such experiments? If they have (and only if they have), it would be relevant to mention their conclusions in the paper.

We agree that this is a highly relevant question. Unfortunately, we did not perform these simulations.

Specific comments:

+ P1L6-10: "*In simulations with chemistry-climate interactions a second, dynamical effect on the AMOC is identified which counteracts the thermal effect. This dynamical mechanism is driven by the stratospheric cooling in response to the reduced solar forcing, which is strongest in the tropics and leads to a weakening of the Northern polar vortex. In simulations with interactive chemistry, these stratospheric changes are strongly amplified by the reduction of stratospheric ozone.*" The point made in these three sentences seems confusing. The first two sentences seem to suggest that the stratospheric cooling is found only in the chemistry-climate simulations while it is in fact found in both but amplified when ozone reduction feedback is included (as suggested by the third sentence) in addition to the direct radiative heating reduction. This may benefit of being clarified.

We rewrote the second part of the abstract:

"In simulations with chemistry-climate interactions a second, dynamical effect on the AMOC is identified. This dynamical mechanism is driven by the stratospheric cooling in response to the reduced solar forcing, which is strongest in the tropics and leads to a weakening of the Northern polar vortex. By stratosphere-troposphere interactions, the stratospheric circulation anomalies induce a negative phase of the Arctic Oscillation in the troposphere which is found to weaken the AMOC through wind stress and heat flux anomalies in the North Atlantic. The dynamic mechanism is present in both ensemble experiments. In the experiment with interactive chemistry, however, it is strongly amplified by stratospheric ozone changes. In the coupled system, both effects counteract and weaken the response of the AMOC to the solar forcing reduction. Neglecting chemistry-climate interactions in model simulations may therefore lead to an overestimation of the AMOC response to solar forcing."

+ P2L12-13: "*The variability of the overturning circulation is furthermore influenced by external forcings (Otterå et al., 2010). Volcanic eruptions have been found to intensify the AMOC on decadal time scales (Otterå et al., 2010; Mignot et al., 2011).*" Since the study particularly investigates the mechanisms, I would suggest here to specify through which mechanisms volcanic eruptions influence AMOC (i.e. direct radiative cooling effect + tendency to induce positive NAO).

Rewritten to:

"So far, the external forcing response of the AMOC has been mainly studied in climate models without interactive atmospheric chemistry (Otterå et al., 2010). Thereby, volcanic eruptions have been found to intensify the AMOC on decadal time scales (Otterå et al., 2010; Mignot et al., 2011), through a reduction of sea surface temperatures and a shift of the North Atlantic Oscillation (NAO) towards its positive phase. "

+ P2L21: change "*trough*" to "through"

Done.

+ P2L34-P3L1: "*This response is modulated by chemistry-climate interactions. In particular, stratospheric ozone reacts to the UV changes and amplifies the stratospheric temperature change (Baldwin and Dunkerton, 2005)*". I think that further explanations on the UV-ozone-temperature interactions may be needed given that they are the source of the difference found Preference to Baldwin and Dunkerton (2005) might not be the best suited for this purpose. The authors could rather refer to the work of J. Haigh in the 1990s (Haigh, 1994 ; 1996). The authors could also refer to section 3.5 of the CCMVal report (and reference therein) which can be found at the following address http://www.sparc-climate.org/publications/sparc-reports/sparc-report-no5/. This chapter particularly details the implication that prescribing constant ozone (as in the NOCHEM experiments of the present study) has on shortwave heating rates associated with changes in the UV.

We have included the following paragraph in the revised introduction:

"The stratospheric response to UV variations is modulated by chemistry-climate interactions (Haigh, 1994, 1996). In particular, stratospheric ozone reacts to solar irradiance changes. The increase of solar UV enhances shortwave heating rate by the ozone absorption (e.g. Forster et al., 2011). Additional solar UV in the Herzberg continuum (λ <242 nm) intensifies ozone production, while UV in Hartley band destroys ozone (e.g. Ball et al., 2016, Figure 1). Because the solar UV variability normally decreases with wavelength the first effect prevails and leads to ozone increase in the middle stratosphere in phase with the increase of the solar UV. In turn the ozone increase gives additional heating with magnitude comparable to primary heating by the increase of solar UV alone (Forster et al., 2011). This process can amplify the efficiency of the earlier mentioned top-down propagation (Kodera and Kuroda, 2002) and is obviously missing if the ozone concentration is prescribed."

+ Section "*2.1 The model*": What about energetic particle effect? SOCOL-MPIOM has parameterizations that allow taking into account GCR and EPP effects (which are linked to solar activity variations) and are suggested to also have an impact on the Northern Hemisphere surface climate (e.g. Rozanov et al. (2012)) through the "top-down" mechanism and thus may also affect the AMOC.

SOCOL-MPIOM includes an EEP and GCR parametrization, but we concentrate on the effects of solar irradiance keeping the same EEP and GCR because they should not be changed in SRM case. Therefore, we think that these processes are not substantially relevant for our study and do not need to be mentioned in the model description.

+ P5L12-20: Here the authors may consider discussing their results in comparison with Chiodo and Polvani (2016).

We have included a comparison with the results of Chiodo and Polvani (2016) in the discussion section of the revised manuscript (see above).

+ P6L4-5: The sea-ice extension and the associated differences between S2-CHEM and S2-NOCHEM experiments are hard to see on Fig 2 which is already quite busy.

We agree, therefore the sea ice is shown again on Fig. 3. However, given the large number of figures we prefer not to add additional figures to the manuscript.

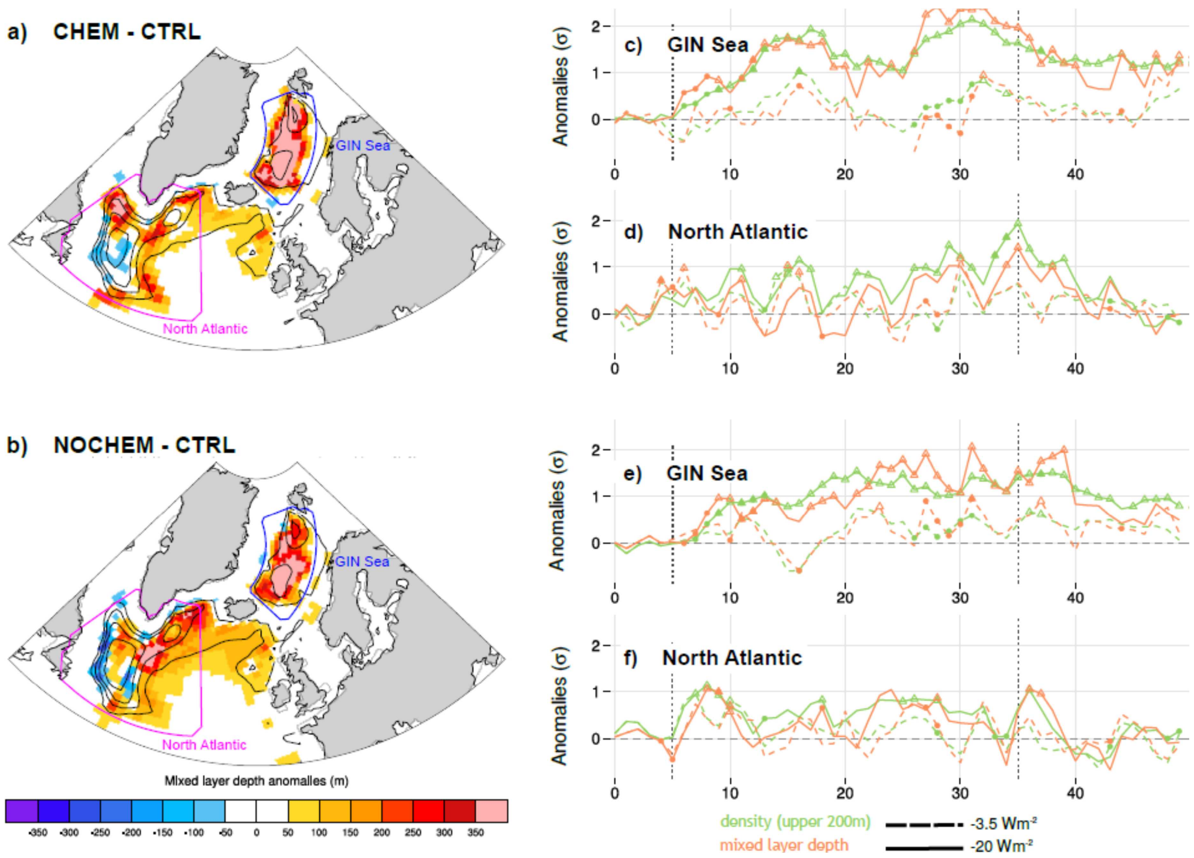
+ P6L13-14: "*Additionally, a significant reduction of the precipitation is found in the North Atlantic, which further increases the salinity*." Please indicate that this is not shown (in brackets).

Done.

+ P6-7: "*3.1 The thermal effect of SRR on the AMOC*": This part contains very interesting material and is very informative. However, I found quite hard to follow the text and figures together. While this is largely due to the fact that I am not used to examine ocean processes, I believe that some improvements could still me made. In particular, one of the key points relies on the differences, between the CHEM and NOCHEM configurations, of the timing of the anomalies development leading to differences in the AMOC response. In this regard, I think that, in addition to spatial patterns (Fig. 3), showing time series (similar to Fig. 1) of the key variables in the key regions may help understanding the timing issue.

We show time series of the mixed layer depth and upper ocean density for the two convective regions (GIN Sea, i.e., Nordic sea, and North Atlantic) below (Fig. R6). However, we prefer not to include these time series in the revised manuscript. The time series are dominated by large variability and it is very hard to identify clear differences between S2_CHEM and S2_NOCHEM from these figures. Furthermore, time series are based on averages over particular region and may miss changes occurring outside of these regions.

Instead of the time series, we modified Figure 3 to display decadal averaged for the first, second, and third year of the SRR period, instead of the first and the second half. Showing 10-yr averages already improves the temporal evolution and allows identifying the different development of the upper ocean anomalies in S2_CHEM and S2_NOCHEM. Furthermore, we rewrote this part of the result section of improve readability.



R 6: Anomaly maps (averaged over the solar minimum) and time series of the mixed layer depth and upper ocean density for the two convective regions (GIN Sea, i.e., Nordic sea, and North Atlantic). S2_CHEM is shown in panels a), c) and d). The results of S2_NOCHEM is shown in b), e), and f). Blue and magenta boxed in a) and b) denote the areas for the time series. The time series of the mixed layer depth and upper ocean density anomalies are normalized using the mean value and standard deviation of the corresponding control experiment.

+ P7L19-20: "*For S2_CHEM, a pronounced weakening of both polar vortices is found.*" Please give the reference to Figs. 4d,e,f in the text and replace "*both polar vortices*" by "NH and SH polar vortices" for clarity concerns.

Done.

+ P7L25: Is it annual anomalies or only winter (NDJFM) anomalies which are shown in Figs 4 and S3? Please clarify.

Fig. 4 and S3 show the annual mean anomalies. This is stated in the caption of Fig. 4 in the revised manuscript.

+ P7L26-27: Again for clarity, one sentence to explain what a SSW is may be useful here.

We have added a short explanation on SSWs:

"The weakening of the NH polar vortex is closely related to the occurrence of sudden stratospheric warming (SSW) events (Fig. 5). SSWs are stratospheric extreme events, in which the westerly flow during winter time is reversed and a strong warming in the polar stratosphere can be observed. SSW events in the NH are associated with a 'break down' of the polar vortex."

+ P8L3-4: "Overall, the downward coupling of wind speed anomalies does not differ substantially between the CHEM and NOCHEM control experiments." Although it is written that the statement concerns "anomalies", I believe that this sentence might be misleading since it seems to suggest that the CHEM and NOCHEM downward influence of the stratosphere on the troposphere are the same. We thus may wonder why we should expect a difference in the AO strength (described in paragraph which follows, P8L5-14). Please make this point clearer (as it is a key point of this paper).

We do not find large differences between the two control experiments, suggesting that the interactive chemistry has no large effect on the dynamics and the variability, when all external forcings are kept constant. Consequently, the influence of the stratosphere on the tropospheric AO is comparable with and without interactive chemistry. This has also been found in earlier studies with SOCOL-MPIOM (compare Muthers et al. 2014.).

However, this does not mean, that no differences are found when a changing external forcing is applied. In fact, we show in our results, that the interactive chemistry leads to strong differences in the stratospheric temperature change to the reduced solar forcing, which causes a stronger weakening of the Northern polar vortex, which in turn leads to a clear difference in the response of the AO. This response is not related to differences in the stratosphere-troposphere coupling between both experiments, but to differences in the stratospheric response.

References:

- Chiodo, G., and L. M. Polvani (2016): Reduction of climate sensitivity to solar forcing due to stratospheric ozone feedback, J. Clim., Doi:10.1175/JCLI-D-15-0721.1.

- Cionni, I., V. Eyring, J.F. Lamarque, W.J. Randel, D.S. Stevenson, F. Wu, G.E. Bodeker, T.G. Shepherd, D.T. Shindell, and D.W. Waugh (2011): Ozone database in support of CMIP5 simulations: Results and corresponding radiative forcing. Atmos. Chem. Phys., 11, 11267-11292, doi:10.5194/acp-11-11267-2011.

- Nowack, P.J., et al., (2015), A large ozone-circulation feedback and its implications for global warming assessments, Nat. Clim. Change., 4, 41-45, doi:10.1038/nclimate2451.

- Rozanov, E., et al. (2012), Influence of the Precipitating Energetic Particles on Atmospheric Chemistry and Climate, Surv. Geophys., 33:483-501, doi:10.1007/s10712-9192-0.

- Son, S.-W., et al. (2008), The impact of Stratospheric Ozone Recovery on the Southern Hemisphere Westerly Jet, Science, Vol 320, Issue 5882, doi:10.1126/science.1155939.

References

- Muthers, S., Anet, J. G., Stenke, A., Raible, C. C., Rozanov, E., Brönnimann, S., Peter, T., Arfeuille, F. X., Shapiro, A. I., Beer, J., Steinhilber, F., Brugnara, Y., and Schmutz, W. (2014b): "The coupled atmosphere-chemistry-ocean model SOCOL-MPIOM", Geosci. Model Dev., 7, 2157–2179, doi:10.5194/gmd-7-2157-2014.

Anonymous Referee #3

We would like to thank referee 3 for his/her constructive and detailed review.

The paper by Muthers and coauthors assesses the potential impact of atmospheric chemistry on the Atlantic meridional overturning circulation (AMOC) in two scenarios of reduced solar incoming radiation. The analysis is performed in ensembles of simulations in which interactive atmospheric chemistry is switched on and off. This allows the authors to detect two competing mechanisms that act toward strengthening and weakening the AMOC: the former as a result of thermally driven changes in upper ocean densities; the latter as a response of a dominating Arctic Oscillation negative phase, which in turn results from changes in the stratospheric circulation. Muthers et al. therefore conclude that the inclusion of atmospheric chemistry in climate models could be essential for a correct representation of solar-driven AMOC changes. These results could be of great relevance for the community and, hence, worth publicating.

However, my main concern about this paper relates the fact that the Introduction, as it is written now, does not allow us to clearly see the novelty behind this investigation, or whether this is relevant at all. The Introduction lacks a clear description – which, on the other hand, does not have to be too long – of previous works on the same or similar fields, so that we can identify from the very beginning what is the "hole in our current knowledge" the authors aim to address. I must admit that this is partly done in the last paragraphs in the Conclusion section; however, it is here too late and must appear earlier in the paper. This task could actually be done at cost of the initial description of the AMOC, which is supplementary (my guess is that any one approaching this paper will already have a clear idea of what the AMOC looks like). The Introduction might thus be kept relatively short. I encourage the authors to revise the Introduction to clarify this aspect. For this reason, I recommend major revisions before considering this work for publications

Thank you. We rewrote large parts of the introduction and removed a number of details on the AMOC description. The motivation for our study is now given earlier in the manuscript. Furthermore, we included two paragraphs on the state of the art in the field of chemistry-climate interactions.

Please have a look at the track-changes file for a full list of the applied modifications.

Other major points

The experiments: A small comment of why control simulations where simulated under 1600 CE conditions is recommendable, as CMIP5, for example, suggested using 1850 CE conditions. Also, why were the simulations run only 30 years? Is there any particular reason?

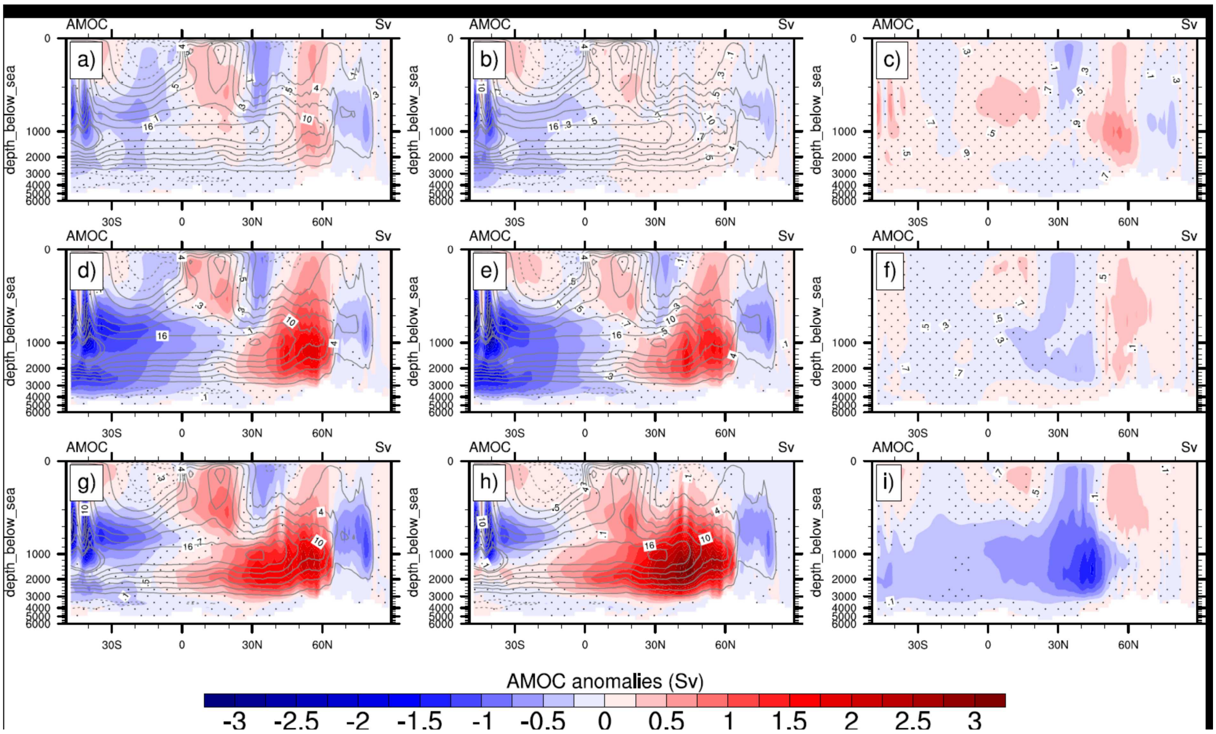
The control experiment, which was used to initialize the ensemble, was part of a study, which focuses on transient climate simulations for the period 1600 to 2100. Therefore, a 1600 control experiment was performed to generate starting conditions for the transient experiments. These experiments are described in Anet et al. 2013, 2014, Muthers et al. 2014.

We have added the following description to the experiment section of the revised manuscript: "The year 1600 was chosen, since a stable long-term control simulation with SOCOL-MPIOM was available from previous studies (Anet et al., 2013a, 2014; Muthers et al., 2014b). Note, the differences in the climatic conditions between 1600 and the commonly used year 1850 are small and both represent a preindustrial climate state."

Results: Could the authors also show the pattern of AMOC anomalies as a result of reduced incoming solar radiation? I think an index alone is not sufficient, and AMOC anomalies might be of different signs on different sites. This might indeed be interesting to show and comment.

The pattern of AMOC anomalies is shown below and we will add this figure to the supplementary material of the revised manuscript. Furthermore, we have added a discussion of the results:

"The differences between the AMOC index for S2_CHEM and S2_NOCHEM are also reflected in the anomaly pattern of the AMOC (Fig. S2). Within the first 10 years the intensification of the circulation is weak. Positive anomalies are found between 40◦N to 65◦N and between the surface and a depth of 2800m depth. During these first 20 years of the reduction period the intensification is slightly larger in S2_CHEM. A pronounced strengthening of the circulation occurs in the second decade of the reduction period. Positive anomalies cover all latitudes from the equator to 65_N and most levels between the surface and 3000m depth. In the second decade the intensification is more pronounced in S2_NOCHEM. In the third decade, finally, a further intensification is found, which is again stronger in S2_NOCHEM."



R 7: Atlantic meridional overturning streamfunction anomalies (Sv) for (a,d,g) S2_CHEM and (b,e,h,e) S2_NOCHEM and (c,f,i) the difference between the two experiments (S2_CHEM -- S2_NOCHEM). Top row (a-c) displays anomalies for the first 10 years of the solar reduction period; anomalies for the second decade are shown in middle (d-f) and the last decade is shown in the bottom row (g-i). Dots denotes non-significant differences (Students t-test, p > 0.05)

Discussion: Discussion might be enriched by putting this work's results into the context, for example, of some solar minima in the recent past, like the Maunder Minimum. Also, it might be interesting to discuss the changes one might expect if solar variability changes were indeed of smaller magnitude, as some reconstruction suggest. Would the authors expect a similar response in the AMOC/climate?

With the smaller magnitude of the TSI change we expect also a weakening of the effect of chemistry climate interactions. In our study we compare the S2 minimum (-20 Wm^{-2}) against the S1 minimum (-3.5 Wm^{-2}). In both experiments we find a weaker AMOC in the simulations with interactive chemistry in comparison to the simulations without interactive chemistry. In the S1 experiments, however, the differences are smaller and less significant.

Nevertheless, we are confident that our results are highly important for studying of past and future climate models, which do not consider chemistry-climate interactions. We discuss this at the end of our manuscript:

"Here, we show for the first time how stratospheric processes modulate the modelled response of the AMOC to solar forcing and identify the importance of chemistry-climate interactions for the response. Hence, previous studies without atmospheric chemistry may overestimate the sensitivity of the AMOC to solar forcing, since the dynamical effect is absent."

Minor Comments

Page 1

L4. SRR acronyms is not used in Abstract L18 . . . upwelling processes that bring the water back . . .

Done.

L19 please, rephrase "this Atlantic circulation" L20 I think, there is no need to bring the Atlantic Meridional Oscillation into the discussion if this is not going to be used any further

Done. L19 rephrased to "the surface branch of the AMOC". The AMO is mentioned, since it has been suggested to be an important component for the multi-decadal climate variations in the European region (e.g., Knight et al, 2006). Since other studies found a close relationship between the AMOC and the AMO we think mentioning this process highlight the relevance of studies on AMOC variability. Therefore, we prefer to keep this sentence.

Page 2

L4-5 Upper salinity also increases due to net evaporation in the tropical North Atlantic L22 Please, remove comma after management L23 GHG has not been defined

L4-5 rewritten to "Additionally, the salt content increases, through evaporation in the tropical regions and salt rejection during sea ice growth." Other modifications applied as suggested.

Page 3

L5 "different mechanisms, how" please, rephrase L9 add comma after chemistry

Rewritten to: "The purpose of this study is to assess the influence of a reduction of the solar forcing on the AMOC."

Page 4

L27 Do experiments here mean simulations? I suggest reviewing the use of these two terms throughout the manuscript, as sometimes one feels they are interchanged.

Thank you. Simulations were indeed meant here. We carefully checked the manuscript and use the terms experiment/simulations in a consistent way now.

L32-33 there is no need to indicate that AO index is multiplied by -1

In our approach it is. We define the AO index by the area averaged sea level pressure north of 70deg N. In this case, a negative anomaly to the long-term average corresponds to a positive phase of the AO. For clarity, we prefer to state explicitly the multiplication by -1.

Page 5

L2 “near-surface (2 m) air temperature” L2-end I wonder why common acronyms are not used throughout the text, such as, SAT, SST, etc. L2-end In many instances it is written: “reduction in temperatures”. This can be perfectly replaced by “cooling” L18 “are related”

Changes applied as suggested. Acronyms are used for terms, which occur multiple times in the manuscript. SST and SAT are not mentioned so often in the text. Moreover, we already use a number of different acronyms (CHEM, NOCHEM, CTRL, …) and introduction additional abbreviations would not improve the readability.

L7-11 This is a topic for the Discussion. It is nonetheless of little relevance for this paper.

We agree, that the relevance for the temperature differences between CHEM and NOCHEM and their relations to the models climate sensitivity are not very relevant the AMOC. However, it is relevant to understand the influence of the chemistry on the surface temperature variations and for the comparison of our results to earlier studies. Based on feedback from reviewer 2, we have included a comparison of our results to the study of Chiodo and Polvani (2016), who analysed the role of chemistry-climate-interaction on the temperature response to solar forcing. Therefore, we would like to keep this brief description of the temperature signals and the comparison with the climate sensitivity.

Page 6

L4-5 It is not clear in which run the larger cooling is found

Changed to: “Furthermore, a larger cooling over the Barents Sea is found in S2_CHEM, which extends towards Northern Eurasia.”

L5-6 do temperatures and sea ice anomalies here refer to the value or the pattern? Please, clarify. Besides, it is said that they are similar, but not to what. Does it mean similar to those in S2?

Sea ice and temperature patterns are similar to the anomalies found in the S2 experiments. Changed to

“In the S1 experiments temperature and sea ice anomaly patterns are weaker but similar to S2 are found and S1_CHEM is characterized by an amplified temperature reduction as well (not shown).”

L12 add comma after “sea ice formation”

done

L15 Here I wonder how relevant it is for the sea ice increase the advective contribution from a stronger AMOC.

Unfortunately, we do not understand this comment.

L17 Replace everywhere in the text Nordic Sea for Nordic Seas, as it stands for Greenland, Norwegian, Iceland seas, and sometime also the Barents Sea.

Done.

L23 please, rephrase ". . . but the significance is reduced"

Rewritten to: "The anomalies in the S1 experiments are similar, but the significance of the differences to the CTRL is lower."

L24 add comma before while

done.

L28 This sentence is probably too long. It could be divided into two. L30 please, clarify or rephrase "in other parts of the North Atlantic"

Rewritten to: "In S2_CHEM, however, a reduction of the density is found near the entrance of the Labrador Sea. This causes a reduction of the deep water formation in this area during the first half of the SRR, which is partially compensated by positive anomalies in the eastern North Atlantic (Fig. 3a)."

L30 remove comma after period L33 remove comma after convection L35 rephrase "Similar to the Nordic Seas" (for example, "As in the Nordic Seas,")

Applied as suggested.

Page 7

L6 add comma after forcing L7 Split the sentence into two. "in comparison to S2_NOCHEM. Similar differences . . . "

Applied as suggested.

L11 This statement might need a citation

We have clarified the statement and we have added a reference:

"Chemistry-climate interactions are most pronounced in the stratosphere (e.g., Dietmüller et al., 2014)."

L17 add comma after forcing L21 add comma before a reduction L23 add comma after Furthermore

Done.

L25 It is interesting to notice that changes in the polar vortex do not seem to go linearly with the reduction in the solar forcing. One should not expect linearity in the response, of course, but it is interesting in any case.

Indeed. We mention this explicitly in the revised manuscript: "These responses highlight the non-linear relationship between the solar forcing and the atmospheric dynamics."

Page 8

L9 add comma after response; change phenomena for phenomenon L10 add comma after AO index

Done.

L12-14 I do not necessarily agree with the authors on some of the interpretations they make from Figure 6 regarding the AO index, which are in these lines exposed. For example, changes in the S1 experiments are mostly nonsignificant, and, although in CHEM there is a shift toward more negative values, in NOCHEM the change is more like a broadening of the distribution, rather than a change to more negative phases. Also, it should be stated here that the AO index in S2_NOCHEM features a first half of mostly negative values, followed by a positive trend towards more positive. This might even be investigated further, as an extra.

We agree, that the significance of the anomalies is weak. Therefore, we have included the boxplot in Figure 6, which shows the statistics of the AO index, averaged over the 30 year SRR period. This supports our findings with a shift towards more negative AO values with reduced solar forcing and the clear difference between experiment with and without interactive chemistry. A widening of the distribution is not visible in the boxplots.

The higher years with negative AO in the first half of the solar minimum and the shift to neutral conditions in the second half is an interesting feature in S2_NOCHEM, which we mention now in the revised manuscript:

"In particular, a negative AO phase tends to occur more often in the first half of the SRR period, while neutral conditions dominate in the second half."

L16 affects

done.

L25 Here a statement connecting changes in temperature and salinity with those in density might be help connect ideas.

Rephrased to: "Since the density of the water decreases with increasing temperature and decreasing salinity, all these changes lead to a pronounced reduction of the mixed layer depth (Fig.f7f)."

L27 Could you explain shortly or cite in the literature why this instantaneous AMOC response to the AO? Is it due to wind forcing? If it were due to heat-driven changes in the convection, as those found during positive or negative phases of the NAO, I would assume some delay in the response of the AMOC

With our setup, we cannot assess, whether heat flux or wind forcing is the dominant mechanism. Sensitivity experiment of Delworth and Zeng (2016) suggested, that the former is more important. Delworth and Zeng (2016) performed sensitivity experiments where they forced an ocean model by different heat flux anomalies resembling a positive phase of the NAO. Their results furthermore show that after about 5-7 years the AMOC responds to this forcing with strengthening of the circulation (compare Fig. 3 in Delworth and Zeng). This shift of a few years agrees with our results, although an exact timing is difficult to estimate from our results. In our Fig. 6 we see that it takes a few years before the AO shift towards a predominant negative phase in S2_CHEM (about year 10 of the simulations). Differences in the AMOC, however, emerge around the year 20 (Fig. 1c), so about 10 years after the AO shift.

We have included a discussion of the results of Delworth and Zeng (2016) to the discussion section of the revised manuscript.

L33 Add comma after As a consequence,

done.

L34-35 Isn't it a reduction in the density? Otherwise, one should not expect a reduction in the convection, but an intensification

Right, thank you. This is corrected in the revised manuscript.

Page 9

Conclusions: I'd call this section Conclusions and Discussion. L6 please, remove comma after chemistry L12 the sentence about the projected future weakening of the AMOC should be connected with the next paragraph

Applied as suggested.

L15 It would be recommendable to compare the magnitude of the projected minimum with that of those implemented in this study, as well as its duration. If the magnitude of this future minimum were much smaller, we might then expect negligible changes in the AMOC strength.

The magnitude of the future solar minimum is at least as uncertain as the magnitude of past solar minima. For the past, proxy based solar forcing reconstructions indicate TSI amplitudes between 6 Wm^{-2} and below 1 Wm^{-2} (for the TSI difference between the Maunder Minimum and present day). While a reduction of 20 Wm^{-2} (S2 experiments) is clearly out of this range the S1 experiments (-3.5Wm^{-2}) are not completely unrealistic.

We have added a sentence on the uncertainty of future TSI change to the revised manuscript:

"Several studies suggest that the sun may enter a grand solar minimum within the next 100 years (Lockwood et al.,2009; Steinhilber and Beer, 2013; Roth and Joos, 2013), although the amplitude of the TSI change is associated with large uncertainties."

L20 please, rephrase. For example, adding after effect "when atmospheric chemistry is taken into account"

Rephrased as suggested.

L25 Many of the elements?

Rephrased to "Parts of the dynamic effect…"

L26 on various time scales. Also, it would be recommendable to indicate which scales in particular the authors refer here

Changed to:

"Parts of the dynamical effect have been reported in previous studies. The relationship between solar variability and the stratospheric circulation has been found for the 11-yr cycle (Kodera and Kuroda, 2002; Mitchell et al., 2015) as well as for grand solar minima (Anet et al., 2013a)."

L25-30 In this paragraph, three different verb tenses are used to talk about results from previous studies. I suggest using only one, maybe past simple?

Changed to:

"Parts of the dynamical effect have been reported in previous studies. The relationship between solar variability and the stratospheric circulation was found for the 11-yr cycle (Kodera and Kuroda, 2002; Mitchell et al., 2015) as well as for grand solar minima (Anet et al., 2013a). Also the projection of the stratospheric anomalies on the AO was reported in previous studies (Kodera, 2003; Ineson et al., 2011; Scaife et al., 2013). Finally, the influence of the AO phase on the overturning was studied (Delworth and Greatbatch, 2000; Eden and Willebrand, 2001; Matthes et al., 2006; Delworth and

Zeng, 2015) and a few studies identified a possible influence of the stratospheric circulation on the overturning (Manzini et al., 2012; Reichler et al., 2012)."

L31 remove comma after for the first time

Done.

Page 10

L2 when chemistry-climate interactions. . . this, I think, is already indicate at the beginning of the sentence L4 remove comma after GHGs L7 add comma after In this case,

Done.

FIGURES Would it be recommendable to add some of the Supplementary Figures to the main text? In particular those that are most referred in the text. There are indeed more Supplementary Figures that main ones.

We have included the former Figure S2 in the main text of the revised manuscript.

Fig. 1 Please, clarify whether the Student's t-test done after or before smoothing? The gray vertical lines indicating the SRR period are black

The Student's is performed using the annual mean values, therefore before the smoothing was applied. This is stated in the caption: "Thick dots denote significant differences in the (un-smoothed) annual mean values between the SRR ensemble and the control ensemble (Student's t-test, $p \leq 0.05$)."

Furthermore, we changed the caption to ''…by vertical lines.'

Fig. 2. Please, clarify why climatologies in panels e and g, and in f and h are different, if they derive from the same control simulation, CHEM and NOCHEM respectively?

We assume the reviewer is referring to Fig 3. The ctrl contour lines are different between e/g and f/h because the ctrl contours are calculated over the same period that was used to calculate the anomalies. Anomalies are expressed for the first and second 15 years of the solar minimum.

Figs. 5 and 6 Gray vertical lines are again black

see above.

Fig. 7 Readjust text to match the panels

Thank you, the caption has been corrected.

Fig. 8 Could you please increase the font size of the smallest text?

Font size has been increased.

Fig. S4. What are the shading and contours respectively?

We have included this information to the revised caption: "Contours and shadings from --8 to 8 m/s (contour step 1 m/s)."

References:

- Anet, J. G., Muthers, S., Rozanov, E., Raible, C. C., Peter, T., Stenke, A., Shapiro, A. I., Beer, J., Steinhilber, F., Brönnimann, S., Arfeuille, F., Brugnara, Y., and Schmutz, W.: Forcing of stratospheric chemistry and dynamics during the Dalton Minimum, Atmos. Chem. Phys., 13, 10951-10967, doi:10.5194/acp-13-10951-2013, 2013.

- Anet, J. G., S. Muthers, E. V. Rozanov, C. C. Raible, A. Stenke, A. I. Shapiro, S. Brönnimann, et al. 2014. "Impact of Solar versus Volcanic Activity Variations on Tropospheric Temperatures and Precipitation during the Dalton Minimum." Climate of the Past 10: 921–938. doi:10.5194/cp-10-921-2014. http://www.clim-past.net/10/921/2014/.

- Delworth, T. L. and Zeng, F.: The impact of the North Atlantic Oscillation on climate through its influence on the Atlantic Meridional Overturning Circulation, J. Clim., 29, 941–962, doi:10.1175/JCLI-D-15-0396.1, 2016.

- Muthers, S., J. G. Anet, a. Stenke, C. C. Raible, E. Rozanov, S. Brönnimann, T. Peter, et al. 2014. "The Coupled Atmosphere–chemistry–ocean Model SOCOL-MPIOM." Geoscientific Model Development 7: 2157–2179. doi:10.5194/gmd-7-2157-2014. http://www.geosci-model-dev.net/7/2157/2014/.

Anonymous Referee #4

We would like to thank referee 4 for his/her constructive and detailed review.

————————- General comments ————————

This paper is presenting different sets of simulations that evaluate the impact of a decrease in Total Solar Irradiance (TSI) over three decades, with a specific attention to the AMOC. It is focusing on the impact chemical changes induced by such a decrease, through comparison of a model not including this process, and another one including it. In both models, the decrease of TSI leads to an AMOC strengthening in the decades following the onset of the decreased TSI. The authors argue that this strengthening is larger when the chemical processes are not accounted for. They attribute such an effect to the impact of stratospheric chemistry has on the AO response to TSI decrease. Indeed, TSI decrease may lead a negative NAO due to larger cooling in the stratosphere associated with ozone depletion, which when reaching the surface may affect air-sea fluxes and wind stress, decreasing in particular salinity, which may diminish salinity in the ocean convection sites, limiting AMOC enhancement.

As the former summary shows it, the amount of results shown in this paper is very significant. The topic is also of large interest, since the climatic impact associated with AMOC is well known as well as its good predictability a few decades ahead, and the TSI is also potentially largely predictable and is believed to decrease substantially in the coming decades. The impact of chemistry in the stratosphere was believed to potentially impact the AMOC response to TSI (e.g. Ottera et al. 2011), and this is the first study I see that tackle this potentially important process.

The paper is generally correctly presented, even though I have a large number of comments to clarify and better present the results. My main concerns are that:

1. the main effect analysed (i.e. the impact of chemistry on AMOC response to TSI decrease) is very small and maybe hardly significant;

We do not agree with this comment of reviewer 4. In Figure 1 c the differences in the AMOC behaviour between S2_CHEM and S2_NOCHEM is very clear and highly significant. Furthermore, significant (but weaker) AMOC differences are found between S1_CHEM and S1_NOCHEM, which confirms the results found in the S2 experiments.

2. the demonstrations are sometimes too rapid;

We clarified several steps of our analysis in the revised manuscript.

3. the amount of nice results is maybe too large, which may request to separate the analysis into two papers, i.e. two parts of the main analysis. The first dedicated to a better understanding of AO/NAO response, which is already largely depicted in the present paper, and constitute a very important results, even if not new. The second one will be dedicated to the analysed of the AMOC, which deserves a few more analysis, especially since it is the main topic of the present paper, but only have a few figures that are directly analysing the process involved in the presented changes.

We do not think that the results should be separated into two papers. The response of the AO/NAO to the stratospheric changes has been reported in numerous previous studies. The response of the AO to either solar forcing or the AO/NAO has also been reported previously. The two topics would therefore confirm previous results but would not present novel results.

The novelty of our study is that we can show that all these (previously reported) processes modulate the response of the AMOC to a reduction in the solar forcing and that, furthermore, interactive chemistry has a strong effect for the response. We are convinced this should be presented in a single paper.

Concerning the impact of the AMOC, I'm not entirely sure that the effect of chemistry leads to significant results. The ensemble mean of the simulation seems a bit different, but no error bar, nor statistical test are applied to confirm the supposed impact. Generally speaking, the differences between the two sets should be more systematically highlighted as in Fig. 4 (right panels), which is not the case everywhere, as well as the error bar associated with ensemble spread. Since this is the main result highlighted in the paper, this should be proven with more statistical confidence, or the main message of the paper should be modified.

We have added several figures showing the differences and significance tests for the differences to the revised manuscript.

For all these reasons, although I found the set of experiments very interesting and potentially improving our understanding of climate dynamics in response to solar forcing, I found the take-home message and general descriptions of the results and logical connections sometimes a bit rapid. I therefore consider that the manuscript need major revisions before to be published, and I will advise the authors to consider the possibility of splitting their results into two parts (and two papers) in order to describe properly the main results and mechanisms discussed.

We rewrote parts of the manuscript to improve the presentation of our results. However, we do think that splitting the paper into two parts is appropriate (see above).

———————- Specific comments: ———————-

- P. 1, l. 20: "is responsible for the temperature conditions in western Europe": there is a lot of debate on this specific topic: cf. Seager et al. (2002). The AMOC does not have only an impact on western Europe and cannot explain the whole climate of this region

We fully agree. We changed this sentence to:

"The surface branch of the AMOC transports heat from the Southern Hemisphere and the tropics towards the North, is closely connected to the Atlantic Multidecadal Oscillation, and contributes to the temperate climatic conditions in western Europe (Knight et al 2006)."

- P. 1, l. 22: "Meehl et al. 2009b": 2009a should come first.

We rewrote large parts of the introduction and Meehl et al. 2009a is now no longer cited.

- P. 1, l. 23: add "in the past" after climatic changes"

done.

- P. 2: l. 13: "eruptions have been found to intensify the AMOC on decadal time scales": this is not just a question of intensification, but rather of variability excitation cf. Swingedouw et al. (2015)

We modified the manuscript accordingly:

"Moreover, volcanic eruptions may excite the variability of the AMOC (Swingedouw et al., 2015)."

- P. 4, l. 30: "monthly mean": This is a surprising choice. By doing so you include large part of so called Ekman wind-driven variability. Have you tried to remove this component, or to consider annual mean to limit its influence.

We have corrected this in the revised manuscript. We use the annual mean of the stream function to calculate the AMOC index.

- P.5, l. 3: what are the spread or error bar associated to the value given (since we are here considered ensemble of simulations.

The temperature difference between S2_CHEM and S2_NOCHEM is not a major finding of our study. Therefore, we did not present a detailed assessment of the differences between the two experiments. We have added two ensemble spread in the Table below.

Experiment	ΔT (K)	standard deviation (K)
S2_CHEM	-1.0	0.04
S2_NOCHEM	-0.9	0.07
S1_CHEM	-0.1	0.10
S1_NOCHEM	-0.1	0.07

The Student's t test suggests that the differences between the S2 experiments are highly significant (p=0.0009984929), while the differences between CHEM and NOCHEM are not significant in the case of the S1 forcing.

- P. 5, l. 8: can you be more specific on the reference that gave the climate sensitivity of the model and the computation you have made. When you gave numbers, you have to be more specific on the way you compute them.

The climate sensitivity of SOCOL-MPIOM and the experiment are described in Muthers et al. (2014). A reference is given in the model description but we will add the reference to this point as well.

- P. 5, l. 19-20: why is outgoing longwave increasing when water vapour increases. Please clarify the process at play here.

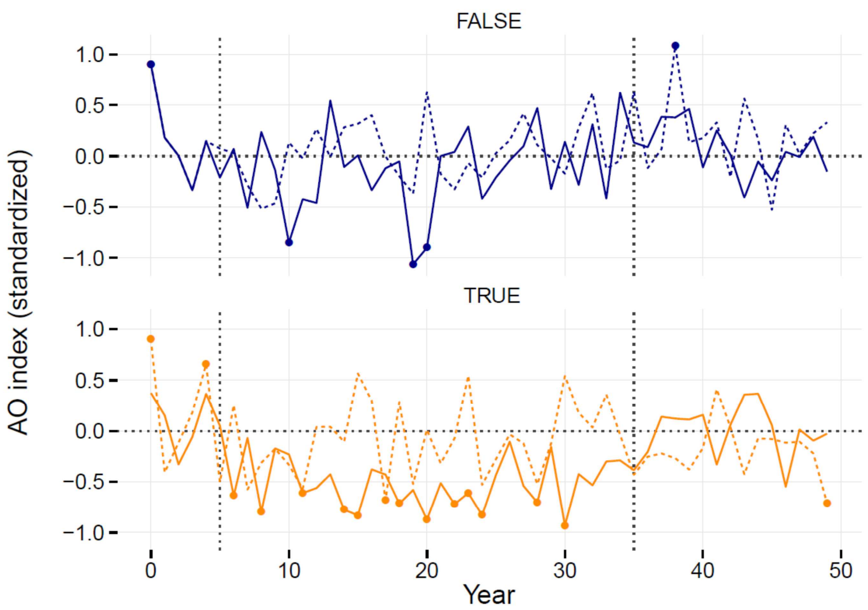
Stratospheric water vapour decreases in the SSR experiments, therefore OLR increases. The ordering of the sentences in the submitted manuscript was a bit misleading. We changed this to:

"In S2_NOCHEM, the largest anomalies (-15%) are found in the tropical upper troposphere, but stratospheric reductions exceed -10% almost everywhere (Fig. S1c). In S2_CHEM, the stratospheric reductions in water vapour are more pronounced (up to -35%), due to the effect of the solar forcing on the oxidation of methane, the most important in-situ source of stratospheric water vapour (Fig. S1b). Due to the greenhouse effect of ozone and water vapour, the outgoing long-wave flux increases more in CHEM than in the NOCHEM and leads to an additional cooling of the troposphere. The positive water vapour anomalies found in the uppermost model levels in the CHEM experiments (Fig. S1b and e) are related to the reduced UV photolysis of the water vapour molecules."

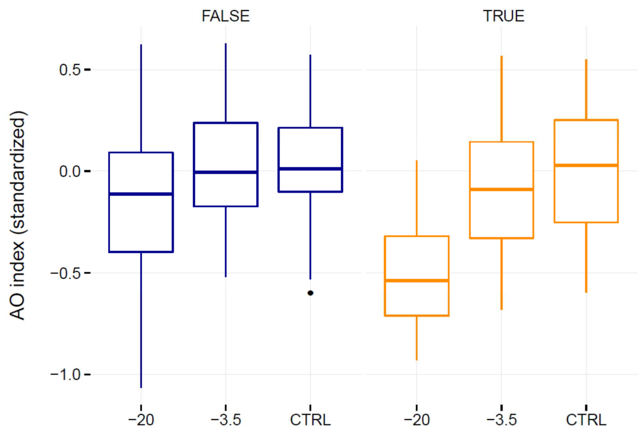
- P. 6, l. 1: why don't you look at the NAO rather than the AO, since you are looking at the North Atlantic region. The two are usually very much linked, but can you confirm this in your model?

For the analysis of the stratosphere troposphere interactions the AO index is the more appropriate parameter. The AMOC index, however, is stronger influenced by the NAO. In our study, the influence of the stratosphere on the AMOC is analysed and therefore, we have to decide for one of the two indices to draw a consistent picture, from the stratosphere down to the ocean.

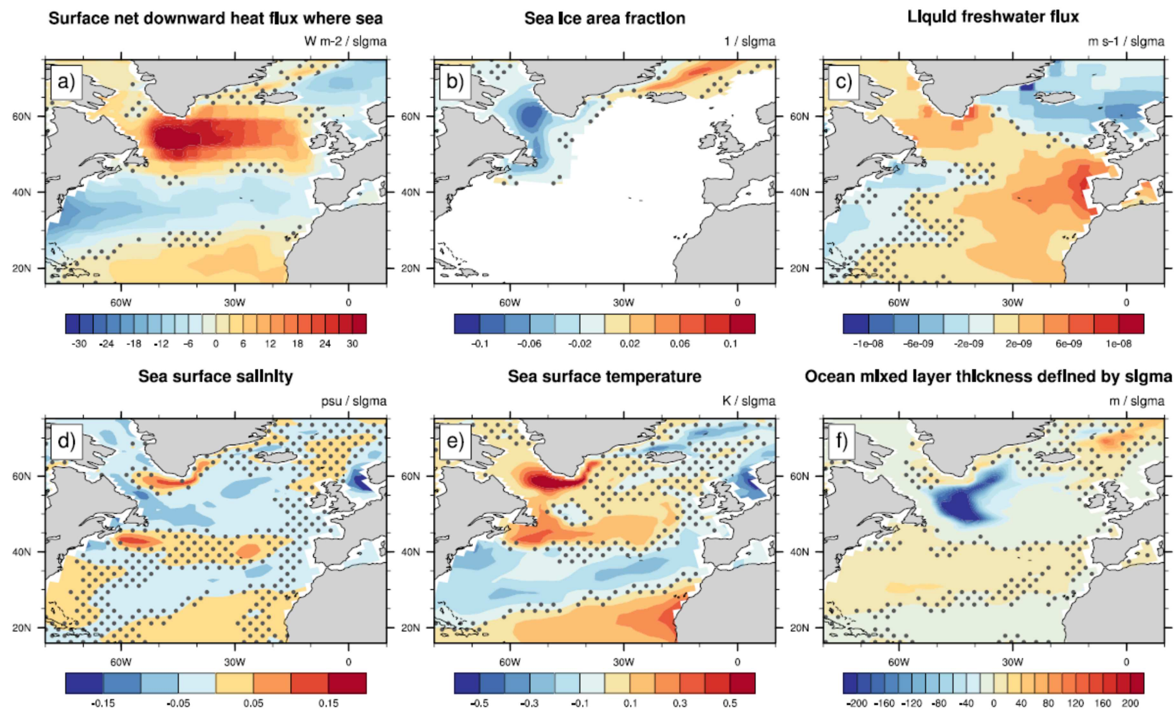
We argue, however, that the decision for one index or the other does not affect the conclusions of our study. Both indices are closely related in SOCOL-MPIOM. For CHEM_CTRL we find correlation coefficient of about 0.71 (0.68 in NOCHEM_CTRL.) For comparison we also performed our analysis with the NAO index (defined by the pressure difference between Iceland and the Azores). The results are given below and do not differ strongly between the results for the AO index.



R 8: Similar to Fig 6 a/b of the submitted manuscript, but for the ensemble mean winter (Nov. – Mar.) NAO index. The NAO is defined by the sea level pressure difference between Iceland and the Azores. Blue lines correspond to the NOCHEM experiments, orange lines to the CHEM experiments. Solid lines resemble the S2 and dashed lines the S1 experiments. Dots indicate winters with significant differences to the CTRL ensemble (Student t-test $p \leq 0.05$).



R 9: Similar to Fig 6 d/e of the submitted manuscript, but for the ensemble mean winter (Nov. – Mar.) NAO index. Blue boxplots correspond to the NOCHEM experiments, orange boxplots to the CHEM experiments.



R 10: Similar to Fig 7 of the submitted manuscript, but for the ensemble mean winter (Nov. – Mar.) NAO index.

- P. 6, l. 9: "the sea ice differences": when? Try to be very precise on what you are talking about

The sea ice difference emerge in the last 20 years of the reduction period. We clarified this in the manuscript:

"The Arctic sea ice differences between CHEM and NOCHEM, which emerge in the last 20 years of the reduction period, and are related to the weaker AMOC in the CHEM experiments and the reduced heat transport into the Arctic."

- P. 6, l. 9: “therefore”: the logical connection is not very clear to me, please clarify it.

See our answer to the previous comment (therefore has been removed).

- P. 6, l. 17: “Nordic Sea”. I am usually seeing “Nordic Seas”, since it is a few seas that you are dealing with (Greenland, Iceland, Norway). The same elsewhere in the ms.

This has been corrected.

- P. 7, l. 8-9: I’m not convinced the anomalies between CHEM and NOCHEM are significant for the AMOC. Please provide appropriate statistics.

We refer here to the differences in the AMOC index between CHEM and NOCHEM. A reference to Figure 1 has been added to the revised manuscript.

The differences between the AMOC in S2_CHEM and S2_NOCHEM are significant (Students t-test, $p < 0.05$) for the years 27, 28, 30, and 32, which corresponds to the end of the solar reduction period. In the revised manuscript we highlight years with significant differences between the CHEM and NOCHEM experiments in Fig. 1.

The significant differences between S2_CHEM and S2_NOCHEM are furthermore obvious from the latitude-depth cross section of the meridional streamfunction in the Atlantic. This figure is included as Fig. S2 in the revised supporting material. In the second half of the solar reduction period the differences are significant in a large region between about 800m to 3000m depth from the Southern hemisphere to 50°N. Between 30°N and 45°N the significant differences reach all the way up to the surface.

- P. 7, l. 11: can you provide a reference or an explanation to support this claim?

We have clarified the statement and we have added a reference:

“Chemistry-climate interactions are most pronounced in the stratosphere (e.g., Dietmüller et al., 2014).”

- P. 7, l. 13: “28K” is this concerning only a grid points?

The term “up to 28 K” described the maximum temperature difference, which is found in one or a few grid points-

- P. 7, l. 20: “-43%”: when? Over the 30-year period?

Yes, -43% when averaged over the 30 year period. We clarified this in the manuscript:

“a reduction of -43% is found in S2_CHEM during the winter season (Nov. to Mar.) when averaged over the SRR period.”

- P. 7, l. 23: what is your definition for the “duration of the winter period”?

The winter period starts with the first day with a westerly daily mean zonal mean wind component at 60N and 10hPa after 1. October and ends with the first day with easterly wind after 1. April.

We clarified this in the manuscript:

“Furthermore, the duration of the winter period with predominant westerly wind is reduced in S2_CHEM by –30% and in S2_NOCHEM by –5% respectively, when defining the start of the winter period by the day with the first occurrence of a westerly daily mean zonal mean wind component at 60N and 10hPa after September and the end by the first day with easterly winds after March."

- P. 7, l. 24-25: a series of number are given, with very poor definition. Please clarify.

See above.

- P. 8, l. 3: "downward coupling": can you define this?

We changed this to "downward propagation".

- P. 8, l. 21: "freshwater flux": from which component? Precipitation? Evaporation? Sea ice?

We refer to the total freshwater flux from all three processes. We clarified this in the revised manuscript.

- P. 8, l. 23: "export of saline water from the Nordic Sea by EGC". The EGC is a very fresh and cold current, so it is not exporting saline water! Do you mean the weakening of this current is increasing the salinity? Please clarify.

Regressing of AO index on upper ocean salinity (Fig. 7d of the submitted manuscript), we found positive salinity signals southward of Greenland. Wind anomalies, corresponding to a negative phase of the AO, probably contributes to a weakening of the EGC. We changed the manuscript accordingly:

"These changes cause a reduction of the salinity (Fig.7d), except for a small region South of Greenland, which may be affected by a weakening of the East Greenland current."

- P. 8, l. 28: "instantaneously": thus, this is likely not related to convection but rather to wind-driven changes. Can you comment on that?

It may be a combination of both. By "instantaneously" we mean, within the same winter season (we changed this in the manuscript). Over the course of a few months, heat flux anomalies related to the AO phase may also affect the convection. Wind forcing, however, may also contribute. With the current setup, we cannot really differentiate between the two processes. In another sensitivity study on the influence of the NAO on the overturning, Delworth and Zeng (2016) stated, that heat flux changes have the largest influence on the AMOC.

- P. 8, l. 31: "weaker intensification": significant? At which level? (please account for autocorrelation when computing degrees of freedom, since the AMOC has very low variability.

At this point we summarize the previous results. The weaker intensification is shown in Fig. 1c. Dots in Fig. 1 represent year, where the SSR ensemble (e.g., S2_CHEM, 10 simulations) differs significantly from the control ensemble (e.g., CTRL_CHEM, 10 simulations). We therefore compare two data sets with 10 values each against each other. There is no autocorrelation, since we do not include any temporal information and the 10 experiments can be considered to be independent.

- P. 9, l. 11: "is also one of the": not really, since in projections, this is the longwave radiation that is mainly affected rather than the solar radiation changes.

Our description was a bit misleading. We clarified this in the revised manuscript:

"This response of the overturning to solar radiation changes has been identified in earlier studies (Cubasch et al., 1997; Latif et al., 2009; Otterå et al., 2010; Swingedouw et al., 2011). Related to increasing global greenhouse gas concentrations and associated surface warming, it is also one of the dominant mechanisms for the projected future weakening of the AMOC (Stocker and Schmittner, 1997; Manabe and Stouffer, 1999; Mikolajewicz and Voss, 2000; Gregory et al., 2005; Stocker et al., 2013)."

- P. 9, l. 20-24: while the impact on the AO is very large, the impact on the AMOC is very weak, why is that? Is it coherent with small effect of AO on AMOC in control? What is the regression value of the AO on the AMOC in this model? Lohman et al. (2009) can be an interesting references concerning long term of a positive NAO on North Atlantic.

The response of the AMOC is a combination of several factors. The AMOC responds to the temperature changes, which cause an intensification of the overturning. In the CHEM experiments the AMOC is furthermore affected by the AO, with the negative AO phase leading to a weakening. Therefore, the response of the AMOC to the AO is already counteracted by the effect of the temperature changes.

We discuss the study of Lohmann et al. in the revised manuscript:

"The influence of the dynamic effect on the AMOC may furthermore depend on the length of the solar reduction period. Lohmann et al. (2009) found a gradual weakening of the subpolar gyre response with time in ocean model simulations forced with a persistent negative phase of the NAO. Additionally, the response of the AMOC may be non-linear and an increase of the solar forcing may change the dynamic effect (Lohmann et al., 2009)."

- P. 9, l. 32: "importance": I think this is a strong statement for a very weak effect in the end. . .

We do not agree. Between S2_CHEM and S2_NOCHEM we find an AMOC difference of about 1 Sv, which can only be attributed to the interactive chemistry. This difference cannot be considered as weak. Moreover, the weaker forced S1 experiments also reveal a clear difference in the AMOC intensities between S1_CHEM and S2_NOCHEM.

- P. 10, l. 1: add "slightly" after "may"

see above, we do not think that the response is weak, therefore a "slightly" would reduce the importance of our study.

- Fig. 1: please compute a statistical test for differences between CHEM and NOCHEM anomalies.

Applied, see above.

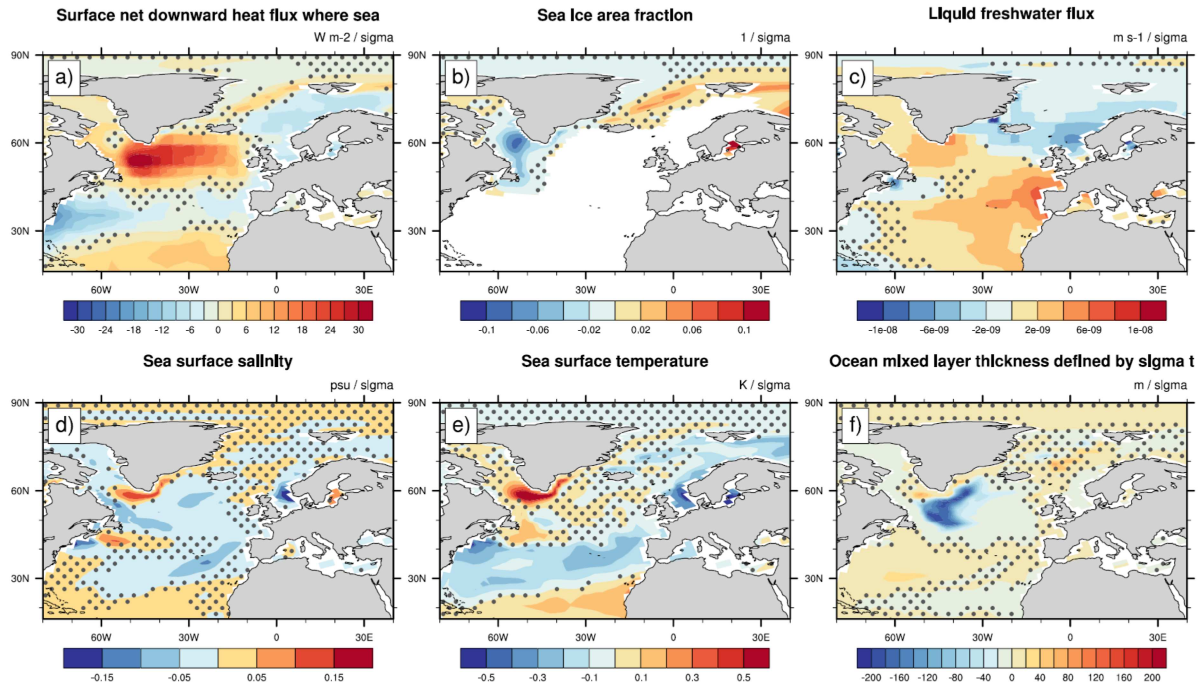
- Figs 2,3, 7: please compute the difference CHEM-NOCHEM as in Fig. 4

We have added the difference CHEM-NOCHEM to Figure 2 and 3. For Figure 7 (and S. 6), which shows the regression of the AO index on different oceanic variables in our control ensembles, the differences (are very small) and not relevant for this study.

- Fig. 7: This is a key figure when trying to understand what is going on for the AMOC, which should be the heart of the paper, given the title. Why is the projection so different than in 3? We want to see what is going in the whole Nordic Seas, including Fram Strait. What about circulation changes (barotropic stream function for instance)? Wind stress? Density? Thermal and salinity component of density? The demonstration of the processes affecting the North Atlantic should be more depicted.

Figure 6 shows the influence of the AO on different oceanic variables in our control ensembles. Anomalies in Figure 3, however, show the influence of the reduced solar forcing on the ocean, which is a combination of atmospheric forcing caused by the AO (comparable to Fig. 7) and changes related to the reduced surface temperatures. Therefore, we expect differences in the response patterns between Fig. 7 and Fig 3.

The key region for the influence of the AO on the overturning is the North Atlantic, therefore, we prefer to show only this region in the paper. Nevertheless, a larger region including Fram Strait is shown below in Figure R12. Here, we find an increase of the sea ice cover in the Nordic Seas, a slight reduction of the precipitation and a slight increase of the mixed layer depth. In comparison, to the anomalies found in the deep water formation region of the North Atlantic, these anomalies are rather small. Therefore, we prefer to focus in the North Atlantic for the manuscript.



R 11: AO regression analysis for CHEM_CTRL, similar to Fig. 7 in the submitted manuscript, but for a larger area.

Figure S2 in this regard is interesting and should come in the main ms., but what is missing on this figure is an indication of the time frame. When are the changes occurring. Each point corresponds to a year from what I understand (with a smoothing of 15 years). Thus the anomalies are firstly thermally driven and then salinity driven. Why is there such a 10-year lag? (which is not clear from Fig. 8 where no time scale is shown).

We will include Figure S2 in the main manuscript. In this figure, each dot corresponds to one year (we will mention this in the caption of the revised manuscript). Anomalies are indeed dominated by temperature changes during roughly the first 10 years, then salinity takes over. At the moment we cannot full explain the mechanisms behind this shift in the response.

Overall, temperature and salinity in the North Atlantic are dominated by three processes in our study: Firstly, the reduced solar forcing leads to a cooling of the ocean surfaces and an increasing salinity due to changes in the precipitation patterns and the sea ice formation. As second process, which affects the North Atlantic Ocean, is the changing tropospheric circulation patterns (negative AO phase), which also affects temperature and salinity through changes in the heat and freshwater flux. Finally, as a third process the intensification of the AMOC leads to enhanced transport of warm and saline water into the North Atlantic. With the current setup it is not possible to separate the different influences on the North Atlantic, in particular since the different processes interact and are associated with different lags.

—————- Bibliography: —————-

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Response of the AMOC to reduced solar radiation – the modulating role of atmospheric-chemistry

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Abstract. The influence of reduced solar forcing (grand solar minimum or geoengineering scenarios like solar radiation management) on the Atlantic meridional overturning circulation (AMOC) is assessed in an ensemble of atmosphere-ocean-chemistry-climate model simulations. Ensemble sensitivity simulations are performed with and without interactive chemistry. Without chemistry-climate interaction the AMOC is intensified in the course of the solar radiation reduction~~(SRR)~~, which is attributed to the thermal effect of the solar forcing: reduced sea surface temperatures and enhanced sea ice formation increase the density of the upper ocean in the North Atlantic and intensify the deepwater formation. In simulations with chemistry-climate interactions a second, dynamical effect on the AMOC is identified~~which counteracts the thermal effect~~. This dynamical mechanism is driven by the stratospheric cooling in response to the reduced solar forcing, which is strongest in the tropics and leads to a weakening of the Northern polar vortex. ~~In simulations with interactive chemistry, these stratospheric changes are strongly amplified by the reduction of stratospheric ozone.~~ By stratosphere-troposphere interactions, the stratospheric circulation anomalies induce a negative phase of the Arctic Oscillation in the troposphere ~~,~~ which is found to weaken the AMOC through wind stress and heat flux anomalies in the North Atlantic. The dynamic mechanism is present in both ensemble experiments. In the experiment with interactive chemistry, however, it is strongly amplified by stratospheric ozone changes. In the coupled system, both effects counteract and weaken the response of the AMOC to the solar forcing reduction. Neglecting chemistry-climate interactions in model simulations may therefore lead to an overestimation of the AMOC response to solar forcing.

1 Introduction

The Atlantic meridional overturning circulation (AMOC) is an important component of climate variability in the North Atlantic region ~~(Stocker, 2013). It consists of (i), surface currents which transport water into the Northern high latitudes; (ii), deepwater formation regions, where dense water is mixed with the deep ocean; (iii), deep currents which transport the water masses southwards, and (iv), upwelling processes to bring the water back to the ocean surface (Kuhlbrodt et al., 2007)~~(Kuhlbrodt et al., 2007; Stock

The surface branch of ~~this Atlantic circulation~~ the AMOC transports heat from the Southern Hemisphere (SH) and the tropics towards the North, is closely connected to the Atlantic Multidecadal Oscillation, and ~~is responsible for~~ contributes to the temperate climatic conditions in western Europe (Knight et al., 2006). ~~Understanding~~ Thus, understanding the variations in the strength of this circulation is ~~of particular relevance for~~ important in particular for future climate change (Stocker and Schmittner, 1997; Ma decadal climate predictions ~~(Griffies and Bryan, 1997; Meehl et al., 2009a). Furthermore, the AMOC has been proposed to be a candidate involved in~~ (Griffies and Bryan, 1997; Meehl et al., 2009b) and with respect to potential abrupt climatic changes as proposed for the past (Stocker and Wright, 1991; Stocker, 2000; Clark et al., 2002).

~~The AMOC is driven by different processes (Wunsch, 2002; Kuhlbrodt et al., 2007; Lozier, 2010). One of them is~~ Several processes are involved in driving the AMOC ranging from internal processes of the climate system such as the thermohaline process ~~, the driver for the deep convection in the North Atlantic. While being transported to the North, the light and warm tropical surface waters lose their heat to the atmosphere. Additionally, the salt content increases, through salt rejection during sea ice growth. At specific locations in the North Atlantic, the density of the water masses reaches values, which enable deep convection. Another important driver is the forcing from the atmospheric circulation. This involves the upper layers of the ocean, which are directly affected by the wind stress~~(Wunsch, 2002; Kuhlbrodt et al., 2007; Lozier, 2010) to extrenal forcing (Otterå et al., 2010). The purpose of this study is to assess the influence of a reduction of the solar forcing on the AMOC. In particular, ~~the North Atlantic Oscillation (NAO), or its hemispheric equivalent the Arctic Oscillation (AO), has been found to influence the AMOCby anomalous fluxes of heat, momentum, and fresh water (Delworth and Greatbatch, 2000; Eden and Willebrand, 2001 Additionally, the surface wind stress is important for the upwelling from deeper layers via a horizontal divergence in the wind driven Ekman transport. The relative importance of both drivers for the AMOC and the temporal variability is still debated (Kuhlbrodt et al., 2007) and may depend on the time scale (Biastoch et al., 2008; Pillar et al., 2016)~~we investigate the role of chemistry-climate interactions in modulating the response of the atmospheric circulation to reduced solar radiation and their effect on the AMOC. To this end, we perform ensemble sensitivity simulations for different solar radiation reductions with a state-of-the-art coupled atmospheric-ocean-chemistry-climate model, where atmospheric chemistry is either enabled or disabled.

~~The variability of the overturning circulation is furthermore influenced by external forcings (Otterå et al., 2010). Volcanic~~

So far, the external forcing response of the AMOC has been mainly studied in climate models without interactive atmospheric chemistry (Otterå et al., 2010). Thereby, volcanic eruptions have been found to intensify the AMOC on decadal time scales (Otterå et al., 2010; Mignot et al., 2011), through a reduction of sea surface temperatures and a shift of the North Atlantic Oscillation (NAO) towards its positive phase. Moreover, volcanic eruptions may excite the variability of the AMOC (Swingedouw et al., 201 The response, however, may depend on the background conditions of the climate system (Zanchettin et al., 2012). An increase in the solar forcing ~~, which leads to positive anomalies in the sea surface temperatures (SSTs),~~ has been found to weaken the AMOC by increasing SSTs and enhancing freshwater input (Cubasch et al., 1997; Latif et al., 2009; Otterå et al., 2010; Swingedouw et al., 2011) and has been proposed to be a driver of Greenland temperature variations (Waple et al., 2002; Kobashi et al., 2015). ~~In addition to the natural forcings, anthropogenic climate change will likely cause a weakening of the AMOC in the 21th century by the increasing SSTs and enhanced freshwater input into the North Atlantic (Stocker and Schmittner, 1997; Manabe and Stouffer, 1999; Mikolajewicz and Voss, 2000; Gregory et al., 2005).~~

Various methods have been discussed to mitigate climate change, either trough a removal of the emitted CO_2 from the atmosphere or through a reduction of the solar radiation absorbed by the Earth. The idea of the solar radiation management, is to balance the radiative forcing increase from GHG by a reduction of the incoming solar radiation. Therefore, the injection of sulphate aerosols into the stratosphere (analogous to the effect of large volcanic eruptions), a change in the Earth's albedo (e.g, marine clouds brightening), or a reduction of the incoming solar radiation in space have been suggested. A reduction of the incoming solar flux in space could be achieved by a large lens or a cloud of mirrors close to the Lagrangian point between the Earth and the Sun (Boucher et al., 2013).

The effect of a change in the incoming solar radiation on the climate system has been studied in numerous studies on past climates (e.g., Shindell et al., 2001; **?**; Anet et al., 2013a, 2014; Schurer et al., 2014), possible impacts on the future climate (Feulner and Rahmstorf, 2010; Anet et al., 2013b; Meehl et al., 2013), as well as for geoengineering techniques to mitigate climate change (Schmidt et al., 2012; Niemeier et al., 2013; Tilmes et al., 2013).

Among many possible influences, a change in the solar forcing may also affect the NAO (Kodera, 2003; Ineson et al., 2011; Swingedouw et al., 2011; Scaife et al., 2013). For example, the circulation in the polar stratosphere during winter (polar night jet) has been proposed to be affected by a change in the ultra-violet (UV) radiation (Kodera and Kuroda, 2002). This response is modulated by chemistry-climate interactions. In particular, stratospheric ozone reacts to the UV changes and amplifies the stratospheric temperature change (Baldwin and Dunkerton, 2005). By stratosphere-troposphere interactions, stratospheric anomalies can propagate down to the troposphere and cause circulation anomalies at the surface (Perlwitz and Graf, 1995)(Perlwitz and Graf, 1995; Muthers et al., 2014a). A positive phase of the NAO is then associated with a strengthening of the polar night jet and vice versa (Baldwin and Dunkerton, 1999, 2001; Thompson and Wallace, 2001) and may also affect the AMOC (Manzini et al., 2012; Reichler et al., 2012).

The purpose of this study is to investigate different mechanisms, how a reduction of the solar radiation affects the AMOC. Furthermore, we assess the role of stratospheric response to UV variations is modulated by chemistry-climate interactions in modulating the response of the atmospheric circulation to reduced solar radiation and their effect on the AMOC. To this end, we perform ensemble simulations for different solar radiation reductions with a coupled atmospheric-ocean-chemistry-climate model interactions (**??**). In particular, stratospheric ozone reacts to solar irradiance changes. The increase of solar UV enhances shortwave heating rate by the ozone absorption (e.g. Forster et al., 2011). Additional solar UV in the Herzberg continuum (λ <242 nm) intensifies ozone production, while UV in the Hartley band destroys ozone (e.g. Ball et al., 2016, Figure 1). Because the solar UV variability decreases with wavelength the first effect prevails and leads to ozone increase in the middle stratosphere in phase with the increase of the solar UV. In turn the ozone increase gives additional heating with magnitude comparable to primary heating by the increase of solar UV alone (Forster et al., 2011). This process can amplify the efficiency of the earlier mentioned top-down propagation (Kodera and Kuroda, 2002) and is obviously missing if the ozone concentration is prescribed.

Still, most of these studies are based on models without interactive atmospheric chemistry. The influence of climate changes on the state of the ozone layer has been recognized already long time ago. The cooling of the stratosphere by greenhouse gases (GHG) slows down catalytic ozone oxidation cycles leading to ozone increase (e.g. Haigh and Pyle, 1982; Revell et al., 2012).

The greenhouse warming accelerates Brewer Dobson circulation reducing ozone in the tropical lower stratosphere and enhancing its abundance over middle to high latitudes (Deckert and Dameris, 2008; Zubov et al., 2013). The ozone changes have substantial implications for the climate. The influence of the ozone recovery associated with the implementation of the Montreal Protocol limitations on the production of ozone destroying substances on the SH has been identified in the observations and model simulations (e.g. Son et al., 2008; Robinson and Erickson, 2015). Recently, it was suggested that the use of interactive chemistry instead of prescribed ozone climatology can influence climate model properties. Dietmüller et al. (2014) showed that the application of interactive chemistry reduces the climate sensitivity by 3-8%. Similar reduction of the climate sensitivity was also found by Muthers et al. (2014b). A more substantial reduction of the model response to 4xCO2 by up to 20% due to taking into account interactive chemistry was reported by Nowack et al. (2014). All these studies attributed the reduction to the changes of ozone, water vapour and clouds in response to climate warming. These conclusions were not confirmed by very recent results of CESM1-WACCM model (Marsh et al., 2016), which found similar ozone response to 4xCO2 but no changes in climate sensitivity. In contrast, Chiodo and Polvani (2016) applied the same model and demonstrated that the interactive ozone introduces a negative feedback leading to a weaker surface warming due to an enhancement of the solar irradiance. Thus, these results show that further experiments are necessary in order to assess the model discrepancies and to deepen our understanding of the ozone feedback and its importance for the simulation of future climate change under the influence of different natural and anthropogenic factors.

The outline of this study is as follows. The model configuration and the experiments are described in section 2. Section 3 presents the results, first for the experiments without interactive atmospheric chemistry followed by an analysis of the differences causes by the chemistry-climate interactions. A summary and concluding discussion is given in section 4.

2 Model and experiments

2.1 The model

We use the coupled atmosphere-ocean-chemistry model SOCOL-MPIOM to simulate the effect of a change in the solar activity on the climate (Muthers et al., 2014b). SOCOL (Stenke et al., 2013) consists of the atmospheric component ECHAM5 (Roeckner et al., 2003) coupled to the chemistry module MEZON (Rozanov et al., 1999; Egorova et al., 2003). The middle atmospheric configuration of ECHAM5 is used (Manzini et al., 2006), which resolves the atmosphere up to 0.01 hPa (about 80 km) with 39 levels. The horizontal resolution is T31, corresponding to a grid size of 3.75° × 3.75°.

The chemistry is directly coupled to ECHAM5 and uses ~~the temperature fields~~ temperature data to calculate the tendency of 41 gas species, taking into account 200 gas-phase, 16 heterogeneous, and 35 photolytical reactions. Optionally, the coupling to MEZON can be disabled. In this case a 3-dimensional time-dependent ozone data set needs to be specified.

The short-wave radiation scheme of SOCOL considers spectral solar irradiance (SSI) values in six spectral bands. Time series for each spectral interval are used as forcing to allow for changes in the spectral composition of the total solar irradiance. The short-wave scheme considers Rayleigh scattering, scattering on aerosols and clouds, and the absorption of UV by O_2, O_3, and 44 other species. ~~With interactive chemistry,~~ Additional parametrizations for the absorption of UV in the Lyman-alpha, Schumann-Runge, Hartley, and Higgins bands are implemented following Egorova et al. (2004)Egorova et al. (2004); **?**. The long-wave scheme considers wavenumbers between 10 cm^{-1} to 3000 cm^{-1} and the absorption effects of takes into account water vapour, CO_2, O_3, N_2O, CH_4, CFC-11, CFC-12, CFC-22, aerosols, and clouds.

With the given vertical resolution, SOCOL is not able to produce a Quasi-Biennial Oscillation (QBO). Thus a QBO nudging is applied (Giorgetta et al., 1999). The time-step of the atmospheric component is 15 minutes, with the full radiation and the chemical computations updates are performed every 2 hours.

SOCOL is coupled to the ocean model MPIOM (Marsland, 2003; Jungclaus et al., 2006) using the OASIS coupler (Budich et al., 2010; Valcke, 2013). MPIOM includes an embedded sea-ice module. To avoid numerical singularities at the North pole, both poles of the rotated Arakawa C grid are shifted and placed over land (Greenland and central Antarctica). The nominal resolution is 3° – varying between 22 and 350 km – with a higher resolution in the deep water formation regions in the North Atlantic and the Weddell Sea. Convection is implemented by greatly enhanced vertical diffusion, when the water column becomes unstable. Sea ice dynamics are based on the viscous-plastic rheology formulated by Hibler (1979). A constant sea ice salinity of 5 psu is assumed. The time-step of the oceanic component is 2 hours and 24 minutes.

2.2 The experiments

Ensemble sensitivity experiments simulations with SOCOL-MPIOM are performed to study the effect of solar radiation reduction (SRR) on the climate system and the AMOC. Such SRRs are caused by either a grand solar minimum or solar radiation management techniques. 10 simulations are carried out for each ensemble experiment; the experiments differ in the solar forcing applied and whether or not chemistry-climate interactions are considered in the model.

Perpetual 1600 AD conditions and zero volcanic aerosols (i.e., excluding the volcanic eruption of Huaynaputina) are applied in all simulations. For the sensitivity simulations only the solar forcing is allowed to change in time. The solar forcing consists of the SSI and photolysis rates.

As reference experiment we perform two control ensembles, CTRL_CHEM and CTRL_NOCHEM, with and without interactive chemistry, respectively. In these experiments all forcings represent the conditions of the year 1600 AD, including the solar forcings of the year 1600 AD. The year 1600 was chosen, since a stable long-term control simulation with SOCOL-MPIOM was available from previous studies (Anet et al., 2013a, 2014; Muthers et al., 2014b). Note, the differences in the climatic conditions between 1600 and the commonly used year 1850 are small and both represent a preindustrial climate state.

The two SRRs simulated for this study are characterized by a step-wise TSI total solar irradiance (TSI) reduction of –3.5 Wm^{-2} and –20 Wm^{-2}, referred to as S1 and S2, respectively (Fig. 1a). The S1 SRR is comparable to a grand solar minima like the Dalton Minimum or Maunder Minimum in a large-amplitude solar forcing reconstruction (e.g. Shapiro et al., 2011). With –20 Wm^{-2} the S2 SRR is comparable to a weak solar radiation management scenario (Kravitz et al., 2011), which may counteract an increase in the radiative forcing from GHG of about 3 Wm^{-2}. The reduction of the solar forcings is switched on at year 5 of a simulation and lasts for 30 years when it is switched off and the simulation is continued for 25 years.

Both SRRs are simulated with and without interactive chemistry and are named S1_CHEM, S2_CHEM, S1_NOCHEM, and S2_NOCHEM in the following. A summary of the experiments performed for this study is given in Table 1.

In the CHEM experiments, ECHAM5 and MEZON are coupled and the atmospheric chemistry responds to the solar radiation changes. In NOCHEM, temporal and spatial ozone variations need to be prescribed. Therefore, a daily 3D ozone climatology is applied, based on a 1600 AD control simulations.

All ensemble simulations are initialized from model year 1300 of a long control simulation with interactive chemistry performed under perpetual 1600 AD conditions (Muthers et al., 2014b). The ensemble members only differ in their initial conditions by slightly perturbing the atmosphere (atmospheric restarts for Jan-1, Jan-2, Jan-3, ...). The oceanic component is always initialized using the same initial conditions.

Note, that we erroneously applied a slightly different solar forcing in 6 of 10 experimentssimulations. This TSI difference of 0.018 $\mathrm{W m^{-2}}$ is caused by a different rounding of the SSI values and lead to very small differences between the control ensemble experiments and the SRR experiments, already prior to the start of the reduction.

The AMOC index is calculated by selecting the maximum in the monthly annual mean meridional overturning streamfunction northward of 28°N and below 300 m. To detect the influence of the stratospheric circulation on the troposphere and the AMOC we use the hemispheric mode of the Northern Hemisphere (NH) the Arctic Oscillation (AO). While the NAO is closer related to the AMOC, the AO has a stronger imprint of stratosphere troposphere interactions. The AO index is defined as the spatially averaged monthly mean sea level pressure north of 70difference between 40°N and 65°N, which is normalized by the mean and the standard deviation of the corresponding control ensemble. Furthermore, the index is multiplied by –1 to reflect the negative phase of the AO by negative values and vice versa. Using a different definition of the AO (EOF based or using the sea level pressure north of 70°N) or an index of the NAO leads to very similar results.

3 Results

Both SRRs leads to a significant reduction of the global mean near surface (2-m) air temperature (Fig. 1b). For the stronger S2 experiment the reduction is more pronounced than for the S1 simulations experiments and reaches -1.0 K and -0.9 K for S2_CHEM and S2_NOCHEM, respectively (averaged over the last 5-yrs of the SRR period). For the S1 experiment, the temperatures reduces by -0.1 K in both ensembles. The temperature instantaneously responds to the imposed radiation drop and reaches the lowest values at the end of the reduction period. The continuous temperature reduction in the course of the SRR, which is well visible in the S2 ensembles, suggests that the model has not yet reached thermal equilibrium. In fact, from the model's equilibrium climate sensitivity (for a doubling of CO_2, compare Muthers et al. (2014b)) an equilibrium temperature response of -1.3 K is expected for S2_CHEM and -1.4 K for S2_NOCHEM. However, a comparison with the CO_2 sensitivity is only a rough estimate, since the climate sensitivity (and the contributions from chemistry-climate interactions) differs between the solar and CO_2 forcing and depends on the sign of the forcing perturbation (Hansen et al., 1997; Schaller et al., 2014).

The larger cooling in the CHEM experiments is related to differences in the stratospheric response. In particular, stratospheric ozone concentrations are reduced due to the reduced UV radiation (Fig. S1 a and d), a process which is not considered in the

NOCHEM experiments. Additionally, water vapour concentrations are affected by the SRR. In S2_NOCHEM, the largest anomalies (-15 %) are found in the tropical upper troposphere, but stratospheric reductions exceed -10 % almost everywhere (Fig. S1c). In S2_CHEM, the stratospheric reductions in water vapour are more pronounced (up to -35 %), due to the effect of the solar forcing on the oxidation of methane, the most important in-situ source of stratospheric water vapour (Fig. S1b). Due to the greenhouse effect of ozone and water vapour, the outgoing long-wave flux increases more in CHEM than in the NOCHEM and leads to an additional cooling of the troposphere. The positive water vapour anomalies found in the uppermost model levels in the CHEM experiments (Fig. S1b and e) is are related to the reduced UV photolysis of the water vapour molecules. Due to the greenhouse effect of ozone and water vapour, the outgoing long-wave flux increases more in CHEM than in the NOCHEM and leads to an additional cooling of the troposphere.

A slight initial reduction of the global mean temperature is also found in the reference ensemble experiments and is related to the initial conditions of the ocean. Using only a slight perturbation in the atmosphere to create the ensemble , the oceanic circulation is only weakly affected With all ensemble simulations sharing the same oceanic conditions in the beginning, the AMOC development of the first years is dominated by the oceanic memory. During the first decade of the experiments a decline of the AMOC from 21.0 to 19.8 Sv is found (Fig. 1c). This decline is very similar in both reference experiments. The minimum state of the AMOC is reached in year 12-13 of the reference experiments and in the following years the AMOC increases to its maximum value of 21.4 Sv in the year 35.

The AMOC is not affected by the SRR during the first few years of the simulation. Starting with simulation year 10, however, and even more pronounced in the second half of the reduction period, the AMOC is significantly stronger in S1_NOCHEM during several years and in S2_NOCHEM for most of the years between year 15 and 35 of the simulationsexperiment. In the CHEM ensemble experiments simulations no significant AMOC intensification is found for S1. In S2_CHEM, the AMOC is significantly stronger during the seconds second half of the SRR period, but the intensification is weaker in comparison to S2_NOCHEM. The differences between the AMOC index for S2_CHEM and S2_NOCHEM are also reflected in the anomaly pattern of the AMOC (Fig. S2). Within the first 10 years the intensification of the circulation is weak. Positive anomalies are found between 40°N to 65°N and between the surface and a depth of 2800 m depth. During these first 20 years of the reduction period the intensification is slightly larger in S2_CHEM. A pronounced strengthening of the circulation occurs in the second decade of the reduction period. Positive anomalies cover all latitudes from the equator to 65°N and most levels between the surface and 3000 m depth. In the second decade the intensification is more pronounced in S2_NOCHEM. In the third decade, finally, a further intensification is found, which is again stronger in S2_NOCHEM. In the following, we will first address the relevant processes being responsible for the AMOC intensification (Sec. 3.1) before we assess the role of chemistry-climate interactions, which are responsible for to explain the lower sensitivity of the AMOC to SRR in the CHEM experiments (Sec. 3.2).

3.1 The thermal effect of SRR on the AMOC

A direct effect of SRR is the reduction in short-wave energy reaching the troposphere and the surface and thus in temperature, which is apparent almost everywhere in the NH (Fig. 2). In the high latitudes the cooling leads to an increase in sea

~~ice throughout the year, which locally (e.g., in the Barents Sea) amplifies the temperature reduction.~~ Averaged over the 30-yr reduction period the sea ice growth in the Barents Sea is stronger in S2_CHEM than in S2_NOCHEM. Furthermore, a larger cooling ~~is found~~ over the Barents Sea is found in S2_CHEM, which extends towards Northern Eurasia. In the S1 experiments ~~similar~~ temperature and sea ice ~~anomalies are found~~ anomaly patterns are weaker but similar to S2 and S1_CHEM is characterized by an amplified temperature reduction as well (not shown). During the first 10 years, when no AMOC differences between the CHEM and NOCHEM experiments are found, the temperature and sea ice anomalies are very similar. The Arctic sea ice differences between CHEM and NOCHEM, which emerge in the last 20 years of the reduction period, are therefore related to the weaker AMOC in the CHEM experiments and the reduced heat transport into the Arctic.

The temperature reduction in the lower atmosphere has a direct effect on the ocean. With a reduction of the upper ocean temperatures and an increased salinity due to the enhanced sea ice formation, the density of the upper ocean increases almost everywhere (Fig. 3~~a-d~~a-i). Additionally, a shift of the storm track and a significant reduction of the precipitation ~~is found~~ in the North Atlantic ~~, which further increases the salinity . Large anomalies are found at the eastern side~~ contributes to the salinity and density increase (not shown). During the first 10 years of the SRR period, differences in the density anomalies in the upper ocean of the North Atlantic are small and not significant, except for a region South of Greenland, where the ~~salinity of the East Greenland current increases due to the sea ice growth in~~ density is significantly higher in S2_NOCHEM (Fig. 3a-c). In the following decade further increases of the upper ocean density are found in both experiments, but the anomalies are again larger in S2_NOCHEM (Fig. 3d-f). Now, the ~~Arctic.Furthermore, salinity increases in the eastern part~~ density anomalies in large parts of the North Atlantic are more pronounced in S2_NOCHEM in comparison to S2_CHEM. In the last 10 years, finally, density anomalies are still strongly positive, but the differences between both experiments weaken (Fig. 3g-i).

Convection takes place in the Nordic ~~Sea~~ Seas and in a region in the North Atlantic close to the Labrador Sea (contours in Fig. 3e-h). The intensity of the deep water formation in these two regions is an important driver of AMOC variability (Jungclaus et al., 2005). Focusing on the changes in the Nordic ~~Sea~~Seas, we find an ~~increased density of the upper ocean water and consequently an~~ intensification of the deep water formation already ~~during the first half~~ for the first 10 years of the reduction period (Fig. 3~~). The density anomalies and the convection anomalies are slightly larger in S2_CHEM. For the second half of the SRR no pronounced differences~~ j-l). A further intensification is found for the second and the third decade, the anomalies between S2_CHEM and S2_NOCHEM~~are found in the Nordic Sea~~, however, are hardly significant. The anomalies in the S1 experiments are similar, but the significance ~~is reduced~~of the differences to the CTRL is lower. Density changes in the Nordic ~~Sea~~ Seas are driven by a combination of temperature and salinity changes (Fig. 4). The temperature changes, however, dominate in the first half of the SRR period, while the increasing salinity drives the density changes in the second half~~(Fig. S2)~~.

In the North Atlantic the density and mixed layer differences between S2_CHEM and S2_NOCHEM are larger~~, in particular for the first 15-yrs~~. During the first 10 years of the SRR ~~. The density~~ period, positive mixed layer depth anomalies are found in S2_NOCHEM ~~increases over the entire North Atlantic and leads to enhanced convection.In~~ (Fig. 3k), while no consistent response is found in S2~~_CHEM, however, a reduction of the density is found near the entrance of the Labrador sea and this causes a reduction of the deep water formation in this area during the first half of the SRR, which is partially compensated by positive anomalies in other parts of the North Atlantic.The second half of the reduction period, is characterized by a~~

further increase of the density anomalies in both experiments: for NOCHEM (Fig. 3j). Consequently, the intensification is significantly stronger in S2_CHEM the negative anomalies disappeared and convection is also enhanced in the Labrador Sea and for NOCHEM (Fig. 3l). A similar picture emerges for the second decade (Fig. 3m-o). In the third decade a clear intensification is obvious in S2_NOCHEM, a reduction of the upper ocean density CHEM, while a slight reduction is found in the Eastern Atlantic. The resulting reduction of the deep water formation, however, is balanced by pronounced intensifications of the convection, in the central Atlantic . Similar to the Nordic SeaS2_NOCHEM in the southern region of the North Atlantic convection zone (Fig. 3p-r). As in the Nordic Seas, the density changes are driven by the reduced temperatures in the first half of the SRR (Fig. S24). In the second half of the SRR period the salt content of the upper ocean increases, while temperatures increase again, related to the intensification of the overturning. The dominance of the salinity changes, nevertheless, leads to a further increase of the density in the second half of the reduction period.

The increasing density and deep water formation in both convective regions help to understand the intensification of the AMOC in the course of the SRR. Driven directly by the temperature response to the reduced solar forcing, this mechanism can be considered as the thermal effect of the SRR on the overturning. However, in S2_CHEM the intensification of the convection in the North Atlantic is delayed in comparison to S2_NOCHEMand similar . Similar differences are found between the two S1 experiments (Fig. 1c). A further mechanism is therefore needed to understand the differences in the AMOC response between the CHEM and NOCHEM experiments.

3.2 The dynamical effect and the role of chemistry-climate interactions

Interactions between the physical and chemical components of the atmosphere are most relevant in the higher atmosphere

Chemistry-climate interactions are most pronounced in the stratosphere (e.g., Dietmüller et al., 2014). In particular, the different response of the stratospheric ozone and water vapour between CHEM and NOCHEM (Fig. S1) leads to pronounced large differences in the stratospheric temperatures. For S2_CHEM temperature anomalies of up to –28 K are found in the upper stratosphere (Fig. 45a). Above 1 hPa the maximum temperature reduction is found in the polar latitudes with a second maximum in the tropics. In the lower and middle stratosphere, the cooling is stronger in the tropics and mid-latitudes. With about –10 K, the maximum temperature reduction in S2_NOCHEM is much smaller than the response in S2_CHEM (Fig. 45b,c). Furthermore, as a consequence of the missing response of the ozone concentrations to the reduced solar forcing, the effect of the lower and middle stratospheric cooling on the meridional temperature gradient is weaker.

The response of the zonal mean wind in the stratosphere agrees well with the temperature anomalies. For S2_CHEM, a pronounced weakening of both the NH and SH polar vortices is found (Fig. 5d-f). Using the zonal mean wind component at 60°N and 10 hPa as index for the intensity of the NH polar vortex (Christiansen, 2001, 2005), a reduction of –43 % is found in S2_CHEM during the winter season (Nov. to Mar.) when averaged over the SRR period. The largest wind anomalies occur during the vortex maximum in January. The reduction in S2_NOCHEM is much weaker (–8 %) than in S2_CHEM. Furthermore, the duration of the winter period with predominant westerly wind is reduced in S2_CHEM by –30 % and in S2_NOCHEM by –5 % respectively, when defining the start of the winter period by the day with the first occurrence of a westerly daily mean zonal mean wind component at 60N and 10hPa after September and the end by the first day with easterly winds after March. Qualitatively similar results are found for the S1 experiments, with NDJFM vortex anomalies of –9 % for S1_CHEM and –2 % for S1_NOCHEM (Fig. S3). These responses highlight the non-linear relationship between the solar forcing and the atmospheric dynamics.

The weakening of the NH polar vortex is closely related to the occurrence of sudden stratospheric warming (SSW) events (Fig. 5). 6). SSWs are stratospheric extreme events, in which the westerly flow during winter time is reversed and a strong warming in the polar stratosphere is observed. SSW events in the NH are associated with a break down of the polar vortex. Following the SSW definition by Charlton and Polvani (2007) almost a doubling of the number of SSW events is found in S2_CHEM (1.34 events/winter in comparison to 0.68 events/winter in CTRL_CHEM). In S1_CHEM an increase to 0.73 events is simulated. Similarly to the NH polar vortex, the effect of the SRR on the SSW events is small in NOCHEM. For S1 the average number of events increases from 0.68 events/winter in CTRL_NOCHEM to 0.70 events/winter in S1_NOCHEM. In S2_NOCHEM an increase to 0.73 events is simulated. While the increase in the mean number of SSW events is small in S2_NOCHEM, a clear reduction of the years with a low number of SSW events is found (lower quartile of the boxplot).

The NH polar vortex and extreme events like SSW affect the tropospheric circulation in the NH by stratosphere-troposphere interactions. A downward propagation of wind speed anomalies from the middle stratosphere to the surface is related to positive and negative phases of the AO (Baldwin and Thompson, 2009). For a negative phase of the AO, negative wind anomalies in the stratosphere occur up to 40 days before the AO event takes place at the surface (Fig. S4). For a positive phase of the AO, the zonal wind anomalies are even stronger (not shown). Overall, the downward coupling propagation of wind speed anomalies does not differ substantially between the CHEM and NOCHEM control experiments.

The stratospheric changes in the course of the SRR therefore affect the tropospheric pressure systems. In Figure 2a the sea level pressure anomalies for S2_CHEM reveal a pattern of positive anomalies over large parts of the Arctic and negative anomalies in the North Atlantic and the Northern Pacific, similar to a negative phase of the AO. In S2_NOCHEM comparable negative and positive pressure patterns are found, but the anomalies are much weaker (Fig. 2b). Due to the strength of the responsethe winter phenomena , the winter phenomenon AO is reflected in the annual mean values (Fig. 2). However, when focusing on the winter season (Nov. to Mar.) and the AO index, the strength of the anomalies in S2_CHEM is even more apparent (Fig. 67). During the entire SRR phase a persistent negative phase of the AO is found in S2_CHEM. In S1_CHEM the tendency towards a negative AO is found as well, although the response is weaker and several years with a positive phase of the AO occur during the SRR. In the NOCHEM experiments the response is in general weaker, but a shift towards negative AO phases a negative AO phase from CTRL_NOCHEM to S1_NOCHEM and S2_NOCHEM is apparent (Fig. 7d). In particular, negative AO phases tend to occur more often in the first half of the SRR period, while neutral conditions dominate in the second half.

Atmospheric chemistry-climate interactions therefore lead to pronounced differences in the dynamical response to the SRR, from the stratosphere down to the surface of the NH high latitudes. With a shift in the pressure pattern which affect the wind systems in the lower atmosphere, these differences have the potential to also modify the oceanic circulation.

The control experiments are used to assess the influence of the AO phase on the North Atlantic. Regressing the AO index on different oceanic variables reveals that a negative AO phase is associated with an increased downward heat flux south of

Greenland and negative heat flux anomalies close to the east coast of North America during winter in CTRL_CHEM (Fig. ~~7~~8a). Sea ice cover is reduced in the Labrador Sea (Fig. ~~7~~8b) and the dynamical changes lead to an increased total freshwater flux into large parts of the North Atlantic, and a reduced flux in the Nordic ~~Sea~~ Seas (Fig. ~~7~~8c). These changes cause a reduction of the salinity (Fig. ~~7~~8d), except for a small region South of Greenland, ~~where the export of saline water from the Nordic Sea by~~ which may be affected by a weakening of the East Greenland current~~leads to positive anomalies~~. Additionally, SSTs increase South of Greenland (Fig. ~~7~~8e), related to the enhanced downward heat flux. ~~All~~ Since the density of the water decreases with increasing temperature and decreasing salinity, all these changes lead to a pronounced reduction of the mixed layer depth (Fig. ~~7~~8f). In CTRL_NOCHEM the effect of the AO is very similar (Fig. S5).

These changes at the ocean surface are also reflected in the AMOC index. In both control experiments the AMOC reacts ~~instantaneously~~ within the same winter season to the AO phase, as detected by the positive correlation between the winter AO and the AMOC index of the same season (Fig. S6). Furthermore, the AO phase has ~~longer~~ long lasting effect on the overturning, reflected in significant positive correlations for lags up to 9 years.

To summarize, the weaker intensification of the AMOC in the CHEM experiments, in comparison to NOCHEM, is related to a second (dynamical) response to the SRR. With interactive chemistry, the stratospheric cooling is strongly amplified by stratospheric ozone loss. As a consequence~~the intensification~~, the weakening of the Northern polar vortex is more pronounced, which has larger effects on the tropospheric circulation patterns, in particular the phase of the AO. The dynamical changes ~~increase~~ decrease the density of the ~~ocean waters in the North Atlantic~~surface ocean waters South of Greenland, reduce convection, and weaken the AMOC. In the NOCHEM experiments a tendency towards a negative phase of the AO is found as well, but less pronounced, due to the absence of chemistry-climate interactions. The dynamical effect on the AMOC is therefore much weaker and the thermal response dominates.

4 Conclusions and Discussions

Sensitivity experiments for different solar minima and model configurations with and without chemistry-climate interactions have been carried out to study the response of the AMOC to reduced solar forcing and the modulating role of chemistry-climate interactions. ~~While without interactive chemistry ,~~ Without interactive chemistry the response of the AMOC is dominated by the direct thermal effect caused by reduced surface temperatures ~~, a~~leading to an intensification of the overturning circulation. A second dynamical effect is identified in the experiments with chemistry-climate interactions and leads to an weakening of the overturning.

The two processes are summarized in Figure ~~8~~9: The thermal effect is related to the reduced short-wave energy reaching the troposphere and the surface and the ensuing cooling of the lower atmosphere and the upper ocean. This increases the sea surface density and enhances convection. This response of the overturning to solar radiation changes has been identified in earlier studies (Cubasch et al., 1997; Latif et al., 2009; Otterå et al., 2010; Swingedouw et al., 2011)~~and~~. Related to increasing global greenhouse gas concentrations and associated surface warming, it is also one of the dominant mechanisms for the projected future weakening of the AMOC (Stocker and Schmittner, 1997; Manabe and Stouffer, 1999; Mikolajewicz and Voss, 2000; Gregory et al., 2005; Stocker et al., 2013).

The thermal response to the reduced solar forcing has also implications for the projected weakening of the AMOC in the 21th century. Several studies suggest that the ~~sun~~ Sun may enter a grand solar minimum within the next 100 years (Lockwood et al., 2009; Steinhilber and Beer, 2013; Roth and Joos, 2013), although the amplitude of the TSI changes is associated with large uncertainties. While the effect on the global mean temperature increase is small (Feulner and Rahmstorf, 2010; Meehl et al., 2013; Anet et al., 2013b), the thermal effect may reduce the projected 21th century AMOC weakening. This is confirmed by ~~simulations of Anet et al. (2013b)where the~~ experiments of Anet et al. (2013b). The AMOC is significantly stronger in the late 21th century, ~~when~~ in ensemble simulations simulations including a grand solar minimum ~~is considered~~ in the second half of the 21th century in comparison to ensemble simulations without a decline of the solar activity (Fig. S7).

The thermal effect, however, is ~~weakened~~ compensated by the dynamical effect when atmospheric chemistry is taken into account. Induced by the reduction of the tropical stratospheric temperatures, a weakening of the NH polar vortex and – by interactions between the stratospheric and tropospheric circulation – a negative phase of the AO, is found in response to the SRR. The circulation changes in the troposphere ~~then~~ in turn cause a weakening of the ~~Atlantic overturning circulation~~ AMOC by anomalous heat and freshwater fluxes. ~~With chemistry-climate interactions, the~~ The dynamical effect is ~~enhanced, related to the amplified~~ amplified by chemistry climate interactions, due to the enhanced stratospheric temperature response related to the effect of the reduced UV radiation on the ozone concentrations.

~~Many of elements~~ Parts of the dynamical effect have been reported in previous studies. The relationship between solar variability and the stratospheric circulation ~~has been found for various time-scales (Kodera and Kuroda, 2002; Anet et al., 2013a; Mitchell et al.~~ found for the 11-yr cycle (Kodera and Kuroda, 2002; Mitchell et al., 2015) as well as for grand solar minima (Anet et al., 2013a). Also the projection of the stratospheric anomalies on the AO ~~is found~~ was reported in previous studies (Kodera, 2003; Ineson et al., 2011; Scaife et al., 2013). Finally, the influence of the AO ~~or NAO~~ phase on the overturning ~~is well studied (Delworth and Greatbatch, 2000; Eden and Willebrand, 2001; Matthes et al., 2006; ?). Furthermore,~~ was studied (Delworth and Greatbatch a few studies identified a possible influence of the stratospheric circulation on the overturning (Manzini et al., 2012; Reichler et al., 2012).

~~Here~~The stratosphere responds very fast to the reduced solar forcing and the tropospheric AO index shifts to a negative phase in the second winter after the onset of the reduction period, although is takes about 5 years, before a persistent negative AO phase is found in S2_CHEM. The response of the AMOC, however, is delayed by several years. A similar delay was reported by Delworth and Zeng (2016) who performed sensitivity experiments with an ocean model forced by different atmospheric conditions. In one experiment a persistent positive phase of the NAO is simulated and the AMOC responds to this forcing with strengthening of the circulation, which is delayed by 5-7 years (compare Fig. 3 in Delworth and Zeng, 2016). This lag of the response agrees with our results, although an exact timing is difficult to estimate from our setup.

The influence of the dynamic effect on the AMOC may furthermore depend on the length of the solar reduction period. Lohmann et al. (2009) found a gradual weakening of the subpolar gyre response with time in ocean model simulations forced with a persistent negative phase of the NAO. Additionally, the response of the AMOC may be non-linear and an increase of the solar forcing may change the dynamic effect (Lohmann et al., 2009).

Recently, Chiodo and Polvani (2016) assessed the role of the interactive chemistry on the temperature and precipitation response to increasing SSI. They identified a reduced sensitivity with interactive chemistry due to the effect of the ozone increase on the short-wave radiation balance. Our results for a SSI reduction indicate a slightly larger temperature sensitivity with interactive chemistry owing to the effect of the stratospheric water vapour and ozone changes on the long-wave radiation balance. These differences may be attributed to model differences or differences in the response of the climate system to increasing and decreasing solar forcing. A possible effect of the differences in the atmospheric response on the AMOC is not discussed by Chiodo and Polvani (2016).

Here, we show for the first time ~~, how theses~~ how stratospheric processes modulate the modelled response of the AMOC to solar forcing and identify the importance of chemistry-climate interactions for the response. Hence, previous studies without atmospheric chemistry may overestimate the sensitivity of the AMOC to solar forcing, since the dynamical effect is absent~~or underestimated, when chemistry-climate interactions are not considered in the simulation~~.

Furthermore, our results reveal possible additional side effects of the solar radiation management technique: A reduction of the incoming solar radiation in space to mitigate the temperature increase caused by the emission of GHGs ~~,~~ might affect the tropospheric circulation patterns in the NH and cause a weakening of ~~the overturning~~ AMOC with climatic consequences, in particular for the temperate climate in western Europe. The dynamical effect is expected to change, however, when the solar radiation is reduced in the Earth's atmosphere, for instance, by stratospheric sulphate aerosols. In this case, a strengthening of the NH polar vortex and a positive phase of the AO may develop, analogous to the response to strong tropical volcanic eruptions (Graf et al., 1993; Kodera, 1994; Stenchikov et al., 2002; Muthers et al., 2014a, 2015). This effect of the positive AO phase may, in turn, lead to an intensification of the AMOC. Future studies shall address the influence of stratospheric sulphate geoengineering on the AMOC and the possible role of chemistry-climate interactions.

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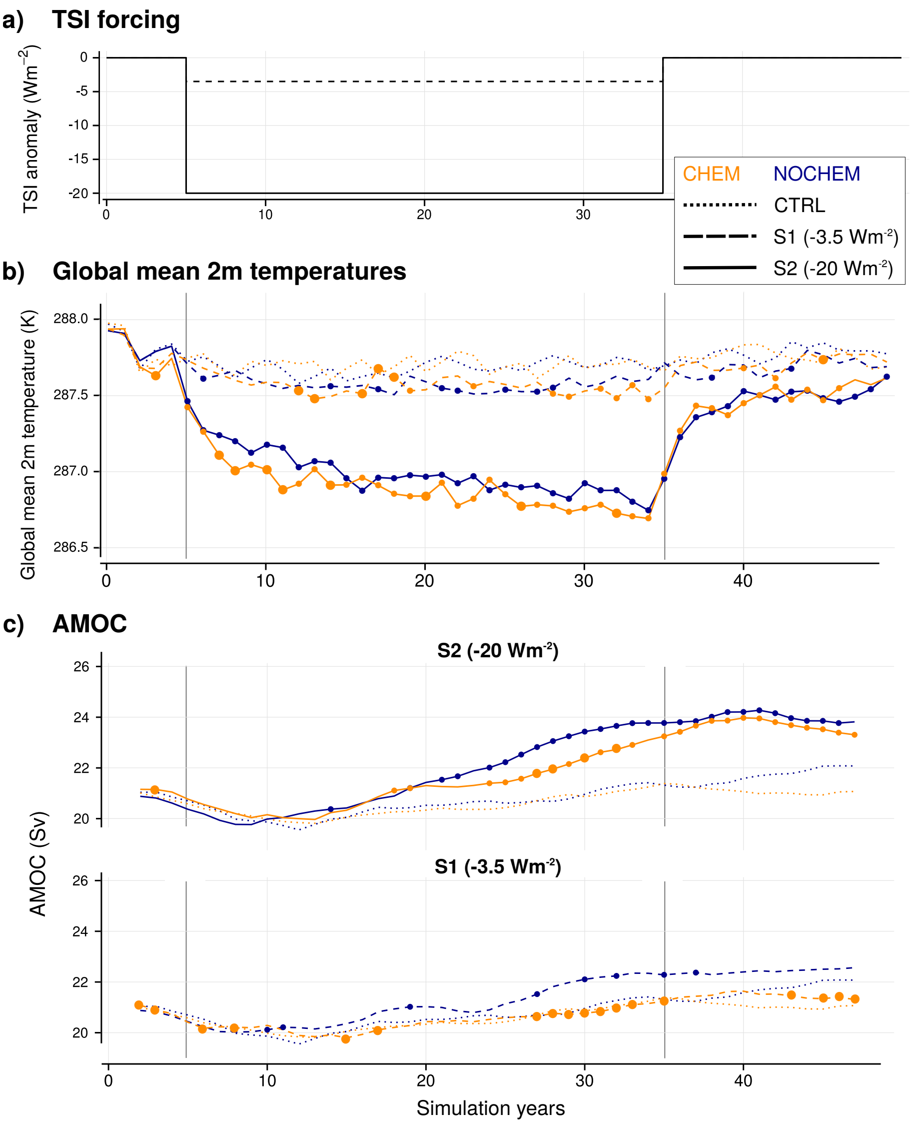

Figure 1. a: Total solar irradiance (TSI) anomaly of –3.5 $\mathrm{W\,m^{-2}}$ (dashed) and –20 $\mathrm{W\,m^{-2}}$ (solid) applied in this study. **b:** Global annual mean ensemble mean 2-m temperature~~in the ensemble experiments~~. **c:** Ensemble mean AMOC index in the different experiments, smoothed using a 5-yr running mean. ~~Thick dots~~ Dots denote significant differences in the (un-smoothed) annual mean values between the SRR ensemble and the control ensemble (Student's t-test, $p \leq 0.05$). Thick dots in the CHEM time series correspond to years with significant differences between the CHEM and NOCHEM experiment ($p \leq 0.05$). The beginning and the end of the SRR period is indicated by ~~the grey~~ vertical lines in panels b and c.

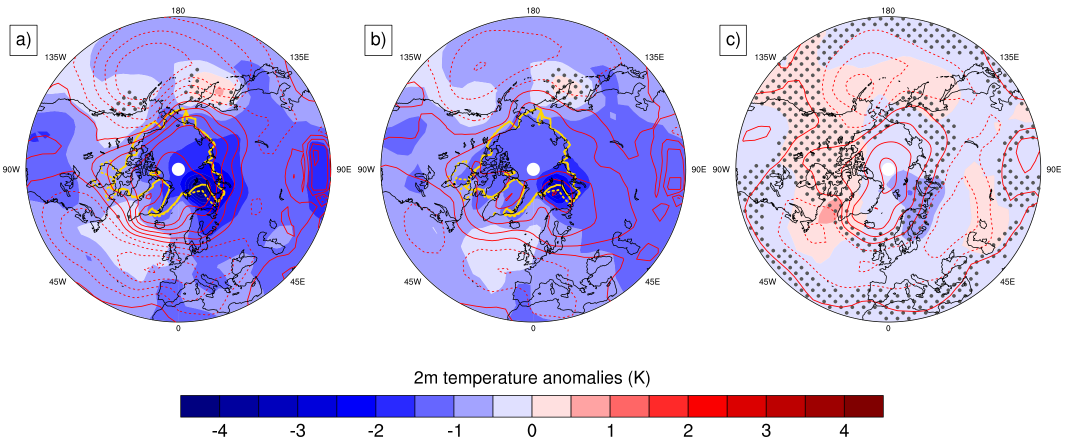

Figure 2. Annual mean 2-m temperature anomalies (colors), sea level pressure anomalies (red contours), and 50 % sea ice extent line (yellow contours) averaged over the SRR period. Temperature and sea level pressure anomalies are calculated relative to the control ensemble mean, for the sea ice extend the values of the control ensemble and the S2 experiments are depicted by the solid and dashed line, respectively. **a:** shows the difference for the S2_CHEM ensemble, the S2_NOCHEM anomalies are shown in **b**. ~~Dark grey dots~~ Panel **c** displays the differences between S2_CHEM and S2_NOCHEM. Dots denotes non-significant temperature differences (Students t-test, p>0.05). The ~~contours step of the~~ sea level pressure ~~contours~~ contour interval is 0.25 hPa and negative sea level pressure anomalies are dashed.

Table 1. Overview of the ensemble experiments used in this study. Each ensemble consists of 10 experiments.

Experiment	TSI [Wm^{-2}]	Chemistry
CTRL_CHEM	const.	Yes
CTRL_NOCHEM	const.	No
S1_CHEM	–3.5	Yes
S1_NOCHEM	–3.5	No
S2_CHEM	–20	Yes
S2_NOCHEM	–20	No

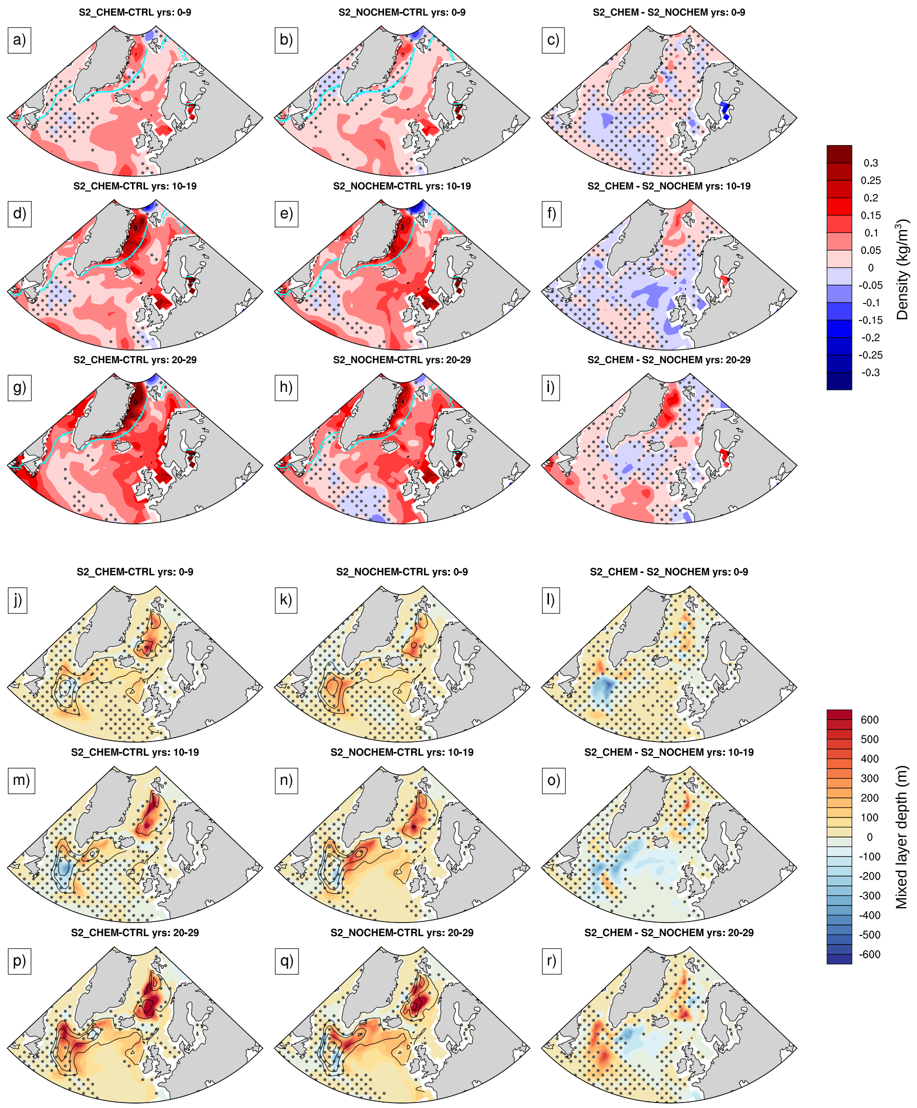

Figure 3. **a-da-i**: S2_CHEM (a,ed,g)and , S2_NOCHEM (b,de,h), and the difference between S2_CHEM and S2_NOCHEM (c,f,i) ensemble mean upper ocean (0–2000–220 m) density anomalies (kg/m^3) for late winter (Jan.-Mar.) averaged over the first 15 years (aa-c), bsecond (d-f), and last 15 years decade (c,dg-i) of the SRR period. Cyan contours display the extend of the 50 % sea ice area for the CTRL ensemble mean (solid line) and the SRR experiments (dashed line). **e-hj-r**: S2_CHEM (ej,gm,p), S2_NOCHEM (k,n,q), and the difference between S2_CHEM and S2_NOCHEM (fl,hi,r) ensemble mean Jan.-Mar. mixed layer depth anomalies (m, shading) averaged over the first 15 years (ej-l), fsecond (m-o), and last 15 years decade (g,hp-r) of the SRR period. Contours denoted the average Jan.-Mar. average mixed layer depth in CTRL_CHEM and CTRL_NOCHEM, respectively, with a contour step of 500 m. Dark grey dots Dots denotes non-significant density or mixed layer depth differences (Students t-test, $p>0.05$).

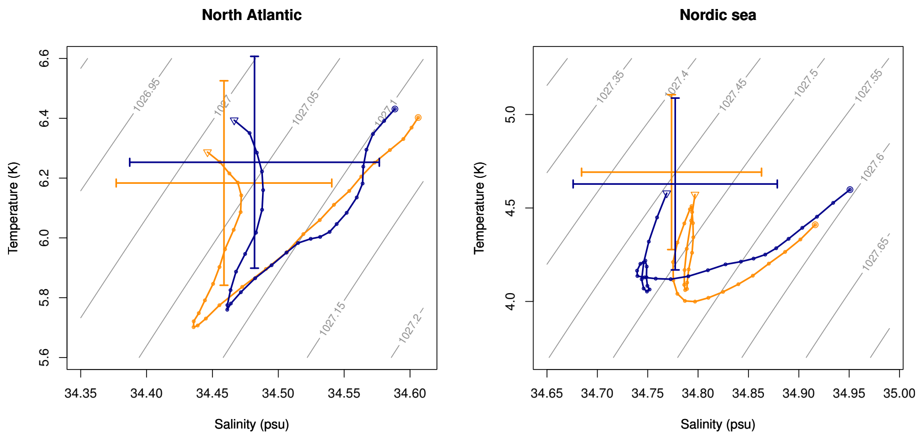

Figure 4. Temperature salinity averaged over the upper 220 m for the two deep water formation region North Atlantic and Nordic Seas. The deep water formation regions cover all grid cells with an annual mean mixed layer depth ≥ 250 m in the corresponding ocean basins. The lines show the salinity and temperature development from the beginning (triangle) to the end (large dot) of the SRR for the S2_CHEM (orange) and S2_NOCHEM (blue) experiments. Each point represent a single year. To improve visibility, the values are smoothed using a 15-yr low pass filter. Error bars denote the mean and the standard deviation of the corresponding control ensembles. Contours represent the water density.

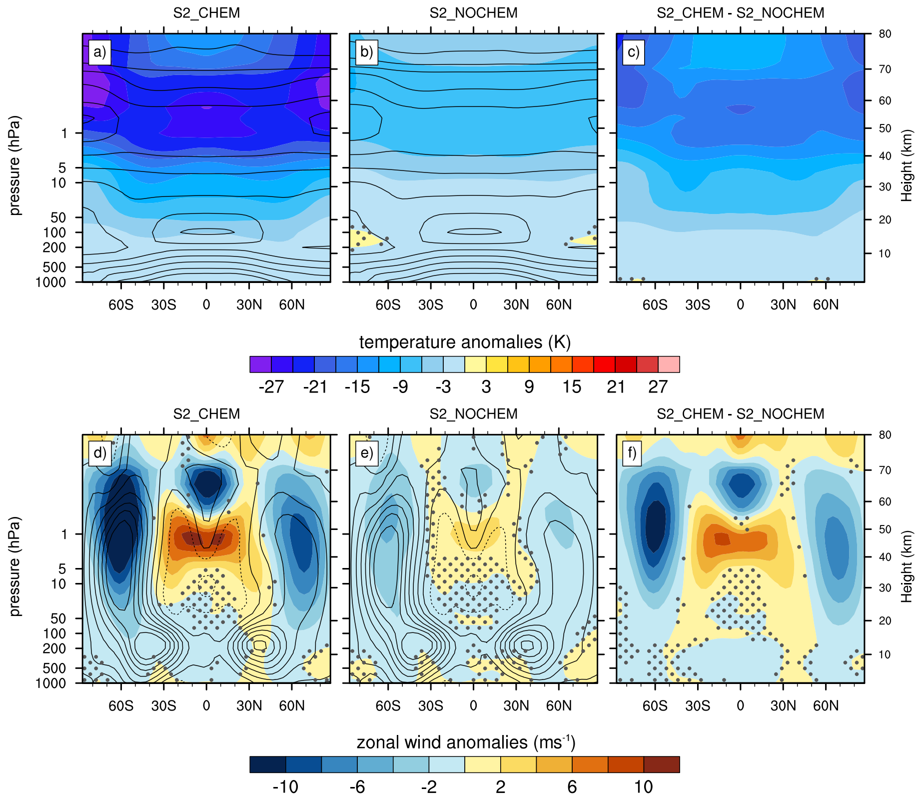

Figure 5. ~~Zonal~~ Annual mean zonal mean temperature (**a-c**) and annual mean zonal mean zonal wind (**d-f**) anomalies in the S2 ~~simulations~~ experiments relative to the control experiments: **a,d** shows the anomalies for the S2_CHEM experiment and **b,e** the results for S2_NOCHEM. The differences between both experiments (S2_CHEM - S2_NOCHEM) are shown in **c,f**. Anomalies are averaged over the 30-yr SRR period. Contours represent the mean state in the control experiments with contours from 180 to 280 K (contour step 15 K) for the temperatures and -30 to 30 $\mathrm{ms^{-1}}$ (contour step 5 $\mathrm{ms^{-1}}$) for the zonal wind. ~~Dark grey dots~~ Dots denotes non-significant temperature differences (Students t-test, p>0.05).

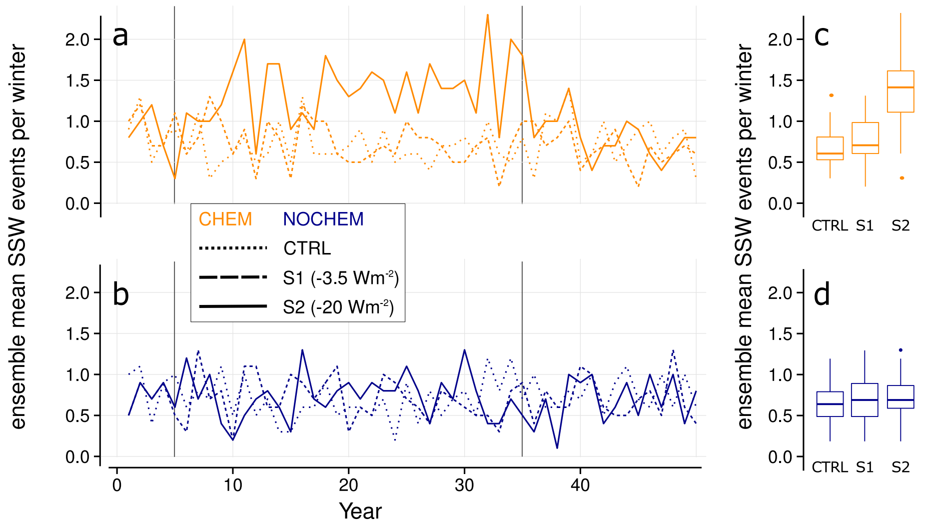

Figure 6. a-b: Ensemble mean number of sudden stratospheric warming events (SSW) per winter season (Nov. to Mar.) as in defined by Charlton and Polvani (2007). **c-d:** Boxplot statistics for the number of SSW events per winter season averaged over the SRR period. The beginning and the end of the SRR period is indicated by ~~the grey~~ vertical lines in panels a and b.

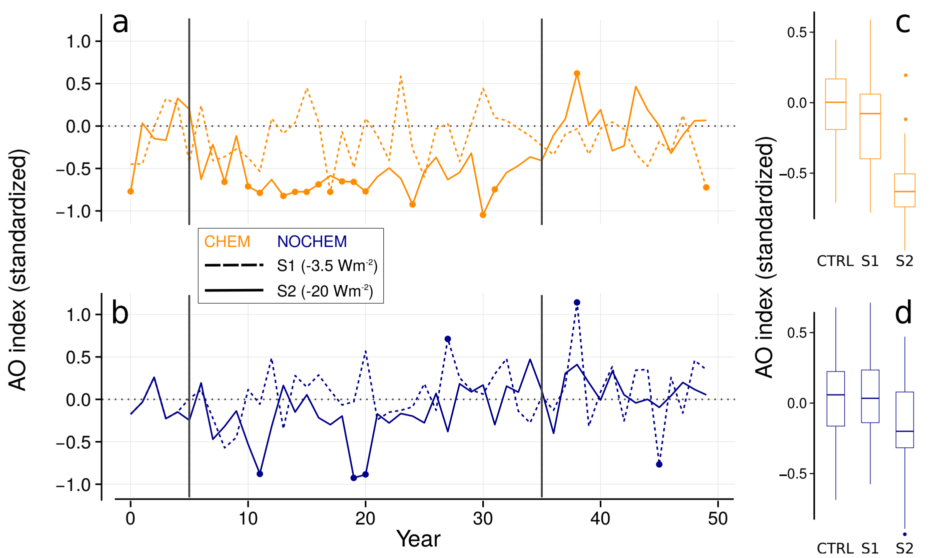

Figure 7. a-b: Ensemble mean AO index (standardized and reversed sea level pressure ~~anomaly north of 70~~difference between 45°N and 65°N) per winter (Nov. to Mar.). Dots indicate winters with significant differences to the CTRL ensemble (Student t-test $p \leq 0.05$). **c-d:** Boxplot statistics for the AO index averaged over the SRR. The beginning and the end of the SRR period is indicated by ~~the grey~~ vertical lines in panels a and b.

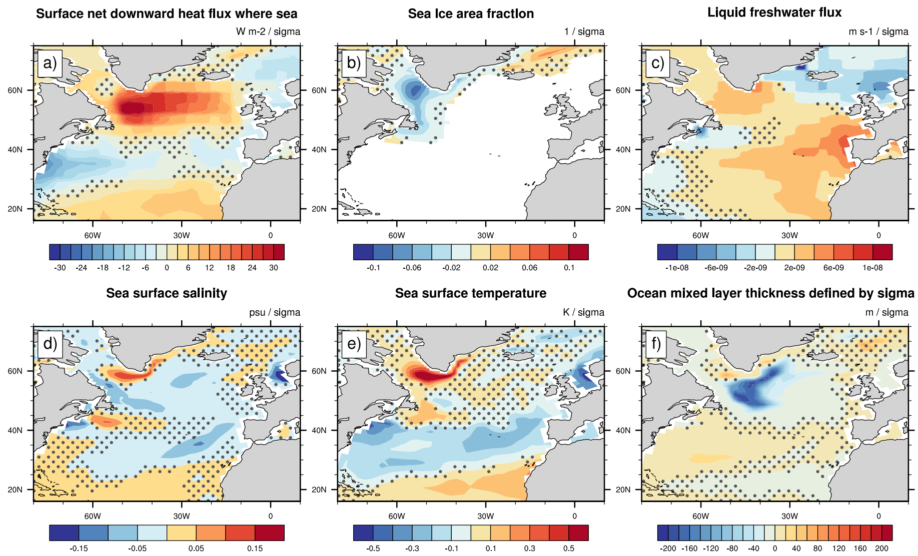

Figure 8. Influence of a negative AO phase on different oceanic variables in CTRL_CHEM during winter (Nov. – Mar.). Linear regression coefficients for **(a)** net downward heat flux, **(b)** ~~mixed layer depth~~sea ice area fraction, **(c)** liquid freshwater flux (evaporation minus precipitation), **(d)** sea ~~ice area fraction~~surface salinity, **(e)** sea surface ~~salinity~~temperature, and **(f)** ~~sea surface temperature~~mixed layer depth. To highlight the influence of a negative AO phase the AO index has been reversed in the regression analysis. ~~Dark grey dots~~ Dots denotes non-significant temperature differences (Students t-test, p>0.05).

~~Flowchart summarizing the thermal and dynamical effect of a change in solar radiation on the AMOC. The sign indicate the correlation between two processes. Dashed boxes represent effects, which are amplified by chemistry-climate interactions.~~

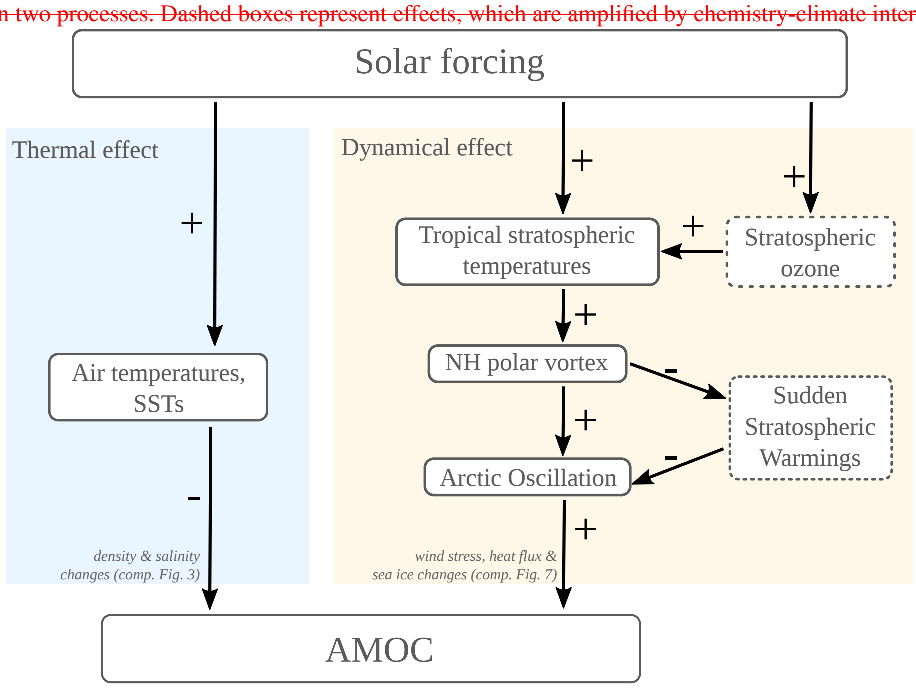

Figure 9. Flowchart summarizing the thermal and dynamical effect of a change in solar radiation on the AMOC. The sign indicate the correlation between two processes. Dashed boxes represent effects, which are amplified by chemistry-climate interactions.