

## Anonymous Referee #3

We would like to thank referee 1 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 publishing.

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

We will rewrite the introduction in revised manuscript.

### **Other major points**

The experiments: A small comment of why control simulations were 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?

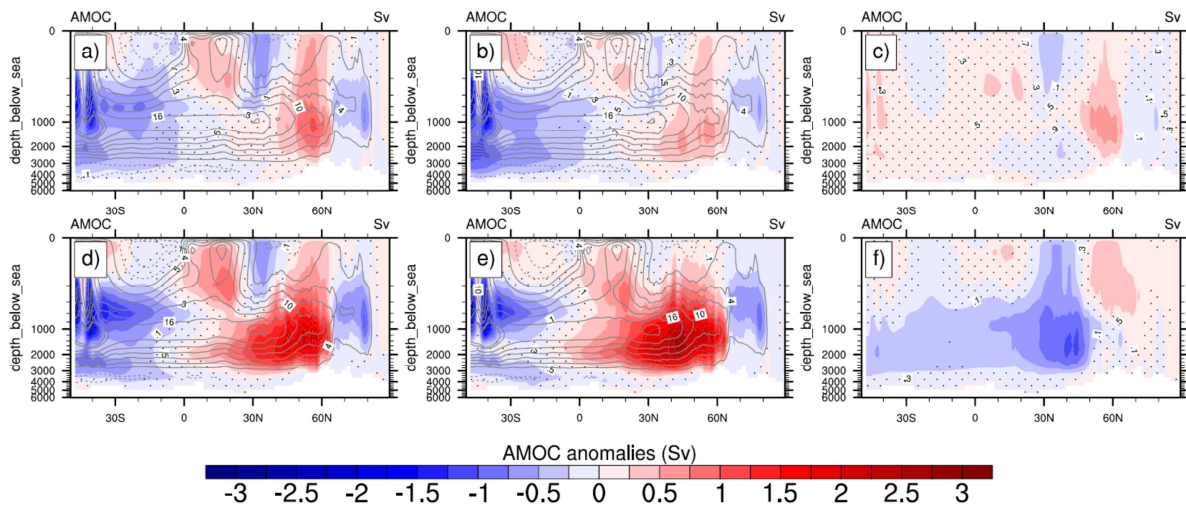
The Control experiment, which was used to initialize the ensemble, was part of a study, which focuses on transient climate simulations for the period 1600 to 2100. Therefore, a 1600 control experiment was performed to generate starting conditions for the transient experiments. These experiments are described 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 15 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 the first half of the reduction period the intensification is slightly larger in S2\_CHEM. A pronounced strengthening of the circulation takes part in the second half 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 half of the reduction period, the intensification is more pronounced in S2\_NOCHEM.”



R 6: Atlantic meridional overturning streamfunction anomalies (Sv) for S2\_CHEM (a,b) and S2\_chem (d,e) and the difference between the two experiments (CHEM-NOCHEM, c,f). Top row (a-c) displays anomalies for the first half of the solar reduction period; anomalies for the second half are shown in the bottom row (d-e).

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?

We will add a brief discussion of our results for recent solar minima in the revised manuscript.

### 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 multidecadal 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 or 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 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 the 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, negative AO phase tend 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

Is it a combination of wind stress and heat flux changes. Delworth and Zeng (2016) performed sensitivity experiments where the forced an ocean model by artificial atmospheric forcing. In one of their experiments they instantaneously switched the atmospheric forcing to an NAO positive state. Their results 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.

In the revised manuscript we will improve the discussion of this effect.

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  $6 \text{ Wm}^{-2}$  and below  $1 \text{ Wm}^{-2}$  (for the TSI difference between the Maunder Minimum and present day). While a reduction of  $20 \text{ Wm}^{-2}$  (S2 experiments) is clearly out of this range the S1 experiments ( $-3.5 \text{ Wm}^{-2}$ ) 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

This will be considered in the revised manuscript.

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?

We will rephrase this paragraph is suggested.

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 will consider this when revising the 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,  $p \leq 0.05$ ).”

We replaced the figures with new versions using a lighter grey colour.

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/>.
- 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/>.