Response to Reviewers

We would like to thank the reviewers for their positive evaluation and helpful comments on our study. Please find below a point-by-point reply (in blue) to the reviewers' comments and suggestions. All changes are highlighted in the attached version of the manuscript.

With kind regards,
Hilla Afargan-Gerstman and co-authors

Comments from the Editor

1. In Fig. 2 you may want to only highlight the relevant boxes in the resp. panels (e.g., only highlight the Barents Sea box in the left column etc)
We have revised Fig.2 as suggested, such that only the relevant box in the respective panels is highlighted.

2. Please indicate how you obtain the (effective) d.o.f. for the confidence intervals that you computed for the Fisher z-test. In particular, did you take into account autocorrelation of the weekly indices, which will reduce the effective d.o.f.?

The Fisher z-test is used in the manuscript for determining the significance of the difference between SSW and non-SSW correlations. Generally, the decorrelation timescale in the North Atlantic has been estimated as 5 to 7 days for the NAO (depending on the dataset used, e.g., Domeisen et al., 2018) and around 6 to 15 days for the NAM, with a peak in mid-winter (Gerber et al., 2008). We compute the decorrelation timescale for air temperature at 850 hPa averaged over the Barents Sea region for daily and weekly means (Fig. 1 below). The decorrelation timescale (T) is estimated by the time interval over which the autocorrelation drops to 1/e. We find that T drops to 1/e after 4 days for the daily data, and after 1 week for the weekly data. Based on these results, we estimate that there is no autocorrelation between weekly indices beyond 1 week. Thus, by using weekly means, rather than a 7-day running average, we account for any autocorrelation below 1 week.

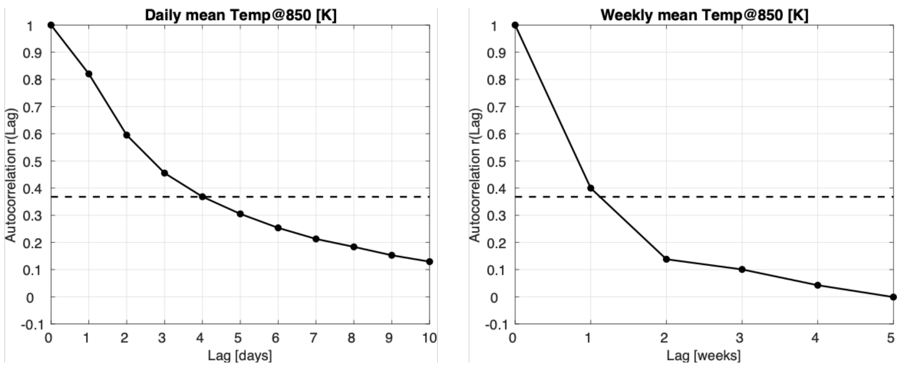

Figure 1: The autocorrelation function of lag time for 850-hPa temperature over the Barents Sea region in DJFM using (left) daily and (right) weekly means. Data is based on ERA-Interim reanalysis (1979–2019). The dashed line is used for estimation of the time lag over which the autocorrelation drops to 1/e.

The number of degrees of freedom relative to the number of observations can be estimated as half the e-folding time (i.e., the time for one-lag autocorrelation to reduce to 1/e). Thus, we use one half of the number of observations as the effective degree of freedom for no SSW periods (n2=276). For the periods following SSW events, we assume the 26 SSW events are independent of each other. Table 1 and Table 2 below shows the outcome of using 1-week and 2-weeks as the decorrelation time after SSW events, respectively. The estimation of n1 is taken as half that time, i.e., 26x2 and 26x4.
In both cases, the difference between SSW and no SSW periods is found to be significant at the 95% level for the Barents Sea ($p<0.05$), whereas for the Norwegian and Labrador Seas the difference is found to be significant

Table 1: Correlation coefficients between weekly means of ZDI and MCAO indices for the sub-regions used in this study, during SSW (r1) and no SSW (r2) periods. Fisher z-transform is used to compute the confidence interval for r1 and r2. z_{stat} represents the z score for the difference between the two correlations, divided by the standard error. The values of n1 and n2 correspond to the d.o.f used in the computation of the standard error. The z'1 values in the table were computed using a 1-week decorrelation time after SSW events.

Sub-region	r1	r2	**n1**	n2	z'1	z'2	z_{stat}	**p-value**
Barents Sea	0.65	0.45	**26x2**	276	0.77	0.49	1.87	**0.03**
Norwegian Sea	0.55	0.49	**26x2**	276	0.63	0.54	0.53	**0.30**
Labrador Sea	-0.46	-0.52	**26x2**	276	-0.50	-0.57	0.51	**0.30**

Table 2: Same as in Table 1, but using 2-weeks as the decorrelation time after SSW events.

Sub-region	r1	r2	**n1**	n2	z'1	z'2	z_{stat}	**p-value**
Barents Sea	0.65	0.45	**26x4**	276	0.77	0.49	2.50	**0.006**
Norwegian Sea	0.55	0.49	**26x4**	276	0.63	0.54	0.71	**0.24**
Labrador Sea	-0.46	-0.52	**26x4**	276	-0.50	-0.57	0.68	**0.25**

only at ~70% for one week decorrelation time, and 75% for two weeks.

To clarify this point in the revised manuscript, we added a statement that the autocorrelation of the weekly indices has been properly accounted for in estimating the degree of freedom (line 195). Particularly, we mention that the Fisher z-test is based on an estimation that there is no autocorrelation between weekly indices after a period of one week in DFJM. Assuming a longer decorrelation times after SSWs (e.g., two weeks) leads to a qualitatively similar conclusion.

Reviewer 1

General comments:

In this manuscript, the authors are evaluating whether there is a relationship between marine cold air outbreaks (MCAOs) and Sudden Stratospheric Warmings (SSWs) in the Barents, Norwegian, and Labrador Seas. The authors conclude that changes in the large-scale tropospheric circulation account for 42% of the MCAO variance in the Barents Sea and 31% of the variance in the Norwegian Sea. They also make a convincing case that there is a significant increase in the correlation between the large-scale tropospheric flow pattern and MCAOs after SSWs in the Barents and Norwegian Seas. The connection to the large-scale tropospheric flow to MCAOs is further found to be correlated with the Scandinavian Trough pattern in the Barents and Norwegian Seas and Greenland Blocking pattern in the Labrador Sea. This manuscript fits within the scope of WCD in that it addresses stratosphere-troposphere coupling and prediction on sub-seasonal to seasonal time scales. In this revised manuscript, the authors have diligently addressed the earlier concerns and I now think that this could be published after some minor revisions outlined below.

Specific comments:

1 The connection to physical processes linking the stratosphere to the surface has been improved in this version, although after reading again, I am still left wondering what physical feature(s) is(are) transporting the cold air into the regions of focus in this study. It makes sense that the lower 500 hPa heights would be associated with the colder air and the related storminess nearby. Papritz et al. (2019) address these processes that are likely relevant in the Norwegian Sea, particularly the tropopause polar vortex (e.g. Cavallo and Hakim 2010).

Changes in the frequency of MCAOs in the North Atlantic have been suggested to arise in the first place from shifts in the strength and the location of cyclone activity. Fletcher et al. (2016) showed that MCAOs occur predominantly in the cold sector of cyclones. This has been further detailed by Papritz and Grams (2018) for the Nordic Seas and the Barents Sea. By considering cyclonic and anticyclonic flow regimes, they demonstrated this relationship showing that the MCAO frequency is enhanced west of positive cyclone frequency anomalies and MCAO occurrence is suppressed in regimes with no or weak cyclone activity across the Nordic Seas and the Barents Sea. In particular, intense storm track activity associated with cyclonic weather regimes is found to be favorable for MCAOs in these regions. Hence, the stratospheric impact on MCAOs is thought to modulate the large-scale flow as reflected in 500 hPa geopotential height, which in turn affects the tracks and frequency of cyclones. The anomalous near surface flow associated with changes to the cyclone tracks then drives changes in the advection of cold air masses and, thus, in the occurrence of MCAOs.

To clarify this point in the manuscript, we have revised part of the Introduction and added a discussion on the physical processes that affect the variability of MCAOs in the northeast North Atlantic (lines 23–35). Additionally, we have revised the order of the panels in Fig. 2 and extended the discussion on cyclone activity as one of the main drivers for MCAOs in these regions.
Another process that is likely relevant for the variability of MCAOs in these regions is the occurrence of cyclonic tropopause polar vortices (e.g. Cavallo and Hakim 2010; Papritz et al. 2019). These vortices can induce especially intense MCAOs over the Nordic Seas when they propagate out of the high Arctic (Papritz et al. 2019). It would be interesting to investigate whether tropopause polar vortices are more or less likely to propagate southward in the aftermath of an SSW. Due to the low frequency of SSWs and the relatively low frequency of tropopause polar vortices, a statistical analysis of this mechanism is unfortunately not possible based on the reanalysis.

2 Line 50: The Labrador Sea is also mentioned in the abstract and on line 55, but just the Norwegian and Barents Seas here.

We added a new sentence on the Labrador Sea (line 60), mentioning that the air-sea fluxes associated with MCAOs may have an impact on dense water formation in this region, and hence on the North Atlantic overturning circulation.

3 Line 129: Please provide a justification for choosing M >= 4K to define moderate-to-strong MCAOs in DJFM climatology.

A separation to weak (< 4 K), moderate (4 to 8 K) and strong (> 8 K) MCAOs by defining thresholds for the MCAO index (M) can be found in Papritz and Spengler (2017). Using these categories, we identify moderate-to-strong MCAOs with a threshold of M >= 4 K (i.e., a combination of moderate and strong categories). As pointed out by Papritz and Spengler (2017), MCAOs with an intensity of in excess of 4 K are associated with notable upward heat fluxes from the ocean to the atmosphere. To clarify this point, we added the following sentence to the manuscript (lines 80-81): "In this study we focus on MCAOs with an MCAO index (Eq. 1) exceeding a threshold of 4 K. This choice of threshold is in accordance with the thresholds used in Papritz and Spengler (2017) and selects moderate-to-strong MCAOs with notable upward heat fluxes from the ocean. Other studies have used slightly different thresholds for the MCAO index (e.g., a threshold of 3 K for moderate MCAO events in Fletcher et al. (2016)) however the results presented in this study are not sensitive to small changes of this threshold (of order of 1-2 K)".

4 Lines 135-160: The interpretation provided that the storminess increases in the Barents, Norwegian and Labrador Seas at the time of MCAOs in the respective regions is not quite accurate. However, the conclusion reached by the authors on lines 142-144 is the correct conclusion. Cold air outbreaks occur when there are northerly winds over those regions, which means that the storms must move slightly east of those regions so that the cold sector (west side) is over the seas themselves. For example, in Figure 2j, there is an increase in storminess in the lower right side of the Barents Sea box but decrease in upper left side (not stated correctly on lines 137-138) and similarly for the Norwegian Sea (Fig. 2k) and Labrador Sea (Fig. 2l). This also applies to the conclusions section on line 265.

We agree with the reviewer's view, that cold air outbreaks occur when cold air masses from the ice-covered polar areas are transported over the ocean, as it typically occurs in the cold sectors of storms. Following this comment, we have revised parts of the Results section (lines 135–160) accordingly. We have also revised the Conclusion section in accordance with this perspective (lines 270–275). We emphasize that the occurrence of MCAOs in each of the regions is associated with increased cyclone frequency east of the domain.

5 Line 140: On point (iii), it looks like in Figure 2g that the strongest northerly wind anomalies are over the Barents Sea with weaker northerly wind anomalies over the Norwegian Sea.

Following the reviewer's comment, we have changed this sentence (line 150) to clarify that strong northerly winds in periods of enhanced MCAOs in the Barents Sea are found over the Norwegian and the Barents Sea in particular (Fig. 2j).

6 Lines 180-190: It is nice that the authors have now considered statistical significance in this revision. However, it is not clear on line 187 what "All correlations...are found to be statistically significant" refers to. It is good that the correlations themselves have p < 0:05, but what about the differences in correlations between

the SSW and climatology or SSW and no SSW? This seems to be addressed in the Labrador Sea correlations only. It should be stated which correlations are and are not significant; perhaps a table with the corresponding p-values would be most helpful.

Following this comment, we have clarified in the manuscript that all correlation coefficients are significant at the 95% level (a statement was added to Fig. 3 and Fig. 4 caption). In addition, in the revised version we included more information of the significance of the difference between SSW and non-SSW correlations computed using Fisher's z-test (lines 194-200). We find that only in the Barents Sea region the differences in weekly ZDI-MCAO correlations between SSW and non-SSW periods is significant at 95%, whereas in the Norwegian and Labrador Sea regions this difference is significant at a lower level of 75%.
The significance of the differences between the GB-MCAO and ST-MCAO correlations for SSW and non-SSW periods is also investigated. The result of this statistical test is summarized in the manuscript as follows (lines 212-214): A significance difference at a 95% level between SSW and non-SSW periods is found only the ST-MCAO relation in the Barents Sea region.

7 Line 209: Where are the authors getting that there is an increase in 15% in the explained variance for the Barents Sea for the ZDI index vs. MCAO? It looks like it should be 18% from Figure 3a.

Corrected. We changed the value of the explain variance to 18% in accordance with the values in Fig. 3a.

8 Line 245: It is easier to see from Figure 6a,b that the circulation over the Barents Sea is "anomalously cyclonic" rather than "cyclonic."

We replaced "cyclonic" to "anomalously cyclonic" as suggested (line 247). We have also rephrased lines 245–250 accordingly.

Technical corrections:

1. Figure 2: The caption should state what the black and green boxes are in each of the panels (as it is in Figure 1 caption).
   Corrected. We added a description of the boxes to Figure 2 caption.

2. It is not necessary to say 'historical' on line 90
   Corrected, replaced this term with "observed".

3. Line 145: enhanced –> moderate-to-strong
   Corrected, also in line 150 (i.e., we show the MCAO anomalies for periods of moderate-to-strong MCAOs in each region).

Reviewer 2

The manuscript has improved substentially after the revision. Thus, I recommend it for publication. Please also check the following comment: L118: Should not it be eastern North Atlantic?

We thank the reviewer for their positive evaluation. We corrected to "northeastern North Atlantic" on this line and throughout the manuscript.

Reviewer 3

The authors have done a good job of addressing the comments from the first round of review. Their effort has greatly improved the manuscript. I think by both broadening the analysis to include all SSW events rather than just a limited subset from the reanalysis period, as well as, including the additional North Atlantic regions into the analysis, the paper provides a compelling synoptic climatological analysis on the occurrence of anomalous MCAO activity after SSW. I have a few minor/technical comments about the framing of the analysis and have included these below.

Minor comments:

1. Title change: The title needs to be more specific to the analysis presented in the paper. The authors only consider sudden stratospheric warming events and not other 'stratospheric influences' like those from final warming events, strong events, etc. Perhaps something like, "Modulation of North Atlantic marine cold air outbreaks following sudden stratospheric warming events" would be more appropriate to the analysis presented.

We thank the reviewer for this suggestion. We have changed the title of the paper accordingly to "Stratospheric influence on North Atlantic marine cold air outbreaks following sudden stratospheric warming events".

2. The authors state that they "aim to shed light on the predictability of MCAOs" on line 58 and re-emphasize this point elsewhere in the discussion of the results. However, this aim should be reworded/scaled back. The analysis does not get into a discussion about our ability to predict MCAO at various timescales (nor should it, as that is not the focus of the analysis), rather shows that MCAOs occur more frequently in some locations and less so in others after SSWs. Perhaps this fact could be used by a simple statistical model to increase predictability, but that is not explicitly discussed. This aim should be reframed, perhaps in terms of mitigating societal/economic impacts (i.e., those discussed in the intro) due to changes in frequency and locations.

Indeed, the ability to predict MCAOs at various timescales is not the focus of this study, which focuses on the influence of large-scale atmospheric patterns in the northeastern North Atlantic on MCAOs in these regions, and their link to sudden stratospheric warmings.
To better address this issue, we have revised several paragraphs in the manuscript. In particular, in the Introduction (lines 62–64) we emphasize that our results aim to shed light on the precursors and occurrence of MCAOs over the Barents and Norwegian Seas, as well as for the Labrador Sea, which is expected to benefit long-range predictability of their extreme impacts. Given the long-lasting influence of SSW events on the tropospheric circulation on mid- and high-latitudes, this connection can potentially be exploited for improving subseasonal MCAO predictions. In addition, by performing linear regression, we have been able to demonstrate a statistical relationship between MCAOs and other atmospheric indices that capture the characteristics of the large-scale flow. Such a connection can be further used for mitigation of societal and economic impacts by providing an estimate of the increase/decrease in MCAO intensity due to a change in the environmental conditions.

3. Fig. 2: A minor suggestion to consider: perhaps you can flip your color bar for the first row of the figure (for MACO) so that cold air is represented by cold colors and warm air is warm colors.

We thank the reviewer for this suggestion. We agree that using cold color scheme for the cold air makes sense in this context, however we prefer to visually distinguish the MCAO anomaly from the northerly wind flow in the lower panels of Fig. 2, and therefore we choose warm colors to demonstrate the enhanced MCAO intensity, rather than cold colors.

References

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