egusphere-2023-2018: Response to Second Review Comments

We thank both referees for carefully reading our revised manuscript and providing constructive comments that further helped improve both the quality and clarity of this work. Below please see our point-by-point responses to all review comments and revisions made to the manuscript. The original comments are in blue.

Referee #1

General comments:

The authors have put a lot of effort into the revisions and have addressed many of my previous concerns. The results are interesting and provide insight into the characteristics of extreme Arctic warm events, defined first per grid point and then as contiguous regions with T2m > 0°C (concurrent warm events). I particularly like the analyses of the concurrent warm events. My major concern is still the same as in the first version of the manuscript, namely the definition of Arctic warm events per grid point (see comment 1 below). Many of my remaining comments concern language and terminology and can be addressed with some rewording.

We thank the referee again for carefully reviewing our manuscript and providing suggestions which greatly improve the clarity of this manuscript. Our responses to the specific comments are shown below, with their original comments in blue.

Specific comments:

1) You have explained in detail why you define Arctic warm events at each grid point separately, but I am still struggling with the fact that adjacent grid points with T2m > 0°C at the same time are referred to as many separate "events". You motivate this with the studies by Moore (2016) and Graham et al. (2017), who used meteorological buoy observations to study the warm event in December 2015. However, even if they looked at different point observations, they did not refer to them as different Arctic warm events – they used the point observations to characterize one single event. I am ok with your method (although I am more convinced by your definition of concurrent warm events, which, however, is not the main focus of the paper), but the problem for me is the word "events" that does not always fit well in the text and can lead to confusion. Maybe you can carefully scan your manuscript and write more often something like "grid points with T2m > 0°C" instead of "Arctic warm events". For instance, you write about the onset of the event (or, in the revised version, the start of the event, which for me is actually the same as the onset) and its termination, but I find the suggestion of the second reviewer much more convincing to use something like "time when a grid point's T2m exceeds / falls below 0°C", as the warm temperatures are most likely simply being advected from one grid point to the next. And instead of short-duration and long-duration events, maybe you could use something like "grid points experiencing the warming for a short / long duration". I understand that this also makes the text more cumbersome, and you can't replace all your mentions of "event" with a formulation like this, but wherever possible this would increase the accuracy of the text and help to minimize confusion for the reader.

Thank you for the suggestions on using different wordings to describe the extreme warming events defined at the grid-point scale, which help to improve the accuracy of the descriptions and avoid potential confusion. Following the referee's suggestions, we explicitly defined extreme warming events using descriptions, such as "defined at the grid-point scale" and "with T2m >= 0℃" wherever appropriate. In addition, when we discussed the start and termination of the extreme warming events, the description "when a grid point's T2m first exceeds/ falls below 0℃" was used to properly define them. Lastly, we also explicitly defined short/long duration events whenever appropriate using something like "grid points experiencing the warming for a short/long duration", as suggested by the referee.

2) I find your new Fig. S4 very interesting, but I am quite surprised by the large number of days per season with at least one grid point with T2m > 0°C. According to this figure, these events are actually not that rare, with most winters having at least one such warm event and many winters even having one in more than 20 out of the 90 days. This is different to the findings of previous studies. For instance, according to Moore 2016, Arctic warm events occur once or twice each decade, and Binder et al. 2017 found 12 out of 36 winters with Arctic warm events. Of course, these studies are based on different methods, different datasets, different study regions, etc., but I am still surprised by the quite different findings. Maybe you could briefly discuss your results and explain why you have a much higher number of events than found in previous studies. Also, your sentence in line 16 in the abstract ("They occur rarely, with a total absence during some winters over most of the region.") and the text in Section 3.1 might be revised a bit. And in my opinion, it would be more informative if you could write in how many of the 42 winters there has been at least one Arctic warm event somewhere in the studied region (your new Fig. S4).

As pointed out by the referee, the occurrence frequency of the Arctic warm events in Moore (2016) and Binder et al. (2017) are based on different methods, different datasets, different study regions, etc. In particular, Moore (2016) defined Arctic warm events as those events with surface air temperature (or T2m) >= 0℃ occurring poleward of 85°N during **December** in JRA55. They identified three Arctic warm events in the study period from 1958 to 2015. As shown in our manuscript, if we restrict our focus to regions poleward of 85°N, there are only 9 days in total when Arctic warm events with T2m >= 0℃ were found during **December-February** from 1979 to 2021. In this case, the difference in the occurrence frequency of the Arctic warm events between our study and Moore (2016) is small. The slightly more events identified in our studies could be attributed to the difference in the definition of the winter season (December versus December-February), the difference in the studied period (1958-2015 versus 1979-2021), and difference in the datasets used (JRA55 versus ERA5). In particular, the period from 2015 to 2021, which included in our study, contains 3 days with T2m >= 0℃ poleward of 85°N. In addition, ERA5 has a higher spatiotemporal resolution compared to JRA55 (0.25° x 0.25° versus 1.25° x 1.25° and hourly versus 6-hourly). This higher spatiotemporal resolution in ERA5 makes the detection of Arctic warm events more likely.
Binder et al. (2017) defined Arctic warm events as those events with T2m >= 0℃ occurring poleward of **82°N** during December-February in ERA-Interim. They found 12 out of 36 winters with Arctic warm events from 1979 to 2014. If we also restrict our focus to regions poleward of 82°N, as shown in Fig. R1, we found 16 out of 36 winters with Arctic warm events from 1979 to 2014 in ERA5, which brings our result much closer to the result in Binder et al. (2017). Again,

the slightly more winters with Arctic warm events found in our study could be attributed to the different dataset (ERA5) with higher spatiotemporal resolution used in our study.
We agree with the referee that, Arctic-Wide, based on Fig. S4, these extreme warming events defined at the grid-point scale are not rare. However, based on Fig. 3, they do occur rarely over many of the grid points where T2m ever reaches or exceeds 0°C during the study period. We thus revise line 16 in the abstract from "*They occur rarely, with a total absence during some winters over most of the region.*" to "*They occur rarely over many grid points, with a total absence during some winters.*" In addition, we also revised line 180 in Section 3.1 from "*In addition to being short-lived, these events also occurred very rarely over the winter high Arctic (Fig. 3).*" to "*In addition to being short-lived, these events also occurred very rarely over many of the grid points of the winter high Arctic (Fig. 3).*"

The following discussion has also been added to Section 3.1:

"*Note that while the occurrence frequency of these extreme warming events can be considered rare over many of the grid points, over the entire high Arctic, they occur quite frequently. There was at least one extreme warming event somewhere in the studied region in 40 out of the 42 studied winters (Fig. S1). This appears to disagree with the findings in Moore (2016) and Binder et al. (2017). Specifically, Moore (2016) found that wintertime Arctic extreme warming events with T2m >= 0°C occur only once or twice each decade. Three events were identified from 1958 to 2015 in their study. Binder et al. (2017) found 12 out of the 36 winters with at least one extreme warming event over the wintertime high Arctic from 1979 to 2014. These seeming discrepancies between the results in our studies and those found in Moore (2016) and Binder et al. (2017) stem mostly from the differences in the datasets used, the definition of the high Arctic and the definition of the winter season. In particular, Moore (2016) defines Arctic extreme warming events as those events occurring poleward of 85°N during December in Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al., 2015). As shown later, there are only 9 days with extreme warming events identified during the studied period if we change the analysis regions to poleward of 85°N, which brings our result much closer to that in Moore (2016). The slightly more events identified in our study can be attributed to the differences in the definition of winter season (i.e., December-February versus December) and datasets used (i.e., ERA5 versus JRA55). Following Binder et al. (2017), when the high Arctic is defined as regions poleward of 82°N, we find 16 out of 36 winters with extreme warming events from 1979 to 2014 (not shown), which also makes our quantitative result more comparable to that in Binder et al. (2017). The remaining difference is likely due to the different spatiotemporal resolution of datasets used between studies (i.e., ERA5 versus ERA-Interim).*"

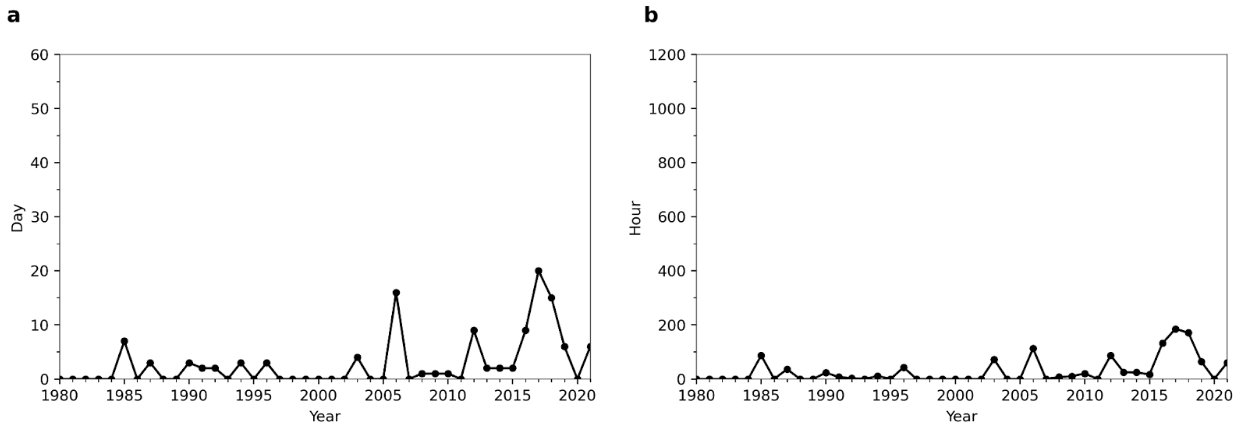

Figure R1. The same as Fig. S4, but with the high Arctic defined as regions poleward of 82°N. Time series in (a) the number of days per season and (b) the number of hours per season with at least one warming event defined at the grid point level occurring poleward of 82°N.

3) Section 2.1: Even though you rewrote large parts of the section, it remains quite difficult to read and to quickly get the relevant information, as you mix in information that rather belongs to the introduction or even the conclusion, and you write a lot about how others defined the events and how the events could be defined, before actually writing how you define them in a different way. My suggestion would be to write a first subsection with the title "Data", where you describe the ERA5 data, then a second subsection "Definition of extreme Arctic warming events", both in a more streamlined form, and a final subsection "Calculation of anomaly fields". For instance, when describing ERA5 I would leave away the first sentence "Results based on previous case studies suggest that extreme warming events with near surface air temperature above 0 °C tend to be short-lived, …", as you already mentioned this in the introduction and here it rather disturbs the flow. And also the last sentence of the paragraph "The results being presented here thus bear significance to our understanding of …" does not really fit into the data and method section but is rather part of the motivation or even the conclusion of the study. And in the subsection where you define the events, I would start with writing something like "In this study, we define Arctic warm events in two ways: first, as grid points with T2M > 0°C, which is the main focus of the study, and second, as contiguous regions with T2m > 0°C … " (and please also add more details about how you define the contiguous events). Afterwards, it is nice if you write about the motivation of defining the events in these ways, and their advantages and disadvantages.

Thank you for the great suggestions on restructuring Section 2.1. Section 2.1 is now broken into three subsections and subsequently revised following the referee's suggestions.

4) I am not always convinced by the words "drivers", "direct drivers" and "directly driving", which are all used very often in the paper (e.g., abstract line 23, Section 3.2 and Section 3.4). In general, there is not just one driver, but it is the interplay between various processes and weather systems that contributes to an Arctic warm event. For instance, in line 23 in the abstract, you write that "ARs are the direct driver for 100% of these event", but I would rather use "associated with" or "related to" (and similarly in many other parts of the text). You already changed the words in some parts of the paper in the revised version, but they still appear in many places where I don't think that they are suitable.

We have used more appropriate wordings in places where “drivers”, “direct drivers” and “directly driving” were originally used.

5) “Subsequent examination reveals the short-lived nature of this event, with the duration of staying above 0°C for less than an hour locally …”
This sentence is not so nice – I would write something like “with buoys close to the North Pole recording temperatures above 0°C for less than an hour …”

We have revised the sentence following the referee’s suggestion.

Referee #2

I highly appreciate the effort of the authors to address both mine and the other reviewer’s concerns and feedback, especially regarding the warm event definition and clearly stating which events are discussed in each section of the manuscript. I am pleased to see that some of our small suggestions were also adapted immediately in the revised manuscript. Thus, I find that the manuscript has now improved a lot. After addressing a few questions and suggestions presented below in terms of a minor review, I am happy to accept this manuscript for publication to the journal. The line references are wrt the reviewed manuscript.

We thank the referee for carefully reviewing our manuscript. The detailed comments provided by the referee help improve the clarity and quality of both the text and figures of the manuscript. Our responses to the specific comments are shown below, with their original comments in blue.

Specific Comments:

- Despite my concerns on the event definition as a grid-point defined event, the authors have succeeded to explain the pros and cons on their selected method. It is true, that grid-point defined warming events favour that one can understand more about what processes affect locally a specific grid point. Thereby, the spatial heterogeneity of characteristics, such as event duration, will be revealed, which might not be the case when looking at events over larger areas. This is also true when investigating e.g., why some grid-points experience earlier melt or freeze-up onset compared to other grid-points, something that could be missing if enlarging the study area. And I agree when the authors write that the large-scale setting differs relative to the relative location of the grid-point that experience warming. The relation to large-scale patterns can still be obtained if using area-based event definitions, but might not indicate as clearly the importance of the relative location. Anyways, thanks for all additional discussions and clarifications regarding the event definition, this will be helpful for the future readers. However, I have a short comment on the discussion authors provide on the temporal requirement between events (which is not obtained in the current analysis), and my concerns of double-counting of similar events. Figure 6 shows the temporal evolution in lag composites for your grid-point events where no interval requirement between consecutive events is applied. In the response documents, the authors provided a similar figure (R9) with a 5-day interval requirement and indicated that the composites do look alike. I don't disagree with the authors, but would like to draw attention to the long-lived events (R9g) with notable differences between the original figure wrt the turbulent heat fluxes (negative values instead of around zero) and IWV around lags -5 to -2. This would indeed suggest on somewhat double counting of events in Fig 6: are these differences only a result of less events included in R9g, or is this really a result of that the previous long-lasting event was actually part of the begin of the next long-lasting event? Maybe one additional notation of this possibility would be good in the manuscript, where Fig 6 is discussed and/or where the authors motivate reasons why not imposing the temporal constraint (around L122).

Thank you for pointing out the difference between Fig. R9g and Fig. 6g. Indeed, after imposing a 5-day interval requirement, the anomalies of turbulent heat fluxes, T2m and IWV become negative. As also nicely suggested by the referee, this is likely caused by the previous long-lasting events being double counted as part of the next long-lasting events prior to their onset. Again, as shown in Fig. R2, imposing the 5-day interval requirement would not change the conclusion regarding the relative position of the SLP dipole for long duration events. To point out the sensitivity of our results to the imposed time interval requirement, the following discussion has been added to Section 2.2 in the revised manuscript:

"*We found that only the surface energy budget of the long duration events (defined in Section 3.2) prior to the onset is sensitive to whether a time interval requirement is imposed. More specifically, imposing a 120-hour interval requirement makes the anomalies of turbulent fluxes, T2m and integrated water vapor decrease from around zero (Fig. 6g) to a negative value from around 5-day lag to 2-day lag (not shown). This suggests that previous long-lasting events are probably double counted as part of the next long-lasting events prior to their onset when no time interval is imposed. Other than that, all the results presented in this study are very similar regardless of whether this additional constraint is imposed or not (not shown). For simplicity, the results being presented in this study are obtained without imposing this constraint.*"

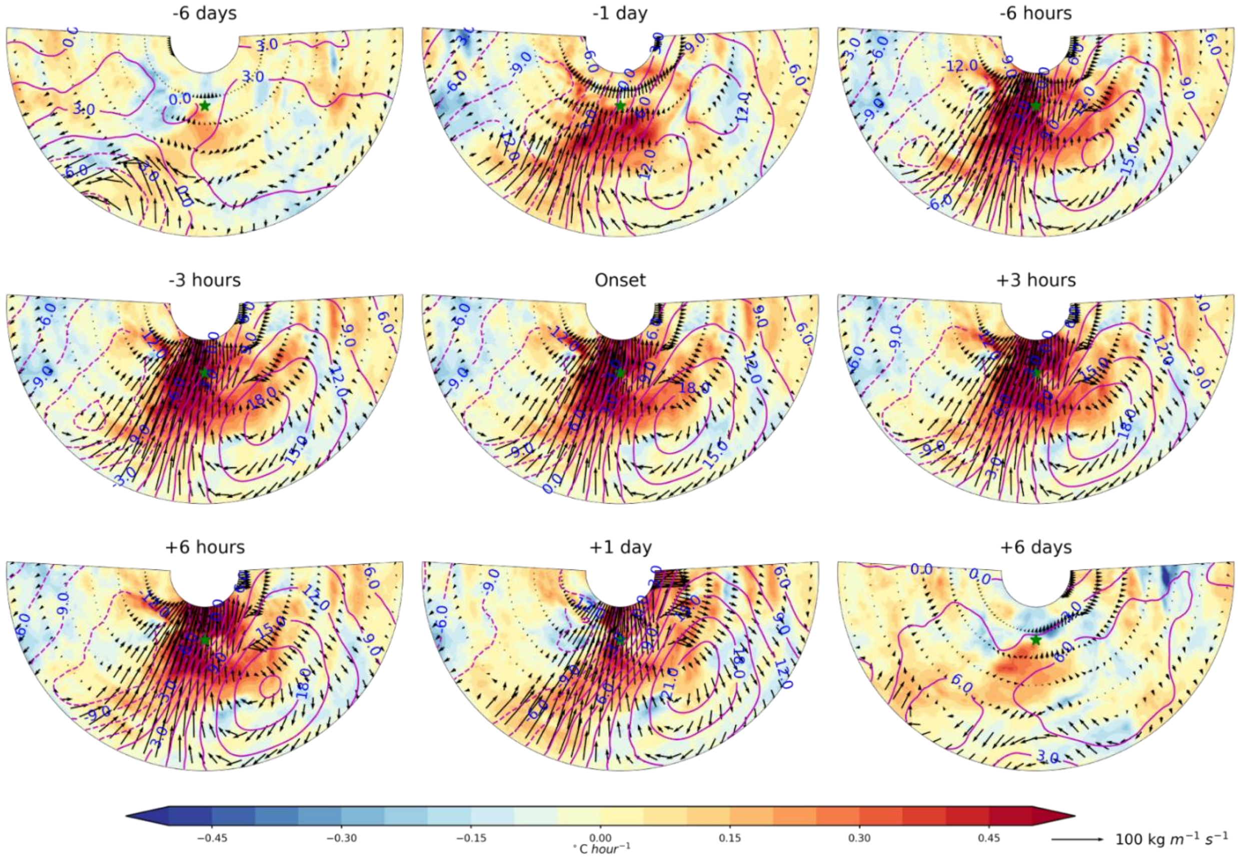

Figure R2. Same as Fig. 9 in the main text, but with a 5-day interval requirement imposed. Composites centred at the event grid point for the temporal evolution of integrated water vapor transport (IVT) anomalies (vectors), sea level pressure (SLP) anomalies (lines) and temperature advection anomalies (shading) before, during and after the start of the long duration extreme warming events (i.e., grid points with T2m >= 0°C at least 40 hours). The green star in each panel marks the grid point where the extreme warming events took place. Regions 5° poleward, 20° equatorward, 100° westward/eastward of the event grid point are included in the composites.

- It is nice to see the additional motivations in dividing your events into poleward and equatorward of ~85N based on the surface types. I was wondering whether the trends in any characteristics shown in Fig. 15 (thanks for the additional subplots for the concurrent events!) take into account this division (into "surface type" based on spatial restrictions)? Would the trends look different in the sub-categories?

This is a great question. However, as has been discussed in Section 3.4, there are only 9 days with T2m >= 0°C poleward of 85°N during the studied period. These nine days occur over six different years. Given such a small sample size of the events over regions poleward of 85°N, it would be difficult to calculate their trends. The trends shown in Fig. 15 thus mostly reflect the trends for the events occurring equatorward of 85°N.

- Abstract: I would suggest adding “2-meter” temperature (L12) as the temperature variable.

  “2-meter” has now been added in the abstract to describe temperature.

- New final paragraph: Thanks for adding this at the end to summarize and indicate possible further research topics. However, there are indeed some previous studies that show e.g., the relationship between persistent atmospheric circulation in March and the minimum sea ice extent in September (see e.g., Kapsch et al. 2019: https://doi.org/10.1007/s00382-018- 4279-z), and the preconditioning of warm winter/delayed freeze-up in autumn for thinner ice next spring (e.g., Stroeve et al. 2018: https://doi.org/10.5194/tc-12-1791-2018). In comparison to these papers, a good addition would be to study these links in the light of your identified warming events, as the authors nicely point out.

  Thank you for pointing us to these two relevant papers. They have been now properly cited in the last paragraph.

  “*Links between March persistent atmospheric circulation and September minimum sea ice extent (Kapsch et al., 2019) and between warm winter and subsequent thinner spring sea ice over the Arctic (Stroeve et al., 2018) have been established by previous studies.*”

- The ECMWF is written out in two sections close to each other (at the end of Introduction and in the beginning of Methods). I would include it when it is mentioned the first time, and just use the acronym when it is mentioned the second time.

  Thank you for spotting this redundancy. Now only the acronym is used when it is mentioned the second time.

- L284: The location of the negative SLP anomalies to the southeast of the events in longlasting events could also hint for a NAO+, a circulation pattern that would favour moisture and heat transport across the Atlantic towards the Scandinavia. The blocking-like persistent positive SLP anomalies over Scandinavia/Urals would then deflect that airflow northwards, towards the warm events. Studies also show that the decay of a NAO+ pattern could lead to an enhancement of the blocking to the east of the NAO pattern, and a warm anomaly in the Arctic. As your Fig. 9 is not exactly a geographic map (as you have centred the plots around the event location), these patterns might not be exactly over Iceland (negative SLP) and Eurasia (positive SLP), but would cover about the correct regions given that the possible locations for the extreme warm events are spatially constrained in the Atlantic sector. Have the authors thought about these possible connections wrt the long-lasting events? Some references, e.g., Luo et al. 2016 (https://doi.org/10.1175/JCLI-D-15-0612.1), Luo et al. 2017 (https://doi.org/10.1088/1748-9326/aa69d0), and Murto et al. 2022 (https://doi.org/10.5194/wcd-3-21-2022).

This is a great question. As has been shown in Luo et al. 2017, the combination of positive NAO and Ural blocking provides an optimal circulation pattern which favors moisture and heat intrusions into the Arctic through the Atlantic pathway. We have shown in our study that extreme warming events defined at the grid-point scale are more likely to occur under AR conditions. We thus believe that positive NAO likely contributes to more occurrences of the extreme warming events, including long-lasting events. To see what sea level pressure (SLP) pattern is associated with increased long-lasting event occurrence frequency, we regress the winter SLP anomaly time series onto the detrended long-lasting event occurrence frequency time series. As shown in Fig. R3, the SLP regression pattern features a blocking-like structure over Northern Eurasia. This seems to suggest that the interannual variability of the long-lasting event frequency is largely controlled by the blocking-like structure, and NAO may play a secondary role. However, a more detailed and quantitative analysis is needed to better establish the relationship between NAO and the occurrence frequency of the long-lasting events.

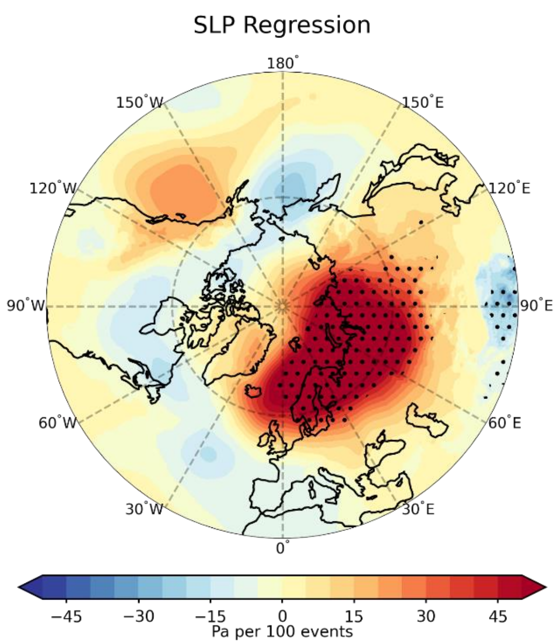

Figure R3. Spatial pattern of the regression of the winter sea level pressure (SLP) anomaly time series onto the detrended long-lasting event occurrence frequency time series. Stippled areas indicate the regression is significant at the 0.05 level based on the Student's t-test.

- L379: deep penetration of ARs associated with an SLP center located more polewards. Could this be related to locally formed Arctic cyclones, with cyclogenesis in the Arctic north of Greenland? There are studies, such as Messori et al. 2018 and Murto et al. 2022, that also find these local cyclones (associated with negative SLP anomalies polewards) to occur around the time of the warm events. Maybe worth to discuss this possibility also in the current manuscript?

It is totally possible that these deep penetration of ARs are associated with locally formed Arctic cyclones. To account for this possibility, the following discussion has been added to Section 3.4 of this manuscript:

"*As has been shown in previous studies (Messori et al., 2018; Murto et al., 2022), the more poleward located negative SLP center could be associated with the locally generated Arctic cyclones.*"

Technical corrections:

- Fig1 caption: I would add "in (b)" between "The purple line" and "denotes…".

  Added.

- Fig1a: to help the readers to look at Fig1a and following the first sentence in the results (at L163), I would add a thin (maybe dashed?) contour to highlight the -20°C isotherm.

  A dashed contour has been added to Fig. 1a to highlight the -20°C isotherm.

- Fig10: It would help the reader to look at the figure if columns had their own titles, e.g., "all concurrent events", "Cluster 1: strong SLP anomaly dipole", "Cluster 2: blocking-like surface anticyclone" and "Cluster 3: strong Greenland SLP anomaly". Similarly for Fig. 11. The number of events in each of the 3 clusters would also be good to know, maybe add in the figure caption for Fig. 10?

  A short title has been added to each column in Figs. 10 and 11. In addition, the number of events in each cluster has also been specified in the caption of Fig. 10.

- Fig 15: some lines cover the text in the legends, which makes it hard to read the legend.

  We have adjusted the figure so that the legends are now not covered by lines.

- All map figures: As the latitude band of 83N is of importance in this study, I would suggest to explicitly mark that latitude in all maps.

We tried marking the 83°N latitude in some of the map figures. After adding the 83°N latitude, these figures appear slightly more distracting to us. To keep the figures clean, we decided not to mark the 83°N latitude in the map figures.

- S2: Thank you for adding the climatological sea ice edge contour. Why did the authors choose a SIC of 50 %? As far as I know, the sea ice edge is usually marked as SIC of 15 %. If the figure stays similar with a SIC of 15 %, I would suggest changing.

  Winter sea ice concentration is always higher than 15% poleward of 80°N during the studied period. We thus decide to draw the climatological 50% sea ice concentration contour.

- L72: "This event was driven by an …" instead of "is".

  Corrected.

- L91: I would add "local" before "extreme warming events" to emphasise the grid-point based defined events, as the authors are here referring to the studies where local buy observations are utilized.

  As suggested by referee #1, this sentence has been removed from the main text.

- L170: Add "mainly" after "Therefore, we focus", because the authors do return to the high Arctic definition later on in the paper, as in the trends.

  Added.

- L292: I would add the temperature unit after the "zero" (mentioned twice on this line)

  These two zeros are referring to the area with T2m >= 0℃. To clarify, the original sentence "*The onset of these concurrent warming events is then defined as the time when the area first exceeds zero (one grid point), and the event ends when the area first falls back to zero.*" has been revised as "*The onset of these concurrent warming events is then defined as the time when the area with T2m >= 0℃ first exceeds zero (one grid point), and the event ends when the area with T2m >= 0℃ first falls back to zero.*"

- L 400: did the authors forget to include "do" prior to "… changes in AR frequency …"?

  We have now added "whether" before "changes in AR frequency".

- L432: shortly remind the readers here what is meant by “concurrent warming events”

  We have added “*defined as a contiguous region with T2m >= 0℃ concurrently*” after “concurrent warming events” to remind readers the meaning of concurrent warming events.