egusphere-2023-2018: Response to Review Comments

We thank both reviewers for their insightful comments and constructive suggestions that 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.

Reviewer #1

General comments:

This study investigates the characteristics of extreme wintertime Arctic warm events, using hourly ERA5 data for the period 1979-2021. In most of the study, Arctic warm events are defined as grid points poleward of 80°N where the two-meter air temperature (T2m) exceeds 0°C. Adjacent grid points with T2m > 0°C at the same time are considered as separate warm events. They find that the events are rare and only occur over the Atlantic sector of the Arctic, with a mean duration of less than half a day. Warm events are associated with positive anomalies in integrated water vapor, downward longwave radiation, sensible heat flux and, in most areas, latent heat flux. They are located in a region of intense sea level pressure (SLP) gradients, with a negative SLP anomaly to the west and a positive anomaly to the southeast, and they typically coincide with atmospheric rivers. In an additional analysis of so-called "concurrent warm events", where events are defined as coherent objects and not as single grid points, they use a K-means clustering method and find three different large-scale circulation clusters, with the first characterized by a strong SLP dipole, the second mainly by a strong surface anticyclone and the third mainly by a strong surface cyclone. Finally, they show positive trends in the number of events (again defined as single grid points with T2m > 0°C), their magnitude and duration over the past 40 years.

Overall, the manuscript is interesting, and the study may be well suited for publication if a couple of scientific comments are addressed, and some formulations are further improved. Some specific suggestions are given below.

We thank the reviewer for taking the time to review our manuscript and providing thoughtful and constructive comments. In particular, the comments on the definition of the warming events and the suggestions on showing the trends in the characteristics of the concurrent warming events helped improve the clarity and quality of our manuscript. Our responses to the specific comments are shown below, with their original comments in blue.

Specific comments:

1) My major comment concerns your definition of Arctic warming events. You call it a warming event when T2m exceeds 0°C at a grid point. If T2m is > 0°C at several neighbouring grid points at the same time, you refer to them as several separate warming events. I find this quite confusing, as it is most likely just one event with a larger spatial extent. You then write that the

duration of the events is often less than 1h (your "short-duration events"), but I assume that they are typically much longer-lived when they can move over several grid points. And according to your description of Fig. 5, the temperature drops very quickly after an Arctic warm event, but this is just the temperature at a specific grid point. The composites in Fig. 6-8 indicate that the warm temperatures are simply being advected to other grid points. I assume there is a lot of double counting in the different figures (for instance, the fields in the composites are considered several times if a warm event spans several grid points). I think you have to be very careful with the interpretation of your results and with the wording. Rather than "warming events", I would typically write something like "grid points with T2m > 0°C" to avoid confusion, and mention where necessary that the fields are considered several times when a warm episode covers more than one grid point.
I find the definition of the "concurrent warming events" much more convincing. If I understood it correctly, there you considered adjacent grid points with T2m > 0°C as one "warming event" and also somehow traced the events in time. How is the tracing working exactly, can the warm events move over several grid points? It would be interesting if you could provide some information about their occurrence frequency in the past 40 years, their duration, their spatial extent and other characteristics. And maybe you do not need to impose a threshold on the area and the duration of these events, as you do so far, but could investigate the characteristics of all of them.

Our study is inspired by Moore (2016) and Graham et al. (2017), both of which used meteorological buoy observations to characterize the late December 2015 North Pole warming event. In both studies, data from these meteorological buoys, located at different locations (grid points) around the North Pole, were used to characterize the same evolving large-scale warming event (defined as concurrent warming event in our study). As mentioned in the original manuscript (line 90), defining Arctic warming events at the grid-point scale can facilitate a direct comparison with the findings in Moore (2016) and Graham et al. (2017). Furthermore, defining these warming events at the grid-point scale can also help us gain new insight into what determines the duration of these events at different locations. For example, we find that the location of the grid points experiencing warming events relative to that of the sea level pressure (SLP) dipole is key in determining the event duration. We also find that long duration events are driven by anomalous downward sensible heat flux (SHF) while anomalous downward longwave (LW) radiation seems to play a more important role in driving short duration events. These insights are hard to obtain if we define warm events from a Lagrangian perspective as a contiguous region with T2m >= 0°C. As events defined in this way would inevitably encompass many grid points at any given time and the events also evolve constantly through space and time.
We do agree with the reviewer that when several neighboring grid points are experiencing T2m >= 0°C simultaneously, we can view them as one event with a larger spatial extent. This perspective is totally valid. In fact, to take this perspective into account, we define the so-called "concurrent warming events" later in the manuscript. In this study, we examine these warming events from both the grid-point scale perspective and the large-scale perspective suggested by the reviewer. However, we focus more on the grid-point scale perspective, following Moore (2016) and Graham et al. (2017), who examined the late December 2015 high Arctic warming event similarly.

It's fairly common to define extreme events at grid-point scale in the literature. For example, when extreme precipitation over midlatitudes is driven by extratropical cyclones or atmospheric rivers, it can occur in many neighboring grid points. This type of extreme precipitation can be treated as one event with a large spatial extent and characterized with contiguous regions exceeding a threshold by tracking them through space and time. However, it is also common to study extreme precipitation at grid-point scale (e.g., Pfahl et al., 2017). Analogously, we believe it is reasonable to define extreme warming events at the grid-point scale as well. Nonetheless, to more explicitly explain why we define warming events at the grid-point scale and to acknowledge the large-scale perspective, we have now added the following text to the Methods section:

"*Case studies based on in-situ buoy observations have been conducted by previous studies to examine the characteristics and drivers of winter extreme warming events over the high Arctic (Moore, 2016; Graham et al., 2017), which characterized extreme warming events using point observations based on meteorological buoys. Since these extreme warming events are usually driven by large-scale circulation (Woods and Caballero, 2016; Moore, 2016; Kim et al., 2017; Messori et al., 2018), when extreme temperature is detected over a grid point, it is common that such extreme temperature can also be found over its neighbouring grid points. Under such conditions, one approach is to define extreme warming events by using contiguous regions with temperature exceeding a predefined threshold. However, to facilitate a more direct comparison with previous case studies shown in Moore (2016) and Graham et al. (2017), here we choose another approach to define extreme warming events at the grid-point scale. Specifically, in this study, extreme warming events are defined as those events with 2-meter air temperature (T2m) over a grid point reaching or exceeding* 0℃ *over the high Arctic that covers the regions poleward of 80°N. Although the focus of this study is on warming events defined at grid-point scale, we also investigate extreme warming events identified by contiguous regions with temperature exceeding a threshold in section 3.3, which complements the results from the grid-point scale perspective.*"

Of course, as pointed out by the reviewer, defining extreme warming events at the grid-point scale can result in double counting of the same large-scale circulation pattern when making composites. In fact, double counting inevitably occurs when creating the composites shown in Figs. 6, 7, and 8 of the original manuscript (Figs. 7, 8, and 9 in the revised manuscript). However, even if the same large-scale pattern occurs multiple times within the same composite or across composites, the relative position of the SLP dipole within the same composite and across composites is what matters. As the purpose of these composites shown in Figs. 6, 7, and 8 is to show that the duration of the warming events is determined by the position of the SLP dipole relative to the location of grid points with the extreme warming events, the double counting here would have minimal impact on our conclusion.
To further show that the impact of the double counting on our conclusion is indeed minimal, we reproduced Figs. 6, 7, and 8 by randomly picking one grid-point scale event at each of those hours with at least one event and compositing all randomly picked events. More specifically, at each hour, we first identify all the grid points with T2m first exceeding 0℃. The number of the grid points with T2m first exceeding 0℃ gives us the number of events at that hour. We then record the duration and position (latitude) of all the identified events of that hour and classify them into different categories (e.g., long duration events, short duration events poleward of

85°N, and short duration events equatorward of 83°N). For the categories with at least one event, we then randomly pick one event from each of those categories. The above steps are repeated for each hour during the study period. Lastly, the randomly picked events of each category are used to construct the composites. This approach can ensure that only one event is selected, even when neighboring grid points are experiencing warming events simultaneously. The same large-scale circulation pattern is thus counted only once. As shown in Figs. R1, R2, and R3, the results based on the composite approach described above closely resemble those presented in Figs. 6, 7, and 8. The only difference is that Figs. R1, R2, and R3 tend to be nosier, especially for the composites of the short duration events poleward of 85°N, owing to the smaller sample size. These results thus further confirm that double counting have minimal impact on our conclusion.
To point out this caveat, the following discussion has been added to the manuscript:

"*As the same large-scale circulation pattern can cause extreme warming events to occur over more than one grid point, it thus can be counted more than once within the same composite or across different composites. However, as the composites are centred at the grid point where the extreme warming event is identified, the position of the same large-scale circulation relative to the grid point would thus differ among the composites centred at different grid points. As we show below, the relative position of the SLP anomalies is what determines the duration of the extreme warming events. The double counting of the same circulation pattern for the composites shown in Figs. 7, 8, and 9 thus has minimal impact on the conclusion.*"

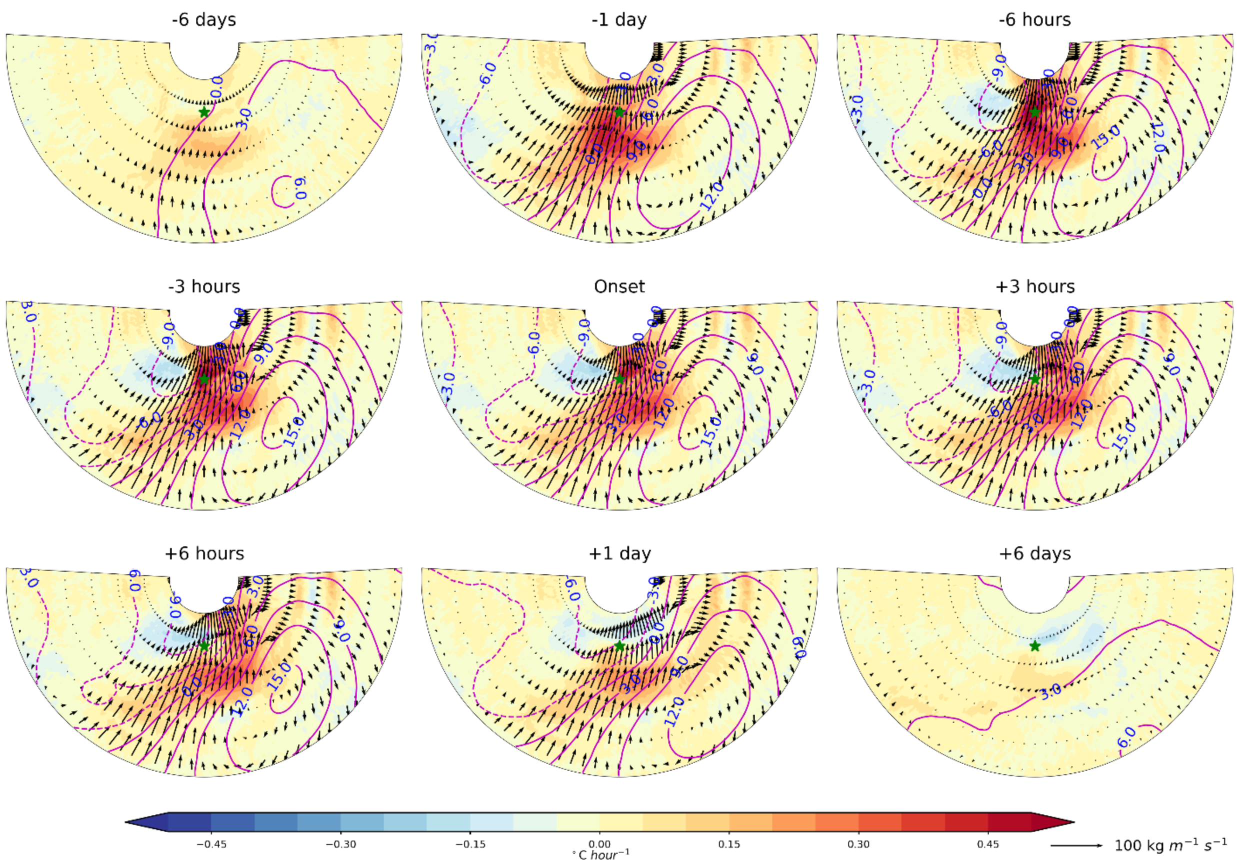

Figure R1. The same as Fig. 6 in the original manuscript (Fig. 7 in the revised manuscript), but based on the event sample obtained by randomly picking one event for each of those hours when at least one event is present. See the response above for a more detailed description of the composite approach.

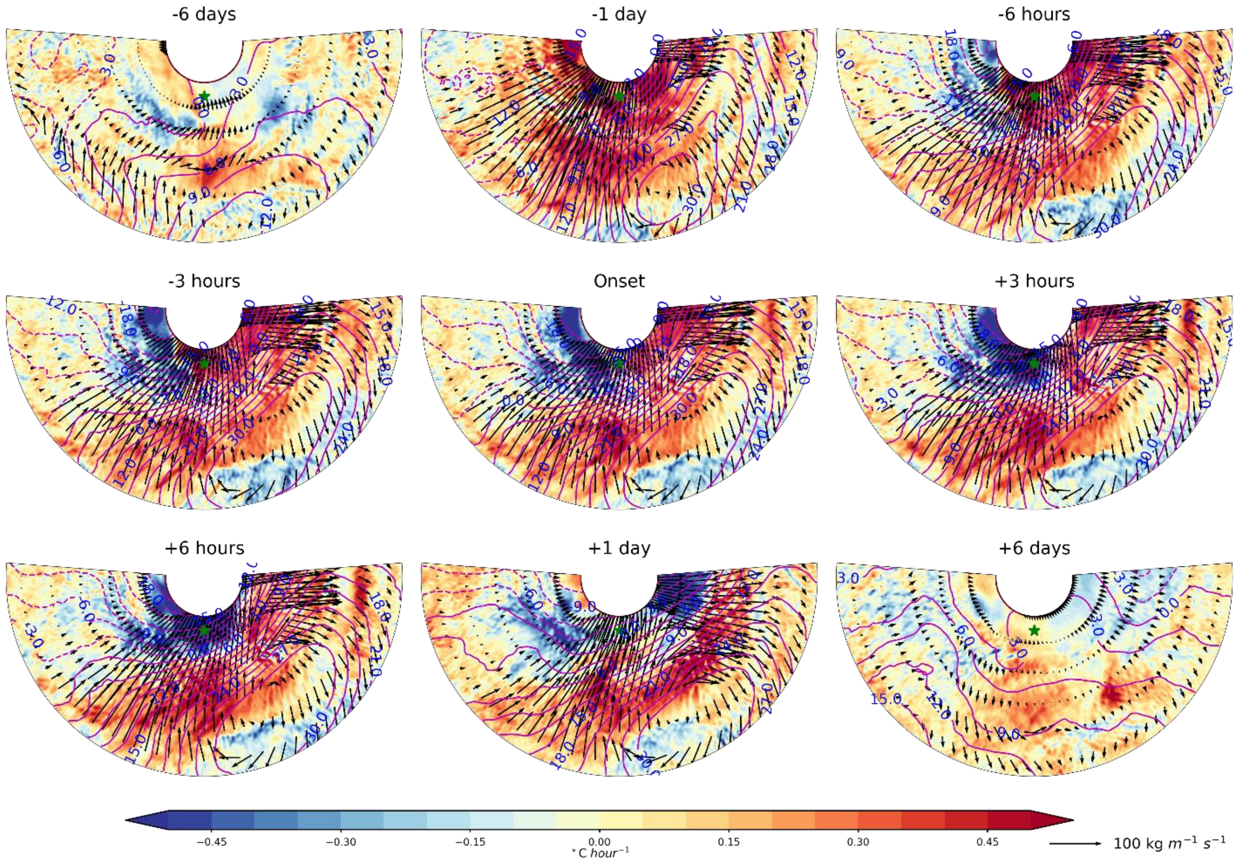

Figure R2. The same as Fig. 7 in the original manuscript (Fig. 8 in the revised manuscript), but based on the event sample obtained by randomly picking one event for each of those hours when at least one event is present. See the response above for a more detailed description of the composite approach.

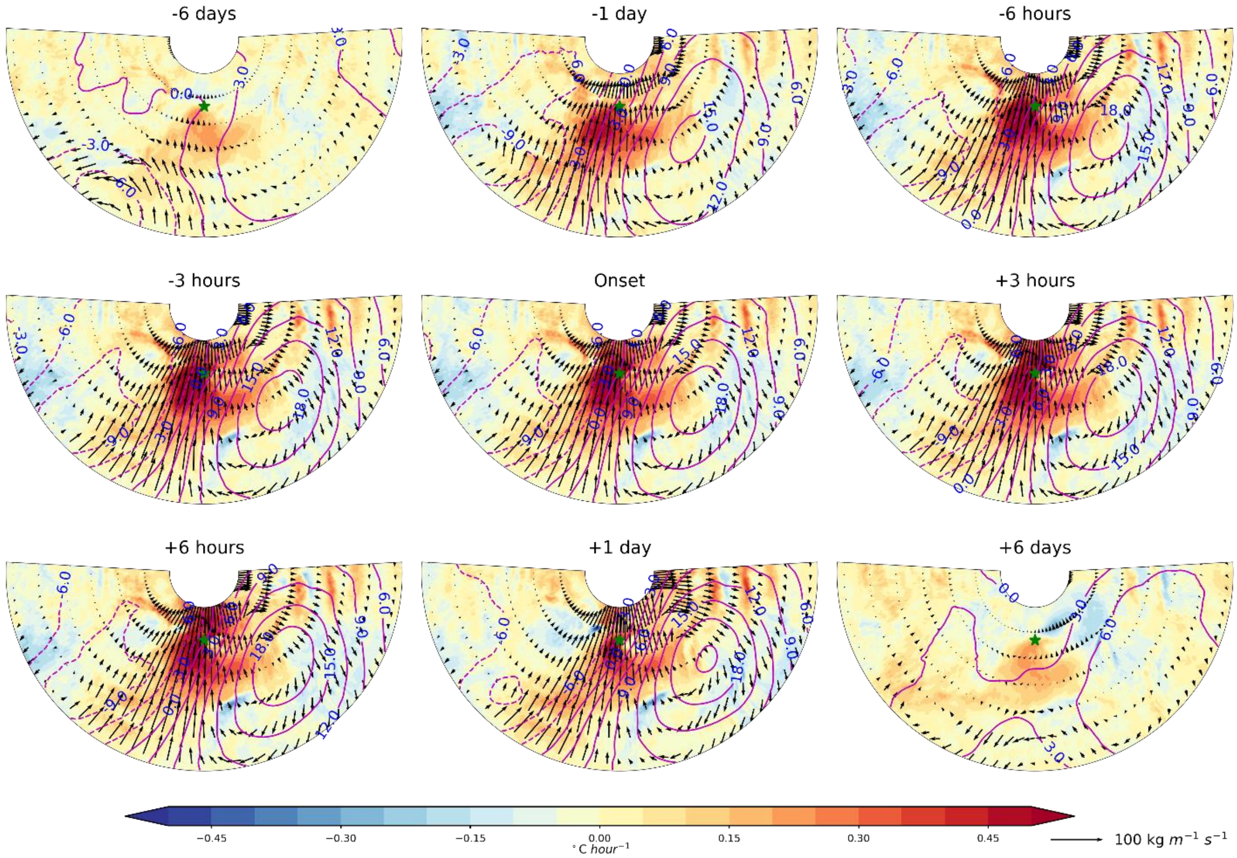

Figure R3. The same as Fig. 8 in the original manuscript (Fig. 9 in the revised manuscript), but based on the event sample obtained by randomly picking one event for each of those hours when at least one event is present. See the response above for a more detailed description of the composite approach.

For the "concurrent warming events", we consider all grid points that experience warming events simultaneously as part of a single event. Since the region where T2m can exceed 0°C is usually small (see Fig. 1b), when many grid points over a region with small spatial extent experience T2m above 0°C at the same time, it is very likely that they are driven by the same large-scale circulation pattern. Visual examination of these concurrent warming events does confirm that they are spatially coherent. We thus did not track the events, nor did we impose the constraint that grid points with T2m above 0°C at the same time have to be all connected to each other. However, we do impose that the peak area with T2m >= 0°C for a single concurrent warming event must be greater than 5×10^9 m^2. This is to ensure that the identified concurrent warming events are driven by large-scale circulation instead of being caused by small-scale local fluctuations of T2m. Although the focus of our study is on the statistics obtained based on events defined at the grid-point scale, we agree with the reviewer that it would also be interesting to characterize the 96 concurrent warming events identified in Section 3.3 of our study and examine their trends in frequency, duration and spatial extent. We have updated Fig. 14 in the original manuscript (Fig. 15 in the revised manuscript) to include trends in the frequency, spatial extent and duration of the concurrent warming events identified in our study. As shown in Figs. R4c and d, the frequency, spatial extent, and the duration of the concurrent warming events all exhibit significant upward trends in the past four decades. The following discussion has been added to Section 3.5 in the revised manuscript:

"*Consistent with these increasing trends in the characteristics of the extreme warming events defined at the grid-point scale, the frequency, spatial extent, and duration of the concurrent warming events defined in Section 3.3 also exhibit significant positive trends in the past four decades (Figs. 15c, d).*"

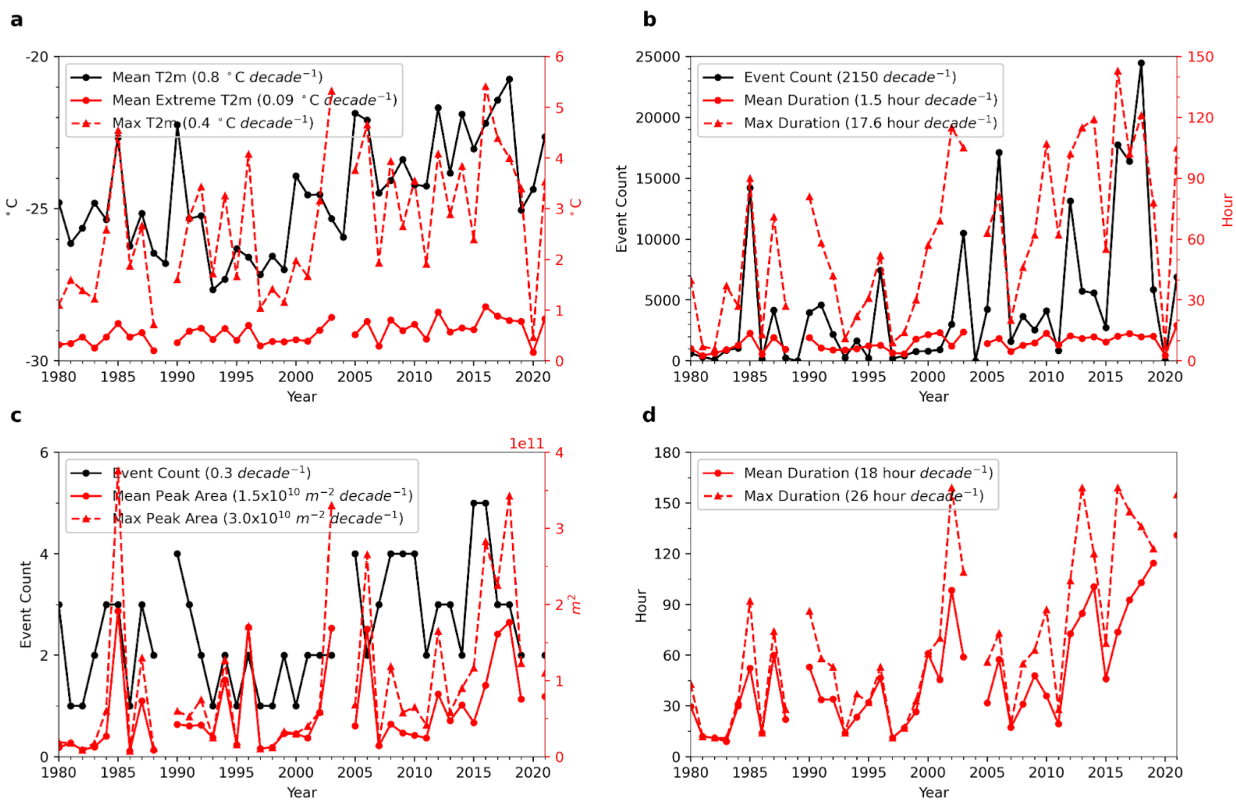

Figure R4. Trends in (a) the area-weighted spatial mean T2m over the entire high Arctic (black solid line with circles), mean T2m only for grid points above 0℃ (red solid line with circles) and the seasonal maximum hourly T2m (red dashed line with triangles) over the high Arctic. (b) is the same as (a), but for the trends in event count (black solid line with circles), mean event duration (red solid line with circles) and seasonal maximum event duration (red dashed line with triangles). (c) and (d) show trends in the characteristics of the 96 concurrent warming events identified in Section 3.3. Trends in (c) the event count (black solid line with circles), mean peak area (solid red line with circles) and seasonal maximum peak area (red dashed line with triangles) of the concurrent warming events. (d) shows the mean duration (red solid line with circles) and seasonal maximum duration (red dashed line with triangles) of the concurrent warming events. For those seasons with only one concurrent warming event, the mean peak area would be the same as the maximum peak area in (c) and the mean duration would be the same as the maximum duration in (d). All trends are significant at the 0.05 level based on the Student's t-test. (Same as Fig. 15 in the revised manuscript).

Reference:

Pfahl, S., O'Gorman, P. & Fischer, E. Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Clim Change* 7, 423–427 (2017). https://doi.org/10.1038/nclimate3287

2) Abstract and section 4: Please specify that you define an "Arctic warming event" as a grid point with T2m > 0°C.

We have specified that the Arctic warming events are defined as a grid point with T2m >= 0 ℃.

3) Lines 15-16: "… with a seasonal occurrence frequency of less than one over most of the regions." Could you be more specific about what you mean with "less than one"? Instead of a decimal number per season, which might be a bit difficult to grasp, it would be more informative if you could write the absolute number of events with T2m > 0°C in the considered time period. As you define the events per grid point, you could provide a mean number over all grid points (or two separate numbers for more southern and more northern latitudes).

Since the extreme warming events are defined at grid-point scale, we simply count the total number of events that happened at each grid point during the 42 winters (1980-2021), and then divide this total count by 42. When the mean seasonal occurrence frequency over a grid point is "less than one", this implies that none is detected during some of the 42 winters at this grid point. If we average the occurrence frequency over all grid points where T2m ever reached or exceeded 0℃ poleward 80˚N, we get a value of 0.45. This also suggests that the mean seasonal occurrence frequency is less than one. According to the spatial distribution of occurrence (Fig. S1a in the original manuscript), it is reasonable to say that "they occur rarely, with a seasonal occurrence frequency less than one over most of the regions". To improve the clarity of this sentence, we have made the following revision to the sentence in line 15-16 of the original manuscript:

"*They occur rarely, with a total absence during some winters over most of the region.*"

In addition, we have made a new figure (Fig. R5) that shows the spatial distribution of the total occurrence frequency of the extreme warming events over the entire study period and included it as Fig. S1 in the revised supplementary document. Accordingly, the following discussion has been added to the Section 3.2 of the revised manuscript:

"*The total number of hours with T2m >= 0℃ over the study period reaches its maximum (more than 1000 hours) over the region near 80°N and between 0°-30°E (Fig. S1). Moving away from this region, the number drops rapidly towards the boundary with regions that have never experienced T2m >= 0℃ during winters of the past four decades.*"

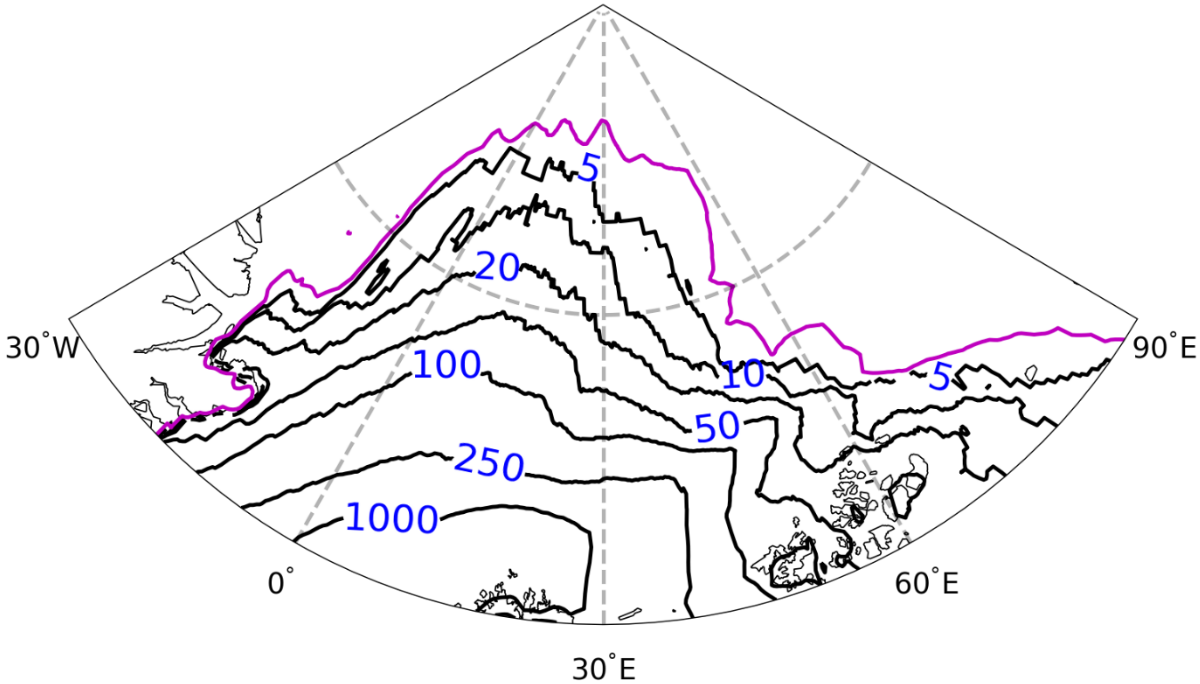

Figure R5. Spatial distribution of the total number of hours with T2m >= 0°C for all winters during 1979-2021. The magenta contour outlines the regions that have ever experienced T2m >= 0°C. (Same as Fig. S1 in the revised supplementary).

4) Lines 69-70: "Subsequent examination reveals … with the duration of staying above 0°C for less than an hour." Which study are you referring to? According to Fig. 1 in Binder et al. 2017 (Geophys. Res. Lett.), maximum temperatures reached values above 0°C during three episodes that each lasted about 1 day, i.e., much longer than 1 hour.

Fig. 1 in Binder et al. (2017) shows the temporal evolution of the domain maximum T2m. The domain in their study is defined as the region poleward of 82°N and between 120°W and 120°E. Therefore, it is reasonable that the warming event in Binder et al. (2017) is more persistent. However, the studies we are referring to are Graham et al. (2017) and Moore (2016), as cited in the sentence before Lines 69-70 of the original manuscript. Fig. 1 in Graham et al. (2017) and Fig. 2 in Moore (2016) show the temporal evolution of surface air temperature observed on meteorological buoys at different locations (grid points) near the pole. Both figures show the short-lived nature of these warming events at the grid-point scale. To clarify, we have added "*locally (Fig. 1 in Graham et al. 2017 and Fig. 2 in Moore, 2016)*" after the sentence in lines 69-70.

5) "This event is driven by an AR-like moisture plume carried into the high Arctic by a cyclone." Please indicate which study you are referring to in this sentence.

We are referring to Fig. 4 in Moore (2016). This reference has been added in the revised manuscript.

6) Please also cite the paper by Messori et al. 2018, J. Climate (doi: 10.1175/JCLI-D-17-0386.1), which also investigates drivers of wintertime Arctic warm events.

Thank you for mentioning this very relevant paper. We have now cited this paper properly in the revised manuscript.

7) Lines 90-92: From the sentence it is not clear based on which dataset you define the extreme warming events. Is it based on buoy observations, as suggested by the title of the subsection and the first sentence, or based on ERA5, which you mention later in the same subsection? If – as I assume – you use ERA5 data to define the events, then I find the title and the first sentence of the subsection rather confusing. Also, in that case I would first describe the ERA5 data in a paragraph and mention the temporal and spatial resolution, the season, the time period you investigate, etc., and only then describe how you identify the extreme warming events. On the other hand, if you use buoy observations, please describe this dataset in more detail. How do you obtain gridded data from buoy observations (Fig. 2)? Furthermore, in that case I would make a separate subsection for the description of the ERA5 data.

Sorry for the confusion. Our study is based solely on the ERA5 data. The buoy observations mentioned in the first sentence were used in Moore (2016) and Graham et al. (2017) that are also cited in the first sentence. We have added "by previous studies" in the first sentence to avoid confusion. The sentence is now revised to "*Case studies based on in-situ buoy observations have been conducted by previous studies to examine the characteristics and drivers of winter extreme warming events over the high Arctic (Moore, 2016; Graham et al., 2017)*".
Furthermore, to improve the flow of Section 2.1, we have now switched the order of the first and second paragraphs of the original manuscript. Section 2.1 now starts with describing the ERA5 dataset and then introduces the definition of the extreme warming events.

8) Line 101: "Results based on previous studies …" Please add references. And maybe this sentence fits better in the introduction than the method section.

Moore (2016) and Graham et al. (2017) have been added as references. As we explained above, this sentence/paragraph has been moved up for a better reasoning of and transition to the methodology of our study.

9) Lines 113-115: How do the trends in DLR, IVT, LHF, SHF and IWV look like, are they all positive? How does the detrending work?

As shown in Fig. R6 below, the trends in DLW (or DLR), IVT and IWV are all positive over the entire high Arctic, especially over the Atlantic sector. For LHF and SHF, they show positive trends over the sea ice covered region of the Atlantic sector, and negative trends over the lower latitude region of the Atlantic sector due to sea ice retreat.
For the detrending, we follow the method used in Wang et al. (2020). For each grid point, we need to remove the seasonal cycle from the time series of hourly data. To obtain the seasonal cycle in the first place, we average the hourly time series across the years from 1979 to 2021 to obtain the raw seasonal cycle first, and then apply a 31-day running mean to the raw seasonal

cycle to obtain the smoothed seasonal cycle used for deseasonalizing the data. After removing the seasonal cycle, we calculate the linear trend based on the deseasonalized data. For each given hour of the winter season, we first calculate the 31-day running mean centered at the hour. The smoothed data is then used to derive the linear trend used for detrending for the hour.
We have updated the paragraph in lines 111-116 of the original manuscript to better explain how the detrending works:

"*Following Wang et al. (2020), all anomalies presented in this study are obtained by first removing the seasonal cycle. To obtain the seasonal cycle in the first place, the hourly time series is averaged across the years from 1979 to 2021 to get a raw seasonal cycle, and then a 31-day running mean is subsequently applied to obtain a smoothed seasonal cycle for de-seasonalizing. The Arctic has experienced amplified warming in the past four decades. This amplified warming results in significant positive trends in the downward longwave radiation (DLW), integrated water vapor transport (IVT) and integrated water vapor (IWV) over nearly the entire high Arctic and significant positive (or negative) trends in the latent heat flux (LHF) and sensible heat flux (SHF) over the sea ice covered (or partially sea ice covered) region of the high Arctic Atlantic sector (not shown). To exclude the effects of these decadal trends, the anomalies of T2m, DLW, IVT, LHF, SHF, and IWV are further detrended after removing the seasonal cycle. Similarly, for any given hour, to obtain the linear trend, a 31-day running mean centered at the hour is first applied to the de-seasonalized data. The smoothed data is then used to derive the linear trend used for the detrending.*"

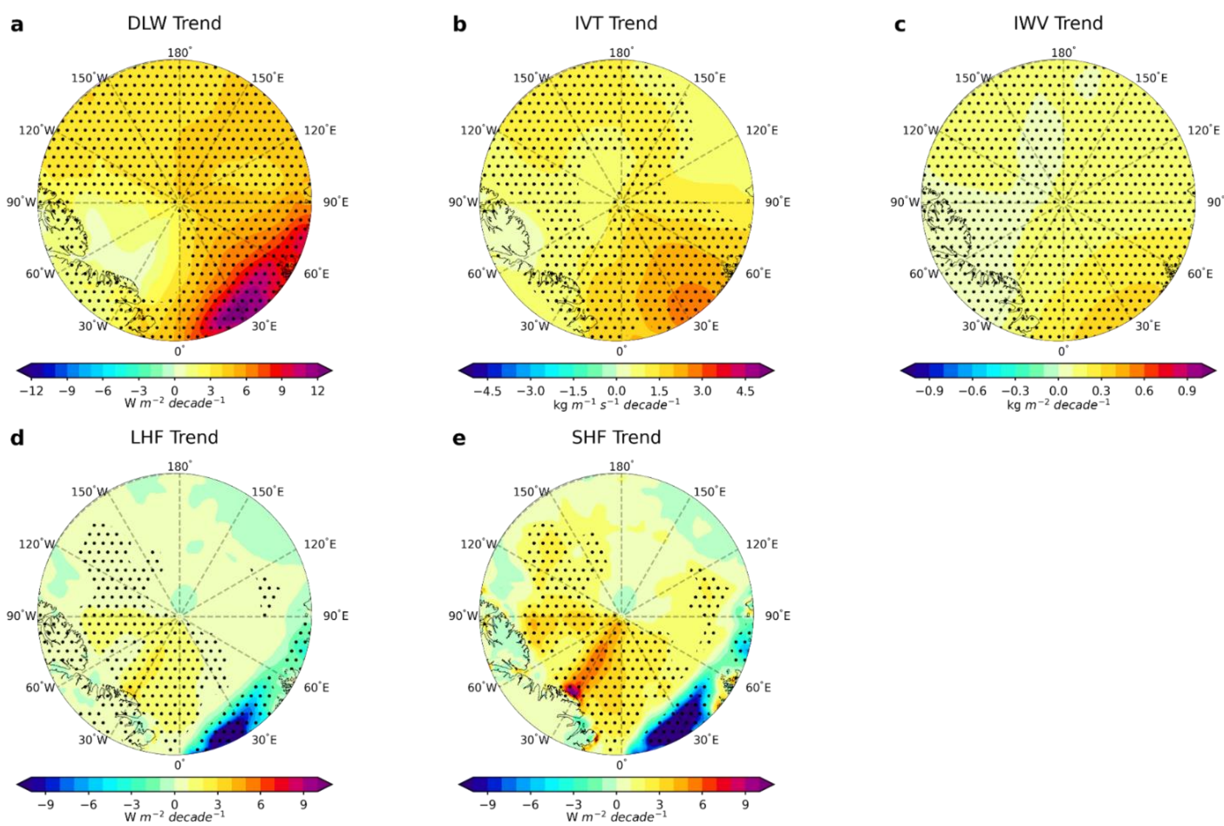

Figure R6. Winter trends in (a) Downward longwave radiation (DLW), (b) integrated water vapor transport (IVT), (c) integrated water vapor (IWV), (d) latent heat flux (LHF) and (e) sensible heat flux

(SHF) from 1980 to 2021. Stippled areas indicate anomalies are significant at the 0.05 level based on the Student's t-test.

Reference:

Wang, Z., Walsh, J., Szymborski, S., and Peng, M.: Rapid Arctic sea ice loss on the synoptic time scale and related atmospheric circulation anomalies, J. Clim., 33, 1597–1617, 2020.

10) Line 158: "Over regions eastward of about 60°N and poleward of about 85°N, the mean duration is shorter than 5 hours." How do you arrive at this statement? There is no data in this region in Figs. 2a,b, right?

Sorry for the confusion. There is no data over regions eastward of about 60°E and poleward of about 85°N. Instead of "poleward of about 85°N", it should be poleward of about 80°N. We have corrected the typo.

11) Lines 165-171: Maybe you can add that it is very likely that two warming events that occur right after each other are driven by the same weather system (as you already pointed out in section 2.1).

Thank you for the suggestion. The following sentence has been added to the paragraph to point out the possible cause of the event clustering:

"*As being shown in Section 3.3, the clustering of these warming events may be driven by the same persistent large-scale circulation that steers successive weather systems into the affected region.*"

12) Fig. 4: What do the fields show exactly? Is it the anomaly of the mean value of IWV, DLR, etc., averaged over all warm events at a specific grid point? And maybe you can add in the caption that positive values in d) and e) indicate fluxes directed from the atmosphere toward the surface.

Yes, they are the mean anomaly values of IWV, DLW, etc., averaged over all extreme warming events at a specific grid point. We have now updated the caption of Fig. 4 to better explain what those fields are and also to point out that positive values in d) and e) indicate fluxes directed from the atmosphere toward the surface.

"*Spatial distribution of the mean anomalies of (a) T2m, (b) column-integrated water vapor (IWV), (c) downward longwave radiation (DLW), (d) sensible heat flux (SHF), (e) latent heat flux (LHF) and (f) horizontal temperature advection averaged over all hours with T2m >= 0 °C over a grid point. Positive values in (d) and (e) indicate fluxes directed from the atmosphere toward the surface. Stippled areas indicate that anomalies are significant at the 0.05 level based on the Student's t-test.*"

13) Line 185: "due likely to the partially open ocean" Would it be possible to overlay a contour of the mean position of the sea ice edge during warm events and in the climatology?

Thank you for the suggestion. We have overlaid the climatological 50% sea ice concentration contour (black contour) and the 50% sea ice concentration contour during warming events (red contour) in Fig. S2 (shown below as Fig. R7).

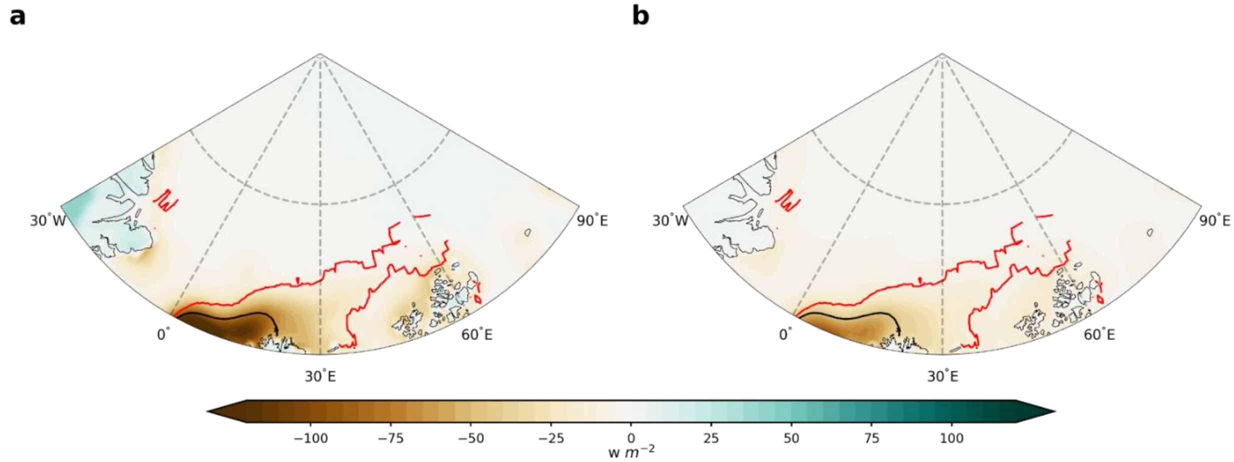

Figure R7. The climatology of (a) sensible heat flux and (b) latent heat flux during winter of 1979-2021. Overlaid are the climatological 50% sea ice concentration contour (in black) and the 50% sea ice concentration contour averaged over all warming events (in red). Positive values indicate the flux is directed downward toward the surface.

14) Line 190-191: "likely caused by the rapid cold and dry advection shortly after the onset of warming events" Do you know why there is cold and dry advection in this region after the onset of the warming events?

Based on Fig. 7 in the original manuscript, this could be caused by the passage of the cold front. The following sentence has been added to provide a possible explanation:

"*As being shown later, such rapid transition to cold and dry advection could be caused by the passage of a cold front.*"

15) Fig. 5: Which one is the curve for T2m, is it the black line labelled "TS" in the legend? If so, please adapt it in the legend. And how are the curves constructed? Do you show the anomaly of the mean T2m, DLW, etc. over all grid points with T2m > 0°C? If so, please be more specific in the figure caption. Also, as mentioned in the first comment, I find it a bit confusing that you write in the caption "for all the warming events", I would rather write something like, "at grid points where T2m > 0°C", because most likely neighbouring grid points with T2m > 0°C at the same time are not separate warming events.

Yes, the black line labeled "TS" is the curve for T2m. For consistency, we have changed "TS" to "T2m" in the legend. These curves are constructed by taking an average of the temporal evolution of various anomaly terms across all warming events. Day 0 corresponds to the onset of the warming events defined at the grid-point scale. To be more specific, we have now updated the caption and explicitly defined extreme warming event in the caption:

"*Temporal evolution of the anomalies of T2m, DLW, SHF, LHF, IWV and temperature advection for all the extreme warming events defined as any grid points with T2m >= 0 °C (a, b), short duration events equatorward of 83°N (c, d), short duration events poleward of 85°N (e, f), and long duration events (g, h). Note that long duration events occur only over regions equatorward of 83°N. These curves are constructed by averaging the temporal evolution of various anomaly terms across all extreme warming events within the different defined groups. There are 191555, 18586, 1642, and 10097 events included in the groups of all events, short duration events equatorward of 83°N, short duration events poleward of 85°N and long duration events, respectively. Day 0 corresponds to the start of the extreme warming event. The shading indicates that the anomalies are significant at the 0.05 level based on the Student's t-test.*"

16) Line 202-203: "These results suggest that a warm and moist winter favours the occurrence of warming events." It could also be the other way around: the warm events contribute to making the winter anomalously warm and moist. Maybe the anomalously high temperatures nine days before the onset of the extreme warming event are related to a previous warm event in some region of the Arctic. For this, a timeline of the number of warm events per season could be interesting.

We totally agree with the reviewer that while a warm and moist winter favors the occurrence of warming events, the occurrence of extreme warming events also contributes to making the winter anomalously warm and moist, and thus precondition the environment that favors the occurrence of the next event. We have now updated the paragraph and included this alternative perspective in the revised manuscript.

"*Even nine days before the start of the extreme warming events, T2m is already 3-4 ℃ higher than normal (Fig. 6a). This is likely because these extreme warming events occur more often during warm winters, but it is also possible that this warm anomaly is preconditioned by a previous warm event. The background temperature over the Atlantic sector, under which these events occur, is thus anomalously warm. Indeed, the occurrence frequency of the events correlates significantly with the winter mean T2m over the Atlantic sector of the Arctic (or the entire Arctic), with a correlation coefficient of about 0.64 (0.61). Consistent with the warm anomalies, both IWV and DLW show positive anomalies. These results suggest that while the occurrence of these extreme warming events contributes to making the background state anomalously warm and moist, a warm and moist winter in turn favours the occurrence of extreme warming events.*"

As for a timeline of the number of warm events per season, if we understand correctly, such a figure has been provided later in the original manuscript in Fig. 14b (Fig. 15b in the revised manuscript), which shows the event count of each winter (black line).

17) Line 204-205: "Both the SHF and DLW play comparable roles in driving these events, …" I find it confusing that you write that SHF and DLW "drive" the Arctic warm events. I assume that it is mainly the large-scale flow configuration that drives these events, i.e., the dipole in the SLP anomalies that you see in your composites (Fig. 6 and 9) and the upper-level flow structure (as

has also been described in previous studies, e.g., Binder et al. 2017, Messori et al. 2018). Also, in the conclusion (line 369), you write that long-duration events are mainly driven by persistent downward SHF anomalies. Maybe you can just write "associated with" instead of "driven by".

We agree with the reviewer that the large-scale circulation pattern associated with the SLP dipole is what fundamentally drives the heat and moisture changes, including the anomalies in SHF, DLW and T2m. However, in order to trigger the extreme warming events, the SLP dipole must first drive the anomalous downward SHF and DLW. In this regard, it is fair to say that both the SHF and DLW are the **direct** drivers of the warming events. We also agree with the reviewer that "associated with" is an alternative terminology to describe the relationship between the surface energy budget terms and the warming events. Accordingly, we have updated the sentence "*Both the SHF and DLW play comparable roles in driving the events…*" in line 205 of the original manuscript to "*Both the SHF and DLW play comparable roles in **directly** driving the events…*" in the revised manuscript. We also changed line 369 in the original manuscript to "*Notably, long-duration events, which occur over regions near 80°N, are mainly **associated with** persistent downward SHF anomalies*".

18) Figs. 6-8, picking up on the first comment: Since neighbouring grid points with T2m > 0°C at the same time are considered as separate events, is it right that they are included several times in your composites? Could it then just be that your "short-duration events" are the grid points located closest to the cold front of the cyclone and the "long-duration events" are grid points located further to the east in the cyclone's warm sector, but they actually occur at the same time and belong to the same warm episode? This indicates that your definition of "warm events" might be problematic.

As we have explained in our response to the first major comment, extreme warming events are often defined in two different ways. One is to define them locally at the grid-point scale, which is adopted in our study. The other is to define them as a contiguous region with spatially peak T2m exceeding a predefined threshold. This second definition is very similar to the "concurrent warming events" defined in our study. These two definitions provide complementary perspectives on studying the warming events.

Based on Figs. 6 and 8 in the original manuscript, which show the composites of the short duration and long duration events equatorward of 83°N, respectively, it is possible that the short duration events more likely occur at the grid points located closer to the cold front while the long duration events more likely occur at the grid points located further to the northeast, in the warm sector of cyclones. This relationship between the relative position of the large-scale circulation and the duration of the warming events can only be revealed when warming events are defined at the grid-point scale. When warming events are defined using the second method described above, all the grid points within a contiguous region with T2m greater than 0 °C are treated as one coherent event, the spatial heterogeneity of the event duration cannot be characterized and would thus have to be neglected.

19) Line 228: "a high anomaly to their southeast and a low anomaly to their west." I guess you mean anomalies in SLP, please write this explicitly. And I would write positive/negative (rather than high/low) SLP anomalies (also in the rest of the manuscript).

Thank you for the suggestion. We have changed the high/low anomaly to positive/negative SLP anomaly throughout the manuscript.

20) Fig. 7: It is difficult to distinguish the IVT anomaly vectors and the SLP anomaly contours. Maybe you can change the colour of either of them? And it appears that there should be more SLP anomaly contours above +21 hPa, but the plotting stops at this threshold, which looks a bit strange.

Thank you for the suggestion. We have updated this figure along with Figs. 6 and 8 of the original manuscript.

21) Line 240-242: "… the high anomaly southeast of the event regions already starts to develop for the long duration events (Fig 8)." Please specify which time step you are referring to.

We have specified that we are referring to the time step six days before the onset of the extreme warming events.

22) Line 317-318: "… for a large fraction of the regions where warming events can occur, ARs are the only weather system capable of triggering the occurrence of the warming events." Fig. 12a simply tells you that warm events typically co-occur with ARs, but I don't agree with your statement that they are the only weather systems that can trigger warm events. In contrast, in most cases it is probably the interplay between various weather systems that is important for triggering the event (like, for instance, the surface cyclones to the west and the anticyclones to the east, which channel the poleward heat and moisture transport, as well as geopotential height anomalies at upper levels, etc.). The AR can only reach the Arctic because of this interplay between various weather systems.

We agree with the reviewer that the interaction between Arctic cyclones to the west and the anticyclones to the east is what causes the formation of Arctic ARs and ultimately drives the occurrence of the warming events. However, when these warming events occur, they are directly under the influence of ARs. To account for the subtlety, we have rewritten the sentence as follows:

"*The results here thus suggest that, for a large fraction of the regions where extreme warming events can occur, the presence of ARs and their impact on and interaction with the local environment (Papritz et al., 2023) likely exert a strong control on the occurrence of these events.*"

23) Fig. 13c is not mentioned in the text.

Lines 333-334 in the original manuscript refer to the results shown in Fig. 13c of the original manuscript. We have now made this sentence explicitly referring to Fig. 13c (Fig. 14c in the revised manuscript).

"*During deep intrusion days, the daily IVT averaged over regions poleward of 85°N and between 15°W-60°E increases substantially from the climatological daily mean of ~25 to ~78 kg m^{-1} s^{-1} (Fig. 14c).*"

24) Fig. 14: Is mean T2m averaged over the entire Arctic poleward of 80°N or only the Atlantic sector that you consider in the rest of your study?

It is averaged over the entire Arctic poleward of 80°N. We have now pointed this out explicitly in the caption.

25) Line 342-343 and Fig. 14b: "The event occurrence frequency has been increasing at a rate of 2150 events per season per decade." Here it would again be helpful if you could specify that you mean the number of grid points with T2M > 0°C. This number of course strongly depends on the grid spacing. I would find it more meaningful if you showed a timeline of the number of days per season (or the number of hours) where the temperature exceeded 0°C in some region of the domain, or a timeline of the number of your so-called "concurrent warming events".

Thank you for the suggestion. We have now explicitly pointed out that this increasing trend is for the events defined at the grid-point scale.

"*The event occurrence frequency has been increasing at a rate of 2150 events per season per decade for the extreme warming events defined at the grid-point scale (Fig. 15b).*"

It is true that the exact number for the trend in the occurrence frequency depends on the grid spacing. However, the exact number for the trend is not very important, what matters more is the significant positive trend, as it informs us that the total area experienced extreme warming events has been increasing.
As suggested by the reviewer, we also plotted the time series of the number of days per season (Fig. R8a) and number of hours per season (Fig. R8b) with at least one warming event (defined at the grid-point scale) occurring poleward of 80°N. Both trends are significantly positive at the 0.05 level. Results based on Fig. R8 have now been included in Section 3.5 of the revised manuscript and Fig. R8 has been included as Fig. S4 in the supplementary.

"*Consistent with the increasing trend in the occurrence frequency, both the number of days and the number of hours with at least one warming event found over the high Arctic exhibit significant upward trends with magnitude of 6.8 days per season per decade and 114 hours per season per decade (Fig. S4).*"

The time series of the number of "concurrent warming events" per season is shown in Fig. R4c and also included as Fig. 15c in the revised manuscript.

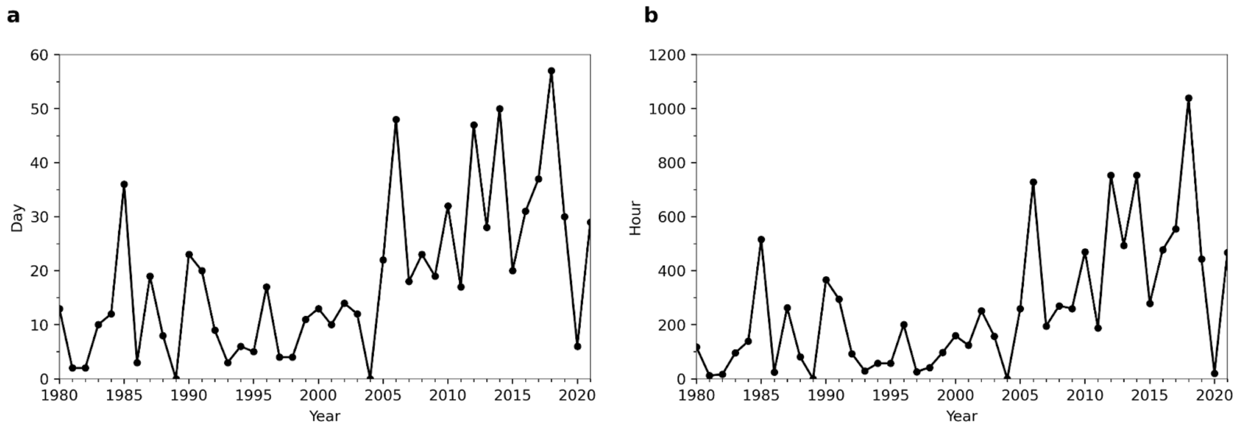

Figure R8. Time series of (a) the number of days per season and (b) the number of hours per season with at least one warming event defined at the grid point level occurring poleward of 80°N.

Technical corrections:

26) Line 14: "over the high Arctic (poleward of 80°N) occurred during 1980-2021" Typo: "that occurred"

Corrected.

27) Line 16: "regions" – maybe better: "region"

Corrected.

28) Lines 41-44: "ranging from … and heatwaves" should be "ranging from … to heatwaves"

Corrected.

29) Line 59: "phenomenon" should be "phenomena"

Corrected.

30) Line 68: "an episode of extreme warming event" should either be rephrased to "an episode of extreme warming" or "an extreme warming event"

We have changed it to "an episode of extreme warming".

31) Fig. 3: "The red vertical line in (c) …" You probably mean (a). And I think you can remove the "6.32" in the top left corner of Fig. 3a (or move it to the right to the position of the red line).

Yes, it should be "The red vertical line in (a)..." We have now removed the number at the top of the Fig. 3a (Fig. 4a in the revised manuscript).

32) Throughout the manuscript: I would place the references in chronological order.

The references are now in chronological order throughout the manuscript.

33) Line 301: "likely plays roles" – maybe better: "likely plays an important role"

We have made the suggested change.

34) Line 339 and caption Fig. 14: "for those above 0°C" should be "for grid points above 0°C"

Corrected.

35) Line 370: "experiencing warming event" should be "experiencing a warming event"

Corrected.

36) Line 371: "to its west" should be "to their west"

Corrected.

37) Line 373: "located at southwest of the grid point with warming event" should be "located southwest of the grid point of the warming event"

Corrected.

38) Line 379: I would write "anticyclone dominance type" and "cyclone dominance type" instead of "high/low dominance type"

We have made the suggested change.

39) Line 398: "are thus can be expected": delete either "are thus" or "can be"

We have deleted "can be".

40) Line 403: "AR detection algorithm" should be "the AR detection algorithm"

Corrected.

Reviewer #2

General comments

This paper presents characteristics of extreme wintertime Arctic extreme events for 1979 – 2021 utilizing hourly ERA5 data. Extreme warm events are defined per grid-point when the hourly near-surface temperature (T2m) reaches or exceeds a threshold of 0 °C in the high Arctic (north of 80°N). The strict spatial and threshold criteria restrict the events only to be found in the Atlantic sector. The authors find that these events are rare and short-lived, usually lasting less than one day. The highest frequency and longest duration of these events are found to be confined to a region close to 80°N and within 0-30°E. These events are further associated with positive anomalies in sensible heat fluxes (largest contribution closest to the lower latitude boundary) and positive anomalies in both IWV and DLW, with largest contributions especially further towards the Arctic interior. Large-scale circulation anomalies with a well-known dipole pattern in the SLP anomalies are found to be favourable for warm and moist air advection into the affected grid-points. A 100% match is found between warming events at northerly latitudes and the co-occurrence of atmospheric rivers (ARs). The grid-point wise defined warming events are then elaborated to regions of several grid-points with temperatures at or above 0 °C, i.e., "concurrent warming events", a method taking into account the spatial extent of such events. Three different large-scale circulation patterns are found to be associated with these regionally defined warming events: a strong dipole in SLP, a blocking-like surface anticyclone or a strong negative SLP anomaly over Greenland. The authors finalize the paper by a trend analysis of grid-point wise defined warming events, where a positive trend in both duration, magnitude and frequency of the events are found. This paper has well-done figures and gives a nice overview of extreme warming events (per grid-point) in the high Arctic, and discusses their drivers with respect to the changes in e.g., SEB anomalies and their relation to large-scale circulation and AR frequency. Most of the results presented here agree and follow results from previous studies. I still have a few concerns regarding the event definition and interpretation of the results presented here. Thus, I suggest minor revision before any possible acceptation of the paper. See comments below for clarifications.

We thank the reviewer for carefully reviewing our manuscript and providing the encouraging, positive comments. The constructive and detailed comments have greatly improved the quality and clarity of this manuscript. Our responses to the specific comments are shown below, with their original comments in blue.

Specific comments

- The authors aim to make a climatological record of warm extreme events and associate these to large-scale circulation patterns and ARs. But this is something that has already been done by previous studies, however, with different dataset (ERA-Interim) and event definitions. For example, Graham et al. (2017) (https://doi.org/10.1002/2017GL073395), a study that is also cited in this paper, do not only use in-situ observations, but also look at the historical record winter warming events in the Arctic using different temperature thresholds. They also find a positive trend in duration and occurrence of warming events. Also, your Fig. 1b is similar to their Fig. 2a, showing maximum 2m temperatures, however they use 6-hourly ERA-Interim data compared to yours hourly ERA5 data. Another study that is completely left out of this paper is Messori et al. (2018) (https://doi.org/10.1175/JCLI-D-17-0386.1), where the drivers behind warm extreme events in the high Arctic are also examined. Please refer to these two studies in your paper for a comparison to similar studies. What is novel in your study compared to theirs? What is the reason for an event definition with a fixed threshold in your study?

Our study is inspired by Moore (2016) and Graham et al. (2017), both of which used buoy observations at different locations (grid points) to examine the evolution of the late December 2015 warming event with near surface temperature (T2m) above 0℃ over the high Arctic. Therefore, as noted in our manuscript (line 90 in the original manuscript), defining the warming event at a grid point with T2m >= ℃ can facilitate a more direct comparison with the two studies mentioned above.
Based on Fig. 2 in Moore (2016) and Fig. 1 in Graham et al. (2017), the duration for the T2m of the warming event staying at or above 0℃ is very short and less than a few hours. Based on their two figures, a dataset with high temporal resolution is needed to better characterize these events. Indeed, as shown in our study (line 153 in the original manuscript and Fig. 2), about 70% of these extreme warming events with T2m >= 0℃ at a grid point lasted less than 12 hours. A dataset with 6-hourly resolution, which was used in both Graham et al. (2017) and Messori et al. (2018), is thus inadequate to characterize these events. Furthermore, defining extreme warming event at the grid-point scale can also provide new insight into processes that determine the duration of the events. For example, we show that the relative position of the sea level pressure (SLP) dipole is important in determining the event duration. Long duration events are driven by anomalous downward sensible heat flux while enhanced downward longwave radiation seems to play a more important role for short duration events. In comparison, factors determining the event duration are not explored in both Graham et al. (2017) and Messori et al. (2018), possibly due partly to the dataset with coarser temporal resolution (6 hourly) used in their studies. In addition, these new insights cannot be obtained if extreme warming events are identified by spatially averaging the T2m over a certain region and then defining those events with the highest spatial average T2m, which is adopted in Messori et al. (2018). We do agree with the reviewer that the findings in Messori et al. (2018) are consistent with and very relevant to our study. Messori et al. (2018) is now properly cited in the revised manuscript.

- Warming event definition:
    - I also find it a bit concerning, as raised by the first reviewer regarding the event definition, that warming events, as the authors name these extremes, are defined based on a fixed temperature threshold (2-m temperature >= 0℃) and for each grid-point separately. What if grid-points close to each other actually belong to the same event that is affected by the same synoptic weather system? Grid-point defined warming events, using a Eulerian approach, don't say that much about the real nature of the synoptic weather event, as this event, let's call it an AR guided by the large-scale circulation, will move and affect grid-points further away in the direction of the AR, leaving the previously affected grid-point to cool. As the authors point out, there can be temperature

fluctuations in hourly data (so that the temperature shortly drops below 0℃), but still be part of the same synoptic event (which has a different impact on the surface temperature depending on the time scale and location). The extent of these intrusions can then also affect adjacent grid-points at the same time step, however, in your study, these two would be counted as two separate events? The authors explain on L98 the method "interval requirement", and state that your results are not affected by the temperature fluctuations. Could you please re-explain how this was done? Could you think of using a longer time span of 4-6 days (representing the synoptic scale) for your requirement? Thus, having less than two days between two warming events (as stated in L168-170) would most likely just be the same event. How about the close-by grids? How often do the authors find that several grid-points experience temperatures above zero degrees at the same time? One way to avoid these issues would be to maybe increase the time from hourly to daily and check for days where the temperature exceeds a threshold in the grid for at least once or up to a certain percentage within the time? The authors could also consider looking at pre-defined regions instead of per grid-point. In Messori et al. (2018), warm extreme events were defined over the polar cap (as in this study) as daily T2m anomalies computed against a transient climatology (long-term trends and seasonality removed) and area-weighted over the study domain. Furthermore, anomalies were smoothed to remove fluctuations and only events at least one week apart were chosen in order to avoid double counting of the same event. Despite this, when considering large-scale drivers, in a study from Murto et al. (2022; also referred to in the current paper), they could associate up to 3 of the warm extreme events from Messori et al. (2018) to one or two consecutive blocking events, suggesting that these warm events were actually one event but affected by a similar large-scale setting. Did the authors of this current paper try to define events using temperature anomalies? The event definition as it is now is for me a bit problematic, and caution must be taken when interpreting the results of your study. Please also point out in the abstract that events are defined per grid point.

We thank the reviewer for raising these concerns which give us the opportunity to clarify. As we have mentioned in the response to the first comment, our study is inspired by previous studies of Moore (2016) and Graham et al. (2017). They use point observations based on meteorological buoys to characterize the late December 2015 high Arctic warming event. This particular warming event garnered a lot of attention because the T2m during the event exceeds 0 ℃ near the north pole. To facilitate a direct comparison between our study and their studies, we thus define the extreme warming event as a grid point with T2m >= ℃ and did not consider defining the events using temperature anomalies. We are particularly interested in those events with T2m >= 0℃.
We agree with the reviewer that when many nearby grid points are experiencing T2m >= 0 ℃ simultaneously, it is likely that they are driven by the same large-scale circulation. It is thus reasonable to treat all of them as one synoptic event. This is exactly the reason why we also define the so-called "concurrent warming events" later in the manuscript. While identifying a warming event as a contiguous region with T2m >= 0 ℃ can help us better understand the real nature of the synoptic weather system, there are questions that can only be answered when such events are defined at the grid-point scale using a Eulerian approach. For example, when a large-scale circulation pattern drives the T2m to exceed 0 ℃ over many nearby grid points at the same time, why is the warming duration

longer at some grid points than the others? This question cannot be answered if all the grid points with T2m >= 0 ℃ are treated as part of one single event. This definition would inevitably ignore the spatial heterogeneity of the event duration within the covered area. However, we can readily answer this kind of question with the Eulerian approach. We believe that defining the events at the grid-point scale and as a contiguous region with T2m exceeding a predefined threshold are two perspectives on studying warming events. Instead of being mutually exclusive, they complement each other. This is very similar to studying extreme precipitation over midlatitudes. Mid-latitude extreme precipitation is often driven by large-scale weather systems, such as atmospheric rivers (ARs). When a small area (or a model grid point) is experiencing extreme precipitation caused by an AR, it is likely that its nearby grid points would also be experiencing extreme precipitation at the same time. Under such a situation, they are driven by the exact same weather system and thus can be treated as part of one single event. However, mid-latitude precipitation extremes are often studied at the grid point level (e.g., Pfahl et al., 2017). Analogously, we believe that it is also a reasonable approach to define warming events at the grid-point scale.

We recognize that when the onset of an event occurs within a few hours of the termination of the previous event over the same grid point, both events are likely associated with the same weather system, such as atmospheric river or cyclone. We thus imposed that if the onset of an event is within 24 hours or 48 hours of the termination of the previous event over the same grid point, the event would have been excluded from any following analyses. We found that our results are not sensitive to whether these constraints are imposed or not. This is because when the gap in between two events is already 1-2 days, it is likely that they are under the influence of different weather systems (e.g., different ARs or cyclones). This happens when an AR family or sequence of cyclones is steered into the Arctic by the atmospheric blocking pattern. Nevertheless, as suggested by the reviewer, we have tested imposing a 5-day time interval requirement. Again, our results are not sensitive to the length of the imposed time interval (Fig. R9).

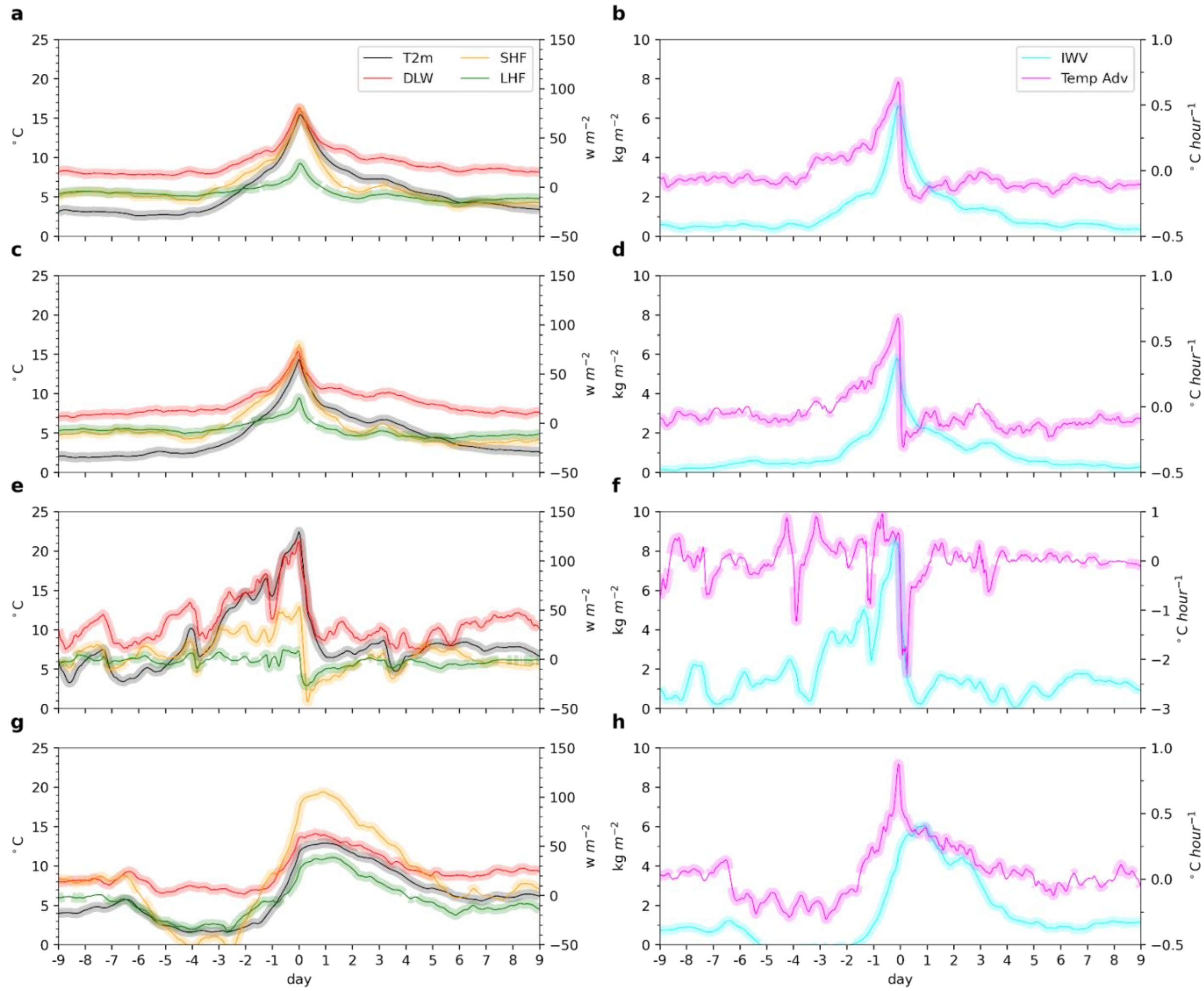

Figure R9. Temporal evolution of the anomalies of T2m, DLW, SHF, LHF, IWV and temperature advection for all the extreme warming events defined as any grid points with T2m >= 0 °C (a, b), short duration events equatorward of 83˚N (c, d), short duration events poleward of 85˚N (e, f), and long duration events (g, h). Note that long duration events occur only over regions equatorward of 83°N. These curves are constructed by averaging the temporal evolution of various anomaly terms across all extreme warming events within the different defined groups. There are 96697, 7771, 1181, and 4835 events included in the groups of all events, short duration events equatorward of 83°N, short duration events poleward of 85°N and long duration events, respectively. Day 0 corresponds to the start of the extreme warming event. The shading indicates that the anomalies are significant at the 0.05 level based on the Student's t-test. (Same as Fig. 6 in the revised manuscript, but with a 5-day interval imposed between successive extreme warming events over the same grid point.)

Reference:

Pfahl, S., O'Gorman, P. & Fischer, E. Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Clim Change* 7, 423–427 (2017). https://doi.org/10.1038/nclimate3287

- Another issue that arises when defining events by a Eulerian perspective is to refer to the "lifecycle" of the event, i.e., with an onset and decay. As written above, ARs tend to move and thereby at a future timestep will affect nearby grid-points. When talking about "onset" and "decay" of an event, it refers to some phenomenon that usually moves and which can be tracked. Thus, the same AR can continue to the next point, but it does not mean that the event has "decayed" when the temperature drops back below zero degrees at another grid-point. I would maybe consider using another word usage here instead of "onset" and "decay" when referring to the warming events at a point. Maybe use "time when a grid-point's T2m exceeds zero degrees"? Close-in-time warming events at one (or nearby) grid-point and the risk of double counting events is then further accumulated in lead/lag composite plots, as in Figs. 6-8. For example, as stated in L230, anomalies 6-days prior to the onset of a warming event could just be a result of a warming event that was present at that lag-time. A timestep at the onset of one event could be same time as the decay of another event. In Fig. 6 it is also clear that the warm air is advected to other regions, which shows that heat is transported further into the Arctic, leading to a temperature drop (and as you name it, decay of the event) at a grid-point when the source of the heat is moved (Woods and Caballero (2016) found, for example, that it takes five days for a moist intrusion to cross the Arctic interior, which is within the timeframe of the event duration here).

  We thank the reviewer for their suggestion on the terminologies used to describe the evolution of the extreme warming events. The term "decay" is not used in our original manuscript. The term "onset" is used to refer to the start of the warming event defined at the grid-point scale. In our revised manuscript, we define the start of the event as "*the event starts when the T2m first reaches or exceeds 0 ℃…*". To avoid any misunderstanding, we have now replaced "onset" with "start" or "the start of the event" in describing the time when a grid point's T2m first reaches or exceeds 0 ℃.

  It is true that double counting occurs for Figs. 6-8 of the original manuscript (Figs. 7-9 in the revised manuscript). The impact of same large-scale circulation pattern can be counted multiple times within one composite or across composites. However, as stated by the reviewer, "a time step at the onset of one event could be the same time step as the decay of another event". When the same large-scale circulation causes the T2m to exceed 0 ℃ over many grid points at the same time, these grid points are at different stages of the event "lifecycle". The position of the large-scale circulation pattern relative to the grid point at which the composite is centered thus differs across these grid points. Although the same large-scale circulation is counted more than one time when constructing the composites shown in Figs. 6-8 of the original manuscript, the relative position of the same large-scale circulation differs depending on the centered grid points and the stage of the event "lifecycle" experienced at these centered grid points. As the purpose of the composites shown in Figs.6-8 of the original manuscript is to demonstrate that the duration of the warming events is determined by the position of the large-scale

circulation pattern relative to the grid points with extreme warm events occurring, the double counting here would have minimal impact on our conclusion.
To further show that the impact of the double counting on our conclusion is indeed minimal, we reproduced Figs. 6, 7, and 8 by randomly picking one grid-point scale event at each of those hours with at least one event and compositing all randomly picked events. More specifically, at each hour, we first identify all the grid points with T2m first exceeding 0°C. The number of the grid points with T2m first exceeding 0°C gives us the number of events at that hour. We then record the duration and position (latitude) of all the identified events of that hour and classify them into different categories (e.g., long duration events, short duration events poleward of 85°N, and short duration events equatorward of 83°N). For the categories with at least one event, we then randomly pick one event from each of those categories. The above steps are repeated for each hour during the study period. Lastly, the randomly picked events of each category are used to construct the composites. This approach can ensure that only one event is selected, even when neighboring grid points are experiencing warming events simultaneously. The same large-scale circulation pattern is thus counted only once. As shown in Figs. R1, R2, and R3, the results based on the composite approach described above closely resemble those presented in Figs. 6, 7, and 8. The only difference is that Figs. R1, R2, and R3 tend to be nosier, especially for the composites of the short duration events poleward of 85°N, owing to the smaller sample size. These results thus further confirm that double counting have minimal impact on our conclusion.
To point out this caveat, the following discussion has been added to the manuscript:

"*As the same large-scale circulation pattern can cause extreme warming events to occur over more than one grid point, it thus can be counted more than once within the same composite or across different composites. However, as the composites are centred at the grid point where the extreme warming event is identified, the position of the same large-scale circulation relative to the grid point would thus differ among the composites centred at different grid points. As we show below, the relative position of the SLP anomalies is what determines the duration of the extreme warming events. The double counting of the same circulation pattern for the composites shown in Figs. 7, 8 and 9 thus has minimal impact on the conclusion.*"

- Spatial restriction: Why did the authors decide to restrict to the polar cap (north of 80N), when events are defined from absolute temperatures? Studies found that warm extremes are mainly located in the Atlantic sector (Graham et al. 2017) and associated with strong moist-air intrusion from the Atlantic that penetrate into the high Arctic (Messori et al. 2018). With a more relaxed temperature threshold, as done in Graham et al. 2017, Pacific warming events can also occur. I would like to see some discussion to why Pacific warming events are not included in this study. For example, sea ice extends further south at the Pacific side and thus airmasses from southerly latitudes have a longer path to cool before reaching into the polar cap compared to Atlantic pathways. A northerly ice edge at the Atlantic side, on the other side, allows the air to collect moisture and heat for a longer time and distance before losing them while traveling northwards. Storm tracks might also be more active over the Atlantic side. In Graham et al. (2017), a southerly latitude band was also chosen for the Pacific side compared to Atlantic to include both sectors with warming sources. Studies also show that ARs from the Pacific side, such as in 2007, can have an important impact on the temperatures in the Arctic. Southerly winds promoted ice-export and the warm and moist air transport over the Beaufort Sea enhanced surface temperatures, and led to anomalous SEB fluxes and the onset of sea ice melt (e.g., Graversen et al. 2011 https://doi.org/10.1007/s00382-010-0809-z and Stroeve et al. 2008 https://doi.org/10.1029/2008EO020001). Please add a bit more discussion around the reason for the chosen study area (distance to sea ice, importance of both transport pathways...) in the introduction and around L147.

We thank the reviewer for their suggestions on the warming events over the Pacific sector of the high Arctic. The Pacific sector is certainly another important pathway for the intrusions of moisture and heat into the high Arctic. As we have pointed out in the response to the first comment, our study is inspired by Moore (2016) and Graham et al. (2017). To facilitate a direct comparison between our study and their studies, we thus restrict our focus only to the high Arctic poleward of 80°N and those events with T2m >= 0°C. More explanations on why we restrict our study to the high Arctic and focus only on those events with T2m >= 0 ℃ over a grid point are provided in Section 2.1 of the revised manuscript. The suggestions of using more relaxed threshold and spatial restriction to enable a robust comparison of warming events between the Pacific and Atlantic sectors would be great for a separate study.

"*Case studies based on in-situ buoy observations have been conducted by previous studies to examine the characteristics and drivers of winter extreme warming events over the high Arctic (Moore, 2016; Graham et al., 2017), which characterized extreme warming events using point observations based on meteorological buoys. Since these extreme warming events are usually driven by large-scale circulation (Woods and Caballero, 2016; Moore, 2016; Kim et al., 2017; Messori et al., 2018), when extreme temperature is detected over a grid point, it is common that such extreme temperature can also be found over its neighbouring grid points. Under such conditions, one approach is to define extreme warming events by using contiguous regions with temperature exceeding a predefined threshold. However, to facilitate a more direct comparison with previous case studies shown in Moore (2016) and Graham et al. (2017), here we choose another approach to define extreme warming events at the grid-point scale. Specifically, in this study, extreme warming events are defined as those events with 2-meter air temperature (T2m) over a grid point reaching or exceeding* 0℃ *over the high Arctic that covers the regions poleward of 80°N.*"

- Concurrent warming events: (Sect. 3.3). For me, this method seems much better, as, to my understanding, these events are defined by finding areas in the Atlantic sector where several grid-points at one timestep satisfy the criterion for warming events. What is the region where these events occur (maybe show on a map figure)? Are these areas coherent, i.e., that the grid points are adjacent to each other? What are the main characteristics for these events (number of points included in one area, duration, trends, seasonal evolution, spatial frequency…)? The lifecycle perspective of these events is again utilized here (onset and decay), which rises similar questions as stated above. How is the decay defined (when the temperature for all or at least one grid point within the area drops below zero)? Again, as stated in L258, close-by areas can also be affected by the same weather event, and here the authors decide to use a 5-day temporal limit, which is good. How is the temporal criterion applied here (on warming events (grid-points) within a region or for separate regions)? The definition of the peak of these events is somewhat unclear: on L263 it is referred to as the hourly time when the area of the grid-points with T2m>=0°C is the largest, but at L281 the authors refer to the peak time of the T2m anomaly when referring to Fig.10. Does the time at maximum area of grids satisfying the criterion always correspond with maximum T2m anomalies? Please clarify. If this is not the case, maybe an intensity measure where both the spatial extent (area) and the average temperature anomaly (magnitude) could be used to define the peak.

As shown in Fig. 1b, only a relatively small region over the Atlantic sector of the high Arctic ever experienced T2m above ℃ (outlined by the magenta contour). Since the concurrent warming events occur when the T2m reaches or exceeds 0 ℃ over many grid points concurrently, this small region defines where these events actually happened.

Since our study region is small, when the T2m reaches or exceeds 0 ℃ simultaneously over many grid points within such a small region, it can be expected that they are driven by the same large-scale circulation and the grid points with T2m >= 0 ℃ are thus adjacent to each other. There are 96 concurrent warming events identified in our study. We manually examined many of the events and confirmed that these events are spatially coherent (not shown).

Time series of the seasonal occurrence frequency, seasonal mean peak area, seasonal maximum peak area, seasonal mean duration and seasonal maximum duration of the 96 concurrent warming events are shown in the updated Fig. 15 in the revised manuscript and shown above as Fig. R4. All these quantities exhibit significant and positive trends in the past four decades.

For these concurrent warming events, their lifecycle (onset, intensification, and decay) reflects the lifecycle of driving large-scale circulation. We believe that it is reasonable to describe the evolution of these events using the lifecycle perspective. For example, the lifecycle perspective has previously been used to characterize the evolution of synoptic sea ice loss events over the Arctic or a predefined subregion within the Arctic (e.g., Wang et al., 2020; Park et al., 2015).

We did not formally define the decay of concurrent warming events in the manuscript, which refers to the stage when the total area with T2m >= 0 ℃ reaches maximum and starts to decrease. The termination of the concurrent warming events is defined as the time when the total area with T2m >= 0 over the high Arctic first drops to zero. The onset of the concurrent warming events refers to the time when the total area with T2m >= 0 ℃ over the high Arctic first rises above zero. If the time interval between the termination of the previous event and the onset of the following event is less than 5 days, we exclude the following event from the analyses. We have updated the manuscript to better explain how this time interval constraint is imposed.

"*We thus impose a constraint that the time interval between the onset of one event and the termination of the subsequent event needs to be longer than five days. Otherwise, the subsequent event is discarded in our analysis of large-scale circulations.*"

The peak of the concurrent warming events is at the time when the total area with T2m >= 0 ℃ reaches maximum. The definition noted in line 263 of the original manuscript is the corrected one. We have changed the line 281 in the original manuscript from "*compared to the peak time of the T2m anomaly composite of all the events*" to "*compared to the T2m anomaly composite at the peak time of all events*" to avoid confusion.

The timing of the maximum T2m anomaly depends on the region defined over which the spatial average is taken. When the spatial average T2m anomaly is taken over the region between -15°W and 60°E and poleward of 80°N, which roughly corresponds to the region ever experienced T2m >= 0 ℃ shown in Fig. 1b, we found that 92 (82) out of the 96 identified concurrent warming events have their peak area occurred within 24 (12) hours of the timing of the maximum T2m anomaly. This suggests that the timing of the peak area of the concurrent warming events corresponds well with the timing of the maximum T2m anomaly over the Atlantic sector of the high Arctic. This correspondence is also reflected in Fig. 9 of the original manuscript (Fig. 10 in the revised manuscript). As can be clearly seen, both SLP anomaly pattern and IVT anomalies reach maximum at day 0, which is the time with the largest area of T2m >= 0 ℃. This suggests that defining the peak of the concurrent warming events based on the total area with T2m >= 0 ℃ is a reasonable approach. The following discussion has been added to Section 3.3 in the revised manuscript:

"*Further analyses show that the timing of the peak area corresponds well with the timing of the maximum T2m anomaly averaged over the Atlantic sector of the high Arctic (-15°W – 60°E and poleward of 80°N, roughly corresponding to the region ever experienced T2m >= 0°C shown in Fig. 1b). For example, 92 (82) out of the 96 identified concurrent warming events have their peak area occurred within 24 (12) hours of the timing of the maximum T2m anomaly.*"

References:

Wang, Z., J. Walsh, S. Szymborski, and M. Peng, 2020: Rapid Arctic Sea Ice Loss on the Synoptic Time Scale and Related Atmospheric Circulation Anomalies. *J. Climate*, **33**, 1597–1617, https://doi.org/10.1175/JCLI-D-19-0528.1

Park, H., S. Lee, S. Son, S. B. Feldstein, and Y. Kosaka, 2015: The Impact of Poleward Moisture and Sensible Heat Flux on Arctic Winter Sea Ice Variability. *J. Climate*, **28**, 5030–5040, https://doi.org/10.1175/JCLI-D-15-0074.1.

- How much does the surface type (ocean, sea ice, leads in sea ice) affect the spatial location of the warming events, and the anomalies in e.g., SEB? Did the authors consider to divide the warming events into ocean and sea ice (with different SIC's) – this could improve the quality of the paper and the interpretations of the results. L185 states that the climatological SHF is upward in winter, which is true over warm ocean or openings in the sea ice. But over sea ice, I think that the climatological values of turbulent fluxes are almost negligible, if not slightly positive. The surface type influence can nicely be seen in S2, with a sharp division between negative and near neutral values at the sea ice edge. Thus, L187 "suppression of the upward THF" is true if the surface is relatively warm, but ARs could also enhance downward THF if the surface is relatively cold (e.g., over sea ice). Discussion about the impact of different surface types on the results shown here would be nice to see and adding the sea ice edge on the climatological plots would be helpful.

  Although it is not stated explicitly in our manuscript, the reason why we divide the short duration events into two groups, one occurring poleward of 85°N and the other occurring equatorward od 83°N, is because we want to understand how the surface type (fully covered by sea ice versus partially covered by sea ice) would affect the SEB during the warming events. As shown in Fig. 5 of the original manuscript (Fig. 6 in the revised manuscript), downward longwave radiation (DLW) dominates the SEB for the short duration event poleward of 85°N while both DLW and sensible heat flux (SHF) play comparable roles for the short duration events equatorward of 83°N. In line 185 of the original manuscript, when we state that "climatologically, the THF over these regions is upward…", we are actually referring to the regions close to 80°N (line 183 in the original manuscript) that are partially covered by sea ice. We agree with the reviewer that the THF is negligible over the fully sea ice covered regions and enhanced downward THF could occur when warming events occur or ARs are present over these regions. We have now explicitly pointed out that the "*suppression of the upward THF*" occurs "*over these partially sea ice covered regions*" in the revised manuscript. We also provided a more detailed explanation on why we divide the short duration events into the two groups.

  "*As shown above, extreme warming events can be divided into the DLW dominated ones that occurred over the fully sea ice covered regions poleward of ~83°N and SHF dominated ones that occurred over the partially sea ice covered regions equatorward of ~83°N (Fig. S2).*"

  A climatological 50% sea ice concentration contour has been added to the updated Fig. S2 in the supplementary and shown in Fig. R7.

- Wording and terminology for the warming events: The authors are not always consistent with the wording of their events: warming events or extreme warming events for the grid-point wise defined events, and concurrent warming events or large-scale events (L378) for a larger region.

Please be consistent with the terminology, and always refer to which events (region or grid-point) the analysis shown in a figure or discussed in the text is referring to. For example, add it to the abstract and conclusions, as well as in figure captions (such as in Fig. 5 for the duration categories). In the abstract it is, for example, not clearly stated that the match between ARs and warming events are done on the concurrent events.

Thank you for the suggestion. We have combed through the manuscript to ensure that the terminologies and wordings are used consistently. “Extreme warming event(s)” is now consistently used to describe those events defined at the grid-point scale. And “concurrent warming event(s)” is used to describe those events with more than one grid point experiencing extreme warming events simultaneously. We have also explicitly defined the events in figure captions.

- The word “driving” or “driver” is used several times in the paper. I would rather write “associated with” or “related to“ instead of driving. For example, in L300, I would rather write that the SLP pattern are “guiding” the ARs or “making a pathway”.

We have made the suggested changes at places where we believe are applicable.

- Figure 2c and Fig. 3a: remove the value shown in the upper left corner but keep it in the captions. Also, I assume the caption for Fig. 3 for the red line should refer to panel (a), not c. I would also suggest to change the color for zero in Fig. 3b to another color to be clearer (blue according to the colorbar means no days or actually more than 0?).

Yes, we are referring to Figs. 3a not 3c for the red line mentioned in the caption. Blue in Fig. 3b means the values are close to zero. Zero value has been masked out. The following sentence has been added to the caption of Fig. 3 (Fig. 4 in the revised manuscript) for clarification.

“*Grid points never experienced an extreme warming event or less than two extreme warming events within a single winter (thus with a mean time interval of zero) have been masked out in (b).*”

We have updated Figs. 2 and 3 as suggested.

- I suggest the authors to add more references, at least when discussing the results of this paper and when comparing directly to other observations or studies (e.g., in L153).

More references have been added to the result section to provide the context for discussion.

- At L158: I assume the authors mean that the duration drops gradually away from the region at 80N, 0-30W to less than 5h north of 85N OR east of 60E (there are no data in the corner north of 85N and east of 60E, right?)

Sorry for the typo. It should be “*Over regions eastward of about 60°E and poleward of about 80°N…*”, not 85°N.

- Figure 4: Would be interesting to see how many grid-points satisfy the temperature criterion over all seasons within the study period, to know if the average e.g., DLW is a result of only a few or several events. The average occurrence of these events (S1) gives some idea about this, but maybe a relative frequency plot would better demonstrate this (so that 100% would refer to the max occurrence of events per grid point over all periods). I also find the Figure S1a to be relevant for the main paper, as main characteristics for events include spatial distribution.

Fig. 12b in the original manuscript is the relative frequency plot that shows the fraction of time with T2m >= 0℃ over all wintertime hourly snapshots during 1979-2021. The relative frequency is very close to zero over most of the regions that have experienced extreme warming events. Fig. 4 in the original manuscript is obtained by taking the average of all anomaly terms over all hours with T2m >= 0 ℃ over the given grid point. To better visualize the sample size that Fig. 4 in the original manuscript is based on, Fig. R5 shows the total number of hours with T2m >= 0 ℃ for the entire study period. As shown in the figure, the number of hours with T2m >= 0℃ decreases rapidly as moving away from the region with the maximum occurrence hours. Near the edge of the regions that experienced T2m >= 0 ℃, the number of hours with T2m >= 0 ℃ is usually less than 5. The following discussion based on Fig. R5 has been added to Section 3.2 of the revised manuscript.

"*The total number of hours with T2m >= 0℃ over the study period reaches* its maximum *(more than 1000 hours) over the region near 80°N and between 0°-30°E (Fig. S1). Moving away from this region, the number drops rapidly towards the boundary with regions that have never experienced T2m >= 0℃ during winters of the past four decades.*"

Fig. R5 has been added to the supplementary as Fig. S1. We have also moved Fig. S1 to the main text of the revised manuscript as Fig. 3.

- I find it interesting to see that you find a relationship between the duration of the events, their locations and associated SEB anomalies. Have you performed any correlation analysis to make your statement stronger? I assume that we would then find higher correlation between longerlasting events (longer duration) and SHF anomalies, whereas shorter-lived events would be correlated with DLW, especially at higher latitudes. Intuitively, I would think longer lasting events are those that penetrate further into the Arctic, but this confusing comes only because of your different way of defining events and their duration (at a fixed point; your longer-lasting events are closer to the warm and moist air source). Maybe worth reminding the reader again what your definition is to avoid possible confusion.

We haven't done any correlation analysis. We have shown that the duration of the extreme warming events depends on their position relative to the SLP dipole. It would be difficult to conduct a correlation analysis between the duration of the extreme warming events and their location relative to the SLP dipole due to the lack of an appropriate metric for measuring such relative location.
We also show that the SEB of the long duration events is dominated by SHF while the SEB of the short duration events is dominated by DLW poleward of 85°N. However, the duration of the

extreme warming events is not necessarily well correlated with the magnitude of the SHF anomalies or DLW anomalies at the start of the events. The location where the extreme warming events occur would confound this correlation. For example, during the start of the long duration events (Fig. 5g in the original manuscript), DLW anomalies are positive. However, the correlation between the duration of the long duration events and the magnitude of the DLW anomalies is negative (about -0.12, with a negligibly small p value). This negative correlation is probably due to the fact that longer duration events are more likely to occur at lower latitude regions closer to 80°N where the DLW anomalies are relatively weak (Fig. 4c in the original manuscript). This negative correlation makes it more difficult to interpret the contribution of DLW anomalies to the SEB of the long duration events. Furthermore, all the short duration events defined in our study have a duration of one hour. Conducting a correlation analysis between the duration of the short duration events and the SEB anomaly terms is not feasible. Although we do find a positive correlation between the duration of the long duration events and the SHF anomalies averaged over the first four days of the events (~0.46 with a negligible p value), in order to keep the manuscript more concise and avoid possible confusion, we have decided not to present the results of the correlation analysis. Definition for the extreme warming event has been provided in the appropriate figure captions to avoid possible confusion.

- When talking about anomalies in SLP or SEB components, for example, we are mainly interested in the sign of the anomaly. Therefore, I would suggest writing “positive/negative” instead of “high/low” when writing about anomalies.

The terms “high” and “low” have now been replaced by “positive” and “negative”, respectively.

- Figure 5: what is the absolute number of events within each sub-category based on duration? A map showing the locations of these grid-points would be nice to see. Further point out in Fig. 5 caption that the durations are defined per grid-point. Could the stronger anomalies shown in Fig. 7 compared to the other ones be a result of less events included in the composite?

The total number is 18586, 1642, and 10097 for the short duration events equatorward of 83°N, short duration events poleward of 85°N and long duration events, respectively. The information about the numbers has now been provided in the figure caption. We have also pointed out that the durations are defined at the grid-point scale in the caption. Since exceeding the 0℃ threshold represents a more extreme condition over the high latitude region, the stronger anomalies shown in Fig. 7 of the original manuscript are thus the result of less, but more extreme events included in the composite. Spatial distributions of the extreme warming events included in each sub-category are shown below (Fig. R10).

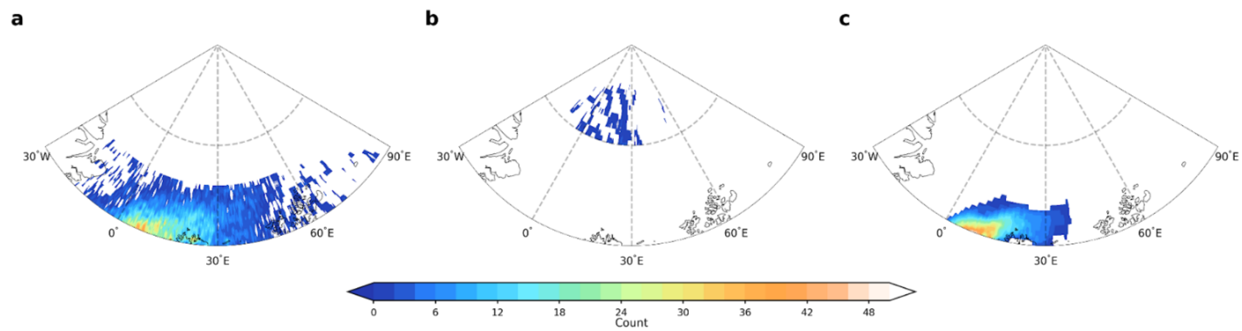

Figure R10. Spatial distribution of the occurrence frequency of the extreme warming events for the (a) short duration events equatorward of 83°N, (b) short duration events poleward of 85°N, and (c) long duration events.

- Figs 6-8: these figures are nice but also a bit messy with so many black lines. I would suggest changing the color for the SLP anomaly contours to purple (as in Fig. 13a).

We have updated these figures as suggested.

- How do the authors think that the spatial patterns of the events (or occurrence and duration) might directly be affected by cyclones or blocking? Adjacent grid-points could be captured by the same cyclone but affected by either the cold advection or the warm sector (L206). Have you looked at cyclone tracks or used blocking detection algorithms to associate your warming events with them (instead of using ARs and SLP anomalies to represent the large-scale setting)? The authors also write “blocking” (L380) in the conclusions despite not using a blocking detection algorithm (?). I would suggest rewriting to “blocking-like structure” and maybe refer to other studies (e.g., Woods and Caballero 2016, Messori et al. 2018 and Murto et al. 2022).

We think that the interaction between cyclones and blocking is what ultimately causes the occurrence of the wintertime extreme warming events and determines their spatial patterns in the high Arctic. As shown in Figs. 7-9 in the revised manuscript, the relative position of the SLP dipole plays a key role in determining the duration of extreme warming events. Furthermore, as shown in Figs. 10-11 in the revised manuscript, different configurations of the SLP dipole affect both the magnitude and spatial distribution of the T2m anomalies. These results all suggest an important role played by the interaction between cyclones and blocking in shaping the spatial patterns of the concurrent warming events.
In this study, instead of focusing on the role of cyclones and blocking that has been examined by previous studies, such as those pointed out by the reviewer, we choose to focus more on the role of ARs. Ultimately, the way via which cyclones and blocking cause the occurrence of the extreme warming events is through guiding the Arctic ARs and their associated heat and moisture into the Arctic. In this sense, we can view ARs as the direct driver of the extreme warming events. We agree with the reviewer that it is more appropriate to describe the positive SLP anomalies as “blocking-like structure” since we didn’t use a detection algorithm to explicitly identify atmospheric blockings. We have replaced “blocking” with “blocking-like structure” or “positive sea level pressure anomalies which resemble blocking” in the revised manuscript.

- In sect. 3.4, why do the authors return back to the grid-point defined warming events to relate them to ARs? Have you looked at how your results would change when using the concurrent warming events?

The link between ARs and the concurrent warming events is shown in Fig. 10 of the original manuscript (Fig. 11 of the revised manuscript). Figs. 10e-h show the AR frequency, which is defined as the fraction of time when a grid point is under AR conditions, during the peak of the concurrent warming events (shaded contours). Compared to the climatological AR frequency that ranges from 0.5-2.5% (solid line contours), the AR frequency during the peak of the concurrent warming events increases substantially, over 30% at some grid points, suggesting that ARs were present over those grid points for more than 30% of the 96 concurrent warming events identified in this study.
As have been pointed out in our response to the reviewer's previous comments, our study is inspired by Moore (2016) and Graham et al. (2017). One of the foci is to understand the connection between wintertime extreme warming events defined at the grid-point scale and Arctic ARs.

- L325: are these nine days of T2m above zero degrees found here in your study? Please mark their locations on a map, e.g., in Fig. 13a. Have you studied the origin of the ARs or utilized the tracking algorithm of the AR shapes, if it was provided with the AR algorithm?
- Figure 10: Are the T2m anomalies shown for all grid-points independent of if the grids are part of a concurrent warming event (or only that the time is at the peak of the event)? Maybe some density lines would be helpful to show where these concurrent warming events are spatially located and how these anomalies extend wrt the originally defined events.

Yes, these nine days with T2m above zero over regions poleward of 85°N are found in our own analyses based on ERA5. As shown in Fig. 1b, the region with T2m >= 0°C poleward of 85°N is very small and confined between 30°W and 60°E. Exact information about where they occur can be found in Fig. R5 shown above.

The AR detection algorithm used in our study has the capability of tracking ARs through space and time. We do think that it is interesting to look at the origin of the ARs affecting the high Arctic. However, since our focus is to investigate the link between ARs and extreme warming events in the high Arctic, rather than the characteristics of ARs, we have decided not to pursue this aspect further in the current study, which should be an interesting topic for a dedicated new study.

T2m anomalies shown in Fig. 10 are the mean T2m anomalies during the peak of the concurrent warming events. They are independent if the grids are part of a concurrent warming event. We have also updated Fig. 10 of the original manuscript (Fig. 11 in the revised manuscript and reproduced below as Fig. R11) to show the fraction of time when a grid point with T2m >= 0 during the peak of the concurrent events (solid line contours in Figs. R11a-d).

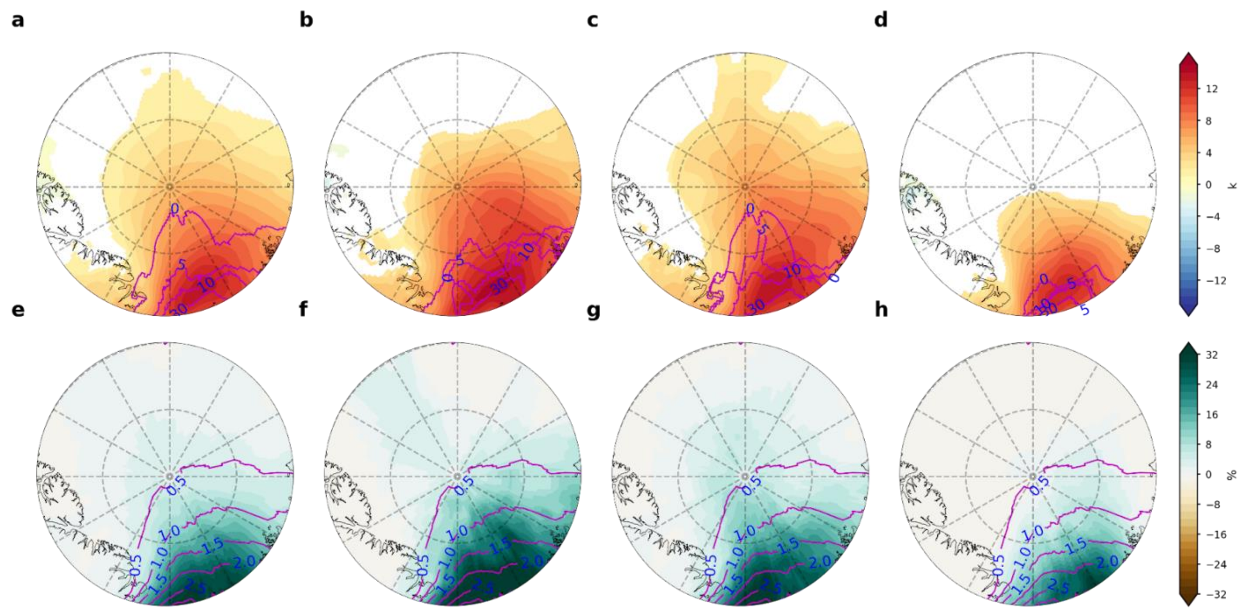

Figure R11. Spatial distribution of mean T2m anomalies and AR frequency during the peak of the concurrent warming events. The peak of the concurrent warming events is defined as the time when the areas with temperature above 0℃ reach maximum. The purple line contours in (a)-(d) depict the fraction of time when the T2m over a grid point reaches or exceeds 0℃ during the peak of the concurrent warming events and (e) – (h) the climatology of winter AR frequency.

- One additional concern is the statement at L318: "ARs are the only weather system capable of triggering the occurrence of the warming events". ARs are definitely important! That grid-points are co-occurring in time and space with ARs (even though 100% overlap), does not, however, directly imply that these warm anomalies can only result from an AR. In a recently published paper (Papritz et al. 2023 https://doi.org/10.1175/JCLI-D-22-0883.1), the relative contributions to the warm potential temperature anomalies extending in the whole tropospheric column (associated with extreme positive SEB anomalies over wintertime Arctic sea ice) were investigated. They found (using backward trajectories) that only airmasses ending up in the middle troposphere had an AR-like evolution, whereas airmasses making up the positive anomalies closest to the surface actually had an Arctic origin! These airmasses were either warmed diabatically while crossing over warmer oceans or when airmasses descend from higher altitudes, but all within the Arctic. It was these two airmasses together that could give rise to these anomalous positive vertically extending potential temperature anomalies. Local processes are thus also important, so I would suggest rewriting this strong sentence and add "likely" or "strong impact" instead of stating ARs are the only driver.

Thank you for the suggestion and pointing us to this interesting and relevant paper. We have rewritten the sentence and properly cited the paper mentioned above.

"*The results here thus suggest that, for a large fraction of the regions where extreme warming events can occur, the presence of ARs and their impact on and interaction with the local environment (Papritz et al., 2023) likely exert a strong control on the occurrence of these events.*"

- Are the trends discussed in Sect. 3.5 based on grid-point defined warming events? Referring here to an absolute number of warming events (2150) does not tell the reader so much, as your events (and the number) are dependent on the grid-size, the temporal resolution of the data etc. Maybe more informative would be to show seasonal trends of days with atleast one warming event per grid point? Or rather use the concurrent warming events here and calculate their trends per decade. I also think that the event definition (a fixed temperature threshold) and with a rapidly warming Arctic, warmer temperatures become more common by default (compared to the first decade of your study period).

Yes, the trends discussed in Section 3.5 are based on the grid-point defined extreme warming events. We agree with the reviewer that the absolute number of the trend in event count depends on both the spatial and temporal resolution of the dataset. However, the exact number of this trend is not very important, what matters more is that it shows that the area with T2m >= 0°C has been increasing in the past four decades. We have included a new figure in the supplementary to show the time series of the number of days per season and the number of hours per season with at least one extreme warming event defined at the grid-point scale occurring poleward of 80°N (Fig. R8). The trends in both time series are significantly positive. We have also updated Fig. 14 in the original manuscript (Fig. 15 in the revised manuscript) to include the trends in various characteristics of the concurrent warming events. We found that the frequency, spatial extent and duration of the concurrent warming events all exhibit positive and significant trends in the past four decades.

- Figure 13c is not referred to in the main text

Lines 333-334 in the original manuscript refer to the results shown in Fig. 13c. We have now made this sentence explicitly referring to Fig. 13c.

- I am also lacking a final concluding statement. The authors nicely summarize the findings of the paper in the final section, and list some limitations. What potential of further studies would your study contribute? One way to tie the final section to the rest of the paper is to answer the questions raised in the introduction in the conclusions.

Thank you for the suggestion. The following paragraph has been added to the revised manuscript as the last paragraph to discuss the implication of our study.

"*Given the critical roles played by the SLP dipole and ARs in determining the occurrence and characteristics of the wintertime extreme warming events, it is important to understand their variability at different timescales and identify large-scale climate modes that are responsible for such variability. An improved understanding on the variability of the SLP dipole and ARs would likely lead to a better understanding and prediction of the Arctic climate across timescales. The results in this study also suggest that a correct representation of the SLP dipole and ARs is key to simulating the occurrence of extreme weather events over the high Arctic at synoptic timescale. As we rely on climate models for future Arctic climate projection, further research is needed to evaluate how well climate models can faithfully represent the SLP dipole and ARs that affect the* *high Arctic. In this study, we focus on the T2m extreme warming events. It is expected that warming events as such would have a considerable impact on the underlying sea ice. As have been shown in this study, these extreme warming events tend to cluster in time. It would be interesting to further investigate their cumulative effects on the longer-term sea ice growth and the subsequent sea ice melt in the following summer. If a link between the occurrence frequency of such warming events and the subsequent summer sea ice minimum can be established, an improved prediction of the SLP dipole and ARs mentioned above would likely further extend the prediction lead time of summer sea ice minimum.*"

- Please add some discussion about ERA5 warm bias to the limitations of this study (relate to the representation of snow and sea ice in ERA5, see e.g., Batrak and Müller 2019 https://doi.org/10.1038/s41467-019-11975-3).

Thank you for pointing us to this interesting and relevant paper. Although the warm bias in ERA5 has been briefly touched upon in Section 2.1 when we introduce the dataset, this paper provides a nice explanation for the causes of the warm bias. Fig. 2a in their paper clearly shows that this warm bias is state-dependent. The warm bias is only pronounced under clear-sky conditions and slightly negative or negligible during anomalously warm periods. This is consistent with what we have discussed in lines 105-107 in the original manuscript: "*However, a recent study points out that the warm bias in ERA5 may be state-dependent, with a positive bias found under radiatively clear condition and a negative bias under opaquely cloudy condition (Herrmannsdörfer et al., 2023).*" This paper has now been cited at the end of the above sentence. In addition, the following discussion has been added to the second-to-last paragraph in the revised manuscript:

"*For example, due to the misrepresentation of sea ice thickness and the absence of snow layer on top of sea ice in the numerical models, reanalysis products, including ERA5, suffer a warm bias over the wintertime ice-cover Arctic under radiatively clear condition (Batrak and Müller, 2019).*"

Technical corrections

I agree on the typing errors pointed out by the first reviewer. Below some minor correction suggestions in addition to them:

- Add a reference to panel (f) for the temperature advection in the figure (Fig. 11) caption
Added.

- I would suggest to add the latitude threshold in the caption for the long-lasting events in Fig. 5g, h
We have explicitly pointed out in the caption that long duration events occur only over regions equatorward of 83°N.

- Be consistent with the terminology used in the text and in the figures. In Figs. 5a and 14a, "TS" is used instead of "T2m" (I assume), it is always referred to as T2m in the main text.
Thank you for pointing this out. We have replaced "TS" with "T2m" in these two figures.

Wintertime Extreme Warming Events in the High Arctic: Characteristics, Drivers, Trends, and the Role of Atmospheric Rivers

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Abstract. An extreme warming event near the North Pole, with temperature rising above 0℃, was observed in late December 2015. This specific event has been attributed to cyclones and their associated moisture intrusions. However, little is known about the characteristics and drivers of similar events in the historical record. Here, using data from ERA5, we study these winter extreme warming events with temperature over a grid point above 0℃ over the high Arctic (poleward of 80°N) that occurred during 1980-2021. In ERA5, such extreme wintertime warming events can only be found over the Atlantic sector. They occur rarely, with a ~~seasonal occurrence frequency less than one~~total absence during some winters over most of the region~~s~~. Furthermore, even when occurring, they tend to be short-lived, with the majority of the events lasting for less than a day. By examining their surface energy budget, we found that these events transition with increasing latitude from a regime dominated by turbulent heat flux into the one dominated by downward longwave radiation. Positive sea level pressure anomalies which resemble b~~B~~locking~~s~~ over the northern Eurasia are identified as a key ingredient in driving these events, as they can effectively deflect the eastward propagating cyclones poleward, leading to intense moisture and heat intrusions into the high Arctic. Using an atmospheric river (AR) detection algorithm, the roles of ARs in directly driving these extreme warming events defined at the grid-point scale are explicitly quantified. The importance of ARs in inducing these events increases with latitude. Poleward of about 83°N, ARs are the direct driver for 100% of these events, corroborating the indispensable roles ARs played in directly driving these events. Over the past four decades, both the frequency, duration, and magnitude of these events have been increasing significantly. As the Arctic continues to warm, these events are likely to increase in both frequency, duration and magnitude, with great implications for the local sea ice, hydrological cycle and ecosystem.

1 Introduction

In recent decades, the Arctic has experienced dramatic changes, with its surface warming at a rate substantially faster than the rest of the world (Serreze and Barry, 2011; Previdi et al., 2021; Rantanen et al., 2022). Such amplified Arctic warming is especially pronounced in winter (Zhang et al., 2021b). Several key mechanisms have been proposed to explain the amplified warming in the Arctic. These proposed mechanisms include local feedbacks, such as the ice-albedo feedback (Kumar et al., 2010; Screen and Simmonds, 2010; Dai et al., 2019), water vapor and cloud feedback (Vavrus, 2004; Beer and Eisenman, 2022), and lapse rate feedback (Pithan and Mauritsen, 2014; Stuecker et al., 2018), and non-local mechanisms that consist of both ocean and atmospheric heat transport (Hwang et al., 2011; Graversen and Burtu, 2016; Singh et al., 2017; Graversen and Langen, 2019). The atmospheric component can be further decomposed into a sensible heat and a latent heat (moisture) component, with the latent heat component playing a more important role (Graversen and Burtu, 2016). Concurrent with this warming trend is the rapid reduction in both sea ice extent and thickness (Serreze and Stroeve, 2015; Stroeve and Notz, 2018). Although it is still highly debated, Arctic warming and sea ice loss can reduce the meridional temperature gradient and have thus been hypothesized to modulate extreme weather events over mid-latitudes through their influence on large-scale circulation there (Cohen et al., 2014; Screen et al., 2018; Zou et al., 2021; Ma et al., 2021). In addition to these strong trends in the mean climate, the Arctic warming may also lead to more frequent occurrence of local synoptic weather extremes, ranging from rapid sea ice loss (Park et al., 2015; Gimeno et al., 2019; Wang et al., 2020; Zhang et al., 2023), rain-on-snow events (Serreze et al., 2021; Dou et al., 2021), extreme Arctic cyclones (Rinke et al., 2017; Parker et al., 2022; Crawford et al., 2022) to~~and~~ heatwaves (Woods and Caballero, 2016; Graham et al., 2017; Dobricic et al., 2020). The increased~~s~~ frequency and intensification of these weather extremes are expected to exert profound impacts on the Arctic ecosystem and local communities (Amstrup et al., 2010; Post et al., 2013; Ford et al., 2021).

It has been found that, besides contributing to the mean warming over the Arctic, atmospheric moisture transport can exert an important influence on many aspects of the Arctic climate. For example, enhanced atmospheric moisture transport into the Arctic in spring can lead to anomalous downward longwave radiation and thus precondition the sea ice for a more rapid melt in the subsequent months (Kapsch et al., 2013; Schröder et al., 2014; Mortin et al., 2016). Spring atmospheric moisture convergence can thus serve as an important predictor for summer minimum sea ice extent. In addition to its effects on the sea ice, recent increases in the Arctic river discharges have also been found to be primarily driven by an increase in poleward atmospheric moisture transport (Zhang et al., 2013). As sea ice continues to decline and atmospheric moisture transport continues to increase, the interannual variability of Arctic precipitation is expected to be increasingly controlled by atmospheric moisture transport (Bintanja et al., 2020).

Studies have shown that the bulk of atmospheric moisture transported into the Arctic is accomplished by episodes of extreme moisture transport events, termed Arctic moisture intrusions or atmospheric rivers (ARs) (Nash et al., 2018; Zhang et al., 2023). ARs, filaments of intense moisture transport in the atmosphere, have traditionally been identified as mid-latitude phenomena~~on~~. Early studies found that, despite occupying only about 10% of the mid-latitude circumference, ARs are responsible for more than 90% of the poleward moisture transport there (Zhu and Newell, 1998). ARs have been studied extensively for mid-latitude regions due to their important contribution to the regional hydrological cycle (Leung and Qian, 2009; Viale et al., 2018; Lavers and Villarini, 2015; Waliser and Guan, 2017; Lamjiri et al., 2017; Pan and Lu, 2020). In recent years, it gets increasingly recognized that ARs also exert considerable impacts on the Arctic climate (Hegyi and Taylor, 2018;

Nash et al., 2018; Zhang et al., 2023). When a large amount of moisture carried by ARs intrudes into the Arctic in a short period of time, the rapid moistening of the lower atmosphere and the resulting cloudy condition and enhanced downward longwave radiation can lead to a rapid rise in surface temperature and substantial sea ice loss. Therefore, ARs are potentially an important driver of extreme events over the Arctic region.

In late December 2015, the high Arctic near the pole experienced an episode of extreme warming event, with surface temperature exceeding 0℃ (Moore, 2016; Graham et al., 2017; Binder et al., 2017). Subsequent examination reveals the short-lived nature of this event, with the duration of staying above 0℃ for less than an hour locally (Fig. 1 in (Graham et al., (2017) and Fig. 2 in (Moore, (2016)). This event is driven by an AR-like moisture plume carried into the high Arctic by a cyclone (Moore, 2016). While this event has been studied in detail, our knowledges about similar events over the high Arctic during winter is far from being complete. To fill this knowledge gap, in this study, using high spatiotemporal resolution data from the European Centre for Medium-Range Weather Forecasts Reanalysis, version 5 (ERA5), we seek to address the following questions: (1) What are the characteristics of extreme warming events in ERA5, in terms of duration, frequency and temporal clustering? (2) How does the surface energy budget evolve during the development of these events? And what is the dominant energy budget term in driving these events? (3) What are the favorable large-scale circulation patterns driving these events? (4) What roles do ARs play in the initiation of these events in particular?

This paper is structured as follows. Section 2 describes the data and the AR detection algorithm used. In section 3, we first show the characteristics of Arctic extreme warming events, in terms of spatial distribution, duration and occurrence frequency. We then investigate the driving mechanisms of these events from the surface energy budget and large-scale circulation perspectives. Attentions are given to those events with very short or very long duration. As will be shown, the large-scale circulation associated with these events exhibits typical patterns that favor the intrusion of moisture into the Arctic. We thus further quantify the role of ARs in directly driving or intensifying these events. Lastly, the trends of Arctic extreme warming events are also explored. In section 4, we conclude by giving a brief summary of the major findings and a discussion on some limitations of this study.

2 Methods

2.1 Definition of extreme high Arctic warming events identified in observational dataset

Results based on previous case studies suggest that extreme warming events with near surface air temperature above 0 °C tend to be short-lived, usually with a duration shorter than a few hours (Moore, 2016; Graham et al., 2017). To examine the spatiotemporal characteristics of these extreme warming events in detail, we thus employ hourly data from the fifth generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5; Hersbach et al., 2020), with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. Previous studies suggest that, compared to in-situ observations, ERA5 exhibits a warm bias in wintertime Arctic surface air temperature (Graham et al., 2019). However, recent studies pointed out that the warm bias in ERA5 may be state-dependent, with a positive bias found under radiatively clear condition and a negative or negligible bias under opaquely cloudy condition (Batrak and Müller, 2019; Herrmannsdörfer et al., 2023). Further research is needed to evaluate the performance of ERA5 under extreme warming conditions over the Arctic. Nevertheless, as described below, extreme warming events defined in this study represent very extreme conditions over the high Arctic during winter. The results being presented here thus bear significance to our understanding of the characteristics and drivers of winter extreme warming events over the high Arctic.

Case studies based on in-situ buoy observations have been conducted by previous studies to examine the characteristics and drivers of winter extreme warming events over the high Arctic (Moore, 2016; Graham et al., 2017), which~~.~~ characterized extreme warming events using point observations based on meteorological buoys. Since these extreme warming events are usually driven by large-scale circulation (Woods and Caballero, 2016; Moore, 2016; Kim et al., 2017; Messori et al., 2018), when extreme temperature is detected over a grid point, it is common that such extreme temperature can also be found over its neighbouring grid points. Under such conditions, one approach is to define extreme warming events by using contiguous regions with temperature exceeding a predefined threshold. However, t~~T~~o facilitate a more direct comparison with previous case studies shown in Moore (2016) and Graham et al. (2017), here we choose another approach to define extreme warming events at the grid-point scale. Specifically, in this study, extreme warming events are defined as those events with 2-meter air temperature (T2m) over a grid point reaching or exceeding 0℃ over the high Arctic that covers the regions poleward of 80°N. Although the focus of this study is on warming events defined at grid-point scale, we also investigate extreme warming events identified by contiguous regions with temperature exceeding a threshold in section 3.3, which complements the results from the grid-point scale perspective. We focus on the winter season (December to February or DJF). The event starts ~~onset is defined as the time~~ when the T2m first reaches or exceeds 0℃, and the event is considered to end at the time when the T2m first drops below 0℃. The time between the start of the event~~onset~~ and termination is considered as the duration of the event. It is possible that T2m can rise to or above 0℃ within a few hours following the termination of a previous extreme warming event over the same grid point. When such situation occurs, it is likely that both extreme warming events are driven by the same weather system. To test how sensitive the results are to these situations, we impose a 24-hour, ~~or~~ 48-hour or 120-hour interval requirement between the termination of an event and the start~~onset~~ of a following event over the same grid point. If the following event occurs within 24, 48 or 120 hours after the termination of the previous event, it is excluded from the analyses. We found that the results 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.

~~Results based on previous case studies seem to suggest that these warming events tend to be short-lived, usually with a duration shorter than a few hours. To examine the spatiotemporal characteristics of these warming events in detail, we thus employ hourly data from the fifth generation European Centre for Medium-Range Weather Forecasts reanalysis (ERA5; Hersbach et al., 2020), with a spatial resolution of 0.25° × 0.25°. Previous studies suggest that, compared to in-situ observations, ERA5 exhibits a warm bias in wintertime Arctic surface air temperature (Graham et al., 2019). However, a recent study points out that the warm bias in ERA5 may be state-dependent, with a positive bias found under radiatively clear condition and a negative bias under opaquely cloudy condition (Herrmannsdörfer et al., 2023). Further research is needed to evaluate the performance~~

of ERA5 under extreme warming conditions over the Arctic. Nevertheless, the warming events defined in this study represent very extreme conditions over the high Arctic during winter. The results presented here thus bear significance to our understanding of the characteristics and drivers of winter extreme warming events over the high Arctic.

Following Wang et al. (2020), aAll anomalies presented in this study are obtained by first removing the seasonal cycle.,. To obtain the seasonal cycle in the first place, the hourly time series is averaged across the years from 1979 to 2021 to get a raw seasonal cycle, and then a 31-day running mean is subsequently applied to obtain a smoothed seasonal cycle for de-seasonalizing. which is defined based on the period of 1979-2021 for each calendar day using the 31-day running mean data. The Arctic has experienced amplified warming in the past four decades. This amplified warming is associated with significant positive trends in the downward longwave radiation (DLW), integrated water vapor transport (IVT) and integrated water vapor (IWV) over nearly the entire high Arctic and significant positive (or negative) trends in the latent heat flux (LHF) and sensible heat flux (SHF) over the sea ice covered (or partially sea ice covered) region of the high Arctic Atlantic sector (not shown). To exclude the effects of thesese decadal - warming trends, the anomalies of T2m, downward longwave radiation (DLW), integrated water vapor transport (IVT), latent heat flux (LHF), sensible heat flux (SHF), and and integrated water vapor (IWV) are further detrended after removing the seasonal cycle. Similarly, for any given hour, to obtain the linear trend, a 31-day running mean centered at the hour is first applied to the de-seasonalized data. The smoothed data is then used to derive the linear trend used for the detrending.the linear trends are based on the period of 1979–2021 for each calendar day using the 31-day running mean of the de-seasonalized data.

2.2 AR detection Algorithm

We use the IVT-based AR detection algorithm developed by Guan and Waliser (2019). This algorithm is an updated version of the original AR detection algorithm, documented in Guan and Waliser (2015), which is one of the earliest and most popular automated AR detection algorithms in the AR community. In addition, it is recommended by the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) for AR research over the high latitudes (Rutz et al., 2019). Notable common criteria employed by both algorithms are as follows: (1) a seasonally and regionally dependent 85^{th} percentile of the IVT magnitude or 100 kg m^{-1} s^{-1}, whichever is larger, is used as the threshold to identify contiguous regions of enhanced IVT ("object"); (2) to ensure coherence, at least half of the grids within the identified object need to have a IVT direction within 45° of the object mean IVT direction; (3) the object mean poleward IVT exceeds 50 kg m^{-1} s^{-1}; lastly (4) the detected object is longer than 2000 km and with a length-to-width ratio exceeding two. Compared to the original algorithm, the updated algorithm includes several major refinements: (1) iterative thresholds are used to increase the chance of an "object" to be detected as AR. In this study, five iterative thresholds are used: 85^{th}, 87.5^{th}, 90^{th}, 92.5^{th} and 95^{th}; (2) improvements are also made on the identification of the AR axis that helps to better characterize the AR length and orientation; (3) the function of tracking of individual ARs across space and time is enabled. By the time when ARs reach the Arctic, they are usually near the end of their life cycle. Following Mattingly et al. (2018), the length requirement for a detected AR is thus relaxed from 2000 km to 1500 km.

The zonal and meridional components of the IVT vector are calculated by vertically integrating the moisture flux at 1000, 850, 700 and 500 mb following:

$$zonal\ IVT = \frac{1}{g}\int_{1000}^{500} uqdp$$

$$meridional\ IVT = \frac{1}{g}\int_{1000}^{500} vqdp$$

where g is the gravitational acceleration, u is the zonal and v is the meridional wind component, and q is specific humidity. Because using hourly data with the original spatial resolution as input to the AR detection algorithm is computationally too expensive, only data at 00, 06, 12, and 18 UTC are used for AR detection. Furthermore, we bi-linearly regrid the data to $1^{\circ} \times 1^{\circ}$ before calculating IVT. The generated AR statistics are then mapped back to the original resolution ($0.25^{\circ} \times 0.25^{\circ}$) using the nearest neighbour method.

3 Results

3.1 Characteristics of the high Arctic extreme warming events

Over most of the high Arctic, winter mean T2m is generally below -20 ℃, with the exception found over a small region near 80°N of the Atlantic sector (Fig. 1a). The mean T2m there can reach as high as -13℃. Given such severe cold conditions over the wintertime high Arctic, temperature above 0℃ indeed represents an extreme condition over there. By examining the maximum hourly T2m of all the winter months (December to February) from 1979 to 2021, we found that only regions over the Atlantic sector ever experienced T2m above 0℃ (Fig. 1b), which is consistent with the fact that the Atlantic sector serves as the major pathway for moisture and heat transport into the Arctic (Dufour et al., 2016; Yang and Magnusdottir, 2017; Papritz et al., 2022). The Pacific sector, as another important pathway for moisture and heat transport into the Arctic (Dufour et al., 2016; Gimeno et al., 2019), has never been warm enough to break 0℃ over 1979-2021, although the winter maximum hourly T2m reached as high as about -1℃. Therefore, we focus on the Atlantic sector from now on.

Consistent with the buoy in-situ observations (Moore, 2016; Graham et al., 2017), these extreme warming events tend to be short-lived, with about 70% and 90% of the events lasting shorter than half a day and one day, respectively (Fig 2c). On average, these events lasted for 11.55 hours. The most long-lasting events are found over the regions close to 80°N between 0°-30°E, with a mean duration of about 16 hours (Fig. 2a). Over this region, those extreme long-lasting events, which are defined as events with duration longer than the local 95th percentile duration, can last longer than two days (Fig. 2b). Moving away from this region, the mean duration drops gradually. Over regions eastward of about 60°E and poleward of about 80~~5~~°N, the mean duration is shorter than five hours. Over those regions, even the extreme long-lasting events tend to last less than 10 hours, further confirming the short-lived nature of these events over the winter high Arctic observed on buoys (Moore, 2016; Graham et al., 2017).

In addition to being short-lived, these events also occurred very rarely over the winter high Arctic (Fig. 3). Regions with mean seasonal occurrence frequency greater than one can only be found over a confined region near 80°N between 0°-30°E (Fig. 3~~S1~~a). Moving away from this region, the occurrence frequency decreases dramatically and becomes less than one over most of the regions. When only those winters with at least one event occurred are considered, the mean occurrence frequency over most regions only increase slightly to 1-2 events per season (Fig. 3~~S1~~b). Besides being rare, by examining the time interval between termination of an event and the start ~~onset~~ of the subsequent event for those winters with at least two events occurring over a grid point, we found that these events tend to exhibit some degree of temporal clustering (Fig. 4~~3~~). About 80% of the events reoccurred in less than five days (Fig. 4~~3~~a). Over those regions where the mean seasonal occurrence frequency is less than one, the mean time interval in between events is usually less than two days, suggesting that these events tend to occur back-to-back (Fig. 4~~3~~b). As being shown in Section 3.3, the clustering of these extreme warming events may be driven by the same persistent large-scale circulation that steers successive weather systems into the affected region. These results suggest that the preconditioning by the previous events likely plays an important role for the initiation of the subsequent events.

3.2 Surface energy budget associated with the high Arctic extreme warming events

It is found that enhanced DLW plays an important role for Arctic warming during winter (Messori et al., 2018; Park et al., 2015; Woods and Caballero, 2016; Murto et al., 2023). To investigate whether DLW also plays a role in the extreme warming events defined in this study, we examine the anomalies of the surface energy budget terms when the T2m >= 0℃. The total number of hours with T2m >= 0°C over the study period reaches its maximum (more than 1000 hours) over the region near 80°N and between 0°-30°E (Fig. S1). Moving away from this region, the number drops rapidly towards the boundary with regions that have never experienced T2m >= 0°C during winters of the past four decades. As shown in Fig. 5~~4~~, when T2m >= 0℃, the atmosphere above is anomalously moist, with IWV anomalies exceeding 4 kg m^{-2} nearly everywhere (Fig. 5~~4~~b). Regional IWV anomalies can reach up to about 9 kg m^{-2}. With the winter IWV climatology being less than 3.5 kg m^{-2} nearly everywhere over the Atlantic sector in the high Arctic (not shown), such moistening of the atmosphere represents 100-300% increases in the IWV and is most likely achieved by intense moisture intrusions from the lower latitudes. Consistent with the moistening of the atmosphere, DLW anomalies also increase substantially everywhere (Fig. 5~~4~~c). The enhancement of the DLW anomalies increases with latitude and can reach up to about 130 W m^{-2} poleward of 85°N. The spatial pattern of the DLW anomalies corresponds well with that of the IWV anomalies, suggesting the importance of enhanced IWV in inducing the anomalous DLW. Over regions close to 80°N, the magnitude of DLW anomalies is relatively weaker. However, the downward turbulent heat flux (THF) anomalies, especially SHF, are substantially intensified (Figs. 5~~4~~d, e). Climatologically, the THF over these regions is upward, with magnitudes reaching more than 100 W m^{-2}, due likely to the partially open ocean underneath (Fig. S2). During extreme warming events, the strong advection of both moisture and heat in the lower atmosphere (Figs. 5~~4~~b, f) likely results in the reversal of the vertical temperature gradient, leading to a strong suppression of the upward THF over these partially sea ice covered regions. In contrast to the spatial pattern of DLW anomalies, the SHF anomalies weaken with latitude. Compared to DLW and SHF, downward LHF anomalies are substantially weaker (Fig. 5~~4~~e), with the magnitude decreasing with latitude and even a reversed sign over the most north-western regions. The anomalous upward LHF over this region is likely caused by the rapid cold and dry advection shortly after the start~~onset~~ of extreme warming events, resulting in a reversal of the moisture gradient and overall weak temperature advection over the region (Fig. 5~~4~~f). As shown later, such a rapid transition to cold and dry advection could be caused by the passage of a cold front. The patterns of these surface energy budget terms suggest that the winter extreme warming events over the high Arctic can be categorized into two types: (1) the DLW dominance type, which usually occurs poleward of about 83°N, and (2) the SHF dominance type, which occurs over the lower latitude regions near 80°N. These results are consistent with Murto et al.~~,~~ (2023) who examines the wintertime high Arctic extreme surface energy budget anomalies and finds that DLW plays an increasingly more important role as events move further into the Arctic.

Next, we examine the temporal evolution of the anomalous surface energy budget for the extreme warming events (Fig. 6~~5~~). Even nine days before the start~~onset~~ of the extreme warming events, T2m is already 3-4 ℃ higher than normal (Fig. 6~~5~~a). This is likely because these extreme warming events occur more often during warm winters,~~.~~ but it is also possible that this warm anomaly is preconditioned by a previous moderately or extremely warm event. The background temperature over the Atlantic sector, under which these events occur, is thus anomalously warm. Indeed, the occurrence frequency of the events correlates significantly with the winter mean T2m over the Atlantic sector of the Arctic (or the entire Arctic), with a correlation coefficient of about 0.64 (0.61). Consistent with the warm anomalies, both IWV and DLW show positive anomalies. These results suggest that while the occurrence of these extreme warming events contributes to making the background state anomalously warm and moist, a warm and moist winter in turn favours the occurrence of extreme warming events. About four days prior to the start~~onset~~ of the events, T2m, all surface energy budget terms, warm advection and IWV start to climb and peak at around the start~~onset~~ of the events. Both the SHF and DLW play comparable roles in directly driving the events, with SHF having a slightly larger magnitude. Following the start~~onset~~ of the events, while the other terms drop more gradually, warm advection ceases immediately and shifts to weak cold advection afterwards, implying the passage of cold fronts.

To understand what determines the duration of the events, we further divide the extreme warming events into short duration events, defined by duration <= the 5^{th} percentile of the duration of all events (1 hour), and long duration events, defined by duration >= the 95^{th} percentile of the duration of all events (40 hours). The long duration events only occur equatorward of 85°N while the short duration events can be found both poleward and equatorward of 85°N. As shown above, extreme warming events can be divided into the DLW dominated ones that occurred over the fully sea ice covered regions poleward of ~83°N ~~(poleward of ~83°N)~~ and SHF dominated ~~(equatorward of ~83°N)~~ ones that occurred over the partially sea ice covered regions equatorward of ~83°N (Fig. S2). We thus further divide the short duration events into those occurring poleward of 85°N and equatorward of 83°N to maximize the differences between these two types of events. Since the composites for all the events are dominated by the events with relatively short duration over lower latitude regions, the temporal evolution of T2m, surface energy budget terms, temperature advection and IWV for the short duration events equatorward of 83°N are very similar to those for all the events (Figs. 6~~5~~c, d vs Figs. 6~~5~~a, b). For the short duration events poleward of 85°N, the anomalies of T2m, DLW, SHF and IWV start to increase about six days prior to the start~~onset~~ of the events, suggesting that more persistent weather patterns are required to initiate the extreme warming events poleward of 85°N (Figs. 6~~5~~e, f). Indeed, these events are dominated by the DLW anomalies, with their magnitude being twice those of the SHF anomalies. Following the start~~onset~~ of the events, all quantities drop sharply. The anomalies of SHF and LHF even reverse sign and the warm advection prior to the start~~onset~~ of the events shifts to strong cold advection. Contrary to the short duration events poleward of 85°N, the long duration events are dominated by SHF anomalies, with their magnitude, in this case, being twice those of the DLW anomalies (Fig. 6~~5~~g). The anomalies did not increase until about two days prior to the start~~onset~~ of the events. Unlike the short duration events, all anomaly terms remain elevated for a prolonged period after the start~~onset~~ of the events, and then gradually level off (Figs. 6~~5~~g, h)

To further investigate the mechanisms that determine the duration of these events, we create anomaly composites for temperature advection, IVT and SLP centred at the grid point where extreme warming events occur. As the same large-scale circulation pattern can cause extreme warming events to occur over more than one grid point, it thus can be counted more than once within the same composite or across different composites. However, as the composites are centred at the grid point where the extreme warming event is identified, the position of the same large-scale circulation relative to the grid point would thus differ among the composites centred at different grid points. As we show below, the relative position of the SLP anomalies is what determines the duration of the extreme warming events. The double counting of the same circulation pattern for the composites shown in Figs. 7, 8, and 9 thus has minimal impact on the conclusion. As shown in Fig. 7~~6~~, the start~~onset~~ of the short duration events equatorward of 83°N is associated with a positive SLP~~high~~ anomaly to their southeast and a negative SLP~~low~~ anomaly to their west. This circulation pattern effectively channels moisture and heat into the regions where the extreme warming events occur (Woods and Caballero, 2016; Messori et al., 2018; Wang et al., 2020). Even six days prior to the start~~onset~~ of the events, the positive SLP~~high~~ anomaly already appears. A weak warm advection can also be found south of the event regions. As time evolves, the positive SLP~~high~~ anomaly deepens, and a negative SLP~~low~~ anomaly starts to develop over the west of the events. Concurrent with these changes in the SLP, moisture transport and warm advection intensify over the event regions. Less than one day prior to the start~~onset~~ of the events, a cold advection anomaly develops west of the events and moves over the event regions immediately following the start~~onset~~ of the events, leading to the drop in T2m. By day six after the start~~onset~~ of the events, the SLP dipole pattern mostly vanishes. For the short duration events poleward of 85°N, the SLP anomaly dipole already starts to develop six days prior to the start~~onset~~ of the events (Fig. 8~~7~~). As time evolves, the dipole pattern intensifies, resulting in a strong SLP gradient over the event regions. Consistent with the presence of the strong SLP gradient, moisture and heat advection enhance greatly compared to the short duration events equatorward of 83°N. Less than one day prior to the start~~onset~~ of the events, a strong cold advection is well developed over the west of the events. It immediately moves over the event regions after the start~~onset~~ of the events, leading to sharp drops in the T2m and other surface energy budget terms. Like the short duration events equatorward of 83°N, the positive SLP~~high~~ anomaly southeast of the event regions already starts to develop for the long duration events six days before the start of the events (Fig. 9~~8~~). However, at the meantime, a negative SLP~~low~~ anomaly can also be found southwest of the event regions. As the events evolve, the positive SLP~~high~~ anomaly intensifies while the negative SLP~~low~~ anomaly extends northward. This configuration in the dipole pattern leads to sustained moisture and heat advection into the event regions. Unlike the short duration events, the cold advection west of the long-duration event regions never develops, allowing the warm anomalies to persist. These results suggest that the position of the negative SLP~~low~~ anomaly relative to the event regions plays a key role in determining the duration of the events. When the negative SLP~~low~~ anomaly is located at the west of event regions, cold advection develops and moves over the event regions immediately after the start~~onset~~ of the events, causing the T2m to fall below 0°C. However, when the negative SLP~~low~~ anomaly locates at the southwest of the event regions, cold advection never develops, resulting in sustained moisture and heat advection into the event regions, leading to prolonged warm anomalies.

3.3 Large-scale circulation associated with concurrent warming events

The analyses presented so far are all based on extreme warming events occurring at grid-point scale. We next focus on large-scale circulations responsible for driving concurrent warming events over a large area of the Atlantic sector. To do that, we first calculate the total area experiencing extreme warming events over the high Arctic at each hourly snapshot. We then identify all the periods with areas experiencing extreme warming events continually greater than one grid point. These periods are defined as a concurrent warming event. 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. It is possible that the termination of one event is followed shortly by the onset of a subsequent event. Under such a situation, these two concurrent warming events are likely influenced by the same large-scale circulation pattern. We thus impose a constraint that the time interval between the onset of one event and the termination of the subsequent event~~two consecutive events~~ needs to be longer than five days. Otherwise, the subsequent event is~~will be~~ discarded in our analysis of large-scale circulations. Lastly, to focus on the most intense events, only those events with a peak area larger than 5×10^{9}~~10~~ m^{-2} are retained for analyses. There are a total of 96 events that satisfy these criteria. Further analyses show that the timing of the peak area corresponds well with the timing of the maximum T2m anomaly averaged over the Atlantic sector of the high Arctic (-15°W – 60°E and poleward of 80°N, roughly corresponding to the region ever experienced T2m >= 0°C shown in Fig. 1b). For example, 92 (82) out of the 96 identified concurrent warming events have their peak area occurred within 24 (12) hours of the timing of the maximum T2m anomaly. As shown in Fig. 10~~9~~ (1^{st} column), even four days prior to the peak of the events (day 0), which is defined as the time when the total area of extreme warming events reaches maximum, a positive~~high~~ SLP anomaly and a negative~~low~~ SLP anomaly start to appear over the northwest Eurasia and west Greenland, respectively. As time evolves, the dipole pattern intensifies, and the negative SLP~~low~~ anomaly also moves poleward. The anomalous dipole reaches maximum magnitude during the peak of the events and channels large amount of moisture into the Arctic. Four days after the peak of the events, the dipole mostly dissipates. These results further corroborate the importance of the anomalous SLP dipole in driving the Arctic weather extremes found in previous studies (Woods and Caballero, 2016; Messori et al., 2018; Wang et al., 2020; Zheng et al., 2022).

To gain a more detailed understanding on the spatiotemporal evolution of the large-scale circulation, we apply a K-means clustering method to the spatiotemporal evolution of all 96 events from six days prior to and after the peak of the events. We varied the numbers of clusters ranging from two to four. Three clusters are identified, which give a good balance between the numbers of events in each cluster and sufficient representation of the large-scale circulation patterns. The first cluster features a strong dipole pattern in the SLP anomalies, with a positive SLP anomaly~~high~~ over northwest Eurasia and a negative SLP anomaly~~low~~ over Greenland (2nd column in Fig. 10~~9~~). As time evolves, the negative~~low~~ SLP anomaly intensifies and propagates into the Arctic and then dissipates over the Laptev Sea, while the positive~~high~~ SLP anomaly remains relatively stationary. The second cluster exhibits a strong and persistent positive~~high~~ SLP anomaly over northern Eurasia, while the negative~~low~~ SLP anomaly is very weak (3rd column in Fig. 10~~9~~). As time evolves, the negative~~low~~ SLP anomaly moves poleward and dissipates rapidly over the Beaufort Sea. Contrary to the second cluster, the positive~~high~~ SLP anomaly in the third cluster is very weak and short-lived (4th column in Fig. 10~~9~~). This cluster is dominated by a negative SLP~~low~~ anomaly over Greenland. Unlike the other two clusters, the negative~~low~~ SLP anomaly predominantly exhibits a westward movement. These results suggest the importance of blocking~~s~~-like structures for steering cyclones into the Arctic and are consistent with previous studies on the roles of blocking~~s~~ in transporting moisture and heat into the Arctic (Papritz, 2020; Papritz and Dunn-Sigouin, 2020; Murto et al., 2022; Papritz et al., 2022).

Different spatial patterns of the large-scale circulation can result in different impacts (Fig. 11~~0~~). Compared to the ~~peak time of the~~ T2m anomaly composite at the peak time of all ~~the~~ events (Fig. 11a), the first cluster, which is dominated by a strong dipole pattern of SLP anomalies, shows an overall stronger warming over the Atlantic sector (Fig. 11~~0~~b). However, the area with significant warming is slightly smaller than that based on all the events. The warming anomalies over the Atlantic sector based on the second cluster, which is dominated by the positive~~high~~ SLP anomaly, are comparable to the composite of all the events, but it exhibits the largest spatial extent compared to those based on all the events and the other two clusters (Fig. 11~~0~~c). Lastly, the warm anomaly based on the third cluster, which is dominated by the negative~~low~~ SLP anomaly, exhibits the weakest warming over the Atlantic sector, and the spatial extent of the warming anomaly also is confined over the Atlantic sector only (Fig. 11~~0~~d). Therefore, the presence of the positive~~high~~ SLP anomalies which resemble~~or~~ blocking~~s~~ are important in determining both the magnitude and spatial extent of the warm anomalies. These results further imply that the persistence of the blocking~~s~~-like structures over the northwest/northern Eurasia can lead to sustained moisture and heat advection into the Arctic. This, in turn, can precondition the ambient in such a way that once a weather system, such as a cyclone, gets steered into the Arctic, it readily triggers the occurrence of the concurrent warming events.

Previous studies have shown that such a dipole pattern in the SLP anomalies is ideal for moisture intrusions or ARs moving into the Arctic (Park et al., 2015; Woods and Caballero, 2016; Messori et al., 2018; Wang et al., 2020; Papritz and Dunn-Sigouin, 2020; Papritz et al., 2022). Indeed, we found that, during the peak time of these concurrent warming events, the AR occurrence frequency, defined as the fraction of time when a grid point is under AR conditions, increases substantially (Figs. 11~~0~~e-h). The AR frequency can even exceed 30%. With the winter climatological AR frequency ranging from about 0.5-2.5% over the region, this represents an over 10-fold increase in AR frequency. Notably, cluster one, which corresponds to the strong dipole pattern in SLP, is most effective in guiding~~driving~~ ARs into the Arctic, while cluster three, which corresponds to the negative~~low-~~ pressure dominated pattern in SLP, is least effective in guiding~~driving~~ ARs into the Arctic.

3.4 Roles of ARs in driving the extreme warming events

The above analyses suggest that a strong moisture and heat transport by ARs likely plays an important role~~s~~ in directly driving the extreme warming events. To better quantify this role of ARs, we first examine the surface energy budget during AR days (Fig. 12~~1~~). Here, AR days experienced over any grid point are defined as those days with at least one 6-hourly time at 00, 06, 12 or 18 UTC under AR conditions. During AR days, the surface is anomalously warm, with T2m anomalies exceeding 10℃ nearly everywhere (Fig. 12~~1~~a). Concurrently, the atmosphere is anomalously moist, with IWV anomalies above 3 kg m^{-2} over most of the area (Fig. 12~~1~~b). ARs also lead to ubiquitous warm advection (Fig. 12~~1~~f). Both the sensible heat and latent heat transported by ARs into the Arctic lead to enhanced DLW anomalies, with a magnitude exceeding 60 W m^{-2} nearly everywhere (Fig. 12~~1~~c). ARs also lead to downward anomalies in both the SHF and LHF, especially over the regions only partially covered by sea ice near 80°N (Figs. 12~~1~~d, e). These results confirm that ARs indeed have a strong warming effect over the high Arctic during winter (Woods and Caballero, 2016; Zhang et al., 2023).

To show the tight connection more explicitly between ARs and the extreme warming events defined at the grid-point scale, Fig. 13~~2~~a shows the fraction of the extreme warming events which occurs during AR days. Equatorward of about 83°N where the background temperature is relatively warm, ARs are not the only direct driver for extreme warming events. There is still a nonnegligible fraction of events that are driven by other weather disturbances. However, the role of ARs becomes increasingly important as the extreme warming events occur over more poleward regions. Poleward of about 83°N, the fraction of extreme warming events that occur during AR days reaches 100%. Further examining the temporal evolution of IVT for the extreme warming events reveals that IVT usually peaks two to three hours prior to the start~~onset~~ of the events (Fig. S3). The results here thus suggest that, for a large fraction of the regions where extreme warming events can occur, the presence of ARs and their impact on and interaction with the local environment (Papritz et al., 2023) likely exert a strong control on~~ARs are the only weather system capable of triggering~~ the occurrence of ~~the~~ these~~warming~~ events. Climatologically, the fraction of time with T2m above zero is very close to zero nearly everywhere, except over a small region near 80°N and between 0°-30°E where the fraction can exceed 6% (Fig. 13~~2~~b). However, if only AR days are considered, the fraction of time with T2m above zero increases substantially (Fig. 13~~2~~c). By defining the ratio of the fraction of time with T2m above zero during AR days to that of all days as the risk ratio, we can see that ARs increase the risk of extreme warming events dramatically, ranging from about 10 times more likely over lower latitude regions to about 50 times more likely over higher latitude regions (Fig. 13~~2~~d). ARs are thus likely the key direct driver of the extreme warming events over the high Arctic during winter.

An in-situ observed extreme warming event happened near the end of 2015 and over regions close to the pole (Moore, 2016). If we focus on the regions poleward of 85°N, there are only nine days when extreme warming events occurred over at least one grid point of the regions from 1979 to 2021. ERA5 successfully simulates the occurrence of the extreme warming event during 12/29/2015-12/30/2015. For all these nine days, ARs can be found intercepting the 85°N latitude over 15°W-60°E for at least one 6-hourly time step of each day, which are defined as AR deep intrusion days, suggesting that all these events are driven directly by ARs. Compared to the AR deep intrusion days without extreme warming events occurring poleward of 85°N, those deep intrusion days with extreme warming events found poleward of 85°N exhibit a much more intense filament of IVT (Figs. 14~~3~~a vs 14~~3~~b). The IVT filament also penetrates deeper into the high Arctic. In line with the stronger IVT, the SLP dipole also intensifies, with the negative SLP~~low~~ center locating more poleward. During deep intrusion days, the daily IVT averaged over regions poleward of 85°N and between 15°W-60°E increases substantially from the climatological daily mean of ~25 to ~78 kg m^{-1} s^{-1} (Fig. 14c). Out of the ten (five) highest daily IVT averaged over the defined region, eight (five) of them are associated with extreme warming events occurring poleward of 85°N, further confirming the extreme nature of these extreme warming events.

3.5 Trends of extreme warming events

In the past four decades, winter mean T2m poleward of 80°N has been increasing significantly at a rate of 0.8 ℃ $decade^{-1}$ (Fig. 15~~4~~a). Consistent with the overall climate warming, both the winter maximum hourly T2m and the mean T2m for grid points~~those~~ above 0℃ increase significantly at 0.4 ℃ $decade^{-1}$ and 0.09 ℃ $decade^{-1}$, respectively. The slower increase of these extreme T2m events is likely due to the presence of underlying sea ice that imposes a constraint on their warming rates. In line with Graham et al. (2017), t~~T~~he background warming also makes the occurrence of the extreme warming events more likely. The event occurrence frequency has been increasing at a rate of 2150 events per season per decade for the extreme warming events defined at the grid-point scale (Fig. 15~~4~~b). Consistent with the increasing trend in the occurrence frequency, both the number of days and the number of hours with at least one extreme warming event found over the high Arctic exhibit significant upward trends with magnitude of 6.8 days per season per decade and 114 hours per season per decade (Fig. S4). At the same time, they also become more persistent, with the mean duration increased by 1.5 hours per decade. The duration of most long-lasting events each year has increased at an even faster rate of 17.6 hours per decade. Consistent with these increasing trends in the characteristics of the extreme warming events defined at the grid-point scale, the frequency, spatial extent, and duration of the concurrent warming events defined in Section 3.3 also exhibit significant positive trends in the past four decades (Figs. 15c, d).

Given the significant increase in both the event frequency and duration, it is natural to ask whether the increases are solely driven by the background warming or changes in AR frequency also play a role. Over the Atlantic sector of the high Arctic, ARs show positive trends over most of the regions in the past four decades (Fig. S5~~4~~a). However, significant trends are only found over a small region near the pole. Following Ma et al. (2020), we further decompose the trends into a dynamical component, driven by changes in atmospheric circulation, and a thermodynamic component, driven by changes in the moisture field. The decomposition reveals a counterbalancing effect between the two components (Text S1 and Fig. S5~~4~~). The moistening of the Arctic atmosphere has resulted in a substantial increase in AR frequency, especially over the regions equatorward of 85°N (Figs. S5~~4~~c and S6~~5~~a). However, the weakening of winds leads to a reduction in the AR frequency (Fig. S5~~4~~b and S6~~5~~b). These two components combined result in insignificant positive trends in the AR frequency over most of the regions. Based on these results, the roles played by changes in AR frequency are likely minor in driving the increase in extreme warming events. Nevertheless, even without any changes in AR frequency, ARs are more likely to induce extreme warming events under a warmer background temperature.

4 Conclusions and Discussions

Using hourly data from ERA5, we perform detailed analyses on the characteristics and drivers of the extreme warming events defined as a grid point with T2m >= 0 °C over the winter high Arctic. Based on ERA5, these events occur predominantly over the Atlantic sector. Except over a small region near 80˚N between 0˚-30˚E, such extreme warming events occur, on average, less frequent than once in each winter. Consistent with in-situ observations (Moore, 2016; Graham et al., 2017), they tend to be short-lived, with a mean duration less than half day. Furthermore, these extreme warming events exhibit some degree of temporal clustering. The temporal clustering identified here could be caused by the clustering of weather systems, as has been found over mid-latitudes for cyclones and ARs (Pinto et al., 2013; Priestley et al., 2017; Fish et al., 2019, 2022). However, further research is still needed to identify whether similar clustering for cyclones and ARs occurs over the high Arctic. By examining their surface energy budget, the extreme warming events can be categorized into two different types: SHF dominance type, which occurs over regions equatorward about 83˚N, and the DLW dominance type, which occurs over regions poleward of about 83˚N. Notably, long-duration events, which occur over regions near 80˚N, are mainly associated with~~driven by~~ persistent downward SHF anomalies. Composite analysis suggests that the position of the grid point experiencing~~-~~ extreme warming events relative to the negative~~low~~ SLP anomaly seems to play a key role in determining the event duration. Short duration events are usually associated with a negative~~low~~ SLP anomaly located to their~~its~~ west. This spatial pattern leads to rapid cold advection after the start~~onset~~ of the events and causes T2m to drop below 0°C. When the negative~~low~~ SLP anomaly is located ~~at~~ southwest of the grid point of the~~with~~ extreme warming event, creating sustained warm advection to the grid point even after the start~~onset~~ of the event, it thus prolongs the event.

The large-scale circulation responsible for the occurrence of warming events over large areas of the Atlantic sector consists of a dipole pattern in the SLP anomalies, with a positive SLP~~high~~ anomaly over the northwest Eurasia and a negative SLP~~low~~ anomaly over Greenland. This dipole pattern can effectively channel heat and moisture into the high Arctic, resulting in a large-scale warming. K-means clustering applied to the spatiotemporal evolution of these concurrent warming~~large-scale~~ events further reveals that they mainly consist of three different types of SLP spatial patterns: dipole dominance type, anticyclone~~high~~ dominance type, and the cyclone~~low~~ dominance type. By steering cyclones into the high Arctic, the positive~~high~~ SLP anomaly which resembles~~or~~ blocking plays an important role in determining both the strength and spatial extent of the concurrent warming events. These large-scale circulations create an ideal environment for moisture intrusions into the Arctic. Using the Guan and Waliser (2019) AR detection algorithm, we show that ARs play a critical role in directly driving the winter high Arctic extreme warming events. Over most of the regions ever experienced extreme warming events, 100% of these events were driven directly by ARs. The chance of having an extreme warming event can even become 50 times higher under AR conditions over some regions than otherwise. ARs are thus potent direct drivers of heat extreme over the high Arctic.

In the past four decades, the wintertime mean T2m over the high Arctic has been increasing significantly at a rate of 0.8 ℃ per decade. Concurrent with this rapid warming in the background temperature is the significant increase in both the frequency, intensity and the duration of extreme warming events defined at the grid-point scale and concurrent warming events. In addition, the spatial extent of the current warming events also exhibits a significant upward trend. In contrary to the significant background warming, despite their positive sign, trends in wintertime AR frequency are not yet significant due to the counterbalancing effect of changes in circulation and the moisture field. The increasing trends in the frequency and duration of wintertime extreme warming events are thus likely driven by the increasingly warming background T2m while the direct contribution from ARs is likely minor. Nevertheless, with continuously amplified warming over the wintertime Arctic and the projected increases in AR activities (Zhang et al., 2021a), the future wintertime high Arctic is expected to witness stronger, more frequent and long-lasting extreme warming events.

The current study does have several limitations. The high spatiotemporal resolution of ERA5 data provides an unprecedented opportunity to investigate the high Arctic wintertime extreme warming events. However, it is known that reanalyses are not real observations. They are produced by numerical models and constrained by limited observations through data assimilation. Biases relative to the actual observations are thus~~ can be~~ expected to exist in reanalysis products (Huang et al., 2017; Graham et al., 2019; Ma et al., 2024). For example, due to the misrepresentation of sea ice thickness and the absence of snow layer on top of sea ice in the numerical models, reanalysis products, including ERA5, suffer a warm bias over the wintertime ice-cover Arctic under radiatively clear condition (Batrak and Müller, 2019). In addition, g~~G~~iven that in-situ observations over the Arctic, which are used to constrain reanalyses, are sparse, the representations of Arctic climate in reanalyses can be further degraded. This limitation calls for more field campaigns to observe the Arctic atmosphere. In-situ observations for the wintertime extreme warming events and Arctic moisture intrusions or ARs are especially valuable in evaluating the representations of these events in reanalyses. Besides the potential uncertainty associated with the ERA5 dataset used here, the AR detection algorithm is another potential source of uncertainties for the results presented in section 3.4. It has been shown that there is a large spread in the detected AR statistics among major global AR detection algorithms participated in ARTMIP (Rutz et al., 2019; Lora et al., 2020). The AR detection algorithm (Guan and Waliser, 2015; 2019) used in this study is one of the very few global AR detection algorithms that can detect noticeable occurrences of ARs over the Arctic. This algorithm is thus recommended by the ARTMIP community for studying high-latitude ARs. For future research focusing on Arctic ARs, intercomparison studies are especially needed to better understand the Arctic AR uncertainties due to AR detection algorithms and/or datasets. The results presented in this study can serve as a good starting point for addressing the limitations discussed above.

Given the critical roles played by the SLP dipole and ARs in determining the occurrence and characteristics of the wintertime extreme warming events, it is important to understand their variability at different timescales and identify large-scale climate modes that are responsible for such variability. An improved understanding on the variability of the SLP dipole and ARs would likely lead to a better understanding and prediction of the Arctic climate across timescales. The results in this study also suggest that a correct representation of the SLP dipole and ARs is key to simulating the occurrence of extreme weather events over the high Arctic at synoptic timescale. As we rely on climate models for future Arctic climate projection, further research is needed to evaluate how well climate models can faithfully represent the SLP dipole and ARs that affect the high Arctic. In this study, we focus on the T2m extreme warming events. It is expected that warming events as such would have a considerable impact on the underlying sea ice. As have been shown in this study, these extreme warming events tend to cluster in time. It would be interesting to further investigate their cumulative effects on the longer-term sea ice growth and the subsequent sea ice melt in the following summer. If a link between the occurrence frequency of such warming events and the subsequent summer sea ice minimum can be established, an improved prediction of the SLP dipole and ARs mentioned above would likely further extend the prediction lead time of summer sea ice minimum.

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Data Availability

ERA5 data can be found at https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

Author Contributions

W.M. conceived the study. W.M. designed the study with contributions from H.W. W.M. performed the analyses and wrote the initial draft of the paper. All authors contributed to interpreting the results, editing, and revising the manuscript.

Competing Interests

At least one of the co-authors is an editor of Atmospheric Chemistry and Physics.

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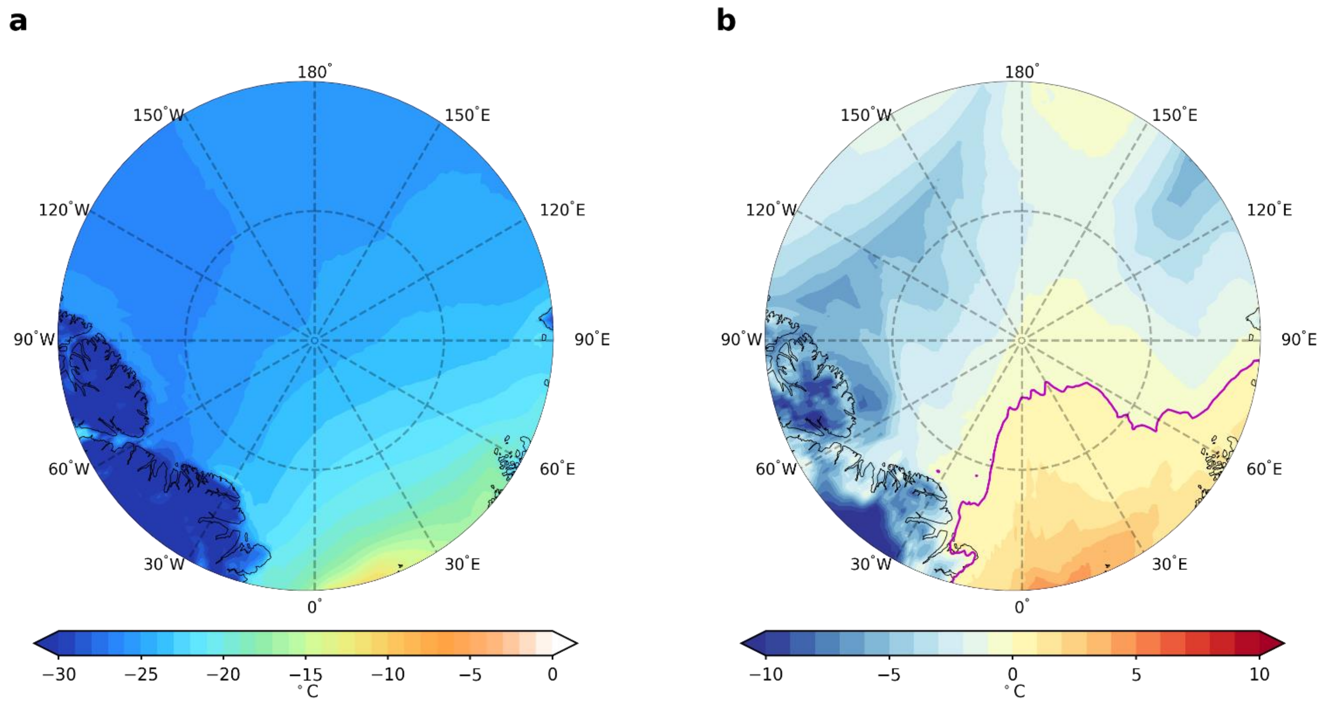
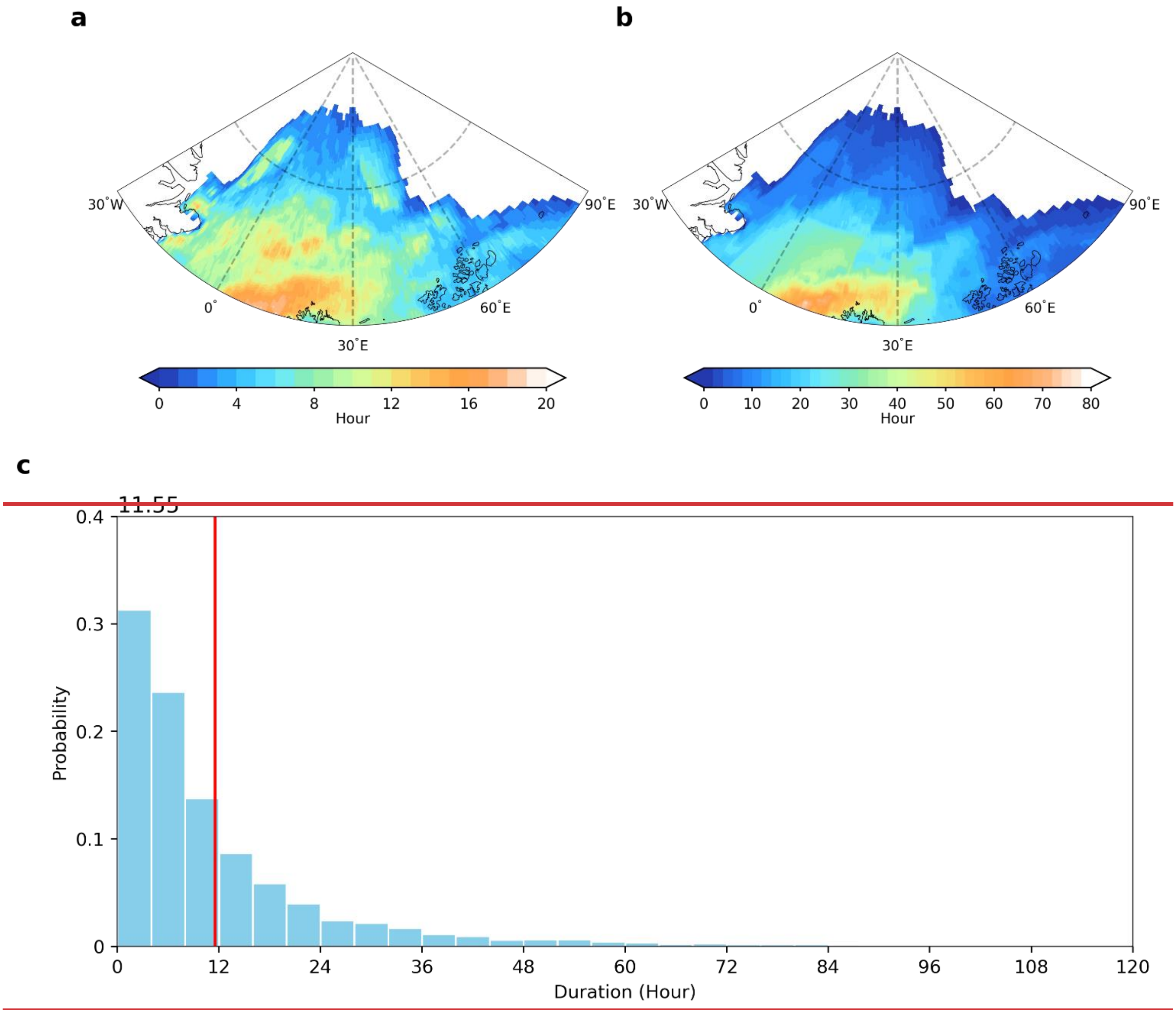


Figure 1. (a) Ttime mean 2-meter air temperature (T2m) and (b) maximum hourly T2m over all winter from 1979 to 2021 in ERA5 reanalysis. The purple line denotes **0**℃.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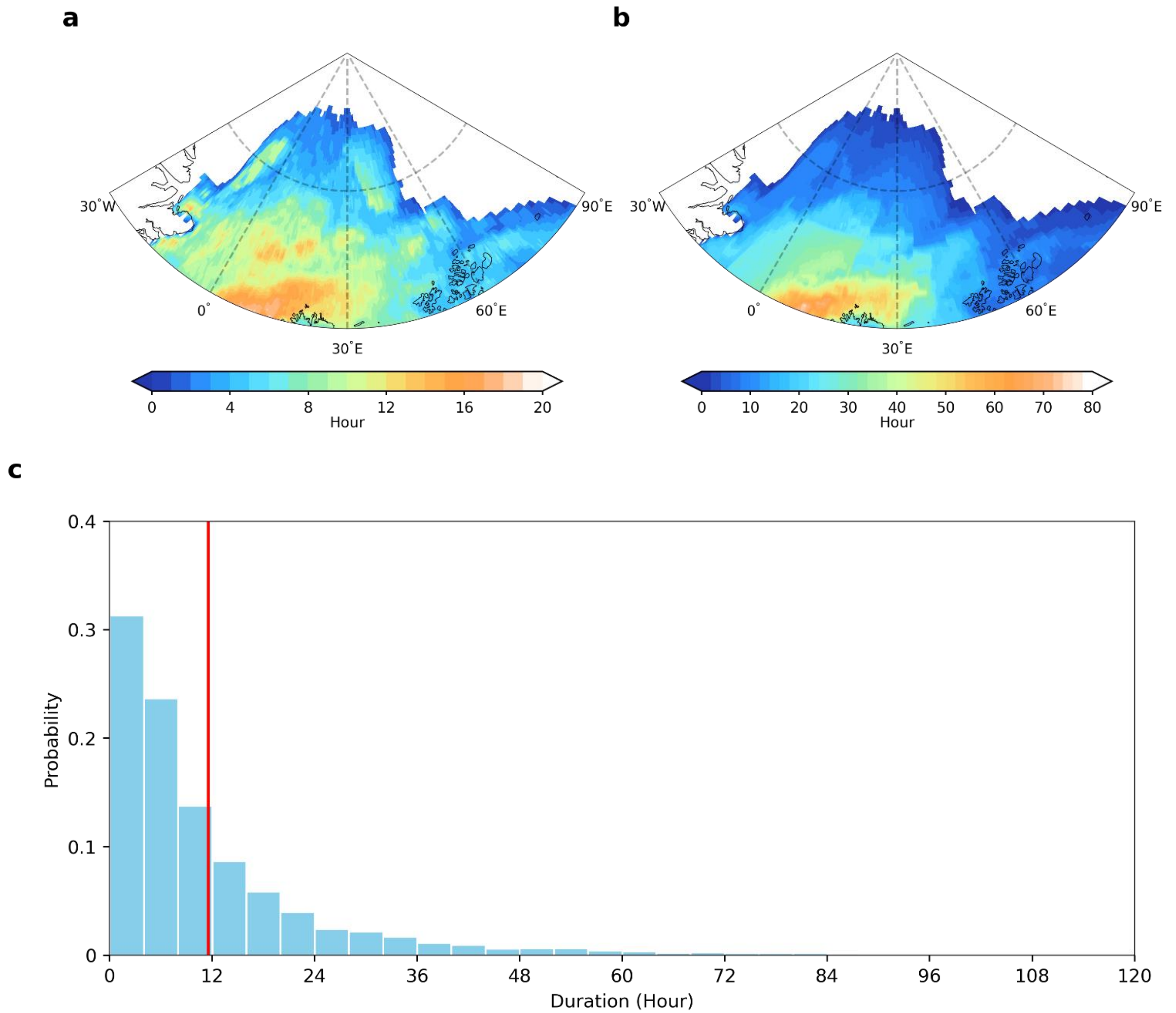


Figure 2. Spatial distribution of the (a) mean duration and (b) extreme duration of the high Arctic extreme warming events defined as a grid point with T2m >= 0 °C. Extreme duration is defined as the local 95th percentile of the duration distribution. (c) Probability density function of the duration distribution for all events happened during winter from 1979 to 2021. The red vertical line in (c) marks the mean of the distribution (11.55 hours).

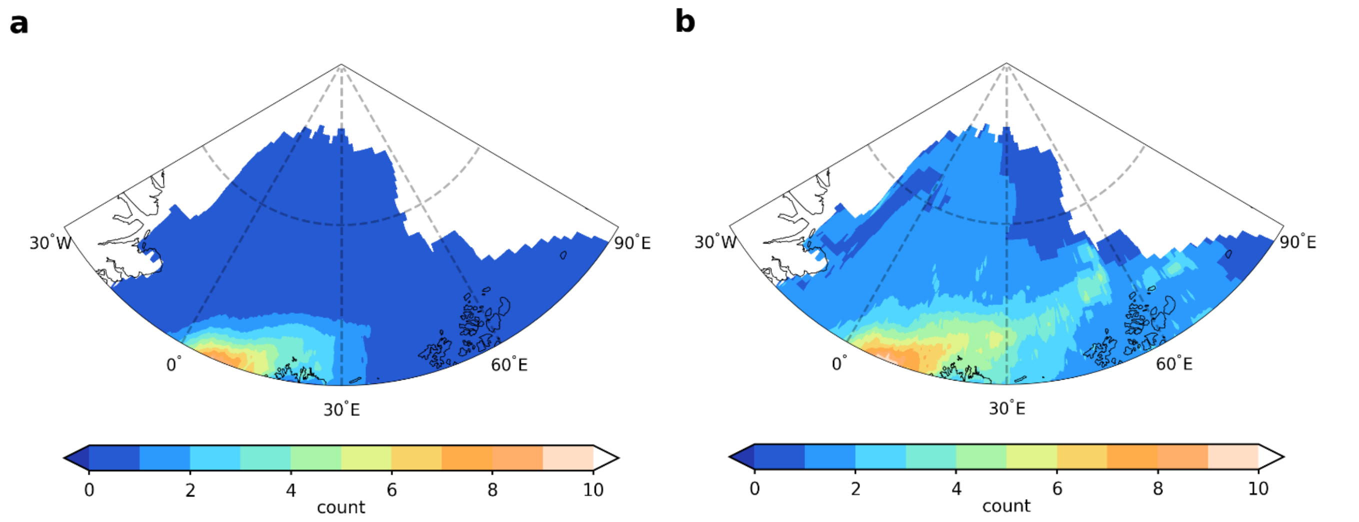
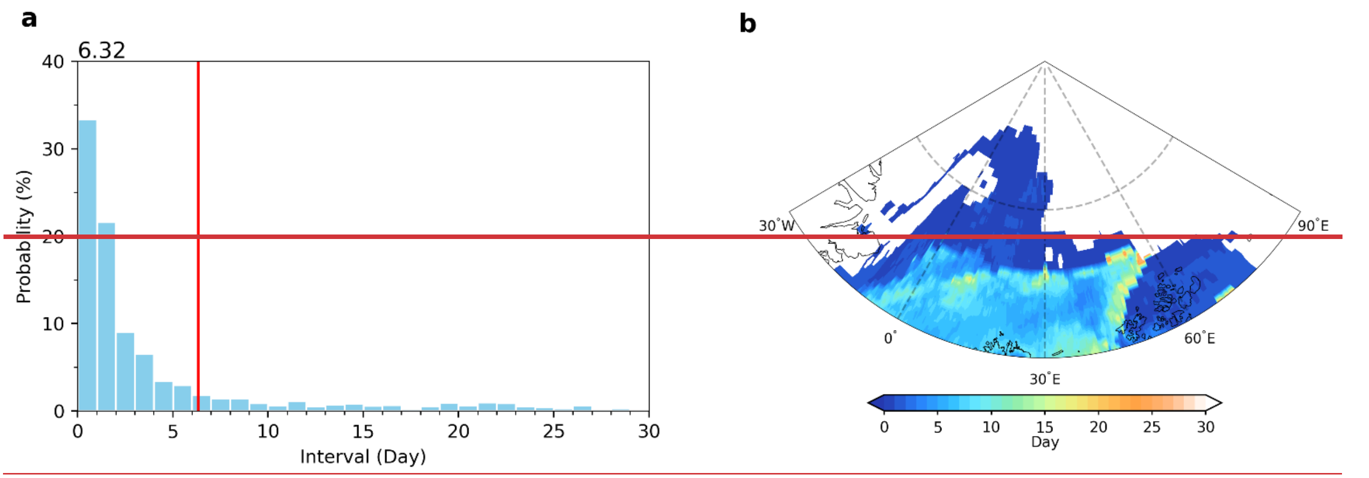


Figure 3. Spatial distribution of (a) the seasonal mean event count for all winters and for (b) only those winters with at least one extreme warming event from 1979-2021.



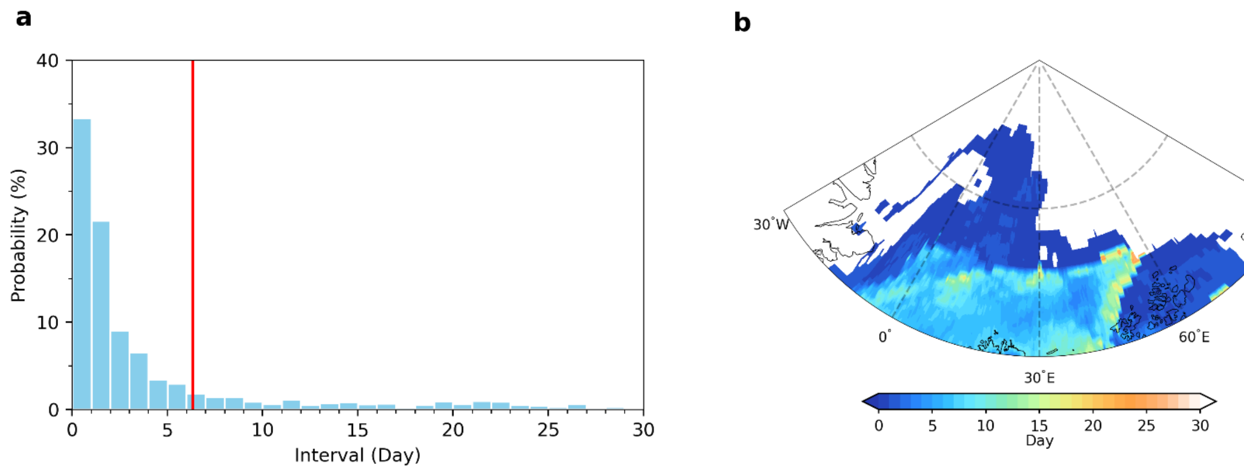


Figure 43. (a) Probability density function of the time interval between the termination of an extreme warming event and the startonset of the following extreme warming event over the same grid point. (b) Spatial distribution for the mean time interval. Grid points never experienced an extreme warming event or less than two extreme warming events within a single winter (thus with a mean time interval of zero) have been masked out in (b) and excluded from (a). The red vertical line in (ae) marks the mean of the distribution (6.32 days).

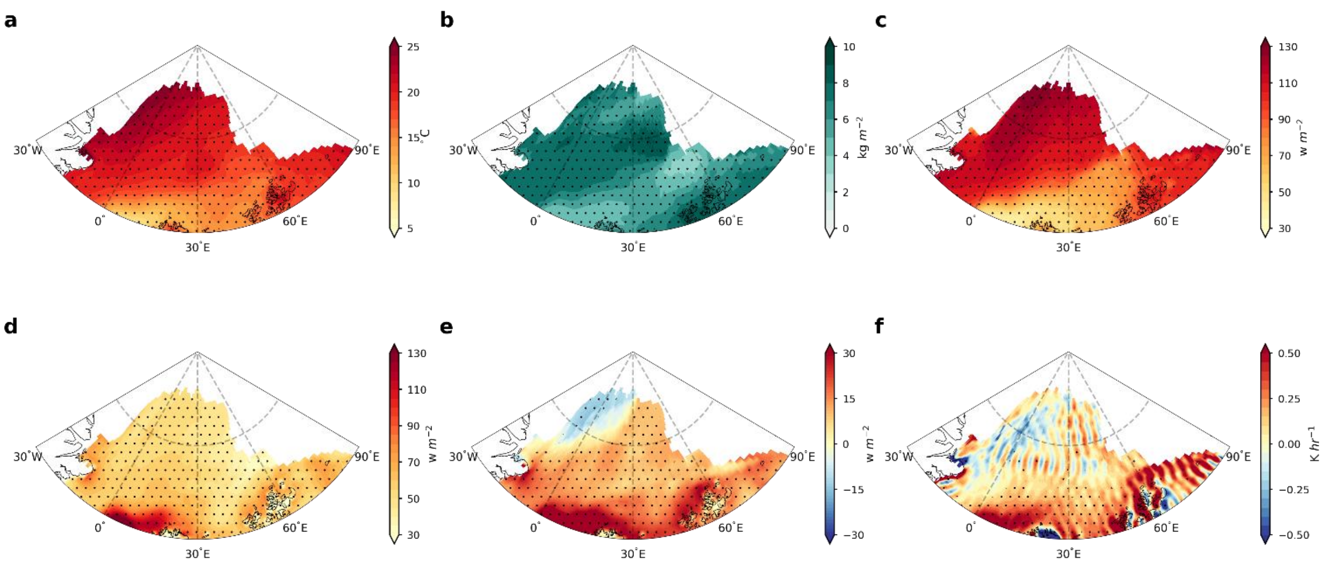
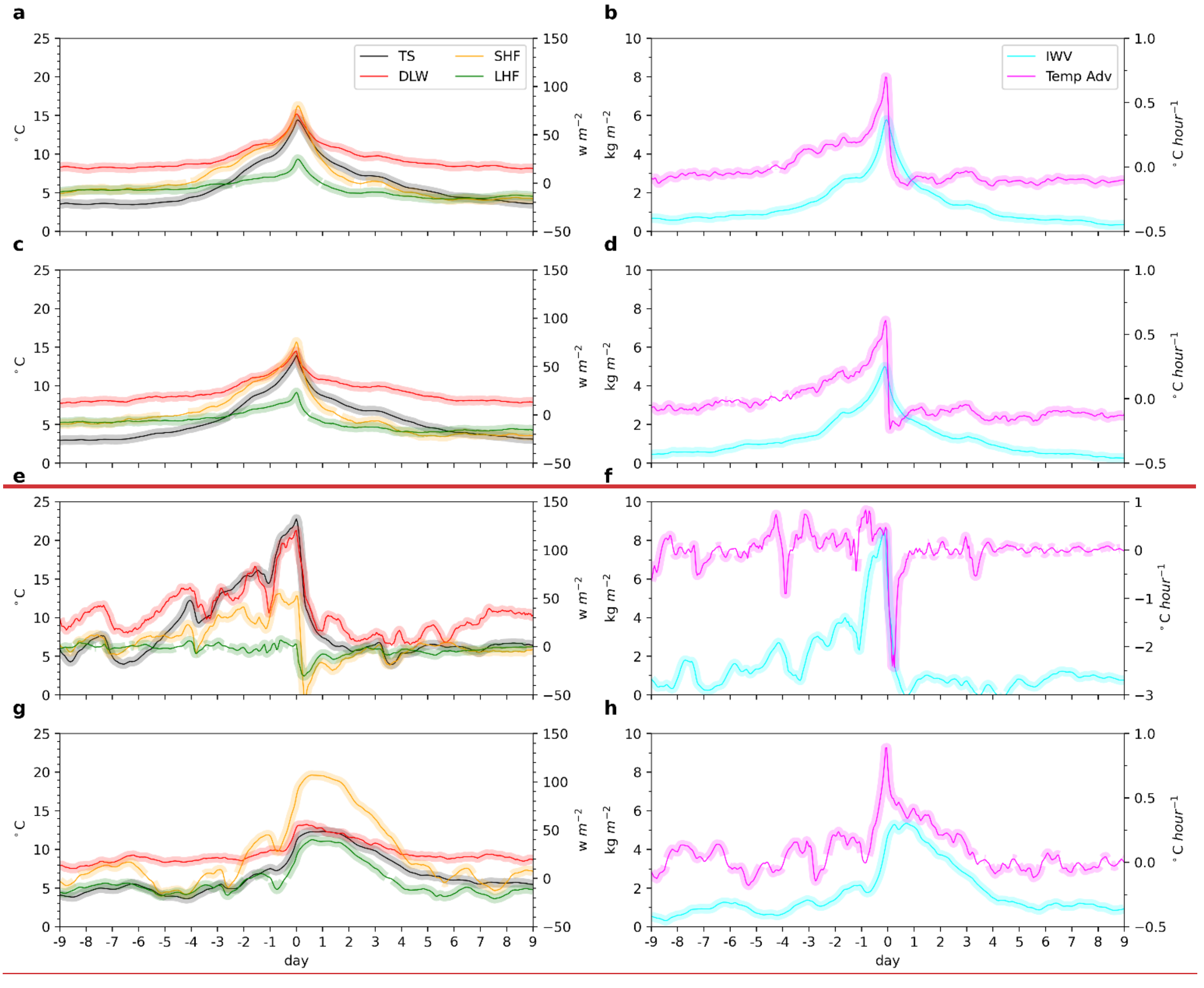


Figure 54. Spatial distribution of the mean anomalies of (a) T2m, (b) column-integrated water vapor (IWV), (c) downward longwave radiation (DLW), (d) sensible heat flux (SHF), (e) latent heat flux (LHF) and (f) horizontal temperature advection averaged over allduring the warming events hours with T2m >= 0 °C over a grid point. Positive values in (d) and (e) indicate fluxes directed from the atmosphere toward the surface. Stippled areas indicate that anomalies are significant at the 0.05 level based on the Student's t-test.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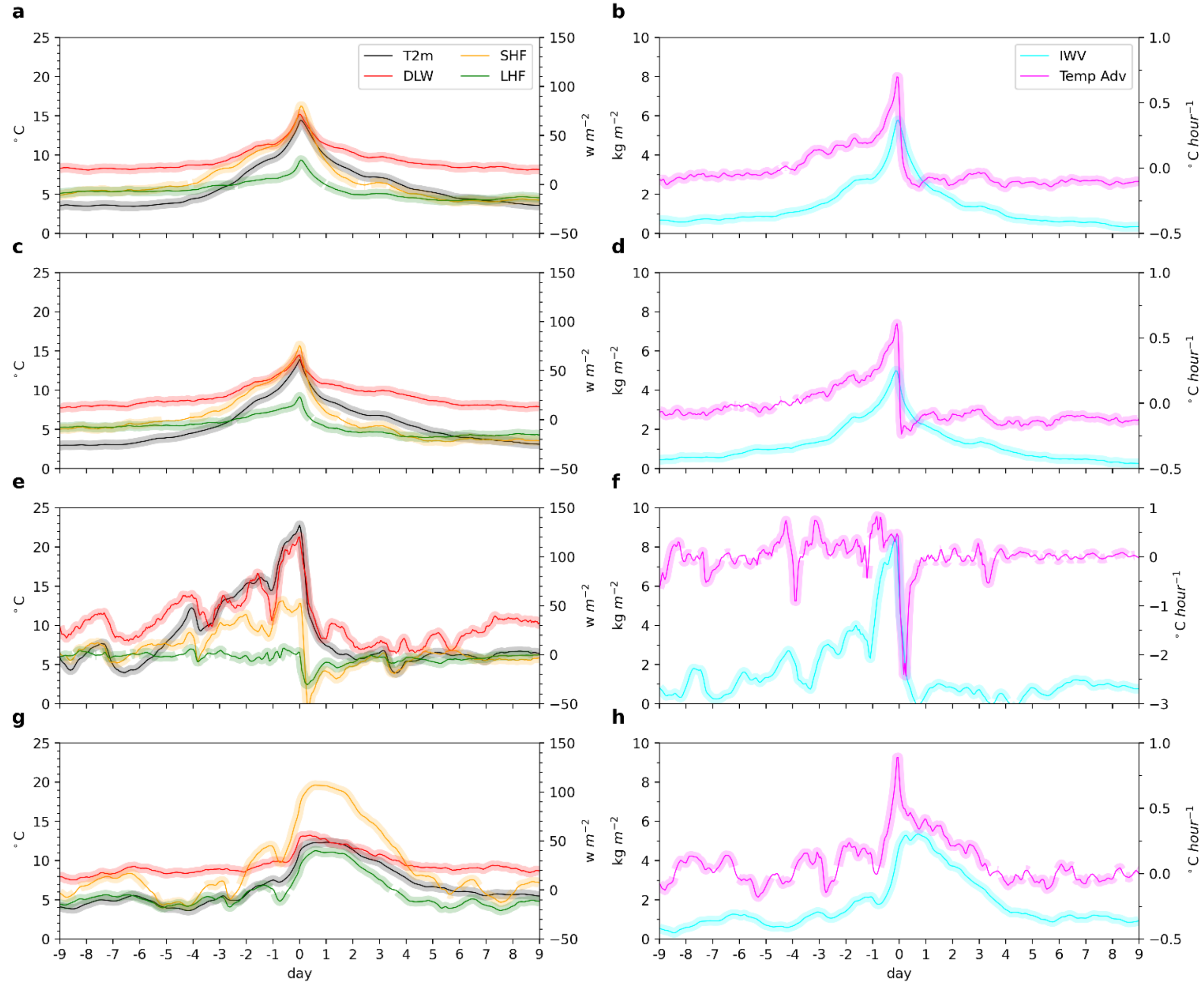
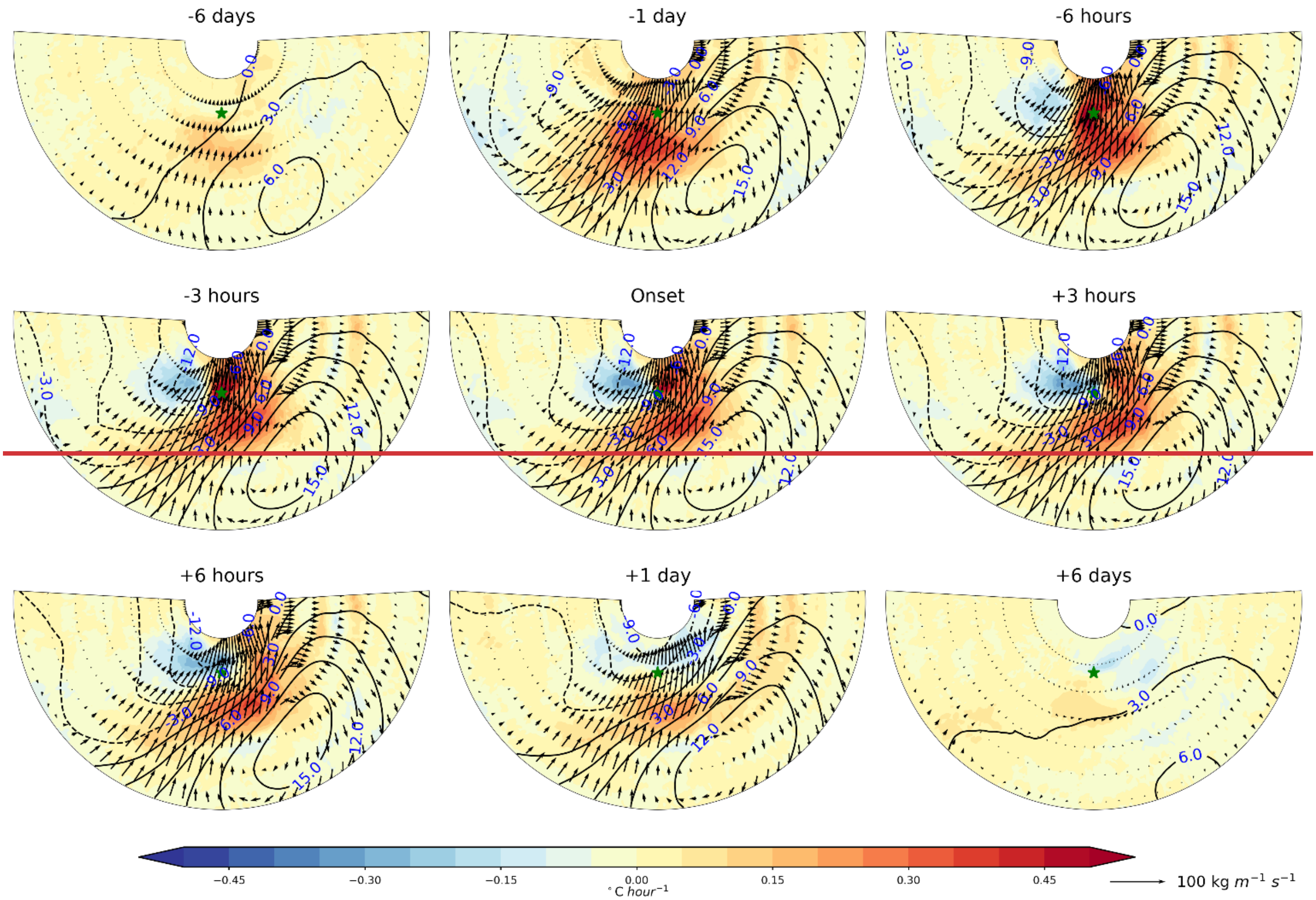


Figure 6~~5~~. Temporal evolution of the anomalies of T2m, DLW, SHF, LHF, IWV and temperature advection for all the extreme warming events defined as any grid points with T2m >= 0 °C (a, b), short duration events equatorward of 83°N (c, d), short duration events poleward of 85°N (e, f), and long duration events (g, h). Note that long duration events occur only over regions equatorward of 83°N. These curves are constructed by averaging the temporal evolution of various anomaly terms across all extreme warming events within the respective groups. There are 191555, 18586, 1642, and 10097 events included in the groups of all events, short duration events equatorward of 83°N, short duration events poleward of 85°N and long duration events, respectively. Day 0 corresponds to the start of an extreme warming event. The shading indicates that the anomalies are significant at the 0.05 level based on the Student's t-test.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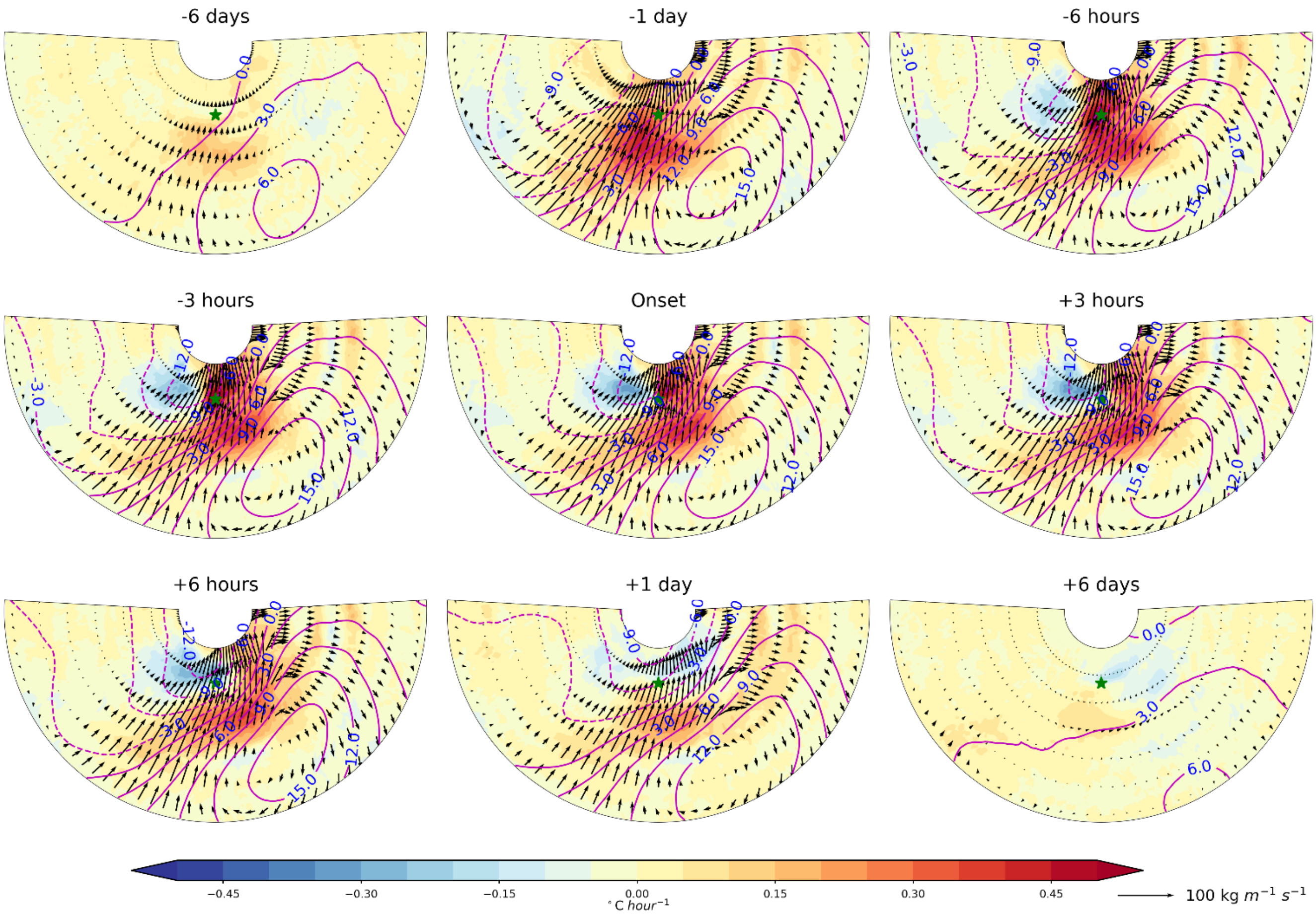
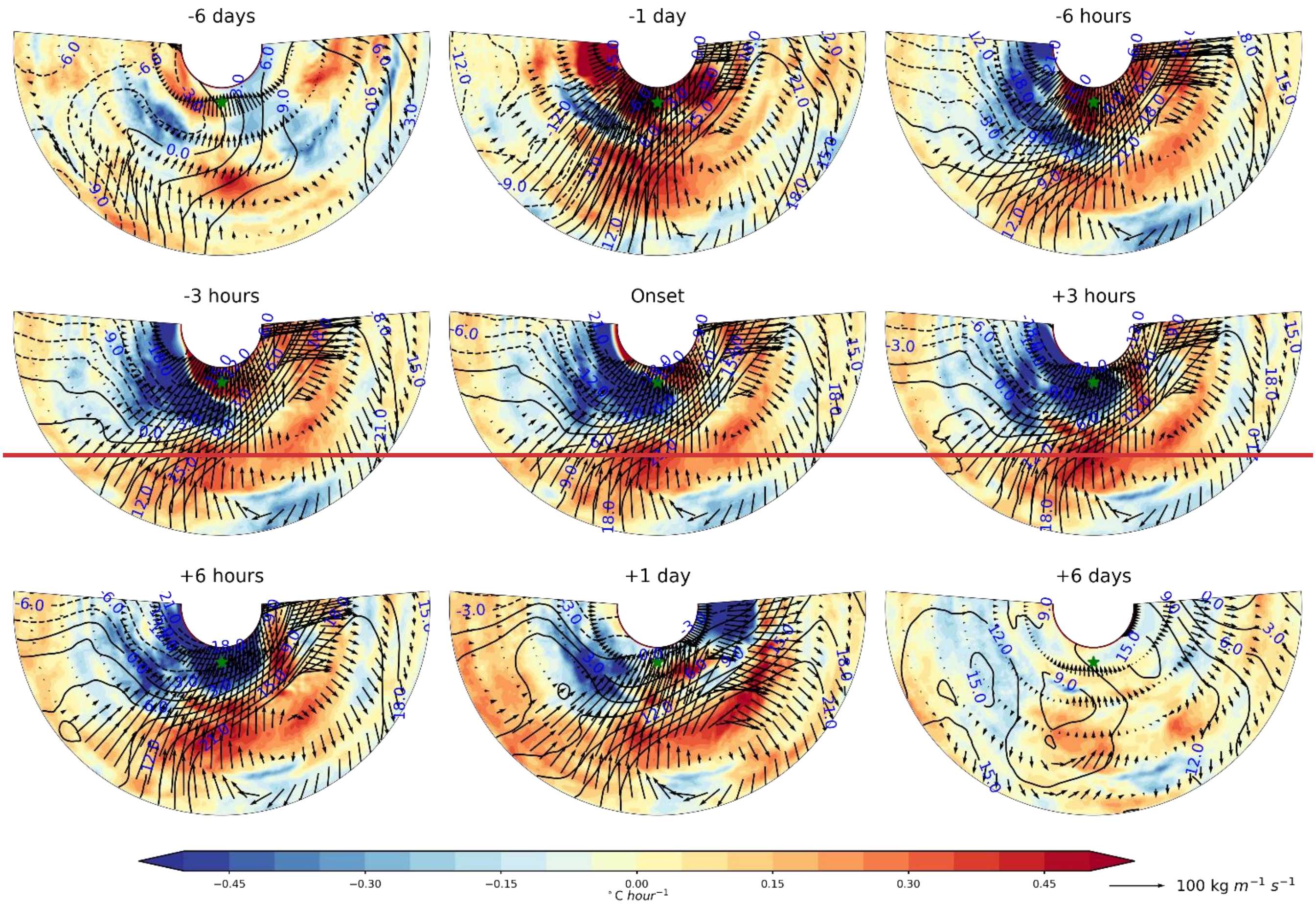


Figure 7~~6~~. Composites centred at the event grid point for the temporal evolution of integrated water vapor transport (IVT) anomalies (vectors), sea level pressure (SLP) anomalies (lines) and temperature advection anomalies (shading) before, during and after the start~~onset~~ of the short duration extreme warming events equatorward of 83°N. The green star in each panel indicates 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.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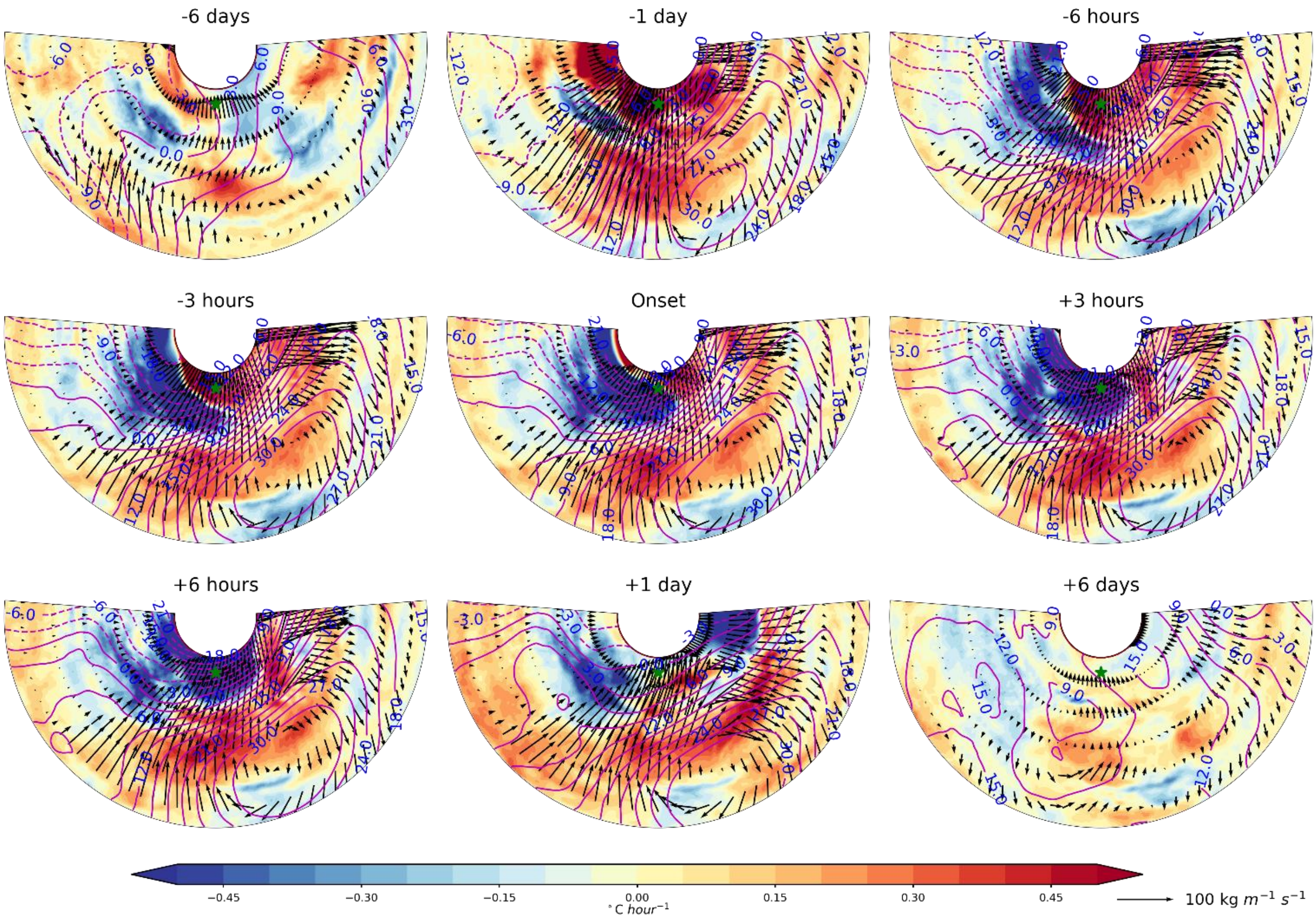
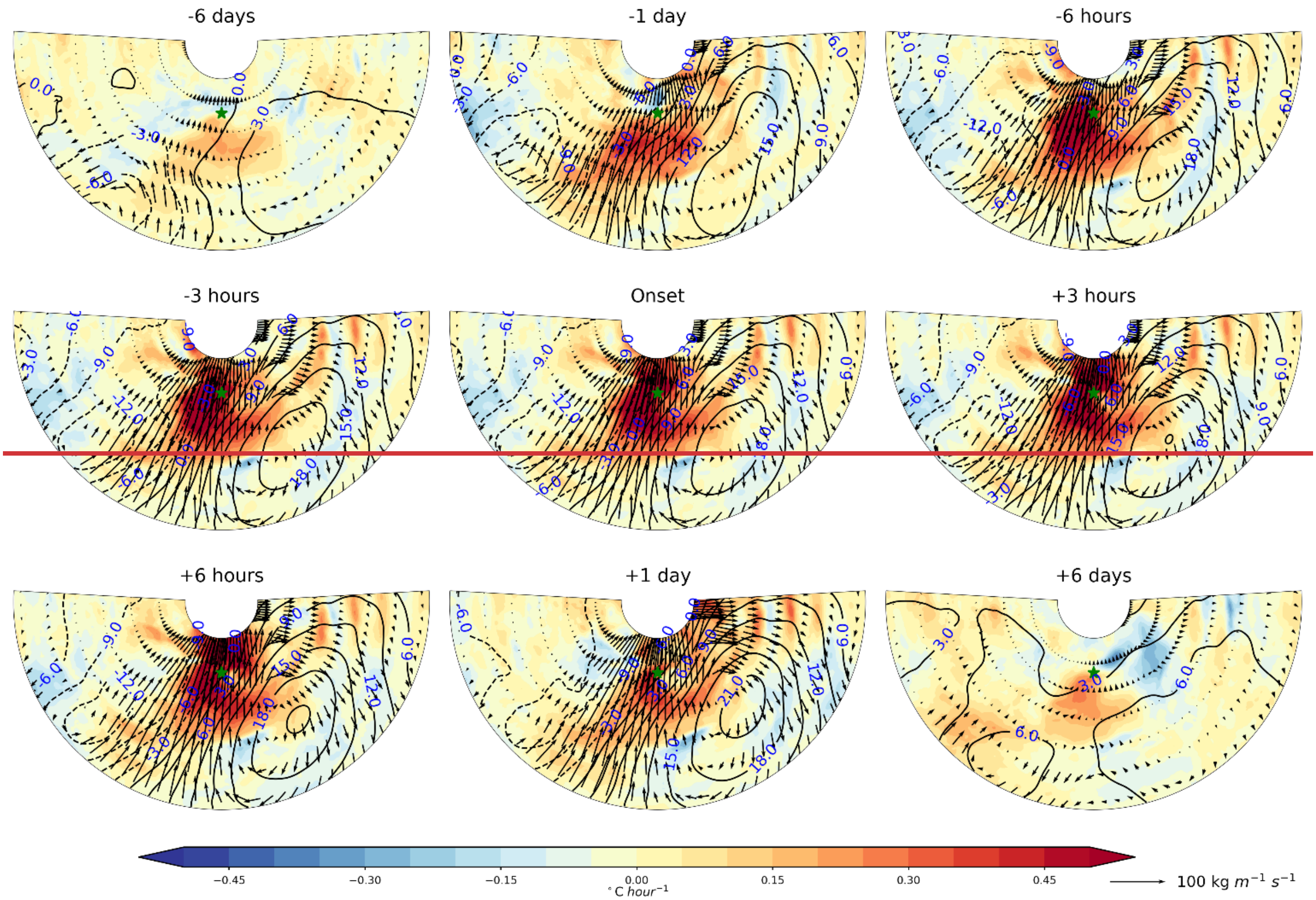


Figure 87. Same as Fig. 76, but for the short duration events poleward of 85°N. Regions 2° poleward, 20° equatorward, 100° westward/eastward of the event grid point are included in the composites.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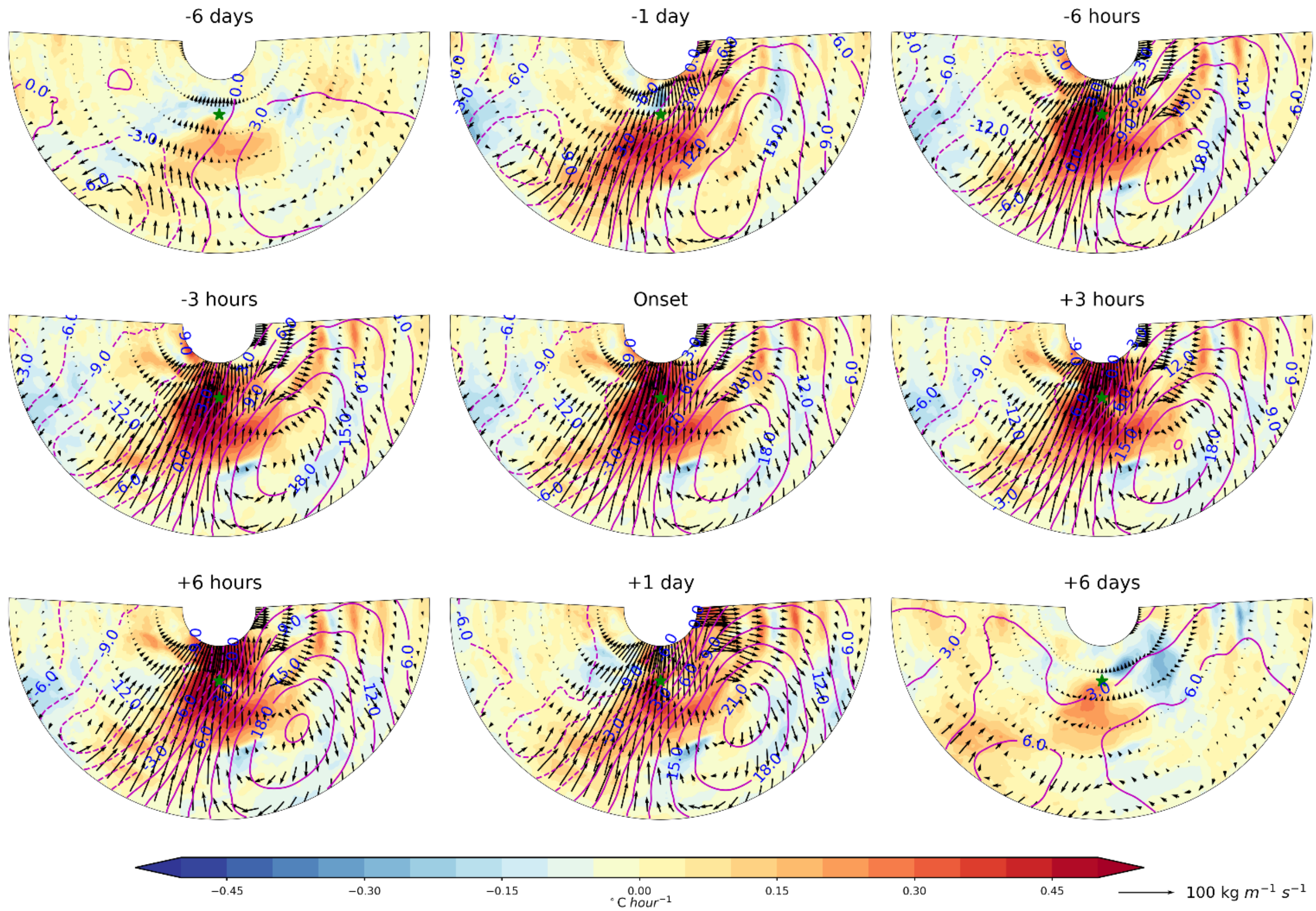

Figure 98. Same as Fig. 76, but for the long duration events.

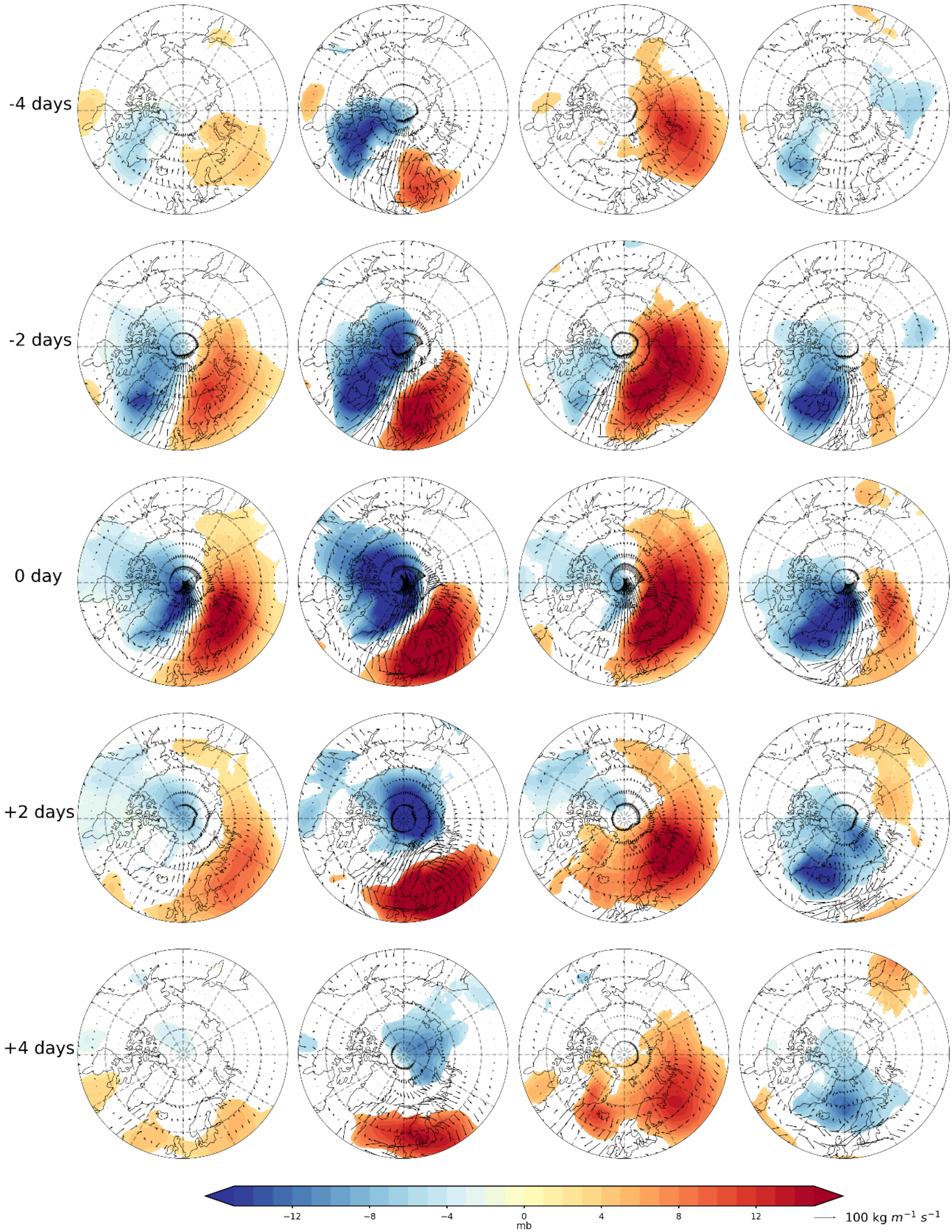
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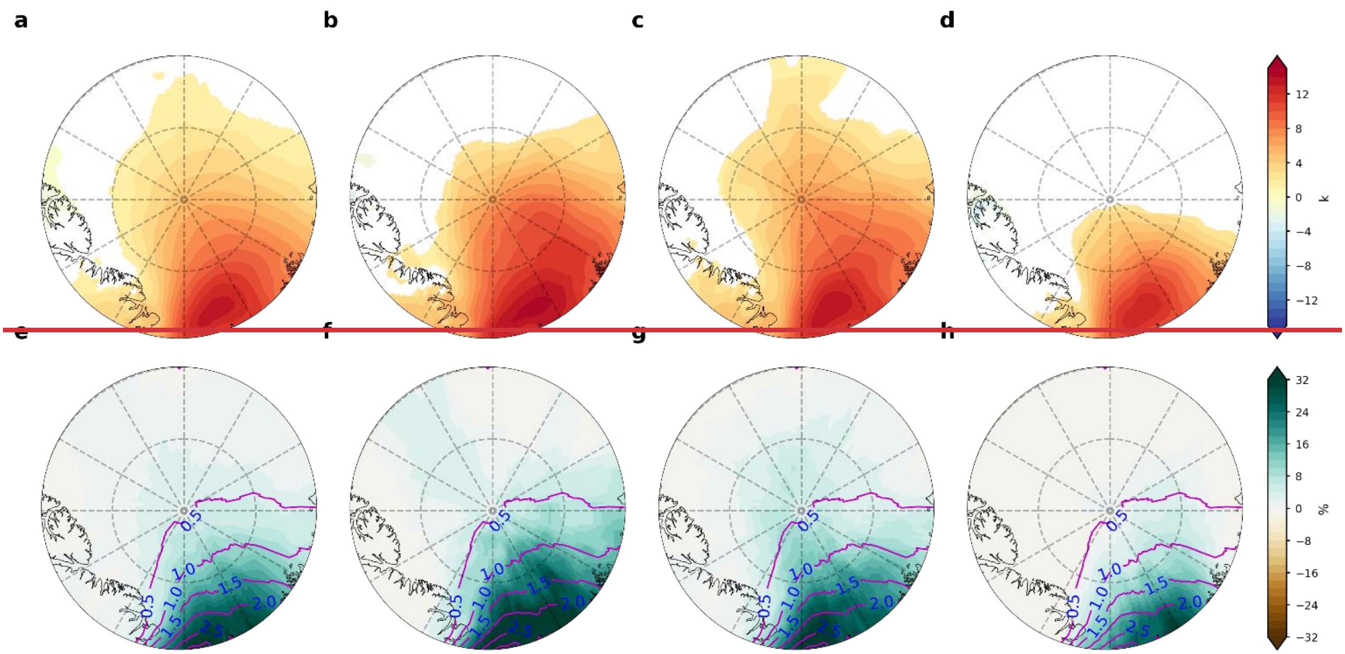
Figure 109. Temporal evolution of the large-scale circulation associated with the concurrent warming events. The shaded contours show the SLP anomalies, and the vectors represent the IVT anomalies. The 1st column describes the composites for all the concurrent warming events. The 2nd, 3rd, and 4th columns show the composites for the 1st, 2nd, and 3rd cluster, respectively, obtained from K-means clustering. Only anomalies that are significant at the 0.05 level based on the Student's t-test are shown. See the definition of concurrent warming events in the text. Day 0 indicates the time with the largest area where temperature exceeds 0℃.



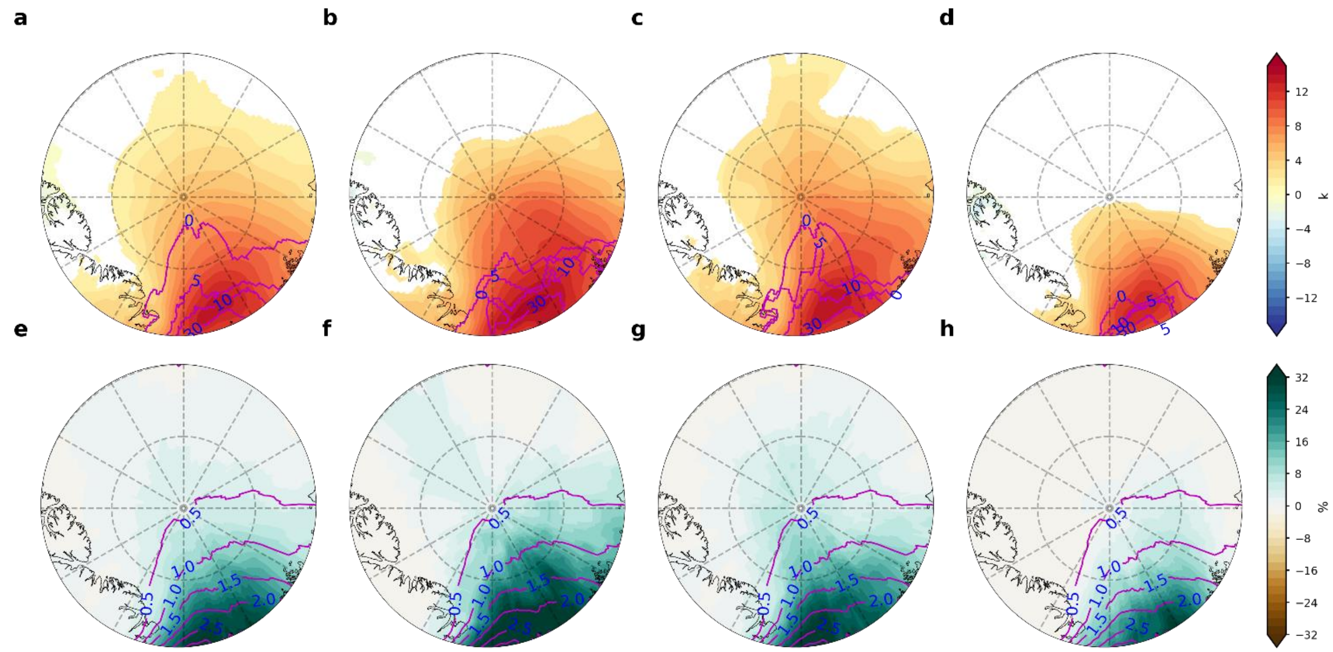


Figure 11~~0~~. Same as Fig. 10~~9~~, but for the T2m anomalies and AR frequency during the peak of the concurrent warming events. The peak of the concurrent warming events is defined as the time when the areas with temperature above 0℃ reach maximum. The purple line contours in (a)-(d) depict the fraction of time when the T2m over a grid point reaches or exceeds 0°C during the peak of the concurrent warming events and (e) – (h) ~~represent~~ the climatology of winter AR frequency.

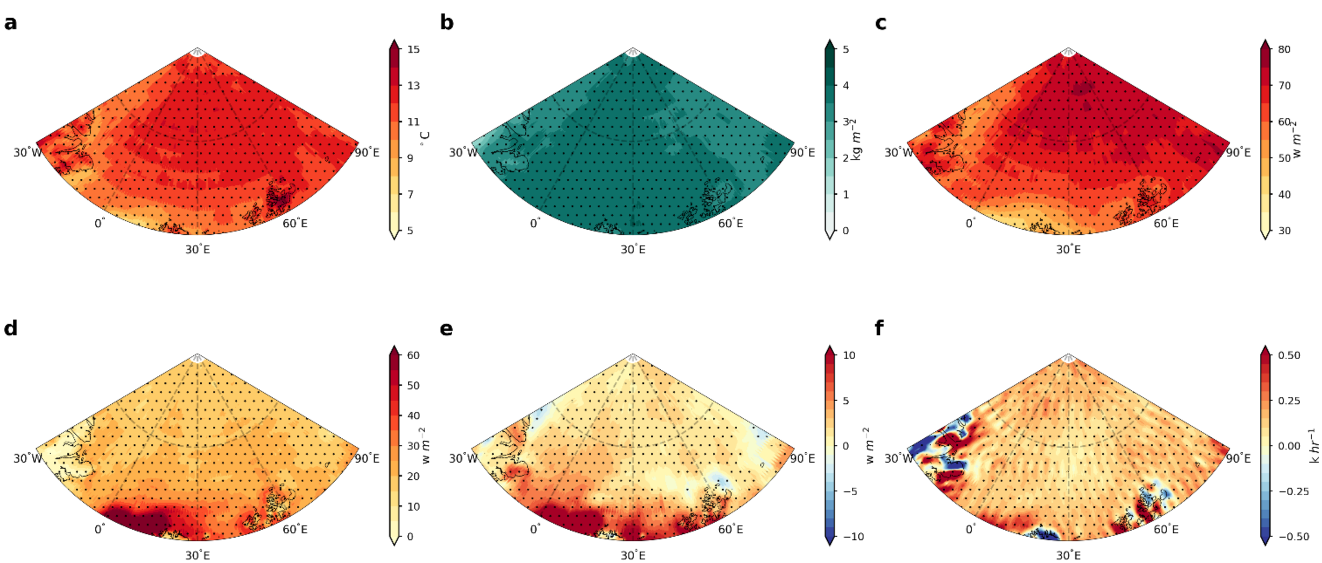


Figure 12~~1~~. Spatial distribution of the anomalies of (a) T2m, (b) IWV, (c) DLW, (d) SHF, (e) LHF and (f) temperature advection during AR days. Stippled areas indicate anomalies are significant at the 0.05 level based on the Student's t-test.

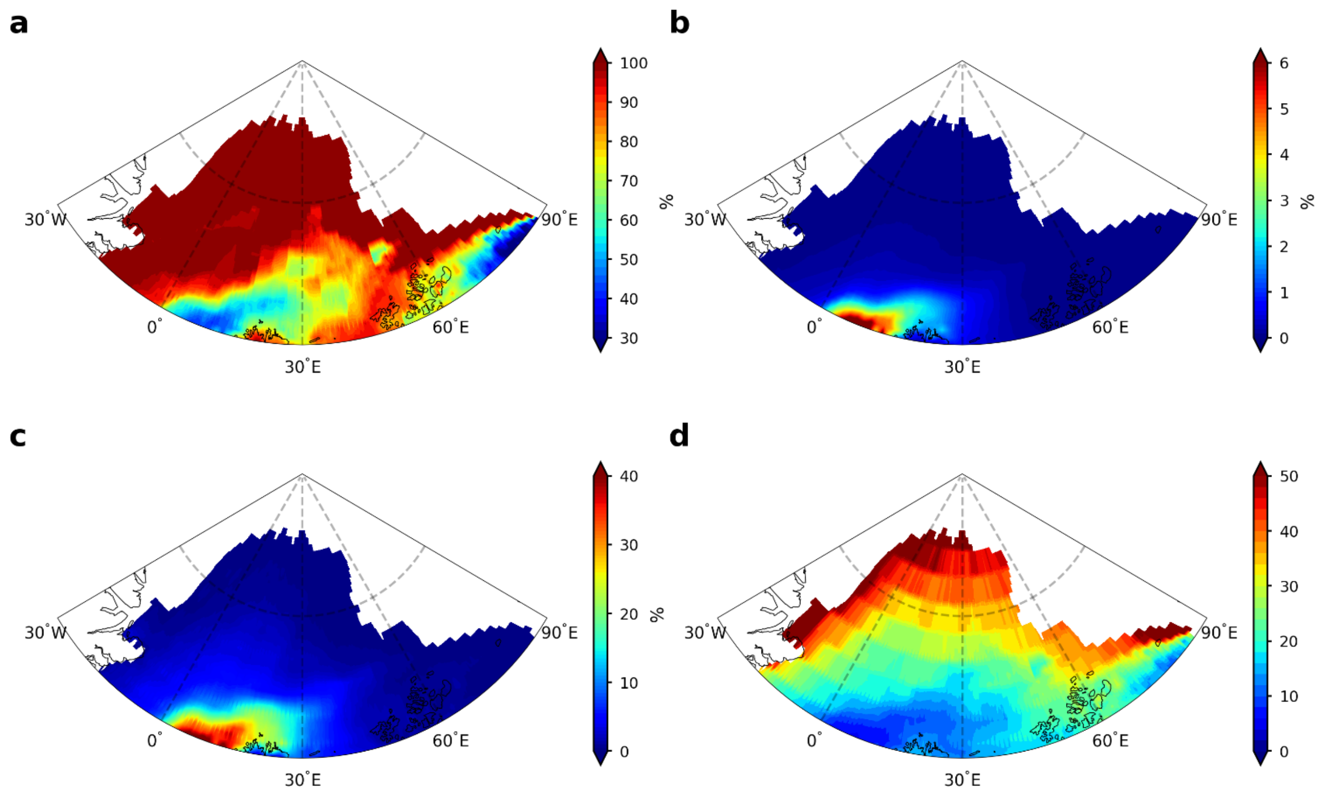


Figure 132. Spatial distribution of (a) the fraction of extreme warming events defined as a grid point with T2m >= 0 °C that occurs during AR days, (b) the fraction of time for all winter hourly snapshots from 1979-2021 with T2m above 0℃, (c) the fraction of time for all AR day hourly snapshots from 1979-2021 with T2m above 0℃, and (d) the risk ratio, which is calculated by dividing (c) by (b).

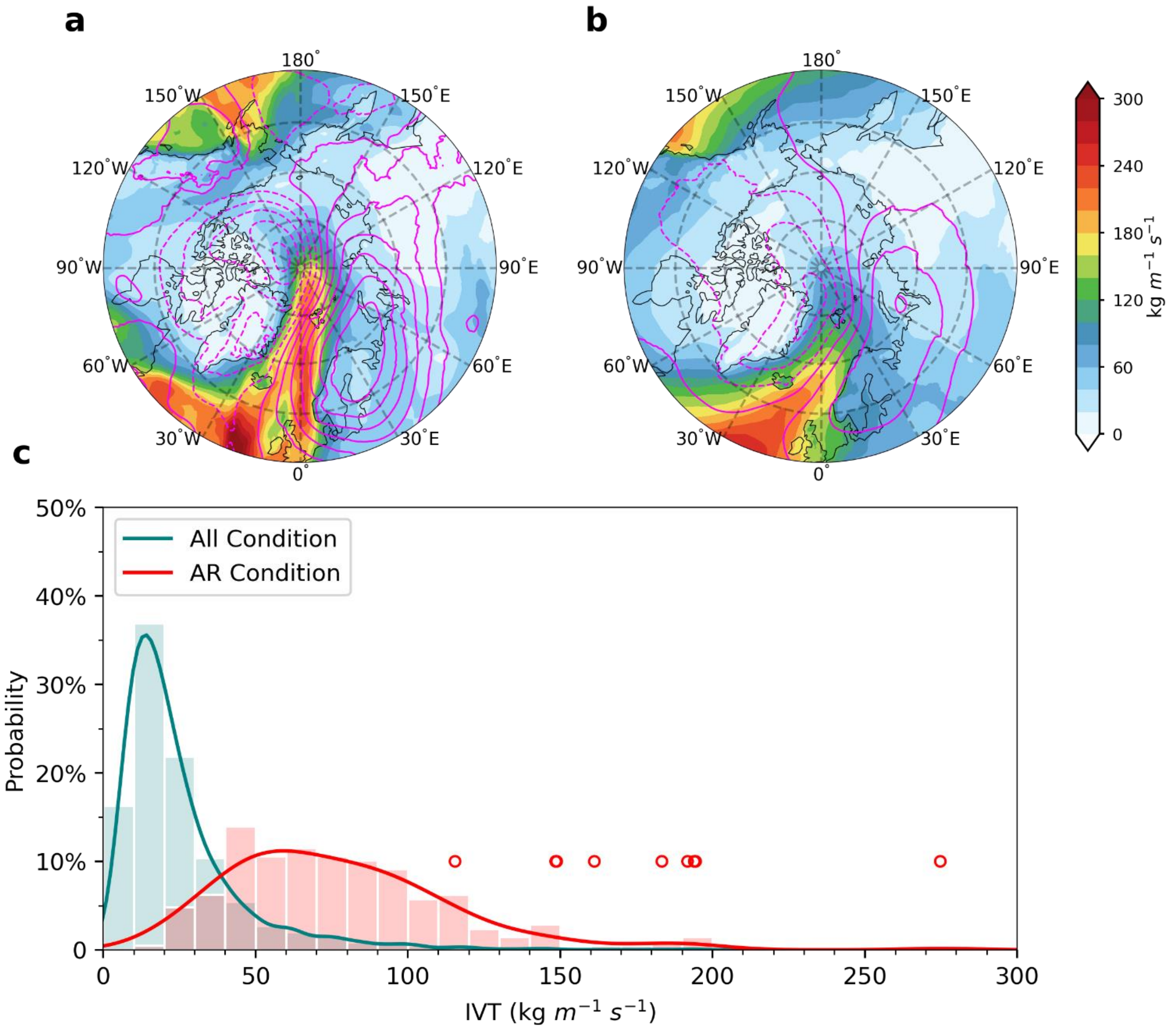
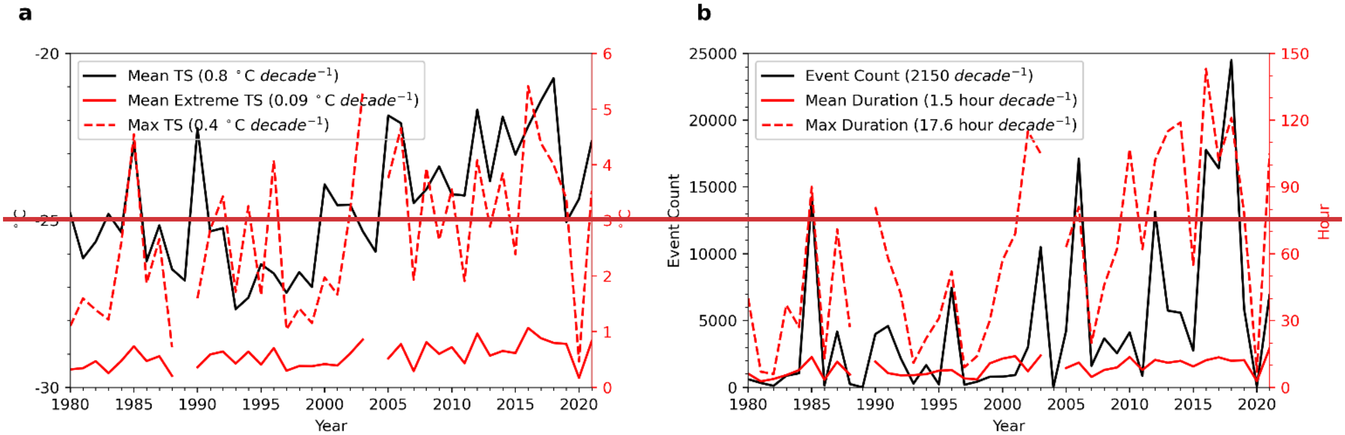


Figure 14~~3~~. Composites of IVT (shaded contours) and SLP anomalies (line contours, solid lines denote positive values while dashed lines denote negative values) for (a) the nine days with extreme warming events occurring poleward of 85˚N, (b) all the days with ARs intercepting 85˚N between 15˚W-60˚E, but no extreme warming events found poleward of 85˚N. (c) Probability density function of the daily IVT averaged over regions poleward of 85˚N and between 15˚W-60˚E. The green bars/line are for all the winter days from 1979-2021, red bars/line are for the days with ARs intercepting 85˚N between 15˚W-60˚E. The open circles are for the nine days with extreme warming events occurring poleward of 85˚N.



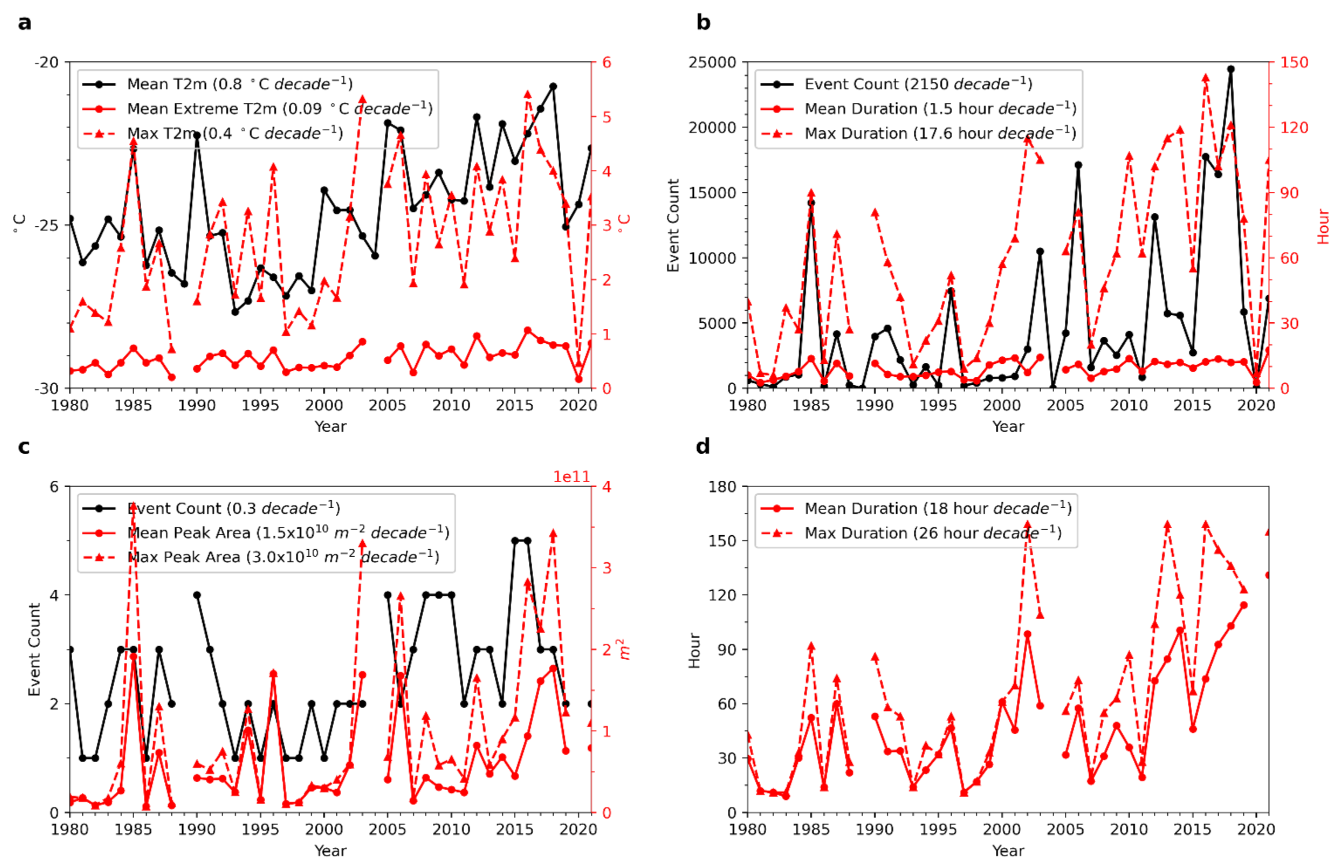


Figure 154. Trends in (a) the area-weighted spatial mean T2m over the entire high Arctic (black solid line with circles), mean T2m only for grid pointsthose above 0°C (red solid line with circles) and the seasonal maximum hourly T2m (red dashed line with triangles) over the high Arctic. (b) is the same as (a), but for the trends in extreme warming event count (black solid line with circles), mean event duration (red solid

line with circles) and seasonal maximum event duration (red dashed line with triangles). (c) and (d) show trends in the characteristics of the 96 concurrent warming events identified in Section 3.3. Trends in (c) the event count (black solid line with circles), mean peak area (solid red line with circles) and seasonal maximum peak area (red dashed line with triangles) of the concurrent warming events. (d) shows the mean duration (red solid line with circles) and seasonal maximum duration (red dashed line with triangles) of the concurrent warming events. For those seasons with only one concurrent warming event, the mean peak area would be the same as the maximum peak area in (c) and the mean duration would be the same as the maximum duration in (d). All trends are significant at the 0.05 level based on the Student's t-test.