Review of "Wintertime Extreme Warming Events in the High Arctic: Characteristics, Drivers, Trends, and the Role of Atmospheric Rivers" by W. Ma et al.

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.

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.

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

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).

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.

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.

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.

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.

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

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?

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?

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).

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.

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?

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?

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.

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.

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".

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.

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).

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.

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.

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.

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

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?

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".

Technical corrections:

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

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

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

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

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

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).

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

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

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

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

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

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"

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

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

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