WCD-2021-18

Identification, characteristics, and dynamics of Arctic extreme seasons

Response to the Reviewers' comments by Katharina Hartmuth, Maxi Boettcher, Heini Wernli, and Lukas Papritz

We thank the editor and both reviewers for their additional, helpful comments. We address each comment point by point below. The editors' and reviewers' comments are given in blue and our responses in black.

Please note, that we always refer to the lines in the **updated, revised manuscript** (document without track changes). We supplement this document with a latexdiff-pdf showing changes since the last version of the manuscript.

Editor

It would be greatly appreciated if the abstract could be streamlined/condensed. Two places where I think this could easily be done: 1) the background/motivation statements (first three sentences), and the main messages from the case studies (L15-L24).

Thank you for this suggestion. We further shortened the abstract.

The reviewers commented that the use of "continuous" (such as in the paragraph starting L284) is a bit confusing. I tend to agree. It's partly because it could mean a succession of positive and negative daily anomalies in X (i.e., a highly variable time series of daily anomalies), which doesn't seem very continuous. Could you come up with an alternative wording?

Thank you for the remark, we think that there may be still some confusion about the meaning of "continuous" in the way we want to use it. As defined in L260ff, a season with a "continuous anomaly" is a season in which the sign of the daily anomaly in a certain parameter does not change during most of the season. This could be, e.g., a season with a positive T_{2m} anomaly on nearly all days of the season (such as for case study DJF 2011/12, see Fig. 9a). In our understanding, the positive T_{2m} anomaly then exists "continuously" throughout a season. Thus, "continuous" does not mean the succession of positive and negative daily anomalies, but rather the opposite (only positive or only negative anomalies). We adapted all relevant lines in the manuscript to clarify the wording. In some places we found it helpful to replace the word "continuous" by the word "persistent".

I'm having a bit of trouble understanding the revised explanation of the 2016/17 case.

Apologies, but we are not sure what causes the trouble. The essence of our explanation did not change since the original submission. The winter 2016/17 was strongly influenced by preconditioning and the very frequent occurrence of CAOs associated with zonally propagating cyclones across the Kara and Barents Seas.

What is meant by "resulting positive relative frequency anomaly" (L446)? Is it just an increased frequency of CAOs?

Yes. The relative frequency anomalies for weather systems as shown in our timeseries (e.g., Fig. 9), indicate the relative occurrence frequency of, e.g., CAOs compared to climatology. Thus, a positive relative frequency anomaly for DJF 2016/17 means that in that winter, more CAOs than usually occurred.

We clarified the meaning of a “relative frequency anomaly” by inserting the following sentence and equation in L393ff:

“The relative frequency anomaly of a specific weather system in a specific season is calculated as:

$$\frac{f_{seas} - f_{clim}}{f_{clim}} * 100$$

where f_{seas} and f_{clim} denote the spatially averaged seasonal-mean weather system frequencies for the season and the climatology, respectively.”

How does the consecutive passage of warm and cold sectors (L445) fit into the explanation?

The consecutive passage of the warm and cold sectors of cyclones through the Kara and Barents Seas in winter 2016/17 is important for the consecutive occurrence of warm air advection, strong precipitation, and enhanced sea ice melt ahead of the cold front and a subsequent CAO behind the cold front (which is even enhanced by the reduced sea ice coverage), leading to intense surface heat fluxes. If, such as in DJF 2011/12, the passage of the cyclones is less zonal and primary the warm sectors of cyclones reach the region of the Kara and Barents Seas, the effects of the warm sector can still be observed, but there is not such a strong increase in CAO frequency and surface heat fluxes.

L185: stronger -> more strongly

Changed as suggested.

L208: suggest: ...of correlations becomes more precise with higher explained variance by...

Changed as suggested.

L231: extra "do" here? Also fix word order: "show either A or B"

Changed as suggested.

L286: "is much larger" - larger than what?

Added “than in summer”: “In winter, the overall T_{2m} variability is much larger than in summer…”

L336: ... to classify the seasonS with... as "extreme seasonS".

Changed as suggested.

L356: summer[s]

Changed as suggested.

L404: "In contrast" isn't right here (CAO frequency is reduced just like cyclone frequency). Maybe "At the same time"?

Changed “in contrast” to “at the same time”.

Fig. 5 caption: The ratio of THE TWO measures...

Changed as suggested.

Reviewer 1

General comments:

The authors evaluate the atmospheric conditions during anomalously extreme seasons in the Arctic. This is performed using a regional principal component (PC) analysis (PCA) from ERA5 data of the first two PCs of all seasons from 1979-2018. The PCA uses six key surface variables and divided spatially into 9 Arctic sub-regions subjectively chosen based on climatological sea ice conditions in either the Nordic Seas, Kara and Barents Seas, and the rest of the Arctic. Results identify 2-3 extreme seasons for each season and in each sub-region. The PCA applied here provides a quantification of how anomalous a season is relative to another season, which variables contribute most to the extreme conditions of the respective season, and how consistent those conditions are during those particular seasons. The authors then choose two extreme or anomalous seasons in the Kara-Barents sea during winter (DJF) and one extreme DJF season over the "High Arctic" to further investigate the synoptic weather conditions that were occurring. The chosen seasons are picked based on their orthogonal, yet anomalous or extreme, projections onto the PCs, as well as their diverse processes.

This research nicely demonstrates how PCs can be used to identify seasonal anomalies and extremes in certain regions of the Arctic. It furthermore demonstrates how to use that information to provide an expectation of how an extreme season was characterized with regard to of one of the six variables and how consistent those conditions were. It is certainly a notable method to identify extreme seasons that might be worth analyzing in further detail at shorter time and space scales if desired. I again thank the authors for their consideration of my comments from the previous version, and now there is a more clear description of the two winter cases (DJF 2011/12 and 2016/17). However, given this extra clarity, I am not sure I agree that the two seasons are "fundamentally" different as stated on line 502.

We changed "fundamentally different" to "differ strongly" (L472).

Otherwise, I don't see any issues and think this should be published once this remaining issue is addressed as described below:

1) Thank you for elaborating on the preconditioning of DJF 2011/12 in the review response. I have re-included my figure from the last revision (Fig. 1), which I think clearly shows the atmospheric response directly over the region of anomalously low SIC would be confined to mainly the KBI region and to some degree KBM during SON. I also included an additional figure showing the SIC anomaly and that the temperature anomalies persist and extend deep in the troposphere almost directly over the region of anomalous SIC through February (Fig. 2). Perhaps due to combining the 3 regions, figure R1 does not capture the negative E∗s due to the more limited area of the surface fluxes while the temperature anomalies more broadly surrounded the region because of a lack of other dynamics moving the air masses elsewhere. Thus, combined with all of the other information, I do not necessarily think the two winters are fundamentally different and share many similarities.

Thank you for the additional explanations. We now avoid the formulation "fundamentally different" because there are indeed also similarities between the two seasons. However, based on our analyses (PCA biplots (Fig. 7), time series of anomalies and weather systems (Figs. 9 and 10), and the preconditioning diagram (Fig. 13)) we conclude that there are important differences that are worth being discussed in some detail.

I do think these extreme cases are an interesting story and should be in this paper. My suggestion would be that since the stories do not end up being very different in my view, that sections 5.1-5.3 could be condensed.

We agree that these sections are detailed, also because of the specific questions and recommendations from the other reviewer during the review process. We think that strongly condensing these sections would not do justice to the curiosity of the other reviewer (and hopefully other future readers). But we carefully checked these sections and shortened several paragraphs where appropriate.

I think this is interesting and is a great demonstration of how sensitive seasonal extremes are to blocking (and how there is still a lot to learn about the onset of blocks). It seems that there was similar preconditioning (positive SST anomalies and negative SIC anomalies) present at the beginning of the season in both cases. In 2011/12, this pattern set up in early autumn following the second lowest September sea ice extent (up to that time) and in 2016/17 it started in the previous late winter or spring. The primary difference appears to be in the atmospheric response.

The amplitude of the negative SIC anomalies at the beginning of the season differs strongly between the two seasons (compare Figs. 9c and 10c, day 1). However, and in our opinion even more important, the amplitude of the positive SST and negative SIC anomalies in the *preceding* seasons do also show large differences, especially in the sea surface temperature, which is about +2.5 K above climatology in autumn 2016 compared to an anomaly of +1 K in autumn 2011. The negative SIC anomaly is similar for both autumn seasons and even a bit smaller in JJA 2016 compared to JJA 2011. However, it existed continuously in the Kara and Barents Seas since autumn 2015, thus most probably (partially) enabled the significantly larger SST anomaly at the beginning of DJF 2016/17. We agree that the atmospheric response to such a preconditioning is not necessarily similar in both seasons. But we think that for example the strong positive SST anomaly at the beginning and during the winter of 2016/17 largely contributed to the increase in CAOs due to increasing the air-sea temperature gradient (additionally to the transport of cold air into the region). For that reason, we think that the (longer-term) surface preconditioning was of higher importance for the unusualness of DJF 2016/17 compared to DJF 2011/12.

For whatever reason, the synoptic patterns were such that they did not favor CAOs in DJF 2011/12 while they did in DJF 2016/17, resulting in different surface fluxes and strong but non-consistently signed temperature anomalies in 2016/17 (i.e., surface cyclone tracks were different because the larger-scale flow pattern was different). Persistent blocking in 2011/12 did not provide a way for heat flux introduced into the atmosphere to be advected elsewhere, while 2016/17 was much more of a transient pattern with less frequent blocks. It is interesting that the larger-scale pattern and block more resembled the SIC anomalies in 2011/12 while not so much in 2016/17, and while these differences are interesting and should be noted, there could be many possible reasons as for why they occurred and therefore I think any additional explanation or speculation is beyond the scope of this study.

We agree and we did not speculate about the reasons why the blocking frequencies differed between the two seasons.

Other specific comments:

1) Lines 490-494: Cyclones also contributed to the low sea ice during the summer of 2016 (e.g., Finocchio et al. 2020; Lukovich et al. 2021).

Thank you for this remark. Indeed, there was some significant sea-ice reduction in the High Arctic following several extreme storms in August 2016 as stated by Lukovich et al. (2021). In this section we do however focus on the Kara and Barents Seas, which were both already ice-free in July, enhanced by already existing anomalies in SIC and SST (Barents Sea) in the previous winter as shown by Petty et al. (2018).

2) In the DJF 2016/17 case study (Section 5.2), the results about that sea ice transport from several cyclones pushes the sea ice edge further north is a little strong with the given evidence. The PIOMAS data in Figure S7 is simply showing the transport vectors. While it looks quite plausible, there are still other factors that can-not be ruled out, such as the impact of waves or upwelling. So I think this part of the discussion on sea ice can be shortened to say that there is an apparent association with sea ice transport and the passage of cyclones.

Thank you for pointing this out. We shortened this part of the discussion to not over-emphasize this seemingly strong relationship between the sea ice reduction and the passage of the cyclones, as other factors could affect the sea ice transport as well.

Reviewer 2

I appreciate the work the authors have done revising the paper. Overall, I am impressed with the amount of work done in this study. The goal to objectively identify extreme Arctic seasons across subregions was ambitious and the authors have successfully achieved it. The case studies are insightful and provide a lot of additional information.

The paper is well written, the analysis is solid and comprehensive. I think what is potentially missing from the analysis is extreme winds (the wind is only mentioned once throughout the paper!); perhaps, this can be covered in future studies. While wind is imbedded into other variables, a strong wind may have a significant direct impact on ecosystems. However, I am not asking for adding this variable to the submitted manuscript.

My very minor suggestion is to show heatmaps Fig.9,10, 14 as a background for time series (frequency anomalies may be indicated in the Captions). In that case, the heat maps will be repeated five times, but it will make easier to related anomalies in variables to a specific circulation regime. I don't know how good this is going to look though. It may also be good to show shading around the running climatological mean as it is hard to say how significant the anomalies are. Lastly, the vertical axis in Fig. 14d can be changed to better represent the range of values (also in Fig. 9d).

Thank you for your comment and the additional suggestions. We added shading around the climatological mean to the timeseries figures (Fig. 9, 10 and 14), which shows the standard deviation of the daily anomalies of the whole study period relative to the transient climatology and is thus a measure of how significant the anomalies are for the winter shown. We further adapted the vertical axis in Figs. 9d and 14d but did not add additional heat map shading, as the plot is already very dense and with the additional shading it would be too confusing.

Fig. 11, caption: to be consistent with (a-c), add '31 January 2017 (day 62)' for (d). SLP is also shown in d, but not mentioned.

Changed as suggested. We further rearranged the figure caption to clarify that SLP contours are shown in (d) as well.

References:

Lukovich, J. V., Stroeve, J. C., Crawford, A., Hamilton, L., Tsamados, M., Heorton, H., Massonnet, F., Summer extreme cyclone impacts on Arctic sea ice, J. Clim., 34, 4817-4834, https://doi.org/10.1175/JCLI-D-19-0925.1, 2021.

Petty, A. A., Stroeve, J. C., Holland, P. R., Boisvert, L. N., Bliss, A. C., Kimura, N., Meier, W. N., The Arctic sea ice cover in 2016: a year of record-low highs and higher-than-expected lows, The Cryosphere, 12, 433-452, https://doi.org/10.5194/tc-12-433-2018, 2018.