Answer to RC2

We thank the anonymous reviewers for their constructive feedback. Please find our answers to their comments below. The original review in italic, our answers in black font below and changes to the manuscript in bold.

1) The investigation makes use of Jakob Runge's causal-effect network's approach. Methodologies of this general type are now in fairly common use in numerous fields (including climate analysis). Having said that, the reader who is not immediately familiar with the design and intricacies of such approaches would not be greatly helped by the brief description of the Runge algorithm presented here at Lines 86-99. The authors should present a broader and more informative qualitative and/or quantitative description of the procedure. This important step will make sure the reader fully appreciates the physical meaning of the results to come.

R1) To start off with a more general introduction to the method we add the following sentences in line 72:

> **Causal-effect networks is an algorithm for causal discovery: the algorithm finds causal links in a dataset without a-priori knowledge on physical mechanisms.**

Additionally, we expand more on the details of the description by adding the following information (new in bold):

> The procedure to find links and gauge their strength is divided into two steps. **In the first, relevant causal and contemporary links for each time series are identified. In the second step, the strength of these links is quantified.**
>
> **To identify the links of a target time series, the correlation between this target time series and, one after the other, all other potentially driving time series are evaluated. For each variable, first the direct correlation is computed and then, in an iterative manner, the partial correlation by including all possible other time series. For all time-series, the time series are also shifted back in time, as the signal in the driven time series will lack behind the signal in the driving time series. This shift is increased from one time step to a maximum time lag tau_m. Only if a link remains significant no matter which subset of time series was included in the correlation analysis, we add another time series to the list of preliminary drivers of the target time series. This procedure is repeated for all time series in the dataset, so that we know all preliminary drivers for all time series.**
>
> In a second step, these preliminary drivers are used to re-evaluate the link strength between each pair of time series by applying multiple linear regression. **We compute the multiple linear regression between a time series, the preliminary drivers of this time series, and, iteratively, one other time series at, one after the other, all possible time lags.**

2) It would also be very helpful to comment on how the structure of Runge scheme compares with other packages which have been used in this sort of investigation. For example, Samarasinghe, S. M., M. C.

McGraw, E. A. Barnes and I. Ebert-Uphoff, 2019: A study of links between the Arctic and the midlatitude jet stream using Granger and Pearl causality. Environmetrics, 30, e2540, doi: 10.1002/env.2540 used Granger causality and Pearl causality in their study of links between lower-latitude atmospheric circulation and Arctic temperatures. They stressed the value of comparing a range of different causality methods to fully understand the relevant processes. This important paper should be cited early in the manuscript as it deals with a topic closely related to the one examined here. Many readers may be familiar with the Granger causality paradigm (C. W. J. Granger, 1969: Investigating causal relations by econometric models and cross-spectral methods. Econometrica, 37, 424-438, doi: 10.2307/1912791. C. W. J. Granger, 1980: Testing for causality: A personal viewpoint. Journal of Economic Dynamics and Control, 2, 329-352, doi: 10.1016/0165-1889(80)90069-x). A few words on how the structure of the present approach compares with that of Granger would be very helpful. (See also the paper of Marie C. McGraw, and Elizabeth A. Barnes, 2018: Memory matters: A case for Granger causality in climate variability studies. Journal of Climate, 31, 3289-3300, doi: 10.1175/JCLI-D-17-0334.1.)

R2) Thank you for your suggestion to include a comparison with a more common approach. We include a paragraph on Granger causality after line 84:

> **Note, that the notion of causation of the causal-effect networks is related to Granger causality (Granger, 1969) which tests whether it is possible to predict the future development of one time-series from the past development of another time series (Runge et al., 2014). Additionally, the first step of the causal-effect networks is an adapted PC-algorithm (Spirtes et al., 2000) based on the idea that we need to exclude common drivers to identify causation (Pearl et al., 2000; Runge et al., 2012).**
>
> **Compared to many other frameworks making use of Granger causality causal-effect networks are very computational efficient even on high dimensions (large N · tau_m), because using results of the first step drastically reduces the complexity of the second step of the causal-effect networks (Runge et al., 2019).**

Additionally, we cite the above-mentioned paper by Samarasinghe et al. (2019) at an appropriate place in the introduction.

3) Lines 17-19: Here also cite the more recent analysis of Simmonds, 2015: Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35-year period 1979-2013. Ann. Glaciol., 56, 18-28.

R3) It is a good idea to start the literature introduction with a study that deals with the connection of the atmosphere (via sea-level pressure) and sea ice in the Arctic as a whole. We change the lines as follows:

> **However, while links from sea ice to large-scale atmospheric processes have been shown (e.g. Samarasinghe et al., 2019; Screen et al., 2018; Luo et al., 2017; Simmonds, 2015), the strongest coupling to the atmosphere is local (Screen and Simmonds, 2010; Screen et al., 2013).**

4) Line 27-28: The reference relating to this important factor is very old. Update this by also referring here to analyses of Lee, S., S. B. Feldstein, ..., 2017: Revisiting the cause of the 1989-2009 Arctic surface warming using the surface energy budget: Downward infrared radiation dominates the surface fluxes. Geophys. Res. Lett., 44, 10,654–10,661. Luo B., and co-authors (2017) Atmospheric circulation patterns which promote winter Arctic sea ice decline. Env. Res. Lett. 12, 054017, doi: 10.1088/1748- 9326/aa69d0.

R4) We included both references within the introduction:

> **Sea ice interacts with the atmosphere on different scales. […] Sea ice influences near-surface temperatures by changing the local energy budget and regulating the moisture and energy which enter the lower atmosphere (Screen and Simmonds, 2010; Screen et al., 2013). This effect is more predominant in all than in spring (Serreze et al., 2009; Serreze and Barry, 2011; Screen et al., 2012). Additionally, downward radiation plays a role in changing the surface fluxes and thereby the surface temperature. Downward radiation has been associated with the moisture fluxes from mid-latitudes into the Arctic, which show a positive trend in recent decades (Lee et al., 2017; Serreze and Barry, 2011).**

5) *Lines 42-47: In this analysis the authors make use of the output of model simulations. They make the argument that they use model data 'to overcome limitations of observations, which are sparse in space and time and not available for all relevant variables'. I find this argument rather weak. Firstly there are a number of quality reanalysis data set which one could argue are the 'best' representation of the 4D atmospheric structure, which use all available observations plus the full gamut of (thermo)dynamic constraints implicit in the assimilating model. These do not extend over a 160-year period used here, but do go back many decades. Another critical issue on this point is that the model used (and indeed any model) will not capture all the appropriate physics, and hence the analysis of causality could be fraught. (Climate model shortcomings are particularly evident in, e.g., air-sea-ice interaction in the MIZ, capturing the Arctic Ocean horizontal and vertical structure, etc.). Overall, the use of model data in investigations such as this can be valuable, and I have no great problem with this here. However, think this justification comment should be presented more honestly, and presented alongside the range of caveats. The authors should remind the reader at appropriate intervals that the results are obtained using simulated data. Also, to make sure that the reader is not misled the words 'simulated' or 'model' should appear in the title.*

R5) To improve on the transparency concerning the use of models we will expand on the above-mentioned paragraph as follows:

> **In contrast to reanalysis, we can run the model with the same forcing several times and can thus produce more data of stable climatic conditions. We are additionally able to compare different time scales and analyse the interactions on a monthly and daily time scale. […] However, for all model and reanalysis studies, it is important to keep in mind that the knowledge we can gain from looking at larger scale is only as good as our understanding of the underlying process we depict in the model.**

We do already include the word 'simulated' in the title and will add more reminders throughout the paper that we are using model data.

6) Lines 53-55: Related to the point of using model data, the authors have not really given us an idea of how realistically the means (and variability) are simulated. The only reference we are given for this is the mean SIC in July, with indications of the max and min (over the 160 years?) in Fig. 2. At least some comment should be made of how realistic this SIC simulation is. Also, the paper the sea ice melt and freeze periods – how well is the SIC simulated at those times of the year? The reader needs to know how well this basic parameter is represented. A worded comparison with the 'climatology' of Cavalieri, D. J., and C. L. Parkinson, 2012: Arctic sea ice variability and trends, 1979-2010. The Cryosphere, 6, 881-889, doi: 10.5194/tc-6-881-2012 should be presented.

R6) We make reference to a detailed comparison of the model results with observational records and reanalysis data within the text. Additionally, we now add observations into our figure and explain, why our model lies on the lower bound of the observations:

> **The model simulations have been validated against observations by (Niederdrenk et al., 2013) and show a realistic mean Arctic climate for this time period. Also, the variability in sea-ice extent and thickness is captured well, being on the lower edge of observations. Due to its high resolution the regional model simulates more realistically than a global model the sea-ice transport within the Arctic (Niederdrenk et al., 2016). For our analysis, we run 40 years repetitively, so we can use 160 years of model output in total. Because the model melts ice directly from the ice edge, as it is not able to simulate realistically land-fast ice and polynyas, it shows less ice within the Laptev Sea compared to observations (see Fig. 4). Nevertheless, the variability of the models lies within the observational records. For this time period the output does not show a drift in sea-ice cover in the Laptev Sea (see Fig. 4) as sea-ice decline accelerated only in the nineties.**

7) Line 86: Python (sp.)

R7) Thank you! Spelling was corrected.

8) *lines 132-133: A nice aspect of the paper is that it deals with both monthly and daily timescales. This dual perspective is a very important, as dealing only with the timescales beyond the synoptic time scale misrepresents the important associated with the presence of cyclones and fronts. These synoptic features exert great impact on the surface-atmosphere fluxes and sea-ice distribution. I strongly suggest this significant part of the analysis be emphasised here, and make reference to the following very relevant papers – Screen JA et al. (2011) Dramatic interannual changes of perennial Arctic sea ice linked to abnormal summer storm activity. J. Geophys. Res. 116: D15105 doi: 10.1029/2011JD015847 Simmonds et al. (2012) The Great Arctic Cy- clone of August 2012. Geophys. Res. Lett. 39: L23709 doi: 10.1029/2012GL054259. Rudeva and co-authors (2014) A comparison of tracking methods for extreme cyclones in the Arctic basin. Tellus 66A: 25252 doi: 10.3402/tellusa.v66.25252.*

R8) We included the papers and highlight the usage of daily AND monthly data within our introduction (Line 42 and following):

> **We are additionally able to compare different time scales and analyse the interactions on a monthly and daily time scale. Previous studies showed that unusual strong storm activities can change the state of the Arctic sea ice in the long run (Screen et al., 2011; Simmonds and Rudeva, 2012, 2014). Such features on short time time scales, for example the appearance of cyclones, can not be seen in an analysis based on monthly means only.**

9) *Line 139-141: At some places in the text the authors make appropriate comments regarding the links when related, and confounding, processes are considered (e.g., at lines 207-213). This is a case in point here. The authors state that 'All these links have a negative sign: higher sea-ice cover is associated with a decrease in specific humidity, thermal downward radiation . . .'. The ambiguity here is that the specific humidity is directly related physically to the thermal downward radiation, and hence these parameters are not independent. On this connection valuable to reference the remarks of Screen, J. A. et al., 2018: Polar climate change as manifest in atmospheric circulation. Current Climate Change Reports, 4, 383-395, doi: 10.1007/s40641-018-0111-4 and a few words should be added as to how this can be disentangled.*

R9) We add a remark that thermal downward radiation and specific humidity are connected at the above-mentioned location in the results section. Since we feel that an explanation would be better placed in the discussion section, we add the following sentences after line 242:

> **Specific humidity and downward longwave radiation are physically closely related as moist air reflects more longwave radiation than dry air giving raise to the water-vapor feedback.**

The above-mentioned reference only briefly deals with moisture and longwave radiation, we add the reference at a more fitting spot in the introduction.

10) Line 141: Change 'less links' to 'fewer links'

R10) We corrected this.

11) Lines 170-174: This observation in connection with the Greenland High etc. is consistent with the results shown by Luo et al., 2019: Weakened potential vorticity barrier linked to recent winter Arctic sea ice loss and midlatitude cold extremes. J. Climate, 32, 4235-4261. Beneficial to the argument to make reference to that paper here.

R11) We include the above-mentioned paper in the discussion at a suitable place (Line 213 and following):

For high sea-ice cover, **similar to previous results from Luo et al. (2019b),** sea-level pressure patterns resemble the negative phase of the Arctic Oscillation index (AO) – a high over the central Arctic Ocean (Wang et al., 2009). We observe a pronounced high over Greenland. This might hint to Greenland blocking, an event which has been linked to a negative North Atlantic Oscillation index (NAO) (thus also a negative AO).

12) Lines 285-293: The authors remind us here that the study has considered the sea ice only in the Laptev Sea. It would be beneficial here (and elsewhere) to keep in mind that the nature of sea ice-atmospheric circulation relationships are known to depend strongly on the particular subregion of the Arctic that is being considered. In particular, sea ice in the Barents and Kara Seas to the west have considerable interactions with the Eurasian land mass of interest here, as distinct from the Laptev results presented in the paper. This is an important point to make, with some specific cases. In this context make reference to the recent studies of . . . Li, M . . .., 2020: Anchoring of atmospheric teleconnection patterns by Arctic sea ice loss and its link to winter cold anomalies in East Asia. Int. J. Climatol., doi: 10.1002/joc.6637. Luo, Wu, and . . ., 2019: The winter midlatitude-Arctic interaction: Effects of North Atlantic SST and high-latitude blocking on Arctic sea ice and Eurasian cooling. Climate Dyn., 52, 2981-3004. Yao and co- authors (2017) Increased quasi-stationarity and persistence of winter Ural Blocking and Eurasian extreme cold events in response to Arctic warming. Part I: Insights from observational analyses. J. Climate 30: 3549–3568

R12) It makes sense to include comparisons to other regions, and we add the following description of the above-mentioned findings in line to clarify the scope of this study in comparison to other studies (after Line 272):

However, we do not rule out that changes in whole-Arctic sea-ice cover or in other regions, such as the Kara and Barents Sea, can have an impact on land through large-scale circulation, such as connections between sea ice and atmospheric circulation patterns have been shown before (e.g. Li et al., 2020; Luo et al., 2019a; Yao et al., 2017; Ogi et al., 2016).

13) Lines 394-395: Please to present full details of this paper ... James E. Overland, Jennifer A. Francis, Edward Hanna and Muyin Wang, 2012: The recent shift in early summer Arctic atmospheric circulation. Geophysical Research Letters, 39, L19804, doi: 10.1029/2012GL053268.

R13) We inserted the missing doi and numbers in the reference list:

Overland, J. E., Francis, J. A., Hanna, E., and Wang, M. Y.: The recent shift in early summer Arctic atmospheric circulation, Geophysical Research Letters, 39, L19 804, https://doi.org/10.1029/2012GL053268, 2012.

Additionally, we went through all references and included the DOI for all references.

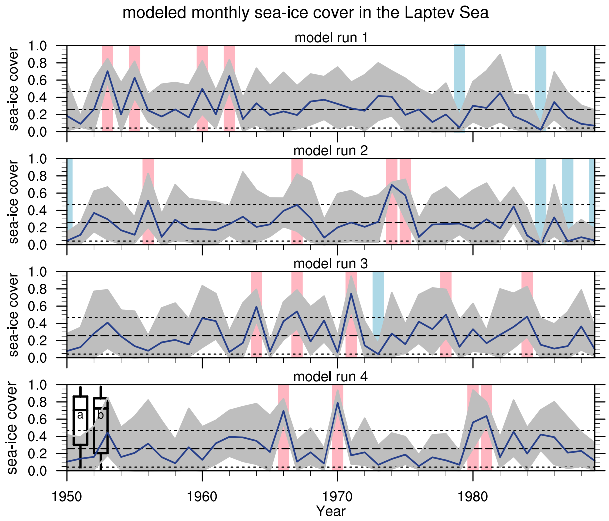

Figure 4. Monthly mean sea-ice cover in the Laptev Sea from June to October in each year. Blue line: mean sea-ice cover over summer and fall period. Grey area: range between minima and maxima of June to October monthly-mean cover. Middle dashed line: average sea-ice cover over all June-to-October means in all years and all model runs, upper/lower dashed line: threshold for composite members (mean plus/minus 1.3 standard deviation), blue/red vertical lines mark composite members for low/high sea-ice cover. The boxplots in the lower panel show satellite data for comparison, using monthly mean ice cover in the Laptev Sea for the month June to October. Box indicates the first and third quartile, middle line the median and the whiskers the minimum and maximum concentrations over all considered monthly means. Data from boxplot (a) taken from the Hadley Centre (HadISST) for time period 1950-1990 (Titchner and Rayner, 2014). Data from boxplot (b) taken from the National Snow and Ice Data Center (NSIDC) for time period 1979-1990 (Fetterer et al., 2016).

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