Reply to the Editor

We want to thank the Editor, David Schroeder, for his work. All suggested changes to the manuscript have been made.
This document comprises of the point-by-point replies to the comments of both reviewers as well as a marked-up version of the manuscript which includes the above-mentioned changes as well as the correction of a few more typos. We also updated the acknowledgements.

Answer to RC1

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

1) First of all, the authors find that the atmosphere mostly drives sea ice conditions in spring, that there's no strong link in summer between sea ice and the atmosphere (nor extending to the adjacent land), but that there's a stronger southward transport of both energy and moisture in low sea ice autumns, when the sea ice starts to freeze again. This is not a new finding. This has been shown before at the pan-Arctic level in several publications by James Screen and co-authors (see e.g. Screen et al., 2012b, 2012a;Screen and Simmonds, 2010) but also others (For example Bintanja and Selten, 2014; Pithan and Mauritsen, 2014; Serreze et al., 2009; Serreze and Barry, 2011). It's surprising that none of these studies have been cited in this paper (although the authors cite another, less relevant, paper by Pithan et al. from the same year. Wrong citation perhaps?). At least some of these should be added next to the papers by Lawrence et. al and Parmentier et al. that are already cited. Btw, the latter found strong correlations only in spring and autumn, but they argued that these correlations were contemporary in spring and only causal in the autumn, which corresponds to the findings by this study (but this is not mentioned here). The work by Graversen et al. is also a nice addition, since it shows a different view on the role of sea ice in arctic amplification (that north-ward atmospheric transport of heat may be more important). An alternate view on arctic amplification is given in the cited paper by Ogi et al but that's a very limited study of just nine weather stations, which is far from enough to grasp the drivers of arctic amplification beyond some local effects. While I appreciate the introduction of causal-effect networks to study ocean-atmosphere interactions, the general conclusions about the role of sea ice in ocean-atmosphere feedbacks are not new and the studied region is rather small, which makes it hard if not impossible to generalize to the whole of the Arctic.

R1) These papers are valuable additions to our introduction. We included the mentioned papers in the first paragraph of the introduction, which we adapted as below. Additionally, we added selected papers as references at appropriate locations throughout the manuscript:

> **To better understand both the mechanisms behind as well as the strength of the interaction between sea ice and land we explore links between sea ice and the atmosphere over land and identify local and large-scale drivers of sea-ice cover in the Laptev Sea. Sea ice interacts with the atmosphere on different scales. 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). 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 fall 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). Little attention has been focused on the physical mechanisms through which variability in sea ice influences the atmosphere over land. Nevertheless, from prior research we know that sea ice can exert such an influence on land (Lawrence et al., 2008; Ogi et al., 2016). Changes in the atmosphere over land, which are attributed to declining sea ice, lead to various responses in the permafrost landscapes,**

ranging from increased methane emissions (Parmentier et al., 2015, 2013) to vegetation productivity (Bhatt et al., 2008; Macias-Fauria et al., 2017) and vegetation composition (Post et al., 2013). Thus, a better understanding of the connection between sea ice and land is valuable, especially since sea ice and the permafrost covering adjacent landmasses are both highly vulnerable to climate change. In this paper, we aim for a better understanding of the physical mechanisms behind the connection of sea ice to the atmosphere over land.

Additionally, we added some of the papers also in the discussion to embed our findings better in the literature, like a reference to Parmentier et al. (2015) at the discussion of the fall fluxes.
It is true that our study focus is on a very small region and we make our argument clearer for the choice of the Laptev Sea. Also, in our conclusions we only hypothesize what this could mean for the Arctic as a whole. Please also refer to our answer R9).

2) *Second, the paper starts of by presenting itself as a study where links are investigated between the ocean, the atmosphere and subsequently the land (i.e. permafrost thaw and carbon fluxes). However, despite using a regionally coupled model, they do not appear to have included a land surface model to actually model the response of the land surface (apart from runoff). So, in the end, the response of permafrost and carbon fluxes to changes in the atmospheric forcing due to sea ice decline remains unclear. The authors mention that this study is a first step, but the introduction suggests that this topic will be investigated in more detail – which isn't the case – and the topic doesn't come back until the conclusions as a possible outcome, but it has not been analyzed. So why lead with this topic in the first sentence of both the abstract and the main text if the paper does not deal with this topic at all? Also here, the literature already holds many examples of possible connections which should be acknowledged if this topic is to be studied at a later stage (see e.g. Bhatt et al., 2010; Macias-Fauria et al., 2017; Parmentier et al., 2013; Post et al., 2013).*

R2) We shifted the focus of the abstract by changing the first sentences as follows:

We investigate how sea ice interacts with the atmosphere over adjacent landmasses in the Laptev Sea Region as a step towards a better understanding of the connection between sea ice and permafrost.

All papers mentioned are now also included in the first paragraph of the introduction. See also R1).

3) *Apart from excluding a land surface model, the model setup also raises a few questions. First of all, why only focus on the Laptev Sea and the adjacent land? The regional model appears to have been run for most of the northern hemisphere and repeating the same analysis for other regions should be trivial. It would also show whether the found connections hold up in other regions where sea ice export is strong (e.g. along the coast of Greenland).*

R3) We want to look at physical mechanisms in depth, so we decided that it is more appropriate to focus on one region, rather than comparing several. We chose the Laptev Sea region, because it shows large interannual variability and borders on Eastern Siberia, which is covered by carbon-rich permafrost landscapes. The only other region with comparable interannual variability in the model is the Barents Sea, which is much more influenced by the North Atlantic than the Laptev Sea. Thus, for extracting the influence of sea ice on land, we deemed the Laptev Sea more fitting. Line 54:

The Laptev Sea is one of the key contributors to net sea-ice production in the Arctic (Bauer et al., 2013; Bareiss and Görgen, 2005) and shows large year-to-year variability (Haas and Eicken, 2001) as can be seen in Fig. 2. Its surrounding landmasses are characterized by near-pristine permafrost landscapes.

4) Also, why did the authors choose to run the model for the era before sea ice melt truly began (1950-1989)? This may lead to an underestimation of the role of sea ice in arctic climate feedbacks. If this is to be investigated, why not do this analysis for the period where sea ice started to decline and perhaps compare to the era of relatively stable ice conditions? The authors also repeat the same time period 4 times, but sea ice conditions are quite different between the four model runs. Why is this? It is not explained in the paper.

R4) Our aim is to first understand the underlying processes, before we investigate possibly interacting changes in the processes. Even if we might underestimate the effects of strong changes, we look at stable conditions instead to be able to extract the possibly weak signal from ice better. A possible next step would be to look at climate change.

The model has internal variability: The atmospheric model nearly covers the whole northern hemisphere and, consequently, can evolve freely without strong constrains by the external forcing. This is precisely the reason why we can run the model with the same forcing repeatedly, thereby prolonging the time series, without having the same values multiple times.

5) *Overall, I think that the study is interesting, but the authors appear to present it as more novel than it is, and they should contextualize it better in the existing literature. A lot of work has been done on this topic, and a rather limited regional analysis over a historical time period with stable sea ice cannot be used in this way to draw strong conclusions on how sea ice decline has affected the whole arctic system, including the adjacent land, in recent decades.*

R5) With the adjustments made in the manuscripts it should be clear, that we focus on the climate before warming and that we focus on one specific region.

6) *A diagram of which time periods and variables are compared to each other would be useful. From the text it can be difficult to follow which is being discussed. Perhaps label them?*

R6) We added a table providing an overview over the variables used in each set-up as well as, in the figure description, a summary of the analysis done. The table is appended to this document. This allows for a better overview. We added additional pointers throughout the paper as to which run was used for a certain conclusion.

7) Page 5, line 94: which drivers of variables? Please specify.

R7) To make it clearer, we changed the sentence as follows:

We look at the connection between land and sea ice especially during June - September when vegetation is photosynthesizing, and sea-ice cover is low and variable. This variability accentuates the differences between high and low sea-ice-cover years which is important for the composite analysis.

8) Page 10, line 195-196: why wasn't the causal effect network reanalyzed with long-wave radiation added? Seems important.

R8) Upward longwave radiation and temperature are highly correlated as the atmosphere is heated from below. To account for an influx of warm air (or cold air) we include the latitudinal and longitudinal temperature and moisture transport. Upward longwave radiation is also more directly connected to sea-ice cover than temperature. To reduce redundancies, we did not include upward longwave radiation in the analysis.

9) Page 14, line 317-321: this conclusion is a rather big statement for an analysis of a limited area during an era of stable sea ice. It's not supported by this study nor the existing literature. Perhaps the link to land has been weak for the Laptev region during 1950-1989 but that doesn't mean it hasn't been strong in the past two decades in the same region or other parts of the Arctic!

R9) With the changes below, the restrictions of the study are clearer.

A general warming and an enhanced hydrological cycle are key features of global climate change (Stocker et al., 2013; Huntington et al., 2006). In our model study we find that lower than usual sea ice in the Laptev Sea causes warming and an increase in air moisture over land, which might add to the above-mentioned trends. Nevertheless, we found the link from sea ice to land to be weak under stable conditions, and, if this relation holds under different conditions, we expect climate change over land to be driven primarily by large-scale circulation.

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 $N \cdot tau_m$), 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.

Analyzing links between simulated Laptev Sea sea ice and atmospheric conditions over adjoining landmasses using causal-effect networks

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Abstract. ~~Studies based on satellite observations have shown that sea-ice cover and temperature in the Arctic tundra correlate well, and links between the two components have been suggested. We investigate links between sea ice and the state of the atmosphere over the adjacent landscapes with a focus on~~ We investigate how sea ice interacts with the atmosphere over adjacent landmasses in the Laptev Sea ~~, a marginal sea of the Arctic Ocean, which had highly variable summer~~ Region as a step towards a better understanding of the connection between sea ice and permafrost. We identify physical mechanisms as well as local and large-scale drivers of sea-ice cover with a focus on one region with highly variable sea-ice cover ~~over the last century~~and high sea-ice productivity: the Laptev Sea region. We analyze the output of ~~a coupled~~ coupled a ocean-sea ice-atmosphere-hydrological discharge model ~~under the climate of the last century utilizing composites of high and low sea-ice cover and a recently developed method called Causal Effect Networks, which identifies temporal links among one-dimensional time series. Assuming that these temporal links indicate causation, we investigate how sea-ice cover may influence the atmosphere over land. We identify the main mechanisms driving ice melt in spring and refreezing in fall~~with two statistical methods. With the recently-developed causal-effect networks we identify temporal links between different variables, while we use composites of high- and low-sea-ice-cover years to reveal spatial patterns and mean changes in variables.

~~In the model , ice melt~~ We find that in the model local sea-ice cover is a driven rather than a driving variable. Springtime melt of sea ice in the Laptev Sea ~~was~~ is mainly controlled by atmospheric large-scale circulation, mediated through meridional wind speed and ice export. ~~Thermodynamic~~ During refreeze in fall thermodynamic variables and feedback mechanisms ~~were important during refreeze~~ are important - sea-ice cover ~~was causally connected to~~ is interconnected with air temperature, thermal radiation and specific humidity. ~~Low ice cover led~~ Though low sea-ice cover leads to an enhanced southward transport of heat ~~, and moisture and low ice cover was linked to higher temperatures and higher humidity over land. However~~and moisture throughout summer, links from sea-ice cover to the atmosphere over land ~~were~~ are weak, and both sea ice in the Laptev Sea and the ~~adjacent landmasses were mainly driven externally.~~ atmospheric conditions over the adjacent landmasses are mainly controlled by common external drivers.

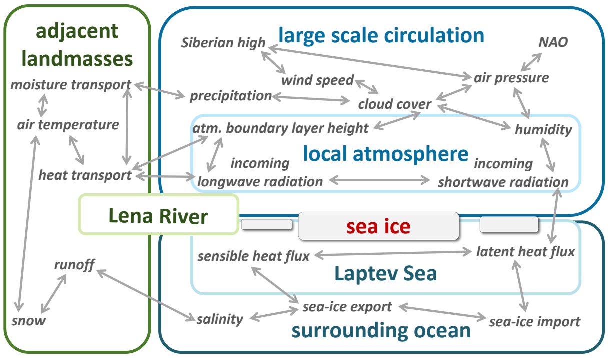

Figure 1. The regional climate system divided into general components (Laptev Sea, local atmosphere, adjacent land), which are embedded in the global climate system (surrounding ocean, atmospheric large-scale circulation) and interact with each other through a range of mechanisms including feedback loops; explanatory links indicated by grey arrows. All model variables used in the following analysis listed in grey.

1 Introduction - Laptev sea ice and permafrost

~~Attributed to global warming, recent years are filled with record lows of Arctic~~ To better understand both the mechanisms behind as well as the strength of the interaction between sea ice and land we explore links between sea ice and the atmosphere over land and identify local and large-scale drivers of sea-ice cover ~~, which expressively underpin a general downward trend (Dong et al., 2013). This trend is overlain by a strong seasonality and interannual variability, especially in the marginal seas (Deser et al., 2000), that cannot be explained by one main mechanism alone~~in the Laptev Sea. Sea ice ~~strongly interacts with many components of the climate system, e. g. ocean salinity, air moisture and temperature fluxes, see Fig. 1 for more examples. Notably, sea ice has a strong influence on the energy balance at the ocean surface. Less sea ice leads to more absorption of radiation, thus warming the surface and reducing ice further. This ice-albedo feedback has been identified as a major mechanism controlling Arctictemperatures and ice extent (Deser et al., 2000; Graversen et al., 2014). Apart from that,~~ interacts with the ~~thickness and state of the turbulently mixed atmospheric boundary layer controls whether air which was warmed at the ocean surface is quickly mixed upward and replaced at the surface or whether the warm air stays close to the surface. The lower warm air is kept,~~ atmosphere on different scales. 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). 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 fall than in spring (Serreze et al., 2009; Serreze and Barry, 2011; Screen et al., 2012). Additionally, downward radiation plays a role in changing the net 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)

. Little attention has been focused on the physical mechanisms through which variability in sea ice influences the atmosphere over land. Nevertheless, from prior research we know that sea ice can exert such an influence on land (Lawrence et al., 2008; Ogi et al., 2016). Changes in the atmosphere over land, which are attributed to declining sea ice, lead to various responses in the permafrost landscapes, ranging from increased methane emissions (Parmentier et al., 2015, 2013) to vegetation productivity (Bhatt et al., 2008; Macias-Fauria et al., 2017) and vegetation composition (Post et al., 2013). Thus, a better understanding of the connection between sea ice and land is valuable, especially since sea ice and the ~~more further warming of the atmosphere is enhanced (~~permafrost covering adjacent landmasses are both highly vulnerable to climate change. In this paper, we aim for a better understanding of the physical mechanisms behind the connection of sea ice to the atmosphere over land.

As mentioned, sea ice has a strong impact on the energy balance of the ocean surface, giving rise to several feedback mechanisms, such as lapse-rate ~~feedback) (Pithan and Mauritsen, 2014).The atmospheric boundary layer height is also one factor deciding how much moisture the air contains. Warm air can absorb more water,and, because water is a strong greenhouse gas, moist air leads to more warming (water-vapor feedback) (Francis and Hunter, 2007) . The above feedbackmechanisms lead to local changes in energy fluxes, which in turn lead to changed fluxes within the atmosphere. This connection between sea ice and the atmosphere over the adjoining landmasses has been studied amongst others by Parmentier et al. (2015). In their analysis of satellite observations and several process-based methane models near-surface air temperature over land and sea-ice variability co-vary throughout many parts of the Arctic leading to the conclusion, that local changes in the energy budget and ensuing temperature variations are the main assumed mediator of a causal link from sea-ice decline to increased methane emissions. Ogi et al. (2016) investigated links between observed sea-level air pressure, two-meter air temperature and sea-ice extent in Hudson Bay and~~ feedback (Pithan and Mauritsen, 2014; Pithan et al., 2013) , water-vapour feedback (Francis and Hunter, 2007) or ice-albedo feedback, which has been identified as a major control on Arctic temperatures (Deser et al., 2000; Graversen et al., 2014; Serreze and Barry, 2011; Serreze et al., 2009). These interconnections all contribute to a strong seasonality and interannual variability of sea ice, especially in the marginal seas of the Arctic Ocean ~~. In contrast to Parmentier et al. (2015), they associated variability in both sea-ice cover and air temperature over the adjacent land with larger-scale atmospheric circulation fields. Additionally, Lawrence et al. (2008) found a connection between rapid sea-ice loss and temperatures on land, and Vaks et al. (2020) connected permafrost stability with the state~~ (Deser et al., 2000). Because different processes might overlay each other when looking at the Arctic as a whole, we focus on one region where we expect a comparably strong connection of sea ice ~~during climate states of the past. But neither of them explains, which changes in the atmosphere lead to~~ and the adjacent land: The Laptev Sea is one of the ~~link and what led to changes in the sea ice distribution.~~

~~In this study we want to complete this picture and disentangle causes and consequences of numerous climate variables. So far, there is no study including all possibly interacting variables pictured in~~ key contributors to net sea-ice production in the Arctic (Bauer et al., 2013; Bareiss and Görgen, 2005) and shows large year-to-year variability (Haas and Eicken, 2001) (Fig. 2). To identify the main processes between sea ice and the atmosphere over permafrost, we include as many variables as possible in our analysis (for an overview of all included variables, see Fig. 1 ~~, focusing on the question if and how variability~~

~~of Arctic sea ice influences the atmospheric state over the adjacent land masses. To overcome limitations of observations , which~~ and Tab. A1). Because observations are sparse in space and time and not available for all relevant variables, we ~~utilize output of a regionally coupled climate model~~ use model output. The big advantage of such a model over observational studies is that we can analyze a very large range of variables in a physically consistent system and in high resolution, both, spatially and temporally. ~~To understand the fundamental interactions between land and sea ice, we use a pre-climate change time period of the last century and use in total 160 years of simulations, thus improving our statistical power.~~ 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 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. 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.

~~To find links within a set of variables and differentiate between spurious correlations, direct links, indirect links and contemporary neighbors we use~~ We use forcing from the time period of 1950 to 1989. In this period and in the Laptev Sea, we do not yet observe a general downward trend of sea ice. We run the model repetitively to improve statistical power. On the thus obtained 160 years of model output we employ two statistical methods. The first is called causal-effect ~~networks (Runge et al., 2012, 2014, 2015). With this method, we gain understanding on temporal dependencies between different climate variables. Beside the analysis of the possible direct connection between sea ice and land temperatures we use the~~ networks, a recently developed method (Runge et al., 2012, 2014, 2015), which has been successfully applied by Kretschmer et al. (2016) to analyze Arctic drivers of midlatitude winter circulation. This method allows us to a) identify the important links in an unbiased way and b) differentiate whether two variables are either subject to a common external forcing or which variable is forcing the other. Building on the results from the causal-effect ~~network to investigate the drivers of sea ice variability itself. To do so, we additionally compare extremely high and low~~ networks, we group model-years with exceptionally high and low sea-ice ~~extent events and the corresponding atmospheric states.~~

~~Due to the fact that different processes might overlay each other when looking at the Arctic as a whole, we rather focus on one region where we expect, if at all, a strong connection of sea ice and the adjacent land: The Laptev Seais one of the key contributors to net sea-ice production in the Arctic (Bauer et al., 2013; Bareiss and Görgen, 2005) and shows large year-to-year variability (Haas and Eicken, 2001) as can be seen in Fig. 2. Its surrounding landmasses are characterized by near-pristine permafrost landscapes. The Permafrost region, where roughly 1300 Gt of soil organic carbon are stored (Hugelius et al., 2014) , is , like sea ice, sensitive to climate change: With rising temperatures, the permafrost carbon pool is projected to be partly released to the atmosphere in form of carbon dioxide and methane (Schuur et al., 2015). Thus, we have two highly sensitive components of the climate system right next to each other, and so far it is unclear how they interact with each other.~~

~~In the following, focusing on the Laptev Sea region, we want to answer: Does sea-ice~~ cover~~have a causal impact on the atmosphere over land, and if yes, is temperature the main mediator as suggested before? What are the main drivers of local~~

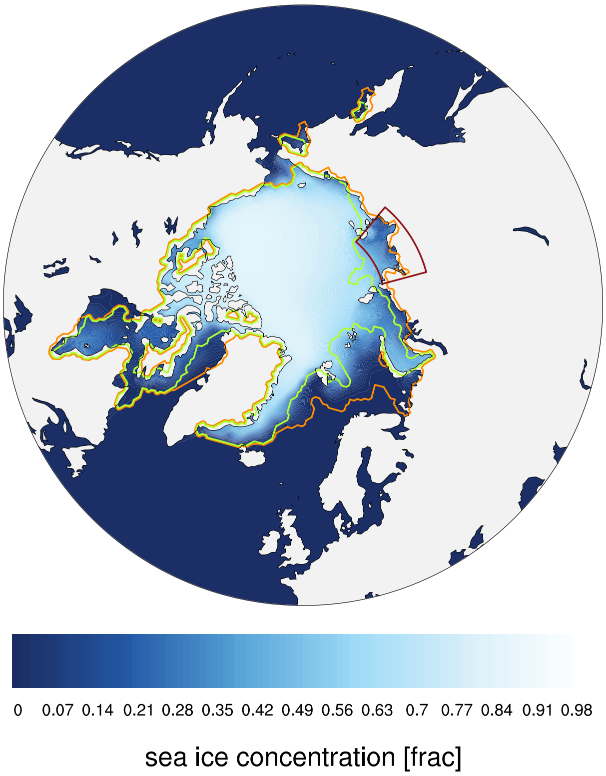

Figure 2. July monthly-mean sea-ice concentration taken from the model described above. Red box indicates Laptev Sea region and area over which one-dimensional time series of sea-ice cover are created. The contour lines show in green the minimum and in orange the maximum sea ice cover. Note, that all of the ocean in the red box might be either ice-covered or ice-free and that the Laptev Sea is one of the areas in the model with the highest variability in monthly July sea-ice cover.

~~sea-ice variability?~~ . These composites reveal spatial patterns and mean changes in variables, allowing us to gain a deeper physical understanding.

In ~~this paper~~the following, we start with introducing the ~~causal effect-network~~ causal-effect networks and the composite analysis. Then, we analyze the impact of sea-ice cover on the atmosphere over land as well as the drivers of sea-ice cover during the onset of the melting season and during refreeze. Finally, we put our results in the wider context~~of global climate change.~~ .

2 Methods

In order to understand links between Laptev sea ice and regional climatic conditions, we analyze the output of a regionally coupled ocean-sea ice-atmosphere-hydrological discharge model with two complementary methods. The model consists of

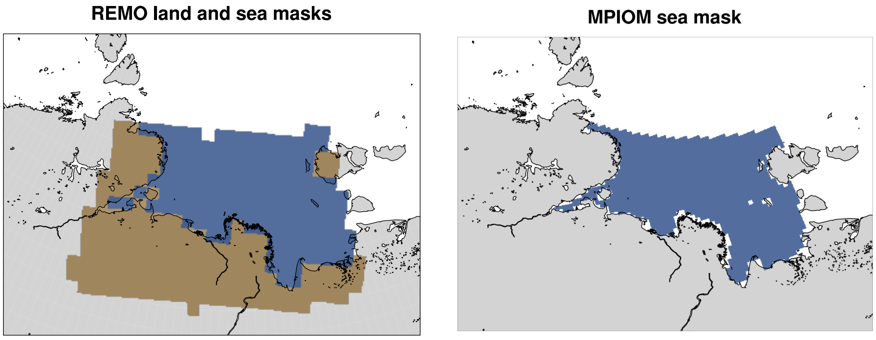

Figure 3. Model grid cells used in the analysis. Blue marks grid cells used for ocean variables, brown signifies land grid cells used to produce one-dimensional time series. MPIOM output is only available over water. REMO output was reduced either over land, over water or over both jointly. Colored areas lie between 105°E - 140°E and 70°N - 77°N.

the global ocean-sea ice model MPIOM ~~(Jungclaus et al., 2013)~~ Jungclaus et al. (2013) coupled to the regional atmosphere model REMO (Jacob and Podzun, 1997; Jacob, 2001), covering most of the northern hemisphere. The atmosphere model has a horizontal resolution of approximately 55 km and 27 vertical levels. In the global ocean model, the grid poles are located over North America and Russia leading to a horizontal resolution of up to 5 km within the Arctic Ocean. The model has 40 vertical levels with varying depth. The regional atmosphere model and the ocean model in the uncoupled domain are forced with model output from the global model MPIOM/ECHAM5 for the time period 1950 - 1989 and the model was run repetitively. Details on the model set-up can be found in ~~Sein et al. (2015); Niederdrenk et al. (2016) and~~ Sein et al. (2015) and Niederdrenk et al. (2013) and on the experimental design in ~~Niederdrenk et al. (2016)~~Niederdrenk et al. (2016).

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. ~~This~~ 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 in the Laptev Sea than observations (see Fig.4). Nevertheless, the variability of the model 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. ~~These model simulations have been validated against observations by Niederdrenk et al. (2013) and show a realistic mean Arctic climate for this time period.~~ Thus, we can use them to examine underlying links between climate and Laptev Sea sea ice assuming no or only little disturbance through model drift or anthropogenic forcing. Sea-ice cover is the quantity we use to represent sea ice in our analysis, since we expect that sea-ice cover has a larger impact on atmosphere-ocean exchange processes than e.g. sea-ice volume. Sea ice covers the Laptev Sea completely during winter, and most variability can be observed during the summer months (see Fig. 2). We, therefore, focus on the summer season to understand what influences sea-ice cover and what is influenced by sea-ice cover.

As a first method we use causal-effect networks, implemented in the ~~Phyton~~ Python package TiGraMITe (Runge et al., 2012, 2014, 2015). Causal-effect networks is an algorithm for causal discovery: the algorithm finds causal links in a dataset without a-priori knowledge on physical mechanisms. Causal-effect networks determine how a perturbation moves through a set of one-dimensional time series. Each time series represents one variable, for example precipitation, and the temporal path of the perturbation is considered as a causal link. 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 lag behind the signal in the driving time series. This shift is increased from one time step to a maximum time lag τ_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 ~~perturbations in each time seriesare found using partial correlations.~~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. ~~Since a causal link implies that a perturbation is observed in the driver before it is observed in the driven~~ We compute the multiple linear regression between a time series, the ~~multiple linear regression is applied repeatedly while shifting the time seriesagainst each other until the time lag between them reaches a predefined maximum.~~ preliminary drivers of this time series, and, iteratively, one other time series at, one after the other, all possible time lags. The results of all multiple linear regressions are then summarized in a causal regression matrix of dimension (N, N, τ_m) where N is the number of time series we use and τ_m is the maximum time lag. Values in this matrix range from zero to one and are similar to a partial correlation coefficient. The threshold when a link is considered significant was set to 0.2, such that in our networks links that are roughly two standard deviations stronger than the mean link between all time series are considered as significant. If we find a lagged link between two time series, we call it "causal". We also consider "contemporary" links, where the time lag is zero. For these links, it is not possible to determine the direction of information flow. Note, that the concept of causation in 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 one time series (Runge et al., 2014). Additionally, the first step of this algorithm is an adapted PC-algorithm (Spirtes et al., 2000) based on the idea that to identify causation we need to exclude common drivers (Pearl et al., 2000; Runge et al., 2012). Compared to many other frameworks making use of Granger causality the above algorithm is very computational efficient even on high dimensions (large $N \cdot \tau_m$), because using results of the first step drastically reduces the complexity of the second step (Runge et al., 2019).

The method becomes more reliable when the set of variables is large. To get a complete picture, we select all variables given in Fig. 1 ~~.~~ and Tab. A1. We spatially reduce the data by either computing averages or sums over the Laptev region. If the variable has a "per-area"-unit, we weight the sum using the grid-cell area. Most of the variables are non-directional scalar fields, but for the vector fields, such as wind, we split them into their zonal (positive sign: West to East) and meridional (positive sign:

South to North) component and reduce them separately. There are not only horizontal but also vertical fluxes. These we either integrate vertically over the atmosphere, or only consider surface fluxes from atmosphere to land, ocean or ice. Lastly, for ice transport, we compute the gross import and export out of and into the Laptev area. The boxes for the atmosphere and ocean model are given in Fig. 3.

To resolve effects on different scales, we analyze both monthly and daily means. When analyzing monthly-mean time series, we consider the past year ($\tau_m = 12$ months) as maximal time lag, while we allow a lag of one week ($\tau_m = 7$ days) in the daily set-up. We look at ~~drivers of variables~~ the connection between land and sea ice especially during June - September when vegetation is photosynthesizing, and sea-ice cover is low and variable. This variability accentuates the differences between high and low sea-ice-cover years which is important for the composite analysis. We additionally investigate what drives sea-ice evolution. To do so, we investigate the phases of strong changes in early ice melt and ice refreeze in spring and fall. While the Laptev Sea is still completely ice-covered in March in most years, sea-ice cover starts declining in April in most years, so we consider the month April, May, June for ice melt. Starting in September, ice cover grows from its minimum extent to a nearly complete cover in November. Consequently, for the ice refreeze we focus on the month of September, October and November. Since our goal is to connect land and sea-ice cover, we only consider the atmosphere over landmasses adjacent to the Laptev Sea (see brown area in Fig. 3) for the summer period (June - September). In contrast, for early ice melt (April - June) and ice refreeze (September - November), we also want to understand what drives sea ice. So for these two cases, we look at the atmosphere over land and ocean together (entire shaded area in Fig. 3).

With causal-effect networks, we can disentangle temporal relationships. To also understand spatial patterns and quantify dependencies, we extend our analysis by using composites of years with exceptionally high and low summer-sea-ice cover in the Laptev Sea between June and October. These months coincide with the months we chose for the summer causal-effect network, but are extended by October to include more of the refreezing phase, which only starts sometime during September. We select all years which deviate from the mean sea-ice state by more than 1.3 standard deviations. We selected 1.3 standard deviations as a threshold to a) only use years with significant (larger than one standard deviation) anomalies in sea-ice cover; and b) to even out number of years contributing to the two composites as well as possible. With 1.3 standard deviations we get 17 years with high sea-ice cover and 7 with low, see Fig. 4.

3 Results

As our main focus lies on the interaction between sea ice and land, we start our analysis by looking at the summer months. The sea ice variability is largest in summer. Afterwards we will cover spring and fall, to find drivers of the melt onset and the refreezing of ice.

3.1 Summer

To understand how sea-ice cover influences the adjacent land, we first look at causal-effect networks during the summer months. Here, both on monthly and on daily scale, we only consider the atmosphere over land, not over the ocean. In this

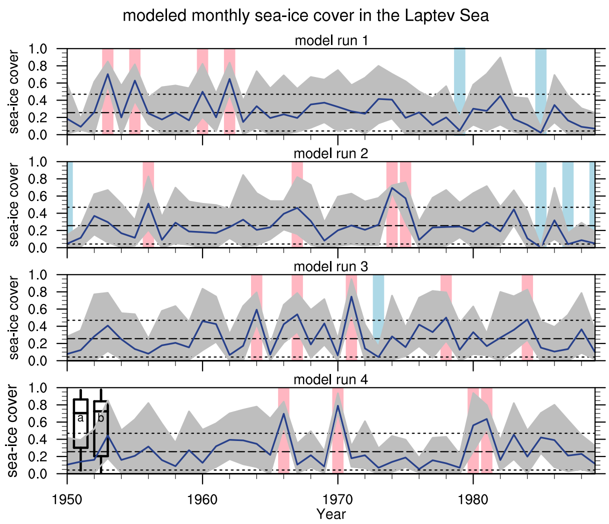

Figure 4. Monthly mean sea-ice cover in the Laptev Sea from June to October in each year. Blue line: mean sea-ice cover over summer and fall period. Grey area: range between minima and maxima of June to October monthly-mean cover. Middle dashed line: average sea-ice cover over all June-to-October means 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).

Table 1. Minimal and maximal values for atmospheric meridional heat (Tv) and moisture (Qv) transport along a transect at 70N. Values were divided by the mean of each grid cell. Distributions of values for both variables displayed as boxplot in Fig. 6

sea ice	**Tv**		**Qv**	
	min	max	min	max
low cover	-67.7	63.8	-21.97	29.3
mean cover	-90.6	90.4	-31.7	58.3
high cover	-87.5	69.0	-25.6	37.7

way, direct interactions between sea surface and the atmosphere are excluded. In Fig. 5(A), we see the results using monthly means throughout the summer months of the causal-effect networks analysis. Links with a strength below a threshold of 0.2 are neglected as insignificant in our analysis. Out of the 16 variables used in the set-up, four are connected to sea-ice cover. The strength of the links to sea ice is weak (average strength: 0.25): The (solely contemporary) connections the variables have between each other are much stronger (mean strength: 0.57). For clarity, these connection are not shown in the figure. There is

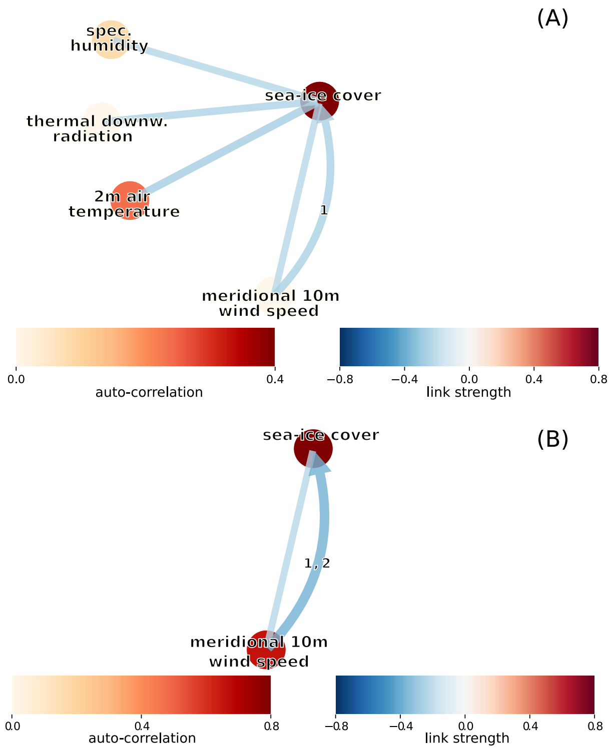

Figure 5. Causal-effect networks using atmospheric time series integrated over the land for summer based on monthly means (A) and daily means (B). Figure includes only those variables which have a significant connection to sea-ice cover. The Color of nodes indicates auto-correlation. Straight lines show contemporaneous links, arrows show causal links with the time lag indexed on the arrow. The color of the arrows represents sign and strength of the link. Blue means that more of one variable coincides with less of the other, whereas red means that changes in the connected variables have the same sign. The link is stronger the darker the color. Variables with significant links to sea-ice cover are specific humidity (spec. humidity) averaged over vertical column, two-meter air temperature (2 m air temperature), meridional ten-meter wind speed (meridional 10 m wind speed) and thermal downward radiation at the surface (thermal downw. radiation).

only one causal link, from meridional wind speed to sea-ice cover, while all other links are contemporary. All these links have a negative sign: higher sea-ice cover is associated with a decrease in ~~specific humidity,~~ the strongly interconnected variables specific humidity and thermal downward radiation at the surface, as well as with 2 m air temperature and 10 m meridional wind speed. Sea-ice cover has ~~less~~ fewer links on daily scale (see Fig. 5(B)) than on the monthly scale. It only links with meridional wind speed, and the only causal link is pointed towards, not away from sea-ice cover, meaning that sea-ice cover is the driven variable.

If we investigate wind with the composites by looking at mean wind-speeds over the Laptev Sea region, we see that wind direction is variable during the summer months, though there is a slight excess of southward wind. While in the mean about 56% of the days during June to September show winds pointing southward, it is about 53% in the low-sea-ice-cover years and

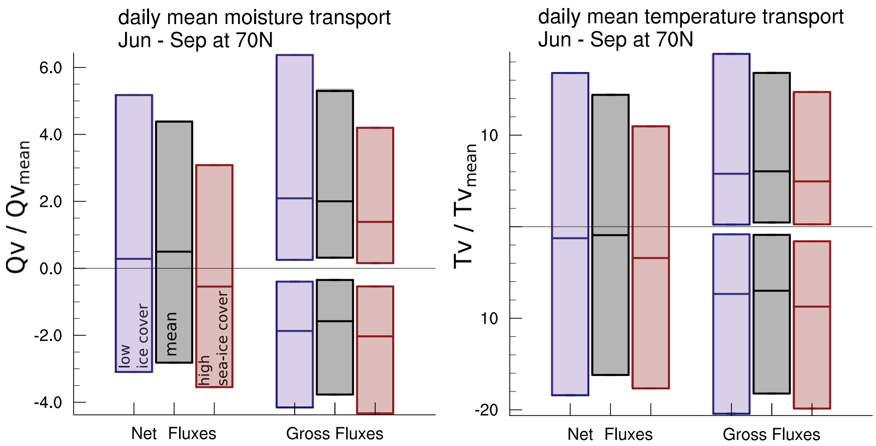

Figure 6. Meridional heat (Tv) and moisture (Qv) fluxes through a transect at the southern border of the area of interest (70 °N). Fluxes were divided by the mean flow through each grid cell over all years. In purple low-sea-ice-cover years are shown, in grey all years and in red high-sea-ice-cover years. 70°N lies just South the coastline on land. We divide the fluxes into net (spatial mean over all data-points at the 70°N edge) and gross (spatial mean over all positive/negative data-points at 70°N boundary). Indicated are the median (centre bar) as well as the first and third quantile of the distribution. For minima and maxima, see Tab. 1.

64% in the high-sea-ice-cover years: High sea-ice cover coincides with a higher fraction of southward wind and vice versa for low sea-ice cover. More precisely, for high-sea-ice-cover years southward transport of moisture and heat is enhanced (see Fig. 6 and Tab. 1). The median of the net flux is lower compared to the mean and this southward shift even leads to a change in sign for moisture transport from net-northerly to net-southerly transport compared to the mean. For low-sea-ice-cover years on the other hand, both north- and southward transport of moisture and heat increases. Again the median is lower than the median of all years for net fluxes. This indicates that the bulk of transport also shifts towards more southward transport, but for low sea-ice cover, there is a higher spread in the distribution, visible in both the net as well as in the gross fluxes. Using a two-sample Kolmogorov-Smirnov test we find that for both moisture and heat transport the high-sea-ice-cover and low-sea-ice-cover distributions are significantly different (p-values < 0.001).

3.2 Early melt season of sea ice

Looking at monthly drivers of the early melt of sea ice in spring and including both the atmosphere over the ocean and over land, we find in total ten variables that have links to sea-ice cover (Fig. 7(A)), and the gross of connections is contemporary (nine variables). Two causal links are found, both of them directed towards sea-ice cover, and with a lag-time of one month. The lagged - causal - links are on average weaker than the contemporary ones.

Returning to the contemporary links, the strongest links connect sea-ice cover to meridional wind speed, sea-ice export and meridional moisture transport respectively. On a daily scale (Fig. 7(B)) zonal wind speed and sea-ice export are still two of the three variables with the strongest connection to sea-ice cover. The third strongest connection now is with sea-ice import. These three directional variables also have causal links influencing sea-ice cover with a time lag of one and two days. Two other variables with causal links pointing towards sea-ice cover are the zonal vector components wind speed and moisture transport. Both have a one-day lag to sea-ice cover, and there is no contemporary link between sea-ice cover and either of the two. On a monthly scale, they have neither a contemporary nor a causal link. Links between sea-ice cover and sea-level pressure, surface longwave downward radiation and specific humidity on the other hand are significant on a monthly but not on a daily scale.

Since the strongest connections that sea-ice cover exhibits during early ice melt are connected to meridional transport and wind, we inspect spatial patterns using the composites for sea-level pressure in May (Fig. 8): We generally have a high over Greenland, but it is stronger for high sea-ice cover than for other years. For high sea-ice cover, we also observe a more distinct polar high, as opposed to low sea-ice cover, when we have a strong high-pressure zone centered over the Chukchi Sea as well as a low over the Kara Sea. Locally over the Laptev Sea, these differences on the large scale lead to contrasting pressure fields. As air flows around pressure systems, we also have vastly different wind patterns in our area of interest. For high sea-ice cover, wind in the Laptev Sea predominantly blows from northeast, carrying air from similar or higher latitudes. For low sea-ice cover on the other hand, we have strong transpolar wind caused by the bipolar pressure field. Consequently, we also have a pronounced transpolar drift of sea ice originating roughly in the Laptev Sea and pointing towards Greenland. Over the Laptev Sea, the average wind direction is northward for low sea-ice cover, and the air masses arrive from southeast, thus carrying comparably warmer air. In the monthly ice-melt causal-effect network (Fig. 7(A)), this warm air is reflected in a contemporary link between air temperature and sea-ice cover.

3.3 Refreezing of the sea in fall

This link is also present during refreeze, when this link is the strongest link of sea-ice cover to any variable (Fig. 7(C)) ~~.~~ in the causal-effect network, which was, as for spring, set up to include the atmosphere over both ocean and land. During ice refreeze the links from sea-ice cover to sea-ice im- and export as well as meridional wind speed are weaker than during the melt onset. Heat and moisture transport do not have significant links to sea-ice cover. The autocorrelation of sea-ice cover, on the other hand, increased from 0.39 to 0.49. The auto-links of air temperature (strength: 0.40) and snow height (strength: 0.53) are also exceptionally strong compared to the other displayed variables. The total number of variables significantly connected to sea-ice cover decreases. The number drops from ten during ice melt to eight during refreeze. Apart from meridional heat and moisture transport, sensible surface heat flux and sea-level pressure disappear to be replaced by snow height and latent surface heat flux. Both of these two variables have only causal and no contemporary links to sea-ice cover. Latent surface heat flux on the other hand is a dependent variable, with a time lag of three month. The lower sea-ice cover is, the higher are the absolute fluxes from ocean to atmosphere. The dependency of sea-ice export on sea-ice cover also changes. The contemporary and the causal link from sea-ice export to sea-ice cover during ice melt is replaced by a causal link from sea-ice cover to sea-ice export - more sea-ice cover leads to more export in the next month. In general, the number of causal links increases in the ice refreeze monthly-mean causal-effect network compared to melt. In addition, during refreeze sea-ice cover is also a preceding variable - during melt sea-ice cover is always the influenced variable.

4 Discussion

4.1 Drivers of sea-ice cover

Tracing influences of sea-ice cover on the atmosphere over land with causal-effect networks is not straightforward: sea-ice cover couples more strongly to atmospheric variables integrated over both land and ocean (Fig. 7(A),(C)) than to the atmosphere over land (Fig. 5). For summer months, where we look solely at the atmosphere over land, we detect no causal link from sea-ice cover to any variable. The contemporary links that sea-ice cover has are weaker and smaller in number than in the causal-effect networks of melt and refreeze where we included the atmosphere over the ocean as well: Sea ice seems to have a stronger impact on the atmosphere directly over the ocean. This is in line with prior findings that the impact of sea ice on the atmosphere is mostly local (Screen et al., 2012, 2013).

A causal link we still observe is from meridional wind speed to sea-ice cover. Moreover, meridional wind speed is the only variable connected to sea-ice cover in the daily-mean summer causal-effect network, when only the atmosphere over land was considered. During early melt, when using both the atmosphere over land and over the ocean, we observe the same dependence of sea-ice cover on meridional wind speed.

In spring, we find a counter-intuitive link from air temperature to sea-ice cover (higher temperatures lead to more sea ice, Fig. 7(A)), which is most likely an artefact of the causal-effect network analysis because of our choice of time series: We include downward longwave radiation in our analysis which is strongly connected to air temperature. But higher air temperatures coincide also with increased upward longwave ratiation, which leads to an energy loss at the surface. This upward longwave radiation was not included in the ~~causal effect~~ causal-effect network. We think that within the analysis the positive link from temperature to sea ice is caused by an overcompensation: The additional energy available at the surface through downward radiation is subtracted from the influence of air temperature on ice, but the energy radiated upward is not. This only becomes important for the causal link rather than the contemporary connection, because for causal links we can subtract the influence of downward radiation at the present and prior time steps reinforcing the overcompensation.

Besides the link from air temperature to sea-ice cover, variables connected to the pressure field have the strongest links to sea-ice cover on both monthly and daily scale. Those include local sea-level pressure, and particularly the north/south components, like meridional wind speed but also meridional moisture transport and sea-ice export. These variables are all strongly interconnected with each other on the monthly scale (Fig. 7(A)). While the variables have only contemporary links to sea-ice cover on monthly scale, they are driving sea-ice cover with a lag of one to two days in the daily-mean causal-effect network (Fig. 7(B)). This is in line with a prior observation-based study from Krumpen et al. (2013), where sea-ice export from February to May has been singled out as one driver of sea-ice cover. The main local variable determining sea-ice cover in the Laptev Sea during early melt is thus meridional wind, which is also one main driver of sea-ice export. The stronger the northward flow the less sea-ice cover. We can support this with our findings in the May composites (Fig. 8): For high-sea-ice-cover years, wind blows from the northeast carrying colder, less humid air, and, for low-sea-ice-cover years, winds are blowing from southeast enhancing transpolar wind and sea-ice export and bringing warmer humid air. (Meridional) wind depends on air pressure. The large-scale patterns of the May pressure field resemble the patterns of previous mostly observational or reanalysis-based studies ~~(Jaiser et al., 2012; Overland et al., 2012; Wang et al., 2009, e.g.)~~ (e.g. Jaiser et al., 2012; Overland et al., 2012; Wang et al., 2009). 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). ~~Additionally, we~~ 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). Greenland blocking has been found to cause strong melt of the Greenland ice sheet (Overland et al., 2012) as well as an enhanced influx of moisture in the North Atlantic Region (Yang and Magnusdottir, 2017). This influx then enhances the water-vapour feedback. Instead of a positive AO pattern, low-sea-ice-cover years match an Arctic Dipole (AD) pattern (Fig. 8, similar to Overland et al. (2012); Wang et al. (2009)): We observe a high over the Chukchi and Beaufort Seas with even significantly higher pressure south of the Chukchi Sea and a low over the Barents Sea. The occurrence of the AD pattern fits well with the causal-effect-network-based result, that meridional wind is strongly connected to sea-ice cover in the Laptev Sea. We have pronounced sea-ice export because the AD pattern leads to anomalies in the meridional wind and a stronger transpolar drift of sea ice, while the AO is more connected to zonal wind promoting either convergence or divergence of sea ice in the Arctic (Wang et al., 2009). Advection of Siberian air masses has been observed to link to extremely low sea-ice cover in the Laptev Sea before, for example by Haas and Eicken (2001). Apart from enhanced ice drift, they stress the importance of atmospheric heat content carried into the Laptev Sea. Additionally, temperature fluctuations caused by advection have been identified as a dominant driver of sea-ice variability by Olonscheck et al. (2019). This agrees well with our findings, since, during melt, meridional wind, air temperature as well as meridional heat transport all have strong links to sea-ice cover. Contrasting, we find that the moisture content of the air transported into the Laptev region plays are comparably ~~large~~ larger role than the heat content of the air. This is in agreement with a satellite- and reanalysis based study by Yang and Magnusdottir (2017) who find that influxes of humid air into high latitudes from the North Atlantic lead to extremely low sea-ice cover in the Greenland, Barents and Kara Seas.

We conclude that during the melt phase, large-scale circulation systems exert a strong influence on the evolution of sea-ice cover. Since melting continues through summer (Kim et al., 2016) until September, the prevailing link from meridional wind speed to sea-ice cover portrays this connection.

During refreeze in fall, meridional wind speed is still important (Fig. 7(B)), but loses its dominance. While the connection between meridional wind speed in the monthly-mean causal-effect network for summer is on the same magnitude as the other connections of sea-ice cover, meridional wind speed is the weakest connection to sea ice during refreeze. Instead, state variables connected to feedback mechanisms, like ice-albedo feedback and water-vapour feedback, are increasingly important and also strongly interconnected. These feedback mechanisms we can already identify during early melt, even though they are less dominant then. In the fall monthly-mean ~~causal effect~~ causal-effect network (Fig. 7(C)), we observe a cluster of specific humidity, downward longwave surface radiation and air temperature. 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-vapour feedback. Additionally, the auto-correlation of sea-ice cover and air temperature rises. Since the strongest connection between air temperature and sea-ice cover is contemporary and the autocorrelation reaches back one time step, this can be interpreted as part of the strong interdependence of these variables. Sea-ice cover (increase) is also driving both latent surface heat flux and sea-ice export, in contrast to ice melt, when sensible heat fluxes and sea-ice export are driving sea ice (loss). The transition from mainly circulation- to mainly feedback-driven sea-ice cover is in agreement with Barton and Veron (2012) who found moisture-related feedback mechanisms to be a strong driver of Laptev sea ice in September and October~~. They also reflect the findings of Rigor et al. (2002): During refreeze, the ocean has to emit heat until it is cool enough to freeze, and this emission is reflected in increases in temperature and specific humidity above the water column.~~ as well with as Arctic-wide findings that sea ice has a stronger impact in fall than in spring (Parmentier et al., 2015; Screen et al., 2013; Serreze et al., 2009; Rigor et al., 2002).

4.2 Influence of sea-ice cover on the atmosphere over land

What does this mean for the connection from sea-ice cover to the atmosphere over land? In summer, we observe a contemporary connection between sea-ice cover and specific humidity over land (Fig. 5). This link is also present in the ice-melt and refreeze monthly-mean ~~causal effect~~ causal-effect networks, where we consider the atmosphere over land and ocean in contrast to the summer, where we focus on the atmosphere over land. To better understand this connection, we inspect the composites. For high-sea-ice-cover years, we observe more days with on average southward wind - this is in compliance with our earlier findings: Ice export is minimized, and wind tends to carry colder air into the Laptev region. More southward wind also means more southward transport of heat and moisture (Fig. 6 and Tab. 1). When open water areas are reduced compared to the mean state, and both humidity and temperature over the ocean are also reduced, so gross southward transport of both moisture and heat increases just because there is more air flowing south. At the same time, gross northward transport decreases. For low-sea-ice-cover years, there are fewer days with southward wind than usual. Still, we have a higher gross southward transport of heat and moisture because the air is warmer and moister over open water. More heat and moisture gets transported per air volume. In contrast to high-sea-ice-cover years, we also have an increase of transport northward corresponding to our earlier findings: Low-sea-ice-cover years are caused by above average northward wind and an influx of warm and moist air from south. If we compute net moisture and heat fluxes for the low-sea-ice-cover years, the median is only marginally shifted towards an increase of southward transport for both variables. It is remarkable that the increase in southward transport more than balances the increase in northward transport we already identified above as the primary cause of above-average sea-ice cover decrease. We conclude that the contemporary links in the monthly-mean summer causal-effect network incorporate causality in both directions: A decrease in sea-ice cover, as in the ice melt period, is most likely initiated by increased meridional wind pointing north. But the increases in temperature and moisture over land which then accompany low sea ice are both cause, when transported northward, and result of the diminished ice cover, due to consequently enhanced southward transport of heat and moisture in air. This is in line with a model study by Lawrence et al. (2008) who find that rapid sea-ice loss leads to warming on land. In contrast to their analysis, we break down this connection from sea ice to land and identify the responsible atmospheric variables. On the spatial (Laptev Sea) and temporal (days to months) scales analyzed here, we do not find a connection via large-scale circulation starting with changes in sea ice. 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, ~~and~~ such connections between sea ice and atmospheric circulation patterns have been shown before ~~(e. g. Ogi et al. (2016)). In contrast to~~

~~Lawrence et al. (2008), who focused on the impact of rapid sea-ice loss,without analyzing its drivers, we investigate drivers and impacts of equilibrium sea-ice variability. We find ,~~ (e.g. Li et al., 2020; Luo et al., 2019a; Yao et al., 2017; Ogi et al., 2016). Concerning local and direct links from sea ice to land in the Laptev Sea region, we find that over land the impact of sea ice is smaller than the impact of large-scale drivers, which simultaneously lead to changes local sea-ice cover.

5 Conclusions

Concerning our research question on the drivers of the sea-ice variability, we conclude from our above model analysis:

- Drivers of sea-ice-cover variability differ during the early melt (April – June) and refreeze (September – November) period. During early melt meridional wind and connected directional variables, like ice-export, are the prime drivers, all of them determined by the large-scale circulation. We find that high sea-ice cover often coincides with an negative Arctic-oscillation pattern, while low sea-ice cover coincides with an Arctic-dipole-like pressure pattern. During refreeze, ~~on the other hand,~~ in line with prior research (Screen et al., 2013; Serreze et al., 2009; Rigor et al., 2002), we conclude that thermodynamic feedback mechanisms related to temperature and moisture determine the speed of ice formation.

Regarding the connection between sea ice and the state of the atmosphere over land, we find:

- Sea-ice cover is primarily connected to the atmosphere directly above it and signals wash out quickly as we move to the land. Nevertheless, during low-sea-ice-cover years southward heat and especially moisture transport is enhanced. Heat and moisture are both variables which have a strong influence on the carbon budget as they affect both photosynthesis and respiration.
- We show that the impact of sea ice on moisture is at least as strong as on temperature. Studies which only focus on temperature overlook an important pathway of information, especially since the coupling is weak.

A possible explanation for the lack of causal links between atmosphere over land and sea-ice cover lies within temporal scales: The daily variations in the signal emitted by sea-ice cover have a significantly smaller impact than other forcings on the atmosphere over land. Otherwise, we would detect links on a daily scale. A potential slow but persistent forcing from sea-ice cover on the other hand might be diluted on a monthly scale due to the fast interactions within the atmosphere, especially because sea-ice cover exerts a remote forcing. We might still detect a link for the slow forcing, but most likely to several atmospheric variables and a contemporary instead of a causal link.

The above analysis was done using the climate of the last century, before the onset of strong changes in the Arctic. The observed loss of sea ice in the Arctic as a whole has been projected to lead to changes in the general circulation pattern, namely via a shift to more negative Arctic Oscillation and North-Atlantic Oscillation indices, which favour high sea-ice cover and thus exert a negative feedback (Jaiser et al., 2012). No clear connection to anthropogenic forcing has been drawn yet for the Arctic Dipole, but from reanalysis we know that there is a higher persistence of this pattern in the 21st century compared to the last

(Overland and Wang, 2010). Depending on which of these two shifts persists over the other we can expected a faster or slower decrease of sea ice in the Laptev Sea.

Since sea ice is generally decreasing, we expect that southward heat and moisture transport from the open ocean to the land will increase. Higher temperatures lead to deeper thawing of the seasonally frozen soil layers during summer due to enhanced southward transport of heat and moisture in air. This increases soil-organic-matter decomposition in the then-unfrozen soils, enhancing greenhouse gas emissions, but temperature is also one of the parameters steering the rate of photosynthesis, to name two of many processes which will be altered. Higher air moisture improves photosynthetic rates (high moisture leads to more efficient carbon fixation), changes the amount of (both short- and longwave) incoming solar radiation due to stronger reflection or, if higher humidity in the air leads to higher precipitation and water tables, the pathway of soil-organic-matter decomposition (Shaver et al., 2000).

A general warming and an enhanced hydrological cycle are key features of global climate change (Stocker et al., 2013; Huntington, 2006)~~, and we have shown that the decrease of Laptev Sea sea ice will add to the strength of this general warming and enhanced hydrological cycle over adjacent landmasses. But, as the connection of sea-ice cover to the atmosphere over land is weak , we conclude that future changes on Arctic landscapes andsea-ice loss are mainly driven .~~. In our model study we find that lower than usual sea ice in the Laptev Sea causes warming and an increase in air moisture over land, which might add to the above-mentioned trends. Nevertheless, we found the link from sea ice to land to be weak under stable conditions, and, if this relation holds under different conditions, we expect climate change over land to be driven primarily by large-scale circulation. Though a general decrease of sea ice in the whole ~~Artic~~ Arctic has an effect on large-scale circulation (Li and Wang, 2013; Jaiser et al., 2012) which then effects the Arctic landmasses, the local and direct link from sea-ice cover to adjacent landmasses appears marginal.

Code and data availability. Primary data and scripts used in this study are archived by the Max Planck Institute for Meteorology and can be obtained by contacting publications@mpimet.mpg.de. The model output is available through Niederdrenk and Mikolajewicz (2014) at https://cera-www.dkrz.de/WDCC/ui/cerasearch/entry?acronym=DKRZ_LTA_899_ds00003

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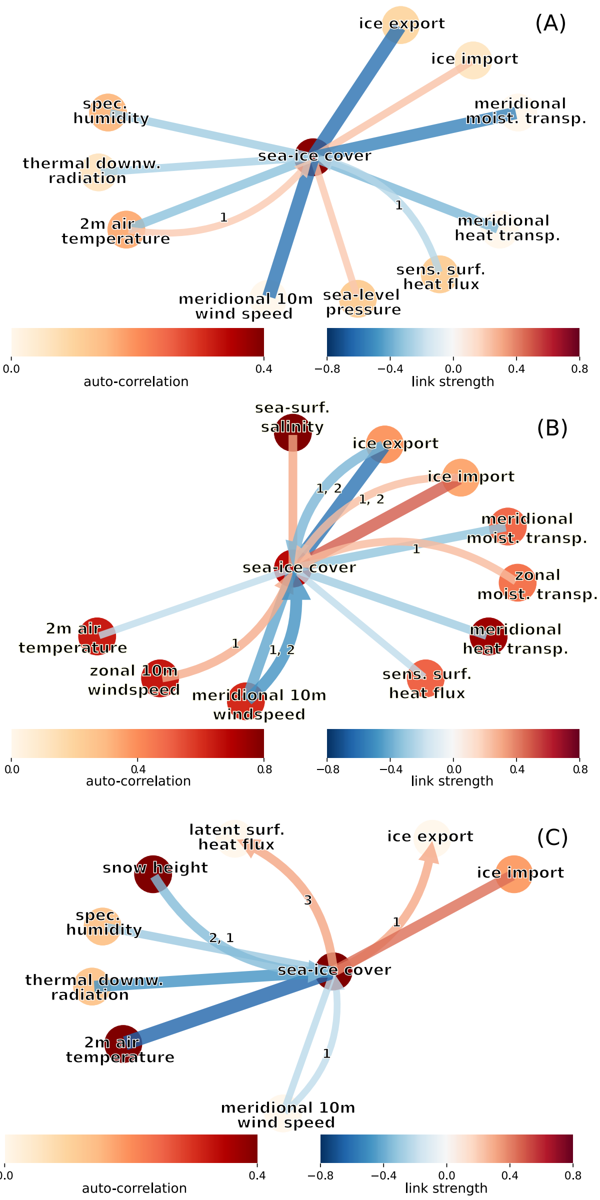

Figure 7. Causal-effect networks considering atmospheric variables over the whole Laptev land and ocean area for ice-melt and ice-refreeze. **(A)** Ice-melt monthly mean. The connection in between the variables (not shown) have a mean strength of 0.44. Contemporary connections between surface longwave downward radiation, air temperature and specific humidity are especially strong (0.77). Same goes for sea-ice im- and export, meridional wind speed, heat and moisture transport (0.626). **(B)** Ice-melt daily means. Similar variables are dominant compared to (A), but more causal links are detected. Note, that the color scale for auto-correlation is different compared to (A) and (C). **(C)** Ice-refreeze monthly mean. Connections between variables (not shown) have a mean strength of 0.44. Contemporary connections between surface longwave downward radiation, air temperature and specific humidity are especially strong (0.79).

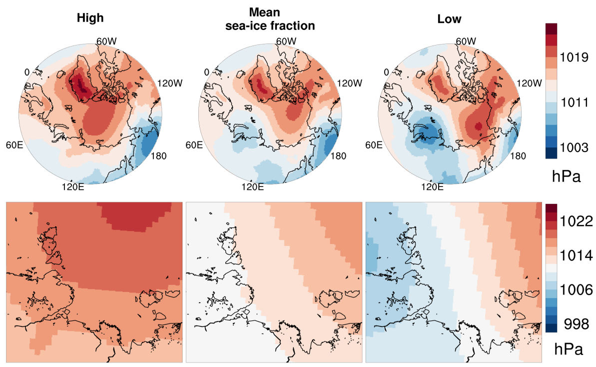

Figure 8. Sea-level air pressure in May on a large scale (upper row) and in the Laptev Sea (lower row). Centre column: May mean of all modelled years; Left/right column: mean over May mean in years of exceptionally high/low sea-ice cover in the Laptev Sea. Dots indicate areas which deviate by at least one standard deviation from the mean state (in the centre column).

variable	reduction method	spring & fall mm	spring & fall dm	summer mm	summer dm
fractional cloud cover	mean	✓	✓	✓	✓
fractional sea-ice cover	mean	✓	✓	✓	✓
gross mass export of sea-ice	transect sum*	✓	✓		
gross mass import of sea-ice	transect sum*	✓	✓		
meridional heat transport‡	mean	✓	✓	✓†	✓†
zonal heat transport‡	mean	✓	✓		
height of ABL	mean	✓	✓	✓	✓
latent heat flux at surface	weighted sum	✓	✓	✓	✓
meridional moisture transport‡	mean	✓	✓	✓†	✓†
zonal moisture transport‡	mean	✓	✓		
NAO index	pressure diff.	✓		✓	
precipitation	sum	✓	✓	✓	✓
absolute downward LW radiation at surface	weighted sum	✓	✓	✓	✓
absolute downward SW radiation at surface	weighted sum	✓	✓	✓	✓
sea-level pressure	mean	✓	✓	✓	✓
sea-surface salinity	mean	✓	✓		
sensible heat flux at surface	weighted sum	✓	✓	✓	✓
Siberian high index	regional SLP	✓		✓	
snow height	mean	✓	✓		
2m temperature	mean	✓	✓	✓	✓
fresh-water flux from land to ocean	sum	✓	✓	✓	✓
spec. humidity‡	mean	✓	✓	✓	✓
10m meridional wind speed	mean	✓	✓	✓	✓
10m zonal wind speed	mean	✓	✓	✓	✓
	$\sum$	24	22	18	16

Table A1. Time series included in Causal-Effect Networks of monthly means (mm) and daily means (dm) to determine dominant drivers of sea-ice in spring and fall in the Laptev Sea as well as the influence of sea ice on the atmosphere over land during the summer. While atmospheric variables were integrated over both land and ocean for spring and fall, only the atmosphere over land was used in the summer Causal-Effect Networks.

* - sea-ice ex- and import are computed by summing the gross positive and negative values of transects at the outer borders of the areas indicated by the masks in Fig. 3.

† - to estimate the influence on land not the mean meridional transport was calculated but the flow through a transect at the southern border of the masked area.

‡ - vertically integrated over all atmospheric model layers.