Dear referee,

thank you for your comprehensive review and helpful suggestions. Since your general comments contain many points dealing with similar issues, we decided to re-group some of them by specific topics instead of providing point-by-point answers to each of them. If not stated otherwise, all references to figures refer to the new figures in this document and not to the figures in the original paper draft.

1) Your first issue concerns a better explanation of the general idea of our method and the separation of flow directions. Specific suggestions were to include a schematic and to start with a more general presentation of trends by using e.g. wind roses.

We think that these are very helpful suggestions and will include a new results section (new 3.1) concerning general trends in the Fram Strait region.

- Starting with the map of sea ice concentration trends (original Fig. 6), we identify regions with the largest sea ice decline and define the specific study regions WNB and GRL and the corresponding ICE boxes used in later sections.
- Afterwards, we present trend maps (without any dependence on wind direction) for temperature, humidity and wind speed for both ERA5 and MERRA-2 data. Exemplary plots for ERA5 temperature and humidity trends are shown in Fig. 1.

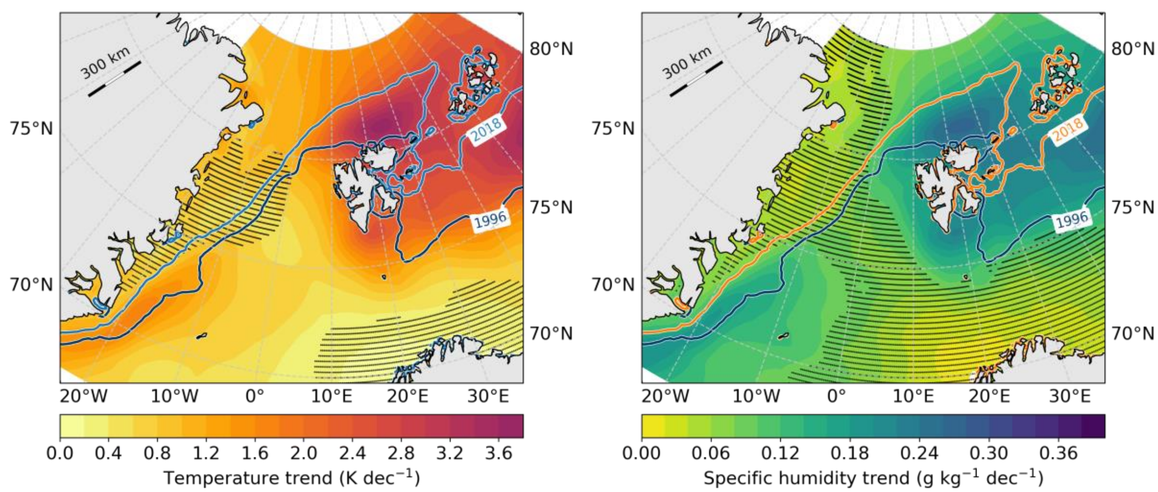

Figure 1: Trends of air temperature (left) and specific humidity (right) based on ERA5 data from 1992 to 2022. Dotted areas are not significant at the 95 %-level. Blue lines denote the 80 % SSM/I-ASI sea ice concentration contours averaged from January to March for two years with large and small SIE, respectively.

- For both regions (WNB and GRL) we look specifically at that area where the ice edge was located in years with a large sea ice cover (e.g. 1996). We then place the ATM boxes in the location with the largest temperature and humidity trends in these areas (see Fig. 2d) and calculate wind roses for the ATM boxes. Examples for temperature are presented in the following figures:

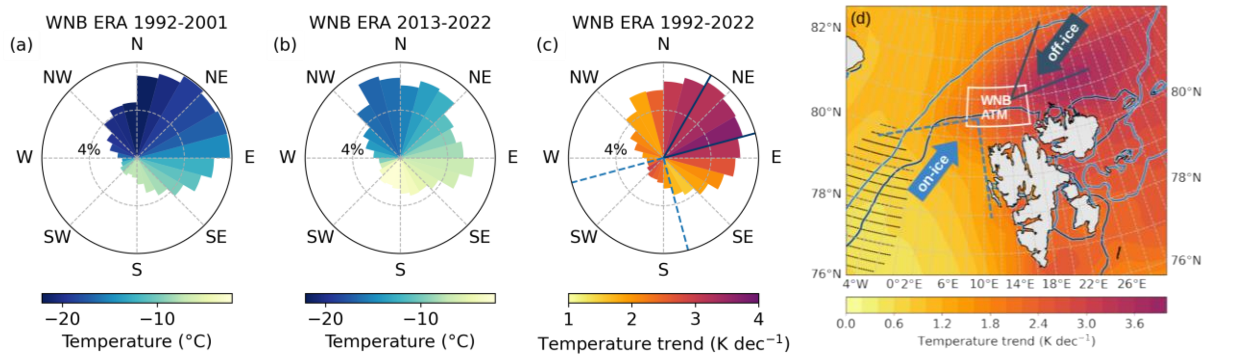

Figure 2: Wind roses for the WNB ATM box based on ERA5 data. The length of the bars indicates the frequency of occurrence within each wind direction bin. The colors indicate average temperatures (a,b) for the first and last 10 years of the study period, and temperature trends over the 31 years (c). Straight dark blue solid lines indicate the off-ice sector and blue dashed lines the on-ice sector (c,d). Sketch illustrating the placement of the ATM box and the wind direction sectors for on- and off-ice flow (d). The background shading shows ERA5 temperature trends (zoom into Fig. 1).

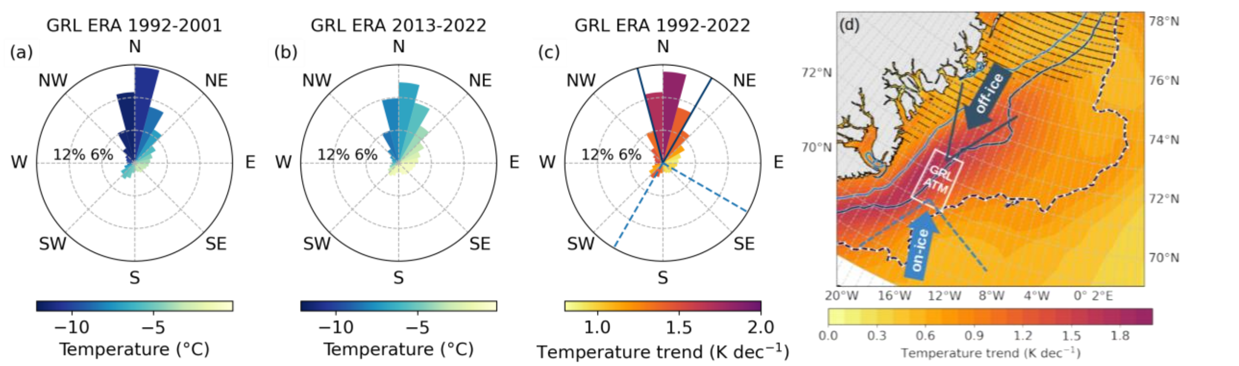

Figure 3: Same as Fig. 2 but for GRL.

- Wind sectors are now chosen according to the following criteria: For off-ice flow, we look at those wind directions for which the flow generally originates from an area covered by sea ice. From those, we select a sector of 45° for which temperature and humidity trends are largest (Fig. 2c and 3c). This results in off-ice sectors of 30°-75° (north-east) for WNB and of 345° to 30° (north) for GRL. For on-ice flow, one could simply assume the opposite sectors - i.e. south-east for WNB and south for GRL. However, these sectors contain only about 5-6 % of all cases and thus we extend the size of the on-ice sector to 90°. The new on-ice sectors then span from 165° to 255° (south-west to south) for WNB and from 120° to 210° (south to south-east) for GRL. An illustration of the sectors and flow directions is shown in Fig. 2d and 3d, which hopefully helps better illustrate the concept of off- and on-ice flow.

- The results for trends and correlations for different flow directions, which were presented in the old Sect. 3.1 and 3.3, are then reprocessed using this new definition of off- and on-ice flow. In the GRL region, this results in only small changes (original Fig. 4 and 11). In the WBN region, changes for temperature are notable but do not change the overall conclusions (Fig. 4 e). The largest changes occur for humidity trends in the WNB region. With the new definition of wind direction sectors, humidity trends are now larger for on-ice flow in all regions (Fig. 4b,e,f). However, there are hardly any changes in the correlation maps (Fig. 5), which look almost identical for temperature and humidity.

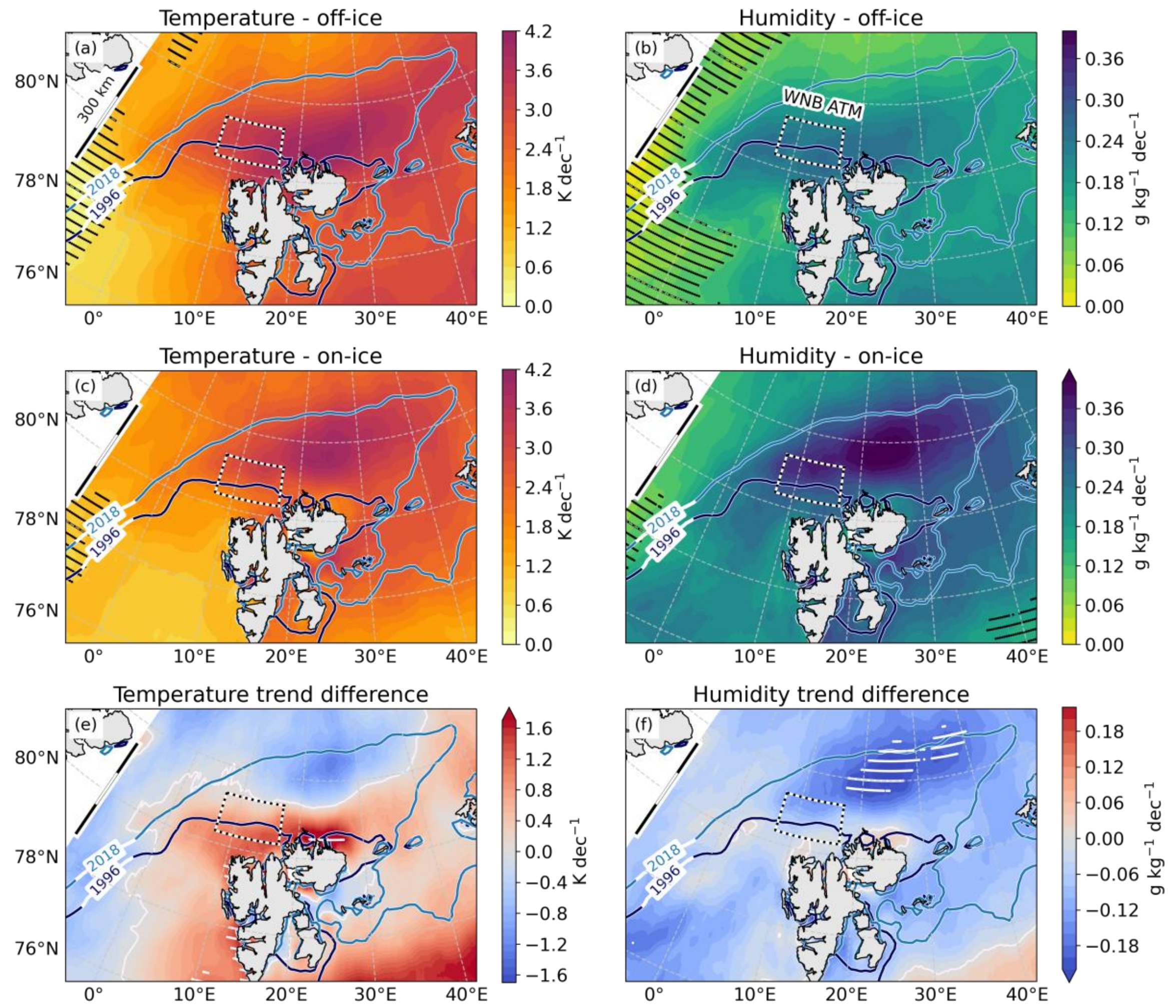

Figure 4: Trend maps in the greater WNB region for ERA5 air temperature (a,c) and specific humidity (b,d) for January to March of the years 1992 to 2022 using only periods with north-easterly winds (a,b) and using periods with all other wind directions (c,d). Black dotted areas are not significant at the 95 %-level. Blue lines denote the 80 % SSM/I-ASI sea ice concentration contours averaged from January to March for two years with large and small SIE, respectively. Panel (e) shows the differences of air temperature trends using north-easterly winds and the trends using all other wind directions (panel (a)

minus panel (c)) and panel (f) shows the corresponding trend differences for specific humidity. White dotted areas in e and f are significant at the 95%-level.

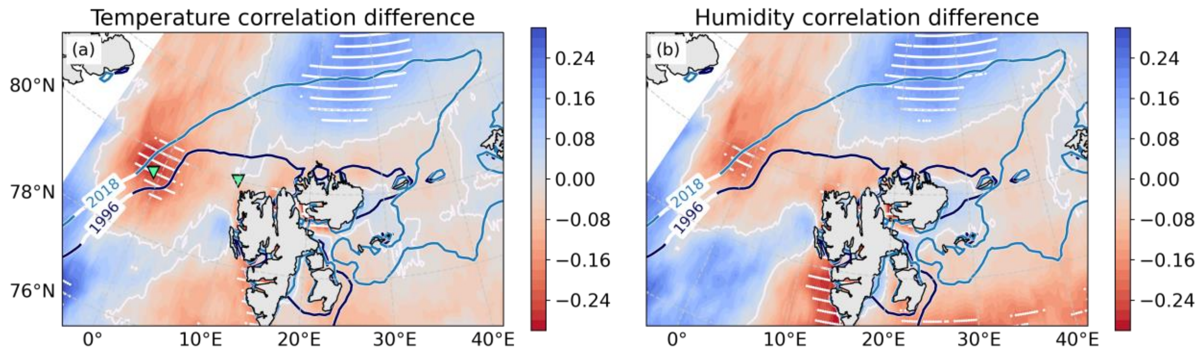

Figure 5: Differences of correlation coefficients between sea ice concentration and (a) temperature and (b) humidity trends (off-ice minus on-ice flow). White dotted areas are significant at the 95 %-level. Blue lines denote the 80 % SSM/I-ASI sea ice concentration contours averaged from January to March for two years with large and small SIE, respectively. Green triangles mark the locations used in Fig. 6.

2) The second issue concerns a generally better explanation of the methodology. What are the implications of the differences between off-ice and on-ice flow? Why is upstream sea ice cover chosen? How can the effect of sea ice cover be entangled from large-scale atmospheric warming or increased ocean heat?

Generally, we will address these issues by slightly adjusting the storyline and the overarching questions of the paper. This different framing of the topic helps to clarify the applied methods. The new structure is derived from the following questions:

1. What are the trends of near surface atmospheric variables in the Fram Strait region?

2. Two typical synoptic situations in this region are cold air outbreaks (CAOs) with cold, dry air flowing from sea ice covered regions towards the open ocean and warm air intrusions bringing in warm and moist air during southerly flows. What atmospheric trends can we observe for these two situations – off-ice flow during CAOs and on-ice flow during warm air intrusions?

3. One factor influencing the strength of CAOs in this region is the open water fetch or the fraction of ocean covered by sea ice. Can we find a relationship between the atmospheric trends over the open ocean in the Fram Strait region and a decrease of sea ice in the upstream region? We address this question by calculating correlations between sea ice cover and atmospheric variables for both on-ice and off-ice flow. During off-ice flow, a decreased sea ice cover means larger fluxes of heat and moisture towards the atmosphere. We would expect negative correlations in this case. During on-ice flow, winds influence the sea ice drift and push the ice edge further to the north/north-east. Furthermore, warm air masses can cause a melting of sea ice, also reducing the sea ice cover. This would also lead to negative correlations.

In regions where negative correlations are stronger for off-ice flow than for on-ice flow the first mechanism likely dominates and vice versa.

We will change the introduction accordingly and also include this information in short paragraphs at the beginning of each section in the results chapter.

- Large scale atmospheric processes can also have an impact on observed atmospheric trends. For example, Wickström et al. (2020) found an increase of the winter cyclone density around Svalbard from 1979 to 2016. The presence of cyclones in this region was accompanied by positive temperature anomalies east of Svalbard. Such large scale synoptic changes certainly influence the trends presented in Fig. 1 above but not the following analyses, where results are separated by wind sectors. It is also possible that the air flowing in from the Central Arctic (for off-ice flow) or from more southern latitudes (for on-ice flow) have become warmer and more humid over time. Such an effect, however, would result in much smoother and more homogeneous trend maps for the different wind direction sectors. For example, it is evident from Fig. 4c and d above for on-ice flow that trends are even larger north of Svalbard, which would not be the case if trends were purely caused by trends within the inflow airmasses.
- An increased inflow of warm water also influences the heat transfer from the ocean to the atmosphere and can thus have an impact on atmospheric trends. Increased ocean heat also causes melting of sea ice. The underlying processes governing the variability of ocean heat flux are very complex and not yet accurately quantified (Charmack et al., 2015). Nielsen et al. (2021) found that while longterm trends in the heat transport into the Arctic Ocean could be dominated by variations in the temperature of the Atlantic Water inflow, changes on shorter time-scales are more likely due to air-ocean interaction dynamics. Their analysis indicates that wind stress is an important factor influencing the variability of the West Spitsbergen Current branches flowing over the Yermak Plateau and thus the overall heat exchange in this region. Thus, it is difficult to look at an isolated ocean impact separately. However, in this study we focus mainly on the impact of sea ice changes on the atmosphere. We do not disentangle whether those sea ice changes were caused by changing wind directions, increased ocean melting or by other factors. Since sea ice insulates the ocean from the atmosphere and greatly reduces heat and moisture exchange, we assume that an increase of the open ocean area will have a much larger impact on air temperature and humidity than an increase of the ocean temperature of a few degrees.

We will now include a detailed discussion of these impacts.

General comments

As I understand it, the main objective of the study is to distinguish impacts on atmospheric temperature and humidity due to “regional sea ice changes” vs “other factors influencing atmospheric conditions”. The separation between the two is done by looking separately at periods of “on-ice” and “off-ice” winds, defined by specific wind direction ranges. I was occasionally confused by this approach; it seems to me that much more space needs to be given to explaining the idea behind this method and what the implications of the observed differences actually are.

See 2).

From what I understand, the authors look to separate temperature/humidity trends due to “effects of changing sea ice cover” vs “other factors” by which they seem to imply warm intrusions from the south. It is not obvious to me that the “on/off-wind” separation is a good way to do this (wouldn’t it be easier to single out southerly winds, for example, or to look at heat transports directly?). Decreased regional sea ice cover presumably does not require “off-ice flow” to affect air temperature/humidity near the ice edge – I am sure the authors are aware of this, but I believe that they should lay out the motivation behind their methodology much more clearly. Moreover, it is not clear to me that the “off-ice” direction necessarily corresponds well to actual off-ice flow.

We adjusted the off-ice wind sectors and contrast them now with southerly on-ice flows. See 1) for details.

The manuscript lacks a thorough discussion of confounding variables, and I often had trouble with the inferred causality. For example, take the statement of L309: “.. correlations for off-ice flow exceed -0.8 for both temperature and humidity and this S.I.C. changes in the upstream region can explain up to two thirds of the observed [temperature and humidity] variability..“. Would they get a different result if they replaced the WNB box with a box to the NW, or just used the same box as for the atmosphere? If not, what are the implications for this statement? And what about large-scale atmospheric warming or increased ocean heat; wouldn’t that affect both variables? I understand that it is hard to pick apart the many interwoven mechanisms at play, but I am missing a more clear and thorough discussion of exactly what the authors have found.

A clearer discussion will be included. See 2) for details.

I do not recommend the publication of this manuscript in its current form; my recommendation is that the paper undergoes major revisions, which I strongly suggest should include a comprehensive overhaul of the paper with the goal of making it much clearer to the reader why the particular approach was chosen, and what one should actually make of the results. I personally suspect that it might be beneficial to separate both the results and discussion into one section dealing with general trends/correlations and another dealing with the difference between on-ice/off-ice winds (although that would certainly not be the only way to go about it).

We now start with a presentation of general trends, followed by a comparison of cases with off-ice and on-ice flow. See 1) for details.

I recognize that the mechanism the authors invoke is somewhat complex, and that I may be missing important aspects out of ignorance. If that is the case, I hope the authors take my input as motivation for providing a clearer framing of the study in a future version of the manuscript.

Specific comments

- The authors need to explain more clearly how their methodology of looking at trends/correlations during different wind directions relates to main objective of the study (separating effects of regional sea ice loss vs “other effects”/southerly heat transport). Perhaps some sort of schematic could be helpful?

The method will be explained in more detail (see 2) for details). A schematic will be included (see Fig. 2d and 3).

- The study relies on the separation between “on-ice” vs “off-ice” winds. These are defined as specific wind direction ranges for the two regions. In my opinion, this choice needs to at least be justified more clearly. For example, would not winds from the NW be more directly “off-ice” at the WNB ATM box than those from the NE? And area the “WNB ICE” box and "fetch line" actually upwind of the “WNB ATM” box during off-ice winds per this definition? It is possible that all of this would be more obvious to a reader more intimately familiar with the region than I am. However, I think it might be helpful in this respect to show some context at the start of the paper; e.g., wind roses with temperature and/or humidity, distribution of temp/hum as functions of wind direction, or map plots of the mean wind/temperature fields during on/off-ice winds might help setting the stage.

Thank you for the suggestion. We think that wind roses are very helpful to present an overview of conditions during different flow directions. They will be included in the results (Fig. 2 and 3). See 1) for details – also concerning the placement of the ATM and ICE boxes.

- It should also be made explicit, or at least discussed in more detail, whether off-ice winds cause a redistribution of heat/moisture within a larger region, or whether this is a mechanism that has caused net increases in heat/moisture in the Barents/Fram Strait area. It was not clear to me from e.g. the trend/correlation difference plots (Fig 3ef, 4cf, 10ef, 11cf) whether the positive/negative regions actually balance out.

All trends for temperature and humidity are positive regardless of wind direction (see Figures 1 and 4), which opposes the hypothesis of a redistribution of heat and moisture in this region.

- I think the authors need to state more clearly whether the differences between trends during “off-ice” and “on-ice” wind conditions are actually statistically different. Does Table 2 indicate that they are not? If so, how does that impact the conclusions?

We now calculate a t-test to compare the significance of the difference of two different trends with slopes *b* and standard errors s_b using the following formula:

$$t = \frac{b_1 - b_2}{s_{b1}^2 + s_{b2}^2}$$

with $df = n_1 + n_2 - 4$ degrees of freedom. Generally, the trends in Table 2 are significantly different only at the 80%-level or not at all. We also indicated areas where trend differences are significant at the 95%-level in the corresponding maps (see Fig. 4e,f). There, also only a small fraction is significant. With the refinement of the research questions and the overall structure of the paper described in 1) and 2) above, however, it is not the main focus of this section – where we analyze trends for on-ice and off-ice flow – to detect whether trends are significantly different. The aim is rather to compare the magnitude of the trends. It is then the goal of the following section to investigate the impact of the sea ice cover on atmospheric conditions. Our analysis of correlations differences already included a significance test.

- Throughout the manuscript, there needs to be a clearer differentiation between trends/effects that are attributed specifically to “off-ice flow” vs to other effects/”general trends”.
  One specific example: From L5 in the abstract (“During off-ice flow..”): It seems necessary here to include the corresponding temperature changes during the other wind directions.
  Another example: Red markers in Figure 9 show the relationship between air temperature NW of Svalbard as a function of WNB S.I.C./polynya length. How different would this figure look if you only included “on-ice” winds?

We will describe the differences between on-ice and off-ice flow in more detail. See also 1) and 2).

Figure 6 is similar to Fig. 9 in the original manuscript, but this time also includes off-ice flow. The left panel shows the more northern of the original two points. Generally, the shape change of temperature with sea ice concentration is very similar for both on-ice and off-ice flow and also correlation values do not differ much. It is evident from Fig. 5 that this point is located in an area where we do not observe large differences in correlations. The right panel thus shows a second point located further west, for which correlations are lower for on-ice flow. Also at this point, the temperature change with sea ice concentration looks very similar for both wind sectors. However, since correlation does not mean causation, different processes are probably related to the observed behavior.

For off-ice flow, reduced sea ice cover allows for an increased heat exchange with the ocean and thus increases air temperatures. Strong on-ice flow generally pushes the ice edge further north and thus decreases sea ice cover. In addition, warmer air increases melting of sea ice. We will discuss these mechanisms in more detail in the corresponding section of the paper.

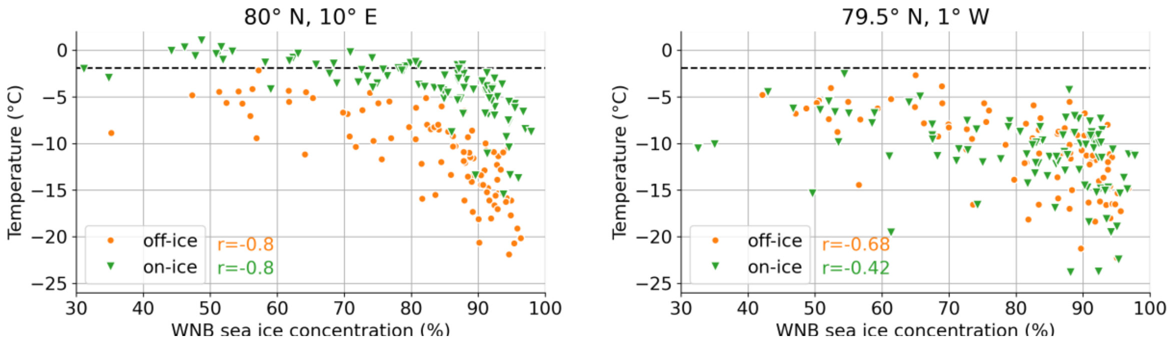

Figure 6: ERA5 air temperature at two locations averaged monthly for periods with off-ice and on-ice north-easterly flow as function of WNB sea ice concentration. Numbers are Spearman rank correlations.

- L129: The formula by Steiger 1980, or a brief description of what it is, should be included.

The formula is based on Fisher's z-transform, where both correlation coefficients *r* are transformed to a *z*-value:

$$z = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$$

and a t-test is applied to the difference z_1-z_2. We will include this description in the paper.

- Figure A1: I am a little confused as to why the SD of sea ice concentration is shown here. Why not just show the actual (winter average) concentration?

In our opinion, the outline of the Odden ice tongue can be visually detected more clearly from the standard deviations than from the mean sea ice concentration. This can be seen from Fig. 7. Nevertheless, we will include maps of the means as an additional figure in the appendix.

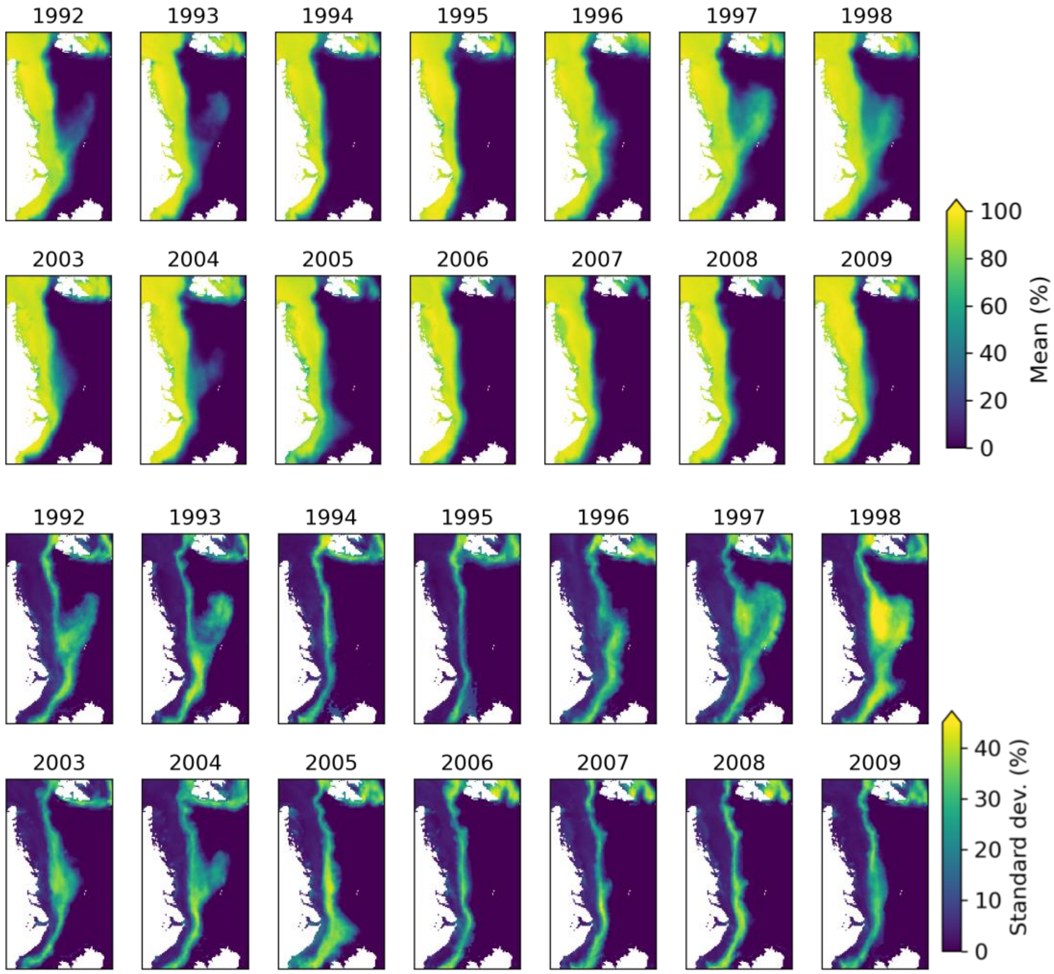

Figure 7: Mean (top) and standard deviation (bottom) of January to March SSM/I-ASI sea ice concentrations.

- Great that the study looks at two different reanalysis products, this strengthens the analysis. Figure 5 shows apparent striking systematic differences in both temperature and humidity – it would be useful if the authors could briefly comment on possible reasons for this (different height levels? known biases?).

We use MERRA-2 data from provided at 10 m height and ERA5 from the lowest model level, which varies roughly from 8 to 10 m height in this region and season. Such a small height difference between the two reanalyses does not explain the observed differences. A few studies have focused on the analysis of systematic differences between reanalyses in this region. Peterson et al. (2017) found that ERA5 has a stronger overestimation of winter temperatures, while MERRA-2 has a stronger overestimation of the downward longwave radiation flux. Yeo et al. (2022) showed that MERRA-2 exhibits a stronger overestimation of near-surface cloud fraction, which increased longwave cloud radiative effects. Overall, more research is required to identify the causes of these reanalysis biases. Nevertheless, we will briefly comment on this issue in the corresponding section of the paper.

In general, I found the figures to be nicely made and helpful. I would suggest a few modifications:

- Add scale bars to the maps (helps to interpret statements like "500 km downstream", etc).
- Clearly label the boxes – e.g. GRB (ICE), GRB (ATM) or similar; it is at times difficult to follow which is which.
- Label the Odden Ice Tongue somewhere in Figure 1. The Odden ice tongue should also be indicated in Fig. 4.
- Revise the colormaps such that warm colors correspond to warm temperatures etc (this would make especially Figures 3/4 a bit more intuitive). Figures 3/10 and 4/11 should at least have the same color showing the same sign of temp/hum change.

The maps now include scale bars (see Fig. 1 and 4) and all boxes will be labeled more clearly (see Fig. 4). The Odden ice tongue (and also the Yermak plateau – see next point) will be labeled in the respective figures.

We now omit the purple end of the colormap for temperature trends so that red colors correspond to regions with the largest warming. The original Fig. 10 and 11 do not show trends but correlation coefficients. We originally chose to use the same color maps as in the original Fig. 3 and 4 to make it easy to distinguish results for temperature and humidity. However, we see that this might be misleading and will now use a different colormap for all correlation plots (original Fig. 10 and 11 a-d) ranging from purple for strong negative correlations to light blue for a correlation of 0.

- The area NW of Svalbard where trends are most affected by off-ice winds (e.g. Fig. 3ab, Fig3ef) seems to correspond roughly to the Yermak Plateau, which from what I understand is an area where the upper ocean is particularly warm and loses a lot of heat and moisture to the atmosphere. Could this play a role in the mechanism that the authors invoke? (Note: I don't expect the authors to go into detail, but I think it warrants a mention).

With the updated definition of wind direction sectors the original Fig. 3 has changed a bit in this specific region (see Fig. 4) so that positive trends do not extend as far to the north-west as before. Nevertheless, we checked whether an impact of the Yermak plateau is notable in the correlation maps (see Fig. 8). It is evident that the area of maximum correlation differences for on-ice and off-ice flow do not align very well with the outline of the Yermak plateau and thus it is unlikely that local heat exchange due to ocean mixing dominates the observed trends for off-ice flow.

Nevertheless, we will mention the general importance of the Yermak plateau on the ocean circulation in this region. See also 2) for details.

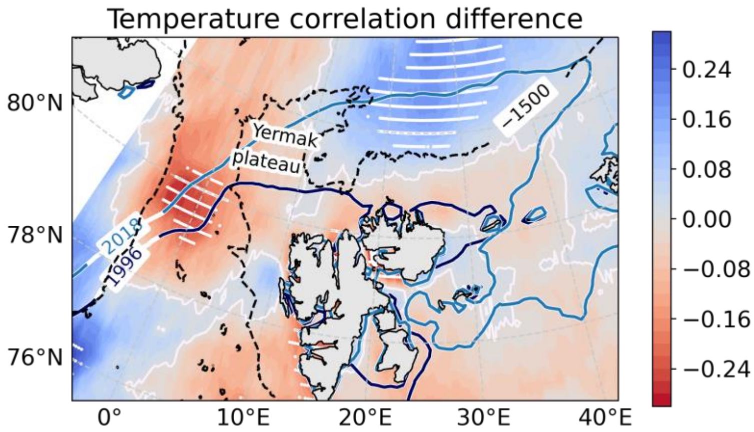

Figure 8: Same as Fig. 5a but with an added isoline at 1500m depth to illustrate the location of the Yermak plateau. Based on GEBCO bathymetry data.

Technical/minor

- L20-22: Meaning is unclear.

The sentence will be rephrased to:

"The strength of the trend also highly depends on the region. Stroeve and Notz (2018) and Onarheim et al. (2018) found that the regions with the largest decrease of SIE were the Beaufort and East Siberian Seas in September and in the Barents and Greenland seas in March."

- L147 and onward: "trends of the frequencies" – I find this use of "frequency" confusing (others may not)

What we mean here is the "frequency of occurrence". This term will be used for clarity.

- L142. "Westerly to northerly": If this refers to the 30-60 degree window, this phrasing seems inaccurate.

This sentence refers to the -45° to 15° window.

- L173: "time series of trends" – meaning unclear

It should read "time series of atmospheric variables" and will be corrected.

- I would advise being careful with the use of "as for"; to me, this reads as "with regard to". (Ex. L189, L245, L280).

We will rephrase to

L189: "Like for WNB, trends are calculated using ..."

L245: "Similar to the atmospheric trends (Sect. 3.1), the general patterns ..."

L280: “This is almost one third larger than trends calculated using periods with all other wind directions, which is a similar result as for WNB.”

References

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