Response to reviewer 1

"Coastal climate variability in Northeast Greenland and the role of changing sea ice and fjord ice"

Shahi et al

Dear Reviewer,

We are very grateful for your very constructive reviews and appreciate the valuable time put into this. By incorporating the reviewer's suggestions, we are confident of having achieved a much more mature manuscript which we hereby submit for your consideration.

In the following, we mark red the comments given by the reviewer, give our answers and comments in black, and indicate how we addressed the amendments in the manuscript in green.

– on behalf of the author team,

Sonika Shahi

Summary

"Coastal climate variability in Northeast Greenland and the role of changing sea ice and fjord ice" by Shahi et al presents a process-level analysis of the local and large-scale drivers of slope temperature gradients (STG) measured at weather stations around the Zackenberg station array. The authors additionally use passive microwave sea ice observations, atmospheric data from UAV retrievals, and ERA5 reanalysis and the Regional Atmospheric Climate Model (RACMO) data fields to evaluate complex associations between nearby Greenland Sea and fjord ice cover conditions, upper-air circulation patterns, and STGs and their impacts on surface mass balance of the adjacent A.P. Olsen (APO) ice cap. Toward understanding these interactions, key findings include high offshore fjord and Greenland sea ice fraction (SIF) is linked with near-surface inversion-like conditions (shallow STG), less snowfall/ablation at APO under anticyclonic upper-air conditions aloft. In the case of low SIF, the opposite associations are found with steep STGs, more snowfall and ablation under a lower pressure/cyclonic regime in the mid-troposphere.

Changes to the regional cryosphere do not typically occur in isolation (i.e., such as local glaciers melt during a warm spell while nearby sea ice does not and vice versa), and the authors put forth a commendable effort to link changes in glacier surface mass balance (SMB) and associated surface-atmosphere interactions within an observation-rich region at Zackenberg. That said, I offer a few suggestions to draw attention more clearly to the paper's themes. In particular, the authors might re-consider if the title reflects the narrative. The authors may also consider what role a changing sea ice/fjord ice cover through time plays in their results. More specific recommendations and minor comments are listed below by line (L) number referencing the submitted version of the manuscript.

We would like to thank the reviewer for his/her time and the positive comments. We have considered all the comments and have modified the manuscript in response. We also adapt the title accordingly as: "The importance of regional sea-ice variability for the coastal climate and near-surface temperature gradients in Northeast Greenland".

General Comment on the Analysis

1) Much like other Arctic marginal seas, summers of the last decade have seen a decline in Greenland Sea ice conditions, which contrast earlier analysis years of the late 1990s and early 2000s when sea ice was more prevalent, for example. Does this change in the ice-coverage and its seasonality (timing of melt and freeze onset) across time impact the interpretation of high versus low sea ice fraction years with regards to the atmospheric processes examined?

That is an interesting and important question and comes up in a similar form yet different wording from Reviewer 2. We put more effort into this topic while initiating this study and plotted the daily sea ice time series (SFig4) to see if the high and low sea ice days are randomly distributed over the study period. We concluded that the distribution was not skewed and rather random, so we did not emphasize it in the initial submission. However, since there is a trend visible in DJF and MAM, we used three different methods to identify breaks when the statistical properties of sea ice potentially changed:

1. We manually selected the middle year of the total period (1996–2020) as a change point i.e., the year 2009, and calculated the atmospheric composites before and after 2009 with respect to sea ice variability.
2. We detrended the sea ice time series using the estimate of the trend component; trends were estimated by applying the Mann-Kendall test at the 5 % significance level and trend strengths were quantified by applying Sen's slope estimator. Then, we calculated the atmospheric composites based on the high (more than 95th percentile) and low (less than 5th percentile) detrended sea ice values (Fig. R1).

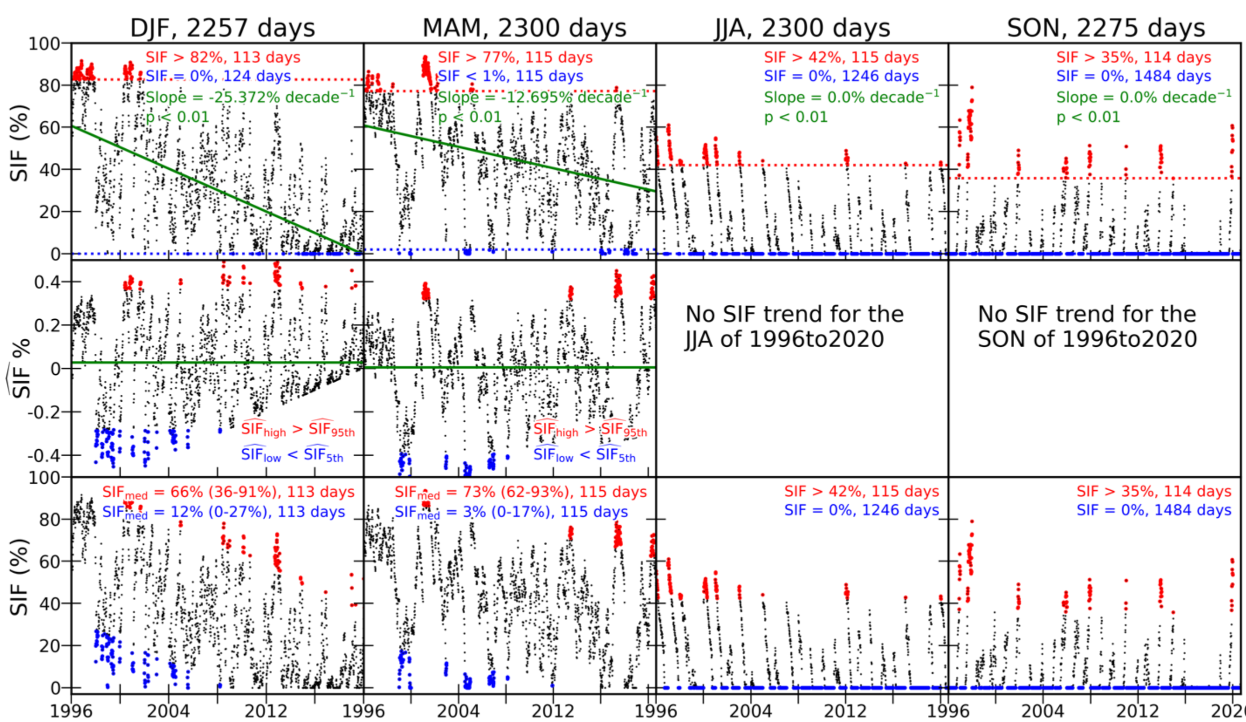

Figure R1. The time series of daily fractional sea-ice cover (SIF in %) zonally (over all grid cells) estimating central tendency (median) over the Greenland Sea for the given season (1996–2020). The upper row

represents the time series of daily SIF, the middle row represents the detrended daily SIF ($\widehat{SIF}$) time series, and the bottom row represents the daily SIF time series with high and low SIF days determined from the $\widehat{SIF}$. The dots represent the SIF and $\widehat{SIF}$ for all day (black dots), high SIF/SIF days (red dots; days when SIF and $\widehat{SIF}$ are more than their respective 95th percentile), and low SIF/SIF days (blue dots; the days when SIF and $\widehat{SIF}$ are less than or equal to their respective 5th percentile) over the period 1996–2020. The red and blue dashed lines represent the 95th and 5th percentiles of SIF and $\widehat{SIF}$ for the given season. The green line represents the trend line and the estimate of the trend (slope and p value) are represented in green text.

3. We applied an offline change point detection algorithm, Kernel change point (Celisse et al., 2018) to detect a significant change in the statistical properties of fractional sea-ice cover (Fig. S5).

We got a similar pattern of SIF anomalies from all three methods, which supports our results and conclusions in the first version of the paper. As the third method is objective and thus more robust, we included only that method in the manuscript (see Section 2.9.2 in the manuscript for detail).

Irrespective of the subperiod identified and used, we find similar patterns of atmospheric composites based on high and low SIF days. Though the mean value of atmospheric variables changed over time due to climate change, the anomalies remain consistent. Thus, the interpretation of the atmospheric process does not change with high and low SIF.

We argue that with climate change and the related evolution of sea ice, the mean atmospheric condition will change as well, however, the anomalies pattern with respect to the newly defined mean (of the subperiod) will not change significantly. So, in the future, due to climate change, decreased sea ice conditions will be more prevalent, which we add to the result (see Section 3.3.3) and discussion (L753–766) of the revised manuscript.

Specific Comments within Sections

L11-25: In the abstract, a concluding sentence on implications of this work in a changing climate is needed, especially with regards to nearby Greenland/fjord SIF and local APO SMB changes. To this end, within this section the authors might consider more clearly emphasizing regional cryosphere coupling in line with the key findings of the paper.

We add the following sentence in the abstract:

"…we speculate that with climate change the Zackenberg region's atmospheric conditions like a decrease in atmospheric stability and surface mass balance (especially in summer), and an increase in precipitation governed by declining sea ice will be more prominent in the future."

L163-164: Was there a threshold established (>+/- x sigma) for establishing these unrealistic data points? Please clarify.

Visual inspection was carried out by investigating the sub-daily time series plot for obvious contextual outliers. We believe using a fixed in the non-stationary time series can lead to mistakenly identifying data as an outlier.

L185: Please be more specific about this "information" - what local camera satellite products and space-time resolutions are used?

With "information" we meant the dates of the fjord ice formation and break up. We modified the text and added detailed information about the camera time resolution as (L185–188):

"The dates for the onset and breakup of fjord-ice in outer Young Sound are mainly based on an automatic digital camera system (74.3° N, 20.2° W), (Rysgaard et al., 2009). The camera is programmed to take one photo a day at 13:20 all year round. In the years when the camera malfunctioned (only a few times) the data is validated with satellite observations."

However, we did not get further information about the satellite products used upon the correspondence with the programme manager. Since fjord ice conditions change very rapidly within a season from entirely ice-covered to entirely ice-free, and since we take daily resolution as the basis, we assume no dependence on image resolution from ground-based camera as even a very poorly resolved camera will give very similar binary results.

L297-299: Was the composites sensitivity to these STG thresholds tested? It would be a good idea to comment on how the results change, if at all, by using different STG strength criteria.

As mentioned in Lines 314–315, in addition to the mean ± half standard deviation as a threshold definition for high vs. low STGs, we used the 25th and 75th percentiles to compute the composite anomaly. With both criteria, the composite anomaly patterns were very similar (in terms of sign: positive or negative (Table R1 and Table S4). This is simply due to the distribution of the data. All the days collected by using the 25th and 75th percentiles have large absolute magnitudes compared to the days collected using the mean ± half standard deviation, hence, resulting in more negative/positive anomalies. For example, the composite anomaly of wind speed for M3 and ZAC stations shows a similar pattern irrespective of the criteria used (Table R1). In order to keep the focus of the manuscript we do not present these results in detail.

Table R1: Anomalies of near-surface variables like wind speed (U_{2m} in m s^{-1}) measured from AWS corresponding to high and low slope temperature gradient between M3 and ZAC (STG_{M3-ZAC} in ^{o}C km^{-1}) days for the given season.

		DJF		MAM		JJA		SON	
		High	Low	High	Low	High	Low	High	Low
M3	STGμ ± 0.5STGσ	-1.6±0.1	2.7±0.4	-0.9±0.1	1.3±0.4	-0.5±0.1	0.7±0.2	-1.3±0.1	1.5±0.3
	25th and 75th STG	-1.6±0.1	3.8±0.5	-0.9±0.1	1.9±0.5	-0.5±0.1	0.9±0.3	-1.3±0.1	2.0±0.4
ZAC	STGμ ± 0.5STGσ	-0.9±0.1	1.5±0.3	-0.5±0.1	0.8±0.2	-0.5±0.0	0.6±0.1	-0.7±0.1	0.8±0.2
	25th and 75th STG	-0.9±0.1	2.2±0.3	-0.5±0.1	1.2±0.2	-0.5±0.0	0.8±0.2	-0.6±0.1	1.0±0.2

As an independent test, we also used a second station pair e.g., M6 and ZAC, which results in the same conclusion that more negative STG_{M6-ZAC} are associated with higher (lower) wind speed at both stations (Table R2).

Table R2: Anomalies of near-surface variables like wind speed (U_{2m} in m s^{-1}) measured from AWS corresponding to high and low slope temperature gradient between M3 and ZAC (STG_{M3-ZAC} in °C km^{-1}) days for the given season.

		DJF		MAM		JJA		SON	
		High	Low	High	Low	High	Low	High	Low
M6	STGμ ± 0.5STGσ	-1.1±0.9	2.7±1.2	-0.6±1.2	2.6±1.5	-0.3±0.5	1.5±0.9	-0.9±0.9	3.2±1.5
ZAC	STGμ ± 0.5STGσ	-1.1±0.1	2.0±0.6	-0.3±0.1	1.0±0.4	-0.4±0.1	0.9±0.4	-0.6±0.1	1.3±0.5

We considered the subjectiveness of the choice of thresholds by both applying different thresholds and different station pairs. While the absolute values naturally change slightly, the sign and the quantity and thus the conclusions remain the same, which is why we opted for a simple threshold scheme.

L321: Are the SIF and STG also non-normally distributed with respect to time also? In other words, is there a year within the respective (seasonal) time series where the mean and/or variance change, and how do composites before/after these potential changepoint(s) affect interpretation of results presented here? Greenland Sea ice cover has changed in terms of freeze/melt onset (see Stroeve et al., 2017 cited in manuscript) and extent through much of the annual cycle (see Peng and Meier, 2018, Annals of Glaciology, doi:10.17/aog.2017.32), so some indication on how the SIF evolution with time affects the frequency of low/high SIF with respect to STG, SMB and related processes should be discussed.

We think this question closely relates to the general comments.

That is a very interesting question and we investigated it further in more detail.

STG is normally distributed; however, SIF is not normally distributed. Keeping the distribution of the data in mind (as mentioned in the manuscript) we also used the 25th and 75th percentile of the STG to test its sensitivity. Since there are data gaps in the station data, it is not recommended to perform the change point detection method in STG. If done so, there is a high chance of getting false positive change points, which is why we only applied the change point detection method in the SIF data.

L454-461: The u10m direction could also be emphasized in this section (I could be wrong, but my understanding is +u = westerly & offshore (in this case), -u = easterly & onshore).

Thank you for the suggestions. The impact of the zonal(u) and meridional(v) wind components on STG is an interesting topic and we briefly explored these wind components before; however, we did not include this part in the manuscript in detail, but we refer to Figure S3 for general prevailing wind patterns.

L477/Figure 8: Might it make sense to flip the color ramp such that more ice (colder conditions) are blue hues and less ice (warmer conditions) are red hues? Figure 11 involving APO SMB applies this rationale to its anomaly SMB color ramp.

Thank you so much for the suggestions. We modified the figure as suggested.

Technical Corrections

L15: near-fjord sea or land ice conditions?

We mean surface type as the presence or absence of snow and near-fjord ice as the presence or absence of ice in Young Sound only. So, we keep the text as it is.

L19: Would suggest removing "Evidently" and start sentence with "A positive…"

Thank you for the suggestions. Modified as suggested.

L21: Instead of "change" I'd recommend adding a descriptor (i.e., reduction)

Modified as suggested.

L67: In the atmospheric science community, zonal references east-west and meridional north-south, so would consider switching terms here for the sake of clarity.

Thank you for the suggestions. Modified as suggested.

L114-116: I'd suggest combining the two sentences, such as "…the present study examines the statistical relationships between STG, SIF, and other atmospheric variables and their physical connections."

Thank you for the suggestions. Modified as suggested.

L119: The year range of ZR temperature monitoring could be listed here.

Thank you for the suggestions. Modified as suggested.

L126: Established by whom (ClimateBasis?) and when in 1995? The following sentences mention 1996 hence clarifying the starting year and month.

Thank you for the suggestions. Modified as suggested.

L136-137: Suggest change "for the entire" to "across Greenland"

Modified as suggested.

L152: Suggest modification to "These datasets provide…"

Thank you for the suggestions. Modified as suggested.

L207: Instead of cross do you mean "x" marker?

Yes. Modified as suggested.

L281-283: This is a bit ambiguous; are there numerical values/ranges associated with steep and shallow STGs?

We use steep and shallow STGs as a comparative vocabulary. We added one example in the manuscript (L285–289) to clarify the use of these terminologies:

"The terminology was used as follows: for a given STG, steeper STG < STG < shallower STG. For example, if the ELR is -6.5 °C km^{-1} and a STG between AP2 and AP1 stations ($STG_{AP2-AP1}$) is -7 °C km^{-1}, and between M3 and ZAC stations (STG_{M3-ZAC}) is -5 °C km^{-1} then ELR is shallower than $STG_{AP2-AP1}$ whereas steeper than STG_{M3-ZAC}. Additionally, we refer to more and less positive STG as 'strong' and 'weak' inversions, respectively."

L347: "During the UAV measurement period?..."

Modified as suggested.

L353-354: If possible, would recommend an estimate of this "same elevation" value.

The information about the elevation is added. It is the elevation of the AWSs but above the ground level: for ZAC 43 m a.g.l. and for M3 420 m a.g.l..

L357: Do you mean "screen-level" on the temperature instrument? Please clarify.

By screen-level temperature, we mean 2 m air temperature. We added this information to the manuscript (L384–385):

"This highlights the potential of AWSs to capture the inversions in the ZR, despite the surface characteristics influencing screen-level (2 m) temperature."

L378: Does "early" need to be in parenthesis here?

We removed the parenthesis.

L380: Do you mean total spring days? Please clarify here and similarly in the sentence that follows.

Yes, a total of 1131 spring days were available for both M3 and ZAC stations. Similarly, 1440 summer days overlapped (and were available) for both stations.

Modified as suggested.

L395/Figure 5: Might a colorbar be added to the figure to depict the SIC gradient (faint to dark blue) that evolves during the freeze-melt periods?

Thanks a lot for the suggestions. We agree that stating "transitional period" has been misleading. Instead of the shading we used in the initial submission that in principle gave an indication of relative sea ice coverage for a given day based on observations during the study period without showing numbers, we add quantitative information in the revised version. We calculate the fraction of occurrence of fjord ice on a given day. For example, a value of 80 % on a day of the year 172 means that 80% of all 21st June during the observation period had fjord ice cover.

L432: Remove comma after "snow" and suggest removing "and as expected," also

Modified as suggested.

L443-444: Would suggest removing this sentence as it does not add substantive summary of the previous results described.

Thank you for the suggestion. However, we consider not removing this sentence as it states the general linkage between synoptic scale condition (from RACMO) and local scale measurements (from AWS).

L450: GrSea sea ice edge averaged for the full period? Please clarify what the dashed black line shows in each panel.

The dashed black line represents the Greenland Sea as defined by the International Hydrographic Organization (available online at http://www.marineregions.org/.). This information is provided in Figure 1. However, for the sake of readability, we added this information to all figures.

L512 and 562-563: "~27 change in SIF" – is this % change? There are a few instances in the paper where sea ice fraction (SIF) is not associated with units.

Thank you so much for pointing out this mistake. We added % after the number.

L564: "…greater impact on the air close to the surface than higher above" such as at what atmospheric layer(s) according to your analyses?

To study the change in the vertical temperature gradient in response to sea ice variability, we use air temperature at five (available) pressure levels (1000 hPa, 925 hPa, 850 hPa, 700 hPa, and 500 hPa) from RACMO (as defined in the Data and method section of the manuscript and in Figure 10). The impact is greater at 1000 hPa (close to the surface) than at the layers above (up to 500 hPa). We added this information to the manuscript (L591–592):

"This result suggests that the variability of sea ice has a greater impact on the air close to the surface (at 1000 hPa) than higher above (at 500 hPa)."

L675: Synoptic-scale time lag of the processes? It is good to acknowledge this timescale as it is relevant to the Stroeve et al. (2017) process interpretation and likely the same timescale of processes that interact in your analysis.

Thank you for the suggestions.

This is a local-scale influence time lag. Stroeve et al. (2017) found a correlation between the timing of melt onset, which occurs on average nine days earlier over the sea ice than on the adjacent ice sheet.

We modified the manuscript accordingly (L740–744):

"However, unlike Stroeve et al. (2017), we did not account for the time lag (1-week lag) effect of the heat transfer from reduced sea-ice areas further inland to the GrIS. This might influence the magnitude of the SMB anomaly. However, considering the short distance between APO and water bodies i.e., Young Sound (~35 km) and the outer coast (~75 km), we speculate a shorter time lag between sea ice melt and ice cap response (though elevation might intervene the interaction)."

L679: Change to "According to the authors,…"

Modified as suggested.