Responses to Reviewer 2

This paper documents an apparent impact of subpolar freshwater anomalies onto the North Atlantic sea surface temperatures (SSTs) in winter and the subsequent summer. These summer SSTs are then argued to drive changes in the atmospheric circulation that drive significant changes in summer temperatures though analysis of reanalysis data and model simulations. Overall, the authors argue that freshwater changes in the North Atlantic can drive a large amount of the variance in European summer temperatures and so argue that such a mechanism could provide significant extra skill in seasonal predictions.

Overall this is an interesting study and presents an exciting set of results. However, I have a number of issues with the manuscript in its current form, which I list below in my major comments. Therefore, I do not recommend publication at this time.

We strongly thank the reviewer for reviewing our manuscript and providing many detailed and constructive comments and suggestions! Your comments and suggestions have helped us to clarify and improve the manuscript.

Major comments

1. My main concern with this manuscript is that the most important results are buried in the appendix - that is the definition of the freshwater budget method, and the results evaluating the impact of freshwater on the North Atlantic SSTs. I note that this is similar to the structure of Oltmanns et al, 2020, in GRL. This usage of the appendix meant that the paper was quite challenging to read as I had to keep flipping back and forth in the paper to try to understand the logic. Furthermore, I would argue that the most important result in the paper is the evaluation of impact of freshwater onto the resulting SST (e.g., section A3). Therefore, I would strongly recommend the authors to move more of the important background information into the main paper and systematically step the reader through the ideas.

Thank you for indicating that the usage of the appendix made it difficult to follow the mass balance approach, and that the link between the freshwater and SST is also an important result. Following your suggestion, we have now integrated Appendix A3 and A4 into the results section. In addition, we have combined Appendix A1 and A2 with the approach section. Thus, the full derivation is now included in the approach section and the results of the mass balance analysis are now included in the results sections.

Still, we think that the link between the freshwater and SST anomalies in winter is only part of the results. The link between freshwater anomalies and the subsequent European summer weather is also an important finding. Thus, we have included additional analyses focusing on the link between the fresh and cold anomalies in winter and the SST anomalies in the subsequent summer, including the role of air-sea feedbacks throughout their evolution (further details are included in your specific comments below).

2. Although I found the results exciting, ultimately the results on the potential impact of freshwater anomalies on Europe were much more uncertain than I feel the authors described. The uncertainty spawns, I think, from the following important reasons.

    - There is little physical understanding of how the summer NAO is leading large freshwater driven SST changes across the subpolar North Atlantic. For example, there is much discussion about how the sign of the relationship between summer NAO and the winter SST anomaly changes at ~0.5, but no reason for this is given. How can we be certain that the freshwater analysis is picking up real physical changes related to changes in freshwater?

Thank you for suggesting adding a physical explanation for the link between the summer NAO and the subsequent freshwater anomalies. In the revised manuscript, we now review the causes of freshwater anomalies associated with both high and low NAO summers.

Consistent with earlier studies, we find that a lower NAO phase is associated enhanced seasonal runoff and melting while a higher NAO phase is associated with an enhanced wind stress curl over the subpolar region, resulting in a stronger subpolar gyre circulation and enhanced advection of fresh, polar water into the subpolar region (Fig. 1). The threshold of ~ -0.5 in the summer NAO corresponds to a critical surface freshening above which the shallower, seasonal freshwater anomalies are mixed down, such that deeper, circulation-driven anomaly signals dominate the hydrography of the subpolar gyre. We also investigated the surface freshwater fluxes (precipitation minus evaporation) but found them to be unimportant for the identified freshwater anomalies.

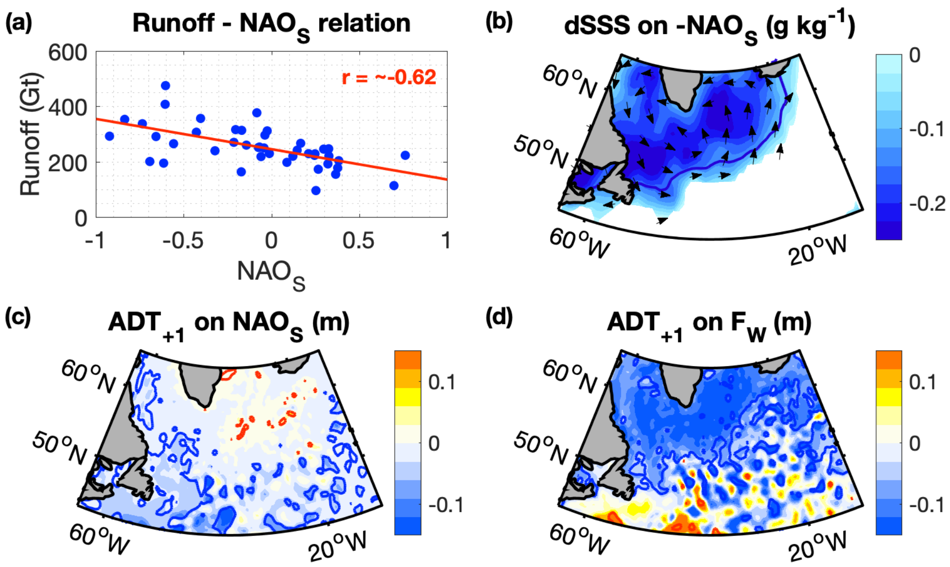

Figure 1: (a) Relationship between the NAO in July and August (NAOs) and the total runoff, integrated over the Greenland ice sheet, in July and August. (b) Regression of the seasonal surface freshening from summer (August) to winter (January to March) onto - NAOs from the preceding summer. Multiplying the summer NAO by '-1' serves the purpose of obtaining an index that is positively correlated with the surface freshening. The seasonal surface freshening has been obtained from a surface mass balance (Oltmanns et al., 2020) and the arrows indicate the mean subpolar gyre circulation, derived from altimetry. (c,d) Regression of the absolute dynamic topography (ADT) in winter (January to March) onto the (c) NAOs and (d) Fw from the preceding summer. A negative ADT anomaly implies a more cyclonic circulation and hence, increased advection of polar water into the region (Häkkinen et al. 2013). The contours in panels b-d delineate the regions that are significant at the 95% confidence level.

The obtained links are consistent with earlier studies on the role of runoff (Bamber et al., 2018; Dukhovskoy et al., 2019) and the subpolar gyre circulation (Häkkinen and Rhines 2009; Häkkinen et al., 2011, 2013; Holliday et al., 2020) for freshwater anomalies in the subpolar North Atlantic.

- Related to the above, the paper focuses on interannual changes - however, there is plenty of observed evidence that there is significant decadal time-scale variability in the subpolar North Atlantic, and so questions arise on what the freshwater analysis, which appears to assume independence between years, is picking up. For example, figure 2c shows that it is the decadal time-scales that dominate the summer NAO time-series, consistent with a southward shift of the North Atlantic Jet (e.g., Dong et al, 2013). Given the low-frequency changes, how can the authors be sure that they are seeing the interannual impact of freshwater changes as opposed to a different, or related, mechanism? For example, is the summer NAO and winter SST responding to another mechanism which is driving both (e.g., large-scale ocean circulation, external forcings etc)? As mentioned below, I think overlaying a timeseries of summer NAO with subpolar SSTs would be useful in seeing the potential importance of these longer timescales.

Thank you for pointing out that the involved timescales of freshwater variability were unclear. In the revised manuscript, we have included an analysis of the longer-term freshwater trend over the last 70 years (Fig. 2). Thus, we find that the summer NAO largely reflects the high frequency, interannual variability of the cold anomaly pattern in the subsequent summer. We also now show the autocorrelation of the summer NAO (Fig. 2f), which is negligible at one-year lag and consistent with the trend of ~-0.002 yr^{-1}, which is only small and not significant.

In the past, decadal switches of the Arctic Ocean Oscillation have led to periodic exports of fresh and cold anomalies from the Arctic into the subpolar North Atlantic (Proshutinsky et al., 2015), which can explain the decadal variability of the SST pattern in winter. However, by using the negative summer NAO as regressor, we filter out low-frequency variability and focus on interannual timescales, consistent with the timescales of European summer weather, which also has a high interannual variability. Since the autocorrelations of the NAO indices, used as regressors in this study, are negligible, we do not expect decadal variability to substantially affect the results.

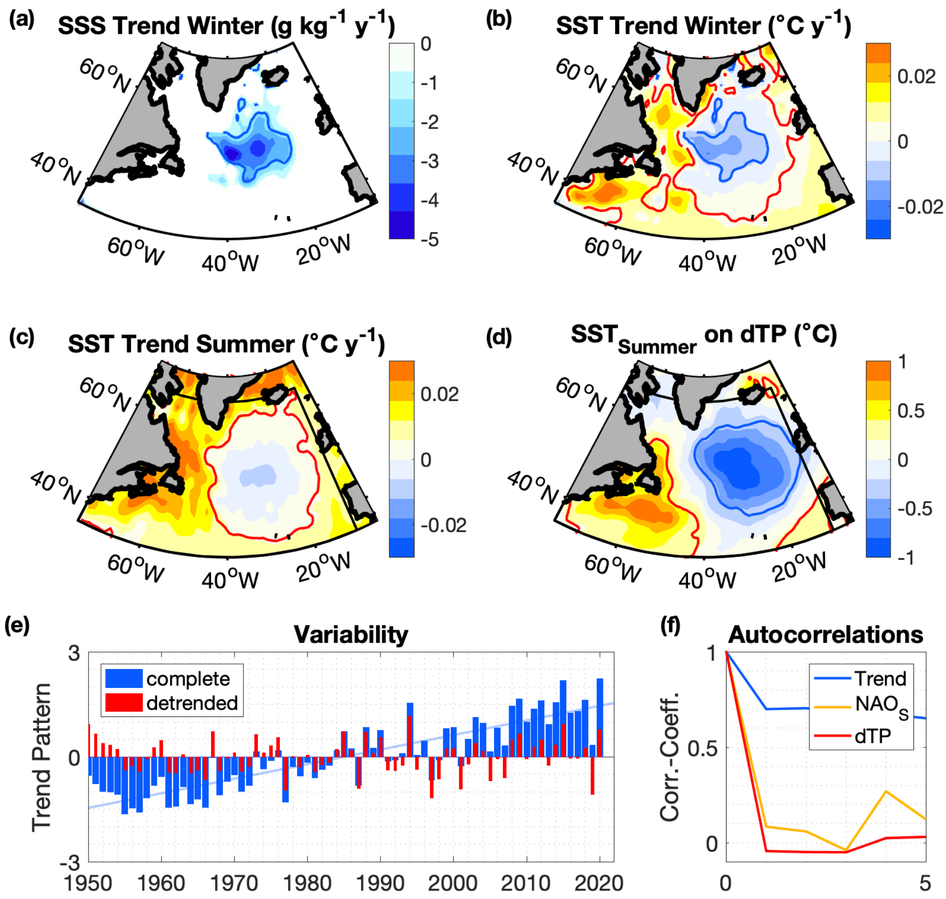

Figure 2: (a,b,c) Linear trend of (a) the SSS, obtained from a surface mass balance, and (b,c) the SST in (a,b) winter (January to March) and (c) summer (July and August) over the last 70 years. (d) Regression of the SST in summer onto the time variability of the detrended SST trend pattern in summer (shown by the red bars in e), obtained by (1) projecting the spatial variability of the SST in summer onto the trend pattern, between 35 °N and 65 °N and between 10 °W and 70 °W (shown by the box in c), and by (2) detrending the resulting time series. Thus, the dTP time series represents the high-frequency variability of the SST trend pattern. Contour lines in panels a-d delineate regions that are significant at the 95% confidence level. (e) Variability of the SST trend pattern in summer (blue bars) and the de-trended time series (red bars). (f) Autocorrelations of the time variability of the trend pattern (blue bars in e), the detrended time series (red bars in e) and the full (un-detrended) summer NAO in July and August.

- The model experiments are interesting, but they do not, of course, explore the impact of freshwater changes on European weather. Indeed, the models are feeling the influence of both SSTs and, presumably, external forcings, and the assumption is that the influence of freshwater can be isolated by focusing on the summer NAO analysis. However, and related to point b, this relies that there are no other mechanisms in play that could explain both the summer NAO and the winter SSTs.

Thank you for pointing out that the role of freshwater anomalies for European summer weather was unclear. To address your comment, we have implemented four main changes:

(1) We have included a description of the drivers of freshwater anomalies. Thus, we provide a physical explanation for the start of the chain of feedbacks. Since the identified drivers (runoff for F_E events and circulation changes for F_W events) are not otherwise linked to European summer weather on the investigated timescales, and occur exactly one year in advance, they challenge the idea that an unknown third mechanism drives both freshwater anomalies and warmer European summers without the two being physically connected.

(2) We have included an analysis of the involved timescales of variability and considered alternative drivers of European summer weather acting on these timescales. Thus, we now show that surface freshening has a trend, superimposed on substantial interannual variability that is reflected in the variability of runoff, obtained from the Greenland climate model MAR (Version 3.12, forced with ERA5). Consistent with the identified drivers of freshwater anomalies, the variability of the summer cold anomaly is significantly correlated with the runoff from the preceding summer (July and August): $r \approx 0.59$, $p \approx 9 \times 10^{-8}$ over the last 72 years, which remains significant after detrending ($r \approx 0.45$, $p \approx 1 \times 10^{-4}$). After considering alternative drivers acting on these timescales, we conclude:

"Combined, the close relationships between the freshwater trend, the SST trends in summer and winter, and the superimposed, high interannual variability of the cold anomaly in summer and of runoff in the year before, point to runoff as a potential trigger of the cold anomaly in summer (Fig. 2c). No other currently known mechanism in the tropics, stratosphere or outside the North Atlantic region, has such a high interannual variability, is simultaneously characterised by a strong and significant trend over the last 70 years, leads to fresh and cold anomalies in winter, and occurs exactly one year before the characteristic summer SST pattern."

(3) To assess whether runoff is a trigger of the SST pattern, rather than only a predictor, we have included an analysis of the ocean-atmosphere feedbacks that contribute to the evolution of the SST pattern in summer. After investigating the surface heat and momentum fluxes and their influences on the ocean and atmosphere with ERA5, remote sensing data, in-situ hydrographic observations from the cold anomaly region, and with the models, we find that the momentum fluxes (wind-driven Ekman transports) contribute to the intensification of the SST signal through the summer, while surface heat fluxes are, in turn, driven by the SST anomalies, contributing to the baroclinic instability in the atmosphere. Thus, we conclude:

"The large-scale SST pattern in winter and its evolution from winter to summer can be explained by air-sea coupling over the full North Atlantic. On the one hand, wind-induced transports and in-situ hydrographic observations from the cold anomaly region demonstrate the relevance of atmospheric forcing in intensifying the SST signals over the North Atlantic. On the other hand, model simulations, forced with prescribed, observed SST reveal the importance of the SST for the large-scale atmospheric circulation, including European summer weather. Given the importance of the involved ocean-atmosphere feedbacks, freshwater cannot be understood as the sole driver of European summer weather. It can, however, initiate a chain of ocean-atmosphere feedbacks that affects European summer weather."

(4) We are more cautious about the wording. Throughout the analyses, we refer to freshwater as a predictor, not as a driver. In the conclusion, we discuss evidence that points to freshwater as a trigger rather than only a predictor, but we are explicit about the involved uncertainties, and we have removed phrases that may previously have caused confusion.

> Indeed, I can't help noticing that the SST patterns being explored in the models (figure 8a and figure 9a and b) look like the cold AMV pattern (e.g., Zhang et al, 2019). Therefore, how can the authors be confident that the atmospheric circulation patterns are being driven by just the subpolar North Atlantic, rather than the tropical North Atlantic?

Thank you for indicating that large-scale ocean-atmosphere feedbacks over the full North Atlantic were insufficiently described. In the revised manuscript we describe them more clearly, both in winter and in summer.

The SST in the subtropical and subpolar regions is highly coupled due to large-scale atmospheric feedbacks. For instance, the large-scale atmospheric circulation anomaly, associated with the subpolar cold anomaly, leads to convergent, wind-induced surface currents in the inter-gyre region, and thus a warm anomaly that emphasises the SST gradient. At the same time, the anti-cyclonic, atmospheric circulation anomaly to the south of the SST front leads to upwelling off the coast of Africa, contributing to the characteristic tri-pole pattern of the AMV.

We have now removed the previous model analyses and replaced it with a new analysis where the underlying SST_{FW} pattern in summer is more clearly linked to the preceding freshwater anomalies. Consistent with the observation that the SST anomalies are largest in the subpolar region and decrease towards the south, it can be explained by the large-scale atmospheric feedbacks associated with freshwater anomalies. This includes a range of timescales, including that of the AMV.

However, we are very cautious in the wording about the role of freshwater in triggering these feedbacks. We refer to freshwater anomalies as predictor. While we discuss evidence in the conclusions that suggests freshwater may act as a trigger of the ocean-atmosphere feedbacks, rather than only a predictor, we clearly state the involved uncertainties.

Minor comments

Line 1 - The paper discusses here and in the introduction the possibility of long-term forced changes in the arctic having an impact on the mid-latitude weather, but then exclusively focuses on interannual variability? This left me slightly confused about what I was supposed to be taking from the analysis, so maybe it worth rethinking the motivation?

Thank you for pointing this out. We have now added an analysis of the long-term variability of freshwater and the implications. Thus, we find that there is a significant freshening trend over the last 70 years, superimposed on substantial interannual variability.

Line 63 - why not just use HadISST rather than merge the two datasets?

We did not manually merge the two datasets ourselves. The merged dataset is freely available and benefits from the optimal interpolation technique used in the NOAA data. We have now added the link in the data description to avoid misunderstandings.

Section 2.2 - how do these simulations differ from CMIP style AMIP runs (e.g., Eyring et al, 2016)?

The simulations were designed to facilitate comparison between different models, like those in Eyring et al. (2016). Thus, they have a pre-determined forcing to facilitate the comparison, which is now clarified. In this case, the simulations were performed with the prescribed, observed SST and sea ice cover and time varying greenhouse gases and ozone.

Section 2.3 - I am confused by the discussion of a trend, in part due to the framing of the paper on understanding the impact of long-term forced changes in the Arctic on the wider climate, but I think the point is that trends over land may alter the relationship with ocean SST anomalies? Please clarify.

The point of this analysis was to remove the effect of Greenhouse gases, not to remove trends, which is now clarified. Thus, we do not distinguish between trends over land and ocean. We have also adjusted the subsequent paper to the motivation in the introduction. Thus, we have added an analysis of the trends in the freshening and SST over the last 70 years.

Line 133 - You state that "we derive indices that exhibit a strong relationship to subpolar temperatures but not to the drivers of density anomalies", but then argue that the summer NAO drives changes in freshwater (which will drive the density anomalies) - can you clarify your point, please?

Thank you for pointing out that this was unclear. We referred to the drivers of density (or in turn temperature and freshwater) anomalies. We consider freshwater as state variable that in turn has drivers (like precipitation or runoff). We have now clarified this in the manuscript. In addition, we have added a section describing the physical links between the summer NAO and the freshwater anomalies in the subsequent winter.

Line 140 - you mention the potential impact for the summer NAO on freshwater, but won't it also affect the heat fluxes too? How do you take account of these in your analysis?

Yes, we do consider the surface fluxes in the mass balance analysis. The surface heat fluxes are included in the buoyancy fluxes, and we also show them separately. Surface heat fluxes can be a driver of SST anomalies or a response. In this case, we find that that the surface fluxes cannot explain the SST anomalies. Instead, the surface flux anomalies are positive over the cold anomaly regions, implying that the ocean loses less heat to the atmosphere, contributing to the increased baroclinic instability in the lower troposphere. We have stated this more clearly now in the revised manuscript.

Line 392 - "...we select all the years that lead to an increase in the slope of the regression line." - I'm uncomfortable about this - it sounds a bit like cherry picking to get a stronger signal (which in turn would affect your conclusions about how important freshwater changes are). Please could the authors justify this choice physically?

The objective of this method is to improve the signal-to-noise ratio between the index and freshwater anomalies. The strong signal between the index and the freshwater anomalies is a pre-requisite for the index to represent freshwater anomalies. We do not use it as the conclusion. We now explain the method more clearly and have integrated the appendices into the main text, making it easier to read.

Following your first suggestion, we have also added a description of the causes of freshwater anomalies associated with high and low NAO summers. Thus, we find that the subsampled indices are also more strongly linked to the physical causes of freshwater anomalies, supporting the subsampling with a dynamical explanation. Thank you for suggesting this!

Figure A1 - I can't help but to see that there is a long-term change in the summer NAO with most negative years occurring after 2000. This is consistent with the long-term trend in summer jet. The question this raises is how important is this longer term variability in the sNAO for your results? One thing that is missing is a time series of subpolar SST, which also shows significant decadal timescale variability. Please add this to figure A1 at least. However, following up on this, previous studies have linked these low frequency variability in the jet to the changes in the subpolar temperatures (e.g., Dong et al, 2016) - therefore, how certain are you that the changes in summer NAO are not reflecting decadal time-scale changes in the subpolar gyre?

We now show the timeseries of the SST pattern linked to freshwater events, including the cold anomaly pattern since it is this pattern that is relevant for European summer weather. While there has been significant decadal variability in the causes of freshwater anomalies in the past, the negative NAO picks out the high-frequency variations, associated with the interannual variability of runoff (see also our response to your second comment).

Line 405 - It's not clear to me why the geostrophic currents are not important - there is nothing in the 95% confidence lines that are related to constant lines of density. Please can you clarify your reasoning here?

Geostrophic currents are, by definition, along lines of constant density. Thus, they cannot lead to an increase or a decrease of density. Importantly, they can, and do, drive freshwater and temperature anomalies. However, the density anomalies associated with freshwater and temperature changes need to compensate each other in geostrophically balanced blows. We have clarified this in the manuscript.

Section A3 - it is not clear why you are regressing the JFM heat fluxes onto your summer NAO? In order to rule out the impact of surface heat fluxes on the JFM SSTs it is the integrated heat fluxes between the summer and JFM that are important?

Thank you for pointing out that this was unclear. We are examining the SST signal in winter, which is typically not influenced by the surface fluxes of the preceding summer because the variability of the surface fluxes in winter is much larger than in summer. To be sure, we have repeated the surface mass balance for the period from summer to winter and found that the results did not change appreciably. This is now stated more clearly in the revised manuscript.

417 - the mean mixed layer is the annual mean mixed layer?

Since we are investigating the SST anomalies in winter, we used the mean mixed layer in winter. As the Reviewer 1 pointed out, however, we should have used the mixed layer depth at the end of the winter. Thus, we have corrected this now.

Line 440 - Please elaborate on the origin of the uncertainty numbers.

Thank you for pointing out that this was not sufficiently clear. The uncertainty originates from neglecting the terms on the righthand side of the mass balance equation. It is obtained by comparing the size of these terms to the size of the terms on the lefthand side. We now devote a full section in the main text to the derivation of freshwater anomalies and their uncertainties.

Figure 3 - what is the data used to plot the SSS anomalies, or are they implied from your mass balance analysis?

Yes, the estimates were obtained from the mass balance analysis. This is now clarified in the revised manuscript. Thank you for pointing out that this was unclear.

Section 4.2 - I think when you mean first summer, you mean the same summer as the summer NAO event? However, it was not clear as you're talking about looking in subsequent summers which I took to be after the winter - please clarify. This is particularly important for figure 6, which is unclear what summers you are looking at.

No, we refer to the European weather in the summer one year after the NAO index. It is not the same summer. This is why the summer NAO can be a such a valuable predictor of European summer weather, one year in advance. We have now clarified this.

Figure 7 - Are you computing the variance explained using all years, or are you only focusing on the years that you have large changes? Either way, how important is the long-term trend in atmospheric circulation shown in figure 2c for your analysis?

The variance is computed over all the years for which the indices are defined. In addition, we have added an analysis of the long-term trends over 70 years. Thus, we find that the NAO mostly picks up the interannual variability. Considering that the autocorrelation of the indices is nearly zero at one-year lag, we do not expect the long-term trend to substantially affect the explained variances. This is now clarified.

Figure 9 - Is the only difference between these figures and that shown in figure 8 (d and f) that they are split across model ensembles? Not clear to me why this is relevant - could you just include the ensemble spread in figure 8 ?

The main point of the figure was to show the spread across the ensemble members and how they compare with the observations. However, we have removed this figure now.

We strongly thank the reviewer for carefully reading and reviewing our manuscript and providing so many detailed and constructive comments and suggestions. Your comments have helped us to clarify and improve the manuscript!

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