8. November 2023

Dear Prof. Pfahl,
Dear Reviewer,

We are pleased to submit a revised version of the manuscript "European summer weather linked to North Atlantic freshwater anomalies in preceding years". Based on the detailed and constructive feedback provided by the reviewer, we have further clarified the manuscript.

The main shortcoming of the last version was the skipping of a step in the derivation of Figure 1, which displays the method, giving rise to confusion. In addition, the description of the main results (the link between freshwater anomalies and European weather anomalies) was not adequately placed into a larger context of existing studies.

Following the reviewer's suggestion, we have carried out a series of minor revisions to add further details and clarifications in the description of the method and the results, and to place the results more adequately into a larger context. Overall, the manuscript has again greatly benefitted from the review. Thus, we thank the editor for the careful handling of our manuscript and the reviewer for, once again, providing such a detailed and constructive assessment.

Detailed changes are explained in the response letter below, where our responses to the reviewer's comments are shown in blue, and the resulting changes are shown in red. Figure and line numbers refer to the revised manuscript without tracked changes.

Sincerely,
Marilena Oltmanns, on behalf of all authors

Responses to Reviewer 1

The authors use statistical analysis of observations and reanalysis data to examine a potential link between freshwater anomalies in the North Atlantic subpolar gyre region and summer weather in Europe in the following year. They propose that stronger freshwater anomalies are associated with a stronger meridional SST gradient between the subpolar and subtropical gyre and consequently increased baroclinic instability in the atmosphere above. The resulting changes in the large-scale circulation lead to significant anomalies in near-surface temperature and precipitation in different parts of Europe. The foundation of the analysis are freshwater indices derived from a mass balance equation that are used to identify freshwater anomalies in relation to simultaneous sea surface temperature (SST) anomalies linked to the North Atlantic Oscillation (NAO).

The current manuscript is another substantial improvement to previous versions and I appreciate the added detail in the derivation of the mass balance and estimation of the freshwater indices, and the more precise description of the results. As outlined in my comments below, there is some remaining uncertainty regarding the construction of the freshwater indices. Additionally, the presentation and description of the central results, i.e., the link between the freshwater anomalies and European summer weather, requires – in my opinion – some larger context and relation to known atmospheric circulation and weather patterns that are described in the literature. Overall, I recommend a series of minor revisions that may appear major due to their extent.

We sincerely thank the reviewer for reviewing our manuscript once more, for acknowledging substantial improvements, and for providing additional suggestions to help us clarify the method and place the results into a larger context.

I. Main Comments:

1. Section 3.2:

1. I now understand why this part has been – and, in part, still is – confusing to me: the threshold of $NAO_S < -0.05$ is based on the non-linear relationship shown in Figure 1d. The y-axis of that figure is ΔSST which "corresponds to the SST difference between the red, subtropical and blue, subpolar 95% confidence regions in panels e (red years) and f (blue years) respectively, relative to the respective means". However, these confidence regions are not known a priori, so I am trying to wrap my head around the specific steps to get from the time series of NAO_S (Figure 1c) and winter SST at each grid point, via the scatter plot in panel d, to the maps in panels a and b. Strictly speaking, you cannot determine the value of ΔSST for Figure 1d, and therefore the threshold of -0.5, until you have the two maps (panels e and f) after the subsampling. The subsampling itself, however, depends on the relationship in Figure 1d, so there must have been some iteration or trial-and-error. Please add more details in the text (before l. 202) to lay out your analysis steps.

Thank you for letting us know that the derivation of the scatter plot was still confusing. The confusion resulted from a discrepancy between the number of steps described in the text, and the number of steps shown in the figure.

Since the scatter plots are largely insensitive to the exact regions, we only showed the scatter plot for the 95% significance regions obtained after the method has been applied. We chose these regions because they cover a large area, nicely demonstrate the effectiveness of the method, and provide a means to directly inspect the robustness of the correlation.

Changes:

To avoid confusion, we have included additional panels in Figure 1, showing each step described in the text.

In addition, we have updated the text, and we now explain (line 208): "The threshold of ~–0.5 was initially identified using box regions for the subpolar and subtropical regions (for instance with latitudinal boundaries between 45 °N and 60 °N for the subpolar region and between 30 °N and 45 °N for the subtropical region). However, the identified relationships are not sensitive to the exact regions."

With the additional steps shown in the figure, it becomes clearer that the distribution of the points in the scatter plots does not appreciably change as the regions, used for the spatial averaging, are adjusted throughout the optimization (compare Figure 1d, h and l).

2. Please define ΔSST in the text. Is this the difference between the regressed SST or the actual SST values in these regions? Is it relative to the respective spatial or temporal mean (over which period)?

   It is the actual SST value, not the regressed SST. The anomalies are relative to the respective (temporal) mean over each subset. The SST anomalies are a vector quantity with only one dimension. They are already spatially averaged over the 95% significance regions.

   We added the word "observed SST difference" to avoid confusion. We now also clearly state in the caption of Figure 1 and in the text that we subtracted the temporal mean over each subset, and we define ΔSST in the text.

   Thank you for helping us to be more precise.

3. Caption of Figure 1: $-NAO_S/+NAO_S$ is confusing – this could be interpreted as positive and negative phase of the NAO. Maybe " $-1 \times NAO_S$" is more obvious.

   Thank you for suggesting this. We have adopted your suggestion.

4. l. 235: Have you looked at the differences of regressions/composites between the included and rejected years? This could potentially help identify or constrain a physical mechanism at play for years with a strong relationship.

Yes, we did. The first outlier was a strong runoff-driven anomaly. However, the anti-cyclonic atmospheric circulation anomaly in the preceding summer (in 2014) extended far to the south. Thus, it was not captured by the NAO index.

The second outlier (with the NAO index in 2019) was also a runoff-driven freshwater anomaly. However, a careful examination of the associated ocean and atmospheric circulation anomalies showed that the subpolar gyre circulation anomaly was still enhanced in this year. Thus, there was not only more freshwater inside the subpolar gyre current system, but in addition, an enhanced redirection of the cold and fresh polar water into the interior subpolar region. As a result, the NAO index underestimated the fresh and cold SST anomaly.

Likewise, we found that for the years, rejected in the second step of the subsampling, the relationship between the subpolar gyre circulation and the SSS anomalies still holds. However, in these years the subpolar gyre circulation is not well captured by the NAO index. Thus, the years, rejected in the second step of the subsampling still correspond to circulation-driven anomalies.

In the end, we decided not to include a detailed description of the outliers and rejected years for the sake of brevity. After all, the underlying mechanisms are still the same as those described in the manuscript. The disagreement with the other years is mostly a matter of the increased variance that inevitably results from including more years. This increased variance is not adequately captured by the NAO index. However, it is not a third, distinct mechanism that is responsible for the associated fresh and cold anomalies.

Through the previous inclusion of Section 4.5, we also clarified that the link between fresh and cold anomalies (and their link to European summer weather) still holds for the rejected years. They are just not well captured by the NAO index.

One of the advantages of the subsampling is to ensure spatial consistency within each subset. This is important because small shifts in the location of the SST front are associated with corresponding shifts in the atmospheric circulation and warm and dry anomalies over Europe in the subsequent summer. For instance, if two years with very different spatial patterns are included in one subset, they can partially cancel each other out.

We clarified that the link between freshwater and cold SST anomalies still holds during the outliers and rejected years (line 227 and Section 4.5).

In addition, we now state that, for the rejected years, the subpolar gyre circulation is still the main driver of cold and fresh anomalies, but the circulation is not well captured by the NAO index in these years (line 363).

Lastly, we now also mention the advantage of the subsampling to reduce the spatial SST variance and thus ensure spatial consistency within the subset (line 480 and 504).

2. Section 4.4: Given the title of the manuscript, this section describes the central result of the study: the statistical link between summer weather and freshwater anomalies in the subpolar gyre in previous years. However, the presentation of the results leaves me as the reader unsatisfied. While I appreciate the added details compared to the previous version, some of the conclusions remain slightly hand-wavy and are missing some larger context:

1. Based on the regressed meridional wind anomalies at 700 hPa, you describe a "northward deflection of the jet stream" following both FE and FW freshwater anomalies that differ in there location between years and subsets. Given that the jet stream occurs at higher altitude, you are rather describing circulation anomalies in the lower troposphere.

   Thank you for pointing this out. We did investigate the winds at higher altitudes and found that the anomalies extend at least up to 500 hPa (the highest altitude we checked). However, we only show the lower component since we expected them to affect the surface weather more directly.

   We have replaced the word "jet stream" by "lower tropospheric winds" at all instances in the results and conclusions sections.

   Regardless of this semantic distinction, I am missing a discussion of the southward anomalies in the 700 hPa winds in Figures 5c and 6b as they can help put these anomalies in the context of known large-scale circulation patterns (e.g., Cassou, 2008; Grams et al., 2017) and their related expressions in surface temperature and precipitation anomalies. Relating your result to previous studies may also help identify physical processes that lead to the anomalies that you describe – is it advection of warmer/dryer air masses or changes in radiation/heat fluxes that can be linked to the large- scale circulation? For example, the anticyclonic circulation anomaly over the North Sea in Figure 6b might be suggestive of a blocking event (reduced winds, increased radiation, less precipitation...) – interestingly, the dry anomalies in Figure 6d are roughly co-located.

   Thank you for suggesting relating our findings to previous studies. We have now added a longer discussion of the observed flow anomalies to place them into a larger context of existing literature. First, we have included a longer discussion of the observed large-scale atmospheric circulation anomaly (for instance line 450). In a subsequent step, we then relate it to earlier studies. For instance, in line 470, we write:

   "Placing the identified atmospheric anomalies into a larger context described in the literature, we find that is representative of blocking anticyclones (Brunner et al., 2018; Kautz et al., 2022). In summer, blocking anticyclones over Europe are typically associated with increased surface pressure and higher surface air temperatures (Brunner et al., 2018; Kautz et al., 2022). Considering that the maximum temperature anomalies in summers after enhanced F_E freshwater anomalies occur east of the northward wind deflection, in the centre of the anticyclonic circulation anomaly, the location of the increased air temperature anomalies is consistent with earlier studies which have attributed the warm anomalies to enhanced shortwave radiation (Kautz et al., 2022; Pfahl, 2014; Sousa et al., 2017). Moreover, the occurrence of the dry anomalies to the east of the warm surface air temperature anomalies likely results from a reduced passage of cyclonic weather systems, which are blocked by the large-scale anticyclonic circulation anomalies (Sousa et al., 2016)."

Accordingly, we have also updated other instances in the text where we describe the large-scale atmospheric circulation anomaly.

2. Figure 5: In order to make it easier for the reader to interpret the regressed anomalies, it might be worthwhile adding another column of maps showing the mean conditions.

   We have now added another column showing the mean conditions (Fig. 5).

3. I do not understand the justification for excluding the 2016 anomalies (caption of Figure 5).

   The freshwater anomaly in Summer 2016 extended over a larger area further south of the North Atlantic Current compared to other years, resulting in enhanced mixing and a patchy meridional SST gradient east of the European coastline, with alternating warm and cold SST anomalies of reduced amplitudes. Consistent with the underlying SST field, we identified a split zonal wind around 0 °E to 10 °E, with one branch extending northward along the European coastline, and another one along the southern Mediterranean Sea. In conclusion, the relationship between the SST, winds, and European temperature anomaly still holds in this year but the spatial patterns just do not map onto the other years, included in that subset.

   We are now acknowledging the limitations of our method to ensure spatial consistency across the events. Specifically, we explain (line 479):

   "A downside of the statistical approach arises from the sensitivity of European summer weather to the exact location of the SST front between the subtropical and subpolar gyres. Small deviations in the spatial characteristics of the SST pattern and lower tropospheric circulation between two years can lead to shifts in the location of the maximum warm and dry anomalies over Europe, partially cancelling each other. Thus, we found that the spatial patterns in Summer 2016 did not match those of the other years included in the F_E subset (Fig. C1). The cold SST anomaly extended further south of the North Atlantic Current, resulting in enhanced mixing and a patchy meridional SST gradient just west of the European coast with two cold anomalies of reduced amplitudes. Consistent with the underlying SST field, we identified a split zonal wind between ~0 °E to ~10 °E, with one branch extending northward along the European coastline, and another one crossing the southern Mediterranean Sea. Accordingly, one warm surface air temperature anomaly covered northern Africa and another warm anomaly occurred along the northwest European coastline (Fig. C1). So, even though the spatial SST pattern in Summer 2016 did not match those in the other summers, we still identify the same close relationship between the SST, tropospheric winds, and European weather anomaly."

Later, we mention (line 504):

"Considering that – from all the years included in each subset (17 and 8 respectively) – only the Summer 2016 exhibited a diverging spatial pattern in SST and atmospheric anomalies, the results suggest that (1) the statistical method is overall successful in selecting years with similar spatial structures, and (2) the spatial consistency for which we selected in winter is, in most cases, maintained through to the subsequent summer."

II. Additional Comments and Suggestions:

1. l. 36: This wording suggests that it is certain that freshwater initiates the causal chain, but only the physical mechanism is unclear.

   Thank you for pointing this out. We have replaced "will" by "could":

2. l. 77-79: You mention that you use monthly – presumably mean – ERA5 output in the analysis. Please clarify: did you estimate the maximum Eady growth rate of the monthly mean circulation or did you compute it from higher-frequency, e.g., daily mean, output that you then averaged over a month? Given the nonlinearities in the equation these two estimates could be quite different, however, I do not expect them to change your results.

   Yes. Thank you for spotting that this has been unclear from the previous phrasing of this section.

   The maximum Eady growth rate is the only nonlinear variable that we computed based on monthly means. Thus, we only use it for a qualitative assessment of the lower tropospheric instability. We agree that using high-frequency output in the calculation is unlikely to affect the overall conclusion that the maximum Eady growth rate is enhanced over the SST front.

   We now clarified that we are using monthly mean output to calculate the maximum Eady growth rate by explaining (line 78): "The maximum Eady growth rate was calculated using monthly mean output from ERA5 to qualitatively assess the baroclinic instability in the lower troposphere over increased meridional SST gradients."

3. l. 195, 197, 246: I am still stumbling over the phrase “lower/higher NAO phase”. I am not familiar with the detail of the previous studies that you refer to in the first two instances, but I would assume the most of them contrasted the two states of the NAO and therefore, I suggest to use “negative/positive NAO phase”. The last instance can be changed to “associated with $NAO_S < -0.5$”.

   Thank you for suggesting this. We have adopted your suggestions.

4. l. 323-325: Please clarify: the runoff-NAO_S relationship is calculated over all years, yet you use it as a potential explanation for F_E freshwater anomalies, i.e.,

only a very specific subset of years. In Figure 3a, this relationship is not that clear if you only consider $NAO_S < -0.5$. If anything, there seems to be a clearer relationship and less spread around the regression line for the F_W years.

Yes, you are right that the relationship between the summer NAO and runoff is less clear for NAO values smaller -0.5. However, we do not use this relationship to explain differences in the freshwater anomalies between individual F_E years. Instead, we use this relationship to explain the difference between F_E and F_W anomalies.

Specifically, we state (line 330): "[...], we find a significant anticorrelation between the summer NAO and runoff (Fig. 3a)". Thus, F_E anomalies are associated with more runoff than F_W anomalies. We are comparing the drivers of freshwater anomalies associated with F_E and F_W with each other, rather than comparing different F_E years with themselves.

Further studies are required to inspect the differences between individual F_E years. However, we think that the wind forcing associated with the NAO index may play a role, by favouring an enhanced surface flow convergence in the subpolar region.

We now explain that the relationship between the NAO index and runoff cannot explain differences within the F_E subset. Instead, it explains the existence of the F_E subset in the first place (line 341).

5. l. 376-377: Please clarify: do you show that "after strong F_E anomalies, the NAO anomaly switches sign from being strongly negative in summer to being strongly positive in winter" or do you infer that from Figure 4b? Out of curiosity, what is the correlation between summer NAO and winter NAO with and without conditioning on F_E years?

   We have followed your suggestion and replaced the sentence with a more quantitative statement (line 388):

   "Over the period 1979 to 2022, and without conditioning on F_E years, the correlation between the NAO in summer (July and August) and the NAO in the subsequent winter (January to March) is r = ~0.12, which is not significant (p = ~0.46). With conditioning on F_E years, the correlation is r= ~–0.74, which is significant (p = ~0.03). Moreover, we find that after all but the two weakest F_E years, the NAO changed from its strongly negative state in summer into a positive state in the subsequent winter."

6. l. 457-459: This sentence is unclear.

   We have split the sentence into smaller parts and simplified it.

7. l. 471: It is easy to get lost here: I think what you are doing is regressing the winter SST on NAO_S for all years, but calculate ΔSST bases on the regions shown in Figure 1e with the resulting time series shown in Figure 7a. Please add more detail to clarify your analysis steps here.

Thank you for pointing out that this was unclear.

The ΔSST index does not involve any new regression on the NAO index. It is defined as the observed subpolar-subtropical SST difference in any given year. We defined the underlying regions based on the significance lines shown in the previous Figure 1e (now Figure 1j). We selected these regions since they cover such a large area of the subpolar and subtropical gyre and clearly define both regions. However, the results are not sensitive to this choice.

We have clarified the text and clearly explain that the SST index covers all years. It is defined as the SST difference between the regions shown in Figure 1j in each individual year, with the resulting timeseries shown in Figure 7a.

8. l. 484: Notably, the T2m anomalies are offset to the east of the V700 anomaly. Similar to my comments on Section 4.4 above, please discuss this in the context of the existing literature and speculate about the physical mechanism.

   The northward V700 anomaly form the western component of a large-scale anticyclonic circulation anomaly over western Europe (see for instance the arrows in Figure 6b). The T2m anomalies are strongest in the centre of the anticyclonic anomalies, which is to the east of the V700 anomalies. This suggests that the temperature anomalies are driven by the radiative forcing in the centre of the anticyclone rather than the direct effect of the horizontal wind anomalies.

   We have now added a longer discussion on the identified, large-scale atmospheric circulation anomalies and placing them into the context of existing literature (see also our response to your Main Comment 3).

9. Figure 7a: What did you normalize the SST difference by? Please add more details in the text.

   We now specify that we normalised the time series by the standard deviation. This also explains why it has no units.

10. l. 525-526: Please clarify: your predictors are F_E and F_W (i.e., NAO_S) and ΔSST, so the common denominator is the atmospheric circulation associated with the summer NAO. How does sea surface salinity constrain weather predictions?

    The ΔSST time series is not related to the summer NAO. The common denominator is the correlation with the SST and freshwater anomalies in winter. Thus, we think this comment has partially been addressed by clarifying your earlier comment (Comment 7).

    We now explain that all indices are representing freshwater (and SST) anomalies. In addition, we have rephrased the sentence to clarify that we are not making any actual weather predictions. Thus, we have removed the word "predictions" from the sentence you referred to.

We further explain in this section (Section 4.6, line 581) and in the discussion (line 630), that estimation of the extent, amplitude, and type of freshwater anomalies in winter can help constrain the subsequent ocean-atmosphere evolution into the summer based on the evolution of past freshwater anomalies with similar spatial patterns. The extent to which past freshwater anomalies can help constrain the future evolution is quantified by the explained variances.

Lastly, we have added a paragraph in the discussion section on the advantages of connecting European summer weather to North Atlantic freshwater anomalies specifically, rather than just using the SST (line 640).

11. l. 535. Please add more details in the discussion of your results with respect to the large-scale circulation (see comments on Section 4.4 above).

    We now explain that the northward deflection of the lower tropospheric winds forms part of a large-scale atmospheric circulation anomaly over the North Atlantic and Europe. The circulation patterns are indicated by the arrows in Figures 5a, 6a and b, and 7c and their characteristics are similar to the patterns described by earlier studies (see our response to your Main Comment 3).

    Accordingly, we have now also updated the discussions in the subsequent parts of the manuscript.

12. Please add more details: how exactly do you “trace the cold SST anomaly back to a freshwater anomaly in the preceding winter”.

    We have removed the word "trace back". Instead, we state:

    "Based on composites [...], we again identify a significant freshwater anomaly in the preceding winter, with the freshwater anomaly covering a large part of the subpolar North Atlantic (Fig. 10f). [...] The similarity of the ocean and atmospheric conditions with those described in the preceding sections supports the relevance of freshwater anomalies in winter for the subsequent ocean-atmosphere evolution into the summer. In addition, the composites suggest that enhanced freshwater anomalies in the subpolar North Atlantic in winter could serve as early warning signs of Europe's warmest and coldest summers approximately half a year in advance."

    Further implications are now discussed in the discussion section.

13. l. 557-558: The northward deflection of the jet stream is a bit too hand-wavy for me. Please discuss this in the context of large-scale atmospheric circulation in summer and associated weather patterns.

    We now explain that the northward deflection of the jet stream forms part of a large-scale atmospheric circulation anomaly and cite earlier studies investigating this study (please also see our responses to your Comment 3).

14. l. 563: Please discuss: the freshwater anomalies themselves are part of the chain reaction that are ultimately linked to the summer NAO. Provocatively

asked: if you wanted to create a statistical model to predict summer weather with one or two year lead time, what information is added by knowing the freshwater anomalies? While I do understand the role of the freshwater anomalies as part of the chain that eventually leads to changes in European weather, I am missing a discussion how knowledge of sea surface salinity can constrain the predictions (see also comment II.10).

If we start in any given winter and would like to constrain the subsequent weather, we would first identify a set of years with similar spatial patterns (but possibly different amplitudes) in the SST. We would then include these years in a regression model to assess the future evolution of the current year. The associated explained variances would provide a measure of the uncertainty.

However, given the limited set of years in the observational period, it would be advantageous if models would better capture the subpolar hydrography and represent freshwater anomalies more accurately. Models could quantify the predictability more exactly by providing a higher number of simulations. In that case, we would not rely on a regression model based on observations only.

We now explain in the discussion section that estimations of the strength, amplitude, and type of freshwater anomalies in winter help constrain the subsequent ocean-atmosphere evolution into the summer, based on the evolution of past freshwater anomalies with similar spatial patterns. The extent to which European summer weather is constrained is quantified by means of the explained variances.

We further explain that the connection to freshwater specifically adds an enhanced predictability on longer timescales since the drivers of freshwater anomalies are traditionally more narrowly defined than for the SST. Runoff and melting, specifically, will likely increase in future, which is expected to increase the meridional SST gradient and associated air-sea feedbacks.

Please also see our responses to your Comment 10.

15. l. 610: What salinity did you use in the evaluation of the buoyancy flux?

Thank you for pointing out that we did not specify the value. We now explain that we used a mean observed salinity of 34.5 g kg^{-1} in the subpolar region.

We point that the results are not sensitive to this value. Typical salinity variations in the subpolar region in winter range from 34.5 to 35. Since the salinity appears in the nominator, and the surface buoyancy flux is over one order of magnitude smaller than the density anomaly associated with the cold anomaly, the exact value has no appreciable effect on the results.

16. l. 664: Regarding the “northward deflection of the jet stream”, please see my comments above.

Following your comments above, we have now added more details on the large-scale atmospheric circulation anomaly.

III. Typos/Wording:

I suggest the following changes:

l. 39: "requiring a fine grid spacing" to "requiring *ocean models* with fine grid spacing"
Caption of Figure 1 d: "SST" to "ΔSST"
l. 227: "0.5" to "-0.5" (minus sign missing)
l. 368: "pariticularly" to "particularly"
l. 371: "circulation" to "atmospheric circulation"
Figure 7: The title of panel e should be T_{+1}
l. 657: "ΔSSS" to "ΔSST"

Thank you for all these suggestions and for spotting the typos. We have adopted all your suggestions.

References:

Cassou, C., 2008. Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation. Nature 455, 523–527. https://doi.org/10.1038/nature07286

Grams, C.M., Beerli, R., Pfenninger, S., Staffell, I., Wernli, H., 2017. Balancing Europe's wind-power output through spatial deployment informed by weather regimes. Nature Clim Change 7, 557–562. https://doi.org/10.1038/nclimate3338

Thank you for your detailed and constructive feedback helping us to clarify and improve this study. It is much appreciated!