REPLY TO ANDREW WINTERS

"A climatological characterization of North Atlantic winter jet streaks and their extremes"

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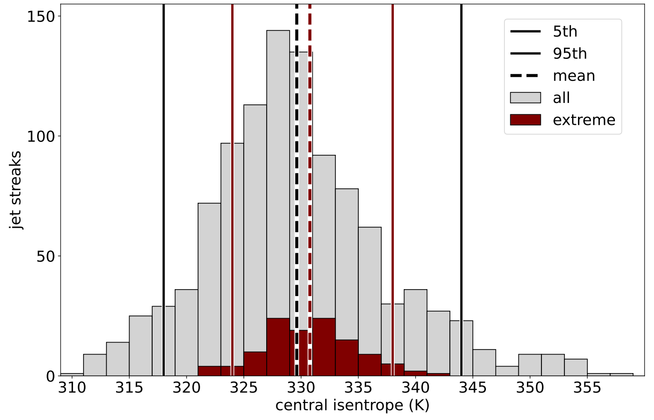

FIGURE 1 Histogram of central isentropes at peak jet streak intensity (θ_{peak}; K) for all jet streaks (grey) and extreme jet streaks, i.e. cases with wind speeds on the central isentrope exceeding 92.5 m s^{-1} on an area of at least 3.62·10^5 km^2) at time of peak jet streak intensity (dark red), and vertical lines indicating the mean (dashed) and the 5th and 95th percentile (solid) of the distributions.

1 | MAJOR COMMENTS

There are some aspects of the methodological approach that might benefit from further clarification:

a. L103: The height of the tropopause on the equatorward side of the jet can often extend as high as 350K during the wintertime, especially in cases of polar/subtropical jet superposition (Winters et al. 2020). Is there a particular motivation for cutting the analyses off at 340K and are you missing anything by not considering isentropic levels above this level say up to levels of 355K? The secondary peak in Fig. 8 at higher potential temperatures partly motivates my concern.

We totally agree and thank you for this comment. We have rerun all of our analysis on a dataset that now includes all isentropes between 310 and 360K. The results of this new analysis (Figure 1) are largely identical with those produced on the basis of the smaller isentropic range, with two notable exceptions:

1. Central isentropes at peak jet streak intensities now reach up to 356K (See Figure 1). Interestingly, the number of jet streaks with central isentropes higher than or equal to 340K at peak jet streak intensity remains roughly the same. This indicates that we did not miss most of the subtropical jet events in our initial analysis, but rather linked their centres to a too low isentrope.
2. the relationship between jet streak duration and peak intensity (Figure 2) is even more robust with the new set of isentropes. We also find a few jet streak events less than before, and they last marginally longer, in the new analysis. Our understanding is that this is due to a higher fidelity in jet streak centre identification and merging of subtropical jet streak centres in time into one event when using the new dataset.

The composites of large-scale flow as well as the make-up of jet streak clusters are largely unaffected.

Once again, we thank you for this suggestion, which makes the study even more rigorous while also helping us to show that our algorithm works for both sub-tropical and sub-polar jet streaks.

b. L124: In many cases the flow can be highly amplified and jet streaks can be meridionally oriented rather than predominantly zonal. How does the methodology handle this common occurrence?

If our understanding of your remark is correct, it refers to cases in which the axis of the jet streak is completely aligned in the S-N direction.. We have two main reasons for thinking that our algorithm is robust:

- Through manual inspection, we confirmed that the algorithm is able to detect jet streaks that are far from zonally oriented. In fact, when analysing the distribution of all jet streak orientations around approximately 14% of have an orientation within 5° of a pure S-N orientation (at time of peak jet streak intensity). For those cases, the jet streak center is – as for most time steps – co-located with the highest wind speed, which allows us to find a tropopause-longitude intersection even for strongly tilted jet streaks.
- While it is true that especially for strong jet streaks the flow can be highly amplified, jet streak centers tend to be close to the ridge crest at time of their peak intensity, which is the time of maximum interest. If the wind speed maximum is locaated close to the ridge crest, the shape of the jet streak is zonal rather than meridional and so is its axis.

c. The selection of specific threshold values and percentiles for the analysis could benefit from more justification. For instance, the choice of 92.5 m/s for extreme peak intensities is not much different than the median of all jet streaks (i.e., its within one standard deviation according to Fig. 6). I find the extreme jet streaks category to be a bit more rigorous since there's an area criterion associated with it.

We agree with you that the category of jet streaks with 'extreme peak intensities' as we used it in the first manuscript is confusing, and since we do not use the category in any of the key analysis of the publication, we removed it. We also added a paragraph explaining the choice of the wind speed threshold in the manuscript now and how we combine wind speed and area thresholds to get to the definition of extreme jet streaks to Section 3.1.

Background: We consider a jet streak as an extreme event if it entails large area covered by high wind speeds at its time of peak intensity and not only a single grid point. We defined the wind speed threshold based on the wind speed climatology over the North Atlantic (92.5 m/s is above the 99.9th percentile for more than 90 % of gridpoints over the NA and for all isentropes between 310 and 360 K). Next, we consider only the events in the upper quartile of areas with wind speeds exceeding this threshold. The set of jet streaks defined as extreme with this approach has an 85 % overlap with defining extreme jet streaks as those with peak intensities above the 92nd percentile of peak jet streak intensities. Thus, there is a high correlation between high peak intensities and large areas of high wind speeds and the combination of wind speed and area thresholds favours the identification of large coherent features.

We hope that this addresses your comment sufficiently.

d. L155: It is conceivable to me that the isentropic level corresponding to the maximum wind speed is likely to change throughout a single event. Is anything done to account for this as part of the analysis and is it necessary?

Yes, as you point out correctly, the central isentrope evolves throughout jet streak evolution. Our algorithm tracks the central isentrope at each time step, such that we can also quantify the increase and decrease of isentropic levels throughout jet streak evolution (See Figure 2). We find that between the time step of peak jet streak intensification and intensity, the central isentrope changes less than 5 K for 80 % of all jet streaks.

Prior to the preparation of the manuscript, we tested both approaches, using either a varying central isentropes or a fixed isentropes (from the time of the peak of the jet streak intensity). We found that the results are rather similar and for simplicity included only the analysis using a fixed isentrope.

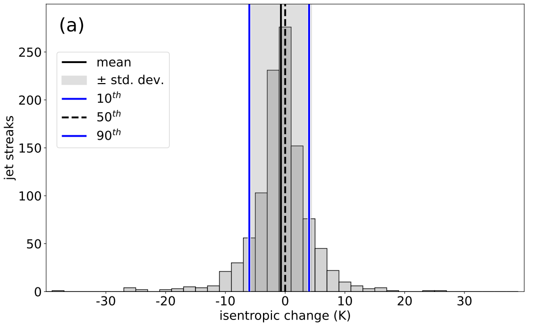

FIGURE 2 Changes in the instantaneous central jet streak isentrope between the time of peak jet streak intensification and peak jet streak intensity for the 1065 North Atlantic winter jet streaks. Histogramm in grey bars, vertical lines show the (black solid) mean, (black dashed) median, and (blue) 10th and 90th percentile (-4 and +6K, respectively) of the distribution.

e. L195: Similar to one of my earlier comments, is any methodology performed to account for the different orientations of jets when compositing (i.e., a rotation of fields so that they are aligned with the jet axis)?

We agree that this would be an additional option in particular for the second part of our study. We do not align the jet axis when compositing, but find that the clustering method does this sufficiently.

The composites as shown in Figure 14–17 are based on statistical clustering, which appears to align all jet axis within individual clusters sufficiently. This can be deduced from the figures on the PV gradient standard deviation (Figure G1), though some in-cluster variability remains.

The results sections show interesting differences and statistics regarding the characteristics of jet streaks and extreme jet streaks, but it might benefit from the application of statistical testing to verify to what extent the differences are statistically significant.

Thank you for your suggestions on statistical testing. We now applied bootstrapping analysis to all important characteristics and notified where differences are robustly shown in those analysis in the results section. We explain our bootstrapping method in the methods section.

a. For instance, could a bootstrap test be applied to the mean wind speeds associated with the different jet regime categories in Table 1 to determine whether they are indeed uniquely different? A similar practice could be applied to the content of Fig. 12 or Table 1.

We adopted this suggestion as proposed and noted where results are robust with respect to the subsample drawn in bootstrapping analysis.

b. In any of the composite analyses, a statistical bootstrap test could be performed to determine to what extent the characteristics of the near-jet environment during extreme jet streaks are significantly different compared to the composites of all jet streaks.

Like above, we adopted this suggestion. We conducted bootstrap analysis for all composites, but only discussed the results explicitly where they were noteworthy, in particular for the PV gradient and precipitation composites as well as the WCB outflow frequencies.

In some of the composites the raw fields are used rather than anomalies (i.e., PV, sea- level pressure). Would using anomalies potentially be more effective given that the climatology of these variables can vary substantially throughout the cool season and potentially bias the analysis, especially if the jet streaks are also located in different parts of

the Atlantic Basin? In addition, I might have missed it, but are the composited fields weighted at all to account for smaller distances between grid points at high latitudes compared to lower latitudes? If not, treating the input maps equally will unfairly weight the composites towards jet streaks that are located at higher latitudes.

We see the advantages and disadvantages of both methods; based on our previous research, anomalies often highlight similar regions as the full flow field, but in certain cases standardised anomalies can also de-emphasize regions that are dynamically relevant. To the first part of the comment: Concerning upper-level fields, after giving it considerable thoughts, we believe that centering on the tropopause and taking the full fields is similar effective in depicting the large-scale flow situations. Interestingly, the spatial variability of jet streak cases within clusters is reduced by the clustering of cyclonic, zonal, and anticyclonic cases. Concerning sea-level pressure, we tested compositing slp-anomalies instead of raw fields and found that, while the features we found without taking the anomalies are still found, the anomalies indeed show an even clearer picture of the low-level weather systems. We therefore changed the SLP- to SLP-anomaly contours in the respective figures.

To the second part of the comment: Yes, you are right, and we do use area-preserving remapping before conducting composite analysis. Fields at higher latitudes are therefore weighted such that they are not overweighted in the composites. We reformulated the description of the remapping method to clarify this point. Thank you for pointing this out.

2 | MINOR COMMENTS

2.1 | Abstract

L3–4: Consider specifying that this upper-level divergence pattern is only specific to Northern Hemisphere jet streaks, since the pattern reverses in the southern hemisphere. If looking for a more unified phrasing you could refer to the regions as "equatorward entrance region" or "poleward exit region".

Thank you for pointing this out. We modified the text according to your suggestion, such that L3–4 now reads: *Upper level divergence in their equatorward entrance and poleward exit regions couples them to surface weather via vertical motion and are regions prone to precipitation formation, which feeds back on the strength of upper level divergence and wind speed via diabatic heat release.*

We also used this phrasing in the introductory paragraph on the 4Q-model now, to be more general.

Consider using a different term rather than "deepening" when referring to the intensification rate of jet streaks, as this is more standard when referring to cyclogenesis rather than jets. Perhaps acceleration could be a suitable alternative term?

Good point again, we modified the sentence accordingly (Line 11–13):

The peak intensity of jet streaks also increases with their lifetime and extreme jet streaks exhibit a prolonged intensification period rather than increased acceleration rates.

2.2 | Introduction

L34: The Harnik et al. (2014) study largely considers merging of the two jets from a seasonal perspective, but this also can occur on synoptic time scales and lead to some of the extreme winds observed in this study (e.g., Winters et al. 2020). It might be worth highlighting this environment as part of the introduction discussion on jet streaks, as well.

Thank you for pointing this out. We added the following lines to the mention of merged jet events to account for this:

A merging of the two jets is an exception, although it has been observed in the past, on seasonal (e.g. Harnik et al., 2014a) timescales. Studies investigating subtropical-polar jet superposition (e.g. Winters and Martin, 2014; Winters et al., 2020) on synoptic timescales showed that such events can be associated with extreme wind speeds and heavy precipitation.

L69: Should the cyclonically curved case favor ascent beneath the left-exit region? I believe the effects of flow curvature and speed changes should theoretically cancel in the right-exit region.

Thanks for pointing this out. This was a typo on our part and is corrected now.

2.3 | Methods and Data

L127: Could you expand a bit more as to why this percentile threshold is chosen? Was it determined empirically, and how sensitive are the results to this chosen threshold?

The threshold was determined empirically with the goal of creating a mask of very high wind speed that

- does not consist of multiple patches that are far away from each other, at least for most time steps (this give a lower bound to the percentile threshold because too small thresholds create multiple patches),
- is one connected area containing the location of maximum wind speed for most cases, and
- is large enough to ensure that, in case of a highly variable wind pattern close to the location of maximum wind speed, the jet streak center is not highly sensitive to the exact location of highest wind speed

The two latter points give an upper bound to the percentile threshold, since a very high threshold would either lead to multiple disconnect patches close to the jet centre, or the resulting mask would be very sensitive to noisy wind patterns close to the jet streak centre.

L134: This wind speed threshold is very defensible, but it might help to offer some citations to other studies that have used comparable thresholds for the jet.

Thanks for that hint, we included some references to better motivate the wind speed threshold:
the following sentences are now part of the jet streak tracking algorithm in Section 2.1.1: *This ensures that the jet streak centre is embedded in the jet stream, and our threshold is in the range of thresholds typically used to define in-jet wind speeds (see, for example Hartmann, 2007; Eichelberger and Hartmann, 2007; Messori et al., 2021, for zonally averaged zonal wind speeds) and (Winters, 2021; Simmons, 2022, for typical wind speeds in the North Atlantic jet stream).*

L223: I'm a bit confused by the terminology, "wind speed curvature". In particular, are you referring to the curvature of the flow that would be associated with troughs and ridges, or more so describing the gradient in wind speeds present within a jet. If the latter, I might recommend rephrasing to avoid any confusion in interpretation by a reader.

It refers to the latter. Thanks for pointing this out. We now refer to this as either simply $\triangle U$, 'horizontal variations in relative vorticity', or 'horizontal Laplacian of wind speed' throughout the text, hoping that all of these are less prone to misunderstanding.

2.4 | Results

L278–280: Could more detail be provided as to why this wind speed threshold is chosen for an extreme jet streak? Why not a much larger wind speed given that this speed seems rather close to the mean of all jet streaks?

See response to your major comment on the wind threshold (Major comment 1c.).

L282–286: These trends certainly do align with the results of Shaw and Miyawaki (2023), but how much of this result can be attributed to more observations over the North Atlantic in more recent decades compared to earlier in the dataset? Discussing potential uncertainties in this result, or evaluating the significance of trends, may benefit the text.

The trends we find are consistent with Simmons (2022) findings on upward trends in wind maxima. Simmons used the background forecast for ERA5, which is less influenced by the increasing ammount of data available to the reanalysis and also finds a slight upward trend that is dominated by interannual and interdecadal variability and not statistically significant. This makes us believe that data availability might of course influence the results, but marginally rather than qualitatively. We now mention Simmons' results in this paragraph and also point out that using the 20-CR dataset and additionally using other reanalysis such as JRA and Merra-2 would be beneficial. We also clarify highlight that, so far, interdecadal variability dominates over the linear trend found in our fit:

These results are well in line with (Simmons, 2022), who also found a slight upward trend in monthly maximum wind speed (0.067 $\pm$0.048 $\mathrm{m\,s^{-1}}$ per year) over North America and the Atlantic (see their Figure 16a). To evaluate the statistical significance and methodolical sensitivity of those trends, it would be beneficial to compare different reanalysis datasets (e.g. JMA JRA-3Q and NASA MERRA-2) and also include a dataset using a fixed observational basis, for example the 20-CR reanalysis.

L295: The bimodal distribution in the central isentrope potentially motivates extending the search range for the core isentrope to higher isentropic levels that cover the entire troposphere.

Indeed. In accordance with your suggestion in your major comment, we updated this analysis and now end up with a new distribution (see Figure 1).

L302: This trend also might relate to the strongest jet streaks being associated with superpositions of the polar and subtropical jet streams, which will feature characteristics of both polar and subtropical jets and strong wind speeds commensurate with those associated with extreme jet streaks.

Yes, good point. We added a sentence to this paragraph to mention this:

The bulk of extreme jet streaks centred around 330 K suggests that some of them are associated with superpositions of the polar and subtropical jet, a result in line with previous research on merged jet regimes (Harnik et al., 2014b; Winters et al., 2020).

L313: This is true for all subsets except for the jet streaks with peak intensities exceeding 105 m/s, if I am reading Fig. 9a correctly. Consider a revision to the text accordingly.

With the rerun analysis, we find slightly different results and reformulated the paragraph accordingly. We now point out the subsets of all jet streaks whose mean lifetime is outside the interquartile range of lifetime of the set of all jet streaks.

L386–390: These are interesting statistics, but would it be possible to perform some type of significance testing, such as a bootstrap test, to evaluate the extent to which these differences in frequencies during jet streak periods are indeed significantly different than climatology?

We performed some bootstrapping to see whether the Frame regime occurrences during peak jet streak intensity differ significantly from the climatology and modified the Figure and text accordingly:

A bootstrap analysis using 1000 resamples of all as well as extreme events (dots and vertical lines in Figure 13) shows that the increased prevalence of the M regime is a robust result of the analysis. While the same is true for the under-representation of the N regime, the likelihood of the S regime is not altered significantly compared to climatology for both all and extreme jet streaks.

L395: Prior to discussing the transitions, it might be worth emphasizing initially that the predominant observation is that jets tend to persist in their genesis regime before discussing the transitions which are secondary in their frequency.

Thank you for pointing this out. We added the following at the beginning of the paragraph to direct the attention of the reader toward the predominance of persistence:

Persistence is a key feature in both extreme and non-extreme jet streak evolution, meaning that the eddy-driven jet typically remains within the Frame regime of jet streak genesis (Fig. 14a, b). For jet streaks during whose evolution different Frame regimes occur, the following results are worth noting: [Text on transitions from before.]

L428: I am having a bit of difficulty locating the figures associated with this discussion in Section E, but they do seem associated with appendix F. References to the pertinent appendix figures to support the discussion in L428–460 would be helpful, as well, to guide the reader.

You are right, of course. Thanks for spotting this and sorry for the confusion in the first read. We corrected the reference and referenced the relevant Figures as you suggested in the paragraph that discusses the general features of all six jet streak clusters. (see section 3.4.1, lines 472ff in the new manuscript.)

L433: It might be worth emphasizing here, or elsewhere in the manuscript, that this result is not particularly surprising from a theoretical standpoint, given that supergeostrophic flow is expected at the apex of upper-tropospheric ridges from consideration of gradient wind balance.

Thank you for this valuable comment. We deemed this thought to be best placed in the conclusion section and therefore placed the following sentence in item 1. of 4.2:

This result is in line with expectations from theory, given that Centrifugal and Coriolis force counteract each other to enforce supergeostrophic balanced flow in Rossby wave ridges, and especially so at their crests.

L501–503: I found this text rather repetitive with that at the end of the previous paragraph. Consider whether this small paragraph might be deleted without any loss of content.

That is a good point toward shortening the manuscript. We removed the paragraph according to your suggestion and merged the bit of information we found worth retaining into the previous paragraph, which now reads (line 541ff):

The cyclone is associated with an elongated SW-to-NE oriented band of enhanced precipitation along its cold front whose intensity changes only marginally between the times of peak intensification and intensity (Fig. 16a – d). The maximum in *cold-frontal precipitation is located below the right jet entrance and is more intense for extreme jet streaks (compare the first vs. second column in Fig. 16).*

L515–517: I am not so sure I agree with this conclusion, as the surface cyclone is much stronger beneath the left-exit region in the extreme subset compared to the non-extreme subset. I would presume the strong pressure gradient in the extreme subset stems from the greater intensity of both the cyclone and anticyclone relative to the non-extreme, zonally-oriented cases.

Again, good point. We revised the sentence to now say (line 556f)

For zonally oriented jet streaks, this difference in the meridional pressure gradient is driven by both stronger cyclones and anticyclones for extreme cases.

and hope that this sufficiently addresses your remark adequately.

2.5 | Appendix

L633: The reference to "westward" in this sentence appears to be incomplete and might need another word or two to complete the sentence.

We agree and revised the statement:

For S-regime jet streaks, the composite jet at upper levels exhibits a westward displacement with respect to the jet at lower levels.

L635–640: This result might also highlight the M-regimes as featuring a greater likelihood of polar and subtropical jet stream superpositions, which would also align with the greater likelihood of extreme jet streaks in this category.

That is true. We included this idea in the new manuscript by slightly rephrasing the paragraph to now be:

This result points toward an increased interaction between upper and lower levels for jet streaks that peak in the M regime and might point toward an increased likelihood of merged jet states in the M regime. It is also consistent with the finding that most extreme jet streaks peak in the M regime and show enhanced lower-level-to-upper-level coupling.

2.6 | Figures and Tables

Table 2: Is there a particular reason why the cluster numbering starts at 0 rather than 1? Also, might it be useful to use more descriptive names for each cluster that are tied to their respective characteristics rather than numbers?

Not in particular. We changed the numbering to start at 1 to avoid any notion that Cluster '0' might be special in a particular way.

On the point regarding more descriptive names: We thought about doing this for all clusters but ended up with only naming the two clusters in descriptive ways that we discuss in detail. Some clusters look qualitatively similar, such that we found it most instructive to only pick the two most important and distinct clusters for descriptive naming. Note also that the other clusters are dropped from the discussion after the first paragraph, such naming them might cause anticipation that would not pay off.

Fig. 1: In panel (a), it is a bit confusing that there is one red arrow that points away from the diagram at the lowest isentropic level. What does this red arrow correspond to and how is it different from the one at the level of maximum wind speed?

This is simply the 'maximum wind speed' axis, but we see how the colour might be confusing. We removed that panel slightly from the isentropic surfaces to avoid confusion about the axis pointing 'away' from anything and transformed the colour of the axis to be black. We hope this makes the schematic more clear and are happy to incorporate more suggestions, should you have further ideas to improve it.

Figure 2: The solid black and dashed black lines that correspond to the mean and median, respectively, are a bit difficult to see against the grey histogram bars. Could different colors be used for these quantities? Similar considerations may also apply to other figures.

Thank you for this suggestion. We tried to use different colours/ linestiles in Figures for which this seemed helpful. This resulted in changes to Figures 2, 6,8, and 9. We hope it makes all the Figures easy to access.

Fig. 9: Some of the dashed lines and solid lines are a bit difficult to see in panel (b). Could they be made a bit thicker? Could the hours associated with lifetimes also be included along the x-axis in panel (a). It is a bit difficult to compare the box and whisker plot values against values along the y-axis on panel (b) – far distance for the eye to travel.

Good points, we made the vertical lines thicker and removed the lines indicating the Frame-regime related values to make the Figure more simple.

Fig. 11: I understand why the authors ordered the panels the way they have, but it seems a bit counter-intuitive that the first timestep of the evolution corresponds to panel (c) for all jet streaks rather than panel (a). Could the panel labelling conventions be changed to match the temporal evolution of the jet streak evolution? The panel labels are also incorrect for the extreme jet streaks and should be (e-h). I noticed similar errors in a few other figures, as well.

We follow the suggestion to harmonize temporal evolution and the progression of labels. We kept the ordering of the panels as is, though, to keep peak intensification and intensity side by side and at the top. We also corrected the labelling for extreme jet streaks and harmonized labelling in other figures. We hope to have caught all cases of erroneous labelling and thank you for looking at this so carefully.

Fig. 12: I might recommend a revision to the caption to not refer to the presence of a low-level jet, which can have a much different definition than the jet features considered in this study. Namely, low-level jets often correspond to isolated low-level wind speed maxima that decay in intensity by some amount with altitude. I don't believe that is the case for the jets considered here. Instead, I might just recommend referring to times in which the jet resides in the S, M, and N regimes.

Thank you for this point. We removed the mention of 'low-level' from the caption to avoid this connotation.

Fig. 13: I like this figure a lot, but it is a bit counterintuitive to me that the N regime is on the bottom and S regime is on the top. Could these regimes be reversed in their position on the plot so that the display of these jet regimes matches their characteristic location on a map?

Yes, good suggestion. We revised the Figure accordingly.

Fig. 16: Might it be possible to include a contour that corresponds to the position of 2-PVU? That way the position of precipitation and surface sea-level pressure anomalies will be easier to link to the upper-level jet structure.

Again, good point. The revised manuscript includes this suggestion for all figures showing low-level variables, including Figures in the Appendix and those showing standard deviation of precipitation.

Fig. E1: Should the time of maximum intensification in this four-panel plot correspond to panel (b) rather than (a), since (a) is described as the start time later on in the caption?

Correct, we changed this.

Fig. F1: It appears the panel labels might be incorrect within this figure, since (a-d) is duplicated for both sets of 4 panels.

Correct, we changed this. (See comment above)

Appendix F Composite Figures: For each group of four panels that correspond to a cluster, could a label be added to more clearly identify which group of panels corresponds to a cluster (i.e., similar to what is done at the top of Fig. 15)

Yes, we revised all Figures in Appendix F accordingly.

Thank you for taking the time to review this study.

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