Authors' Response to Reviewer 1

General Comments. This study uses ERA5 reanalyses for 43 extended winters to classify North Atlantic and European extratropical cyclones according to their intensity, based on multiple dynamical and impact-related measures. They perform a principle component analysis and a cluster analysis to find four clusters of extratropical cyclones that differ in terms of intensity, geographical location and characteristics. Cluster HighSSI is associated with the highest mean values in many intensity measures (e.g., low-level vorticity and wind speed), followed by cluster Intense. Despite a relatively small occurrence frequency ($<$10% of all cyclones), HighSSI contains a large fraction of well-known impactful storms. Most cyclones belong to cluster AvgMST (~44%). They have average intensities and occur preferentially over the main North Atlantic storm track. Cyclones in cluster Weak occur in about 25% of all cases, have relatively weak intensities and mainly occur in the Mediterranean and over Europe.

Overall, the manuscript is interesting to read, the storyline is clear, the methods are appropriate, and the general conclusions are sound. Below are a few minor comments and suggestions.

Response: We would like to thank you for the feedback and the valuable comments which helped improve the quality of our manuscript. We have carefully addressed all the issues item by item as follows.

Specific comments:

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Comment 1

The paper is rather long. This is not a criticism in itself, as the paper is well-written and interesting. However, maybe you can consider shortening the description of the datasets and methods a bit, such that the reader does not have to wait until page 11 for the results. For instance, although nicely written, it might not be necessary to mention all advantages and disadvantages of ERA5, which is a well-known and widely used reanalysis dataset. And in the result section you might consider moving Fig. 9 and its description to the supplement, to shorten the manuscript a bit (but I would also be fine if you left it in the main part).

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Response:

We have shortened the data section including the description of ERA5 advantages and disadvantages. Individual sentences have been revised for the sake of brevity and clarity. We have also combined the discussion of Figure 9 with that of Figure 8 to reduce the amount of text. However, we feel that it is necessary to include Figure 9 in the main text as it shows details which are not evident in Figure 8 (e.g. almost equal proportion of cluster HighSSI ETCs in each area and large proportion of cluster AvgMST ETCs in Europe). These reductions in text partly compensate the revisions made based on reviewer comments, but overall the length of the paper has remained unchanged. See also related Specific Comment 2 of Reviewer 1 and Minor Comments 8, 9, and General Comments of Reviewer 4.

Comment 2

Abstract and conclusions: Most of the abstract describes your method, but it would be nice if you could add some sentences about your results (e.g., the percentage of cyclones in each of the four clusters and the differences between the clusters in intensity, geographical location and characteristics, etc.). Similarly in the conclusions. As the paper is quite long, a summary of the main results would be helpful.

Response:

A few sentences have been added to the abstract to include more details about the results. The part of the abstract now reads:

The cluster analysis is able to produce four clusters between which cyclones differ in terms of their intensity, life cycle characteristics such as deepening rate and lifetime, and geographical location. The on average second most intense cluster contains around a fifth of all cyclones which occur mostly at the start of the North Atlantic storm track. Average intensity cyclones comprise nearly half of all cyclones and occur mostly at the northeastern parts of the storm track. Fourth of all cyclones belong to the cluster of on average the weakest cyclones which are found mostly over Europe and in the Mediterranean. The on average intense cyclones constitute less than a tenth of all tracks and occur almost equally everywhere. Based on average magnitude, most intensity measures are arranged in the same order between the clusters. There is also a link between average intensity and deepening rate, lifetime, and mean propagation speed of cyclones in the clusters.

The conclusions have been expanded by replacing the sentence

One cluster has on average weak ETCs (cluster Weak), another one average ones (cluster AvgMST), and two clusters more intense ones (clusters Intense and HighSSI), with the most overlap in the distributions of the intensity measures in

the latter two.

with

Cluster Weak has on average the weakest ETCs (25.54 % of all ETCs), cluster AvgMST contains average intensity ETCs (44.42 %), and clusters Intense and HighSSI are composed of more intense ETCs (21.46 % and 8.57 %, respectively). Based on average magnitudes, most of the intensity measures have the clusters in the same order. However, the clusters are not discrete in the feature space defined by the intensity measures since there is overlap in the distributions of the intensity measures between the clusters. The most overlap is between clusters Intense and HighSSI.

and by adding the sentence

The average intensity of ETCs in the clusters can be qualitatively linked to their deepening rate, lifetime, and mean propagation speed.

Although we have shortened some sections of the text (see Comment 1 of Reviewer 1), these additions contribute to the text not being shorter than before revision.

Comment 3
Fig. 8a-d: Please add the units to the colorbar.

Response:

The colourbar label has been changed from "Difference with full climatology" to "Difference in number of tracks".

Comment 4

Fig. 10: Do I understand correctly that the positive trend in the number of intense cyclones and the negative trend in the number of weak cyclones indicates that the cyclones moved from the weak to the intense cluster because of the increase in cyclone-related precipitation?

Response:

If we understand the question correctly, yes, this is essentially the effect. Cluster Intense ETCs have on average larger precipitation values than cluster Weak ETCs. Precipitation values are on average higher towards the end of the time series, which we think is the main reason more Intense ETCs and less Weak ETCs occur at the end of the time series compared to the beginning.

Comment 5

Section 4: To define the clusters, you use four wind-related measures (WS850, VO, WFP and SSI), but only one measure for precipitation. Is this the reason why the cluster analysis discriminates intensity more based on wind than precipitation (see for instance Fig. 6b, c), and that cyclones with heavy precipitation but weak winds like Apollo belong to cluster weak rather than Intense? Is this a weakness of the method?

Response:

Thank you for your important comment. To answer your first question, we think that the stronger discrimination based on wind-related measures rather than precipitation is more linked to the shapes of the measures' distributions than the number of measures. Precipitation has smaller variance than WS850, VO or WFP (but higher than SSI) so it is more "difficult" for the cluster analysis to create non-overlapping clusters in terms of precipitation. For Apollo, we believe in a complementary explanation. The region of

interest encompassed the eastern coast of North America and the open ocean, two areas with larger storm-associated precipitation than in Europe (Hawcroft et al., 2012). As a result, the average precipitation (as depicted in section 4.2) is relatively high for Europe. This also explains why most of the XWS storms fall in the center of PC2 (see Figure 11). This explanation has been added to the discussion.

To answer your second question, the entry feature set (WS850, VO, WFP, SSI and PRECIP) has been chosen for interpretability purposes and not for efficiency. Because, the redundancy in wind-related features would be mainly considered as a drawback in a Machine Learning sense (Yu and Liu, 2004). This means that they don't individually create very much further discrimination between the clusters. Having said that, the method is inherently weak in this sense, as we state in line 565.

Comment 6

Section 4: I find it interesting that many of the well-known storms have below-average precipitation (Fig. 11). You say that this is because you picked many of the storms from the XWS catalogue that uses wind-based measures. I know the paper is already rather long, but maybe you can consider including a few more European cyclones that led to heavy precipitation events. It would be interesting to see whether they are located close to Apollo or rather somewhere else in the phase space.

Response:

We further note that the below-average precipitation in many of the European cyclones can be explained by the average precipitation value being affected by many cyclones occurring over the ocean, which makes the value larger compared to many storms occurring over land as discussed in Comment 5 of Reviewer 1. An explanation of this has been added to the discussion in the paper.

We agree with the reviewer's comment that it would be interesting to investigate more

well-known storms. However, there are quite many storms in the analysis and, as the reviewer noted, the paper is already rather long. Thus, we prefer leaving it for future work. We have added a short example script to the Zenodo repository with the trained sPCA included (Cornér et al., 2024). A reader can use this model and their own data (or our data) to see to where any storm which can be described with the 11 intensity measures falls in the sPCA space. A script has been provided which does the same for the GMM as well. This script predicts the clusters of objects which can be described with the reduced set of intensity measures, i.e., VO, WS850, PRECIP, WFP, and SSI. Mentions of these models have been added to the text as well. The use of the trained models is discussed also in General Comment 1 of Reviewer 2.

> ### Comment 7
>
> Section 4, line 558: "Moreover, ETCs which do have high precipitation values over land areas occur mostly over North America (not shown)." Where do you get this statement from, is it from your dataset? Over Europe ETCs can also produce substantial amounts of precipitation.

Response:

The statement is true for ETCs in our dataset. The sentence has been reformulated to convey this information more clearly. Another modification to the sentence has been made to indicate that high precipitation values are not restricted to only North America, but that in our dataset the highest values on average occur there:

> Moreover, in our dataset ETCs which do have high precipitation values over land areas occur mostly over North America (not shown).

This is in agreement with Hawcroft et al. (2012), who show that the east coast of North America receives more precipitation than Europe and proportionally more of it is associated with ETCs. This is also consistent with the fact that many European storms

do not seem to have high precipitation values, which is discussed in Specific Comment 5 of Reviewer 1. This is now clarified in the discussion in the paper.

Typos and wording:

> **Comment 8**
>
> Line 79: "Section 4 contains .. and Section 6 concludes ..." Section 5 is not mentioned.

Response:

The sentence has been modified to include a mention of each section.

> **Comment 9**
>
> Line 118: "small scale" – maybe better: "small-scale"

Response:

We agree with the reviewer's comment and changed the word accordingly.

> **Comment 10**
>
> Lines 135: "beginning from" should be "beginning at"

Response:

We agree with the reviewer's comment and changed the expression accordingly.

Comment 11

Line 148: Should it be "obtain" instead of "contain"?

Response:

We agree with the reviewer's comment and changed the word accordingly.

Comment 12

Line 151: "... and are available as in the reanalysis." The wording is a bit cumbersome, maybe you can reformulate the sentence.

Response:

The sentence has been reformulated from

> and are available as is in the reanalysis.

to

> and can be obtained from the reanalysis with no or minimal post-processing.

Comment 13

Fig. 1: The abbreviation "ONDJFM" has not been introduced. It would fit in the last sentence of Section 2.1.

Response:

Since the abbreviation was used only once in the manuscript, we have removed it and replaced it with "October–March".

Comment 14

Line 167: remove empty space between double parentheses.

Response:

The empty space has been removed.

Comment 15

Lines 210, 214, 215: "in (each) grid point" should be "at (each) grid point"

Response:

The prepositions have been changed from "in" to "at" in the mentioned lines (also in line 188).

Comment 16

Line 211: "... whereas Leckebusch et al. (2008a) ..." This part of the sentence is difficult to understand, consider reformulating it. Is it actually necessary?

Response:

We agree with the reviewer that the explanation of the SSI used by Leckebusch et al. (2008) is not necessary and have thus removed this from the text.

Comment 17

Line 234: "For PRECIP, the chosen time is 12 hours before the time of maximum VO, for the same reason." Can you be a bit more specific and briefly motivate why you investigate PRECIP 12h before the time of maximum VO, i.e., at a different time than the other variables? (It does make sense to me, as the peak in precipitation often occurs before the peak in VO, and I guess you suggest this when you write "for the same reason", but the sentence is a bit vague.)

Response:

The sentence has been made clearer. What previously was

> For PRECIP, the chosen time is 12 hours before the time of maximum VO, for the same reason.

has been changed to

> The maximum precipitation rate occurs on average 12 h before time of maximum VO (see Fig. S5f). For this reason, PRECIP is evaluated at this time step.

Comment 18

Line 296: "all 11 of the intensity measures" – I would write "all 11 intensity measures"

Response:

The expression has been revised accordingly.

Comment 19

Table 1: The description of the column "Distance" could be more precise in the caption.

Response:

The description has been made more precise and now reads:

> the maximum distance from the VO maximum (in geodesic degrees) to which the values are searched for

Comment 20

Caption Fig. 2: "times in the tracks" – I would write "times along the tracks"

Response:

The expression has been modified accordingly.

Comment 21

Caption Fig. 3: "An absolute value of Pearson's r is shown for correlations involving MSLPa to aid comparison with other coefficients." I don't know what you are referring to (I don't see anything that is different for MSLPa compared to the other measures).

Response:

The correlation between MSLPa and e.g. VO is negative as MSLPa decreases for a stronger storm whereas VO increases. The sentence lacked information and has now been made more explicit from

> An absolute value of Pearson's r is shown for correlations involving MSLPa to aid comparison with other coefficients.

to

> All values of Pearson's r involving MSLPa are negative, but an absolute value is shown for them to aid comparison with other coefficients.

Comment 22

Line 474: "Atlantic" – I would write "North Atlantic"

Response:

The expression has been changed accordingly. It has also been changed in the caption of Figure 9 and in the text discussing the figure to ensure consistency.

Comment 23

Line 489: Do you mean the southeastern instead of the northeastern coast?

Response:

The word has been changed to "eastern" to be more general.

Comment 24

Line 490: "... storm track, and elsewhere ... " I would split the sentence into two: "... storm track. Elsewhere ... "

Response:

The sentence has been modified accordingly.

> ### Comment 25
>
> Line 496: consider reformulating the sentence to "As in cluster Intense, the highest track densities occur at the start of the storm track." The second part of sentence I would leave away, as the values are increased everywhere in the main storm track and not only at the beginning.

Response:

The sentence has been modified accordingly.

> ### Comment 26
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> Line 499: What do you mean by "discontinuous"? Consider reformulating the sentence.

Response:

Discontinuous in this context means that the distribution of track density has multiple local maxima as opposed to a single one. The clusters other than HighSSI have their extreme track density values in certain locations from which the values increase/decrease continuously. To briefly clarify this in the text, the sentence has been reformulated from

> the values in this area are more discontinuous, which is likely due to the effect of normalization.

to

the values in this area are more discontinuous with multiple local maxima, which is likely due to the effect of normalization.

Comment 27

Caption Fig. 6: "The percentages in parentheses indicate how large proportion of all tracks is in each cluster." Better: "... indicate the proportion of all tracks in each cluster"

Response:

The sentence has been modified accordingly.

Comment 28

Line 502: "over Europe"

Response:

The expression has been changed accordingly.

Comment 29

Line 586: "likened" – Typo: "linked"

Response:

The expression has been changed accordingly.

Comment 30

Line 591: "performed analysis" should be "performed an analysis" or "performed analyses"

Response:

The expression has been changed to "performed an analysis".

Comment 31

Line 608: Maybe you can briefly mention what the Petterssen and Smebye types A and B are.

Response:

A sentence explaining the features of these ETC types has been added:

> Type A ETCs are associated with development in a baroclinic zone with weak upper-level and strong lower-level forcing. Type B ETCs develop on a pre-existing upper-level trough with strong upper-level forcing and initially weak lower-level forcing.

Comment 32

Line 665: "correlation of coefficient" should be "correlation coefficient"

Response:

The expression has been changed accordingly.

Comment 33

Lines 662 and 669: I would change "had" to "has" and "were" to "are" to consistently use present tense.

Response:

The tense has been made consistent accordingly.

Comment 34

Line 666: "This, along with the fact that a much larger proportion of named impactful storms than all ETCs belong to cluster HighSSI, . . . " Complicated wording, consider reformulating it.

Response:

The sentence has been reformulated from

> This, along with the fact that a much larger proportion of named impactful storms than all ETCs belong to cluster HighSSI

to

> This, along with the fact that a large majority (81 %) of named impactful storms belong to cluster HighSSI despite the cluster accounting for less than 10 % of all ETCs

> **Comment 35**
>
> Line 671: "... but HighSSI ETCs are almost as frequent everywhere, given the distribution of ETC occurrence in the domain." This part of the sentence is a bit difficult to understand, consider reformulating it.

Response:

The expression has been changed from

> given the distribution of ETC occurrence in the domain

to

> when normalized with respect to the climatological distribution of ETC occurrence

References

M. K. Hawcroft, L. C. Shaffrey, K. I. Hodges, and H. F. Dacre. How much Northern Hemisphere precipitation is associated with extratropical cyclones? 39(24), 2012. doi: 10.1029/2012GL053866.

Lei Yu and Huan Liu. Efficient feature selection via analysis of relevance and redundancy. *The Journal of Machine Learning Research*, 5:1205–1224, 2004.

Joona Cornér, Clément Bouvier, Benjamin Doiteau, Florian Pantillon, and Victoria A. Sinclair. *Classification of extratropical cyclones using multiple measures of intensity: Data and Python code*, September 2024. URL `https://doi.org/10.5281/zenodo.11384417`.

Gregor C. Leckebusch, Dominik Renggli, and Uwe Ulbrich. Development and application of an objective storm severity measure for the Northeast Atlantic region. 17:575–587,

2008. doi: 10.1127/0941-2948/2008/0323. URL `https://api.semanticscholar.org/CorpusID:123018345`.