Reviewer #2

General comments

RC: ***This manuscript uses lightning observations to identify convective trends in Europe and further investigates the role of the NAO and its anomalous activity on convection. The use of observed lightning data reveals trends that counter proxy-based estimates, raising questions about the comparability of proxies to observations of convection. The article focuses on large-scale outbreaks, that are identified using a spatio-temporal clustering algorithm. Overall, the work is presented well and cohesively. Some additional discussion of current literature, additional interpretation/reasoning and clarifying aspects are necessary, however. Below the line-by-line remarks detail the exact locations. More major comments are denoted in bold, where more technical remarks are in regular font.***

AR: We would like to express our gratitude to the anonymous referee for reviewing the manuscript and providing valuable comments. Implementing the suggested adjustments has significantly improved this publication.

We would also like to include a slight modification of your statement in our first conclusion point:

> These negative trends, which seem to contradict proxy-based estimates, raise questions about the comparability of proxies with observations of convection.

Specific comments

RC: ***Line 39: Recently, quite a lot of literature on regional climate modeling and convection has emerged, that should be referenced here (Cui et al., 2025, Thurnherr et al., 2025, Brennan et al., 2025, Feldmann et al., 2025, Kahraman et al., 2024)***

AR: We thank you for the suggested literature. After looking into it, we agree that it adds additional value and have implemented all of them in the manuscript by adding the following references in line 39:

> ... Cui et al., 2024; Kahraman et al., 2024; Brennan et al., 2025; Feldmann et al., 2025).

Regardless of this addition, we would like to note, that this paper was initially submitted on the 13th of September 2024, before these studies were published.

RC: ***Line 216: I understand giving the clustering a separate sub-chapter, however, I think it would be beneficial to clarify, that this basically still belongs to the development of methods.***

AR: Thank you for mentioning this. As the authors, we also had a lengthy discussion about where to position the clustering chapter. Due to the scope of the topic and the scientific findings that have already emerged from its technical design, we have decided to give clustering its own chapter.

RC: ***Line 305: Nice or Venice? The discussed regions do not match the city mention of Nice...***

AR: Thank you for pointing out this mistake. We have removed 'Nice' from the list and added the following for further clarification:

> ... at the northern slopes of the Po valley ...

RC: ***Line 306f: This would benefit from some references / literature support***

AR: We thank you for suggesting literature here and included the following references in line 307:

> Nisi et al. 2018; ...

and the following reference in line 310

> (similar to Galanaki et al. 2018)

RC: ***End of Section 4: This requires some discussion regarding the length of time periods necessary to robustly identify trends. E.g. Nisi et al., 2018 show no measurable hail trend in Switzerland for 15 years, however, Wilhelm et al., 2024 show a significant positive trend, when evaluating 70 years by exploiting reconstruction techniques. The 20-year period here is still rather short and while significance testing accounts for interannual variability, decadal trends (such as driven by anomalous NAO activity) can still overlay a multi-decadal climate change trend.***

AR: That is an important issue and something worth discussing here, thanks for mentioning it. The second reviewer also commented on this, so we suggest adding the following statement in line 350:

> This underscores the necessity for further discussion: First of all, it is important to note that the lightning data covers only a relatively short period of 20 years. Consequently, the calculated trend may merely reflect decadal variability, which obscures an underlying, more protracted positive trend. Nevertheless, an increase in atmospheric instability has been measurable since the beginning of the 21st century (Battaglioli et al., 2023; Chen and Dai, 2023; Mohr and Kunz, 2013). Therefore, based on the modeling of thunderstorm activity using reanalysis data in the aforementioned studies, an increase should also be reflected in the lightning data. On the other hand, Manzato et al. (2025) showed that there has been no measurable increase in the accompanying phenomena of thunderstorms (hail, heavy rainfall, convective wind gusts) despite a simultaneous increase in atmospheric instability in northern Italy. This raises the question of whether the negative trends in the lightning data can be attributed to changes in the characteristics or organizational forms of thunderstorms, for example resulting in fewer CGs per thunderstorm, or whether statistical ingredient-based modeling of thunderstorm activity could miss some of the underlying mechanisms of convective storms (as also discussed by Manzato et al., 2025).

RC: ***Line 370: In-text quantifications like this are challenging to visualize as a reader. I would recommend either using a table, if the explicit number should be mentioned, or a visualization with e. g. a bar chart.***

AR: We thank you for pointing this out. The exact numbers were added here to give the reader the possibility to visually rank the earlier shown CCEs. But your objection is of course justified. So it might be better to only mention the largest and smallest CCE and their temporal and spatial characteristics here. We therefore changed the sentence in line 370 to:

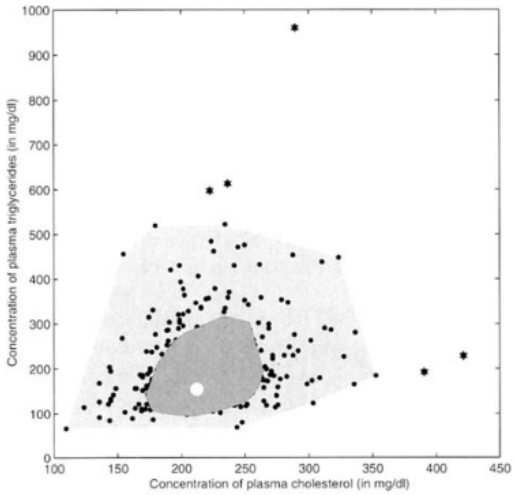

Figure 1: Illustration of a bagplot and the underlying two dimensional point cloud, from Rousseeuw et al. (1999).

> As an exemplary illustration, the spatial extension of the largest (northernmost, red) and smallest (southernmost, purple) CCE shown in Fig. 5b are 246 713 and 4 690 km^2 and with a duration of 11.3 and 1.8 hours respectively.

RC: ***Line 371: The discussion on lifetime deserves a little bit more nuance. While isloated thunderstorms can have a > 1 h lifecycle, their lightning-active time tends to be shorter than the overall lifecycle. Events with at least 40 CG strikes certainly select towards more intense / larger storms, that tend to have longer lifecycles as well (e.g. Feldmann et al., 2023, Wapler et al., 2017).***

AR: Thank you for raising this point. For our analysis, only the lightning-active time of the overall lifecycle of a thunderstorm is relevant. We would add this explicitly at line 375:

> ..., which can have a lifetime of less than one hour and an even shorter lightning-active period.

RC: ***Fig. 9: Please include the information of the displayed percentile either directly in the plot, or in the caption.***

AR: We are not entirely sure if it refers to panel (a) on the left, but we assume that this is the case. The so-called 'bags' shown here are not directly percentiles, even though the interpretation is almost identical. But although it is comparable to the box and whiskers of a one-dimensional box plot, they do not directly represent specific percentiles. In fact, these are convex polygons, the outer corner points of which are determined by the underlying points of the point cloud in a more complex way. To get a quick visual impression, refer to Fig. 1 from Rousseeuw et al. (1999): The inner bag contains 50 % of all points, whereas the outer bag is determined by inflating the inner bag by a factor of three (for visibility aspects we use a factor of six). The mathematical precise definition of the so-called bags is more complex, for more details, please refer to Rousseeuw et al. (1999).

RC: ***Line 455: This argument on how the negative NAO affects thunderstorm environments should apply to the contradicting proxy studies as well. Some reflection here on where the differences might come from, would be***

greatly appreciated. Is it differing time periods? Do the proxies not adequately represent convective activity, despite being developed on observational data?

AR: We thank you for pointing this out, and we appreciate getting into this in more detail. We think there are some important points to mention:

Indeed, there is a study considering thunderstorm-relevant parameters and their relationship to the NAO, and they show similar tendencies (speaking of NAO- corresponding with negative anomalies of the equivalent potential temperature Θ_e over Western Europe, (see. Piper and Kunz, 2017, Fig.13b).

Apart from that, the question of why proxy-based thunderstorm analysis and lightning data analysis seem to differ is an open question and needs to be investigated further. A recently published study investigating the relationship between thunderstorm-related extremes (hail, heavy rainfall, convective wind gusts) and convective parameters also shows differences in their trends (Manzato et al., 2025). One possible explanation would be the one discussed here: Changes in thunderstorm potential (which is captured by reanalysis) do not imply an automatic accompanying increase in the lightning activity, so further differentiation into thunderstorm types (and therefore the lightning intensity per thunderstorm) must be taken into account. This was basically one of the initial ideas to perform a cluster analysis of lightning data to see whether convective active areas (here the CCEs) are showing any trends.

Additionally, it is worth mentioning that proxy studies indicating increasing trends are mostly based on time series that are up to three times longer. Most studies based on reanalysis data do not consider the influence of decadal variability on NAO variability in Europe. This issue has already been addressed at line 350, and we believe that it does not require further discussion at this stage.

RC: ***Line 478: remove "more" -- is it really more storms that are smaller, or is it just a larger fraction of the total storm population, which could still be a smaller absolute number?***

AR: Thanks for mentioning this. Yes, it's only a larger fraction of the total storm population. So, 'more' is removed here to be precise.

RC: ***Note: Comment 14 has been divided into two separate parts. End of section 6: How does lightning activity depend on system size? Does flash rate per km change with system size (see e.g. Feldmann et al., 2023)? Ideally, this aspect would deserve another figure.***

AR: Thanks for mentioning this issue. During our studies, we also thought about investigating the relationship between flash rate and system size. But there is a major challenge: As can be seen in Fig. 5, for example, the largest CCE (northernmost) contains different thunderstorm systems. Some long-lasting isolated cells (very likely supercells), but also multicellular convection, and also isolated cells with, in comparison to the potential supercells, lower lightning density. Additionally, by construction, larger CCEs tend to encompass larger areas without any lightning. This means a calculated flash rate per area ($\frac{\text{flashes}}{10^3\ km^2\ \text{hour}}$) is mainly decreasing with increasing CCE area. But this does not mean that the comprised convective systems themselves have a lower flash rate. In fact, speaking from looking into some individual sample cases, both exist: Large CCEs with an encapsulation without any areas where lightning is absent and have a high flash rate, but in cases of 'unfortunate' spatial locations of the containing convective systems, the flash rate is relatively low. This can also be seen by looking at the distribution of the flash density for different CCE size classes (see Fig. 2). Above a certain size ($> 10\,000\,\text{km}^3$), the distributions of the flash density are almost identical and more or less independent of the size class.

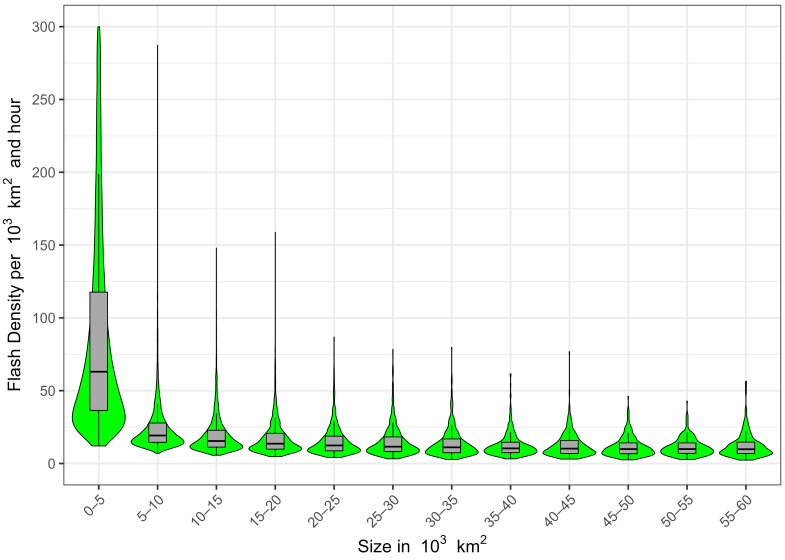

Figure 2: Distribution of the flash density per CCE size classes.

Additionally, there is quite a high correlation between the size and duration of 0.75, but no correlation is present between size and flash density (-0.023). Therefore, it is difficult to draw conclusions about the convective systems (with or without high flash rates) contained within, which is the actual question of interest.

RC: ***How do these results compare to Ghasemifard et al., 2024; where it is concluded that convective trends in Europe are not coupled to synoptic trends?***

AR: Thank you for highlighting this important issue. This has already been discussed with the authors of the aforementioned study. The conclusion of Ghasemifard et al. (2024) is based on investigations of the relationship between thunderstorm activity and the classification of large-scale flow configurations. In comparison, the NAO is a coarser classification than the ones used by Ghasemifard et al. (2024). Furthermore, changes in the relationship between thunderstorm-related atmospheric parameters (such as those used by Ghasemifard et al. 2024, to model thunderstorm occurrence) and actual lightning occurrence are not considered.

The main conclusion of our paper is rather that an unusual accumulation of NAO- years is a possible explanation for the observed negative trend in Western Europe. Ghasemifard et al. (2024), on the other hand, ask whether positive trends in modeled thunderstorm activity based on reanalysis data can be explained by changes in large-scale synoptic flow configurations. They answer this with 'no'. Therefore, in our opinion, the results presented in our paper should not be viewed as contradictory.

RC: ***Lines 496ff: What decades do these studies consider? May this play a role in the comparison?***

AR: Thank you for asking this important question. These studies are based on reanalysis data with much longer time series. This is has already been discussed in the additional statement in line 350 so we just refer to this here:

However, it is important to note that the aforementioned studies, which are based on reanalysis data, cover a much longer time period.

Technical corrections

RC: ***Line 47: Twice "For example" in sentence; Line 390: remove more; Line 440: The French-Swiss border region is the Jura, not the Prealps.; Line 485: double EUCLID***

AR: We would like to express our gratitude for the resulting improvement in the comprehensibility of the manuscript. We thank you for the technical corrections and addressed and incorporated all of them in the text.

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