Reviewer #1

General comments

RC: ***This article analyzes lightning data collected between 2001 and 2021 in Central Western Europe using a solid statistical method. The analysis was conducted on both gridded data and convective clustered events. The effect of NAO on lightning frequency and convective clustered events was also investigated. The article is suitable for NHESS. It is well written, and the structure is well crafted. The methodology is robust and clearly explained, with an appropriate level of detail. The figures are informative and comprehensive. The results are noteworthy and original, making the work deserving of publication. However, I have some minor comments that I recommend addressing before publication.***

AR: We would like to thank the anonymous referee for reviewing the manuscript and providing such valuable feedback. We would also like to express our gratitude for the improvements to the manuscript's comprehensibility that this feedback has brought about.

Specific comments

RC: ***Eq. 3: I assume "AR" refers to autoregression. It would be helpful to clarify this in bullet point 3. Additionally, I am not very familiar with the TFPW method — could you expand on how AR(1) is defined and how it was computed in this specific application? Thank you.***

AR: Thank you for pointing this out. Indeed, "AR" refers here to autoregression. To clarify this, we suggest changing bullet point 3 to:

> Removal of the autoregressive lag-1 process (AR(1), which is the correlation between the time series y_{t} and the time series $y_{\mathrm{t}-1}$) from y_{t}, so called pre-whitening (PW):

RC: ***Line 166: do border points fail to meet the density criteria because they do not exceed the minPts value? I suggest clarifying this***

AR: Yes, the border points fail to meet the density criteria. The density criteria expressed in words mean: 'not enough points (< minPts) are within the predefined temporal and spatial neighbourhood.' We would add this explicitly in brackets at the end of the sentence in Line 166:

> $(q_{\mathrm{BorderPts}} < minPts)$

RC: ***Line 245: How did you determine the values [20, 80] and [15, 25]? Earlier, you mentioned 30 km and 20 minutes as initial guesses for parameter selection. Are you selecting parameter ranges at the edges of the strongest gradient region? I assume this is because a strong gradient implies the exclusion of strokes that truly belong to convective clusters. I suggest adding a sentence to further explain the rationale behind choosing these parameter ranges.***

AR: Thank you for raising this point. The parameter ranges are indeed determined by the edges of the strongest gradient regions. There is no deterministic algorithm for determining 'optimal' density values. In a one-dimensional case (DBSCAN), therefore, kNN-Distance plots are used to determine an optimal threshold. See Fig. 1 for further clarification: on the y-axis, the distance to the fourth-nearest-neigbour (4NN, or more

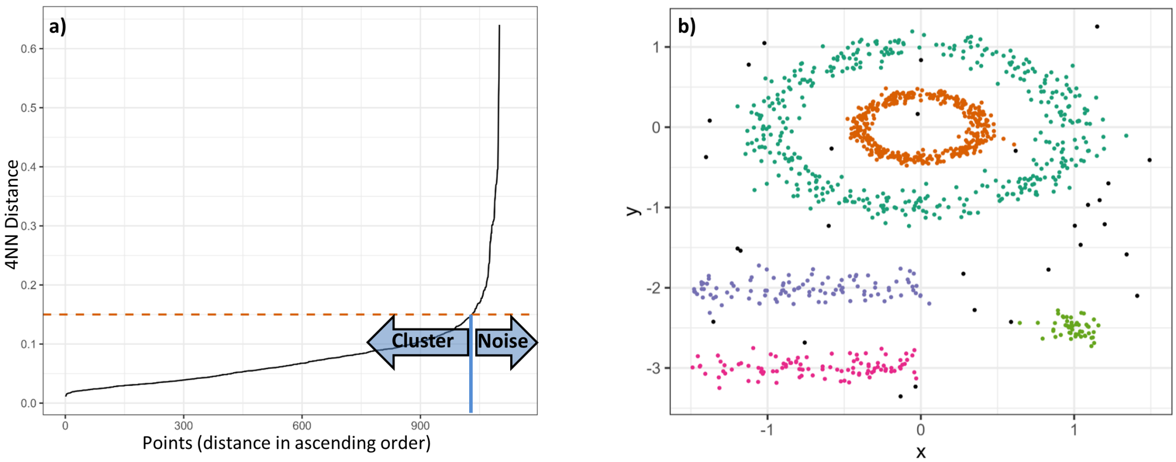

Figure 1: Illustration of how to determine the 'optimal' density-defining parameters. (a) the distance of each point in b) to the 4th-nearest neigbour in ascending order and the choosen parameter (0.15) to distinguish between cluster and noise. (b) The resulting clusters after applying the DBSCAN-Algorithm with the parameters $minPts$ and ϵ_{space}.

generally, kNN) of all points (x-axis) in ascending order is plotted. The so-called 'knee' of the graph between $y = [0.1,\ 0.2]$ would correspond to the spatio-temporal values $[20, 80]$ and $[15, 25]$ mentioned here. Any value for ϵ_{space} = $[0.1, 0.2]$ would generate fairly similar clusters. Lower values (close to 0.1) would transform some border points into noise, and higher values (close to 0.2) would transform some noise into border points. However, this would only result in minor changes to the shape, location, and overall appearance of the resulting clusters.

To summarize this briefly we modified the following sentences from line 244f:

> Using this method, it is now possible to specify a range of values, denoted by $\mathbb{W}$, for the meaningful parameters ϵ_{space} and ϵ_{time} from these areas with strong gradients: $\mathbb{W}_{\epsilon_{\text{space}}} = [20, 80] \wedge \mathbb{W}_{\epsilon_{\text{time}}} = [15, 25]$. Each combination of parameters obtained from $\mathbb{W}$ then produces clusters with only marginal differences, which should have an insignificant influence on the results presented in later chapters. Additionally, there is only a slight dependence on *minPts*, meaning that $\mathbb{W}$ is relatively independent of the required minimum number of CG strokes.

RC: ***Line 264: How is the concavity parameter defined?***

AR: The concavity parameter determines whether an 'indentation' into the convex hull around a point cloud is appropriate. It is therefore a relative measure of the concavity of the resulting hull. The value of 1 results in a relatively detailed shape, whereas higher values result in a convex hull (without 'indentations'). This is the basic idea behind the algorithm of Park and Oh (2012) algorithm for determining the depth to which a convex hull should be 'dug' to produce the desired concave hull for a point cloud. The basic concept can be understood by looking at Fig.2: If (length of edge)/(decision distance) $>$ concavity, then a new connection is added to the hull. This process is repeated for all connections at the edge. It continues until none of them satisfy the condition.

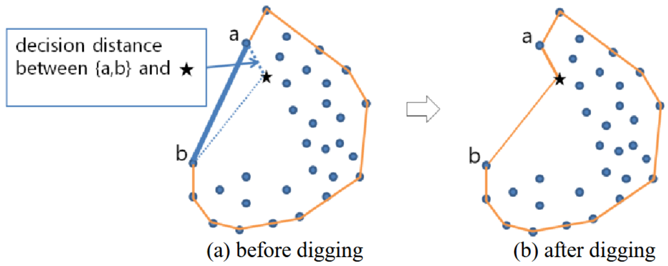

Fig. 5. Example of decision distance and digging

Figure 2: The illustration of the process of 'digging' from (Park and Oh, 2012).

We actually think that this description has too much detail to include in the manuscript. Regardless of this, your comment made us realize that we did not apply the initial alpha shapes algorithm by Edelsbrunner et al. (1983), but rather a further development by Park and Oh (2012). Therefore, we will leave the explanation as it is and refer to the correct algorithm in lines 265 and 269 for further details.:

line 265: An concave hull algorithm Park and Oh (2012), based on the so-called alpha shapes method (Edelsbrunner et al., 1983), line 269: for further details refer to Park and Oh (2012).

RC: ***Line 272: It appears that the increase in the mean area ratio ends around 2.4. Why do you indicate it ends at 2.2?***

AR: Thank you for pointing this out. Yes, 2.4 is correct here, we changed this accordingly.

RC: ***Line 295: The higher values might also be due to more intense thunderstorms with high electrical activity, though these are rare. Storm initiation in the Adriatic Sea is difficult, but when a storm forms on the surrounding orography and crosses the sea, it often intensifies due to high moisture availability. I have observed this pattern several times in late summer. Stationary storms are not very common over the sea; they typically form near the orography.***

AR: Thank you for your profound explanation and we would change line 295 to:

Kotroni and Lagouvardos (2016) argue that this is due to the relatively stationary and isolated thunderstorm systems that tend to occur over the Adriatic Sea. Additionally, thunderstorms that originate due to orography in close proximity could intensify due to the higher moisture content typically found present over the sea. This could result in an increase in intensity and thus also in lightning activity.

RC: ***Line 309: Florence is more inland than the observed local minimum. It looks like it is more centered in the "Piana di Pisa", which is the second largest alluvial plain in Italy after the Po Valley.***

AR: We thank you for helping with a profound knowledge of the orography in Italy. We will replace the sentence accordingly:

> In the valley of Piana di Pisa (halfway between Florence and the Mediterranean Sea), we observe a local minimum of around 4 TDs.

RC: ***Figure 6: Manzato et al. (2022) found that the maximum lightning density in NE Italy is much higher than in other parts of the Alps. They also used EUCLID data, although for a slightly different period (2005–2019). Your figure shows higher lightning density in Central Italy and Bosnia. Do you have any idea why this discrepancy occurs? Even accounting for the difference in spatial resolution, the variation is difficult to explain. I recommend addressing this point in the manuscript.***

AR: Thank you for pointing out this discrepancy. Having looked into the lightning density per year, we can see that, in 2003, there was a positive anomaly of up to nine thunderstorm days in Central Italy. Additionally, we only used lightning data from May to August and not the whole year as has been used by Manzato et al. (2022). These two factors could explain the discrepancy. Additionally, the non-linear color scale should be considered, as this makes the maximum in NE Italy compared to Manzato et al. (2022) seem visually less pronounced in comparison. We will amend the caption of Figure 6 to explicitly mention the non-linearity of the color scale.

> Note that the color scales are not linear.

RC: ***Line 346-352: Manzato et al (2025) found a similar results. While in NE Italy instability and moisture is raising according to the radiosoundings data, there is not a significant trend of rainfalls, hailstorms and lightning in the same region. I suggest adding this reference.***

AR: Thank you for bringing this work to our attention. It makes an exciting contribution to scientific discourse. Unfortunately, it had not been published by the time this paper was submitted in September 2024. In addition, Reviewer 2 also provided feedback on this point, so we suggest incorporating this paragraph into the text 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 (e. g 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 statistical ingredient-based modeling of thunderstorm activity could miss some of the underlying mechanisms of convective storms (Manzato et al., 2025), or 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.

RC: ***Lines 471-473: computing the correlation between Fig. 10a and 7a over France (i.e., between lightning trend and odds ratio) maybe can strengthen your result. I suggest performing this analysis.***

AR: We thank you for this suggestion. We performed a Spearman correlation test and obtained a value of 0.28 (see Fig. 3 left). This value increases to 0.51, when only significant odds ratio (OR) values are considered (see Fig. 3 right). In both cases, the p-value is below 0.001.

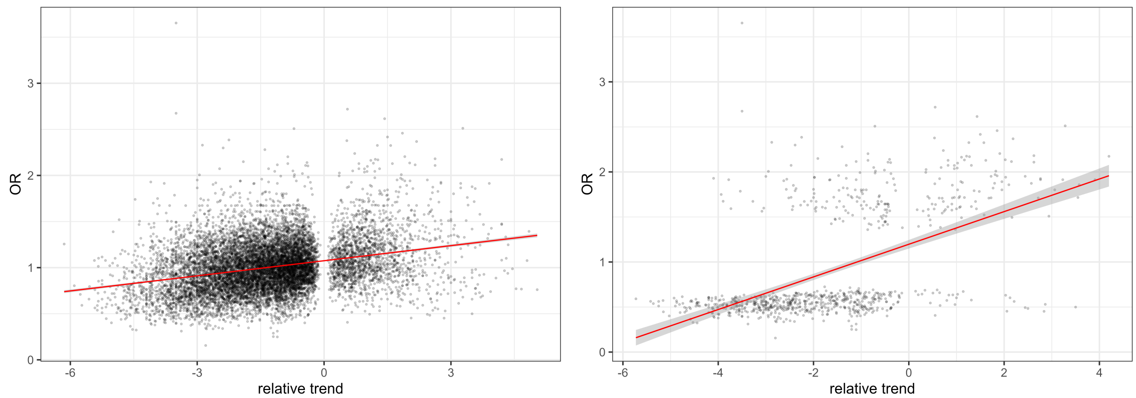

Figure 3: Correlation between OR (all: left; only significant OR: right) and the TD trend. The correlation coefficient equals to 0.28 (left) and 0.51 (right).

However, before concluding that there is only a weak relationship between these variables, it is important to consider the following: This correlation analysis is grid-based, meaning that single, isolated values are given the same importance as grid points embedded in contiguous areas with significant positive or negative OR. For example, Fig. 10a shows that only the region in France stands out as an area with contiguous significant negative values. This indicates that a reduction in thunderstorm activity can be observed over a larger contiguous area of France during NAO-. Additionally, we believe that this analysis is more indicative of a tendency toward a reduction in thunderstorm activity during NAO- in larger regions. Therefore, the correlation of actual values from trends and OR should not be overemphasized.

RC: ***Line 496: those studies are based on proxies from reanalysis data or soundings. Your study is based on observations of lightnings. I recommend emphasizing this important distinction, which enhances the significance of your findings.***

AR: We thank you for this emphasis and would recommend the following alteration of the sentence in 496:

> In contrast to previous studies based on thunderstorm proxies derived from reanalysis data (e. g. Allen et al. 2018; Raedler et al. 2019; Taszarek et al. 2021), most parts of France and Germany show negative trends in both TDs and CG stroke density (derived from direct lightning measurements) in this study. [...] It should also be kept in mind that the above studies, which are based on reanalysis data, also cover a longer time period.

RC: ***Lines 511-514: I recommend explicitly stating that, based on your findings, there appears to be no clear effect of climate change on lightning frequency during the studied period, whereas internal climate variability (specifically NAO fluctuations) has a strong impact. This is an important conclusion. Since the introduction discusses previous studies on thunderstorms and climate change (lines 45–54), a concluding remark on this key result is highly appropriate.***

AR: Thank you for mentioning this important issue. We think that additional research is needed to draw such a far-reaching conclusion. It is possible that, in addition to rising temperatures and the associated increase in instability, climate change also has an impact on the NAO and other factors influencing thunderstorm activity. Nevertheless, we would add the following fifth point in line 511:

> Despite measurable increases in instability caused by global warming, no increase in lightning frequency was observed across large parts of Western and Central Europe during the study period. However, decadal climate variability (here specifically fluctuations in the NAO) seems to have had a measurable impact.

Technical corrections

RC: ***Technical corrections: Line 88: suggest using "CCEs" instead of "convective clustered events" for consistency.; Eq. 5: p is not defined, probably is the sample point. Please clarify; Line 270: By "all," do you refer to all clusters detected in the selected example, or in the entire dataset?; Line 401: I suggest avoiding the term "obvious." While a trend exists, it is not particularly strong.; Figure 10: It may be helpful to include the black box over France from Fig. 1 in panel (a) of this figure as well.; Line 452: I suggest adding a geographic reference for the Shetland Islands. Since they are not shown in Fig. 1a, consider adding "northeast of Scotland."; Line 525: space missing after the parenthesis***

AR: We thank you for the technical corrections and addressed and incorporated all of them in the text.

References

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