Dear Referees 1 and 2:

We thank both referees (R1 and R2) for their careful and substantive comments on both the content and presentation of our NHESS discussion paper "*Characterisation and modelling of lightning strokes as point events in time and space*" (egusphere-2024-2733). We have revised the manuscript accordingly and provide detailed, point-by-point responses below.

We are grateful for these constructive suggestions, which have led to substantial improvements in the clarity, focus, and presentation of the manuscript. The revised version more clearly articulates the methodological contributions, clarifies the interpretation of the lightning data, and improves the overall structure and readability.

Across the manuscript, we have made several substantial revisions in response to the referees' comments:

- **Significant reduction in length and improved focus**:
  The manuscript has been shortened to 51 pages through the removal of redundant material, particularly in Sections 2 and 3, and by sharpening the emphasis on the novel methodological contributions from Sections 4 onwards with expanded analysis and discussion.
- **Substantial reduction and consolidation of figures**:
  We have removed 8 figures from the main manuscript (Figures 3, 5, 7, 8, 10, 11, 13 and 21) and 1 figure from the appendix (Appendix F), reducing duplication across figures, and retaining only those that directly support the key arguments presented in the manuscript. Several visualisations have been consolidated. The multiple 3D plots in Figures 2 and 3 have been aggregated into four subfigures in Figure 2, removing the duplicate 3D views and adding simplified 2D representations. Figure 21 has been aggregated with Figure 20, unifying the 3D visualisations and their discussion.
- **Streamlining of Section 3**:
  Section 3 has been substantially condensed to retain only the material necessary to explain storm assignment and provide context for the subsequent methodological analysis.
- **Clarification of lightning terminology and physical interpretation**:
  We now explicitly define the ATDnet observations as **lightning strokes** (not strikes), clarifying also the distinction between inter-stroke and inter-flash processes throughout the manuscript, and carefully framing our analysis as statistical characterisation of a detection-level point process.
- **Reframing of inter-event time analysis**:
  We explicitly acknowledge the bimodal nature of inter-event time distributions and their interpretation as a combination of inter-stroke and inter-flash processes. The presentation of this analysis has been simplified, and overly detailed figures removed.
- **Improved interpretation of storm propagation speed**:
  We have added discussion of physical plausibility, clarified the influence of intra-flash variability, and improved the interpretation of the storm propagation speed characterisation results.
- **Moderation and clarification of novelty claims**:
  We clarify that the contribution lies in the **spatio-temporal modelling framework and synthetic data generation**, rather than storm tracking itself, and we better position the work within the existing literature.
- **Consistency and technical improvements**:
  Units for storm propagation speed are now given in **m s^{-1}** (with km h^{-1} left in brackets), repeated citations have been removed, and tables/appendices have been streamlined.

Below, we provide detailed replies to each of the reviewer's comments. Line numbers referred to in our replies below are from our revised manuscript, while figure, table and section numbers are from original manuscript.

Referee 1 Comments	Changes made in paper
R1.1 Length of the paper. At 66 pages the manuscript it a bit too long for the reader to follow. I also counted 36 figures (including appendices). I suggest that the authors revise the number of pages and figures/tables downwards as this is a bit too long for a reader to follow and understand.	**Changes based on R1.1** Length of the paper We agree that manuscript was longer than necessary. In the revised version, to improve the focus and emphasise the research results of this manuscript, we have substantially reduced the overall length by streamlining background material, consolidating figures, and having non-essential material in the Appendix. The paper has been reduced to 51 pages including appendices, and 8 figures have been removed from main manuscript and 1 figure from appendices. **Table 2** has been removed from **Section 3**. For **Sections 5** and **6** we kept most of the appendices (except removing **Appendix F**) to provide additional visual information for various methodological steps or analytical results for other storms that are not analysed directly in the main manuscript. If necessary for additional clarity, we can further revise and reduce the material in the Appendix even more.
R1.2 The novel part of the paper really starts in the authors' section 4 onwards. Section 3 (which includes 12 figures and tables) over 15 pages appears to be the same data plotted multiple times and I'm not sure how much the additional plots are adding to the paper. Some specifics are below: a. The same lightning strikes are plotting in three dimensions (northing, easting, time) in figures 2, 3, 4 and 5. You should consider if all these figures are appropriate and if it would be possible to display the same data on just one or two figures. b. The data presented in figure 8 is the plotted again in figure B2 with different projections. This suggests that the method used to plot the data isn't that good. Could you instead use 2D subplots (e.g. northing vs time, easting vs time, northing vs easting) instead of a 3D one? This would make the data clearer to visualise. c. I'm also not sure what the plots in figures 7 and 10 add to the paper	**Changes based on R1.2** Structure and redundancy of Section 3 We agree that the novel methodological contribution of the paper begins in **Section 4**, and that **Section 3** is currently too long, given its purpose. We have therefore substantially condensed **Section 3**, by removing the various three-dimensional figures and the corresponding discussion with the aim of retaining only the material necessary to explain how the lightning data were assigned to individual storms and to provide sufficient context for the subsequent novel analysis. In particular: a. and b. We agree that **Figures 2–5** show overlapping information in different 3D visualisations and that the repeated plotting of the same data in different 3D projections is not optimal. We have consolidated them into displaying the unassigned lightning strokes as a subfigure in **Figure 2** and showing the final assigned 3D visualisation in **Figure 3** only for the first case study. For the second case study, only the final two-dimensional view is left after assignment is complete with **Table 1** serving as the summary table of assignment procedure for both case studies. We believe that now, once the assignment procedure is explained in-depth for the first case study, it is easier to follow the same procedure for the second case study, and no duplicate visualisations of the assignment steps are necessary. c. We agree that **Figures 7** and **10** add limited additional insight beyond what is already conveyed by the storm tracks and spatial plots, particularly where spread in one coordinate direction is minimal. We have removed these figures and replaced the spatial plots with 2D visualisations of northing-time, easting-time and

Referee 1 Comments	Changes made in paper
(especially in figure 10 where there's not much spread in the Easting direction). d. What additional information does Table 2 provide that can't already be judged from the lightning maps provided?	northing-easting lightning stroke data for both case studies (**Figure 2** and **Appendix Figure C1**). d. We agree that **Table 2** largely summarises information that can already be also inferred from the added 2D spatial plots and we have removed it from the paper together with the spatial plots of the already assigned individual thunderstorms.
R1.3 Similarly, while section 2 is much shorter than section 3, I think you could shrink the size of this section down and provide a smaller Table A1 (just detailing the reference, the natural hazard and a short summary (1-4 words) of the mathematical model). The reader can then read the papers if they need any further information.	**Changes based on R.1.3** Section 2 and Table A1 We agree that **Section 2** can be shortened. In the revised manuscript, we have condensed **Section 2** by removing redundant and duplicated content, while preserving all information essential to the study. **Table A1** has been updated and shortened as suggested.
R1.4 What is the reader meant to understand after studying figure 11? I understand that you want to remove the inter-event data, but this could be shown on a much smaller sample, without having to provide a noisy figure (which is when followed by similar figures in Fig. D1).	**Changes based on R1.4** Figure 11 and Appendix D We agree that **Figure 11** is overly detailed for its purpose and that the same point could be illustrated more concisely. We removed the figure as it demonstrated a relatively simple procedure and its description was expanded in text and **Appendix D** was kept to provide a visual overview of the procedure.
R1.5 Are Figures F1-F6 and appendix F necessary given the information is summarised in Table 3?	**Changes based on R1.5** Appendix F (Figures F1-F6) We agree that **Figures F1–F6** largely duplicate information already summarised in **Table 3**. We have removed them from the Appendix.
R1.6 Overall, what do you want the reader to understand when they read your paper? Emphasize the novel work you have done and don't include anything which isn't appropriate to the paper.	**Changes based on R1.6** Overall focus and take-home message We agree that the manuscript would benefit from a clearer emphasis on its novel contributions. In the revised version, we have sharpened the focus of **Section 7** and **8** to more clearly articulate (i) the methodological contribution of treating lightning strokes as spatio-temporal point events associated with moving storm systems, and (ii) the value of the resulting characterisation for synthetic data generation and related applications. **Section 7** has been reworked to explicitly address and focus on five aspects of the manuscript: (A) relevance to different categories of thunderstorms, (B) lightning inter-event time characterisation, (C) estimating lightning cluster movement speeds, (D) estimating lightning cluster spatial spread, and (E) overall motivation and limitations. For each aspect, the discussion has been refocused on identifying the novel work and contextualising the results within the broader literature.

Referee 1 Comments	Changes made in paper
R1.7 Minor Comments **R1.7a** Repeated citations: there is no need to constantly repeat citations. For example, I can see that Gaffard et al. (2008) is cited in the captions of Figures 1, 5, 6, 8 and 9. It should be possible to just cite once and then **R1.7b.** I can only see two yellow stars on figures 3 and 4, yet I would expect there to be four (2 x radar stations at 2 x times). This may be a function of the way you are plotting the data. **R1.7c.** The text on figure 15 seems a bit grainy, especially in the legends and axis labels. I'm also not sure what the blue #of events bars actually add to your analysis here.	**Changes based on R1.7** Minor comments 1.7a. We agree that repeated citations in figure captions are unnecessary. We have removed unnecessarily duplicated citations so that sources such as Gaffard et al. (2008) are cited once where appropriate and not repeatedly throughout figure captions. 1.7b. For **Figures 3** and **4**, only two radar station locations were used for the first case study, corresponding to the available data at the selected times. We have noted this in the figure captions to avoid confusion. 1.7c. We have checked the resolution of **Figure 15** and do not spot any difficulty in clarity of axis labels and legends. The number of events per either spatial or temporal lag aid in understanding the distribution of the lag values for each thunderstorm. While not directly used in further analysis and for generating synthetic datasets, they add a quantitative comparison between thunderstorms on lag value distribution. If necessary for overall figure clarify, we can remove them.

Referee 2 Comments	Changes made
R2.1 Need to correctly define the measured physical process under analysis, and not refer to lightning as "strikes", which is not a well-defined scientific term in this context. ATDnet is a VLF radio receiver network that detects lightning strokes, which are the individual pulses of current occurring during the complete lightning discharge process, known as a flash. Since there are normally several strokes in an individual flash (hence the tendency of lightning to flicker when observed optically), the distinction is therefore important for quantitative interpretation. Consequently, clarity is needed throughout, especially section 4.2 where the inter-stroke period and inter-flash periods are merged into a generalised "inter-event" time period, despite being two very different variables.	**Changes based on R2.1** Definitions of the measured physical process We thank the reviewer for this detailed and important clarification regarding lightning terminology and the physical interpretation of the ATDnet observations. We agree that ATDnet detects individual lightning strokes rather than complete lightning flashes, and that the distinction between strokes and flashes is important for physical interpretation. Therefore, in the revised manuscript, we have (i) explicitly defined the measured physical process at the outset in **Sections 2** and **3**, clarifying that the ATDnet system records individual VLF-detected lightning strokes (**Lines 137–141**), and (ii) revised the terminology used throughout to avoid the ambiguous term "lightning strikes", replacing it with "lightning strokes" where appropriate. We have also clearly stated that flashes are not directly reconstructed in this study and that multiple detected strokes may belong to a single flash. Regarding **Section 4.2**, we acknowledge that the current presentation does not sufficiently distinguish between inter-stroke and inter-flash times. We have clarified that the analysed "inter-event" time variable represents the time separation between successive detected strokes in the ATDnet dataset, rather than a physically homogeneous process (**Lines 314–317**). We have explicitly discussed the implications of this aggregation, noting that the resulting inter-event time distribution combines short inter-stroke intervals within flashes and longer inter-flash intervals, and that this reflects the resolution and nature of the available observations rather than an assumption of physical equivalence (**Lines 474–481**). We have further emphasised that the objective of the analysis is statistical characterisation of the observed spatio-temporal point process at the detection level, rather than physical inference of lightning discharge mechanisms. These clarifications ensure consistency with established lightning terminology while maintaining transparency about the limitations and scope of the modelling and analytical framework.
R2.2 Storm cell tracking algorithms based on lightning location data are not new and are already an evolving but well-established feature in both academic research (including recent NHESS publication) and many commercial real-time lightning location products, although not currently for	**Changes based on R2.2** Storm cell tracking novelty We thank the reviewer for this clarification and agree that storm cell tracking based on lightning location data is an established and actively developing area in both the academic literature, including recent NHESS publications, and in commercial real-time lightning products. We did not intend to imply that lightning-based storm tracking is novel per se, but our focus is primarily on the modelling aspects of storm cells.

Referee 2 Comments	Changes made
ATDnet. This is contrary to the authors suggestion of novelty (discussion, line 748-9), so further support will need to be presented to clarify the novelty of their approach.	This modelling approach can be used to generate synthetic datasets for clustering validation, but its aim is not to identify storm cell tracks as such. The novelty of the presented research lies in extending the approach to model lightning strokes as spatio-temporal point events. We acknowledge that the various storm tracking and clustering approaches can be used to replace the relatively simplistic lightning stroke assignment procedure presented in the manuscript. Our intention was also to highlight that, to our knowledge, such approaches have not previously been developed or demonstrated using ATDnet lightning data alone, without reliance on additional meteorological data sources (e.g. radar, satellite, or model fields), and that this distinction was not articulated clearly enough in the manuscript. We have reworked **Section 7** to have a paragraph E. Motivation for the implemented modelling approach and its limitations (**Lines 774–797**) that highlights the motivation, novelty and limitations of the modelling approach presented in this manuscript. In the revised manuscript, we have therefore (i) moderated the novelty claim in **Section 7**, (ii) explicitly distinguished our approach from existing storm tracking methodologies that integrate lightning with auxiliary datasets, and (iii) clearly specified the scope and nature of the contribution, namely a data-driven, spatio-temporal characterisation and modelling framework applied to ATDnet stroke-level observations. We have also identified and reviewed two recent publications (Augenstein et al., 2025; Poelman et al., 2024), to add additional contextualisation within the existing literature in **Section 4.1**.
R2.3 Distinction on charts is made over the different statistics for northing and easting spatial characteristics, although given the separation is only due to individual storm propagation direction, it is difficult to see how this distinction can be usefully applied to further understanding of lightning spatial characteristics more generally. Instead, using a coordinate system related to storm propagation direction (which in this case appears approximately linear) may offer more scientific insight in lightning spatial distribution during storm evolution.	**Changes based on R2.3** Spatial spread reassessment We thank the reviewer for this insightful suggestion and agree that expressing spatial characteristics in a coordinate system aligned with storm propagation direction has the potential to provide additional physical insight into lightning spatial distributions during storm evolution. Our manuscript separates northing and easting statistics primarily to remain consistent with the native projected coordinate system of the ATDnet data and to provide a transparent, assumption-minimal characterisation of spatial spread. As noted by the reviewer, this separation largely reflects storm propagation direction rather than intrinsic anisotropy in lightning behaviour. We have discussed this point internally and recognise that a storm-relative coordinate framework (e.g. along-track and cross-track distances) could offer a more physically meaningful

Referee 2 Comments	Changes made
	interpretation of lightning spatial structure that would allow for comparison between different storms. However, adopting such a transformation yields substantive additional uncertainty in the track estimation, with respect to the assumption of linear storm track. This point is directly addressed in **Sections 4.4** and **7**. We acknowledge that a storm-relative decomposition would offer additional scientific insight into the intrinsic spatial structure of the lightning distribution, independently of storm orientation, and we identify this as a valuable direction for future work (**Lines 425**–**432**; **760**–**769**). We note that for the purpose of the synthetic model developed in this study, the fixed geographic coordinate system remains appropriate. The model generates stroke locations as a spatial spread around a moving point source, where the northing and easting components are sampled independently from the observed distributions and combined to produce a 2D spatial offset. In this framework, the geographic coordinate system is internally consistent, as the movement speed and direction estimated in **Section 4.3** already account for the storm propagation direction. The northing and easting distributions therefore serve as direct inputs to the model without requiring a coordinate rotation.
R2.4 Section 2.1 Line 75. Whilst the authors correctly describe the simplified charge structure of a "typical" thunderstorm, it has been well established in geophysical literature that not all lightning-producing thunderstorms have this basic charge configuration, especially those which produce the severe storms described in this manuscript, which would likely have been at least tripolar.	**Changes based on R2.4** Storm structure We thank the reviewer for this important clarification. We agree that the simplified dipolar charge structure described in **Section 2.1** does not capture the full range of charge configurations observed in lightning-producing thunderstorms, particularly in severe convective systems, which commonly exhibit more complex (e.g. tripolar or multi-layer) charge structures. In the revised manuscript, we have explicitly acknowledged this limitation of the simplified description and expanded the discussion in **Section 2.1** to note that severe thunderstorms—such as those analysed in this study—are frequently associated with more complex charge configurations documented in the literature (**Lines 80**–**83**). We have clarified that the brief description in **Section 2.1** is intended solely as a high-level contextual overview and does not imply that the analysed storms conform to a purely dipolar structure (**Lines 88**–**90).** This clarification better aligns the background discussion with established understanding of thunderstorm electrification while maintaining the focus of the paper on lightning strokes treated as spatio-temporal point events rather than on detailed storm electrification physics.

Referee 2 Comments	Changes made
R2.5a Section 5.1 First paragraph is confusing. What is meant by storms being visually different in time? The lack of clarity that the "inter event times" is a convolution of both inter-stroke and inter-flash data means that the removal of "relatively large" or "longer" periods is not well justified in terms of separating physical characteristics. Was the separation therefore made considering changes in flash rate? **R2.5b.** Whilst it is acknowledged that the emphasis of their work is on statistical rather than physics-based modelling, the authors cannot adequately interpret their "inter-event" period statistical distributions without acknowledging that two distinct physical processes are responsible for this distribution. These are inter-stroke (the fundamental output of ATDnet, attributed to current pulses during individual flashes, which will account for the ~0.2s peak) and inter-flash period, which will be the peak around a few seconds duration for these quite active storms, related to the charging processes within the storms. Consequently, figure 13 is largely a function of the storm's flash rate evolution with time, making the description in terms of inter-event time distribution morphology rather over-complicated for what is a common property used to describe thunderstorm activity. The authors make some association with their inter-event periods and previously published inter-stroke means afterwards in the discussion section (around lines 736-744) suggesting they may be already aware of the underlying physical processes involved, although there is still no explicit link made to their bimodal distribution being a combination of inter-stroke and inter-flash periods. This would also allow	**Changes based on R2.5abc** Inter-event time distribution and movement speed We thank the reviewer for this detailed and constructive set of comments, which raise several closely related issues concerning (i) the physical interpretation of the inter-event time distributions, (ii) the clarity and justification of the data selection described in **Section 5.1**, and (iii) the interpretation and physical plausibility of storm propagation speeds inferred from lightning data. We agree that the wording in the first paragraph of **Section 5.1** is currently unclear. In particular, the phrase "visually different in time" is not precise and does not explain the rationale used to define subsets of the lightning data. We also agree that, given the nature of the ATDnet observations, the analysed "inter-event" time series represents a composite of two distinct physical processes: short inter-stroke intervals associated with multiple strokes occurring within individual lightning flashes, and longer inter-flash intervals associated with storm-scale charging and discharge processes. This distinction was not made sufficiently explicit. We have rewritten **Section 5.1** to include a more detailed acknowledgment and analysis of the bimodal structure (**Lines 462–477**). We further acknowledge the reviewer's point that the criteria used to remove "relatively large" or "longer" inter-event periods in **Section 5.1** are not sufficiently justified in physical terms under the current framing. The data selection was not explicitly based on changes in flash rate, nor on a formal separation of inter-stroke and inter-flash regimes, and this limitation is not adequately discussed. We agree that this requires clearer explanation of the intent and limitations of the selection procedure, particularly in the context of the composite nature of the inter-event time variable. We have therefore removed the very detailed presentation of the trivial inter-event time removal in **Figure 11** and removed material on hourly empirical distributions of inter-event times in **Figure 13**. The focus of **Section 5.1** is shifted towards emphasizing the bimodal structure of the data and limitations to the trivial inter-event time removal procedure are acknowledged in **Section 7** (**Lines 709–716**). With respect to storm propagation speed, we agree that additional clarification is required. In particular, the manuscript does not currently provide sufficient contextual discussion to allow the reader to assess the physical plausibility of the inferred speeds (e.g. values up to ~111 km h^{-1}). We also acknowledge that very short inter-event durations, associated with intra-flash stroke activity, do not represent storm-scale

Referee 2 Comments	Changes made
exploration of any association between inter-stroke variability and flash rate/storm evolution. **R2.5c.** Storm propagation speed is inferred from the lightning data, including RMSE, but no insight on its likely validity to overall cell motion from independent sources is provided. For instance, was a 111 kph (31m/s) storm propagation speed feasible for the synoptic conditions of the time? Even accepting the study is purely statistical, the lack of a basic meteorological plausibility assessment makes it difficult for the reader to form an opinion on the reliability of this statistical technique for simulating or tracking other thunderstorms. It appears that all inter-event durations were used for speed estimation. Since values shorter than ~0.5s represent inter-stroke periods, they relate to the spatial distribution of individual strokes within a lightning flash and not storm motion. It is not clear whether this "noise" was accounted for in the estimation of storm speed, or how the development, motion and dissipation of multiple lightning cores within a single storm relative to the overall storm propagation could be accounted for, noting the interesting propagation of fine elements representing these cores (e.g. figure F6) were identified by the authors.	motion and primarily contribute to scatter in the spatio-temporal point cloud, forming a cluster around the flash. In the plane-fit framework used here, the only consideration would be for changes in strokes-per-flash as the storm moves. Such conditions would then affect the plane-fit solution. We have rewritten **Section 4.3** and **Section 5.2** to further emphasise these interpretability considerations when applying the selected movement speed estimation methodologies on the data (**Lines 378–383; 510–512; 524–531**). Overall, we think that that these comments highlighted the need for clearer physical framing and more explicit interpretation of the analysed variables, rather than a fundamental change to the underlying statistical methodology. In the revised manuscript, we have therefore focused on (i) explicitly acknowledging the composite nature of the inter-event time distributions given the stroke-level nature of the ATDnet observations, (ii) clarifying the rationale and limitations of the data selection described in **Section 5.1**, and (iii) more carefully contextualising the storm propagation speeds inferred from plane fitting as storm-scale averages derived from a spatio-temporal point cloud that includes both inter-stroke and inter-flash variability. We emphasise that, given the available data, identification of space-time location of flashes is not possible, and our revisions prioritise transparency of interpretation and robustness of inference rather than introducing additional model complexity or reanalysis beyond the scope of this study.
R2.6 Consider reducing the number of graphs to the ones which really demonstrate your points.	**Changes based on R2.6** Number of figures We agree with the reviewer that the number of figures in the current manuscript may detract from the clarity of the main take-away messages. In the revised manuscript, we have streamlined the presentation by retaining only those figures that directly support the core methodological and interpretive points, and by also aggregating several figures to provide a more concise discussion. This revision was undertaken in coordination with similar comments from Reviewer 1 regarding manuscript length and overall focus, with the aim of improving readability while

Referee 2 Comments	Changes made
	preserving transparency and reproducibility of the analysis. The paper has been reduced to 51 pages including appendices, and 8 figures have been removed from main manuscript and 1 figure from appendices. **Table 2** has been removed from **Section 3**. For **Sections 5** and **6** we kept most of the appendices (except removing **Appendix F**) to provide additional visual information for various methodological steps or analytical results for other storms that are not analysed directly in the main manuscript. If necessary for additional clarity, we can further revise and reduce the material in the Appendix even more.
R2.7 Technical Correction. Movement speeds were stated with the units of km/h, but it would be more consistent with broader scientific literature to use the SI units of m/s.	**Changes based on R2.7** Technical corrections We agree with the reviewer that expressing movement speeds in SI units improves consistency with the broader scientific literature. In the revised manuscript, we have converted all reported storm propagation speeds from km h^{-1} to m s^{-1} and updated the associated text, tables, and figures accordingly. This includes replotting any figures where movement speed units are shown, to ensure consistency throughout the manuscript (**Figure 15**). We have left storm propagation speeds in km h^{-1} in brackets to contextualise the results with any scientific literature where SI units are not used.