Dear Referees 1 and 2:

We thank the two 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 strikes as point events in time and space*" (egusphere-2024-2733).

We thank R1 for noting that the "second half of the paper (from section 4 onwards) appears very novel and is what the authors should emphasise in their revised manuscript" and we agree with R1 that the manuscript can be reduced in size to enhance readability and the overall contribution. We also thank R2 for their detailed comments, and have attempted to address these issues in our comments below.

As this is a discussion paper, our replies below set out (i) how we interpret each comment, and (ii) the specific changes we propose to implement in the revised manuscript. We will ensure that all modifications are incorporated consistently across the paper, figures and tables.

Referee 1 Comments	Response to Referee 1
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.	**Author Reply to R1.1** Length of the paper We agree that, at its current length, the manuscript is longer than necessary. In the revised version, we will substantially reduce the overall length by streamlining background material, consolidating figures, and moving non-essential material to the Appendix. This will require some rewriting to ensure consistency of cross-references, but we agree that this is both feasible and desirable.
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.	**Author Reply to 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 will therefore substantially condense Section 3, 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. We agree that Figures 2–5 show largely overlapping information in different 3D visualisations. We will consolidate into a reduced number of figures, retaining only those that are strictly necessary to illustrate the storm assignment methodology and focus on one particular case study to illustrate the assignment. b. We agree that the repeated plotting of the same data in different 3D projections (e.g. Figures 8 and B2) is not optimal. In the revised manuscript, we will replace some 3D visualisations with clearer 2D subplots, which should reduce redundancy. 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 will either remove these figures or

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c. I'm also not sure what the plots in figures 7 and 10 add to the 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?	move them to the Appendix, depending on whether they are required for completeness. d. We agree that Table 2 largely summarises information that can already be inferred from the spatial plots. We will reassess whether this table is necessary in the main text and, if retained, clarify its added value or move it to the Appendix.
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.	**Author Reply to R1.3** Section 2 and Table A1 We agree that Section 2 can be shortened. In the revised manuscript, we will condense this section and reduce the size of Table A1 to include only the reference, the natural hazard, and a brief description of the mathematical modelling approach. We will update cross-references accordingly.
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).	**Author Reply to 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 will move this figure, and the related figures in Appendix D, to the Appendix or replace them with a simplified example that better serves the explanatory purpose without unnecessary visual noise.
R1.5 Are Figures F1-F6 and appendix F necessary given the information is summarised in Table 3?	**Author Reply to R1.5** Appendix F (Figures F1–F6) We agree that Figures F1–F6 largely duplicate information already summarised in Table 3. We will reassess the necessity of these figures and, unless a clear additional insight can be demonstrated, remove 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.	**Author Reply to 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 will sharpen the focus of the Conclusions and Discussion 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. Material that does not directly support these aims will be reduced or removed.
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	**Author Reply to R1.7** Minor comments 1.7a. We agree that repeated citations in figure captions are unnecessary. We will rationalise citations so that sources such as Gaffard et al. (2008) are cited once where appropriate and not repeatedly throughout figure captions.

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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.	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 will clarify this in the figure captions to avoid confusion. 1.7c. We will check the resolution of Figure 15 and improve it if necessary to ensure clarity of axis labels and legends. We will also reassess whether the blue bars indicating the number of events add sufficient value to justify their inclusion.

Referee 2 Comments	Response to Referee 2
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.	**Author Reply to 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, strictly speaking, ATDnet detects individual lightning strokes rather than complete lightning flashes, and that the distinction between strokes and flashes—and their respective temporal characteristics—is important for physical interpretation. Therefore, in the revised manuscript, we will (i) explicitly define the measured physical process at the outset, clarifying that the ATDnet system records individual VLF-detected lightning strokes, and (ii) revise the terminology used throughout to avoid the ambiguous term “lightning strikes”, replacing it with “lightning strokes” where appropriate. We will also clearly state 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 will therefore clarify 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. We will explicitly discuss 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. We will further emphasise 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 will 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	**Author Reply to 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

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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.	intend to imply that lightning-based storm tracking is novel per se. Our intention was instead 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 current manuscript. We acknowledge that this point is currently overstated in the Discussion. In the revised manuscript, we will (i) moderate the novelty claim accordingly, (ii) explicitly distinguish our approach from existing storm tracking methodologies that integrate lightning with auxiliary datasets, and (iii) clearly specify the scope and nature of the contribution, namely a data-driven, spatio-temporal characterisation and modelling framework applied to ATDnet stroke-level observations. We will also identify and review the recent NHESS publication(s) as suggested along with other publications since submission of our paper to ensure appropriate contextualisation within the existing literature. As part of this revision, we will return to the previously reviewed publications to refine the positioning of our work and to ensure that the contribution is framed accurately and transparently relative to prior studies.
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.	**Author reply to 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 current presentation 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 interpretation of lightning spatial structure. We will therefore revisit this aspect of the analysis to assess whether adopting such a transformation yields substantive additional

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	insight beyond the existing results. Depending on the outcome, we will either (i) revise the spatial characterisation accordingly, or (ii) explicitly justify retaining the current coordinate-based approach while clarifying its interpretive limitations. In either case, we will ensure that the revised manuscript addresses this point directly and makes clear the implications of the chosen coordinate framework for interpretation of lightning spatial characteristics.
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.	**Author reply to 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 will explicitly acknowledge this limitation of the simplified description and expand the discussion to note that severe thunderstorms—such as those analysed in this study—are frequently associated with more complex charge configurations documented in the literature. We will clarify 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. This clarification will better align the background discussion with established understanding of thunderstorm electrification while maintaining the focus of the paper on lightning strikes treated as spatio-temporal point events rather than on detailed storm electrification physics.
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	**Author reply to 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

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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 exploration of any association between inter-stroke variability and flash rate/storm evolution.	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 is not made sufficiently explicit in the current manuscript. As the reviewer correctly notes, the resulting bimodal inter-event time distributions (including the ~0.1–0.2 s peak and the several-second peak) are therefore most naturally interpreted as reflecting inter-stroke and inter-flash processes, respectively. While this interpretation is implicitly acknowledged later in the Discussion through comparison with published inter-stroke statistics, the manuscript does not explicitly link the observed bimodality to these underlying physical mechanisms, nor does it clearly frame Figure 13 in terms of the temporal evolution of flash rate. We agree that this omission weakens the physical interpretability of the results and leads to an overly complicated description of inter-event time distribution morphology. 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.
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	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 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 condition would then affect the plane-fit solution. The current manuscript does not address this consideration sufficiently and will be addressed through further analysis.

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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.	Overall, we agree that these comments highlight 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 will therefore focus 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 intra-flash and inter-flash variability. We emphasise that, given the available data, identification of space-time location of flashes is not possible, and our revisions will therefore 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.	**Author reply to 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 will streamline the presentation by retaining only those figures that directly support the core methodological and interpretive points, and by moving more detailed or supplementary figures to the Appendix. This revision will be undertaken in coordination with similar comments from Reviewer 1 regarding manuscript length and overall focus, with the aim of improving readability while preserving transparency and reproducibility of the analysis.
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.	**Author reply to 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 will convert all reported storm propagation speeds from km h^{-1} to m s^{-1} and update the associated text, tables, and figures accordingly. This will include replotting any figures where movement speed units are shown, to ensure consistency throughout the manuscript.