

Reply to Reviewer 1

Reviewer's general comments: *The manuscript proposes a novel method using remote sensing technology to determine Extreme Coherent Gust with Direction change (ECD) parameters. The manuscript provides adequate background and derives standardized parameters based on lidar, SCADA, and in-situ measurements. The proposed methodology and procedures are generally sound and well-described. The findings reveal the spatial variability of this type of complex flow and demonstrate how these events deviate from the IEC standard, posing unique challenges for wind farm power generation. We recommend this manuscript for publication following the adaptations listed below.*

Reply: The authors would like to thank the reviewer for their effort in reviewing our paper, and for their constructive comments and insightful recommendations. We have provided responses to each specific comment from the reviewer and made corresponding changes to our revised manuscript as presented below.

1. **Reviewer comment:** *Because the manuscript relies on data from a large field campaign, detailed information regarding data treatment is essential. While the authors describe the filter thresholds adopted for the lidars, the manuscript lacks information on data filtering for the in-situ measurements (3.3), turbine anemometers (3.4) and, more importantly, the radars. As the radar measurements exhibit some data vacancies (shown already in Fig. 4), we suggest elaborating on the filtering and rejection criteria, as well as any interpolation methods if used. Please give more details than line 94.*

Reply: No data filtering is applied to the met station data. The turbine anemometer data are resampled to a consistent sampling frequency of 5 s to facilitate the ramp fitting procedure. This note has been added to Sect. 3.4. For the radar data, the radial velocity data from each radar undergo automated quality control prior to any dual-Doppler synthesis, using the custom processing suite developed by Texas Tech University and described in Hirth et al. (2024). This quality control procedure makes use of the information contained in the full set of radar moments output by the signal processor, applying thresholding and statistical analyses tuned to identify and remove erroneous radial velocity returns, including ground clutter, stationary point-target returns, and wind turbine artifacts. Automated horizontal alignment checks and corrections are also performed based on the total return power signatures relative to the locations of known point targets (i.e., the turbines). Importantly, data removed by this quality control are rejected rather than reconstructed. No interpolation or gap-filling across data voids is performed at any stage of the processing, and Cartesian grid points without sufficient valid radial velocity measurements from both radars are left empty and are excluded from all subsequent analysis. The data vacancies visible in Fig. 4 and others therefore correspond to grid points where returns were removed by quality control or where atmospheric scatterers were insufficient to produce a valid meteorological velocity estimate. This information has been added to the manuscript in Sect. 3.1, along with a note in Sect. 5 to explain the vacancies

in Fig. 4: “Note that vacancies in the radar data are regions without sufficient valid velocity measurements, as identified by the quality control procedure described in Sect. 3.1.”

2. **Reviewer comment:** *Section 4 notes that 26 wind ramp events were identified but only 6 are analyzed in detail, with the selection based on concurrent precipitation observations and sufficient dual-Doppler radar coverage. While the authors acknowledge this is not a frequency assessment, we would like to suggest the authors briefly discuss whether this selection criterion could bias the reported ramp characteristics and clarify how many events were excluded due to radar data quality (see comment 1) versus the non-precipitation atmosphere.*

Reply: Of the 26 ramp events identified, four were excluded due to lack of precipitation observed in weather radar data. The remaining 16 were excluded due to lack of sufficient high quality and continuous dual-Doppler radar data. Note that for the current analysis, the quality of dual-Doppler radar data required is higher than for most applications. In order to detect the front and fit the ramp function to each front cross-section for up to 11 consecutive time steps, the dual-Doppler radar data must be continuous and free of large gaps for durations up to 25 minutes. In time-averaged steady-state situations, gaps in the data can be averaged out, but that is not possible in the current time-resolved analysis.

Radar data availability depends on the distance from the radars and the presence of scatterers such as pollen and dust in the air. A previous investigation into the X-band radar system reported average data availabilities of 72%, 58%, 35%, and 18% at distances of 3 km, 10 km, 20 km, and 30 km from the radars (Hirth et al. 2017). In the current study, we select intervals where radar data is available over the entire 30 km range to capture the evolution of the outflow boundaries over as long a distance as possible.

The relationship between atmospheric conditions and the distribution of the scatterers that determine radar data availability is not fully understood. The same previous study showed that data availability peaks at night, with a secondary peak in the afternoon (Hirth et al. 2017). In the current investigation, all six events occur between 01:30 and 10:30 UTC, corresponding to 20:30 and 05:30 local time, consistent with the nocturnal peak in data availability. The occurrence of these events at night is also consistent with long-observed diurnal patterns of spring and summer thunderstorm activity. Wallace (1975), for example, showed that thunderstorms occur most frequently around midnight local time over the central United States, including Oklahoma. These convective systems originate over the Rocky Mountains, then travel down the sloped terrain and arrive in the Great Plains at night (Carbone et al. 2002).

However, whether the events analyzed here had the highest quality radar data due to the properties of the radar system or the properties of the storm cannot currently be determined.

This discussion has been summarized in Sect. 4 of the revised manuscript, as follows: “Hirth et al. (2017) showed that data availability of the X-band radar system depends on the diurnal cycle and the distribution of scatterers in the atmosphere. Peak availability occurs at night.

Peak thunderstorm activity in Oklahoma has also been shown to occur at night, as convective systems originating in the Rocky Mountains in the late afternoon travel down the sloped terrain into the Great Plains (Wallace 1975; Carbone et al. 2002). The six events analyzed in the current investigation occur between 01:30 and 10:30 UTC (20:30 and 05:30 local time), although whether they exhibit the highest data availability due to properties of the radar system or properties of the thunderstorm outflow cannot currently be determined. Regardless, the selection of events with high radar data availability may bias the results towards events with qualities that the radars favor, such as the presence of scatterers in the atmosphere.”

3. **Reviewer comment:** *There appear to be several Dual-Doppler radar synthesis techniques available, while the manuscript only briefly mentions that radial wind speeds are interpolated onto a three-dimensional Cartesian grid (lines 95–99). Extending from Comment 1, more elaboration should be appended here. Each individual radar generates radial wind speeds that are not uniform in spatial resolution. The further the measurement is from the radar, the greater the spacing between adjacent measurement points. The 0.5 degree across-beam resolution (line 91), the azimuthal spacing at the far edge of the ~30 km range is approximately 260 m (~ 5 times coarser than the 50 m horizontal grid resolution). Is it true that the synthesis data have a regular horizontal resolution of 50 m and a vertical resolution of 25 m across the full radar domain? How representative is a 50 m grid at far ranges? We suggest the authors elaborate on how the synthesis process accounts for this range-dependent resolution effect, and clarify whether the effective spatial resolution varies across the domain.*

Reply: The synthesized fields are stored on a Cartesian grid with uniform 50 m horizontal and 25 m vertical spacing across the full domain. However, we agree that uniform grid spacing must not be conflated with uniform effective resolution, and the effective spatial resolution does vary across the domain, as described below. The native sampling of each radar is 9 m along-beam at all ranges, with a 0.5° half-power beamwidth in both azimuth and elevation. The azimuthal dimension is oversampled at 0.35° (Hirth et al., 2024), so at the far edge of the analysis domain (~30 km range) the azimuthal sampling interval is approximately 180 m, while the beamwidth corresponds to an across-beam dimension of approximately 260 m, as the reviewer notes. The quality-controlled radial velocity fields from each radar are interpolated from their native polar coordinates onto the pre-defined Cartesian grid using a radius of influence (ROI) that increases both horizontally (from 10 to 200 m) and vertically (from 5 to 75 m) with increasing range from the radar, after which the paired volumes from the two radars undergo the dual-Doppler synthesis to produce horizontal vector fields (Hirth et al., 2024). The chosen ROI depends on the measurement goals of the user. For the AWAKEN project, given the anticipated diverse data users, we wanted to ensure consistent grid interpolation out to the maximum range given such a large domain and relatively large evolution in underlying measurement resolution across this domain. In other words, we wanted to make sure the full domain was fully filled without gaps or obvious objective analysis (OA) artifacts. Several ROI permutations were tested as part of the deployment configuration. Any user of the data can go

back to the raw measurements and perform their own OA and quality control to meet their specific project objectives. A note about the range-dependent resolution effect has been added to Sect. 3.1, as follows: “Note that a uniform grid is used to maximize the utility of the dataset, but due to the radar scanning pattern, the azimuthal sampling interval increases to ~ 180 m at the far edge of the domain. Therefore, the effective spatial resolution of the reconstructed velocity field decreases with distance from the radars.” It has also been added to the first paragraph of Sect. 6: “Even at the edge of the domain farthest from the radars, where the spatial resolution is 180 m (see Sect. 3.1), 10 m s^{-1} wind speed corresponds to 18 s temporal resolution, still much finer than 2 minutes.”

4. **Reviewer comment:** *As noted in the manuscript line 100, the dual-Doppler radars are not synchronized and perform relatively slow scans, introducing a temporal ambiguity of 2 to 4 minutes. In the context of gust propagation, this time lag is not trivial (a gust moving at 15 m/s travels 1.9 km within this time period). While the naturally longer rise times observed make physical sense, calculating the rise time by combining a fit-derived spatial rise distance (Sect. 6.2) with an ensemble-averaged boundary propagation speed (Sect. 6.1) introduces uncertainty. We recommend adding a discussion paragraph to address these uncertainties or providing error estimates, particularly when comparing these space-time converted results to the standard IEC temporal method. In this regard, we note that the propagation speed is itself derived from volume-to-volume boundary displacements during this 2 to 4 minute interval (Sect. 6.1, lines 180–185). The temporal resolution limitation is therefore still present, as it is directly inherited through propagation into all reported rise time values in Table 2. Furthermore, propagation speed is computed as an averaged quantity while boundary displacement is a local measurement, applying a single mean propagation speed across the entire boundary implicitly assumes spatially uniform flow. More elaboration on this limitation and how it enters the resultant rise time should be given/quantified.*

Reply: We thank the reviewer for raising this important point. In the revised version of the manuscript, we have included uncertainty estimates on all of the provided values derived from the propagation speed and ramp fit. For the propagation speed, the uncertainty due to spatial variability is calculated from the standard deviation of the boundary displacement at each point along the boundary.

While the two radars are not synchronized, both scan the domain in 124 s. Accounting for the deceleration after a completed volume and the re-acceleration at the start of the next, the north radar takes ~ 126 s between the start of each scan, while the south radar takes ~ 127 s between scan starts. Therefore, the drift in temporal alignment of the radars is much smaller than the Δt between adjacent scans, and at a given point in the radar domain, the time elapsed between adjacent scans remains relatively constant. The effect of the temporal misalignment between radars is much smaller than the effect of the relatively long scan duration. Each radar scans a series of 145-degree sectors at 18 different elevation tilts in 124 s. As described in Sect. 3.1 of the manuscript, the radial wind speed measurements are interpolated to a grid with ten vertical

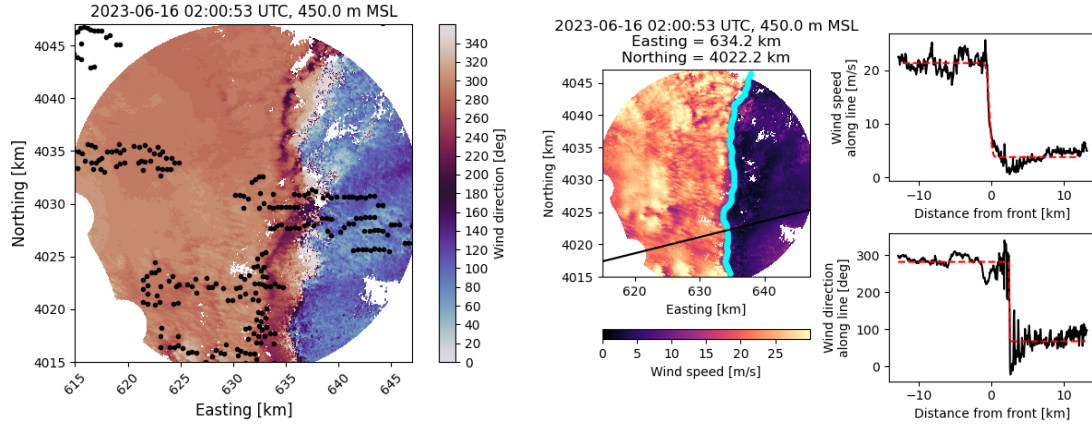
levels. Therefore, each Cartesian grid point contains information from multiple time points within the scan duration, and the velocity field can be interpreted as a two-minute average. Any uncertainty in the outflow boundary location resulting from the scan duration would manifest as spatial variability, i.e., the boundary is slightly ahead or behind in different parts of the domain. This spatial variability has been accounted for in the standard deviation of the boundary displacement described above.

For converting a rise distance into the rise time experienced at a fixed point, for a passage lasting tens to hundreds of seconds, the interval-mean speed is appropriate, provided that propagation is steady over the interval. From Fig. 6, the largest sustained acceleration magnitude among the six cases is 0.004 m s^{-2} , corresponding to a change of at most 5% of the propagation speed. The temporal resolution limitation therefore contributes a much smaller uncertainty than the spatial variability.

The propagation speed uncertainty is propagated into the uncertainty reported for the Δt values presented in Table 2. See the reply to Reviewer comment 6 for more detail on the uncertainty calculation.

5. **Reviewer comment:** *In Fig. 10(i), several bins exhibit near-zero Δt_{θ} values, which appear physically implausible given the spatial resolution and propagation speeds. The manuscript does not describe any quality control applied to the curve-fitting results such as goodness-of-fit thresholds or lower rejection bounds. It is unclear whether these near-zero values represent genuine sharp wind direction transitions, degraded fitting quality, or artifacts of using the wind speed boundary to define the perpendicular cross-section direction in a case where the wind speed and direction boundaries are non-coincident (as is the case for 2023-06-16, line 164). The authors should clarify the curve-fitting acceptance criteria and discuss whether these values are physically meaningful or should be excluded.*

Reply: For the 2023-06-16 case, the propagation speed remains between 12 and 19 m/s. With a spatial resolution of 50 m, these speeds correspond to temporal resolutions of 4.2 and 2.6 s. The minimum value of Δt_{θ} in Fig. 10(i) is 10.5 s, which is above the minimum limit. In the contour map of radar-derived wind direction shown below, the wind direction boundary is very sharp in the southern part of the domain where this value was recorded.



Per the reviewer’s suggestion, we have included additional information describing the curve fitting procedure and the acceptance criteria. Curve fitting is performed using `scipy.optimize.curve_fit`

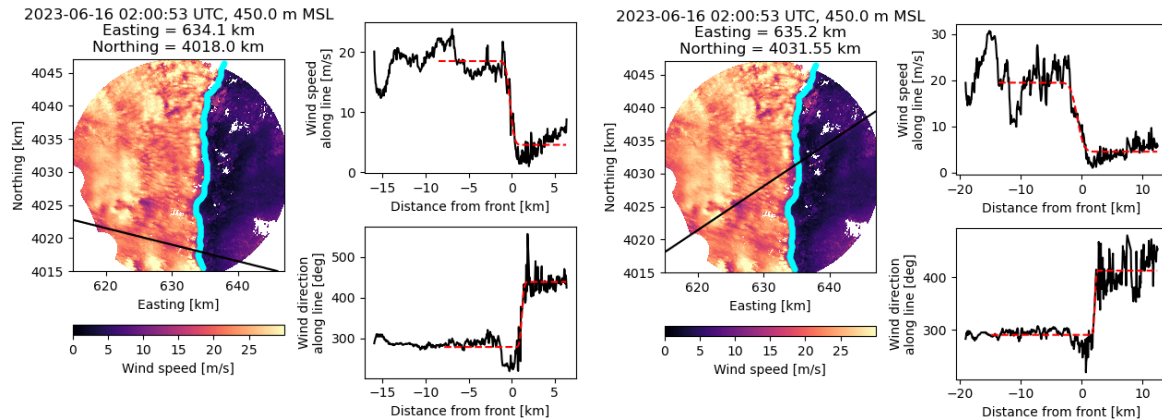
(https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html), which outputs the covariance matrix of the optimal fitted values, alongside the values themselves. The square root of the diagonal of this matrix provides the standard deviation errors on the parameters. The condition number of the covariance matrix can also be used as an indicator of the reliability of the fit results. In the current study, points where any of the parameter errors are above the 90th percentile or where the condition number is greater than 10^{10} are excluded. This information about the acceptance criteria has been added to Sect. 6.2, as follows: “The square root of the diagonal of the covariance matrix of the fitted parameters provides one standard deviation errors on the parameters. These error estimates are used to characterize the uncertainty of the parameters and to eliminate outliers with errors above the 90th percentile. Points with covariance matrix condition numbers greater than 10^{10} are also excluded.”

6. **Reviewer comment:** *As a general comment for the methodology used, Fig. 8 and Fig. 10 (f)(g)(h)(i) demonstrate large variability in radar-derived ramp parameters along the outflow boundary. The manuscript attributes some of this variability to inhomogeneous flow features (lines 327–329), no metrics are provided to distinguish physically driven variability from methodological ones, such as the range-dependent increase in effective radar volume (noted in Comment 2) and the absence of quality control of the curve-fitting procedure (Sect. 6.2). We suggest the authors provide fitting quality metrics or discuss how these methodological factors may contribute to the observed variability.*

Reply: In the revised manuscript, fitting quality metrics have been implemented, as described in the reply to the previous comment, reducing methodological variability. The spatial variability of the propagation speed, the standard deviation error from the curve fitting procedure, and the spatial variability of the curve fit-derived rise distance are all propagated into the uncertainty estimates for Δt in Table 2. While the methodological uncertainties cannot be entirely separated from the uncertainty due to spatial variability, the standard deviation error

from the curve fit tends to be an order of magnitude lower than the standard deviation of the distribution of rise distances, indicating that spatial variability is the primary driver of the large uncertainties presented in Table 2. Note that even the methodological uncertainty (i.e., curve fit standard deviations) is partially related to spatial variability in the deviations of wind speed and direction cross-sections from the conventional ramp shape; the velocity cross-sections exhibit more spatial variability than can be captured by the conventional ramp function. This discussion has been added to the first paragraph of Sect. 7.1 in the revised manuscript.

Radar-derived velocity fields presented throughout the manuscript provide further support for the idea that variability is primarily driven by inhomogeneity in the flow. See, for example, Fig. 9, which shows how much $\Delta\theta$ can change along the boundary and as the boundary moves through the domain. As another example, the two images below show wind speed and direction cross-sections at two different points along the boundary presented in Fig. 10 of the manuscript. The cross-section on the left exhibits a steeper wind speed slope than the one on the right, consistent with the differences in Δt_u at 4020 and 4030 km Northing shown in Fig. 10(g) of the manuscript.



7. **Reviewer comment:** *The radar-based method extends gust quantification into the spatial domain, and it is clear this approach is not expected to compare one-on-one to the standard point measurement method. To strengthen the paper's practical impact, we suggest explicitly outlining the operational advantages of using this proposed spatial method (predictive wind farm control...etc.) alongside a discussion of its limitations regarding space-time volume averaging.*

Reply: The primary advantage of the radar-based method is its ability to characterize the spatial variability of the outflow boundary, which provides a more complete picture of the event. As demonstrated in Sect. 7.2, neighboring wind turbines can experience different ramp properties and therefore respond differently. A single point measurement would have limited predictive capability, since it only sees one instance of a highly variable event. The radar-based method enables a more comprehensive characterization of the event, including the mean and standard deviation of its properties and its evolution over space and time. With this

information, wind farm operators can predict the range of possible turbine responses and forecast wind farm power generation from a probabilistic perspective. This text has been added to the end of Sect. 7.2 of the revised manuscript.

Notes regarding volume averaging have been added to Sects. 3.1 and 6 of the revised manuscript, as described in the reply to Reviewer comment 3.

8. **Reviewer comment:** *Line 57: “Section 2” is inconsistent with “Sect. X” used in other texts.*

Reply: “Section 2” is used in line 57 of the original manuscript because it begins a sentence, while other uses of “Sect.” appear in running text. This is following the guidelines for authors regarding the use of “Figure” vs. “Fig.” (<https://www.wind-energy-science.net/submission.html#figurestables>)

9. **Reviewer comment:** *Equation (3): should use smaller or equal ($\leq$) for the first condition. Otherwise, 4 m/s has not been included in either condition.*

Reply: The “<” in Equation 3 has been changed to “ $\leq$ ” in the revised manuscript.

10. **Reviewer comment:** *Line 129 states that events are identified when the wind speed changes "at least 4 m/s" between adjacent 10-minute periods, while the Figure 3 caption describes a "ramp with wind speed change greater than 5 m/s". We suggest aligning these thresholds.*

Reply: The caption of Fig. 3 has been changed to be consistent with the text.

11. **Reviewer comment:** *Line 164: ... propagate (south) eastward...: need a space, or south-eastward.*

Reply: This line has been revised to read “propagate **eastward or southeastward**” for clarity.

12. **Reviewer comment:** *Line 190: “the 2024-05-24 (case study?) exhibits the largest deceleration”. This sentence seems to miss a word.*

Reply: We have added the word “**case**” to this sentence.

13. **Reviewer comment:** *Fig. 10 captions: Site C1a and Site D seem to be inconsistent.*

Reply: We thank the reviewer for pointing out this error. We have changed “Site D” to “Site **C1a**” in the figure caption.

14. **Reviewer comment:** *Line 352-353: Suggest using standard terminology “cut-out” instead of cut-off.*

Reply: We have changed “cut-off” to “**cut-out**” in the revised manuscript.

15. **Reviewer comment:** *Line 405 to 457: Several references have twice <https://doi.org>.*

Reply: We thank the reviewer for bringing this issue to our attention. We have corrected it in the revised manuscript.

Additional References:

- Carbone, R. E., J. D. Tuttle, D. A. Ahijevych, & S. B. Trier. (2002). "Inferences of Predictability Associated with Warm Season Precipitation Episodes." *Journal of the Atmospheric Sciences*, 59, 2033–56. [https://doi.org/10.1175/1520-0469\(2002\)059%253C2033:IOPAWW%253E2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059%253C2033:IOPAWW%253E2.0.CO;2).
- Hirth, B. D., Schroeder, J. L., & Guynes, J. G. (2017). Diurnal evolution of wind structure and data availability measured by the DOE prototype radar system. *Journal of Physics: Conference Series*, 926, 012003. <https://doi.org/10.1088/1742-6596/926/1/012003>
- Wallace, J. M. (1975). Diurnal Variations in Precipitation and Thunderstorm Frequency over the Conterminous United States. *Monthly Weather Review*, 103, 406–19. [https://doi.org/10.1175/1520-0493\(1975\)103%253C0406:DVIPAT%253E2.0.CO;2](https://doi.org/10.1175/1520-0493(1975)103%253C0406:DVIPAT%253E2.0.CO;2)

Reply to Reviewer 2

Reviewer's general comments: *This manuscript presents a detailed analysis of thunderstorm outflow-induced wind ramps based on multi-lidar observations. The dataset is valuable, and it is clear that a significant amount of work has gone into the data processing, event characterization, and analysis. In particular, the results concerning the spatial variability of the events and the apparent mismatch between changes in wind speed and wind direction are interesting and potentially novel. However, the manuscript would benefit from substantial restructuring, a clearer statement of its scientific objectives, and a more careful interpretation of the comparison with the IEC Extreme Coherent Gust with Direction Change (ECD).*

The manuscript contains a valuable dataset and several interesting analyses. In particular, the spatial structure of the events, their variability, and the apparent mismatch in timing and rise rates between speed and direction changes appear to provide genuinely new insights. However, the manuscript would benefit from a clearer research focus, a more concise structure, and a more cautious treatment of comparisons with IEC design conditions. I encourage the authors to strengthen the motivation and novelty around the observed spatiotemporal characteristics of the events and reduce the emphasis on direct comparisons with the ECD, which are difficult to interpret given the limited sample size and the fundamentally different purposes of the observed events and the IEC design model.

Reply: The authors would like to thank the reviewer for their effort in reviewing our paper, and for their constructive comments and insightful recommendations. We have provided responses to each specific comment from the reviewer and made corresponding changes to our revised manuscript as presented below.

1. **Reviewer comment:** *Clarify the research objectives and contribution: At present, I find it difficult to identify the main research question of the study and how it is specifically connected to wind energy applications. While the manuscript contains a large amount of analysis, the scientific focus is not sufficiently clear. I encourage the authors to formulate clear research questions early in the manuscript and ensure that the subsequent analysis is structured around answering them. In my view, the most novel aspects of the work are the observed spatial variability of the events and the mismatch in timing and rise time between wind speed and wind direction changes. These findings deserve greater emphasis and could form the central focus of the paper. In contrast, the comparison with the IEC ECD appears less convincing in its current form and tends to dominate the discussion despite a limited basis for comparison.*

Reply: The goal of this work is to better understand how wind turbine manufacturers and wind farm developers/operators can account for events caused by severe weather. Currently, the IEC framework is the primary avenue for incorporating such extreme events into turbine design and operation. Therefore, we investigate whether the IEC standard is capable of representing the events that we have observed. Spatial variability and rise time mismatch are examples of features observed in the real events that are not captured by the standard, but have important

implications for wind turbine design and operation. We have emphasized this focus throughout the manuscript. We also reworked the last paragraph of the introduction to clarify the scientific goals of the study.

2. **Reviewer comment:** *Interpretation of the comparison with IEC extreme event: Several parts of the manuscript imply a direct comparison between the six observed thunderstorm outflow events and the ECD. I do not believe such a comparison is fully justified without additional context. The IEC ECD is not intended to represent a thunderstorm outflow event. Rather, it represents an unspecified extreme wind event with a recurrence period of 50 years. By contrast, the events analyzed in this study are individual observed cases whose recurrence periods are unknown and are not demonstrated to correspond to 50-year events. This important distinction should be clearly acknowledged throughout the manuscript. Related to this point, the statement that the ECD represents a "worst-case scenario" is not strictly correct. The ECD represents an extreme design event. Because the relevant parameters are modeled together and are not necessarily independent, the fact that one observed parameter exceeds the corresponding ECD value does not imply that the event exceeds the design condition as a whole. The manuscript should avoid such interpretations. More generally, it is unclear what the authors intend to demonstrate through the ECD comparison. Are they attempting to show that the ECD is insufficiently conservative, or simply that real events exhibit different characteristics (which has already been done)? Such questions cannot be convincingly addressed using statistics from only six events and should therefore be discussed more cautiously.*

Reply: As discussed in the reply to the previous comment, we compare with the IEC standard because it is currently the primary way extremes are accounted for in turbine design. Regarding the ECD specifically, the recurrence period of this event is not specified in the standard. Rather, it is described as a “transient case that has been selected as a potentially critical event in the life of a wind turbine.” We have removed descriptions of the ECD as a worst-case scenario, replacing them with the “**potentially critical event**” language used in the standard itself. We have also reworded the discussion of parameters that exceed the values in the standard. We agree that a single parameter exceeding the ECD value does not imply that the event exceeds the design condition. To clarify this point, we have changed the sentence to read: “Some of the cases observed here exhibit **individual** parameters that exceed **the values specified in the standard**.” Indeed, in the following sentences we argue that, even though some events exhibit larger values of certain parameters, they are not expected to be more “critical” than the ECD when taken as a whole. The goal, instead, is to conduct a thorough comparison, including differences and similarities, between the real and IEC-defined events. In particular, we aim to show that features of real events that are not captured in the standard, beyond the magnitude of the ramp parameters, have implications for turbine design and operation. These features include the deviation from the idealized ramp shape and the lag between the wind direction and wind speed change. We also emphasize the variability between different events, performing our analysis from a case study, rather than statistical, perspective.

3. **Reviewer comment:** *Literature context: The discussion would benefit from additional references. The manuscript cites Kelly et al. in a manner that could be interpreted as a study specifically of thunderstorm gust fronts. However, Kelly et al. investigated extreme wind ramps more broadly, a category that includes but is not limited to thunderstorm gust fronts. The corresponding text should be revised to better reflect the scope of that work. Another relevant study is Hannesdóttir et al. (<https://wes.copernicus.org/articles/8/231/2023/>), which investigates extreme coherent gusts and associated turbine loading and includes extrapolation to 50-year return levels. This perspective is particularly relevant to the discussion of extreme-event characterization and design implications. Furthermore, the statement that shorter-timescale changes may be more damaging to turbines because they provide less time for control-system response is supported by previous work, including Hannesdóttir et al. (<https://wes.copernicus.org/articles/8/231/2023/>). Adding references here would strengthen the discussion, which currently reads somewhat speculatively.*

Reply: References to Kelly et al. (2021) have been modified to clarify the scope of that work. We thank the reviewer for bringing Hannesdóttir et al. (2023) to our attention. It is highly relevant to the current work and strengthens our discussion of the impact of the observed events on turbine loads. References to this study have been added to the Introduction and Sect. 7.1.

4. **Reviewer comment:** *Methodological clarification: Several aspects of the methodology require further clarification: The manuscript refers to an edge/boundary detection methodology. Is this an existing method from the literature, and if so, please provide an appropriate citation (other than the scikit Python library)? If it is a new adaptation, this should be clearly stated.*

Reply: The tools in the scikit Python library are well established within the image processing community, but have not, to our knowledge, been applied to outflow boundary detection in radar data. To clarify the novelty of this technique, we have modified the text in Sect. 5 to read: “Image processing tools from the scikit-image Python library (van der Walt et al., 2014) have been adapted to the novel application of outflow boundary detection in radar data using the following procedure”.

5. **Reviewer comment:** *Characterization methodology: Line 271 states: "Having developed a method for characterizing thunderstorm outflow-induced wind ramps..." This wording overstates the contribution. The authors appear to have modified and applied an existing characterization framework rather than developed an entirely new method. This statement needs rephrasing to more accurately reflect the contribution.*

Reply: We rephrased this sentence to read: “Having adapted the wind ramp characterization method from Hannesdóttir and Kelly (2019) to thunderstorm outflows captured by dual-Doppler radar...”

6. **Reviewer comment:** *Discussion and conclusion: The discussion and the conclusions become somewhat unfocused. I suggest shortening these sections and concentrating on the primary*

findings that are directly supported by the presented analysis. The conclusions introduce several new topics that are not sufficiently developed in the main manuscript. The final paragraphs of the conclusion introduce several new concepts, including wind farm control strategies, forecasting applications, economic impacts, grid resilience. These topics have not been discussed in the preceding sections and therefore feel disconnected from the rest of the manuscript. I recommend removing most of this material from the conclusion. The conclusion should focus on the main findings of the present study and their direct implications.

Reply: Per the reviewer's suggestion, we have removed much of the speculative material from the Conclusion. We have retained the content that refers to direct applications of the current work, as well as its limitations and directions for future work.

7. **Reviewer comment:** *Line 105: The sentence describing the lidar scan duration is unclear. It is not evident whether the approximately 5 s refers to the complete scan sequence or only the vertical beam measurement. Please rephrase for clarity.*

Reply: The 5 s duration refers to the complete scan sequence. The sentence has been rewritten for clarity, as follows: "The lidar conducts a five-beam profiling scan, including one vertical beam. [The entire scan](#) takes ~5 s to complete."

8. **Reviewer comment:** *The carrier-to-noise ratio threshold differs between the two lidars. Please explain the reason for using different thresholds.*

Reply: The carrier-to-noise ratio thresholds were selected by instrument owners. In the revised version of the manuscript, however, the -22 dB threshold is applied to both lidars for consistency. This is the default threshold used by the Windcube software. Note that changing the carrier-to-noise ratio threshold did not modify any of the results presented in the manuscript.

9. **Reviewer comment:** *In Table 2, some boundaries appear to be defined using wind direction and others using wind speed. The rationale for this choice is not clear and should be explained.*

Reply: Explanation of the selection of wind speed vs. wind direction for the boundary definition is provided at the end of Sect. 5. In each case, either the wind speed or wind direction forms a smoother boundary, as seen in Fig. 5. Whichever boundary is smoother is used to define the outflow boundary in each case. The caption of Table 2 refers the reader to Sect. 5 where this explanation is provided.