Response to Reviewers – "Analysis of convective cell development with split and merge events using a graph-based methodology"

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We thank the reviewers for their comments on our submitted manuscript. We have copied the comments of the reviewers in black here and include our response to each individual comment in blue. We also include a `latexdiff` version of the manuscript to this response that shows the detailed changes from the original submission.

Reviewer 1

General Comments

This paper addresses the important challenge of accounting for storm splits and mergers in storm tracking algorithms. The authors demonstrate that spatiotemporal graphs are a natural fit for this problem. The storm detection, tracking, and graph creation methods are clearly explained and well justified. An excellent case is made for the use of graph-based storm tracking in storm nowcasting algorithms.

We thank the reviewer for the comments.

Specific Comments

To avoid confusion between the notions of predicting storm initiation and predicting development of existing storms, I recommend replacing “development” with “evolution” in at least some instances, including within the title.

As suggested, we have replaced "development" with "evolution" in the manuscript title and some other instances throughout the text (please see the latexdiff file for exact locations).

In the Intro, consider additionally citing Skinner et al. (2018, Wea. and Forecasting) and Heinselman et al. (2025, Wea. and Forecasting) as examples of storm object identification and storm nowcasting studies, respectively.

We have cited the suggested studies in the introduction. We were unable to find Heinselman et al. (2025, Wea. and Forecasting) study, but assume that the reviewer referred to Heinselman et al. (2024, Wea. and Forecasting) study instead.

The x’s in Fig. 3 are somewhat difficult to see.

We have increased the size of the x’s denoting radar locations to make them easier to see.

Section 4: For clarity, I recommend emphasizing/reminding that the statistics presented here are valid for cell events, not for entire cell lifetimes.

We have emphasized this at the end of the beginning of Section 4.

L374–375: Why is the smaller sample size likely to bias the rates of increase/decrease low? Is this a post hoc assumption?

We have removed the statement about the smaller sample size being the reason for the lower rates of increase/decrease from the text. A possible explanation for the lower increase/decrease rates might be that the merge-split events tend to have larger areas than merge or split events (Figure 8), which might lead to lower (mean) increase/decrease rates (because the rate is presented relative to values at t_0). Our preliminary analysis did not show substantial differences between the increase/decrease rates of merge-split and merge or splits events when grouped according to t_0 cell area. However, when grouped in this way, the sample sizes are small which makes them difficult to compare.

Technical Corrections

L265: Figure 1 $\rightarrow$ Figure 3

Corrected.

Reviewer 2

The manuscript presents an interesting and very complex topic, such as the tracking of convective cells in environments with multiple splittings and mergings. It is one of the most challenging issues in short-term forecasting due to the nature of multicell systems, with many interactions across different scales.

We thank the reviewer for the comments.

1. Consider a more recent reference (at least add one) for VIL introduction (L131)
   We thank the reviewer for the pointing out the lack of current references here. We have added citations to Hu et al. 2019 and Tuftedal et al. 2024 as studies that also use VIL for cell identification on lines 131-132 (in revised version).

2. Figure 2 is a bit confusing. t0 is not the current time, and it should be clearly explained. Furthermore, regarding this scheme, I have not been able to find the validity period. I mean, until when can a certain scheme be used for nowcasting?
   t_0 is the time step at which the event node exists (event node is the cell whose evolution the analysis focuses on). We have clarified this in the caption of Figure 2 and in Table 1.

   In this study, the proposed methodology is used for post-event analysis of the cells; in this context, "current time" is not clearly defined. In the text and in Table 1, the word "current" is used to refer to e.g. the cell or timestep that is being processed at that moment in the algorithm and thus the "current timestep" would change throughout the processing.

   We assume that the reviewer meant "current time" in the context of nowcasting, in which case we understand "current time" to mean "the time of the last observations used to create the nowcast".

   The motivation of the methodology proposed in this study is not directly nowcasting, but analysis of the impact of cell features (such as Zdr columns) to cell development, or verification of nowcasting

models combined with a methodology as the one presented by our previous study (Ritvanen et al. 2025). If the proposed methodology is used in nowcasting models, t_0 would most likely be the "current time", although, some nowcasting model could also use some other definition of "current time".

However, the proposed methodology is not directly applicable for nowcasting; rather, it can be used to gather information of the cell tracks that can then be used for nowcasting. Thus, we have not specified a validity period since it would depend more on the nowcasting model and its skill and limitations than the methodology proposed in the study.

3. A doubt regarding the cell identification: have you tested in highly efficient precipitation clouds without ice particles or scarce ones? Is this technique effective in these cases? Please comment in the text.
The aim of the study is to present a methodology to analyse the cell tracks once the cells have been identified and tracked. Thus, we have not tested other cell identification algorithms. However, as long as the cell identification and tracking algorithms are able to identify and track the cells consistently in time, the proposed methodology can be applied. If the cells are identified and tracked so that the constructed cell tracks have poor temporal continuity (e.g., tracks that exist only for few timesteps), the proposed methodology would not provide much benefit for the analysis; however, the same would be true for any time series analysis of the cell tracks. In these cases, the identification and tracking algorithm would need to be adjusted to create more consistent cell tracks.

   As discussed in the introduction (lines 62-74 in submitted version), splits and merges, whether caused by the cell identification and tracking algorithms or meteorological processes, will always be an issue in the analysis of cell tracks. In cases where the cell identification and tracking would be only slightly impacted (for example, if a cell is wrongly identified as two cells at one time step, producing first a split followed by a merge once the cell is again identified as one cell), the proposed methodology would allow one to account for this in the analysis and thus partially mitigate the uncertainty caused by issues in the cell identification algorithm.

   We have added a mention of this in the discussion section (lines 424-425 in revised version).

4. Another point referring to the cell identification: "Contiguous area identified from a radar image; represents an observation of a convective storm" is very vague and needs more precision. Are you considering single-threshold or multiple ones? Are you considering the same values for all the months? Note that VIL is highly sensitive to the seasonal variation. How have you solved this point?
We have clarified in Table 1 that the "cell" is the result of the cell identification algorithm and "cell track" is the result of the tracking algorithm. The definition of the cell in Table 1 is purposefully general, because the proposed methodology does not in itself depend on how the convective cells are identified or defined. Rather, the cell definition and identification (e.g. whether to use a fixed threshold or some multi-threshold identification scheme) should depend on the goals of the study. As such, one could use e.g. a seasonally varying threshold or identification algorithm, as long as any further analysis is adjusted to account for the differences in the cell identification.

   In this study, we are using a fixed threshold in VIL for the cell identification. A fixed VIL value also allows comparing the features of the identified cells, such as cell area or mean rain rate, to each other; with a varying threshold such comparisons (as required, e.g., to produce Figure 10) would be questionable. Our aim for the cell identification was to analyze rainfall and thus we kept the VIL threshold low to include as much of the rainfall in the cells to the analysis as possible. Note that we are applying the lowest possible VIL threshold to discriminate from background values in our dataset. Furthermore, the

analysis presented in the study is limited to summer months (May-September), and in the results (Figure 10) we further limit to cells with higher VIL values.

5. The presented examples are very illustrative, but I miss a more difficult situation, for instance, from May or September, with lower VIL values and, therefore, a more complex cell identification.
   The aim of the study is to present the methodology that can be used to analyse the cells once they have been identified and tracked, and in our opinion the current case studies present the methodology sufficiently. Thus, we consider case studies that would focus on complexities of the cell identification algorithm (rather than the complexity resulting from the splits and merges) to be outside of the scope of this study.

6. Figure 6: Why do the ZDr index values not coincide with those of the other variables? (e.g. left panel, most representative cell index is 3, but for Zdr is 1)
   We have carefully reviewed Figure 6 and do not find the issue that the reviewer is describing. Note that for the median ZdrC height (panels e and k) only some cells have values, so at some times the "most representative" cell is not visible because it does not have a ZdrC feature. Additionally, the median ZdrC height values are quantized at 100 m resolution (due to the vertical resolution of the product); this causes some cell values to be on top of one another in (k) panel. The points with multiple cells with the same value have the indices of the cells above and below the point.

   To clarify the figure, we have added the bold/dashed lines to indicate the "most representative" track in panels (a) and (g), and clarified the handling of missing values in the figure caption.

7. For the same figure, I understand that the current time is 18.05 and 10.05, respectively. Is this it? Please, clarify
   If the case studies would be used for nowcasting, the "current time" (please see the answer to 2nd comment regarding our interpretation of "current time") would be 17.35 and 09.35, respectively. These are the timesteps that are referred to as t_0 in these case studies. To clarify this, we have added the t_0 times to the captions of Figures 4 and 5.

8. "Thus, the impact of splits and merges to the analysis depends on the definition of the cells that the analysis focuses on." I think the Authors should provide more information about this point, maybe with a discussion referring to other Authors.
   The aim of this statement is to say, that since the portion of cells with splits or merges varies depending on how the subset of analysed cells is selected, their significance to the analysis varies. If the cells with splits and merges make up a large portion of the analysed dataset (e.g. in the cells with maximum VIL $\geq$ 20 kg/m^2), they contribute more to the analysis compared to a dataset where cells with splits and merges consist a smaller proportion.

   We have clarified this in the text on line 333-334 (revised version) by changing "definition of the cells" to "selection of the cells".

9. Regarding the number of splittings and mergings, have you found any correlation with the size of the cells?
   We have not directly studied if the number of splits and merges correlates with the cell size. As discussed in Section 4.1 (lines 341-349 and Figure 8), split and merge event cells tend to be much larger than other cells, and the distributions of cell areas for cells involved in splits and merges (Figure 8d and 8e) have slightly smaller peaks at small cell areas, indicating that the cells tend be slightly larger. However, as mentioned in the text, the samples in Figures 8d and 8e only include the cells that are part of the

subgraph of some split, merge, or merge-split event, and they are thus not directly representative of all cells involved in splits and merges. Nevertheless, the correlation of cell size with splits and merges is an interesting topic and a good suggestion for further studies using the proposed methodology.

10. I don't understand the source of this conclusion: "It was documented that splits and merges occurred in 7.2% of all identified cells, and they were more frequent in cells with maximum VIL ≥ 20.0 kg m-2 (17.9%) or containing ZdrC features (11.7%)" (I were not able to find in the Results any comment regarding this)
    These results are specified on Lines 328 - 332 (in submitted manuscript version).

References

Hu, Jiaxi et al. (2019). "Tracking and Characterization of Convective Cells through Their Maturation into Stratiform Storm Elements Using Polarimetric Radar and Lightning Detection". In: *Atmospheric Research* 226, pp. 192–207. ISSN: 01698095. DOI: 10/ggk6g7.

Ritvanen, Jenna et al. (2025). "Cell-Tracking-Based Framework for Assessing Nowcasting Model Skill in Reproducing Growth and Decay of Convective Rainfall". In: *Geoscientific Model Development* 18.5, pp. 1851–1878. ISSN: 1991-959X. DOI: 10.5194/gmd-18-1851-2025.

Tuftedal, Kristofer S. et al. (2024). "Shallow- and Deep-Convection Characteristics in the Greater Houston, Texas, Area Using Cell Tracking Methodology". In: *Atmospheric Chemistry and Physics* 24.9, pp. 5637–5657. ISSN: 1680-7316. DOI: 10.5194/acp-24-5637-2024.