Response to RC2

Authors' responses are in red italics

Recommendation: minor revisions

General

By using automated front detection and convective cell tracking data, this study analyzes the environmental conditions and lifting mechanisms influencing convection near cold fronts in warm seasons in Germany. Results show that pre-surface-frontal cells tend to form in areas with the highest surface dew points and CAPE. Other front relative regions also support cell formation, though with lower CAPE and dew points compared to non-cell regions. Mid-level humidity helps distinguish post-frontal cell locations from non-cell regions. Pre-surface-frontal cells experience strong large-scale lifting at 850 hPa and 700 hPa, with high convective inhibition. Significant large-scale lifting also appears post-frontal, especially at 500 hPa. Additionally, less sunshine was observed before cell initiation compared to non-cell regions, suggesting that solar heating may not drive most cold-frontal cell initiation.

This study provides a valuable analysis of the atmospheric conditions that influence convection near cold fronts. I find the subject interesting and well within the scope of WCD. It is well written, has a clear structure, and good illustrations. However, I have a couple of minor concerns which can maybe be solved with more explanations. I expand on some of these concerns below and outline additional minor/technical comments.

We thank the reviewer for taking the time to review the manuscript and for their construct comments and feedback. We are glad that the reviewer supports the publishing of this article in WCD subject to revisions.

Specific comments

- The authors study the warm-season in Germany, but only convection related to frontal zones. I assume that a large part of convection occurs in situations with weak synoptic forcing as well. Can the authors comment on the overall relevance of frontal convection in Germany? Moreover, several field experiments were carried out to better understand convection initiation in Germany. At least some of those with their main findings should be cited.

  The primary focus of the current study is on cold-frontal cell environments and lifting mechanisms. However, in Pacey et al. (2023) we did look at climatological differences between cold-frontal and non-cold-frontal convective cells. For example, we found on days where cells initiated in proximity to cold fronts over twice as many cells are detected compared to non-cold-frontal cell days. Furthermore, we found differences in the fraction of cell days associated with cold fronts depending on the location in Germany, with cell days in north-western Germany and southern Germany being most and least associated with cold fronts, respectively. We will include some brief discussion of these findings in the introduction.

Regarding field campaigns in Germany (e.g. COPS; Wulfmeyer et al. 2011), we have focused the literature in the introduction on previous studies on the environments in which convective storms form over longer timeseries since this is a primary focus of this study and not on individual case studies and field campaigns. However, we agree that more background on the general topic of convective initiation in Germany would be useful, particularly in the 3rd paragraph of the introduction. In the revised manuscript, we will include discussion of COPS regarding frontal lifting and local lifting from orography. Thank you for the nice suggestion.

We note that it would also be an interesting focus for future work to look at non-cold-frontal cell environments and lifting mechanisms in comparison to cold-frontal.

- Some general information about convection initiation is given in the introduction. However, the multiple effects of mountains or land-surface heterogeneities are not mentioned. I recommend enlarging that section with these points, particularly the role of low-level convergence zones.

  Like the point above, we will include discussion of low-level convergence zones that can be created near orography (e.g. Figure 1; Wulfmeyer et al. 2011). Thank you for the nice suggestion.

- One aspect I may have missed in the manuscript is the fact that even if CAPE values are lower in post-frontal regions, the atmosphere is often unstable due to the advection of colder air at higher levels. Warming by solar radiation is then often sufficient to initiate convection in large areas.

  Indeed, the cold air advection aloft combined with surface heating can increase CAPE. The insolation can also act as a trigger for convection. We would assume this is particularly important for increasing CAPE on the post-700-frontal side, whereas moisture advection would be more important on the pre-700-frontal side. The origin of CAPE generation is not a key focus of this study, so we have not addressed it in too much detail. We do however mention the importance of solar heating on the post-700-frontal side in section 4.3.

- I am a bit concerned about the fact that pre-surface-frontal cells form in environments with the highest CAPE AND strongest CIN. High CAPE values usually occur at low altitudes of the LFC which also often is associated with smaller values of CIN. Please comment on this.

We are not sure if we have fully understood the reviewer's comment. Maybe the reviewer is suggesting a lower LFC may allow higher CAPE as in theory the vertical distance over which a parcel is positively buoyant could be larger. CAPE is dependent on different factors though, e.g. surface heating, near-surface moisture and lapse rates (particularly in the mid-levels). If strong CIN is present, this means more lifting is required to lift parcels to their LFC where they can then utilise the CAPE. In turn, this could mean that convection is not triggered until later in the day following further solar heating and moisture advection (thus increasing CAPE). Figure 2 (surface dew points) seems to indicate that the surface moisture availability is one key contributor higher CAPE. We hypothesise that the stronger CIN for *example could allow additional moisture build up near the surface before convection is triggered.*

- The authors detect and track convective cells based on radar data from the DWD. Radar-derived precipitation adjusted to surface observations is also available from the DWD on the same domain. I wonder why this data set is not used for precipitation? Precipitation and in particular convective precipitation is certainly not best represented in the ERA5 data set.

  We assume the author is specifically referring to section 3.8 and Figure 11. As the reviewer mentions, convective precipitation is not expected to be represented well in ERA5. The aim of section 3.8 is to assess how it is represented at cell grid points, cell regions and non-cell regions. If ERA5 exhibited no skill at all, we would expect no significant difference in the mean between convective grid points and non-cell regions. The purpose of 3.8 is not to analyse the exact rainfall totals, for which a combined radar/rain gauge product would be more suitable as the reviewer suggests. We suggest adding an extra sentence in section 3.8 to make this clearer. Thank you for mentioning this point.

- Why do you need a smoothing of ϑ_e and why 30 times?

  This was chosen subjectively based on looking at several case studies. There is no standard practice when smoothing as it depends on the resolution of the dataset. More smoothing reduces the strength of gradients. Smoothing 50 times while using a lower gradient threshold would have yielded the similar results. Smoothing becomes particularly important when using convection-permitting models with higher resolution. We will note that this choice was subjective. Thank you for raising this point.

- P6: You state that cold fronts reach the southern parts of Germany less frequently. Is this related to the more complex terrain there?

  Indeed, we believe this is related to the terrain. In Pacey et al. (2023), we clustered different front types and found a common type where fronts become distorted and curve around the shape of the Alps. The reviewer is referred to Figure 9 of Pacey et al. (2023) if they are still interested.

- P6, L162: You state that wind shear affects convective initiation. Wind shear, however, is not a trigger mechanism, it is decisive for the evolution and organisation of the initiated convection. I suggest to write that it affects convection and not convective initiation.

  There has been some research showing that wind shear is relevant for the transition from shallow to deep convection, we reference a good overview of the topic on L163 (Peters et al. 2022). As an example, one way shear may negatively contribute towards this transition is through increased entrainment in high shear environments (e.g. Markowski and Richardson, 2010; their section 7.2.1). Of course, this also depends on the background environmental relative humidity. Further research is still required in this area, but this is not a key focus of our study. Nevertheless, we still think it is important to highlight that the relevance of wind shear extends beyond convective organisation.

- As for convective precipitation, I doubt that the vertical velocity in the ERA5 data set is really representative for deep convection. Please comment.

There may have been a misunderstanding regarding our remarks on the representation of convection in ERA5. We would not expect precipitation rates in ERA5 to be equivalent to those that would be observed where convective cells were detected. Likewise, the vertical velocity would not be comparable to individual updrafts. Nevertheless, given there is a significant difference in the convective precipitation mean between convective cell grid points and non-cell grid points shows some signal of convection being triggered in the parameterization scheme in the right place and time. The triggered parameterised convection may then feedback on the vertical velocity field due to condensation and latent heat release (and hence further ascent).

We will rephrase this paragraph mentioning some of the points above. Thank you for bringing this to our attention.

- What are the implications for forecasting convective storms near frontal zones?

Are there any ways to improve numerical models with these findings?

We thank the reviewer for posing these interesting questions. The findings in study highlight the complexity of the environments in which convective storms form since they vary depending on the distance from the front. For example, we find greater importance of upper-level large-scale lifting post-frontal compared to pre-surface-frontal. A forecaster therefore could focus more on upper-level lifting when assessing the probability of convective cell initiation post-frontal.

This reality complicates representation of convection in numerical models since parameterizations should (in theory) be applicable globally. Here, we show even in Germany the importance of different factors controlling cell initiation varies depending on the front relative region.

Technical comments

- P3, L85: Paramter → Parameter

Thank you for noticing this typo, this will be revised.

- Line breaks occur between numbers and their units troughout the entire manuscript (e.g. P4, L117-118). Please correct that everywhere.

Thank you for picking up on this, we will revise this.

- P6, L151: ...bin at ~~at~~ the current...

Thank you for noticing this typo, this will be revised.

- P6, L165: A full list... ~~are~~ **is** shown...

Thank you for noticing this typo, this will be revised.

- P6, L177: The quasi-geostrophic forcing for ascending and descending motion can be **measured** using the Q-vector convergence... I think ”measured” is not the best word here as this is not a measurement. Maybe ”expressed” or ”described” are better options.

  We agree "expressed" is a better word here. Thank you for the suggestion.

- P10, L286: This result highlights the importance of upper-level forcing **particularly** on the development of convective cells **particularly** at the 700 hPa front and also post-700-frontal. Please rephrase.

  We will remove both occurrences of 'particularly' from the text since it is not necessary to convey the point. Thank you for pointing this out.

- P14, L408: 16 C → 16°C

  Thank you for pointing this out. This will be amended.

- P17, Fig. 2 caption: celcius → Celsius

  Thank you for noticing this typo, this will be revised.

- P20, Fig. 7 caption: Postive → Positive

  Thank you for noticing this typo, this will be revised.

- P29, L509: 1. ~~aufl.,~~ edn.

  Thank you for noticing this typo, this will be revised.

<u>References</u>

Pacey, G., Pfahl, S., Schielicke, L., and Wapler, K.: The climatology and nature of warm-season convective cells in cold-frontal environments over Germany, Natural Hazards and Earth System Sciences, 23, 3703–3721, https://doi.org/10.5194/nhess-23-3703-2023, 2023.

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