Authors' responses in red italics

RC3: 'Comment on nhess-2023-39', Anonymous Referee #3, 05 May 2023 reply

General comments:

This study analyses the location and characteristics of deep moist convection associated with cold fronts over central Europe. Many novel insights are gained and nicely embedded in the existing literature. Overall, the methods, structure, and the figures are of a high quality. I don't have any reasons for rejection and my comments can mostly be seen as suggestions, although I agree with some of the concerns of reviewer #2 (see major comment 3 below).

We thank the reviewer for taking the time to review the manuscript and for their constructive feedback. The revised manuscript will include several changes based on the reviewer's comments which are outlined in more detail below under each specific comment.

Major comments:

1) line 132: The bias in Fig. 1 looks more than "slight". If it were a weak bias, shouldn't more fronts be expected towards the Atlantic where strong lows are originating from? Or is the theta gradient increasing over land? I think some more discussion for why the dataset is still useful for your purpose seems warranted, e.g., that you are mostly interested in fronts with convection impacting central Europe.

We will revise the manuscript indicating there is a bias towards the NW and SE of the domain and since we focus on Germany this does not affect the results, thank you for the suggestion. However, we note that several other front climatologies also did not find the highest front frequency in the Northern Atlantic e.g., Fig. 5c in Schemm et al. (2015) and Figure 7 in Niebler et al. (2022).

2) 159 Do you think any biases resulted from only counting the first cell detection? I think the approach is good enough, but I could imagine that long-lived cells change their location relative to the front over time?

Figures 4 and 5 in the current manuscript were also created using cells at all detection times and no significant differences were observed. From Figure 10a and Figure 10b in the current manuscript we see that cells have a typical lifetime between 15-20 minutes and propagate at a speed of between 45–65 km hr^{-1} in cold frontal environments. The mean distance a cell propagates is therefore between 11–21km. We produce the results in 50 km intervals, supporting why we see no significant differences by including cells at later detection times. The *primary motivation for only counting the first detection was to remove duplicate counting of cells.*

3) Perhaps my main point of criticism (or the aspect of the study which could be improved the most) is that although you discuss lift mechanisms ahead and at the front, not much analysis is done to locate these features relative to the 700hPa front location. I realize that this is not easy and changes a lot from case to case, but since the study claims to describe the “nature of cold-frontal convection”, a deeper analysis seems warranted. For instance, is it possible to add the locations of the surface front and pre-frontal convergence relative to the 700hPa front in Figs. 4 and 5 (or rather the range of locations in your dataset, e.g., as a box and whisker)? Could this be estimated from the ERA5 data you used? An alternative would be to go through some cases manually and indicate these boundary positions for each case in the plots.

We thank the reviewer for their feedback. We will include the figure below (Figure R1) which shows the climatological convergence at different pressure levels as a function of the distance from the 700 hPa front. This shows the typical lift at different distances from the front and at different height levels. This was originally planned to be left for a future publication, but we agree this analysis would be useful for readers. The climatological value of CAPE, surface dewpoint and solar radiation are also overlayed.

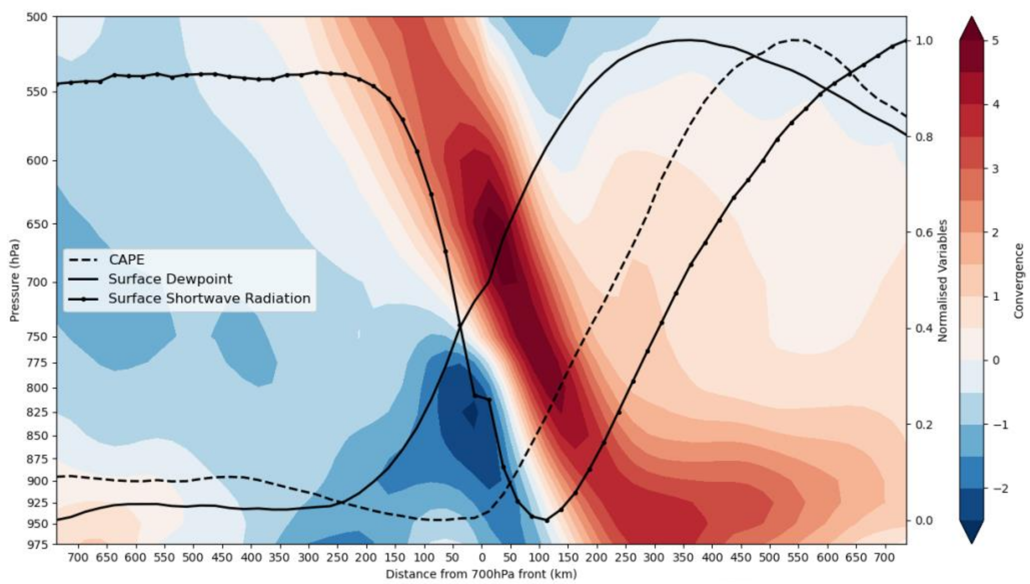
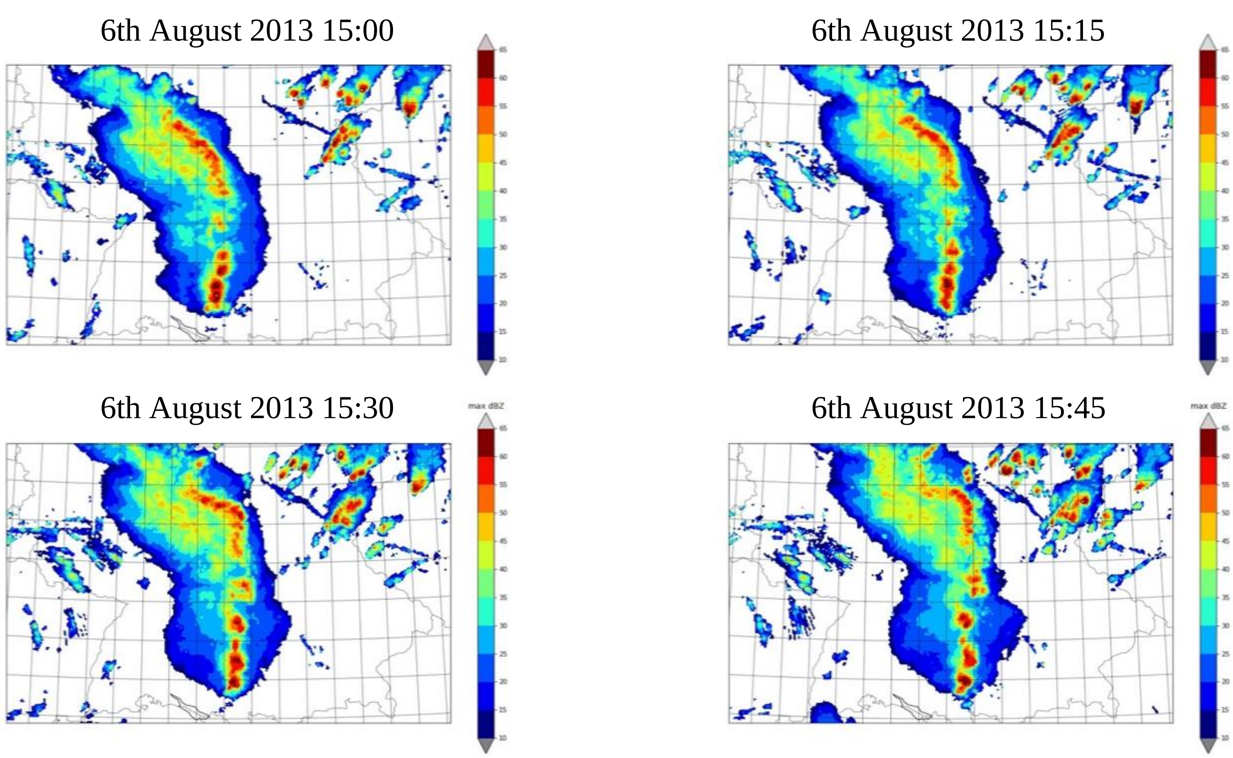


Figure R1: Climatological convergence between 975 hPa and 500 hPa (shaded), MUCAPE (dashed line), surface dewpoint (straight line), surface shortwave radiation (straight dotted line). Excluding convergence, the climatological values of the variables are normalised between 0 and 1 so the distribution around the front can be compared. Variables were derived in ERA5 data.

4) 295 Looking at the number of cells might be misleading because larger storm systems (MCS) result in less cells counted even though they have a larger impact. You don't need to change the analysis but this should be made clear again to the reader. In general, strengths and weaknesses of the KONRAD dataset are not discussed much.

Another example would be that you speculate that the pre-frontal diurnal cycle is broader because of more MCS. Wouldn’t that also mean that less individual cells were detected there (because one MCS has larger but less cells)? The opposite is seen in Fig. 10c. Is that because of flaws in the detection algorithm?

We have seen from a few case study examples that MCS’s are typically associated with a larger number of cells. There are two explanations for this, firstly a continuous line exceeding 46 dBZ may not always be present, therefore several cells are detected within an MCS. Secondly, due to cell recycling in an MCS, KONRAD will likely detect new cells at subsequent timesteps. See an example case below (Figure R2) with 4 radar timesteps shown (15-minute interval) and KONRAD cell detections at 5-minute intervals (bottom) for a case study in August 2013. We will not include these figures in the manuscript but we will include additional discussion about cell detections in KONRAD during a typcial MCS event.



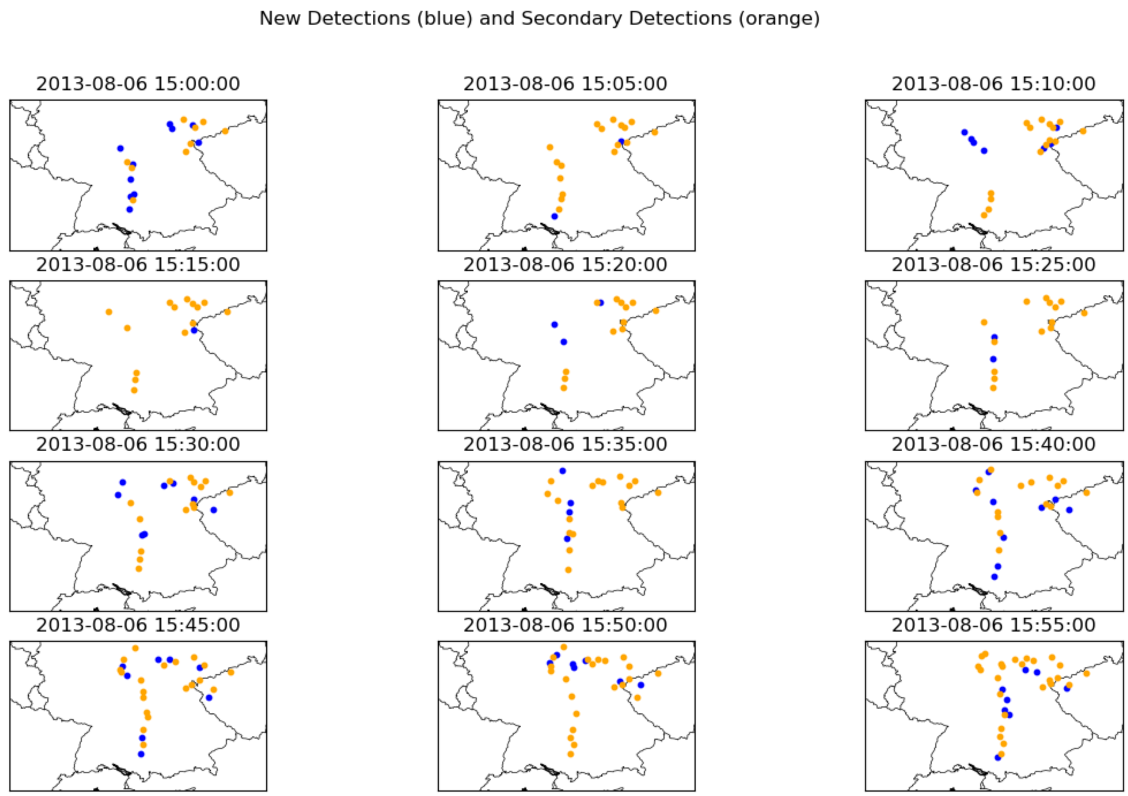


Figure R2: OPERA Radar Data showing max dBZ (Huuskonen et al. 2014; Saltikoff et al. 2019) (top). KONRAD cell detections with first detections in blue and secondary (or later) detections in orange (bottom).

Minor comments and technical corrections:

24-25 An alternative to this explanation would be varying DMC ingredients (e.g., CAPE) in different regions along the front. *We will add a line that reads "Furthermore, the importance of difference mechanisms may vary across the front, e.g., stronger synoptic lift near the front but increases in solar heating away from the front." Thank you for the suggestion.*

26-38 There is a lot of good content here, but the text seems a bit unstructured. For instance, pre-frontal convergence lines are also a result of an ageostrophic circulation (Dahl and Fischer 2016), not only the lift at the front. Also, you could make a bit clearer that you start discussing mechanisms ahead of the front, then at the front and then behind, for instance by ending the first sentence (l. 27) with "… location relative to the front.” And then starting the next sentence with “Ahead of the front, …”. *We will add that pre-frontal convergence lines are also a result of ageostrophic circulation, thank you for the suggestion. Indeed, the sentence will be clearer by saying“…. depending on the convective initiation location relative to the front”. Thank you.*

41-42 I’m not quite sure if I understand the point. If this holds true for a surface observer, why is it not true? Are you referring to the fact that the convective cloud is not necessarily in the same location as the heaviest precipitation? *We are pointing out that if convection is observed shortly after the passage of the surface front, the saturated cloud region is largely on the warm-side of the front thus is not post-frontal. Indeed, the precipitation falls to the ground into the cooler post-frontal airmass, but the cell itself is typically on the warm-side of the front.*

97-98 If I understand correctly, “higher” would only be true for cold fronts, because for warm fronts v_f would be negative. Did you mean to say the magnitude of v_f is higher with stronger advection? *Yes, thank you. We will revise the manuscript accordingly.*

101-104 Remains unclear how L was determined. Is it a continuous length of points where the other criteria were met? What about brief gaps in the boundary detection? *The coordinates of where TFP=0 are located using interpolation. The distance from each adjacent point was calculated and summed for the whole line. In the event there is a gap this is considered a separate feature and not added to the total length. We will expand on our current explanation in L101–102 including the information mentioned above.*

141 “At the start of this study,” (comma in English after such introductory words for a sentence” *Thank you.*

section 2.2 in general: Just a suggestion, but I would bring in the hail, lightning, and mesocyclone detection methods later when they are needed. Jumping back and forth between the different dBZ thresholds was a bit confusing here. *We did consider this, but we felt it would disrupt the flow of the results to include such technical definitions in the results section. We will include the different thresholds in a table so it is easier for the reader refer back to.*

155 Make clear what “such” is referring to. I’m assuming you mean the hail, lightning and mesocyclone detections? *Thanks for the suggestion, indeed it is referring to the hail flag, lightning and mesocyclone definitions. We will revise the manuscript accordingly.*

163 comma behind “2.2”. *Thank you.*

164 I like this numbering of criteria. Makes it really clear. *Thank you for the feedback.*

185 Comma after “September” *Thank you, we will make changes to the revised manuscript.*

187 and 262 One convective cell is a fairly low threshold. Days with >1 and >100 days are weighted equally with this method, correct? Perhaps discuss this caveat of considering cell days by e.g., showing a histogram of the number of cells per cell day to make clear that most cell days were really days with much convective activity?

The one cell per day criterion is just to assign a day as a cold-frontal or non-cold-frontal cell day. For this analysis we are actually interested in the mean number of cells per day so by just selecting days with say >20 cells would add a bias to the results.

189 Associated “with” *Thank you.*

239-240 There is a clear secondary maximum around 750 km ahead of the front in Fig. 5, which is interesting. Do you speculate that this is just free convection in the warm sector or pre-frontal convergence serving as another (weak) trigger? By the way, I really like this Figure. Is it necessary to have non-linear color scheme. It may look nicer but I think it makes it harder to interpret the numbers. If it’s necessary, it should at least be mentioned in the caption. *From Figure 4 we see that between 600–750 km the cell frequency remains stable with a slight increase. It is plausible that this is linked to pre-surface-frontal convergence lines as they are usually found around 300km ahead of the surface front. We will add additional discussion in the updated manuscript, thank you for bringing this to our attention.*

Since there are a lot more cells pre-700hPa-frontal compared to post-700hPa-frontal it is necessary to use a non-linear colorbar to highlight the post-700hPa-frontal diurnal cycle. We will note this in the figure caption, thank you for the suggestion.

248-255 How do supercells fit into this picture? Their long lifetime could also lead to a broader diurnal cycle. You only mention Wapler (2016) briefly and without context. *We will add a line after the Wapler (2016) reference that says “This indicates that supercells, which typically have a longer lifetime, may also be linked to the observed weakened diurnal cycle”. Thank you for the suggestion.*

259 First time reading this, I was confused what you mean by “vary”. It might just be me, but if you refer to the spatial distribution, it's clearer to say something like: "The frequency of convective events varies in different parts of Europe." *Thank you for the suggestion, this will indeed make it clearer to readers. We will revise accordingly.*

268-270 Sounds like you believe this is due to a general increase towards the south / the mountains. Your resolution is fairly coarse, but the spatial distribution you observe would also be consistent with mesoscale enhanced convective activity in local parts of Germany, e.g., South of Stuttgart (Piper 2017 Fig. 3, Kunz 2010). *Thank you for the reference, we will add this to the revised manuscript.*

295 Here and elsewhere: “Colorbar” *Thank you.*

303 This is consistent with enhanced activity in the Erzgebirge region (Piper Kunz 2017). *Thank you for the reference, we will add this to the revised manuscript.*

322 Such a pattern is also often associated with advection of an elevated mixed layer from Southwest Europe and pre-frontal convergence lines (Dahl and Fischer 2016). *Thank you for suggestion and reference, we will add these details to the revised manuscript.*

378-385 This last paragraph was a nice finish and the results are plausible. The conclusion section is also nice and precise. *Thank you for the feedback.*

Fig. 8 I also liked this Figure and analysis. Could you add the average number of cells per event over whole domain in the top of each subplot? Even though some clusters might be rare, their impact/number of cells might be large, so giving the reader information about the typical number of cells could be useful. *The number of cells per grid box is already normalised by the number of timesteps in the cluster accounting for rare cluster types.*

Fig. 10 Also very informative plot. Titles for each subplot would be helpful to avoid having to jump between caption and plot. *Thank you for the nice suggestion, we will recreate the figure for the new manuscript.*

References

Huuskonen, A., E. Saltikoff, and I. Holleman, 2014: The operational weather radar network in Europe. Bull. Amer. Meteor. Soc., ***95****, 897–907, https://doi.org/10.1175/BAMS-D-12-00216.1.*

Schemm, S., Rudeva, I., and Simmonds, I.: Extratropical fronts in the lower troposphere–global perspectives obtained from two automated methods, 2015: Quarterly Journal of the Royal Meteorological Society, 141, 1686–1698, https://doi.org/10.1002/qj.2471

Saltikoff, E., and Coauthors, 2019: OPERA the Radar Project. Atmosphere, ***10****, 320, https://doi.org/10.3390/atmos10060320.*

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