

We would like to thank the reviewer for the detailed and constructive feedback. Below, we outline how we propose to address each of the comments and suggestions in detail. We do believe that these remarks have substantially contributed to improving the quality of our manuscript.

General

Can the methodology be applied to the whole dataset? Is it a necessary precondition to select individual events, as you did?

→ In principle, the method can be applied to an entire data set, and we definitely see the benefit in doing so. However, extending the time-period to several months or weeks would significantly increase the computational resources needed. We would like to include the following explanation in the original draft:

Line 61: "In principle, the proposed method can be applied to any data set that is defined on a uniform spatio-temporal grid and does not contain any missing values. In practice, computational capacities limit the manageable data size. This study aims to provide new scale-aware analysis approaches for assessing changes in heavy precipitation events, taking into account that changes can manifest themselves differently at different scales. Scale-aware analysis is used to investigate the structure of heavy precipitation events across Germany."

What is the purpose of finding the 50x50 km event window, when the wavelet transform is applied to the whole domain?

→ The aim here is, to define a number of high impact precipitation extremes for further analysis. When defining extreme events using the whole domain, we loose our focus on high impact events. We would like to add more detailed information in the text:

Line 162: Add: "We consider an event to be intense if the total amount of precipitation within a limited area and a limited time is particularly high. Specifically, we select the top 100 events based on the total precipitation volume accumulated within a 2-day window over a spatial domain of 50km × 50km. An area measuring 50 km × 50 km is relatively small compared to the area affected by heavy precipitation events. It is primarily intended to cover the core area of maximum precipitation and is used exclusively for event detection in this study. The location and intensity of the recorded events are shown in Fig. 2, with known extreme precipitation events with severe impacts over Germany among the six strongest events."

Line 167: Add: "There are multiple approaches to defining extreme precipitation events. One alternative we considered was the use of predefined events, such as those listed in the DWD CatRaRe catalogue (Lengfeld et al., 2025). However, our results are not sensitive to the specific choice of event definition, as the main findings remain robust across different selection approaches."

Line 169: Add: "To analyze the events identified, we use a much larger space-time window to ensure that we capture the entire spatial and temporal extend of each event"

Why didn't you fill the whole 128 elements in the time dimension with data, but 94 elements and filled the rest with zeros?

→ We looked at a time frame of four days, assuming that this period is sufficient to cover the analyzed events in their entirety. The use of 128 time steps would also be sufficient; we examined this using the wavelet spectra and did not find any significant differences. We would like to include the following explanation:

Line 179: "Temporally, we are interested in a four-day interval to cover the event. To achieve a temporal extension of $128 = 2^7$ time steps, we extended time steps via zero-padding. A time window of 128 time steps instead of 94 would also be possible, but the differences in the results are negligible."

Why didn't you apply the WT continuously for 3-day and compare the evolution over, e.g., two weeks? Is the result jumpy?

→ We are unsure whether we have understood this question correctly, especially regarding the benefit in applying the WT over a sequence of several weeks. We tested this proposal using the two weeks around the flood event in 2002 as an example and found that some smoothed estimator from the characteristic scale as we show in Fig. 3 can be derived from this. The development of spatial scales over time can be carried out much more easily using a two-dimensional WT for each time step, as we have applied in Fig. 3. As can be seen in Fig. 3, the temporal evolution is not jumpy as well.

What is the benefit of the proposed method? What do the results reveal in terms of 'structure'?

→ Thanks for pointing this out. The second reviewer also noted that the discussion of our method comes a bit short. We would like to include the following statements:

Line 317: "Using the six most intense precipitation events as illustrative examples, we demonstrated how our three-dimensional WT framework, namely the derived wavelet spectrum reveals contributions from different spatial and temporal scales within precipitation events. To the best of our knowledge, no comparable approach currently exists that enables an equally effective and scale-resolved decomposition. We conclude that the wavelet spectrum is particularly suited for analyzing individual events. Possible applications include comparing specific

precipitation events or how they are represented in different data sets.”

Line 341: ”In summary, the proposed characteristic variables constitute a robust and transferable tool for quantifying the mean spatiotemporal properties of precipitation events. They are particularly well suited for the systematic analysis and comparison of multiple events, and allow for consistent comparisons across different datasets or scenarios. A more comprehensive assessment, including convection-permitting climate model simulations, is planned for future work. The method enables a scale-aware analysis of spatiotemporal processes that also propagate in space. The information about quantifiable changes supports their physical interpretation, as dynamic processes generally occur on definable spatial and temporal scales, and changes might affect the processes differently. Such an analysis can provide new insights, particularly when assessing changes caused by anthropogenic greenhouse gas emissions.”

specific comments

L25: What is ”high-quality”? Rewrite?

→ We agree and would change it to “high resolution”

L82-84: Briefly state why you choose DT-CWT over, e.g., Daubechies. Why would you choose more complex, if you find no substantial performance?

→ We agree that our original draft lacks a detailed discussion on this point. In principle, every wavelet family has its advantages and disadvantages. The DT-CWT is complex, but provides better shift invariance compared to e.g Daubechies wavelets, which means that DT-CWT is more robust to small shifts of the signal in space and time. We would like to rewrite the paragraph as follows:

Line 82-84: “Compared to more traditional, real value wavelet families, such as Haar or Daubechies wavelets, the DT-CWT exhibits improved shift invariance, meaning that its coefficients are more robust to small spatial and temporal displacements of the signal (Kingsbury, 1998). In principle, the proposed method can be implemented with any wavelet family. We tested several alternatives, including Haar and Daubechies wavelets, but did not observe any substantial performance advantage over the DT-CWT in terms of computational efficiency.”

L60-64: This is a crucial jump. First you introduce the method, then you say that there is some continuous data, and then you select 100 events. I think there is a gap to be filled. It would be helpful to articulate on what data the method can be applied to, e.g., only extreme cases, or also to a whole reanalysis?

- Are you applying the method on the whole data of 2001-2024, or 100 events?
- At this point I am confused if the selection of events is necessary? Or can I apply it on 30-years of reanalysis too? Why 100 events and not the whole dataset?

Maybe you put details in section 2 (next comment)

→ We agree that a more detailed description would be beneficial. We would adjust our manuscript as follows:
Line 19-20: Rewrite ”In order to investigate the processes through which climate change affects such heavy precipitation events, homogeneous data with high temporal and spatial resolution are required.”

Line 61: Add ”Acknowledging the reviewers first comment, we already provide more detailed information about the requirements on the dataset in Line 61.”

Similarly as above, L145-146: The transition from section 2 to 3 is rough. At the end of section 2, the reader has the method, but doesn’t necessarily know on which kind of data it can be applied, etc. Provide details to:

- What are the limitations of the method?
- What are there requirements for the data/observations? can it be applied to satellite- derived precipitation data and station data?
- How long needs the timeseries to be?

Finally, a reader would benefit from a step-by-step list of what a user needs to do to apply the method to a new dataset.

→ Thanks for pointing this out. We see that we can give more information on this and would like to include the following explanations:

Line 135: “We first apply the 1D DT-CWT and obtain wavelet coefficients at each grid point. Subsequently, a 2D DT-CWT is applied at each scale. The resulting wavelet coefficients are then converted into spectral energies according to Eq. 8”

Line 149: “The method presented here is applicable to any three-dimensional data set defined on a uniform grid without missing values. E.g. an application to data sets comprising three spatial dimensions, including the horizontal height is possible. However, When analysing further variables, such as temperature or wind speed,

alternative wavelet families may be more appropriate to ensure an optimal representation and filtering of the underlying signal characteristics. In the present study, we employ a combination of a 2D WT and 1D WT to distinguish between spatial and temporal scales. Alternatively, a combination of three 1D WTs would allow a full separation of the three dimensions considered here (i.e. the x-,y-directions and time)”

L153: I doubt that 24 years of data are suitable for long-term climate trend analysis?!

→ We agree with this and would like to remove this sentence.

Title: ”Revealing the structure of precipitation extremes”:

- From the description of the method I concluded that it gives characteristics not only for extremes but also the whole distribution, right?

→ This is right. We suggest to change the title to ”Revealing the structure of heavy precipitation events: a spatio-temporal wavelet approach to weaken the reference to extreme value statistics.

- Are the results characteristics of extremes or of the whole German domain during the 94 hours that went into the wavelet transform?

→ Yes that is right. We are aware that the title does not reflect that we look at the whole precipitation over Germany during the event, but we consider the influence of precipitation outside to be negligible as their precipitation sums are small in comparison.

L217: ” the orientation along a straight line can be attributed to the movement of precipitation systems through space.” Please clarify. Also, the reference is German, so please briefly describe what you mean

→ Thanks! We see that the explanation comes a bit short. We would like to include more explanation as follows: “A prominent and recurring feature across all spectra is the concentration of energy along a straight line with an approximate slope of one. This can be attributed to the movement of precipitation systems through space, as can be shown from the definition of characteristic speed ($U = L/T$). In the logarithmic presentation, this can be rewritten as $\log T = \log L - \log U$ (Kraus,2004). Accordingly, the y-intercept gives an estimate of the characteristic speed and the magnitude of the energy along this line reflects underlying space and time scales, which we do not further consider in this study. For reference, we included lines indicating a characteristic speed of 5 km/h, 10 km/h and 20 km/h in Fig. 4.”

L302-305: This can be shortened and formulated more boldly, e.g. remove ”only” and the sentence ”Although ...” could be placed in the methods section.

→ Yes we can do that

L312: ” Although we initially rely on the simplified concept illustrated by Kraus (2004)” This half-sentence is confusing here. Maybe it can be (re)moved?

→ Thanks for pointing that out. We agree that this half sentence can be removed.

Typos

L48: ”its”

L226: ”Tab. 2” You meant table 1?

→ Thanks for noticing. We’d be happy to correct that.