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Reply document to reviewer comments 1 and 2

Understanding the Interannual Variability of Hail in Switzerland

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The authors thank the reviewers for their thorough evaluation of the manuscript and for their overall positive assessment. The constructive feedback has helped us identify areas where clarification and additional information were needed to improve the manuscript. We have addressed all comments in detail in the following document.

The reviewers' comments are presented in black, and our responses are provided in **blue**. Changes made to the original manuscript are indicated using ~~**red strikethrough**~~ for deleted text and **blue** for newly added text. All line numbers refer to the originally submitted version of the manuscript.

Additionally, to the revised manuscript, we have attached a pdf containing the manuscript with the changes highlighted.

Review #1:

This manuscript highlights the large, and local scale patterns accompanied with high and low frequency hail years in Switzerland. Analysis is conducted on both the north, and the south side of the Swiss Alps, due to the differences in their respective convection-triggering mechanisms. The manuscript is very intriguing and well-written. My main suggestions are adding further analysis comparing the large scale patterns associated with the north, and south Alps strong hail years (see comments below).

Comments:

1. #28 - instead of moisture deficit, maybe just moisture conditions?
   We thank the reviewer for this suggestion and agree that "moisture conditions" is a broader and more appropriate term in this context. We have revised the text accordingly.

2. #32-34: no action item, love the way this is laid out!
   Thank you for this positive feedback!

3. #35-37: can the authors elaborate a little, for each of these scenarios? A few sentences are enough.

   Thank you for this helpful suggestion. We have expanded this section by adding a few examples:

   "[...] For example, the convergence of nocturnal katabatic (downslope) flows may induce convective initiation on the southern side of the Alps, while daytime hailstorms frequently initiate over the foothills and propagate toward higher elevations (Nisi et al. 2020). In addition, katabatic flows associated with downdrafts can trigger new hailstorms (Trefalt et al. 2018) and mountain valleys with lakes can modify low-level moisture and channel storm inflow, thereby supporting more frequent supercell development (Feldmann et al. 2024). [...]"

4. #53: What is differential vorticity advection?
   Thank you for pointing this out. We have clarified the wording by specifying that we refer to *"differential positive vorticity advection (i.e., positive vorticity advection increasing with height)",* which induces quasi-geostrophic large-scale ascent ahead of upper-level troughs and thereby supports deep convection.

5. #56: theta_e is not defined.
   We thank the reviewer for the thorough check. We have now defined θe (equivalent potential temperature) at its first occurrence in the manuscript.

6. #78: So -> thus.
   Done

7. #94: I'm not sure what the question means.
   We assume the reviewer is referring to the third research question. We agree that its wording could be clearer and have revised it as follows:

   "~~How do seasonal background conditions compare with those observed on hail and non-hail days?~~ How do seasonal mean conditions during active hail seasons compare with the conditions on hail and non-hail days within those seasons?"

8. #108: or ->and. Can the authors briefly explain how and why two different time formats are used?
Corrected, thank you. The majority of ERA5 variables analyzed in this study are based on hourly ERA5 data. The only exceptions are the blocking, PV cutoff/streamer and RWB diagnostics, which are computed from 6-hourly ERA5 potential vorticity fields. These diagnostics are subsequently aggregated to daily frequencies, which are the quantities analyzed in this study. Since the 6-hourly PV diagnostics were already available and only daily frequencies were required, we retained the original temporal resolution. To avoid confusion, we have removed the reference to 6-hourly data from the general ERA5 description and now explicitly state the temporal resolution in the respective paragraphs describing the blocking and PV diagnostics.

9. #115: Can the author elaborate on the motivation of "singling out" and examining blocking frequency?
We thank the reviewer for this comment. We investigated atmospheric blocking because it is a persistent large-scale circulation regime that may modulate hail activity over periods of days to weeks by maintaining hail-favorable synoptic environments. Depending on its location, blocking can promote the repeated advection and persistence of warm, moist, and unstable air masses over Central Europe. Previous studies have shown that North Atlantic and Scandinavian blocking are associated with enhanced thunderstorm and hail activity over Central Europe (Mohr et al 2019, Mohr et al. 2020, Augenstein 2025), including an association between enhanced blocking frequency and serially clustered hail occurrence in Switzerland (Barras et al. 2021). Furthermore, blocking has been shown to substantially increase the frequency of upstream PV cutoffs, which may provide mesoscale forcing supporting convective initiation (Mohr et al. 2020). A recent study by Mohr et al. (2026) further demonstrated that approximately half of all radar-based potential hail-track days in Germany occurred under atmospheric blocking regimes. We have expanded the Introduction to better explain this motivation:

"In addition, atmospheric blocking over the North Atlantic, Scandinavia, and the Baltic Sea can enhance hail frequency by ~~promoting the persistence of storm-favorable circulation patterns (Barras et al., 2021; Mohr et al., 2019, 2020)~~ maintaining persistent large-scale circulation patterns that favor the advection of warm, moist, and unstable air into Central Europe while inhibiting the eastward progression of weather systems (Mohr et al., 2019, 2020, Barras et al. 2021). Such long-lived circulation regimes have been associated with serially clustered hail occurrence in Switzerland (Barras et al. 2021) and more than half of radar-based potential hail tracks in Germany over the last two decades (Mohr et al. 2026). Furthermore, blocking has been shown to increase the frequency of upstream PV cutoffs, providing mesoscale forcing for convective initiation (Mohr et al. 2020)."

In addition to blocking, we also analyzed other indicators of large-scale dynamics, including PV cutoffs, PV streamers, and Rossby wave breaking (RWB). While blocking frequency, PV cutoff frequency, and PV streamer frequency exhibited robust and statistically significant relationships with interannual hail variability, the RWB patterns proved highly sensitive to the chosen identification method. We therefore focused our analysis on the more robust large-scale dynamical indicators.

10. #138: Citation format error
Corrected, thank you.

11. #187-188: I think I get this statement, but I'm not sure. Do you mean that we see this type of anomalies potentially because this type of anomaly is frequently occurring, regardless of active or non-active hail year? Can the authors elaborate on this?
    Thank you for pointing this out. We realize that this statement was ambiguous. Here we are **not** comparing *active* and *inactive* hail seasons (or *all seasons*). Rather, the question is how the seasonal-mean anomaly pattern during **active** hail seasons arises. Specifically, this active-year seasonal-mean anomaly could either reflect a single persistent circulation anomaly throughout these active seasons or the repeated re-establishment of similar synoptic configurations during active hail seasons. The purpose of the R-metric analysis is to distinguish between these two possibilities. The significant positive recurrence anomalies indicate that, during active hail seasons, similar ridge–trough patterns recur repeatedly rather than resulting from a single quasi-stationary circulation anomaly. We have revised the text to clarify this point:

    "~~Although the zonally oriented wavetrain over the Atlantic points to a transient flow situation, the seasonal composites themselves cannot distinguish between persistent anomalies and the repeated re-establishment of similar patterns. To address this, we examine the recurrence (R-metric) of the 500-hPa meridional wind between 35° N and 65° N throughout the year 7 190 195 200 205 210 215 220 (Fig. 3).~~ To determine whether the seasonal anomaly pattern during active hail seasons reflects persistent circulation anomalies or the repeated occurrence of similar synoptic configurations, we examine the recurrence (R-metric) of the 500 hPa meridional wind between 35° N and 65° N throughout the year (Fig. 3). The R-metric represents the recurrence of similar large-scale flow patterns on subseasonal timescales. Significant positive R anomalies are present across most of the hail season over the study area and Central Europe, ~~indicating the recurrent formation of similar large-scale flow patterns (ridge–trough patterns~~, indicating that during active hail seasons, similar large-scale ridge–trough configurations are repeatedly re-established rather than maintained as a single persistent circulation anomaly. [...]"

12. Fig.3 caption:Suggest moving the 'the R-metic represents...' part into the main manuscript body, where R-metris is first mentioned.
    We agree and have revised Line 190 accordingly:
    "[...] The R-metric represents the recurrence of similar large-scale flow patterns on subseasonal timescales. [...]"

13. #212: Since it is mentioned, suggesting adding a brief summary on why the aforementioned large scale conditions are favorable (this would also nicely follow the logic of #32-34).
    Thank you for the suggestion. We have added a brief summary:

    "Overall, these large-scale anomaly patterns indicate that hail-active seasons are characterized not by a single persistent circulation anomaly, but by the repeated re-establishment of a synoptic configuration favorable for hail formation. The recurrent ridge--trough--ridge Rossby wave train promotes southerly warm and moist air advection into northern Switzerland, while repeated upstream trough passages provide dynamical forcing for ascent and convective initiation. Positive SST anomalies in the Mediterranean and the Bay of Biscay may further enhance lower-tropospheric moisture availability. Together, these factors establish a favorable large-scale background state for recurrent hail-producing convection."

14. #234: Is this sentence jumbled?
    Thank you for pointing this out. We have revised the sentence for clarity:

"~~In the study area, significant soil-moisture anomalies are absent, but a pronounced west–east soil-moisture gradient is present just upstream, with more humid conditions in the west and significant dry anomalies in the east (Fig. 4i).~~ In the study area, soil-moisture anomalies are generally weak and not statistically significant. However, a pronounced west–east soil-moisture gradient extends across the surrounding region, with wetter-than-average conditions upstream over western France and significant dry anomalies downstream toward eastern Europe (Fig. 4i)."

15. #252-253: The boundary layer alone cannot determine CIN and CAPE. Suggesting also discussing the overall vertical thermodynamics profile.
    We absolutely agree and thank the reviewer for pointing out this oversight. We have revised the text to clarify that CAPE and CIN are determined by the vertical thermodynamic structure rather than by the boundary layer alone:
    "The large-scale forcing meets favorable local thermodynamic conditions, including positive temperature and specific humidity anomalies over northern Switzerland and positive Mediterranean SST anomalies. The combination allows for the formation of warm and moist but unsaturated boundary layers and a favorable vertical thermodynamic structure, resulting in enhanced CAPE and moderate CIN."

    Additionally we have revised Line 223f to mention the thermodynamic structure:
    "[...] ~~The resulting warm and moist conditions over the study area favor enhanced instability and contribute to above-average CAPE, which is crucial for the development of deep moist convection.~~ The resulting warm and moist conditions at the surface and in the lower to mid troposphere over the study area are consistent with a favorable vertical thermodynamic structure that promotes enhanced instability, contributing to above-average CAPE and supporting the strong updrafts required for hail growth. Accordingly, CAPE anomalies (Fig. 4g) are strongly positive over southern Central Europe and the Mediterranean. [...]"

16. #254: I understand the aforementioned conditions are favorable for deep moist conditions, but hail doesn't seem to be specifically looped in. Can the authors elaborate on the chain of logic? Even if it's just more supercell-esque stable, long living storms -> more hail. Also, does the active hail year correspond to the active storm years in the region? It may be interesting to check.
    Thank you for this helpful suggestion. We agree that the link between the identified thermodynamic conditions and hail formation should be made more explicit. We have therefore revised Section 4.1.2 (*Local thermodynamic conditions*) and Section 4.1.3 (*Summary south*) accordingly.

    Regarding your second point, unfortunately, our long-term dataset only reconstructs hail occurrence and does not include all convective storms, so the same analysis cannot be performed over the full study period. However, Nisi et al. (2018) discuss this question (see their Figures 5 and 6). They find no correlation between the overall number of storms and the number of hail storms. On the contrary, they state that "High hailstorm frequencies are not related to the general increase in the number of convective storms. On the contrary, a convective season with a large number of storms does not typically coincide with a positive hailstorm anomaly".

17. #321: Is there a way to check if the high CIN promotes less disorganized storms (as the authors previously mentioned)?
    Thank you for this interesting suggestion. Unfortunately, this cannot be assessed with the present approach. Addressing this question would require either numerical simulations

incorporating the complex topography of Switzerland or an analysis of different convective storm types in Switzerland together with their thermodynamic environments. However, previous studies (e.g., Taszarek et al., 2020) have already shown that more negative CIN is generally associated with larger hailstones and an increased likelihood of tornadoes. In our reconstructed hail time series, hail days are defined using the radar-based POH (Probability of Hail) product by requiring daily POH > 80% over an area of at least 400/500 km^2 within the southern/northern Swiss radar domain. This criterion likely captures many organized hail-producing storms, but it may also include days with multiple smaller, less organized hail storms. As a result, our dataset does not allow us to distinguish between different storm modes or confirm whether enhanced CIN preferentially favors more organized convection also in the Swiss setting.

18. #329-330: Can the authors briefly explain how the goal of this analysis differs from the R-metic ones?

    We agree that the distinction between this analysis and the R-metric analysis was not sufficiently clear. We have therefore clarified the beginning of the section as follows:

    "~~*A central question in interpreting the previous seasonal composites is the extent to which the seasonal-mean anomalies are shaped by the environments on hail days themselves, as opposed to reflecting a more persistent background state.*~~ *A central question in interpreting the previous seasonal composites is the extent to which the seasonal-mean anomalies are shaped by the environments on hail days themselves, as opposed to reflecting a seasonal 'background state'. Unlike the R-metric, which assesses whether the seasonal circulation anomalies result from persistent or recurrent synoptic configurations, the following analysis examines whether the seasonal anomalies are primarily determined by hail-day environments or by the seasonal background conditions. This distinction helps identify which variables primarily reflect seasonal preconditioning and which are mainly associated with event-scale hail-day environments*."

19. #334-335: Correct me if I'm wrong- I'm trying to interpret Fig 8. If the strongest-year seasonal mean leans closer towards hail days (row 3,4) and differs a lot from all non-hail days (row 1,2), that means the seasonal mean of the variable examined is more relevant to frequent hail occurrences. On the other hand, if the strongest-year seasonal mean has virtually little difference compared to non-hail days (like SST here), the seasonal mean of the variable examined is not especially relevant. Does this sound right?

    Thank you for this question. The purpose of this analysis is not to assess the relative importance of individual variables for frequent hail occurrence (this is instead addressed in Appendix Fig. A5), but rather to distinguish whether seasonal anomalies primarily reflect a persistent seasonal background state or conditions that develop specifically on hail days.

    Variables for which the seasonal means (row 5) resemble the non-hail day composites during active seasons (row 2; e.g., SST in southern Switzerland) likely represent persistent background conditions that precondition the atmosphere throughout the season. In contrast, variables for which the seasonal means (row 5) more closely resemble the hail-day composites (rows 3 and 4; e.g., CAPE) and differ substantially from the non-hail day composites (row 2) are more indicative of conditions that develop preferentially shortly before hail events. More generally, this comparison helps distinguish variables associated with seasonal preconditioning from those reflecting event-scale processes, thereby indicating which variables may be most informative at different lead times for seasonal hail prediction.

As an additional example, consider near-surface temperature (T2m). In southern Switzerland, the two non-hail day composites (rows 1 and 2) are very similar, indicating that non-hail days during active seasons are not systematically warmer than non-hail days in average seasons. However, hail days (rows 3 and 4) exhibit pronounced positive temperature anomalies, suggesting that warm near-surface conditions are associated with hail occurrence but develop primarily during individual hail events rather than representing a persistent seasonal background state. This contrasts with northern Switzerland, where positive temperature anomalies are also evident on non-hail days during active seasons, indicating that elevated T2m constitutes part of the seasonal preconditioning for hail-favorable environments.

More generally, the similarity between the seasonal mean (row 5) and the hail-day composites (rows 3 and 4) should not be interpreted as evidence that a variable is inherently more important for hail occurrence. Instead, it also reflects the frequency of hail days within the seasonal composite: the more hail days occur during a season, the more strongly the characteristic hail environment contributes to the seasonal mean. Consequently, variables whose anomalies are largely confined to hail days will increasingly be reflected in the seasonal average as hail frequency increases.

For clarity, we have added the following sentences after Line 335:
"Interpreting the comparisons between rows relies on two key relationships. Variables that already differ between the two non-hail day composites (rows~1 and~2) indicate seasonal preconditioning during active hail seasons. In contrast, variables that become substantially more anomalous on hail days (rows 3 and 4) than on non-hail days (rows 1 and 2) primarily reflect event-scale hail-day environments."

20. #351-352. Cool observations! What do you think this indicates specifically? Z500, SST and T2m are less relevant/only come into effect in indicating hail frequency when the anomalies reach a certain degree?

    Thank you for this observation. Our interpretation is not that Z500, SST, and T2m become relevant only once a certain anomaly threshold is exceeded. Rather, the comparison suggests that these variables characterize the seasonal background state during active hail seasons, as they are already anomalous on non-hail days in the most active seasons (row 2) relative to non-hail days in average seasons (row 1). This indicates that they represent a persistent large-scale preconditioning of the atmosphere. In contrast, CAPE, CIN, and 850 hPa specific humidity remain similar between the two non-hail day composites and become strongly anomalous primarily on hail days. This suggests that they are more closely associated with event-scale processes that determine whether convection is initiated under an already favorable large-scale environment.

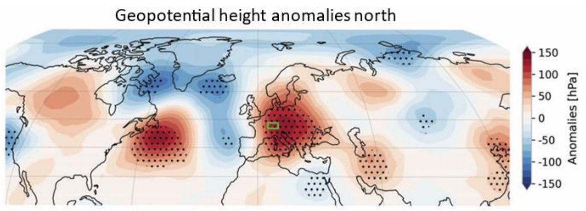
    The current weather situation in Switzerland provides a useful illustration. A European upper-level ridge can persist for several days, together with anomalously warm SSTs and high near-surface temperatures. Whether hail-producing convection actually develops on a given day then depends on shorter-term processes, such as the position of Switzerland relative to the ridge and the resulting local thermodynamic conditions. Consequently, the background-state anomalies persist even on days with little or no convection, whereas the event-scale anomalies emerge primarily on hail days. We have clarified this interpretation in the revised manuscript.

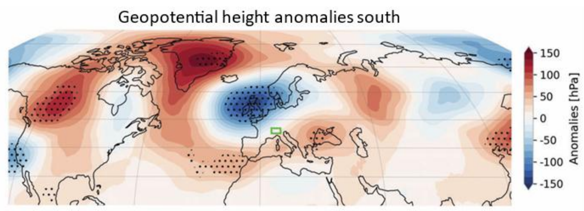
    "Notably, the two non-hail day composites (row 1 and 2) differ in sign primarily for Z500, SST, and surface temperature, while they remain similar for CAPE, CIN, and 850 hPa specific humidity. This indicates that large-scale circulation, SST, and surface temperature are already anomalous during non-hail days of active seasons, suggesting that they characterize the seasonal background state rather than conditions unique to hail days. In contrast, CAPE, CIN, and 850~hPa specific humidity remain similar between the two non-hail day composites but become substantially more anomalous on hail days, indicating that they primarily characterize event-scale hail-day environments rather than persistent seasonal preconditioning. [...]"

21. #366-367: Seems like the two explanations are directly contradicting each other (unless it's the authors' intention).
Indeed, this was the author's intention, as the present analysis does not allow us to distinguish the causal role of Mediterranean SST anomalies. They may either actively contribute to hail-favorable conditions by eg. enhancing lower-tropospheric moisture availability or simply reflect the prevailing large-scale circulation associated with hail-active seasons.

22. #398: It would be really nice to have a side by side comparison for the north, and south anomaly setup (e.g., Fig 2a and Fig 5a, in the style of FIg. 10 or Fig A5) with one of two paragraphs explaining why the differences occur.

Thank you for this suggestion. We were not entirely sure which side-by-side comparison you had in mind, as the comment refers to Sections 5 and 6, whereas the suggested comparison appears to concern the large-scale circulation anomalies presented in Figs. 2a and 5a (Section 4). We prepared a side-by-side comparison of these 500 hPa geopotential height anomaly patterns, but were unsure whether this addresses your suggestion, as the figure alone does not explain the differences discussed in the seasonal composite analysis (Section 5) or the precursor analysis (Section 6). Moreover, the large-scale circulation patterns and their relationship to hail formation are already discussed in detail in Sections 4.1.1 and 4.2.1. If this is nevertheless the comparison you had in mind, we would be happy to include it in the Appendix together if the reviewer deems it necessary.





Regarding the second part of your comment, we can only speculate that the contrasting patterns may reflect the different climatological environments north and south of the Alps, together with the influence of Alpine topography and different preferred large-scale teleconnection states. Northern Switzerland appears to require stronger thermodynamic preconditioning to reach the convective threshold, whereas southern Switzerland is climatologically closer to convection favoring threshold and therefore more sensitive to synoptic configurations that promote elevated mixed-layer formation and triggering processes. However, establishing the relative importance of these mechanisms would require dedicated dynamical analyses that are beyond the scope of the present study.

23. #403-409: Can the authors explain why these differences exist? (see the last comment).

Thank you for this interesting question. The differing precursor patterns suggest that seasonal preconditioning may involve different land–atmosphere memory mechanisms north and south of the Alps, or may simply reflect that active hail seasons in the two regions are associated with different preferred summer circulation regimes that are themselves preceded by distinct winter circulation anomalies. This interpretation is further supported by the differing teleconnection relationships identified for the two regions and different temporal aggregations. However, the present composite analysis does not allow us to determine the dynamical mechanisms linking the winter anomalies, teleconnection patterns, and subsequent summer circulation, and we therefore would like to refrain from drawing causal conclusions.

24. #432: Can we move Fig. A5 into the main text? It's a really nice figure and extensively discussed in the manuscript.
    Thank you for this positive feedback. As both reviewers independently suggested moving Figure A5 into the main text, we have adopted this change in the revised manuscript.

25. #440: Why is some northern-strongest hail year not also southern-strongest hail year then, if the north is characterized by stronger anomalies? What is the limiting factor for the south in those years?

    Thank you for this interesting observation. The standardized anomalies describe the magnitude of the seasonal departures from each region's climatology, but they do not imply that the same seasons must necessarily be the most hail-active in both regions. Although southern Switzerland requires only relatively modest seasonal anomalies because it is climatologically closer to the convective threshold, hail activity there still depends on the simultaneous occurrence of favorable synoptic, thermodynamic, and mesoscale conditions.

    More generally, our results highlight that no single factor (e.g. warm SSTs) determines whether a season becomes hail-active. Rather, hail activity emerges from the combined influence of recurrent synoptic forcing, thermodynamic preconditioning, and slowly evolving boundary conditions. While some large-scale features, such as warm Mediterranean SSTs, Central European ridging, and enhanced southerly moisture transport, can promote hail activity in both regions (which is also why five of the ten most active seasons are shared), each region ultimately requires its own combination of favorable conditions. The relative importance of these factors is also likely to vary from season to season, reflecting the multiple pathways that can lead to hailstorm development.

    We speculate that the differences between the two regions may often be governed by subtle variations in the upper-level circulation, which can influence the timing and location of lifting, moisture transport, and convective initiation. Such differences may determine whether otherwise favorable background conditions ultimately result in frequent hail in northern or southern Switzerland.

26. #444-448: Very cool summaries! No action item here.
    Thank you for the positive feedback!

27. #518: Steepened -> reduced? (inversion-like?) Unless I completely got it wrong.
    Thank you for pointing this out. Our intention was to refer to the steep lapse rates **within the elevated mixed layer above** the capping inversion, rather than to the inversion itself. We have removed «~~lapse rates are steepened above the boundary layer while~~» in Line 518 to avoid confusion.

28. #544: Can the authors elaborate on the "this" in together this.
    Thank you for pointing this out. We have revised the wording to "these results" (Line 544) for clarity.

Review #2:

This manuscript investigates large- and local-scale atmospheric patterns associated with hail-active years in Switzerland. The analysis is conducted separately for northern and southern Switzerland, and highlights the similarities and differences of the discussed mechanisms. The manuscript is well written and clearly structured. The methodology is robust and explained with an appropriate level of detail. The figures are informative and comprehensive, and the results are both original and noteworthy, making the study suitable for publication. I have only minor comments that should be addressed prior to publication.

Comments:

1. Line 5-10: In the previous sentence the two geographic regions (north and south of the Swiss Alps) are mentioned. In line 5 it is a little unclear to which region the description refers to. I understood it as a general statement referring to both. A clarification could help the reader.
   Yes, exactly, we were referring to both regions. To avoid ambiguity, we have clarified the sentence by adding: *"In both regions, […]"* which should make the reference clearer for the reader.
2. Line 25: The parenthesis should appear before the line break.
   We thank the reviewer for the careful reading. Done.
3. Line 36: I recommend using the phrase "...modulated by complex terrain..." here, instead of "...interactions are further complicated by complex terrain..."
   We agree and have revised the wording accordingly to use "modulated by complex terrain".
4. Line 48: I think "lapse rate" should be without a hyphen here.
   Done.
5. Line 56: I would recommend removing the hyphen in "British-Isles" (although it is usable here) but British Isles is a familiar proper noun.
   Done.
6. Line 56: Θe has not yet been introduced.
   We thank the reviewer for the thorough review. We have now defined θe (equivalent potential temperature) at its first occurrence in the manuscript.
7. Line 59 and 60: The citations are not in the correct order.
   Corrected.
8. Line 62: One need a comma after "instead", additionally remove the "the" duplication.
   Corrected, thank you for the careful reading.
9. Line 75: The citations are not in chronological order.
   Corrected. We apologize for the recurring citation formatting issues and have carefully reviewed the references to ensure consistency throughout.
10. Line 70-75: The literature regarding the NAO and thunderstorm activity in Europe is not quite accurately portrayed here. See the 40th comment for a more detailed explanation.
    We thank the reviewer for catching this oversight. We agree that our original wording oversimplified the relationship between the NAO and convective activity. We have revised Lines 70–75 to more accurately reflect the cited literature, but kept the details to the Discussion section, following comment #40.

"[...] For Europe, instead the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), East Atlantic (EA), and Scandinavian (SCAND) patterns have been identified as key modulators of thunderstorm and hailstorm variability on seasonal and yearly timescales (Giaiotti et al., 2003; Piper and Kunz, 2017; Piper et al., 2019; Augenstein et al., 2025). ~~Negative NAO phases have been associated with reduced convective activity in Central Europe, whereas positive phases of the EA and SCAND patterns favor storm-favorable conditions in Central Europe through anomalies in temperature and flow fields (Piper et al., 2019; Piper and Kunz, 2017; Augenstein et al., 2025).~~ While the influence of the NAO on convective activity appears to be complex and regionally dependent, positive phases of the EA and SCAND patterns have consistently been associated with storm-favorable circulation and thermodynamic conditions across parts of Central Europe (Piper and Kunz, 2017; Piper et al., 2019; Augenstein et al., 2025). [...]"

11. Line 77: Additionally, Augenstein (2025) found a further intensification of thunder-storm activity during positive SST anomalies of the Mediterranean during Scandi-navian Blocking patterns. Scandinavian Blocking is already associated with more frequent thunderstorm occurrence in central Europe (Mohr et al., 2019).
    We thank the reviewer for this helpful suggestion. We have added the requested information and citation of Augenstein (2025) by including the following sentence after line 77:

    "[...] Positive summer sea surface temperature (SST) anomalies in the Bay of Biscay or the Mediterranean have been linked to enhanced convective activity over western Europe (Piper et al., 2019). Augenstein (2025) further report intensified thunderstorm activity across much of central Europe during positive Mediterranean SST anomalies in combination with Scandinavian blocking. [...]"

    The role of atmospheric blocking in enhancing thunderstorm frequency was already introduced earlier in the manuscript in line 59. To improve clarity, we have refined the wording in that section by explicitly including "Scandinavia":

    "In addition, atmospheric blocking over the North Atlantic, Scandinavia, and the Baltic Sea can enhance hail frequency by promoting the persistence of storm-favorable circulation patterns (Mohr et al., 2019, 2020; Barras et al., 2021)."

12. Line 83: this sentence seems a bit out of context. I would consider removing it, providing a better logical reading flow. Additionally, consider merging this paragraph with the previous. Furthermore, the sentence ,"Improving our understanding of how..." could be used as the start for a new paragraph leading to the main purpose and goal for this paper.
    We agree with the reviewer on this and have removed the sentence in line 83. Further we have added a transition sentence and restructured the paragraph slightly:

    "[...] ~~With global warming, dynamic changes (e.g., in circulation patterns or synoptic forcing) remain considerably more uncer tain than thermodynamic changes (e.g., warming-driven moisture increases, Seneviratne et al., 2021).~~ All of these potential influences on hail frequency highlight the strong coupling between the atmosphere, ocean, and land surface, and underscore the role of dynamical processes in shaping convective environments. In weather and climate models, small perturbations in the large-scale flow can amplify downstream (Grams et al. 2018), cascading into substantial differences in convective environments. Improving our understanding of how hail-favorable conditions are generated, maintained, and modulated by mesoscale and synoptic dynamics is therefore essential for

reducing uncertainties in process understanding, (sub-seasonal) forecasting, and climate projections. Despite growing recognition of the diverse drivers of interannual hail variability, region-specific studies remain scarce. To address this gap, we [...]"

13. Line 85: I would recommend using a comma after "...and climate models".
    Done.
14. Line 88: I guess its more about sub-seasonal forecasting, not forecasting in general?
    We agree that the relevance is especially strong for sub-seasonal forecasting. At the same time, we believe that improved process understanding also benefits weather forecasting more broadly, as the same mesoscale and synoptic mechanisms govern the formation and evolution of hail-favorable environments on shorter timescales. To reflect the reviewer's suggestion, we have modified the text to read "(sub-seasonal) forecasting" (see our response to Comment 12).
15. Line 93-94: Although it is understandable from the context that "northern" and "southern Switzerland" refer to the northern and southern parts of the Swiss radar domain, this appears to be the first time where this terminology is explicitly introduced. On first reading, the use of different terms between the first and second research question is somewhat confusing. I would therefore recommend using a consistent naming convention for the scientific questions and explicitly stating in the data section that "northern/southern Switzerland" is used synonymously with the respective radar domains.
    We thank the reviewer for this helpful suggestion and agree that a consistent terminology improves clarity. We have therefore adopted the naming convention "northern Switzerland" and "southern Switzerland" consistently throughout the manuscript. In addition, we now explicitly define these terms in the Data section (Lines 102–104):

    "[...] This dataset provides a binary time series indicating daily hail occurrence for two study areas, north and south of the Alps, within the Swiss radar domain, which also includes parts of southern France, southern Germany, and northern Italy (Fig. 1) during the hail-prone months (April--September) from 1959 to 2022. For simplicity, these two study areas are hereafter referred to as northern and southern Switzerland, respectively. [...]"
16. Line 96: I would recommend slightly rephrasing this research question. In its current form, it mainly invites a simple yes/no answer ("Can we identify..."), whereas the analysis actually investigates which precursor signals are associated with active hail seasons and to what extent they may be useful for seasonal forecasting. A formulation reflecting this more explicitly may therefore better represent the objectives of the study.

    We agree with the reviewer and have revised the fourth research question to:
    "~~Which precursors of active hail seasons can be identified?~~ Which precursor signals are associated with active hail seasons?"
17. Line 109-114: This part could possibly be improved by linking the methodological choices more directly to their purpose. For example, formulations such as "...to re-duce the influence of long-term thermodynamic trends, an 8-year moving window was applied..." and "...additionally, a 30-day moving window was used to reduce..." may help clarify the reasoning behind these choices.

    Thank you for this suggestion. We have revised Lines 109-114 accordingly:
    "~~Daily anomalies are calculated for all ERA5 variables with respect to a mean and standard deviation estimated from a 30-day 8-year moving window around a given day, similarly to~~

~~*Pfleiderer et al. (2019) and Tuel and Martius (2024). This procedure removes the seasonal cycle and reduces the influence of long-term thermodynamic trends (e.g., warming-driven increases in instability), without eliminating all low frequency climate variability, thereby allowing the analysis to focus also on circulation-related effects.*~~ *To reduce the influence of long-term thermodynamic trends (e.g., warming-driven increases in instability), daily anomalies are calculated with respect to a mean and standard deviation estimated from an 8-year moving window, following Pfleiderer et al. (2019) and Tuel et al. (2024). Additionally, a 30-day moving window centered on each calendar day is used to remove the seasonal cycle. This approach retains low-frequency climate variability, thereby allowing the analysis to focus on circulation-related effects."*

18. Line 129: "...(Richman, 1986) and (Barnston and Livezey, 1987)." Style of citation should be "...Richman (1986) and Barnston and Livezey (1987)."
Thank you, corrected.

19. Line 130-134: It could be worthwhile to test similar calculations while excluding months with only weak teleconnection index values (e.g. considering only values > |0.5|). This would help to filter out the less pronounced large-scale configurations that are likely to have only a limited influence on hail occurrence in Switzerland and which would then be overshadowed by other factors.
Thank you for this suggestion. Restricting the analysis to periods with pronounced teleconnection phases (e.g., index values > |0.5|) is indeed an interesting approach and could help isolate the influence of particularly strong teleconnection events. However, the aim of our analysis is to quantify the overall relationship between the modes of variability and hail activity over the full observational record, rather than the conditional response during strong teleconnection phases only. Applying such a threshold would substantially reduce the sample size and introduce an additional methodological choice, making the results less directly comparable across the different teleconnection indices. We therefore chose to retain all observations and interpret the teleconnection analysis as a broad characterization of large-scale variability. Furthermore, the anomaly analyses presented in the manuscript already investigate the associated atmospheric circulation, oceanic, and thermodynamic conditions directly, allowing us to assess the underlying physical mechanisms without conditioning on teleconnection strength. We therefore expect the suggested analysis to largely complement, rather than fundamentally extend, the current results.

20. Table 1: I would suggest slightly increasing the spacing between the rows corresponding to the northern and southern regions to improve visual separation.
Thank you for this helpful suggestion. We have revised Table 1 to improve the visual separation between the northern and southern regions by adding a horizontal dividing line between the two sections.

21. Line 159-169: These points are very important and well developed, and they provide a strong foundation for the subsequent discussion and conclusions. Depending on the intended structure, parts of these points might also fit well within the discussion section.

    Thank you for this positive feedback. We already highlighted this point in the Summary (Lines 569–571). Following your suggestion, we have now also incorporated it into the Discussion (Lines 428ff):

    "Corresponding analyses of the ten least active hail seasons (Supplementary Material) reveal largely opposite anomaly patterns, supporting the robustness of the identified

relationships and indicating that hail-active and hail-inactive seasons are characterized by distinct large-scale environments"

22. Line 177: The abbreviation SST has already been introduced, additionally, I suggest moving "(Fig. 2)" at the end of the sentence.
    Thank you for the thorough reading. We have removed the redundant definition of SST and moved the figure reference to the end of the sentence. The revised sentence now reads:
    " [...], as well as ~~sea surface temperature (~~SST~~) (Fig. 2)~~ for the entire hail season (Fig. 2)."

23. Line 180: It is not exactly clear what is meant by "...this Central European ridge...". Clarify this to avoid ambiguity.
    We have revised Line 179f to improve clarity:
    "A Rossby wave train extends across the North Atlantic, consisting of a ridge over the western Atlantic, a NNW–SSE-tilted trough over the eastern Atlantic, and a downstream ridge over Central Europe. Northern Switzerland lies on the western flank of this Central European ridge, where the 850 hPa flow is predominantly southerly (shown in Fig. 4d)."

24. Line 178-180: The wording here should be more precise: We are examining pressure anomalies here and therefore cannot interpret them directly as specific synoptic (dynamic) configurations, even though, in practice, the findings discussed here indicate exactly the synoptic patterns described here (in Line 187 - 188 the authors explain this). It may be helpful to move this explanation earlier?

    Thank you for this helpful comment. We agree and have revised the paragraph to distinguish more clearly between the seasonal-mean Z500 anomaly pattern and the underlying synoptic configurations. Specifically, we now describe the Z500 anomalies as being consistent with the recurrent occurrence of a ridge–trough–ridge pattern, rather than interpreting the anomalies themselves as the synoptic pattern. We have also moved the explanation regarding the distinction between persistent anomalies and the repeated re-establishment of similar flow patterns to this paragraph for clarity:

    "During active hail seasons, the Z500 composites reveal a pronounced upper-level anomaly pattern across the North Atlantic–European sector (Fig. 2a). ~~A Rossby wave train extends across the North Atlantic, consisting of a ridge over the western Atlantic, a NNW–SSE-tilted trough over the eastern Atlantic, and a downstream ridge over Europe.~~ The alternating positive and negative geopotential height anomalies point to the recurrent occurrence of a meridionally oriented Rossby wave train with a ridge--trough--ridge configuration, consisting of positive anomalies over the western Atlantic, a NNW--SSE-oriented negative anomaly over the eastern Atlantic and positive anomalies over Central Europe. Because these are seasonal-mean anomalies, they should not be interpreted as a single persistent synoptic configuration. Instead, they may reflect either persistent circulation anomalies or the repeated re-establishment of similar flow patterns, as examined below using the R-metric. Northern Switzerland lies on the western flank ~~of this Central European ridge~~ of the positive Z500 anomaly over Central Europe, where the 850~hPa flow is predominantly southerly (shown in Fig. 4d). In individual synoptic situations, the western flank of a ridge ahead of an approaching trough is a dynamically active transition zone [...]"

    Additionally, we reviewed the remainder of the manuscript for similar wording and revised it where necessary.

25. Line 196: Use dashes rather than hyphens here: "ridge-trough-ridge".
    Removed following the previous comment.

26. Figure 4 and Figure 7: In the caption, the 500-hPa geopotential height anomaly contours are described as being plotted "in steps of 30 DAM". Interpreted as 30 decameters (300 m), this would be unusually large and I am not sure whether this is consistent with the figure.
Thank you for pointing this out. You are correct. The contours represent geopotential height anomalies with a contour interval of 30 m (geopotential meters), not 30 dam. We have corrected the figure captions accordingly.

27. Line: 213: The formulation "besides … also requires…" may underemphasize the role of large-scale forcing in shaping local instability. A more coupled wording could improve accuracy here.

    We agree and have revised the sentence accordingly:
    "~~Besides favorable large-scale conditions, hail storm formation also requires local instability.~~ Following Doswell et al. (1987) the favorable large-scale circulation described above must establish a local thermodynamic environment conducive to hail formation, characterized by sufficient instability and moisture availability."

28. Section 4.1.1 and Section 4.1.2: Figure references are here inconsistently placed, sometimes following the variable name (e. g. "blocking frequency anomalies (Fig. 2c)") and sometimes appearing at the end of the sentence. For consistency and read-ability, I recommend using a uniform style throughout the manuscript (either consistently after the variable or at the end of the sentence). This is also the case in other parts of the manuscript, but I found it particularly noticeable here.

    Thank you for this helpful suggestion. We have revised the manuscript to consistently place figure references at the end of each sentence for improved readability

29. Line 219-222: The contrasting signals between specific humidity and relative humidity anomalies at both levels are physically consistent with the strong positive temperature anomalies, which increase saturation vapor pressure. In this context, the decrease in relative humidity is likely a thermodynamic response to warming, even under increased atmospheric moisture content. It may be helpful to state this more explicitly to avoid possible ambiguity in interpretation. The term "saturation vapor deficit" is not commonly used; if vapor pressure deficit is intended, it would be preferable to use the standard terminology. Additionally, the term "demonstrates" is somewhat strong in this context (if not explicitly calculated), and I would suggest replacing it with a more cautious formulation such as "strongly suggests."
Thank you for this helpful comment. We have revised the text to more explicitly explain the thermodynamic relationship between temperature, specific humidity, and relative humidity, replaced "saturation vapor deficit" with the standard term "vapor pressure deficit," and softened the wording accordingly:

    "~~This contrast in the sign of specific versus relative humidity anomalies demonstrates high saturation vapor deficit.~~ This contrast in the sign of specific versus relative humidity anomalies is consistent with the strong positive temperature anomalies, which increase the saturation vapor pressure. As a result, relative humidity decreases despite the increase in absolute moisture, indicating an enhanced vapor pressure deficit. "

30. Line 250: In reference to the 27th comment, a possible alternative formulation could be "…the large-scale forcing provides the dynamical framework for favorable local conditions…"

    We agree and have revised Line 250 following your suggestion:

“The large-scale forcing ~~meets~~ provides the dynamical framework for favorable local thermodynamic conditions, including positive temperature and specific humidity anomalies over northern Switzerland and positive Mediterranean SST anomalies.”

31. Line 312: The use of repeatedly closed and reopened parentheses should be avoided. In addition, the sentence would benefit from rephrasing to improve readability.

    We thank the reviewer for his thorough review. Adjusted.

32. Line 326: The sentence is slightly repetitive due to the repeated use of “support.” I would suggest rephrasing for improved readability and flow, for example by re-placing one occurrence with “favor” or “promote”.

    Thank you for this suggestion. We have replaced one occurrence of "support" with "promote" to improve readability.

33. Line 360: The use of repeatedly closed and reopened parentheses should be avoided.
    Adjusted.

34. Line 360-361: This interpretation is reasonable, but the wording appears somewhat overly mechanistic. A slightly different formulation may therefore be preferable, for example something like: “This suggests that the processes associated with hail formation are qualitatively similar across seasons, but occur with greater magnitude during particularly hail-active years.”
    We agree and have revised Line 360 to:

    “~~This suggests that while the physical mechanisms governing hail formation remain the same, they operate more intensely during particularly active seasons.~~ This suggests that the physical processes associated with hail formation are qualitatively similar across seasons, but they occur with greater magnitude during particularly hail-active seasons.”

35. Line 415: This could benefit from citations: (Mantua et al., 1997) (Newman et al., 2016)

    Thank you for the suggestion, the citations were added to Line 415.

36. Line 426: I would suggest removing the first part of the sentence, as it could be somewhat misleading. I assume that by “key processes” the authors refer to the typical thermodynamic and dynamical processes associated with hail formation, which may be expressed more explicitly.

    We agree and have revised Line 426 accordingly:

    “[…] ~~While the key processes governing hail formation are similar north and south of the Alps, the predominant seasonal-mean circulation, as well as the sign and magnitude of the associated thermodynamic and stability anomalies, differ between the two regions.~~ However, the predominant seasonal-mean circulation, as well as the sign and magnitude of the associated thermodynamic and stability anomalies, differ between the two study regions. […]”

37. Line 432: The use of repeatedly closed and reopened parentheses should be avoided, maybe just use a comma to merge them.
    Adjusted following comment #28.

38. Line 446: There appears to be a typo “or and” in the sentence (likely intended as “and”).
    Thank you, corrected.

39. Line 445-458: I find the discussion here, the methodological approach and conclusions solid and compelling. The section could be further strengthened by moving Figure A5 into the main text here, as it appears highly relevant to the presented arguments.

    Thank you for this positive feedback. As both reviewers independently suggested moving Figure A5 into the main text, we have adopted this change in the revised manuscript.

40. Line 459-470: The statement "Previous studies have linked enhanced convective storm activity in Central Europe to the negative phase of the NAO" is actually not supported by the first three cited studies. Giaiotti et al. (2003) does not report enhanced convective storm activity in Central Europe during negative NAO phases. In contrast, Piper and Kunz (2017) and Piper et al. (2019) present results that are not consistent with such a general linkage, showing reduced convective storm activity during positive NAO phases in western and central Europe despite thunderstorm-favourable atmospheric conditions, which would in fact suggest the opposite relationship. Augenstein et al. (2025) reports reduced thunderstorm activity during negative NAO phases, and this discrepancy is further discussed in Augenstein (2025, see p. 130). In fact, the authors' results appear generally consistent with Augenstein (2025) and, when interpreted correctly, also with Piper and Kunz (2017) and Piper et al. (2019). The paragraph should therefore be revised accordingly to accurately reflect the cited literature.

    Thank you for this careful and very helpful clarification. We agree that our original wording oversimplified the relationship between the NAO and convective storm activity and did not accurately reflect the cited literature. We have therefore substantially revised this paragraph:

    "~~Our results position annual hail variability within the broader context of large-scale teleconnection patterns that modulate atmospheric circulation over the North Atlantic–European sector. Previous studies have linked enhanced convective storm activity in Central Europe to the negative phase of the NAO (Giaiotti et al., 2003; Piper and Kunz, 2017; Piper et al., 2019; Augenstein et al., 2025). In contrast, the Z500 anomaly patterns associated with active hail seasons in northern Switzerland project more strongly onto a positive NAO-like structure. Additional correlation analyses (see appendix Fig. A1 and Fig. A2) reveal only very weak relationships with the NAO, with weakly positive correlations of the NAO to the northern Swiss hail activity and weakly negative correlations to the southern Swiss hail activity. This ambiguous NAO signal is in line with earlier work showing that the NAO exerts opposing dynamical and thermodynamical influences on convection. Negative NAO phases tend to favor large-scale ascent through more frequent shortwave troughs but are often associated with reduced low-level moisture availability, whereas positive NAO phases suppress synoptic-scale lifting while enhancing moisture transport into Europe (Piper et al., 2019; Augenstein et al., 2025). These opposing effects can offset each other, resulting in weak or regionally inconsistent relationships between the NAO and convective activity.~~ Our results position annual hail variability within the broader context of large-scale teleconnection patterns that modulate atmospheric circulation over the North Atlantic-European sector. Previous studies have identified a complex and regionally dependent relationship between the NAO and convective storm activity. While Piper and Kunz (2017) and Piper et al. (2019)reported reduced observed thunderstorm activity during positive NAO phases over western and central Europe, they also found that positive NAO phases are associated with more thunderstorm-favorable thermodynamic environments. In contrast, Augenstein et al. (2025) reported increased thunderstorm activity during positive NAO phases over parts of western Europe and attributed the apparent discrepancy with Piper and Kunz (2017) primarily to seasonal effects.

Our Z500 anomaly patterns associated with active hail seasons in northern Switzerland project more strongly onto a positive NAO-like structure. However, additional correlation analyses reveal only weak relationships with the NAO, with opposing signs depending on study region and time scale (Appendix Figs. A1 and A2). This weak NAO signal is consistent with previous work showing that the NAO exerts competing dynamical and thermodynamical influences on convection. Negative NAO phases are associated with large-scale ascent through more frequent shortwave troughs but are often associated with reduced low-level moisture availability, whereas positive NAO phases suppress large-scale lifting while enhancing moisture transport into Europe (Piper et al., 2019). These competing effects can offset one another, leading to weak or regionally varying relationships between the NAO and convective activity."

41. Line 481-490: This is a very interesting and well-written discussion. The link to Pacific SST anomalies and the resulting implications for seasonal predictability are plausible. The authors appropriately acknowledge the limitations regarding causality, which strengthens the argument in my opinion.
    We thank the reviewer for this positive assessment!

42. Line 529: Change the order of the cited literature.
    Corrected, thank you.

43. Figure A6: To avoid confusion, the label of the colorbar could be simply written out?
    Thank you for this suggestion. We agree and have revised the label accordingly.

44. I am somewhat unsure about the current title. As it stands, it may give the impression that the study provides a comprehensive explanation of the causes of inter-annual variability. While the work clearly identifies key drivers and makes a valuable contribution to understanding this variability, the title may come across as somewhat strong in its claim. In my view, more cautious formulations such as "Towards understanding. . . " or "Identifying the major drivers. . . " might be more precise and appropriate.

    We thank the reviewer for this suggestion. We agree that the original title may have implied a more comprehensive understanding than intended. To better reflect the scope of the study, we have revised the title to: "*Towards Understanding the Interannual Variability of Hail in Switzerland*".