Review of "Physical Processes Leading to Extremes Day-to-day Temperatures Change, Part 1: Present-day Climate"

by Kalpana Hamal and Stephan Pfahl submitted to Weather and Climate Dynamics

General comments

This manuscript investigates the mechanisms behind extreme day-to-day warming and cooling events at four locations around the globe. To this end, changes in the mean circulation patterns at these locations are examined and variations in the behavior of air parcel trajectories are identified. That way, the study quantifies the contributions of transport (advection), adiabatic heating, and diabatic heating to extreme day-to-day temperature changes. The authors find that advection is the main factor driving extreme temperature changes in the extratropics, whereas advection is of lesser importance for extreme temperature changes in the tropics. I find the study interesting, especially because it focuses on extreme temperature changes rather than extreme temperatures themselves, offering a new perspective on temperature variability in the atmosphere. I do not have significant scientific concerns. However, I see considerable potential for improving the language used. I feel that often inappropriate or too imprecise phrasing detracts from the content and makes it difficult to fully grasp the intended message. I recommend a thorough revision of the manuscript, with each sentence being carefully reviewed for clarity and logical flow. Therefore, I suggest publication after major revisions. Below, I have compiled a list of questions and some ideas for improving the text.

We would like to thank the reviewer for their helpful comments. Our responses are printed in blue whereas the reviewer questions are in black. In addition to addressing the individual comments, we will review the manuscript for clarity and flow.

Major comments

1. To me, it is often unclear whether the text is addressing temperature extremes or extreme temperature variability. I believe this is due to imprecise terminology. For example, throughout the text, the terms "warm events" and "cold events" are used to describe extreme day-to-day temperature change events. However, I find these expressions somewhat misleading, as they may imply that you are looking at warm and cold temperature extremes themselves, rather than on extreme warming and cooling events. The text would be much clearer if "warm events" were replaced with "warming events" and "cold events" with "cooling events." The same is true for the expression "DTDT extremes", which I think should be better replaced by something like "extreme DTDT changes". Furthermore, at some points (introduction, summary), you make a connection between your work and studies focusing on the mechanisms behind the development of warm and cold temperature extremes. I think it should be made clearer at this point that an extreme temperature event does not necessarily have to be linked to extreme temperature variability. A sudden temperature increase does not necessarily occur when it gets particularly hot, and similarly, a sharp temperature drop does not have to happen when it is particularly cold.

   Response: Thank you for your feedback. Throughout the paper, we will use 'warming events' and 'cooling events' instead of 'warm events' and 'cold events,' which improves clarity. We will also rephrase 'DTDT extremes' as 'extreme DTDT changes' to avoid ambiguity.

   We appreciate your comment and agree that it is important to clarify the distinction between extreme temperature events and extreme DTDT changes. While we acknowledge that extreme temperature events and extreme DTDT changes are not necessarily linked, our focus on daily temperature extremes in the introduction provides context for atmospheric circulation patterns, particularly given the limited literature on extreme DTDT variability.

Our analysis, as also indicated by Equation (5), shows that variations in σ_T primarily determine the spatial variability of σ_{DTDT}. Additionally, we explore the relationship between DTDT changes and specific quantiles (deciles) of T_t and T_{t-1}, as illustrated in Figure R1. Extreme warming events are associated with changes from lower-middle temperature quantiles (T_{t-1}) to middle-higher temperature quantiles (T_t), while the reverse is true for cooling events. Thus, extreme DTDT changes typically occur when T_t predominantly falls within the tail quantiles (stippling in Figure R1).

$$\sigma_{DTDT} = \sigma_T \sqrt{2\,(1-r_{1,T})} \qquad (5)$$

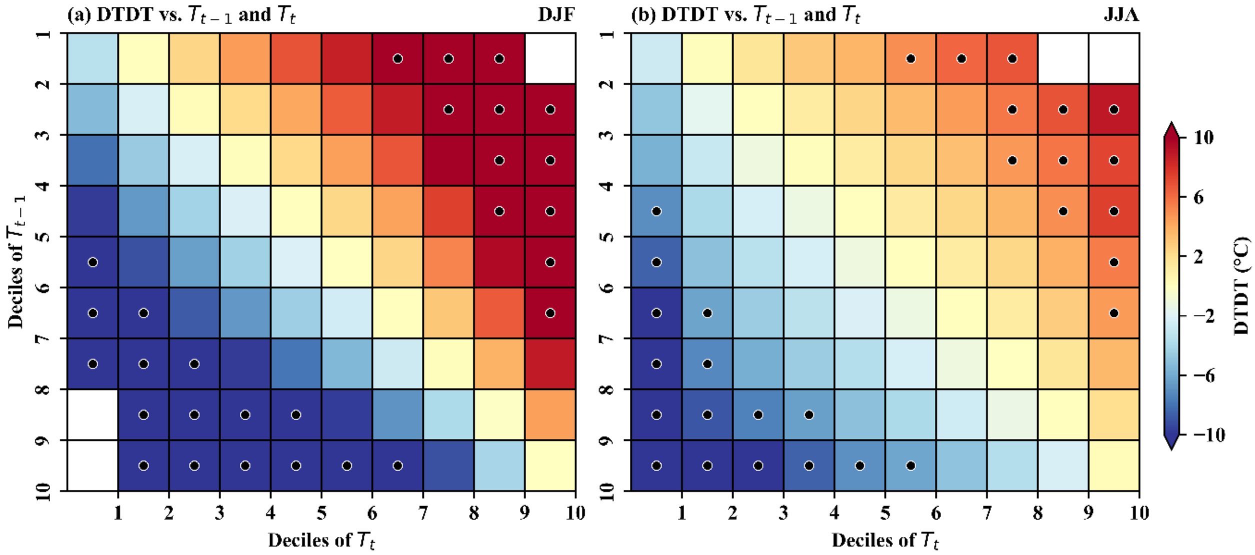

Figure R1. Heatmaps of the relationship between DTDT change and the deciles of temperature on the previous day (T_{t-1}) and the event day (T_t) for December-February (DJF) and (b) June-August (JJA) for North America. The x-axis and y-axis represent deciles of T_t and T_{t-1}, while the color shading indicates DTDT changes, with red and blue colors indicating warming and cooling, respectively. The black circles represent extreme DTDT changes.

To further illustrate the differences in atmospheric circulation between extreme DTDT changes and daily extreme events, for example, the corresponding composites for the winter season and the selected location in North America are shown in Figure R2. They reveal similar circulation patterns, which, however, are more pronounced in the case of daily temperature extremes (Figure R2). Similar results are observed at other grid points. We will add this analysis as a supplementary.

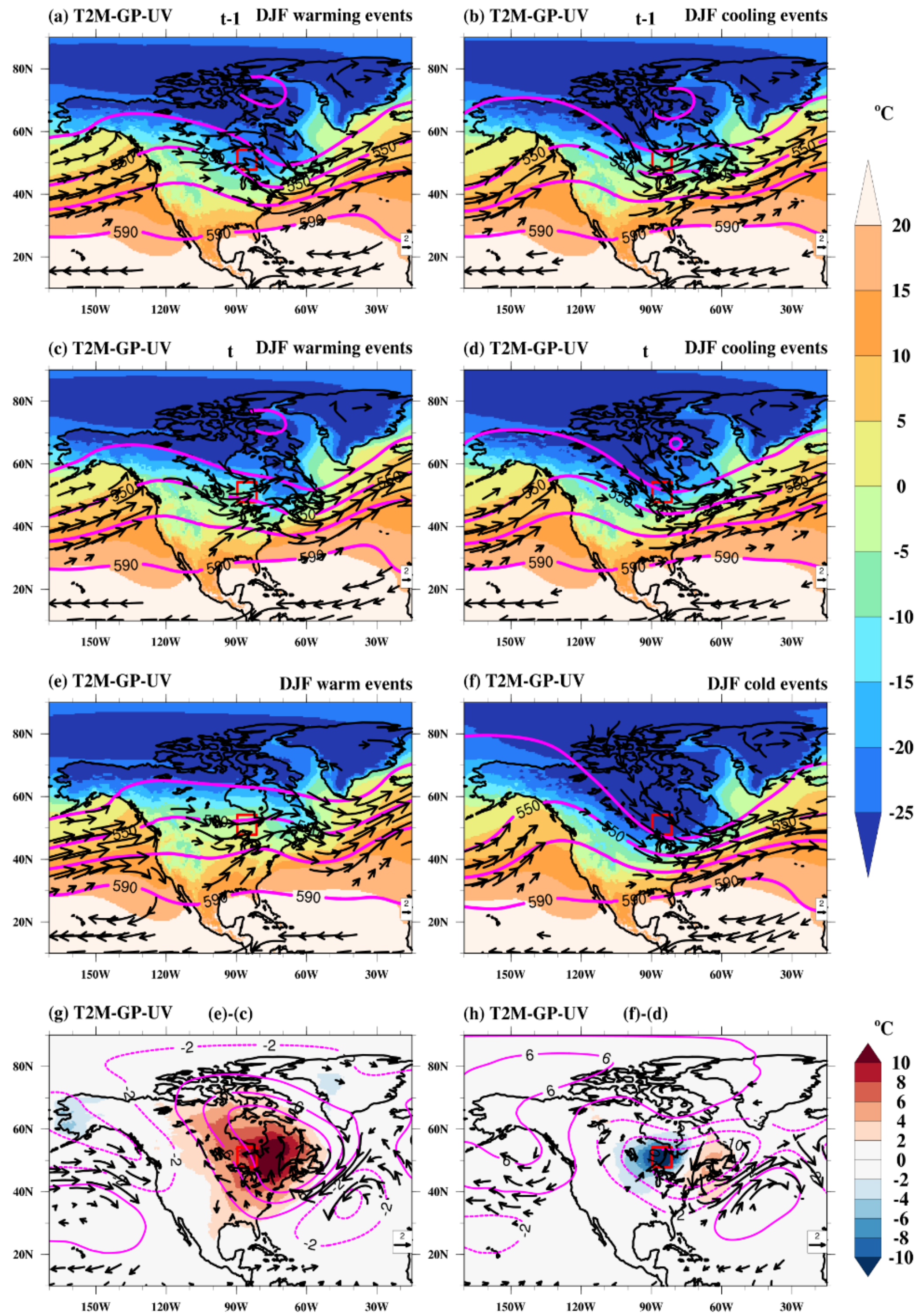

Figure R2. Composite of near-surface temperature (T2M, °C, color shading), wind at 850 hPa (UV, m/s, vectors), and Geopotential height at 500 hPa (GP, gpm, magenta contours) on the (a, c) previous day (t-1) and (b, d) event day (t) of warming (a,b) and cooling events (c,d) during December-February (DJF) at a selected grid in North America (red box). Composites of (e) warm and (f) cold events, defined with the 5th and 95th percentiles of the daily temperature distribution as thresholds, are shown in the third row, and the difference between daily extremes (panels e and f) and DTDT extremes (panels c and d) are shown in panels g-h. Note that in a-f wind vectors ≥5m/s and in g-h wind vector anomalies ≥1m/s are plotted. The dotted and bold magenta contours in g-h indicate negative and positive values of geopotential, respectively.

2. Overall, I feel that the term "advection" is not applied with sufficient precision. At times, it is used when showing instantaneous wind fields (e.g. L210, L2022), and at other times when discussing trajectories and the transport of air masses (e.g. L211, L217). I believe it is crucial to be very careful about when the term "advection" is used and when it might be more appropriate to use a different term, especially considering that the existing literature is not always clear on this matter. Furthermore, I think it would be very helpful to clarify what is meant by "cold air advection" and "warm air advection," i.e. with respect to what is the air cold or warm. I believe what you mean is that, for instance, the air transported to the location on the day of a cooling event is originally colder than the air that was transported there the previous day. I think it would be very beneficial to be more precise here.

   Response: Thank you for the suggestion. We will update the usage of the term advection and clarify the cold advection and warm advection terms in the methodology. To avoid confusion, the term will be used exclusively in the discussion of air mass transport (trajectories) and not anymore for wind composites.

   Technically, the advection term in our Lagrangian budget is defined as follows: As most temperature extremes were found to develop within a 2–3-day timescale (Bieli et al., 2015), we selected 3-day backward trajectories for the budget calculations in our study. $\overline{T}_t^{-3d}$ represents the average temperature of the air parcels initialized on the day of the extreme event, three days before their arrival at the target location, while $\overline{T}_{t-1}^{-3d}$ represents the corresponding temperature for the air parcels initialized one day earlier. The expression $\delta_T^{-3d} = \overline{T}_t^{-3d} - \overline{T}_{t-1}^{-3d}$ thus captures the difference in temperature between the air parcels three days before their arrival. Assuming no further temperature changes occurred during transport, the DTDT change is solely due to these initial differences. This suggests that variations in the advection of air parcels with different original temperatures between the previous day and the day of the event cause the temperature changes. This is why we refer to this term as an advection term. When the temperature of the air parcels initialized on the previous day ($\overline{T}_{t-1}^{-3d}$) is higher than the temperature of the air parcels at the event ($\overline{T}_t^{-3d}$), this represents a shift from warmer air to colder air on the event day, which is referred to as cold air advection. The reverse is true for warm air advection.

3. My last major comment relates to adiabatic warming. Whenever you describe the temperature at t-1, you write something similar to L216: “Accordingly, the temperature at t-1 is mainly determined by cold air advection, mitigated by adiabatic warming, ...”. I was wondering if it is not always the case that an air mass at the surface undergoes adiabatic warming. If so, is it truly necessary—or perhaps redundant—to specify each time that the temperature has been affected by some adiabatic warming? The same applies to the initial temperature, which is always lower than the final temperature. I believe the text could be condensed on this point such that greater emphasis on the differences between day t-1 and day t is given.

   Response: Thank you for the suggestion. Our approach involves studying the temperature evolution on each of the two days individually, followed by analyzing their differences. While the air masses always undergo adiabatic warming (since they arrive near the surface), the magnitude of this warming can be different, with some air masses descending more than others. Accordingly, the contribution to DTDT changes can be both negative or positive, depending on typical differences in the strength of the descent between the two days. Our results indicate that the mean effect of such changes in adiabatic warming is relatively small in many regions, but they contribute substantially to event-to-event variability.

   Nevertheless, we understand the reviewer's point that the text should mainly focus on explaining the differences between the two days that make up the DTDT changes, and we will thus further condense the descriptions of the evolution during the individual days.

Minor comments

1. L102-117: This paragraph is very hard to follow. I think this is because the expressions used in the formulas are not well described and because equations (3) and (4) are never explained in the text. I suggest to break down the equations to what is really important and introducing the equations step by step, instead of a full block of equations.

   Response: We will explain equations 1-5 in more detail:

   This study defines DTDT change, denoted as δ_T, as the difference in daily mean near-surface air temperature between the previous day (T_{t-1}) and the day of the event (T_t), as shown in Eq. (1).

   $$\delta_T = (T_t - T_{t-1}) \quad (1)$$

   The average daily temperature change, μ_{DTDT} reflects the difference between the temperatures at the start (T_0) and end (T_n) of the time series (Eq. 2).

   $$\mu_{DTDT} = \frac{1}{n}\sum_{t=1}^{n}(T_t - T_{t-1}) = T_n - T_0 \quad (2)$$

   To capture typical day-to-day temperature changes, we thus use the standard deviation, σ_{DTDT}, as shown in Eq. (3).

   $$\sigma_{DTDT}^2 = \frac{1}{n}\sum_{t=1}^{n}(T_t - T_{t-1})^2 \quad (3)$$

   By inserting the average daily temperature μ_T and multiplying out the square bracket, we find a relationship between σ_{DTDT}, the standard deviation of the daily mean temperature (σ_T) and the covariance between consecutive days ($COV(T_t, T_{t-1})$):

   $$\sigma_{DTDT}^2 = \frac{1}{n}\sum_{t=1}^{n}((T_t - \mu_T) - (T_{t-1} - \mu_T))^2$$
   $$= \frac{1}{n}\sum_{t=1}^{n}((T_t - \mu_T)^2 + (T_{t-1} - \mu_T)^2 - 2(T_t - \mu_T)(T_{t-1} - \mu_T)$$
   $$\approx 2\sigma_T^2 - 2COV(T_t, T_{t-1}) \quad (4)$$

   The approximation in equation (4) is associated with the fact that, for large n, both $\frac{1}{n}\sum_{t=1}^{n}(T_{t-1} - \mu_T))^2$ and $\frac{1}{n}\sum_{t=1}^{n}(T_t - \mu_T))^2$ are good estimators of σ_T^2. Finally, the standard deviation of DTDT can thus be expressed as a function of the usual standard deviation (σ_T) and the lag-1 autocorrelation $r_{1,T}$ of daily mean temperature, as shown in Eq. (5).

   $$\sigma_{DTDT} = \sigma_T\sqrt{2(1-r_{1,T})} \quad (5)$$

2. L121-122: The number of identified events should differ between the ERA5 data and the HadGHCND data, since their used periods differ. To which dataset do the numbers refer to?

   Response: Yes, it is true that the number of events differs depending on the choice of datasets. We used HadGHCND data for the comparison of DTDT variability patterns with ERA5 in Figures 1 and 2. For extreme DTDT events, we only used the ERA5 dataset, as shown in Figure 2 (in the paper). The sentence will be updated accordingly in the paper.

3. L131: To better understand the underlying mechanism of what?

   Response: We will add the following: "To better understand the underlying mechanisms of extreme DTDT changes"

4. L133: Instead of "apply a novel" "introduce a novel" to make clear that this precise decomposition has not been used before?

   Response: We will change this.

5. L133: Lagrangian temperature variability decomposition?

   Response: We will change this.

6. L137: The phrase "The Lagrangian decomposition of DTDT changes, as approximated by the trajectories" is odd, since the trajectories do not approximate the Lagrangian decomposition. Rather, the Lagrangian decomposition is obtained from computed trajectories.

   Response: We will change this.

7. L 141: What is decomposed?

   Response: The sentence will be improved as "The DTDT change has been decomposed into three contributing factors"

8. L142: I think at this point it would be very worth noting that advection in this approach refers to something different than in the approach by Röthlisberger and Papritz (relates to major comment 2).

   Response: Yes, we have used a different method to calculate the advection term than Röthlisberger and Papritz (2023). For daily temperature extremes, they use horizontal advection of the air parcel in the direction of the climatological temperature gradient. As we did not decompose the temperature into anomalies and climatology (which is less useful for the analysis of DTDT changes, for which the temperature is not necessarily very anomalous on both involved days), we have used a simpler definition, as explained in our response to the second major comment. This explanation will be added to the revised manuscript.

9. L149: instead of "magnitude of σ changes," either "magnitude of DTDT variations, quantified by σ", or simply "magnitude of σ"

   Response: We will improve the sentence as "Both the HadGHCND and ERA5 datasets reveal that the magnitude of DTDT variations, quantified by σ_{DTDT} is larger…"

10. L150-153: Here it is written "the variability is larger during DJF than in JJA", followed by "the variability is above 3 °C in DJF compared to 1-4 °C in JJA". However, 4 °C is larger than 3 °C, such that one could conclude that the variability in JJA is larger than in DJF. Please rephrase this sentence more precisely.

    Response: We will rephrase to "In DJF, σ_{DTDT} is above 4°C in many regions (Figures 1a-b), compared to 1-4°C during JJA (Figures 2a-b)".

11. L150-153: Here it is shown that the magnitude in DTDT changes is larger in DJF than in JJA, irrespective of the hemisphere. This means that in the northern hemisphere, the magnitude of DTDT changes is larger in winter than in summer. In contrast, in the southern hemisphere, the magnitude of DTDT changes is larger in summer than in winter. Is this behavior expected? Can

you think of any explanations for this behavior?

Response: We expect this behavior during the northern hemisphere winter, as the atmospheric circulation is stronger (Figure 4 in the paper). As anticipated, both warming and cooling events in the hemisphere are primarily driven by advection. In the southern hemisphere, the seasonality is less clear and depends on the region and dataset. We will mitigate our statement in the manuscript accordingly. For our selected location in southern Australia, the large DTDT changes during the DJF season (summer for this region), are due to a more dominant role of diabatic processes associated with stronger heating of the air masses over the continent due to stronger surface fluxes in summer.

12. L153: rephrase "remain consistently"

Response: We will rephrase to "However, σ_{DTDT} is around 1-2°C in the tropics and 1-3°C over higher-latitude land regions in the southern hemisphere…."

13. L153/L155 and other lines: Similar to comment to L149: To my understanding the phrases "σ variations" and "σ changes" do not make sense. I think it would be more accurate to simply use "σ".

Response: We will change this.

14. L159-161: "Since the magnitude of σ changes can be expressed as a function of …, Figures 1 and 2 show these related quantities." Again, I think this sentence is not properly formulated. The Figures 1 and 2 do not show the other quantities because σ can be expressed as a function of them. It is rather that you decided to show them as they are part of the computation of σ.

Response: The sentence will be reformulated: "According to equation 5, the magnitude of DTDT temperature changes can be expressed as a function of the standard deviation σ_T, and lag-1 autocorrelation $r_{1,T}$ of daily mean temperature, which are also shown in Fig. 1 and 2."

15. Figure 1/Figure 2: It would be helpful to use the same colorbars in Figure 1 and Figure 2 to enable an easier comparison.

Response: We will adapt the color bar for easier comparison in the revised manuscript.

16. L183/185: I think it is incorrect to use the phrase "leads to" here. Replace by something like "associated with".

Response: We will change this.

17. L184: "smaller" instead of "lower"?

Response: We will change this.

18. L209: I feel that the phrase "southerly airflow around its western flank" is somewhat misleading as it suggests that you refer to trajectories/air parcels. But what is shown in Figure 4a is the wind.

Response: We will change this to "southerly winds around its western flank".

19. L211: Similar to the previous comment. I do not think that you can really see "cold air advection" in this plot. You see northerly winds blowing across a temperature gradient, suggesting cold air advection.

Response: We will change this.

20. L207/L214: I was wondering whether the word “distinct” is appropriate

    Response: We will change this.

21. here. L214: What is meant by “limited” diabatic cooling?

    Response: We will change this to "Some diabatic cooling".

22. L215-216: I suggest mentioning once that the residual is small, e.g., as the last sentence in the section "Lagrangian Temperature Decomposition," and then omitting it in the following text and the figures.

    Response: We will add: “The residual is typically small and is thus not further discussed in the following text and the figures”

23. L222: Again, I think the use of the word advection is somewhat misleading here. I suggest to use “southwesterly wind” instead of “southwesterly advection” (se major comment 2).

    Response: We will change this.

24. Caption Figure 4: You write “selected grid point” but shown is a “grid box”.

    Response: We will change this.

25. L249-267: To shorten the entire paragraph: Could you simply say that a DJF cooling event is essentially the same as a "reversed" DJF warming event? To me, Figures 4a and 4d look quite similar, as well as Figures 4b and 4c. And Figure 5k is more or less the same as Figure 5l, just mirrored.

    Response: We will streamline and shorten this paragraph, focusing on the reversed behavior between warming and cooling events.

26. L285: I suggest to cross the “which are only briefly discussed”, since it gets clear from the “focuses on JJA” that the focus is not on DJF.

    Response: We will change this.

27. L333: For instance, at this point it would be very beneficial to be precise of what is meant by cold air advection and warm air advection, i.e. with respect to what is the air cold or warm (see major comment 2).

    Response: We will add the meaning of cold air advection and warm air advection to the methodology part.

28. L356/L385/L385/L493: What do you mean with “distinct” patterns and “specific” circulation patterns? Do you mean that all events exhibit a similar pattern, e.g., in the 500 hPa geopotential height? If so, I think you cannot deduce that from the plots, as you only show the mean circulation across all events, which might differ substantially from one event to another.

    Response: Yes, we have plotted mean circulation across all events, and event-to-event variability is not quantified here. Nevertheless, if the circulation anomalies between the events were completely different, no consistent mean anomaly would emerge. We will briefly discuss this in the manuscript, also in context with the circulation anomalies shown in the response to reviewer 2 (their major comment 3).

29. L356-373: Are you referring to cooling or warming events here?

    Response: We are referring to warming events, which will be mentioned in the paragraph in the revised version.

30. L387-388: At this point, I think one must be very careful with the phrasing. You are looking at a budget, so you cannot say that term 1 and term 2 cancel each other out, leaving only term 3 as important! Imagine term 1 being +5 K, term 2 being -5 K, and term 3 being +5 K. You cannot say that term 1 and term 2 cancel each other out, leaving only term 3 as important, nor can you say that term 2 and term 3 cancel each other out, leaving only term 1 as important.

    Response: You are right, and we will rewrite the paragraph accordingly.

31. L416-425: Again, to shorten the paragraph: Could you simply say that DJF cooling events are essentially the same as a "reversed" DJF warming event?

    Response: We will change this.

32. L393: I suggest to write "… **presumably** contributing to larger diabatic heating and higher temperatures"

    Response: We will change this.

33. L500: To better connect to the first part of the sentence, you could insert something like "while the contributions of adiabatic and diabatic processes are generally smaller and vary more in space and also between warm and cold events".

    Response: We will change this

34. L513/514: Here, scientific debate is still going on. There are also studies saying that heat waves in the mid-latitudes are driven by advection (e.g., Harpaz et al. 2014, Sousa et al. 2019, partly Röthlisberger and Papritz 2023).

    Response: We will add a more nuanced discussion here.

35. L537: I do not understand what is meant by the sentence "is approximated through the average temperatures of the trajectories initiated on the corresponding day at their initiation time".

    Response: We will add the following explanation: "This is an approximation, as the trajectories are initialized from different heights above the surface, assuming (and sampling) a well-mixed near-surface layer."

Technical correction

36. Title: temperature without plural?

    Response: We will change this

37. L120: 5th and 95th percentiles of the DTDT change distribution

    Response: We will change this

38. L125, 136: no plural, DTDT change event?

Response: We will change this

39. L190: DTDT variation

    Response: We will change this

40. L193: DTDT variation events

    Response: We will change this

41. L194: DTDT variations

    Response: We will change this

42. Figures: I think it would be helpful to keep the direction of panel labeling consistent across all figures.

    Response: We will keep all the panel labels in the vertical direction.

43. L202/284/353/…: Should we invest in the mechanisms?

    Response: We will change this

44. L220: On the days of the ...

    Response: We will change this

45. L241: smaller in magnitude?

    Response: We will change this

46. L339: compared to

    Response: We will change this

47. L445: result from

    Response: We will change this

References

Bieli, M., Pfahl, S., and Wernli, H.: A Lagrangian investigation of hot and cold temperature extremes in Europe, Quarterly Journal of the Royal Meteorological Society, 141, 98-108, 2015.

Röthlisberger, M. and Papritz, L.: Quantifying the physical processes leading to atmospheric hot extremes at a global scale, Nature Geoscience, 16, 210-216, 2023.