Review of "Physical Processes Leading to Extreme day-to-day Temperatures Changes, Part I: Present-day Climate"

The work of Hamal and Pfhal investigates the physical processes of extremes in the day-to-day variability of near-surface temperature (DTDT) using the ERA5 data set. They use both composites maps and Lagrangian backward trajectories tracking to quantify the mechanisms for these extreme changes in temperature. Their main conclusion is that these extremes are mainly driven by changes in advection in the extra-tropics while the situation is more balanced in the tropics with important contributions from diabatic processes.
The paper is well written and the research question is clearly stated and interesting. The analyses carried out in the paper are careful, well explained and scientifically sound. I should say that the results are not particularly jaw-dropping – I would have guessed that advection was the main contributor of extremes of DTDT in the extra-tropics – but they are nonetheless interesting for documenting these mechanisms. I have some suggestions to improve the quality of the communications of the results and some additional analyses. Therefore I recommend major revisions at this stage, see below for my comments.

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. **Use of ERA5 and HadGHCND:** I think the comparison between the DTDT variability in ERA5 and HadGHCND is problematic. As the authors show in their Figure 1, there are large differences between the two data sets that are probably not physical. The reason is likely because HadGHCND interpolates station data to construct a gridded data set which likely smooths out the daily variability (rather than lack of station coverage I think). In my opinion, this makes the HadGHCND data set particularly not suited for the study that you are doing here. That being said, it is true that the authors mainly compare the spatial patterns rather than the absolute values of sigma_DTDT between the two data sets. If you really want to compare the absolute values found with ERA5 with measured data you should probably go directly to station data. For these reasons, I would discourage to show the comparison with HadGHCND in the figures of the main text: the authors can include it in supplementary materials if they really want to do this comparison. In this case they should also discuss the differences between the two data sets more. Moreover, the rest of the paper does not use HadGHCND.

   Response: We agree with the reviewer that the HadGHCND dataset may have smoothed out the variability due to spatial interpolation and the limited number of stations. This can be verified by comparing the HadGHCND dataset with the Berkeley Earth Surface Temperature (BEST) dataset (Figure R1a-h), which incorporates additional data sources beyond HadGHCND. This comparison shows an increased variability pattern in the northern hemisphere for both DJF and JJA (Figures R1b and d). Furthermore, this allows for a more robust comparison with the ERA5 data for all the quantities (Figure R2).

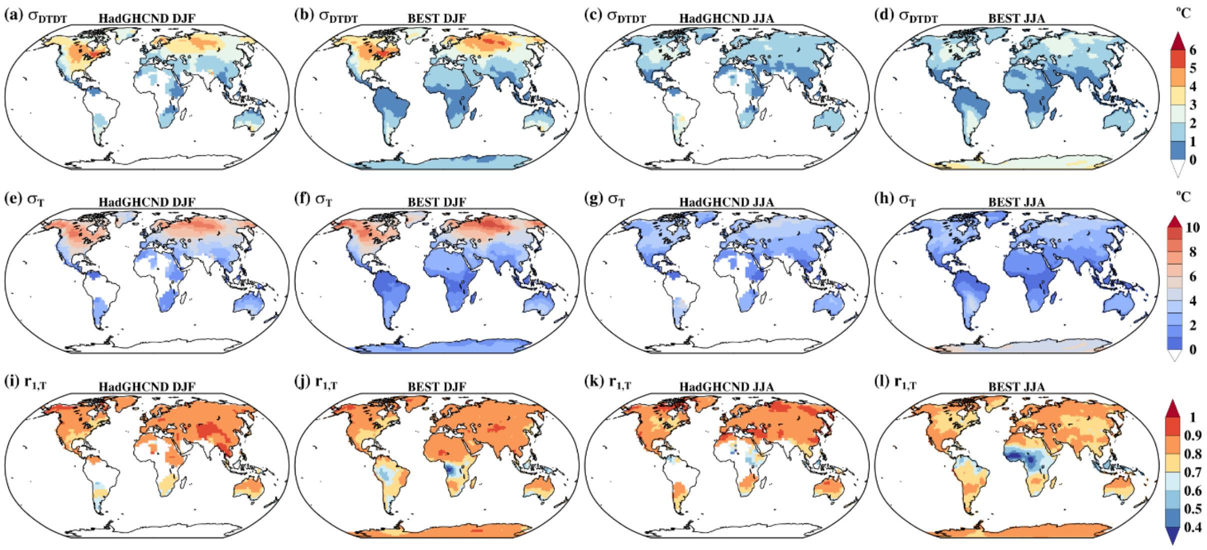

Figure R1. (a-d) Standard deviation of DTDT variations (σ_{DTDT}, °C), (e-h)) standard deviation of daily mean temperature (σ_T, °C), and (i-l) lag-1 autocorrelation of daily mean temperature ($r_{1,T}$) in December-February (DJF) and June-August (JJA) derived from the HadGHCND and BEST datasets.

Following the reviewer's suggestion, we will use only ERA5 data for the main manuscript, while this observational analysis will be moved to the supplementary material.

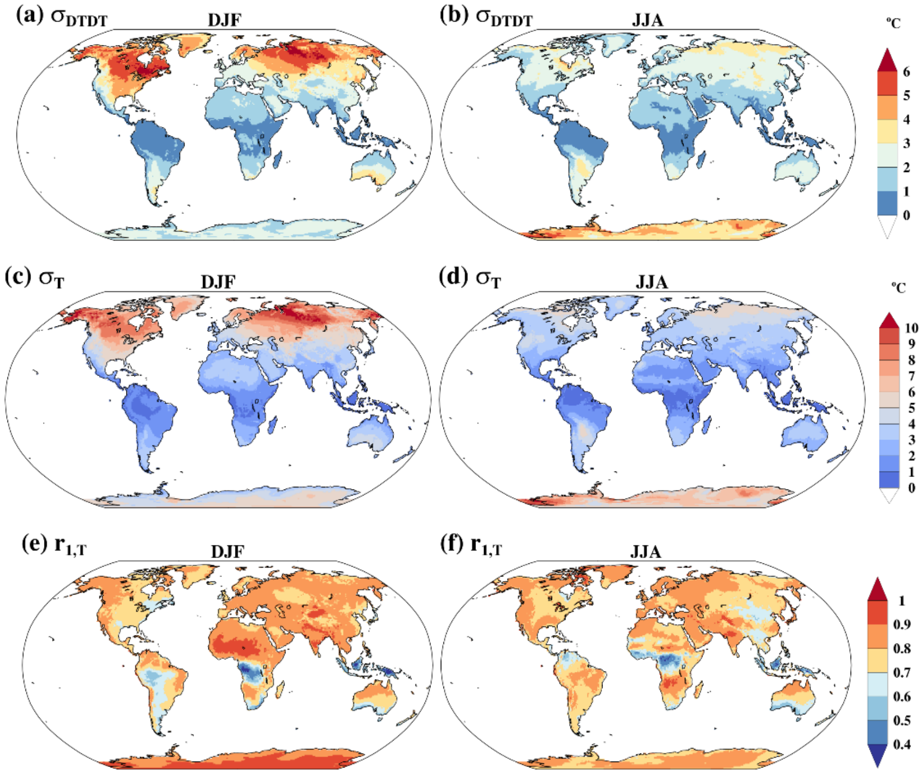

Figure R2. (a, b) Standard deviation of DTDT variations (σ_{DTDT}, °C), (c, d) standard deviation of daily mean temperature (σ_T, °C), and (e, f) lag-1 autocorrelation of daily mean temperature ($r_{1,T}$) in December-February (DJF, 1st column) and June-August (JJA, 2nd column) derived from the ERA5 datasets.

2. **Statistical suggestions:** a. I think it would be interesting to show (at least for the grid points studied) the distribution of delta_T and the quantiles that you are selecting. In particular it would be interesting to see whether the distribution is symmetric. You could for example compute, in addition t its standard deviation, its kurtosis and show the corresponding map.

   Response: Thank you for your suggestions. We have calculated the DTDT distribution for each selected location during DJF and JJA, as shown in Figure R3. In DJF, North America exhibits the highest variability with a broad distribution, while South America shows the lowest variability with a sharper peak. Europe and Australia display moderate variability, with intermediate kurtosis values and slight distribution asymmetry. However, in JJA, South America becomes more variable, while North America, Europe, and Australia maintain relatively stable distributions with lower variability compared to DJF. Additionally, the distributions become more negatively skewed in JJA. We will add this result to the supplementary material.

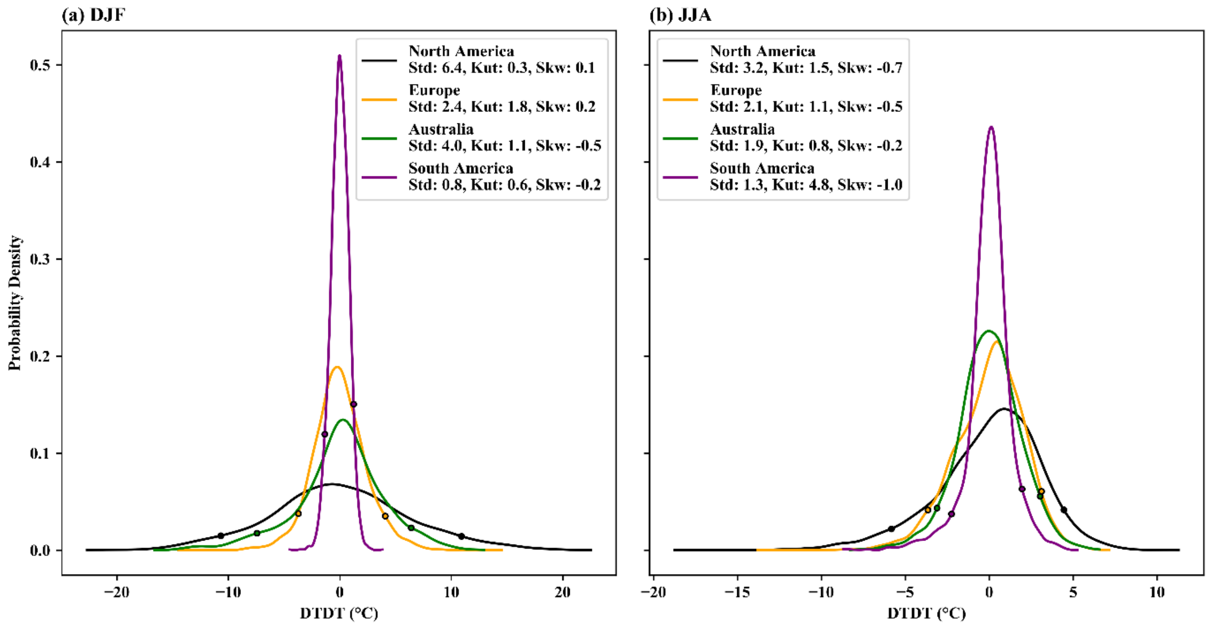

Figure R3. Day-to-day temperature (DTDT) distribution curves over the selected regions: North America (black), Europe (orange), Australia (green), and South America (purple) for (a) December-February (DJF) and (b) June-August (JJA). The small dots on the left and right represent the 5th and 95th percentiles, respectively.

b. One question I had while reading the paper is how much the extremes of delta_T relate to extremes of T, in other words: do your warming/cooling events also correspond to warm/cool extremes? I think it would be super interesting to show how the extremes of delta_T are linked to the quantiles of T_t and T_t-1. For example, do extreme warming events happen because we start from a very cold quantile and we end up in the middle of the temperature distribution or do we start from the middle of the distribution and end up in the right tail? The physical processes in these two situations are likely different.

Response: Thank you for your insightful suggestion. We have illustrated the relationship between DTDT changes and the specific quantiles (terciles) of T_t and T_{t-1} in Figure R4. Our analysis reveals that extreme warming events originate in the lower to middle-temperature quantiles of T_{t-1} and shift toward the middle to higher quantiles of T_t. Conversely, extreme cooling events typically begin in the middle to higher quantiles of T_{t-1} and shift to the middle to lower quantiles of T_t. We will incorporate this analysis into the manuscript in Section 3.2.

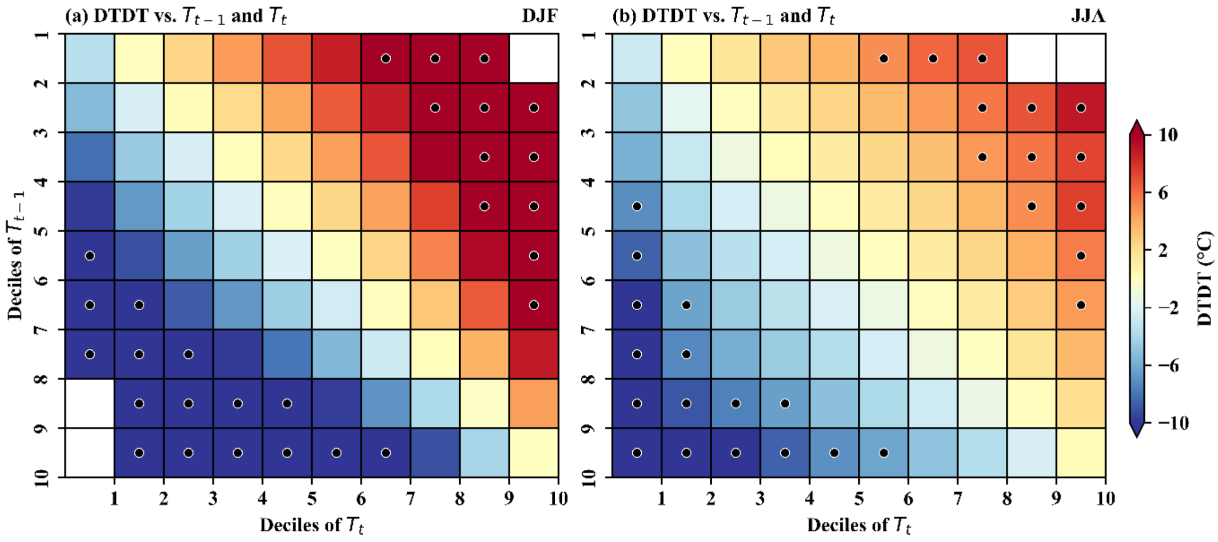

Figure R4. Heatmaps of the relationship between DTDT change and the deciles of temperature on the previous day (T_{t-1}) and the event day (T_t) for December-February (DJF) and (b) June-August (JJA) for North America. The x-axis and y-axis represent deciles of T_t and T_{t-1}, while the color shading indicates DTDT changes, with red and blue colors indicating warming and cooling, respectively. The black circles represent extreme DTDT changes.

3. **Comparison with climatology:** I find it really interesting that in Figure 4-5 and others the warming and cooling events seem the reverse of one another. As advection seems to be the largest contributor, it seems to me that extremes of sigma_DTDT happens as if this mechanism was switched on or off: warming events happen because the northward advection was switched off and vice versa for cold events. This leads me to my question which is not unrelated to my previous comment 2.a., how are the dynamical situations that you identify unusual with respect to climatology? Is it the starting point that is dynamically unusual or the end point? To be more clear, it seems to me that you should probably do your composite maps also in anomalies.

   Response: Thank you for your insightful suggestion. We have analyzed the atmospheric circulation anomalies for the two days involved in an extreme DTDT change event with respect to the seasonal climatology, revealing significant deviations from the mean. Specifically, warming events are associated with southerly wind anomalies and higher geopotential heights (Figure R5), while cooling events are linked to northerly wind anomalies and lower geopotential heights. We will add this to the supplementary.

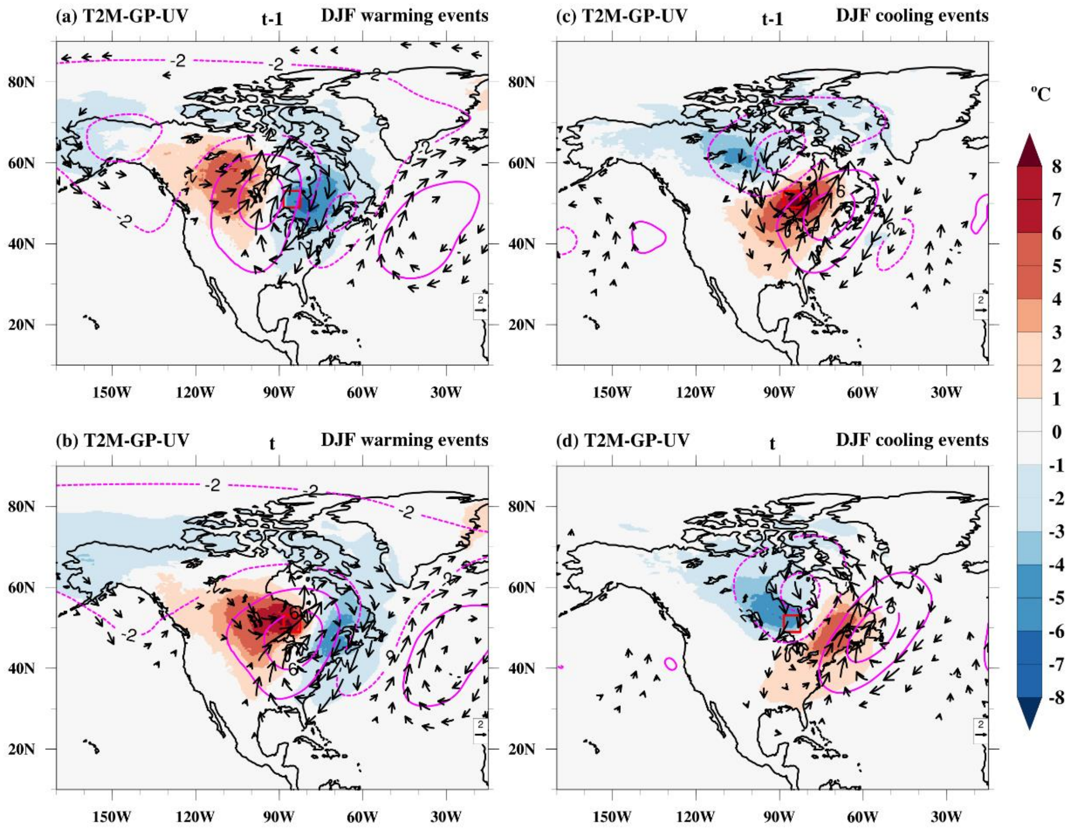

Figure R5. Composite of near-surface temperature anomalies (T2M, °C, color shading), wind anomalies at 850 hPa (UV, m/s, vectors), and geopotential height anomalies at 500 hPa (GP, gpm, magenta contours, dotted and bold magenta contours show negative and positive values, respectively) with respect to seasonal mean on the (a, c) previous day (t-1) and (b, d) event day (t) of the warming (a,b) and cooling events (c,d) during December-February (DJF) at a selected grid in North America (red grid). Note that wind vector anomalies ≥2m/s are plotted.

4. **Extremes of DTDT and fronts:** the fact that advection is the main factor of extremes in DTDT in the extra-tropics is not super surprising and that is what I would expect because of the existence of atmospheric fronts (some may even argue that fronts are by definition extremes of DTDT). I am surprised that the authors do not mention at all these structures. Can you say a word about how your analysis and results relate to the literature on frontal structures? Moreover, it seems to me that frontal structures are well identified in the climate variability literature as being the mechanism for day-to-day variability (e.g. Ghil and Lucarini (2020)), maybe you could also mention that in the broader context of your work.

   Response: We agree that atmospheric fronts play a pivotal role in shaping DTDT extremes in the extratropics. Baroclinic instability drives the formation of frontal structures, which are closely linked to the development of cyclones and anticyclones and serve as key drivers of day-to-day temperature variability (Ghil and Lucarini, 2020). In the composite anomalies of warming events, the transition from cold air masses on the preceding day to warm air masses on the event day corresponds to the passage of warm fronts, which are associated with strong spatial temperature gradients (Figure R5a-b). This phenomenon has been extensively studied and confirmed for European DTDT extremes using different frontal structures (cold, warm, and occluded) (Piskala and Huth, 2020). Our primary objective was to identify the dominant processes driving DTDT extremes. Since our study did not include a database of frontal passages, we initially did not reference this aspect in our analysis. However, we will now incorporate a discussion of this topic, including references to the papers mentioned above, in both the introduction and discussion sections.

Minor comments

1. Paragraph L49: in this paragraph you are mainly talking about hot and cold extremes, which are rather different from the extremes in DTDT that you are looking at. This may be confusing for the reader, please be more clear about how the extremes per se relate to the extremes of DTDT (see also my major comment 2).

   Response: We agree that extreme daily temperature events and extreme DTDT change events are two different things. However, there is limited literature on the variability of DTDT extremes; we introduce daily temperature extremes to provide the context for atmospheric circulation in the introduction. Furthermore, Equation 5 and Figure R4 illustrate how DTDT variability relates to daily temperature variability. Additionally, our analysis of composites of extreme DTDT and daily extreme events reveals similar circulation patterns, which are, however, more pronounced in the case of daily temperature extremes shown in the response to reviewer 1 (their major comment 1).

2. For clarity, I think you should detail a bit more the terms in eq 1-5. In particular, equation 4 is not necessary to me and may be confusing. Moreover, you should explain what the approximation means in equation 3 (explain why this is actually a very good approximation and the errors involved are small because of the typical time scale of the seasonal cycle).

   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).

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

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).

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

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

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

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})):

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

$$= \frac{1}{n}\sum_{t=1}^{n}((T_t - \mu_T)^2 + (T_{t-1} - \mu_T)^2 - 2(T_t - \mu_T)(T_{t-1} - \mu_T)$$

$$\approx 2\sigma_T^2 - 2\mathrm{COV}(T_t, T_{t-1}) \qquad (4)$$

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).

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

3. L126: can you detail a bit more why those choices were made, especially the date and time of the initialization of the backward trajectory.

   Response: We will add a more detailed explanation:

   The Lagrangian analysis tool (LAGRANTO), introduced by Sprenger and Wernli (2015), is used to calculate backward trajectories of near-surface air masses on days associated with extreme DTDT changes from 1980 to 2020. The trajectories are initialized at 18 UTC on both the preceding day (t-1) and on the event day (t) at 10, 30, 50, and 100 hPa above the surface at the corresponding grid cells. Similar to previous studies on extreme temperatures (Zschenderlein et al., 2019), the different initialization heights are used to sample a near-surface layer that is assumed to be well-mixed. The time difference of 24 hours between the two initializations allows for a proper separation of the air masses before and after the temperature change. Although we use LAGRANTO to calculate 10-day backward trajectories, extremes typically develop on a timescale of 2–3 days (Bieli et al., 2015; Röthlisberger and Papritz, 2023). Therefore, we focus on 3-day backward trajectories for our analysis. Various variables of interest, including latitude, longitude, pressure, temperature, and potential temperature, are interpolated along the trajectory paths and saved at 1-hour intervals.

4. Equation 6: this is more for my understanding: given that you are looking at air parcels close to the ground, how can the adiabatic contribution be anything else than positive?

   Response: 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.

5. Figure 1: the colors scale in all panels is unfortunate. You are showing only positive, non-divergent values therefore you should not use a divergent color maps which is misleading for the reader. Also, because you compare between panels a,b and c,d, the values of the color map should have the same range. Finally, you should probably use the Robinson projection.

   Response: Thank you for your suggestion. We experimented with a non-divergent color bar but found that the differences in the spatial distribution of DTDT were less clear. To maintain clarity and consistency, we will use the same color bar across all figures, with a similar range for direct comparison. Additionally, we will apply the Robinson projection to improve the representation of spatial patterns (e.g., Figure R1).

6. L149 and following: You mention the “magnitude of sigma_DTDT changes.” I am not sure what this refers to. If I understand correctly, you should rather talk about the “magnitude of sigma_DTDT.”

   Response: Thank you for the suggestion. We will change this to “magnitude of σ_{DTDT}”.

7. L174: what are “the deep tropics” ?

   Response: Here, we mean to indicate the core equatorial region.

8. Because you are studying land grid points only and their proportion varies a lot between the latitudes, I am not sure the zonal means in Figure 1 and following are really relevant: the reader can

see by themselves that there is a marked latitudinal gradient of the quantities you are displaying. Also, do you have an explanation for why in the southern hemisphere the variability is much smaller than in the northern hemisphere for the grid points with the same absolute latitude?

Response: Thank you for the suggestion. We will remove the zonal mean representation (e.g., Figure R1).

While, in general, differences in the land-ocean distribution and corresponding spatial temperature gradients may lead to different magnitudes of the variability between the hemispheres (via advection), we do not think that the variability in the southern hemisphere is much smaller than in the Northern Hemisphere at the same latitude. The fact that the maps have shown the latitude range from 60°S to 90°N might make the comparison a bit difficult before. However, we have now extended maps to 90°S and 90°N, and a larger magnitude of DTDT is clearly observed in high latitudes, such as Antarctica (Figure R2).

The variability in the Southern Hemisphere is generally lower than in the Northern Hemisphere at the same latitude in DJF. As shown earlier, advection is the key driver of this variability, and the magnitude is thus related to horizontal temperature gradients. In the Northern Hemisphere, larger land masses are associated with larger temperature contrasts between continents and ocean, while in the Southern Hemisphere, in particular at latitudes south of 40°S, such land-sea differences are much smaller due to the small land fraction and the dominance of oceanic air masses. During JJA, when the meridional temperature gradient is larger in the Southern Hemisphere, the magnitude of the variability becomes more comparable between the two hemispheres.

9. L205: “DJF warm events”: I would strongly discourage you from using this phrasing for the events you are studying because it is really misleading for the reader. You should talk about warming/cooling events.

   Response: We will change “warm/cold events” to “warming/cooling events".

10. Fig4: a. Please define more precisely near surface temperature: is it T2M? b. I would suggest not to use absolute values for composite maps: first because there is still the seasonal cycle (how do you handle that by the way?) and second because it is difficult to read and the sudden change of temperature from t-1 to t is not very clear. Maybe simply use anomaly maps and/or make a difference between the map at t and at t-1?

    Response: Yes, near-surface temperature (T2M) is indeed used, as mentioned in the methodology section. In response to the reviewer's suggestion, we have plotted composite maps for the two days involved in an extreme DTDT change event relative to the seasonal climatology, highlighting significant deviations from the mean (Figure R5). We appreciate the reviewer's recommendation, as the sudden temperature change from t-1 to t is now clearly evident.

    Additionally, we plotted the difference between the event day and the previous day, along with the absolute values, to illustrate both the changes and their magnitudes (Figure R6). In the revised manuscript, we will present the circulation patterns on each day along with their differences, while the climatology anomalies will be included in the supplementary material.

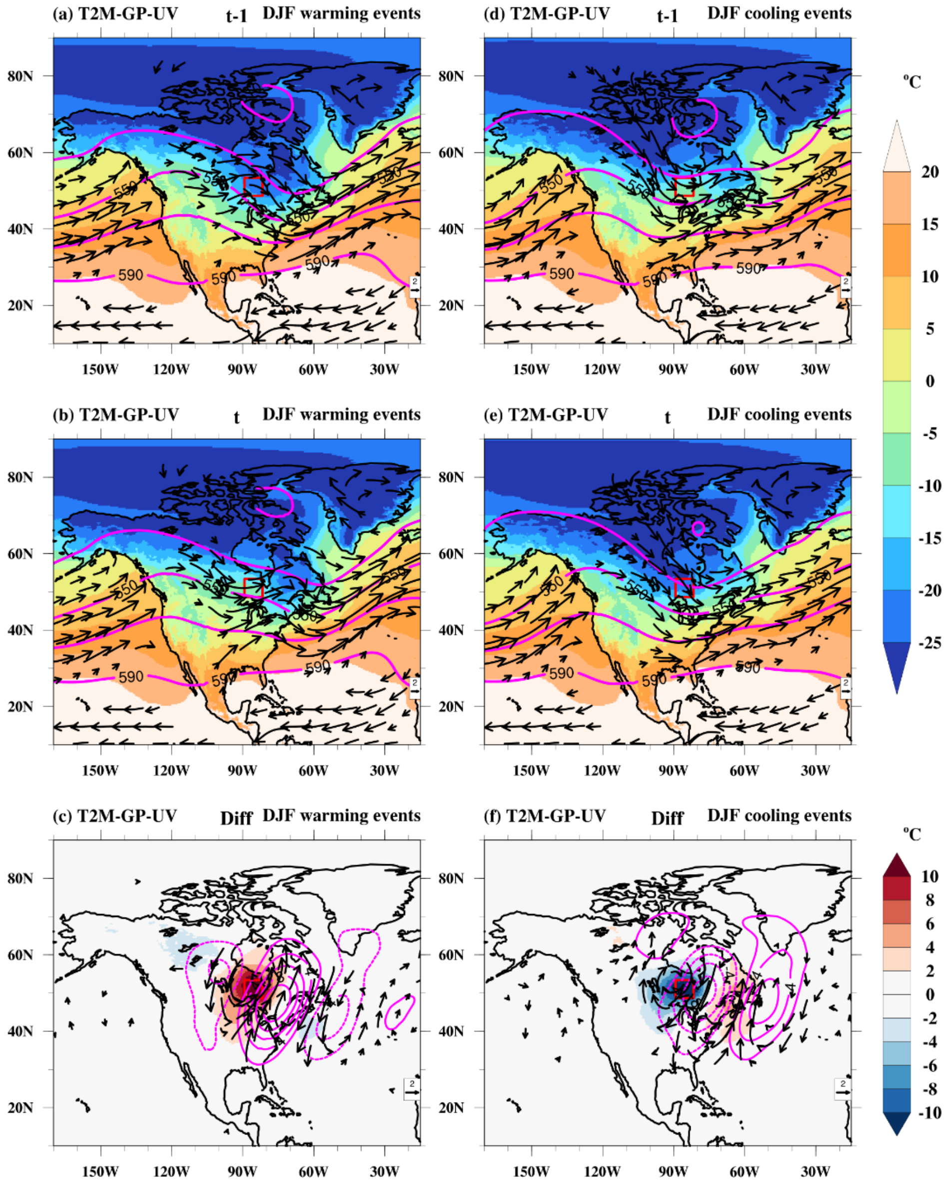

Figure R6. Composite of near-surface temperature (T2M, °C, color shading), wind at 850 hPa (UV, m/s, vectors), and geopotential height at 500 hPa (GP, gpm, magenta contours) on the (a, c) previous day (t-1), (b, d) event day (t) and (c, f) difference of event day and previous day of the warming (a-c) and cooling (d-f) events during December-February (DJF) at a selected grid in North America (red grid). Note that (a-d) wind vectors ≥5m/s and (e-f) wind anomalies ≥1m/s are plotted. The dotted and bold magenta contour in c and f indicate negative and positive geopotential height differences, respectively.

11. Figure 5 and alike: it would be clearer for the reader if you could indicate explicitly on the figure (not only in the legend) if those are DJF or JJA events**.**

    Response: Thank you for the suggestion. We now indicate whether DJF or JJA events are shown in the Figures themselves (e.g. Figure R6).

12. L431: “To systematically investigate the mechanism driving DTDT extremes over the subtropics in the southern hemisphere during DJF and JJA, we select a specific location in Australia”: to me this sentence sounds self-contradictory, how can you systematically investigate if you look at only one grid point?

Response: We have improved this sentence structure as "To investigate the mechanism driving extremes DTDT events over the subtropics in the southern hemisphere during DJF and JJA, we select a specific location in Australia."

13. The conclusions reached are based on the analysis of only some grid points at various longitudes/latitudes. Although I think the conclusions reached can probably be extended to the other grid points in the vicinity, I think the authors should be a bit more cautious in their concluding statements.

    Response: The results for a few additional grid points (Northern Asia, Southern South America, South Asia, Africa, and Western North America) are presented in the supplementary material. Nevertheless, we will revise the wording to make it more cautious regarding potential spatial variability.

14. L531: "This dominant effect of advection also explains why the magnitude of DTDT changes is typically larger in the extratropics, where horizontal temperature gradients and wind velocities are larger compared to the tropics": this statement is likely true but deserves more evidence.

    Response: Here, we are not sure which kind of evidence the reviewer would like to see. Based on our composite analysis of atmospheric circulation and 3d backward trajectories, we show that advection dominates DTDT changes in the extratropics. The fact that horizontal temperature gradients and wind velocities are larger in the extratropics than in the tropics is evident from basic climatological data. The relationship between advection, wind velocity, and temperature gradient is clear from the Eulerian version of the thermodynamic equation, where the advection term is written as the scalar product of the horizontal wind vector and temperature gradient. Finally, the magnitude of the adiabatic and diabatic terms in our Lagrangian budgets are of the same magnitude in the extratropics and tropics and thus cannot compensate for the difference in advection. A note on the last point will be added to the conclusion section.

References

Ghil, M., & Lucarini, V. (2020). The physics of climate variability and climate change. *Reviews of Modern Physics*, *92*(3), 035002.

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.

Piskala, V. and Huth, R.: Asymmetry of day-to-day temperature changes and its causes, Theoretical and Applied Climatology, 140, 683-690, 2020.

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

Zschenderlein, P., Fink, A. H., Pfahl, S., and Wernli, H.: Processes determining heat waves across different European climates, Quarterly Journal of the Royal Meteorological Society, 145, 2973-2989, 2019.