 # REVIEWER 1

Review of "Exploring the interplay between observed warming, atmospheric circulation, and soil-atmosphere feedbacks on heatwaves in a temperate mountain region" by Lemus-Canovas et al.

This study investigates the physical drivers of two heatwaves that occurred in a temperate mountain region in 2022. The authors systematically quantified the contributions of adiabatic, diabatic, and advective processes to temperature trends. Their analysis revealed that the June heatwave was primarily driven by advection, while the July heatwave was largely caused by subsidence. By employing flow analogues, the study further demonstrated that heatwaves during 1986–2021 were more intense compared to those during 1950–1985. Additionally, the authors highlighted how interactions between synoptic circulation, topography, and soil moisture contribute to the spatial variability of temperature. This research provides valuable insights into the mechanisms behind heatwaves and underscores the role of land-atmosphere interactions in amplifying such events. While the manuscript is generally well-written, a few points require further clarification.

We sincerely appreciate the time and effort you have dedicated to reviewing our manuscript. Your constructive comments and suggestions have helped us improve the clarity and robustness of our study. Below, we provide a detailed response, where our revisions and clarifications are highlighted in bold.

Major comments

- Lines 104-106. What is the magnitude of the diabatic term compared to other terms in Equation (1)?

  Indeed, it is a third of the other components during the June 2022 case and similar magnitude in the July 2022 case. We decided therefore to remove this sentence since it can mislead and it is not part of the methodology. The results are described in detail in section 3.2

- Lines 127-158. Could you make a schematic of how the flow analogue experiments are conducted, clearly showing all the steps? For example, how do you reconstruct the expected mean Tx?

- **We appreciate your comment. We have not included an additional figure in the manuscript, as a schematic representation of the flow analogue methodology is already available in Jézéquel et al. (2018), which is cited in our study.**

Regarding the reconstruction of the expected mean Tx, this process is described in detail in lines 135-143 of the manuscript.

- Figure 1. The temperature is lower than 14 °C, which is quite low compared to heatwaves in general, although the temperatures in the identified periods are heatwaves statistically. Could you show that such a temperature is really a concern?
- **These temperatures (+14ºC above the mean) represent anomalies rather than absolute values, as indicated in the figure caption.**
- Lines 256-263. The temperature difference between the two periods from Figure 5b is at least half of that from Figure 5a. You cannot say that the temperature difference between the analogs of the two climate periods is mainly linked to a long-term trend, unless the difference from Figure 5b is much smaller than that from Figure 5a.
- **We appreciate your comment. We agree that some bias remains when the analogue trend is removed, i.e. the Tx temperature change can be partly attributed to factors other than the long-term trend. In this context, we have already mentioned that land-atmosphere interactions could play an important role and we have shown this in section 3.3.2.**
- Lines 271-274. Could you provide more explanations on the spatial structure of synoptic situations? Why RMSD could clearly represent the spatial structure?

We have provided a detailed explanation of the role of the RMSD and the spatial structure of the analogues in lines 282-291. In addition, we have included a new figure in the supplementary material comparing the observed and analogue spatial composites of Z500 to provide greater robustness to our arguments (Figure S3).

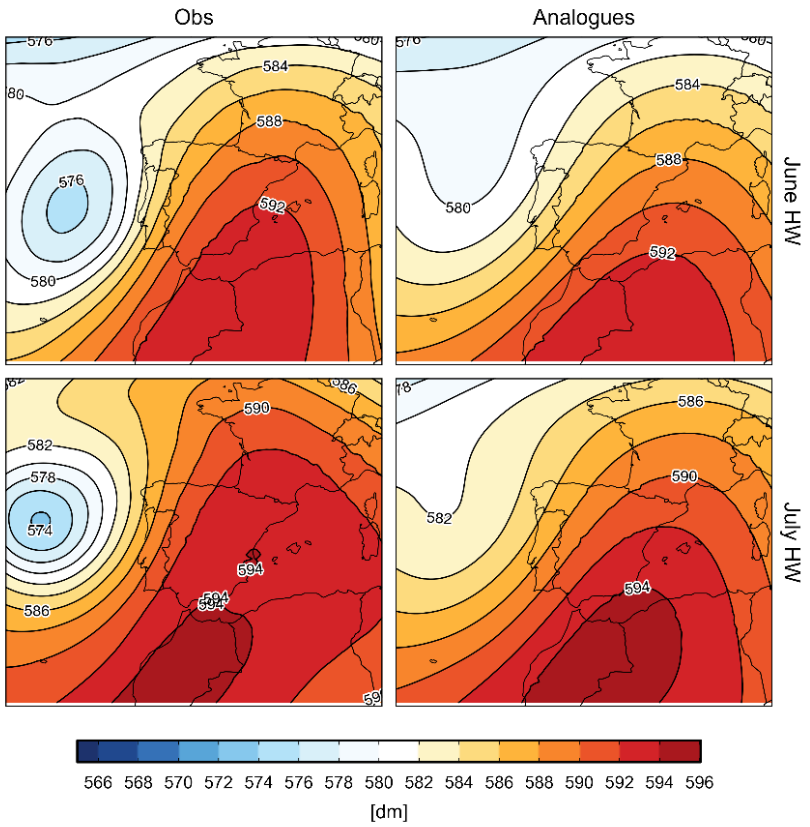


Figure S3. Observed and analogue Z500 pattern for the June and July heatwaves. The analogues were selected for the period 1950-2021, following the procedure described in the methods section.

Minor comments

Line 58. Tx is maximum temperature but is not explicitly defined.

Thank you for your comment. Tx and Tn are defined in line 60

Lines 110-120. The same should be used everywhere.

In section 2.2.3 the variables used are different from Tx and Tn, as T is the mean daily temperature.

Line 263. Inconsistent font size

Solved. Thank you.

 # REVIEWER 2

In the manuscript “Exploring the interplay between observed warming, atmospheric circulation, and soil-atmosphere feedbacks on heatwaves in a temperate mountain region," Lemus-Canovas et al. investigated the thermodynamic processes that contributed to the two most intense heatwaves in the Pyrenees during 2022. The authors then evaluated temperature anomalies during analogous synoptic events in reanalysis data to draw conclusions on the relative roles of anthropogenic warming vs. land-atmosphere feedbacks on heatwave intensity. Ultimately, the authors conclude that global mean warming due to anthropogenic greenhouse gas emissions underlies the trend in maximum surface air temperature anomalies in the Pyrenees and surrounding areas. Still, land-atmosphere feedbacks related to reduced soil moisture conditions in the days preceding heatwave events, particularly in the low lying areas south of the Pyrenees, can amplify warming during an event.

The study is well-motivated and addresses important questions regarding the role of topography in shaping the spatial distribution of surface temperature anomalies during extreme heat events. The results seem highly relevant for evaluating local and regional vulnerability to future heatwaves in the greater Pyrenean area. The analyses are logical and support the text well. The results presented would be a great addition to the literature and I do feel the study is fit for publication in *Natural Hazards and Earth System Sciences* following revisions.

We sincerely appreciate the time and effort you have dedicated to reviewing our manuscript. We acknowledge your insightful feedback and have carefully addressed each of your concerns. Below, we provide a detailed response, where our revisions and clarifications are highlighted in bold.

General Comments:

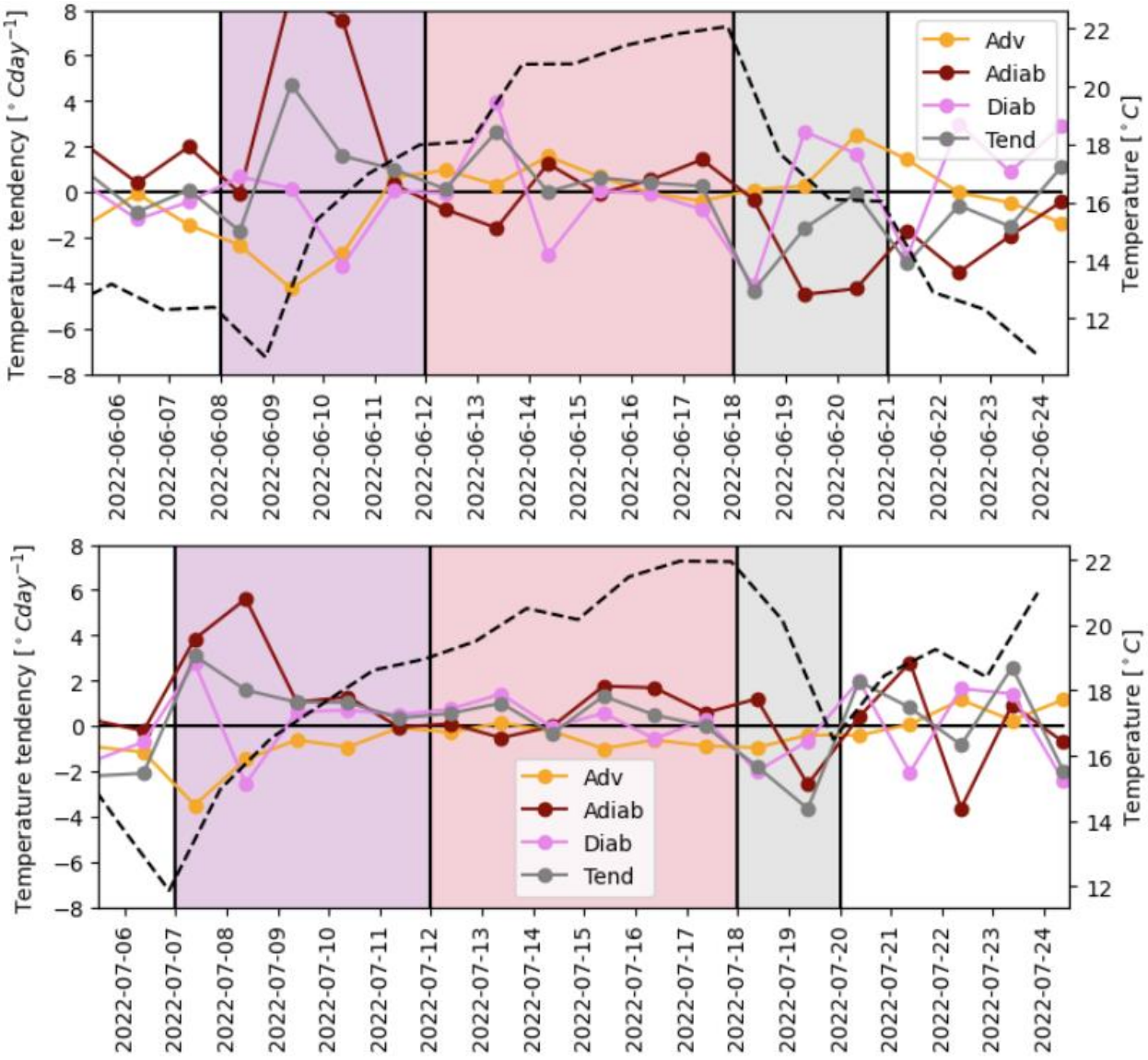
I think you need to justify that the thermodynamic processes operating at 700 hPa are significantly correlated to the surface environment. It is reasonable to perform your analysis at this pressure level to avoid intersecting with the topography as long as you can demonstrate that the surface conditions are directly responding to changes in the 700 hPa conditions.

Thank you for your comment. Indeed, with this analysis we do not want to demonstrate the direct changes on the surface conditions, since, as we show later, we observe that it cannot explain the low amplification in the Ebro valley (line 248 and figure 4). Here we want to understand together the previous (figure 2) and the following analysis (figure 4), the processes that produce the general changes aloft the mountains, not caused directly by the soil conditions. Since it may be not clear, we slightly modified the following sentence (lines 217-219):

“To better understand the different physical mechanisms that gave rise to the high temperatures in the Pyrenees region, we separately quantified the temperature trendchanges aloft the mountains due to adiabatic, diabatic and advective processes (Fig.

3). We conducted this analysis for both heatwaves at 700 hPa, to avoid the influence of the terrain in the analysis."

Furthermore, to be sure that conditions at 700 hPa are robust enough we repeated the analysis at a slight lower level, leading to similar but not equal conditions:



Even though the authors use daily minimum temperatures (Tn) to evaluate heatwave occurrence and intensity, these results never make it into the paper. Given the importance of Tn in regard to human impacts, the authors might want to consider adding in any analyses and/or discussion on the drivers of anomalously warm Tn and if this varied between the two heatwaves at all?

Thank you for this valuable suggestion. We acknowledge the importance of minimum temperatures (Tn) in assessing the human impact of heatwaves, particularly in relation to

nighttime heat stress. However, in the Pyrenees, tropical nights (Tn ≥ 20°C) are extremely rare (Cuadrat et al., 2024), and their impact on human health and ecosystems is minimal compared to other regions where nighttime heat is a major concern (Lemus-Canovas et al., 2024).

Given this context, we focused our analysis on maximum temperatures (Tx), as they are more directly linked to the thermodynamic processes driving heatwave intensity, such as advection, subsidence, and land-atmosphere feedbacks.

Cuadrat, J. M., Serrano-Notivoli, R., Prohom, M., Cunillera, J., Tejedor, E., Saz, M. Á., de Luis, M., Llabrés-Brustenga, A., and Soubeyroux, J.-M.: Climate of the Pyrenees: Extremes indices and long-term trends, Science of The Total Environment, 933, 173052, https://doi.org/10.1016/j.scitotenv.2024.173052, 2024.

Lemus-Canovas, M., Montesinos-Ciuró, E., Cearreta-Innocenti, T., Serrano-Notivoli, R., and Royé, D.: Attribution of the unprecedented heat event of August 2023 in Barcelona (Spain) to observed and projected global warming, Urban Climate, 56, 102019, https://doi.org/10.1016/j.uclim.2024.102019, 2024.

I found it a little bit difficult to follow the results section describing the flow analogs, which could just be due to my unfamiliarity with this method. If I'm reading your plots correctly, it seems that the RMSD of the flow analogs is ~25-50% of the magnitude of the geopotential height anomaly associated with the 2022 events relative to climatology. Could you elaborate on if the size of the flow analog RMSD relative to the size of the 2022 geopotential height anomalies impacts their utility in any way?

Thank you for raising this point. The RMSD values indicate the inherent variability of atmospheric circulation but do not diminish the utility of the analog method. The goal of flow analogs is not to perfectly replicate the 2022 patterns but to identify past circulation states that are dynamically similar enough to provide insight into the thermodynamic contributions to heatwave intensity in our region of interest.

In our case, the median RMSD remains stable across periods, indicating that the synoptic structures associated with heatwaves have not changed significantly over time. This suggests that the observed temperature changes are primarily driven by thermodynamic factors rather than dynamic ones. Additionally, our analysis of the trend in the frequency of these analogues did not reveal any statistically significant changes (Fig S2).

Anyway, we have provided a detailed explanation on the above points between lines 283-287.

Would it be worthwhile to include a supplemental figure showing a composite of the Z500 field for the 30 flow analogs for the two events in order to get a sense of where the circulation patterns agree or disagree? For example, it could be useful to see if the flow analogs are well matched over the subtropical ridge area but disagree on the strength of the low over the Atlantic.

Thank you for your suggestion. We have included the suggested figure in the supplementary (new Figure S3). We found that the extracted analogues do not accurately capture the low-pressure system in the western Atlantic, while the subtropical ridge, which is the main driver of the event in the Pyrenees, is well represented (New figure S3). This

ensures that our analysis remains fully valid for our region of interest. We have also detailed this issue in the manuscript: please, see L288-291.

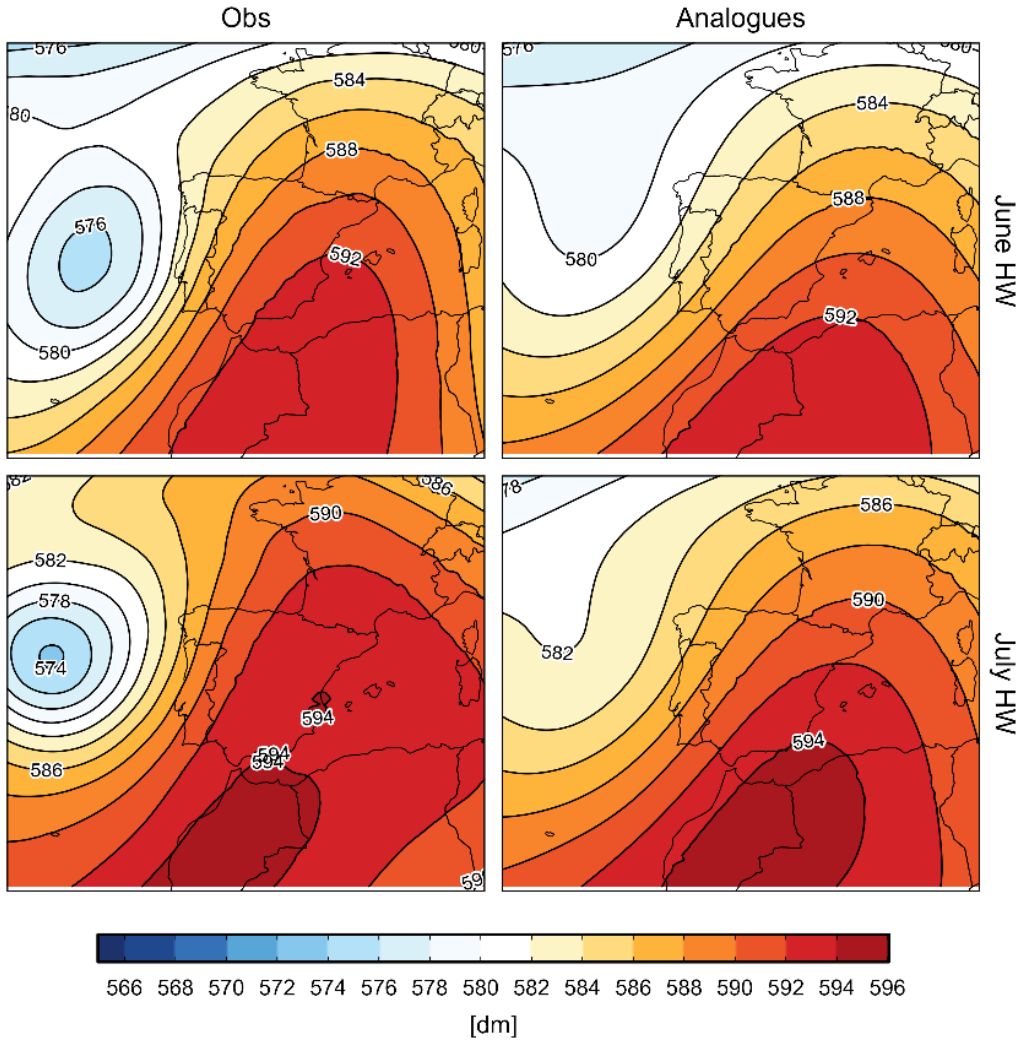


Figure S3. Observed and analogue Z500 pattern for the June and July heatwaves. The analogues were selected for the period 1950-2021, following the procedure described in the methods section.

Also, do you expect that the flow analogs are more relevant for characterizing the July heatwave in which you suggest that weaker wind patterns meant that the impact of the anomalously high geopotential height and subsidence was greater during this event than during the June heatwave?

Thank you for your insightful question. Flow analogs are relevant for characterising both heatwaves, as they are based on finding past and present synoptic situations that are dynamically similar at the Z500 level (Fig S3). As shown in Figure 1, the geopotential height

patterns in June and July 2022 were not drastically different, reinforcing the applicability of the analog approach in both cases.

However, an important distinction is that the analogs found for the July heatwave are less similar to the observed situation compared to those for the June event. This suggests that the July heatwave was a more anomalous event in the context of historical synoptic patterns for that time of year. Conversely, the analogs for June are closer to the actual observed conditions, indicating that this event had more precedents in past circulation states. We pointed out this in lines 285-287.

Based on Fig 5, the Tx anomalies associated with the 2022 heatwaves is beyond the 99th percentile of the historical data, so an extreme outlier. Was the soil moisture anomaly during this event also a significant outlier?

Thank you for your comment. Figure 5 does not show any information related to percentiles. We would appreciate it if the reviewer could clarify exactly to what figure is referring to. In figure 5, the boxplots represent the distribution of Tx anomalies from the analogues, while the magenta dot corresponds to the observed Tx value. Additionally, soil moisture anomalies distributions based on the analogues were analyzed in Figures S4 and S5 for the three study locations: Huesca, Encamp, and Tarbes.

Given that you found only small impacts of non-linear interactions in the reanalysis data, I'm wondering if this is just because of the limitations of the data in being able to capture the rarity of the 2022 event? I think you try to explain this in the conclusions by proposing a negative feedback between low cloud formation and Tx warming during hot and dry conditions that mitigates extreme temperatures in the higher topography regions. Is there any evidence to support this in your data, did you look at the low level cloud fields or cloud radiative effects?

Thank you again for your insightful questions. While reanalysis data may have limitations in fully capturing the rarity of the 2022 event, we have also analysed soil moisture effects using an independent observational dataset (Figure S7), which shows relatively consistent results with the reanalysis data.

In this study, we have primarily focused on the role of soil moisture and its influence on sensible and latent heat fluxes, which are intrinsically evaluated through the coupling metric. The potential influence of cloud cover is indeed an interesting aspect; however, we believe it warrants a dedicated work that is beyond the scope of this study. For this reason, we have discussed this aspect in the discussion section rather than in the main body of the paper.

Specific Comments:

Lines 44—45: "However, a more local approach is lacking for mountain areas and their surrounding regions." Can you be more specific about what a "more local approach" is in relation to the studies cited in the previous statement.

Done. Please, check the new text added between lines 44 and 46.

Lines 46—49: this sentence is very long, considering breaking it up to improve clarity.

Done.

Line 53: for (2), I think you want to specify that you're examining the role of anthropogenic greenhouse gas forcing on the intensity of the heatwaves, "climate change" feels a bit too vague

Thanks for the suggestion. We have rephrased it. Please, see L54.

Lines 51—55: It's not clear to me how objective (3) is different than (1)

We have rewritten the objectives. The first aims to analyse the dynamic and thermodynamic characteristics of the two events, while the third focuses mainly on exploring land-atmosphere interactions.

Line 58: I think these are listed backwards – typically Tx is associated with maximum temperature and Tn with minimum temperature (and this seems to be the convention used in the rest of the manuscript).

You are right. Thanks for pointing out this issue.

Line 61: Here you begin to shorten heatwave to HW, however, you use the term heatwave several times in the introduction already. You should be consistent about calling HW after the first instance of using heatwave. See also Section 2.2.1, where you switch between using heatwave and HW, creating more inconsistency.

Thank you for your comment. We have now ensured consistency by using "heatwave" instead of "HW" throughout the manuscript.

Line 74: unclear if the text inside of the parentheses is the long name related to CLIMPY or if it is just explaining what CLIMPY is?

We have suppressed the text between the parentheses as we have briefly explained what the project is about.

Section 2.2.2 and Section 2.2.3: both are labelled "Thermodynamic Equation"

Thank you for pointing out this error. The correct title is "Soil moisture-temperature coupling metric"

Lines 128—129: The first sentence of this section needs to be re-written in order to make it clear what the purpose of the analogue experiments are. As the sentence "We use the analogue approach, which …" is currently written, it does not explain what you use the analogue approach to do.

Done. Please, see L. 129

Figure 1: The first sentence of the caption seems incomplete "(a) Intensity and duration of the summer 2022." I believe the dots refer to the intensity/duration of heat above some threshold during JJA 2022 but the sentence reads like they correspond to differences in the intensity of the

summer itself. The figure caption needs to be checked for consistency overall – the authors I think accidentally use “y” instead of “and” at one point and the soil moisture units aren’t appropriately superscripted. Also, the labels of the 3 cities on panel a are small and a bit pixelated, making them difficult to read.

We have carefully reviewed all the comments you provided, and we have addressed the issues identified in the figure caption.

Line 162: I believe the ‘a’ in this sentence is a typo

Corrected.

Lines 193—194: “However, the July HW exhibited higher 500 hPa geopotential height anomalies than the June HW, with up to 40 meters of geopotential more” sounds quite awkward. More appropriate phrasing would be something like “500 hPa geopotential height anomalies were up to 40 m greater during the July HW than the June HW” or “Compared to the June HW, geopotential height anomalies during the July HW were up to 40 m greater.”

Thank you. We have improved this sentence with your suggestion.

Lines 195—197: Reference Figure 2a.

Done

Figure 2: add a row of panels showing the differences between the two heatwaves?

We appreciate your suggestion. However, we feel that the figure is already quite dense and the differences between the two heatwaves are easy to see at a glance.

Line 206: I don’t believe that you definitively demonstrated that both heatwaves were caused by the subtropical ridging. It would be more accurate to say that both heatwaves occurred during periods of stronger ridging.

We have replaced “caused” by “synoptically dominated".

Lines 214—219: It would be helpful if you could provide a sense for the days associated with each phase. For example, the “preconditioning” phase corresponds to days -4 to -2 preceding the maximum Tx of the heatwave. Or better yet, reference the color shading in Figure 3 (e.g. preconditioning (Fig. 3, purple shading).

Thank you for the idea. We agree that might help the reader. We changed accordingly, but we defined it as respect to the beginning of the build-up phase of the heatwave to make it more easy to understand.

Figure 3: If this is a timeseries of days from the beginning of each heatwave episode, why does the x-axis not start at 0 and why are all of the days negative? I would expect that either the peak temperature day would correspond to day 0 and the preceding days negative and subsequent days positive, or that the onset of the change in temperature (beginning of purple phase) would be 0 and all subsequent days positive?

The x-axis represents the day of the month, but we agree that the dash is confusing. As suggested, we modify it so the day at the beginning of the heatwave be the day 0 and the reference. We think that this suggestion improves the understanding of the processes.

Lines 248—250: Can you provide a metric that describes how close the 30 flow analogues actually are to the 2022 events? Perhaps standard deviation or RMSE between the 30 analogue composite and the event? Okay I see that you do get to this on Lines 271—274 (referencing panels 5c,f), but I wonder if it should be mentioned earlier in the section?

We have extended the interpretation of the RMSD in relation to the selected analogues, as discussed earlier. This can be found on lines 279-291.

Line 263: erroneous change in font size?

Corrected.

Lines 277—278: This sentence reads awkwardly, re-phrase to improve clarity.

Rephrased. L 295-297

Lines 397—398: The boundary layer, by definition, extends to the surface so this statement is a bit confusing. Perhaps it is the mixing between the warmer boundary layer air and cooler mid-tropospheric air masses?

We have rephrased this sentence for clarity. Lines 417-419.