Kroll et al., egusphere-2025-4391: “Increased heating of the land surface as hot-dry events persist” - Response to referee comment 1

We are grateful to the referee for their thorough review which we believe strengthens our methods and discussion. We include our response to each comment and suggestion with the planned modifications in an updated version of the manuscript.

Summary:

This study examines how atmospheric forcing and land-surface processes interact to shape the development and persistence of high temperatures during dry events, based on reanalysis data from the 1980s to the 2010s. By distinguishing between heat onset and heat persistence within soil moisture defined dry periods, the authors assess the respective roles of incoming shortwave radiation and evaporation. They find that the fraction of dry events accompanied by high temperatures has increased markedly, although no clear long-term trend emerges in the evolution of shortwave radiation and evaporation during these events. The analysis suggests that increased radiation primarily contributes to the onset of heat, while evaporative cooling can mitigate early heat development in humid regions but loses influence during persistent or more arid hot-dry conditions.

Overall comments: The manuscript addresses a timely and relevant question regarding the drivers of heat onset and persistence during dry events; however, the current methodological framework is not sufficiently robust to support the strength of the attribution claims made. The analysis relies largely on descriptive week-to-week changes, which limits the ability to draw firm conclusions about relative importance or causality. As presented, the reasoning linking changes in shortwave radiation and evaporation to temperature evolution remains somewhat speculative and not adequately supported by rigorous statistical testing or sensitivity analyses. The exclusive focus on two drivers is also insufficiently justified, particularly given the well-established roles of atmospheric circulation, advection, cloud dynamics, and other land-atmosphere feedback in shaping heat extremes. Several spatial patterns are interpreted qualitatively without adequate quantitative substantiation. Furthermore, key methodological definitions require clarification, and the presentation of figures and language would benefit from substantial revision. In its current form, the study does not provide sufficiently strong analytical evidence to substantiate its central conclusions, and major methodological and conceptual revisions is necessary.

Major Comments:

The methodology appears insufficient for the attribution claims made in the paper. The identification of heat onset and persistence relies primarily on percentile-based thresholds, but the attribution of drivers is based largely on descriptive analysis. The conclusions regarding the relative importance of different drivers would be more convincing if supported by more robust statistical or causal analyses.

We thank the reviewer for pointing out the limited presentation of the relevance of the selected factors. In general, temperature can change due to three factors: advection, adiabatic processes and diabatic processes, like sensible heat flux (Röthlisberger & Papritz, 2023). We will adapt the introduction and schematic figure (preliminary version in Fig. 1) to outline this more clearly. Additionally, we set up a heat budget diagnostic to strengthen our justification for selecting the driving factors. We will compare the contribution of sensible heat flux (dependent on radiation and evaporation) to the observed temperature change with the contribution of advection. We can therefore better quantify the importance of sensible heat flux for temperature dynamics during dryness.

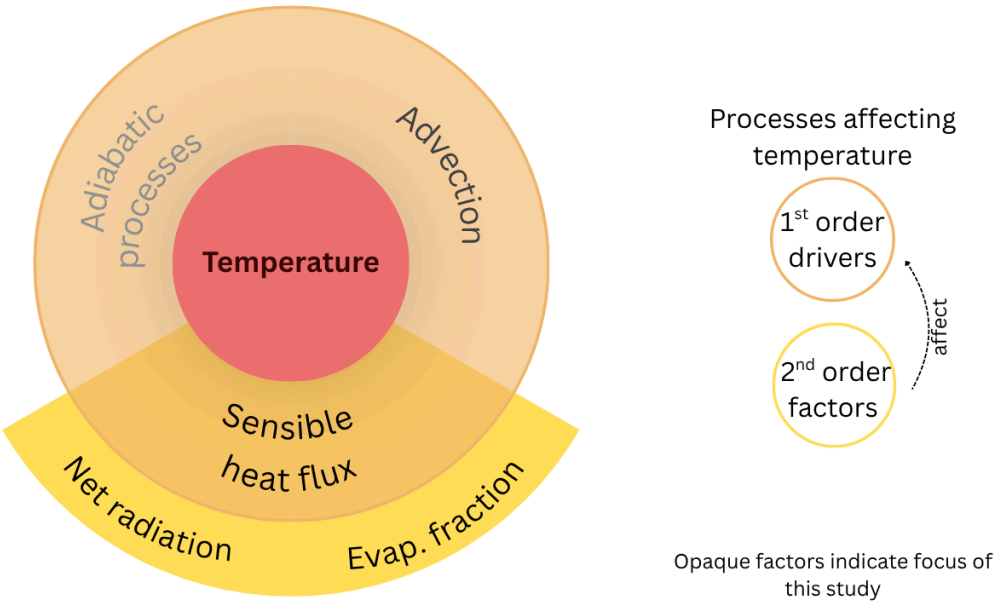

Figure 1: Adjusted schematic representation of 1st order drivers of temperature change and selected 2nd order factors influencing sensible heat flux as a focus of this study.

The authors rely mainly on shortwave radiation and evapotranspiration as drivers of heat onset and persistence. However, several other variables can influence these processes, such as vapor pressure deficit (VPD), soil temperature, ground evaporation, atmospheric circulation indices etc. The authors should justify why only two variables were selected or expand the analysis to include additional relevant drivers.

We thank the reviewer for highlighting the importance of clearly motivating the variable drivers choice. We will adapt our introduction to clearly outline the first order contributors to temperature development: advection, sensible heat flux and adiabatic processes. As we do not aim to fully close the atmospheric heat budget, we will focus on the contribution of sensible heat flux in comparison to advection in terms of induced temperature change. Consequently, we redefine our variable selection analyzing evaporative fraction and net radiation in the revised manuscript as these directly determine the magnitude of the sensible heat flux (diabatic heating). Evaporative fraction describes the land surface contribution to sensible heat flux more accurately than evaporation. Furthermore, net radiation represents the energy input more precisely compared to incoming shortwave radiation.

The manuscript acknowledges that processes such as advection and atmospheric circulation may drive heat persistence. However, these processes are not explicitly analyzed. The authors should include at least some atmospheric circulation or advection metrics to demonstrate their potential role

We thank the reviewer for their suggestion to include a variable representing atmospheric circulation or advection. To address this comment, we will compare the contribution of sensible heat flux to temperature change along with the contribution of advection. We will extend our analysis by incorporating a first-order lower-atmospheric heat-budget diagnostic, rather than a complete closure of the atmospheric heat budget. We will estimate horizontal temperature advection from the wind components and temperature gradients and compare its contribution to surface warming from diabatic heating, i.e., surface sensible heat flux. The revised analysis will compare i) the observed temperature tendency (eq. 1), ii) the temperature tendency associated with sensible heat flux (eq. 2), and iii) the tendency associated with horizontal thermal advection (eq. 3). Any remaining imbalance will be presented as a residual term, acknowledging that additional processes (e.g., adiabatic warming) are not explicitly represented.

$$\left(\frac{dT}{dt}\right)_{obs.} = T_t - T_{t-1} \qquad \text{eq. 1}$$

$$\left(\frac{dT}{dt}\right)_{H} = \frac{H_{t-1}}{\rho \cdot c_p \cdot z} \qquad \text{eq. 2}$$

$$\left(\frac{dT}{dt}\right)_{Adv} = -(u \cdot dTdx + v \cdot dTdy) \qquad \text{eq. 3}$$

With T referring to temperature, t referring to time, H corresponding to sensible heat flux, ρ refers to the density of the air, c_p to the specific heat capacity of air, z to the boundary layer height, u and v to the eastward and northward component of the wind, respectively.

A more formal causal attribution could be performed using: Partial correlation analysis, Multiple regression, or other statistical attribution approaches. This would allow the authors to quantify the relative importance of different drivers, especially in the identified hotspots.

We acknowledge the reviewer's suggestion to quantify relative feature importance as an approach to causally attribute our analysis. Nevertheless, because of the limited data points for the extreme events distribution and the low variability within the temperature values during hot-dry periods, we think that any regression or modelling approaches would present limitations. To address the reviewer's concern while maintaining a physically interpretable framework, we will extend the analysis by incorporating a first-order lower-atmospheric heat-budget diagnostic as previously mentioned. We believe this additional analysis strengthens the causal attribution of the study and directly addresses the reviewer's concern regarding the role of atmospheric processes.

The role of vegetation is only represented through tree cover fraction. However, vegetation structure and biome type are likely to influence the response of heat and drought events. The analysis could be extended to comparison of responses across biomes (e.g., forests, grasslands, croplands) and provide spatial maps showing structural or biome-dependent effects. This would add ecological context and strengthen the interpretation of the results.

We thank the reviewer for this suggestion. We agree that both vegetation structure and biome type can influence the development and persistence of compound events. To further explore this aspect, we will extend the analysis by stratifying the results across major eco-climatic regions using established classifications (e.g., Köppen-Geiger climate zones or global land cover categories). This will allow us to provide spatial context about the relative importance of radiation and evaporative fraction, sensible heat flux, and atmospheric advection across these regions.

Several statements describing spatial patterns are qualitative and would benefit from quantitative support. For example: Line 135: Identification of regional hotspots, Line 149: Relationship between net radiation and shortwave radiation, Line 157: Regional differences in ET, SWdown, and soil moisture responses. These statements should be accompanied by quantitative metrics, regional statistics, comparative tables or plots

We thank the reviewer for the suggestion. We will include a quantitative summary supplementary table to support the qualitative statements based on regions defined by a cluster of grid cells that exceed the 90th percentile of ΔT, which we use to identify the most pronounced hotspot areas.

The manuscript attributes some of the radiation changes to cloud dynamics, for example: Line 166: Dissipation of clouds leading to increased SWdown. Line 239: Minor cloud cover reducing SWdown during persistence. However, these statements are speculative and not supported by explicit analysis. The authors should include a cloud-related variable (e.g., cloud fraction or radiation components) to demonstrate this mechanism quantitatively.

We thank the reviewer for the suggestion to investigate a cloud-cover related variable. We support our discussion and interpretation of the results now by illustrating week-to-week changes in cloud cover fraction.

The relationship between heat onset and drought onset is not clearly explained. The authors should clarify: Whether heat onset corresponds to the beginning of drought. Or whether heat onset is defined independently of drought development. This distinction is important for interpreting compound events.

We thank the reviewer for making us aware of the imprecise definition of heat onset vs drought onset. We only consider heat onsets that take place within a dry period. However, heat onsets do not need to align in time with when the dry period starts. Actually, during a dry period hot weeks can occur several times. Specifically, the definition of heat onset refers to the temperature conditions in the previous two weeks. Heat persistence makes reference to conditions when one week or less separates two (or more) hot weeks during the same dry period.

In Figure 2, the authors indicate that the median was used for all analyses (Figure 3-4). It would be helpful for the authors to clarify why the median was selected instead of other statistical measures. A brief explanation, particularly regarding the data distribution, presence of outliers, or other methodological considerations, would improve clarity and strengthen the justification of the approach.

We thank the reviewer for the comment. The median was chosen instead of other statistical measures, for instance the mean, because most of the analyzed variables exhibit skewed distributions across time and space. In such cases, the median provides a robust measure of central tendency that is less sensitive to outliers and better captures the typical variable response across grid cells.

No time series are shown to illustrate the temporal evolution of key variables across decades or within individual dry events. Including time series plots of temperature, shortwave radiation, and evapotranspiration would improve transparency and help substantiate the claims about temporal dynamics and trends.

We agree with the reviewer that an illustration of the temporal development of temperature, sensible heat flux, advection, net radiation and evaporative fraction during dry events would help understanding the ongoing processes. However, we also acknowledge - in line with comments from reviewer 2 - that combining multiple events and grid cells can complicate interpretability, e.g. due to the heterogeneity in the development of hot extremes. We therefore plan to visualize time series of the respective variables for e. g. each tree cover-long-term dryness regime or biome illustrating the median and standard deviation across all events and grid cells in one respective regime.

The histograms currently present only the global distribution. Including separate histograms for different regions would enable clearer comparison of regional patterns. These additional figures could be provided in the appendix to maintain the flow of the main text while offering more detailed regional insights.

We thank the reviewer for this suggestion. We will add supplementary histograms stratified by eco-climatic regions (e. g. based tree cover-dryness regimes or biomes) which will allow a more detailed comparison of regional patterns.

The definition of aridity (Table 2) should be clearly explained in the Methods or Results section before the term is introduced. The exact range used for classification also needs to be specified to ensure clarity and reproducibility. Additionally, including a map that illustrates the spatial distribution of aridity would facilitate clearer comparison across regions and enhance the overall presentation of the results.

We thank the reviewer for this suggestion. We will introduce the definition of aridity more precisely, as well as the exact range used and what each class represents. We refer to aridity as an indicator of long-term dryness computed as long-term mean net radiation divided by long-term mean unit-adjusted precipitation. We understand regions with a long-term dryness below 1 as humid, whereas regions above 1 are referred to as arid in the manuscript. Semi-arid regions refer to regions with a long-term dryness of 1-2.
Additionally, we will add a map illustrating long-term dryness classes and tree cover classes (see Fig. 2) and tree cover-long-term dryness regimes (see Fig. 3) in the supplementary material.

Long-term dryness classes

Mean tree cover fraction

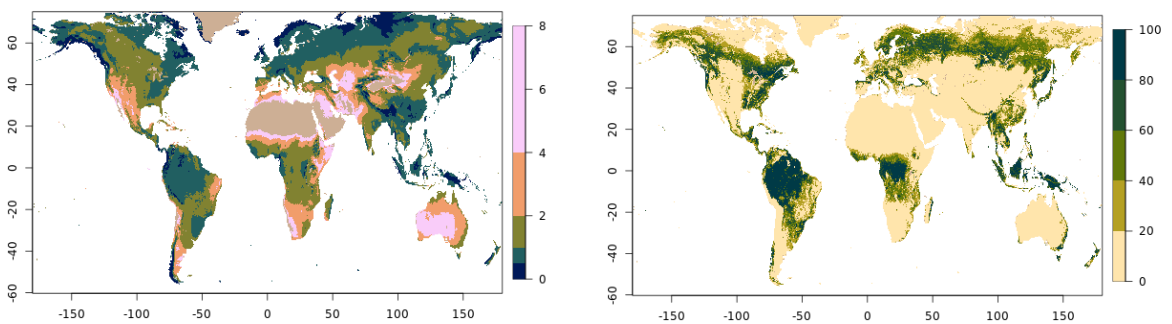

Figure 2: Illustration of spatial distribution of long-term dryness categories (left) and mean tree cover fraction (right).

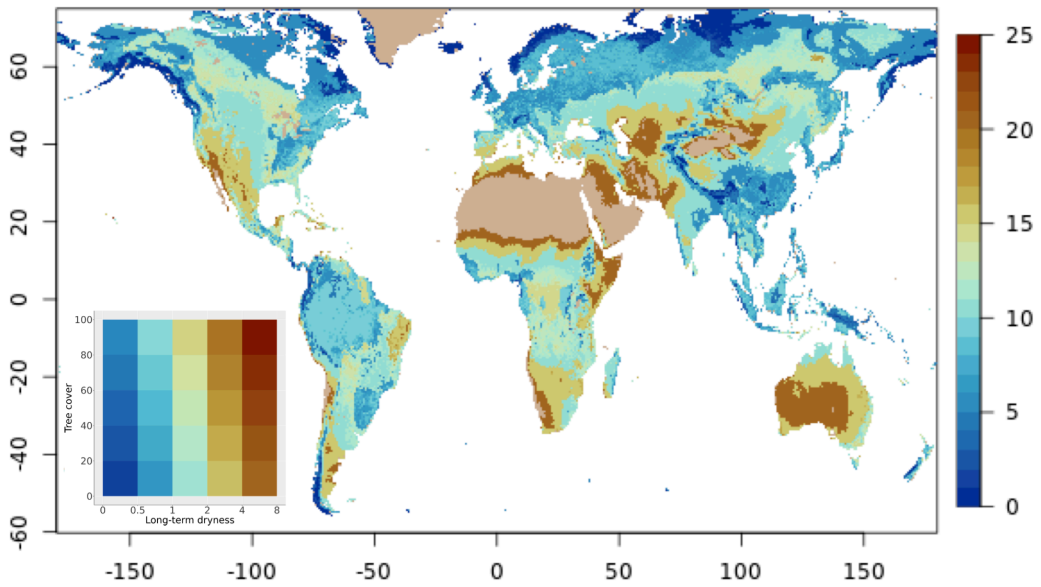

Figure 3: Illustration of tree cover and long-term dryness regimes. The heatmap in the lower left corner illustrates the color code applied in the map.

Minor Comments:

The overall language in the manuscript appears somewhat casual, and there are a few grammatical and punctuation issues. The authors are encouraged to revise the manuscript carefully for language accuracy. Punctuation issues are noticeable in Lines 123, 125, 171, and 197.

We thank the reviewer for spotting the punctuation issues. We will adapt the language style accordingly.

Some sentences require rephrasing for clarity and readability. For example:

Line 51: “For example, atmospheric circulation creates persistent weather patterns leading to the build-up of high temperatures (Brunner et al., 2017; Barriopedro et al., 2023). On a regional scale, advection of warm air can further increase temperatures during dry periods (Miralles et al., 2019; Schumacher et al., 2019) and secondly, diel dynamics in the local boundary layer support the persistence of high temperatures by trapping and reintroducing warm air to the surface-near air (Miralles et al., 2014).”. The description of atmospheric circulation, advection, and boundary-layer processes is long and difficult to follow. The sentence should be broken into shorter, clearer statements.

Line 193: “Independent of what causes the temperature increases resulting from increased H during dryness - i) increases in SW_down, ii) SW_down increases in

combination with SM-suppressed ET or iii) other factors - magnitudes are comparable" The sentence describing different mechanisms leading to temperature increases during dryness is complex and difficult to interpret. It should be simplified and restructured for clarity.

The mentioned sentences will be broken down to be better understandable as shown below for one of the listed examples. We thank the reviewer for pointing to these complex paragraphs.

"For example, atmospheric circulation creates persistent weather patterns that favor the development of high temperatures (Brunner et al., 2017; Barriopedro et al., 2023). At the regional scale, advection of warm air can further enhance temperatures during dry periods (Miralles et al., 2019; Schumacher et al., 2019). In addition, daily dynamics of the local boundary layer can contribute to the persistence of high temperatures by confining warm air and then releasing it near the surface (Miralles et al., 2014)."

The figure captions require further development, as they are currently too brief and do not provide sufficient detail for readers to fully understand the figures. Detailed captions should clearly describe the content, variables, and key elements of each figure which would improve clarity and enhance the overall readability of the manuscript.

We thank the reviewer for their feedback. We will revise the figure captions accordingly.

Figure 1: Use a consistent font style throughout the figure. The sensible heat flux label is currently overlapping with the clipart, which reduces clarity. Also, clearly define what "T" represents in the figure. Consider making the labels bold, increasing the line thickness, and enlarging and bolding the arrows to improve readability. These adjustments will make the figure clearer and more visually effective.
We thank the reviewer for the suggestions to improve Figure 1. We will adapt the illustration and improve the description in the caption to clarify the message that it conveys. A preliminary version of the schematic figure (Figure 1 in the manuscript) can be found above, labelled as fig. 1.

References

Röthlisberger, M., & Papritz, L. (2023). Quantifying the physical processes leading to atmospheric hot extremes at a global scale. *Nature Geoscience*, *16*(3), 210-216.