Responses to Reviewers' Comments

for

A Multivariate Analysis of Atmospheric Drivers for Western European Heatwaves

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Submitted to

Earth System Dynamics

by

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Authors’ Response to the Editor

Dear Dr. Kai Kornhuber,

We would like to thank you for handling our manuscript and for providing the opportunity to submit a revised version of our work, "A Multivariate Analysis of Atmospheric Drivers for Western European Heatwaves".

In this revision, we have addressed Reviewer #2’s points by carefully reframing our discussion in the manuscript:

1. We expanded the physical descriptions to demonstrate that the VAE captures distinct structural circulation geometries, rather than merely sorting by calendar season.
2. We integrated the reviewer’s suggested literature to acknowledge the nonlinear complexities of these drivers, moving beyond the simplifications of linear detrending.

All changes are highlighted in the revised manuscript and included in this response letter. We believe these textual refinements resolve the remaining concerns and look forward to your decision.

Sincerely,
Dr. Aytaç Paçal
(on behalf of the co-authors)

Response to Reviewer 2 Comments

for

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Authors' Response to Reviewer 1

General Comments. I thank the authors for their elaborate response, and for having incorporated the additional analysis in the manuscript. Nevertheless, I still have some doubts about the article, especially considering the following two points. But I'd like to leave it up to the editor to see if they are small enough to accept the paper in its current form.

Response:

We thank the reviewer for their continued careful reading and for these two thoughtful points. We address each below. We note that both concerns are matters of interpretation and framing, and we have revised the manuscript text accordingly without altering any results.

Major Comment 1

1. The clusters you find still resemble the seasons – which makes me doubt the interpretation of your results and thereby the usefulness of the analysis. For example, you define cluster 1 as a "UK High" or "Omega Block" (L325), which you compare to the results from Happé et al. (2024) and Rouges et al. (2023) who both focusses on summer heatwaves only, yet in your results you find 0 summer heatwaves belong in this cluster (Fig 4, top right panel). Actually, a blocking high pattern usually causes colder conditions during winter. To me this result is therefore confusing.

Response:

We thank the reviewer for raising this point, which has helped us clarify the interpretation of Cluster #1. The confusion stems from an ambiguity in our original wording, which we have now modified. The labels "UK High" and "omega block" were intended to describe the topology of the circulation pattern, namely a persistent anticyclonic anomaly centered over the British Isles and Western Europe with positive geopotential height anomalies and suppressed cloud cover, and not a summer-specific phenomenon or an absolute-temperature outcome.

Our heatwave detection is threshold-based and seasonally relative. As described in Section 2.2, for each grid cell we calculate the 90th percentile threshold for each calendar day using a 15-day moving window, so an event entering the dataset is, by construction, anomalously warm relative to its own season's climatology, not relative to summer. A winter event in Cluster #1 therefore represents a winter warm spell, i.e., anomalous warmth relative to the winter baseline, and does not imply summer-like absolute temperatures.

Our own results are physically consistent with this interpretation. In Figure 5, Cluster 1 exhibits weak positive 2-meter temperature anomaly, precisely what one expects for a winter-dominated cluster in which the circulation pattern drives anomalous, but not absolutely extreme, warmth. Cluster #1 is thus not a summer-type heatwave, and our revised text now states this explicitly rather than inviting the reader to equate it with the summer events studied by Happé et al. (2024) and Rouges et al. (2023). The comparison to those studies is now framed strictly as a comparison of circulation structure, with the explicit clarification that we find this structure operating in a different (winter) seasonal context and producing a different (anomaly-relative) thermal outcome.

Abstract:
... When analyzing non-detrended data, recent summer heatwaves occupy a distinct region in the latent space, consistent with the strong warming-driven intensification of these events. However, analyses of detrended data reveal structural shifts in atmospheric configurations across all seasons, indicating that the VAE captures changes in the multivariate structure of heatwave-related variables beyond simple mean warming. Composite anomaly maps further show coherent pre-onset patterns across variables. ...

Line 330 ... In Figures 7 and 8, cluster *#1* exhibits a circulation structure that is topologically similar to the UK High cluster in Happé et al. (2024) and the omega block in Rouges et al. (2023) for the onset day of the heatwaves, persistent anticyclonic anomaly centered over the British Isles and Western Europe, with positive geopotential height anomalies, suppressed cloud cover, and warm advection from the Atlantic. This comparison refers to the *dynamical structure* of the circulation pattern, not to its seasonal context or absolute temperature anomaly levels. Cluster *#1* is dominated by winter events and contain no summer heatwaves (Figure 4e) and accordingly shows weak positive 2-meter temperature anomaly (Figure 5). Because our heatwave sample detection method is seasonal threshold-based (Section 3.3), an event in this cluster represents anomalous warmth relative to its own seasonal climatology, i.e., a winter warm spell, rather than absolute heat comparable to summer. While Happé et al. (2024) found this UK high pattern in summer (JJA) months and Rouges et al. (2023) found this pattern in extended summer (May to September) months, our analysis, which uses standardized anomalies relative to each calendar day's local climatology, reveals that structurally analogous circulation configurations also drive anomalous warmth during winter months relative to the winter baseline. This is consistent with previous studies documenting that winter warm spells over Europe are associated with positive geopotential height anomalies and anticyclonic blocking, as shown in Figure 15 (Tomczyk et al. 2019; Leach et al. 2021). . . .

Line 394 . . . These interacting atmospheric mechanisms help explain why the latent space representations of summer heatwave samples (see Figure 4) are distinctly clustered and separate from the rest of the dataset. The isolation of this cluster underscores that summer heatwaves are not driven by simple linear temperature increases, but by a highly nonlinear interplay between specific dynamical configurations (like the deep North Atlantic trough) and intense thermodynamic processes. As heatwaves intensify and high temperatures rise more rapidly in Europe and other mid-latitude regions (Beobide-Arsuaga et al. 2025; Perkins-Kirkpatrick and Lewis 2020; Bischof et al. 2023; Paçal et al. 2023), enhanced land-atmosphere coupling and moisture deficits physically alter the atmospheric state (Chen et al. 2026; Shaw et al. 2024). Since the VAE is sensitive to these complex, coupled multivariate structures, recent extreme summer events diverge sharply from the historical distribution learned during training. . . .

Major Comment 2

2. With the new detrended analysis comparison you discuss the new results. Specifically, you discuss thermodynamic vs dynamical changes based on latent space shifts, yet use only a linear detrending on the input data. I believe that splitting thermodynamic and dynamical contributions is more complex than that. This requires some more attention if you frame it like thermodynamical vs dynamical changes, otherwise I think reframing this is needed to not draw wrong conclusions. Literature as reference:

- Laura Suarez-Gutierrez et al. (2020). "Dynamical and thermodynamical drivers of variability in European summer heat extremes". In: *Climate Dynamics* 54, pp. 4351–4366. DOI: `10.1007/s00382-020-05233-2`
- Jitendra Singh, Sebastian Sippel, and Erich M. Fischer (Nov. 2023). "Circulation dampened heat extremes intensification over the Midwest USA and amplified over Western Europe". In: *Communications Earth & Environment* 4, p. 432. DOI: `10.1038/s43247-023-01096-7`
- Dominik L. Schumacher et al. (2024). "Exacerbated summer European warming not captured by climate models neglecting long-term aerosol changes". In: *Communications Earth & Environment* 5, p. 182. DOI: `10.1038/s43247-024-01332-8`

Response:

We thank the reviewer for this important methodological point and for pointing us to the relevant literature. Separation of thermodynamic and dynamical contributions to heatwave changes is considerably more complex than what linear detrending can achieve (Shaw et al. 2024). Linear detrending removes the linear component of the long-term mean trend in each variable, but it does not account for nonlinear warming trends, changes in variability, or the coupling between thermodynamic and dynamical processes. We have revised the relevant passages throughout the manuscript to reframe the detrended analysis more conservatively.

Line 263 . . . This finding is consistent with recent projections that changes in internal variability and moisture limitations can enhance land-atmosphere feedbacks, particularly in central and northern Europe, thereby altering the nature of extreme events (Beobide-Arsuaga et al. 2025). After removing the linear warming trend from the input fields, structural shifts in atmospheric configurations persist across all seasons, indicating that the model captures changes in the multivariate structure of heatwave-related variables that are not explained by the linear warming trend. However, linear detrending removes only the slow, monotonic component of each input variable, while the residual still contains nonlinear thermodynamic effects and circulation variability (Shaw et al. 2024; Suarez-Gutierrez et al. 2020; Singh, Sippel, and Fischer 2023; Schumacher et al. 2024). The residual shifts reported here should therefore be interpreted as evidence that the multivariate structure of heatwave-related variables is evolving, rather than as a quantitative attribution to circulation dynamics. ...

Line 405 ... The separation of these two clusters directly demonstrates that the VAE's latent space captures distinct physical atmospheric configurations, rather than merely sorting events by the season. Although both clusters occur during the same transition months, they represent fundamentally different dynamical regimes. Cluster *#3* is driven by a thermodynamic pathway dominated by enhanced solar radiation and clear skies, while Cluster *#4* is linked to stronger large-scale pressure anomalies and advection. ...

Line 482 ... Despite the data being standardized, the VAE organizes heatwave samples into clusters that align with seasonal differences, suggesting that seasonal signals are embedded in the atmospheric patterns of the test period. We note that the persistence of seasonal grouping despite year-round, deseasonalized, and standardized inputs indicates that the multivariate circulation structure of heatwaves differs systematically across seasons. The clearest illustration is the pair of transition-season clusters *#3* and *#4*, which contains same seasonal samples (MAM and SON) yet display near-opposite *z500*, wind, and humidity structures, confirming that the clustering separates dynamical regimes and not merely calendar months.

Our statistical validation confirms that these latent space shifts are not mere artifacts of the temporal split or thermodynamic trends. The Hotelling's T^2 tests reveal highly significant temporal shifts ($p < 0.001$) across all seasons in both detrended and non-detrended data. The contrasting seasonal responses to detrending indicate that the removable linear component of the latent-space shift is largest in summer, consistent with the strong warming-driven intensification of recent summer heatwaves (Mazdiyasni et al. 2019; Beobide-Arsuaga et al. 2025), whereas substantial shifts persist in the other seasons once the linear trend is removed. While the warming-related component dominates the summer heatwave separation signal, the robust shifts maintained in other seasons demonstrate that the VAE successfully captures genuine structural changes in atmospheric dynamics that were not present during the training period. ...

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