Large-scale drivers of compounding hot and dry events in three breadbasket regions

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Response to the Reviewers' comments

We thank the Editors and the Reviewers for their interest in our manuscript and the valuable comments they have provided which contributed to improve the robustness of the results and the overall quality of the paper.
A point-by-point response to the reviewers' comments is provided below.

Reviewer 1

General comment: *"Castillo et al. investigate the occurrence of joint hot dry – events in three mid-latitude regions and provide a large-scale dynamical perspective by analysing Rossby wave composites. Compound events and the atmospheric drivers can be of high interest in the context of high impact low likelihood events such as concurrent breadbasket failures and therefore deserve some attention. The analysis is nicely done and the results are interesting. However, while the authors present a solid framework for investigating such events based on historical reanalysis the present manuscript falls short in delivering answers to some of the most pressing questions in this discourse, namely: To what extent is agricultural production affected (or at least regions of agricultural production) by hot dry events, is there a higher risk of concurrent breadbasket failures expected from atmosphere dynamical changes alone? To what degree do Rossby waves favour concurrent hot-dry events across the mid-latitudes and is this effect important compared to other drivers/teleconnections, e.g. internal variability? What can we say about historical trends and future expectations? Answers to these questions lie at the fingertips of the authors, as most of the data seems to be provided (hot dry events, wave events, …) but a quantitative analysis is missing. I would therefore suggest major revisions to address my more specific comments below."*

Response: We thank the reviewer for this comment. We agree that many aspects of the paper need to be improved, particularly the assessment of the robustness of the physical mechanisms proposed to explain the association between the circulation anomalies and the occurrence of the compound hot-dry events. However, we highlight that the focus of the paper is to provide a physical frame for the compound occurrence of hot-dry events in the northern mid-latitudes, which could be used to improve the predictability of such events. For this reason, we removed the multidecadal trend from the data to focus on the internal dynamics, rather than on the effect of the external forcing. Future projections are beyond the scope of this paper, as well as the assessment of impacts on the agricultural sector. Target regions have been selected for including some of the most important global breadbaskets and being representative of the main landmasses in the Northern Hemisphere and meet the need to sample different dynamical patterns and provide knowledge to be used for impact studies. We provide in the following a detailed description of the additional analysis we performed and the modifications to the text we implemented to address your concerns.

Major

Comment 1: *"l. 91 More recent drought studies usually rely on the SPEI instead of the SPI as it acknowledges the role of evapotranspiration due to high temperatures (e.g. Gebrechorkos et al. 2025), the effect that the authors* *name as the driving force connecting warming and more severe hot-dry events in l. 37 and the fact that authors want to investigate 'physical drivers'. Results should not depend on this choice substantially, but it would be important to understand the differences using an example. E.g. is this why no trends are detected (Fig. 4), while the authors argue in their intro that combined hot-dry extremes become more relevant in a warmer climate? A section to motivate the indicator choice explicitly in the text would be useful as well."*

Response 1: We thank the reviewer for this point. We agree that SPEI is more suitable to characterize drought in a context of rising temperatures, because it includes potential evapotranspiration (PET) in addition to precipitation and is therefore sensitive to temperature-related changes in evaporative demand (Vicente-Serrano et al., 2010). In this work, however, our aim is to diagnose the large-scale atmospheric drivers associated with compound hot and dry conditions. For this reason, we intentionally define the dry component using the Standardized Precipitation Index (SPI3), which represents meteorological drought based solely on precipitation deficits. This choice is also consistent with the World Meteorological Organization recommendations for meteorological drought monitoring (Svoboda et al., 2012) and other studies that have used SPI in compound event definition (Guo et al., 2025; Ionita, 2024; Wu et al., 2021). Importantly, our compound-event framework already includes an explicit temperature-based definition of heat extremes. This separation reduces redundancy between the two components of the compound occurrence definition and avoids accounting temperature effects twice. Using SPEI would therefore introduce temperature information into both the hot and dry components, potentially reducing the independence between the two variables. The use of SPI3 together with an independent heat indicator aims to isolate precipitation deficits from temperature anomalies more clearly and thereby facilitate interpretation of the associated circulation patterns.

We have clarified this motivation in the methods section (L.96), where we now state:

"In this study, drought conditions at each grid point are identified by using the Standardized Precipitation Index (SPI), which is a commonly used index for meteorological drought recommended by the World Meteorological Organization (Svoboda et al., 2012) and widely used in compound hot-dry event studies (e.g., Guo et al., 2025; Ionita et al., 2021; Wu et al., 2021). This selection is motivated by the fact that our compound-event framework identifies heat extremes explicitly from temperature, and we aim to keep the dry component independent from temperature to facilitate a cleaner dynamical interpretation of compound hot-dry co-occurrence."

Regarding the reviewer's question about the absence of trends in Fig. 4: We clarify that the absence of trends in Fig. 4 is a methodological consequence of our 30-year shifting climatological baseline for the definition of SPI3 and the calculation of the 90th percentile for temperature. This approach intentionally reduces the influence of slow mean-state changes, such as long-term warming trends, and instead emphasizes anomalous hot-dry conditions emerging within the internal dynamics. Therefore, long-term trends in the fraction of area with compound hot and dry conditions are not necessarily expected within this framework, even in a warming climate. The aim is to investigate the mechanisms leading to the compounding, without being misled by increasing compounding made more likely just due to increasing temperatures. This is stated in line 110 and line 126 of the revised manuscript.

Comment 2: "*l.147 it seems as if the selection of regions is not directly informed by local agricultural production as done e.g in Kornhuber et al. 2023 or Vogel et al. 2019. Thus, strictly speaking these are just 'SREX regions' and not necessarily 'breadbasket regions'. The analysis is therefore fairly close to earlier studies from Sarhadi et* *al. 2019, Zhou et al. 2023 and Nasong et al. 2025, that are not cited in the present manuscript. It remains open how much of the global production of the named cereal crops is accounted for by focussing on these three specific areas, that include large ocean regions and areas that do not feature relevant agricultural activity (e.g. Northern Africa), but leave out Eastern Europe (while the Russian Heatwave is discussed as the prime example in the introduction) and India/Pakistan which was affected by a heatwave in 2022 as well (arguably in Spring not in Summer, see Aadhar & Mishra 2023) with severe agricultural impacts. Another open question would be, why were other mid-lat. regions in the northern hemisphere left out? The selection of these specific locations will almost certainly impose Rossby waves as a driving pattern as they are symmetrically distanced across the mid-latitudes. E.g. choosing zonally elongated regions will favour lower wavenumbers that relate to surface anomalies of a larger extent zonal extent, compared to higher wavenumbers."*

Response 2: We thank the reviewer for this detailed comment. We agree that our selected domains correspond to IPCC/SREX regions and not explicitly isolate agricultural production areas using crop data. However, the use of SREX/IPCC regions to investigate compound hot and dry events and heat and precipitation extremes has precedent in previous studies. For example, Raymond et al., (2022) and Dietz et al., (2025). In the latter one, different maize breadbaskets were analyzed using SREX regions that encompass major agricultural production areas. Raymond et al., 2022 also used SRE/IPCC definition and analyzed over main maize-breadbasket regions in the world.

The scope of our paper is to investigate the large-scale circulation patterns associated with compound hot and dry conditions across major Northern Hemisphere midlatitude regions that include major agricultural areas, rather than define agricultural production hotspots quantitatively. To avoid confusion, we modified line 151 and wrote "to encompass some breadbasket regions in the Northern Hemisphere."

We also thank the reviewer for pointing out additional relevant studies investigating dry and hot conditions (Sarhadi et al., 2018), climate extremes (Zhou et al., 2023), concurrent heat extremes (Nasong et al., 2025). These references have now been added to the introduction (line 37, and line 68) of previous work on compound hot and dry extremes and concurrent heat extremes, in the revised manuscript.

The selected domains were chosen following regional frameworks found in previous studies investigating synchronized crop failures across agriculturally relevant Northern Hemisphere regions (e.g. Gaupp et al., 2020; Kornhuber et al., 2020; Dietz et al., 2025). We agree that other regions such as South Asia are also relevant for hot and dry events and their agricultural impacts, but it was not included in the analysis to keep it focused on mid-latitude dynamics during June July August compound events. Much of South Asia lies outside the latitude belt used for the planetary-wave analysis and is strongly affected by the distinct dynamics and precipitation seasonality of the summer monsoon. Central Asia was also excluded to not get results too similar to the Euro-Mediterranean region and keep the manuscript informative and as much as possible compact.

We appreciate the reviewer's comment regarding the possible influence of the geographical location of the selected regions on the detected circulation patterns. However, the selected regions were not chosen to impose Rossby-wave-like structures. The focus on these Northern Hemisphere midlatitudes is motivated by previous literature identifying amplified quasi-stationary Rossby waves as drivers of summer heat extremes (i.e. only hot events) for similar regions. In addition, our results do not exclusively identify low zonal wavenumbers. Different dominant wavenumbers are identified across regions and event categories, suggesting that the detected patterns are not only determined by the location of the selected domains.

We also highlight that the identification of compound hot and dry events and identification of high fraction of area events to get the composites of the atmospheric drivers is conducted over land only, and grid-points over the ocean are not included in the computations.

Comment 3: *"Could the authors reflect more quantitively on the relationship between hot/dry events and wave events? Is their concurrence significant? How do Wave events that relate to hot/dry events different from those that don't relate to hot dry events? Could there be other driver(s) that preconditions the events?"*
Response 3: Thanks for your question, which give us the opportunity to provide more robust evidence to our conclusions. To address your points, we first compare the meridional wind structure and zonal wavenumber distribution during months characterized by impactful compound hot and dry conditions (high fraction of area, high-FA, events) with months characterized by limited impact (low-FA events). The composites of high-FA events show a clear wave structure in v250, which results from an overall synchronization of the ridges and troughs associated with the individual events (Fig. R1a-c), suggesting that the circulation anomalies are not randomly phased. A southerly-northerly structure, leading to anticyclonic circulations, is particularly evident over NA and EM (Fig. R1a,b), whereas the synchronization of the individual wave patterns in less evident over AS (Fig R1c). This wave structure may favor the recurrent development of ridging and subsidence over the target regions, which enhances surface warming, suppress precipitation and contribute to maintain the compound hot-dry conditions. In contrast, the low-FA months (Fig. R1d-f) overall display non-in-phase wave-like structures, resulting in no prevailing circulation patters in the target regions, except for NA (Fig. R1b), where the mean pattern displays a northerly-southerly structure, consistent with cyclonic conditions. We then conclude that the circulation anomalies we see in Figures 5, 7, 9 in the new version of the manuscript are a robust feature associated with the occurrence of high FA events in the target regions.

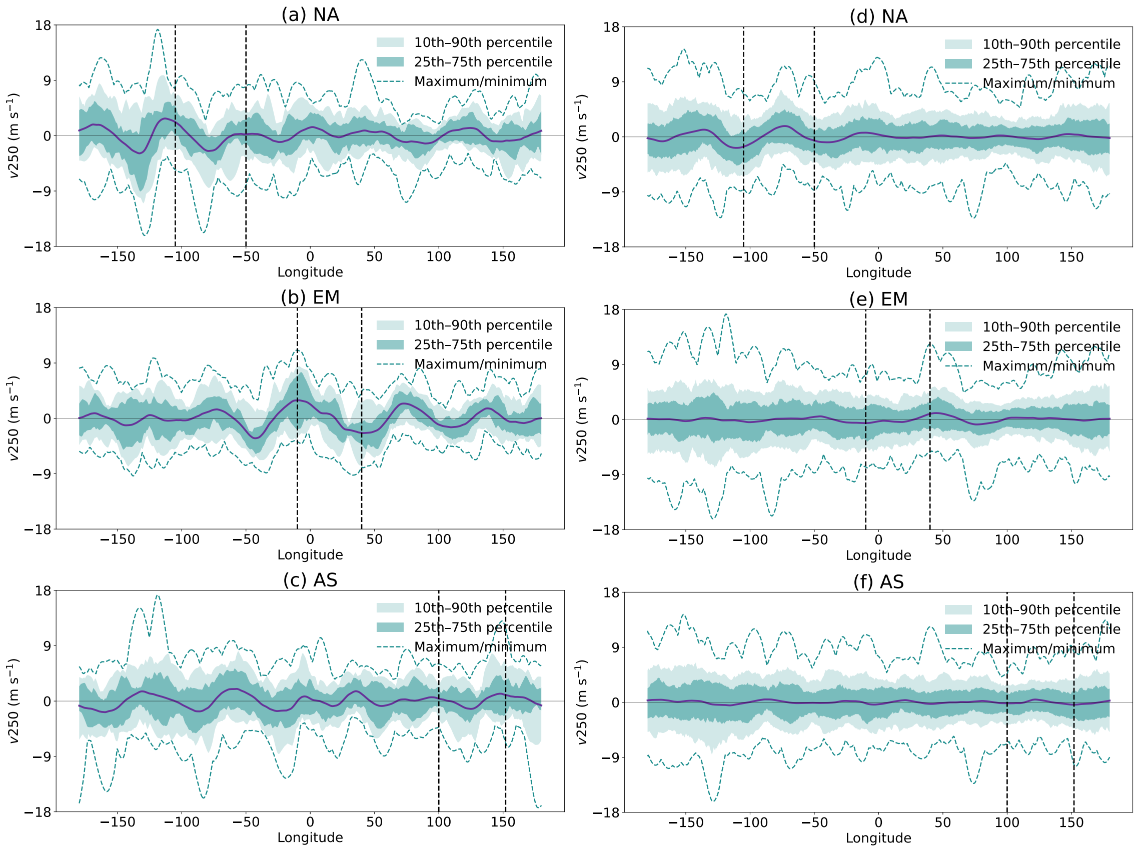

Figure R1. Meridional component of the wind at 250 (v250), averaged over the 57.5 ºN - 37.5 ºN belt. On the left column, composites of 19 high FA events; on the right column, composites of 92 low FA events, in (a,d) North America (NA), (b,e) Euro-Mediterranean (EM) and (c,f) Eastern Asia (AS). Purple lines indicate the composite mean, dark green bands indicate the interquartile range, light green bands indicate the 10th-90th percentile range, dashed green lines indicate maxima and minima, while vertical black dashed lines indicate the longitudinal extension of the selected regions.

In addition, we analyze the distributions of the wave numbers associated with high FA and low FA events (Fig. R2). We quantified differences in the dominant zonal-wavenumber distributions using a repeated random subsampling analysis. In North America, high FA months are characterized by wavenumbers 5 and 6, with median frequencies of 40 and 50%, respectively, compared with 30% and 40% during low FA months (Fig. R2a). The Euro-Mediterranean region shows an increased occurrence of wavenumber 7 during high FA events of twice its frequency during low FA events, with lower frequencies of wavenumber 5 and 6 (Fig. R2b). In Eastern Asia, high FA months indicate higher frequencies around wavenumber 6, with a median frequency close to 60%, compared with the 40% frequency during low FA events (Fig. R2c). Wavenumbers 4 and 5 occur more frequently during low FA events. Furthermore, a chi-squared test at 95% level of confidence indicates that, in all the target regions, the frequencies observed during high-FA events are significantly different from the frequencies expected during low-FA events. In particular, high-FA events are significantly associated with wavenumbers 5 and 6 in NA, wavenumber 7 in EM and wavenumber 6 in AS (Fig. R2c).

This additional analysis of the wave structures associated with the high FA events now complement the manuscript in the main text and the Appendix. Specifically, Figure R1 replaces Figure A4, which now is A3, and Figures R2a,b,c replace Figures 5f, 7f, 9f, respectively.

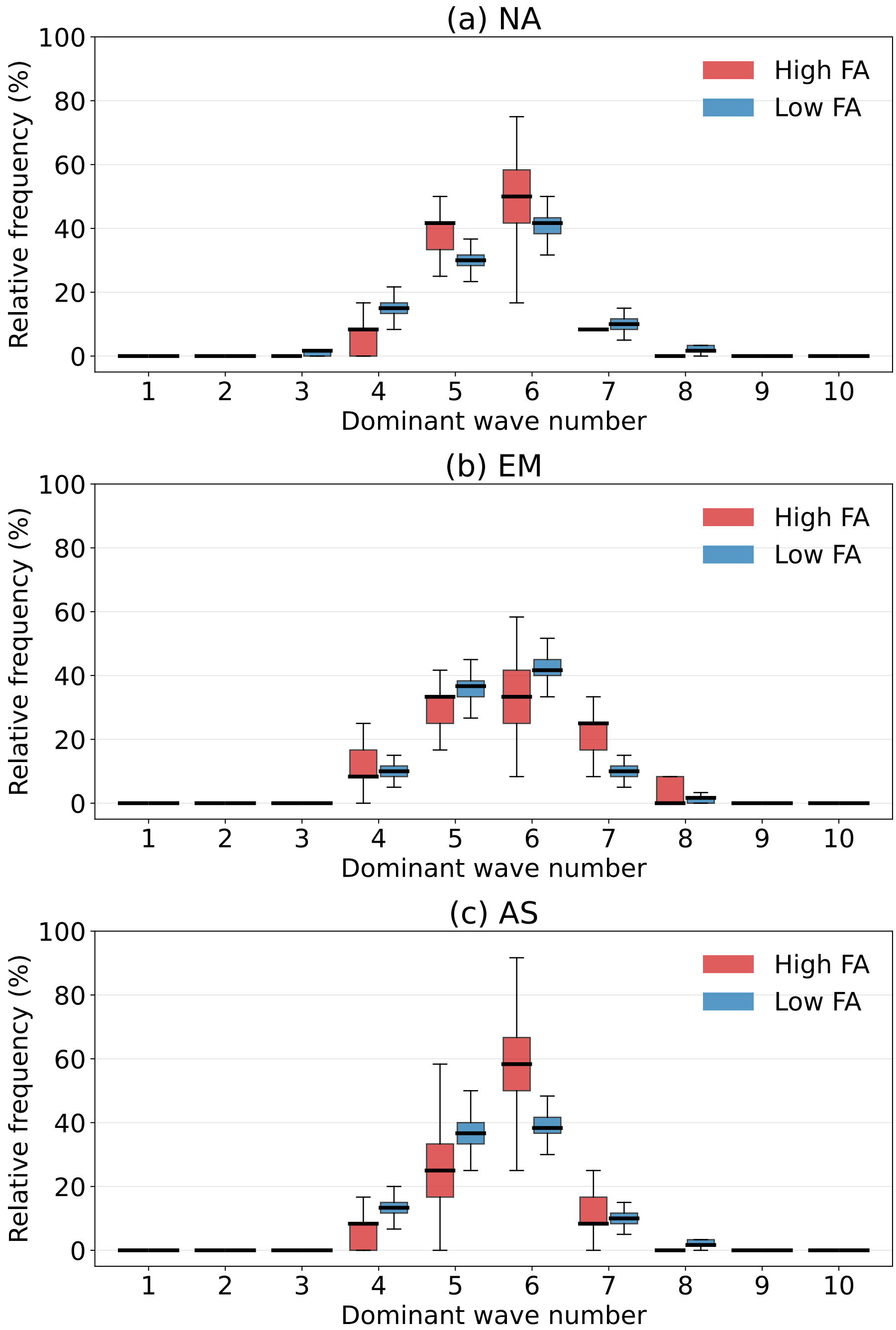

Figure R2. Relative frequency distributions of the dominant zonal wavenumbers during high FA (red) and low FA events (blue) with COHDE for (a) North America, (b) Euro-Mediterranean and (c) Eastern Asia. The distributions were obtained from 1000 repeated random subsampling realizations. In each realization 120 months were randomly selected from the complete record and the FA thresholds and wavenumber frequencies were recalculated for each subsample.

Once the robustness of the wave patterns associated with the high-FA events is shown, we also demonstrate how the installation of such a circulation feature leads to the triggering and maintenance of the hot-dry conditions in the target regions. In Figures R3-5, Hovmöller diagrams and line plots show the composites of anomalous geopotential height at 500 hPa (z500), zonal wind at 250 hPa (u250), and surface sensible (SSHF) and latent heat fluxes (SLHF) for 19 high-FA events in the target regions, from 30 days before the hot-dry events, to 30 days after.

For events in North America (Figure R3), positive z500 anomalies are already present above the western part of the region before the beginning of the event and become more pronounced near its onset (Fig. R3a). During the first part of the event, the anomaly remains within a similar longitude range while progressively changing in amplitude and spatial extent, indicating there was a persistent and slowly evolving ridge feature. Towards the end of the event, the positive anomaly weakens and the ridge structure is less pronounced, while the whole structure start moving to the east after the termination of the event. The u250 latitude-time composite shows the evolution of the upper-level zonal flow over the NA region (Fig. R3d). Before the event, positive u250 anomalies occur at higher midlatitudes, while negative anomalies are present southwards, indicating a northward displacement of the westerly jet stream. During the event, the zonal wind anomalies become less organized, indicating a disruption of the jet stream, associated with the installation of the atmospheric ridge. The SSHF composite shows negative values from the pre-event through the event (Fig. R3b). These negative anomalies indicate enhanced upward sensible heat transfer from the land surface to the atmosphere according to the ERA5 convention. This may reflect the influence of soil moisture deficits before the event, which constraint the energy used for evaporation and allow a larger amount of the available surface energy to be transferred to the atmosphere as sensible heat. The SSHF anomaly reduces after the event. The SLHF composite shows that the surface response develops and becomes more pronounced after the formation of the circulation anomaly (Fig. R3c). The positive SLHF anomalies during the event indicate a reduction in upward latent heat flux (according to ERA5 convention positive-downward) and are consistent with suppressed evaporation and reduced evaporative cooling. This response is weak before the event month and strengthens after its onset, which suggests that the temperature-evaporation feedback may reinforce, rather than initiate, hot and dry conditions.

Taken together, these results suggest a physically consistent sequence for NA events. A large scale upper tropospheric wave develops before the event and trigger the formation of a persistent ridge over NA, resulting in a disruption of the westerly jet stream. The ridge favors subsidence, reduced cloudiness and precipitation, and enhanced surface heating. As the event develops, reduced evaporation from precipitation deficit leads to weaker latent heat cooling, which further amplify the surface warming and drying.

Figure R3 is included in the new version of the manuscript as Figure 6. Related discussion is added to the main text at Line 271.

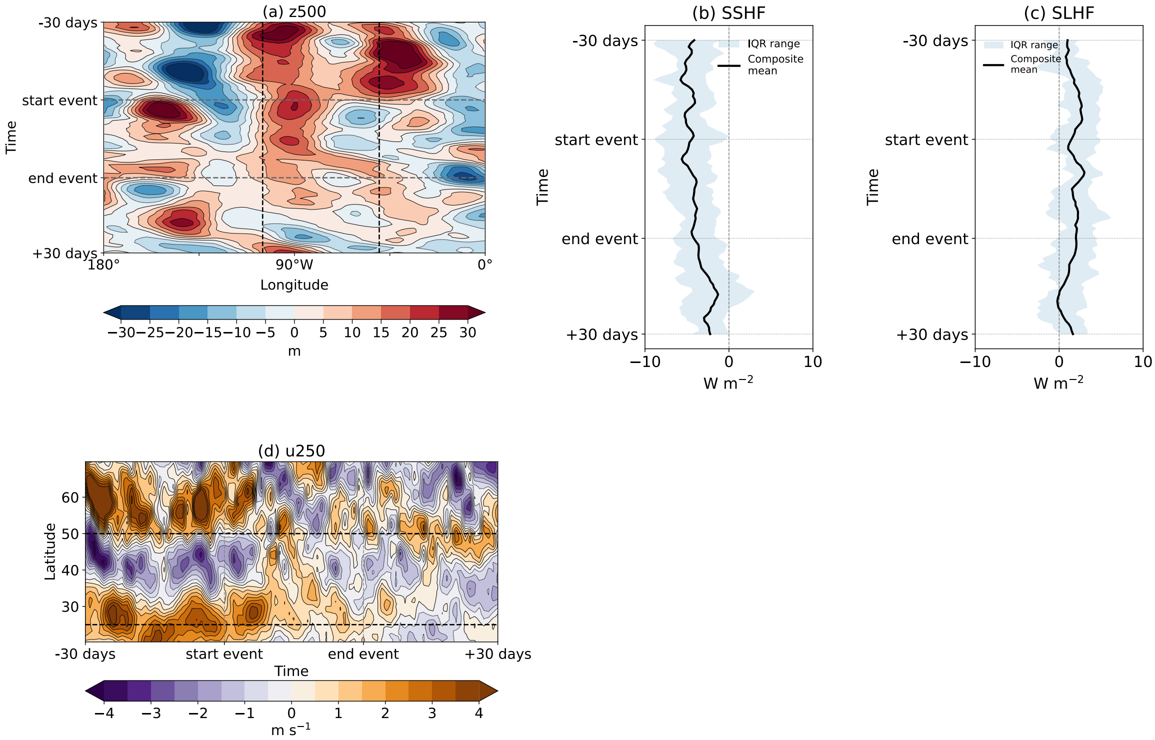

Figure R3. Composites of the daily evolution of the atmospheric circulation variables and surface heat fluxes associated with the 19 high FA events in North America. For each event and variable, daily anomalies are calculated by removing the corresponding daily climatology and filtered using a 7-day centered running mean. The event windows were aligned on a common event-centered time axis and subsequently composited across the 19 events. (a) Time-longitude Hövmoller diagram of daily 500 hPa geopotential height (z500) anomalies averaged over 37.5 - 57.5 °N. (b) Surface sensible heat flux and in (c) surface latent heat flux (SLHF) anomalies regionally averaged over North America, with the shaded area indicating the interquartile range across the 19 events. (d) Latitude- time Hövmoller diagram of daily 250 hPa zonal wind (u250) anomalies averaged over 110 – 45 ° W. Horizontal dashed grey lines indicate the beginning and end of the event while vertical dashed lines in delimit the longitudinal boundaries of NA region in panel (a), while the horizontal dashed lines in panel (d) show the latitudinal boundaries and the vertical dashed lines show the beginning and end of the event.

For events in the EM, positive z500 anomalies move from the west above the region before the event onset, to intensify during the first part of the event and eventually weaken and start moving eastward at the termination of the event (Fig. R4a). The evolution of the z500 anomalies indicate a slowdown of a transient westerly wave-like circulation pattern, which evolve in a quasi-stationary ridge above the EM during the event. The u250 composite shows intense positive anomalies juxtaposed to negative anomalies affecting EM before and just after the onset, which eventually migrate to the north in the second part of the event (Fig. R4d). This evolution is consistent with a displacement of the westerly jet stream from the EM to the north. The surface heat fluxes evolve consistently with the development of the hot and dry conditions. The regional SSHF composite is negative before the events start and during the events onset values become more negative. These negative anomalies indicate an enhanced upward transfer of sensible heat from the surface to the atmosphere (Fig. R4b). In contrast, the regional SLHF composite show weak positive anomalies before and during the event (Fig. R4c), which indicates a reduction in the upward latent heath flux and weaker evaporative cooling within the EM region due to the persistence of the atmospheric ridge. However, the positive SLHF anomalies associated with EM events are less robust with respect to those observed for the NA events.

This indicates that the events in EM are associated with the development and persistence of a mid-tropospheric ridge from a westerly disturbance, consistent with the observed hot conditions, while the northward displacement of the jet stream leads to a precipitation deficit. The feedback triggered by the reduction in the evaporative cooling contributes to maintaining the surface heat and dryness during the event. However, the limited amplitude of the SLHF negative anomalies, likely due to the availability of moisture from the Mediterranean Sea, indicates that the temperature-evaporation feedback is less efficient, explaining the lower frequency in the EM events with respect to NA.

Figure R4 is included in the new version of the manuscript as Figure 8. Related discussion is added to the main text at Line 336.

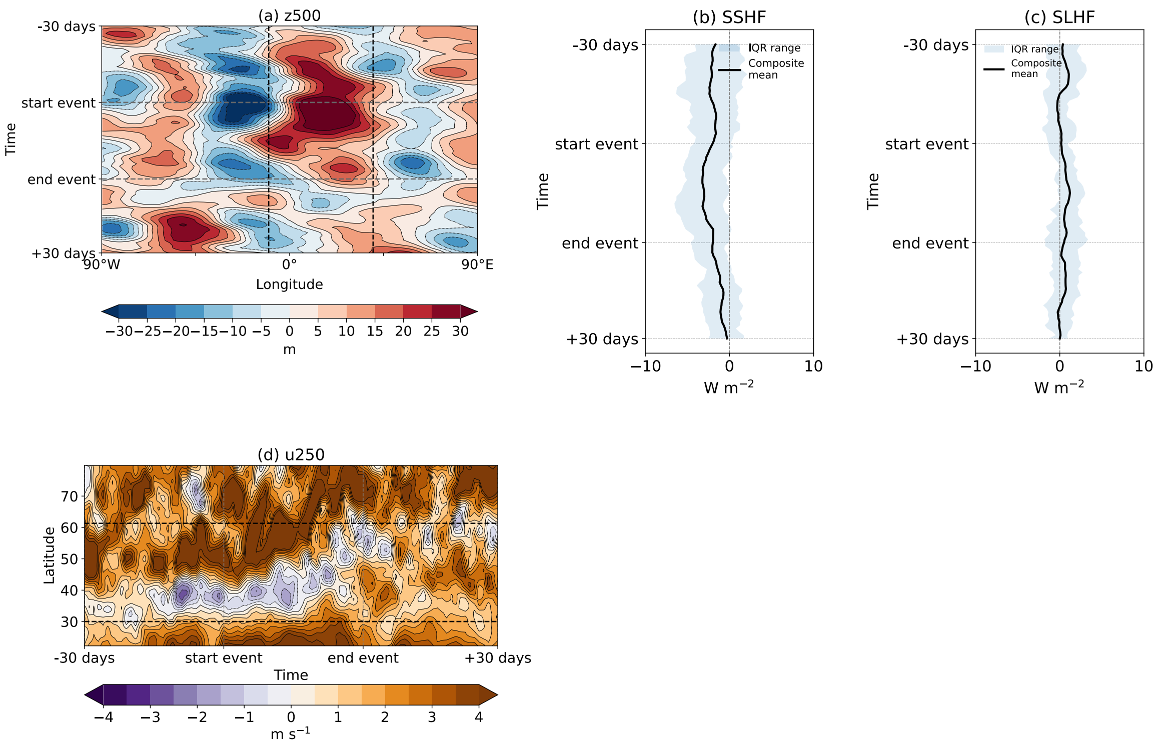

Figure R4. Same as Fig. R4 but for EM. In (d), 250 hPa zonal wind anomalies were averaged over 20ºW-45ºE.

The analysis of the circulation anomalies associated with the AS events show a westerly disturbance in the v250, transiting above the region without resulting in any stationary ridging (Fig. R5), indicating that the mid-latitude Rossby-wave dynamics has limited effect on the occurrence of hot and dry events. However, a sensitivity analysis using a lower latitude band (25-45 ºN) reveals positive z500 anomalies reaching up to 15 m before, during and after the event month within the region (not shown). This indicates that the main positive anomalies are located southwards and that the common midlatitude average captures its northern side. The anomaly evolves through time and is less continuous than the ridges identified for NA and EM, which suggests a more transient circulation configuration. A stationary positive-negative dipole in u250 (Fig. R5d) is observed during the event, indicating weakened upper-level westerlies over central and southern AS and a stronger flow to the north, respectively. Those anomalies are consistent with a northward displacement of the subtropical jet stream. The displacement of the jet stream results in anticyclonic circulation leading the weak negative SSHF anomalies before and throughout most of the event (Fig. R5b). This indicates a slight enhance of upward sensible heat transfer from surface to the atmosphere. Negative SLHF anomalies occur near the event onset and during parts of the event, indicating enhanced upward latent heat flux and evaporative cooling. In this non-water-limited monsoonal region, a precipitation deficit does not necessarily imply a depletion of soil moisture, and evaporation may be maintained under high atmospheric evaporative demand while soil moisture is still available. In addition, the spatial heterogeneity of eastern Asia and the averaging of SLHF across the full region may obscure contrasting responses between compound-event and unaffected grid cells.

These results suggest that the high FA compound hot dry events in AS are associated with a transient anticyclonic circulation resulting from the northward displacement of the subtropical jet stream. Due to the moisture availability in the region, the evaporative cooling is more effective than in NA and the EM, leading to less frequent events associated with weaker temperature anomalies.

Figure R5 is included in the new version of the manuscript as Figure 10. Related discussion is added to the main text at Line 384.

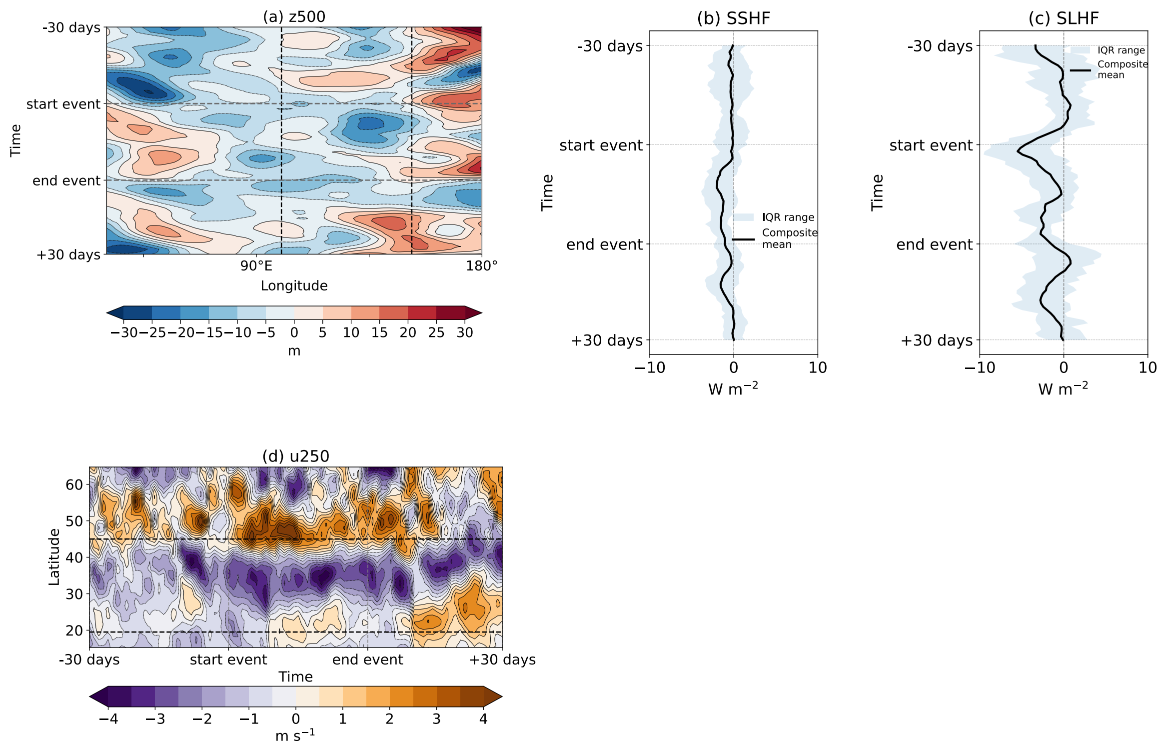

Figure R5. Same as Fig. R4 but for AS. In (d), 250 hPa zonal wind anomalies were averaged over 95-160ºE.

Comment 4: *"One question that remains unanswered is the joint likelihood of seeing all three regions affected by hot/dry events and to what degree the large-scale circulation plays a role."*

Response 4: Thanks for your question. In our analysis, we did not identify cases in which all three selected regions were simultaneously affected by high-FA events (Fig. A4). Rather, the co-occurring events detected in our study involve pairs of regions, as described in lines 318 and 365 and shown in Fig. A4 of the revised manuscript. As the number of such events is small (only 7 pairs), a climatological analysis would not be statistically robust, therefore we decided not to place further emphasis on it in the discussion.

Minor:

Comment 5: *L.16 'Our study highlights that the spatial extent..' as a last sentence for an abstract this could be more to the point. Do the authors refer to the hemispheric localization or the size of the individual anomalies.*

Response 5: We thank the reviewer for pointing out this. Here, we refer to the spatial coverage (the size of the affected area) of compound hot and dry events. We have revised the sentence accordingly to clarify this point in line 16 and 17:

"Our study highlights that the spatial coverage of compound hot and dry events across the selected regions provides a useful metric for assessing regional impacts."

Comment 6: *L.37 a few references would be good here, as this would support the main claim of this sentence.*

Response 6: We thank the reviewer for this suggestion. We revised the manuscript and made the following changes (line 35-37):

"Among the different types of compound extreme events, the multivariate co-occurrence of hot and dry events has received increasing attention in the last years (Sarhadi et al., 2018; Zhou et al., 2023), as such events are becoming more frequent under anthropogenic climate change and are projected to further increase with warming (Sarhadi et al., 2018; Seneviratne et al., 2021; Zscheischler et al., 2020; Bevacqua et al., 2022)"

Comment 7: *L. 58 two papers that investigated Rossby Waves, hot-dry events and their impacts on Agriculture and Ecosystems seem to be missing here, possibly putting the authors claim that these have not been investigated in combination so far in perspective:*

- *Lian, X., Li, Y., Liu, J. et al. Northern ecosystem productivity reduced by Rossby-wave-driven hot–dry conditions. Nat. Geosci. 18, 615–623 (2025). https://doi.org/10.1038/s41561-025-01722-3*
- *Kornhuber, K., Lesk, C., Schleussner, C.F. et al. Risks of synchronized low yields are underestimated in climate and crop model projections. Nat Commun 14, 3528 (2023). https://doi.org/10.1038/s41467-023-38906-7*

Response 7: We thank the reviewer for highlighting these two relevant studies. We have added both references and revised the Introduction to better situate our analysis within this recent literature (L. 63).

"More recent studies have investigated the links between specific Rossby wave configurations, associated surface conditions, and their impacts on ecosystem productivity and crop yields (Kornhuber et al., 2023; Lian et al., 2025). However, the circulation anomalies and the role of different Rossby wave patterns in raising persistent COHDEs across Northern Hemisphere regions is still not clear."

Comment 8: *L. 58 the authors likely wanted to cite Raymond et al. 2022 here?*

Response 8: Yes, thank you for noticing this, we already corrected the citation in the manuscript.

Comment 9: *l.61 the research questions could be a bit clearer, what do the authors mean with 'characteristics', what do they mean with 'large circulation patterns' if not Rossby waves, in particular as the authors seem to limit their analysis to a Rossby wave metric?*

Response 9: We thank the reviewer for pointing this out. In the revised manuscript we clarified what is meant by "characteristics" of compound hot and dry events, namely their spatial extent, frequency/occurrence, regional distribution, and temporal evolution. We also clarified the wording "large circulation patterns" to indicate that we refer to large-scale atmospheric circulation anomalies associated with high fraction of area events, including anomalies in variables such as geopotential height, wind and near-surface atmospheric variables. The Rossby-wave analysis is then used as a specific diagnostic to assess whether these large-scale anomalies are consistent with specific Rossby-wave numbers.

L. 66: "In this study, we address the following questions: What are the characteristics of COHDEs, in terms of their frequency, spatial extent, and temporal evolution, in specific regions that are important for crop yield, i.e. regions including the so-called breadbaskets (Gaupp et al., 2019, 2020; Kornhuber et al., 2020a), in the Northern Hemisphere? Which large-scale atmospheric circulation anomalies are associated with the occurrence of COHDEs affecting large areas? Are these anomalies related to Rossby-wave patterns?"

Comment 10: *Figure 2, if different colors and scattertypes are used, please add a legend or at least a description in the caption.*

Response 10: Thank you for this comment. We have revised the caption of Figure 2 to clarify the meaning of the different colours and marker types, as follows:

"Figure 2: Distribution of the monthly hot day index and SPI for three different grid cells located within the three selected regions (North America, NA (41.48ºN, 100.62ºW), in the first row; Euro-Mediterranean, EM (45.7ºN, 3.3ºE), in the second row; Eastern Asia, AS (43.37ºN, 123.53ºE), in the third row). June, July and August are displayed in columns, shown in green, blue and pink, respectively. Different markers are associated with the three regions: circles for NA, squares for EM, and triangles for AS. The dashed lines show the thresholds that are used to identify hot events, i.e., 84.2th percentile of the monthly hot day index, and dry events, i.e., SPI=-1. The upper right area shows the compound events in these grid cells. Kendall's τ as rank correlation coefficient provides a measure of the strength of the dependence between hot and dry events."

Comment 11: *Figures: this might be a compression artefact when converting to .pdf but figures should be provided in higher resolution.*

Response 11: Thank you for this comment. We have revised the figures and replaced the figures in the manuscript with higher-resolution versions to avoid compression artefacts during PDF conversion.

Comment 12: *Figure 4. Can something be said about the trends? Why are statistics for JJA not shown? As these form the basis for Fig. 3 this would be good to see.*

Response 12: Thanks for your question. We clarified the question/comment about the trends in major comment 1. We showed in lines 185-186 that the only statistical positive trend that we found was in July in the Northern Hemisphere. We did not add the other statistics since we did not find statistically significant trends in the other regions, consistently with the use of a moving-window baseline that reduces the influence of long-term climate change. We clarified this in the revised manuscript:

L. 190: "The FA in the Northern Hemisphere affected by COHDEs (Fig. 4a) varies across the years, with different notable peaks. For June and August, a Mann-Kendall test indicates no significant trend, which is consistent with the use of a moving-window baseline that removes long-term climate change effects. July is the only exception, characterized by a weak positive trend (slope=0.02, p=0.01). For the three selected regions (NA, EM and AS), the Mann-Kendall test does not show statistically significant trends in the FA for any summer month."

Comment 13: *l. 235 this abbreviation has not been introduced yet?*
Response 13: Thank you for the question/suggestion. The abbreviation was introduced in line 75, in the data subsection when we described the atmospheric variables used in the study for analysis.

Comment 14: *Fig. 5 how are events aligned, drought / heat are captured on a 3 months basis, while v-winds/waves are detected daily?*
Response 14: We thank the reviewer for this question. The COHDEs were identified at monthly resolution, and the meridional wind fields used for the Rossby-wave analysis were also monthly averaged before applying the Fourier decomposition. We corrected this in the manuscript: L.175 "For each high FA event, the wavenumber of the anomalous mean westerly flow at mid latitudes is determined by applying a fast Fourier transform to the monthly v250 anomalies spatially averaged from 37.5ºN to 57.5ºN (Kornhuber et al., 2019; Petoukhov et al., 2013)".

Reviewer 2
General comment: "*This manuscript provides a nice overview of the linkage between compound hot and dry events and the atmospheric circulation. The authors showcase the well documented typical atmospheric patterns associated with such events - strong anticyclones centered of the region of hot and dry conditions, with the often expected strong surface heating through surface sensible heat flux. I enjoyed the addition of the long wave heat flux to extend on the radiative budget discussion. My primary concerns with the paper were that I felt it could've gone further in the analysis of the events (eg. how did we get to these patterns? how long-lived were they?) and attributing a more nuanced exploration of the data. Such analysis will help differentiate this study from the ample literature linking strong anticyclones/blocking to hot and dry conditions. Whether these are major or minor revisions will really be up to what the authors have at hand for their analysis.*"
Response: We thank the reviewer for this comment. We agree that some aspects of the paper need to be improved, particularly the investigation of physical mechanisms we propose to explain the association between the circulation anomalies and the occurrence of the hot-dry events. We provide in the following a detailed description of the additional analysis we performed and the modifications to the text we implemented to address your concerns.

Major comment: *I would've liked to have seen a more clear and complete story of what lead to these events. For example, in the discussion there is a commentary on the sources of waves that could influence wave-5/6/7 patterns (eg. lines 334-338; 356-371). The authors could have also addressed this in the paper (for example through lagged composites or Hovmöller diagrams), which would have both solidified their discussion (which I felt was reaching for connection to the prior literature in places without the evidence to support it), and provided a lot more emphasis to their results. Adding to this, an exploration of the stationarity and synoptic support of these features would've been beneficial. For example, a blocking index could be applied to this work to see how well traditional blocking indices perform in identifying these features. Another example could be a lagged composite analysis of* *the fields in figures 5-7, which could show both what types of synoptic features helped establish these patterns (eg. was it blocking? Rossby wave breaking? diabatic reinforcement of a ridge? etc.) as well as what sort of pre-conditioning of the surface environment was in place (eg. was this a rapid-onset scenario, or was there a lead-up?).*

Response: Many thanks for this comment. We present additional analysis in Response 3 to Reviewer 1, where, we performed using daily data to demonstrate the robustness of the association between detected hot-dry conditions in the target regions and the identified wave patterns, along with evidence of the evolution of the physical mechanisms triggering and maintaining the hot-dry conditions.

Minor/Technical editing comments

Comment 1. *L40 and L42: Get rid of the " 's " after each year.*

Response 1: Thank you, we revised the manuscript and made these changes.

Comment 2. *L49-51: Please define which ENSO index you're referencing here.*

Response 2: Thank you for pointing this out. We have revised the text to specify that Hao et al., (2018) represented ENSO using the Niño 3.4 SST index, defined as the area averaged SST from 5ºS-5ºN and 170º-120ºW. We also clarified that Hoerling et al., (2013) attributed the 2011 Texas drought-heat event to La Niña-related tropical Pacific SST anomalies rather than using a specific ENSO index. Kopp et al., (2017) and Zscheischler et al. (2020) are now cited for the general role of large-scale modes such as ENSO as common forcing of compound events.

L. 50: "However, large scale dynamics like El Niño-Southern Oscillation (ENSO) can act as common forcing of compound weather and climate events, mainly through the excitation of Rossby-wave patterns (Kopp et al., 2017; Zscheischler et al., 2020). For example, using the Niño 3.4 SST index (NINO34), defined as the area averaged sea surface temperature from 5 ºS-5 ºN and 170-120 ºW, Hao et al. (2018) found a relationship between NINO34 and the occurrence of compound dry and hot events in different regions, including southeastern Asia. On the other side, drought and heat events in Texas are associated with La Niña conditions consisting of a cold tropical east Pacific Ocean (Horling et al., 2013)."

Comment 3: *L73: How sensitive is your analysis to the use of 2m temperature compared to, say, 850 hPa temperature? Is the 2m T subject to biases?*

Response 3: We thank the reviewer for this question. We chose t2m over 850 hPa temperature for the hot day definition for the following reasons. First, near-surface temperature is the physically relevant variable for the surface and near surface impacts our study is motivated by. Heat stress on crops, ecosystems and human health is governed by conditions at or near surface, not by free tropospheric temperature, though we acknowledge that lower troposphere dynamics is very important for the processes at the surface. Second, this keeps the hot day definition consistent with the drought definition, which is based on surface precipitation (SPI3). Furthermore, this selection aligns with the convention in the compound hot dry event literature we build on (e.g., Hao et al., 2018, 2022; Zscheischler and Seneviratne, 2017) which similarly defines the hot events using near surface temperature. In ERA5, 2-m temperature is a diagnostic near surface variable derived from the modelled surface and lowest atmospheric level and may therefore reflect uncertainties in the representation of surface and boundary layer processes. However, evaluations against observations show that ERA5 generally performs well in representing near surface temperature variability and identifying extreme temperature in US, Canada and China which are within our regions of study (Sheridan et al., 2020; Xu et al., 2022). Furthermore, ERA5 2-m temperature has also been widely used to identify hot extremes and heatwaves at regional to hemispheric scales, including through local percentile based definitions similar to that applied here (Lhotka and Kyselý, 2024; Patterson, 2023; Uckan et al., 2024).

Comment 4. *L76-79: What lead to the decision to use this dataset rather than the ERA5 precipitation?*
Response 4: Thank you for this question. We selected CRU because it is an observation-based product, whereas ERA5 is a reanalysis combining model forecasts and assimilated observations. Total precipitation is not an analyzed field directly derived from rain-gauge measurements. Instead, it is obtained from short range model forecast. Therefore, total precipitation is generated by the model's resolved dynamics and parameterized cloud and convection processes, which can cause biases as documented by Lavers et al. (2022). In particular, ERA5 showed an overall wet bias, associated with an overestimation of precipitation on observed dry days. Furthermore, ERA5 precipitation errors increase during summer in the extratropics, showing a wet bias in southeast Asia and a dry bias over the United States (Lavers et al., 2022). These limitations are relevant to our JJA analysis and may affect the low precipitation tail used to calculate SPI and identify drought conditions.

Comment 5. *L90-91: Please provide some references to your sentence here on the SPI and it being a common index for meteorological drought.*
Response 5: Thank you for your comment, we gave a more robust justification to the choice of SPI as an indicator for meteorological drought. We further answered this in Response 1 to Reviewer 1.

Comment 6. *L91-93: I found the discussion on Gringorten plotting position (and this sentence in general) unclear as written.*
Response 6: Thank you for pointing this out. We have revised this part of the Methods in the manuscript at line 101.
"We calculate the 3-month SPI (SPI3) using a non-parametric standardized index using empirical precipitation probabilities estimated with the help of Gringorten plotting position, following Gringorten (1963), Hao and AghaKouchak (2014) and Farahmand and AghaKouchak (2015). At each grid point, precipitation data for each target month is accumulated over that month and the two preceding months. For each calendar month, the resulting 3-month precipitation totals are ranked across the years of the reference period. The ranks are converted into empirical non exceedance probabilities using the Gringorten plotting position. The resulting empirical probabilities are then converted into SPI defined by Farahmand and AghaKouchak (2015) as:

$$\text{SPI3}= \varphi^{-1}(P_i)$$

where P_i is the empirical probability of precipitation, derived above, and φ is the standard normal distribution function. We use SPI3 based on CRU precipitation, using as reference a 30-year shifted baseline, starting in the 1960-1989 and ending in the 1991-2020 period."

Comment 7. *L105-106: Why is this a stand-alone paragraph? As written it's just a sentence.*
Response 7: Thank you, we revised the manuscript and wrote the sentence along with the above paragraph.

Comment 8. *L105-106: I wasn't sure on your approach here to the statistics associated with the SPI3 and the hot days index. Is your SPI3 index really Gaussian (or close to it)? Precipitation data rarely is, making your analysis approach here a bit dangerous (percentiles require a normal distribution typically).*
Response 8: Thank you for raising this point. We agree that precipitation is rarely represented by a Gaussian distribution. SPI accounts for this by transforming cumulative precipitation probabilities onto a standard-normal scale, rather than applying standard-deviation thresholds directly to the original precipitation value (McKee et al., 1993; Svoboda, et al., 2012). In our nonparametric approach these probabilities are estimated empirically, as we described in Response 6. Thus, SPI3 is expressed on a standard normal scale by construction, and SPI3 $\leq$-1 corresponds to a cumulative probability of approximately 0.158. The empirical threshold for the monthly hot day index was selected as the corresponding upper-tail threshold leaving approximately 15.8% of data above it. We have clarified this in the revised manuscript at Line 118.

Comment 9. *L178-179: Is this trend driven by a single region, or by all 3? It may be interesting to look at the trends for all 3 regions. In addition, it may be helpful to look at the monthly trends/means individually (rather than how you have them shown in figure 4 (in other words, it might be helpful to decompose this by looking at it less from the annual standpoint and instead to look at the trends/statistics of each month).*
Response 9: Thank you for this suggestion. In line 192 we specify that the only trend we found was in the whole Northern Hemisphere during July. The lack of a pronounced long-term trend is a consequence of the methodological framework applied in our data. Both, temperature and SPI3 thresholds are calculated using a 30 year moving climatological baseline, separately for each calendar month and grid cell. Consequently, slow changes in the underlaying temperature and precipitation distributions are removed before the FA by COHDEs is calculated. For this reason, separate trend analyses for June, July and August, or for each region individually would also show limited long-term trends. A more detailed explanation is also provided in Response 1 to Reviewer 1.

Comment 10. *L194 (and general definition of EM region): I get why you defined the regions the way you did, but it feels like an unfortunate missed opportunity that you include so much empty space (Mediterranean Sea) and don't include portions of northern Europe and the Isles. It may be worth including these?*
Response 10: We thank the reviewer for this suggestion. As explained in Response 2 to Reviewer 1, although the geographical domain includes a substantial portion of the Mediterranean Sea, our analysis follows the IPCC regional definitions adopted in previous studies investigating compound hot and dry extremes within agricultural regions. We agree that northern Europe and the British Isles are also relevant for the occurrence of hot and dry events. However, including them would extend the domain towards higher latitudes characterized by strongly maritime climates, different precipitation and temperature seasonality than the continental areas within the Euro-Mediterranean region. This would broaden the climatic and dynamical scope of the Euro-Mediterranean region. The aim of the study is not to provide an exhaustive analysis of all European regions, but to investigate large-scale circulation patterns associated with COHDEs in selected Northern Hemisphere midlatitude regions that encompass agricultural regions.

Comment 11. *F3: A more discrete colorbar for panel (a) would be helpful here.*
Response 11: Thank you for the suggestion, we made the changes of the figure in the revised manuscript.

Comment 12. *L237-241: Though I do appreciate the use of upper level patterns to diagnose the flow here, I wonder about instead using a lower-tropospheric variable when linking to surface heat flux anomalies. There's a lot that can happen between 250/500 and the surface from a cloud or otherwise standpoint.*
Response 12: Thanks for your comment. We agree that also the lower troposphere is important to determine the drivers of the dynamics at the surface. However, we decide to limit the analysis to the upper troposphere for different reasons: 1. Because the focus of the paper is the large scale circulation, we want to detail the role of waves and teleconnections, being much more detectable in the mid-upper troposphere; 2. Our analysis show circulation structures rather barotropic, therefore we assume that the same structure is conserved down to the surface; 3. We want to keep the paper as much compact as possible, and focus on the variables we consider relevant to support our conclusions.

Comment 13. *L247: You should swap the order of A3 and A4 given the order you're referencing them in the text.*
Response 13: Thank you for this suggestion. We agreed that the order should be changed and we made the changes in the revised manuscript.

Comment 14. *F5-7: It would be helpful to add the v250 and u250 climatology, or the composites for each respective figure, to your panels g and h to supplement the discussion. Same thing for A2 (also on A2 it's really hard to see your hatching).*
Response 14: Thank you for this suggestion. Climatological contours of z500, u250 and v250 have now been added to the corresponding composites in Fig. A2 of the revised manuscript. The visibility of the significance hatching in Fig. A2 has also been improved. These figures have been revised into the Appendix as Figure A2.

Comment 15. *L264: I'm not sure what the approximately symbol is meaning in front of your greater than symbol. Please aim to be specific.*
Response 15: Thanks for spotting this, we correct this inappropriate use of the symbol**.**

Comment 16. *L265: Careful here (and elsewhere) to stay with scientific notation.*
Response 16: Thank you, we already corrected this in the revised manuscript.

Comment 17. *17: L269-270: Your SLHF looks less potent than over North America - does this have to do with the proximity to the Mediterranean Sea?*
Response 17: Thanks for the useful insight. We agree that the proximity of the Mediterranean Sea may contribute to the weaker and less spatially potent SLHF anomalies compared with North America. We revised the manuscript according to this suggestion at Lines 325-328.
"However, these SLHF anomalies are weaker than over North America. This difference may partly reflect the heterogeneous hydroclimatic conditions of the Euro-Mediterranean region, including the influence from the

Mediterranean Sea. Previous work has identified the Mediterranean as a transitional climate region in which summer evapotranspiration is constrained by soil-moisture availability (Materia et al., 2022)"

Comment 18. *L333: Please flip the order of 5 and 6 for your wavenumbers here*
Response 18: Thank you, we made the changes in the revised manuscript.

Comment 19. *L344: Is this double jet structure linked to anticyclonic Rossby wave breaking?*
Response 19: Thank you for this comment. Rossby wave breaking followed by blocking has been proposed as one mechanism that can split the upper-level jet and generate a double jet structure (Rousi et al., 2022). Anticyclonic Rossby wave breaking has also been associated with persistent hot spells over Europe and the Mediterranean (Pappert et al., 2024). We have added this possible dynamical connection to the discussion at line 453.

Comment 20. *L380: I find the sentence starting with 'By using a fraction ...' vague and confusing - please aim to be more direct.*
Response 20: Thanks for pointing this. We agree that the original sentence was vague and we have revised the manuscript. Changes are made in now line 491.
"By using trend insensitive metrics, i.e. not affected by long-term changes in the occurrence of individual hot and dry events, we show that COHDEs are a recurrent feature of the climate internal dynamics in Northern Hemisphere and in the selected regions".

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