Response letter

In this response letter, we put the text of the reviewers in bold, and the questions are numbered as Q1, Q2 etc. Our answer starts with Answer and is in normal font-weight. The text in the manuscript is put in quotation marks. The revised texts are underlined. An empty line separates the questions.

1 Response to Referee No. 3

The manuscript titled 'Identification of compound drought and heatwave events on a daily scale and across four seasons' is well-written and discussed. Compound drought and heatwave (CDHW) are highly relevant and critical issues in today's world. I have the following comments on the paper:

Q1: McKee et al., 1993, is a very old reference now, many drought products are based on daily or Weekly data, so I think the author's argument that, generally, droughts are identified based on monthly magnitude is not strong enough.

Answer: According to the review's suggestions that the argument is not strong enough, we revised the text by adding the latest references and giving more demonstrations. The entire paragraph is as shown below, where the changed texts are underlined:

"The identification of CDHW events lies at the core of temporal trend and frequency analyses. However, the coarse temporal resolution and scale inconsistency of the indices used hamper the reliability of existing studies. Droughts are commonly identified on the basis of monthly magnitude variations in historical climate variables (McKee et al., 1993; Ridder et al., 2020; Salvador et al., 2020), and therefore completely ignore the intramonthly distribution, while heatwaves are usually obtained on a daily scale. For example, the *3-month* Standardized Precipitation Index (SPI) for meteorological droughts and the *daily* temperature index for heatwaves are a popular pair of indices that are used for identifying compound events (see, e.g., Geirinhas et al. (2021)). This coarse scale of the drought index and the mismatch of scales between the drought and heatwave indices could entail some bias on the actual start and/or end dates as well as the severity of droughts, further affecting the identification of CDHW events. Recent studies have upscaled the scale of drought events to a weekly, 5-day, or daily scale (Mukherjee and Mishra, 2021; Wang et al., 2020; Li et al., 2020; Mo and Lettenmaier, 2015; Yuan et al., 2023). For example, Mukherjee and Mishra (2021) identified a drought week when the self-calibrated Palmer Drought Severity Index (Wells et al., 2004) falls below the 10th percentile, thus regarding short dry spells (a week) as drought events; Wang et al. (2020) calculated daily Standardized Precipitation Evapotranspiration Index (SPEI) values and identified a drought event as a period of consecutive days with SPEI below a given threshold (such as -1.0). While these identification methods enhance the temporal resolution, they also introduce a new challenge. They may result in a large number of short dry spells and/or mutually dependent ones. Consequently, the droughts identified might not be extreme or independent. Therefore, additional efforts are needed to address the issues of coarse resolution and scale inconsistency.”

Q2: Regarding the seasonal CDHW, the definition of heat waves and drought needs to be properly adjusted for summer and winter, as they will have different consequences.

Answer: We agree that the effects of CDHW in summer or winter seasons may be different, and this difference may change with the research objects, such as the effects of CDHW on insects, crops, and even broader ecological systems. However, we do not opt to change the definition of heat waves or droughts across seasons as this may make the analyses very complicated. Using a unified definition makes it easier for researchers to compare effects across seasons, even though CDHW events in different seasons may cause different (ecological) consequences.

Q3: The introduction section needs improvement. Please specify the novelty of the work in the introduction section, as previous studies have already discussed CDHW at daily scale.

Answer: We appreciate the feedback on emphasizing the novelty of our work in the introduction. While it’s true that previous studies, like the one by Ridder et al. (2020), have discussed CDHW events on a daily scale, these studies often combine monthly drought data with daily heatwave analysis. For example, they calculate monthly Standardized Precipitation Index (SPI) values and then extend these monthly values to daily data, which does not capture the day-to-day variability of droughts.

In response to reviewer’s suggestion, we have updated the third paragraph of the introduction to clearly outline the innovative aspects of our research, and please see the answers to Q1 or the revised manuscript for details.

Q4: Only one lat/long data record has been analyzed, which needs to be expanded to a bigger area.

Answer: The decision to use only one station stems from the availability of an extensive dataset spanning 120 years of daily observations at Uccle. This time series, the longest in Belgium, provides a robust foundation for developing and validating the method proposed in our research. By concentrating on a single station with such a lengthy record, we aim to capitalize on the wealth of historical climate data, allowing us to build and refine our identification method effectively.

However, we recognize the importance of applying this method to more locations to further test its performance. In fact, during the review period of this manuscript, we have applied this method to identify the droughts, heatwaves, pluvials, and cold-waves of England in our latest research. A preprint is available online ($https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4728550$).

Q5: It will be good to compare the impact of all historical CDHW on crop yield and vegetation.

Answer: We also believe that it is interesting to explore the impacts of historical CDHW on crop yield or vegetation. However, it is a heavy workload, and many interesting questions can be discussed. Indeed, we are working on another study about how compound extreme events across growth stages impact the final winter wheat yields in France. We applied the identification method proposed in this manuscript, and the early-stage results indicate significant associations between extreme events and crop yields.

This manuscript, however, is primarily focused on the identification method. We provide a detailed introduction to the concept and calculations of the method. The results are analyzed by comparing them to those obtained using monthly scale identification, showcasing a more precise identification of start and end dates. Furthermore, we have conducted a small validation experiment to highlight the advantages of our method, as detailed in subsection 3.6.

Therefore, we think the reviewer's suggestion is interesting, and we are indeed working on a related topic, but incorporating such an analysis into this paper might divert from its main focus.

Q6: Please expand SPI in line 88. Also, give a first-level definition of what is SPI and SHI in words.

Answer: The full name of the abbreviation SPI (Standardized Precipitation Index) was introduced when it first appeared in the introduction (Line 32). We added a definition of SPI and SHI in words at the beginning of subsection 2.2 as below:

"We use the daily SPI (McKee et al., 1993) and SHI (Standardized Heatwave Index) (Raei et al., 2018) as indices to identify droughts and heatwaves, respectively. SPI (resp. SHI) is a standardized index to quantify to what extent precipitation (resp. temperature) deviates from the climatological average. SPI (resp. SHI) describes dry (resp. hot) spells according to the probability of occurrence in a reference period."

Q7: In the moving window, are you taking mean? Then specify that. (line 95).

Answer: In the moving window, we use the past 30 years as the historical reference period then we calculate the SHI.

Q8: It would be helpful if the spatial and temporal extent of the study is defined in section 2.1.

Answer: In section 2.1, we have introduced that the spatial extent is one station and the temporal extent is from 19010 to 2020, and the text is shown below:

"Daily minimum/maximum temperatures from 1901 to 2020 were acquired from the climatological station of the Royal Meteorological Institute (RMI) of Belgium in Uccle (50°47′55″ N, 4°21′29″ E, 100 m a.s.l.), while daily rainfall was obtained from 10-minute precipitation time series recorded at the same site."

2 Response to Referee No. 4

This paper introduces a method for identifying compound drought/heatwave events on a daily basis. In general, the study is well-written and the chosen topic is suitable for the journal. The authors have addressed most of the comments made by previous reviewers, but there are a few remaining issues that need to be resolved before publication, along with some minor concerns mentioned below.

In particular, the authors should clarify the specific term for drought. Droughts are generally categorized into two major types including conventional droughts and flash droughts. The conventional droughts are referred to those events that last longer and they are usually assessed on a monthly scale, while flash droughts are those events that develop and intensify rapidly, which have shorter durations (e.g. 20 days). In this study, while the authors proposed a method to

detect droughts on a daily basis, they did not mention flash droughts or use specific method to detect droughts with short duration (e.g. 15, or 20 days). The major problem is that authors defined droughts on a daily basis using daily SPI, which I am afraid that it might not be a right approach. The SPI is used in various studies to define droughts on monthly scale, but it cannot detect rapid onset and development of droughts in finer temporal scales (e.g. 15 day in this study), as it might lead to false or unreliable drought signals, because flash droughts cause an intense reduction in soil moisture and a short reduction in precipitation without affecting soil or plants might not be a drought. Therefore, to capture these droughts, meteorological drought indices, including evaporation (potential or actual evaporation) should be used in the analysis, such as SSI (Standardized Soil moisture Index), SPEI or SNPI.

Answer: We understand the reviewer's concerns. The concept of drought is complex, and defining droughts remains a challenging issue. Drought is a natural phenomenon and it relates to multiple Earth's spheres, such as the atmosphere (dry atmosphere), lithosphere (dry land surface), subsurface layers (dry deep land), and hydrosphere (dry runoff). Besides the common sense of "water deficit" in drought definitions, the community has not yet reached a consensus on a perfect drought index. Numerous drought indices exist, each addressing different facets of this natural phenomenon, including the Standardized Precipitation Index (SPI), z-score, Standardized Precipitation Evapotranspiration Index (SPEI, which is derived from SPI and incorporates evapotranspiration), and soil moisture (used for identifying flash droughts by Yuan et al. (2023)), SSI, SNPI, TVDI (temperature vegetation dryness index), GRACE Groundwater Drought Index, and so on.

We chose SPI for several reasons: firstly, SPI is a basic and widely used index; secondly, our final aim is to study compound drought and heatwave events, and heatwaves are defined using temperatures. For droughts, we did not consider the temperature-included indices (such as SPEI) to avoid the double consideration of the temperature. This approach aligns with many studies on CDHW events, such as (Ridder et al., 2020; Salvador et al., 2020; Geirinhas et al., 2021).

We also agree that there could be better indices than SPI for capturing agricultural droughts or flash droughts. Higher temperatures increase evapotranspiration, rapidly depleting soil moisture and affecting agricultural systems, even if the precipitation anomaly is not so extreme. It is interesting to investigate the connections and distinctions between CDHW events and flash droughts, as both are linked to water deficits and are influenced by temperature. In such investigations, the method presented in this paper could be applied to the index that is best suited for the considered application.

Q1: Specific Comments: Page 2, line 30: what about flash droughts? Recent studies focused on the concurrent occurrence of flash droughts and heatwave. This type of droughts usually occur in finer time scales (e.g. 20 days). So, the statement 'Generally, droughts are identified ...' might not be true. The authors could at least mention flash droughts in this paragraph. Besides, heatwaves can be the driver of flash droughts in some cases (Mo et al. 2015).

Answer: According to the reviewer's suggestions, we revised the introduction of droughts and added more references. To avoid repetition, the improved paragraph is seen in the answer to Q1 for Referee No. 3 or the revised manuscript.

Q2: Page 4, line 89: please add 'respectively' to the end of this sentence: 'as indices to identify droughts and heatwaves.'

Answer: We have added 'respectively' to the end of this sentence, the revised sentence is shown as:

"We use the daily SPI (McKee et al., 1993) and SHI (Standardized Heatwave Index) (Raei et al., 2018) as indices to identify droughts and heatwaves, respectively."

Q3: In the caption of Figure S1, please correct 30-years. It should be ''in the past 30-year" or ''30 years".

Answer: Thanks for pointing out this problem, we modified the sentence as below:

"Results indicate it is effective to account for climate non-stationarity by using the past 30 years as the historical reference period instead of the whole period."

Q4: Line 131-136: while the selection of probability function significantly influences the values of an indicator, why did you not use at least one non-parametric function? The most attractive feature of the non-parametric drought frameworks is that it leads to statistically consistent drought indicators based on different variables (Farahmand and Aghakouchak, 2015). Most drought indicators rely on a representative parametric probability distribution function that fits the data. However, a parametric distribution function may not fit the data. Non-parametric drought indicators do not assume representative parametric distributions.

Answer: We acknowledge the merits of non-parametric drought frameworks highlighted in existing literature, such as Farahmand and AghaKouchak (2015). Our preference for parametric distributions over non-parametric ones was based on two key considerations.

First, while non-parametric methods simplify calculations by eliminating the need for data fitting, they require a larger dataset to ensure robustness. Given our study's reliance on 30 years of observational data (considering the non-stationarity of temperature data, the past 30 years is used as the historical reference period), we were concerned about the sufficiency of this period for the reliable application of non-parametric methods. Second, our literature review revealed a relatively limited adoption of non-parametric distributions for drought index calculations; the literature still prefers the traditional way, even for recent studies (see, e.g., Ridder et al. (2020); Salvador et al. (2020)). In this way, we followed the more classic way to calculate the SPI and SHI. We give several commonly used distributions in the literature, and the most fitting distribution for the data is chosen by the criterion of minimizing the Akaike Information Criterion (AIC). Overall, we agree that non-parametric distributions are a possible choice, but we chose a conservative but safe parametric distribution in this study.

Q5: In page 6, line 155, please add description for m and i for both SPI and SHI.

Answer: In line 155, we introduce the "where $\mathrm{SPI_d}$ and $\mathrm{SHI_h}$ are the corresponding pre-identification thresholds". There is no need of m and i for $\mathrm{SPI_d}$ and $\mathrm{SHI_h}$, as for all year m and day i, we apply the same threshold.

Q6: While the authors explain the reason for using data from only one station (mainly because of availability of relatively long P and T records) in response to previous referees, still I'm not sure whether this approach would be practical in other regions or not. Several factors affect the occurrence, severity and characteristics of droughts, heatwaves, and

compound extremes. By using just one station, the authors neglect important factors such as background aridity and weather patterns in their study and it still remains unclear how this methodology works in different climatic zones.

Answer: We recognize the importance of applying this method to more locations to further test its performance. During the review period of this manuscript, we have applied the proposed removal and merging method to identify droughts, heatwaves, pluvials, and coldwaves in England with 71 years of data in our latest research. Now, the preprint is available online ($https://papers.ssrn.com/sol3/papers.cfm?abstract_i d = 4728550$). We explored the association between the severity of extreme climate events and changes in butterfly abundance. The findings indicate that extreme climate events can be effectively identified using this method, which means the method works well in England. To highlight this concern, we add a limitation statement in the conclusion:

"We used one station to demonstrate the method, and further studies are needed to validate whether the proposed identification method works well in different climatic zones."

Q7: While the authors enhanced the conclusion as suggested by referee2, it still needs further improvement and lacks a comprehensive representation of results and assessments.

Q8: In line 419: please include references for this statement 'the increasing temperatures contribute to the increase in CDHW events, which aligns with the current literature.'

Q9: In line 421: either further explain this statement 'which could be explained by physical mechanisms.' or add some references.

Q10: In line 422: I am not sure about this statement 'our daily-scale identification captures variations that monthly or weekly scales often miss', because I did not see any weekly analysis that confirms this assertion.

Answer: Questions Q7 to Q10 all point to conclusions. According to the comments, we revised the conclusion by adding the corresponding references, improving the precision of expression, and enhancing the comprehensive representation of results and assessments. The improved conclusions are as follows:

"We proposed a method for identifying droughts, heatwaves, and compound events. The identification on a daily scale systematically and objectively removed minor spells and merged mutually dependent ones. The analysis conducted at Uccle demonstrates the effectiveness of the proposed method in four ways. First, the values of removal thresholds exhibit the desired behavior, adapting effectively to varying accumulation periods and pre-identification thresholds. Second, the frequency of occurrence of heatwaves and CDHW events has increased in the period 1961–2020 compared to 1901–1960, and the increasing temperatures contribute to the increase in CDHW events, which aligns with the current literature (Manning et al., 2019). Moreover, the occurrence of CDHW events shows seasonal patterns, with the occurrences of droughts and heatwaves being negatively dependent in winter, but positively dependent in the other three seasons, which could be explained by atmospheric and land-atmosphere interactions. Fourth, a validation experiment based on this positive dependence in summer demonstrated the robustness of the proposed method compared to commonly used methods. We used one station to demonstrate the method, and further studies are needed to validate whether the proposed identification method works well in different climatic zones.

By upscaling the temporal resolution to a finer one, our daily-scale identification captures variations that monthly scales often miss, providing more precise event start and end dates for droughts and CDHW events. This more precise identification could enhance the capacity for detection, assessment, monitoring, and early warning of both drought events and CDHW events.

Furthermore, our definition in relative terms allows for identifying heatwaves and CDHW events across all four seasons, including non-summer periods. This expanded understanding is crucial as it sheds light on the ecological repercussions that extend beyond the confines of the traditional summer-focused perspective. The ecological impacts of CDHW events in non-summer seasons are also significant. For instance, in regions characterized by temperate continental and temperate monsoon climates, CDHW events in non-summer seasons link to wildfire weather (Tian et al., 2011). In such regions, the winter season itself often represents the dry season, characterized by reduced precipitation and frequent strong winds. The dry season becomes even drier when drought conditions co-occur with abnormally high temperatures. This exacerbates the dryness of the soil and the atmosphere, accelerating the drying of forest litter and setting the stage for an elevated risk of wildfires. "

References

Farahmand, A. and AghaKouchak, A.: A generalized framework for deriving nonparametric standardized drought indicators, Advances in Water Resources, 76, 140–145, 2015.

Geirinhas, J. L., Russo, A., Libonati, R., Sousa, P. M., Miralles, D. G., and Trigo, R. M.: Recent increasing frequency of compound summer drought and heatwaves in Southeast Brazil, Environmental Research Letters, 16, 034 036, 2021.

Li, J., Wang, Z., Wu, X., Xu, C.-Y., Guo, S., and Chen, X.: Toward monitoring short-term droughts using a novel daily scale, standardized antecedent precipitation evapotranspiration index, Journal of Hydrometeorology, 21, 891–908, 2020.

Manning, C., Widmann, M., Bevacqua, E., Van Loon, A. F., Maraun, D., and Vrac, M.: Increased probability of compound long-duration dry and hot events in Europe during summer (1950–2013), Environmental Research Letters, 14, 094 006, 2019.

McKee, T. B., Doesken, N. J., Kleist, J., et al.: The relationship of drought frequency and duration to time scales, in: Proceedings of the 8th Conference on Applied Climatology, vol. 17, pp. 179–183, California, 1993.

Mo, K. C. and Lettenmaier, D. P.: Heat wave flash droughts in decline, Geophysical Research Letters, 42, 2823–2829, 2015.

Mukherjee, S. and Mishra, A. K.: Increase in compound drought and heatwaves in a warming world, Geophysical Research Letters, 48, e2020GL090 617, 2021.

Raei, E., Nikoo, M. R., AghaKouchak, A., Mazdiyasni, O., and Sadegh, M.: GHWR, a multi-method global heatwave and warm-spell record and toolbox, Scientific data, 5, 1–15, 2018.

Ridder, N. N., Pitman, A. J., Westra, S., Ukkola, A., Do, H. X., Bador, M., Hirsch, A. L., Evans, J. P., Di Luca, A., and Zscheischler, J.: Global hotspots for the occurrence of compound events, Nature communications, 11, 1–10, 2020.

Salvador, C., Nieto, R., Linares, C., Díaz, J., and Gimeno, L.: Short-term effects of drought on daily mortality in Spain from 2000 to 2009, Environmental research, 183, 109 200, 2020.

Tian, X., McRae, D. J., Jin, J., Shu, L., Zhao, F., and Wang, M.: Wildfires and the Canadian Forest Fire Weather Index system for the Daxing'anling region of China, International Journal of Wildland Fire, 20, 963–973, 2011.

Wang, Q., Zeng, J., Qi, J., Zhang, X., Zeng, Y., Shui, W., Xu, Z., Zhang, R., and Wu, X.: A multi-scale daily SPEI dataset for drought monitoring at observation stations over the mainland China from 1961 to 2018, Earth System Science Data Discussions, 2020, 1–33, 2020.

Wells, N., Goddard, S., and Hayes, M. J.: A self-calibrating Palmer drought severity index, Journal of climate, 17, 2335–2351, 2004.

Yuan, X., Wang, Y., Ji, P., Wu, P., Sheffield, J., and Otkin, J. A.: A global transition to flash droughts under climate change, Science, 380, 187–191, 2023.