Response letter to RC2

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. An empty line separates the questions.

This study presents a method to identify compound drought/heatwave daily events as well as develop a set of indices that can be used to characterize such events. The paper is well organized and the topic is appropriate for the journal. However, there are a couple of issues that should be addressed before publication (along with some other minor issues outlined below).

Answer: We sincerely appreciate the reviewer's constructive feedback and thoughtful suggestions concerning the manuscript. Below, we address the issues raised and provide our responses to each of them.

Q1: In particular, given the definition of drought and heatwave events I'm not sure that a "precise identification of the start and end dates of an event" is really realistic, I would probably focus more on things like duration etc. which are important and somewhat remove the aspect of a specific start/end date.

Answer: Thank you for raising this important point. You're absolutely correct that achieving an "accurate" identification of drought and heatwave events can be challenging, particularly due to the variability in literature in how these events are defined.

In our study, when we refer to "more precise identification", we are emphasizing the enhancement of the temporal resolution in event identification, specifically at a daily scale. This finer temporal scale allows us to capture variations that might be missed when using monthly scales.

To illustrate this, let's consider an example as discussed in Section 3.2 in the manuscript. In the summer of 1976 at Uccle, the meteorological drought event ended on July 11, followed by heavy precipitation on July 12, which terminated the previous meteorological drought event. If we were to use a monthly scale for identification, this drought event would be recorded as ending on June 30. There is an 11-day difference in the ending dates, and this distinction is particularly significant because it coincided with a heatwave event. Consequently, the corresponding compound events of type d-and-h lasted *18 days* when identified on a daily basis, as opposed to *8 days* when identified on a monthly basis. By employing identification on a daily basis, we can pinpoint starting or ending dates that fall in the middle of the month with more precision, which contributes to a more accurate duration for compound events.

Q2 & Q3: Also, there is not much discussion on validating the identification of these compound events and although it is a difficult task I would have liked to see some additional text/analysis. A discussion section is also missing that would add some more details on how the results compare in the context of other studies;

Answer: We acknowledge the importance of discussion and validation in scientific research. Indeed, validating the identification of droughts, heatwaves, and compound events is challenging due to the inherent difficulty in measuring the exact start and end dates. Inspired by the reviewer's question, we have conceived an idea for indirect validation.

We know from well-established physical mechanisms that there exists a strong positive land-atmospheric feedback between droughts and heatwaves during the summer. So, droughts and heatwaves are highly dependent in the summer.

To quantify this dependence, we employ the likelihood multiplication factor (Ridder et al., 2020), denoted as LMF. It is calculated as $\text{LMF} = \frac{P_{\text{d-and-h}}}{P_{\text{d}} \times P_{\text{h}}}$, where P_{d}, P_{h}, and $P_{\text{d-and-h}}$ represent the probability of a day being in drought, heatwave, and CDHW events, respectively. In the case of independence, LMF equals 1; if droughts and heatwaves are positively dependent, LMF exceeds 1 and increases with the strength of dependence.

Back to our identification method, it comprises three crucial steps: pre-identification, removal, and merging. These steps categorize spells into two distinct groups:

A: Drought and heatwave events using the proposed identification method.

B: Short dry and heatwave spells that are removed in the removal step but still fall below (or above) the pre-identification threshold.

So, combined with the known physical mechanisms, if our proposed method is effective, the removed spells should not represent drought or heatwave events. Therefore, we expect that the removed spells (group B) will exhibit less dependence than the events (group A) during the summer. We expect the following behaviors during the summer season:

(1) LMF$_\text{A}$ should be greater than 1;

(2) LMF$_\text{A}$ should be greater than LMF$_\text{B}$.

We calculated LMF$_\text{A}$, LMF$_\text{B}$, and LMF$_\text{A}$ − LMF$_\text{B}$ in June, July and August. Because different accumulation period lengths and/or pre-identification thresholds for droughts and heatwaves could result in different CDHW events, we consider all possible combinations: $N_{\text{d}} = 15, 30, 45, 60, 90$ d, $N_{\text{h}} = 3, 5, 7, 10, 15$ d, SPI_{d} = -0.5, -1, -1.3, SHI_{h} = 0.5, 1, 1.3, resulting in $5 \times 5 \times 3 \times 3 = 225$ scenarios in total, see Table **??** in the manuscript for the corresponding removal and merging thresholds for each case.

The validation results are presented in Figure 1, and we observed the expected behaviors.

Firstly, LMF$_\text{A}$ consistently exceeds 1 across all scenarios, indicating that the identified droughts and heatwaves exhibit positive dependence during the summer season. LMFB tends to be closer to 1 compared to LMFA, suggesting that the removed dry and heatwave spells are closer to being independent.

Secondly, LMF$_\text{A}$ − LMF$_\text{B}$ >0 in all 225 scenarios, which means the identified droughts and heatwaves always have a stronger positive dependence than the removed dry and heatwave spells.

In existing studies on the identification of drought and heatwave events, it is common practice to employ subjective and fixed minimum duration for excluding minor spells. For instance, many studies retain drought events only if they persist for more than 30 days to focus on significant events (Brunner and Stahl, 2023; Xu et al., 2023; Christian et al., 2021). Similarly, heatwave events are commonly identified as lasting at least 3 consecutive days (Ridder et al., 2020; Yin et al., 2023).
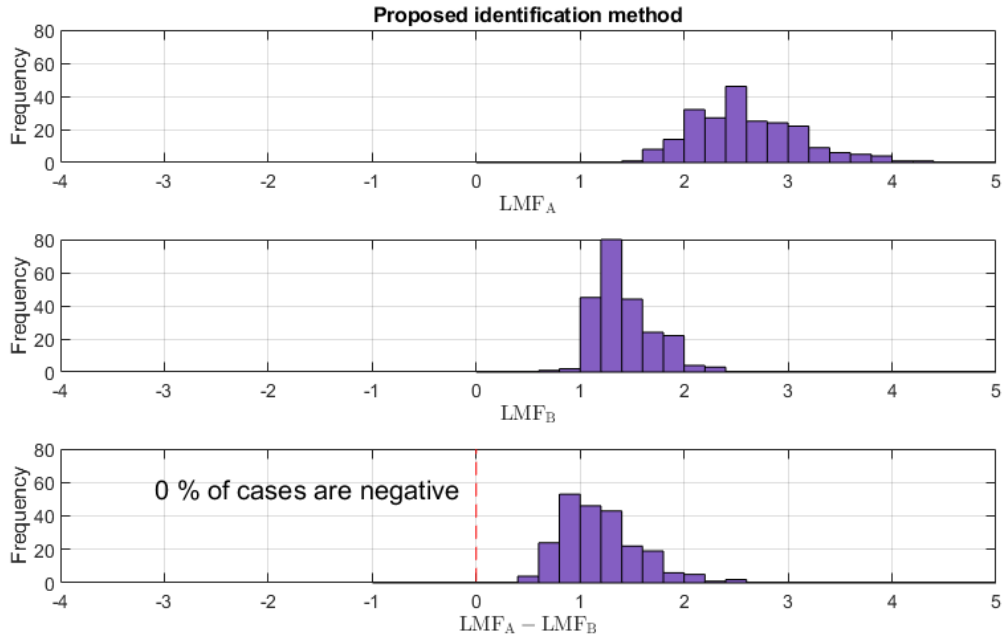
Figure 1. LMF_A, LMF_B, and $LMF_A - LMF_B$ by using the proposed removal and merging method. $LMF = \frac{P_{\text{d-and-h}}}{P_d \times P_h}$ and $LMF = 1$ means independence. A: Drought and heatwave events using the proposed identification method; B: Short dry and heatwave spells that are removed in the removal step but still fall below (or above) the pre-identification threshold.

However, we raise a concern regarding the rationality of applying fixed removal thresholds across varying lengths of accumulation periods and pre-identification thresholds such as in Xu et al. (2023). To investigate this concern, we conducted a similar analysis but using fixed removal thresholds (30 days for droughts and 3 days for heatwaves) instead of the thresholds obtained by the proposed method. In this analysis, we also categorized the identified events into two groups:

A2: drought and heatwave events identified using the fixed removal threshold method.

B2: dry and heatwave spells with a duration shorter than the fixed removal thresholds.

Similarly, we calculate LMF_{A2}, LMF_{B2}, and $LMF_{A2} - LMF_{B2}$ in all 225 scenarios, as shown in Figure 2. Our aim is to evaluate whether these scenarios exhibited the two expected behaviors.

The results confirmed the first expected behavior: LMF_{A2} consistently exceeded 1 in all scenarios. However, it is noteworthy that the second expected behavior, $LMF_{A2} - LMF_{B2} > 0$, was not always observed. Approximately 16% of cases yielded negative values for $LMF_{A2} - LMF_{B2}$, implying that the removed drought and heatwave spells exhibited a larger degree of dependence than the identified events. This outcome deviates from the expected behavior.
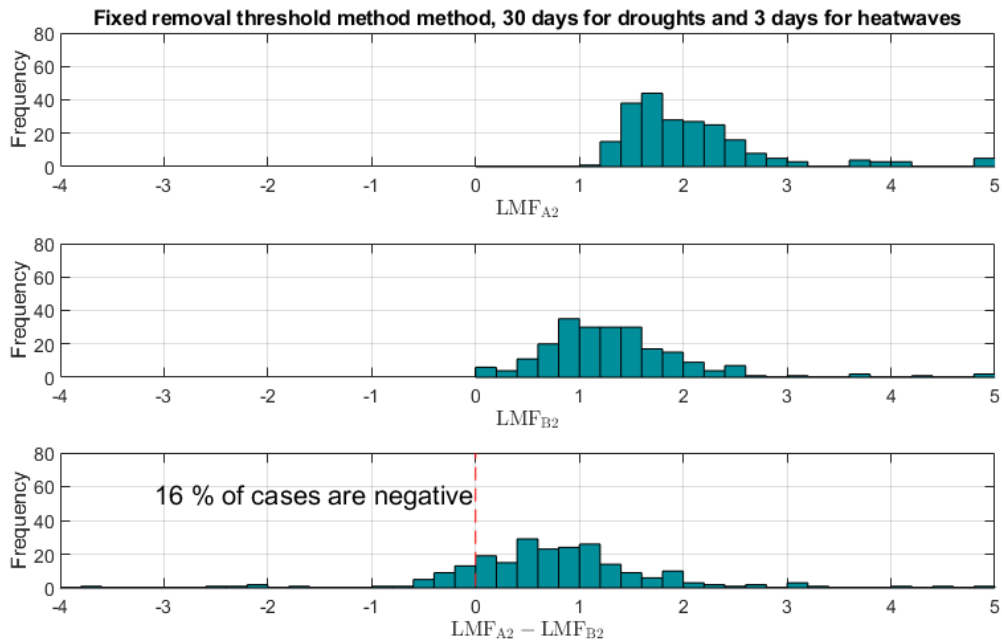
Figure 2. LMF_{A2}, LMF_{B2}, and $LMF_{A2} - LMF_{B2}$ by using the subjective minimum duration method. A2: drought and heatwave events identified using the fixed removal threshold method; B2: dry and heatwave spells with a duration shorter than the fixed removal thresholds.

In conclusion, the application of a fixed removal threshold method for various accumulation periods and pre-identification thresholds of droughts and heatwaves introduces the potential risk of generating inconsistent and unreasonable results. In contrast, our removal and merging method effectively addresses this challenge during validation.

In response to the reviewer's feedback, we intend to introduce an additional section in our manuscript that discusses the above validation idea.

Q4: also, the implications of identifying the compound events can be expanded upon slightly (as the authors seem to attempt in the final sentence of the Conclusions section).

Answer: We will delve deeper into the implications arising from the identification of CDHW events through providing additional context in the discussion section regarding the ecological impacts of CDHW events occurring across all four seasons.

"In this study, a notable departure from existing research is the recognition that CDHW events are not exclusive to the summer season or extensions thereof. We have observed CDHW events across all 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. When drought conditions co-occur with abnormally high temperatures, the dry season becomes even drier. This exacerbates the aridity of the soil and the atmosphere, accelerating the drying of forest litter. Consequently, the moisture content in the ecosystem is further reduced, setting the stage for an elevated risk of forest fires."

Q5: Line 29: is the "coarse resolution" referring to spatial, temporal or both? From the next sentence it seems it's temporal but it'd be good to be explicit here.

Answer: We mean the temporal resolution. We will promptly make the necessary adjustments in the manuscript.

Q6: Introduction is otherwise well written.

Answer: Thank you for the reviewer's positive feedback on the introduction of our manuscript.

Q7: Line 76-80: I don't find this adds much value. Instead, an overview of the experimental design and its rationale would work better here.

Answer: We will rewrite Lines 76-80 to provide a concise summary of our method and link it with the questions we aim to answer. Here is the revised text:

"This section mainly describes the identification method of CDHW events, which includes three steps. First, we define a drought and heatwave and calculate the indices for addressing research questions (a) and (b). Then, we identify drought and heatwave events from daily indices for addressing question (c). Finally, we identify CDHW events from drought and heatwave events for addressing question (d)".

Q8: Line 82: why was only one meteorological station used in the study?

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 longest-time series 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 test further its performance, which is one of the main works we are going to do next.

Q9: Line 84: perhaps use "have been used in many studies" instead of "have been subjected to many studies"?

Answer: We agree that the phrase "have been used in many studies" is more precise and effectively conveys what we intended. In the upcoming revision, we will make the change to "These high-quality observations have been used in many studies".

Q10: Line 132-134: to what degree does the choice of distribution change the calculation of the indices? The use of AIC is an objective way of selecting the distribution, but what is the sensitivity of SPI/SHI?

Answer: To address this, we analyzed the frequency of distribution selections based on the lowest AIC values in the calculation of SPI and SHI, as illustrated in Figure 3. In the calculation of SPI, the Gamma distribution was the most frequently selected, followed by the GEV and Burr distributions. For SHI, a wider array of distributions, including the Normal, Gamma, GEV, Inverse Gaussian, EV, Logistic, Loglogistic, and Burr distributions, were observed.

Regarding the sensitivity of SPI and SHI to the choice of distribution, we conducted a comparison between values calculated using fixed distributions (commonly chosen: Gamma and GEV for SPI, Normal and GEV for SHI) and the values in our study. This comparison is depicted in Figure 4. Our findings indicate that the choice of distribution can significantly influence the indices' values, especially in the tails of the distribution that are particularly relevant for extreme events. For example, we observed several instances of problematic SHI values when using the GEV distribution, as indicated by the grey circle. Existing studies, like by Mishra and Singh (2010), Laimighofer and Laaha (2022), also highlighted this uncertainty in indices caused by the choice of the distribution to be fitted.

In response to the reviewer's feedback, we intend to add one paragraph to introduce the choice of distribution for SPI and SHI at the start of the results section and extra text to discuss it in the discussion section.
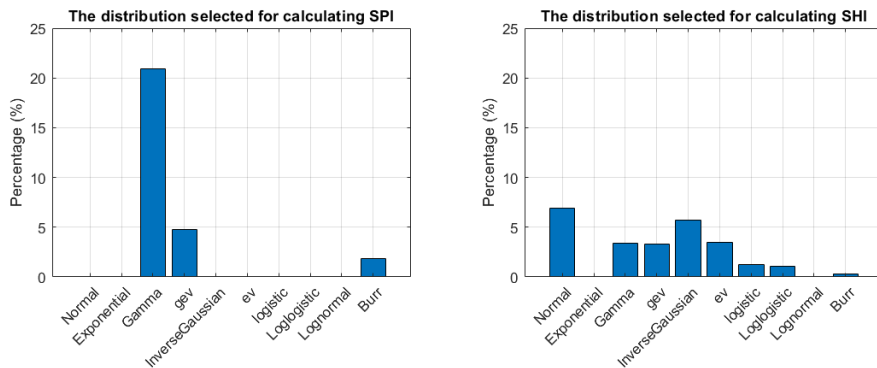

Figure 3. The frequency of the distribution selected with the lowest value for the AIC in the calculation of SPI and SHI

Q11: Line 148: the etymology of the term "deficiency" refers to quality, I'm wondering if there could be a better term to describe "how close two neighboring spells are" (unless I misunderstood the definition). Perhaps "proximity"?

Answer: Upon reflection, we concur that the term "proximity" is a more suitable choice to convey the concept of closeness or nearness between two spells. We will make the necessary adjustments in our manuscript to replace "deficiency" with "proximity" to enhance clarity and precision in our descriptions.

Q12: Line 168: I would remove the word "Concretely" here, perhaps "Particularly"?
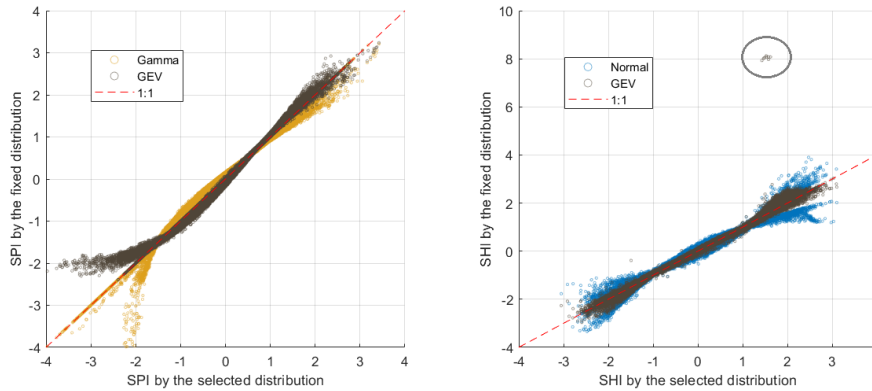
Figure 4. The differences in SPI (left) and SHI (right) values from the choice of the distribution to be fitted.

Answer: We appreciate the reviewer's suggestion regarding using the word "concretely" in the context of our manuscript. However, upon careful consideration of the context and the text flow, we have opted to retain the term "concretely."

After describing the statistical assumption in the last paragraph, the word "concretely" emphasizes the specificity and precision of the actions being taken. It signals to the reader that we are delineating the criteria for removing and merging spells.

Q13: Line 230: not sure you need a separate subsection for this.

Answer: We appreciate the reviewer's feedback on the organization of our manuscript. In light of the reviewer's comments, particularly Q2 and Q3, we have recognized the need to include more comprehensive discussions about validating the identification method. In the validation discussion, we will use the probabilities of occurrence, so this content reappears throughout the paper, not only in the results section (Section 3.4: Seasonality) but also in the discussion. Given the significance of this topic, we have opted to create a separate subsection. This decision aims to assist readers in quickly getting the calculations and concepts related to the probabilities of occurrence.

Q14: Line 309: why specifically these values for Nd, Nh?

Answer: The reviewer's observation is entirely valid; indeed, there are 225 potential combinations for analyzing compound drought-heatwave (CDHW) events, given the ranges of parameters available ($N_\mathrm{d} = 15, 30, 45, 60, 90$ d; $N_\mathrm{h} = 3, 5, 7, 10, 15$ d; $\mathrm{SPI_d}$ = -0.5, -1, -1.3; $\mathrm{SHI_h}$ = 0.5, 1, 1.3).

The specific values of $N_\mathrm{d} = 15$ d and $N_\mathrm{h} = 3$ d were chosen based on their prevalence in the existing literature. These values have been commonly employed in previous studies for the following reasons:

- $N_\mathrm{d} = 15$ d: This duration is frequently used in meteorological drought event identification. It strikes a balance between capturing the onset and progression of droughts while avoiding overemphasis on short-lived events.

- $N_h = 3$ d: In the case of heatwave events, the Standardized Heatwave Index (SHI) application is still relatively nascent as non-summer heatwaves are not commonly recognized. However, the study by Raei et al. (2018) recommends an accumulation period of $N_h = 3$ d for SHI. This choice aligns with their findings and reflects the current state of research in this area.

By selecting these values, we aimed to maintain consistency with established practices in the field while also ensuring the feasibility of our analysis. We appreciate the reviewer's interest in this aspect of our method and hope this explanation clarifies our rationale for the specific choices.

Q15: Line 360-374: the Conclusions section is somewhat poorly written. For instance, the last sentence seems out of place while the statement "The results confirmed the effectiveness of the proposed method" needs a bit more context.

Answer: We appreciate the reviewer's insights and agree that clarity and coherence are vital in summarizing our study's findings. According to this feedback, we rewrite the Conclusion as below:

"We proposed a method for identifying drought, heatwave, 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 several ways. First, the values of removal thresholds exhibit the desired behavior, adapting effectively to varying accumulation periods and pre-identification thresholds. Moreover, 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. Besides that, 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 physical mechanisms could explain.

As expected, our daily-scale identification captures variations that monthly or weekly scales often miss, providing more precise event start and end dates. This 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, a feature valuable for ecological research."

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