Response to Reviewer 3 Comments

MS No.: hess-2024-245

Thanks to the reviewer for reviewing our manuscript. We sincerely appreciate the time and effort you dedicated to carefully evaluating our work and providing valuable comments and suggestions. Your insights have significantly contributed to improving the quality of our manuscript. We have addressed each of your comments accordingly, and our responses are provided below. Reviewer comments are highlighted in red, while our responses are in black.

This study presents a global assessment of combined drought indicator (CDI) in identifying socio-economic drought impacts at the subnational level and compares it with single hydro-meteorological drought indices, such as SPI, STI, NDVI, and SSI. The GDIS dataset was utilized to represent observed socio-economic drought impacts. The authors found that CDI outperforms any single drought index in detecting drought events. Its performance is even higher when short drought events lasting 2 months or less are excluded in the analysis. This study highlights the importance of using CDI to evaluate socio-economic drought impacts.

Assessment

This paper analyzes the performance of CDI in identifying drought events recorded in the GDIS database. Furthermore, the study compares the performance of CDI with individual hydro-meteorological drought indices in detecting droughts. I find the work and its findings interesting, especially when I look at the title, which suggests an assessment of socio-economic drought impacts. However, the aim and title of the manuscript seems misleading. Additionally, the manuscript contains some typos and formatting issues. Below, I provide four general comments, aimed at improvement and clarification. I suggest the authors consider these comments in their revised manuscript.

General Comments

I have four general comments regarding the manuscript:

1. The aim of this paper is to evaluate the performance of multiple drought indices, including CDI to pinpoint drought areas recorded in the GDIS database. This objective is also stated in the abstract. However, the title suggests an assessment of socio-economic drought impacts using both single and combined drought indicators. When I read the paper, I do not find any results related to drought impacts; instead, the analysis focusses solely on drought occurrences. I expected to see socio-economic impacts, such as economic loses, human mortality, etc. Therefore, I suggest either incorporating an analysis of socio-economic impacts or modifying the title to better reflect the study's aim and findings. I personally make a clear definition between event and impact.

We thank the reviewer for the helpful comment and for suggesting a title change based on the analysis and results presented. We agree that the original title may have conveyed a misleading impression that our study analyzes socio-economic drought impacts, such as economic losses or human health consequences, whereas our focus is specifically on drought events as recorded in the GDIS database. Following the reviewer's suggestion, we have revised the title to better reflect the actual scope of our work. The updated title is: **"Global Assessment of Socio-Economic Drought Events at Sub-National Scale: A Comparative Analysis of Combined Versus Single Drought Indicators."**

By using the term "events" rather than "impacts," we aim to clearly distinguish that our analysis concerns to the detection and characterization of recorded drought occurrences, not their quantified impacts. This distinction aligns with the reviewer's own helpful clarification between event and impact, which we found valuable in refining the manuscript.

The introduction section could be better structured for improved readability and logical flow. Currently, the introduction negins with a general statement about droughts (paragraph 1), followed by socio-economic drought impacts (paragraph 2), GDIS database (paragraph 3), and then go back again to drought types and indicators (paragraph 4), and finally discusses the CDI (paragraph 5). To enhance the coherence, I suggest reorganizing the introduction so that the discussion on droughts (paragraphs 1, 4, 5) comes first and then followed by impacts and the impact database (paragraph 2 and 3). By doing this, it would create a more logical and improve the overall flow of the paper.

We thank the reviewer for the suggestion regarding the structure of the introduction section. As recommended, we have reorganized the content to improve logical flow and coherence. The revised introduction now begins with a discussion on drought types, indicators, and the CDI, followed by sections on socio-economic drought impacts and the GDIS database. The updated introduction section is as follows (revised manuscript, section 1, line 35-130):

Droughts are a complex phenomenon and have profound, long-lasting impacts on various sectors, including agriculture, water resources, industry, energy, and socio-economic conditions. For instance, in August 2021, a severe drought event affected 52% of crop yields in the Western United States, and in June 2019, Chennai, India, declared "day zero" due to almost no water remaining in all main reservoirs (Hossain Anika Tasnimand MacMurchy, 2022). Climate projections indicate a future trend of increased frequency and severity in drought occurrences worldwide, amplifying their impacts on various sectors (Vicente-Serrano et al., 2022). These examples emphasize the urgent need for enhanced drought preparedness mechanisms and accurate drought impact assessment techniques in the coming years. When addressing drought assessment, one of the major challenges is in understanding the exact propagation of drought hazard (meteorological/agricultural or hydrological) to its socio-economic repercussions.

Droughts do not have a specific universally accepted definition. They are defined based on their association with different sectors and unique characteristics. Based on drought types and sectors, a number of drought assessment techniques and indices have been used worldwide to quantify and monitor drought conditions. To assess meteorological droughts, several indices such as the Standardized Precipitation Index (SPI)(Mckee et al., 1993), Standardized Precipitation Evaporation Index (SPEI)(Vicente-Serrano et al., 2010), and Temperature Condition Index (TCI)(Kogan, 1995) were extensively used. The World Meteorological Organization (WMO) recommends (Svoboda et al., 2012) SPI, which is widely used in many regions. For example, Bhunia et al. (2020), Blain et al. (2022), Kazemzadeh et al. (2022), Livada and Assimakopoulos, (2007), Zhang et al. (2012), used SPI to assess drought over Greece, United Kingdom, Iran, India, and China, respectively. SPEI has been used in drought projection studies across the United Kingdom (Reyniers et al., 2023), the United States(Costanza et al., 2023), and the global (Vicente-Serrano et al., 2022) level, indicating an increase in severe drought events in these areas in upcoming years. To assess agricultural droughts, the Standardized Soil Moisture Index (SMI), Vegetation Condition Index (VCI), Normalized Difference Vegetation Index (NDVI), and Vegetation Health Index (VHI) have been widely recognized as effective indicators. Ding et al. (2022), Sandeep et al. (2021), Tao et al. (2021) used the NDVI-based drought indices to perform detailed assessments of vegetation health and vigor in Australia, India, and China, respectively. Grillaki (2019) applied SMI to reveal a significant rise in drought severity across Europe in recent years. Liu et al. (2022) investigated soil moisture dynamics in East Africa using a space-time perspective to identify the underlying causes of drought. By a novel Eco-hydrological reanalysis, Sawada (2018) quantified the drought propagation from soil moisture to vegetation across the globe, highlighting that deeper soil layers exhibit delayed recovery from stressful conditions compared to shallow layers. To assess hydrological droughts and their impacts on water resources and ecosystems, commonly used metrics include the Standardized Streamflow Index (SSI), Reservoir Storage Index (RSI), and Standardized Runoff Index (SRI). To understand surface water security, Mishra (2020) examined long-term trends in hydrological droughts across India using SRI. Forootan et al. (2019) conducted a global assessment of hydrological droughts, highlighting the strong regional impact of the North Atlantic Oscillation and Indian Ocean Dipole.

The studies mentioned above provided drought indicators that were based primarily on a single input variable or were sector-specific (either meteorological, agricultural, or hydrological). However, some works suggested that drought is a much more complex and multiphase phenomenon, resulting from various factors rather than just a single parameter(Jiao et al., 2019a; Kulkarni and Gedam, 2018; Sepulcre-Canto et al., 2012). Hence, to understand droughts more accurately, the integration of multiple variables is needed, and it has a higher potential than single-variable-based traditional drought indices. This integrated approach can provide a more comprehensive understanding of droughts, considering the relationships between various contributing factors and the resulting impacts across different sectors. Recognizing the significance of combining multiple variables in drought monitoring, Svoboda et al. (2002) developed a drought monitoring system (US Drought Monitor) for the United States, which has been extensively used for regular practices in the United States. More recently, the near real-time Vegetation Drought Response Index (VegDRI) was developed and implemented in South Korea (Nam et al., 2018) and the USA (Brown et al., 2008), demonstrating more detailed and improved spatial drought patterns compared to multi-variable based drought indicators. This VegDRI was developed by integrating eight climatic and biophysical datasets (SPI, Palmer drought severity index, performance of average seasonal greenness, start of seasonal anomalies, soil availability water capacity, irrigated agriculture, and ecological regions). In 2023, Guillory et al. (2023) developed the Australian Drought Monitor, integrating SPI, NDVI, soil moisture, and evapotranspiration, which has become a valuable tool in Queensland's official drought declaration process. Bayissa et al. (2019b), Huang et al. (2019), Kulkarni et al. (2020a), and Sepulcre-Canto et al. (2012) have developed and tested Combine Drought Indicators (CDI), demonstrating higher accuracy over Ethiopia, India, China, and Europe, respectively.

Previous studies often used proxies such as crop yield, reservoir storage, or vegetation dynamics to assess the societal impacts of droughts. Leng and Hall (2019) used crop yield sensitivity as a proxy for socio-economic impact and evaluated droughts in major drought-prone countries. Similarly, Sawada et al. (2020), Bayissa et al. (2019), Udmale et al. (2020), Wu and Wilhite (2004) used agricultural productivity as a proxy to measure the socio-economic repercussions of droughts on a regional scale in North Africa, Ethiopia, India, and the USA, respectively. The water availability in reservoirs during drought periods can provide insights into on-ground socio-economic stress conditions; hence,Tiwari and Mishra (2019) Wu et al. (2018) considered reservoir storage as a proxy for socio-economic impacts and identified drought-affected areas in India and China. However, the direct link between drought hazards and their socio-economic repercussions is still underexplored. One major reason for this gap is the lack of available socio-economic impact data. Until a few years ago, the U.S. Drought Impact Reporter, the European Drought Impact Report Inventory, or newspaper information were the only direct socio-economic impact assessment methods available. However, these tools were region-specific and did not offer global coverage. To understand global disaster vulnerability and risk, many previous works, such as Below et al. (2007), Panwar and Sen (2020) Shen and Hwang (2019), used the Emergency Event Datasets (EM-DAT: Guha-Sapir D. et al. 2014). However, the use of this dataset in text format presents limitations, highlighting the need for a more comprehensive, globally inclusive dataset to better understand the socio-economic impact of droughts.

Recently, the Geocoded Disaster (GDIS) dataset has been developed based on EM-DAT, offering geocoded disaster locations at a subnational level (Rosvold and H. Buhaug., 2021). By addressing the limitations of EM-DAT, the GDIS dataset provides detailed information on socio-economically affected areas and administrative units in GIS polygon format. In this paper, we used this newly developed GDIS dataset, and show that it enables us to explore the less understood link between drought hazards and their socio-economic repercussions more accurately and comprehensively.

Despite many works on single-variable and multi-variable drought indicators, very few have investigated how useful these indices are in globally exploring the links between drought hazards and their socio-economic repercussions. In this study, we globally applied four commonly used drought indicators—SPI, STI, NDVI, and SSI and compared these four traditional indices with GDIS to evaluate how well they represent the socio-economic impacts of droughts. Then, inspired by the successful regional examples of CDI, we also developed a new CDI on a global scale using two meteorological (rainfall and temperature) and two agricultural (soil moisture and NDVI) variables. To the best of our knowledge, very few studies (Hao et al., 2014; Sánchez et al., 2018; Wang and Sun, 2023) have considered a global scale for their combined drought indicators, and none have compared and demonstrated the superior capability of such indicators over single-parameter-based traditional indices in global drought assessment. In addition, no studies have assessed the skill of drought indicators in identifying sub-national socio-economic impacts globally, although the sub-national disaster dataset (i.e., GDIS) recently made it possible. In the present paper, we addressed the following key points.

1. Understanding the link between global drought hazards and their socio-economic impacts at the subnational scale using GDIS data.

2. Developing a new global combine drought indicator to enhance the precision and reliability of drought assessment (agro-climatological as well as socio-economic) and assessing its performance in detecting GDIS drought events.
3. Checking the performance of the commonly used traditional drought indicators (SPI, STI, NDVI, and SSI) in identifying sub-national socio-economic impacts of droughts (i.e., their association with GDIS).

To achieve the stated objectives, our study was structured into three main components. Initially, we conducted an analysis of global GDIS data to identify and select drought events at the subnational level. Later, a new global CDI was developed, and its performance in identifying GDIS events was assessed. Following this, we evaluated the effectiveness of four single-variable-based traditional indicators (SPI, SSI, STI, and NDVI) in detecting the GDIS events compared to CDI. As a result, our research produced a comprehensive global framework for assessing drought impact, integrating agroclimatology hazard data with socio-economic impacts. This framework offers potential benefits for drought-prone regions worldwide, facilitating improved drought management strategies and informed policy and decision-making processes.

2. If the GDIS database includes different types of drought impacts, such as economic loses, human mortality, forest fire, yield loses, etc, I suggest establishing a link between drought indicators and their corresponding impacts. For example, if NDVI is the selected indicator for a certain region, I expect that agricultural impact is the dominant impact in that region. If the selected indicator is SPI, then maybe the dominant impact on that region might be related to meteorological drought, and so on. Or at least, I recommend discussing these relationship in the paper.

Thank you for this thoughtful suggestion. While the GDIS dataset includes general information such as the number of affected people and fatalities, it does not consistently categorize the type of socio-economic impact (e.g., agricultural loss, mortality, economic damage) in a structured format. Therefore, this study does not attempt to link specific impact types with particular drought indicators. Instead, the focus is on evaluating whether drought events identified by CDI and other indices align with GDIS-reported events that reflect broader socio-economic consequences. We agree that future research could benefit from exploring such impact-specific relationships where detailed data are available.

3. Regarding drought indicators, the accumulation periods used for analyzing SPI, STI, and SSI are not clearly stated. I suspect that the authors have only used 1 month accumulation period. I suggest reconsidering the use of the term SSI for soil moisture drought. In many publications, SSI refers to the Standardized Streamflow Index, which is used to identify streamflow drought. The standardized soil moisture index is commonly referred as SMI or SSMI.

We thank the reviewer for pointing this out. Yes, we confirm that a 1-month accumulation period was used for analyzing SPI, STI, and SSI in this study. The choice of a 1-month timescale was intentional, as it has several advantages for our analysis. Specifically, it is more sensitive to short-term changes, capturing rapid variations in agro-climatic variables. This is important for assessing early-stage drought conditions and understanding drought impacts triggered by short-term events. Additionally, it aligns with the GDIS timescale, as GDIS provides data on a monthly level, which helps in more accurate event-level analysis. Several previous studies were also referred, that support the use of a 1-month timescale for capturing short-term drought dynamics.These details have also been included in the revised manuscript (section 3.1, line 213 to 217) as follows:

"In this study, a 1-month accumulation period was used for SPI, STI, and SSMI to capture short-term drought dynamics. This timescale is sensitive to rapid changes in agro-climatic conditions and supports early-stage drought detection. It also aligns with the monthly resolution of GDIS data, enabling accurate event-level analysis. The choice enhances consistency between drought indicators and the event database."

Thank you for the suggestion and for highlighting the potential confusion with the abbreviation "SSI." In the revised manuscript, we have updated the terminology to "SSMI" to refer to the Standardized Soil Moisture Index, which is more commonly used in the literature.

Line by line comments

L refers to line and P refers to page.

P1: Abstract: I suggest to expand the abstract in order to capture the summary of your study. I missed an explanation about PCA and results on long and short drought durations. In the EGU journal, you can have longer abstract.

Thank you for this suggestion. The abstract has been expanded in the revised manuscript as follows:

"The accurate assessment of the propagation of drought hazards to socio-economic impacts poses a significant challenge and is still less explored. To address this, we analyzed a sub-national disaster dataset called the Geocoded Disaster (GDIS) and evaluated the skills of multiple drought indices to pinpoint global drought areas identified by GDIS. For the comparative analysis, a widely used Standardized Precipitation Index (SPI), Normalized Difference Vegetation Index (NDVI), Standardized Soil Moisture Index (SSMI), and Standardized Temperature Index (STI) were globally computed at the subnational level for the period 2001–2021. Out of 1641 drought events recorded in GDIS, NDVI identified 1541 (93.9%), SPI 1458 (88.8%), STI 1439 (87.7%), and SSMI 1376 (83.9%) events, respectively. NDVI showed better performance in highly vegetated areas due to its sensitivity to precipitation and soil moisture and its inverse relationship with temperature.

Recognizing the limitations of single-input drought indices in capturing the complex propagation of droughts, we also introduced a novel Combined Drought Indicator (CDI), which integrates meteorological (rainfall and temperature), and agricultural (NDVI and Soil moisture) anomalies using a weighted approach to identify droughts and play a key role in minimizing inaccuracies in drought assessment. CDI successfully identified 1550 (94.5%) of the GDIS documented drought events, outperforming all individual indices. Based on CDI, the highest frequency of severe droughts (>7 events) was observed in sub-Saharan Africa and South Asia. It also captured persistent droughts in Argentina, Brazil, the Horn of Africa, western India, and north China; areas that are highly vulnerable to socio-economic droughts. Our findings highlight the importance of using CDI for improved identification of socio-economic drought events and for prioritizing regions at greater risk."

P1L12: In this sentence, the study area should be mentioned, which is global. I only found this in Line 15.

Thank you. As suggested, the study area (global) has now been added to the third line of the revised manuscript: '…evaluated the skills of multiple drought indices to pinpoint global drought areas identified by GDIS.'

P2L36: Here the authors can see an example of reference typo.

Thank you. The referenced typo has now been corrected to (Hossain et al., 2022).

P2L40: In the last sentence of paragraph 1, the authors mention about drought propagation from meteorological drought to socio-economic drought. However, I miss an explanation on drought types. Later in paragraph 4, I read meteorological drought, agricultural drought, and hydrological drought.

In the revised manuscript, the introduction section has been reorganized. Hence, the missing explanation gap has now been answered.

P2L48: Again, I see typo on references -> Tiwari and Mishra (2019) "and" Wu et al. (2018).

Thank you. The referenced typo has now been corrected to : Tiwari and Mishra (2019) and Wu et al. (2018)

P2L52: Please provide references for DIR and EDII.

Thank you for this suggestion. The references have been included in the revised manuscript as follows;

DIR : (National Drought Mitigation Centre, 2025) : Drought Impact Reporter (DIR) | Drought.gov: https://www.drought.gov/data-maps-tools/drought-impact-reporter-dir, last access: 26 March 2025.

EDII : European Drought Centre, 2025): European Drought Impact Report Inventory (EDII) and European Drought Reference (EDR) database - European Drought Centre: https://europeandroughtcentre.com/news/european-drought-impact-report-inventory-edii-and-european-drought-reference-edr-database/, last access: 26 March 2025.

P2L54: Again, missing comma between references.

Thank you for pointing out this. In the revised manuscript, all the references are correctly cited.

P2L59-63: I suggest the authors to explain more about GDIS. Or at least describe GDIS in detail in the method section.

Thank you for the suggestion. We agree that a more detailed description of GDIS improves clarity. We have expanded the Data section 2.5 to provide additional information on the spatial structure, content, and relevance of GDIS, including its advantage over EM-DAT in capturing subnational impact data. The revised explanation in the manuscript (Section 2.5, lines 167–176) is as follows:

"The Global Disaster Identifier System (GDIS) dataset is a geocoded dataset distributed by SEDAC (NASA) that links disaster events to specific administrative boundaries (Rosvold and H. Buhaug., 2021). It builds upon the EM-DAT database by adding spatial GIS information, providing polygons for subnational regions affected by specific disaster events. Each event is tagged with the type of hazard (e.g., drought, flood, cyclone), the time period, and the affected regions at the sub-national level. In this study, only drought events were extracted from GDIS for the years 2001 to 2021. The GDIS dataset is based on the EM-DAT dataset. EM-DAT records a natural disaster when it meets any of the following conditions: 10 or more fatalities, impacts 100 or more individuals, or prompts a declaration of a state of emergency along with a request for international aid.

The use of GDIS, instead of relying solely on EM-DAT, adds spatial specificity and improves the ability to evaluate drought impacts in different regions, especially in developing countries where vulnerability is high. However, it's worth noting that GDIS coverage is not globally uniform and may be affected by underreporting in certain regions."

P3L77: Missing word "and" between Sandeep et al. (2021) and Tao et al. (2021).

Thanks. The references have been corrected and updated in the revised manuscript.

P3L91: Missing space between parameter and (Jiao et al., 2019a). Starting from here, I will not mention one by one the typo regarding missing space or in references. Please check carefully throughout the manuscript.

Thank you for pointing out the formatting errors. In the revised manuscript, a space has been added between 'parameter' and '(Jio et al., 2019a)'. The rest of the write-up has also been carefully checked for formatting and typographical errors.

P3L95-97: European Drought Observatory (EDO) also utilizes combined drought indices.

Thank you for this information. This reference have been included in the revised manuscript (line 95).

EDO: (European Environment Agency, 2025) : European Drought Observatory (EDO) — European Environment Agency: https://www.eea.europa.eu/policy-documents/european-drought-observatory-edo, last access: 26 March 2025.

P4L122: Here, it is clearly stated GDIS drought events and not impacts.

Thank you for your comment. Yes, it is a GDIS drought event, not an impact. In the revised manuscript, we have carefully distinguished between the terms 'impacts' and 'events' and used them appropriately.

P5L139: Better use x for indicating resolution.

Thanks. We agree with your comment, and in the revised manuscript, to indicate resolution x has been used instead of *.

P5L141: In this sentence, the authors mention: to explore the linkage between drought indicators and "socio-economic impacts". It is drought impacts or drought events? It is very confusing. I make a clear distinction between event and impact (see my general comment).

Thank you for this comment. We agree that it is important to distinguish clearly between drought events and their impacts. In the context of this study, we refer specifically to GDIS events, which represent drought events that have been recorded due to their associated socio-economic impacts. We have revised the manuscript wording to clarify this distinction and avoid confusion between the terms "event" and "impact."

P5L152: The authors may remove the word "originally" since ERA5 Land already has spatial resolution of 0.1 degree.

Thank you. In the revised manuscript, we have removed the word 'originally' when referring to the spatial resolution of ERA5.

P6L170: Define what is socio-economic impact of drought in the GDIS data.

Thank you for this comment. In the GDIS dataset, a socio-economic impact of drought is considered to have occurred when a drought event meets one or more of the EM-DAT disaster inclusion criteria. (i) it causes at least 10 deaths, (ii) affects 100 or more people, (iii) leads to a state of emergency declaration, or results in a call for international assistance. These criteria reflect real-life impacts such as food insecurity, loss of livelihoods, reduced agricultural output, water shortages, or displacement. We have added this clarification to the revised manuscript (Section 2.5).

P6L175: Disaster no or disaster number?

Thank you for pointing this out. We have corrected it to 'disaster number' instead of 'disaster no.' in the revised manuscript.

P8L232-233: I think *i*th and *j*th should be in italic.

Thanks for the comment. In the revised manuscript, ith and jth have been written as *i*-th and *j*-th.

P9L253-254: How about if drought indices indicate drought but GDIS not, so is it false alarm?

Thank you for this question. Yes, we did find a few instances where drought indices indicated drought severity, but these were not detected by GDIS. For example, the CDI detected severe drought in South Argentina during 2014–15 and in Namibia in 2013. Additionally, the CDI identified drought conditions over parts of Europe in 2018 that were not reflected in the GDIS data. These discrepancies may be due to adaptation techniques or practices implemented in these regions, which effectively managed agro-climatic extremes or hazards without significantly affecting local socio-economic conditions. Additionally, it is important to note that GDIS does not fully capture all drought events globally, particularly in regions with limited disaster reporting infrastructure or under-documented local impacts. This explanation has been included in the revised manuscript in Section 4.2, lines 434-439 as follows:

"CDI detected severe drought events in South Argentina during 2014–15, Namibia in 2013, and parts of Europe in 2018, which were not reflected in GDIS event records. These instances highlight that; not all agro-climatic droughts lead to recorded socio-economic impacts, especially in regions with strong adaptation and mitigation capacities. Practices such as advanced irrigation, drought-resistant crop varieties, or effective early warning systems may help manage the agricultural and societal impacts of climatic stress, thereby reducing the likelihood of such events being recorded in GDIS."

P13: Figure 4, please provide alphabets a, b, c, and d for each figure in Figure 4.

Thank you for the suggestion to add sub-details to the figure. This will indeed help readers better understand the content. In the revised manuscript, we have included captions for each subfigure. Additionally, we have modified the figure title to include sub-numbering. The updated figure and its title are as follows;

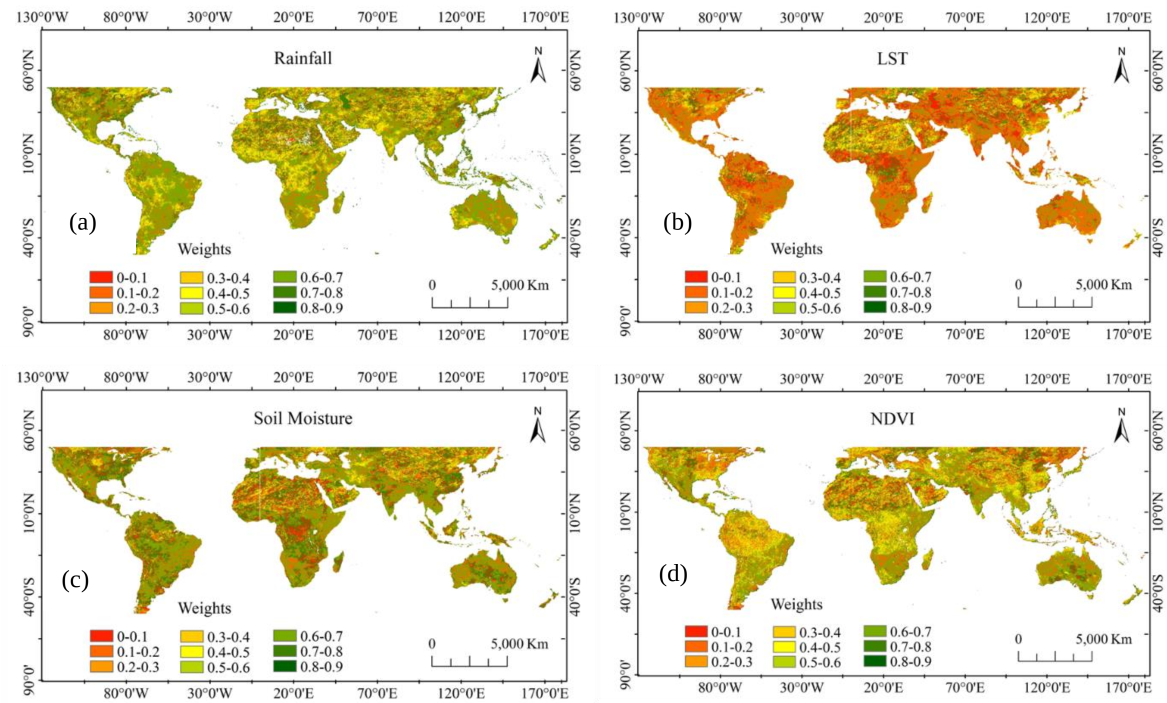


Figure 4. Example of pixel-based weights for the four input variables of CDI: rainfall (a), LST (b), soil moisture (c), and NDVI (d), calculated using the PCA method for a sample month (April). The weights range from 0 to 1, with colors varying from dark red (lower weights) to dark green (higher weights).

P14L350: Same as Figure 4, please provide alphabets for Figure 5. Here the authors refer to Figure 5a but there is no figure 5a.

As suggested by the reviewer, sub-details (alphabet labels) have been added to Figure 5, similar to Figure 4, in the revised manuscript. The updated figure and its title are as follows:0

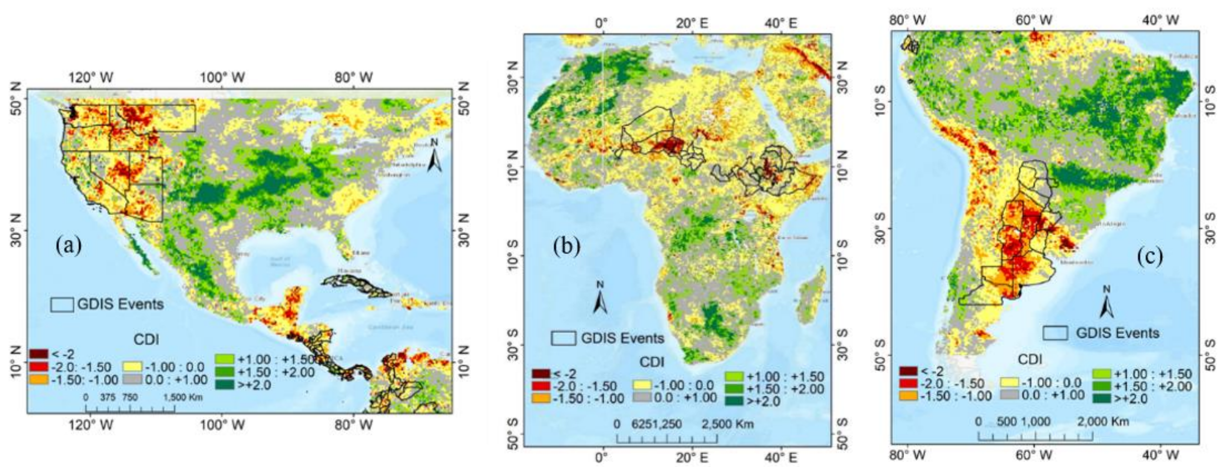


Figure 5. Assessment of Drought Using CDI with Overlay of GDIS Events over America (June 2015) (a), Africa (June 2009) (b), and South America (August 2009) (c). The black polygons

represent GIS polygons from GDIS, indicating drought-affected administrative units based on GDIS data. The base maps display CDI results for the respective GDIS drought months, ranging from dark brown (indicating extreme dry conditions) to dark green (indicating extreme wet conditions). The alignment of GDIS polygons with droughts detected by CDI demonstrates the CDI's capability to accurately identify GDIS droughts during the respective periods.

P14L355: What is AEP?

Thank you. AEP has been used as an abbreviation for Actual Event Period. Since the full form was already introduced in Table 2, we referred to it as AEP in this section. However, in the revised manuscript, we have also added the full form of AEP in the main text for clarity.

P14L360: The authors can also explain about false alarm. Furthermore, Table 2 is summarizing the findings and it is worth detailed explanation, such as the results with and without short droughts and the shifting.

Thank you for raising the point about false alarms. We did observe instances where CDI detected drought conditions that were not reflected in GDIS, and vice versa.

Despite the higher association of CDI in detecting GDIS events, there were a few instances (e.g., Burundi, and parts of Thailand) where CDI failed to capture GDIS events. The smaller spatial extents (subnational scales in Southeast Asia or parts of Africa) could be one reason for this discrepancy. Additionally, these regions might be experiencing other types of stress beyond agro-climatological factors (as indicated by CDI) that contribute to the GDIS events. It was also found that CDI identified stress conditions in some locations that were not reflected in GDIS. For instance, CDI detected severe drought in South Argentina during 2014-15 and Namibia in 2013. Additionally, CDI identified drought conditions over parts of Europe in 2018 that weren't reflected in GDIS data. These disparities may arise from adaptation techniques or practices implemented in these regions, effectively managing agro-climatic extremes or hazards without significantly impacting local socio-economic conditions. The same detailed reasoning behind these discrepancies is provided in the revised manuscript, Section 4.2, line 385

We agree that not all the details from Table 2 were explained in the text earlier. However, in the revised manuscript (Section 4.2), we have now included those results. The detailed findings are as follows;

In the first criterion, when considering one month prior to the AEP and using a threshold of -1, CDI detected 1,954 events, accounting for 91.22% of the total. When the threshold was changed to 0, 2,130 events (99.44%) were identified by CDI in alignment with GDIS. When short-duration drought events were excluded under the same criterion, CDI detected 1,573 events (95.86%) at the -1 threshold and 1,637 events (99.76%) at the 0 threshold. Under the second criterion, two months prior to AEP, CDI detected 2,010 events (93.84%) using a threshold of -1 and 2,137 events (99.77%) when the threshold was adjusted to 0. Excluding short drought events in this scenario, CDI identified 1,587 events (96.71%) at the -1 threshold and 1,637 events (99.76%) at the 0 threshold. In the final criterion, with considering three months prior to AEP, CDI detected 2,042 events (95.33%) at the -1 threshold and 100% of events at the zero threshold. After excluding short drought cases, 1,589 events (96.83%) were captured at the -1 threshold, and again, all events (100%) were identified at the 0 threshold. These results highlight that GDIS events, which appear to occur in specific months, may actually be the outcome of agro-climatic variability occurring one, two, or even three months prior to the reported event, rather than being confined to that specific month alone.

P15L376: Beside the number, I think it is more meaningful to also present the percentage. How many percent drought was detected.

Thank you for this suggestion. We agree that adding percentages makes the analysis more meaningful and easier to understand. In the revised manuscript, percentages have been incorporated into the written analysis, and all relevant percentages have also been added to Table 2.

P16L409: Lower threshold here means index below 0 or long drought duration? I think the latter.

Thank you for the question. In our analysis, the term 'lower threshold' refers to the CDI index value used to detect drought events (-1 or 0). A threshold of -1 is stricter, meaning it represents more severe drought conditions, while a threshold of 0 is more relaxed. This does not refer to drought duration.

P17L426-433: In this paragraph, the authors could highlight which shifting month yields highest performance and false alarm.

Thank you for the suggestion. Based on our analysis, the three-month prior shifting criterion, particularly with a threshold of 0, yielded the highest detection performance, capturing 100% of the GDIS events. However, this setting may also introduce a higher possibility of false alarms, as events detected further in advance may not always correspond to actual socio-economic impacts. Conversely, the one-month prior shift with a threshold of -1 showed lower detection rates (88%), suggesting fewer false alarms but also reduced sensitivity. We have now highlighted these observations in the revised manuscript (section 4.2) to better clarify the relationship between early detection and the risk of false positives. These observations are mentioned in section 4.2, line 395 as follows:

"Among the shifting windows, the three-month prior criterion with a threshold of 0 demonstrated the highest detection rate, capturing 100% of GDIS events. However, this also suggests a higher likelihood of false alarms, as early indicators may not always align with actual drought impacts."

P19: Figure 8. The authors could make a bold line for threshold -1 in order to improve the readability.

Thank you. As per the reviewer's suggestion, the threshold line at -1 has been bolded in Figure 8 to enhance readability.

P19L471-472: Where can I see the figures showing the correlation between CDI and hydro-meteorological indices? The authors could provide these figures in the Appendix.

Thank you for the suggestion. In the revised manuscript the correlation results for a sample month (April) are presented in Figure 9. This figure illustrates the spatial correlation between CDI and key hydro-meteorological indices, including SPI, STI, NDVI, and SSMI.

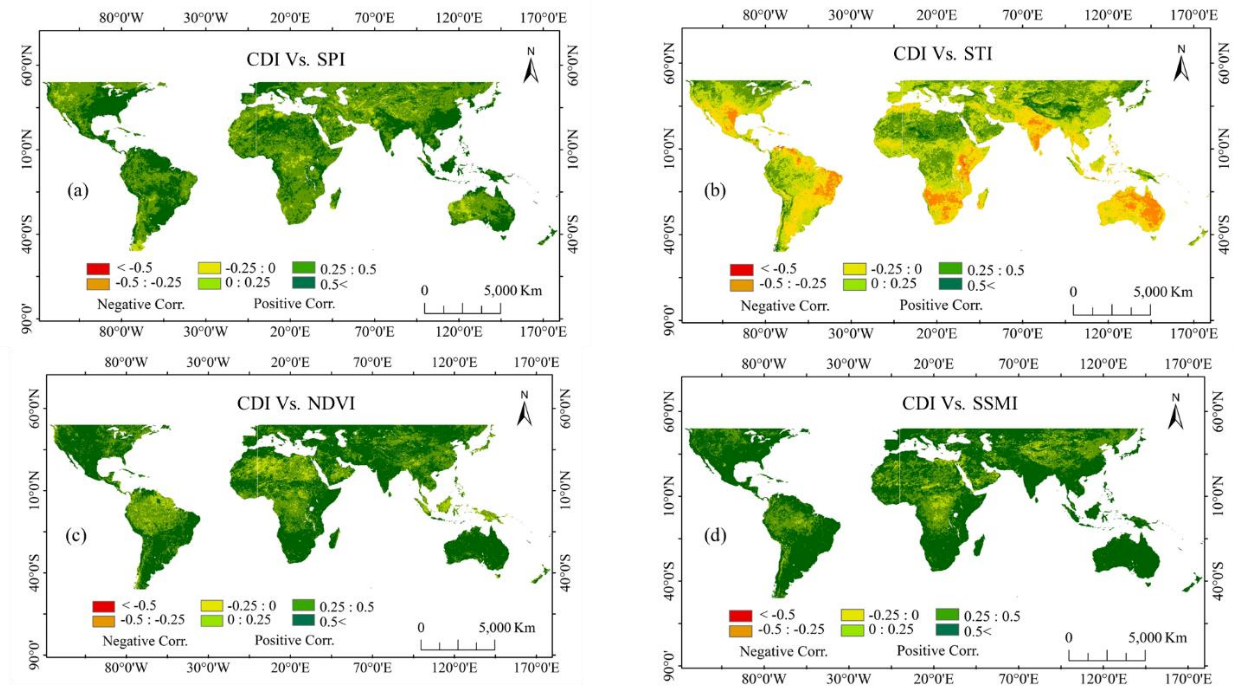


Figure 9. Spatial Correlation Between CDI and Single Input-Based Traditional Indices for a Sample Month (April): (a) CDI vs. SPI, (b) CDI vs. STI, (c) CDI vs. NDVI, and (d) CDI vs. SSMI. Negative correlations are represented by shades from yellow to red, while positive correlations are shown in shades from light green to dark green.

P21L501-502: Make it clear that SPI-1 and SPI-3 are effective to detect meteorological and agricultural droughts while longer time scales are better for detecting hydrological droughts.

Thank you for your valuable suggestion. We agree with this observation and have revised the manuscript accordingly. The updated text now clarifies that SPI-1 and SPI-3 are typically used to detect meteorological and agricultural droughts, respectively, while longer time scales such as SPI-6 or SPI-12 are more appropriate for identifying hydrological droughts. This clarification has been included in Section Five (discussion), Lines 574-580 of the revised manuscript. The revised text is as follows;

“Previous studies, whether regional or global, often relied on single-parameter-based indices for drought monitoring, such as SPI (Ji and Peters, 2003; Liu et al., 2022; Mckee et al., 1993). Each of these has limitations for understanding drought. For instance, SPI is commonly used, but its effectiveness depends heavily on the selected time scale. Shorter time scales, such as SPI-1 and SPI-3, are effective for detecting meteorological and agricultural droughts, respectively, while longer time scales (e.g., SPI-6 or SPI-12) are more suitable for identifying hydrological droughts. However, in regions with distinct wet and dry seasons, SPI can sometimes misrepresent actual drought conditions, for example, a short-term SPI may indicate drought during a naturally dry season, even when annual water availability remains within normal limits."

P21L530: Or maybe the impact is not related to meteorological drought impact?

Thank you for the insightful comment. We agree that the observed impact on the Horn of Africa may not be solely attributed to meteorological drought. The GDIS-detected drought event reflects agricultural or hydrological drought conditions, which are not fully captured by SPI. In response to your suggestion, we have revised the paragraph to include this explanation.

The updated text in the revised manuscript (Section 5: Discussion, Lines: 610-616) is as follows:

*"*One such inconsistency was observed in the Horn of Africa, where the CDI and other indices identified a GDIS drought event, but the SPI did not. This discrepancy could be due to less pronounced precipitation anomalies in the SPI for this region, where baseline rainfall is already low and may not reflect drought conditions accurately. Additionally, it is possible that the observed impact was not solely related to meteorological drought but rather to agricultural or hydrological drought. Factors such as reduced soil moisture, land degradation, or soil types with low water retention capacity, captured by SSMI, STI, NDVI, and CDI, may have played a more significant role in triggering the event*."*

P21L533: Same, maybe the impact is not related to soil moisture drought impact.

Thank you for the helpful comment. We agree that the drought impact in North Argentina may not have been primarily related to soil moisture conditions. While the presence of the Paraná River could buffer soil moisture variability, the observed drought event might have been driven by meteorological factors such as reduced rainfall or elevated temperatures, which may not be captured by SSMI. In response, we have revised the manuscript to include this alternative explanation.

The updated paragraph in the revised manuscript (Section 5: Discussion, Lines: 616-621) is as follows:

"Another example is from North Argentina (South America), where the SSMI failed to detect a drought that was identified by other indices. This disparity might be due to the presence of the Paraná River, the second-largest river in South America, which provides a significant source of soil moisture. Therefore, the SSMI might not reflect drought conditions. However, it is also possible that the impact was not directly related to soil moisture but instead resulted from meteorological factors such as reduced rainfall or elevated temperatures, which could lead to drought and socio-economic stress, as reflected in GDIS."

P23L571: Do the authors mean takeaway message?

Thank you for the comment. Yes, we wanted to convey that the association between CDI and GDIS is one of the key takeaway messages of the study. To improve clarity, we have revised the sentence in the manuscript.

The updated sentence now reads: "The association between the CDI and the GDIS is one of the key takeaway messages of our study, as it directly addresses the gap in understanding actual drought hazards and their socio-economic impacts."

P23L580-581: I think the statement here is very weak saying that lack of availability of high-res hydrological data. There are some high-res hydrological models that provide hydrological data. The Lisflood hydrological model of Europe provide 1x1 km spatial data for streamflow and soil moisture. Or do the authors mean in situ observation?

Thank you for this helpful comment. We agree that there are high-resolution hydrological datasets available from models such as LISFLOOD, particularly for specific regions like Europe. Our original intent was to highlight the limited global availability of consistent, high-resolution hydrological data, whether observed or modeled that can be used uniformly across diverse regions. While regional models exist, their spatial coverage and consistency vary globally, which poses challenges for global-scale analysis. We have revised the manuscript (lines 683-688) to clarify this point.

The updated sentence: "Due to the limited availability of consistent and high-resolution hydrological data at the global scale, hydrological variables were not included in this study. This may have contributed to certain disparities in detecting GDIS events. While regional high-resolution modeled datasets (e.g., LISFLOOD in Europe) are available, the lack of globally consistent and validated hydrological data remains a constraint. In future work, we will aim to incorporate hydrological variables where feasible and explore alternative methods for computing CDI weights to further improve drought detection and its linkage to socio-economic events."

P23L592-593: Mention again the agricultural and meteorological drought indicators.

Thank you for the suggestion. In the revised manuscript, meteorological and agricultural variables have been explicitly mentioned again in the conclusion section line 703. The updated sentence: "To address this limitation, we developed a new Combined Drought Indicator (CDI) that integrates two agricultural (Soil Moisture and NDVI) and two meteorological (Rainfall and Temperature) variables to assess drought conditions."

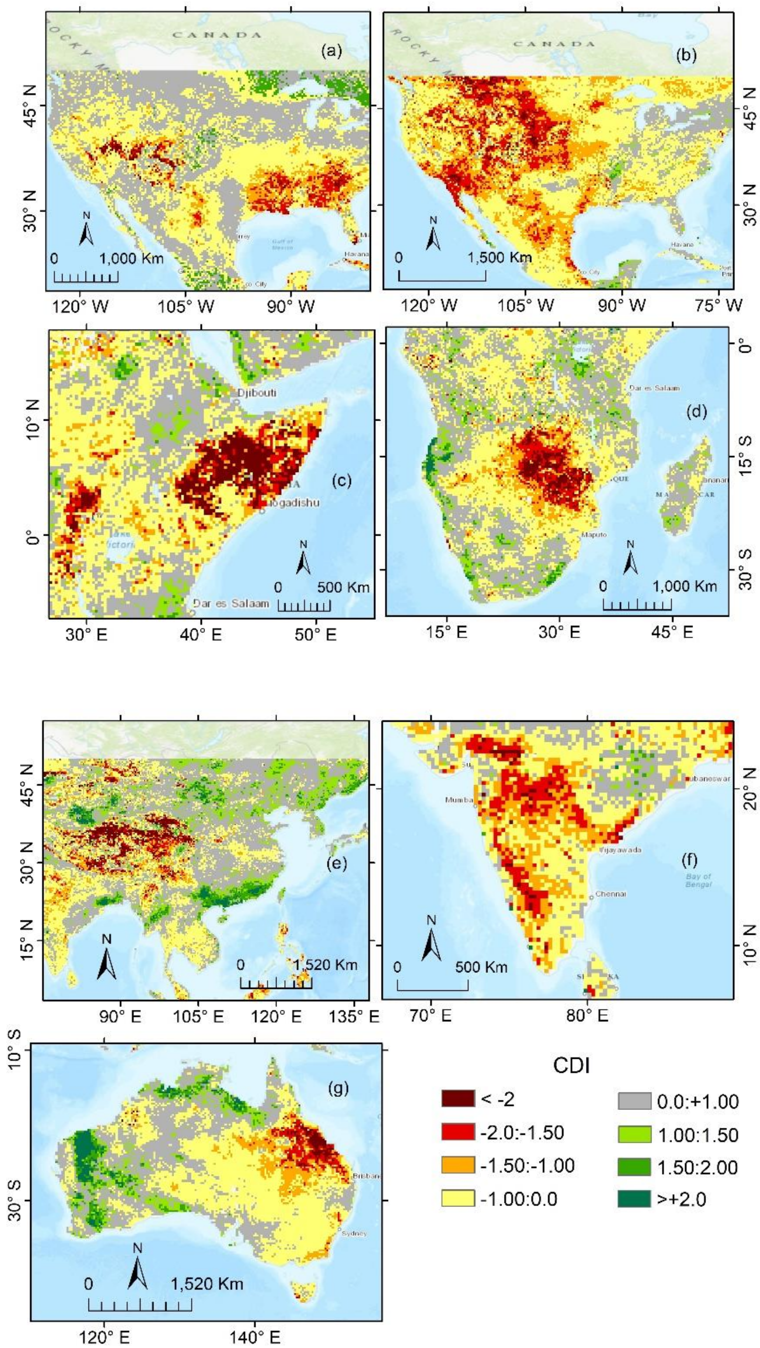
P24L601-602: Does GDIS provide drought socio-economic impacts or just drought events? (see my general comment). Please make it clear.

Thank you for the comment. We acknowledge the need for clarification. GDIS provides information on drought events, not direct socio-economic impacts. This distinction has now been clearly stated in the revised manuscript (Section 6: conclusion, Line 715). The updated sentence:

“The GDIS dataset provides direct socio-economic hazard event information and can be a valuable validation tool for drought indices.”

P32: Figure Appendix 1: missing figure g.

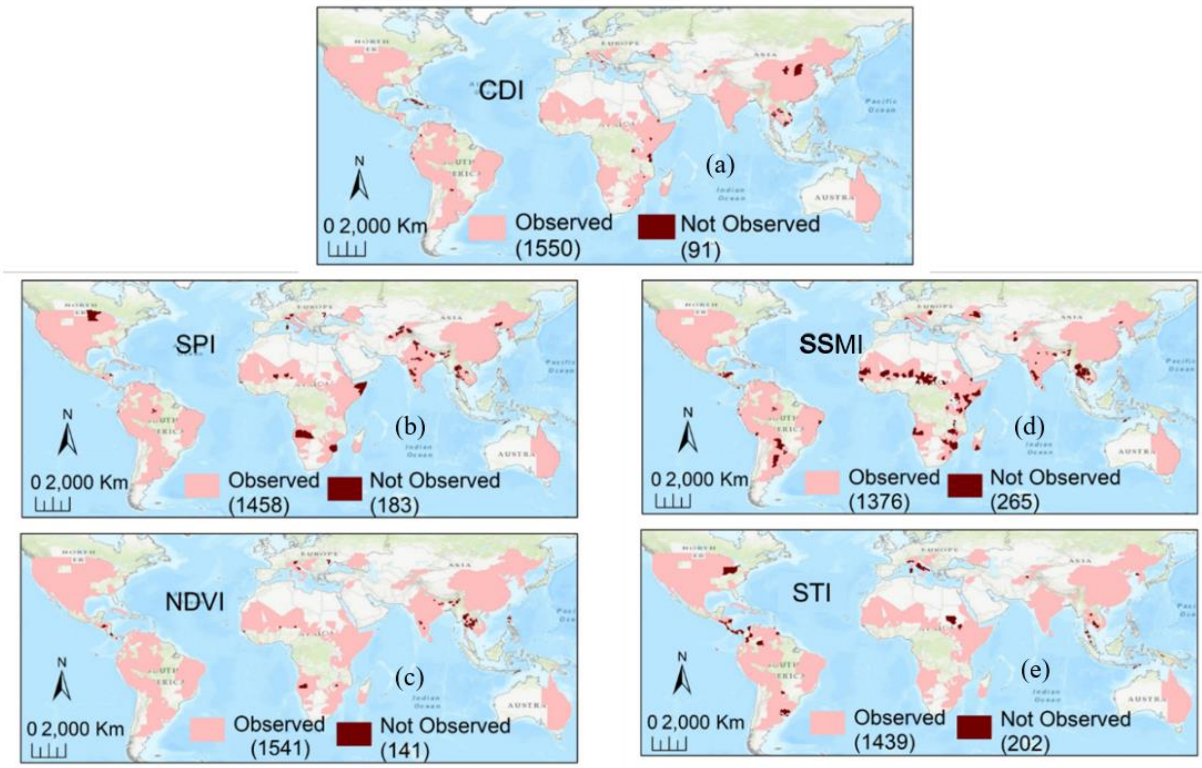
Thank you for pointing out this oversight. In the revised manuscript, Figure g has been added to Appendix 1 to correct the error. The updated figure is as follows:



Appendix 1. Significant drought events detected by CDI in various global regions include: (a) the USA in August 2007 and (b) July 2012, (c) the Horn of Africa in July 2015, (d) Malawi and Zambia in February 2016, (e) western and northern China in July 2015, (f) India in July 2015, and (g) Australia in January 2019.

P33: Provide alphabetical figures.

Thank you for your comment. In the revised manuscript, the figures in Appendix 3 have been arranged alphabetically. The updated figure is as follows.



Appendix 3: Spatial locations-wise performance of CDI (a), SPI (b), NDVI (c), SSMI (d), and STI (e) in detecting GDIS events, where consistent events detected by each index are shown in pink, while inconsistent GDIS events (not observed) are shown in dark brown. The drought identification criteria were set to events during the actual drought period without considering short droughts (total GDIS events count = 1641).

********************** Thank You **********************