Answer to comments of Anonymous Referee #1

The original comments of Referee #1 are in black color and indicated by “R:”. Replies by the authors (“A”) are colored in green. Actions are introduced by “Action:”, changes done in the manuscript are in italics.

General Comment:

The authors introduce two global drought indicators, derived from modeled soil moisture and streamflow, which are based on the approach proposed by Cammalleri et al. (2016) for soil moisture over Europe. The goal of the study is well presented overall, and the analysis is clear. However, in my opinion, the focus on two indicators make the analysis weaker rather than stronger, and the potentiality of the research is not explored in full. For the first index, the authors introduce some modification to the original formulation of the DSI, but they fail in providing a proof that the proposed simplification is better/equal to the original formulation. For the second, there is much more space or analysis and discussion on the water demand component of the index, which is a key point of the analysis that is not fully explored. In my opinion, the first part of the analysis is not sufficiently interesting, at least compared to the second, and I suggest to focus solely on the novelty of the streamflow drought and expanding this section fora more efficient delivery of the key message. Overall, I think that the paper has a very good potential, but it needs some major reworks to focus more on the strengths of the research.

A: Thank you for the overall positive comments. We have addressed all your specific comments in the sections below. However, first and foremost, we would like to address here the major suggestion to solely focus on the streamflow drought. Instead of totally removing SMDAI and its analysis altogether from this paper, we believe it is beneficial for the manuscript to relate computed values of SMDAI and QDAI to each other (in addition to just presenting them independently), by analyzing propagation of drought from soil moisture to streamflow.

Action: We have added a new subsection 4.4 which discusses the propagation of drought from soil moisture to streamflow

“4.4 Propagation of drought from soil moisture to streamflow as indicated by SMDAI and QDAI

As can be expected from the flow path of water on the continents, below normal precipitation occurs before below normal soil moisture. Below normal streamflow may occur even later, but only if streamflow at a certain location is not dominated by local conditions and not conditions in a distant upstream area. This so-called drought propagation can be identified by drought hazard indicators for the respective variables (van Loon, (2013). Knowledge about the dynamics of drought propagation supports monitoring drought development and drought mitigation as it allows to estimate, for example, impacts of the early meteorological drought on various sectors at different stages of its propagation through the water cycle. The purely physical propagation may be expected to be best observed by purely *anomaly-based indicators, e.g., using standardized drought indicators for the variables: precipitation, soil moisture, and streamflow. Here, we want to explore drought propagation from soil moisture drought to streamflow drought using the deficit-anomaly indicators SMDAI and QDAI.*

For the example of a grid cell in Germany (42.25N, -121.75 E), drought propagation is identified during the 2003 Central European (CEU) summer drought (Figure 11). Comparing the set of time series for d_{soil}*,* p_{soil}*, SMDAI with* $SSFI$ *and* d_Q*,* p_Q *and QDAI, we observe a lag of one month in the onset of streamflow drought and a two-month delay in the termination of streamflow drought as indicated by QDAI compared to soil moisture drought indicated by SMDAI. Soil moisture drought lasted from March to October 2003, the streamflow drought from April to December 2003. The drought periods by SMDAI and QDAI are driven by their anomaly components* p_{soil} *and , respectively. However, the highest anomaly of soil moisture is already reached May, and the highest streamflow anomaly only in August. This would indicate a time lag between peak soil and streamflow drought of three months. However, considering SMDAI and QDAI, the time lag is zero, as both peak in August, as soil moisture deficit in March is low. QDAI and* p_Q *(as well as* $SSFI$*) peak in the same month because human water demand in this grid cell is small as compared to the water demand of the ecosystem which is assumed to be a fraction of streamflow. Overall, an extreme soil moisture drought event from June to August 2003 as identified by SMDAI was accompanied and prolonged by a severe streamflow drought event from July to October as identified by QDAI.*

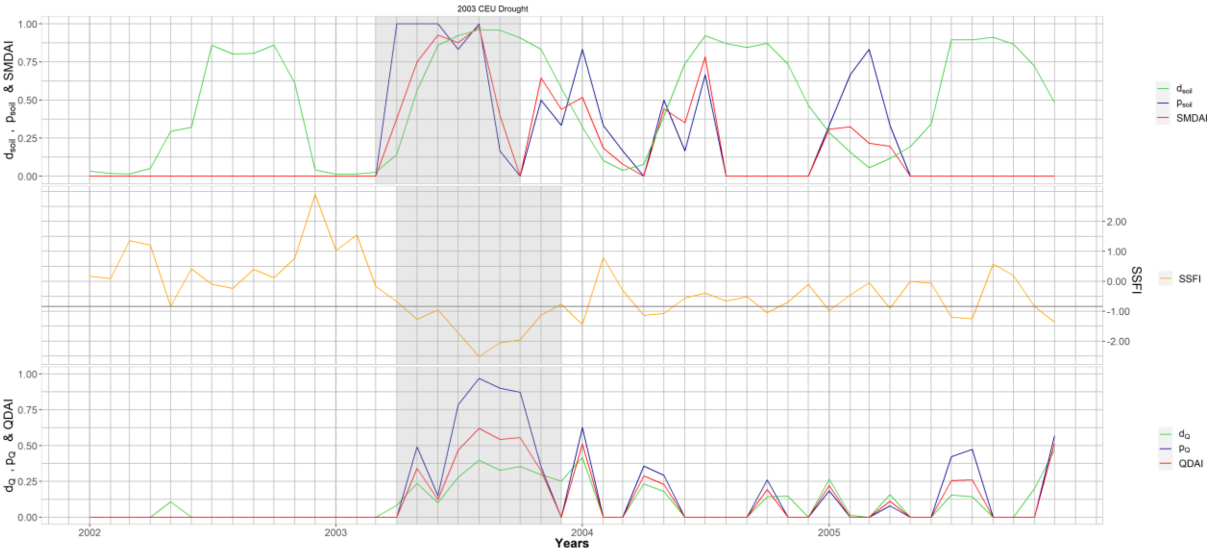

Figure 11. Drought propagation from soil moisture to streamflow: example of a time series (2002 – 2005) of monthly of d_{soil}*,* p_{soil}*,* d_Q*,* p_Q*, SMDAI and QDAI for a grid cell in Germany."*

Specific comments:

R: Introduction - The authors highlights how anomaly-based indicators are usually meteorological indicators, whereas deficit-based indicators are usually soil moisture/evapotranspiration indicators. However, they fail to highlight the reason behind this, which is the difficulty (impossibility?) to define a deficit threshold for a meteorological quantity in absence of a clear target (how much rainfall is enough rainfall?),which is instead more straightforward for plant water demand. This is a key point, an very important for the streamflow drought, where water demand can be defined, but is again much more complex than vegetation demand. I suggest the authors to expand this concept in the introduction to give more impact to the introduction of this concept in streamflow drought.

A: We agree with the reviewer that a better formulation of these key points is required.

Action: We replaced the second paragraph of the introduction by

" Some researchers have quantified drought by only considering the deficit aspect of drought, i.e., by computing the difference between an optimal water quantity and the actual quantity ("less water than required"). ***Deficit-based indicators*** *have only derived for assessing drought risk for vegetation, as optimal water quantities can be defined by either the field capacity of the soil (Sridhar et al. 2008) or potential evapotranspiration. For the latter, the deficit is computed either as the difference between potential evapotranspiration and precipitation (Hogg et al. 2013)or between potential and actual evapotranspiration. A drawback of these deficit-based drought hazard indicators is that they indicate strong drought in arid and (semi)arid regions, even though the vegetation in these regions is adapted to generally lower soil moisture (Cammalleri et al. 2016). Deficit-based indicators cannot be meaningfully derived for the variable precipitation only as the definition of an optimal precipitation amount depends on the user of the precipitation water. It is, however, conceptually meaningful to determine deficits for human water supply based on the variable streamflow, defining the deficit as the difference between the demand for water from the river and the actual streamflow. To the best of our knowledge, streamflow drought has not, as yet, been characterized by a deficit-based drought indicator."*

R: Methods and data - More details on the water demand modules of WaterGAP should be provided, since this is a key component of the streamflow drought index.

A: We agree with the reviewer.

Action: We replaced the first three sentences of Section 2.1 by the following two paragraphs:

" In this study, we use the output of the latest version of the global hydrological and water use model WaterGAP 2.2d (Müller Schmied et al. 2020). WaterGAP consists of three major components: the water use models, the linking model GSWUSE and the global hydrological model (WGHM). The water use models compute water use in the five sectors household, manufacturing, cooling of thermal power plants, livestock and irrigation. Household and manufacturing water use is computed based on national statistics (Flörke et al. 2013). The amount of water required for cooling of thermal power plants is calculated based on location, type and size of power plants and annual time series of thermal electricity production (Flörke et al. 2013). The globally small amount of livestock water use is determined from the number of livestock and livestock-specific water use values (Alcamo et al. 2003). Irrigation water use is computed based on information on irrigated area and climate for each grid cell. The irrigation model first computes cell-specific cropping patterns and growing periods and then irrigation consumptive water use, distinguishing only rice and non-rice crops (Döll and Lehner 2002). The irrigated areas are changing over time (Siebert et al. 2015).

The water use models do not take into account the source of the sectoral water abstractions. This is done by GWSWUSE, which computes monthly time series of 0.5° grid-cell values of human water abstractions from 1) surface water bodies (river, lakes and man-made reservoirs) and 2) groundwater, for each of the five sectors, as well as the respective net abstractions from both sources (Döll et al. 2012). A comparison of simulated annual sectoral water abstractions per country to independent values from the AQUASTAT database of FAO showed a rather high similarity between the two data sets (Müller Schmied et al. 2020)."

R: As stated in the general comment, I would ditch completely the analysis on SMDAI. There is not enough novelty in the modified index as it is, and the introduce modification are not sufficiently tested against the DSI to conclude that this proposed formulation is better/equal to the original (few maps on a specific month of 2003 are not enough). There may be still interest in fully analyzing SMDAI at global scale, since the DSI was tested only over Europe, but this can be the focus of a full expanded paper on this topic, where a detailed inter comparison can be performed.

A: The comment of completely ditching analysis on SMDAI has been addressed before. On the other suggestion, in the paper, we do not state that SMDAI better indicates drought conditions than DSI. We conclude that both result in very similar quantitative drought hazard values while SMDAI is computed in a more straightforward way without the need of introducing an additional mapping equation.

Action: We have modified the paragraph in section 2.2.2 as

"Cammalleri et al. (2016) calculated p_{soil} using the mode instead of median as the reference for the normal status of d_{soil}. The computation of p_{soil} from $F(d_{soil})$ was carried out in two steps. First, for d_{soil} values that are greater than or equal to the mode, a new standardized cumulative distribution function $F\ *(d_{soil})$ is computed (Eq. 3 in Cammalleri et al., 2016). Subsequently, mapping of $F\ *(d_{soil})$ values ranging from 0.6 to 1 onto the p_{soil} range of [0, 1], an exponential function (Eq. 4 in Cammalleri et al., 2016) was employed. This exponential function was developed to fit subjectively defined pairs of $F*(d_{soil})$ and p_{soil} (Table 1 in Cammalleri et al., 2016). In this study, we have simplified the more complex approach of Cammalleri et al. (2016) by relying directly on $F(d_{soil})$ for mapping $F(d_{soil})$ onto p_{soil} according to Eq. 3. In our opinion, there is no added value in defining an arbitrary exponential mapping function for deriving an indicator for the probability of a drought occurrence (p_{soil}). Further, like most other drought researchers, we prefer the median to the mode, as among 30 deficit values, which are rational numbers, there is no true mode, i.e., no value that occurs most often. The relation between the anomaly component of SMDAI (i.e., p_{soil}) to the non-exceedance probability of the soil moisture deficit ($F(d_{soil})$) and the pertaining return periods, z-scores, and class names, according to Agnew (2000) as well as the anomaly component of DSI (p_DSI) are presented in Table 1. A comparison of p_{soil} to p_DSI values as a function of ($F(d_{soil})$) as presented in Table 1 is shown in Figure S1 and the slight differences between p_{soil} and p_DSI, as well as DSI and SMDAI, computed with WaterGAP output for August 2003 at the global scale are presented in Figure S2. For the period 1981-2010, SMDAI is, averaged over all grid cells, 0.05 larger than DSI."

R: Results - Removing the analysis on SMDAI will also give more space to the QDAI, which is more interesting in my opinion and truly a novelty. However, the analysis is currently lacking in depth in my opinion. As an example, rather than focusing on a single month globally (August 2003), the authors may show some continental maps for different local events. At the moment, its very difficult to draw any consideration of such large maps in which the interesting data are only on a small region. The analysis of the impact of different ecological flow is also very interesting, but it needs to be expanded beyond a couple of months.

A: Comment on removing the analysis on SMDAI has been addressed before. On providing continental maps for different local events as well as more analysis on ecological flow, we agree to the suggestion.

Action: We have added a new paragraph in section 4.2

"Further differences between QDAI values computed for alternative EFR are explored for two widely known drought events, the South Asian drought of 2009 (Neena et al. 2011) and the North American drought of 2002 (Seager 2007). Figure 9 presents the spatial extent of both the droughts detected by QDAI at a continental scale (left panels of figure 9) for August 2009 and March 2002, respectively. Time series plots (right panels of Figure 9) for an Indian grid cell (75.75 E, 24.75 N top panel), as well as another for a USA grid cell (-110.75 E, 44.25 N bottom panel), provide a better understanding of the sensitivity of QDAI to EFR. As expected, QDAI values calculated with EFR = 0 (green) are lower and drought periods shorter than if it is assumed that water needs to remain in the river for the well-being of the ecosystems. Interestingly, short but severe drought in the Indian grid cell in 2002, 2006, and 2010 have almost equal QDAI values for all three EFR alternatives.

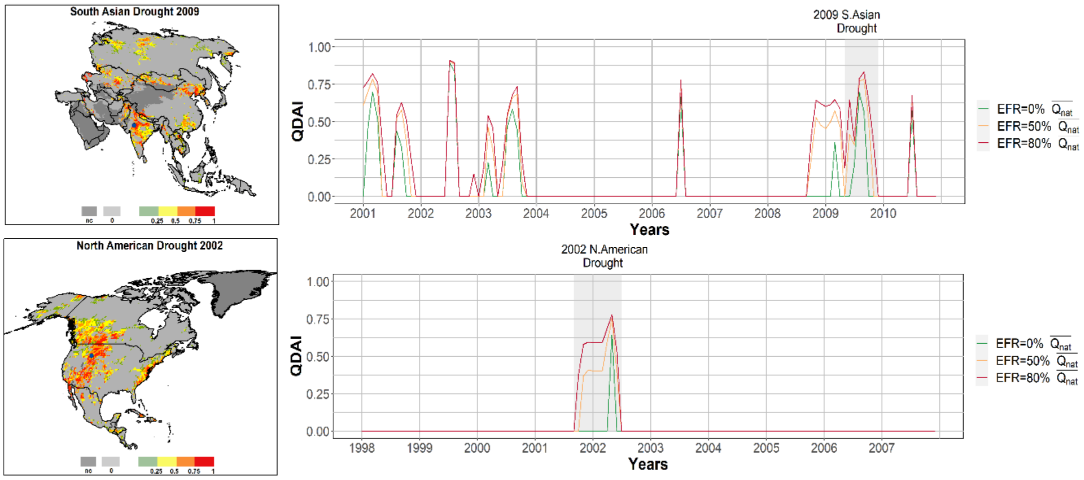

Figure 9. Continental maps of QDAI for Asia and Northern America for August 2009 and March 2002 respectively (left panels) with blue points showing the location of the Indian and USA grid cells. Time series of different QDAI with alternative EFR (right panels) for Indian grid cell for 2001-2010 and USA grid cell for 1998 – 2007 and nc are grid cells which are not computed due to land cover"

R: Finally, the comparison with the SSFI is very useful to give a benchmark to the new index, but it needs to be expanded as well. Is the number of drought event different for different regions?

A: We agree comparison of QDAI with SSFI is a useful addition to the paper. A comparision of the fraction of months under drought conditions at global scale is added.

Action: We have added new lines in section 4.3

"Globally averaged, the fraction of months under drought during 1981-2010 is 16.0% according to QDAI and 19.1% according to SSFI. This reflects that QDAI only identifies a drought condition if there is, in addition to the anomalously low flow, a water deficit."

Reference

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