Anonymous Referee #1

Received and published: 19 August 2019

In this manuscript, the authors compare the climatological features of two intense drought events over Europe, the 2003 and 2018 heatwaves. From a climatological analysis, they carry on to analyze the effect of both events on European vegetation. The authors' results are based on a suite of statistical analyses of MODIS-based vegetation indices combined with a widely used land cover map. Their main conclusion is that the 2018 heatwave had a stronger effect on European vegetation than the 2003 one.

General comments

Overall the manuscript is well written and follows a logic questioning line going from the climatology of the heatwave to the effect on vegetation. However, I am not convinced by the relevancy of the way the main question is addressed. From the first climatological data shown by the authors it is obvious that the 2003 and 2018 events are very different in terms of location (baltic countries in 2018 versus central Europe in 2003) and timing (july was the beginning of the 2003 heatwave whereas it was the end of the 2018 one) and, even though it is not shown, in initial conditions. These crucial differences are however mostly ignored in the way the analyses are designed, potentially pointing to severe flaws in the results, that I detail below. This observation leads me to suggest more detailed analyses be carried out before publication.

Thank you very much for your constructive review, which highlights important aspects and potential ambiguities and will help us to considerably improve our manuscript. While we agree with most of your critiques, we would like to emphasize that we do not ignore the differences of the two drought events: Fig. 6 was particularly designed to highlight that the peak of the drought-response in different land-cover types was delayed in 2003. As shown in Fig. 6 the lowest value of mean NDVI-quantiles of coniferous and mixed forests was lower in 2018 compared to 2003, while broadleaved forests displayed more similar NDVI-quantiles. Regarding arable land and pastures the lowest values occurred later in time and were lower in 2003. We refer to these results in lines 247-250 in the initial submission. Moreover, section 4.2.2 of the initial submission discusses possible effects related to the differing location, i.e. the drought 2018 hit potentially less adapted ecosystems at higher latitudes which may have caused the observed stronger ecosystem response in 2018. We agree, that these points need more emphasis and we will do so in the revision of our manuscript by:

1) *Visualizing the temporal development of climatic conditions in a similar manner as for NDVI in Fig 6 in the main text and adding an animated gif to the supplementary which depicts the spatiotemporal development of climatic water balance anomalies (i.e. an animated version of Fig. 3 from January to October) to quantify the preceding initial conditions of the two events (moist winter and early spring in 2018 thus beneficial conditions at the onset of 2018 vs. dry late winter in 2003 thus less beneficial initial conditions in 2003) and the development in course of the drought events,*
2) *Providing yet another supplementary gif which will visualize the temporal development of NDVI quantiles using maps and histograms (animated version of Fig. 4 throughout the growing season) from beginning of May until end of October to allow for assessing the temporal development of the two drought events,*
3) *Comparing and modelling the climatic features and ecosystem response representative of the peak of drought in each year (i.e. July/DOY 209 in 2018 vs. Aug/DOY 241 in 2003) instead of for July/DOY 209 only and revise the underlying analyses of Figs. 4, 5, and 7 accordingly.*

4) *Emphasizing the spatiotemporal effects in the discussion, in section 4.2.2.*

As can be seen in the figures attached to this reply, these additional analyses confirm our initial conclusion since:

I) *The area featuring extreme drought (lower than 2 negative standard deviations) was larger in 2018 compared to 2003 (1.4 times larger, i.e. 1.35 million km² in 2018 vs. 950,000 km² in 2003).*

II) *The drought response of the considered ecosystems affected a larger area in 2018 compared to 2003 (again 1.4 times larger, i.e. 820,000 km² featuring the lowest quantile in 2018 and 570,000 km² in 2003).*

III) *The drought response was stronger in 2018 compared to 2003 as expressed by significantly steeper regression slopes, the differences between 2003 and 2018 now even became stronger.*

Please also find a detailed point by point reply to the comments raised by referee #1 in the supplementary pdf.

Detailed comments

Effect of heatwave timing, duration and legacy

The analyses carried out, only encompassing the greenness index in july of both years, seem too superficial to draw the far-reaching conclusions the authors make. First on heatwave timing, the stronger NDVI signal in july 2018 compared to july 2003 could be the result of the difference in timing. This point is ignored when concluding that the 2018 heatwave had a stronger effect on European ecosystems than the 2003 one.

We agree that the different timing of the drought and heatwaves likely resulted in a different timing of vegetation response, as was shown already in Fig. 6 and mentioned in lines 247-250. To better visualize the observed temporal development, we will add a gif showing the temporal development of the climatic conditions, as mentioned in the reply to the general comment. We will also add supplementary gifs which depict the temporal development of NDVI from beginning of May until end of October (as can be seen here: http://www.lsai.wzw.tum.de/index.php?id=77 for 2003 and http://www.lsai.wzw.tum.de/index.php?id=75 for 2018). Moreover, we will add time-series comparable to those shown in Fig. 6 for CWB to provide a direct comparison between the climatic features of the drought affected areas in 2003 and 2018. We agree, that the temporal differences need to be pointed out more clearly, wherefore we – next to the additional analyses - will add a corresponding paragraph to the discussion where we discuss the additional analyses and the importance of drought timing.

Second, as mentioned as a discussion item, the legacy of water balance can be very important for heatwave effects on forests especially. Even though this is be a major point underlying the relevancy of the question asked, no data or analysis shown tries to compare the water conditions prior to both heatwaves. An analysis of both heatwaves time evolution and the comparison of each heatwave's end month, that could then be different from one to the other could be an option.

We agree that the water balance legacy effects are relevant, wherefore we will add according analyses to the manuscript. In particular, we will visualize the development of integrated CWB over time, i.e. including preceding winter conditions and extending until the end of the growing *season (as done for NDVI in Fig. 6). We acknowledge your suggestion to compare different months with each other. We will compare VI quantiles representing DOY 241 in 2003 and DOY 209 in 2018 in Figs. 4 and 5, and use the corresponding VI-quantiles and CWB for the modelling exercise in Fig. 7 and the mixed model. Please see the attached figures for an impression on how Figs. 4 and 7 change due to these analyses amendments.*

Heatwave location defining the ecosystems affected

Another point that undermines the results presented is the comparison of vegetation types in absolute terms without a prior description of vegetation types affected in each case that might be very different. Even though this information is essential to make sense of a comparison of the effects on vegetation of two climatic events, it is hardly discussed and made very hard to see in the way the data are processed. For example the varying y-axis ranges in figure 5 hide the relative weights of each vegetation type with water deficit or water surplus. Figure S3 might be more explicit to this regard by considering relative vegetation cover.

Maybe we misunderstood your comment, but we struggle to reproduce your statement that the effects of the different locations of the drought are 'hardly discussed'. Section 4.2.2 particularly deals with the possible effect of the differing drought epicenters, where we highlight that different ecosystems' adaptation to drought likely caused the stronger ecosystem response in 2018. To account for your critique, we will add a paragraph to the corresponding methods section, highlighting the fact that the drought-affected areas differ between 2003 and 2018, which leads to varying absolute areas as well as different vegetation types that were affected. To make the picture more complete and readers aware of the uneven distribution of areas affected by the severe drought in 2003 and 2018, we will moreover add a figure to the supplementary which depicts the absolute spatial contributions of the selected land-cover types to the drought-areas. Moreover, we will add a map to the supplementary, which depicts the CLC-classes used for the analyses across Europe. However, given the nature of the utilized data for land-cover classification, it is not possible to differentiate these classes further. We are aware that this is associated with potential problems, a fact that we recommend to take into consideration in follow up studies in lines 334 to 337 of the initial submission.

Also, we would like to emphasize the importance of Fig. 5 for the main aim of the paper, i.e. to compare 2003 with 2018. This figure fulfills two different tasks. On the one hand, we use it to show the absolute areas of drought affected ecosystems but separated by land-cover type. On the other hand, we use Fig. 5 to visualize how the quantiles are distributed within the 3 different classes of CWB-anomalies which indicates the effect of CWB on quantile-distributions. We are therefore convinced, that Fig. 5 provides an important message, namely that the area featuring extreme drought (CWB <-2) was several times higher in 2018 (already mentioned in the results of CWB anomalies) but that this larger area was unevenly distributed among the different vegetation types. That is, while the affected area of pastures was lower in 2018, arable land, as well as mixed and coniferous forests expressed much larger areas in comparison to 2003. We agree, that information is also needed on the relative contribution of each land-cover type to the drought affected areas, which is the reason why we also supplied Fig. S3 and report the corresponding results in lines 245-246 in the initial submission. We however deem these results as of lower importance, since they 'just' show that most (but not all) of the relative contributions were similar in 2003 and 2018, thus hide the fact that a much larger area was affected in 2018. Since the main emphasis of the paper is to compare the absolute drought effects, histograms relying on absolute areas are mandatory.

Statistical indices

Finally, another aspect of the manuscript that makes it less convincing is the choice of the figures and complex statistical indices derived. For example figure 5 is hard to interprete. What is the implication of high NDVIs combined with low CWB? In general, the methods section is very concise, making it easy to read but also lacking some key points to help the reader understand the many indices used. For example even though they are widely used NDVI and EVI should be defined. Also, heat load variable is not defined and is sometimes written heat load and sometimes heat-load. If it is simply Tmax call it this.

Thanks for your suggestion to define NDVI and EVI, which we will do, in tandem with generally elaborating the methods section to better explain what we did and why we did this. Moreover, we will rename heat load to Tmax.

In fact, all data transformations are widely known, frequently used across environmental sciences, and rather simple: z-transformation to transform raw values into anomalies, ranking the data to obtain quantiles. The presented descriptive statistics are also not complex: means and standard deviations as well as total areas passing specific thresholds. As for inferential statistics, we present simple linear ordinary least squares regressions between NDVI-quantiles and CWB, and a mixed-effect model, of which the latter might be considered as more involved, but is developing towards a highly recommended standard for inference in ecological studies (e.g., Bolker et al. 2009).

Bolker, B., Brooks, M., Clark, C., Geange, S., Poulsen, J., Stevens, M., & White, J. (2009). Generalized linear mixed models: a practical guide for ecology and evolution. Trends in Ecology and Evolution. Retrieved from http://dx.doi.org/10.1016/j.tree.2008.10.008

As mentioned in the reply to your previous comment, Fig. 5 serves two tasks, i.e. 1) highlighting the much higher area of affected ecosystems with a different distribution among land-cover types and 2) exemplifying the effect of CWB on the distribution of quantiles. Under normal conditions, quantiles will express a uniform distribution, while a skewed distribution indicates abnormal conditions, such as for the classes with CWB < -2 and CWB > 2. Showing the skewed quantile distributions directly leads to the modelling exercises shown in Fig. 7.
The outlined amount of combinations with high NDVI but low CWB is relatively low and much lower than expected if assuming a uniform quantile-distribution due to the significant impact of CWB-deficit on NDVI quantiles. The reason for why we yet observe high NDVI-values despite low CWB is likely related to the different spatial resolutions of the used products, i.e. climate data with 0.5° resolution and satellite data with 231 m resolution. That is, within one climate grid cell elevational differences and variations in groundwater levels (e.g. along rivers or lake shores) will modify the vegetation response to gridded CWB, since the coarse resolution of the climate data neither capture small-scale climatic variations due to elevation nor represent groundwater levels. We will add a corresponding paragraph to the discussion to make this clearer.