Vulnerability of European ecosystems to two compound dry and hot summers in 2018 and 2019

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Response to reviewers

Reviewer #1

R1C1: I appreciate the authors' efforts in responding to all of my initial comments and suggested edits. I recommend the revised manuscript for publication in Earth System Dynamics.

Thank you for acknowledging our effort and the constructive review, which helped improving the manuscript substantially.

Reviewer #2

R2C1: The streamlined version of the methods and the revised presentation of results are now clearer and easier to follow. I have just a handful of remaining comments, which I list below.

We appreciate the reviewer's positive evaluation of our revision effort. We address the additional comments below.

R2C2: "Compound event" is (implicitly) used with two meanings in the manuscript. One is relative to co-occurring dry and hot conditions. The other refers to the occurrence of these conditions in two subsequent here. I suggest making these two meanings explicit, before specifying that the focus is on the temporal compounding of compound events. This is because co-occurring dry and hot conditions could also be of interest, given their multiplicative effects on vegetation (the 'hotter drought' now mentioned more prominently; see e.g. Suzuki et al 2014 New Phytologist), but not the focus of this work. I think this would be of help in underlining where the main novelty lies.

Thank you for pointing out that this was not clear, and for the excellent reference. We have revised Figure 1 (new version reproduced below) as well as the last paragraphs of the introduction, where these concepts are introduced:

> *"From a hydrometeorological perspective, each of the dry and hot summers in 2018 and 2019 (DH18 and DH19, respectively) can be considered a multivariate compound event in that both high temperatures and strong drought conditions were observed (Zscheischler and Fischer 2020). Taken together, they can be considered a temporally compound event (Zscheischler et al. 2020). For example, Boergens et al. (2020) have shown that while soil-moisture deficits in summer 2019 were not as pronounced as in 2018, total water storage was lower in 2019 due to the water storage deficit resulting from the 2018 event. Given the unprecedented magnitude of DH18, it is likely that at least some ecosystems had not yet fully recovered in 2019. Therefore, from an ecological perspective, DH19 could additionally be considered a preconditioned compound event, where the impact of DH18 may affect the response to DH19 (Fig. 1)."*
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> *"Using both remote-sensing data and an update of the simulations by (Bastos et al., 2020a), we attempt to separate these different effects, namely: how the combination of hot and dry conditions affected the vulnerability of ecosystems to the two events (multivariate compound event), how the repetition of a dry and hot summer affected the response to DH19 (temporally compound event)*

and how inter-annual legacy effects due to impacts of DH18 affected ecosystem vulnerability to DH19 (preconditioned compound event).
We first use a statistical modelling approach to evaluate whether signs of increased vegetation vulnerability to DH18 and DH19 can be found and to attribute changes in vulnerability to inter-annual legacies and other modulating effects. We then compare observation-based results to updated simulations by state-of-the-art land-surface models and dynamic global vegetation models (for simplicity referred to as LSMs) designed to isolate the impacts of DH18 and legacy effects (Bastos et al., 2020a)."

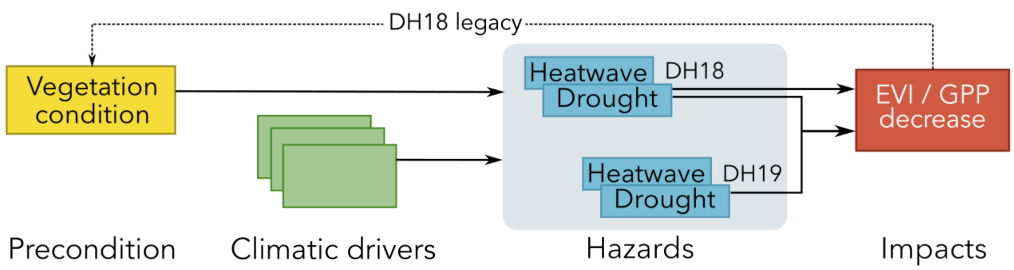

Figure R1: New version of Figure 1. For simplicity, we removed the global change box, and make the two multivariate compound events (DH18 and DH19) more explicit. We also follow a color code more similar to Zscheischler et al. (2020) to facilitate the interpretation of the figure.

R2C3: In Fig. 2 it would be helpful to specify the meaning of the rectangle. Is that the study region? Or was that defined based on the occurrence of the conditions, as written in the caption?
The rectangle corresponds to the study region, which is the domain affected by two consecutive hot and dry summers. This is now clarified in the figure caption.

R2C4: In the definition of tree cover (Fig. 6), does the low tree cover refer to the 5% lower or lowest tree cover, i.e., the 5% of pixels that have the lowest tree cover in the dataset? How much does this translate to, in terms of tree cover, approximately? And how about the top 5%? I think it is important to give a sense of what tree cover level the bars refer to.
Thanks for the important suggestion. We added the following sentence in Fig. 6 caption:

> *"High TC pixels have tree cover fractions above 58% and low TC have virtually no trees (TC<0.4)."*

We also added small precisions to the text when referring to low TC pixels.

L374 and elsewhere: 'tree cover' as opposed to 'forest cover' for clarity and consistency
Thanks for noting the inconsistency, it is now corrected.

Reviewer #3

R3C1: The paper reads much better now. The results and discussion sections are improved significantly.
My only minor comment is to spell out "JJA" and "MAM" for the general audience.
Thanks for the feedback. We now spell out the months when JJA and MAM are introduced.

R3C2: Also, I would like to see one or two paragraphs be added as the implications for interdisciplinary research and future research.

We have accordingly rephrased the conclusions section:

> *The summers of 2018 and 2019 were both exceptionally hot and dry over Central Europe, and both were associated with widespread vegetation browning and tree mortality events. Here we propose an approach that analyses this event as a combination of three types of compound events Zscheischler et al. (2020) that consider: (i) the compound effects of hot and dry conditions; (ii) the effect of repeated stress conditions in 2019 and (3) the legacy effects from DH18 impacts in preconditioning the impacts of DH19. Using statistical and process-based modelling, we quantify these effects and identify modulating effects, e.g. by land-cover composition. This approach can be extended to other types of events that may not fall in a single type of compound event.*
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> *Based on remote-sensing data, we find signs of degradation trajectories in 20% of the study area, with vegetation browning in spite of drought alleviation in DH19. We showed that inter-annual legacies from DH18 played an important preconditioning role in amplifying the impacts of DH19. While LSMs simulated well the impacts of the first event (DH18), they showed limited skill in simulating the impacts of the subsequent compound event (DH19).*
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> *Our results show that compounding effects of multiple and repeated stressors and ecological dynamics can result in non-linear and unexpected impacts Schuldt et al (2020), that LSMs still cannot realistically simulate. Attribution of inter-annual legacy effects from DH18 and of LSM errors to internal processes (e.g. drought-induced damage and mortality) or others such as insect outbreaks remains challenging because of up-to-date datasets on tree mortality, tree carbon reserves or spatially-explicit information on biotic disturbances are very limited.*
>
> *Since extreme DH events are projected to become more common in the coming decades, better understanding the interactions and feedbacks between climate extremes, natural disturbances and ecosystem dynamics is fundamental to anticipate threats to the stability of forests in the temperate regions and elsewhere. Overlooking these effects may result in an overestimation of the resilience of the CO2 sink to climate change.*