Response to Anonymous Referee #1

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Summary:

This manuscript presents a case study analysis to examine the impacts of compound events through a comparison of hydrological (via soil moisture) and biospheric (via GPP) perspectives in the season preceding, and during, the Russian 2010 heatwave. The paper provides a case for why singular extreme events need to be examined under different perspectives to understand the full implications of these events across multiple sectors. It is a nice study however I was anticipating a more indepth analysis of the processes that connect the two events. Its almost there and perhaps only requires minor revision of the text to achieve this.

Response: We would like to thank the reviewer for the positive evaluation of our manuscript and agree that the discussion regarding the processes connecting the hydrometeorological and biopsheric event, and the connections between the spring and summer events can be substantially improved. We do our very best to provide a more in-depth discussion which hopefully addresses the reviewer's concerns. Specifically, we will add a paragraph to the introduction (see reply to 1), and the discussion (see reply to 3).
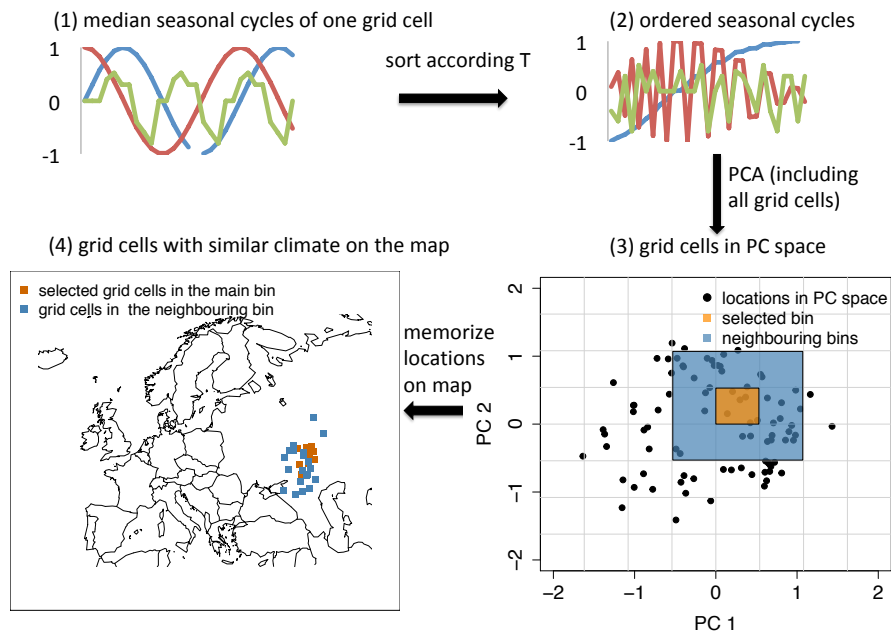
Main Comments:

1) The hydrological event and the biospheric events don't have the same spatial coverage which makes it hard for those new to the concept of compound events to appreciate how the events evaluated in the manuscript are indeed related. Could the authors perhaps provide a stronger case for why these distinctive events should be considered together beyond the 'different disciplinary perspectives' by delving into how one may be a result of the other. The commentary around Figure 1 on page 3 makes it difficult to reconcile the fact that the two events are related. Perhaps part of the confusion also stems from having a spring event, a summer event and then considering these events defined in terms of either the biospheric and hydrological perspective (so effectively giving 4 events to compare). I think this can be resolved by amending the text and including more discussion on how these events fit together.

Response: We highly appreciate the reviewers' perspective on compound events. We already elaborate a little bit on the biospheric response to heatwaves and droughts (p. 2, l.25-31), but we agree with the reviewer, that the link between biosphere and atmosphere, as well as spring and summer is not well explained. Thus, we will extend the commentary around Figure 1 and elaborate on connections between hydrometeorology and biosphere as well as spring and summer (p.3, l.5) as follows:

Temperature anomalies exceeded more than 10~K in both spring and summer, but they lead to distinctive anomalies in gross primary productivity (GPP). Positive GPP anomalies occurred during the spring event, whereas negative GPP anomalies are occurring during the summer heatwave. The positive GPP response in spring might be a reaction to warmer, more optimal spring temperatures (Wang et al, 2017) possibly accompanied by enough water availability. However, negative GPP anomalies in summer occurred only in areas south of 55°N (Fig. 1c) indicating that the GPP response involves much more processes than high temperatures and drought during the unique RHW. As already indicated by Smith, 2011, the connection between biosphere and hydrometeorology is much more complex than just a direct one-to-one mapping. Further complicating this issue is the fact that the summer event cannot be investigated without the previous spring, as both seasons are inherently related via memory effects in water availability. Increased GPP in spring may negatively influence soil moisture and thus GPP during summer (Buermann et al., 2013). In Summary, comparing ...

2) The narrative in section 2.2 was hard to follow in that there is some information that may be better to remove (e.g. defining extremes using global thresholds) or a dependence on jargon that not everyone may understand (some examples noted in the minor comments). Given that the manuscript aims to articulate a methodology for extracting information on compound events this could be revised. Would it be possible to add some illustration to the schematic in Figure 2 to clarify how the spatiotemporal segments are defined and extracted.

Response: We agree with the reviewer, that section 2.2 can be improved. We will completely revise the section. We will remove unecessary parts (e.g. the global thresholds) and avoid jargon whenever possible. We will add the following schematic Figure to illustrate the extraction of the spatial segments.

(1) median seasonal cycles of one grid cell

1

0

-1

sort according T →

(2) ordered seasonal cycles

1

0

-1

↓ PCA (including all grid cells)

(4) grid cells with similar climate on the map

■ selected grid cells in the main bin
■ grid cells in the neighbouring bin

← memorize locations on map

(3) grid cells in PC space

● locations in PC space
■ selected bin
■ neighbouring bins

PC 2

PC 1

3) I was a bit disappointed in the lack of discussion of the processes involved that led to this combination of events over Spring and Summer. Figure 7 provides some insight into how the unique the RHW event was but stronger statements could be made about whether the spring event was a necessary condition for the RHW.

Response: We agree with the reviewer, that it would indeed be very nice to show the connection between summer and spring events and whether this kind of unique summer events only happen preconditioned on an anomalous spring. However, this would require running process based model simulations (as some of the coauthors already did for evaluating the general presence of spring summer compensation effects in Sippel et al. 2017) which goes beyond the scope of this paper - focussing more on a statistical detection. We agree that this is a very relevant question that can be addressed in a follow up study.

To address the reviewer's need for process based connections between the spring and summer events we suggest to intensify the discussion about the biophysical processes that could link spring and summer anomalies. Several works suggest that spring warming leads to depleted soil moisture in summer, thus amplifying the summer droughts (e.g., Buermann et al., 2013, ERL, Wolf et al., 2016, PNAS). To address this issue, we will add a paragraph to the introduction (see reply to 1), and we will add a paragraph before p.12, l. 22 – p. 13, l. 10. with a more in-depth discussion as folows:

Another important aspect is that the combination of the anomalous spring and the unique heatwave in summer might be inherently connected via land surface feedbacks. Buermann et al., 2013 showed that warmer springs going in hand with earlier vegetation activity negatively affect soil moisture in summer. It is a general observation that warm and dry springs enhance summer temperatures during droughts, which suggests the presence of soil-moisture temperature feedbacks across seasons (Haslinger et al., 2017). In case of the Russian heatwave 2010, soil moisture was one of the main drivers (Hauser et al., 2016), in hand with persistent atmospheric pressure patterns (Miralles et al., 2014). Thus, we suspect that the spring event is connected to the summer heatwave in 2010, if not setting the preconditions for a heatwave of this unique magnitude.

4) The concluding paragraph seems to suggest that the positive GPP anomaly in spring offsets the negative anomaly in summer such that the net effect is a positive impact. This is slightly misleading given there were still substantial consequences on crop productivity in summer. This makes it hard to reconcile the 'GPP compensation' as necessarily a positive impact. This text needs careful revising.

Response: We would like to thank the reviewer for pointing us that the concluding paragraph could be misunderstood. Our intention was not to suggest that the integrated net effect of the events in Russia 2010 was a positive one in terms of carbon budget and tried our best to avoid this kind of misunderstanding, e.g. state that in the first part of the concluding sentence (p.14, l. 16): "Although the integrated impact on gross primary production of the hydrometeorological conditions is strongly negative, it is important to notice the strong compensatory effects due to differently affected ecosystem types, as well as duration and timing of the extreme events." We will replace „strong" with „partial" to avoid missunderstandings.
To prevent further misunderstanding, we will exchange "compensate" with "partly compensate" or "compensation" with "partial compensation" in the conclusions, and the abstract. Furthermore, we will add a sentence on p. 14, l.11 clarifying this once more: "Please note, that the integrated impact of the 2010 events on the carbon balance is strongly negative."

 Minor Comments:

5) There are a couple of instances where the text is awkward and could be revised e.g. page 2 line

21: 'In 2010 the depleted state of soil moisture was one important driver which locally amplified the high temperature regime' could be written as 'In 2010 a negative soil moisture contributed to increased temperatures'

Response: We thank the reviewer and we will change it accordingly and go once again through the text to find such awkward instances.

6) When calculating anomalies, it is still useful to know what they are anomalous to. Please include the reference period to which the anomalies are derived from for all figures that are showing anomalies.

Response: We agree with the reviewer and add this information as suggested to Fig. 1, 4, 6, 8, A1, B1.

7) I don't understand the phrase 'impact-agnostic approach' on Page 3

Response: "Impact-agnostic" may be just our own jargon. We meant here, that our approach is independent, whether the event is related to a positive or a negative impact. We will remove the phrase.

8) Page 3-4 "For instance, a popular approach is to consider an observation in a single (ideally normally distributed) anomaly variable to be extreme if it deviates by more then two standard deviations from the variable's mean values." Perhaps include references here that use this approach. Many studies on extremes also use other definitions from the Expert Team on Sector-specific Climate Indices (ET-SCI) which use percentile thresholds to identify extremes.

Response: We will include references as suggested by the reviewer.

9) Page 4, line 11: replace 'constellations' with 'combinations'

Response: We will replace it.

10) Page 4, last paragraph: it may be useful to note the native resolution of the datasets that are used. I gather that the regridding of the land cover classification was done using a conservative or nearest neighbour approach?

Response: We thank the reviewer for the suggestion. The spatial resolution of the original data-

sets will be provided. Regridding the land cover classification (original: 300m) was done by using the major land cover class for the new resolution. We will add this information accordingly.

11) Page 5, first paragraph: is there a reason why the median is used? Obviously because it is less susceptible to outliers but perhaps worth noting why. I'm also not sure who would define regional extremes using a global threshold so perhaps omit this suggestion and simplify the narrative.

Response: We thank the reviewer for this important comment: Yes, we used the median because it is less susceptible to outliers. We will add this explanation (p.5, l.3) and remove the part about global thresholds (p.5, l.6-9).

12) Page 5, line 20: 'sort the median seasonal cycles according to the permutation of temperature' I'm not sure what is meant by 'permutation of temperature'

Response: We thank the reviewer for pointing to this jargon issue. We meant that the seasonal cycle of temperature is sorted (e.g. high to low). We memorize the order (permutation) and apply the same ordering to the other seasonal cycles. We will change the text to explain exactly what we did.

13) It would be nice if Figure 4 and Figure B2 could be combined as this shows the contrast between the hydrometeorological and biospheric events and at the moment this feels concealed in the present form

Response: We will combine them as new Figure 4.

14) Don't forget to do a spell check!

Response: We will go through the text once again. We also highly appreciate that Biogeosciences now performs a carful language check previous to publication.

15) Page 9, second paragraph: I'm not quite comfortable with the phrase "In total, 41% of the summer carbon losses are compensated by an anomalously productive spring" because it implies that there was a recovery in GPP after the summer event which we don't actually know here. We only know that impact of the summer event is not as severe as it could have been because of the

excess productivity in spring. Perhaps this can be resolved by using a word other than 'compensation'.

Response: We thank the reviewer pointing to the potential misunderstanding regarding the "compenstion" effect and to the relevance of recovery after the heatwave. We checked for "extreme" GPP anomalies after the summer event, but we could not find any. Thus, vegetation might still be slightly less productive than the years before and after, but it is still considered to be within "normal" variability by the detection approach. This suggests that the effect of the heatwave is limited in time, and that ecosystems are able to recover relatively quickly. We will add a sentence of post-heatwave recovery in the manuscript on p.9, l.6.

Regarding the reviewer's concerns about the "compensation" effect we will rewrite the sentence to: "If we consider the annually-integrated effect of the spring and summer anomalies, spring carbon gains are estimated to offset 41% of the subsequent carbon losses in summer." In other cases, we would like to stick to the term "compensation" because it is already coined by previous literature on this topic (e.g. Wolf et al., 2016,; Sippel et al., 2017).

16) I like the narrative discussing the results according to vegetation type as this goes a long way to understanding differences in the spatiotemporal structure of the events.

Response: We would like to thank the reviewer for this positive feedback.

17) The narrative for Figure 7 is too concise, here would be an opportunity to emphasise how unique the RHW compound event really was

Response: We will add a few sentences on that.

18) Last sentence on page 13 seems to be contradictory to the narrative of the second paragraph on this page.

Response: We thank the reviewer for pointing to this issue. We will make clear in the beginning of the second paragraph that the compensation effects mentioned there are more general and not directly related to the case study of the Russian heatwave (p.13, l.12): "They show that in general warm springs increasingly compensate summer productivity losses in Europe, ..."

19) Page 14, line 3: 'constellation' makes me think of stars. I think 'conditions' would be more appropriate here.

Response: We will change it as suggested.

20) Page 14, line 11: "this finding highlights the importance of forest ecosystems to mitigate the impacts of climate extremes" Be careful here, as there is some location dependence. Furthermore, how much is this a necessary result of the preconditioning in spring? The focus of the paper isn't the mitigation potential of forests so perhaps its better to remove this statement.

Response: We will remove the statement.

21) The text in supplementary section S1 seems to be repetition of the text in the main manuscript. Either elaborate more or remove.

Response: We will remove it from the supplementary and merge the information into the revised paragraph 2.2 (spatiotemporal segmentation).

22) Supplementary Figure S3 4 – x axis labels: what is 'tempanoms' and how is this distinct from 'temp' – I'm guessing it's the anomaly? The caption needs more information to understand what is actually plotted here. Is the data aggregated to obtain the spatial mean or are all grid cells used to construct the linear models?

Response: We apologize for the bad labeling of Figure S3 4. We will change it in T anomalies and the other abbreviations accordingly. We will also add more information about the section in the main manuscript (as a request from reviewer#2) and revise the paragraph at S3, add explainations about the methods to the text, and add information to the caption. Regarding the reviewers question on the aggregation: All grid cells are used to construct the linear models without aggregation.