Contrasting biosphere responses to hydrometeorological extremes: revisiting the 2010 western Russian Heatwave

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Abstract. Combined droughts and heatwaves are among those compound extreme events that induce severe impacts on the terrestrial biosphere and human health. A record breaking hot and dry compound event hit western Russia in summer 2010 (Russian heatwave, RHW). Events of this kind are ~~typically studied either~~ relevant from a hydrometeorological perspective, ~~or with a focus on impacts in the terrestrial biosphere such as~~ but also interesting from an biospheric point of view because of their impacts on ecosystems, e.g., reductions of the terrestrial carbon storage. ~~These different perspectives might not only require different strategies for event detection, but also change interpretations and impact assessment. To exemplify this issue, we~~ Integrating both perspectives might facilitate our knowledge about the RHW. We revisit the RHW both from a biospheric and a hydrometeorological perspective. We ~~consider several hydrometeorological and biospheric variables agnostically as inputs to~~ apply a recently developed multivariate anomaly detection approach ~~. Our analysis of biospheric variables reveals that the RHWwas preceded by increased gross ecosystem production in spring that partly compensated the reduced summer production, but remained unconsidered in earlier impact oriented studies. We also find that~~ to a set of hydrometeorological variables, and then to multiple biospheric variables relevant to describe the RHW. One main finding is that the extreme event identified in the hydrometeorological variables leads to multidirectional responses in biospheric variables, e.g., positive and negative anomalies in gross primary production (GPP). In particular, the region of reduced summer ecosystem production does not match the area identified as extreme in the hydrometeorological variables. The reason is that forest-dominated ecosystems in the higher latitudes respond with unusually high productivity to the RHW~~, leading overall to a~~. Furthermore, the RHW was preceded by an anomalously warm spring, which leads annually integrated to a partial compensation of 54% (36% in the preceding spring, 18% in summer) of the reduced ~~gross primary production (GPP)~~ GPP in southern agriculturally dominated ecosystems. Our results show that an ecosystem-specific and multivariate perspective on extreme events can reveal multiple facets of extreme events by simultaneously integrating several data streams irrespective of impact direction and the variables' domain~~(here "biosphere" or "hydrometeorology"). Focusing on negative impacts in specific variables e.g. a vegetation index, leads to a spatiotemporally delineation of extreme events that is inconsistent with the hydrometeorological conditions and and~~

~~can limit the interpretation of their impacts on the terrestrial biosphere.~~ . Our study exemplifies the need for robust multivariate analytic approaches to detect extreme events in both hydrometeorological conditions and associated biosphere responses to fully characterize the effects of extremes, including possible compensatory effects in space and time.

Keywords. compound events, multivariate extreme events, gross primary productivity, heatwaves, droughts, spring-summer compensation.

1 Introduction

One consequence of global climate change is that the intensity and frequency of heatwaves will most likely be increasing in the coming decades (Seneviratne et al., 2012). Heatwaves co-occurring with droughts form so-called compound events, for which we can expect severe impacts on the functioning of land ecosystems ~~(e.g. primary production, von Buttlar et al., 2018)~~ (e.g., primary produc may affect human well-being (e.g., via reduced crop yields, health impacts) (e.g., Scheffran et al., 2012; Reichstein et al., 2013; Lesk et al., 2016). Investigating historical extreme events offers important insights for deriving mitigation strategies in the future.

One well-known example of a compound extreme event is the 2010 western Russian heatwave (RHW). The RHW was one of the most severe heatwaves on record, probably breaking temperature records of several centuries (Barriopedro et al., 2011). It was accompanied by extensive wild and peat fires with smoke plumes about 1.6 km high at the peak of the heatwave in early August, and estimated emissions of around 77 Tg carbon due to multiple fire events (Guo et al., 2017). Carbon losses due to reduced vegetation activity are estimated to be in the same order of magnitude as losses due to fires ~~(90Tg, Bastos et al., 2014)~~(90 Tg, Bastos et al., 2014). The amount of emitted carbon monoxide is almost comparable to the anthropogenic emissions in this region (Konovalov et al., 2011). Approximately 55,000 cases of death have been attributed to health impacts of the RHW (Barriopedro et al., 2011).

The RHW is often associated with ~~a~~ an atmospheric blocking situation (Matsueda, 2011), leading to a persistent anticyclonic weather pattern in Eastern Europe (Dole et al., 2011; Petoukhov et al., 2013; Schubert et al., 2014; Kornhuber et al., 2016).

However, to fully understand the developments and impacts of heatwaves or droughts, apart from hydrometeorological drivers, associated land-surface dynamics and feedbacks need to be considered (Seneviratne et al., 2010). For instance, under persistent anticyclonic and dry conditions, land-atmosphere feedbacks are expected to further amplify the magnitude of heatwaves via enhanced sensible heat fluxes, as shown also for the RHW (Miralles et al., 2014; Hauser et al., 2016). These feedback mechanisms highlight the importance of depleted soil moisture to heatwaves. In 2010 ~~the depleted state of soil moisture was one important driver which locally amplified the high temperature regime~~ a negative soil moisture contributed to increased temperatures (Hauser et al., 2016). It is a general observation that the combination of anticyclonic weather regimes and initially dry conditions prior to the event amplifies heatwaves in most cases (Quesada et al., 2012).

The direct impacts of such extreme events on ecosystems are manifold. Summer heat and drought typically reduce (or even inhibit) photosynthesis, hence reducing the carbon uptake potential of ecosystems (Reichstein et al., 2013). However, the magnitude of these impacts varies between ecosystems (Frank et al., 2015), and the resulting net effects are still under debate, particularly for heatwaves ~~(von Buttlar et al., 2018)~~(**?**). However, in-depth investigations of a number of individual events such as the European ~~heat summer~~ heatwave 2003 (Ciais et al., 2005), the 2000-2004 and 2012 droughts in North America (Schwalm et al., 2012; Wolf et al., 2016), and the RHW (Bastos et al., 2014) agree on an overall tendency towards negative impacts on the carbon accumulation potential.

The RHW has been thoroughly investigated from ~~an~~ a hydrometeorological point of view linking the atmospheric blocking to the large-scale positive anomalies in air temperatures and negative anomalies in water availability (e.g., Barriopedro et al., 2011; Rahmstorf and Coumou, 2011). The event has been also well investigated with an emphasis on the biospheric impacts describing the negative anomalies in ecosystem productivity and related vegetation indices (e.g., Bastos et al., 2014). ~~However, investigating the two domains in isolation might lead to an inconsistent description and thus interpretation of what is thought to represent the very same extreme event. If we only look at~~ However, comparing the reports of areas affected by these studies reveals some discrepancies. Hydrometeorological anomalies point at much larger areas affected compared to biosphere response patterns. Fig. 1 shows the zonal evolution of the RHW ~~(Fig. 1), we~~ in both domains. We find that the spatiotemporal patterns of the temperature anomaly does not match the zonal anomaly in vegetation productivity anomalies. Thus, an integrated assessment including the hydrometeorological and the biospheric domain simultaneously may facilitate our knowledge about the RHW.

The figure reveals an unusually warm period during spring and one longer heatwave during summertime (Fig. 1a). Temperature anomalies exceeded more than 10 K in both spring and summer, ~~while negative~~ but they lead to distinctive anomalies in gross primary productivity (GPP)~~occurred~~ . 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 $^{\circ}N$ (Fig. 1c) ~~. Comparing~~ 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 these two Hovmöller diagrams shows that (1) the affected latitudinal range of the negative GPP anomaly is much smaller than the positive temperature anomaly and (2) ~~one may easily overlook the positive GPP anomaly during springthat coincides with an anomalous warm state.~~

~~The inconsistency of spatiotemporal anomalies in the hydrometeorological conditions and biosphere responses during the RHW reflects different disciplinary perspectives. We suspect that this domain-specific point of view might become an issue in studies of this kind.~~ the evolution of the summer impacts should consider potential carry over effects of positive GPP anomalies during spring, as earlier studies showed that increased spring GPP may negatively influence soil moisture and thus GPP during summer (Buermann et al., 2013). The objective of this paper is ~~therefore~~ to revisit the RHW and to investigate ~~differences in the description and consequent interpretation of the very same extreme event , when adopting a biospheric vs. hydrometeorological point of view. Moving from a compartment-specific perspective towards an integrated one requires a shift in the methodological focus~~the GPP response during the spring event and the summer heatwave in detail by equitably investigating spatiotemporal anomalies in hydrometeological drivers and ecological variables.

This kind of integrated assessment requires a generic methodological approach. Here, we use a multivariate extreme event detection approach that (1) does not differentiate between a positive and a negative extreme event, and (2) can equally be applied on any set of time series, regardless of whether they describe the biospheric or the hydrometeorological domain. We expect that we can reveal previously overlooked facets in the RHW and discuss whether ~~an impact-agnostic approach as presented here may complement compartmental/domain approaches facilitating~~ our approach may facilitate a broader perspective and improved interpretation of extreme events and their impacts.

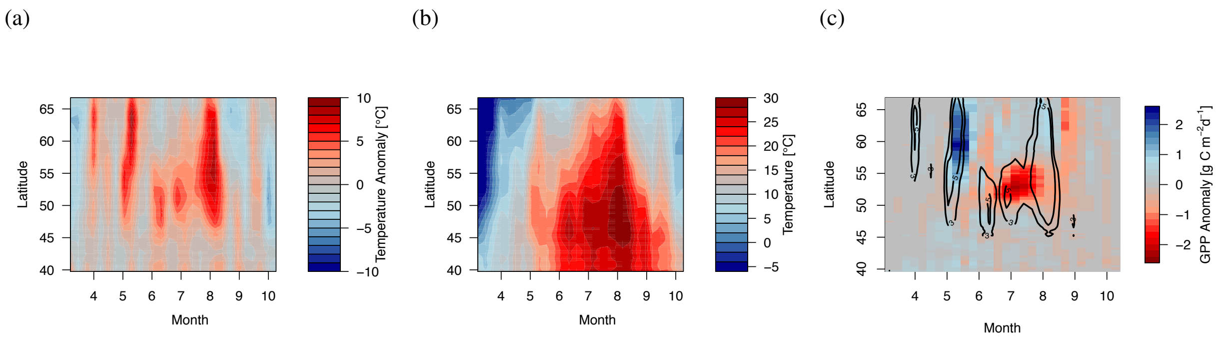


Figure 1. Longitudinal average (30.25 to 60.0 ° E) of (a) temperature anomalies (reference period: 2001-2011), (b) absolute temperature, and (c) GPP anomalies in 2010 with a contour of temperature anomalies (+3 K, +5 K).

2 Methods & data

~~A simple~~

2.1 Rationale

One approach to detect extreme events like the RHW could be ~~using a peak-over-threshold scheme~~ to identify the peaks over some threshold in the marginal distribution of ~~variables~~ a variable (or its anomaly) of interest. For instance, ~~a popular approach is to consider an observation in a single (ideally normally distributed) anomaly variable to be extreme if it deviates~~ one could identify values that deviate by more than two standard deviations from the variable's mean values ~~. By using these kind of univariate approaches for hydrometeorological variables, the RHW can be characterized by~~ (Hansen et al., 2012; Sippel et al., 2015). However, univariate approaches only allow to characterize an event by e.g. extremely high temperature anomalies, lack of precipitation~~and~~ , or very low soil moisture ~~, which amplified the heatwave (e.g., Miralles et al., 2014; Hauser et al., 2016) . From this characterization it can be seen~~ but not their compound anomaly. However, from earlier studies (e.g., Miralles et al., 2014; Hauser et al., 2 know that more than one variable is involved in the RHW ~~, which is thus~~ and a multivariate extreme event detection (i.e., a compound event) (e.g., Leonard et al., 2014; Zscheischler and Seneviratne, 2017) is more feasible. Multivariate algorithms to detect extreme events ~~can therefore be~~ are expected to offer ~~additional detection capabilities for simultaneous anomalies in multiple variables (e.g., Zimek et al., 2012; Bevacqua et al., 2017; Flach et al., 2017; Mahony and Cannon, 2018).~~

~~Multivariate extreme event detection methods account for~~ more robust detection capabilities when accounting for dependencies and correlations among the selected variables (e.g., Zimek et al., 2012; Bevacqua et al., 2017; Flach et al., 2017; Mahony and Cannon, Multivariate extreme event detection considers all observable dimensions of the domain simultaneously. With a multivariate approach one may, for instance, detect very rare ~~constellations~~ combinations of variables even if the individual variables are not extreme. In the following, we detect the anomalies in a multivariate variable space in two sets of variables describing (1) the hydrometeorological conditions, and (2) the biospheric response. The workflow involves a data pre-processing to compute anomalies, a step for dimensionality reduction to not be biased by redundancies among variables. Based on the reduced data-space, an anomaly score is computed that can then be used as threshold. For various reasons, however, in practice the threshold needs to be computed across multiple spatial grid cells of comparable phenology.

2.2 Data and pre-processing

Our dataset for analysing the hydrometeorological domain includes those variables which we consider to be of particular importance for processes taking place during extreme events in the biosphere based on prior process knowledge (Larcher, 2003) and empirical analysis (von Buttlar et al., 2018). The hydrometeorological dataset consists of air temperature, radiation, relative humidity (original resolution $0.71°$)(all three from ERA-INTERIM, Dee et al., 2011), precipitation ~~(Adler et al., 2003)~~(original resolution $1°$)(Adler et al., 2003), and surface moisture (resolution $0.25°$)(http://www.gleam.eu, v3.1a, Miralles et al., 2011; Martens et al., 2017). We consider surface moisture to be a hydrometeorological variable due to its importance for drought detection, although we notice that surface moisture is influenced by biospheric processes. We use gross primary productivity (GPP), latent heat flux (LE), sensible heat flux (H) (resolution $0.25°$)(all three from FLUXCOM-RS, Tramontana et al., 2016), and the fraction of absorbed photosynthetic active radiation ~~(FAPAR, moderate resolution imaging spectroradiometer (MODIS) based FAP~~ resolution 1 km) (FAPAR, moderate resolution imaging spectroradiometer (MODIS) based FAPAR Myneni et al., 2002) to describe the land surface dynamics. We consider turbulent fluxes to be biospheric response variables because they are strongly determined by processes in the terrestrial biosphere.

The selected variables cover the spatial extent of Europe (latitude $34.5 - 71.5° N$; longitude: $-18 - 60.5° E$) and are regridded on a spatial resolution of $0.25°$ from 2001 to 2011 in an eight-daily temporal resolution. To check for differences in land cover types, we estimate the ~~main~~ major land cover type of the European Space Agency Climate Change Initiative land cover classification on a spatial resolution $0.25°$ (original: 300 m). To check for consistency of our findings among other variables (Sect. 3.2), we additionally use terrestrial ecosystem respiration (TER) and net ecosystem productivity (NEP, both originating from FLUXCOM-RS, Tramontana et al., 2016).

2.3 ~~Preprocessing and spatiotemporal segmentation~~

The actual event detection is realized on the anomalies of these data sets. To compute the anomalies, For each variable under consideration, we ~~compute~~ first estimate the seasonality as a smoothed median seasonal cycle per grid cell~~to obtain an estimate of seasonality. We subtract the seasonal cycle~~ . We use the median instead of the mean as it is less susceptible to outliers. We then subtract these seasonal cycles from each variable and year to obtain a multivariate data cube of ~~deviations from the median seasonality~~ anomalies (Fig. 3, step 1). ~~In this multivariate anomaly data cube, we fill small data gaps with~~ Small data gaps are set to zeros to ensure that they are not detected as anomalies. The gap filling is necessary for a multivariate detection approach as there are many more cases in which one variable is missing in the multivariate cube compared to a univariate data stream.

~~To define extreme events in this multivariate data cube several approaches are possible. One approach would be to define thresholds globally. Spatiotemporal points exceeding the global threshold would be flagged as extreme event. However, the data is spatially heteroscedastic, i. e. a global approach detects extreme events in predominantly in high variance regions and is blind to regions with low variance. Another approach would be to define a certain threshold locally within each grid cell. This approach would assume~~

2.3 Feature extraction and anomaly detection

We use a multivariate anomaly detection algorithm proposed by Flach et al. (2017) and apply it separately to two sets of variables for the biosphere and hydrometeorology. The method expects a multivariate set of anomalies and projects them to a reduced space via principal component analysis, retaining a number of principal components that explain more than 95% of the variance (Fig. 3, step 3b). This procedure accounts for linear correlations in the data only by removing redundancies among the variable anomalies.

We compute an anomaly score via kernel density estimation (KDE, Parzen, 1962; Harmeling et al., 2006) in the reduced anomaly space (Fig. 3, step 4). KDE showed very good performance among different other options to detect multivariate anomalies in previous experiments (Flach et al., 2017). One strength of KDE is that it considers nonlinear dependencies among dimensions (Fig. 4). The anomaly scores are transformed into normalized ranks between 1.0 (very anomalous, data point in the margins of the multivariate distribution) and 0.0 (completely normal, data point in the dense region of the multivariate distribution; Fig. 3, step 5). In this univariate index of compound extremes, it is legitimate to use a classical threshold that can be intuitively analysed. However, to avoid an equal spatial distribution of ~~extreme events which is particularly problematic for rather short time series as the ones under scrutiny. We use an alternative approach which compares grid cells to other grid cells with similar phenologyrecently developed~~ event occurrences we do not apply this multivariate anomaly detection per pixel, but rather by region.

2.4 Spatiotemporal segmentation

The spatiotemporal segmentation aims to identify spatial areas of comparable phenology, climate and seasonality. For identifying these regions, we follow the strategy described by Mahecha et al. (2017) and extend it to the multivariate case~~by also including similar climatology. The regional approach is important in our case to get robust regional estimates of thresholds defining extreme events in rather short time series via spatial replicates. The main idea behind the scheme for identifying similar phenology and climate~~ . The main idea is that the (now spatial) principal components of the mean seasonal cycles ~~and~~ can be used for classifying regions according to their ~~mean~~ characteristic temporal dynamics.

The procedure for extracting spatial segments of similar grid cells works as follows ~~(for a detailed description see Supplementary Materia~~ (for a detailed description see Mahecha et al., 2017):

(1) estimate the median seasonal cycle in each grid cell and of each variable individually and standardize the median seasonal cycles to zero mean and unit variance ~~. Sort the~~ to get the cycles comparable across different units (Fig. 2 (1)).

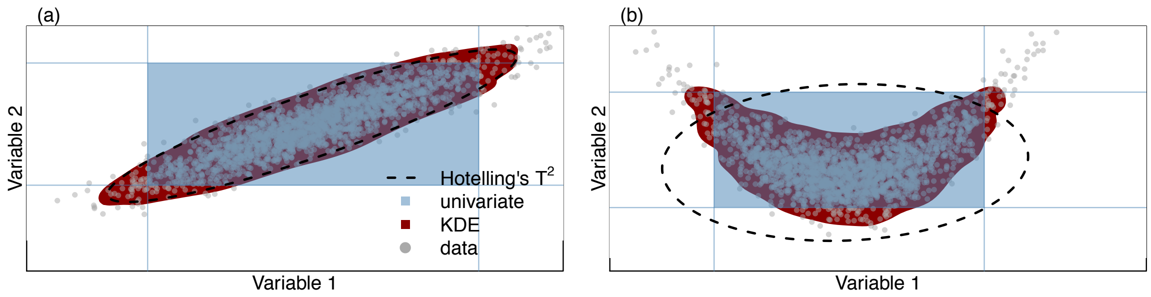


Figure 2. Illustration of the multivariate anomaly detection algorithm with two variables. The data has: (a) linear dependencies (multivariate normal) and (b) a nonlinear dependency structure. Univariate extreme event detection does not follow the shape of the data, whereas algorithms assuming a multivariate normal distribution (Hotelling's T^2, Lowry and Woodall, 1992) are suitable for case (a); kernel density estimation (KDE) gets the shape of the data in both cases (a) and (b). 5% extreme anomalies are outside the shaded areas (region of "normality") for all three algorithms.

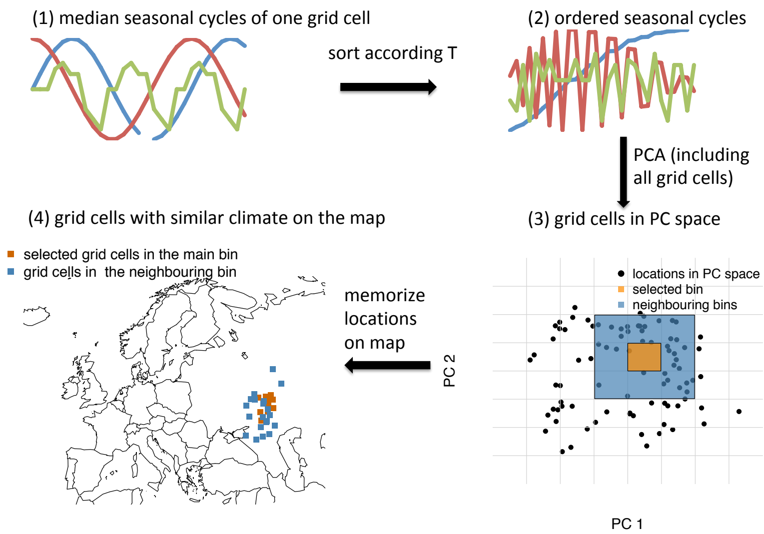


Figure 3. Illustration of the spatial segmentation procedure with two principal components.

(2) To remove the effect of different phasing (similar, but only lagged seasonal cycles), we sort the median seasonal cycles according to a variable showing a strong seasonality, which is temperature in our case. Thus, we memorize how to bring temperature in a sorted increasing or decreasing order (the 'permutation' of temperature) and apply the same permutation to the ~~permutation of temperature to remove the effect of different phasing and concatenate the~~ other median seasonal cycles (Fig. 2 (2)). We prepare the data for dimensionality reduction by concatenating the seasonal cycle of all variables ~~. (2) Apply~~

to a matrix seasonal cycles × space. We apply a principal component analysis (PCA) to reduce the ~~temporal~~ dimension of the concatenated median seasonal cycles.

(3) ~~Select grid cells~~We select locations (grid cells) of similar phenology and climate by dividing the orthogonal principal component subspace into equally sized bins ~~.~~ (Fig. 2 (3)). We used $N_{PC} = 4$ components in this step, explaining 71% of variance. The bins are sufficiently small compared to the length of the principal components to ensure a fine binning of very similar phenology and climate.

(4) ~~Select one grid cell and grid cells in their neighbouring bins to obtain overlapping spatial segments of similar phenology and climate.~~ We compute the multivariate anomaly score in an overlapping moving window for all grid cells that fall into one of the bins (the central bin and the neighbouring binds, Fig. 2 (4)).

~~After identifying similar regions one approach is to detect multivariate anomalies and define thresholds of the obtained anomaly scores in each of the spatially overlapping segments. However, the data also exhibits a changing variance within the year~~ A final detail to consider is the effect of changing seasonal variance (temporal heteroscedasticity)~~, the variance is e. g. higher during growing season in the set of biosphere variables. These heteroscedastic~~ . These patterns lead to detecting extreme events predominantly during the high-variance ~~season.To avoid these seasonal patterns~~ seasons (i.e. summer times). To avoid seasonal biases in the extreme event detection~~scheme, we extract the season in a temporally~~ , we additionally apply the entire anomaly detection scheme to seasonally overlapping moving window ~~(9 observations, 72 days) and compare it to the same season in other yearsin the same grid cell and to the same season in grid cells with similar climate and phenology.~~ across years.

Within the spatiotemporal segmentation procedure, we ensure that the number of observations is at least 198 (9 time steps × 11 years, at least one spatial replicate). ~~We run the following anomaly detection workflow in each segment (Fig. 3, step 2).~~

~~Data processing for detecting multivariate anomalies.~~

2.5 ~~Feature extraction and anomaly detection~~

~~We apply the multivariate anomaly detection algorithm separately to the set of variables representing the biosphere and the hydrometeorology with a workflow proposed by Flach et al. (2017). In each spatiotemporal segment of the multivariate anomaly data cube we standardize the data to zero mean and unit variance (Fig. 3, step 3a). Subsequently, we calculate principal components (von Storch and Zwiers, 2001) of the variables in each spatiotemporal segment, thus representing the variables by orthogonal transformed vectors and retaining a number of principal components that explain more than 95% of the variance of this spatial segment (Fig. 3, step 3b). This procedure accounts for linear correlations in the data only and removes "unimportant" high dimensionality.~~

~~We choose kernel density estimation (KDE, Parzen, 1962; Harmeling et al., 2006) for multivariate extreme event detection in feature space (Fig. 3, step 4). KDE showed very good performance among different other options to detect multivariate anomalies in previous experiments (Flach et al., 2017). It considers nonlinear dependencies among principal components to obtain an anomaly score (Fig. 4). The anomaly scores are transformed into normalized ranks between 1.0 (very anomalous, data point in the margins of the multivariate distribution) and 0.0 (completely normal, data point in the dense region of the~~

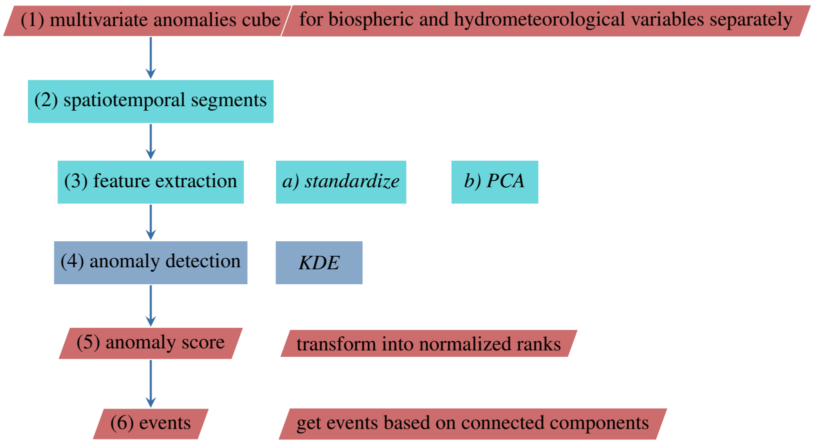


Figure 4. ~~Illustration of the multivariate anomaly detection algorithm with two variables. The data has: (a) linear dependencies (multivariate normal) and (b) a nonlinear dependency structure. Univariate extreme event detection does not follow the shape of the data, whereas algorithms assuming a multivariate normal distribution (Hotelling's T^2, Lowry and Woodall, 1992) are suitable~~ Data processing for ~~case (a); kernel density estimation (KDE) gets the shape of the data in both cases (a) and (b). 5% extreme~~ detecting multivariate anomalies~~are outside the shaded areas (region of "normality") for all three algorithms~~.

~~multivariate distribution) in each overlapping spatiotemporal segment (Fig. 3, step 5).~~ To reunify the spatiotemporal segments, we assign the normalized anomaly scores temporally to the time step in the center of the temporal moving window and spatially to the grid cell in the central bin of similar climate and phenology.

2.5 Statistics of extreme events

We assume that 5% of the data are anomalous in each overlapping spatiotemporal segment and convert the anomaly scores into binary information. However, the main results of compensation effects are not sensitive to this threshold selection (Supplementary materials S3, varying the threshold between 1% to 10%). To compute statistics based on the spatiotemporal structure of each extreme event, we follow an approach developed by Lloyd-Hughes (2011); Zscheischler et al. (2013) and compute the connections between spatiotemporal extremes if they are connected within a ~~$3x3x3$~~ $3 \times 3 \times 3$ (lon × lat × time) cube. Each connected anomaly is considered as a single event (Fig. 3, step 6). In this way, we observe event-based statistics, i.e., affected area (km^2), affected volume ($km^2 \cdot$ days), centroids of the area and histograms of the single variable anomalies stratified according to different ecosystem types (land cover classes). Furthermore, we observe the response of individual variables to the multivariate event by computing the area weighted sum of the variable during the event in which the variable of interest is positive relative to the seasonal cycle (res^+) or negative, respectively (res^-). For many biospheric variables, one expects a mainly negative response to hydrometeorological extreme events like heatwaves or droughts (Larcher, 2003; von Buttlar et al., 2018). Thus, we define compensation of a specific variable to be the absolute fraction of res^+ from res^-. The balance of a variable is the sum of res^+ and res^-. Centroids of res^+ and res^- are computed as average of the affected longitudes, latitudes, and time period, weighted with the number of affected grid cells at this longitude, latitudes, and time period, and its respective anomaly score. They are to compute the spatial and temporal distance between res^+ and res^-. Affected area, volume, response and centroids take the spherical geometry of the Earth into account by weighting the affected grid cells with the cosine of the respective latitude.

3 Results

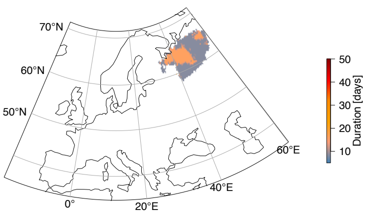
3.1 Extreme events in western Russia in 2010

We identify two multivariate extreme events in the set of hydrometeorological variables in western Russia 2010, based on the spatiotemporal connectivity (more details Supplementary Materials ~~S2~~S1). The two extreme events are separated by approximately one week of normal conditions towards the end of May:

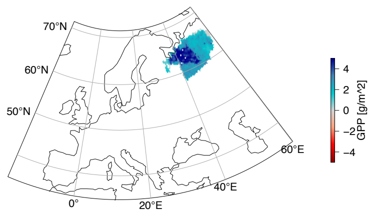
- hydrometeorological spring event: anomaly of the hydrometeorological variables in western Russia during May ranging from longitude 30.25 - 60.0 ° E, latitude $\geq 55° N$ (Fig. 5a, b)
- hydrometeorological summer event: anomaly of the hydrometeorological variables in western Russia, June to August, ranging from longitude 28.75 - 60.25° E, latitude 48.25 - 66.75 $°N$. This event is usually referred to as Russian Heatwave (RHW) 2010 (e.g., Barriopedro et al., 2011; Rahmstorf and Coumou, 2011) (Fig. 5c, d).

Both multivariate hydrometeorological anomalies partly overlap with a multivariate anomaly in the set of biosphere variables (biospheric spring event and biospheric summer event). Of specific interest is that the area affected by anomalous hydrometeorological summer conditions is remarkably larger than the one detectable in the biospheric variables (biospheric summer event, $2.4 \cdot 10^6$ vs. $1.1 \cdot 10^6$ km^2, Tab. 1). This fact might already indicate that biosphere responses are more nuanced than the hydrometeorological events and do not simply follow the extent of the hydrometeorological anomaly. As indicated e.g., also by Smith (2011), a hydrometeorological extreme event does not necessarily imply an extreme response.

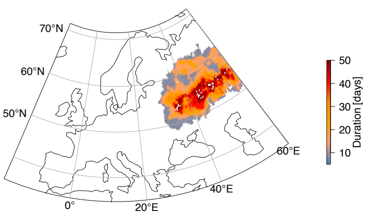
(a) duration of the hydrometeorological spring event



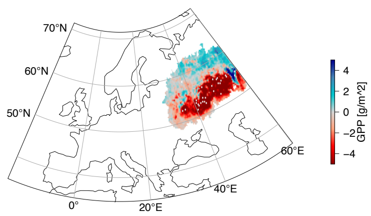
(b) sum of GPP during the hydrometeorological spring event



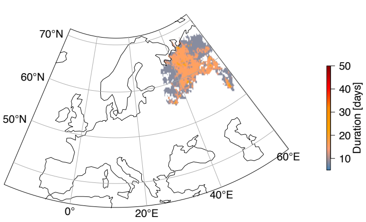
(c) duration of the hydrometeorological summer event



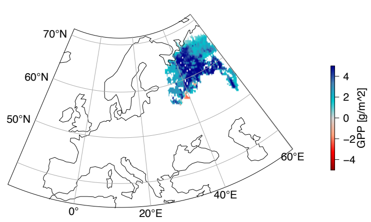
(d) sum of GPP during the hydrometeorological summer event



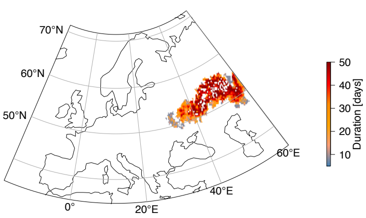
(e) duration of the biospheric spring event



(f) sum of GPP during the biospheric spring event



(g) duration of the biospheric summer event



(h) sum of GPP during the biospheric summer event

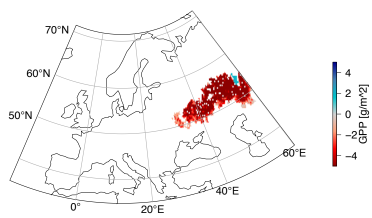


Figure 5. Left column: temporal duration of the (a) ~~the~~ hydrometeorological spring event~~and~~, (c) ~~the~~ hydrometeorological summer event, and biospheric events (e),(g). Right column: corresponding GPP response, i.e., the sum of deviations from the seasonal cycle during the event for the (b) ~~the~~ hydrometeorological spring event~~and~~, (d) ~~the~~ hydrometeorological summer event, and biospheric events (f), (h). While the GPP response during the hydrometeorological spring event is entirely positive (more productive than usual, b), GPP response during the hydrometeorological summer event differs between higher latitudes ($> 55°$ N, short-lasting, positive) and lower latitudes (long-lasting, negative).

3.1.1 Hydrometeorogical events

As GPP is a key determinant of ecosystem–atmosphere carbon fluxes~~and well described~~, we focus on the gross primary productivity (GPP) response to the multivariate ~~hydromteorological~~ hydrometeorological anomaly: We find that the GPP response is entirely positive during the short-lasting ~~hydromteorological~~ hydrometeorological spring event (+17.8 Tg C, Tab. 1), while it is mainly negative during the summer (+8.8 Tg C, −49 Tg C, Tab. 1). Nonetheless, 18% of the GPP summer losses ~~during the RHW~~ associated with the RHW in the southern region are instantaneously compensated by over-productive vegetation in the northern latitudes. If we estimate the annually integrated effect of ~~summer and spring~~ the anomalies, another 36% of the carbon losses are compensated during spring in higher latitudes. Please note, that we did not find extreme events after summer, which implies a fast recovery of vegetation activity after summer. Integration over the spring and summer events thus equals the annual integration. Overall, we find that 54% of the negative GPP ~~responses~~ anomalies are compensated either because of the positive spring anomalies or across ecosystems during summer. These compensation effects reduce the negative carbon impact of integrated annual (spring and summer) hydrometeorological event from −49.0 Tg C to −24 Tg C in total (Tab. 1).

3.1.2 Biospheric events

Moving the focus to the multivariate biosphere events (biospheric spring and biospheric summer event), which overlap with the hydrometeorological events, we find that GPP responses based on the biospheric spring event are almost entirely positive (+33.8 Tg C), and based on the biospheric summer event almost entirely negative (−82.6 Tg C). ~~In total,~~ If we consider the annually-integrated effect of the spring and summer anomalies, spring carbon gains are estimated to offset 41% of the ~~summer carbon losses are compensated by an anomalously productive spring~~ subsequent carbon losses in summer (56 days earlier) in the higher latitudes (514 km distance of the centroids, Tab. 1). To further examine these findings, we check for these kind of compensation effects among different variables and another GPP dataset in the following section. Note that the dataset of biosphere variables includes GPP itself. Computing the responses based on the extent of the biospheric event is nevertheless useful, as an extreme event in the biosphere variables is not exclusively restricted to extreme conditions in the hydrometeorological conditions (Smith, 2011).

3.2 Compensation in other data-sets and variables

The ~~integrated (spring and summer)~~ annually-integrated compensation effect in GPP is highly consistent among different variables. For instance, NEP (excluding fire) shows ~~this~~ such kind of compensation, but also FAPAR and LE (Tab. 2). Sensible heat flux, on the other hand, is high during the hydrometeorological summer event (biospheric summer event), as well as the hydrometeorological spring event (biospheric spring event) as expected for strong positive temperature anomalies. However, some of the remote sensing data products might be affected by high fire induced aerosol loadings during the heatwave that affect atmospheric optical thickness (e.g., Guo et al., 2017; Konovalov et al., 2011). Exploring an almost entirely climate-driven GPP product (FLUXCOM RS+METEO, Jung et al., 2017) also shows the integrated compensation effect, although

Table 1. Statistics of the extreme events, based on their spatiotemporal connected structure: affected area, affected volume, positive and negative GPP response to the event, compensation of the negative response (comp.), as well as average spatial and temporal distance between the parts of the events with positive and negative responses.

event	area $[km^2]$	volume $[km^2 \cdot days]$	GPP comp.	res^+_{GPP}	res^-_{GPP}	spatial [km]	temporal [d]
hydrometeorological							
spring	$0.77 \cdot 10^6$	$0.81 \cdot 10^7$	-	$17.8\,Tg$	-		
summer	$2.44 \cdot 10^6$	$5.79 \cdot 10^7$	0.18	$8.8\,Tg$	$-49.0\,Tg$	499	-4
integrated	$3.29 \cdot 10^6$	$6.60 \cdot 10^7$	0.56	$26.6\,Tg$	$-49.0\,Tg$	452	-34
biospheric							
spring	$1.25 \cdot 10^6$	$1.48 \cdot 10^7$	117.04	$33.8\,Tg$	$-0.3\,Tg$	756	-16
summer	$1.06 \cdot 10^6$	$4.22 \cdot 10^7$	0.00	$0.4\,Tg$	$-82.4\,Tg$	962	50
integrated	$2.28 \cdot 10^6$	$5.70 \cdot 10^7$	0.41	$34.2\,Tg$	$-82.7\,Tg$	514	-56

Table 2. Compensation of negative responses to the western Russian events in 2010 based on the integrated biospheric or hydrometeorological events is consistent over different variables and data sets.

	hydrometeorological events			biospheric events		
Variable	res^+ $[Tg]$	res^- $[Tg]$	Comp. [%]	res^+ $[Tg]$	res^- $[Tg]$	Comp. [%]
NEP	$17.53\,Tg$	$-34.03\,Tg$	51.5	$23.45\,Tg$	$-48.49\,Tg$	48.4
LE	$19.90\,Tg$	$-53.97\,Tg$	36.9	$16.34\,Tg$	$-102.81\,Tg$	15.9
FAPAR	1.89	$-4.03\,Tg$	47.0	$2.52\,Tg$	$-6.61\,Tg$	38.1
TER	$18.97\,Tg$	$-11.06\,Tg$	171.4	$13.71\,Tg$	$-23.43\,Tg$	58.5

much lesser pronounced (Appendix A1). Thus, we are confident that the observed compensation effect is not related to the optical thickness during the RHW.

3.3 Influence of Vegetation Types

In Fig. 6 we present the histograms of GPP anomalies for different land cover classes (forests, grasslands and crops) based on hydrometeorological spring event, hydrometeorological summer event, biospheric spring event, and biospheric summer event, respectively (Fig. B1) to highlight two aspects: First, during the spring event (hydrometeorological spring or biospheric spring), forests react almost entirely with positive GPP anomalies (Fig. 6a). ~~Thus,~~ Forests in this region are energy-limited, so the timing of the extreme event (e.g., positive temperature anomalies in spring) leads to hydrometeorological conditions which are favourable for vegetation productivity, as absolute spring temperatures are still below the temperature optimum of GPP (Fig. 8a, Wolf et al., 2016; Wang et al., 2017).

Second, during the hydrometeorological summer event, we observe positive to neutral GPP responses in forests, whereas crops and grasslands react strongly negative (Fig. 6b). The positive versus negative GPP responses almost entirely reflect the

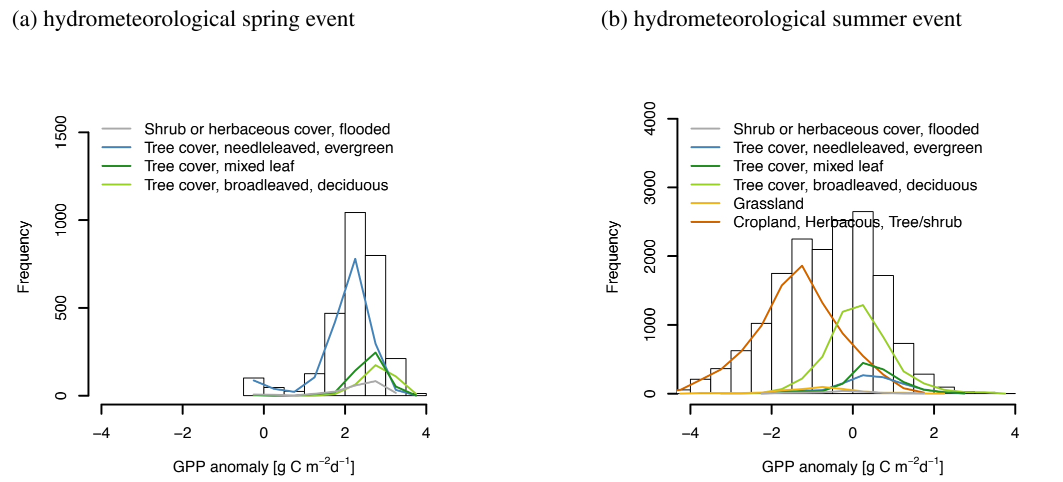


Figure 6. Histogram of GPP anomalies (reference period: 2001-2011) for different land cover classes based on the spatio–temporal extent of (a) the hydrometeorological spring event and (b) the hydrometeorological summer event. Bars denote the sum of all vegetation classes.

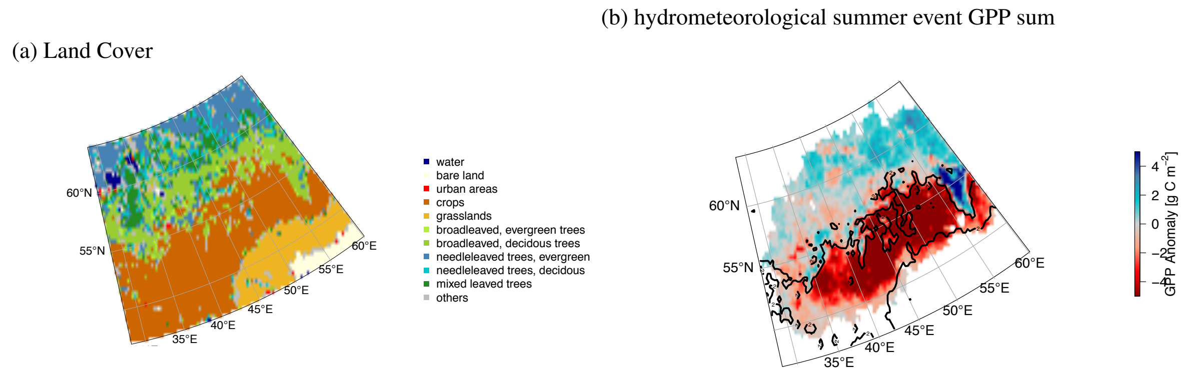


Figure 7. (a) Dominant land cover classes of a spatial extent of the RHW. (b) The boundaries of the different ecosystem types (forest-dominated ecosystems vs. agriculture-dominated ecosystems, denoted by the black contour line) match the observed patterns of the GPP response (reference period for the calculating anomalies: 2001-2011) during the hydrometeorological summer event.

map of dominant vegetation types (forest vs. agricultural ecosystems, Fig. 7). ~~In fact, we can also show that from a statistical point of view vegetation type is the most important factor explaining the GPP response in summertime, followed by radiation anomalies and duration (Supplementary S3).~~ However, different vegetation types exhibit a transition from higher latitudes (predominantly forest ecosystems) to lower latitudes (dominated by agricultural ecosystems). Thus, the different responses of vegetation types might be confounded by the fact that absolute temperatures also follow a latitudinal gradient (Fig. 1b). Absolute temperatures for agricultural ecosystems are higher and far beyond the temperature optimum of GPP (8c), whereas

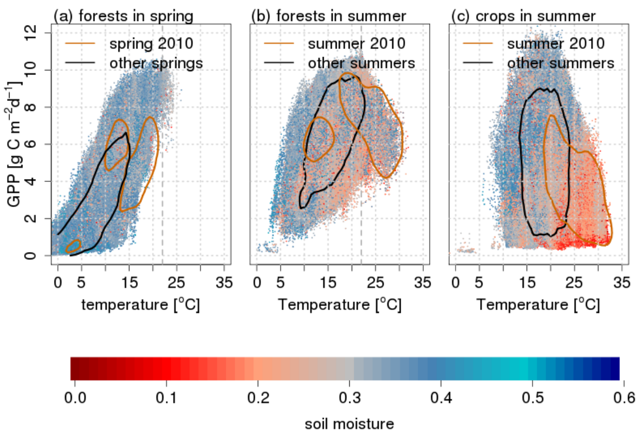


Figure 8. Temperature optimality for GPP in (a) forests during spring, (b) forests during summer, and (c) crops during summer. Contour lines enclose 75% of the data points.

forest-dominated ecosystems at higher latitudes experience temperatures just slightly above the temperature optimum of GPP (8b). The response of forest ecosystems partly reflects this kind of latitudinal gradient: forest ecosystems in the lower latitudes react positively to the spring temperature anomaly and then tend to react more negatively to the summer heatwave than forest ecosystems in higher latitudes. Forest ecosystems in higher latitudes are still productive in terms of GPP during the peak of the heatwave (Fig. 9). ~~This finding is accompanied by consistently higher~~

To disentangle the variable importance of the different confounding factors, we run a simple linear regression model which tries to explain GPP as function of the hydrometeorological driver variables (temperature, precipitation, radiation, surface moisture, including their anomalies and absolute values), as well as vegetation type, duration and latitude (Supplementary S2). We use an algorithm after Chevan and Sutherland (1991) which extracts the independent contribution of the variable importance related to this particular variable regardless of the model complexity or dependencies among variables. The model reveals from a statistical point of view, that vegetation type and the latitudinal gradient are the most important variables explaining GPP during the summer event, followed by the hydrometeorological drivers. Access to deeper water and soil type as well as non-linear feedbacks are factors which are not represented in the model, but might explain the high importance of latitude. Apart from vegetation type being important for the GPP response, underlying water use efficiency (calculated according to Zhou et al. (2014) is consistently higher in forest-dominated ecosystems compared to agriculture-dominated ecosystems (Appendix Fig. C1a), and higher evaporative fraction in forest ecosystems during the peak of the heatwave (Appendix Fig. C1b).

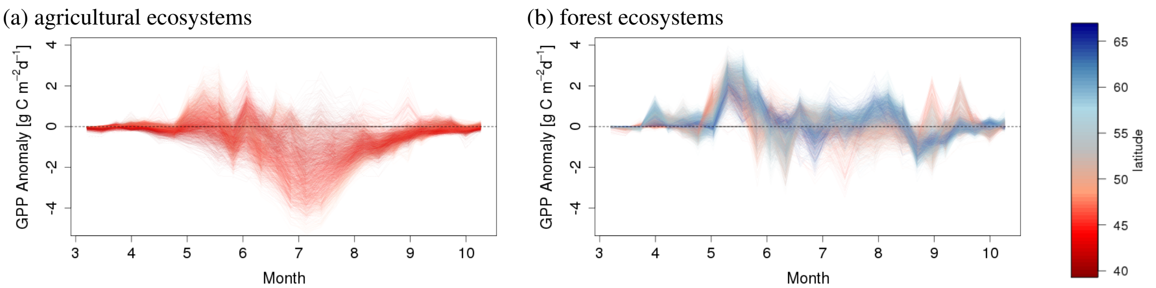


Figure 9. Temporal evolution of the GPP anomaly (reference period: 2001-2011) for (a) agricultural ecosystems and (b) forest ecosystems, colored according to the latitude.

4 Discussion

In this paper we show that the hydrometeorological extreme events affecting western Russia in spring and summer 2010 do not fully correspond to the observed vegetation responses. Positive to neutral GPP responses prevail in higher latitudes during summer, whereas strong negative impacts on GPP can be found in lower latitudes. We interpret this effect by different water management strategies of forest vs. agricultural ecosystems (Teuling et al., 2010; van Heerwaarden and Teuling, 2014) that meet a general latitudinal temperature gradient. Apart from a more efficient water usage of forest-dominated ecosystems, access to deeper soil water might be another reason of ecosystem-specific responses (Fan et al., 2017; Yang et al., 2016). Note that the latitudinal temperature gradient alone might explain differences in the response within ecosystems in summer and between spring and summer, but does not sufficiently explain differentiated GPP responses in summer among different ecosystems (predominantly forest vs. agricultural ecosystems).

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 and Blöschl, 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.

~~Compensations of~~ The integration of the carbon balance over spring and summer might be justified by assumed connections between spring and summer as outlined before. However, we would like to note that a common annual integration and assessment of compensatory effects of the carbon balance over events during the growing season equals the integration over spring and summer for this particular case, as we did not find any events after summertime. The absence of events after the summer heatwave which implies a fast recovery of the ecosystems.

Compensations of the carbon balance during hydrometeorological extreme events have been reported in earlier studies. ~~For instance~~On the one hand, Wolf et al. (2016) report that a warm spring season preceding the 2012 US summer drought reduced the impact on the carbon cycle on the one side. Yet on the other ~~side~~ hand, the increased spring productivity amplified the reduction in summer productivity by spring–summer carry-over effects via soil moisture depletion: higher spring productivity leads to higher water consumption in spring. The high water additionally consumed during spring reduces the water availability in summer and thereby affects productivity during the following summer. However, it remains unclear whether this observation was a singular case, or whether this compensation effect could become a characteristic pattern to be regularly expected in a warmer world. In this ~~paper~~study, we provide some evidence for presumed comparable compensation effects. In contrast to the discussion in Wolf et al. (2016), the RHW compensation does not exclusively occur temporally, i.e., spring compensating for summer losses, but rather spatially distinct forest ecosystems are identified as drivers for this compensation. Spatially compensating ecosystem effects to drought have been observed earlier in mountainous ecosystems that respond differently than lowlands during the European heatwave 2003 (Reichstein et al., 2007).

Following up on ~~these~~ such compensation effects, Sippel et al. (2017) use ensemble model simulations to disentangle the contribution of spring compensation vs. spring carry-over effects on a larger scale. They show that in general warm springs increasingly compensate summer productivity losses in Europe, whereas spring–summer carry-over effects are constantly counteracting this compensation. Also Mankin et al. (2017, 2018) note that increased spring productivity with spring–summer carry-over effects can be observed in earth system models. We can confirm the general finding on spring compensation effects of summer productivity losses in observations for our case study on the RHW. Without using model simulations it is difficult to quantify spring–summer carry-over effects via soil moisture depletion. In case of the RHW only very few areas are anomalously productive in terms of GPP in spring and unproductive in summer as well. Thus, we suspect that exclusively temporal spring–summer carry-over effects play a rather small role for the RHW. However, we also emphasize that longer-term effects, such as compensation in subsequent year through species changes for instance (Wagg et al., 2017), have not been considered in the present study and likely remain hard to quantify beyond dedicated experiments.

The RHW is probably among the best studied extreme events in the ~~northern hemisphere~~Northern Hemisphere. However, the compensation effects reported in this study have only received marginal attention so far. For instance, Wright et al. (2014) mention positive NDVI anomalies in spring 2010, but then focus largely on productivity losses in the Eurasian wheat belt. Similarly, Bastos et al. (2014) focus on a spatial extent of the biosphere impacts that only partly includes forest ecosystems at higher latitudes. Our estimation of carbon losses due to decreased vegetation activity (82 Tg C) is comparable to the one of Bastos et al. (2014) (90 Tg C). Similar to the ~~resutls~~ results of our study, Yoshida et al. (2015) report reductions in photosynthetic activity in agriculture-dominated ecosystems during the RHW, but only small to no reductions in forest ecosystems during summertime. However, their interpretations focus on the summer heatwave. Nevertheless, re-evaluating impact maps ~~(published e.g. in Wright et al., 2014; Yoshida et al., 2015; Zscheischler et al., 2015)~~ (published e.g., in Wright et al., 2014; Yoshida et al., the light of our findings suggests that their evidence supports the presence of compensation effects during the RHW. When it comes to extreme events, the general tendency in many existing studies is naturally to focus on negative impacts as they are of particular interest for society (Bastos et al., 2014; Wright et al., 2014; Yoshida et al., 2015; Zscheischler et al., 2015).

~~Thus~~Regarding the RHW in particular, compensation effects remain unconsidered in previous studies ~~on the RHW~~ to the best of our knowledge.

5 Conclusions

We re-analysed biospheric and ~~hydromteorological~~ hydrometeorological conditions in western Russia 2010 with a generic spatiotemporal multivariate anomaly detection algorithm. We find that the hydrometeorological ~~constellation~~ conditions and the biospheric responses exhibit two anomalous extreme events, one in late spring (May) and one over the entire summer (June, July, August), covering large areas of western Russia. For the summer event, we find that the spatially homogeneous anomaly pattern (characterized by high solar radiation and temperature, low relative humidity and precipitation) translate into a bimodal biosphere response. Forest ecosystems in higher latitudes show a positive anomaly in gross primary productivity, while agricultural systems decrease their productivity dramatically.

If we consider the ~~integrated spring and summer~~ annually integrated effect of the anomalous hydrometeorological conditions, we find that forest ecosystems partly compensate for 54% (36% during spring, 18% during summer) of the productivity losses experienced in agricultural ecosystems. ~~On the one hand, this finding highlights the importance of forest ecosystems to mitigate the impacts of climate extremes. On the other hand, however, this finding does~~ Please note, that the annually integrated impact of the 2010 events on the carbon balance is strongly negative. Our findings do not alleviate the consequences of extreme events for food security in agricultural ecosystems.

From a methodological point of view, this study emphasizes the importance of considering the multivariate nature of anomalies. From this study, we learn that it is insightful to consider both, the possibility of negative as well as of positive impacts, and assess their annually integrated compensation. Although the integrated impact on gross primary production of the hydrometeorological conditions is strongly negative, it is important to notice the ~~strong~~ partial compensatory effects due to differently affected ecosystem types, as well as ~~duration and~~ timing of the extreme events.

Appendix A: Comparison with METEO + RS

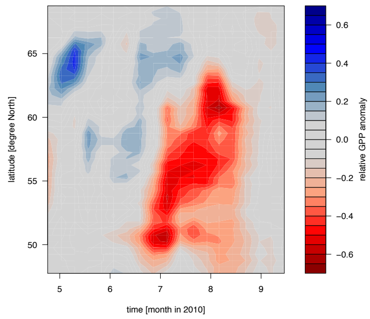


Figure A1. The longitudinal (30.25-60.25° E) average of the GPP anomalies during the RHW 2010, based on the Climate Research Unit observation-based climate variables (CRUNCEPv6, New et al., 2000) driven GPP product originating from FLUXCOM RS+METEO (Jung et al., 2017) shows similar but weaker compensation effects. 28% of the negative GPP response to the RHW are compensated based on the shown latitude-longitude subset.

Appendix B: Biosphere response

(a) biospheric spring event

(b) biospheric summer event

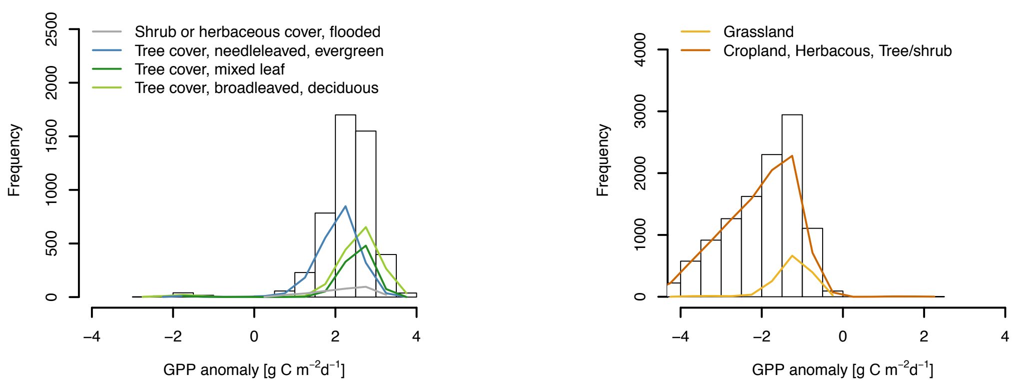


Figure B1. Histogram of GPP anomalies (reference period: 2001-2011) for different land cover classes constrained by a) biospheric spring and b) biospheric summer event.

~~(a) biospheric spring event duration(b) biospheric spring event GPP sum(c) biospheric summer event duration(d) biospheric summer event GPP sumLeft hand side: temporal duration of (a) biospheric spring, and (c) biospheric summer event. Right hand side: corresponding GPP response, i.e. the deviation from the seasonal cycle during the event for (b) biospheric spring, and (d) biospheric summer event. The Biospheric summer event is missing the positive response of forests at higher latitudes, as the response was positive, but is not considered to be "extremely" positive. Therefore, it is not detected by the multivariate algorithm.~~

Appendix C: Water use efficiency and evaporative fraction of different land cover types

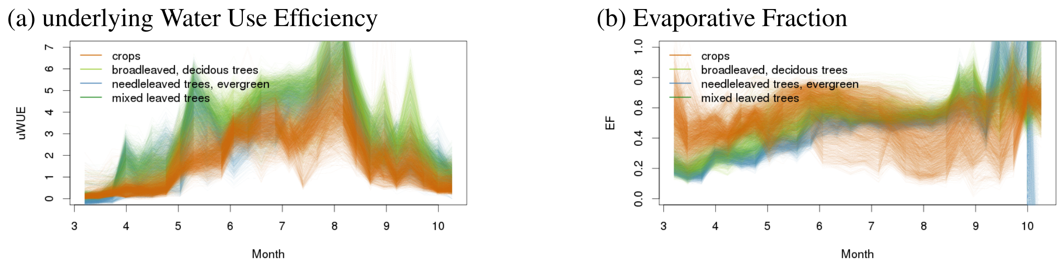


Figure C1. (a) Underlying water use efficiency (uWUE) and (b) evaporative fraction (EF) of the area affected by the RHW in 2010. uWUE is calculated according to Zhou et al. (2014) including vapour pressure deficit. In contrast to WUE, uWUE attempts to correct for differences in temperature and vapour pressure deficit to a certain degree.

Author contributions. MF and MDM designed the study in collaboration with SS, FG, ABa, ABr and MR. MF conducted the analysis and wrote the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This research received funding by the European Space Agency (project "Earth System Data Lab") and the European Union's Horizon 2020 research and innovation programme (project "BACI", grant agreement no 64176). The authors are grateful to the FLUXCOM initiative (http://www.fluxcom.org) for providing the data. MF acknowledges support by the International Max Planck Research School for Global Biogeochemical Cycles (IMPRS). Furthermore, the authors would like to thank Sebastian Bathiany for crucial discussions on the topic, Jürgen Knauer for his expertise on water use efficiency, Julia Kiefer for her kind language check, as well as Victor Brovkin and Sophia Walther helping to improve the manuscript. Two anonymous reviewers provided valuable suggestions for improvement.

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Response to Anonymous Referee #1

Received and published: 24 April 2018

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:

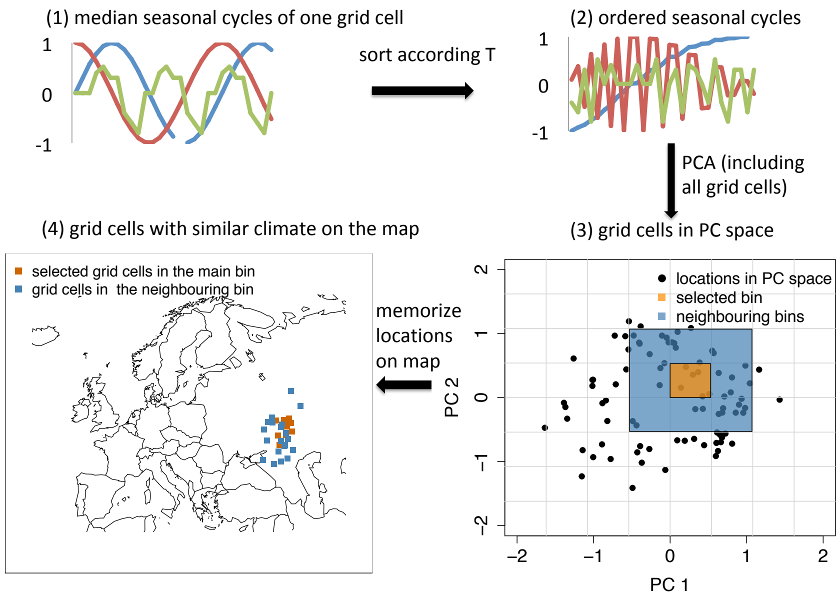
1) The hydrological event and the biospheric events don't have the same spatial coverage which makes it hard for those new to the concept of compound events to appreciate how the events evaluated in the manuscript are indeed related. Could the authors perhaps provide a stronger case for why these distinctive 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.



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, ..."

Furthermore we will emphasize that the last sentence on p.13 is only related to the RHW: "Regarding the RHW in particular, compensation effects remain unconsidered in previous studies to the best of our knowledge".

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.

Response to Anonymous Referee #2

Received and published: 2 May 2018

Review for bg-2018-130, Flach et al., "Contrasting biosphere responses to hydrometeorological extremes: revisiting the 2010 western Russian Heatwave."

Flach and colleagues, using a multivariate spatiotemporal anomaly detection algorithm on both climate and ecosystem variables, assess the response of productivity to the Russian heat wave of 2010. Motivated by the potential for inconsistencies in the climate event and the biospheric impact (which they suggest is a function of disciplinary divides) they find that an anomalous spring warming event in both the biosphere and climate increased GPP prior to the actual heat wave itself, which occurred later in summer, thus offsetting the negative productivity effects. They note that the compensation occurs in different ecosystems–losses dominated in lower latitude managed ecosytems, such as crop land, while spring gains dominated in higher latitude forested regions. During the heat event itself, they attributed the differential response of forests and crops to different water management strategies of the vegetation classes. Overall the paper is a nice contribution and appears methodologically sound (if not a bit overcomplicated in places). I have a few comments and suggestions for the authors to consider that I hope will help improve the clarity and argument of the paper.

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

Main comments:

1. Stated motivation: While I am sympathetic to the larger issue that climate extremes and climate impacts are distinct domains and that extremes may not necessarily map to impacts, I find parts of the introduction to be somewhat of a 'straw man.' The hydro and bio perspectives generally do agree on the Russian heat wave–warm temperatures, along with dry soils leads to carbon loss. Consider the fact, for example, that the authors' very own agnostic algorithm finds the same two events in both the met and bio fields; it suggests that the RHW at least, this disconnect does not lead to inconsistent interpretations or conclusions among different disciplines. The notion that there isn't a one-to-one mapping between the geophysical event and the biophysical impact is certainly important for accurately representing the total effects as a

function of the differential vulnerabilities of ecosystems. The authors rightfully emphasize this. However, the notion that this issue is emblematic of some kind of disciplinary divide is over-reach, or at the very least, is not supported by the literature the authors cite here. I heartedly agree that a call for an integrative perspective is a good one, as it can provide both a richer treatment of an extreme event and a basis for better impacts prediction, but the way the introduction is cast at present overstates the extent to which disciplinary perspectives are or were an issue in some kind of misdiagnosis of the RHW. This can be seen, for example, at 3.10, where the authors state that because the GPP declines were not as large as the temperature anomalies in Fig. 1, that this is somehow reflective of "different disciplinary perspectives" rather than of the complexity of the Earth system itself. . .leading the authors to "suspect [. . .it] might become an issue in studies of this kind." If the authors provided a stronger basis in the literature of inconsistent conclusions of the impacts of the RHW or similar events based on disciplinary divides, then sure, the way the intro is written can stand, but I think as is, it overstates it as a problem and diminishes the scientific conclusions of the paper, which are interesting in and of themselves. The point is, those interesting results and the science itself, gets a bit lost in the straw man discourse. Edits to the text can fix this.

Response: We would like to thank the reviewer for the positive view on the scientific conclusions of our manuscript. We agree with the reviewer, that we somehow overstated the disciplinary differences on the existing literature at the basis of the Russian Heatwave. We will carefully revise the abstract and the introduction to fix issues of this kind. In particular, we will rephrase the motivation at 3.10. along the lines the reviewer suggested (more focused on our own results, highlighting the call for an integrated perspective):
"The objective of this paper is therefore to revisit the RHW and to investigate the GPP response during the spring event and the summer heatwave when adopting a hydrometeological driver vs. a biospheric perpective."
Furthermore, we will reformulate the sentence on 3.2-3 to: "However, an integrated assessment including the hydrometeorological and the biospheric domain may facilitate our knowledge about the RHW. In particular, we highlight one aspect of the RHW which can easily be seen, i.e., if we look at the zonal evolution of the RHW in both domains" and remove two sentences in the abstract (1.5 and 1.16-17).

2. Two events v. one event: My comment here is a corollary to the above about how the paper is cast relative to the literature. The authors are taking two separate events in 2010, an anomalous spring and an anomalous summer, and integrating the impacts across those two events and casting it as the net effects of the RHW, rather than simply examining the net consequence of the RHW itself. Certainly the spring event is crucial to providing a picture of GPP over the growing season and this approach makes sense for the effects of the full growing season on GPP: the extent to which the spring anomaly primed, compensated, or otherwise interacted with the RHW is important. But conceptually the authors need to make clear that simply combining them does not constitute the carbon response to the RHW, for as written, the RHW impacts are presented as the net effects of two separate events, rather than just the heat wave. Given the motivation the authors lead with (i.e., that there is an inherent potential for some kind of mismatch from the atmosphere down and the biosphere up), calling the impact of the RHW the integration of two distinct events seems like an issue. Perhaps the results should be recast around the compensation effects of spring growth on total growing season GPP in the year of the Russian heat wave. I think just making this distinction clearer is important. The net impact of the RHW is not growing season GPP, which includes the anomalous spring, it's just the GPP loss during the RHW. These integrations can be seen in Tables 1 and 2, S4.1, etc. Further complicating this is the fact that the actual losses and gains of GPP are domain integrated, and the domain integration is a function of the detection algorithm. Certainly the authors discuss that the compensation occurs in a fundamentally different part of the domain and land cover class than the heat wave impacts, so I find the combination a bit misleading–it occurs in a different location and time than the actual heat wave–1TgC in crops is fundamentally different than that for forests (though from a carbon accounting perspective perhaps not). This again, is just about how the results are presented, particularly the res+/res-, not the results themselves.

Response: We would like to thank the reviewer for this comment. We apologize if the net effects of the Russian Heatwave (RHW) can be misunderstood as integrated spring and summer effect. We will carefully revise the manuscript to address this issue. Furthermore, we did not mention in the manuscript, that there is no event after summer. Thus the annual integration over the events in the growing season in 2010 equals the integration over spring and summer. We add a sentence to clarify this issue on p.9, l.6: "Please note, that we did not find extreme events after summer, which implies a fast recovery of vegetations activity after summer. Integrations over the spring *and summer events thus equals the annual integration." Furthermore, we will reformulate "integrated over spring and summer" to "annually integrated".*

Reviewer #1 expressed concerns along the same lines, particularly with respect to process based connections between the spring and summer event. We will provide a more in-depth discussion abouth how the spring and summer event might be related:

First, we will add a paragraph to the introduction (p.5, l.3): "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 ... "

Second, we will add a paragraph to the discussion p.12, l. 22 – p. 13, l. 10. 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. "

3. Merits of the detection approach: Part of the basis of this manuscript is that a much more sophisticated detection approach is needed to accurately represent the biophysical impacts of

climate extremes. If one simply did the detection–as is typical– at the grid point scale on the hydrometeorological fields and then composited on the biophysical fields for the same dates as the meteorological anomaly, would the results and/or conclusions substantially differ? At 5.10 the authors claim that for a short time series a traditional threshold approach would be problematic. Is there evidence for this? The authors still have to perform a sensitivity analysis of their results to the chosen threshold (S4.1). At some places the paper feels needlessly complex– perhaps the authors could better justify their complicated analytical choices?

Response: We would like to thank the reviewer for the critical analysis of our detection approach. The main advantage of our multivariate detection approach is that we can integrate information about several variables simultaneously and might also detect rare combinations of variables which are not detected as extreme individually (4.9-14). However, the events in Russia 2010 are not an example of this kind. Thus, we agree with the reviewer, that it is possible to get similar results by combining several univariate detection approaches for the Russian heatwave. Combining univariate detection approaches would require to choose a threshold for each variable individually. Performing a full sensitivity analysis of the choosen thresholds would lead to a combination of many possible thresholds which would render high dimensional unfeasable.

We would like to thank the reviewer pointing us to our claim at 5.10. which might be suspect to missunderstanding. Our intention was not to state that the traditional threshold approach itself is problematic. We wanted to state that the underlying assumption (equal distribution of extreme events among all grid cells) is most likely not met for short time series (here: 11 years). A 10% threshold in a 10 year time series would seelct one extreme year in each grid cell (not more, not less). There are regions where extremes events occur more often or are longer than one year, e.g., California (Griffin, D., and K. J. Anchukaitis, 2014 , GRL) or where by chance no extreme event at all is occuring in the given time frame. Our spatiotemporal segmentation is addressing this issue by choosing thresholds over larger areas with compareable climate and phenology. As a request also from Reviewer#1 we will completely revise the section 2.2 including a new schematic figure for the spatiotemporal extraction. In this process, we will rephrase the given part above, which is suspect to missunderstanding. Furthermore, we will justify complicated analytical choices as suggested by the reviewer, remove unneccessary parts (global thresholds, local thresholds), merge it with the information in S1, and avoid jargon whenever possible.

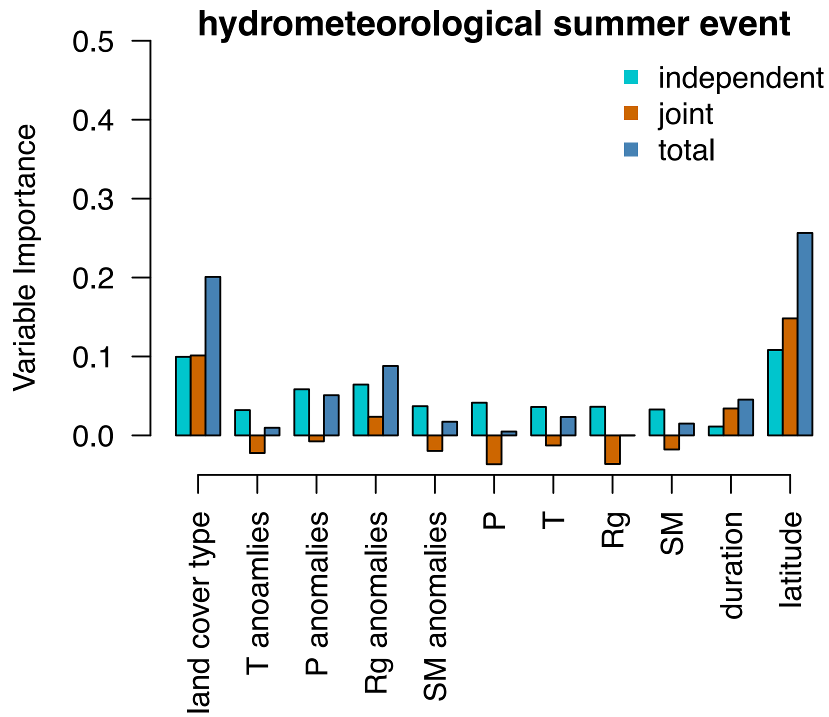
4. Model of factors explaining the GPP response. This section (S3), which is referred to in the main, but relegated to the Supplemental could be better emphasized and explained. For example, the factors in the hierarchical modeling approach are not independent. Are interaction variables used to address this issue? Given the confounding of latitude and temperature and land cover class, why not add latitude to the regression hierarchy to see its explanatory power, given the sentiment at 12.3?

Response: We would like to thank the reviewer for his interest in the Section S3 and agree that the section can be much better emphasized and explained. We will carefully revise the section and introduce more information in the main manuscript on 12.1. The factors in the hierarchical modeling approach are indeed not independent. However, the hierarchical partitioning after Chevan and Sutherland (1991), is exactly made for this kind of issues. The method extracts the independent contribution of interacting variables.

We would also like to thank the reviewer for the idea to extent the regression model with the factor latitude. Indeed, latitude has a very high independent explanatory power (Figure below) which is comparable to the importance of land cover type in summertime. The high independent explanatory power indicates that latitude provides additional information, which is not already contained in the other factors (e.g., land cover type or absolute temperatures). In particular access to deeper water (and soil type) might be factors not contained in the model, but also changing with latitude and therefore possibly explaining the importance of latitude. Apart from including more information about the method, we will include more information on S3 in the main manuscript and the new results in section 3.3 with the following paragraph and reformulate other sections if necessary:

"To disentangle the variable importance of the different confounding factors, we run a simple linear regression model which tries to explain GPP as function of the hydrometeorological driver variables (temperature, precipitation, radiation, surface moisture, anomalies and absolute values), as well as vegetation type, duration and latitude (Supplementary S3). We use an algorithm after \citet{Chevan:1991wg} which extracts the independent contribution of the variable importance related to this particular variable regardless of the model complexity or dependencies among variables.

The model reveals from a statistical point of view, that vegetation type and the latitudinal gradient are the most important variables explaining GPP during the summer event, followed by the hydrometeorological drivers. Access to deeper water and soil type as well as non-linear feedbacks are factors which are not represented in the model, but might explain the high variable importance of latitude.“



5. Attribution to uWUE differences. The authors attribute the reduced GPP declines during the summer event of forests in part due to the uWUE. Certainly this has a role to play. One could also imagine uWUE being an explanatory variable in the model presented in section S3 as well–could the authors add that? It seems like the authors are positioned to better attribute whether it was the absolute magnitude of the temperature itself (which diminished as a function of latitude) or something innate to the land cover classes (and their underlying WUE), which just so happens to vary as a function of latitude. The model seems like an ideal place to disassociate these factors.

*Response: In general we like the idea to add uWUE as a explanatory variable in the model. However, uWUE is defined as GPP * VPD^0.5 / ET. Thus adding uWUE as factor to the model* *would be somehow circular, as the target variable (GPP) is contained in the possible factor uWUE. Thus, we think adding uWUE would be inappropriate from a statistical point of view.*

Regarding the spring event and soil moisture depletion carry-over effects under forcing discussed at 12.22-13.6, Mankin et al., Journal of Climate 2017 and Mankin et al. GRL 2018 note that increased productivity is associated with such carry over effects in some of the models, regionally and globally under forcing.

We would like to thank the reviewer for the two additional references which we found very interesting. We will add the references to the discussion about soil moisture carry over effects.

Minor comments:

11.5: I don't understand the soil moisture in Fig. 7. Is it the normalized measure? Is it the m3/m3? Can the authors add contours if the forests separate by latitude in 7b?

Response: It is m3/m3.

Grammar/spelling throughout could be improved.

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

1.16: (e.g., a vegetation index)

Response: The sentence will be removed to address major comment 1)

inconsistency in comma usage after e.g. and i.e.

Response: Will be checked for consistency

2.29: not sure the name is "heat summer"

Response: changed into "European heatwave 2003"

2.32: a, not an hydrometeorological

Response: Will be changed

5.8: grammar (“in high”)

Response: Will be corrected

5.4: Why not leave them as missing data?

Response: We would like to thank the reviewer for this comment. Indeed, it would be an option to leave the data as missing in case all variables are missing at one observation, excluding the observation from the multivariate detection. However, in comparison to univariate event detection, our multivariate algorithm requires that all variables are available. Thus, there are many more missing instances, i.e., cases which have only one of the variables missing, all others are available. We will add the following sentence on that:

“The gap filling is necessary for a multivariate detection approach as there are many more cases in which one variable is missing in the multivariate cube compared to a univariate data stream.“

21.32 “spatiotemporal” not “. . .temporla”

Response: Will be corrected

Author contributions: “wrote” not “ote"

Response: Will be corrected