Supporting Information for "Vegetation modulates the impact of climate extremes on gross primary production" by Flach et. al.

Case Studies

To illustrate the range of relative drought and heat anomalies, we report on different high and low impact extreme events in our data base in the following.

Case Study: European Heatwave 2003

The European heatwave 2003 (classified here as compounding drought and heatwave) started in April, peaked on the 14th of July and finished in September with a maximal duration of 104 days (Figure 1). The affected volume was $33 \cdot 10^6$ km^2d. Total reduction in GPP is estimated here as -11 gC $m^{-2}month^{-1}$, which is less than reported in (Ciais et al. 2005) (-28 gC $m^{-2}month^{-1}$). Differences can be seen especially for forested ecosystems in the low mountain ranges (Vosges, Thuringian Forests, Black Forest, Ardennes, Rhenish Massif, Taunus) and a larger area with enhanced productivity around the Alps (Figure 1). Comparing our results with eddy covariance site level data (Ciais et al. 2005, Reichstein et al. 2007) from literature reveals that site level data and Fluxcom-RS agree on the direction of the GPP anomalies for DE-Hai (both negative), FR-Hes (both negative), FR-Lbr (both positive), and disagree for BE-Vie, DE-Tha (both positive by FLUXCOM-RS, negative at the tower site).

Case Study: US drought and heatwave 2012

The US drought and heatwave in 2012 started in April, peaked on June, 29th, and ended mid October with a maximal duration of 144 days. The affected volume was $12 \cdot 10^6$ km^2d. Total reduction in GPP is estimated here as -15 gC $m^{-2}month^{-1}$. However, on average forests increase their productivity by 13% (22 gC $m^{-2}month^{-1}$). The one common affected tower site from literature (US-MMS) (Wolf et al. 2016) is in agreement with FLUXCOM-RS (both agree on a negative impact) (Figure 2).

Case Study: Russian Heatwave 2010

The Russian heatwave 2010 is one of the most impacting events in our data base (Fig. 3, classified here as compounding drought and heatwave).

It started in June, peaked on July, 19th, and ended in September with a maximal duration of 80 days. The affected volume was $87 \cdot 10^6$ km^2d. The total reduction in GPP is estimated here as 72 TgC, roughly comparable to (Bastos et al. 2014) (90 TgC). We estimated losses in agricultural ecosystems to be 22% compared to the normal GPP average, which is comparable e.g. to estimates from (Wegren 2010) (grain harvest reduction of one third). However, we also estimate forests to enhance their productivity by 5% during the event. We could not find eddy covariance tower based estimates of carbon losses in literature.

Case Study: European heatwave 2018

The summer drought and heatwave in Mid-Europe 2018 started in June, peaked on July, 24th and lasted until August (Fig. 4). It was associated with a relative reduction in GPP by 10 % (6%) in agricultural (other) ecosystems. However, forests on average still are still productive as usual (± 0 %). These differences between forests and agricultural ecosystems are also reported in (Buras et al. 2019).

Case Study: Drought in Brazil 2012

The drought in Brazil 2012 is another high impact event in our data base (Fig. 5). It started in April, peaked on May, 2nd, and lasted until September, with a maximum duration of 136 days. The affected volume was $24 \cdot 10^6$ km^2d. Total reduction in carbon is estimated to be -36 TgC. We are not aware of any tower or model based comparison of this number. The affected area is in agreement with maps published in (Marengo et al. 2013).

Case Study: Horn of Africa 2009

The drought at the greater Horn of Africa 2009 (Fig. 6 is classified here as compounding drought and heatwave). It started in July, peaked on August, 14th, and lasted until September. The affected volume was $23 \cdot 10^6$ km^2d. Total reduction in GPP is estimated to be 20 TgC. There have been no eddy covariance towers in the affected region 2009, but the event is also reported in (Nicholson 2014).

Case Study: Indian heatwave 2009

The Indian heatwave 2009 is one of the least impacting (most enhanced GPP) events in our data base (Fig. 7). It started in May, peaked at August, 1st. and lasted until September. The affected volume of the event is $45 \cdot 10^6$ km^2d. The peak of the event is 53 days before peak of the growing season. Although it is classified as a relative drought and heatwave, there is still water available for large areas during the event (Fig. 7 (d), 25%, mean surface moisture during event). The conditions are associated with increased productivity by 6 % (12%) in agricultural (forest) ecosystems and enhances total GPP by 13 TgC compared to the other years. The event presents the strongest enhancement of GPP of a single event in our data base. We can find warnings related to drought reduced agricultural yields in literature (Neena et al. 2011). However, the Organisation for Economic Co-operation and Development (OECD) reports a 4% increase in the wheat production for India 2009 (OECD 2009).

Case Study: Siberian heatwave 2011

The Siberian heatwave in 2011 another example of the least impacting event in our data base (Fig. 8). It starts in May, peaks on June, 1st. and lasts until the end of June. The affected volume is $31 \cdot 10^6$ km^2d. The peak of the heatwave is 41 days before peak growing season and it is has a maximum duration of 40 days, but shows a rather short duration for large parts of the event (Fig. 8). Water seems to be available during the heatwave (27%, mean surface moisture during event). These conditions are associated with an enhancement of GPP by 34 % (29 %) in forests (other) ecosystems (43 TgC) in other ecosystems. The event illustrates that a relative detection of drought and heat anomalies also includes events which are not severely affecting vegetation but can be beneficial for vegetation especially in Northern latitudes for which temperature and surface moisture conditions are still moderate.

Case Study: China drought 2011

The drought (and heatwave) in Southern China 2011 is one of the events in our data base (Fig. 9) showing strong differences among a East-West gradient. It starts in July 2006, peaks on August, 21th and lasts until September. The affected volume is $38 \cdot 10^6$ km^2d. Maximum duration is 72 days, 31 days after peak growing season. Eastern agricultural (-7 TgC) areas are strongly affected by the event in contrast to other ecosystems (+7 TgC) in the western parts of the affected area. These dipole-like structures can also be seen in maps of mean temperature and surface moisture during the event. Forests are partly associated with enhanced productivity, especially in regions with high temperatures and available surface moisture. This is interpreted as a positive reaction to the available radiation during the heatwave part of the event (Song et al. 2019).

East Europe 2015

The summer drought and heatwave affecting Europe with a focus on East Europe in 2015 started in June, peaked on August, 2nd and lasted until September. It was relatively short lasting for most of the affected area (< 20 days), and probably therefore affecting productivity not so strongly (Total impact: -0.5 TgC agriculture, +5 TgC forests), although the affected volume was comparable to other high-impact extreme events ($21 \cdot 10^6$ km^2d).

Amazon 2010

The Amazon drought 2010 is one of the well-known high-impact events of the last decade. It is classified here as a compounding drought and heatwave. It started in October 2009, peaked on January, 25th and lasts until March with a maximal duration of 184 days. It affected both, forests, and other ecosystems which reduced GPP by 7%, 9% respectively. The affected volume ($107 \cdot 10^6$ km^2d) is among the highest in our data base (Fig. 11).

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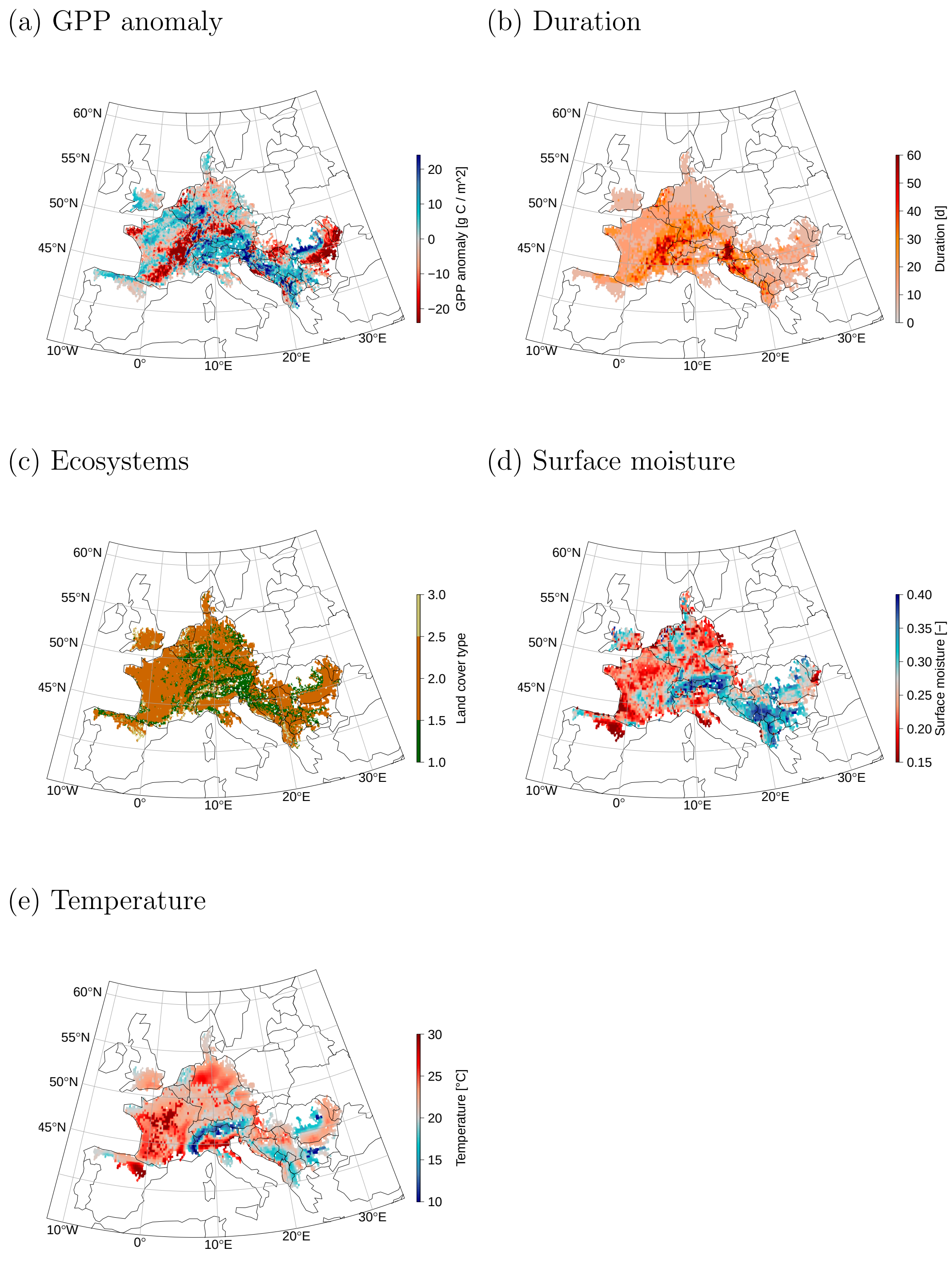


Figure 1: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the European heatwave 2003.

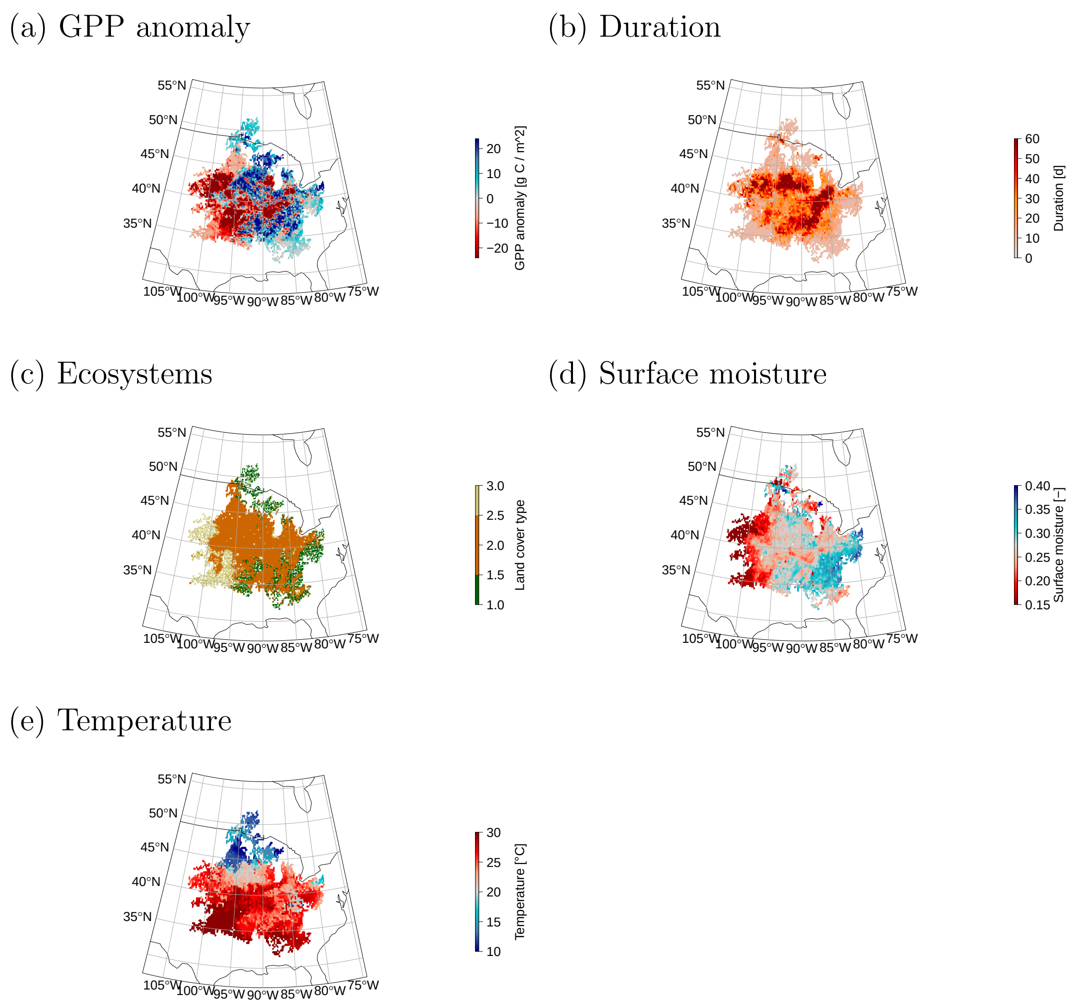


Figure 2: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the US 2012 drought and heatwave.

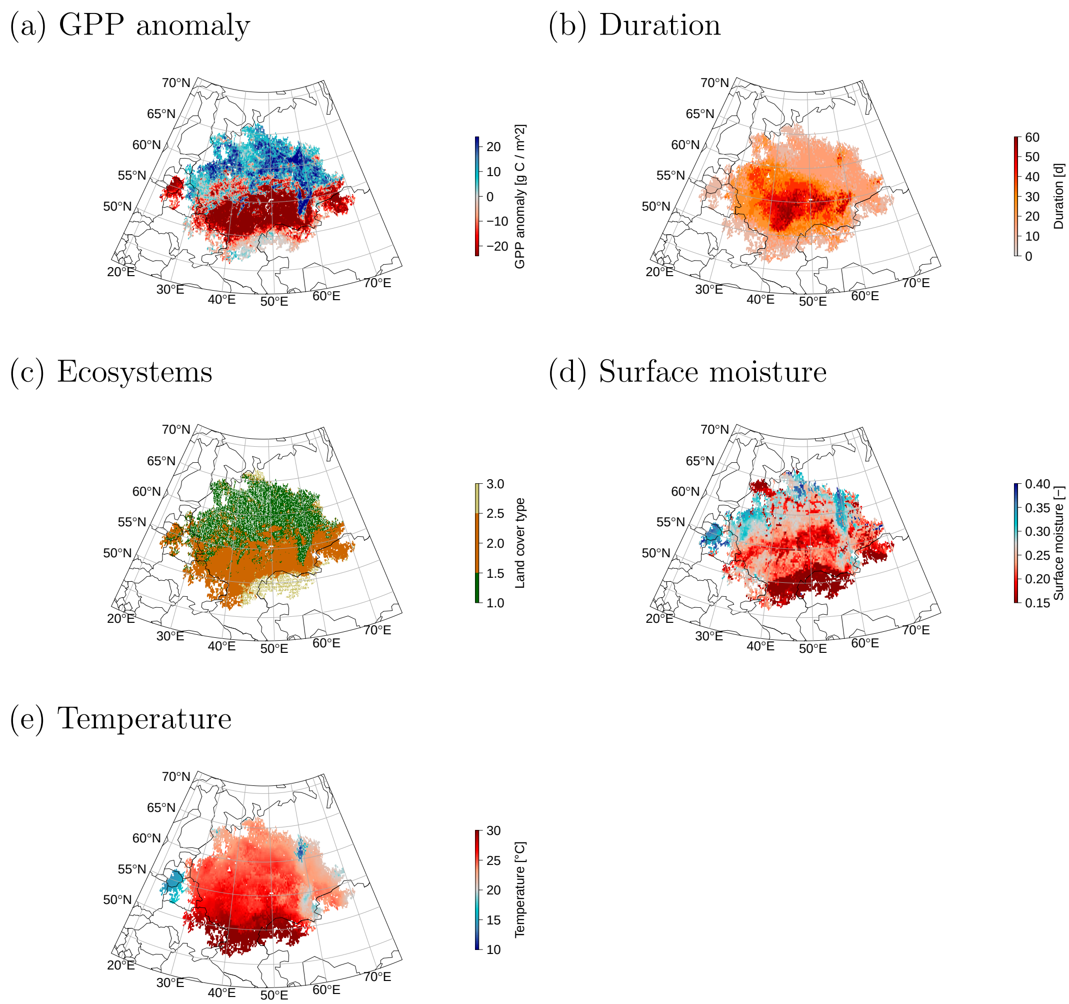


Figure 3: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the Russian heatwave 2010.

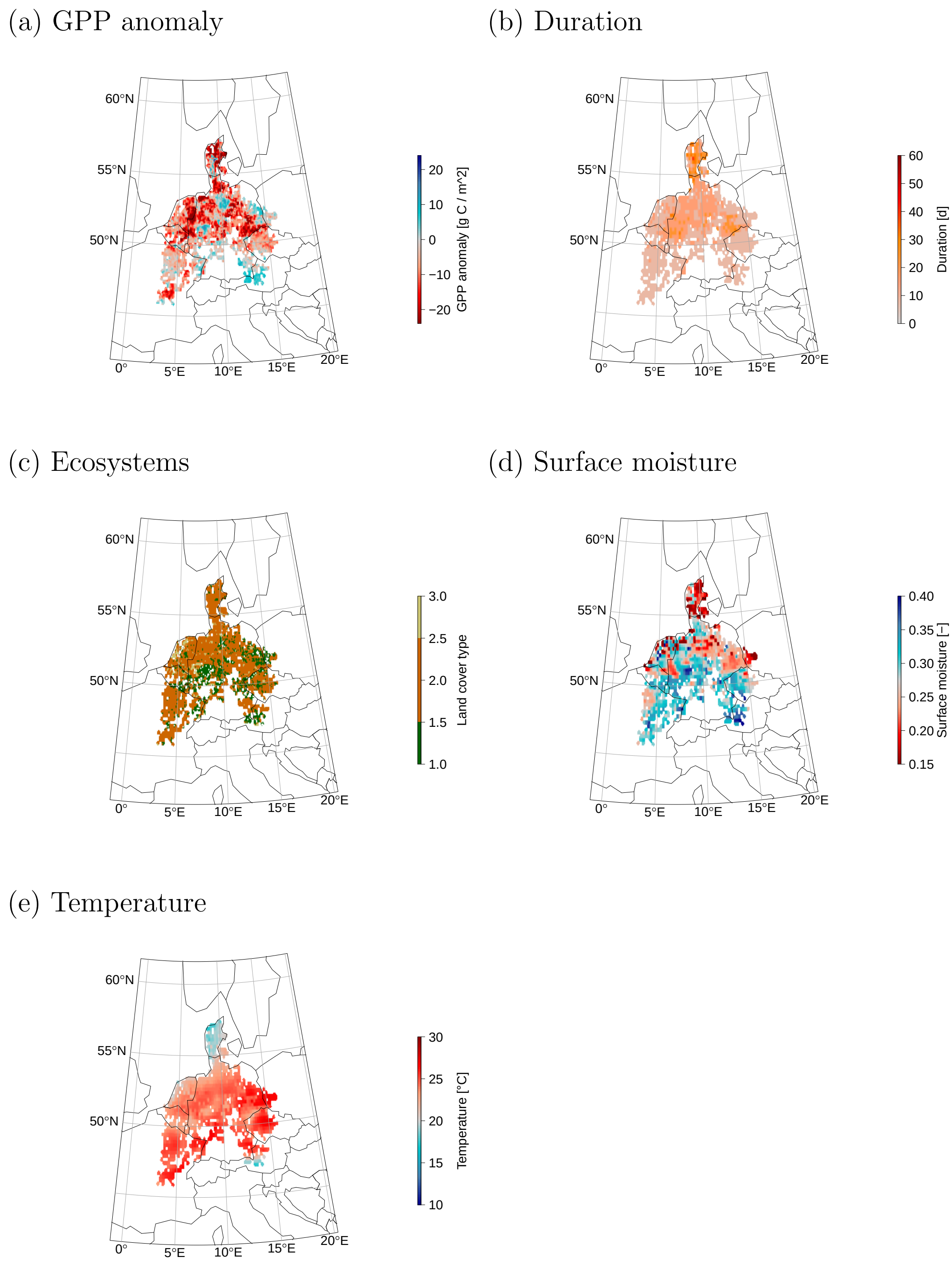
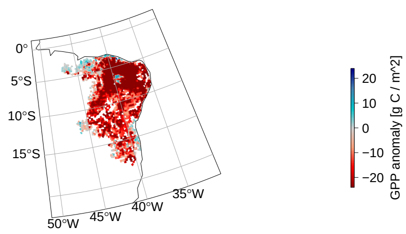
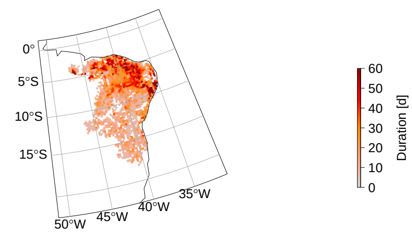


Figure 4: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the European heatwave 2018.

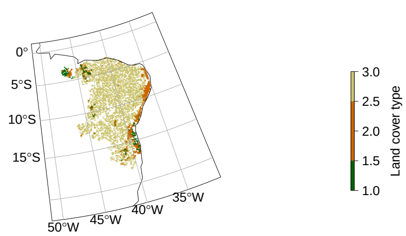
(a) GPP anomaly



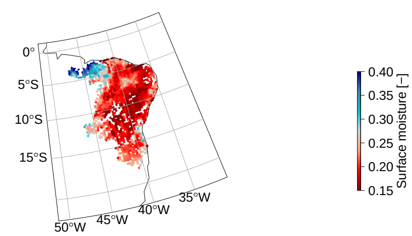
(b) Duration



(c) Ecosystems



(d) Surface moisture



(e) Temperature

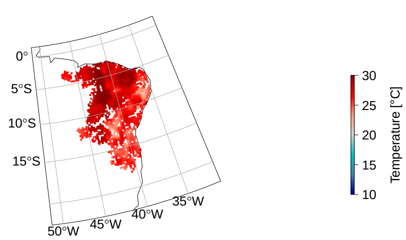
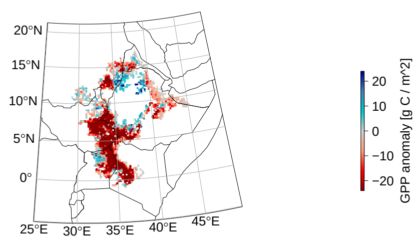
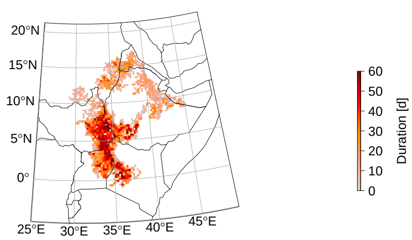


Figure 5: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the drought in Brazil 2012.

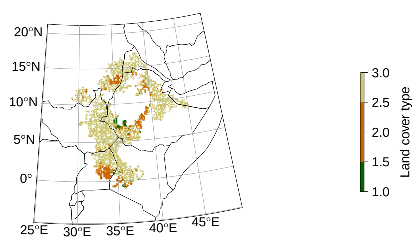
(a) GPP anomaly



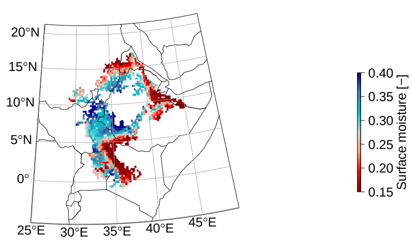
(b) Duration



(c) Ecosystems



(d) Surface moisture



(e) Temperature

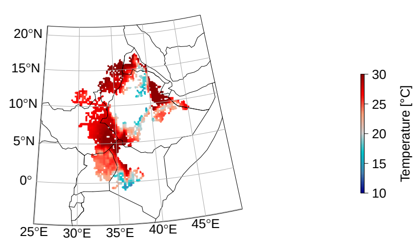


Figure 6: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the drought at the greater Horn of Africa 2009.

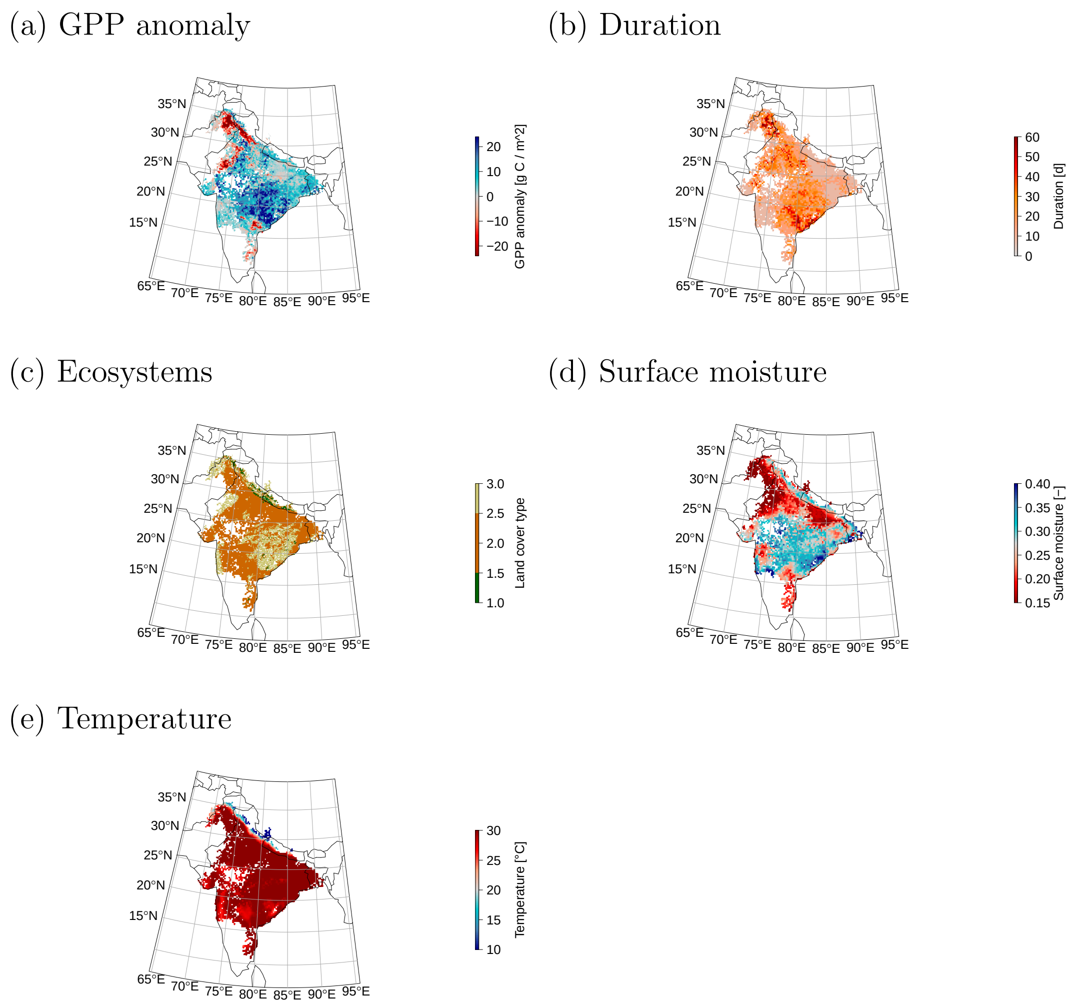


Figure 7: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the Indian heatwave 2009.

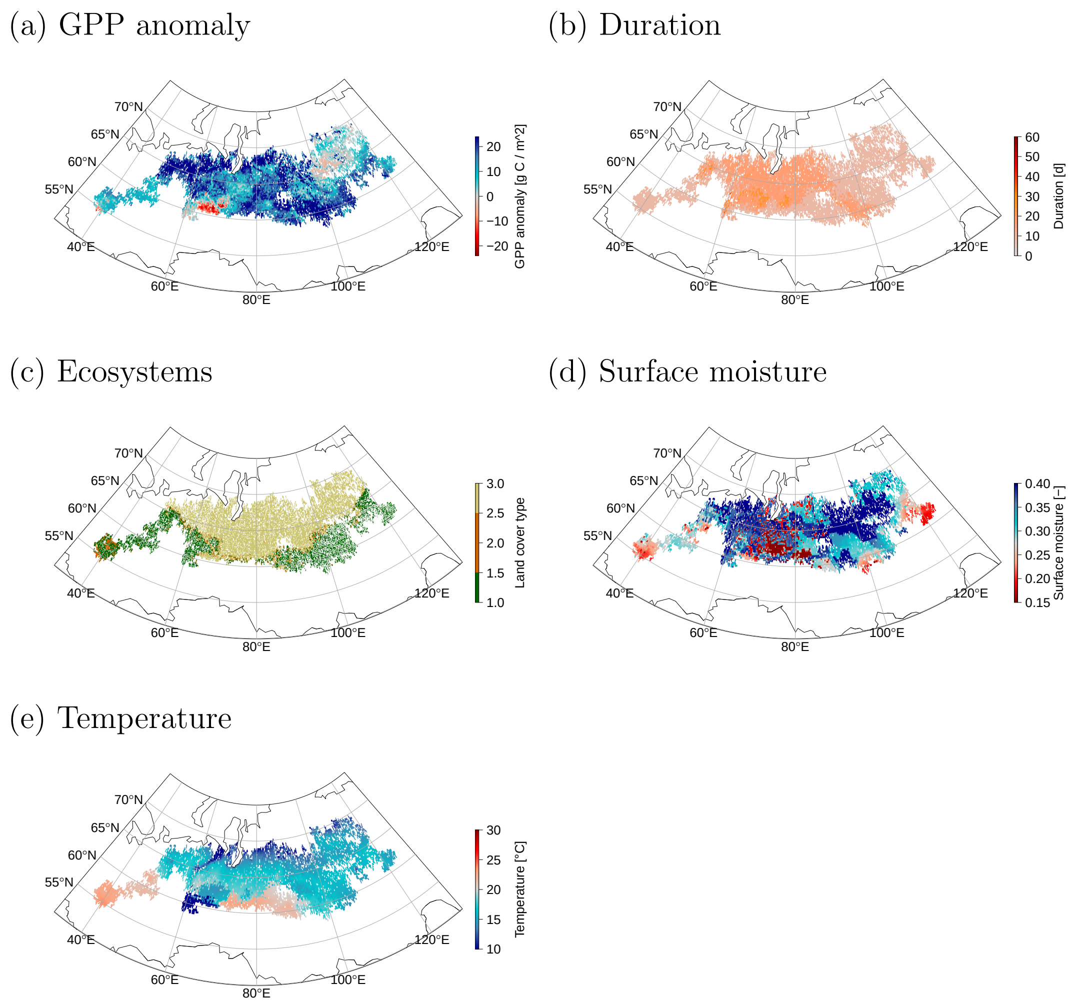


Figure 8: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the Siberian heatwave 2011.

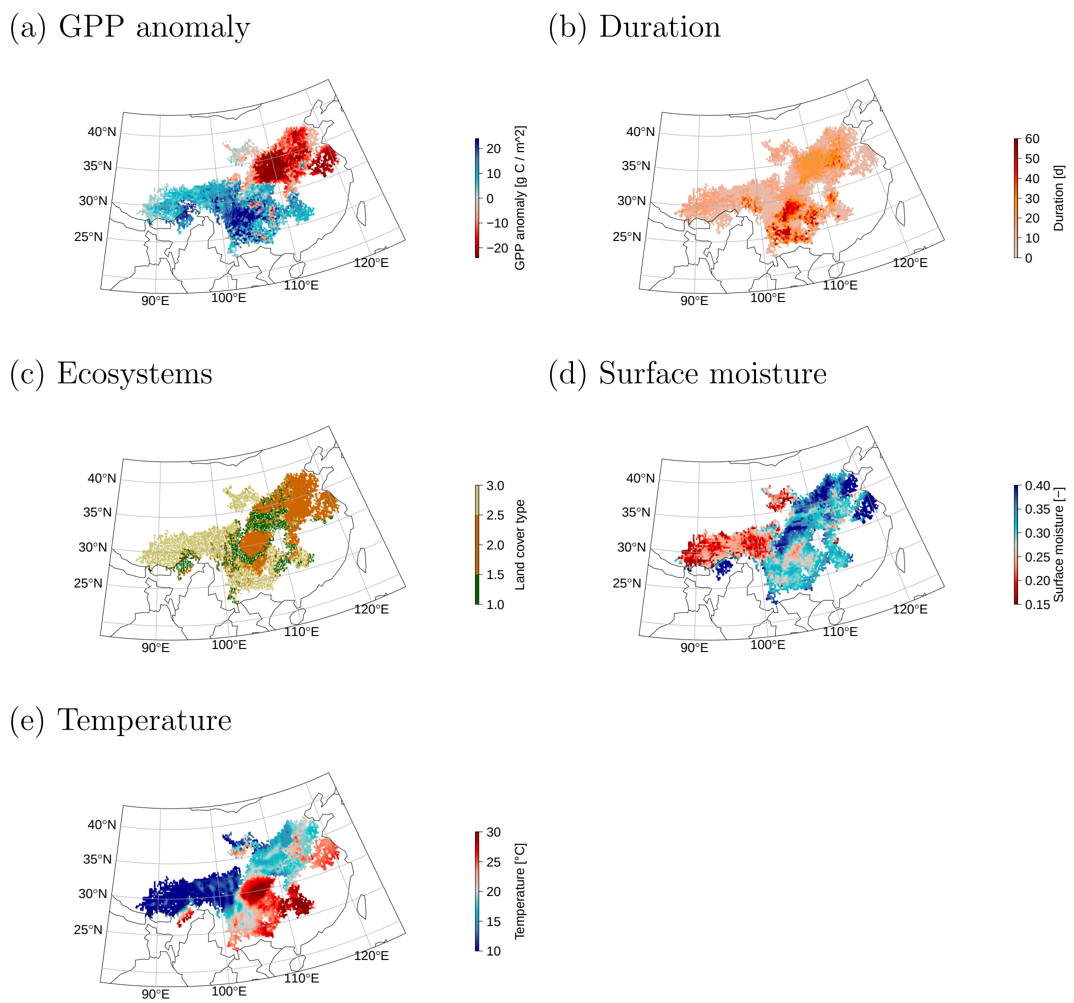


Figure 9: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the China drought 2011.

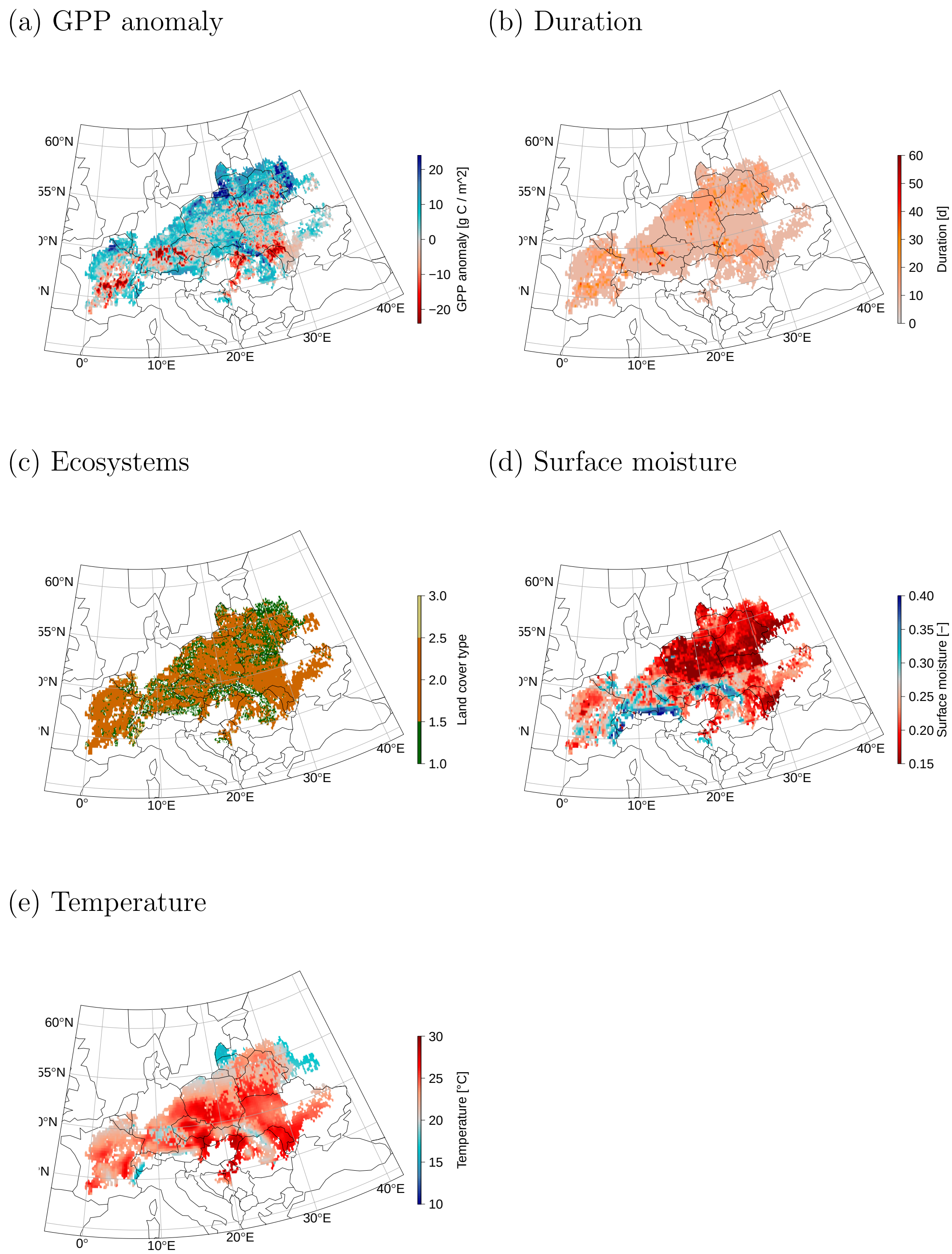


Figure 10: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the Drought and heatwave in East Europe 2015.

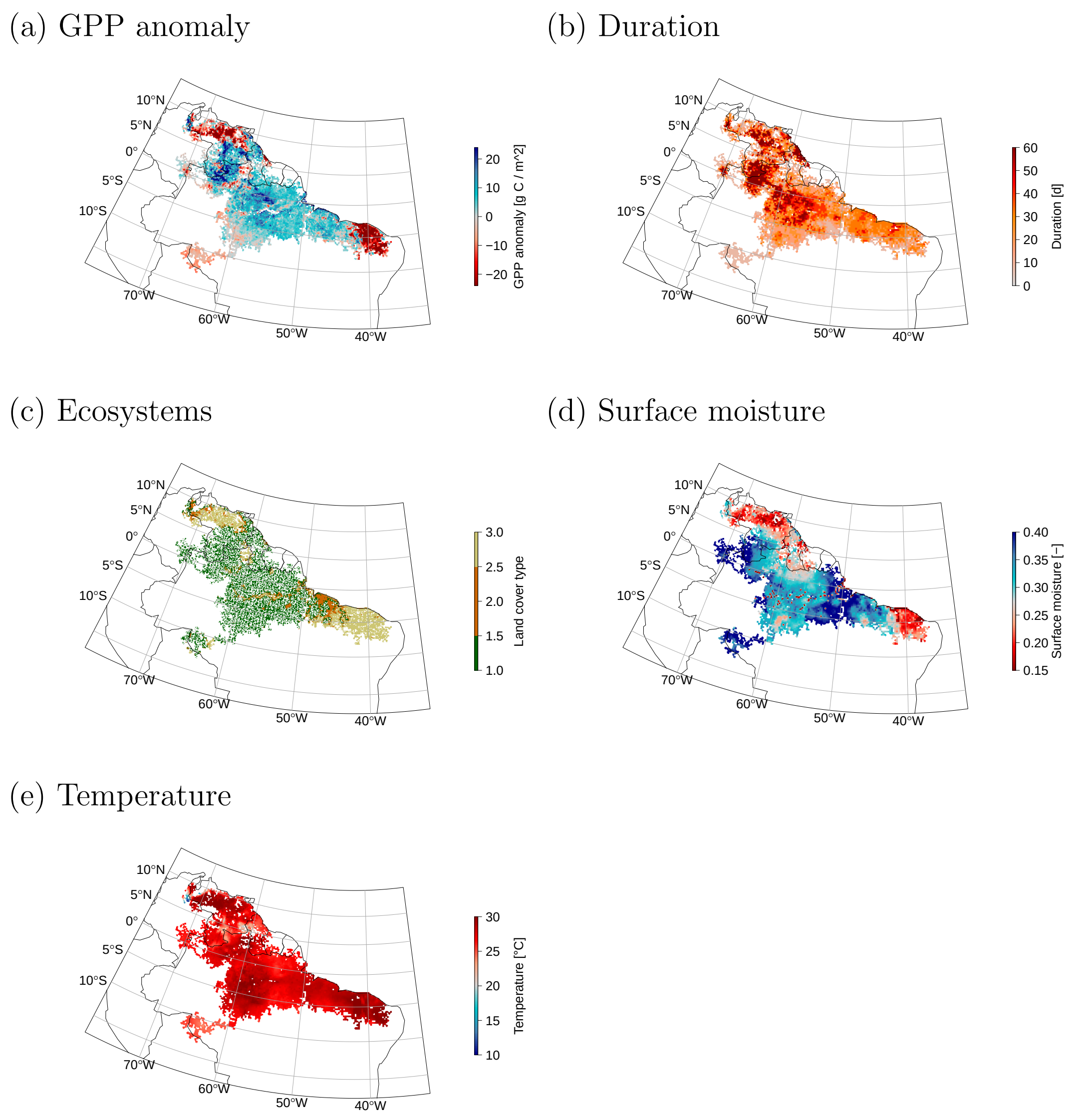


Figure 11: (a) Impact on GPP anomalies, (b) duration, (c) affected ecosystem types, (d) surface moisture conditions, and (e) temperature conditions associated with the Amazon drought 2010.