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Comparing the impacts of 2003 and 2010 heatwaves in NPP over Europe

A. Bastos [1], C. M. Gouveia[1,2], R. M. Trigo[1,2], and S. W. Running[1,3]

[1]Instituto Dom Luiz, Universidade de Lisboa, Lisboa, Portugal
[2]Universidade Lusófona, Lisboa, Portugal
[3]Numerical Terradynamic Simulation Group, University of Montana, Missoula, MT, USA

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Correspondence to: A. Bastos (afbastos@fc.ul.pt)

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Abstract

In the last decade, Europe was stricken by two outstanding heatwaves, the 2003 event in Western Europe and the recent 2010 episode over Russia. Both extreme events were characterised by record-breaking temperatures, and widespread socio-economic impacts, including significant increments on mortality rates, decreases in crop production and in hydroelectric production. This work aims to assess the influence of both mega-heatwaves on vegetation carbon uptake, using yearly Net Primary Production (NPP) and monthly Net Photosynthesis (PsN) data derived from satellite imagery obtained from MODIS for the period 2000–2011.

In 2010, markedly low productivity was observed over a very large area in Russia, at monthly, seasonal and yearly scales, falling below 50 % of average NPP. This decrease in NPP in 2010 was far more intense than the one affecting Western Europe in 2003, which corresponded to 20–30 % of the average, and affected a much larger extent. Total NPP anomalies reached −19 Tg C for the selected regions in France during 2003 and −94 Tg C for western Russia in 2010, which corresponds almost to the magnitude of total NPP anomaly during 2010 for the whole Europe.

Overall, the widespread negative PsN anomalies in both regions match the patterns of very high temperature values preceded by a long period of below-average precipitation, leading to strong soil moisture deficits, stressing the role of soil-atmosphere coupling. In the case of 2003 heatwave, results indicate a strong influence of moisture deficits coupled with high temperatures in the response of vegetation, while for the 2010 event very high temperatures appear to be the main driver of very low NPP.

1 Introduction

Heatwaves in Europe are expected to become more frequent, intense and long lasting, mostly due to the increase in mean summer temperature and corresponding variability (Luterbacher et al., 2004; Meehl and Tebaldi, 2004; Fischer and Schär, 2010). The first decade of the 21st century in Europe was particularly prone to extremely warm events (Coumou and Rahmstorf, 2012). Thus, besides the warm summers of 2002, 2006 and 2007, this decade registered two extreme events in magnitude, spatial extent and duration, the so called mega-heatwaves in 2003 and 2010 (Barriopedro et al., 2011).

In 2003, Europe registered the warmest summer in 500 yr, with record-breaking temperatures being reached at the daily, weekly and monthly scales in western and central Europe. In large sectors of France and the Iberian Peninsula, daily maximum temperatures were between 7.5 °C and 12.5 °C above the 1961–1990 average for several weeks (Luterbacher et al., 2004; Trigo et al., 2005; García-Herrera et al., 2010). According to several authors this event was so extreme in central Europe that it fell completely outside the range of any extreme episodes observed before, even for stations with more than 100 yr of daily data (Schär et al., 2004). In this regard despite the intrinsic difficulties in computing robust return periods for such an event, the 2003 was considered extremely rare and with a low probability of occurring again in a near future (Schär et al., 2004).

Yet in 2010, Europe was stricken by an even warmer summer, with a very large extent over western Russia registering temperatures 4 standard deviations above the reference mean for a wide range of temporal aggregations (weekly, monthly, seasonal). Barriopedro et al. (2011) have shown that the 2010 heatwave affected a much larger extent and was far more intense than the 2003 event, with record-breaking area of about 2 million km^2 against about 1 million km^2 in central Europe in 2003. These heatwaves were responsible for a significant increase of human mortality, unusual large fires and widespread impacts in ecosystems and crop yields (Trigo et al., 2005; García-Herrera et al., 2010; Barriopedro et al., 2011).

Several works have stressed the role of land-atmosphere coupling, particularly soil-moisture feedbacks, in climate variability and extremes in Europe (Seneviratne et al., 2006; Hirschi et al., 2011). Both 2003 and 2010 heatwaves were associated with persistent anti-cyclonic conditions from late spring to summer and with precipitation deficits

BGD
10, 15879–15911, 2013

from late winter until August. The latter, combined with increased radiation flux during late winter and spring, contributed to a rapid reduction in soil moisture through enhanced evaporation and led to persistent drought conditions. Low precipitation and soil moisture deficits during summer amplified the high temperatures reached during the heatwaves, as the reduction in evaporation was compensated by an increase in sensible heat flux (Ferranti and Viterbo, 2006; Fischer et al., 2007; García-Herrera et al., 2010; Barriopedro et al., 2011).

The enhancement in carbon uptake by ecosystems observed in past decades, particularly in Europe, has been attributed to increased atmospheric CO_2 concentration and warmer springs (Zhou et al., 2001; Nemani et al., 2003; Menzel et al., 2006; Le Quéré et al., 2009; de Jong et al., 2013). However, several studies have pointed that these effects may be offset in the future due to different mechanims such as: (a) temperature increase in other seasons (Piao et al., 2008); (b) higher temperature variability or climate extremes (Heimann and Reichstein, 2008; Zhao and Running, 2010; Schwalm et al., 2012); and (c) changes in precipitation regimes (Angert et al., 2005). For instance, Ciais et al. (2005) estimated the 2003 heatwave to have reverted the equivalent of four years of net carbon uptake by European ecosystems. Additionally, Gouveia et al. (2008) found a reverse response of vegetation activity to increases in temperature during spring or summer in northern Europe while Peng et al. (2013) have stressed the assymetric effect of changes in minimum and maximum temperatures. Given the existing feedbacks between land and atmosphere and the importance of the land CO_2 sink in the global carbon budget (Ballantyne et al., 2012), reducing uncertainties about the future behavior of ecosystems is particularly relevant for earth system science (Meir et al., 2006; Friedlingstein and Prentice, 2010; Reichstein et al., 2013).

Understanding the role of climate extremes on ecosystems is, thus, of great interest, particularly in Europe, where ecosystems remove 7–12 % of the corresponding anthropogenic CO_2 emissions and constitute one of the most important global CO_2 forest sinks (Janssens et al., 2003; Pan et al., 2011). However, we must acknowledge that the link between climatic and ecosystem extremes is not always so straightforward

BGD
10, 15879–15911, 2013

to establish as it may be anticipated within the climate community. Smith (2011) has brought attention to the fact that the extremeness of a climatic event may not always translate into an extreme ecological response (Kreyling et al., 2008; Jentsch et al., 2011). Considering these limitations Smith (2011) proposed a framework to analyse the ecological impact of a climatic extreme that requires an extreme ecosystem response to be observed and attributable to the period of the extreme climatic event. Zscheischler et al. (2013) have also stressed the importance of spacio-temporal analysis to attribute biospheric responses to extreme climatic events. This work aims to (i) perform a spatio-temporal analysis and comparison of the impact of the 2003 and 2010 mega-heatwaves on carbon uptake by ecosystems; (ii) assess how exceptional was the response of ecosystems to both heatwaves and; (iii) identify the physical variables driving ecosystems' dynamics.

2 Data

2.1 NPP data

The work relies extensively on the improved C5 MOD 17 datasets which are derived from the MODIS-NPP algorithm (Running et al., 2004) using daily meteorological data from the NCEP/DOE II Reanalyzes as described in Zhao and Running (2010) and Zhao et al. (2006).This collection is an improvement of the C4 MOD17 data as described in Zhao et al. (2005), having lower uncertainties due to corrections in the meteorological inputs, in the quality control of the input radiometric data as well as a recalibration of the biome parameters. MOD17 products have been shown to reproduce seasonal and inter-annual variability across a wide variety of biomes, especially in sub-tropical to polar latitudes (Running et al., 2004; Mu et al., 2007; Schubert et al., 2012; Hasenauer et al., 2012; Frazier et al., 2013) and to capture the impact of the 2003 heatwave in Europe (Reichstein et al., 2007).

For annual NPP analysis, MOD17A3 annual global NPP dataset was used, while for the seasonal analysis the work relied on MOD17A2 monthly Net Photosynthesis (PsN) dataset. PsN corresponds to the difference between Gross Primary Production and maintenance respiration in leaves and fine roots. Growth and woody tissues respiration are only subtracted by the end of year to compute annual NPP (Running et al., 2004). Despite lacking growth and woody respiration terms, PsN provides useful information about the seasonal behaviour of carbon uptake by ecosystems.

Both NPP and PsN datasets are provided at 1 km spatial resolution and were selected for a 12 yr period spanning from 2000 to 2011, over a region covering Europe, between 34.6° N and 73.5° N and 12.1° W and 46.8° E. Annual NPP and monthly PsN anomaly fields (hereafter NPP_{anom} and PsN_{anom}, respectively) were computed as the annual departure from the corresponding long-term average in the study period. Yearly NPP_{anom} was also computed as percentage of average, defined as the median of the 12 yr period from 2000–2011 excluding the extreme year under consideration (i.e., either 2003 or 2010), to avoid the bias effect on the average of the extremely low values registered during the heatwaves.

2.2 Land-cover data

Land-cover was assessed by Global Land Cover 2000 (GLC2000) dataset, provided by the Global Environment Monitoring Unit of the European Commission Joint Research Centre (http://bioval.jrc.ec.europa.eu). The use of GLC2000 instead of the following land-cover product GLOBCOVER (2005–2006) was due to the impact of the 2003 event in several biomes in Western Europe, therefore potentially conducting to misleading conclusions over that part. GLC2000 makes use of a dataset of 14 months of pre-processed daily global data acquired by the VEGETATION instrument on board the SPOT 4 satellite, and information is stratified into 22 classes of land-cover. GLC2000 data are provided at 1 km spatial resolution and were selected over the study region, i.e. from 34.6° N and 73.5° N and 12.1° W to 46.8° E. Six land-cover types were selected, corresponding to the main types in both regions stricken by the heatwaves,

BGD
10, 15879–15911, 2013
Impacts of 2003 and 2010 heatwaves in NPP
A. Bastos et al.

being referred to as: BLd (broad-leaved deciduous); NLe (needle-leaved evergreen); ML (mixed leaved); H (herbaceous); C/M (cultivated/managed); MCS (mosaic cropland and shrub).

2.3 Climate data

Monthly fields of average temperature at 2 m (T), average snow depth (SD) and volumetric soil water (SW) at four different levels (1 to 4), 0–7 cm, 7–28 cm, 28–100 cm and 100–289 cm, as in Balsamo et al., 2009), were extracted from ERA-Interim reanalyses (Dee et al., 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF). Data are organized on a regular grid at 0.75° spatial resolution over a region extending from 34.5° to 75° N and −13.5° W to 48° E and were selected for the study period 2000–2011.

Precipitation data was extracted from the Global Precipitation Climatology Centre (GPCC) monitoring product which is based in near-real time rain gauge observations and provides monthly mean global precipitation (P) fields at 1° spatial resolution (Rudolf and Schneider, 2005) and data were selected on a region between 34° to 74° N and −12° W to 47° E, between 2000 and 2011. Monthly anomalies were computed for each climate variable after removing the seasonal cycle, and are henceforth indicated as $\text{VARIABLE}_{\text{anom}}$.

3 Results

3.1 Impact on annual NPP

Total NPP anomaly over the 12 yr period was integrated for the whole Europe as well as separately for the western (longitude < 25° E) and eastern (longitude ≥ 25° E) sectors, as shown in Fig. 1a. The years 2003 and 2010 correspond to the minimum values over the period, with very low NPP anomalies (∼ −100 Tg C in both years) at the European

BGD
10, 15879–15911, 2013

scale, due to strong anomalies in Western Europe, in 2003, and in the eastern sector, for 2010.

NPP_{anom} fields for the two years (Fig. 1b) provide a better representation of the spatial variability of such low anomalies. In 2003 widespread negative anomalies were observed throughout most of Europe, with a region over southern and central France achieving anomalies lower than $-0.2\,kg\,C\,m^{-2}\,yr^{-1}$. Northern Scandinavia, UK and Ireland and western Russia registered positive, although low, anomalies. On the contrary, in 2010 it is possible to observe a large extent in western Russia with very low anomalies (below $-0.2\,kg\,C\,m^{-2}\,yr^{-1}$) while vegetation activity over most of Western Europe was close to average or even higher (Iberia, the Balkans and the area around the Black sea). The two regions with anomalies below $-0.2\,kg\,C\,m^{-2}\,yr^{-1}$ in 2003 and 2010 correspond roughly to the centers of the highest temperature anomalies registered during the summer heatwaves in each year (García-Herrera et al., 2010; Barriopedro et al., 2011) and were accordingly selected (boxes in Fig. 1b) for the following analysis, being henceforth referred to as HW03 and HW10. HW03 covers an area of $102\,000\,km^2$, while HW10 covers a much larger extent, of about $660\,000\,km^2$. Average NPP_{anom} over HW03 was $-0.19\,kg\,C\,m^{-2}\,yr^{-1}$, slightly higher than the value in HW10 ($-0.14\,kg\,C\,m^{-2}\,yr^{-1}$), however when integrating over the area, total NPP_{anom} in HW03 was -19 Tg C while in HW10 reached -94 Tg C, corresponding approximately toabout 85 % of total NPP anomaly during 2010 for the whole Europe.

When compared to the average productivity, anomalies in western Russia in 2010 were remarkably lower than the ones in France in 2003 (Fig. 1c). Although very similar in absolute magnitude, the anomalies in HW03 correspond to reductions of about 20 % of the average annual productivity while in 2010 NPP fell below 50 % (or less) of the average NPP over practically all of HW10. The 2010 heatwave in Russia appears, therefore, to have had a stronger impact on ecosystems than the 2003 event in France. However, the analysis of the annual fields does not provide a detailed assessment of the impacts of the heatwave events, which occurred during a few summer weeks. Following Smith (2011) and Zscheischler et al. (2013) a more comprehensive spatio-temporal analysis is required in order to assess if there was in fact an extreme ecological response to this climatic extreme, the amplitude of such extreme ecological event and, if it can be attributed to the referred heatwaves.

3.2 Impact on the seasonal cycle

The PsN seasonal cycle in 2003 and 2010 for the selected regions was compared to the corresponding climatology (Fig. 2a). Region HW03 presents a longer and more productive average seasonal cycle, reaching peak PsN values between 0.15 to 0.2 $\mathrm{kg\,C\,m^{-2}\,month^{-1}}$ while in HW10 vegetation is generally dormant from November until March and does not reach productivity values above 0.15 $\mathrm{kg\,C\,m^{-2}\,month^{-1}}$, explaining the differences in annual productivity mentioned previously. Moreover the range of PsN values – as expressed by the 10–90 % variability band – is also represented for both regions and is characterized by larger values during summer months.

During 2003, HW03 experienced lower than average PsN during most of winter and spring (Fig. 2a, bottom) although still inside the 10–90 % variability range over the study period (Fig. 2a, top). From May and until October, vegetation activity was exceptionally disturbed, in particular during the summer months (JJA), when remarkably low anomalies (below −0.05 $\mathrm{kg\,C\,m^{-2}\,month^{-1}}$) were reached. It should be emphasized that the HW03 reached the strongest magnitude in early August 2003, however it was preceded by an extremely warm month of June (García-Herrera et al., 2010; Barriopedro et al., 2011). In HW10, 2010 started as a relatively average year, with PsN within the 10–90 % percentiles (Fig. 2a, top) and slightly positive anomalies during the beginning of the growing season (April–May) (Fig. 2a, bottom). These were rapidly offset during summer, especially in July and August, when anomalies below −0.05 $\mathrm{kg\,C\,m^{-2}\,month^{-1}}$ were observed. It is worth noting that in both regions August was the month registering the largest departure from the 10–90 % range, coinciding with the strongest period of the heatwave events, which, in our view, confirms the existence of an extreme ecological response to the extreme climatic events.

BGD
10, 15879–15911, 2013

The impact on the seasonal cycle is also evident in the spatial assessment of the peak of productivity, shown in Fig. 2b. In 2003, large sectors of central Europe reveal an earlier peak, as is the case of western Russia in 2010. It is worth noting that the difference in the timing of PsN peak is not due to an actual shortening or phase change in the seasonal cycle, but rather to a suppression of vegetation activity during late spring and summer, when PsN usually peaks. An interesting feature is the opposite response (later PsN peak) observed in western Russia and Ukraine during 2003 and in France during 2010, suggesting the existence of a dipole driving vegetation response in these two regions.

Accumulated PsN was evaluated for both regions in the years corresponding to the heatwaves (Fig. 3a, coloured lines) and compared to the respective climatology (Fig. 3a, boxplots). As observed in the seasonal cycle, the cumulative balances of PsN in both regions start to depart from the median only by the end of spring and present much lower accumulation rates during summer, especially in August. In magnitude, the difference between the curves corresponding to the cumulative PsN in the year of the heatwave and the median is quite similar for both regions (about $0.25\,\mathrm{kg\,C\,m^{-2}}$), however, relative to the corresponding standard deviation, the impact of the heatwave on PsN in HW10 was slightly higher, reaching -2.8σ in August 2010, while in HW03 the departure in August 2003 was -2.4σ. Following summer, cumulative PsN curves for the two extreme years follow a similar trajectory as the respective climatologies, thus the negative balance is mainly due to the decrease in PsN rates during JJA.

The same analysis was performed for each of the main land-cover types (Fig. 3b) thus allowing to distinguish distinct behaviours. The three types of forests (BLd, NLe and ML), the most productive land-cover types together with herbaceous, were the ones being affected more severely, as given by the departure of PsN from the climatological range of variability.

In HW03 all forest types registered null or slightly negative PsN (i.e. turning into a source of CO_2) from July to August, while all the other land-cover types maintained low accumulation rates. Again, this evolution between July and August 2003 reflects to a certain extent the double nature of the 2003 heatwave in Western Europe with an early peak in June and a stronger one in August (García-Herrera et al., 2010; Barriopedro et al., 2011). Cultivated and managed areas were the ones with a weaker response to the heatwaves, which in the case of HW10 does not even fall outside the climatological variability range. This feature suggests either higher resistance of these ecosystems or the existence of human intervention, at least to some degree, in order to minimize the impacts of the heatwave.

Table 1 summarizes the land-cover composition of each region and the respective end-of-year balances of PsN relative to the median, over the total area and discriminated for the main land-cover types. The land-cover composition for the two boxes considered varies substantially. Thus the HW03 region is mainly composed by cultivated and managed areas (43 %), with forests representing 26 %, while the HW10 box presents a higher percentage of forests (almost 37 %) and about 30 % of cultivated and managed areas.

By the end of the year, the relative PsN balance was −0.23 kg C m^{-2}) for HW03 and −0.19 kg C m^{-2} for HW10. Yet, when integrating over the affected area, and since HW10 is about six times larger than HW03, the overall loss is much higher for HW10 (−125 Tg C) than for HW03 (−23 Tg C). In HW03, broad-leaved and mixed forests, as well as herbaceous were the ones with greater relative losses, of more than 0.30 kg C m^{-2} in absolute magnitude, although when integrating over the area, the main contributors to the total losses were broad-leaved forests (−6 Tg C), herbaceous (−7 Tg C) and cultivated and managed areas (−7 Tg C).

In the case of HW10, the relative losses are lower than in HW03, with broad-leaved forests being also the most affected land-cover type (−0.23 kg C m^{-2}), together with the other forest types. Forests are the largest contributors to the total losses (−45 Tg C), as BLd corresponds to −25 Tg C and ML to −20 Tg C of the total balance, yet, since cultivated and managed areas represent a large fraction of HW10, these areas also have a great contribution to the total losses (−36 Tg C).

BGD
10, 15879–15911, 2013

3.3 Climate drivers

Assessing whether the major decreases in PsN during summer were a direct response to the high temperatures registered during the heatwaves, requires a preliminary analysis of the spatial patterns of monthly PsN_{anom} fields during 2003 and 2010 (Figs. 4 and 5, respectively) and comparison with the corresponding climate patterns.

Western and Central Europe experienced low levels of productivity from the early beginning of 2003 (Fig. 4). In April, very low PsN_{anom} values were observed in the Balkans, but were followed by two months of enhanced productivity. In June a large area of PsN anomalies below $-0.2\,kg\,C\,m^{-2}$ formed over southern and central France (the region corresponding to HW03), which remained approximately stable during July. In August, PSN_{anom} below $-0.2\,kg\,C\,m^{-2}$ spread over most of western and central Europe. It is worth noting the strongly enhanced productivity observed in western Russia and some sectors of Eastern Europe during the summer, especially July and August, of 2003.

In 2010, more contrasting patterns were observed (Fig. 5). High productivity in May over most of western Russia and eastern Europe was then followed in June by PsN_{anom} values below $-0.2\,kg\,C\,m^{-2}$ on a very large region centered in western Russia, while throughout most of Europe high positive anomalies were observed. In July, the region with very low PsN_{anom} spread northwestwards affecting some parts of Scandinavia, UK and northern Germany and Poland. In August, the area of low PsN_{anom} values over western Russia was further enlarged southwards, while in many sectors of western and central Europe PsN was remarkably enhanced.

In order to identify which climate variables had a stronger impact on the described PsN anomalies, monthly fields of T_{anom}, P_{anom}, SD_{anom}, and SW_{anom} in both years were assessed. Figures 6 and 7 summarize results for spring and summer months (March to September) in 2003 and 2010, respectively, for T_{anom}, P_{anom}, $SW1_{anom}$ and $SW4_{anom}$.

The stronger PsN anomalies mentioned previously appear to closely match the periods with higher temperature anomalies (Figs. 6a and 7a). In particular, in April 2003 the

BGD
10, 15879–15911, 2013

Balkan region experienced temperatures 3–4 °C above average and in southern and central France temperatures reached anomalies higher than 4 °C in June and August of the same year (Fig. 6a). However, in July 2003, temperatures in this region were only about 1 °C above average, and still very low PsN anomalies persisted, suggesting that other factors may also be relevant to understand ecosystems' dynamics. Strong precipitation deficits were observed (Fig. 6b) throughout most of central and western Europe in 2003, especially in early spring (March) and all the summer months, where P_{anom} values below 50 mm month^{-1} were registered. These results for temperature and precipitation during the 2003 confirm those obtained previously (e.g. García-Herrera et al., 2010; Barriopedro et al., 2011). In fact, soil moisture deficits in top and deep layers (Fig. 6c and d) were observed in central Europe during spring and summer, particularly at the top layer (SW1), but were remarkably exacerbated between June and August. The soil moisture deficits in 2003 are in line with results obtained in previous works (e.g. Ferranti and Viterbo, 2006; Fischer et al., 2007).

In 2010, spring started with relatively cool or average temperature conditions (March and April) over most of Europe (Fig. 7a). However, in May, temperature anomalies of about 3–4 °C were registered over western Russia, persisting and further increasing during summer months (JJA). In particular, a very large extent around Moscow reached T_{anom} values over 5 °C for two consecutive months (JA). Cooler than average temperatures were generally observed over the rest of Europe, except during July, when positive T_{anom} values were registered practically over all regions. Precipitation patterns (Fig. 7b) are not as clear as in the case of 2003, although small precipitation deficits appear to have prevailed during spring in western Russia. In June and July, P_{anom} values below −50 mm month^{-1} were observed over western Russia, and also in northern Germany and Poland and the UK. These precipitation deficits are also reflected in SD_{anom} fields (not shown) which present negative anomalies during all winter and early spring in that region. In spring 2010, soil moisture fields are characterized by different dynamics on the top and deep layers. In March, in western Russia and Scandinavia, while on the top layer (Fig. 7c) $SW1_{anom}$ values above 4 % were regis-

BGD
10, 15879–15911, 2013

tered, in the deeper layer ($SW4_{anom}$, Fig. 7d), soil moisture was 1 % to 4 % lower than average. This enhancement of soil moisture on the top layer was possibly due to an earlier snowmelt in the beginning of spring (not shown), in accordance to Barriopedro et al. (2011). $SW4_{anom}$ dynamics in the rest of spring and summer follows $SW1_{anom}$ although with attenuation and an apparent lag of about a month, with SW1 achieving a prominent negative value in July and August while SW4 presents the (less intense) peak anomalies in August and September.

These results were summarized for the two selected regions HW03 and HW10 in Fig. 8, where the seasonal cycles of PsN vs. T, SW1 and SW4 during the heatwave year are compared to the respective climatological cycles (black curve). Generally, PsN increases with increasing T during winter and spring, peaking in late spring (region HW03) or early summer (region HW10). In the region HW10, the amplitude of the annual cycle of T is higher, and domant period appears clearly associated to those months with negative or very low T. Both areas are characterised by wet winters and dry summers, with soil water peaking at lower values in late summer. The region corresponding to HW10 is, in general, wetter than HW03 at both top and deep layers and presents higher seasonal variability of the annual cycle.

In HW03, the biggest departure from the climatological seasonal cycle in 2003 occurs during JJA with increasing temperature and remarkable SW1 deficits (Fig. 8a). In September, although temperature returns to average values, PsN is still below normal, matching the reduction still observed in soil moisture at the top and deeper layers. After October, PsN returns to normal values as well as T and SW1, while in SW4 large deficits still remain. The dynamics of HW10 during 2010 is very similar to the one described for HW03 (Fig. 8b), with the biggest departures of PsN from the climatological cycle being registered in summer months, with increased temperatures and reduced soil moisture in the top layer, especially during August.

The patterns suggest a differentiated response to high temperatures in distinct periods of the phenological cycle. For instance, in May 2010, very high temperature and relatively small moisture deficits (~ -1 %), are associated to an enhancement of PsN

(Figs. 2b and 5) in western Russia. Since May corresponds to the beginning of the phenological cycle (Figs. 2b and 3a), increased temperatures may increase photosynthesis rate (Nemani et al., 2003), provided that soil moisture deficits are not extreme.

In both years, the patterns observed in PsN dynamics (Figs. 4, 5 and 8) depend crucially on the evolution of temperature but also, to some extent, of soil moisture, particularly in the top layer (Figs. 6c, 7c and 8). The combination of high temperature with long-term precipitation deficits increases soil moisture depletion, producing a positive feedback that further enhances the heatwave intensity, as Seneviratne et al. (2006) and Hirschi et al. (2011) have shown.

The departure relative to the mean cycle, despite useful to understand the evolution of climate conditions during each year, does not provide sufficient insight about the relative impact of each variable in the ecosystems' response. Therefore, T_{anom} and SW1_{anom} during the heatwave years were compared to three year composites of the best years (high annual productivity) and worst years (low annual productivity), without considering the heatwave year for each region (Fig. 9). In the case of HW03, it is evident that the heatwave was associated to both temperature and soil moisture anomalies that fell well outside the corresponding worst years composite. In HW03, the composite for the best years is associated with temperatures above average during spring and below average during summer. Although the variability range in SW1 is not very pronounced, best years are related to soil moisture enhancement during summer. In 2003, T_{anom} was more than 3 °C above the corresponding values for the composite of the worst years while SW1_{anom} in July and August fell below the values in worst years by more than 2 %. In the case of HW10, T_{anom} was above the values for the worst years during most of the growing season, however SW1_{anom} values do not appear to fall far for the variability range of that region. In fact, during May and June the values are even higher than in the worst years. This difference in the results indicates different contributions of each variable to the extreme response of ecosystems during the heatwave. While in HW03, the extreme response of ecosystems appears to be driven by a combination of high temperatures and strong soil moisture deficits, in HW10, and despite soil

BGD
10, 15879–15911, 2013

moisture being lower than average, it was comparable to other low productivity years. Therefore, in the case of HW10, the extremely low productivity values observed during the heatwave event appear to be mostly due to the high temperatures registered.

4 Discussion and final remarks

The two outstanding heatwaves in 2003 and 2010 in Europe had a strong impact on the carbon balance of ecosystems at the monthly, seasonal and annual scale. Both events led to annual NPP anomalies of about $-0.2\,\mathrm{kg\,C\,m^{-2}\,yr^{-1}}$, although the 2010 event affected a much larger area. Since western Russia is a less productive region, the very low NPP anomalies in Western Europe in 2003 corresponded, thus, to only about 20 % of average NPP, while in Russia in 2010, NPP reductions of about 50 % were registered.

The high temperatures during summer months had significant impacts on the phenological cycle of vegetation in the affected areas in both years, as the major breaks in productivity were observed in those months corresponding to the most productive phases of the cycle. As a consequence, by the end of each year, the cumulative balance of PsN was remarkably reduced for both regions affecting all the main land-cover types. The impact of the 2010 heatwave in western Russia was slightly higher than the 2003 one in southern France in terms of departure of the reference mean and 10–90 % variability range, despite presenting lower absolute values. Broad-leaved forests were the land-cover types most severely impacted by the heatwaves in both regions, while cultivated and managed areas, especially those in Russia in 2010, were the ones presenting lower impacts, which may be due either to higher resistance of ecosystems or to human intervention. In terms of total cumulative losses, since cultivated and managed areas occupy a large extent of the considered regions, they imply a great contribution to the regional balance in both regions, together with forests, especially broad-leaved. Furthermore, the total cumulative $\mathrm{PsN_{anom}}$ in HW10 was substantially higher (-125 Tg C) than in HW03 (-23 Tg C), because a much larger extent was affected. The

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
BGD
10, 15879–15911, 2013
Impacts of 2003 and 2010 heatwaves in NPP
A. Bastos et al.

end-of-year values of NPP_{anom} (−19 Tg C for HW03 and −94 Tg C for HW10) are lower than the corresponding PsN_{anom}, which indicates a reduction in growth and woody respiration rates. These results are consistent with the reducion in plant respiration rates during the 2003 heatwave described by Ciais et al. (2005) and Reichstein et al. (2007).

Monthly PsN_{anom} fields show a clear decrease in productivity in summer months for both years, coinciding with the periods of higher temperature anomalies and lower soil moisture content, particularly at the top levels. In the case of Russia in 2010, soil moisture deficits during summer, despite being low, are not outside the range of variability during the study period.

The declines in PsN appear, thus, to be a response to heat (increased auto-trophic respiration) and water stress conditions promoted both by high temperatures and reduced soil water availability in all depths. Despite being clearly associated to the periods of the heatwave events (June/August 2003 and June to August in 2010), the large anomalies observed in PsN do not appear to be simply attributable to anomalous temperatures, particularly in the case of 2003 heatwave. It is particularly difficult to disentangle the effects of prolonged drought and extreme heat during summer since high temperatures and soil moisture deficits are coupled through a positive feedback (Seneviratne et al., 2006; Hirschi et al., 2011; Reichstein et al., 2013).

The comparison of the two events in 2003 and 2010 allows distinguishing different behaviours. While in 2003 the observed declines in PsN suggest a strong impact of the long drought preceding the heatwave, in 2010 extremely high temperatures appear to be the main factor leading to low PsN, since soil moisture anomalies are withing the range of variability over the period. This difference emphasizes the fact that an extreme climatic event (a heatwave) may lead to distinct responses of ecosystems (Reichstein et al., 2013), either because of the combined effect with other disturbance (e.g. drought) or the different ability of ecosystems to cope with extreme climate conditions.

BGD
10, 15879–15911, 2013

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BGD

10, 15879–15911, 2013

Impacts of 2003 and 2010 heatwaves in NPP

A. Bastos et al.

Table 1. Difference between total accumulated PsN during 2003 (HW03) and 2010 (HW10) for the main land-cover types in each region and the total area. Land-cover types are classified according to GLC2000 and correspond to: BLd broad-leaved deciduous; NLe needle-leaved evergreen; ML mixed leaved; H herbaceous; C/M cultivated/managed; mCS mosaic cropland and shrub.

		Total	BLd	NLe	ML	H	C/M	mCS
ΔPsN ($\mathrm{kg\,C\,m^{-2}}$)	HW03	−0.23	−0.32	−0.27	−0.31	−0.30	−0.16	−0.21
	HW10	−0.19	−0.27	−0.23	−0.22	−0.19	−0.18	−0.17
ΔPsN (Tg C)	HW03	−23	−6	−1	−1	−7	−7	−1
	HW10	−125	−25	−10	−20	−8	−36	−12
%	HW03	–	18.9	4.3	2.8	22.8	43.4	6.9
	HW10	–	14.8	6.9	14.9	6.4	30.1	10

BGD
10, 15879–15911, 2013

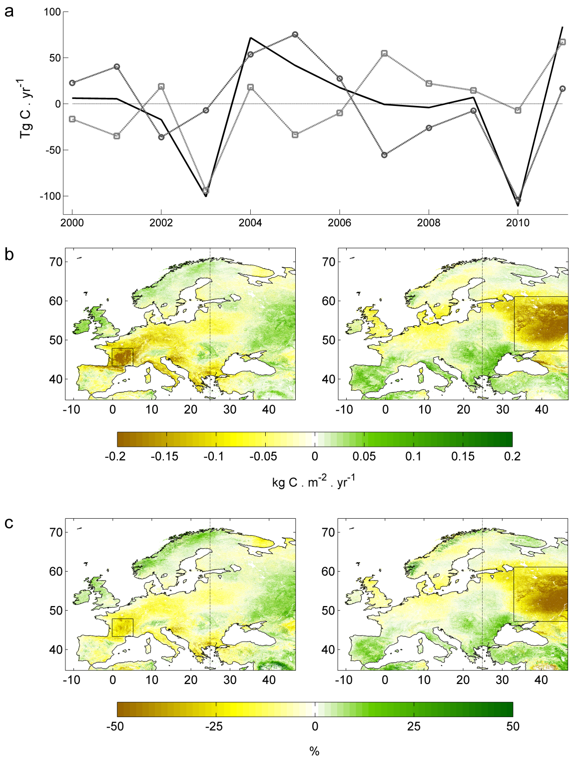

Fig. 1. Annual NPP anomalies over Europe: **(a)** integrated NPP anomaly between 2000 and 2011 for Europe (solid black), western Europe (light grey dashed, circles) and eastern Europe (dark grey dashed, squares); **(b)** NPP_{anom} fields for 2003 (left) and 2010 (right); NPP_{anom} expressed as percentage of mean NPP for 2003 (left) and 2010 (right). The dashed lines in **(b)** and **(c)** separate the western and eastern European sectors used to compute the time-series in **(a)**. The reference period 2000–2011 excluding each year (2003 or 2010), to avoid the bias effect on the average of the extremely low values registered during the heatwaves.

BGD
10, 15879–15911, 2013

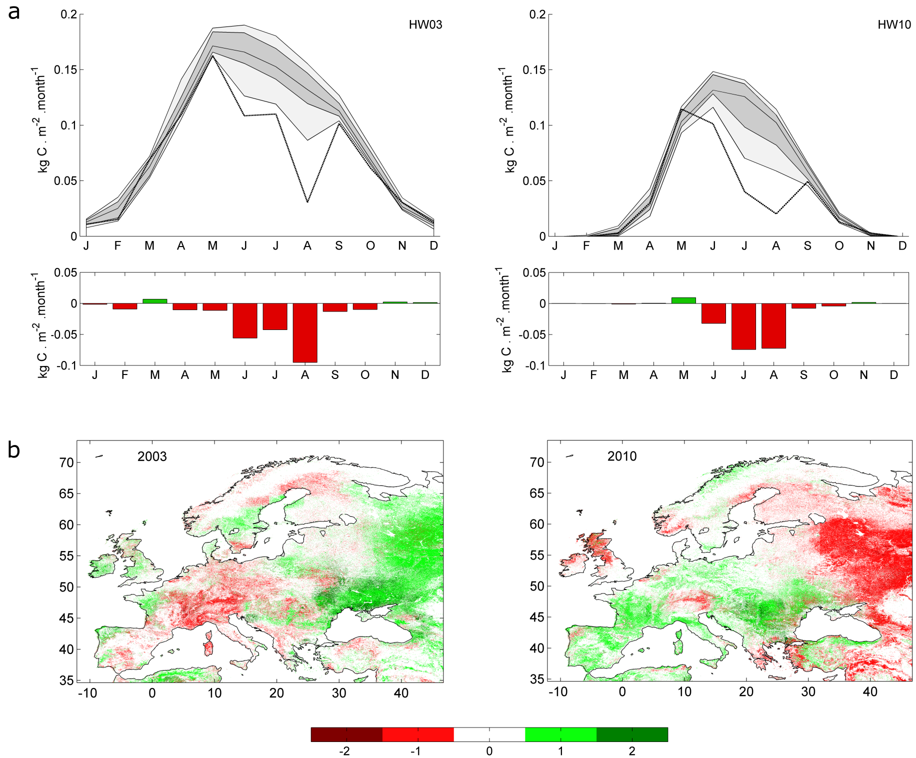

Fig. 2. (a) Climatology of the seasonal cycle of monthly PsN (shaded areas) for the reference period 2000–2011 averaged over the two selected regions HW03 (left) and HW10 (right). Light grey interval delimits the 10 % and 90 % percentiles; dark grey delimits the 25 % and 75 % percentiles; solid black line corresponds to the median. Dashed bold line corresponds to the seasonal cycle for the heatwave years, 2003 for HW03 and 2010 for HW10 and the corresponding seasonal anomalies are represented in the bottom panel. **(b)** Temporal difference in the peak of the seasonal cycle relative to the average peak month on the reference period 2000–2011 for 2003 (left) and 2010 (right).

BGD
10, 15879–15911, 2013

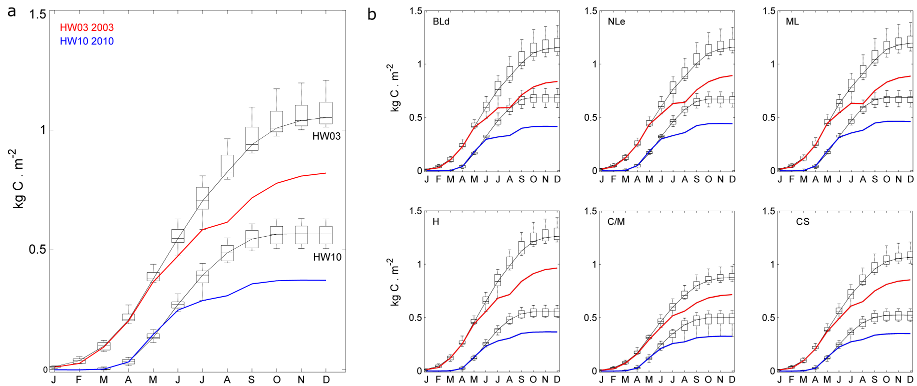

Fig. 3. (a) Accumulated monthly PsN climatology (box plots and black lines) for the two selected regions HW03 and HW10. Boxes represent the $\pm 0.5\sigma$ range and whiskers extend to the most extreme data that are not outliers. Accumulated monthly PsN for 2003 in region HW03 (red) and for 2010 in region HW10 (blue). **(b)** as in **(a)** but for each of the main land-cover types: BLd (broad-leaved deciduous), NLe (needle-leaved evergreen), ML (mixed-leaved), H (herbaceous), C/M (cultivated/managed areas), MCS (mosaic cropland and shrubland).

BGD
10, 15879–15911, 2013

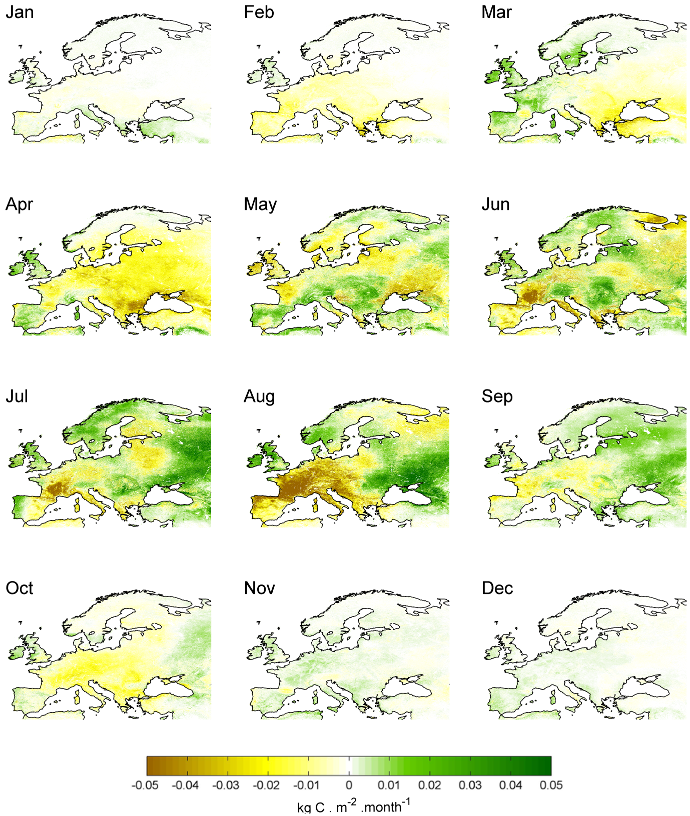

Fig. 4. Monthly PsN_{anom} fields during 2003.

BGD
10, 15879–15911, 2013

Impacts of 2003 and 2010 heatwaves in NPP

A. Bastos et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

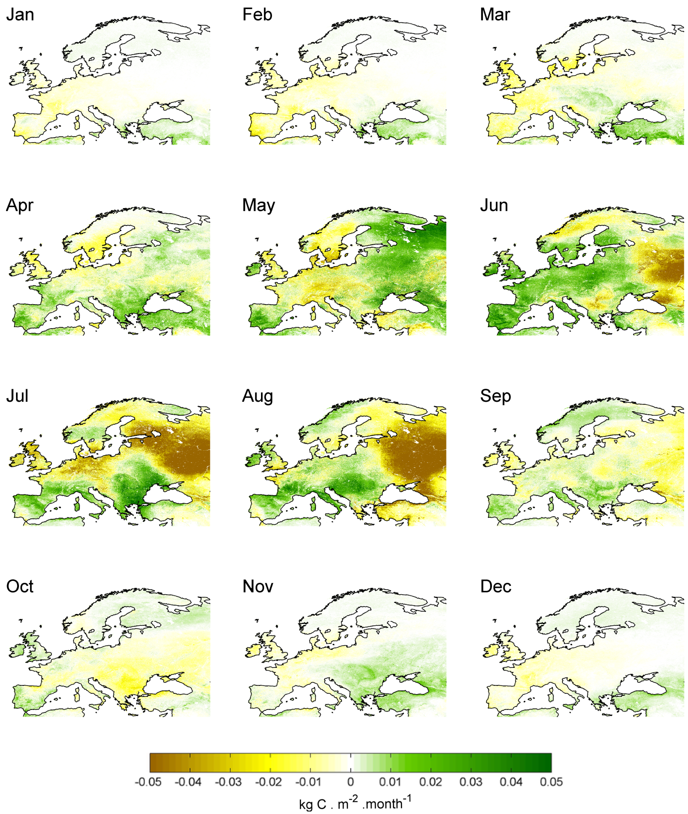

Fig. 5. Monthly PsN_{anom} fields during 2010.

BGD
10, 15879–15911, 2013

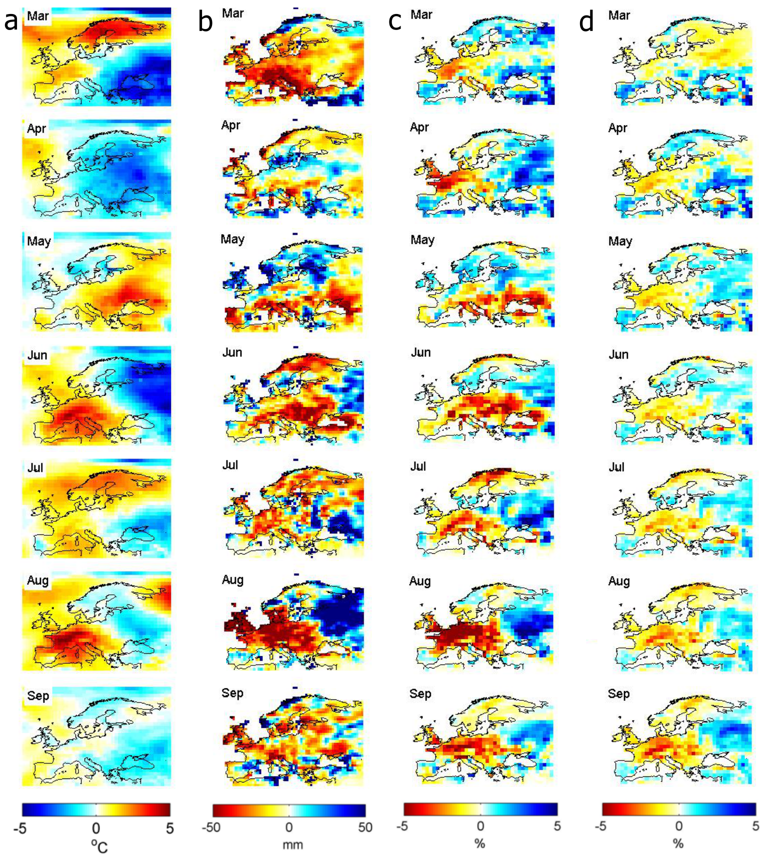

Fig. 6. Monthly climate anomalies over Europe during spring and summer 2003: **(a)** average temperature at 2 m (T_{anom}); **(b)** precipitation (P_{anom}); **(c)** volumetric soil water at level 1, 0–7 cm ($SW1_{anom}$) and **(d)** volumetric soil water at level 4, 100–289 cm ($SW4_{anom}$).

BGD
10, 15879–15911, 2013
Impacts of 2003 and 2010 heatwaves in NPP
A. Bastos et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

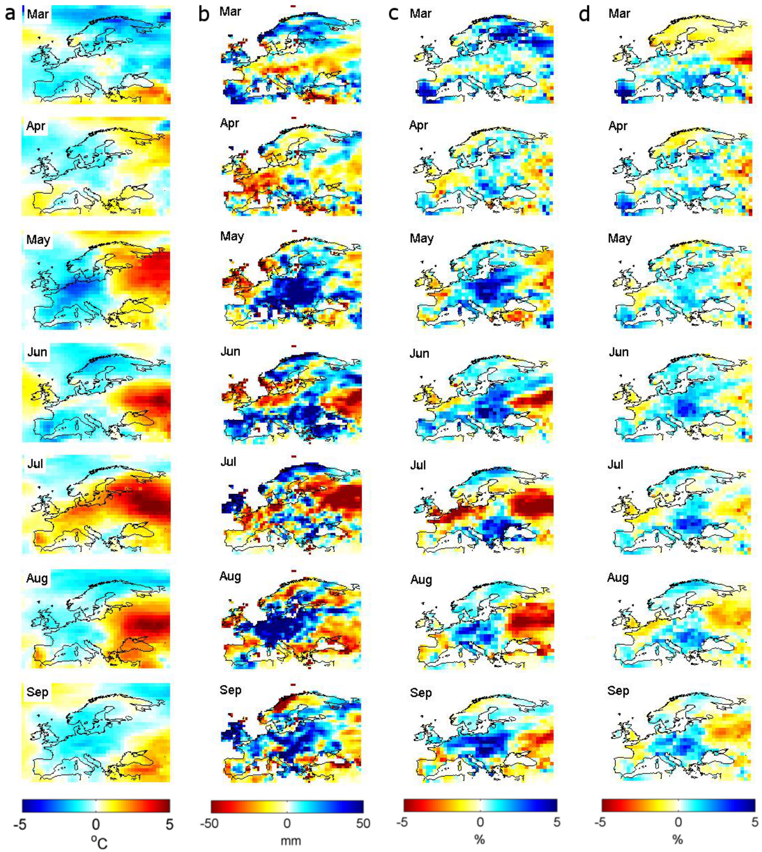

Fig. 7. As in Fig. 6, but for 2010.

BGD
10, 15879–15911, 2013

Impacts of 2003 and 2010 heatwaves in NPP

A. Bastos et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

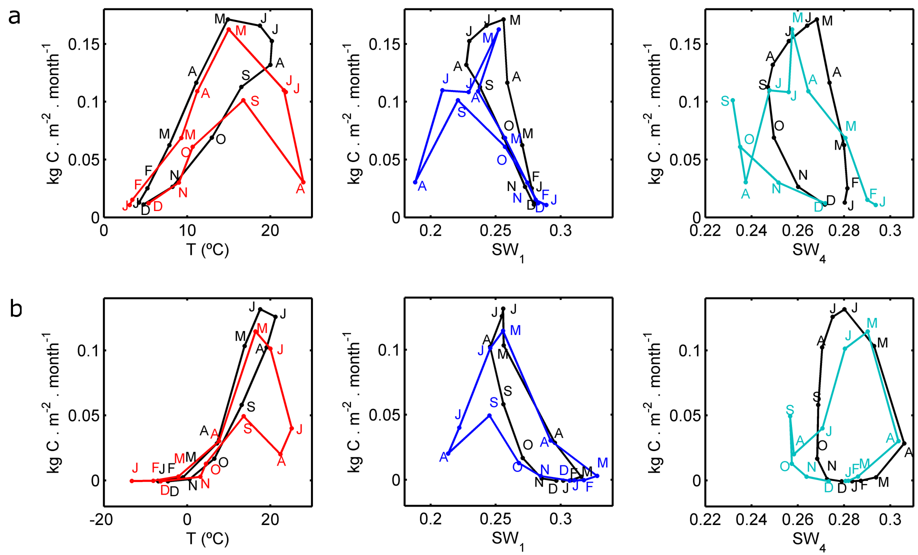

Fig. 8. Climatological seasonal cycle (black lines) and seasonal cycle on the heatwave year (coloured lines) of T (left panel, red lines), SW1 (central panel, blue lines) and SW4 (right panel, cyan lines), for **(a)** HW03, heatwave year 2003 and **(b)** HW10, heatwave year 2010.

BGD
10, 15879–15911, 2013

Impacts of 2003 and 2010 heatwaves in NPP

A. Bastos et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

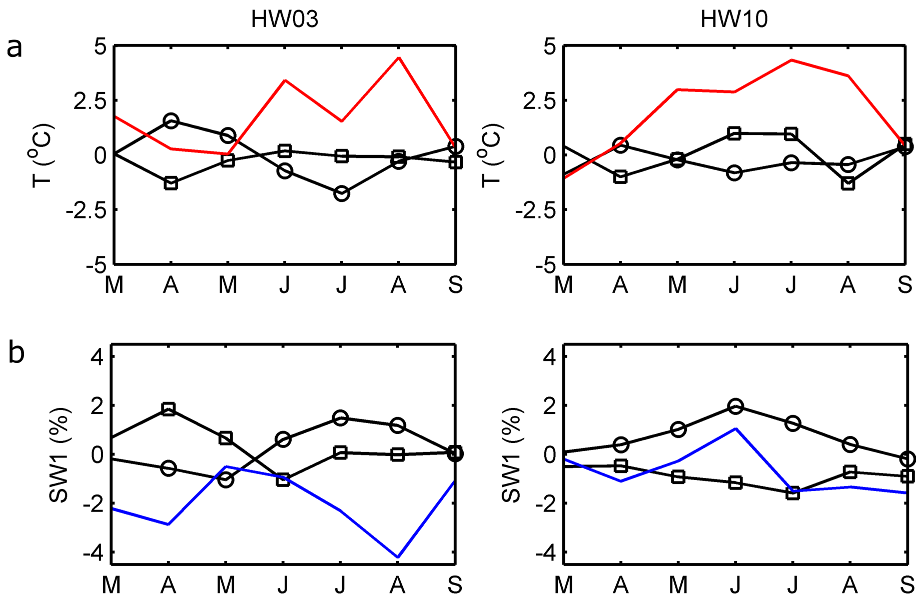

Fig. 9. Monthly values from March to September of **(a)** T_{anom}, **(b)** P_{anom}, **(c)** $SW1_{anom}$, averaged over each region for: composites of best years (black line, circles), worse years (black line, squares), and 2003 (HW03, color lines, left panel) or 2010 (HW10, color lines, right panel). For HW03 the high (low) years are 2000/2007/2011 (2001/2004/2005) and for HW10 the high (low) years are 2001/2004/2005 (2002/2009/2011).

BGD
10, 15879–15911, 2013

Impacts of 2003 and 2010 heatwaves in NPP

A. Bastos et al.